44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
21 - 23 July 2008, Hartford, CT

AIAA 2008-4675

Numerical Predictions of Enhanced Ion Confinement in a Multi-grid IEC Device

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A system of multiple grids is potentially capable of improving the efficiency of Inertial Electrostatic Confinement (IEC) fusion devices. Poor ion confinement in conventional IECs is the primary reason for low fusion gain. The asymmetries due to a single grid cathode and stalk limit ions to fewer than ~10-15 passes through the device regardless of collisions. Multiple grid systems are shown via a particle in cell simulation to allow ions to recirculate indefinitely in a collisionless system. Background pressure can then be reduced without loss of total fusion output, improving both fusion output and efficiency. System density is limited by the build-up of un-neutralized space charge in the recirculating ion beams. A Particle-in-Cell code provides observations of total system density versus device size and input current. A hybrid device operating with low input currents and high recirculation at moderate background pressures should provide IEC neutron generators with significantly increased electrical efficiency.

Nomenclature

i_{in}	=	total input current
$\sigma_{fus}(KE_0)$	=	fusion cross section at center potential
$<\sigma_a>_p$	=	path averaged cross-section for atomic collisions
R_{cat}	=	cathode radius
R_a	=	anode radius
η_{pulse}	=	efficiency due to pulsing nature of core density
n_c	=	peak core density
$<\sigma_{fus}v>_{core}$	=	core-averaged value of fusion cross-section

I. Introduction

Inertial Electrostatic Confinement (IEC) Fusion, operates by electrostatically trapping fusion fuel ions in a spherical system of overlapping ion beams. The general set-up of an IEC is shown in Fig. 1. Ions are confined by electric fields supported by spherical grids. Grids are welded from stainless steel and refractory metal wire and the system is enclosed in a vacuum chamber. Ions are created at the anode via a glow discharge, electron impact ionization, or ion guns. As ions are accelerated into the device center, fusion occurs between ions colliding with each other and with the background gas. Most of the ions that do not fuse on the first pass move towards the anode and are reflected. Ions then return to the core for another pass and this process repeats, yielding many opportunities to fuse. Fusion products stream away from the device core and are either collected by a solid wall thermal-based energy conversion system or a gridded electrostatic energy conversion system.[1,2] The IEC is promising for the

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simplicity of the concept, its inherent low mass, and the possible suitability to aneutronic fuels and direct energy conversion[3].

The IEC concept was invented by Philo T. Farnsworth, the inventor of television. His first patent was filed in January 11, 1962, followed by several others.[4,5,6] Supported by the ITT Corporation, Farnsworth and Hirsch constructed a device which used 6 inwardly directed ion guns mounted on a sphere, all injecting into a central cavity to produce 10^{10} neutrons per second in steady state operation using Deuterium gas. Despite this early success (their fusion output has yet to be exceeded), the gain of the device was quite low, a Q of $\sim 3 \cdot 10^{-4}$ (Ref. 7 and 8). Many groups have since tried to improve the performance of IECs with little success, although the concept has been identified as a promising neutron source for radiological, medical and industrial applications.

All of the experiments until recently have operated at relatively high pressures, in the range of 0.1-50 milliTorr. McGuire and Sedwick[9] identified that the low pressure operation is required to improve the efficiency of IECs by reducing charge exchange and ionization collision between the ions and the background gas. In addition, the ions must be capable of recirculating in the device for many passes. Standard single cathode grid IECs show poor ion confinement characteristics due to asymmetries in the electric field produced by the grid and its high-voltage stalk. Multiple grids are presented here as a way to improve the ion confinement characteristics of IECs, allowing more efficient operation at lower pressures.[10,11]

