MAGNETIC CORE MULTI-GRID IEC CONCEPT USING p-^{11}B. R.J. Sedwick, 3146 G.L. Martin Hall, University of Maryland, College Park, MD, 20742.

Introduction: Of the various methods that have been considered for fusion power generation, Inertial Electrostatic Confinement (IEC) is hands-down the black sheep. Considered early on as offering a possible solution to burning advanced fuels, subsequent analyses concluded that not only would the IEC not provide any advantage in this regard, but rapid thermalization of the ions would not even allow for efficiently fusing D-T. The situation is not unlike the late 1950's and early 1960's, when stellarators where plagued with seemingly fundamental instabilities that resulted in rapid pump out. However, pushing forward, the Bohm barrier was eventually broken in a toroidal machine, leading to the birth of the Tokamak and the continuation of a long and fruitful research effort into magnetic confinement. In the case of the IEC, the time that has elapsed between identifying the major operational problems and their potential resolution has exceeded the tolerance of the fusion community, leaving the IEC to be considered a largely dead-end technology with regard to power generation.

The research presented here represents just one research group's approach to addressing the major limitations and criticisms of the IEC. The overall system concept will be described in the context of different loss timescales, discussing how the various design elements are meant to improve the performance.

Concept Overview: *Increased Particle Confinement Time:* Research by McGuire and Sedwick [1] showed that the two main life-limiters of ions in a gridded IEC system are charge exchange with background gas and grid impact. The defocusing effect of the cathode grid and support stalks will typically limit the ions to about 10 passes through the system – far fewer than would allow for a significant fusion rate to develop. They proposed that if a mechanism could be found to mitigate this defocusing effect, operation in a high vacuum could increase the ion lifetime by several orders of magnitude.

It was realized that the single grid cathode presented a highly defocusing acceleration of the ions into the core, causing ions that were slightly off-axis of a preferred beam-line to rapidly assume a chaotic path, impacting the grid after approx-imately 10 passes. By introducing multiple concentric grids (each in the "shadow" of the one inside it as seen from the core) the beam-lines can be made to focus the ions, increasing their lifetimes by many orders of magnitude. Shadowing the grids in this way maintains the same level of transparency, which is important for allowing the fusion products to escape the system. The effect of additional grids on particle confinement is shown in Figure 1. [2]

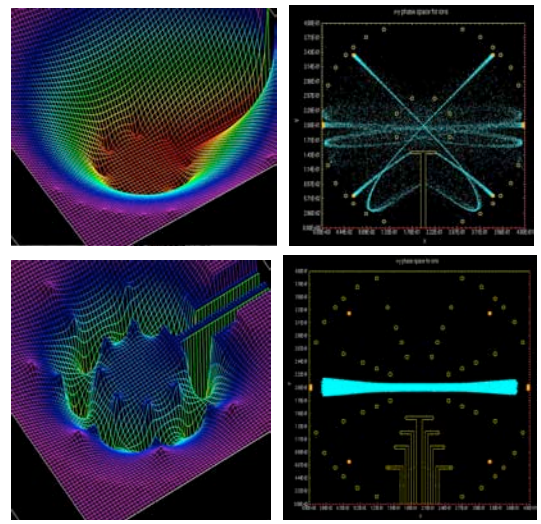

Figure 1. Single Cathode grid and stalk produce a highly defocusing beam-line (top left) resulting in chaotic ion paths terminating on the grid (top right). Additional grids shield this effect (bottom left) and greatly extend ion lifetime (bottom right). Particle simulations by commercial particle-in-cell (PIC) code.

Mitigating thermalization: The dominant source of thermalization is the highly probable small angle collisions that occur. In a non-gridded or single-grid IEC, these occur throughout the volume, resulting in deflection of ions away from the desired radial trajectories that take them to the core of the device. This is how thermalization causes defocusing. As the angular momentum of the ions (relative to the core) increases, their radial energy is converted to azimuthal energy and eventually the system settles to a Boltzmann distribution over the entire device, with low energy ions filling the core. Rosenberg and Krall [3] argued that the residence time of the ions at the outer turning points was so much longer than in both the "bulk" and core of the device that the ions would tend to thermalize into a Maxwellian distribution at the periphery and still look predominantly mono-energetic in the core. Nevins [4] then countered this with a follow-on analysis (using different simplifying assumptions) demonstrating that the thermalization in the bulk would be just as significant as that at the periphery, resulting in global thermalization.

