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Finite Element Method Simulation Studies of a Planar Geometry IEC Fusion Device

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16th US-Japan Workshop on Fusion Neutron Sources for Nuclear Assay and Alternate Applications
30 September - 2 October 2014
Fusion Technology Institute
University of Wisconsin-Madison

1.

Introduction

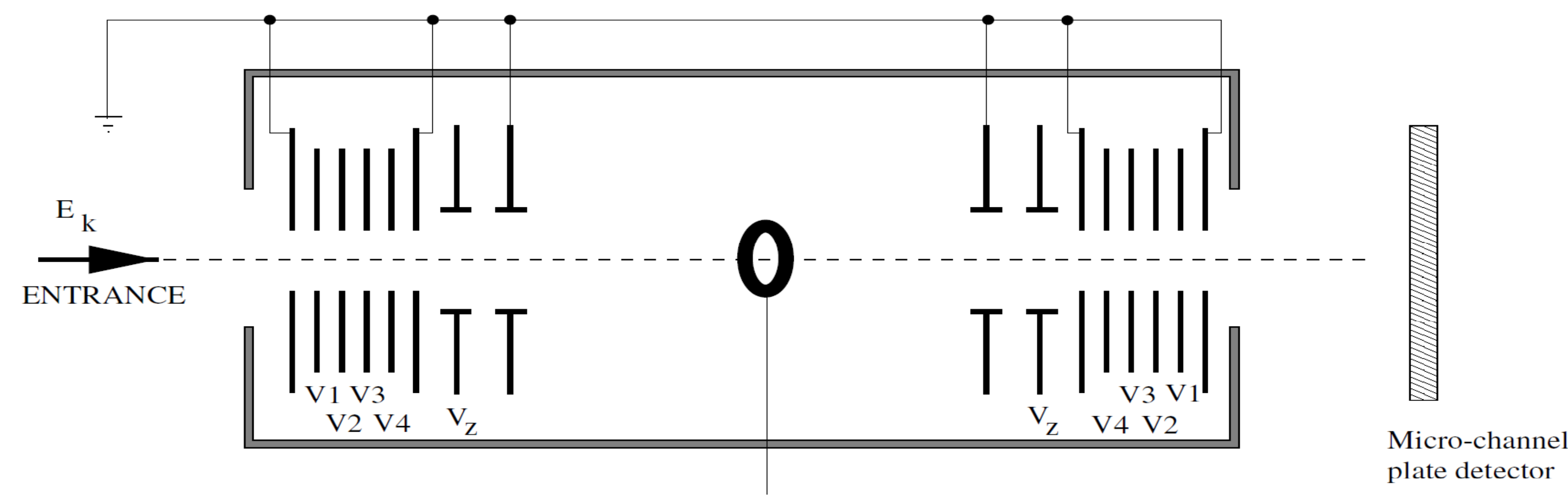
In the classic gridded inertial electrostatic confinement (IEC) fusion reactor, ion bombardment of the grid leads to heating, thermionic electron emission, and significant power loss; and the heating can ultimately melt the grid. Gridless IEC devices have sought to overcome these limitations. In addition, efforts have been made to design devices that could trap more ions, and hence increase fusion rate, by increasing the size of the ion orbit "turning region" where space charge limits the ion storage capacity.[1] The planar geometry IEC fusion device is a new gridless geometry that offers the potential for greater ion capacity and higher fusion yield via a larger ion turning space region compared to the classic spherical and other previous geometries while at the same time avoiding the disadvantages of the grid.[2,3] Initial studies of ion trajectories in this type of device using charged particle optics software (SIMION®) showed favorable ion trapping behavior,[2,3] and a prototype device has been constructed. To further study ion behavior in the device, and in particular to simulate the fusion yield, a finite element method (FEM) model is being explored using COMSOL® multiphysics software.

The concept of a planar geometry electrostatic ion trap can be visualized by considering a cross section of a linear electrostatic ion trap (examples shown in Figure 1) rotated about a central vertical axis to give the structure shown in Figure 2 (shown as a cutaway view with a few possible recirculating ion trajectories shown in red). In the planar trap, the negative potential (for positive ion trapping) is on the two central pin electrodes. In the planar trap, the ion "turnaround region" (where space charge limits the ion capacity of the trap) is spread around a full circle (Figure 3). This increased turning region, in theory, should result in a larger ion trapping capacity than a linear trap or even a spherical IEC device (where the "beams" in "star mode" from the grid apertures effectively result in a relatively small number of linear traps).

2.

Electrostatic Ion Traps

a.



b.

