Characterization of Beam Aberrations due to Magnetic Field Tilt in DIVA for Massively Parallel Electron Beam Lithography

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Abstract:

Theoretically, electron beam systems can achieve sub-nanometer resolution, limited only by diffraction and spherical aberration. While this makes them attractive for meeting the future demands of nanolithography, single beam systems today are slow compared to optical methods because space charge effects limit the usable write current. Multibeam systems circumvent this limitation by distributing the total current over many spatially separate beams.

One such system, known as DIVA, takes advantage of the properties of the simplest electron lens, a uniform axial magnetic field, to image an array of apertures at unity magnification. We propose a theoretical model of electron motion due to a misaligned axial magnetic field in order to determine if astigmatism correctors will be necessary in the multibeam system. Pending experimental verification, magnetic field tilt does not seem to be a significant source of aberrations within modest mechanical tolerances (less than 10 mrad).

Introduction:

Theoretically, electron beam systems can achieve sub-nanometer resolution, limited only by diffraction and spherical aberration. E-beam lithography systems currently available, such as the Leica VB6-UHR-EWF, have demonstrated features sizes of less than 10 nm [1], far exceeding the resolution of the best optical machines. While this makes them attractive for meeting the demands of nanolithography, single column systems today are slow compared to optical methods. This is due to the electron-electron interactions that blur the beam as current is increased, limiting the amount of current that can pass down a single column.

Multi-axis systems overcome this limit by distributing the total write current over many spatially separate beams writing simultaneously. DIVA (DIstributed axis, Variable Aperture), proposed by Groves et al. [2], uses a uniform axial magnetic field to form an image of an array of apertures at unity magnification and can accommodate as many as 10,000 beams. Advantages of this configuration include extreme simplicity of the optics, scalability, and low aberrations. Previous work with uniform field systems has successfully demonstrated unity magnification SEM operation for a single beam, with resolution determined only by the size of the beam-limiting aperture [3].

In order to extend the current system to multiple beams, it is necessary to know what tolerances need to be met so that all beams perform equally well. Of particular concern is the possibility that astigmatism correctors will be needed for each beam, which could compromise the simplicity and scalability of the system. One likely source of astigmatism in the current system is magnetic field tilt with respect to the mechanically defined optic axis (Figure 1).

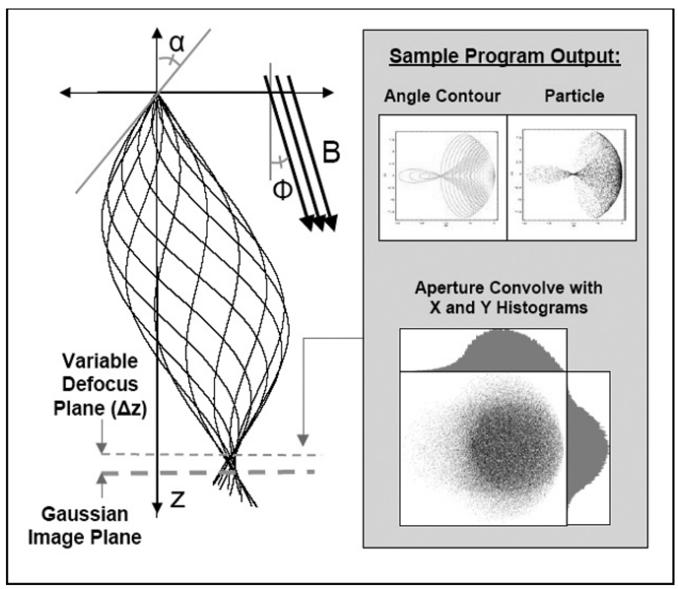

Figure 1: Schematic of particle motion in a uniform B-field tilted φ with respect to the z-axis for a beam with half-angle α. A computer program calculates particle positions in any plane perpendicular to the z-axis, producing the three types of output shown.

Theoretical Model:

A non-relativistic particle moving in the presence of electric and magnetic fields feels a force given by the Lorentz Force Law, $F = q(E+vxB)$. For a particle moving in a uniform magnetic field tilted at an angle φ

(a)

$$v_x'(t) = -\omega v_y(t)\cos\phi$$
$$v_y'(t) = -\omega (v_z(t)\sin\phi - v_x(t)\cos\phi)$$
$$v_z'(t) = \omega v_y(t)\sin\phi$$

(b)

$$x(t) = \frac{1}{\omega}\left(v_{0x}\,\omega t\sin^2\phi + \cos\phi\,(v_{0y}(\cos(\omega t) - 1) + v_{0z}\sin\phi\,(\omega t - \sin(\omega t))) + v_{0x}\cos^2\phi\,\sin(\omega t)\right)$$
$$y(t) = \frac{1}{\omega}\left(v_{0z}\sin\phi\,(\cos(\omega t) - 1) + v_{0y}\sin(\omega t) + v_{0x}\cos\phi\,(\cos(\omega t) - 1)\right)$$
$$z(t) = \frac{1}{\omega}\left(v_{0z}\,\omega t\cos^2\phi + v_{0x}\cos\phi\sin\phi\,(\omega t - \sin(\omega t)) + \sin\phi\,(v_{0y}(1 - \cos(\omega t)) + v_{0z}\sin\phi\sin(\omega t))\right)$$