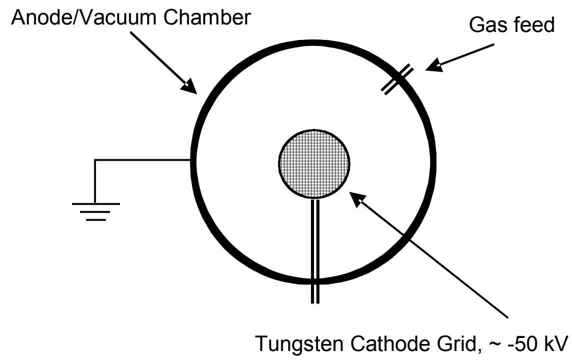

Figure 1. Conventional IEC Schematic

II. Multiple Grids

The innovation described here is to replace the single cathode grid with a system of nested, spherical electrostatic grids. The multiple grids improve the ion confinement by creating focusing channels and by shielding out the gross asymmetry caused by the high voltage feedthrough.

The commercially available OOPIC Pro Particle-in-Cell code was used to develop the multiple grid concept and produce the following results[12]. The Particle-in-Cell, PIC, code was necessary to include the effect of the ion's self-charge on the beam dynamics as the recirculating ion charge builds with improved confinement. Fig. 2 shows the 2D planar PIC model of a single grid IEC with an equatorial beam and two diagonal beam lines, including an anode grid, cathode grid, high voltage stalk, and six ion injectors. In all the cases presented, the background pressure is assumed to be $10 \cdot 10^{-10}$ Torr so that background collisions are negligible. Argon ions are used and the lowest grid voltage is -10 kV, and the device diameter is 40 cm, consistent with experimental parameters of laboratory experiments[13].

The single grid shows poor confinement characteristics. The upper diagonal injector ion beams make one pass through the device, but are then drawn into the stalk after a single pass, while the lower diagonal beams do not reach the center at all. The equatorial ion beams make a few passes, but are kicked off of the purely radial trajectories by the cathode grid and survive only a few passes. The asymmetry in the electric potential caused by the stalk is clearly seen in Fig. 4, below. While in a full 3-D experiment, the ions would not necessarily impact the stalk after their initial pass through the system, the ion paths are representative of the short lifetimes that occur as a result of potential asymmetries.

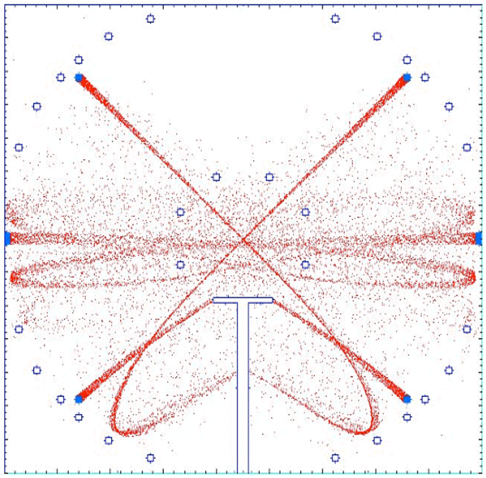

Fig. 2. Conventional, Single Grid IEC

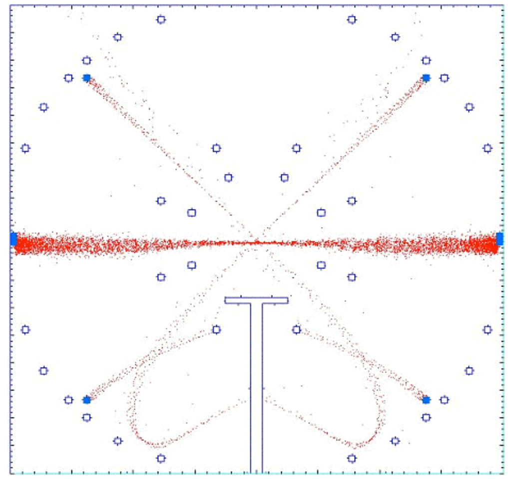

Figure 3. Double Grid Configuration

In Fig. 3, above, a second grid is added so that the innermost grid is now set at -2 kV and the second grid is at -10 kV. The double grids create an electrostatic lens field structure that steers the ion back onto radial paths. Field penetration maintains the center at a potential lower than the innermost grid, but somewhat higher than the single grid case.

