High-Current Pulsed Operation of an Inertial-Electrostatic Confinement (IEC) Device

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Abstract - Recent advances in pulsed power supply technology has allowed the Star Mode Inertial-Electrostatic Confinement (IEC) to pulse to high currents, 17 A, at a peak voltage of 50 kV, and a pulse width of 100 μs at a frequency of 10 Hz. These results represent an increase in cathode currents of three orders of magnitude over steady state sources. Neutron production at the peak of the pulse was found to be $\sim 10^9$ n/s of D-D neutrons. This increase in pulsed current operation, and corresponding linear scaling of fusion reaction rates, represents a significant step forward in the development of IEC controlled fusion. An "effective-Q" of this operation was calculated to be 6×10^{-5}. Analysis of IEC operation at higher current indicates that breakeven, with an effective-Q of 1.0, might be reached with additional increase in cathode current of only ~2 orders of magnitude.

INTRODUCTION

Inertial-Electrostatic Confinement of a fusion plasma can occur when high energy ions converge in either a spherical, or cylindrical, geometry. The converging ions build up a positive space charge that attracts electrons; the resulting dual species plasma will oscillate, forming a series of "virtual" cathodes and anodes. In this manner, a relatively high density of ions can be confined at non-Maxwellian energy distributions for the purpose of controlled nuclear fusion. The ions may be introduced via either the ionization of background neutral gas or the injection of ions from an external source. The electrons, conversely, can be supplied through ion collisions with the cathode, or (again) from the ionization of the background neutral gas.

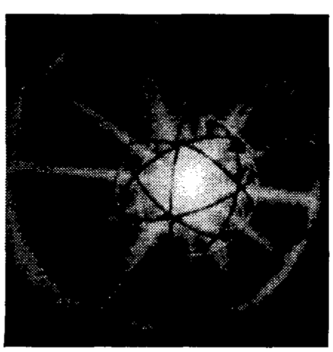

Figure 1. IEC Reactor Core in Star Mode.

The approach to fusion using IEC was originally conceived by P. Farnsworth[1], and later studied experimentally by Hirsch[2]. However little was done to study this concept until R. W. Bussard[3] and G. H. Miley[4] renewed studies in the early 1990s.

The basic IEC approach pursued here (spherical devices with grids operating in the star mode) was subsequently conceived by Miley, et al.,[5,6] as part of an IEC-based fusion neutron source project at the U. of Illinois (UI). This configuration is now being commercialized by Daimler-Chrysler Aerospace Corp. (the first commercial application of a confined, fusing plasma!)[7]. This basic concept was significantly extended by the development of pulsed operation at high peak currents as described here.

Figure 1 is a photo of an IEC core operating in the "star mode". Ion beams, clearly visible in the photo, are formed by the potential set up by the grid structure. The beams pass through the center of the grid opening, reducing grid-ion collisions and enhancing focussing at the center of the sphere.

DESIGN OF IEC PULSED EXPERIMENTS

The IEC experimental reactor vessel uses a 61-cm spherical vacuum vessel with multiple ports to

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[1] P.T. Farnsworth, "Electric Discharge Device for Producing Interactions Between Nuclei," U.S. Patent No. 3,358,402, issued June 28, 1966.

[2] R. Hirsch "Inertial-Electrostatic Confinement of Ionized Fusion Gasses," *J. Appl. Phys.*, 38, 11, 4522 (1967).

[3] Bussard, R. W., *Fusion Technology*, Vol. 19, No. 2, p. 273-293 (1991).

[4] Miley, G.H., "Dense Core Plasma in an Inertial-Electrostatic Confinement Device," *1991 U.S.-Japan Workshop on Nuclear Fusion in Dense Plasmas*, Austin, TX (1991).

[5] Miley, G.H., Nadler, J., et al., "An Inertial Electrostatic Confinement Neutron/Proton Source," *Third International Conference on Dense Z Pinches*, eds. Haines, M., and Knight, A., *AIP Conference Proceedings 299*, AIP Press, 675-689 (1994).