(c)

$$t = \frac{1}{v_{0z}}\left(wd + df + \frac{2n\pi}{\omega}\sin\phi\,(v_{0x}\cos\phi + v_{0z}\sin\phi)\right)$$

Figure 2: (a) Nonrelativistic equations of motion for an electron in a B-field tilted by φ where ω is the cyclotron frequency eB/m. (b) Second integral solution. (c) Time of flight approximation.

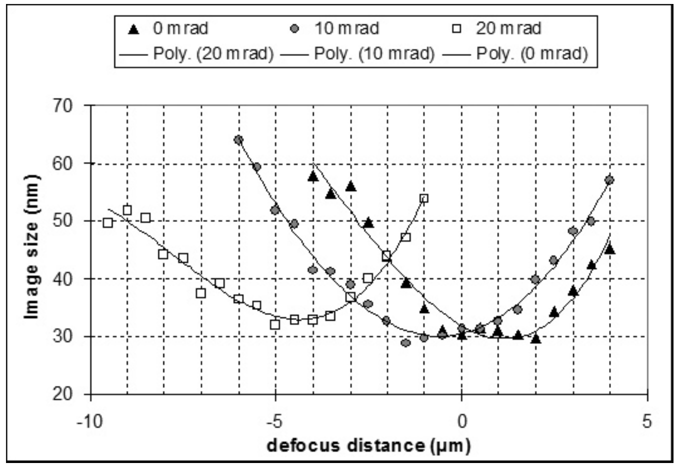

Figure 3: Size of aberrated image from a 25 nm aperture: sqrt($x_{FWHM}^2 + y_{FWHM}^2$), through focus. At 20 mrad of tilt, depth of focus is impacted.

with respect to the z-axis, the equations of motion are given by Figures 2a and 2b.

Mathematica® programs were used to calculate particle positions given a set of initial velocities. The programs produced particle plots and contours of equal launch angle, varying magnetic field tilt and defocus distance. Blur in x and y of the aperture image was found by convolving the particle plot data with the aperture shape, generating x and y histograms, and finding the full width at half maximum for each (Fig1).

Results:

The tri-lobed shapes of the angular contour plots (Figure 1) suggest that the dominant aberration type is elliptical coma [4], and not simple astigmatism as was expected. We ran the aperture image program for a 10 keV monoenergetic beam with a 10 mrad half-angle at a 10 mm working distance, using a 25 nm aperture with 0, 10, and 20 mrad tilt at 0.5 μm steps through focus. The depth of focus, or trough width for a given image size, is comparable in the 0 and 10 mrad cases, but significantly worse in the 20 mrad case. (Figure 3). Additionally, the 20 mrad case showed significant astigmatism while the 10 mrad case did not (Figure 4).

Conclusions and Future Work:

According to the proposed model, magnetic field tilt will not be a major source of astigmatism in DIVA, provided that modest mechanical tolerances are met. The system resolution is unaffected for tilt angles as large as 10 mrad, which should be easy to achieve in the multibeam system. The system chamber has been fabricated to within 0.002″ over the 12″ reference surface, which corresponds to a maximum tilt of 0.2 mrad. A micrometer stage has been constructed to tilt the chamber of the single-beam DIVA within the magnetic field in order to measure tilt-induced aberrations. Pending experimental verification, astigmatism correctors should not be necessary in the multibeam system.

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References:

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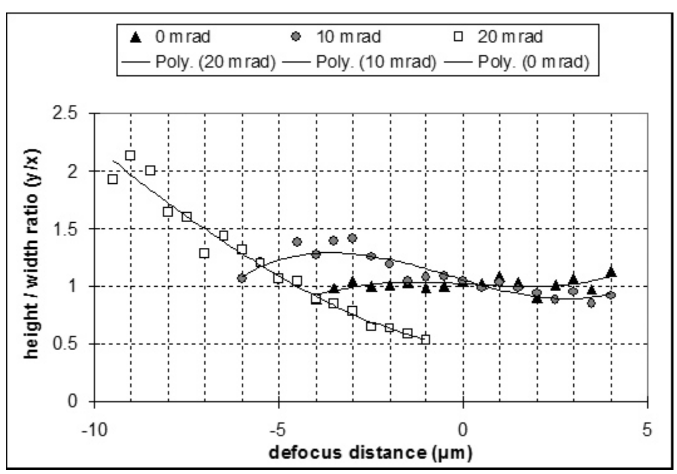

Figure 4: Ratio between FWHM measurements from x and y histograms through focus. Stigmators would be helpful for correcting aberrations in the 20 mrad case, but probably not in the 10 mrad case.