OPTICS

Software for Electron and Ion Beam Column Design

- An integrated workplace for simulating and optimizing electron and ion beam columns

Base Packages (OPTICS & OPTICS-Lite)
- Field computation
- Imaging and paraxial focusing properties
- Primary geometrical and chromatic aberrations
- Graphical output of fields, trajectories and aberration spot diagrams, etc.
- OPTICS is for complex systems of multiple lenses and deflectors
- OPTICS-Lite is for single lens systems only

Optional Upgrades:
- DYNAMIC – For designing dynamic deflection aberration correctors
- REFINE – Column optimization to minimize aberrations
- TOLERANCE – To simulate aberrations due to mechanical asymmetries
- ABER-5 – To simulate aberrations up to fifth-order terms
- DYNAMIC-5 – For dynamic deflection aberrations up to 5th-order
- REFINE-5 – Column optimization up to 5th-order
- RB3 – For rocking beam deflection systems
- RB5 – Rocking beam capability up to 5th-order

Graphical User Interface Features:
- Multiple Document Interface (MDI) for simulating several electron optical elements and columns in a unified environment
- Batch processing capability

System Requirements:
- Runs under Microsoft Operating System (Windows 8, 7, Vista or XP)
OPTICS FAMILY OVERVIEW

The OPTICS software is a package for the simulation and computer aided design of electron optical columns consisting of any combination of electron lenses and deflectors\(^1\). Its purpose is to assist the electron optical designers with three main tasks:

1. Computing field distributions in individual electron lenses and deflectors.
2. Computing the optical properties and aberrations of any combination of such elements.
3. Graphical display of the effects of the aberrations.

The electrostatic and magnetic lens fields are computed by the first-order finite element method (FEM). For magnetic lenses, the field can be computed in the polepiece region with a scalar potential, or throughout the complete lens, including the magnetic circuit and coil windings, with a vector potential. Magnetic saturation is handled with numerically specified B-H curves.

The deflection system can have up to three independent channels (main, sub and tertiary field). Each channel can be either electrostatic or magnetic. The deflectors are used to scan the beam over a 2D area in the image plane or, alternatively, they can be used to scan and rock (or tilt) the beam\(^2\). Systems for correcting some of the deflection aberrations, involving dynamic focus lenses and stigmators, can be designed using the optional DYNAMIC module.

Optical effects of asymmetry errors in the construction and alignment of the column can be investigated using the optional TOLERANCE module, which can simulate placement errors in individual electrode, wires and plates or misalignments and tilts of complete lenses or deflectors.

The aberrations are computed using specially derived aberration integrals, which enable fast and accurate computation of the required coefficients. The base OPTICS package computes geometrical aberrations of third order, and the chromatic aberrations of first order. Higher order aberrations can be computed with additional optional modules\(^3\).

Screen shots of the program are shown on the next pages. The operation of the program is controlled through the menus and speed buttons at the top of the screen.

Field Computations

Figure 1 shows a simulation of the field distribution in a magnetic lens. The screen is divided into four panels. The upper half of the screen shows, on the left, the data that defines the finite element layout, and, on the right, the actual layout of the mesh. In the lower half of the screen, the results of the magnetic field computation are shown, consisting of the computed data for the axial flux density distribution \(B(z)\) (lower left) and the corresponding graph of \(B(z)\) (lower right). In this environment, it is easy to modify the input data and observe the effects immediately. The mesh data can be edited directly, in the top left hand panel, and the effect on the mesh layout immediately displayed in the top right hand panel. The corresponding change in the field distribution can then be observed, both numerically and graphically, in the bottom panels, just by clicking a button.

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\(^1\) OPTICS-Lite is for single-lens systems only – it does not handle deflectors
\(^2\) Using the Rocking Beam options RB3 or RB5
\(^3\) Using the ABER-5, DYNAMIC-5 and REFINE-5 modules
Figure 1. Screen shot showing field computation in a magnetic lens

**Column Simulations**

Figure 2 illustrates the simulation of a complete electron optical column. The screen is again divided into four panels. The top panels show the data and layout for the column, while the bottom panels show the numerical values of the aberration coefficients and a spot diagram of the aberration effects. The imaging conditions, such as numerical aperture and field size can be altered by the user and the corresponding effects on the aberrations can be observed interactively.

