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First Experiments Using a Radial Mirror Analyzer Attachment Prototype for Scanning Electron Microscopes

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Recently, Hoang and Khursheed reported a Radial Mirror Analyzer (RMA) design to be fitted as an attachment inside the specimen chambers of scanning electron microscope (SEM) or scanning ion microscope [1]. The RMA is rotationally symmetric about the primary beam axis, capable of 2π radian detection, and has a predicted relative energy resolution of better than 0.025% for a polar angular spread of ±6°, around an order of magnitude better than the well-known Cylindrical Mirror Analyzer CMA) for the same acceptance angle [2], and comparable to the best energy resolution of the Hemispherical Deflection Analyzer (HDA) [3]. A slightly improved design of the RMA was reported by Khursheed *et al*. [4] where the main curved deflector plates were replaced by straight segment electrodes (in the r-z plane), making the analyzer easier to manufacture and a factor of two improvement in the relative energy resolution was reported. Such high energy resolution performance makes the RMA suited for a variety of different applications such as Auger Electron Spectrometry (AES) and X-ray photoelectron spectroscopy (XPS). The relatively high transmittance of the analyzer (comparable to the CMA) comes from its rotationally symmetric design in the azimuthal direction and second-order focusing properties.

Figure 1 shows the layout of the RMA design and simulated ray paths for scanning electron/ion microscopes. Scattered electrons/ions leave the specimen located below the analyzer on its rotational plane of symmetry (primary beam axis); they enter the analyzer through a grid, are mirrored down by negatively biased electrodes, exit the analyzer through another grid, and are brought to focus beneath it on a horizontal detector. A conical shaped outer zero volt plate allows for the analyzer to fit under the lower pole–piece of a scanning electron/ion microscope objective lens. This arrangement minimizes the working distance (the distance between the objective lens lower pole–piece and the specimen), allowing the scanning electron/ion microscope to operate in a high spatial resolution imaging mode while at the same time analyzing the energy spectrum of scattered electrons/ions.

Based on the latest simulation design using the 2D package of Lorentz software [5], a first prototype of the RMA was fabricated to fit as an attachment inside a Philips ESEM XL30 FEG SEM. The main design philosophy was to allow the SEM to operate in the normal imaging mode while concurrently acquiring signals using the analyzer. Figure 2a illustrates how the RMA prototype fits inside the SEM; the analyzer is mounted on a XY manipulator fitted onto one of the ports of the SEM chamber while Figure 2b shows the perspective view of the 3D model of the analyzer. The XY manipulator facilitates the movement of the analyzer to bring it close to the final pole piece of the SEM and occupy the typical position of a BSE detector during energy spectrum acquisition and to withdraw the analyzer when not in use. Such a design also allows for the working distance to be typically less than 10 mm (a best possible working distance of 7 mm for this prototype design) which means that the analyzer can be used to capture the scattered energy spectrum while the conventional SE detector can continue to operate normally, acquiring nanometer resolution topographical images.

The RMA design focuses the transmitted electrons in such a way that electron trajectories travel radially out upon exit, and do not naturally converge to a point, unlike the second order focusing toroidal energy analyzer design reported by Khursheed and Hoang [6]. Ideally, some kind of post-analyzer arrangement is required to redirect all wider azimuthal angle electrons towards the primary beam axis and focus them on to a single detector placed below the specimen stage. However, for this preliminary prototype experiment, this was not done due to space and time constraints. Instead, a Scintillator–PMT arrangement (with the scintillator biased at +5 kV), fixed to the bottom of a 0 V shielded box (as shown in Figure 2a) was placed below the RMA exit slit aperture. The high positive bias on the scintillator causes the secondaries exiting the analyzer at different azimuthal angles to be pulled towards it. Experimental SE spectra, obtained from the initial prototype of the RMA are presented in Figure 2c. The experiments were conducted with a primary beam energy of 10 keV (beam current 150 pA) inside the Philips ESEM XL30 FEG SEM, and the deflection voltage was ramped in steps of 200 mV. A silicon wafer coated with a 300 nm thick gold layer was used as the specimen. Analysis of the SE analyzer signals shown in Figure 2c reveals that the SE signal levels are much lower than expected. These experimental result points towards low transport efficiency from the RMA slit to the PMT, which is at present, is not designed to capture electrons that exit at wider azimuthal angles. A new detection strategy is required, in order to redirect and focus the electrons exiting at different azimuthal angles on to a single detector, two such possibilities are highlighted in Figure 3.

