

# Recent Trends

## in Charged Particle Optics and Surface Physics Instrumentation

Proceedings  
of the 8<sup>th</sup> International Seminar,  
held in Skalský dvůr near Brno, Czech Republic,  
from July 8 to 12, 2002,  
organised by  
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Edited by Luděk Frank

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## SCHEDULE

### OF THE SEMINAR SESSIONS / ROUND TABLE DISCUSSIONS

#### Tuesday July 9

- 09.30            **Computations for electron optics I**  
(moderated by E. Munro, F. Read)
- 11.30            **Computations for electron optics II**  
(moderated by P. Hawkes, B. Lencová)
- 14.30            **E-beams in semiconductor diagnostics and production**  
(moderated by M. Mankos, R. Spehr, I. Müllerová, L. Frank)
- 16.30            **Poster session**  
(moderated by P. Hawkes, H. Rose, G. Schönhense)

#### Wednesday July 10

- 09.30            **Electron fundamentals**  
(moderated by F. Hasselbach, P. Sonnentag, H. Wittels)
- 11.30            **Environmental SEM, cathodoluminescence in SEM**  
(moderated by J. Jiráček, V. Romanovský, P. Schauer)

#### Thursday July 11

- 09.30            **Correction of aberrations**  
(moderated by H. Rose, F. Read, G. Schönhense)
- 11.30            **Future of design and use of the (low voltage) TEM**  
(moderated by A. Delong, V. Kolařík)
- 14.30            **Permanent magnet optics and non-traditional objective lenses for SEM**  
(moderated by B. Lencová, A. Kursheed, A. Delong)
- 16.30            **Photoemission electron microscopy**  
(moderated by G. Schönhense, M. Escher, G. Marx)

## PREFACE

It is not easy, but hopefully also not necessary, to adopt always a fully new approach to the preface when it opens new volume of a series of proceedings from regularly organised meetings. This Seminar on Recent Trends in Charged Particle Optics and Surface Physics Instrumentation is already the eighth in sequence. But there might be somebody not having had heard about the meeting so that the history could be briefly summarized once again. The germ was the traditional summer seminar held in the Institute of Scientific Instruments in Brno on the occasion of visits of Professor Tom Mulvey from University of Aston in Birmingham. His presence justified the seminar English spoken and he always excellently fulfilled his role of moderator and commentator. In anticipation of historical movements we started to extend the participation already in summer 1989. That time five foreign guests attended the meeting still taking place in the Institute's library. In 1990, there were as many as 30 participants from 5 countries. The third seminar in 1992 was moved to hotel Skalský dvůr in Bohemian-Moravian Highlands where it repeats since that time. Traditionally about forty or fifty people were present and the meeting schedule has stabilised.

The fifth seminar was the first one to which the proceedings were published. The proceedings of the sixth seminar appeared technically a bit better but nothing at all was published from the next meeting in 2000. This took place immediately after the 12<sup>th</sup> European Congress on Electron Microscopy in Brno and the organisers hesitated to force the participants into writing one more text about (most probably) a similar topic. So this brochure should resemble that from 1998 and we hope for additional in future, always better and better but suggesting the tradition by their consistent design.

The set of up to ten topics, which fill the seminar time of five half-days, has been variously composed of issues from electron optics and surface examination and often the second part of the heading was less present. The same is true this time but still the surface methods are not only present but even start to penetrate new regions like the semiconductor processing and examination, progressively more surface sensitive at growing device integration.

One cannot overlook certain crisis developing itself in attendance at scientific congresses and conferences. The meetings seem to be too many and, thanks to powerful tools for electronic communication, people seem to be less willing to travel. We are repeatedly a bit afraid and at least curious whether this trend is going to impact on us as well. Again not – when looking onto the list of participants one can only be happy in having opportunity to be there.

From its beginnings, the seminar is claimed to be a meeting devoted more to putting questions not answered yet than to reporting results. This spirit usually does not really dominate in introductory presentations and posters but used to be remarkable in discussions. Let us looking forward to impulses that will arise this time from hours spent in well-known hall the door of which opens to the lakeside.

I would like to thank in advance to all who contributed to the eighth Recent Trends in any respect.

Luděk Frank

## CONTENTS

|                                                                                                                                                                              |    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| SIMULATION OF ELECTRON OPTICAL SYSTEMS BY DIRECT RAY-TRACING THROUGH ANALYTICALLY FITTED FIELDS<br>Eric Munro                                                                | 7  |
| ACCURATE CALCULATION OF BOERSCH ENERGY SPREADING<br>F. H. Read and N. J. Bowring                                                                                             | 11 |
| ACCURACY OF POTENTIAL COMPUTATIONS WITH FOFEM<br>Bohumila Lencová                                                                                                            | 13 |
| IS THIS BEM USEFUL FOR THE COMPUTATION OF MAGNETIC LENSES?<br>Bohumila Lencová                                                                                               | 15 |
| MISALIGNMENT ABERRATIONS<br>David Dvořák                                                                                                                                     | 17 |
| CALCULATION OF THE BEAM PROFILE<br>Martin Oral                                                                                                                               | 19 |
| CATHODE OBJECTIVE LENSES IN HIGH THROUGHPUT APPLICATIONS<br>M. Mankos and D. Adler                                                                                           | 21 |
| SECONDARY ELECTRON CONTRAST OF DOPED REGIONS IN SEMICONDUCTOR – A MATTER OF SURFACE TREATMENT?<br>L. Frank, I. Müllerová and M. M. El-Gomati                                 | 25 |
| DESIGN AND SIMULATION OF A MINIATURISED ELECTROSTATIC COLUMN FOR HIGH PROBE CURRENT<br>S. Schubert, R.Y. Lutsch, M. Rauscher, D. Winkler and E. Plies                        | 27 |
| SCANNING UNIT WITH PRINTED CIRCUIT SADDLE COIL FOR RESOLUTION MEASUREMENT IN A MINIATURISED ELECTROSTATIC LENS SYSTEM<br>M. Rauscher, R. Y. Lutsch, S. Schubert and E. Plies | 29 |
| THE PARALLEL CYLINDRICAL MIRROR ANALYZER<br>F. H. Read, D. Cubric, S. Kumisharo and A. Walker                                                                                | 32 |
| FULLY ELECTROSTATIC LOW ENERGY SCANNING ELECTRON COLUMN<br>V. Romanovský, M. M. El-Gomati, L. Frank and I. Müllerová                                                         | 33 |

|                                                                                                        |    |
|--------------------------------------------------------------------------------------------------------|----|
| AN ULTRAHIGH VACUUM SCANNING LOW ENERGY ELECTRON<br>MICROSCOPE FOR SURFACE STUDIES                     | 35 |
| I. Müllerová and L. Frank                                                                              |    |
| ACQUISITION OF MULTI-DIMENSIONAL IMAGE IN THE SCANNING<br>ELECTRON MICROSCOPE                          | 37 |
| Miroslav Horáček                                                                                       |    |
| EXPERIMENTAL VERIFICATION OF ANTICORRELATIONS IN A BEAM OF<br>FREE ELECTRONS ('ELECTRON ANTIBUNCHING') | 39 |
| H. Kiesel, A. Renz and F. Hasselbach                                                                   |    |
| THE WIEN FILTER, WHICH-PATH INFORMATION, AND DECOHERENCE                                               | 41 |
| P. Sonnentag and F. Hasselbach                                                                         |    |
| DEVELOPMENT AND TEST OF A POLARIZED COOLED ELECTRON GUN                                                | 45 |
| H. Wittel and F. Hasselbach                                                                            |    |
| IMPROVEMENT OF SINGLE CRYSTAL SCINTILLATOR PROPERTIES<br>IN SEM DETECTORS                              | 47 |
| R. Aufrata and P. Schauer                                                                              |    |
| COMBINED DETECTOR FOR BSE, SE AND BSE+SE DETECTION IN A LOW<br>VOLTAGE SEM                             | 49 |
| R. Aufrata, J. Jiráček, V. Romanovský and J. Špinka                                                    |    |
| X-RAY MICROANALYSIS IN ESEM AND LV SEM                                                                 | 51 |
| R. Aufrata, J. Jiráček and J. Špinka                                                                   |    |
| DETECTION OF SIGNAL ELECTRONS AT HIGHER PRESSURE IN THE<br>SPECIMEN CHAMBER                            | 55 |
| J. Jiráček, R. Aufrata and J. Špinka                                                                   |    |
| INFLUENCE OF SIZE OF IONIZATION DETECTOR ELECTRODE SYSTEM<br>ON SIGNAL DETECTION IN ESEM               | 57 |
| L. Schneider and J. Jiráček                                                                            |    |
| INFLUENCE OF PRIMARY ELECTRON ENERGY ON SIGNAL<br>DETECTED IN ESEM                                     | 61 |
| Radek Drnovský                                                                                         |    |
| INFLUENCE OF THE GAS USED ON AMPLIFICATION OF SIGNALS<br>IN ENVIRONMENTAL SEM                          | 63 |
| V. Romanovský, V. Neděla and R. Aufrata                                                                |    |

|                                                                                                                                                                                                                                                    |    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| DISPERSION AND DETECTION OF SIGNAL ELECTRONS<br>IN ENVIRONMENTAL SEM<br>V. Romanovský, V. Neděla and O. Hutaf                                                                                                                                      | 65 |
| CATHODOLUMINESCENCE SPECTRA MEASUREMENT<br>P. Schauer and R. Aufrata                                                                                                                                                                               | 67 |
| CHROMATIC AND SPHERICAL ABERRATION CORRECTION USING TIME<br>-DEPENDENT ACCELERATION AND LENS FIELDS<br>G. Schönhense and H. Spiecker                                                                                                               | 71 |
| COMPUTER SIMULATION OF AN ELECTROSTATIC ABERRATION<br>CORRECTOR FOR A LOW-VOLTAGE SCANNING ELECTRON MICROSCOPE<br>L. A. Baranova, F. H. Read and D. Cubric                                                                                         | 74 |
| MORE USER-FRIENDLY ELECTRON MICROSCOPES<br>A. Delong and V. Kolařík                                                                                                                                                                                | 75 |
| SCANNING MODES IN LOW VOLTAGE TEM<br>P. Štěpán and E. Coufalová                                                                                                                                                                                    | 81 |
| PERMANENT MAGNET LENS ATTACHMENTS FOR THE SEM<br>Anjam Khursheed                                                                                                                                                                                   | 83 |
| IMAGING SUB-NANOSECOND PROCESSES USING PHOTOEMISSION<br>ELECTRON MICROSCOPY<br>G. Schönhense, A. Oelsner, A. Krasnyuk, C. M. Schneider, M. Bauer and<br>M. Aeschlimann                                                                             | 87 |
| RECENT RESULTS WITH ENERGY FILTERED PEEM USING A RETARDING<br>FIELD ANALYSER: IMAGING OF FIELD-EMITTER ARRAYS, XPS- AND<br>UPS- PHOTOELECTRONS<br>M. Escher, M. Merkel, Ch. Ziethen, P. Bernhard, G. Schönhense,<br>D. Funnemann and J. Westermann | 91 |
| PHOTOEMISSION ELECTRON MICROSCOPY AND MAGNETO-OPTICAL<br>KERR EFFECT: A COMPARISON OF PROBING DEPTHS<br>G. K. L. Marx and R. Allenspach                                                                                                            | 93 |
| OPTIMISATION OF AN ELECTROSTATIC TETRODE OBJECTIVE<br>FOR XPEEM<br>M. Escher, M. Merkel and G. Schönhense                                                                                                                                          | 95 |

# SIMULATION OF ELECTRON OPTICAL SYSTEMS BY DIRECT RAY-TRACING THROUGH ANALYTICALLY FITTED FIELDS

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## 1. Introduction – Concept and Advantages of Direct Ray-Tracing

For simulation of electron and ion beam systems, *direct ray-tracing* offers an attractive alternative to the more conventional method of paraxial ray-tracing and aberration integrals. Direct ray-tracing is similar in concept to methods used in conventional light optical design, and it offers great conceptual simplicity, generality and robustness. In order to make direct ray-tracing work successfully in electron optics, the key requirement is to obtain sufficiently accurate and self-consistent values of the electric and magnetic fields in the lenses and deflectors, for the ray-tracing to be accurate and meaningful. This is achieved in the present work by representing the field distributions analytically using series of *Hermite functions*.

Direct ray-tracing in electron optics has several key advantages. Entire bunches of particles can be ray-traced simultaneously, so Coulomb interaction effects can easily be simulated. Multipole lenses can be handled as easily as round lenses. Higher-rank aberrations are handled automatically. Trajectories are computed as functions of time, without restrictions on ray slopes or directions, so cathode lenses, electron mirrors, ion traps, etc, are handled straightforwardly, without special treatments. Effects of asymmetry errors, which simply introduce additional parasitic multipole field components, can easily be evaluated. In the following sections, the method is summarized and an illustrative example is presented.

## 2. Analytic Representation of the Electric and Magnetic Fields Using Hermite Series

The electric and magnetic fields of each optical element can in general be expressed as a sum of round lens fields plus multipole components, each of which are characterized by a set of *axial field functions* (round lens, dipole, quadrupole, hexapole field function, etc.). The axial field functions for each optical element are first computed numerically at discrete points along the optical axis, using any convenient numerical method. For example, Figure 1(a) and 1(b) shows an electrostatic octopole lens, excited as a quadrupole, and Figure 1(c) shows the quadrupole field function, computed using a 3D finite difference method.

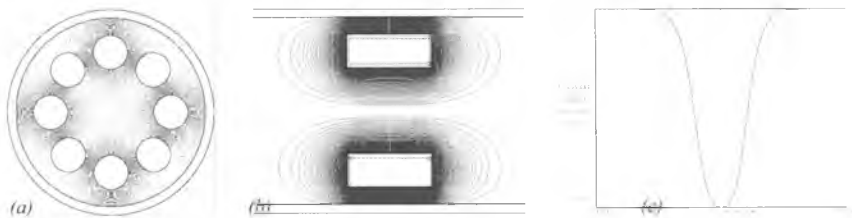


Figure 1: (a) An octopole lens excited as a quadrupole; (b) Side view; (c) Computed quadrupole field function.

Each axial field function (such as that in Figure 1(c)) is now fitted with an *exact analytic function*, using a series of *Hermite basis functions*. The Hermite functions are defined as:

$$h_n(x) = \frac{1}{\sqrt{\pi 2^n n!}} H_n(x) \exp\left(-\frac{1}{2}x^2\right), \quad \text{for } n = 0, 1, 2, \dots \quad (1)$$

where  $H_n(x)$  is the *Hermite polynomial of degree n*. The Hermite functions form a complete set of basis functions, which are both orthogonal and normalized (so-called "orthonormal"):

$$\int_{-\infty}^{+\infty} h_m(x) h_n(x) dx = \begin{cases} 0 & (m \neq n) \\ 1 & (m = n) \end{cases} \quad (2)$$

The high-order functions can be computed rapidly using the following recursion formulas:

$$h_0(x) = \pi^{-0.25} \exp\left(-\frac{1}{2}x^2\right), \quad h_1(x) = \sqrt{2} x h_0(x), \quad h_i(x) = \{\sqrt{2} x h_{i-1}(x) - \sqrt{i-1} h_{i-2}(x)\} / \sqrt{i} \quad (3)$$

Graphs of the first eight Hermite basis functions,  $h_0(x) - h_7(x)$ , are shown in Figure 2.

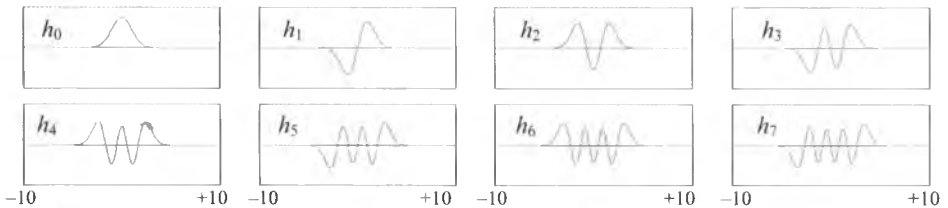


Figure 2: Graphs of the first eight Hermite basis functions. (Horizontal range  $\pm 10$ , Vertical range  $\pm 2$ ).

It can be seen that these Hermite basis functions are analogous to the basis functions of a Fourier series, except that they all go to zero at large axial distances. This property makes them ideal for fitting axial field functions, which generally have a finite axial extent. To fit an axial field function,  $Q(z)$ , (see Figure 3), we first define a dimensionless variable,  $x$ :

$$x = \frac{z - z_c}{a} \quad (4)$$

as a normalized measure of the axial position  $z$ , where  $z_c$  is an axial coordinate chosen near the central peak of the field and  $a$  is a representative measure of its half-width.

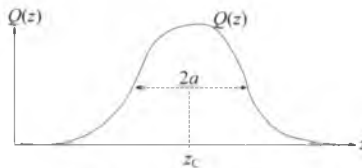


Figure 3: A numerically computed axial field function,  $Q(z)$ .

We then fit the function  $Q(z)$  using  $M$  terms of the Hermite series basis set, thus:

$$f(x) = \sum_{m=0}^M C_m h_m(x) \quad (5)$$

The coefficients,  $C_m$ , are calculated using the formula:

$$C_m = \int_{-\infty}^{+\infty} Q(x) h_m(x) dx \quad (6)$$

The more terms taken in the fit (i.e. the larger the value of  $M$ ), the closer the agreement between the computed function and fitted function. Many axial functions can be fitted closely

with relatively few terms of the series. This is shown in Figure 4, where the axial function of Figure 1 is fitted with an increasing number of terms of the Hermite basis set. In this example, a good fit is obtained with  $M = 8$ .



Figure 4: Fitting the axial function of Figure 1 using increasing numbers of Hermite basis functions.

In this way, each axial function is represented by an *exact analytic function*. Since these functions are also analytically differentiable, the fields at any off-axis point can now be computed to arbitrary precision by power series expansions. The resulting fields are exact solutions of Laplace’s equation at every point, and are ideal for use in direct ray-tracing.

3. Accurate Direct Ray-Tracing, Including the Effects of Discrete Coulomb Interactions

Direct ray-tracing through these analytic fields is performed using a fifth-order Runge-Kutta method, with adaptive step size error control. A self-consistency of order of 1 picometre over an axial range of 1 metre can easily be achieved. This accuracy is ample for use as an electron optical simulation and design tool. Electron trajectories are computed with time as independent variable, so cathode lenses and electron mirrors can be handled as easily as ordinary lenses, and aberrations of all orders are automatically included in the simulation. Complete bunches of particles can be ray-traced simultaneously. For complete bunches, by adding the inter-particle fields (Figure 5) to the external fields, the combined effects of Coulomb interactions and lens aberrations can be simulated in a consistent and rigorous way. The Coulomb forces can be computed, on each time step, using a hierarchical tree code algorithm, that computes the forces between  $N$  particles in a time proportional to  $N \log_2 N$ . Spot diagrams of the blur and distortion at the final image plane can be plotted out (Figure 6).

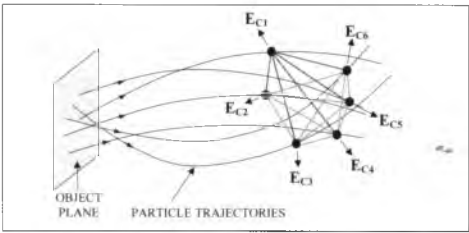


Figure 5: Direct ray-trace for a bunch of particles, including electric fields  $E_{C_i}$  due to the Coulomb interactions.

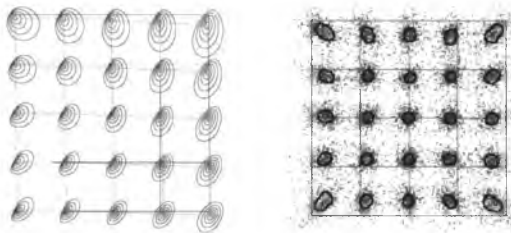


Figure 6: Spot diagrams with (a) Systematic initial conditions; (b) Random initial conditions.

#### 4. Illustrative Example

Figure 7 shows illustrative results for a multipole imaging system, containing four quadrupole lenses, with a beam energy of 10 keV, imaging a 5  $\mu\text{m}$  square spot with a beam half-angle of 2 mrad. Figure 7(a) shows the spot shape at the image plane, and Figure 7(b) shows histograms of the particle deviations and rise distances in  $x$  and  $y$ , at a negligibly small beam current. Figure 7(c) and 7(d) show corresponding results for a beam current of 500 nA, taking Coulomb interactions into account. Figure 7(e) and 7(f) show results at the same current of 500 nA, with a 100  $\mu\text{m}$   $x$ -misalignment of one of the multipole electrodes; this final example thus shows the combined effect of Coulomb interactions and electrode asymmetries.

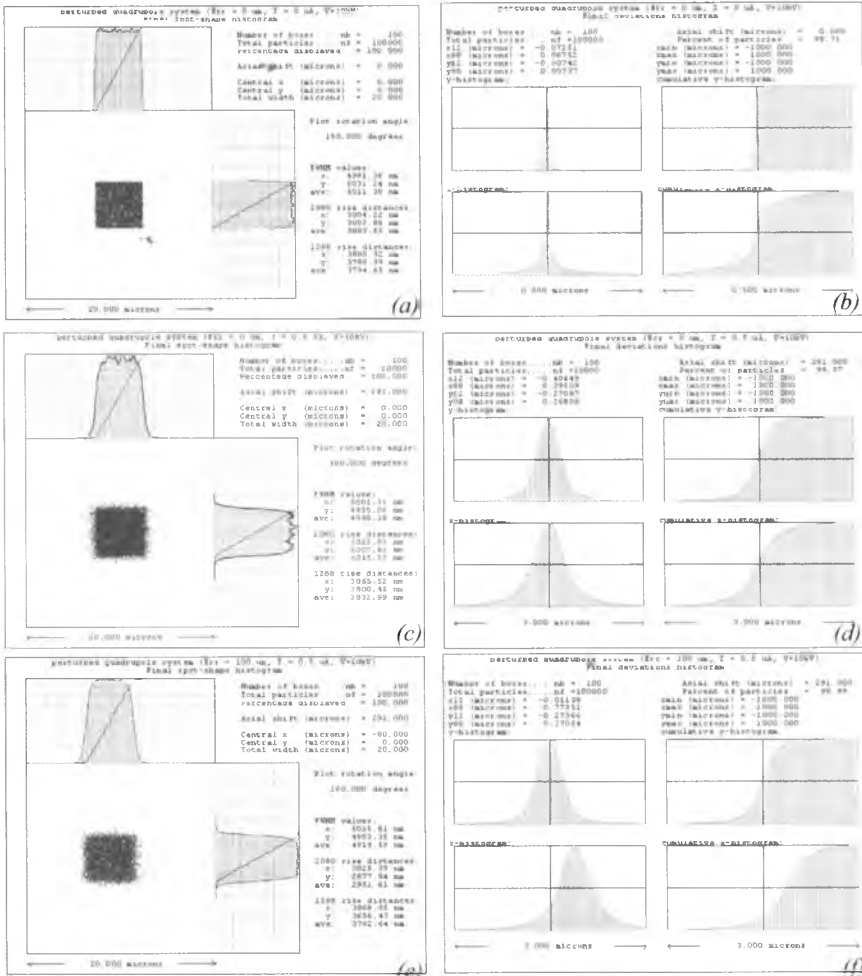


Figure 7: Results for a system of four quadrupole lenses. (a) Spot diagram at image plane and (b) Deviations histograms at image plane, at low beam current. (c) and (d) Corresponding results at 500 nA current. (e) and (f) Corresponding results at 500 nA beam current, with 100  $\mu\text{m}$   $x$ -misalignment of one electrode.

## ACCURATE CALCULATION OF BOERSCH ENERGY SPREADING

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The effects of stochastic electron-electron interactions in beams have been the subject of many theoretical and computational studies (see for example the reviews [1-3]). Many different approximations have been used. In the present study we have tried to avoid all approximations, except the uncertainties that are inherent in a computational Monte-Carlo calculation. As a first example we have applied our technique to the energy spreading in a converging round beam, first studied carefully by Loeffler [4].

The strategy that we use is as follows:

- (1) A converging beam with the required angle of convergence and waist diameter is simulated using a large number  $N$  of randomly selected trajectories. At a later stage of the strategy the number  $N$  will be extrapolated to infinity (using a power series in  $1/N$ ). The beam exists for a distance  $s$  on either side of the waist. This distance will later be extrapolated to infinity.
- (2) Each trajectory in the beam is integrated in small steps (the length of which will later be extrapolated to zero) using a specially developed computer program that automatically takes account of collective (i.e. non-stochastic) space-charge spreading.
- (3) At each step of each trajectory the average velocity is taken as the velocity of an electron  $e_1$  that might be coulomb scattered by the other electrons in the beam.
- (4) The program searches for the nearest other trajectory and uses its velocity as a representative velocity for the nearest electron  $e_2$  in the beam.
- (5) The velocities of  $e_1$  and  $e_2$  are used to establish their relative velocity  $u_{rel}$  in the centre of mass system and then the duration  $dt$  of the step is used to define a path length  $l = u_{rel}dt$ .
- (6) Using the fact that the transverse spatial probability distribution of the electrons is an invertible distribution [5] it can be shown that the transverse distance  $r$  to the nearest electron is given by

$$r = (-\ln(1-R)/\pi nl)^{1/2}$$

where  $R$  is a random number from 0 to 1 and  $n$  is the density of electrons in the beam.

- (7) The angle  $\theta$  by which electron  $e_1$  is scattered is then given by the well-known expression for the Rutherford scattering of a non-relativistic particle

$$\tan(\theta/2) = K/(mbu_{rel}^2)$$

where the effective impact parameter  $b$  is  $r/2$  and the effective force constant  $K$  is  $e^2/4\pi\epsilon_0$ .

- (8) The angle  $\theta$  and a random scattering angle  $\varphi$  about the direction  $u_{rel}$  are then used to find the velocity of the scattered electron  $e_l$  in the centre of mass system and hence its new direction and energy in the laboratory system.
- (9) The changes in the velocity of electron  $e_l$  at each step are added sequentially to give its final direction, position and energy.
- (10) After carrying out stages (3) to (9) for all the trajectories the properties of the final beam are characterized in terms of energy and spatial spreading.
- (11) The input parameters are varied so that the results can be extrapolated as mentioned above.

The results obtained for the energy spreading in the system defined by by Loeffler [4] and treated more carefully and accurately by Rose and Spehr [1] will be presented at the conference.

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- [4] K.H. Loeffler, Z. f. Ang. Phys. **27** (1969) 145.
- [5] A.L. Garcia: Numerical Methods for Physics, 2nd ed. Prentice Hall, New Jersey 2000.

## ACCURACY OF POTENTIAL COMPUTATIONS WITH FOFEM

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The first order finite element method (FOFEM) is often used for electron optical computations because of its ability to handle local dependence of material properties and complicated geometry of the electron optical elements. We use a topologically regular mesh based on irregular quadrilaterals. In order to avoid local computation error, we prefer to use meshes with a smoothly graded mesh step. It is possible to obtain accurate solution of most 2D problems that arise in electron optics [1-3]. In order to give an idea of computation speed with the FOFEM, in a mesh with 200000 points we can obtain the potential distribution in less than 1 minute on a 1 GHz PC. The previously used mesh sizes had mostly a few thousand points; such a computation needs just a fraction of a second. For meshes with  $n$  points in the radial direction and  $m$  points in the  $z$  direction the computation time is proportional to  $n^2m$ . The computation needs below 32 MB RAM. An important practical aspect of each computation program is the user interface. Our standard user interface is a DOS program used since 1990 [4].

We have shown that the potential of multipole fields (magnetic deflectors and multipoles made of saddle and toroidal coils in the presence of rotationally symmetric magnetic materials and electrostatic multipoles defined on cut cylindrical surfaces) are obtained with more than sufficient accuracy for all needs in electron optics [1]. It would be nice to know also the accuracy of the results of the rotationally symmetric lenses. Because of the short computation times and low memory requirements we have introduced a simple and practical method of the estimate of accuracy of the computed potential. The advantage of this method is that it provides an estimate of the error at every point of the mesh for given electrostatic or magnetic lens. In the past the accuracy has been estimated only for points lying on the optical axis [5] (except for [6]). The axial values do not help in identifying the sources of errors. For this we need the display of error in two dimensions. These errors can be quite small, and so it is mostly impossible to identify them from the display of equipotentials. If we manage to produce equipotentials of the error of the potential, we can identify sources of these errors or we can try to find a procedure how to get rid of them. In order to obtain a difference of potential computed in two different fine meshes, even in the same coarse mesh, we would require an accurate 2D interpolation in the potential in a finer mesh to get potential at all points of the lower density mesh. Even if we have such a method, the ZRP method [6], at our disposal, such computations would be time consuming.