Figure 2. Screen shot showing simulation of the aberrations of a complete electron optical column
Post-Processing Tools

OPTICS has a set of comprehensive post-processing tools and Figure 3 shows the post-processing control screen.

![Post-processing control screen](image)

Figure 3. Post-processing control screen

As examples, Figures 4 and 5 show the aberration spot diagrams without and with the asymmetry aberrations included, which correspond to unchecking and checking the Asymmetry Aberration checkbox on the control screen shown in Figure 3.

![Aberration spot diagram without asymmetry aberrations](image)

Figure 4. Aberration spot diagram without the asymmetry aberrations included
Figure 5. Aberration spot diagram with the asymmetry aberrations included

The post-processing tools also include the ability to generate plots computed using a Point Spread Function (PSF). This method provides the current density distribution of the PSF and a quantitative assessment of the aberrations, defined in terms of the rise distance of the PSF, in a through-focal series of planes. The rise distance of a PSF has been proven to be equivalent to the pattern edge sharpness, which can be measured experimentally. For these types of diagram, extra plotting data is required and the right-hand side of the Plotting Conditions Data form will become active if these diagram types are selected (see Figure 6).

Figure 7 shows an example of spots and contours for a through-focal set of planes for the PSF located at the top right corner of a shaped beam on axis. Figure 8 shows an example of spots and contours at selected axial plane for a shaped beam on the axis.

Figure 6. Post-processing control screen for PSF-type plot
DYNAMIC Module (Optional)

The DYNAMIC module can analyse electrostatic and magnetic stigmators and dynamic focus lenses in the main OPTICS environment. Figure 9 shows the analysis of a scanning microscope column with magnetic condenser lens, conical combined magnetic and electrostatic retarding field objective lens, dual channel canning deflection system, with main field dynamic stigmator and dynamic focus lens. The DYNAMIC module computes the fields in the stigmators (e.g. see Figure 9 – upper picture) and dynamic focus lenses and the optical properties takes into account the presence of these dynamic correction elements in the complete column (Figure 9 – lower picture).

The field functions of the stigmators and dynamic focus lenses are used to compute the required strengths to correct the deflection astigmatism and field curvature, respectively. DYNAMIC module computes and outputs the dynamic correction coefficients for the stigmators and dynamic focus lenses in the systems, as shown in Table 1.
Figure 9. SEM analysis, including dynamic deflection correction element. Top picture shows the field analysis of an electrostatic stigmators, the bottom picture shows the overall system analysis.

<table>
<thead>
<tr>
<th>Table 1. Third-order dynamic correction coefficients</th>
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</thead>
<tbody>
<tr>
<td><strong>STIGMATOR COEFFICIENTS (for 1 mm x-deflection):</strong></td>
</tr>
<tr>
<td>0 deg elements</td>
</tr>
<tr>
<td><strong>MAIN-FIELD STIGMATOR 1 .... NORMAL</strong></td>
</tr>
<tr>
<td>4-FOLD</td>
</tr>
<tr>
<td><strong>DYNAMIC FOCUS LENS COEFFICIENTS (for 1 mm x-deflection):</strong></td>
</tr>
<tr>
<td><strong>MAIN-FIELD DYN LENS 1 ..........</strong></td>
</tr>
</tbody>
</table>
**REFINE Module (Optional)**

The purpose of REFINE is to take an initial design of electron or ion beam column, and interactively refine the design to optimize the performance by minimizing the aberrations.

REFINE is useful, because in a particle beam column there are many design parameters that can be varied, such as the positions, sizes and relative strengths of each lens and deflector, and the rotation angle of each deflector. There are a large number of aberrations, which each depend on the variable parameters, and so the overall aberration is a very complicated non-linear function of the variable parameters. In such situations, the use of an optimization procedure is very useful, and generally yields designs with significantly better properties than those found by trial and error.