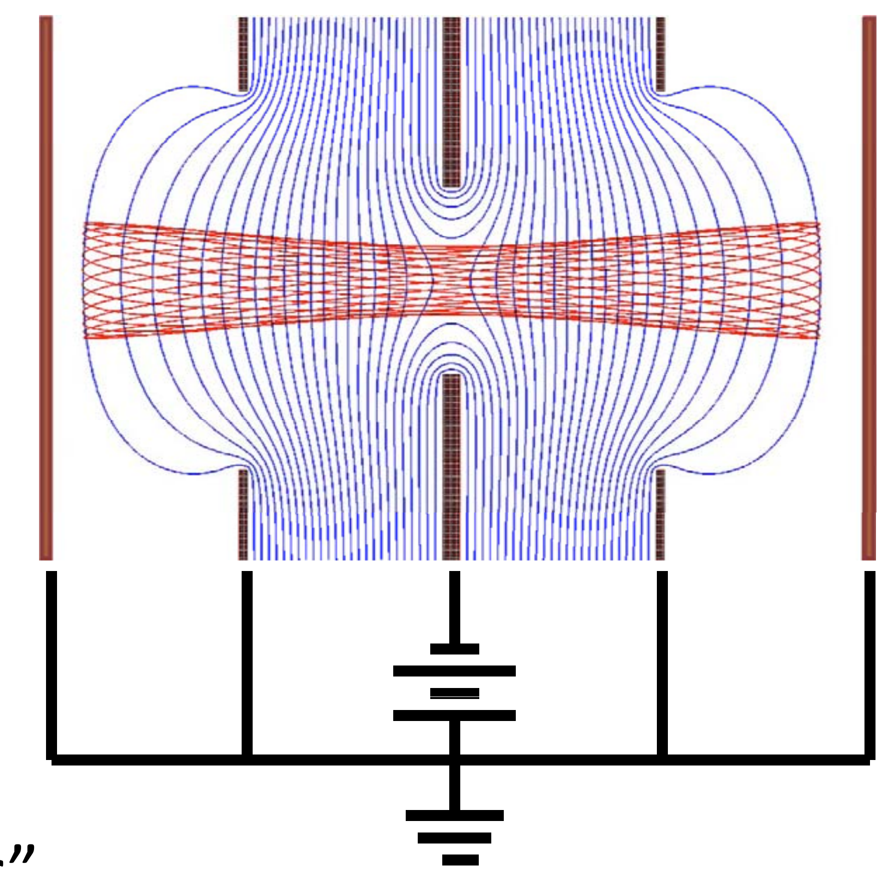


Figure 1. Linear electrostatic ion traps; a) Zaifman, *et al.* [4] b) Ermakov & Hinch. [5] Negative potential on center electrode relative to end "mirror" electrodes traps positive ions in a manner analogous to an optical resonator.

1.