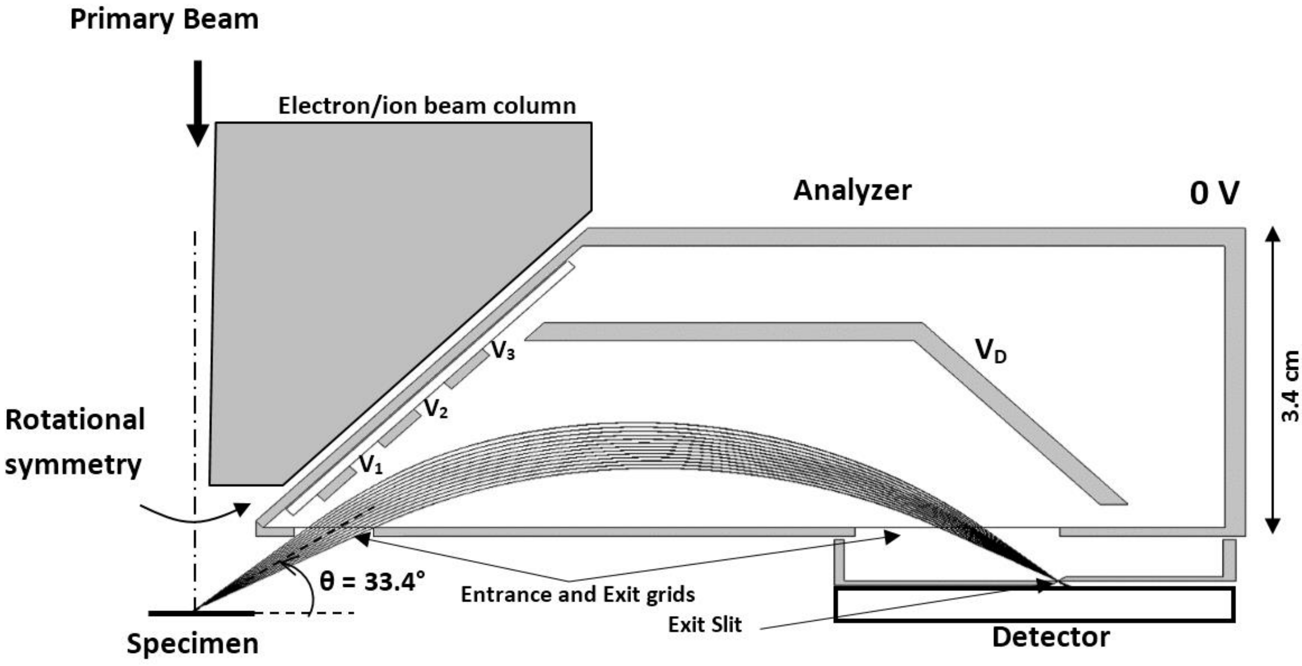

Figure 1. Simulated trajectory paths through the Radial Mirror Analyzer (RMA) design by Hoang *et al.* [1,4], 13 rays are plot over a polar angular spread ($\Delta\theta$) of ± 6° in uniform angular steps, shown here from the specimen to the detector plane at the central energy E_p (determined by voltage bias on V_1, V_2, V_3, and V_D at –0.172 E_P, –0.47 E_P, –0.57 E_P and –0.54 E_P, respectively).

The first strategy proposed, shown in Figure 3a, is to use a toroidal electric sector analyzer placed below the RMA exit aperture slit, deflecting all transmitted electrons back towards the primary beam axis, and focusing them on to single detector placed below the specimen stage. Another possibility is illustrated in Figure 3b, where the scattered electrons that come out of the exit slit of the analyzer are accelerated and made to strike a scintillator which converts these electrons into photons, after which the photons are optically transmitted to an on-axis channeltron using a highly reflective optical conical mirror arrangement. Future work will try out both methods and compare them experimentally.