The equatorial beams are now well-confined by the double grid, but the diagonal beam behavior is still dominated by the effect of the stalk asymmetry. Additional grids serve mainly to shield out the stalk asymmetry. A third and fourth grid are added in the region in between the anode and double grids at a potential slightly above the local background. These are shown in Fig. 5. This creates a focusing channel for the ions in addition to establishing gross spherical symmetry.

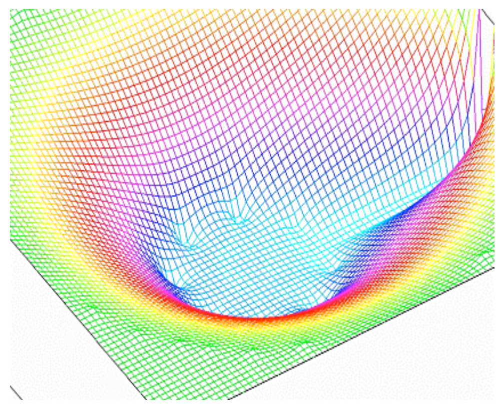

Fig. 4, Electric potential for single grid OOPIC model

With the stalk effectively shielded, the diagonal beams are now able to recirculate for many passes. The shielding of the stalk is shown in the new potential structure in Fig 6. With improved ion confinement and continuous injection of new ions, the recirculating current builds with time. Eventually the self-charge becomes de-focusing and ultimately limits the amount of re-circulating current. The PIC model was used to observe the density limits for various levels of input current and overall device size.

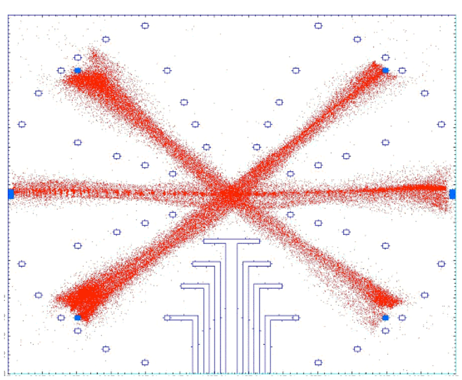

Fig. 5. Four grid configuration

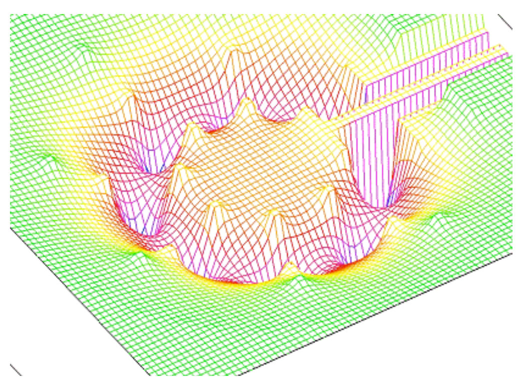

Fig. 6. Electric potential for single grid OOPIC model

III. Observations of Behavior

For the first few passes, the well-confined ion beams remain fairly uniform, but as the charge builds, significant bunching is observed in the beams. The bunching begins as a short wavelength phenomenon, but gradually evolves into long wavelength bunching with each beam line consisting of only 2 opposing bunches. At long times bunches on each beam line synchronize and the system is characterized by bunches on all the beam lines collapsing into the center of the device at the same time. The details of the synchronization phenomenon are treated in detail in McGuire[10]. The steady-state behavior of the multiple grid IEC is characterized here by the peak potential and density in the center of the device. The pulsing center potential as a function of time is shown in Fig. 7 for steady 10 microamp injection current at each ion injector. Starting with the outer grid moving inward, the voltages on the grids are: -200 volts, -2,000 volts, -10,000 volts, and -2,000 volts. The anode grid is held at 100 volts. The system of grids results in a one pass period of $4 \cdot 10^{-6}$ seconds. This bounce period corresponds to a frequency of 250 kHz and the gross pulsing behavior occurs at the same frequency as the individual ion bounce frequency.