We have managed to apply a method that is just a simple extension of the existing software package. It is based on comparing the results of the computation with a given mesh and with another fine mesh using twice the number of mesh points in each direction in such a way that the points existing in the lower density mesh are present also in the finer mesh – so it is possible to compare the values of potential obtained at the points of the lower density mesh. The number of points is easy to double if we use constant mesh step but also if we use a graded mesh. The difference of the potential at each mesh point of the lower density mesh gives an estimate of the computation error, and so we can easily visualize the sources of errors, if we display this potential difference in the same way as we display the equipotentials. Even if we cannot display the equipotentials of the FEM computations in meshes with more

than 200000 mesh points with the current interface program, the "error potential" can be displayed because is known only at the points of the lower density mesh.

The advantage of this method is that the modifications of the computation part of program package are actually very small. If we select the option with accuracy test, standard computation is performed first in given mesh and the potential at the mesh points and potential and field on the axis are stored. Then the computation with two times denser mesh in each direction is done, and the new additional output file contains just the difference of the new potential at the points of the coarser mesh and the one computed before. We can then display this difference with the same user interface. We also make the output file with the difference of the axial potential, for electrostatic lenses also the difference in field on the axis. Because the memory requirements are proportional to the number of points, we need about 128 MB RAM for the computation with 800000 mesh points. However, 256 MB RAM is fairly standard for 32-bit Windows. The computation time with the largest mesh is around 6 minutes. We do not suppose that such an analysis will be performed for every data set, although we stress again that the computation time with meshes containing the maximum number of points of close to a million points are short enough.

As described above, we get as an error the difference of the computation in the mesh with a typical step  $h$  and another one with the step  $h/2$ . However, we want to know how large is the error of the given computation with step  $h$ , i.e. the difference from the given computation from that with an infinite number of points [7]. The answer depends on the character of the error, which we can obtain from another computation with step  $h/4$ , or, if the mesh would be too large, we can use a mesh with step  $2h$ . If the difference between the computation with step  $h$  and  $h/2$  has the character of the error proportional to  $h^n$ , then the actual error is rather equal to  $2^n / (2^n - 1)$ , i.e. for quadratic dependence ( $n=2$ ) it should be multiplied by a factor  $4/3$ , for  $n=1$  (linear dependence) by a factor of 2, for  $n=2/3$  by 2.70 and for  $n=1/2$  by 3.41. Unfortunately, the exponent  $n$  we can find only for simple test geometries and for a simple mesh (e.g. constant step in a significant part of the lens). Let us remind that the computation error is equal to zero on the electrode or on the border where we specify Dirichlet boundary condition, e.g. a constant value of the field.

The use of the new method will be demonstrated on several test examples, which are suitable for the estimate of the character of the computation error. The method is important for use in practical computations. Even if the character of the error potential can give quite a complicated picture, it clearly points to the places in the mesh where the mesh geometry or density should be changed to lower the error. Similarly, the display of the error at the points on the axis of rotation symmetry allows us to visualize critical parts of the design and eventually to correct for the computation error.

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## IS THIS BEM USEFUL FOR THE COMPUTATION OF MAGNETIC LENSES?

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A new technique of boundary element method was proposed by Kasper in [1] under the title "An advanced boundary element method for the calculation of magnetic lenses"; see also the recent volume of AIEP [2]. What is new here? Obviously, for unsaturated lenses some of the formulas look a bit different than in [3] and the table in [1] is also different from that in [3].

As an illustration of the power of the method an open lens according to Shao and Lin [4] is studied (this paper is actually not cited in [1] but it is given in [2], p. 228). Further, it is clearly stated that such lenses cannot be computed with FEM because "it is extremely difficult to construct a mesh system of 500x500 in such a way that the far-reaching field is included adequately". This contradicts our discussion in [5] cited by Kasper in [2]! Another Kasper's extra requirement is that all the sharp corners of magnetic circuit must be rounded (which "does not cause an essential deviation from reality"). As the main reason it is given that at these sharp corners one must observe "saturation which is confined to a very narrow domain", an effect that is mostly not observed in the practical computations of unsaturated lenses.

What the author means by the difficulty to calculate magnetic lenses with the finite element method in large meshes? He even cites our paper on the combination of BEM and FEM [6] (this program is unfortunately gone with the mainframe computer 10 years ago). Moreover, we have shown in [5] that it is possible to calculate open lenses successfully; then we had maximum 32000 mesh points at our disposal. Fig. 1 (lens geometry and fluxlines) and Fig. 2 (fine mesh, iron saturation and axial flux density in the polepiece region) show that the problem can be analyzed already with some 80000 mesh-points. We have put the border 1 m away from the lens with 1.2 mm inner radius and 1.2 mm snout thickness; then 98.74 % of excitation A-turns are inside the border. If we apply Neumann boundary condition, we get 100.02 % of excitation, and the maximum  $B(z)$  is higher only by 0.8 % (0.20278 T instead of 0.20261 T). What is the accuracy of the results? If we calculate with 30 points in the inner radius, we get maximum  $B(z)$  of 0.20427 T, and with 60 mesh points in the gap (the mesh has then almost 800000 points) we get 0.20433 T (see more on our method of accuracy estimate and maximum mesh size in these proceedings). It is thus shown that the results discussed in [1] can easily be obtained with standard first order finite element method [7], which can easily compute meshes with up to one million points.

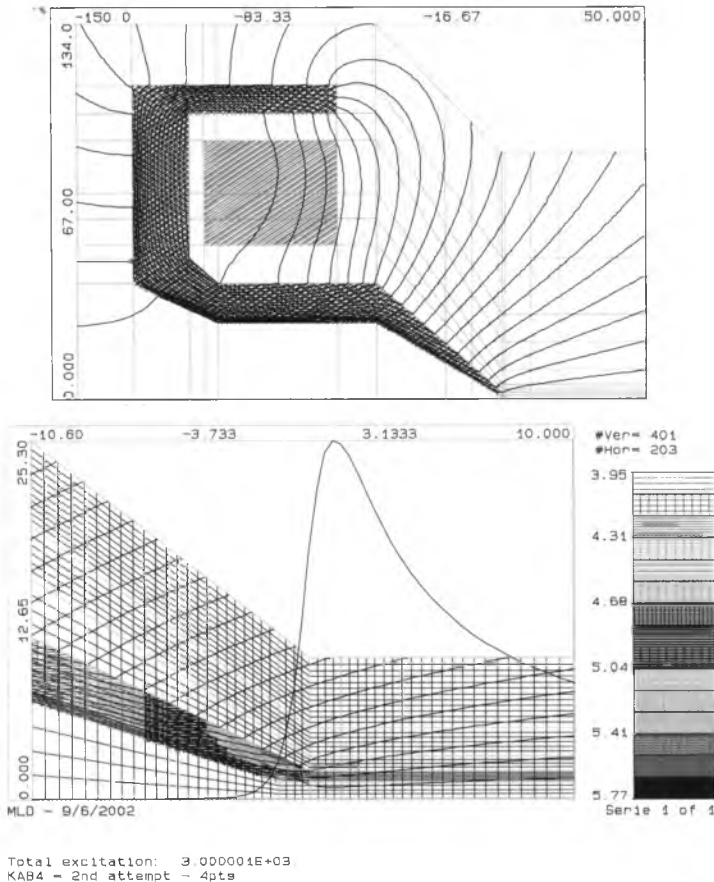
The other example is a simple saturated asymmetric objective lens studied by Munro (see figs. 17-21 in [8]); it was used as a test lens in a diploma thesis by Zeh in 1986 in Tübingen, see [2]. The saturation phenomena are in the "advanced method" taken into account by including only the tangential component of field  $H$  to estimate the saturation, and the behavior of the magnetization inside the yoke is thus ignored. This is not physically feasible and the results also show that the error maximum  $B(z)$  at 15000 At is 10 %. The non-advanced BEM methods previously used were correct but rejected because of the complications in computed iron saturation. A citation from [1]: "The price to be paid for their omission (of nonlinear space currents) is that the field in ferromagnetic yoke itself cannot be calculated correctly, but this drawback is not serious as long as the field of the optically relevant domain can be approximated fairly well." In most objective lenses two or even more

different magnetic materials are used and the saturation pattern is quite complicated. So even here the advanced method is of no use for practice.

We can thus conclude that the BEM discussed by Kasper [1,2] has no chance to replace FEM. Not only open lens can be computed with sufficient accuracy and to a full satisfaction of even a demanding user. Also for the study of saturated lenses we do not need any approximate method.

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## MISALIGNMENT ABERRATIONS

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Misalignment aberrations arise from (small) imperfections of lens geometry - either because of the inaccuracy in the manufacturing of individual elements (like electrodes and/or pole-piece defects) or the misalignment of the optical elements in the system (tilted or shifted element). Under such circumstances the ideal symmetry is disturbed and additional parasitic fields are produced. In the effect they are producing additional image aberrations.

The first type of errors primarily occurs due to manufacturing faults if the surfaces are not sufficiently planar and/or apertures are not sufficiently circular. For example, an essentially rotationally symmetric lens showing slight ellipticity of electrodes produces small quadrupole field. The aim of the computation is to establish necessary manufacturing tolerances.

The second type of errors is caused by an incorrect assembly, when positioning the elements of a lens or more lenses with respect to one another. Under this category come all errors like shifting the lenses off axis, their tilt and in the case of multi-electrode lenses mismatching a single of them. From analysis of these errors we want, as a result of computations, to improve the performance and introduce efficient correction elements.

The computation of aberrations starts with the analysis of the geometry of the problem. The unperturbed geometry with basic symmetry is defined as well as the perturbed geometry of the lower symmetry. The analysis proceeds in two steps. In the first step the unperturbed field is found. In the second step we add the perturbation field due to the symmetry breaking using perturbation method developed by P.A. Sturrock [3]. Having the total field available, by solving the trajectory equations we acquire the paraxial trajectories and the aberration coefficients. Such coefficients now include the aberrations of the unperturbed system as well as errors due to parasitic fields.

So far we have concentrated on understanding the theory of parasitic fields [3] as well as on obtaining correct expression of the aberration terms and understanding the derivation of aberration coefficients [1]. Now we are trying to compute the parasitic multipole fields in misaligned electrostatic lenses using program packages ELD for the unperturbed field and EMD for the perturbation fields. The influence of these fields on the image is analysed by the accurate ray tracing with the TRC package [2]. The results of the case numerical simulation for a simple thin lens are shown in Fig. 1.

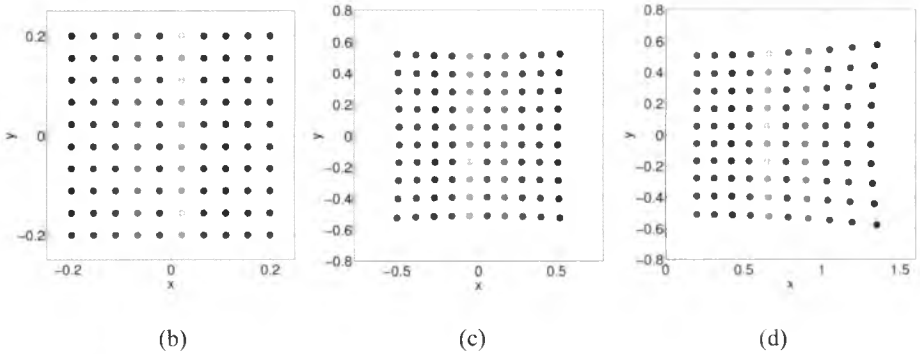
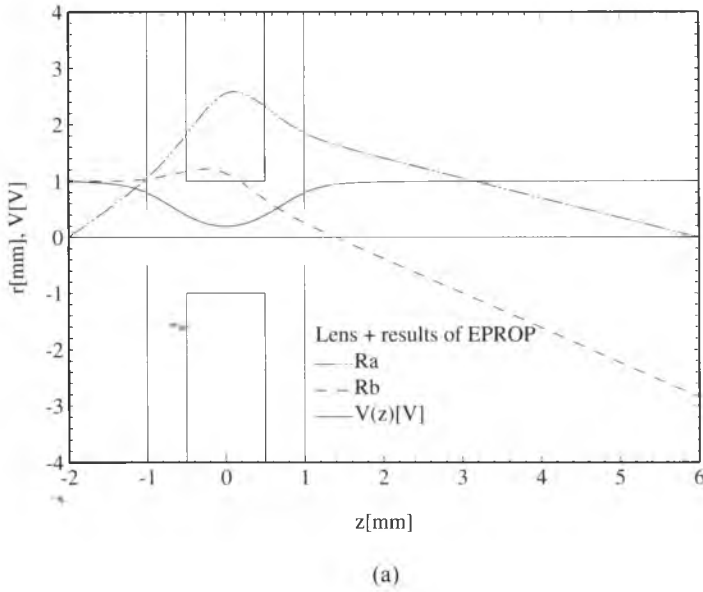


Figure 1: (a) Lens+results of EPROP; (b) the original object has half-width 0.2mm in both x and y directions and it is symmetrical about optical axis; (c) the image by the rotationally symmetric lens shows 3rd order distortion; (d) distribution of electrons after the lens shifted in x axis by 0.2mm.

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## CALCULATION OF THE BEAM PROFILE

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The beam profile provides local current density distribution of a particle beam. From the known distribution we can optimize the axial position of the specimen in a SEM, understand image aberrations or find optimum function of electron or ion analyzers. Graphical plot of the profile as a function of the  $z$  coordinate shows what is happening with the beam when it passes through the optical system. The first attempts of graphical presentation of the beam aberrations and profiles based on aberration theory are discussed in the recent diploma thesis [1].

In this paper a simple calculation of current density  $j(r)$  of rotationally symmetric beam after an electrostatic lens is shown. We consider a point object from which a monochromatic beam of particles is started. We also do not consider diffraction effects; such a computation would be suitable for ion beams.

Let us suppose that we know the current density distribution in some entrance plane  $z_a$  before the lens. We divide the radial interval  $[0, r_{am})$ , where  $r_{am}$  is the maximum extent of the beam, into  $m$  small intervals  $[0, r_{a1})$ ,  $[0, r_{a2})$ , ...,  $[r_{a(m-1)}, r_{am})$  that are not necessarily equally wide. From the current density  $j(z_a)$  between the radii  $r_{ak}$  and  $r_{ak+1}$  the current is

$$I_{ak} = \pi j(r_a) \cos(\theta_j(r)) (r_{ak}^2 - r_{ak+1}^2),$$

where  $\theta_j(r)$  is the angle between  $j(r)$  and the optical axis. This angle is typically very small, so we can put  $\cos(\theta_j(r)) = 1$ .

In the observation plane  $z = z_b$  behind the lens we choose another set of dividing points  $r_{bk}$  in  $n$  intervals. If  $n$  is smaller than  $m$  by an order or two in magnitude, we can assume that the particles in given interval  $[r_{bl}, r_{bl+1})$  come from several, say  $S$ , intervals in the entrance plane  $z_a$ ; these intervals do not have to be one next to another. So the total current density in the  $l$ -th interval in the observation plane is

$$j_b(R_{bl}) = \frac{I_{bl}}{\pi(r_{bl+1}^2 - r_{bl}^2)} = \frac{\sum_{s=1}^S I_{ak_{ls}}}{\pi(r_{bl+1}^2 - r_{bl}^2)} \quad (1.1)$$

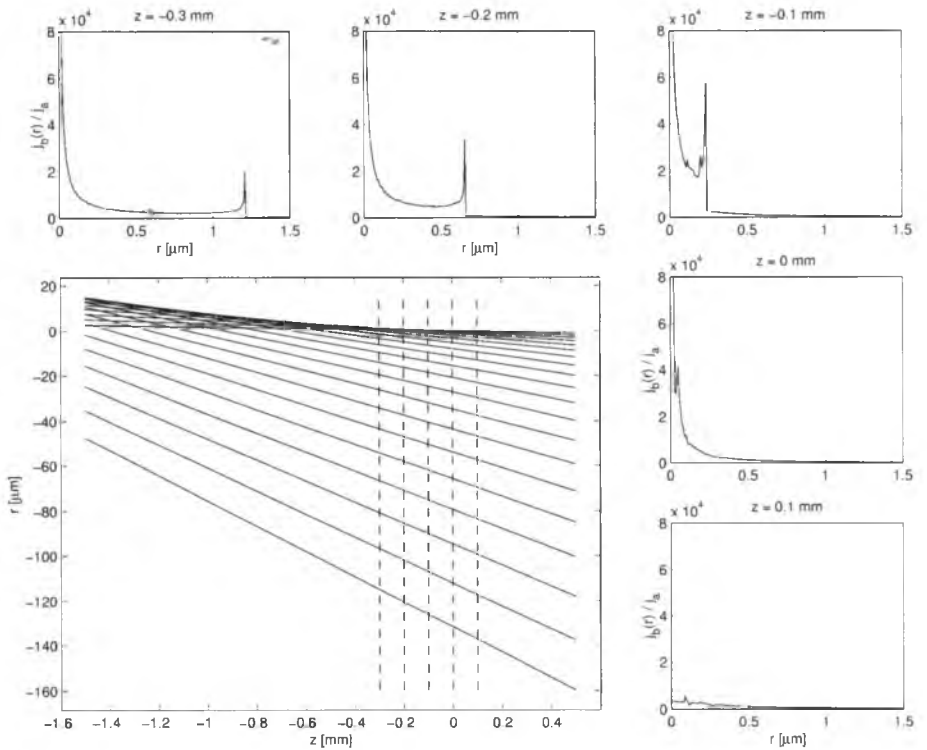
where  $R_{bl}$  is the center of the  $l$ -th interval.

In order to find the values of the index  $k_{l,s}$  of the point in the observation plane, we have to calculate the paths of particles. We need the start positions in  $z_a$  and end positions in  $z_b$ . Each interval in the entrance plane is represented by a "test particle" started from the center of the interval with a given angle. (In some cases we may consider several test particles with various directions and energies). Then we obtain its coordinate in  $z_b$  and thus the index  $l$  of the interval in the observation plane. Moreover, if  $z_b$  is outside any strong electrostatic and magnetic field, i.e. the trajectories are straight enough, we can get the radii in planes close to given  $z_b$ .

Any accurate ray tracing program can be used to find from the start points in  $z_a$  the end points in  $z_b$  for the trajectories of test particles, e.g. TRASYS in multi-trace mode [2]. The ray tracing programs are more general, because they allow computations in any combination of electric and magnetic fields. In some cases we can evaluate only the paraxial properties and aberration coefficients with programs like EPROP, PROP or COMBI [3]. These results are

obtained very fast, and also the evaluation of the beam profile for a give set of initial conditions is fast, as shown in [1].

To demonstrate this computation method, we have calculated intensity profiles after a symmetric unipotential electrostatic lens with length 2 mm and diameter of outer thin aperture electrodes  $D=1$  mm, shown in [4]. The particles with unit energy were started at a point object 2 mm in front of the lens and they were focused at 6 mm from the lens (see [4]). The central electrode 1mm thick with inner diameter 2 mm has a voltage  $-0.197$  V. The input current density profile is constant up to  $0.2$  mm and the number of trajectories is equal to the number of intervals  $m=1\,000\,000$ . The figure shows the beam profile at several  $z$  planes close to the gaussian image plane  $z=z_i$ .



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## CATHODE OBJECTIVE LENSES IN HIGH THROUGHPUT APPLICATIONS

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Cathode objective lenses were employed in the past in a variety of electron microscopes, including low-energy electron microscopes [1,2], photoemission electron microscopes [3,4] and low-voltage secondary electron microscopes [5]. Increasingly, these lenses are finding applications in scanning electron beam tools used in the semiconductor industry, i.e. in electron beam inspection, review and metrology [6,7] and are being developed for pattern generation [8]. The continuing trend toward smaller features however poses a formidable problem for scanning electron beam tools due to their relatively low throughput: the number of pixels to be examined or written on a wafer results in inspection and writing times that exceed practical limits. One of the possible approaches to circumvent this problem is to replace the serial acquisition process of scanning electron microscopes with a parallel scheme, where a two-dimensional image is detected on a scintillating screen and further processed on a computer.

In electron lithography, a certain number of electrons must be deposited in each pixel at the substrate to expose the resist. Similarly, in wafer inspection, a certain number of electrons must be accumulated in each sensor pixel to provide a useful signal with a sufficient signal-to-noise ratio. The throughput is determined by the time required to deliver this electron dose, so it is proportional to the maximum total electron current. However, the large current required delivering the needed throughput results in increased electron-electron (e-e) interactions, which blur the image and result in a loss of resolution.

We have used the IMAGE software package from MEBS Ltd. [9] in our e-e interactions calculations. The software computes electron-optical properties by propagating bunches of particles through realistic electromagnetic fields using Monte Carlo simulation of the trajectories through the accelerating region and thick lens fields. The software can predict the combined effects of the aberrations (geometrical and chromatic) and the e-e interactions in a cathode objective lens, in a rigorous unified way. In particular, this allows calculating accurately the impact of electron-electron interactions in the accelerating region, where electrons are starting at rest at large angles of up to 90 degrees, and in the following optically thick lens, which so far have been neglected or treated by approximations only.

In a cathode objective lens, electrons are generated by illuminating the surface of the substrate with photons or low-energy electrons. Three commonly used cathode objectives with constant accelerating field are considered: decelerating and accelerating electrostatic, and combined magnetic lenses. All three lenses have an accelerating field of approximately 5 kV/mm at the substrate surface at maximum beam energy of 20 kV. The geometry of the focusing electrodes and polepieces was chosen to give a practical lens design capable of forming a 4-5 times magnified image of reasonable size (few hundreds of  $\mu\text{m}$ ) at a distance of 200 mm above the wafer. In the decelerating electrostatic lens, the electrons are slowed down to energy of approximately 4 keV, and in the accelerating electrostatic lens, the electrons are accelerated up to energy of approximately 66 keV. In the magnetic lens the electron energy remains constant.

Increased throughput requires a large total beam current, which results in increased e-e interactions. The e-e interactions affect the imaging properties of the cathode objective lens by increasing the beam energy spread (Boersch effect), and introducing blur (trajectory displacement effect) and space charge defocus [10]. The Boersch effect affects the electron-optical performance by increasing the chromatic aberration contribution. The trajectory displacement (Loeffler) effect, which manifests itself as a stochastic lateral shift in electron positions and velocities, directly deteriorates the imaging quality of the lens. Both the Boersch and trajectory displacement effects cannot be corrected, only reduced. The space charge defocus, determined by the averaged charge density in the beam, results in a defocus of the image from the Gaussian plane and a change in magnification. Due to the non-uniform and time-dependent charge distribution, the defocus cannot always be eliminated completely by refocusing the lenses of the system [12].

The e-e interactions can be reduced for a given beam current in the cathode objective lens by increasing the illuminated area, which decreases the current density. The beam blur is calculated for a range of field sizes and total beam currents. The emission area has a square shape, with a uniform current density distribution. The angular intensity distribution is Lambertian, and the initial energy has a Maxwell-Boltzmann distribution peaked at 0.25 eV (i.e. photoelectrons).

The performance of the three cathode objective lens types is compared in Fig. 1, which shows the functional dependence of the beam blur at the Gaussian focus plane upon current density for a range of beam currents at 20 keV. For each current and field size, the blur  $d_{ee}$  due to e-e interactions is calculated by subtracting the blur  $d_0$  at very low currents from the total blur  $d_t$  using a Gaussian quadrature, i.e.  $d_{ee}^2 = d_t^2 - d_0^2$ . At very low beam currents, all three lenses are capable of achieving a blur of approximately 70 nm at 20 keV and 140 nm at 10 keV. No pupil aperture is used so that all the electrons are detected. We evaluate the total blur near the optical axis, where the resolution of the virtual image formed by the accelerating field is limited by the spherical and chromatic aberration and electron-electron interactions. The focus is on the effect of electron-electron interactions; the contribution from off-axis aberrations, which can limit the available field size at the substrate, is not considered here. As expected, at a given total beam current  $d_{ee}$  decreases with decreasing current density. Interestingly, the rate of decrease is larger at lower current densities and higher currents. For the higher current density range, the accelerating electrostatic lens has the smallest e-e interactions induced blur  $d_{ee}$ , followed by the magnetic and decelerating electrostatic lens. However, the rate of the rate of decrease is significantly larger for the decelerating electrostatic lens at lower current densities, and eventually results in the least blur  $d_{ee}$  at low current densities.

In general, the e-e interactions and the associated blur  $d_{ee}$  does not vary strongly with the type of the lens used, and other practical aspects of lens design can be considered to optimize the overall performance of the cathode objective. The calculations of e-e interactions induced blur  $d_{ee}$ , illustrated here allow us to conclude that these cathode objective lenses are a feasible option for high throughput electron beam systems.

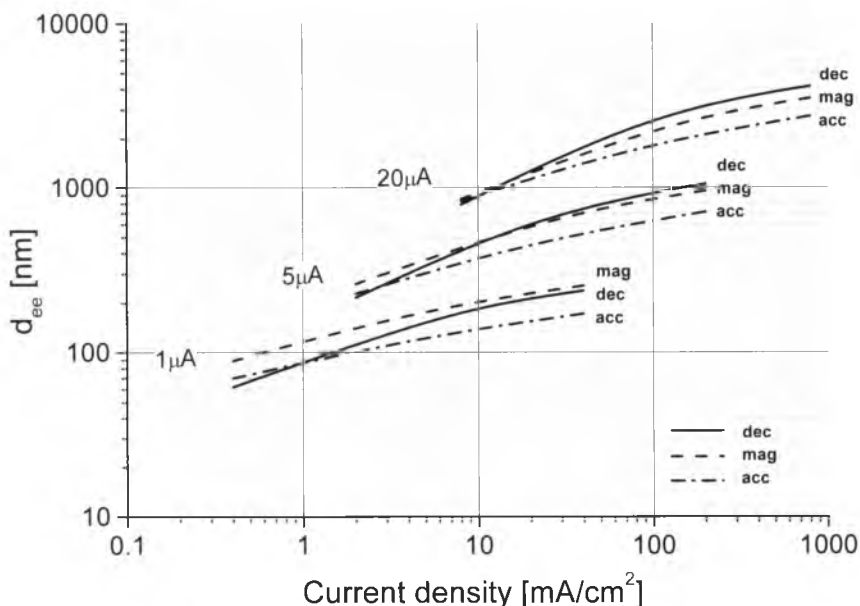


Figure 1: E-e interactions induced blur as a function of current density for varying total beam currents for currents from  $1\mu\text{A}$  to  $20\mu\text{A}$  at  $20\text{ kV}$  in a decelerating and accelerating electrostatic, and combined magnetic lens.

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## SECONDARY ELECTRON CONTRAST OF DOPED REGIONS IN SEMICONDUCTOR – A MATTER OF SURFACE TREATMENT?

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Direct observation of doped patterns in semiconductor, usually on cleaved sections through multilayers but recently also in plan views of patterned doping of a technological layer, is acquiring high interest because of its straightforward application in the semiconductor technology. Plenty of experimental data has been collected [1-4] from conventional SEM observation and recently first results showed improved contrasts attainable with specimen immersed into electric field [5,6]. Main features are the sign of contrast – the p-type regions are always brighter than the n-type ones, and the contrast grows toward lower energies.

Some particulars regarding the contrast interpretation and model of the contrast mechanism can be found in the literature and most complete summary was presented by Sealy et al. [4]. All these attempts relied upon the local differences in the ionization energy and only recently at least the surface states were taken into account both via associated band bending and subsurface electric field creation. Contrary to this, El-Gomati and Wells [5] were first who interpreted the contrast as solely caused by the metal-semiconductor contacts between the carbonaceous contamination layer and the specimen. The carbon contamination was most likely presented in all experiments announced so far.

This report aims at summarizing the main points indicating the important role of the surface status, the surface heterogeneity in particular, in the contrast formation. The data were acquired solely for specimens dipped in HF, which is a step known to passivate the surface against oxidation and also passivate the acceptor states. It has been found that:

- A. if the p/n structure is coated with a Ni film of about 10 nm thick, the contrast does not change (i.e. the p-type is brighter), but
- B. if the coating material is Cr, the contrast changes the sign and the n-type is brighter;
- C. when the cathode lens is used and the specimen is immersed into electric field, the contrast significantly grows but the increase is much higher under medium vacuum conditions compared to UHV;
- D. after in-situ removing the surface layer by ions, one gets the brightness lowered for both p- and n-type.

