Planar geometry inertial electrostatic confinement fusion device

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Abstract. In the classic gridded inertial electrostatic confinement (IEC) fusion reactor, ion bombardment of the grid leads to heating, thermionic electron emission, significant power loss, and ultimately melting of the grid. Gridless IEC devices have sought to overcome these limitations. Klein reported a gridless device in which ions are circulated as a linear beam in an electrostatic analogue of an optical resonator. To overcome limits of stored ions due to space charge effects at the turning regions, the device employed multiple overlapping traps. The work reported here seeks to further increase the turning region space in a gridless trap by employing a planar geometry. Ion trapping in the planar device was examined by simulating trajectories of $^2$H$^+$ ions with SIMION 8.1 software. Simulations were carried out using multiple potentials as in Klein’s device and for a single potential trap as a planar analogue of the anharmonic ion trap. Scattering by background gas was simulated using a hard sphere collision model, and the results suggested the device will require operation at low pressure with a separate ion source.

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 causing device failure [1]. Gridless IEC devices have sought to overcome these limitations. Klein reported a gridless device called the "Multiple Ambipolar Beam Line Experiment" ("MARBLE") [2] in which ions are circulated as a linear beam in an electrostatic analog of an optical resonator (figure 1). The MARBLE design was inspired by the linear electrostatic ion trap developed by Zajfmann, et al. (figure 2) [3] and the simpler "anharmonic ion trap" (figure 3) [4]. The number of ions stored in any electrostatic trap is limited by the space charge at the points of lowest velocity, i.e. the turning points of the recirculating ion beam, and the number of stored ions limits the fusion rate. The MARBLE device employed multiple overlapping traps in the same physical space to enable the trapping of more ions in an effort to increase fusion rate.

Figure 1. Cross section of the MARBLE device showing three of the five recirculating ion beams (adapted from [2]).
The spherical gridded fusor (shown in cross section in figure 4) operates by accelerating ions formed outside the grid toward the center of the device. Ions that pass through the grid continue toward the opposite wall where they are reflected and recirculate until undergoing a collision. In theory, the spherical fusor can trap recirculating ion beams throughout the full solid angle space of the sphere maximizing the area of the turning region. Thus, it should be able to accommodate more trapped ions than any configuration of linear ion traps. However, in the gridded spherical fusor the circulating ions self-organize into beams through the grid openings forming the "star mode" that seems to be essential for maximum fusion rate [5]. This cannot be overcome by increasing the number of openings in the grid, because practical limitations on wire size causes reduced transparency, and grid transparency is directly related to fusion rate. Thus, the spherical device is effectively a discrete beam device. The device described here has the potential for an improved gridless geometry by enabling a full circular angle of beam trajectories with the turning region spread around the full circle. Although a planar ion trap mass spectrometer was recently proposed [6], it does not appear that this geometry has been explored for an IEC fusion device.

Figure 2. Linear electrostatic ion trap (from [3]). Figure 3. Anharmonic ion trap (adapted from [4]).

Figure 4. Cross section of a spherical gridded fusor. Figure 5. Cutaway view of a planar electrostatic ion trap.
2. Description of the Planar Geometry IEC Fusion Device

Linear electrostatic ion traps have cylindrical symmetry about the ion beam axis. If one envisions taking the cross section of a linear trap and rotating it about a central axis perpendicular to the ion motion, the result is a planar beam device with a series of concentric rings above and below the ion beams as shown in figure 5. If all of the ring electrodes are grounded and a negative potential is placed on the center pins, the device is a planar analogue of the trap shown in figure 3 (subsequently referred to as Case 1). Operating the device with a gradient of positive potentials on alternate rings, with the intervening rings and center electrodes grounded, yields a planar analogue of the MARBLE device (subsequently referred to Case 2). Both Case 1 and Case 2 were simulated using the electrode configuration shown in cross section in figure 6.

3. Simulation Studies

Simulations were carried out using SIMION 8.1 software to predict the trajectories of deuterium ions in a planar ion trap device. Case 1 and Case 2 were modelled under vacuum conditions. If the ions are generated in the model with even a small amount of energy (0.1 eV) in the tangential direction, they will quickly spread out all around the trap as shown in figure 7, suggesting that the planar trap will allow trapping of ions with trajectories throughout the full circular angle space.

Case 1 (figure 8) and Case 2 (figure 9) were modelled with 300°K isotropic ions generated in a single 2 mm radius spherical space near the periphery of the device. A series of different potentials were examined for Case 2, but none gave trapping as good as in Case 1. The ions had insufficient tangential velocity to spread around the full circular angle in the trapping time.
Simulations were also carried out for the device using bevelled edge electrodes as in the MARBLE device in figure 1 (Case 3). Figure 10 shows simulated ion trajectories for the Case 3 device. Using the same number of electrodes, the same cross section shapes, and the same potentials as in the reported device [2], $^2\text{H}^+$ ions could be trapped for as long as 16 seconds allowing the trajectories to spread around the full circular space.

![Figure 9](image1.png)

**Figure 9.** SIMION simulated ion trajectories for Case 2 device (+10, 0, 6.5, 0, 5.5, 0, 4.0, 0 kV; 300°K $^2\text{H}^+$ ions). Cross section view (left); cutaway view (center); potential surface view (right).

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![Figure 10](image2.png)

**Figure 10.** SIMION simulated ion trajectories for Case 3 device (+10, 0, 6.6, 0, 5.1, 0, 3.1, 0, 1.5 kV; 300°K $^2\text{H}^+$ ions). Cross section view (left); cutaway view (center); potential surface view (right).

4. **Effects of Background Gas Collisions**

A fusion device requires the presence of fuel, so vacuum simulations do not give a true picture of ion behaviour in a functional device. The system was therefore modelled in the presence of background gas using a hard sphere elastic collision model [7] to examine the effect of collisional scattering upon the ion trapping. Figure 11 shows the scattering in a Case 1 device at pressures of deuterium gas from 1 Pa (which totally destroys trapping) to $10^{-4}$ Pa. (where trapping is comparable to vacuum). Similar results were obtained for the Case 3 device (figure 12). These scattering simulations suggest that the planar trap may not be useful at pressures normally used in devices with ion formation from simple Paschen discharge, and that other means of ion generation will be required. A commercial residual gas analyser (Brooks Instruments, VQM) based upon the single potential linear trap shown in figure 3 generates ions within the trap using an electron beam injected from a filament outside the trap. The same method could be used in a planar trap fusion device to enable operation at lower pressures.
5. Conclusions

These simulations suggest that a planar geometry device could function as proposed and offer improved performance over previous geometries. The simulated trapping in the Case 3 device (figure 10) was sufficiently long to enable the recirculating ion trajectories to spread around the full circular...
space, thus supporting the basic premise that the planar geometry device should enable trapping of more ions and yield a higher fusion rate than previous geometries. However, the scattering simulations suggest that the device may require operation at lower pressure than normally used in gridded spherical devices. A prototype device is under construction.

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