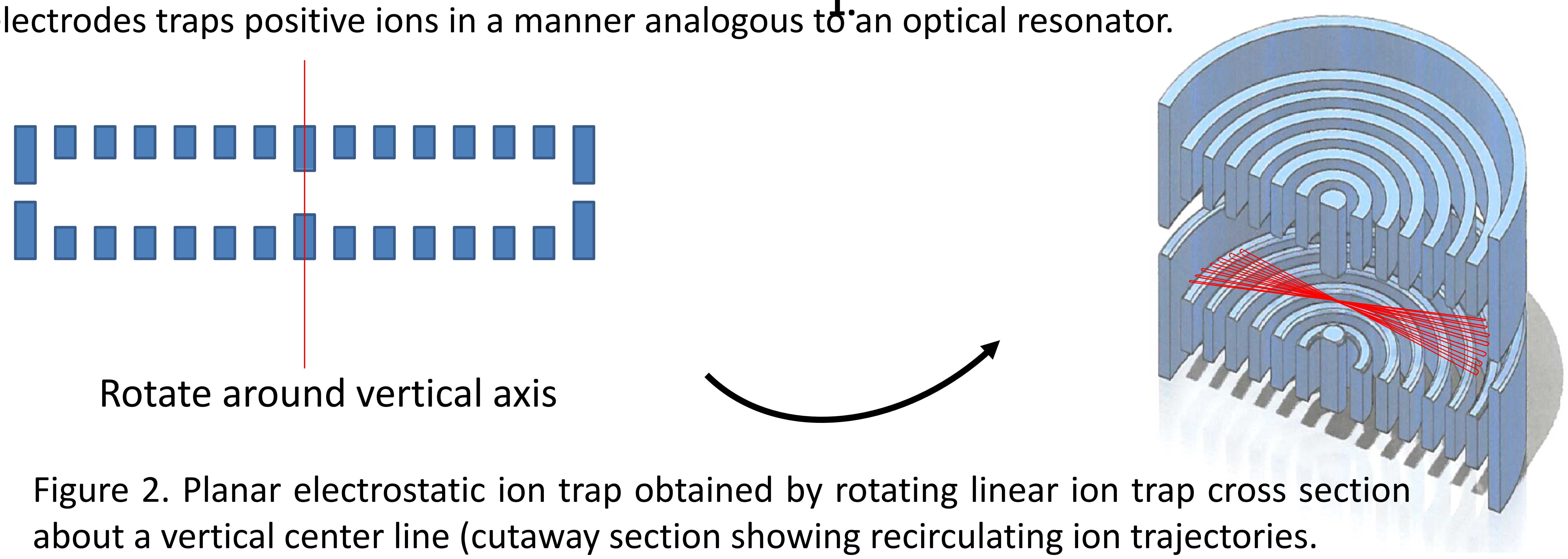


Figure 2. Planar electrostatic ion trap obtained by rotating linear ion trap cross section about a vertical center line (cutaway section showing recirculating ion trajectories.

3.

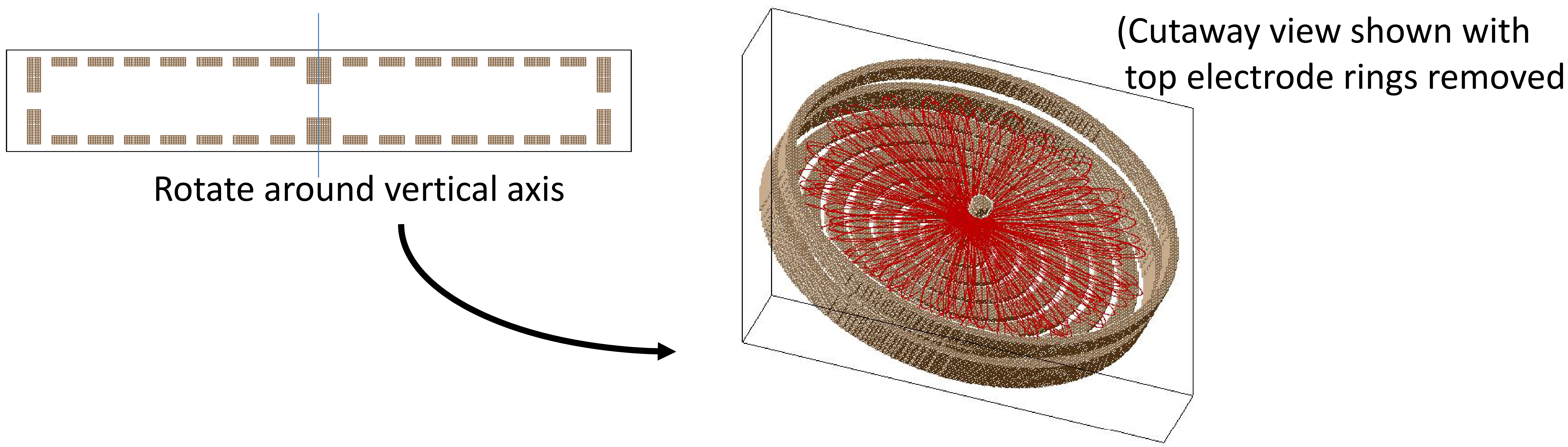


Figure 3 – SIMION simulation of ion trajectories in a planar trap for ions originating at a single point near the periphery with 0.1 eV tangential energy.[2] The ion trajectories spread around the full circle maximizing the turning region space.