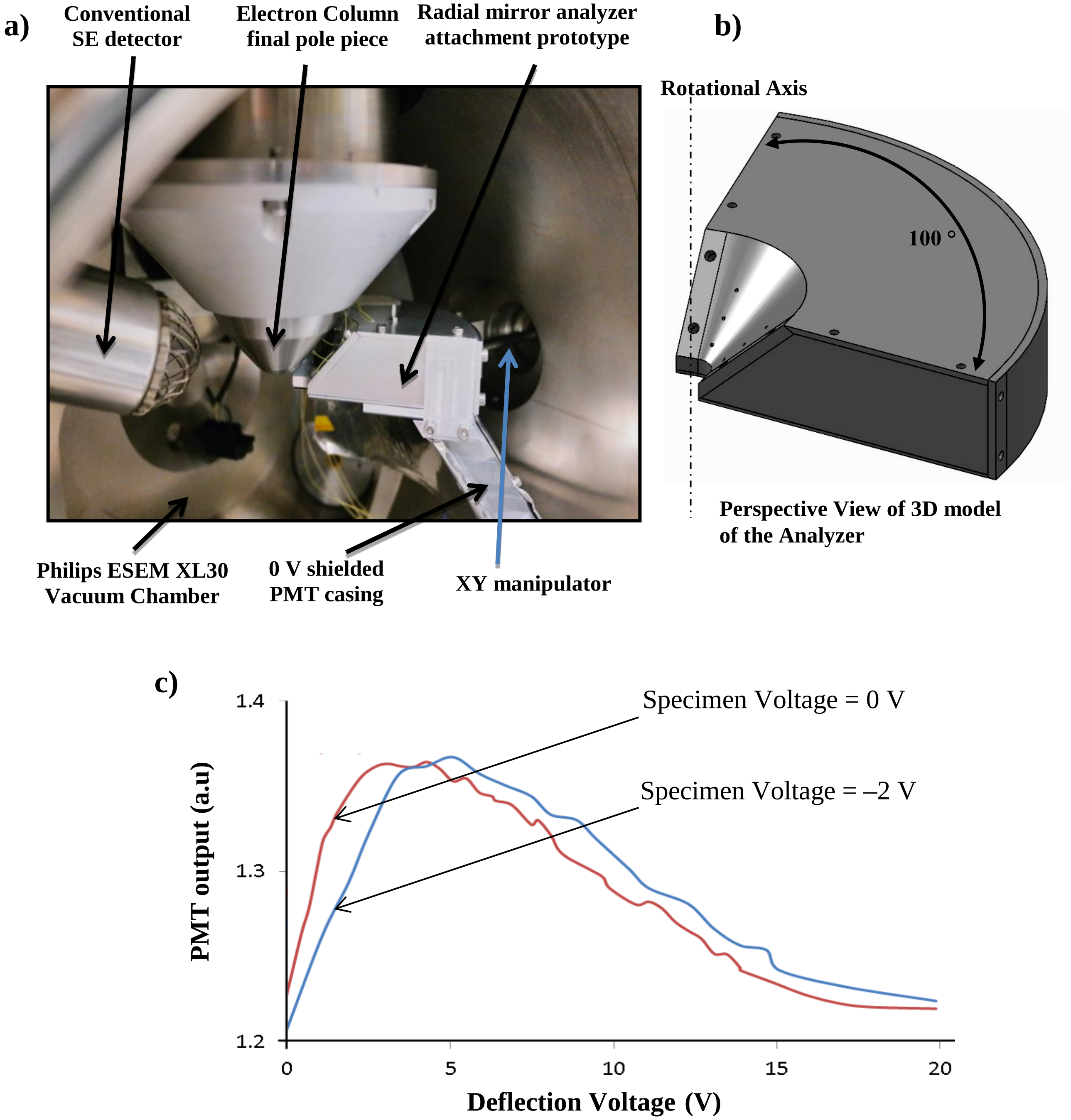

Figure 2. (a) A photo of the RMA attachment integrated inside the SEM with other components. Such a mounting of the analyzer facilitates operation of the SEM in the normal imaging mode. (b) Three dimensional perspective view of the RMA attachment showing the azimuthal deflection angle of 100°. (c) Experimental SE analyzer signals obtained using the first experimental prototype of the RMA.