Hypothetical explanation of all these phenomena can be based on formation of surface potential barriers, including those connected with metal-semiconductor contacts upon the specimen surface. Let us suppose that after HF dipping the silicon surface does not oxidize and the energy bands are flat. Then, a metal-semiconductor contact forms a barrier repelling the electrons backward (the Schottky contact) on n-type silicon whenever the work function of the metal is higher than that of silicon while for the opposite relation between the work functions, the barrier appears on the p-type [7]. This arrangement enables the observations A and B to be immediately explained – the relevant work function relations are as needed. Because also the work function of carbon surpasses that of silicon, the situation is like with the Ni coating, with the carbonaceous contamination more intensive under worse vacuum

conditions. Moreover, the metal – n-type contact is here biased in the reverse polarity, which further lowers the n-type emission. Thus, the item C. is also explained. The in-situ ion beam bombardment can be expected to remove both the contamination and passivation layers so that acceptor-like surface states become re-activated for both p- and n-type. After trapping electrons, these states create a surface barrier again, which generally lowers the secondary emission from silicon, as mentioned under D.

Because some contrast is still available even after ion-beam surface cleaning, it is obvious that only a majority but not full secondary electron contrast is due to surface barriers – this also follows from previous studies. Most probably some not high contrast is caused by local differences in the ionization energy, and this basic contrast level can be strongly increased or, under some circumstances, inverted by phenomena connected with the surface barriers, decisively dependent on the surface status, i.e. contamination, cleanliness, etc.

Some features of this model need more elaboration and also experiments should be extended to remaining combinations of the doping and substrate types. Important will be to incorporate also other preparation techniques, particularly methods for removal of the oxide masks without surface passivation, and to verify their impact onto contrast formation.

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## DESIGN AND SIMULATION OF A MINIATURISED ELECTROSTATIC COLUMN FOR HIGH PROBE CURRENT

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### Introduction

Calculations for a miniaturised low energy high current electron optical column consisting of an electron emitter, two electrostatic lenses, a scanning system and a secondary electron (SE) detector are presented. The assembly of the individual elements is based on conventional components. A common Schottky emitter minimodul is used as electron source. The electrostatic lenses are made of simple platinum apertures used in conventional electron microscopy as beam limiting apertures. The deflection elements are made of printed saddle coils based on double-copper-coated Kapton foils. The SE are detected by means of a modified customary scintillator-photomultiplier combination.

### Column design

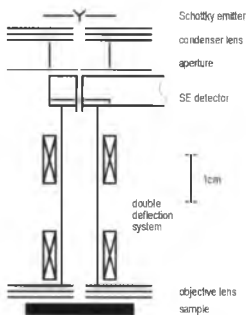


Fig. 1: Column overview



Fig. 2: Schematic view of the condenser lens



Fig. 3: Schematic view of the objective lens

The experimental system (fig. 1) currently being built is about 50 mm in height. In the intermediate region between condenser (fig. 2) and objective [1] lens (fig. 3) the primary electron beam can be varied between converging and diverging mode. This leaves enough space to place a double deflection system consisting of magnetic deflection elements [2] as well as a detector between the lenses (fig. 1). The SE are accelerated through the objective lens towards the in-column detector. Detection efficiency is additionally increased by applying an extraction field at the sample. The detector region between the two lenses is set to a potential of 6 kV relative to the sample. This high potential is used to accelerate the SE making them detectable by a scintillator-photomultiplier combination.

The system is optimised for final energies of the primary beam  $E_{PB} \leq 1$  keV, a working distance  $wd = 1$  mm (between last lens diaphragm and sample) and an electric field at the sample of 500 V/mm. The goal was to achieve a resolution of 50 nm with a probe current greater than 50 nA.

Primary beam calculations

Calculations are presented for beam energies between 0,4 keV and 1 keV. The condenser lens is assumed to be operated in internal deceleration mode, while both modes - internal deceleration as well as acceleration mode - are investigated in case of the objective lens. Assuming an angular current intensity of  $I_{\theta} = 0,5$  mA/sterad, a virtual source size of  $d_{vs} = 20$  nm, an energy width (FWHM) of  $\Delta E = 1,2$  eV, and allowing an electric extraction field at the sample of  $E_{sample} = 500$  V/mm the goal to obtain a resolution of 50 nm with a probe current greater than 50 nA is easily achievable.

Collection efficiency of secondary electrons

The SE are accelerated through the objective lens towards the detector. An electric extraction field at the sample helps collecting the SE leaving the sample at starting angles up to 90°. Passing the objective lens the SE are accelerated to an energy of 6 keV towards the detector. SE trajectories were calculated for focusing conditions of the primary beam between 400 eV and 1 keV. These calculations were made for acceleration as well as the deceleration mode of the objective lens.

Placing the detector (bore diameter 1 mm) 30 mm above the objective lens and assuming a cosine distribution for the starting angles as well as a Maxwell distribution for the energy with the maximum at 2 eV, the following collection efficiencies for SE with starting energies of up to 10 eV are obtained:

|                               | $E_{PB}=400$ eV<br>decel. | $E_{PB}=400$ eV<br>accel. | $E_{PB}=600$ eV<br>decel. | $E_{PB}=600$ eV<br>accel. | $E_{PB}=1$ keV<br>decel. |
|-------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|--------------------------|
| SE passing the objective lens | 64%                       | 87%                       | 60%                       | 85%                       | 50%                      |
| SE lost in primary beam hole  | 29%                       | 17%                       | 16%                       | 17%                       | 17%                      |
| collection efficiency         | 35%                       | 70%                       | 44%                       | 68%                       | 33%                      |

The field calculations and simulations of trajectories were carried out with the program Electron Optical Systems (EOS) of Prof. E. Kasper.

Conclusions

The presented calculations for a miniaturised low energy high current electron optical column show that a resolution of 50 nm with a probe current greater than 50 nA is achievable. The objective lens may be operated in internal deceleration as well as acceleration mode. Besides it has been shown that a sufficiently large number of SE are able to pass through the lens in both modes, thus enabling in-column detection.

The acceleration mode yields better results for the primary beam performance as well as for the SE detection.

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# SCANNING UNIT WITH PRINTED CIRCUIT SADDLE COIL FOR RESOLUTION MEASUREMENT IN A MINIATURISED ELECTROSTATIC LENS SYSTEM

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## Introduction

In scanning electron microscopy resolution (probe size) measurements are most easily realised by employing visual information, i.e. determining the smallest visible structure in images of a suitable test specimen. Furthermore, by use of image information the alignment of the system's optical axis can readily be achieved.

Thus, a simple scanning and image acquisition system has been set up in order to verify the calculated performance of an experimental miniaturised electrostatic lens system optimised for high-resolution low-voltage applications [1]. The latter consists of a Schottky emitter with extractor and an optimised miniature immersion lens built of conventional platinum apertures (as used in electron microscopy) according to [2].

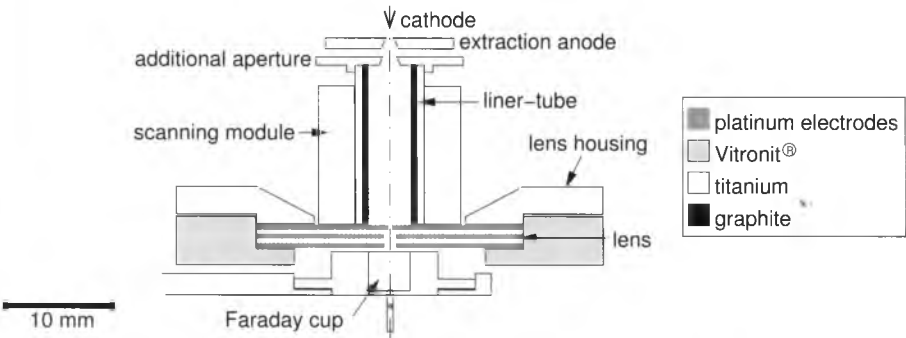


Figure 1: Experimental set-up

## Scanning Unit

Scanning of the beam is performed using a special saddle coil deflector based on printed circuit technique [3] that is situated in the field free region between extractor and first lens electrode (fig. 1). The saddle coil structure is transferred to a double-sided copper-coated Kapton foil by means of photolithography and subsequently wound on a cylindrical former. With this technique also more complicated winding distributions can easily be realised. Therefore an optimised structure with respect to minimisation of higher order harmonics [4] has been investigated numerically.

Due to the limited available space within the system the overall height of the scanning module is kept at approximately 15 mm. Fig. 2 shows the individual components of the scanning module as well as the completed assembly. A commercial system (ADDA II®, Soft

Imaging System) is used for generating the scan ramps and visualising the image intensity, which corresponds to the Faraday cup signal of a suitable transmission object (e.g. a fine gold-coated carbon grid – quantifoil<sup>®</sup>, Fig. 3)

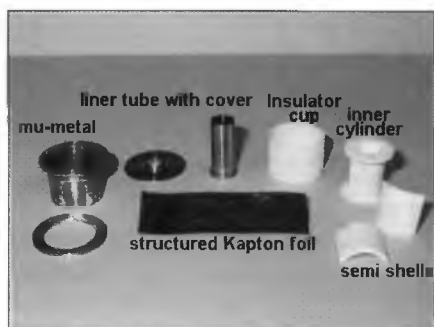


Figure 2: Scanning unit. Left: Individual components. Right: Completed assembly.

### Application to Resolution Measurement [1]

Unfortunately, due to the remaining astigmatism the visualisation of small structures proved not to be feasible. Hence, resolution measurement is performed by first acquiring an image of the specimen and subsequently calculating a linescan across one of the grid bars. The resulting intensity profile as shown in fig. 4 can then be used to estimate the probe size either by the 12%-88% method or by a least-square fit using an appropriate analytical function (i.e. the Gaussian error function). At present an experimental value of 31 nm at a primary beam energy of 1 keV has been measured. This value is still large compared to the theoretical value of 5 nm. However, as is clearly visible from fig. 3 the resolution is limited by the remaining astigmatism and will improve once the latter can be corrected.

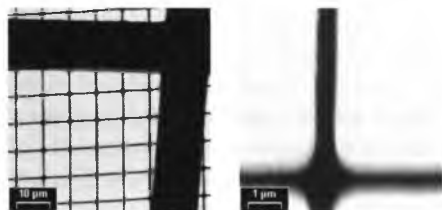


Figure 3: quantifoil<sup>®</sup> grid: Left: Overview of test specimen on a TEM grid. Right: Magnified grid bar.

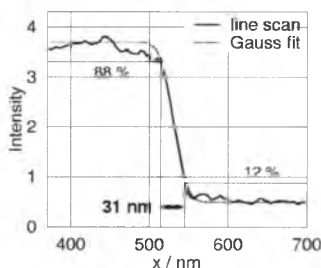


Figure 4: Resolution measurement. Line scan across grid bar showing 12%-88% method and fit using the error function.

### Conclusion and Outlook

Using a simple scanning unit with a saddle coil deflector module it was possible to successfully perform alignment as well as resolution measurements in a miniaturised electrostatic lens system.

The compact design of the scanning module allows piecing together of modules for multi-stage deflection. Furthermore, several layers of structured Kapton foil may be used to additionally provide for astigmatism correction.

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## THE PARALLEL CYLINDRICAL MIRROR ANALYZER

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It seems that in all the known electrostatic charged particle energy analysers, with the exception of the hyperbolic field analyser (HFA) [1,2], the range of energies that can be covered at any one time is small, the ratio of the range of energy to the mean energy being typically less than 0.1. It would be an advantage to be able to analyse a complete energy spectrum simultaneously. This can be described as 'parallel acquisition'. The HFA is able to do this. It would be a further advantage to be able to accept and analyse particles that are emitted over a wide range of angles in the transverse direction (i.e. normal to the plane of energy dispersion). The HFA is not able to do this because it has planar geometry. Finally it would also be an advantage to be able to switch to a second-order focusing mode so that a narrow energy region can be analysed with a higher resolution. It seems that the HFA does not have a second-order focusing mode.

A new type of electrostatic analyser has been described [3] that is able to accept a wide range of energy and that has axial symmetry, so that it can accept over the complete range of azimuthal directions. The new analyser also has a second-order focusing mode. The analyser is similar to the well known cylindrical mirror analyser [4,5] except that a linear (or approximately linear) potential variation is applied to the outer cylinder.

Here we describe the development of one of the configurations of the new analyser, the 'axis-to-disk' configuration. The potential variation on the outer cylinder is applied by using a series of narrow cylinders each of which is at a uniform potential. The inner cylinder continues to be at ground potential. The space between the two cylinders is closed at one end by a disk which is at ground potential and on which one or more detectors are mounted, and is closed at the other end by a disk that has a non-uniform potential drop along its radial direction. The system is simulated using the CPO2D program [6].

The field between the cylinders reflects the trajectories towards the detectors on the grounded disk when the entrance angles are high. Conditions have been found for which a range of energies (e.g. 40 to 640 eV) can be focused at the grounded disc. Conditions have also been found for which there is second-order focusing. The energy at which second-order focusing occurs is just below the limit at which first order focusing is found. Therefore the outer part of the detector could be used for collecting parallel acquisition spectra after which the applied voltages could be scaled and the inner part of the detector used to observe a selected part of the spectrum with higher energy resolution.

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## FULLY ELECTROSTATIC LOW ENERGY SCANNING ELECTRON COLUMN

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The exploitation of low-energy electrons for examination of the material surfaces has several advantages. One of them is a small depth penetration of the primary electrons (PE) to the observed material. At low energies the charging effects on non-conductive or slightly conductive specimens are suppressed and also radiation damage of the observed specimen is decreased. Since the secondary electron (SE) yield is high, the signal to noise ratio (SNR) is about one order of magnitude larger than those in microscopes operated at 20 kV. Moreover, exploitation of low-energy electrons enables observation of differently doped semiconductor regions [1,2]. However, the use of the primary electrons with low energy brings some problems e.g. low source brightness, increased aberrations and increased sensitivity to stray fields (e.g. defocusing of the probe by SE collecting field).

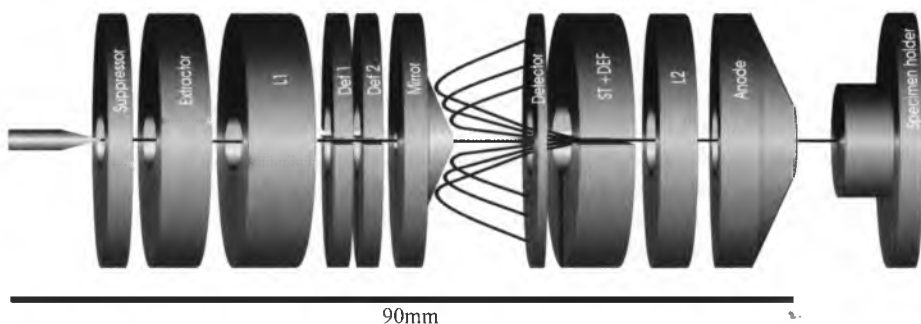


Figure 1: Schematic of the new design of the fully electrostatic low energy scanning electron column

The first miniature electrostatic microscope with the field emission cathode was constructed at the University of York in cooperation with the ISI AS CR in Brno several years ago [3,4]. The microscopy was fully functional, although during its usage several constructional changes were necessary. Figure 1 shows the schematic configuration of the new microscope. For a better efficiency of detection it was necessary to reduce the size of the mirror opening to 0.2 mm. This is mainly important from the viewpoint of SE detection with the energy up to 5 eV. Nevertheless, so small bore restricted the viewfield too much. Therefore, it was necessary to move the stigmator-deflector (ST+DEF) unit below the mirror. Furthermore, one of the most challenging problems was the mechanical alignment of the whole microscope. For this scope, it was chosen a construction consisting of two independent subassemblies. The alignment of the individual parts is carried out by steel rods produced with high exactness. Thereafter, the aligned parts were screwed together in a jig. The alignment is finished electronically by using two independent deflector units (Def1 and Def2). These electrodes are positioned behind the mirror as shown in Fig. 1. In order to enhance the resolution, the column was added by one more electrostatic (objective) lens (L2).

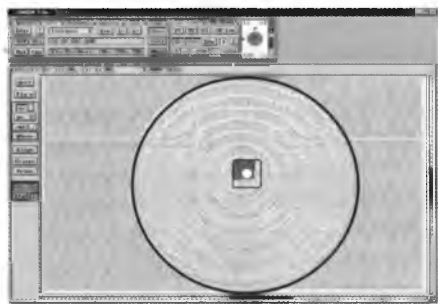


Figure 2: SIMION simulation without voltages on the scan unit

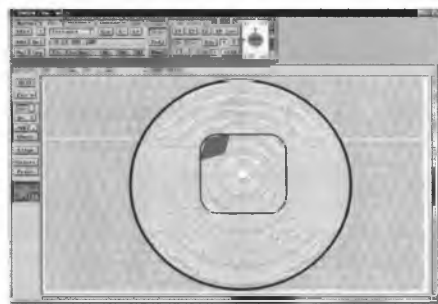


Figure 3: SIMION simulation for  $-50V$  on one electrode of the scan unit

With the in-lens mode the specimen is negatively biased. Primary electrons (PE) are decelerated to the specimen and interact with the surface with their low energy. The signal electrons are accelerated via specimen potential, impact the mirror and generate there secondary electrons. These are again accelerated and detected. The collector is divided into six parts connected to separate amplifiers. The control computer can display six independent pictures from each channel or the summed signal. The angular distribution of signal electrons depends of the angle of incidence of the electron beam and surface topography and crystallinity. Comparison of signals from opposite detectors serves also for alignment of the deceleration field. The summed signal offers a higher signal to noise ratio (SNR).

In this set-up, the sigmator-deflector unit influences also trajectories of the signal electrons. For better understanding of the ray diagram, SIMION program vers. 7.0, allowing for 3D simulations, was used. In Figure 2 the result of the simulation is shown for the signal electrons with energy 10 eV and starting angle  $\pm 10^\circ$  that impact the mirror when no voltages are on the scanning unit. The square indicates the viewfield on the specimen surface. Figure 3 shows the same situation except that one electrode of the scan unit is biased to  $-50V$ . We can notice that the impacted area is much bigger. This means that operation of the scan unit influences the signal amplification in each of the six channels and further simulations should be made in order to map the situation for various magnifications and for the deflection plates accordingly excited.

Future development steps include purchase of better image acquisition software. The column is intended for installation into a CMA analyzer of Auger electrons in order to combine the surface sensitivity of AES with that of slow electrons.

This project was supported by the Royal Society (UK) and by internal project of ISI Brno.

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## AN ULTRAHIGH VACUUM SCANNING LOW ENERGY ELECTRON MICROSCOPE FOR SURFACE STUDIES

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In the course of recent six years, a complex device for examination of clean and well-defined surfaces with low energy electrons under ultrahigh vacuum conditions has been developed and put into operation. The apparatus is intended for exploration of novel image contrasts, available at landing energies of the scanning primary beam below 100 eV, under a residual pressure in the specimen vicinity in the order of  $10^{-10}$  mbar.

The instrument consists of three vacuum chambers: the observation chamber, a chamber for in-situ preparations and the loading chamber of the air lock.

The observation chamber is equipped with a two-lens field emission electrostatic electron column with electronically variable aperture (FEI Corp.). The energy range of primary electrons spans from 1 to 25 kV with the ultimate resolution limit 12 nm at 25 kV and 0.1 nA beam current; maximum beam current is declared to be 100 nA. Main signal detector is that for low and very low energy SEM, based on the cathode lens principle [1,2]. Negatively biased specimen forms the cathode of the lens while the detector scintillator, consisting of the bored single crystal YAG disc, finely movable in all three axes, serves as the anode at ground potential. Signal electrons are collimated onto the detector by the cathode lens field and, therefore, high detection efficiency is available down to lowest energies.

The observation chamber further contains a quadrupole mass spectrometer type QMS 200 (Balzers), operating within the mass range 1 to 200 amu and the pressure scale  $10^{-4}$ - $10^{-11}$  mbar with the Faraday cup or  $10^{-5}$ - $10^{-14}$  mbar with the channeltron. The device is available for studies of desorption under electron impact and also serves as the leak detector of top sensitivity. Additional detectors under construction include a conventional Everhart-Thornley detector of secondary electrons and the hyperbolic field analyser [3] for parallel acquisition of electron spectra.

The preparation chamber contains a scanning ion beam gun for surface cleaning (IQE 12/38, Specs) with differential pumping. This is planned for in-situ specimen cleaning and also for depth profiling and cratering of multilayers at low ion energies, large tilt and continuous specimen rotation. The chamber equipment will be completed by a set of cells for directed evaporation of metals.

The specimen loading and manipulation system is in the final step of manufacture. This incorporates two UHV specimen stages and a loading trail for insertion of the specimen holder into the air-lock chamber. Specimen transport from the air-lock chamber into the preparation chamber and further to the observation chamber is made by means of a manipulator driven by magnets from outside (DeLong Instruments, Ltd., Brno). The specimen stage for the observation chamber features the x and y movements  $\pm 5$  mm, z-axis movement  $\pm 10.5$  mm, rotation  $\pm 8^\circ$  and two mutually perpendicular tilts up to  $\pm 5^\circ$ . The specimen manipulator for the preparation chamber has the x- and y-axis shifts up to  $\pm 6$  mm, z-axis movement  $\pm 15$  mm, continuous rotation and one tilt within  $\pm 60^\circ$ . Both manipulators accept a specimen holder, which bears five separate HV-insulated electric connections (for

specimen itself, for the heating filament and thermocouple). The specimen heating is planned up to 1400°C. Specimen exchange, together with restoration of the operating vacuum, has been tested to last not more than 1 hour.

The observation and preparation chambers are evacuated by means of oil-free pumps and their bake-out up to 180°C is automated.

The SEM mode is controlled by a dedicated PC based system for scanning control and image data acquisition, processing and archiving (system Satellite, Tescan, Ltd., Brno). The same PC controls also the quadrupole mass spectrometer.

Guaranteed resolution of the gun is 12 nm at 25 keV. We have tested the real image resolution for various landing energies of electrons and obtained the resolution of 13 nm at 10 keV, 25 nm at 1 keV and 41 nm at 10 eV - see Figure 1. The high-resolution gold-on-carbon test specimen S168T (Agar) was used for the experiment. The edge width was determined between 10% and 90% levels of the signal slope. In the course of the device development, the resolution was improved by implementation of a system for passive vibration damping but still the mechanical vibrations seem to be the limiting factor – the microscope will be moved to the ground floor outside the main institute building.

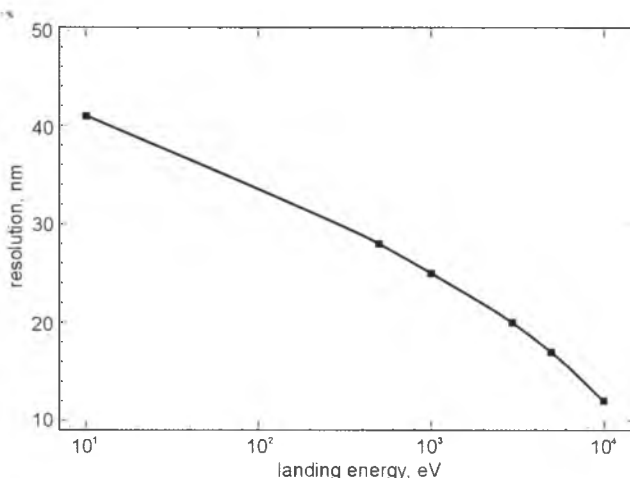


Figure 1: The energy dependence of the image resolution as measured in the cathode lens mode with the primary beam energy 10 keV.

First experiments were performed with makeshift specimen manipulators, featuring only a limited scope of the specimen movements, and oriented to contrasts of doping patterns in silicon throughout the energy scale down to units of eV [4].

The specimen manipulators and the loading mechanism were completely designed by Mr. Pavel Klein. Support of the Grant Agency of AS CR under grant no. A1065901 is gratefully acknowledged.

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## ACQUISITION OF MULTI-DIMENSIONAL IMAGE IN THE SCANNING ELECTRON MICROSCOPE

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The possibilities of acquisition of the energy spectrum of signal electrons or angular distribution for every point of the scanning matrix on the specimen in SEM were studied and suitable fast position sensitive detector was designed.

The basic task for the scanning electron microscope (SEM) is to acquire two-dimensional image of the surface of the observed specimen in topographical or material contrast mode, depending on the type of detector used. The detectors collect the sum of signal electrons, i.e. work as integral detectors and can not acquire angular or energy distributions of electrons. To obtain more information from the specimen we can use the spherical detector for detection of the angular distribution of signal electrons, or some energy sensitive detector for acquisition of the energy spectrum. Usual procedure is to acquire two-dimensional image of the specimen, next to select a limited number of points from which we would like to obtain energy spectrum information, then to direct the primary electron beam on these points and measure energy spectrum point by point.

Thanks to advance in computer techniques and detectors technology we can automatize and extend acquisition of additional information from whole specimen. At present we can obtain additional 2D information when detecting angular distribution of the signal electrons using area selective detector, or additional 1D information when sensing the electron energy spectrum using energy selective line detector. The main problem in realisation of such microscope is not in time consumption or memory consumption in the control computer but in time consumption of the electron detection. Let us consider the scanning matrix of  $512 \times 512$  pixels. We would like to acquire the multidimensional image in max. 10 min. Thus, the maximum time for acquisition of the angular distribution or energy spectrum from one specimen point is  $t = 600\text{s} / (512 \times 512) = 2.3\text{ ms}$ . For detection of the angular distribution of electrons in such short time we decided to design a detector based on the areal thinned back-side illuminated CCD sensor working in the direct electron-bombarded mode (EBCCD) (Fig. 1). The time shortage is the main reason why we cannot use any commercially available camera. Such cameras are usually optimized for very long integration and process time (slow-scan CCD cameras) and are equipped with high resolution sensor and cooler.

From the point of speed the key parameter of EBCCD (Fig. 2) is the gain  $G$  of electron bombarded semiconductor (EBS) (a number of signal electrons in the potential well generated by one incident electron), which is related to the incident particle energy  $E$ . For a real CCD sensor we must calculate the EBS gain  $G$  as  $G = E \varepsilon(E) / (3.65\text{ eV})$  where  $\varepsilon(E)$  is the detection efficiency of the CCD. In practice, the front-side illuminated CCD shows a reasonable efficiency ( $\varepsilon > 0.1$ ) at energy from 8 - 12 keV upwards, depending on the sensor type. The available thinned back-side illuminated CCDs have an efficiency higher than 0.1 at energies below 5 keV. To meet our resolution and timing requirements we chose the back illuminated high performance CCD sensor CCD39-02 ( $80 \times 80$  pixels) from Marconi. For the well capacity of  $N_c = 300 \times 10^3$  electrons and uniform distribution of the signal beam, the total number of electrons to be generated in all potential wells is  $N_w = 300 \times 10^3 \times 80 \times 80 = 1.9 \times 10^9$

electrons. We assume signal beam current  $I_b = 10^{-9}$  A. To generate this amount of electrons we need a sensor with  $G = N_w q / I_b t = 1.9 \times 10^9 \times 1.6 \times 10^{-19} / 1 \times 10^{-9} \times 2 \times 10^{-3} = 152$ . From equation above we get the needed value  $\varepsilon(5 \text{ keV}) = 152 \times 3.65 / 5 \times 10^3 = 0.11$ . Consequently, the thinned back-side illuminated CCD could fulfil our requirements.

The dynamic range of the EBCCD is limited by the readout noise plus dark signal nonuniformity. For the low integration time used ( $< 10$  ms) the readout noise is dominant and the dynamic range of standard EBCCD at room temperature (i.e. without cooling) is  $\sim 60$  dB. The brightness resolution (number of grey levels) can be calculated as  $D = N_c / G$  and is comparable with the dynamic range for  $G = 300$ . For  $G < 300$  the dynamic range is fully utilised and the number of observable grey levels is only limited by the readout noise while for  $G = 300$  the integration time is minimized. To carry on optimum level of the EBCCD gain we must set the energy of the bombarding electrons on a level which follows from the energy dependency of the detection efficiency. For this purpose, already published [1,2] arrangement of the electron optics of the microscope is suitable.

The detector for the position sensitive detection of low energy signal electrons has been developed and measurements under electron bombardment are being carried out.

The experiment is supported by the grant no. 102/00/P001 provided by the Grant Agency of the Czech Republic.



Figure 1: Experimental configuration of the detector in the microscope chamber (with the shielding removed).