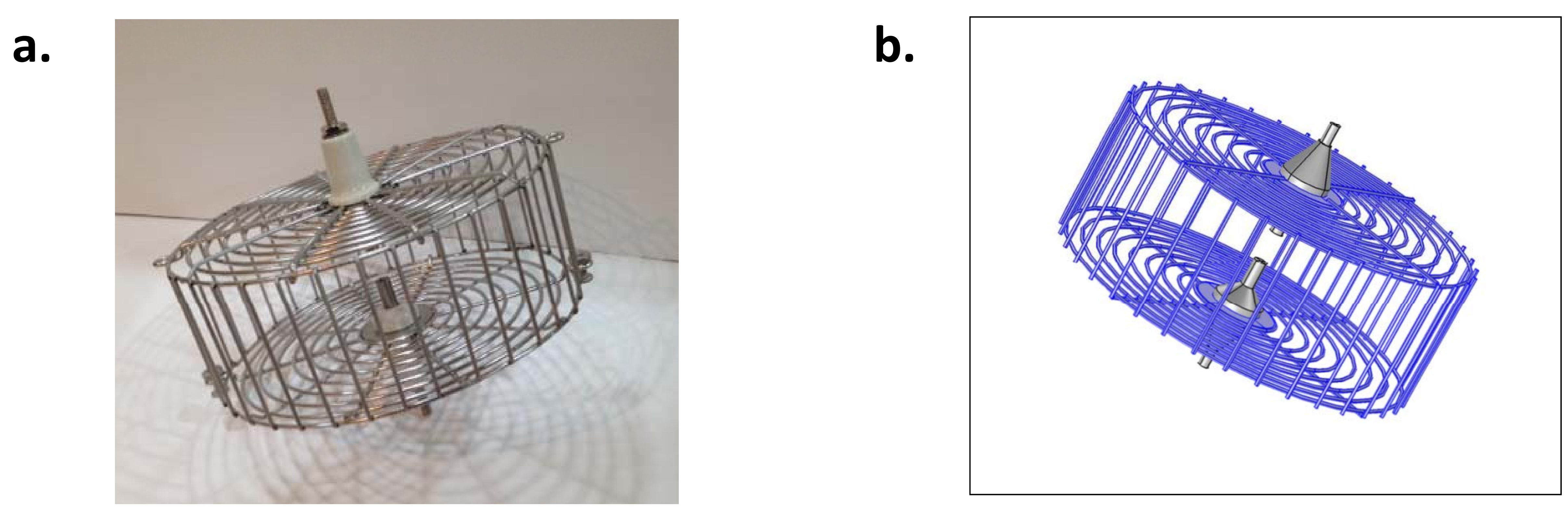


Figure 4. (a.) Prototype planar geometry IEC fusion device, (b.) COMSOL® model of the device.

4.

Methods

The prototype device shown in Figure 4a was constructed from 1/16 inch 304 stainless steel rod stock by spot welding. The rings were obtained from stainless steel fan grills. Stainless steel fender washers were spot welded to each face for mounting porcelain feedthrough insulators (Daburn Electronics, Dover, NJ) with 10-24 threaded studs. The pin electrodes are 304 stainless steel threaded standoffs (10-24; 0.250 dia., 0.500 long). The design of the initial prototype was driven largely by available standard components.

The earlier reported ion trajectory simulations[2,3] (e.g. that in Figure 3) were carried out using SIMION 8.0 charged particle optics software. The simulations reported here are the initial results from efforts to develop a finite element method simulation model of the device using COMSOL 4.4 multiphysics software. This model should enable not only ion trajectory and scattering collision simulations, but also simulation of collision events resulting in fusion reactions to guide efforts to optimize the fusion yield of the device.

The electrostatic potentials were calculated using a stationary study with the default meshing. These calculated potentials were used as input parameters for the subsequent studies of ion trajectories using the COMSOL Charged Particle Tracing module. Particle trajectories were simulated using singly-charged deuterium ions released from either the interior surface of the vacuum vessel or from the boundaries of a simulated electron beam injected into the trap from an exterior filament (Figure 6b). The ions were generated with a randomly directed thermal velocity (0.03 eV; 330° K).

5. Results

Figure 4b shows the geometry of the COMSOL® model of the prototype device. The first step in the simulations is to calculate the electrostatic potential field within the device. Figure 5a(top) shows a plot of the potentials on a plane through the central axis of the device (i.e. through the axis of the center pin electrodes) with -10 kV on the central pin electrodes and the cage grounded. Figure 5a(bottom) shows the potential profile along a line on this plane through the center of the device (i.e. through the center of the space between the pin electrodes). From the plot in Figure 5a(top) , it appears that a large part of the interior of the initital prototype device has no significant electric field and would therefore be expected to contribute little to the function of the device. The profile in Figure 5a(bottom), however, shows that although the field gradient is concentrated near the center of the device, the outer areas still have some small gradient. This profile could actually prove to be useful in increasing the radial space of the turning region since the turning points for ions with a small spread of radial energy would be spread over a larger area than if there were a steep gradient in this region.

The profile in Figure 5a(bottom) also shows that although a potential of -10 kV is applied to the electrodes, the maximum potential drop seen by the ions recirculating through the central space is only about 6 kV. Thus the maximum ion energy available for fusion collisions is only about 60% of the applied potential. This is in contrast to a gridded spherical IEC reactor where (given sufficient grid diameter) the central potential well (neglecting space charge effects) is expected to be equal to the applied potential. This situation would be expected to be approached by increasing the width of the area between the pins in the planar device. Increasing the pin radius to 6 mm (Figure 5b) increased the calculated well depth by a third, and increasing it to 9 mm (Figure 5c) yielded a potential well of almost 90 % of the applied potential. Thus, even the initial electrostatic potential calculations suggested a significant improvement in the prototype that can be accomplished without major modification.