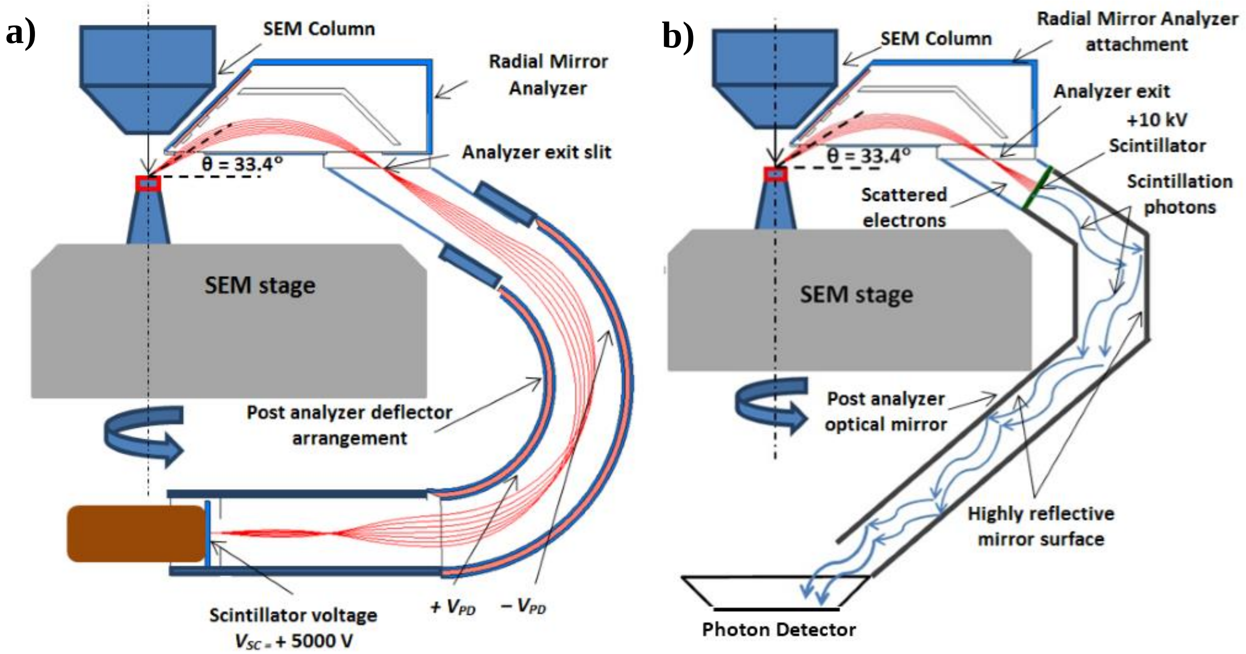

Figure 3. Proposed post analyzer deflector arrangements for the RMA attachment for signal collection in the entire azimuthal direction (a) Post analyzer toroidal electric sector arrangement. 7 rays are plot over a polar angular spread ($\Delta\theta$) of ± 6° in uniform angular steps, shown here from the specimen to the scintillator of the PMT through the post analyzer deflector, at the central energy E_P. The magnitude of V_{PD} was experimentally calculated to be 0.436 E_P. (b) Post analyzer optical mirror technique to achieve high signal–to–noise.

Practical implementation of the theoretical design of the RMA naturally leads to the question of how the energy resolution of the RMA is affected when fine metal grids are used to define the ideal 0 V surface planes that form the entrance and exit of the analyzer. The electric fields inside the analyzer will naturally “punch–through” the gaps in wire grids, changing electron trajectory paths, and thereby degrading the analyzer relative energy resolution. The following analysis is based upon using a simple grid model consisting of metal radial wires that appear to radiate out from the rotationally symmetric axis of the analyzer and spread out in the azimuthal direction. Such a grid arrangement is shown in Figure 4a.

Radial grid wires were defined by azimuthal angles ranging from ϕ_1 to ϕ_2 measured from an even symmetry plane in a unit grid cell, as shown in Figure 4b. A grid wire height of 100 μm was used for these simulations. The percentage transparency of the grid is therefore given by $(\phi_1/\phi_2) \times 100$. The angle $(\phi_2 - \phi_1)$ was fixed at 0.2º, and the angle ϕ_1 was varied in order to generate different grid transparencies. Three-dimensional simulations to compute all field distributions and electron trajectory ray paths were carried out using the 3D version of Lorentz program [5].