There are powerful graphical instrument panels built into the software, so that the user has significant control over the optimization process, including interactive control over the weighting factors assigned to each aberration and constraints on the range over which each variable parameter is allowed to change. The variable parameters are the axial position, size and relative strength of each lens and deflector, and the rotation angle of each deflector. The quantity to be minimised is a weighted sum of squares of all the individual aberrations. Starting from an initial design, the program alters each variable parameter by a small amount, and recomputes the aberrations. This yields the partial derivative of each aberration with respect to each variable parameter. A least squares equation is then solved, to find the change in each variable that would minimize the weighted sum of squares of the aberrations in the "least squares" sense, if the partial derivatives were to remain constant. To ensure stability, a positive damping factor is introduced into the principal diagonal elements of the least squares matrix. The calculation is repeated for several values of the damping factor, and the damping factor which minimizes the target function is selected using a one-dimensional binary search. This constitutes one optimization cycle. The entire cycle is repeated several times, until a local minimum is reached.

Figure 10 shows the window to set up the variables for the optimization process:

![Optimization control screen](image)

Figure 10. Optimization control screen

Figure 11 shows the aberration spot diagrams before and after four optimization cycles.
Figure 11. Optimization Process Window for after four optimization cycles for the sample data.

**TOLERANCE Module (Optional)**

TOLERANCE is used for computing the effects of tolerancing errors in complete columns, containing any combination of electrostatic and magnetic lenses and deflectors. It computes the asymmetry aberrations caused by small mechanical imperfections in the construction and alignment of the individual optical components of the column enabling tolerances to be assigned for the construction and alignment, to ensure that the system will perform in accordance with its design specifications.

TOLERANCE handles the effects of misalignments and tilts of complete lenses and deflectors, relative to the optical axis of the column. The software also computes the effects of axial and radial misalignments, tilts and ellipticities of any individual polepiece, coil winding or electrode of any lens or deflector in the column. In the case of deflectors, the software also handles the effects of azimuthal misalignments of individual coil windings or electrodes.

TOLERANCE can also handle static deflectors and stigmators. The static deflectors are used to correct the first-order image shifts due to misalignment and tilt of lens electrodes or polepieces; and the static stigmators are used to correct the astigmatism due to ellipticity of lens electrodes or polepieces. In this case, the static deflection and stigmation field functions are computed, using the field computation functions of the core OPTICS package plus the optional DYNAMIC module, respectively. The software computes the additional aberrations due to the static deflectors and stigmators. The software also calculates the required signals for correcting the first-order image shifts and beam tilts due to the specified misalignments and tilts of the lens polepieces and electrodes, and the astigmatism due to the specified ellipticities of the lens polepieces and electrodes.

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4 The static stigmator function requires the optional DYNAMIC module to be active in the OPTICS GUI.
In OPTICS, the TOLERANCE module is integrated seamlessly into the main graphical user interface. Figure 12 shows a simulation of the perturbation field due to misalignment of an electrode in an electrostatic lens.

*Figure 12. Electrostatic lens simulation, with the computed axial perturbation field functions displayed numerically and graphically in the lower part of the screen*

For a complete column, the user can assign the asymmetry errors to each optical element by clicking the Asy Errors button, which starts the Asymmetry Errors window, as shown in Figure 13.

*Figure 13. Asymmetry errors window*

After assigning the asymmetry errors, the user can compute the asymmetry aberrations by clicking the Aberration button.

Figures 14 and 15 show the aberration spot diagrams without and with the asymmetry aberrations included.
ABER-5 Module (Optional)

In systems where the field size, aperture angle, deflection angle or deflection scan area are large, the primary aberrations may not be the sole significant contributor to the total spot size and higher-order aberration effects can become significant. ABER-5 extends the capabilities of the OPTICS package to compute the higher-order aberrations of complete columns – specifically the fifth-order geometrical and third-order chromatic aberrations. The accurate prediction of these higher-order aberrations is important in designing electron and ion beam systems which use large-area projection or large-field scanning.

ABER-5 handles the same types of systems as the OPTICS package. This includes columns with any combination of electrostatic and magnetic lenses and deflectors. Gaussian round beams or extended shaped beams can be handled. The deflection can be dual-channel (main and sub field), using multipole and planar deflectors, and the $x$ and $y$ deflectors can be located either at the same axial location or at sequential positions along the $z$-axis. All the rotationally symmetric and multipole aberrations are computed, including the fourfold aberrations of fifth-order, created by both the third and fifth harmonics of the deflection fields.