Observe that the central potential steadily rises from the background value of -2,620 volts up to -2,580 volts. The bunching phenomenon then grows until the system reaches a steady state at about $5 \cdot 10^{-4}$ sec. At this point, the peak central potential is about -2,500 volts and the minimum voltage is about -2,590 volts, 300 volts above the background. This 300 volt space charge is due to the newly injected ions which haven't had time to incorporate into the system of bunches.

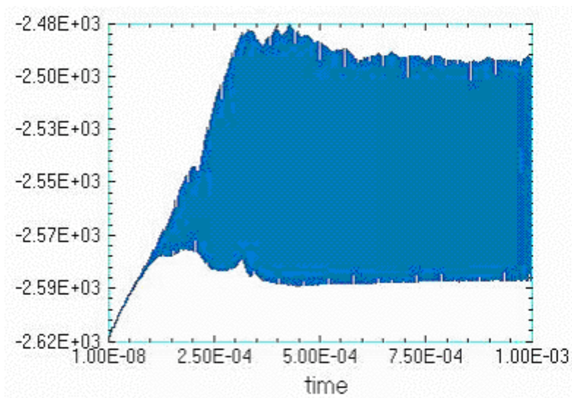

Fig. 7. Center potential vs. time of OOPIC model of a multiple grid IEC

The mechanism by which ions are lost in the system varies depending in the level of ion injection. For high levels of ion injection current, the majority of ions are lost to the cathode grids. As shown in Fig. 8, a Deuterium injection current of 100 milli-Amps per beam results in filamentation of the ion beams and steady-state behavior is reached after only 50 passes. The separate ion beam filaments repel each other, filling up the ion channel and causing the ions to impact the innermost grid. Pulsing is still observed, but the shorter confinement times stops the pulsing from dominating the behavior.

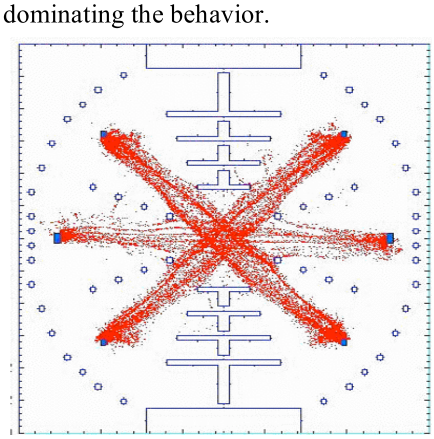

Fig. 8. Ion map for 100 mA Deuterium multi-grid IEC

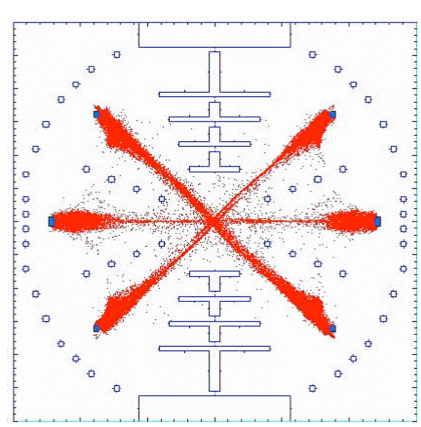

Fig. 9. Ion map for 1 mA Deuterium Multi-grid IEC

Lower levels of ion injection results in a more ordered system as recirculating current builds over a longer time. Fig. 9 shows the behavior of 1 milli-Amp Deuterium ion injection per beam, reaching steady state at 500 passes. The pulsing now fully dominates the ion behavior. Further, the ions now are lost mainly to the anode grid structure as bunches are reflected, and very few ions impact the inner grid structures.