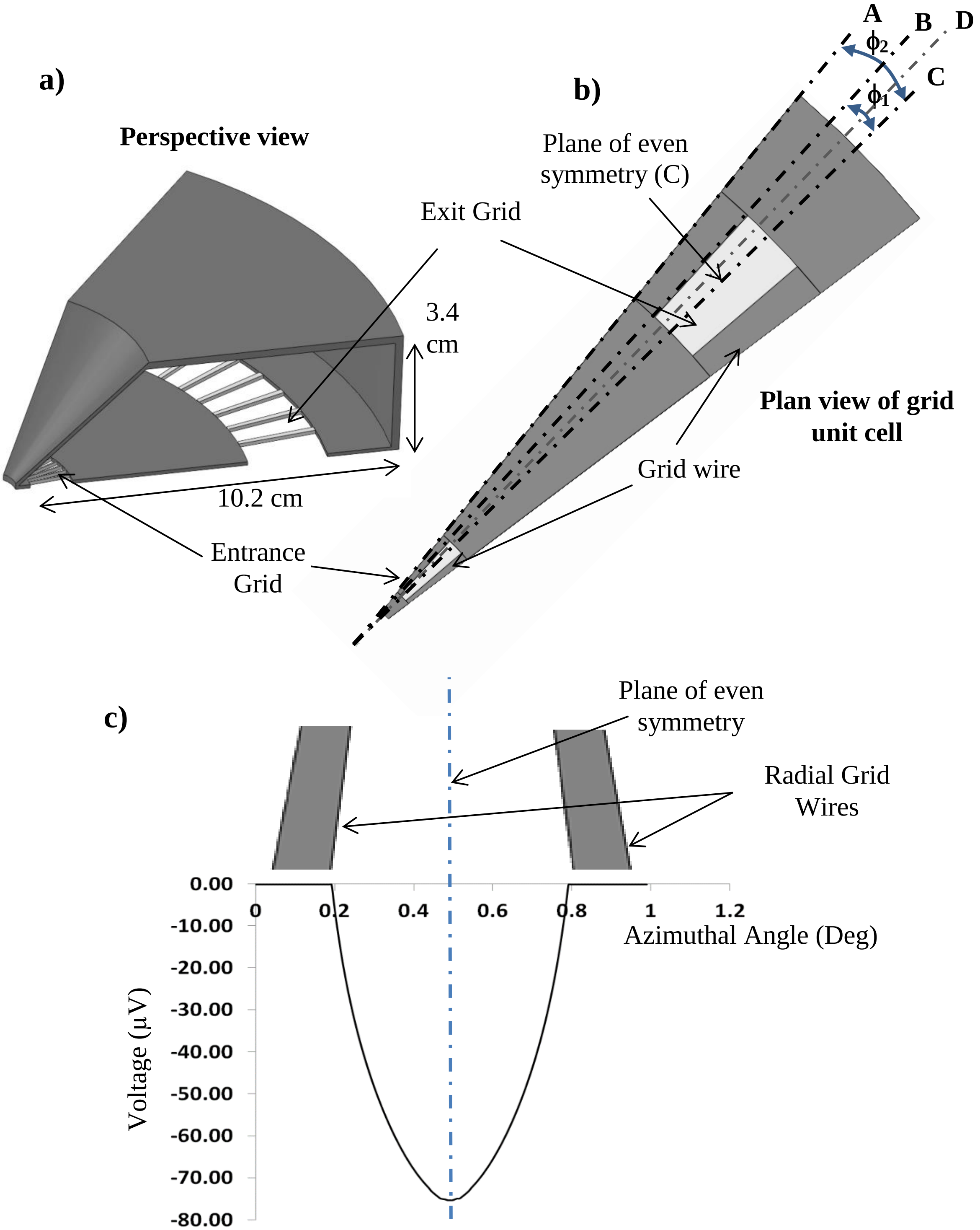

Figure 4. Simulation of analyzer entrance/exit radial wire grids: (a) Three dimensional perspective view (b) Plan view of a simulation grid unit cell model. (c) Simulated voltage distribution as a function of azimuthal angle. The graph is plot along the even symmetry line for a transparency of 75% and the main deflector electrode of the analyzer is set to – 0.54 V (for 1 eV pass energy of the analyzer).

In Figure 4b, plane C represents the plane of even symmetry, while plane D lies midway between plane C and the inner face of the grid wire (plane B). The relative energy resolution for a polar angular spread of ±6° that does not take into account grid effects via Lorentz 3EM is predicted to be 0.013%. In the presence of grids, the simulated energy resolution along plane C (even symmetry line) was found to be 0.036%, 0.031% and 0.026% for grid transparencies of 75%, 66% and 50% respectively, which changed to 0.048%, 0.054% and 0.057% along plane D.

The deterioration in the energy resolution is caused by the potential in the gap between two grid wires (at 0 V) being lowered due to the negative potential distribution inside the analyzer, reaching a minimum at the even plane of symmetry, as shown by Figure 4c. For electrons that travel along the even plane of symmetry, the dip in potential at the entrance grid causes them to follow different trajectory paths in the R-Z plane, degrading their energy resolution by a factor of two for a 50% transparency grid. For electrons launched in plane D, in addition to a dip in potential, electrons experience a force along the azimuthal direction, causing their paths to be non-radial, and this has the effect of degrading the predicted energy resolution even further, by over a factor of four (0.057%) for a 50% grid transparency. Decreasing the grid transparency does not help for electrons that travel along plane D, however, it should be noted for a polar grid layout (grid wires also in the tangential direction), deflection in the tangential (azimuthal) direction will be considerably reduced. For electrons that travel closer to the radial grid (between plane D and B), their deflection (in the azimuthal direction) causes them to collide with the exit grid, and they are not transmitted. Although these initial results predict that the energy resolution will be degraded by the presence of radial wire entrance/exit grids, it also points towards the need to carry out more simulations for other mesh geometries [7].

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