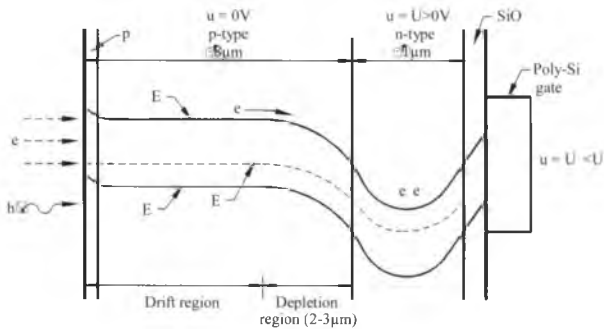


Figure 2: Thinned back-side illuminated CCD

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## EXPERIMENTAL VERIFICATION OF ANTICORRELATIONS IN A BEAM OF FREE ELECTRONS ('ELECTRON ANTIBUNCHING')

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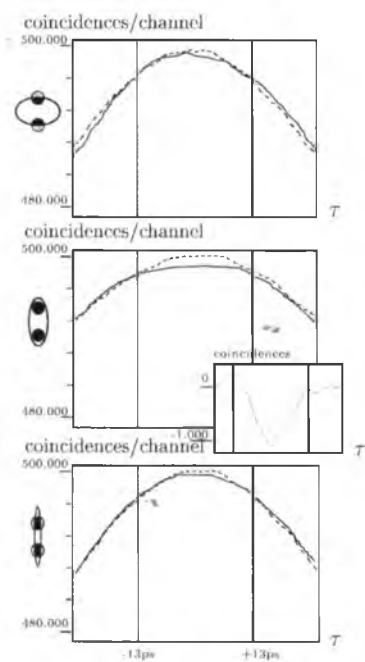
The astronomers Hanbury Brown and Twiss (HBT) were the first to observe in 1956 that the fluctuations in the counting rate of photons originating from uncorrelated point sources become, within the coherently illuminated area, slightly enhanced compared to a random sequence of classical particles [1]. This at a first glance mysterious formation of correlations in the process of propagation turns out to be a consequence of quantum interference between two indistinguishable photons and of Bose-Einstein statistics [2]. The latter requires that the composite wave function is a symmetrized superposition of the two possible paths. For fermions, by virtue of the Pauli principle, no two particles are allowed to be in the same state. The corresponding antisymmetrized two-particle wave function excludes overlapping wave trains, i.e., simultaneous arrivals of two fermions at contiguous, coherently illuminated detectors are forbidden. We succeeded, in spite of the low mean number (degeneracy) of  $\sim 10^{-4}$  electrons per cell in phase space, to observe these anticorrelations for a beam of *free* electrons for the first time.

The coincidence method chosen in the present 'antibunching' experiment is an alternative to HBT's correlation procedure for gathering information about correlations in a stream of particles [3]: Two detectors are coherently illuminated by an electron field emitter. According to the Pauli principle no two electrons of a certain spin direction are allowed to be in the same quantum state, i.e. to arrive at both detectors simultaneously. In other words, if our detectors had a time resolution corresponding to the coherence time  $T_c$ , which is in the order of  $10^{-14}$  s, no coincidences would be observed. (In our unpolarized beam, suppression of fluctuations is only 50% compared to a polarized one. Fluctuations in orthogonal polarizations are independent).

The time resolution of our fast coincidence counter of  $T_r = 26$  ps was about three orders of magnitude less than the coherence time. For incoherent illumination of the detectors the electrons behave like classical particles. Due to the insufficient time resolution a certain random coincidence rate is observed. By changing the illumination from incoherent to coherent we expect a reduction of the random coincidences (by a factor  $T_c/T_r$  of about  $10^{-3}$  in our experiment) due to the fact that within the first  $10^{-14}$  s after arrival of an electron no second one is allowed to arrive.

Our experimental set-up corresponds to HBT's stellar interferometer: The tiny effective virtual source of an electron field emitter illuminates via magnifying quadrupoles and image intensifying channel plates two small collectors. With increasing angular magnification the effective lateral distance of the collectors decreases and their illumination changes from incoherent to totally coherent. In turn, a continuous increase of anticorrelations of arrival times of the electrons at the collectors is expected. Features of our cold  $\langle 100 \rangle$  oriented tungsten field emitter are: Extraction voltage 900 V, total current 1.5  $\mu$ A, energy width  $\Delta E_{FWHM}$  of 0.3 eV which corresponds to a standard deviation of  $\Delta E$  of  $\sim 0.13$  eV, virtual source diameter  $\sim 36$  nm, brightness  $4.4 \times 10^7$  A/(cm<sup>2</sup> sr), coherence time  $T_c = 3.25 \times 10^{-14}$  s, coherent particle current  $4.7 \times 10^9$  1/s, degeneracy  $1.6 \times 10^{-4}$ .

In order to prove antibunching a total of four spectra were accumulated for about 30 hrs each:



the first for incoherent illumination of the detectors (dashed lines in Fig. 1), the following for partially, totally and the last again for partially coherent illumination (full lines in Fig. 1). The evaluation procedure of the experimental raw time spectra consisted of smoothing and normalizing the spectra followed by visually superimposing the incoherent with the coherent resp. partially coherent spectra. The antibunching signal  $S$ , i.e. the missing coincidences  $\Delta N$  in the coherent and partially coherent versus the incoherent spectrum becomes visible as a flattening of the peak in Fig. 1 within the time resolution window of  $\pm 13$  ps. In the inset of Fig. 1,  $N_{\text{coh}} - N_{\text{incoh}}$  is given. The measured relative reduction in coincidences for fully coherent illumination amounts to  $S_{\text{rel}} = 1.26 \times 10^{-3}$  with a signal to noise ratio  $S/N$  of 3 (Fig. 1, middle). It agrees with the theoretically expected value calculated from the characteristic features of our cold tungsten field emitter.

Figure 1: Antibunching as a function of coherence of illumination of the collectors (see text). In the pictograms the ellipses represent the coherently illuminated areas, the circles the collector areas. The coherently illuminated parts are marked in black.

The application of electron antibunching in future electron microscopes, e.g., by substituting a conventional field emitter by a polarized one [4] is very promising: Polarized electrons are prevented from approaching each other to within distances of less than a coherence length due to the Pauli principle. Consequently, a drastic reduction of the anomalous energy broadening [5,6] is expected. The energy spread of such a source at low temperatures is on the order of 0.1 eV and should remain low also at high currents. Additionally, according to O. Scherzer [7], when the illumination of the specimen is more homogeneous, radiation damage is reduced.

The support from the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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## THE WIEN FILTER, WHICH-PATH INFORMATION, AND DECOHERENCE

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The Wien filter (i.e., a homogeneous electric and a homogeneous magnetic field both perpendicular to the optical axis and to each other) is usually used as an energy analyzer or a monochromator for electron and ion beams. In an electron interferometer, it acts as a wave-packet shifting device for the laterally separated coherent electron wave packets [1,2]. The Wien filter is said to be in its matched (or compensated) state if the electric and magnetic force for particles travelling on the optical axis and having the main energy component of the electron beam cancel each other, i.e.  $E = v B$  where  $E$  is the electric field strength,  $B$  the magnetic induction, and  $v$  the main velocity component of the beam. If this condition is fulfilled the phase difference between the two wave packets is left unchanged by the Wien filter. This is due to equal but opposite phase shifts caused by the electric scalar and the magnetic vector potential (Aharonov-Bohm phase shifts). The longitudinal wave-packet shift is caused by different electric potentials on the two laterally separated paths in the Wien filter leading to different group velocities. The acceleration and deceleration of the wave packets actually takes place in the fringing fields of the Wien filter capacitor. If the two wave packets have the same position in the direction of the optical axis before entering the Wien filter the longitudinal shift caused by the filter leads to a decreasing overlap of the two wave packets when they are superimposed again (see Fig. 1).

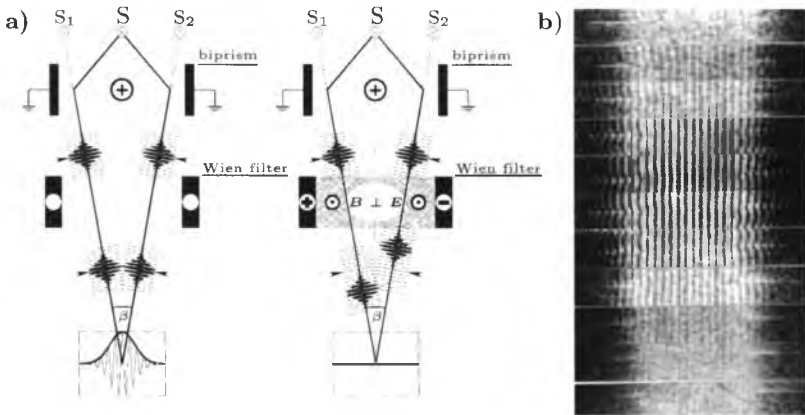


Figure 1: a) Electron biprism interferometer with Wien filter switched off (left) and Wien filter in its excited state (right): The wave packet shift exceeding the coherence length leads to the disappearance of the interference fringes. b) Restoration of contrast by a Wien filter: The longitudinal shift of the wave packets caused by electrostatic deflection elements (top) can be compensated (middle) and overcompensated (bottom) with the Wien filter [2]. The 11 micrographs correspond to 11 different excitations of the Wien filter, increasing from top to bottom.

The decreasing overlap with increasing excitation of the filter manifests itself in a decreasing fringe contrast. The value of the longitudinal shift for vanishing fringe contrast is identical to the coherence length of the electron beam; by Fourier analyzing the decrease of

contrast as a function of the longitudinal shift, the energy spectrum of the particles can be measured in analogy with Michelson's visibility spectroscopy for light [3].

The decrease in contrast of the interference fringes with increasing excitation of the Wien filter can be interpreted as being due to the increasing (*possibility* of getting) which-path ("welcher Weg") information arising from the different times of flight of the two wave packets – though in present experiments we cannot really get this information because of the lack of knowledge of the instant of time when the electron was emitted. The fact that increasing which-path information leads to a decrease in contrast is a manifestation of wave-particle duality – the more we know about the path of the electron – a particle property – the less wave behaviour (interference) we get. This relation can also be grasped mathematically by the formula  $V^2 + D^2 \leq 1$  where  $V$  denotes visibility and  $D$  distinguishability of the paths [4,5]. But because the spreading of the wave packets leads to an increasing overlap between them, the time of arrival becomes more and more unsuitable as an observable for measuring the distinguishability when the distance to the source is increased.

Another way to interpret the decrease in contrast is to consider the delay between the two wave packets as a kind of entanglement: If we write the ordinary state space of the particle as a tensor product of the state space  $X$  of positions on the detection screen and of the state space  $Z$  of positions orthogonal to that screen (i.e., along the optical axis  $z$ ), then because of the longitudinal distance  $\Delta z$  of the positions of the maxima of the wave packets we have entanglement of the states in  $X$  with those in  $Z$ . Yet this is only fully justified if the state of the split wave packet before entering the Wien filter is itself not an entangled state but a product state in  $X \otimes Z$ . In this case, when the excitation of the Wien filter is increased, we really have entanglement with increasingly orthogonal states in  $Z$ . Such entanglement leads to a loss of contrast because states which are entangled with orthogonal states in another state space cannot interfere with respect to any observable acting on only the first space.

The loss of contrast caused by the Wien filter is totally reversible: By combining two Wien filters with opposite excitation, the effect of the first of these can be undone. Again, this can be interpreted in different ways, either by the loss of which-path information or by the fact that the  $z$ -coordinates of the maxima of the two parts of the wave packet are made equal again. The second Wien filter can be looked upon as a quantum eraser, but with the difference that we do not lose intensity by this process. This is because we do not project onto – or at least detect in correlation with – a 'labelling space' state (of which both packets have equal components), but instead make the two labelling states equal.

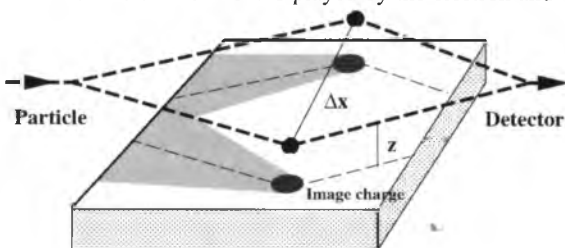
Furthermore, this demonstrates that coherence is not lost but only hidden after the first filter. Fig. 1b shows how interference which was lost due to the electrostatic fields of the deflection elements is restored by the Wien filter. (This process is explicitly described in [2].)

So far we have dealt exclusively with reversible loss of coherence being due to reversible entanglement. In contrast, *decoherence* [6] is the emergence of classical features of quantum systems through the irreversible formation of quantum correlations (entanglement) with the environment, caused by an unavoidable interaction between the system and its environment. Decoherence can explain, for example, why we do not observe superpositions of position eigenstates (e.g., a table being here and over there at the same time, or a pointer of a measuring instrument indicating different outcomes simultaneously) or Schrödinger cats (a cat being both dead and alive) in our everyday lives. Decoherence is a first step to solve the measurement problem of quantum physics as it can account for the fact that one does not observe a superposition of different outcomes of a measurement.

In case of the Wien filter the experiments show that there is no decoherence emerging from the – doubtlessly, absolutely *reversible* – interaction of the electron with the electromagnetic fields or with the environment (capacitor plates of the Wien filter). The latter is negligible due to the large distance to the capacitor plates as we will see in the following.

An experiment on decoherence in which a highly controllable environment is realized by a conducting plate has been proposed by Anglin and Zurek [7] and is being in progress in our laboratory. A charged particle beam (in our case an electron beam) is split and both wave packets travel over a conducting plate with finite resistivity before they form an interference pattern (see Fig. 2). Contrast, being a measure for decoherence, is influenced by two parameters: One is the height  $y$  of the trajectories over the conducting plate, the other is the spatial separation  $\Delta x$  of the coherent beams. The decoherence time is proportional to  $y^3/(\Delta x)^2$ . The reason for decoherence is the following: An electron above a conducting plate causes an induced charge in the plate, and as the electron moves, so does the induced charge. Therefore we get an electric current in the plate which encounters ohmic resistance, thus a disturbance of the electron and phonon gas in the plate results. This disturbance is different for the two *paths* of the electron. So we get *entanglement* of the beam electron with the electron and phonon gas inside the plate. As dissipation is an *irreversible* process, a record of the electron's path *remains* when the electron has crossed the plate and the two parts of the beam are brought together again. So in this model experiment the object which gets 'classical' properties is the beam electron and the role of the environment is played by the electron and phonon gas in the conducting plate.

Figure 2: Sketch of decoherence experiment [7]. The two different trajectories of the electron over the conducting plate lead to different disturbances (shaded regions) in the electron and phonon gas inside the plate.



By varying the parameters  $y$  and  $\Delta x$  (as well as the resistivity of the plate), we can adjust the strength of decoherence ranging from negligible to strong decoherence and so reproduce the transition from quantum to classical behaviour.

For our experiment we use a compact rigid electron interferometer [8]. The electron beam emerging from the field emission diode electron gun is aligned to the optical axis by an electrostatic double deflection element. Then the beam is split by a negatively charged Möllenstedt biprism. The lateral separation of the two rays is enlarged by an electrostatic quadrupole (positively charged in the plane of the beams). After passing the conducting plate, the rays are directed towards each other by an oppositely charged quadrupole. The superposition angle is diminished by another quadrupole in order to get larger fringe spacing. As usual, the primary interference field is magnified by two quadrupoles. To compensate for slight misalignment, coils to rotate the image and deflection elements are incorporated. The height of the beams over the plate can be adjusted as well mechanically by moving the plate as electron-optically by double deflection elements before and after the plate (Fig. 3)

In general, the electrostatic deflection elements will cause longitudinal shifts of the two wave packets relative to each other. Hence there will be loss of contrast also due to this effect which is absolutely reversible. Therefore, to discriminate between this and the loss of

contrast ensuing from decoherence, it is indispensable to introduce a Wien filter in the beam path to compensate for this longitudinal shift. By varying the excitation of the matched Wien filter we can change the longitudinal distance between the interfering wave packets and so vary contrast (see Fig. 1) until it takes its maximum value which is then determined by the strength of decoherence.

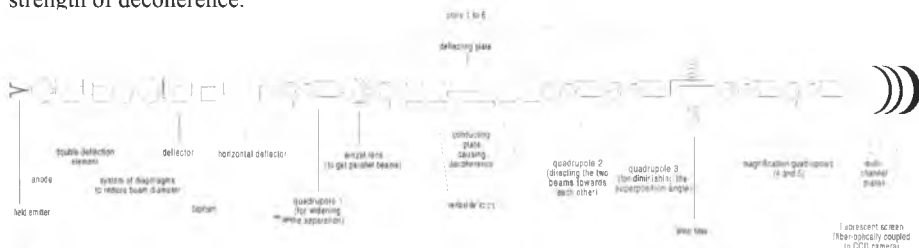


Figure 3: Schematic set-up of the experiment. All electron-optical components which are possibly necessary for perfect adjustment are shown in this drawing.

Support of the experiment on decoherence by Deutsche Forschungsgemeinschaft under contract No. HA 1063/20 is gratefully acknowledged.

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DEVELOPMENT AND TEST OF A POLARIZED COOLED ELECTRON GUN

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After the successful realization of a spherically corrected objective lens for electron microscopes by Rose [1] it is now necessary to reduce the chromatic aberration to reach sub-Ångström resolution. The energy spread of electron beams is caused by the energy distribution of the field emission process and the Boersch broadening in regions of high current density. Two ways to reduce the aberration disk caused by chromatic aberration are conceivable: Firstly, using of a monochromator to diminish the energy width of the electron beam to about 0.2eV putting up with an unavoidable loss of brightness and intensity. Secondly, using an electron gun with an intrinsic energy spread low also at high current densities. The reason for the Boersch effect are Coulomb interactions of the electrons. In 1983 Rose and Spehr [2] predicted that the anomalous energy broadening in crossovers could be reduced drastically by using a polarized electron gun. Because of the Pauli principle in a totally polarized electron beam every phase space cell is occupied by at most one electron. Therefore the distance of electrons also in high current density regions can't be smaller than about a coherence length. Consequently their Coulomb interaction and the anomalous Boersch broadening should be drastically reduced. In the present work we develop such a polarized electron gun, investigate in a first step the energy broadening at low currents and in a second step we want to explore whether the energy spread remains small at currents in  $\mu$ A-region necessary for electron microscopy.

For the development of a polarized electron gun we picked up an idea from a group in Bielefeld [3, 4] who investigated this source for low currents. Onto a normal single crystalline <100>-oriented tungsten tip a thin layer of the ferromagnetic europium sulfide (EuS) is evaporated and cooled below its Curie-temperature of 16.5K. The band structure of EuS and the emission mechanism (see text) are depicted in Fig. 1.

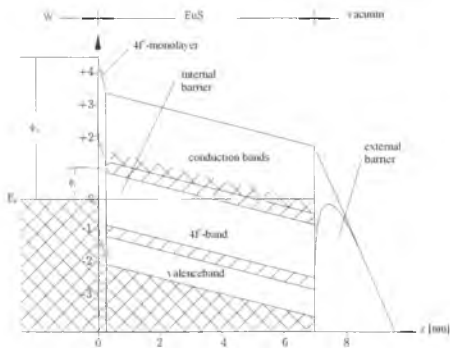


Figure 1: Bandstructure of EuS and emission process of polarized electrons

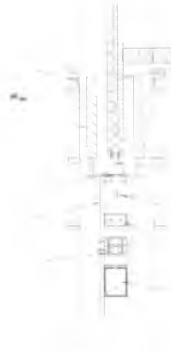


Figure 2: Experimental set-up

The band structure of EuS in its ferromagnetic states shows a half filled localized  $4f^7$ -band between valence band and conduction band. Hund's rule tells us that all electrons in the  $4f^7$ -band have the same spin orientation. Magnetic exchange interaction leads to a splitting of the conduction band into two bands with respect to spin orientation. After applying a high external extraction field to the tip, the conduction bands are tilt down beneath the Fermi level of tungsten so that electrons tunnel through an internal tunnel barrier into the EuS and then into vacuum. In EuS the electrons occupy spin states with a preferred spin orientation so that the EuS layer acts as a spin filter.

The results of the Bielefeld group were very promising. A polarization degree  $P$  of 85% and an energy spread as low as 0.1 to 0.2eV were reached at beam currents of only a few tens of nA (see Table 1).

The experimental set-up of our source is shown in Fig. 2. The tip is mounted onto a helium cryostate and can be evaporated with EuS through the hole of the anode by an EuS-oven, which can be brought onto the tip axis during evaporation. After evaporation of EuS onto the tip it is important to temper the EuS-layer in a very critical annealing process to get a single crystalline structure of EuS and a layer with uniform thickness. The electron beam can be deflected by double deflectors and focused by electric and magnetic lenses. The energy distribution will be measured with a Faraday cup retarding field spectrometer. The test of this energy spectrometer is in progress.

In the following table a comparison of the properties of several electron guns used in electron microscopy is shown. In an earlier work in our group [5] the brightness of the gun was measured to  $B = 9.2 \text{ A/cm}^2 \cdot \text{sr}$  at an extraction voltage of almost 1kV and a total current of 3.6μA. The energy spread and the degree of polarization of the EuS-W source are result of the measurements of the Bielefeld group at currents of a few nA.

| Emitter | $T$<br>[K] | $I$<br>[μA] | $r$<br>[nm] | $E$<br>[eV] | $P$<br>[%] | $U$<br>[kV] | $B$<br>[ $10^7 \text{ A/cm}^2 \cdot \text{sr}$ ] | $B$<br>[ $10^9 \text{ A/cm}^2 \cdot \text{sr}$ ] |
|---------|------------|-------------|-------------|-------------|------------|-------------|--------------------------------------------------|--------------------------------------------------|
| EuS-W   | 10         | 3.6         | 1.3         | 0.1...0.2   | 85         | 0.93        | 9.2                                              | 10                                               |
| W       | 300        | 1.0         | 16          | 0.4         | 0          | 50          | 100                                              | 2                                                |
| ZrO-W   | 1800       | 80          | 4           | 1.0...1.5   | 0          | 4           | 142                                              | 36                                               |
| LaB     | 1800       | 200         | $10^4$      | 0.5         | 0          | 20          | 0.1                                              | 0.005                                            |

Table 1: Comparison of the properties of several electron guns:  $r$ vs: virtual source radius,  $P$ : Polarization degree,  $U$ e: extraction voltage,  $B$ : brightness at extraction voltage and the calculated brightness at 100 kV.

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## IMPROVEMENT OF SINGLE CRYSTAL SCINTILLATOR PROPERTIES IN SEM DETECTORS

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Properties of the scintillation – PMT detection system in SEM depend on the properties of the scintillator and the light guide, for all. Efficient electron-photon energy transfer, very short decay time of luminescence and an efficient transfer of photons along the light guide to the photomultiplier are the decisive properties for the efficient detection system.

A variety of the scintillation materials have been proposed for the detection of signal electrons in SEM. Nevertheless, the range of the suitable scintillators is restricted to powder phosphor of yttrium silicate (phosphor P47), plastic scintillators (NE 102 A) and single crystal scintillator based on yttrium aluminium garnet (YAG) and perovskite (YAP) [1]

YAP single crystal has not been used for the detection of signal electrons commercially until nowadays. Relatively short wavelength of maximum light emission at 370 nm was a very serious limitation for commercial using of YAP because the light transmission of 370 nm wavelength is very low in light guide made from an organic glass. Quartz glass is more suitable material but relatively expensive [2].

Further problem was very high self-absorption of the generated light emission itself (20% in 5 mm thick single crystal).

One more problem was found in the polishing process of the YAP surface. The surface is very easily scratched and these cracks contain certain amounts of impurities from mechanically polishing material.

First of all, a special light guide material was developed for transmission of light of 370 nm wavelength. This organic glass contains special organic dopants increasing the light transmission in a short wavelength region of spectra (Fig. 1). The light from YAP is transmitted to 95 % in the light guide rod 150 mm in length and 20 mm in diameter.

Secondly, owing to the additional treatment of the YAP single crystal discs in oxygen and hydrogen atmosphere at very high temperature, the colour centres in the YAP or YAG crystal lattice have been suppressed. Self-absorption of generated light was halved to approx. 10 % in YAP.

Thirdly, owing to the modified technological process of growing the YAP single crystals and the additional treatment of the YAP discs, the decay time  $1/e$  has been shortened from the older value of 30 ns to 17 ns now, for the incident electron energy of 10 keV (Fig. 2)

Fourthly, the polishing process of the YAP surface causes penetration of polishing microparticles into the surface microcracks. They can be removed by a washing process only, in a special mixture of acids at a suitable temperature. The smoothness of the YAP surface is decreased by this treatment but the relative efficiency of the electron-photon transfer is increased. Schema of the surface relief is shown in Fig. 3A,B.

All these technological steps enable to improve the scintillation properties of single crystal scintillators, namely of YAP, which has the shortest decay time from all single crystal scintillators. Its wavelength is spectrally well matched to all alkaline photocathodes, so that there is no problem regarding the choice of PMT. The short wavelength light transmission of

newly developed light guide from organic glass ensures achievement of high efficiency in the light transfer from YAP to the PMT photocathode.

New YAP is now very efficient single crystal scintillator, suitable for all types of the detectors in SEM. It can replace YAG single crystals used up to date in the BSE detector.

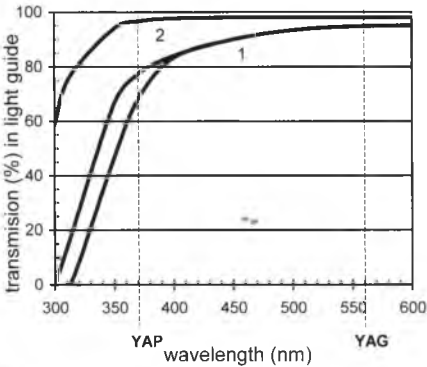


Figure 1: Transmission spectra of the commercial standard organic glass (1) and newly modified organic glass (2).

Figure 2: Time characteristics of YAP and YAG ( $1/\tau_{YAP} = 17\text{ ns}$ ,  $1/\tau_{YAG} = 70\text{ ns}$ ).

Figure 3: Schematic relief of the single crystal surface after the polishing process A and after the additional treatment B.

Fig. 1.

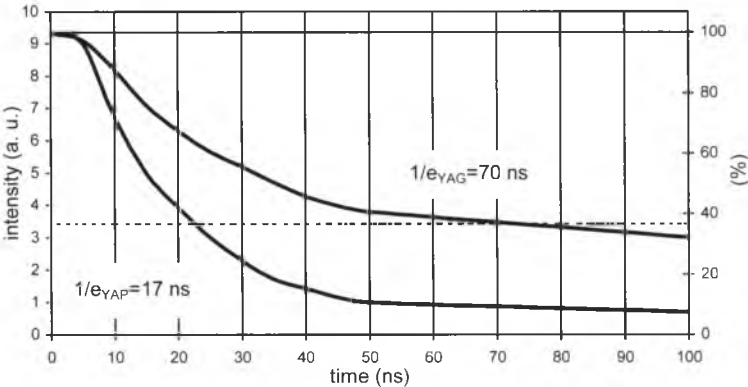


Fig. 2.

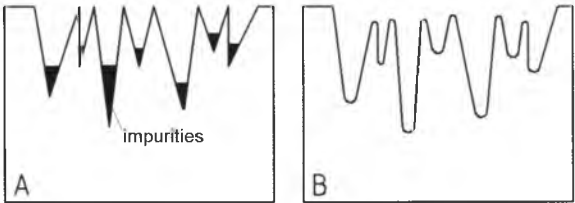


Fig. 3.

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## COMBINED DETECTOR FOR BSE, SE AND BSE+SE DETECTION IN A LOW VOLTAGE SEM

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Specimen observation at a low accelerating voltage of the electron beam (around 1 kV) is new and attractive technique of scanning electron microscopy. While detection of the signal of secondary electrons (SE) with the help of the scintillation-photomultiplier system described by Everhart-Thornley [1] does not depend on the primary beam energy, the detection of backscattered electrons (BSE), having their energy only a bit lower than energy of the beam, is limited by a low sensitivity of semiconductor or channel plate detectors to electrons of energy below 2 keV.

The threshold energy of the scintillation-photomultiplier BSE detector with a high efficient scintillator, made of the single crystal YAG or YAP, amounts to 1.3+1.2 keV. The light output of the detector, achieved for BSE below the threshold energy, is very low and practically unusable. Insufficient number of photons, generated due to incidence of one low energy electron on the scintillator, is the main reason for this problem. The reasons also include relatively low quantum efficiency of all known scintillators (not more than 7%) and complicated transfer of photons from the scintillator to the photomultiplier [2].