The software computes the higher-order aberrations using specially derived aberration integrals, in the following way. The axial field functions of the lenses and deflectors are first obtained with the SOFEM package. (The high accuracy inherent in the fields computed with the SOFEM software is essential for obtaining accurate values of the high-order derivatives of the axial field functions.) The

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5 Purchase of SOFEM is a prerequisite for the ABER-5 module
radial expansions of these field functions, up to fifth-order terms in the off-axis distance, are then obtained by taking several axial derivatives of each axial field function. The principal paraxial rays are computed, by retaining only the first-order terms in the field expansions. Then, in the next approximation, the third-order terms in the field expansions are retained in order to compute the third-order geometrical aberrations, using aberration integrals in the standard way. These primary aberration integrals are evaluated using the principal paraxial rays. After that, in the final approximation, the fifth-order terms in the field expansions are retained in order to compute the fifth-order geometrical aberrations, using specially derived aberration integrals.

An example is shown in Figure 16 of a mixed electric and magnetic focusing and deflection system, where the scan field size is 12 mm. Figure 17 shows the effects of the higher-order aberrations in such a system are significant.

Figure 16. Mixed (electric and magnetic) focusing and deflection system
(z_0 = 0 mm, z_i = 450 mm, \alpha_i = 5 mrad, field = 12 mm, V_i = 25kV, \Delta V = 2.5 eV)

Figure 17. Aberration spot diagrams for the mixed (electric and magnetic) focusing and deflection system
**DYNAMIC-5 Module (Optional)**

The DYNAMIC-5 module can analyse electrostatic and magnetic stigmators and dynamic focus lenses in the main OPTICS environment (just like DYNAMIC) but compute the aberrations up to 5th-order terms (similar to ABER-5).

For systems with large deflection angle or scan field size, it is often required to compensate not only the primary deflection field curvature and astigmatism (see the DYNAMIC module), but also the fifth-order field curvature and astigmatism. The DYNAMIC-5 module computes the fields in the stigmators using the SOFEM field module and then computes the required strengths on the stigmators and dynamic focus lenses required to compensate the 5th-order field curvature and astigmatism. DYNAMIC-5 will then compute the residual aberrations after the dynamic corrections to 5th-order have been applied.

![Figure 18. SEM column, including dynamic deflection correction elements for the main field deflection channel to compensate third-order and fifth-order deflection astigmatism and field curvature.](image)

**FIFTH-ORDER DYNAMIC CORRECTION COEFFICIENTS**

<table>
<thead>
<tr>
<th>STIGMATOR COEFFICIENTS</th>
<th>(for 1 mm main x-deflection):</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 deg elements 45 deg elements</td>
<td></td>
</tr>
<tr>
<td>MAIN-FIELD STIGMATOR 1 ..... NORMAL -4.667209e+00 -9.380774e+00 Volts</td>
<td></td>
</tr>
<tr>
<td>4-FOLD 0.000000e+00 0.000000e+00 Volts</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>DYNAMIC FOCUS LENS COEFFICIENTS</th>
<th>(for 1 mm main x-deflection):</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN-FIELD DYN LENS 1 ............ -4.694767e-03 Ampere-turns</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2. Fifth-order dynamic correction coefficients for the system illustrated in Figure 18*

**REFINE-5 Module (Optional)**

The REFINE-5 module extends the functionality of REFINE to allow optimisation of the aberrations up to 5th-order terms. Additional interfaces are provided which allow the user to control the 5th-order terms that are to be minimised by specifying weighting factors for each group of fifth-order aberrations. The variable parameters of the system (also specified

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6 Required in addition to DYNAMIC-5
interactively by the user) are adjusted to minimise the weighted sum of the aberrations. The weighting factors can be specified for any combination of 3rd-order and 5th-order aberration terms.