IV. Multiple Grid Scaling

Density scaling with size

The scaling of the peak density with device dimension is expected to be very strong, as smaller devices should support much higher ion densities for a given cathode voltage. The hypothesis is that the density is limited by space charge effects, governed by the potentials on the grids and the density of ions in the system. For a cloud of ions in the core with uniform density, the peak potential within the cloud varies as inverse of the square of the cloud radius.

A numerical experiment using the OOPIC model is used to test this hypothesis. The peak central ion density will be used as a characteristic density to compare three different device scale sizes. The first is the baseline laboratory device with a diameter of 40 cm, along with devices of 20 cm and 80 cm diameters. The computational time step is adjusted accordingly, and the Argon injection current is set to produce steady-state populations after about ten passes. A high gain reactor would trickle ions into the system to achieve higher lifetimes, but as will be shown in the next section, the highest density for a given system occurs when ions are 'flooded' into the system. The overall behavior of each model is similar, including the steady-state synchronized oscillations. The confinement properties for the different scales are similar and the core radius thus roughly scales linearly with the device size. The density scaling is shown below in Fig. 10.

The peak density shows a clear inverse square relation to the device diameter. Assuming that the core, beam-beam reactions dominate in the low pressure regime, the fusion reaction rate varies as the square of the peak density times the core radius cubed. The overall beam-beam fusion rate thus scales inversely with device size. This suggests that scaling non-neutralized multiple grid IECs to larger sizes would be counter-productive. There are practical limits to miniaturization, such as arcing with the high voltages involved and the complexity of the multiple grid system.

Density scaling with input current

In order to improve the efficiency of the IEC concept, the system should be run at high levels of recirculation so that ions have many opportunities to fuse. The multiple grid IEC allows for very low input currents to build into high recirculating currents, but a weak dependence on steady-state peak ion density with input current is observed. Results for Argon and higher voltage Deuterium models are presented in Fig. 11. The voltages for the Argon and Deuterium cases are considerably different in magnitude, but the potential distribution among the grids is essentially the same, resulting in similar confinement behavior. The Argon runs were limited to -10 kV, characteristic to laboratory experiments for comparison.[11] The Deuterium simulations were executed at much higher voltages of approximately -200 kV, characteristic of eventual fusion reactors.

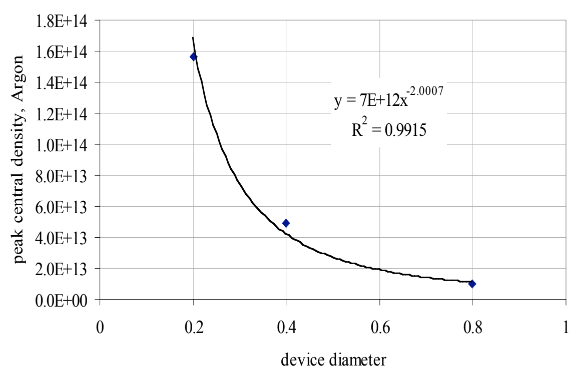

Fig. 10. Peak center density vs. diameter for Ar+

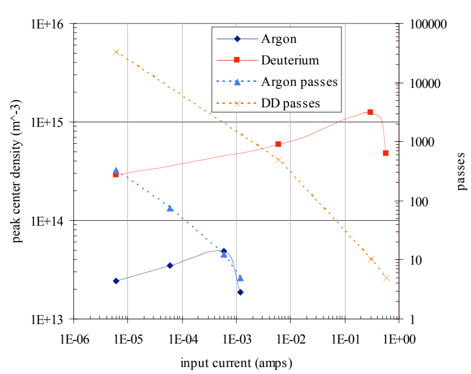

Fig. 11. Steady-state peak density (m^{-3}) and confinement time (passes) versus input current in amps for Ar+ and D+