It has been found numerically [3], and verified experimentally [5], that in the multi-grid IEC design presented here, the well-confined ion beams quickly destabilize radially to form ion packets as a result of the classical counter-streaming ion instability. However, these packets are stable (long-lived) as a result of the trap kinematics [6]. In addition, the packets become synchronized such that they meet in the core of the device simultaneously (Figure 2). This provides a possible way of circumventing the defocusing effects of thermalization on the ions.

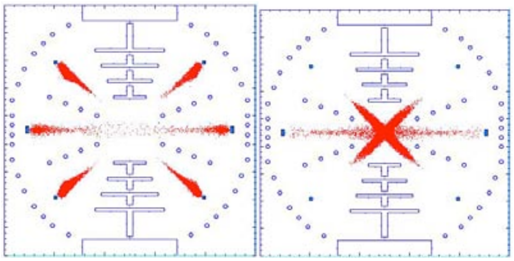

Figure 2. Well-confined beams will quickly form packets as a result of beam-beam instabilities, but these packets are then stable and synchronized among the beam-lines.

The formation of synchronized packets in the current multi-grid system results in inter-packet collisions occurring only in the core of the device when the packets meet. Here, small angle deflections will only deflect ions onto other nearby radial (or nearly radial) paths, still within the same beam-line. In addition, the packets will indeed spend the majority of their time at the outer perimeter where they will tend to thermalize locally into a Maxwellian distribution. The average angular momentum of the packets relative to the core remains zero, and the mean energy of the packets will not decrease over time, at least as a result of ion-ion collisions. Other effects, to be discussed shortly will still cause a decrease in ion energy over time.

Core neutralization: Obtaining high densities in the core is not possible if only ions are present in this region. The space-charge will not allow for it. To mitigate this problem, electrons can be introduced into the core of the device, provided they are not allowed to freely stream out to the anode. The approach to this problem is two-fold. First, the innermost grid can be biased positively relative to the "true" cathode, which would then be at a slightly larger radial distance. This will help to electrostatically confine electrons to the core, even as ions are allowed to recirculate through this region. A more substantial method of mitigation is to confine the electrons with an appropriately shaped magnetic field. Such a field has been implemented by Bussard in his Polywell^{TM} "cusped" field configuration, where the fields are generated electromagnetically. The magnetic fields necessary to properly confine the high energy electrons require a substantial current, so instead a grid constructed of rare Earth magnetic material is proposed, as shown conceptually in Figure 3. Unlike an electrically generated cusped field, where null lines permit leakage out of the system, the configuration shown here has no nulls. The material is radially magnetized, so that field lines start at the outer surface, bend back through the openings and then terminate on the inner surface, providing magnetic plugs in each hole.

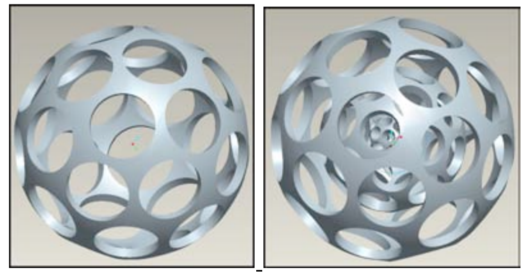

Figure 3. Left: 3D magnet generated in ProEngineer. Right: Concentric magnets forming the mult-grid geometry.

Additional topics*:* The paper will go on to discuss additional topics such as the effect of high angle scatter in the device core and shielding against the asymmetries introduced by feedstalks. Current research efforts for numerically modeling the electron confinement and extending the modeling to beyond the thermalization timescales using a GPU driven hybrid PIC code will be discusses and results presented.

References:

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[6] Zajfman, D., et al., "Self-bunching Effect in an Ion-trap Resonator," J. *Opt. Soc. Am. B*, **20**, 1028 (2005).