Solution to this problem is to accelerate the BSE before they impinge upon the scintillator. If a positive voltage is applied to the conductive coating of the scintillator, an electrostatic field is produced in which all signal electrons (SE and BSE) emitted from the specimen are gradually accelerated in the direction of the field and they impinge upon the scintillator with an energy corresponding to the voltage on the scintillator.

There are several ideas how to form the geometry of this field [3]. The easiest way is to cover the scintillator with a metal conductive layer, positively biased to e.g. 4 kV. If the scintillator is exposed to impact of BSE, i.e. located close beneath the pole piece, all fast BSE are accelerated in the field direction and impinge upon the scintillator. But in this case not only BSE but also SE are accelerated toward the scintillator. The resulting image is formed by a mixture of SE and BSE and represents both the topographical and material contrast of the specimen.

SE detection can be suppressed by a retarding grid placed tightly under the scintillator electrode and supplied by a low negative voltage of approx. -50 to -80 V. The negatively biased retarding grid shields entirely SE leaving the specimen. The detector detects only BSE and the image of the specimen contains the material contrast.

If an image with higher content of SE is to be recorded, the detector must be retracted into a position outside the impact of BSE. The SE detector must be located in a suitable distance from the specimen. SE should be extracted toward the scintillator by electrostatic field so that BSE with a relatively high energy reach the scintillator in a very low number only. The scintillator is supplied with a higher voltage of + 6 kV and the grid below the scintillator is supplied with 100 V positive voltage. Some small portion of BSE can be attracted and impact the scintillator but the image character is dominated by the topographical contrast of SE.

In this way, the above described detector can be used for detection of low energy BSE (ranging from 0.5 to 3 keV), high energy BSE (between 3 and 30 keV), as well as for detection of SE or a mixture of SE and BSE.

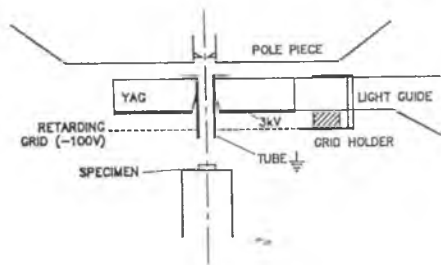


Fig. 1

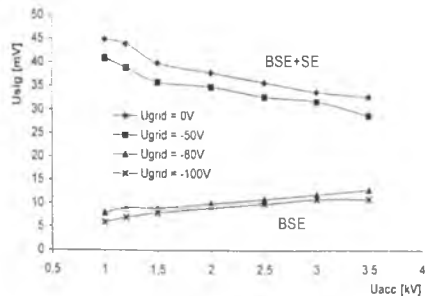


Fig. 2

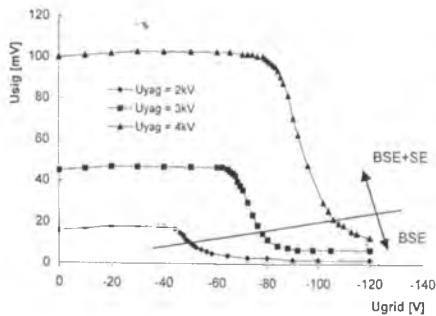


Fig. 3

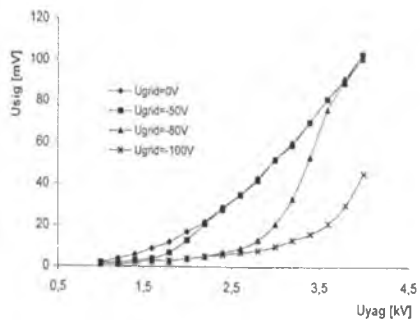


Fig. 4

Figure 1: Low voltage configuration of YAG-BSE detector

Figure 2: The SE and BSE signals as functions of the accelerating voltage of the beam.

Figure 3: The SE and BSE signals vs. the scintillator voltage for various voltages on the retarding grid

Figure 4: The BSE and SE+BSE signals vs. the retarding grid voltage for various voltages on the scintillator.

This project was supported by the Grant Agency of the Czech Republic under grant No. 102/01/1271.

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## X-RAY MICROANALYSIS IN ESEM AND LV SEM

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The scattering of primary electrons to so-called skirt, appearing in the range of pressures used in regimes of LV SEM (low vacuum) as well as in ESEM, has no substantial influence on the spatial resolution for commonly used types of imaging in the scanning electron microscope. It demonstrates itself just as a higher share of the noise signal. What is more, it brings known substantial advantages, as that no preparation or modification of non-conductive samples is needed and observation of liquid phase containing specimens is made possible.

As regards the X-ray analysis, the situation is rather more complicated.

In the ESEM the presence of gas in the specimen chamber influences the results obtained by X-ray microanalysis, which is caused by two effects.

- interaction of electrons with the gaseous environment leading to generation of X-ray signals
- scattering of the primary beam electrons to so-called skirt, which causes generation of the X-ray signals also in the vicinity of the observed area on the specimen.

The first effect can be partly suppressed by reducing the distance, which primary electrons pass within the gaseous environment. G. Gilpin and D.C. Sigeo [1] carried out experiments with a sample of carbon and cyanobacterium *Anabaena cylindrica* at accelerating voltage of the beam 10 kV and for 100 s lifetime. The specimens were cooled by a Peltier stage to the temperature of 6-8 °C. The probe spot diameter of 0.7 μm was used. The typical count rate was taken to be  $1-2 \times 10^3$  cps. Peak/background (P/B) ratios were determined with respect to the background in vicinity of the characteristic peak. For the carbon specimen in the high vacuum (where the influence of gas does not demonstrate itself) a dominant carbon peak was detected but also a small oxygen peak appeared because of impurities in the material. Insertion of water vapor into the specimen chamber led to increase in the P/B ratio for oxygen because of contribution of the water molecules. It is interesting that the P/B ratio for carbon did not change substantially for pressures up to approx. 1300 Pa. For a frozen biological specimen comparison was made with situation in vacuum as well as with the same specimen not frozen at higher pressures. A scope of elements contained in the specimen was found up to the pressure of 684 Pa identical to that in vacuum. Despite the P/B ratio was reduced, of course. The measurements were carried out also in the argon atmosphere. An interesting effect was demonstrated: for water at higher pressures a strongly nonlinear increase of the oxygen peak occurred, while for Ar a linear dependency was found out. Further interesting results concern the influence of the specimen distance, etc. The authors stated that the X-ray microanalysis in ESEM provides with useful information, which, nevertheless, needs careful interpretation.

Robert A. Carlton [2] focused himself on optimisation of working conditions for X-ray analysis in ESEM. He changed the accelerating voltage of the beam from 10 to 20 kV and worked at pressures from 66 to 665 Pa. He states that in most spectra the elements of the substrate were detected as well. But X-ray counts can be expected also from the construction

materials so that these materials should be chosen carefully. Experiments showed that the presence of undesirable particles up to distance of one millimetre from the target can contribute to the X-ray spectrum. It seems possible that an orientation effect of such particles exists, according to their position between the detector and target. Some of them can influence the resulting spectrum, while other particles do not have to. He estimated, that the specimen used as a standard should have minimum diameter of 2 mm. In the argon atmosphere he observed a gas fluorescence. His results support the idea that optimum X-ray microanalysis in ESEM should be performed at a minimum trajectory of primary electrons within the gas and he recommends also to turn the attention to minimisation of the accelerating voltage, consistent with the optimum overvoltage requirements of the elements under examination.

The contribution of Jorgen B. Bilde-Sorensen and Charlotte C. Appel [3] with interesting main idea of correction of the skirt influence is based on the fact, that electrons scattered in the gaseous environment can extend the source of the X-ray spectra up to a distance of several hundreds of  $\mu\text{m}$  from the beam spot. Thus, the spatial resolution for X-ray spectrometry can be strongly influenced. They designed a method of the pressure variation. This method enables extrapolation of spectral measurements taken at higher pressures to the "zero" pressure. For so called single scattering regime the ratio of not dispersed electrons is given as

$$I / I_0 = \exp(-p \sigma L / k T),$$

where  $p$  is the pressure,  $\sigma$  is the total scattering cross section of the gas being used,  $L$  – distance (path of electrons),  $k$  – Boltzmann constant and  $T$  – absolute temperature.

The total count rate for a given X-ray line is

$$c_T = c_u \exp(-p m) + c_s [1 - \exp(-p m)];$$

$c_u$  – count rate that would be obtained without any scattering of the primary electrons,

$c_s$  – count rate that would be obtained if all electrons were scattered once, and

$$m = \sigma L / K T.$$

It is possible to rewrite the equation into the form

$$c_T = (c_u - c_s) \exp(-p m) + c_s.$$

By transformation to the linear dependency  $y = k x + q$  and determination of  $(c_u - c_s)$  and  $c_s$  for several (at least two) measured values  $c_T$  and  $p$ , we can find linear regression for the given dependency. These spectral measurements meet the criteria of Poisson statistics, and therefore the standard deviation of total counts equals the square root of those counts.

Examples of the dependencies for the Cu – Ni interface are presented in Figs. 1 and 2. The number of Ni counts per second increases with the decrease of pressure so that this is the useful signal.

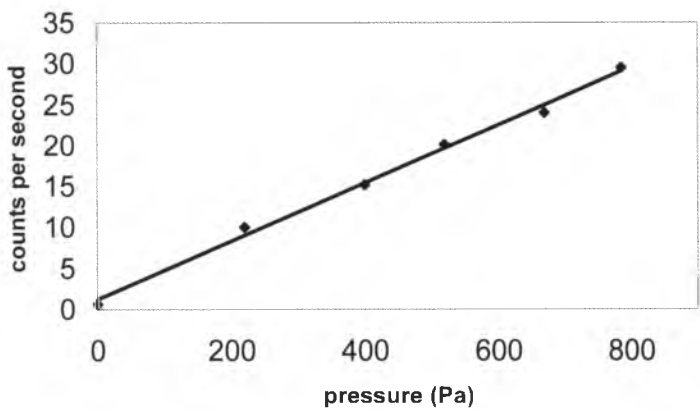


Figure 1: Counts per second for Cu Ka as a function of pressure, acquired from a point on pure Ni, 10  $\mu\text{m}$  away of a straight interface to pure Cu [3].  
It is obvious from the figure that for the zero pressure the number of counts decreases to zero, so that the signal formed by electrons scattered in so called skirt is in question.

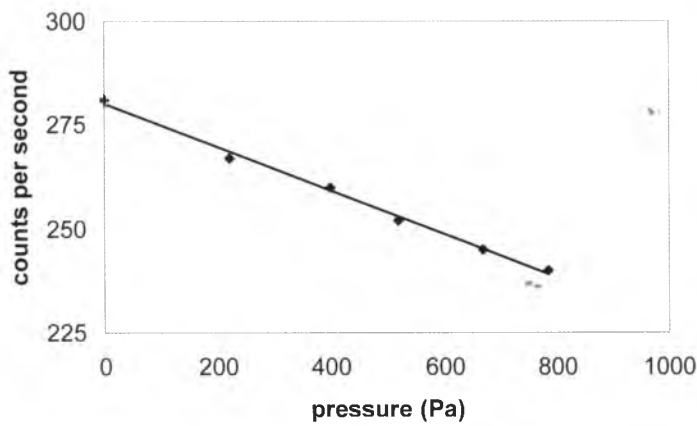


Figure 2: Counts per second for Ni Ka as a function of pressure, measured in a point on pure Ni, 10  $\mu\text{m}$  off a straight interface to pure Cu [3].

One can conclude that the above mentioned method is very advantageous for improvement of possibilities of the X-ray microanalysis in ESEM and enables one to assess the true specimen composition easily via measurement of 4 or 5 values for different pressures.

This work was supported by the Grant Agency of the Czech Republic, grant No:102/01/1271.

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## DETECTION OF SIGNAL ELECTRONS AT HIGHER PRESSURE IN THE SPECIMEN CHAMBER

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The advantages of the scanning electron microscopy working at higher pressures in the specimen chamber are connected with the possibility of observation of specimens structures, which are difficultly observable without previous preparation for microscopes working with pressures in the specimen chamber under  $10^{-2}$  Pa. The pressure in the specimen chamber up to approx. 2000 Pa brings the possibility of observation of specimens, which release gases, specimens containing liquid phase, including wet biological preparations, reactions on the phase interfaces, etc. At higher pressures in the specimen chamber it is also not necessary - due to neutralisation of the surface negative charge by gas ions - to coat electrically non-conductive specimens by a conductive layer.

For detection of signal electrons at higher pressures scintillation and ionisation detectors are usually exploited. In our case the scintillation detector is constructed as a double-deck one and serves for detection of backscattered electrons. YAG:Ce has been used as the scintillation material. The scintillator with a central hole in the bottom detector ensures the integrated function of the BSE signal detector and the pressure-limiting aperture, necessary for limitation of the gas flow at microscopes working with higher pressures in the specimen chamber. The single crystals in both detection stages are symmetrically divided into the right and left halves. The interface between them is provided with an optical reflecting layer. Both detection stages thus provide two paired signals, separately from the left and right half. The possibility for further processing of signals from both halves of the individual stages and their mutual combination create preconditions for the achievement of a higher material or topographic contrast from the studied specimen [1]. The bottom scintillation detector is used for detection of backscattered electrons at working specimen/detector distances usually within 1 – 3 mm. At larger working distance and also pressure in the specimen chamber, the level of the detected signal decreases. In order to work at high pressures, when the signal detected at the working distance of mere 1 mm is of bad quality, suppression of the electron scattering in the high pressure environment requires to reduce the working distance even below this level. In the case given a significant part of backscattered electrons escapes through the central hole of the bottom scintillator to the upper space. Hence, it is advantageous to detect these backscattered electrons by the upper stage of the scintillation detector.

At higher pressures the ionisation detector detects the products of collisions of electrons with the gaseous environment in the specimen chamber. The gas ionisation is contributed by the secondary electrons (SE) as well as the backscattered electrons (BSE) and primary electrons (PE). The electric field formed between the electrode of the ionisation detector and the specimen, which is on the earth potential, provides the necessary energy for ionisation to the secondary electrons and to the products of ionisation. The computations of shares of the individual sources as regards the total detected signal for specific conditions of the specimen observation [2] show, that the SE share is biggest, PE share is lesser, while the smallest part of the signal is formed by BSE. Typical dependency of the signal level on the pressure for different working distances of the specimen is depicted in Figure 1.

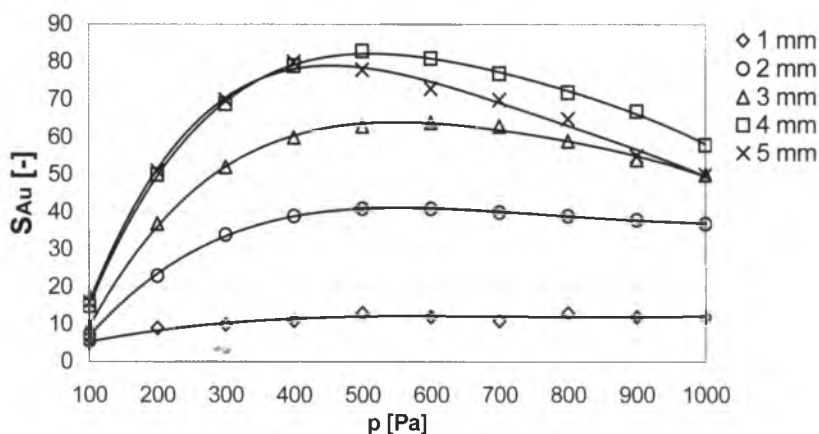


Figure 1: Dependency of the signal from gold on the pressure for different working distances. Ionisation detector, environment of water vapors, the voltage on the detector electrode of 350 V, energy of primary electrons of 20 keV.

Unlike the detection by scintillation detector the signal level shows maximum for a given working distance at a certain value of pressure, at which the conditions for impact ionisation in gas are optimum. This value of pressure decreases with increasing working distance. The extent of the signal amplification by the impact ionisation as well as the position of the maximum is dependent on the gaseous environment used in the specimen chamber. Use of the saturated water vapours instead of a residual air brings several times higher signal amplification, shift of the maximum toward higher pressures, and otherwise it is advantageous from the viewpoint of prevention of drying up of wet specimens.

## Conclusion

Scintillation and ionisation detectors exploited for detection of signals at higher pressures in the specimen chamber enable detection of backscattered electrons and/or secondary electrons with a contribution of the backscattered ones. While the signal detected by the scintillation detector decreases with the growing pressure in the specimen chamber, for ionisation detector the maximum of the signal amplification by the impact ionisation in gaseous environment at a certain value of pressure is typical. This value can be influenced by the choice of the working conditions as well as the gaseous environment used.

This work was supported by the Grant Agency of the Czech Republic, grant No.102/01/1271.

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## INFLUENCE OF SIZE OF THE IONISATION DETECTOR ELECTRODE SYSTEM ON SIGNAL DETECTION IN ESEM

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### Introduction

The Environmental Scanning Electron Microscope (ESEM) is a new form of Scanning Electron Microscope (SEM), which supports a gaseous atmosphere and the presence of liquid water in the specimen chamber. This opens up new possibilities for the use of ESEM to the study of many biological and wet based systems, which previously could not be observed.

609 Pa is the minimum pressure, at which we can observe wet samples without any degradation by evaporation. Nowadays scanning electrons microscopes are called environmental if they operate with pressure from 300 to 2000 Pa.

### Theoretical background

Ionization detector is a device, which uses the atmosphere in the specimen chamber for the detection and amplification of the signal electrons.

The theoretical principles of gas ionisation were described in detail in [5]. The total amplified ion current can be found by summing all cascade contributions. These contributions are given by

*primary electrons:*

$$I_{PEG} = I_{PE} S_{PE} p k \quad (1)$$

*secondary electrons:*

$$I_{SEG} = I_{PE} \delta k \alpha \quad (2)$$

*and backscattered electrons:*

$$I_{BSEG} = I_{PE} \eta S_{BSE} p k \frac{\bar{d}}{d} \quad (3)$$

Where  $I_{PE}$  is primary beam current;  $p$  is pressure;  $d$  is working distance,  $\bar{d}$  BSE path length;  $\delta$  and  $\eta$  are SE and BSE coefficients and  $k$  is:

$$k = \frac{\exp(\alpha d) - 1}{\alpha \{1 - \gamma [\exp(\alpha d) - 1]\}}$$

where  $\alpha$  and  $\gamma$  are Townsend first and second ionisation coefficients, respectively.

With knowledge of the ionisation properties of a given gas, we can calculate the amplification of electrons in the gas as a function of pressure, working distance and electron beam energy.

Detection volumes allocated with concentric annular electrodes of the ionisation detector are shown on Fig. 1. The electrode with the smallest radius collects mainly secondary electrons, larger ones collect growing contribution of backscattered electrons.

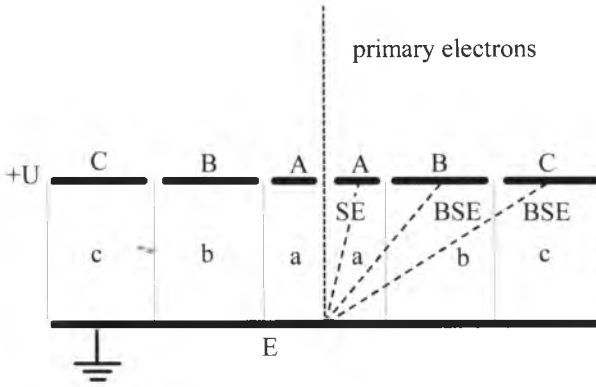


Figure 1: Separation of detection volumes by concentric annular electrodes with uniform electric field. In volume (a) SE are mainly detected, in volumes (b) and (c) various types of BSE are detected [1].

### Experiment

We prepared three different annular electrode systems of the ionisation detector in order to determine how the size of the electrode affects the detected signal and its dependence on the pressure in the specimen chamber. The inner electrode radius was for all electrodes the same (1.1 mm). The outer radius changed and was 3.3, 7 and 14 mm - see Fig. 2.

For these three electrodes we measured the dependence of the signal, obtained from specimens of gold and carbon, on the working pressure of air in interval from 100 to 1000 Pa. The primary beam current was the same for all experiments, 140 pA, as measured at the pressure 20 Pa in the specimen chamber. The dependence was measured with electrode voltages 300 V and working distance between specimen and detector 1, 2, 3, 4 and 5 mm.

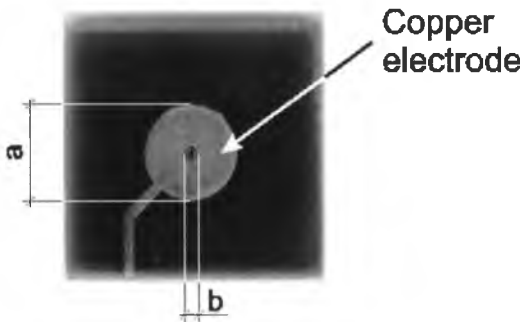


Figure 2: Collector electrode prepared by PCB technology. Inner radius  $b = 1.1$  mm, outer radius  $a = 3.3$ , 7 and 14 mm.

Results of measurement

The measured dependences of the relative signal level from the gold specimen on pressure for all three electrodes are shown in Fig. 3.

Similar dependences of the material contrast are shown in Fig. 4. Material contrast, in our case, is taken as the difference of relative signals from gold and carbon specimens.

Both dependences are plotted for the working distance 4 mm. The signal level was the highest for this working distance for all three electrodes.

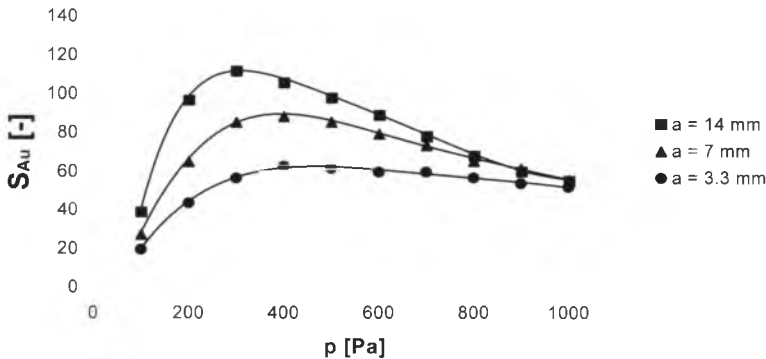


Figure 3: Dependences of the relative signal level from the gold specimen on working pressure for electrodes with outer diameter 14, 7, 3.3 mm. Working distance 4 mm, electrode voltage 300 V, primary beam current 140 pA.

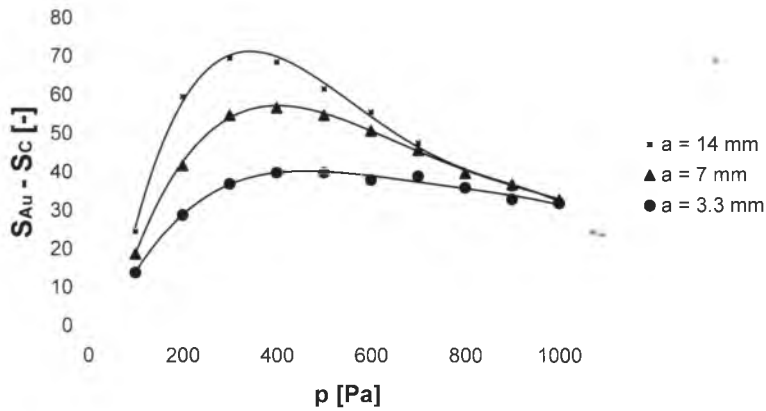


Figure 4: Dependences of the material contrast on pressure for electrodes with outer diameter 14, 7, 3.3 mm. Working distance 4 mm and voltage 300 V, primary beam current 140 pA.

Conclusion

The experiments proved that the relative signal level from the gold specimen, as well as the material contrast, are the highest when the largest annular electrode is used. This

electrode collects SE and almost all BSE, so that contribution of BSE in the process of impact ionisation is maximum. The best conditions for the sample observation by this electrode are working distance 4 mm and air pressure 300 – 400 Pa in the specimen chamber.

It is evident that the maximum of the signal amplification and contrast with increasing radius of the electrode moves to lower pressures. Both trends are caused by the contribution of backscattered electrons to the total detected signal that grows with increasing dimension of the electrode.

The experiment is supported by the grant no. 102/01/1271 provided by the Grant Agency of the Czech Republic.

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## INFLUENCE OF PRIMARY ELECTRON ENERGY ON THE SIGNAL DETECTED IN ESEM

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### Summary

This work is focused on the influence of the primary electron energy on signal detection with ionisation and scintillation detectors in the environmental scanning electron microscope.

### 1. Introduction

Ionisation and scintillation detectors are used for detection of the signal electrons in the environmental scanning electron microscope (ESEM). The principle of the ionisation detector is based on amplifying effect of the impact ionisation. Signal of electrons is amplified in gaseous environment in the specimen chamber of the ESEM [1]. Scintillation detector detects only backscattered electrons (BSEs) at environmental conditions. Energy of these electrons is sufficient to excite scintillation in the scintillator of this detector.

For both detectors the level of the detected signal depends on the gas pressure in the specimen chamber. Experiment is focused on influence of the primary electron energy on the signal detected with these detectors.

### 2. Experiment

Construction of the used detector combines ionisation and scintillation detector in one system (Fig. 1.). The single crystal (yttrium aluminium garnet doped with Ce) with the central hole of about 500  $\mu\text{m}$  in diameter is located above the sample and is used as the pressure-limiting

aperture [2] separating spaces with different pressures of gases. This design provides the detection of BSE with large collection angle under environmental conditions. Thin ITO layer circle electrode on the bottom of the single crystal with a potential up to 500 V affects the impact ionisation in the gas environment and is used as a collection electrode of the ionisation detector.

The dependencies of the signal level on the pressure of water vapours in the range from 100 to 1000 Pa were measured for different values of primary electron energies. The measurements were carried out on the standard specimen of gold with a constant value of the primary beam current of 140 pA.

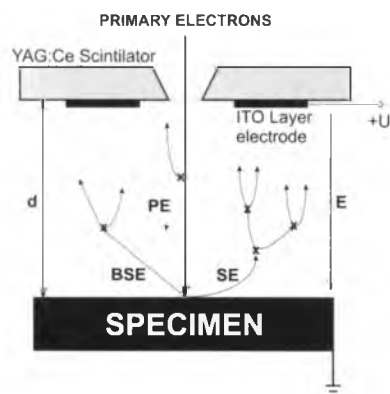


Figure 1: Configuration of the detection

The measured dependencies are plotted for the scintillation detector in Fig. 2. Similar dependencies for the ionisation detector are shown in Fig. 3.

### 3. Conclusion

The measured dependencies for the scintillation detector show that the signal level declines with decreasing primary electron energy. The reason is the larger scattering of primary and backscattered electrons with gas molecules at lower energies. The increasing pressure of the water vapours causes scattering of primary and backscattered electrons too and signal level drops.

For the ionisation detector the increasing contribution of the impact ionisation of BSE with lower energy of the detected signal probably compensates the higher scattering of the lower energy primary electrons in gas environment. The signal level softly increases with decreasing primary electron energy.

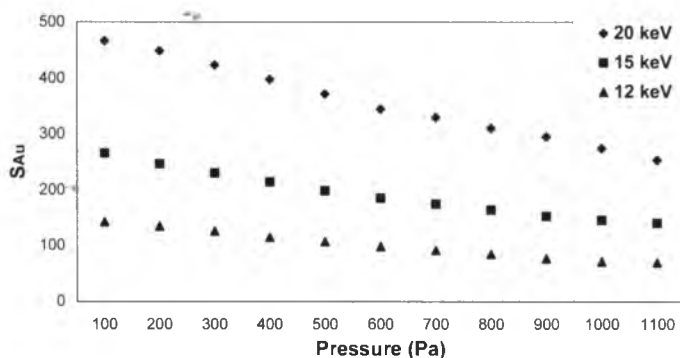


Figure 2: Dependencies of signal level from gold on pressure of water vapours for scintillation detector. Primary electron energy 20, 15 and 12 keV, working distance 1 mm.