6.

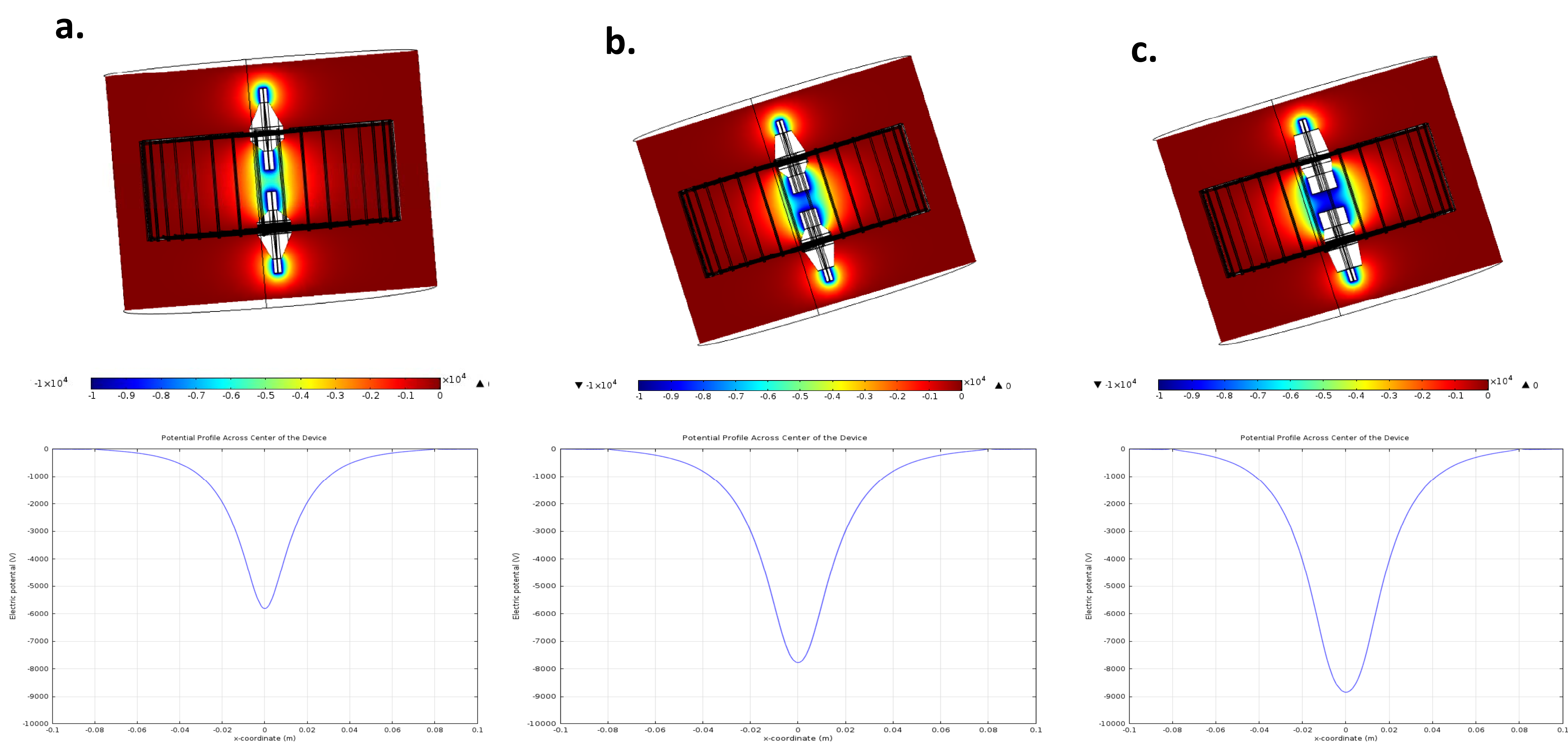


Figure 5. Calculated electrostatic potentials with the pin electrodes at -10 kV and the cage grounded shown on a central plane (top) and the potential profile on a line across the center (bottom).
a.) 3 mm radius pin electrode; b.) 6 mm radius pin electrode; c.) 3 mm radius pin electrode.

Ion trajectory simulations with ions generated outside the trap (i.e. in the region between the cage and the vacuum chamber wall) showed poor trapping. Generation of ions within the trap would improve trapping. Figure 6 shows a possible approach to generating the ions within the trap.