The peak density versus input current for deuterium reaches a maximum near a total injection current of only 0.3 amps. The peak density at lower currents scales as '$i^{0.13}$'. The peak lifetime measured in number of passes varies as '$i^{-0.76}$', a lower power law than the inverse linear relationship one might expect. It is unclear to what extent the deviation from an inverse square law is due to numerical error resulting from the level of computational grid refinement. The data on the left side of the chart becomes increasingly difficult to collect, as the simulation time becomes very large. The Deuterium model for 6 μAmp total injection reached steady state at 33,000 passes, ~13.3 million time steps and 2 weeks of continuous desktop computer time. Argon is included as it is the gas of choice for follow-on laboratory experiments[11].

V. Hybrid Neutron Generators

The peak densities found here for a completely non-neutralized system are several orders of magnitude too low to produce significant fusion power. Also, the densities achieved with purely beam-beam operation at ultra low pressures (10^{-10} Torr) are insufficient for portable neutron generators. However, for the near-term application of IECs for portable neutron production, one could run in a 'hybrid' mode. By operating at a background gas pressure in between the ultra low pressures assumed above (10^{-10} Torr) and the pressures used in IECs operating in the glow discharge regime (10^{-3} Torr), the fusion rates can be increased by beam-background collisions, but with at least an order of magnitude improvement in confinement time so that the devices are more electrically efficient and economical.

The gains in efficiency over conventional systems come chiefly from the fact that when the beams are well synchronized at low input currents the ions tend to impact the anode structures instead of the cathode grids, causing significantly less electrical loss. Additionally, since the ions are lost to the anode for most cases, the electron streaming losses are minimal. For the cases where ion current is high, the ions are lost to the innermost grid, held at a potential far higher than the main cathode grid, for this study -40 kV and -200 kV respectively. The electron streaming losses for the high input current cases are also eliminated since the innermost grid forms an electron sink.

The gains in efficiency require that the synchronization mechanism be preserved. The background pressure can then be set so that the confinement limits found above do not exceed the effective confinement limits due to background collisions. Thus the fusion events are dominated by beam-background collisions, but the most likely ion loss mechanism is the synchronization confinement limit. The hybrid operating pressure varies from $1\cdot10^{-8}$ torr for the lowest input current to $6\cdot10^{-5}$ torr for the highest input current. Rate estimates including beam-background and beam-beam reactions in the core are calculated by Eq. 2 with an operating pressure set so that the confinement limit due to pressure is equal to the confinement limits shown in Fig. 11.

$$\dot{r} = \left(\frac{i_{in}}{e}\right)\frac{\sigma_{fus}\left(KE_o\right)}{\left\langle\sigma_a\right\rangle_p}\left(\frac{R_{cat}}{R_a}\right) + \eta_{pulse}\frac{n_c^2}{3}\pi R_c^3\left\langle\sigma_{fus}v\right\rangle_{core} \tag{1}$$

The nomenclature follows from Ref. 9, where $\sigma_{fus}(KE_o) = 1.3\cdot10^{-28}$ m^2, $\langle\sigma_a\rangle_p = 1\cdot10^{-19}$ m^2 and $\langle\sigma_{fus}v\rangle_{core} = 1.45\cdot10^{-20}$ m^3/s for DT at 50 keV[10].

Fig. 12 shows the increase in fusion output for a hybrid system over a purely beam-beam system at a given input powers. The dotted line shows the linear trend for a traditional IEC system, although with a reduced loss per ion of 40 keV compared to 200 keV and the assumption of no electron streaming losses, which are of the same order as the ion losses for single grid IEC systems. The large improvement in efficiency is primarily due to the greatly reduced electrical loss per ion injected at low injection currents.