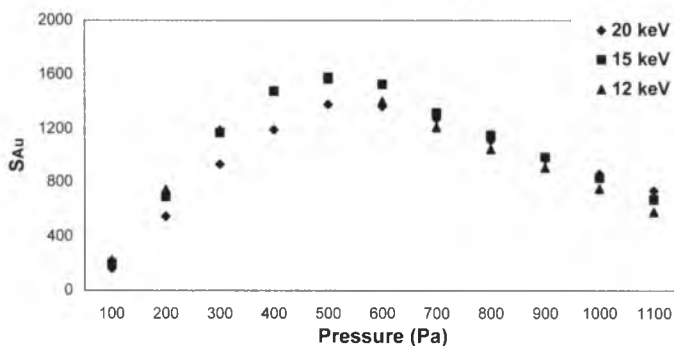


Figure 3: Dependencies of signal level from gold on pressure of water vapours for ionisation detector. Primary electron energy 20, 15 and 12 keV, working distance 4 mm, voltage on ionisation detector electrode 400 V.

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## INFLUENCE OF THE GAS USED ON AMPLIFICATION OF SIGNALS IN ENVIRONMENTAL SEM

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Commercially available Environmental and Low Vacuum scanning electron microscopy permits a low pressure of gas in the specimen chamber [1]. These instruments are possible to be used for observing uncoated nonconductive or pure conductive or water containing specimens without the necessary drying and using other special preparation techniques. Contemporarily, these microscopes come in use mainly in biology, medicine, as well as in the semiconductor industry. As the principle of these microscopes allows the presence of gas in the specimen chamber, the area of their application can be much wider. It is the ability to stabilize specimens thermodynamically for static experiments or effect of chemical or kinetic changes for dynamical experiments that is relevant. However, the situation becomes more complicated because the gas surrounding the specimen plays its role at magnification and consequent detection of the SE signal and takes part at the creation of the signal background. The aim of this paper is to provide a background into the behaviour of various gases in the environmental SEM as an aid to researchers designing experiments.

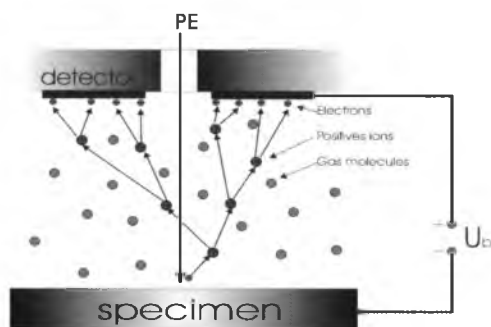


Figure 1: Configuration of ionisation detector for environmental SEM

The calculations of the amplification of the ionisation detectors in environmental SEM microscopes have been a very complicated matter. For partial simplification the parallel electrode system has been considered, which is presented in Fig 1. The size of the resulting amplification of the detector is dependent on the gas pressure in the specimen chamber, working distance, energy of the primary beam electrons, type and properties of the working gas and the voltage on the electrodes of the detector. The computation of the amplification has been analyzed in [2] by using the Paschen's law. Then, we can calculate the

amplification by applying the product of pressure and distance. The voltage on the electrodes can be increased only up to a certain limit, from which the sustained discharge starts changing to the self-sustained discharge. Our aim was to find this limit, because from the viewpoint of the amplification it represents the best working conditions for the given configuration of the system. Fig. 2. shows the realized measurements of three parameters obtained from the specimen by line scan. The first parameter (T) is the signal magnitude from a scratch on gold, which characterizes the significance of the topographical contrast. The second parameter (M) is the difference

between signals from gold and carbon. Therefore, the size of M shows the share of the material contrast. The third parameter (P) is the signal obtained from the edge of the scratch. The size of P determines the share of the edge contrast in signal.

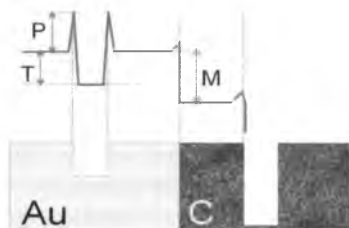


Figure 2: Detail of the surface of the used specimen

However, because of the small size of its molecules and their easy pervasion through the aperture, a dramatic pressure increase is caused in the differential chamber. Experiments with the use of the  $\text{SF}_6$  gas were also carried out. It was used as a model of electronegative gas. The experiments with this gas aimed at showing the influence of the gas electro-negativity to the detection. The result was a decrease in signal caused by the loss of signal electrons by the capture on the molecules of the  $\text{SF}_6$  type of radical.

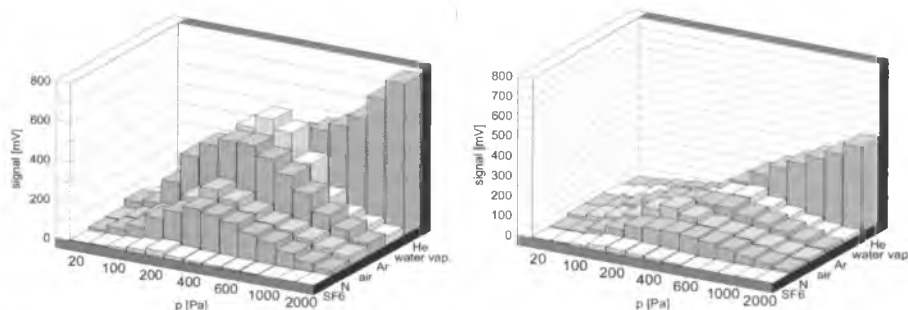


Figure 3: The measured dependencies of the signal size a) T and b) M for different gases at the working distance 2mm and voltage on the electrodes of 300V.

This project was supported by the Grant Agency of the Czech Rep., No102/01/1271, and by internal grant of ISI Brno.

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## DISPERSION AND DETECTION OF SIGNAL ELECTRONS IN ENVIRONMENTAL SEM

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The environmental scanning microscope is based on convenient adaptation of classical SEM employing the focused primary electron beam. For the proper function of the electron gun the pressure in this part of the microscope must be less than  $10^{-3}$  Pa. The working pressure in the specimen chamber in environmental microscope reaches the order of hundreds of Pa [1]. Therefore, the effective vacuum separation of these two parts is necessary. This can be obtained by the use of two or more apertures limiting the gas flow. It is also necessary to evacuate the space between the apertures by a vacuum pump of a high pumping speed [2]. The increasing of pressure in the specimen chamber brings some difficulties, especially the dispersion of signal electrons by the influence of interaction with the gaseous environment.

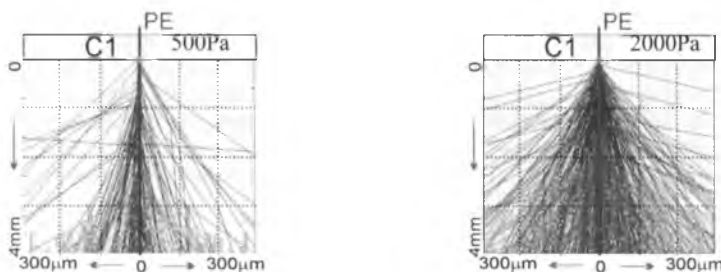


Figure 1: Simulation of dispersion of PE in the specimen chamber: at the pressure of 500 Pa, 63.7% PE is not dispersed while at 2000 Pa only 16% PE is not dispersed.

The simulations were carried out by using the program "Electron flight simulator, ver. 3.1" intended especially for calculations of dispersion of electron beam in gases and solids. The program uses the Monte Carlo method for calculation of the electron trajectory. In Figure 1 there are the results of the simulation for air and energy of primary electrons of 20kV. Owing to dispersion of primary electrons, caused by the collisions with gaseous environment, the primary electron beam is surrounded by a skirt. Thus, the primary beam spot on the specimen broadens.

The skirt of scattered electrons is distributed over such a large area, as shown in Fig. 1, that the average over the specimen structures produces a nearly constant background, which can be subtracted by adjustment of the black level of the signal. A highly resolved image can thus be obtained from the signal generated by unscattered electrons. Under certain observation conditions a resolution comparable to conventional SEM can be obtained also in the environmental SEM.

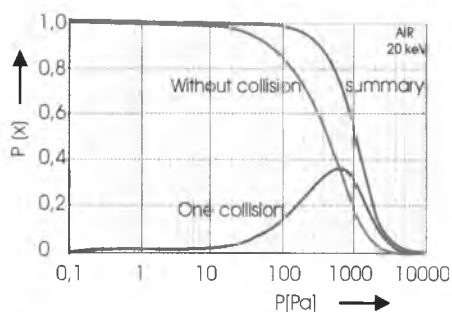


Figure 2: Calculated probability of electron beam landing on the specimen without a collision and after one collision.

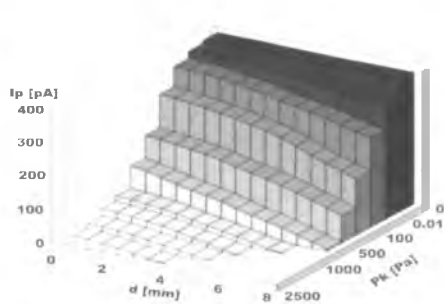


Figure 3: The specimen current in the dependency of the pressure in specimen chamber ( $P_k$ ) and on the distance ( $d$ )

Measurement was performed to quantify the influence of the pressure in the specimen chamber ( $p_k$ ) and the working distance ( $d$ ) on decreasing of the primary beam current. The current in vacuum was set to 400 pA. The dependency was determined for the pressure from  $10^{-3}$  to 2500 Pa at the working distance from 0 to 8 mm. Measurement showed that the pressure in the specimen chamber has bigger influence to the drop of the primary current ( $I_p$ ). In Fig. 2 one can notice a threshold at 200 Pa, where the collision processes between the primary electrons (PE) and gas start asserting themselves to a greater amount. The dependency of the BSE dispersion will have a similar shape so that the efficiency of the scintillation BSE detector will dramatically decrease with the increasing pressure. In Fig. 2 the probability of the electron landing on the specimen without any collision and with one collision is calculated for air at the working distance of 2mm. For the calculation of this dependency the following relation was exploited:

$$P(x) = \frac{m^x e^{-m}}{x!}$$

where  $x$  is the number of collisions and  $m = \sigma n L$  ( $\sigma$  is the molecule cross-section,  $n$  concentration of molecules and  $L$  the trajectory length).

One can conclude that for the configuration considered and from the viewpoint of primary electrons it is reasonable to work with pressures in the specimen chamber up to 2000 Pa and to use the working distance up to 4 mm. For the calculations and measurement the sizes of 0.15 mm for the upper aperture and 0.5 mm for the bottom aperture were chosen, which are suitable for reaching the vacuum conditions and partly meet the requirements for the viewfield size.

The drop of the primary current with the increasing working distance is of linear character and the dependency is inferior to the influence of pressure. Hence, the use of the product of  $P_k$  and  $d$  as a characteristic of ESEM is justified within a limited interval only

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CATHODOLUMINESCENCE SPECTRA MEASUREMENT

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1. Introduction

In our laboratory the equipment for the investigation of cathodoluminescent (CL) properties of solid specimens has been built [1]. The equipment is based on the completely rebuilt Tesla BS242 electron microscope, supplied by the light collection UV transmitting system, and by a fast and efficient photomultiplier tube (PMT) as the detection unit. The CL properties of specimens (slim disks) can be measured in continuous or pulse modes. So, in addition to the efficiency and decay times the emission spectra can be measured for 10 keV electron beams.

2. Measurement system

The layout of the measurement system is shown in Fig. 1. Contrary to the direct measurement of the efficiency or decay characteristics, at the spectral measurement the CL emission is guided to the entrance slit of the mirror monochromator (Carl Zeiss Jena SPM 2), and the PMT (EMI 9558B) is positioned at the output slit of the monochromator. As the signal to

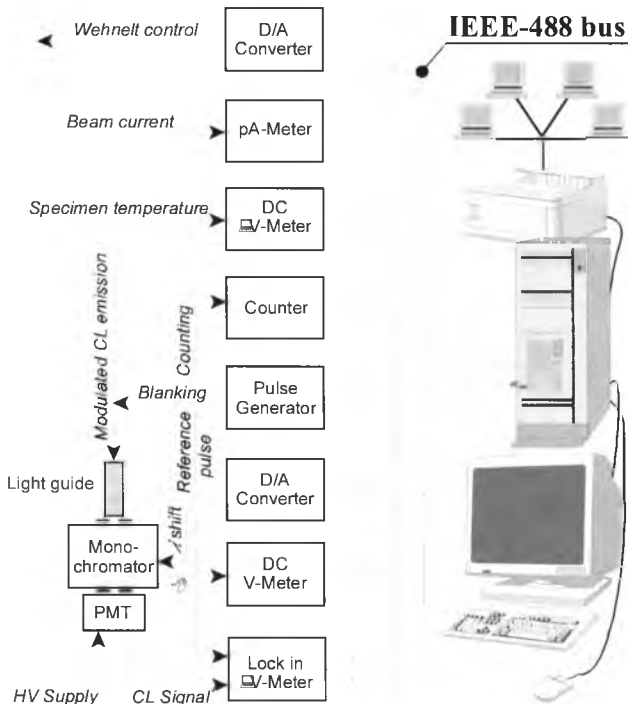


Figure 1: IEEE-488 bus layout for the control of the CL emission spectra measurement.

noise/background ratios of most of spectral lines are very small, it is necessary to measure the CL emission in a synchronous mode using the modulated beam and a lock-in nanovoltmeter. The reference pulse is taken from the triggering output of the beam modulating generator. The manual shift of the monochromator wavelength was replaced by a small unit with the electromotor controllable using the D/A converter and PC. The wavelength shift is grabbed using a revolution sensor. An investigated transparent specimen (with a transparent substrate if necessary) is positioned in the specimen chamber [2] facing the light guide. The blanking diaphragm is placed above the specimen. The specimen can be heated, and the temperature can be measured. The Faraday cage was used to the beam current measurement and to the consequential Wehnelt control.

### 3. Control and measurement bus

The individual instruments are connected to the general purpose interface bus (GPIB, known as IEEE-488 standard), and the measuring apparatus is controlled by the PC, that also processes the obtained data. The GPIB bus is driven using the Agilent Technologies 82350A PCI GPIB interface card shown in Fig. 2. This card with built-in buffering de-couples GPIB transfers from the PCI bus transfers. The buffering provides I/O and system performance that is superior to direct memory access (DMA) up to 750 KB/s. The card is software configurable and compatible with the plug-and-play standard. The GPIB bus is formed by this card connected to individual GPIB equipped instruments via GPIB cables. The GPIB card was controlled using Agilent Virtual Instrument Software Architecture (VISA) I/O drivers for Windows 98. The VISA I/O library was preferred for the measurement, because it is designed according to the VXI plug&play (System Alliance) standard that allows different instruments to run on the same system. Contrary to VISA, the alternative Agilent Standard Instrument Control Library (SICL - developed by HP and Agilent) is portable at the source code level from one system to another with little changes.



*Figure 2: The Agilent 82350A PCI GPIB card having the IEEE-488 interface for accessing and controlling instruments and for data exchange.*

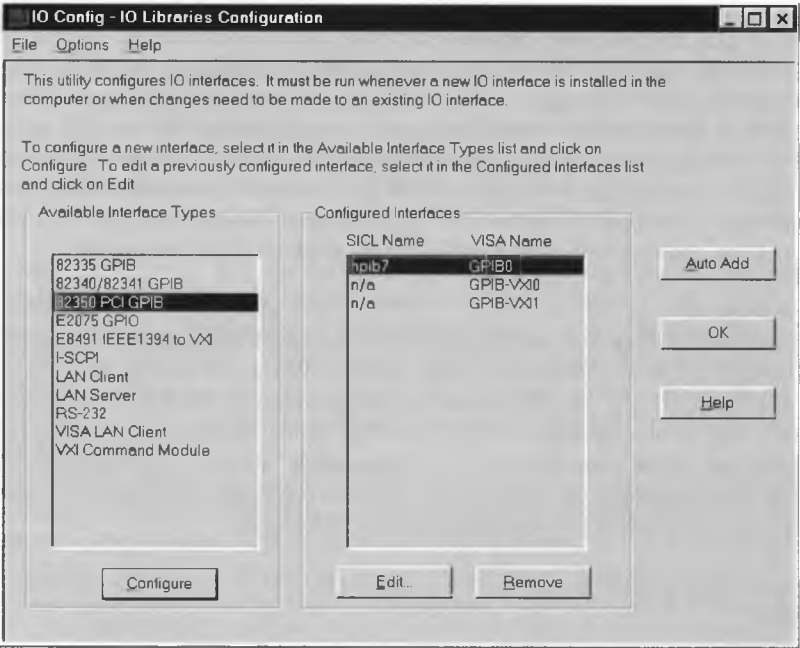


Figure 3: The main window of the IO Config. This utility assists for the setup of the GPIB interface.

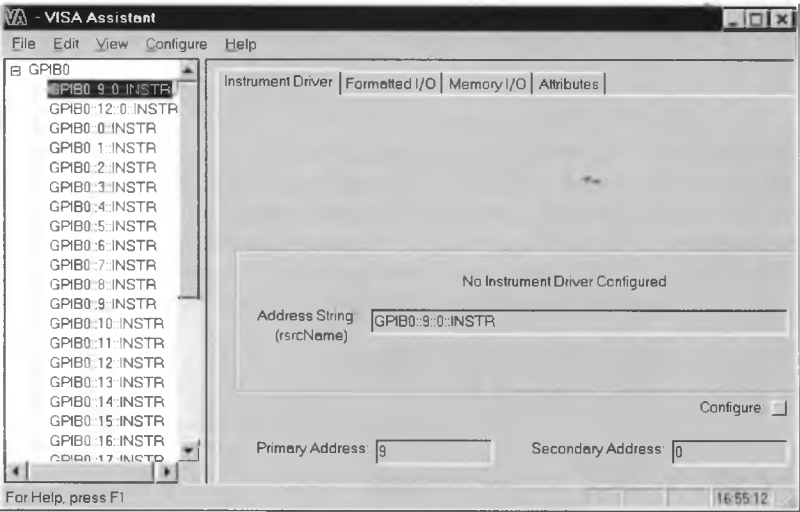


Figure 4: Typical window of the VISA Assistant utility showing the system instrument view.

#### **4. I/O Configuration**

The GPIB card and bus were adjusted and tested for the measurement using Agilent IO Config and VISA Assistant utilities. The interface must be configured before it is used with the I/O libraries. IO Config (Fig. 3) assigned the interface name and logical unit number to the GPIB card, as well as other necessary configuration values for the interface. This information is passed in the parameter string of the function called in the program. The VISA Assistant utility (Fig. 4) was used for the test of the GPIB bus. It was used to send and receive strings to instruments which support formatted I/O. VISA Assistant also allowed us to read and write memory areas, and to describe attributes that are associated with the instruments.

#### **5. Measurement**

Utilising the MS Windows 98 and the Agilent I/O Libraries, it was possible to control the data flow through the bus to/from the Agilent 34970A data acquisition switch unit, Agilent 34401A multimeters, and other IEEE-488 equipped instruments. The PC was connected to the network, and remote operations were available. After application of the wavelength calibration and signal corrections for the photocathode sensitivity emission spectra were obtained. The data measuring and processing software (including calibration and corrections) was written in the Borland C++ using the Agilent IO Libraries.

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## CHROMATIC AND SPHERICAL ABERRATION CORRECTION USING TIME - DEPENDENT ACCELERATION AND LENS FIELDS

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Scherzer's famous work on the impossibility to correct the chromatic and spherical aberrations in electron-optical systems composed of round lenses [1] has initiated many attempts to find a way circumventing his theorem. Despite of extensive work, it was only very recently that the spherical aberration of a TEM was successfully reduced by multipole elements [2] and mirror correctors are just ready to prove their capability of correcting chromatic and spherical aberrations in cathode-lens microscopes [3]. Technically, both ways are very demanding.

Besides multipole- or mirror-elements there is another way of circumventing the preconditions of Scherzer's theorem, i.e. the application of time-dependent lens fields [4]. Early attempts, the so-called "high-frequency lenses" (for an overview, see [5]) failed because the crucial phase condition between the microwave-excited lens and the necessary bunching of the electron beam could not be fulfilled. We present a novel theoretical ansatz for both  $c_c$  and  $c_s$  correction in photoemission electron microscopy (PEEM) and low-energy electron microscopy (LEEM) making use of the highly precise time structure of pulsed photon sources like electron storage rings or pulsed lasers, e.g. driving the photocathode of a LEEM. The new approach is based on rapid switching of acceleration fields or lens fields and / or time-resolved image detection. As the electrons' time of flight is an important parameter, the method is especially useful in low-energy microscopy. We do not aim at the ultimate resolution like most of the previous attempts on aberration correction, but rather at a substantial enhancement of the imaging performance at moderate resolution in the range of a few nanometers.

### ***C<sub>c</sub> - correction***

The contribution of the chromatic aberration is most important for Synchrotron-radiation excited PEEM (X-PEEM). Due to the high photon energies in the soft x-ray range, the energy distribution of the low-energy secondary electrons being imaged is several eV wide thus giving rise to a dominant chromatic term  $\delta_c = c_c \propto \Delta E / E$ . The  $c_c$ -corrector exploits the time-of-flight of electrons with different energies in a drift space [6]. The spatial and temporal dispersion at the end of the drift space facilitates three ways of correction:

1. The straight-forward way is to *actively vary the excitation of part of the lens system* synchronized with the pulsed electron beam such that for all electron energies (arriving one after the other) proper focusing is achieved.
2. An alternative way is to introduce a switchable (parabolic) acceleration field behind the drift space which will *invert the energy distribution* of the electrons. As all electron-optical elements behind the accelerator act on the inverted energy distribution, the

chromatic aberration of the subsequent lens system is inverted, too. Proper design of accelerator and lens parameters can thus achieve a complete cancellation of the positive and negative  $c_c$  values corresponding to the lens optics *before* and *after* the accelerator, respectively.

3. Finally, *time-resolved image detection* in combination with numerical image processing can correct the lateral chromatic aberration (=energy-dependent image magnification), image rotation or shift. Recently, we have demonstrated that already a time-of-flight filter (i.e. energy *selection* like in a dispersive imaging energy filter) yields a substantial increase of resolution in X-PEEM [7]. Figure 1 shows a first example of true *correction* by dividing an image obtained using the x,y,t-resolving delayline detector [8] into partial images ("time-slabs") representing small energy intervals, see Fig. 1a. Without time resolution the sum-image of all time-slabs shows a strong chromatic aberration, Fig. 1b. The lateral chromatic aberration in the partial images is now corrected by re-scaling each image with the appropriate factor. Finally, all re-scaled images are summed up again so that no intensity is lost, Fig. 1c. The clear gain in resolution and contrast between b and c is evident. Here, the microscope optics was kept static so that only the 0 ns image in Fig. 1a is in focus. Synchronous variation of the focusing voltage will yield an additional gain in resolution.

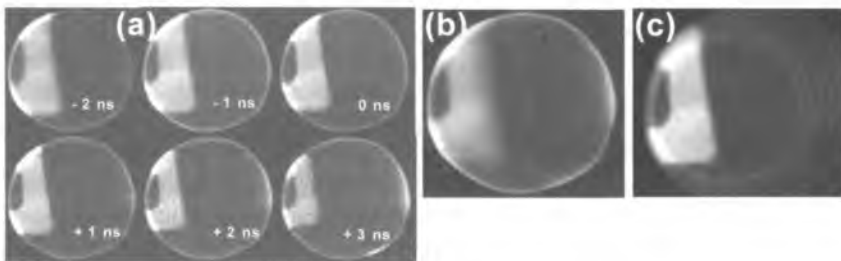


Figure 1: Correction of lateral chromatic aberration utilizing time-dependent image detection and software-assisted correction (raw data courtesy A. Oelsner, Univ. Mainz). (a) Series of partial images corresponding to different arrival times, (b) raw image without time resolution, (c) corrected image, i.e. sum of re-scaled partial images (FoV = 30  $\mu\text{m}$ , large contrast aperture)

### **$C_s$ - correction**

Whereas the ways of  $c_c$ -correction have no analog in photon optics, the  $c_s$ -corrector resembles an optical achromat. It makes use of the fact that time-dependent fields open ways of realising a diverging lens with an inverted  $c_s$  (and  $c_c$ ) in its virtual image [4]. One possibility is to rapidly switch off the lens field as soon as the electrons enter the region with negative radial force component (i.e. the converging part of the lens field). Experimentally, this requires a very fast rise-time of the switch because otherwise the energy distribution will be broadened and, in turn, chromatic aberration increases. We will give quantitative estimations of  $c_c$  and  $c_s$  correction on the basis of present state-of-the-art electronic pulsers.

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## COMPUTER SIMULATION OF AN ELECTROSTATIC ABERRATION CORRECTOR FOR A LOW-VOLTAGE SCANNING ELECTRON MICROSCOPE

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The resolution of low-voltage scanning electron microscopes is limited by the spherical and chromatic aberrations of the objective lens. The spherical aberration is usually the more important in practice since the electron energy spread can be restricted by a good monochromator. Among a number of ways suggested by Scherzer for the aberration correction, employing a multipole corrector seems the more promising. It has been shown experimentally [1] that in a low-voltage SEM equipped with a quadrupole-octupole corrector the resolution limit can be reduced.

We have set up a computer simulation of the quadrupole-octupole corrector using the three-dimensional program CPO3D [2]. The aims of the study are analysis and optimization of the electron-optical characteristics of the corrector. It would be difficult to do so experimentally while a computer simulation allows a large number of different systems to be analyzed accurately and in a reasonable time.

The system that has been simulated consists of seven aligned cylindrical electrodes each of which is cut by longitudinal slots into eight equal parts to form a combined quadrupole-octupole lens. With this simulation one can study correctors that consist of 6 lenses of the same length or 4 lenses of unequal lengths. A procedure has been developed for adjusting the quadrupole voltages to form a telescopic mode that gives an outgoing parallel beam for an incoming parallel beam and is characterized by a unity transfer matrix. It has been found that when the geometrical length of the two inner lenses is twice as long as the length of the two outer lenses the values of the quadrupole voltages and aberration coefficients have their minimum values.

The reduction of the spherical aberration by means of activating the octupole voltages has been studied. Two sets of octupole voltages have been found one of which corrects the intrinsic spherical aberration of the corrector and the other corrects the total spherical aberration of the corrector plus objective lens. The dependence of the spherical and chromatic aberrations on the mean voltage (mid-acceleration) applied to the inner lenses of the quadrupole-octupole system has been examined [3]. It has been found that the mean voltage alone cannot correct the spherical and chromatic aberration of the objective lens. Nevertheless the mid-acceleration mode should be used for the reduction of the chromatic aberration of the corrector itself.

The tolerance limits to mechanical defects of the corrector have also been studied.

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## MORE USER-FRIENDLY ELECTRON MICROSCOPES

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### 1. Introduction

It is beyond any doubt that electron microscopes are capable of contributing a great deal to the achievement of scientific knowledge, which cannot be achieved otherwise. Randomly selected examples may include medical diagnostics (thin sections, viruses and others), nanometer resolution material diagnostics, environment diagnostics as well as a number of other areas. Their further dissemination, along with a generation change over will no doubt be highly desirable. Current electron microscopes (particularly, TEMs) are being accepted with certain embarrassment and reservations. One of the main reasons consists in the fact that the current electron microscope is a relatively expensive piece of equipment. Some types are also rather bulky and difficult to install. Therefore, the question arises whether or not it might be practicable to produce – provided that some compromise is resorted to – routine, desktop-design, easy-to-transport microscopes, featuring low power demand and little place requirements and, last but not least, more attractive prices than the current general-purpose microscopes. Given that the price of a fairly good optical microscope ranges from 100,000 to 200,000 USD, so this is just the sum, which should not be exceeded by most electron microscopes.

### 2. Ways for dimension decrease of electron lenses

Having a look at a TEM design (the situation being similar with SEMs), it is apparent that there are hardly any savings to implement on it. The microscope overall dimensions are determined mainly by the electron lens size. Particularly, the design of a good-quality objective lens is usually well optimised. Therefore, it can hardly be reduced in size considerably, unless we choose to change the only adjustment-accessible parameter, i.e., the exciting coil current density. This is the approach chosen by T. Mulvey [1]. His papers are commonly known. From these papers it follows that a magnetic electron lens with a remarkably reduced magnetic circuit is contrivable provided that there is a way to dissipate a considerable power from the heavily current-loaded exciting coil. Although this problem may be solved in principle, any such solution features an essential drawback, namely, the high input power, most of which must be dissipated by means of a cooling medium, preferably water. This is why this solution has not appeared in commercially available microscopes.

