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Circumventing Scherzer's Theorem: Large Numerical Aperture Objective Lenses for Pulsed Electron Microscopy

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Scherzer's theorem states that all static round magnetic and electro-static electron lenses possess positive spherical aberration [1]. As a result, in recent years, much effort has been invested in techniques to correct for the spatial aberrations (Cs) of objective lenses in high resolution electron microscopy. For pulsed electron sources, such as those required for ultrafast transmission electron microscopy (UTEM), an alternative strategy for Cs aberration correction is possible through the use of the dynamic lensing properties of RF cavities [2] that, when operated in the appropriate oscillation mode, can possess negative spherical aberration [3]. For single-shot imaging UTEM, which requires ~ 10^8 electrons/pulse, simulations indicate that a large numerical aperture (NA > 0.1) objective lens will also be required to mitigate against deleterious space-charge effects [4] – effectively by minimizing the time electrons experience a high charge density. Here, we present a theoretical analysis of the possibility of using the focusing properties of RF cavities to compensate for the spherical aberration of large NA objective lenses for pulsed electron microscopy.

Round (i.e., cylindrically symmetric) magnetic lenses focus an incident electron beam through a net radial force whose *magnitude* may be written in a power series; $F_r(r) = c_1 r + c_3 r^3 + \ldots$, where the coefficients c_n are dependent upon the spatial distributions of the radial and axial lens fields. For the case of a perfect lens, where all parallel incident electrons no matter how far off axis are focused to the same axial point, c_3 and all higher coefficients are zero. Figure 1(a) shows a 50kV electron trajectory simulation for a simple, large-aperture, 10mm focal length, static magnetic lens (a coil with no pole pieces) which clearly indicates the expected positive spherical aberration in the focal region ($c_3 > 0$). In contrast, the spherical aberration is negative ($c_3 < 0$) for the spatial focusing action of a suitably synchronized cylindrical RF cavity oscillating on the transverse magnetic $TM_{01}o$ mode (Figure 1(b)). This is due to the $J_1(r)$ Bessel function variation of the azimuthal magnetic $B\varphi$ field which results in $F_r(r) = c_1\left(\frac{r}{a} - \frac{1}{8}\left(\frac{r}{a}\right)^3 + \ldots\right)$, where a is the radius of the RF cavity. A 'doublet' lens consisting of these two electron lenses may then be envisaged with a net zero value of c_3. Figure 1 (c) shows the 50kV electron trajectory simulation for such a 10mm focal length doublet lens which exhibits excellent focusing properties over a NA of 0.1 (i.e., a focused beam semi convergence angle of 100mrad).

The TM_{010} RF cavity mode is also expected to exhibit spatial lensing due to the divergence of the oscillating axial electric field at the entrance and exit beam apertures [4], which suggests that the TM_{011} RF mode, with zero oscillating electric field strength at the apertures, may be a more prac-tical. Other cylindrical RF cavity modes, such as the transverse electric (TE_{01q}) modes commonly used in the telecommunications, are also expected to possess focusing properties with negative spherical aberration. Their possible use as electron optical elements and the restrictions imposed on the electron (pulse) transit time through the RF cavity and its mode frequency will be discussed.

References:
[1] O. Scherzer, *Zeitschrift für Physik, 101* (1936), p.593-603.
[2] L.C. Oldfield, Ph.D. Thesis, University of Cambridge (1973).
[3] P.L.E.M. Pasmans et al, *Ultramicroscopy,* **127** (2013), p. 19-24.
[4] J.A. Berger and W.A. Schroeder, *J. Appl. Phys.,* **108** (2010), p. 124905.
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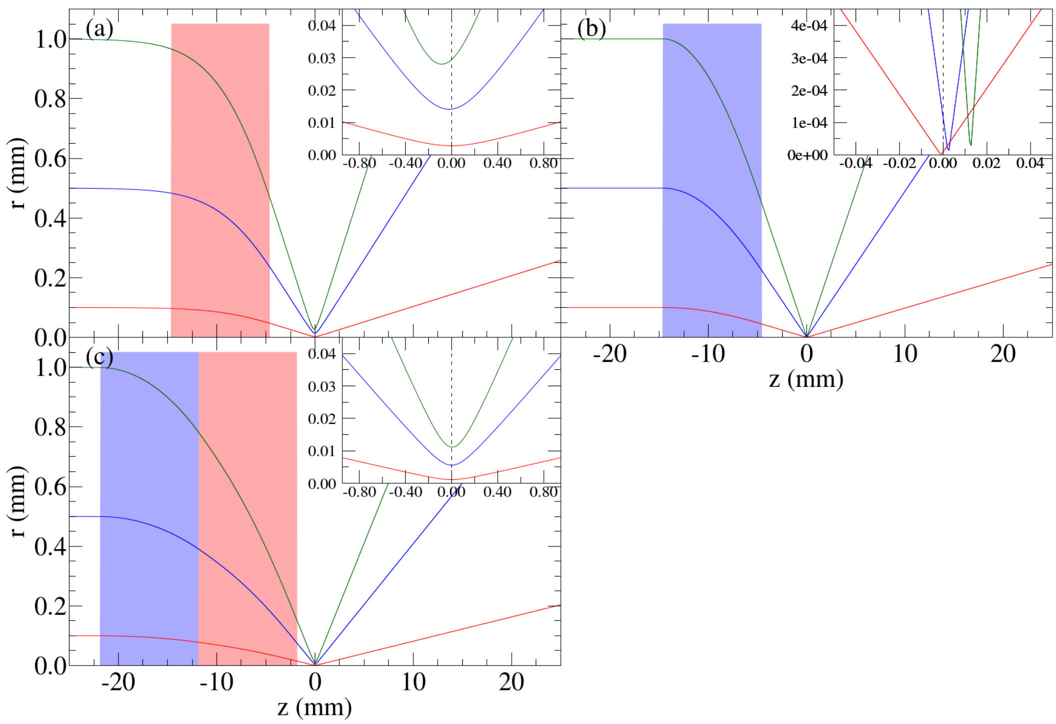

FIG. 1: Trajectory simulations for 50kV electrons incident at off-axis distances of 0.1, 0.5, and 1.0mm on 10mm focal length electron lenses: (a) a round magnetic lens (a coil with no pole pieces); (b) an RF cavity oscillating on the TM010 mode; and (c) the RF-cavity/magnetic-lens doublet designed to minimize spherical aberrations. In each case, the upper right insert shows the focal region with the dashed vertical line indicating the low convergence angle (NA < 0.01) focal plane of the lens.