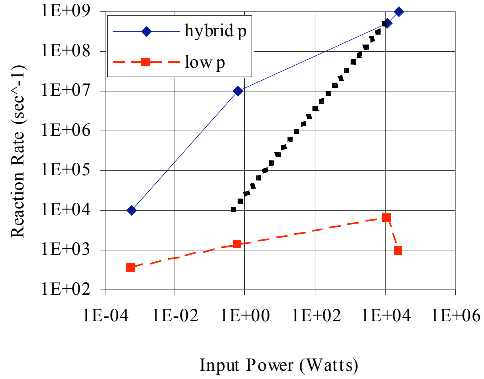

Fig. 12. Reaction rate (sec^{-1}) vs. input power (watts) for hybrid and low pressure systems

The electrical gain of the system is calculated by Eq. 3 as electric power produced divided by electrical power input.

$$Q = \eta_{power}\left(\frac{E_{fus}}{\Gamma}\right)\left[\frac{\sigma_{fus}\left(KE_o\right)}{\left\langle\sigma_a\right\rangle_p}\left(\frac{R_{cat}}{R_a}\right)+\eta_{pulse}\left(\frac{e}{i_{in}}\right)\frac{n_c^2}{3}\pi R_c^3\left\langle\sigma_{fus}v\right\rangle_{core}\right] \qquad (2)$$

'η_{power}' is the power conversion efficiency, assumed to be 50% here, a relatively low value for direct energy conversion. 'E_{fus}' is the fusion energy liberated in a given reaction, equal to 17.6 MeV for DT. 'Γ' is the energy lost per ion, equal to 40 keV for ions lost to the innermost grid. Ions lost to the anode structures are assumed to cost 100 eV due to the cost of ionization of the ion. The gain is plotted below in Fig. 13.

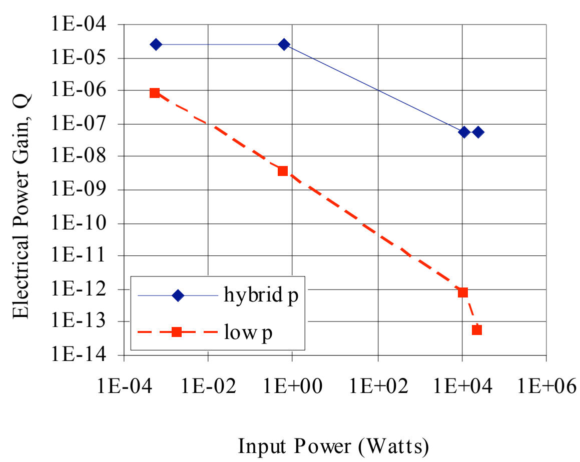

Fig. 13. Electrical power gain vs. input power (watts) for hybrid and low pressure systems

The hybrid system in Fig. 13 shows a higher efficiency low power regime and a lower efficiency high power regime. One can also see that as input power is reduced the purely beam-beam system is becoming more efficient, but the gain of the hybrid system effectively plateaus. The operating point for a hybrid design can then be chosen as a trade between reaction rate and efficiency. Additionally, the system could be reduced in size to boost the output somewhat. A characteristic 80 cm diameter hybrid DT system with 1 Watt input power should produce ~10^7 reactions/second. With 100 Watts input power, the same system should produce ~10^8 reactions per second.

V. Conclusion

Multiple grids are shown to increase the ion lifetime in IEC devices from 10-15 passes to over 33,000 passes in Particle-in-Cell simulations. Improved confinement characteristics of the multiple grids allow the peak ion density to be largely decoupled from the level of injection current. Non-neutralized density limits for practical device sizes preclude the production of significant amounts of fusion power for a pure beam-beam system. Higher rates useful for portable neutron sources should be possible by using higher operating pressures, while still providing significantly higher electrical efficiencies than current IEC devices.

Acknowledgments

This work was supported as doctoral research under a Department of Defense, National Defense Science and Engineering Graduate (NDSEG) Fellowship. Further support was provided by the MIT Space Systems Laboratory.

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