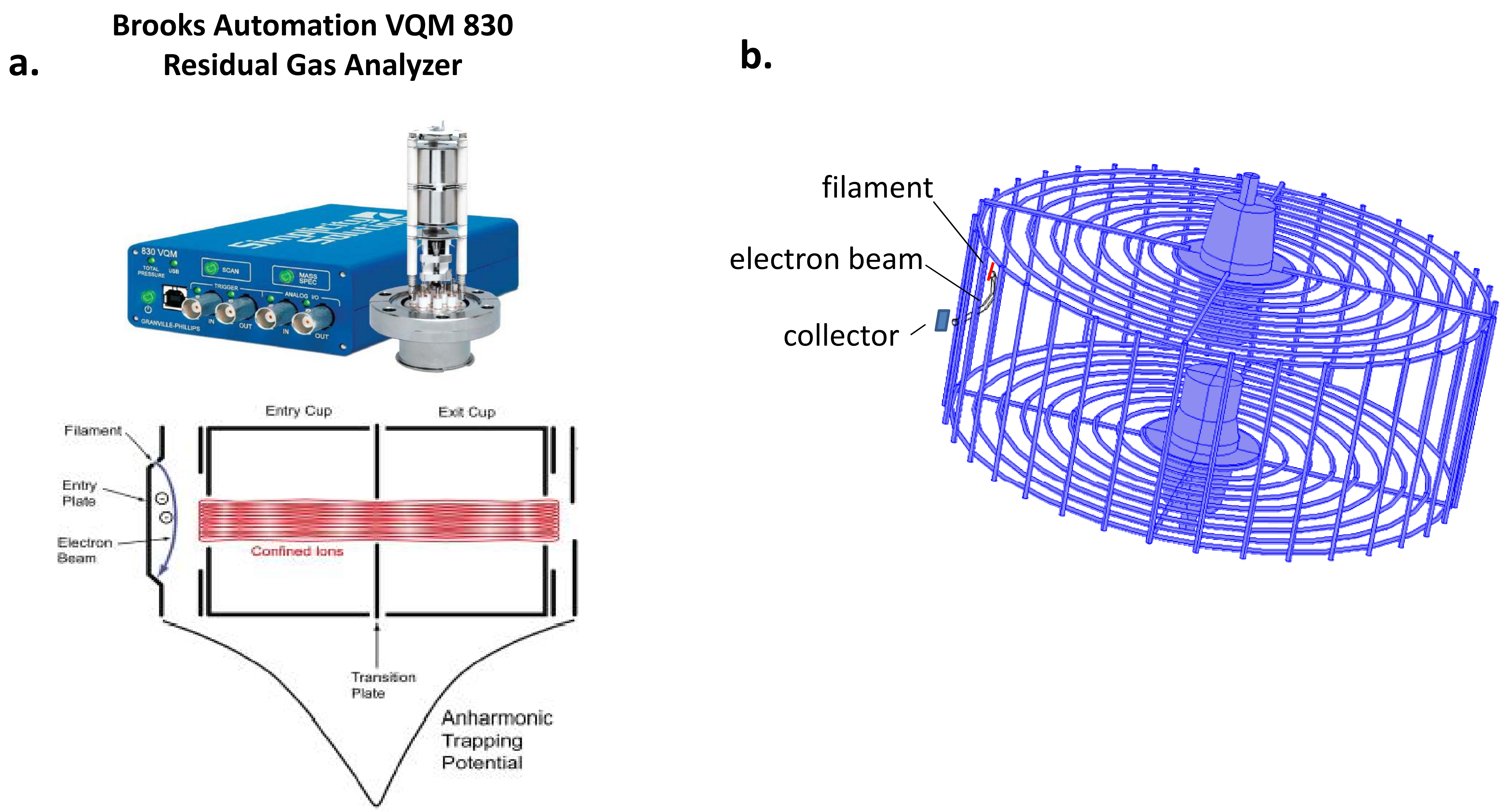


Figure 6. a.) Linear electrostatic trap device that generates ions ionization within the trap by electron impact (EI). b.) Planar IEC reactor model with EI source within the trap (filament and collector outside the cage).

8.

Ion trajectory simulations were carried out for ions generated by EI along the electron beam path shown in Figure 6b. Figure 7 shows the simulated trajectories.