We made an attempt to replace the exciting coil with advanced-design permanent magnets, although we were aware of the crucial problem to overcome - the difficult control of the magnetic field, in conjunction with no possibility to annul the magnetic field at need. The most up-to-date permanent magnets make it possible to produce magnetic lenses with parameters considerably different from those of AlNiCo magnets used formerly. Tentative calculations based on the software provided by B. Lencová [2] have shown that – with regard to the need to realize high diameter-to-length ratio magnets – similar parameters as those of T. Mulvey's lenses may be achieved [3]. Fig. 1 shows a simplified section of a low-voltage TEM objective lens in comparison with an exciting coil equipped objective lens. As 2 gaps had to be created in the permanent magnet magnetic circuit, one gap was used to act as a short-focus condenser lens, while the other as a second zone objective lens (Tab.1).

It proved feasible – in connection with a diameter and high brightness electron source – to design an electron-optical system to be applicable as both a lens microscope (TEM), and

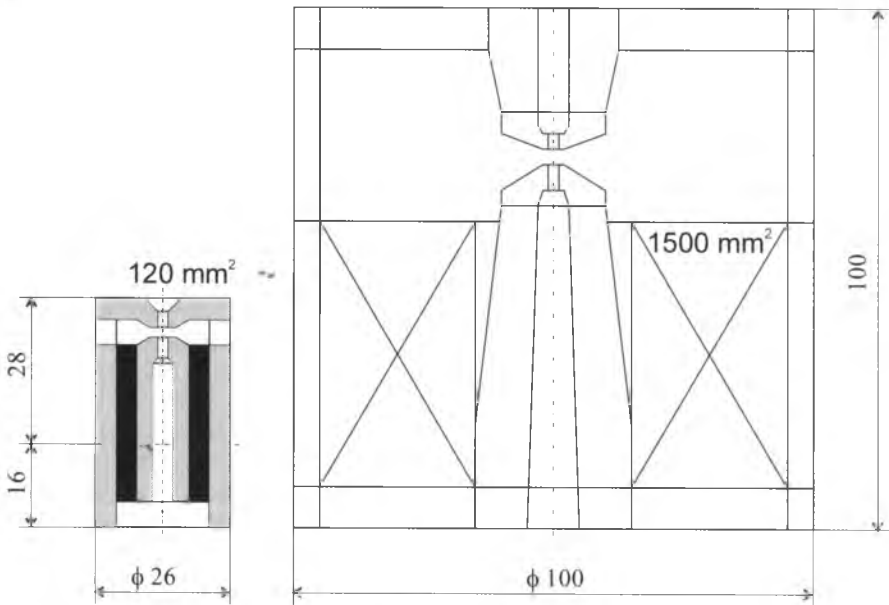


Figure 1: Objective lenses with the same maximum flux density  $B_{\text{max}}$   
a) with permanent magnet b) with exciting coil.

a scanning microscope (STEM, SEM), featuring a fairly simple switch-over procedure from one operating mode to another (Fig.2).

The low-voltage TEM has not been designed to be a mere simplified version of a TEM, but, rather, as a microscope allowing to increase the image contrast of low-contrast objects, such as, biological objects, without heavy-metal contrasting, which might have led to artefacts. The envisaged goal appears to be achieved.

Table 1: Calculated (measured) parameters of the objective lens with permanent magnet.

|                                             | 5 keV ( $\lambda=0.0173$ nm) | 60 keV ( $\lambda=0.005$ nm) |
|---------------------------------------------|------------------------------|------------------------------|
| Maximum flux density (T)                    | 1.15 (measured 1.15)         | 1.77 (measured 1.77)         |
| Focal length (mm)                           | 0.516                        | 0.739                        |
| Cs (mm)                                     | 0.273                        | 0.567                        |
| Cc (mm)                                     | 0.354                        | 0.500                        |
| $\Delta U$ (eV)                             | 0.5 (0.3)                    | 0.5 (0.25)                   |
| $\delta$ (nm) resolution                    | 1.2 (measured 2.0)           | 0.32 (theor.)                |
| $\alpha_{\text{opt}}$ (rad)                 | $1.5 \cdot 10^{-2}$          | $0.96 \cdot 10^{-3}$         |
| Exciting parameter (amperturns/ $U^{1/2}$ ) | 35.8                         | 18.7                         |

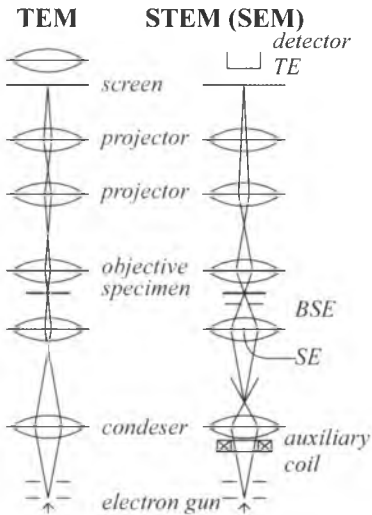


Figure 2: Ray diagrams of TEM and STEM (SEM).

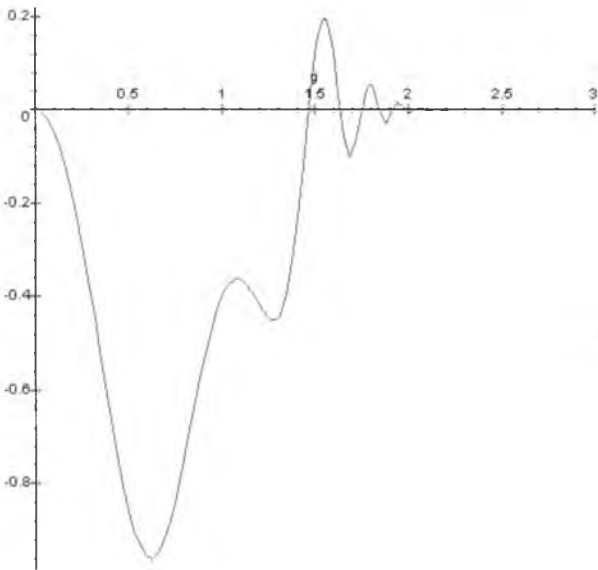


Figure3: Contrast transfer function (CTF) for 5 keV.

The contrast transfer function (CTF) (Fig.3) shows that it is particularly the chromatic aberration to act as the main resolution power limiting factor. Its correction will be inevitable in the future if a remarkably higher resolution is to be achieved. As the low-voltage microscope has its specific application area, an attempt was made to produce a TEM whose beam energy was to be higher. An energy of 60 keV has proved to be a good compromise, as will be shown below. Fig. 4 shows a simplified section of an objective lens of the same design as in the case of the 5 kV TEM, and, as above, in comparison with an exciting-coil equipped objective lens with the same value of  $B_{max}$  for both lenses. In Tab.1 the objective lens parameters are listed.

Fig. 5 shows the contrast transfer functions (CTF). We may conclude, above all, that for a well-designed 60 keV objective lens the resolution power limiting factor is the spherical aberration rather than the chromatic one. The initial resolution power threshold, 0.33 nm, may further be improved to reach 0.12 nm provided that the spherical aberration is corrected by means of an existing method. If, in addition, the chromatic aberration is reduced, too, the achievable theoretical resolution power will equal 0.1 nm for the parameters listed in Tab.1.

Application of permanent magnet based electron objective lenses makes it therefore possible to produce electron microscopes featuring satisfactory resolution even when considerably reduced in size.

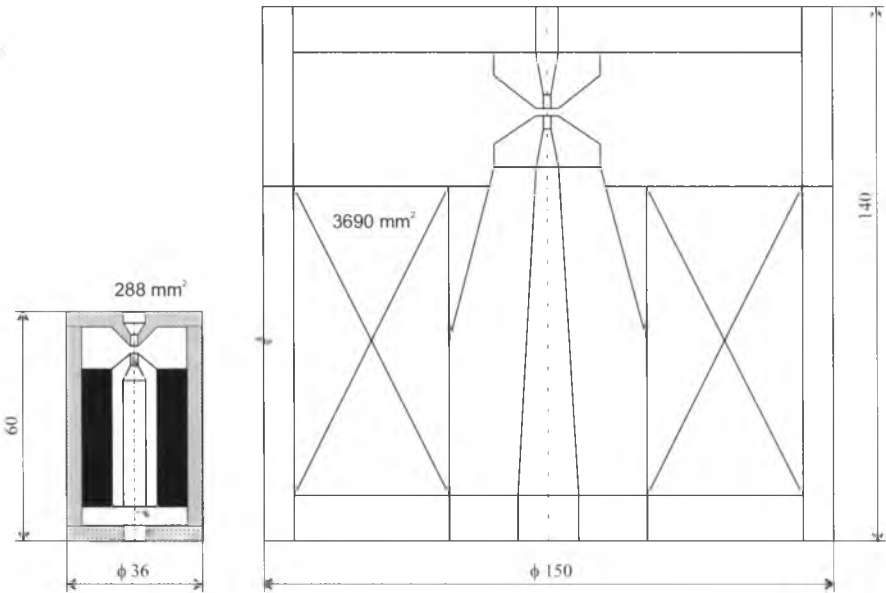


Figure 4: Objective lenses with the same maximum flux density  $B_{0max}$ .  
a) with permanent magnet, b) with exciting coil.

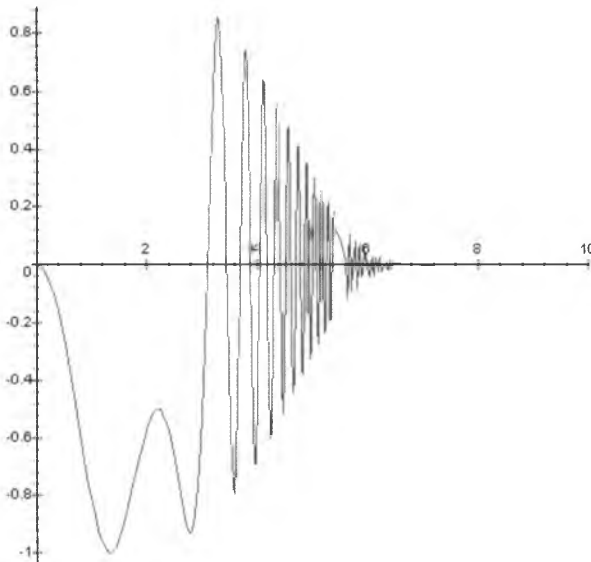


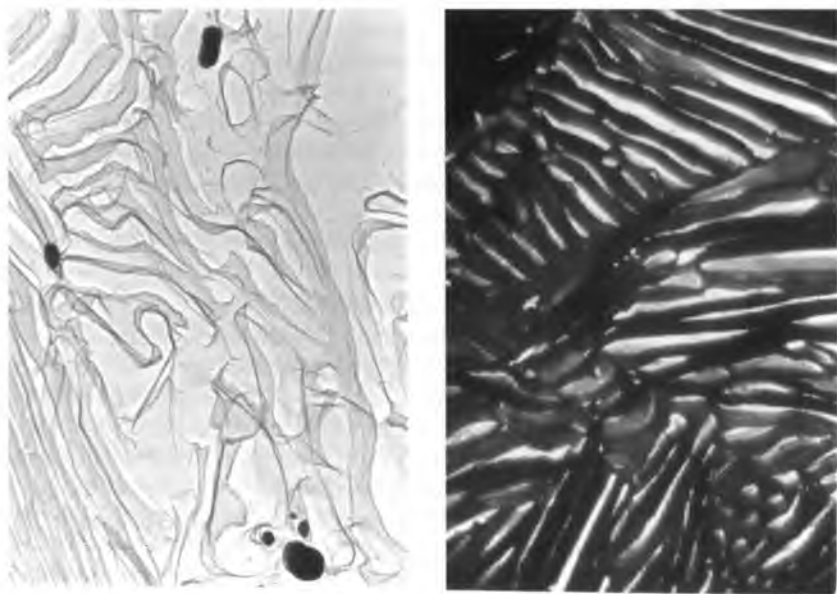
Figure 5: Contrast transfer function (CTF) for 60 keV.

### 3. Simplified projection system

The next TEM operating node is the projection system with the final image viewing and recording chamber. Especially, this part contributes the greatest deal to the total microscope weight. So, for example, the image viewing chamber may weigh as much as 120 kg. It is to be noted that a present-day image recording system, consisting of a cathodoluminescence screen (most usually, single-crystalline YAG), fibre

optics and a CCD camera, makes it possible to not only record the image but also display it in a monitor screen. In this way, the current projection system and the image-viewing chamber are becoming useless.

In the low-voltage microscope, we have chosen to use a high-quality objective lens of an optical microscope to serve as a coupling element between the luminescence screen and the CCD camera. In this way, a portion of the overall electron-optical magnification has been taken over by this objective lens. In conjunction with the electronic magnification of the CCD camera, the monitor screen image magnification may reach 1000 and 200 for the beam energy of 5 keV and 60 keV, respectively. The electron microscope projection system is thus reduced in length considerably. At the same time, the large numerical aperture of the objective lens increases the transmissivity of the whole detection system. The detection quantum efficiency DQE reaches as much as 0.7, which means that a single electron in the imaging beam gives rise to 0.6 electrons in the CCD camera.



*Figure 6: Carbon replica of pearlitic steel. Left - 100 keV. Right - 5 keV.*

A very promising detection system is the CCD chip, on the back side of which the electron beam is incident. The chip is made thinner and its detection quantum efficiency is very high. For an electron beam energy ranging from 6 to 8 keV, it reaches as many as 1000 signal electrons per a single primary electron. Simultaneously, the service life of such a CCD detector (1050 x 1050 dpi), which is currently used as an image intensifier, turned to be extended significantly.

A camera equipped with such a chip costs round 30,000 USD, which is quite a lot (the chip itself costs from 14,000 to 16,000 USD). It is to be hoped that the price will be reduced gradually.

The low-voltage 5 keV electron imaging beam microscope shows that both approaches to the device size and weight reduction, i.e., application of permanent magnet electron lenses and a light objective lens based projection system have proved to be successful.

Currently, the microscope is reaching a resolution of about 2 nm (this applies to the version with 4 mm pole piece bores spaced at a distance of 5 mm from each other). Especially, the expected growth in contrast has been confirmed. Fig.6 shows a carbon replica of pearlitic steel, slightly contrasted with heavy metals. Whereas the 5 keV electron beam generated image features an outstanding contrast, the 100 keV electron image has given rise to hardly any contrast in such a thin metal coating layer.

The microscope may also operate as a scanning system (STEM or SEM with SE or BSE). The STEM imaging has an advantage of eliminating the effect of chromatic aberration, which is due to the inelastic scattering of electrons in slightly thicker objects (thin sections).

Based on the experience gained with the low-voltage electron TEM, we have designed a 60 keV TEM/STEM/SEM, in desktop design, of the similar concept as that of the low-voltage TEM. The theoretical parameters of such a device have been quoted above. It will not differ in size and layout from the 5 keV TEM too much.

#### 4. Conclusion

In our opinion, the mentioned electron microscopes could be considered as routine equipment, allowing the user to solve a great number of problems, for which the application of electron microscopes appears to be particularly beneficial. There are naturally some areas left, in which high resolution or challenging analytical applications require considerably higher electron energies (200 to 400 keV). However these cannot be considered routine-operation specific. The need for such apparatuses, especially for research oriented tasks, will obviously be lower and their utilization could be primarily cost-effective in specialized research and development centres. However, their price will always be by an order of magnitude higher than that of routine-oriented devices.

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## SCANNING MODES IN LOW VOLTAGE TEM

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Low voltage transmission electron microscope (LVTEM) with 5 keV electron energy [1,2] was enlarged of scanning modes as scanning transmission mode (STEM) with 3.5 and 5 keV electron energy, scanning mode with secondary electrons detection (SE) and scanning mode with back scattered electrons detection (BSE). The main idea why a low voltage TEM was developed, is an important gain of contrast at low acceleration voltages. This improvement is interesting especially for low atomic number materials which has to be artificially changed (stained, shadowed...) to obtain better contrast at standard 100 keV or higher electron energies.

The detector for STEM uses as scintillator the YAG-Ce screen, which forms a converter of electron image in TEM mode. The detector for SE SEM uses P47 scintillator and for BSE SEM uses solid state detector. The field emission gun (FEG) with the Schottky cathode represents very small virtual source, which needs a relatively small demagnification. This is done by the magnetic field of the first part of objective working as second zone lens (Suzuki lens with permanent magnets). The disadvantage of this design is that the magnetic field can not be controlled, and only the accelerating voltage and the Z-object position can be changed. It can be used only electron energy around 3.5 and 5 keV.

LVTEM is able to image low atomic number samples without any staining or shadowing by heavy metals [3]. There is only requirement for specimens - to be as thin as possible, which means around 20 nm. The sample preparation of such thin specimen could be for some materials very difficult. STEM mode can be than powerful tool for thicker samples. The typical example of STEM image is on fig.1, which is a small gold particles on carbon film. The contrast is very high for an unstained sample and the resolution is also sufficient. We can clearly observe membranes of the nucleus and the other microstructures. From the same reason of elimination of inelastic scattering the STEM can be successfully applied for observation of stained samples (fig.2 and 3a).

The detection of secondary (SE) and back scattered electrons (BSE) could be very useful for very thick samples with a surface microstructure but as it is obvious on the figure 3b, the material contrast is also observable and could be successfully used for thicker or stained specimens. The last example of LVEM imaging possibilities are two pictures from BSE mode on figure 4a and b. The specimen is a bulk Mo tape, which was observed in topographic and material contrast.

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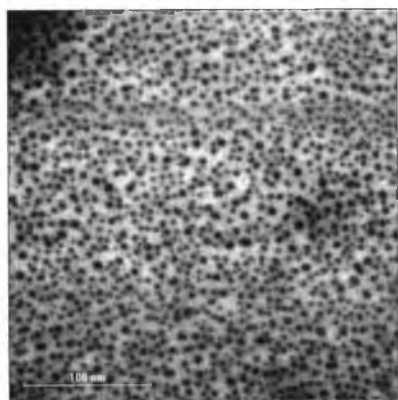


Figure 1: Gold particles on carbon film.

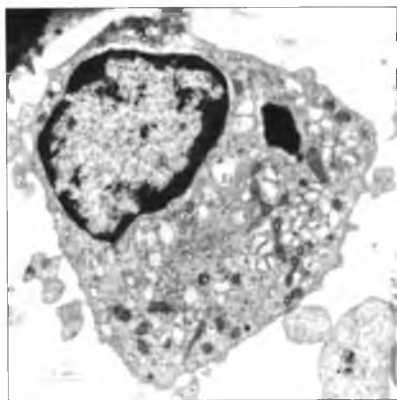


Figure 2: 85 nm thick stained section (lymphocyte).

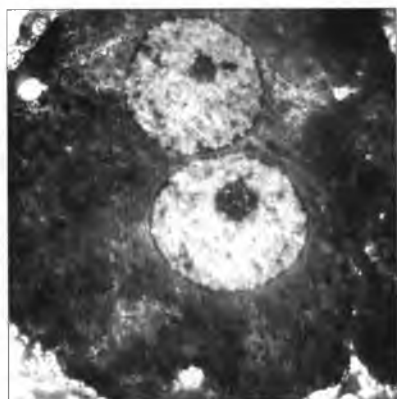


Figure 3a: 60 nm thick stained section (rat's liver).

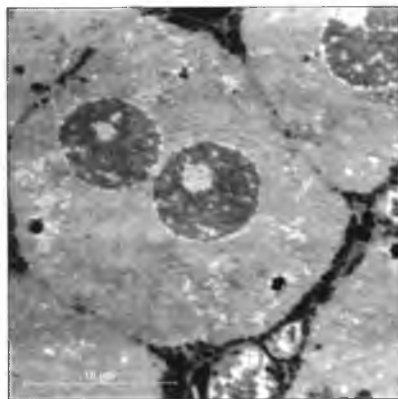


Figure 3b: BSE material contrast (compare with Figure 3a).



Figure 4a: BSE channeling contrast (Mo tape).



Figure 4b: BSE topography image (compare with Fig. 4a).

## PERMANENT MAGNET LENS ATTACHMENTS FOR THE SEM

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In this paper, a variety of different permanent magnet lens designs will be presented in the context of improving the performance of conventional Scanning Electron Microscopes (SEM).

Firstly, it will be shown how an add-on lens attachment can improve the image resolution of a conventional SEM and extend its mode of operation down to low landing energies ( $< 1$  keV). The add-on lens attachment is placed on top of the normal specimen stage, below the SEM objective lens. The SEM is operated as normal, where the objective lens is used for fine focusing of the image. The specimen is placed within the add-on lens unit, which consists of an iron circuit and a NbFeB permanent magnet slab, as shown in Figure 1. A secondary electron image of the add-on lens top plate hole is first imaged, and centred via specimen stage movement. The strength of the SEM objective lens is then readjusted to focus the primary beam on to the specimen.

A primary beam is retarded to low landing voltages by biasing the specimen negatively. Field distributions were calculated by some of the KEOS programmes [1], which use the finite element method. Other programmes in KEOS, using standard third-order perturbation of the paraxial equation, were then used to calculate the on-axis aberrations for the add-on lens. The focal length,  $f$ , the spherical aberration coefficient,  $C_s$  and the chromatic aberration coefficient,  $C_c$ , were calculated for a 6 kV primary beam retarded down to have landing beam energies of 1 keV and 600 eV. The primary beam was assumed to be parallel at the entrance of the lens (zero magnification condition). The simulation results are summarised in Table 1. The calculated aberration coefficients are less than 251  $\mu\text{m}$ , which is typically more than a factor of two smaller than those predicted for the corresponding pure magnetic immersion add-on lens.

| Landing energy | $f$ ( $\mu\text{m}$ ) | $C_s$ ( $\mu\text{m}$ ) | $C_c$ ( $\mu\text{m}$ ) |
|----------------|-----------------------|-------------------------|-------------------------|
| 1 keV          | 718                   | 235                     | 251                     |
| 600 eV         | 600                   | 164                     | 173                     |

Table 1: Simulation predictions for aberrations of mixed field lens attachment

To predict the image resolution from the simulated aberration coefficients, the root-sum formula reported by Barth and Kruit is used [2]. Using the root-sum formula for the beam energy spread of 2 eV (tungsten gun), the probe diameter is predicted to be 2.67 nm for a landing energy of 1 keV, and 3.26 nm for a landing energy of 600 eV. The probe diameters here are aberration limited ones, in that they do not take into account the gun brightness.

Figure 2a shows the image obtained with a conventional JEOL 5600 tungsten gun SEM (without any lens attachment) for a primary beam voltage of 1 kV for a tin-on-carbon test specimen. Very little of the specimen can be resolved. Figure 2b shows an image using the add-on lens attachment for a landing energy of 600 eV (primary beam voltage of 4 kV and specimen biased to -3.4 kV). There is obviously a dramatic improvement in resolution when the add-on

lens attachment is used. To estimate the improved resolution by using the add-on lens attachment, a line scan was taken across a 600 eV landing energy secondary electron image. The resolution is taken to be the distance over which the signal rises from approximately 30% to 80% of its height, and it was found to be 3.6 nm. This resolution compares favourably with the simulated aberration limited prediction of 3.26 nm. It should be noted that normally, the tungsten gun SEM used for these experiments is not able to provide such low landing energy images, and even at high landing energies, the very best resolution quoted for the SEM is 4 nm.

Another example of how permanent magnet lenses can be used as SEM attachments is shown in Figure 3. Here a compact magnetic immersion lens is used to enable an SEM to operate in the transmission mode, effectively transforming it into a Scanning Transmission Electron Microscope (STEM). A backscattered detector is placed on the specimen stage, and the lens attachment is placed directly above it. The specimen is placed in the middle of the upper gap of the lens attachment. The add-on lens is 24 mm high and can generate a peak axial field strength of around 1.5 Tesla in the upper gap of the lens. Simulation predicts that a parallel incoming 30 keV primary beam will have a focal length of 0.956 mm, a spherical aberration coefficient ( $C_s$ ) of 0.627 mm and a chromatic aberration coefficient ( $C_c$ ) of 0.696 mm. Using the Barth and Kruit root-sum formula for combining aberrations, and assuming that there is an energy spread of 0.4 eV in the primary beam, typical for a thermal field emission system, the aberration limited probe diameter at the specimen surface is predicted to be 0.325 nm. These simulation results therefore predict that the add-on transmission lens will have a resolution capability similar to dedicated STEM systems.

Figures 4a and 4b compare dark field images obtained on a Philips XL30 SEM for the Agar Lacey Carbon Film S166-3 specimen, with and without the add-on lens attachment. This specimen consists of a thin film of carbon (< 100 nm) that has holes in it for a variety of different TEM applications. An image magnification of 100,000 and primary beam energy of 30 kV is used. The dark field image taken with the transmission add-on lens attachment appears to have higher edge definition, and superior resolution.

Further experimental results will be presented for a high resolution gold-on-carbon TEM specimen to show that an image resolution of around 0.3 nm can be attained, close to what is predicted by simulation. The spatial resolution in these images may well be the highest resolution ever to be obtained by a conventional SEM.

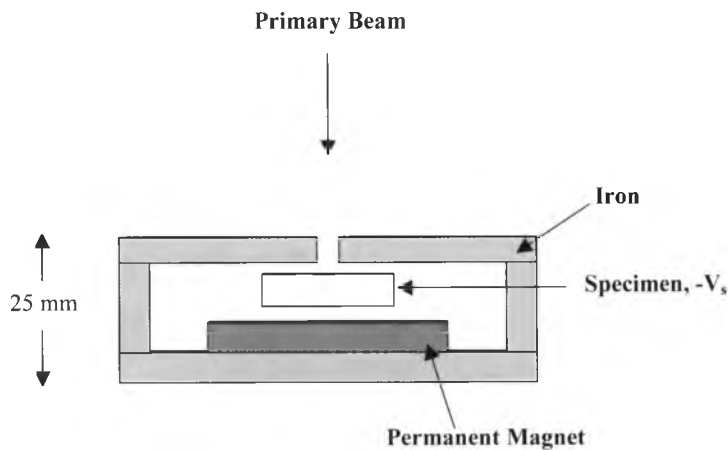


Figure 1: A Mixed Field Immersion Lens Attachment

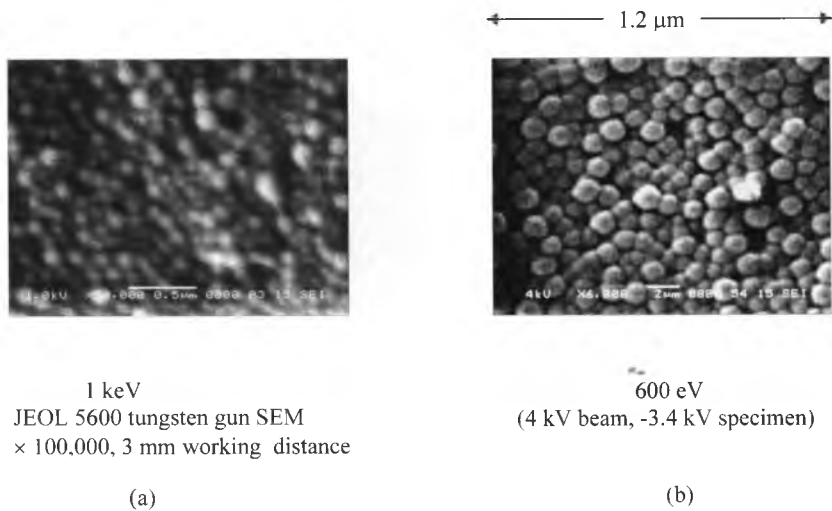


Figure 2: Experimental results from the mixed field immersion lens attachment  
(a) Without lens attachment  
(b) With lens attachment

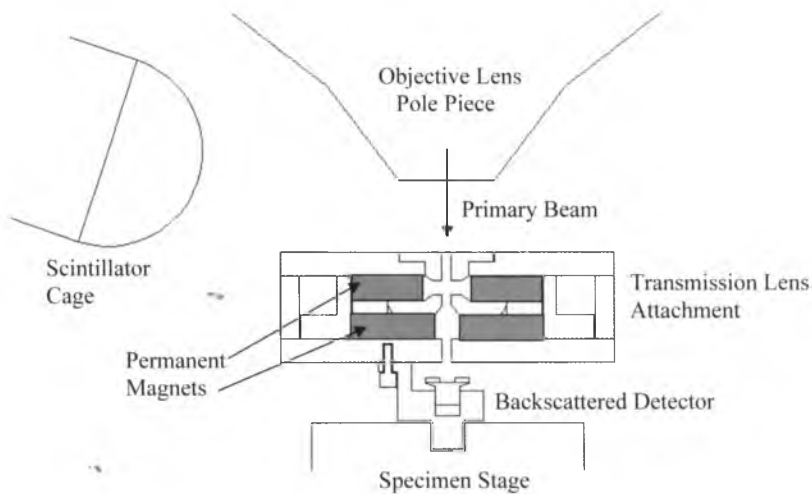


Figure 3: Transmission lens attachment

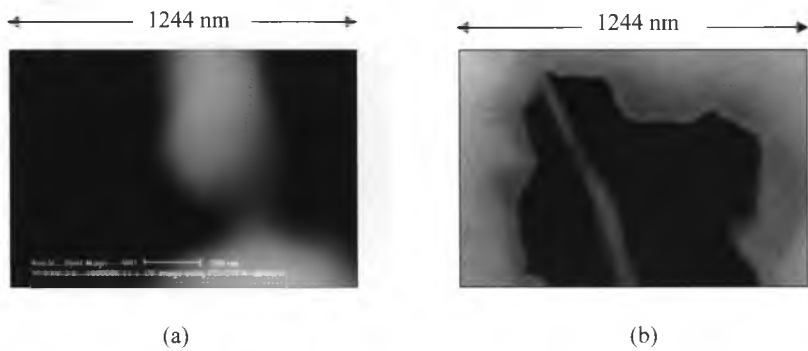


Figure 4: Dark field images on a Philips XL30 field emission SEM  
(a) Using conventional SEM optics  
(b) With add-on transmission lens attachment

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## IMAGING SUB-NANOSECOND PROCESSES USING PHOTOEMISSION ELECTRON MICROSCOPY

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Owing to its parallel image acquisition, photoemission electron microscopy (PEEM) is well-suited for real-time observation of fast processes on surfaces. Pulsed excitation sources like lasers or synchrotron radiation, fast electric pulsers for the study of magnetic switching, and/or time-resolved detection can be utilized. A standard approach being also used in light-optical imaging is stroboscopic illumination of a periodic (or quasi-periodic) process. A similar technique is pump-probe excitation via pulsed laser radiation. Alternatively, time-resolved image detection with sub-ns resolution can be employed. In this case the excitation source does not need to have any time structure. We report on two recent experiments, one employing synchrotron radiation and the other one femtosecond laser pulses.