**Figure 19. Weighting factors control screen, showing the tab for setting the fifth-order terms**

![Weighting factors control screen](image)

**Figure 20. Spot diagrams for a sample system. Left: 3rd order aberrations for system before optimization; Middle: 3rd-order+5th-order aberrations for system before optimization; Right: 3rd-order+5th-order aberrations for system after optimization of all aberrations up to fifth-order**

**ROCKING BEAM Capability (Optional)**

Traditionally, the deflection systems modelled in OPTICS have been of a scanning type, which enable the beam to be scanned over a specified region of the image plane. Recently, it has become important to be able to rock or tilt the beam about a specified position in the image plane. The rocking of the beam is required for several reasons, for example: to be able to probe the sides of tall or deep structures on the image plane in an inspection machine; to adjust the beam angle arbitrarily at any given point in wafer plane for optimal writing performance in a lithography column; to create a stereoscopic pair of images in a SEM, etc. To this end, we have enhanced OPTICS to enable the deflectors to act in a rocking (or tilting) mode.

Two rocking beam options are available:
**RB3** – allows the aberrations of rocking beam systems to be computed up to 3rd-order terms;
**RB5** – allows the aberrations of rocking beam systems to be computed up to 5th-order terms.

In OPTICS, a maximum of three deflection channels (main, sub and tertiary channel) are permitted and the RB3 and RB5 options will allow any of these to be assigned as a rocking beam channel, so the system can have a mixed scanning and rocking beam deflection system. For the rocking beam channel, there can be any number of deflectors to steer the beam, and any one of these can be specified as a control deflector which is auto-adjusted by the software to give zero net positional deflection for that channel. The user specifies the master deflection signal for the rocking channel and RB3 and RB5 compute the required excitation and rotation angle for the adjustable deflector, as well as the angular deflection sensitivity of the rocking channel. Furthermore the aberration coefficients are expressed in powers of (amongst other things) the master deflection signal, enabling the positional aberration disk sizes to be computed and plotted as functions of the rocking beam deflection master signal.

![Figure 21. SEM column with dual channel deflection system, where the main channel is used to rock the beam and the sub channel is used for scanning](image)

**Figure 21.** SEM column with dual channel deflection system, where the main channel is used to rock the beam and the sub channel is used for scanning

![Figure 22. Spot diagrams for the system shown in Figure 21: Left picture, for a main field signal of (1,1) Amps, which corresponds to 1° of tilt; Right picture, for a main field signal of (2,2) A, which corresponds to 2.2° of tilt.](image)

**Figure 22.** Spot diagrams for the system shown in Figure 21: Left picture, for a main field signal of (1,1) Amps, which corresponds to 1° of tilt; Right picture, for a main field signal of (2,2) A, which corresponds to 2.2° of tilt.

As well as the positional aberrations, RB3 and RB5 also compute the slope aberrations for the rocking beam systems. This is a powerful enhancement because, as well as errors in the placement of the beam, in a rocking system there will also be errors in the tilt angle of the beam, according to the master signal on the rocking channel deflectors. By knowing both the positional...
and slope aberrations, the user can monitor the fidelity of the placement and angle of the beam impinging on the target.

**OPTICS-Lite (Round-Lens-Only Option)**

The full OPTICS suite is an extremely powerful design tool with many complex features. Often, however, a user will just want to know some basic properties of their optical system, for example the spherical aberration of the objective lens. To cater for this need, we have developed a version of OPTICS with some of the most desirable tools for round lenses – we call this OPTICS-Lite.

OPTICS-Lite will handle a single magnetic lens, or a single electrostatic lens or one of each type of lens in a single column. It will enable the lens fields to be computed using first-order finite element method and allow plots of the mesh layouts, equipotentials and axial field functions of the lenses.

OPTICS-Lite will autofocus the system, using the specified focus variables, and will compute the paraxial properties and primary aberrations. In addition, basic tolerancing capabilities are included to enable the asymmetry fields and aberrations to be computed for specified mechanical errors in the system.

Graphical post-processing of the computed optical properties, including spot plots and current density profiles in the spot are provided.

OPTICS-Lite can also act as a pathway into the OPTICS base package and from there onto the full OPTICS suite via the optional modules described in the previous sections. All data and results prepared for and generated by OPTICS-Lite are compatible with the full OPTICS suite.

![Figure 23 Screenshot of OPTICS-Lite being used to analyse a combined electric and magnetic objective lens with tolerancing errors.](image)