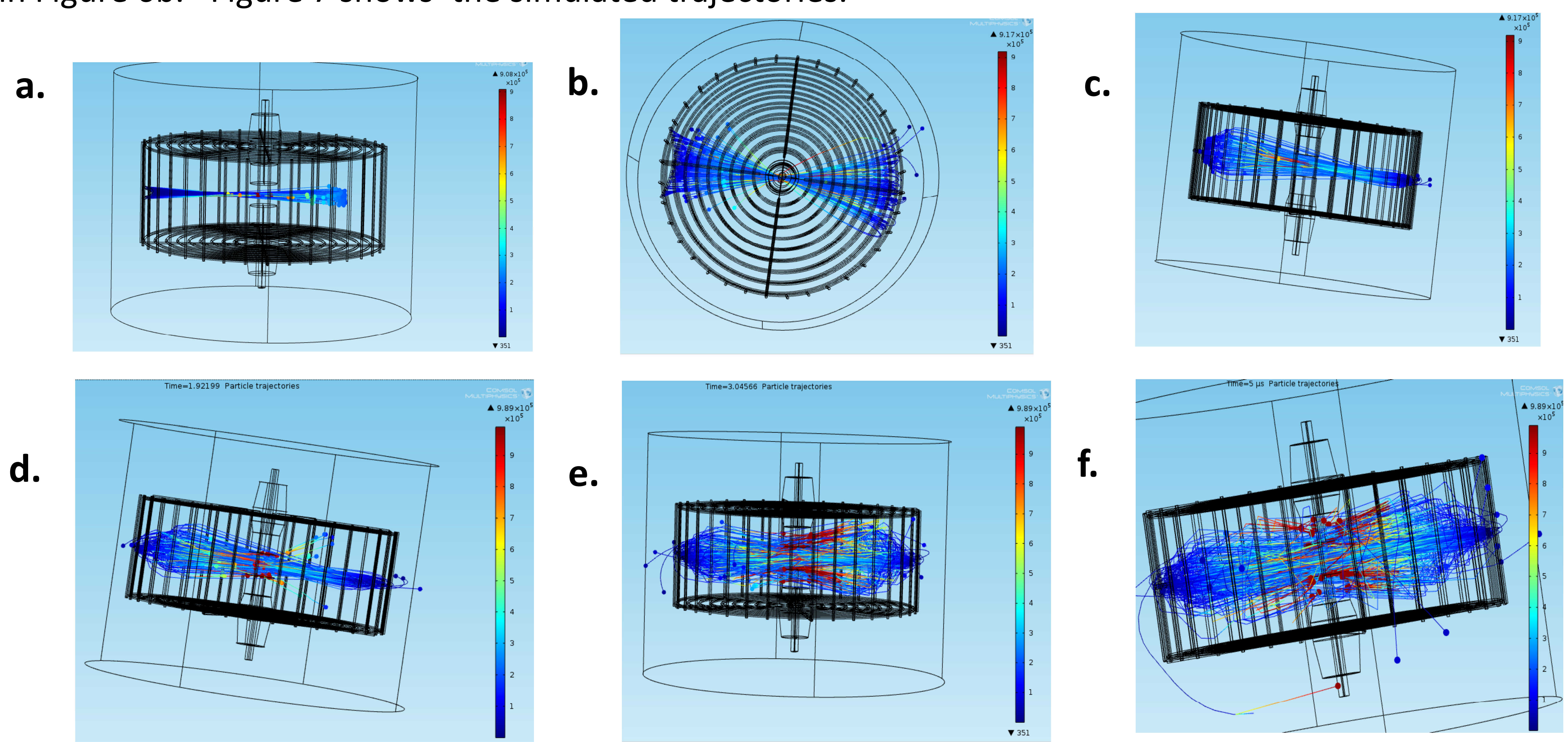


Figure 7. a.) Ion cloud at the beginning of the simulation. b. and c.) Ions reflected upon approaching the opposite cage wall. d.) At 1.9 µs, some ions are beginning to be lost by impact upon the pin electrodes (red dots). e.) At 3 µs, the ion cloud is significantly expanded, but most of the ions are still recirculating. f.) The ion trajectories at the end of 5 µs of simulation (167 minutes computer time on single Core i7, 2.00 GHz processor).

9.

Conclusions

The data shown here are some initial results from efforts to implement a FEM simulation of the planar geometry IEC fusion device. The electrostatic field calculations suggested a change for improving the prototype device to achieve a deeper potential well from a given applied voltage. Trajectory simulations showed somewhat poorer trapping behavior in the first prototype design than in the models previously simulated using charged particle optics (CPO) software. Computing trajectories using the FEM approach also took significantly more computation time than the CPO method. The ultimate goal is a simulation that includes both scattering and nuclear fusion collisions, but it is already apparently that computational load of the FEM approach will preclude individual simulations of any significant number of individual particles and require a particle in cell (PIC) or other approximation for computational feasibility.