### *Dynamics of fast magnetization processes*

is being studied using magnetic X-ray circular dichroism (MXCD) at BESSY II (Berlin). Switching in Permalloy dots was induced by a fast magnetic field pulse generated by passing a short current pulse through a strip-line. Figure 1 shows a PEEM-image: the magnetic dots on the strip-line (grey bar) appear sharp and only those on the insulator on both sides of the strip-line evidently suffer from charging. The image was taken by means of a special time-resolving image detector, the so called delayline-detector (single electron counting with x,y,t-resolution). We originally achieved a time-resolution of about 500 ps [1], now 150 ps (cooperation with the group of Prof. H. Schmidt-Böcking, Univ. Frankfurt). In an early approach we used a commercial ultrafast gated CCD camera with a minimum gate-interval below 500 ps [2]. Owing to its parallel detection of all arrival times, the efficiency of the delayline detector turned out to be much higher. Time resolution in the present experiment, however, is mainly limited by the electric pulse conditions at the stripline being characterized by a rise-time of the order of 1 ns.

The strip-line geometry is illustrated in Figure 2 (left part). A short current pulse **I** passing through the copper strip line prepared lithographically on SiO induces a magnetic field **H** as indicated. The insulator material and its thickness are chosen to achieve a 50 Ohm impedance. The integral along a closed line of magnetic field equals the current passing

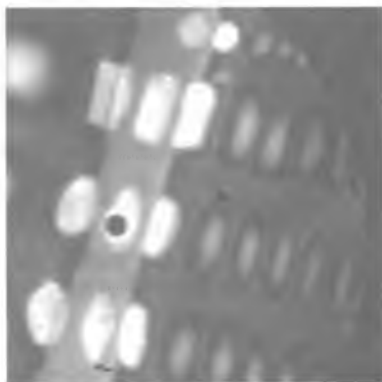


Figure 1: PEEM image of a Cu strip line with ferromagnetic Permalloy micro-structures on Si (FoV = 200  $\mu\text{m}$ )

through the field loop, i.e.  $\int H ds = I$ . For the given pulser and strip-line geometry (width  $b = 10 - 50 \mu\text{m}$ , thickness  $d$  about  $100 \text{ nm}$ ) we obtain field pulses reaching a maximum of  $10 \text{ mT}$ , sufficient to switch the magnetization of the Permalloy dots.

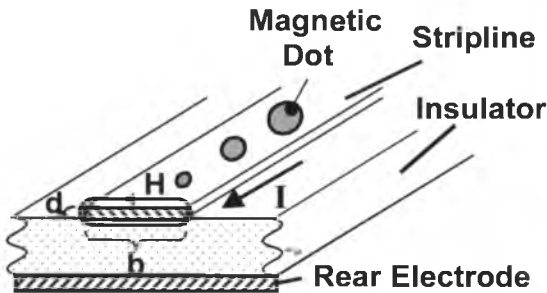


Figure 2: Geometry of the magnetic strip-line sample (left) and difference image of two PEEM images, one obtained in the static case (small constant field applied) and the other one with magnetic field pulses being applied at a rate of  $1 \text{ MHz}$  (right).

The first results indicate that the short magnetic field pulses cause only a tolerable “blur” of the image. The example shown in Figure 2 (right part) is a difference image of a static and a dynamic image with applied field pulses at a rate of  $1 \text{ MHz}$ . The difference image reveals distortions on both sides of the strip line where the local gradient of the field component parallel to the surface is maximum. On the flat top surface of the strip line, however, the image of the dots is not significantly distorted.

The image series shown in Figure 3 presents the change in magnetic contrast in a  $6 \mu\text{m}$  dot vs. the time-delay between field pulse and “time-slab” set by the delayline detector (steps of  $4.4 \text{ ns}$ ). The measurement was performed using pulsed synchrotron radiation at BESSY II (Berlin) exploiting the MXCD-contrast (for a recent review, see [3]). The change in contrast indicates a variation of the magnetization structure. The time difference of  $13 \text{ ns}$  between the first image (dark grey level within the dot) and fourth image (bright grey level) is far too large to reflect the intrinsic switching time of a Permalloy dot. It is likely that a reflection of the current pulse in the electrical connectors gives rise to the observed behavior. Despite of this problem of impedance matching in our first experiment the result of Figure 3 shows that magnetic imaging on the time scale of a ns or less is feasible.

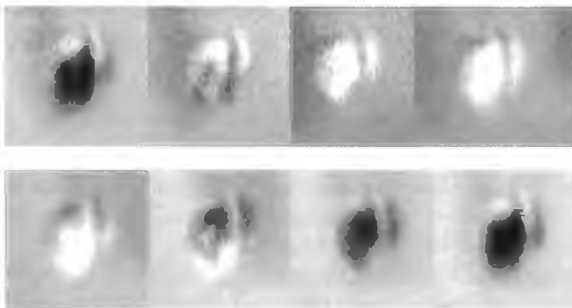


Figure 3: Time dependence of MXCD contrast in a  $6 \mu\text{m}$  Permalloy dot on the strip line. The time zero (top left image) is defined by the magnetic field pulse, the increment between adjacent images is  $4.4 \text{ ns}$ .

**Hot-electron lifetime contrast** on the femtosecond scale is observed using a pump-probe technique. As compared with synchrotron radiation (photon pulses typically 50 ps) fs-lasers provide pulses being about three orders of magnitude shorter. In this regime it becomes possible to directly observe “hot-electron dynamics” at metal and semiconductor surfaces [4]. In the first pump-probe PEEM experiment [5] illustrated in Figure 4 a pulsed Ti:Sapphire laser (40 fs, second harmonic  $h\nu = 3.2$  eV, pulse energy  $<1$  nJ) was used as excitation source for the PEEM. A variable optical delay between pump and probe pulse allows to study the lifetime of the electrons excited by the pump pulse. Since the laser runs at a repetition rate of 80 MHz only a few photoelectrons are produced per photon pulse. Space charge effects cannot occur at these conditions.

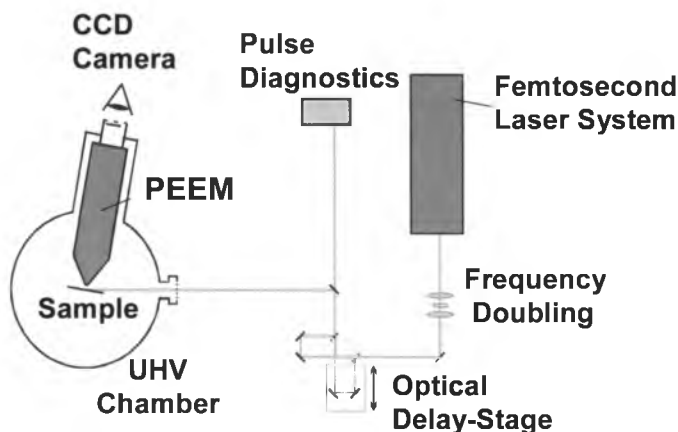


Figure 4: Schematic set-up for the observation of femtosecond electron dynamics in a photoemission microscope (PEEM).

As  $h\nu$  is smaller than the work function of the sample, one-photon transitions are strictly ruled out at the given conditions. At least two photons are required to obtain photoemission. Figure 5 schematically shows the energy-level diagram of such a two-photon transition. The first photon  $h\nu_1$  (“pump photon”) excites an electron from the valence band region into an unoccupied state between the Fermi energy  $E_F$  and the vacuum level  $E_{vac}$ . In the diagram the time axis is pointing to the right. This excited state (several eV above  $E_F$ ) has a short lifetime and decays via a transition into a state close to  $E_F$  (arrow pointing downwards). The second photon  $h\nu_2$  (“probe photon”) arrives at a later time with the time delay being precisely selectable by the optical delay stage, cf. Figure 4. If the “hot electron” is still in its excited state, the second photon can lift it to a state above the vacuum level and thus create a free photoelectron. Finally, these photoelectrons generated by two photons form the image in PEEM.

Obviously the local lifetime of the “hot electrons” determines the local image intensity if the time delay between  $h\nu_1$  and  $h\nu_2$  is varied in the region of the lifetime. This facilitates a quantitative determination of the lifetime by recording the image intensity as function of the time delay. Furthermore, the lifetime distribution on an inhomogeneous sample surface can be made visible as “lifetime contrast”.

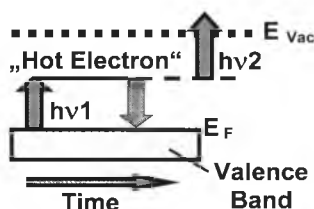


Figure 5: Energy-level versus time scheme describing hot-electron dynamics observed in two-photon photoemission.  $E_F$  and  $E_{vac}$  denote the Fermi and vacuum level, respectively. The pump-probe technique allows a variable time delay between pump pulse ( $h\nu_1$ ) and probe pulse ( $h\nu_2$ ).



Figure 6: Lifetime contrast of hot electrons in a Ag microstructure (hexagons) on a gallium arsenide surface. Left: two-photon photoemission image without time delay, centre: pump-probe image with 60 fs delay ("lifetime image", single-pulse background subtracted), right: pump-probe image with 200 fs delay. FoV = 60  $\mu\text{m}$ . (from [5])

A first example of lifetime imaging is shown in Figure 6. A Ag-microstructure (hexagons) was grown on a GaAs surface. In the two-photon photoemission image without time delay (left panel) a contrast arises only at the rims of the Ag hexagons (the bright area is an artifact). If the pump and probe pulse are delayed by 60 fs (centre panel), the uncovered GaAs bars appear brighter than the Ag hexagons thus giving evidence of a higher hot-electron lifetime in the semiconductor. At 200 fs delay (right panel) this difference has almost disappeared since now most hot electrons in both materials have undergone a deexcitation transition before the probe pulse arrives.

Femtosecond-laser excitation offers a new contrast method for PEEM and gives access to the characteristics of hot-electron dynamics at high spatial resolution. In the near future it will allow to study the fs-physics of charge carriers in nanostructured and low-dimensional systems as well as local melting [6] or other phase transitions on the ps- or ns-scale.

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## RECENT RESULTS WITH ENERGY FILTERED PEEM USING A RETARDING FIELD ANALYSER: IMAGING OF FIELD-EMITTER ARRAYS, XPS- AND UPS-PHOTOELECTRONS

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Growing demand for spectroscopic information in microscopy triggered the development of energy filters for microspectroscopic or spectromicroscopic applications [1]. Here we present recent results with the retarding field analyser IEF (Imaging Energy Filter) [2] attached to the Photoelectron Emission Microscopy (FOCUS-IS-PEEM) that is able to provide high-pass filtered images. Three examples will be presented.

The first example are results with *field emission sites of a thin cathode ray tube device* structure [3]. Each pixel of the device consists of a  $15 \times 84 \mu\text{m}^2$  area where randomly grown field emitters are distributed. The field emitters are pyramidal structures about 150nm wide covered by a aperture acting as an anode electrode. As a voltage is applied to the emitters (typically less than 30V) the field emission starts. Fig. 1 compares the imaging of photo-emitted and field-emitted electrons. While with threshold photoemission the emissions site cannot be resolved probably due to field distortion in the vicinity of the emitters, the strength of emission microscopy appears clear with imaging the field-emitted electrons. Besides the spatial distribution of the emitting sites (only part of all emitters) also their brightness and temporal behaviour can be examined. By moving the contrast aperture the angular distribution of different emitters can be distinguished.

Yet with a low voltage of about 10 V the photoemission is equalled by the field emission. This is

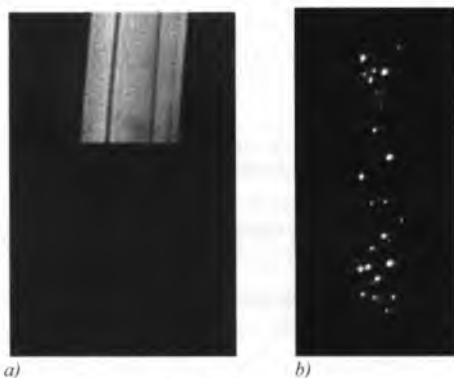


Figure 1: Images of the field emission sites.

a) threshold photoemission PEEM with Hg-lamp ( $h\nu=4.9\text{eV}$ ) b) Imaging of field-emitted electrons.

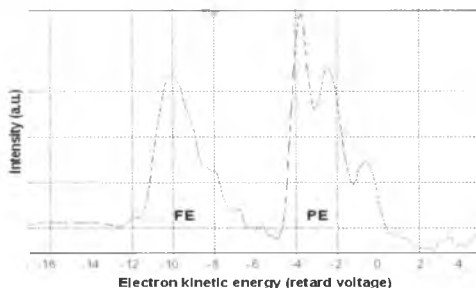


Figure 2: Microspectroscopy of field emission sites. The differentiated high-pass spectrum shows both photoemission (PE) and field emission (FE) peaks in the energy distribution.

shown in Fig. 2 by the spectroscopic results. The position of the field emission peak corresponds to the voltage applied; the width of the peak becomes sharper as fewer sites are examined. The broadening of the photoemission energy distribution results from the changing surface potentials due to the device structure.

As the second example the feasibility of *imaging XPS electrons* is proven. A sample prepared by evaporating Ag-squares (12.7 $\mu\text{m}$  period) on a tantalum foil was imaged with syn-

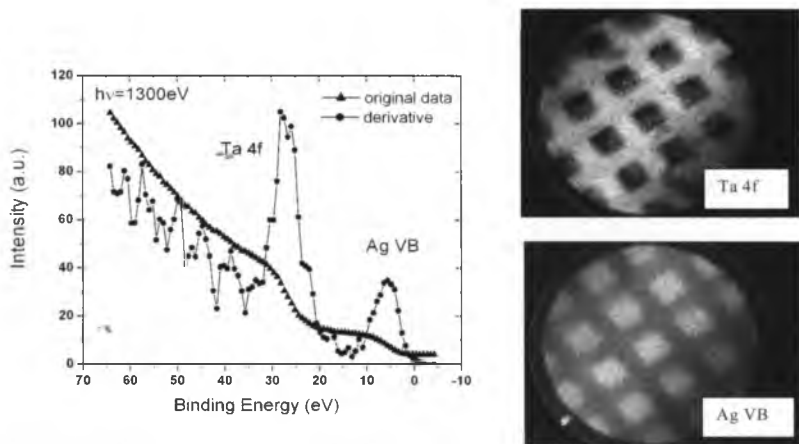


Figure 3: left: high-pass spectrum and derivative of the Ag squares on Ta with 1300eV photon excitation. right: bandpass images corresponding to the Ta4f (top) and Ag-valence band peak.

chrotron radiation at the U49/1-SGM undulator beamline at Bessy II. Spectroscopic results were obtained with radiation up to 1300eV photon energy, which corresponds to existing laboratory X-ray sources. Fig. 3 shows the spectrum near the Fermi edge. The Ag valence-band structure and the Ta 4f electrons are prominent features. Band-pass images of the spectroscopic features show the spatial distribution of the Ag squares (bottom) and the underlying Ta-foil (top). With 700eV excitation a spatial resolution of 140nm with XPS-electrons has been obtained. Microspectroscopy of a sample area of 250 $\times$ 250nm<sup>2</sup> was shown to be possible.

Up to now the resolution of microspectroscopy with a retarding field analyser was limited by the mesh size of used grids. Standard grids used in both examples shown above were obtained with 65 $\mu\text{m}$  mesh grids whose energy resolution is only 0.5eV in best cases. Also the grid pattern could be discerned for certain settings of the retarding electron optics. These drawbacks are overcome by reducing the grid size down to 8.5 $\mu\text{m}$ . First measurements show that the grids are not visible for all settings and an energy resolution of <150meV could be proven. This result was obtained with a unstructured Ag sample and 21.2eV excitation. An expected better spatial resolution due to the lower chromatic aberration of difference images has yet to be shown.

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## PHOTOEMISSION ELECTRON MICROSCOPY AND MAGNETO-OPTICAL KERR EFFECT: A COMPARISON OF PROBING DEPTHS

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Photoemission electron microscopy (PEEM) has proven to be an invaluable analytical tool for the investigation of magnetism on a submicron scale. PEEM experiments are generally done at a synchrotron, because a tunable, high-flux x-ray source is needed to excite core-level electrons in sufficient quantity. The decay of these excited electrons produces a cascade of secondary electrons, which is detected. Because specific core levels are involved, synchrotron-PEEM is able to collect element-specific information. Recently it has been shown that a dichroic effect exists also for excitations near the emission threshold, i.e., in the conduction band [1]. Such a laboratory-type PEEM works with an UV light source ("UV-PEEM") and is conceptually rather simple compared with PEEM at synchrotrons. In particular, the emitted electrons are mainly photoelectrons that have not suffered additional scattering processes in the sample.

Synchrotron-PEEM is able to map magnetic structures below nonmagnetic overlayers [2]. The probing depth is on the order of several tens of nanometers, as expected for the low-energetic part of the secondary electron cascade [3]. The situation is less clear for UV-PEEM: The emitted electrons originate from both the magnetic film and the nonmagnetic overlayer, without a possibility to distinguish them by elemental analysis. Here we report on an experimental study to determine the probing depth in UV-PEEM, and compare it with the probing depth of a related all-optical experiment, the magneto-optical Kerr effect. In the Ag/Fe model system, it is found that the probing depth of UV-PEEM is essentially given by the penetration depth of the photons.

The linear magnetic dichroism as observed by UV-PEEM requires the same geometry as the transverse Kerr effect: The magnetization direction is perpendicular to the plane of incidence of the incoming light, whereas the light polarization lies within the scattering plane. Experimentally, we have used unpolarized light from a Hg high-pressure arc lamp (100 W,  $h\nu$  [ 5 eV). The electron optics of the PEEM consist of a triode objective lens, a transfer lens, a projective lens, and a fluorescent screen read out by a 12-bit CCD camera. A contrast aperture resides in the back focal plane of the objective lens. The magneto-optical Kerr effect was measured in a microscope with the Hg lamp, followed by a band filter for green light (512 nm). The longitudinal Kerr effect was used, with an angle of incidence of  $45^\circ$ .

Polycrystalline Fe films of 90 nm thickness were grown by molecular beam epitaxy at room temperature onto Si(100) wafers covered by native oxide. Subsequently, a Ag overlayer of varying thickness has been deposited through a shadow mask. The Ag thickness has been determined during growth by a quartz microbalance, and calibrated ex-situ by profilometry.

To determine the attenuation of the magnetic signal by the overlayer, the number of electrons  $I$  emitted from oppositely magnetized domains in the Fe film has been measured. The experimental asymmetry  $A_P$  hence is defined as  $A_P = (I(M+) - I(M-)) / (I(M+) + I(M-))$ , with  $M+$  ( $M-$ ) being the magnetization parallel (antiparallel) to the scattering plane normal. The coupling of the incoming light to the number of electrons emitted can be understood by the

Maxwell equations and the theory for emission of free electrons, and leads to  $I \sim D_z^{-2}$ , with  $D_z$  being the displacement vector perpendicular to the surface [1].

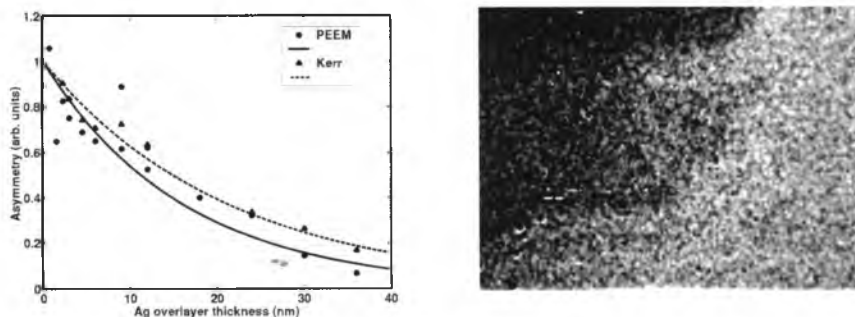


Figure 1: (left) Experimentally determined asymmetries vs. Ag overlayer thickness. The data have been normalized to vanishing Ag thickness. A fit to the data with an exponential decay law yields a probing depth of  $\lambda_P = 16.2$  nm for PEEM and of  $\lambda_K = 21.5$  nm for Kerr; (right) PEEM image for a Ag thickness of 24 nm. The field of view is  $200 \times 140 \mu\text{m}^2$ .

Figure 1 shows the experimentally determined asymmetries vs. overlayer thickness from a series of UV-PEEM images. A fit to the data with an exponential decay law  $A_P \sim \exp(-d/\lambda_P)$  yields a probing depth of  $\lambda_P = 16.2$  nm. Quite analogously, the asymmetry  $A_K$  in the Kerr effect can be determined and fitted to  $A_K \sim \exp(-d/\lambda_K)$ , with  $\lambda_K = 21.5$  nm, which agrees with the value of 21.3 nm calculated from the optical constants  $n$  and  $k$  of Ag [4] at a wavelength of 512 nm.

We conclude that UV-PEEM is capable of imaging magnetic domain patterns in Fe buried below more than 30 nm of Ag. The probing depth determined from the attenuation of the domain contrast is close to the probing depth of the magneto-optical Kerr effect, which means that the penetration depth of light is the determining factor for the depth sensitivity. The escape depth of the photoelectrons at 5 eV above the Fermi energy is larger than the probing depth of the incoming photon, in agreement with the large inelastic mean free path predicted by the “universal” curve [3]. Hence, both UV-PEEM, with only 5 eV photon energy, and synchrotron-PEEM, with excitation energies in the keV range, probe bulk magnetism. This means that elemental sensitivity is not needed for an investigation of buried magnetic layers. A further consequence from these results concerns a related technique, namely, low-energy electron microscopy (LEEM): The common belief that LEEM is a highly surface-sensitive technique in the range of low energy (0–10 eV) hence is no longer justified [5].

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## OPTIMISATION OF AN ELECTROSTATIC TETRODE OBJECTIVE FOR XPEEM

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The ultimate lateral resolution of a typical Photoelectron Emission Microscope (PEEM) crucially depends on an optimised contrast aperture to balance the diffraction term with the spherical and chromatic aberrations. For PEEM applications without energy filtering the type of the objective lens plays an important role as has been shown by Chmelik et al [1]. The authors found for all configurations examined a best resolution below 10 nm which is sufficient for many practical applications.

Many PEEM users do not aim at the ultimate resolution, but at higher intensity, that can be realised with larger apertures. For example applications with X-ray excitation (XPEEM), where bright laboratory sources are yet to come need higher intensity to get manageable conditions. Synchrotron applications with limited beamtime, or spectro-microscopic studies where series of images have to be taken need highest intensity to get short exposure times.

With larger apertures the contributions of the objective's spherical and chromatic aberrations to the resolution deterioration become essentially large, and thus an optimisation of the objective geometry is mandatory.

The goal of our study was to obtain an optimised geometry for an electrostatic tetrode objective. We have chosen an electrostatic objective for two reasons. First the sample should be at ground potential to allow easy in-situ preparation (cooling, heating, etc.) and the column energy of the electrons should be as low as possible to allow easy adaptation of retarding [2] or dispersive [3] energy filters or TOF-detectors [4]. Furthermore the investigation of magnetic samples [5,6] without disturbance of the magnetic properties is feasible.

The largest influence on the properties of an electrostatic tetrode objective lens, as shown in Fig. 1 gives the second electrode (Focus). We calculated the spherical and chromatic aberration coefficients for geometries with varying length  $L$  and diameter  $D$  of the focussing electrode. The bore of the extractor electrode and the microscope column were kept constant as well as the sample distance that was chosen to withstand an accelerating voltage of 30kV. For each geometry the column potential was varied from 0.6 of the extractor potential down to the point where no focussing with a fixed image position was possible. The calculations were made by direct ray tracing using Simion 6.0.

Knowing the constant aberration due to the accelerating field, the aberration coefficients of the lens (without extractor field) can be calculated. Fig. 2 shows the lens aberration coefficients for a typical electrode length with varied diameters.

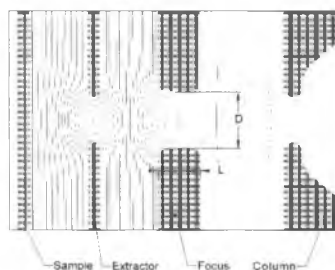


Figure 1: Geometry of the electrostatic tetrode objective studied with typical equipotentials.

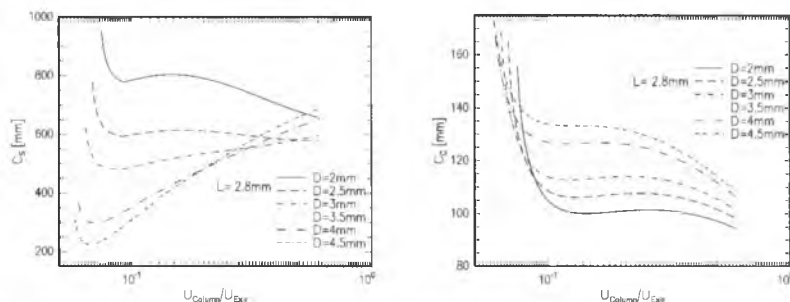


Figure 2: Calculated spherical (left) and chromatic (right) aberration coefficients for different geometries and column voltages.  $D$  and  $L$  are defined in Figure 1.

As expected the spherical aberration can be minimised for larger electrode diameters where the lens filling is smaller. This is the most pronounced dependence and can give a reduction up to a factor of four for low column potentials, where also the absolute minimum is found. The chromatic aberration is lower for high column voltages and small diameters; the dependence on the geometry is less pronounced.

To find the optimum working conditions we took the disc of confusion resulting in the objective lens' image blur as a figure of merit. For XPEEM this figure of merit is mainly dependent on the objective aperture, it defines the angle spread and – through its low-pass behaviour – also the energy spread [7]. Fig. 3 shows this quantity for a large aperture (300 $\mu$ m diameter for 1.2kV column voltage), typical for the working conditions aimed to.

The findings show that the best results can be obtained with the column potential near the focussing voltage.

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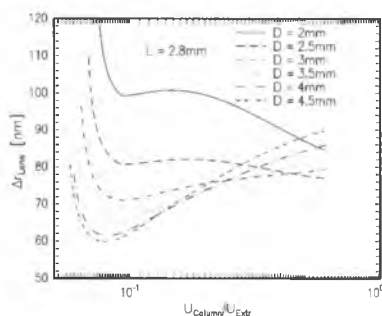


Figure 3: Figure of merit for a 300 $\mu$ m contrast aperture. The large aperture results in an energy distribution with 2.4eV width for XUV excitation. The radius of the aberration disc  $\Delta r$  refers to sample coordinates.