References

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5. A. V. Ermakov and B. J. Hinch, An electrostatic autoresonant ion trap mass spectrometer**,** *Review of Scientific Instruments* **81**, 013107, 2010.

10.

Additional Data

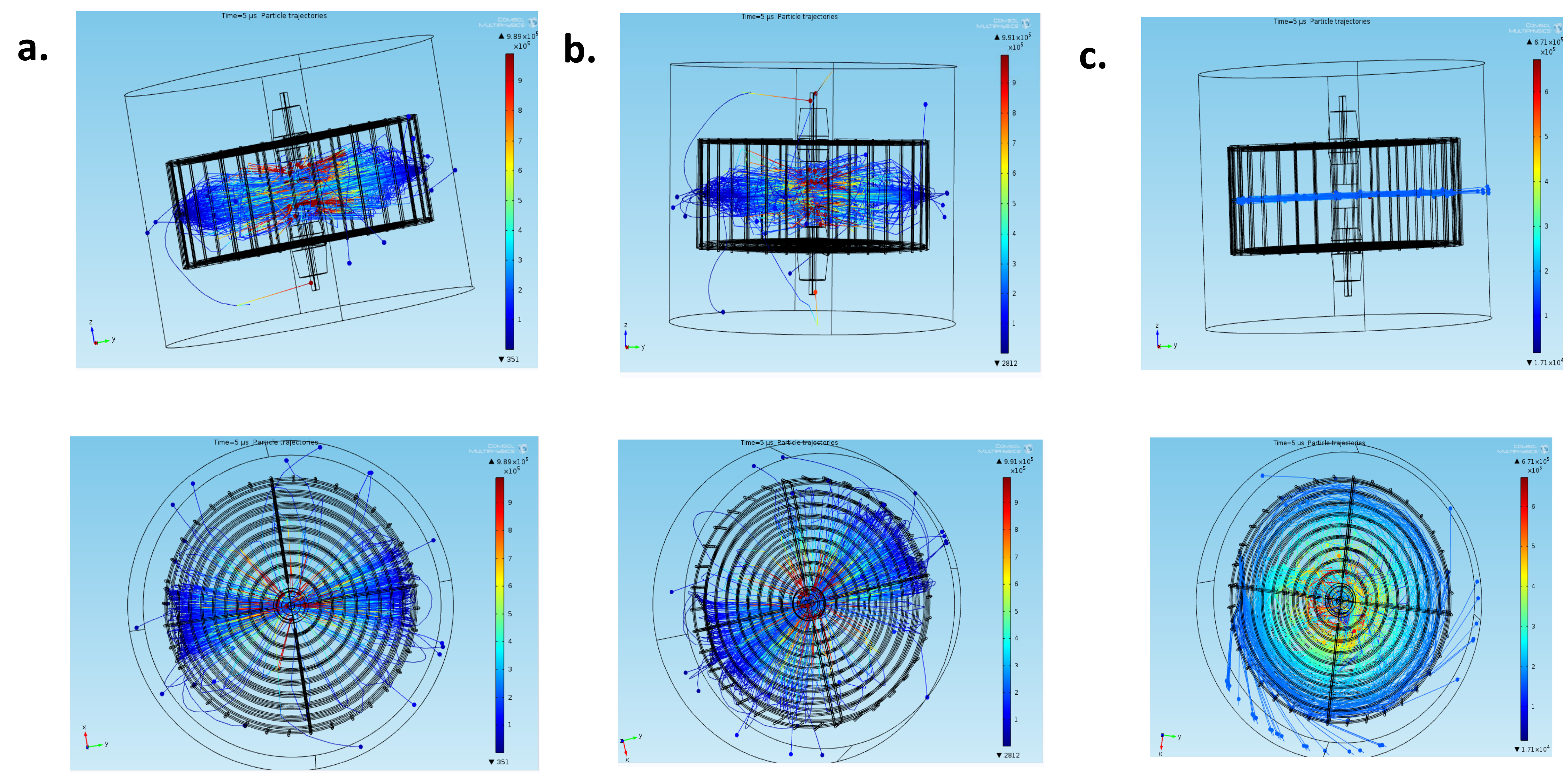

Figure 8. a.) Trajectories at the end of the 5 µs simulation as in Figure 7f. b.) Trajectories from 5 µs simulation when ions are generated with 0.3 eV of tangential energy showing increased radial spread of the ion trajectory cloud. (187 minutes computer time on single Core i7, 2.00 GHz processor). c.) Trajectories from 5 µs simulation when ions are generated with 3.0 eV of tangential energy. (110 minutes computer time on single Core i7, 2.00 GHz processor).