[6] Miley, G.H., Nadler, J, et al., "Discharge Characteristics of the Spherical Inertial Electrostatic Confinement (IEC) Device," *IEEE Transactions of Plasma Science* (Oct. 1997).

[7] Sved, J., "The Commercial IEC Portable Neutron Source," *Trans. of the ANS*, 77, 504, (1997).

accommodate power feed-through's and diagnostics. A high-voltage power feed-through provides the cathode-grid 50-80 kV. One, two, or sometimes three grids are used inside the vessel; the inner-most grid is the main cathode; additional grids are used for controlling electron clouds for background gas ionization.

Prior operation of IEC experiments has concentrated on steady-state operation[5,6]. However, pulsed operation appears desirable to achieve the high currents required to generate increased reaction rates. A transmission line-type pulser was developed for these experiments (Fig. 2). It consists of a high-voltage DC power supply (0 – 5 kV) grounded at one end and connected in series with charging "choke" inductors (~8 H total). The chokes limit the rate at which the energy storage capacitors are charged. Two energy storage capacitors are then wired in parallel and placed in series with a 30-mH inductor and connected to a pulse transformer (1:10 step-up ratio). The opposite lead of the step-up transformer leads to a diode array, which prevents possible reflections from damaging either the pulser or the steady-state power supply. A hydrogen-thyratron switch initiates the pulse and discharge the energy storage capacitors. Figure 3 shows the voltage and current output of a typical pulse. One division on the voltage trace is equal to 1-kV; one division on the current trace is 1 A. Note how the voltage drops from ground (which is at the top), while the current rises from the middle of the scope. The time scale is 50 μs per division, so the entire pulse lasts on the order of 100 μs.

To measure nuclear fusion reaction rates, a neutron diagnostic was developed to count the 2.54-MeV (D-D) fusion neutrons. Use of conventional steady state detectors is prevented by their inherent "dead time." To overcome this problem, a silver-foil (Ag-foil) activation detector was designed and built, employing several Geiger-Muller tubes covered in thin silver foil and set at the center of a block of polyethylene (to thermalize the fast neutrons). The half-life of the activated Ag is on the order of a half of a minute. Therefore, the IEC is pulsed at 10 Hz for several half-lives to "saturate" the activated Ag.

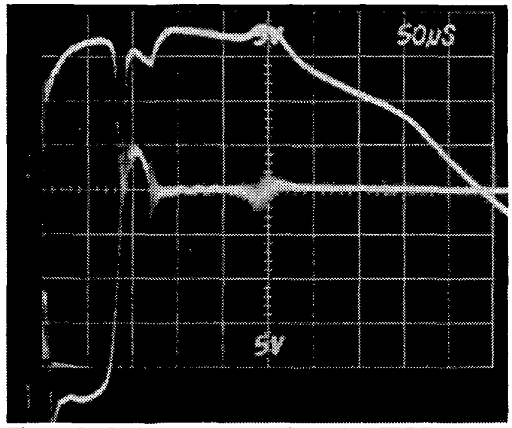

Figure 3. Oscilloscope trace of a typical IEC Reactor Pulse.

Then the IEC is rapidly turned off and the gamma rays from decay of the activated Ag are counted. Calibration employed a radioisotope (Pu-Be) neutron source.

RESULTS OF IEC PULSING

A key objective of these experiments was to demonstrate that dynamic evolution of accelerating fields to generate energetic ions required for fusion could be achieved in the pulse mode. Neutron production as a function of pulsed current for several different cathode-grid designs is presented in Fig. 4. Data was collected for pulsed operation for cathode voltages of 40 - 50 kV, and currents up to 17 A; a peak yield of 8 x 10^8 n/s was obtained at the maximum current.

The data in Fig. 4 was taken with two different grids. A relatively small reference grid (called Grid A) was used for the first set of measurements; a second, larger grid was used for the remaining points in the figure (Grid B). Operation with the smaller Grid A produced a slight, but significantly lower fusion reaction rate compared to the larger Grid B. This is expected since the larger grid allows for a lower neutral background pressure in accordance with Paschen theory of breakdown. This lower pressure

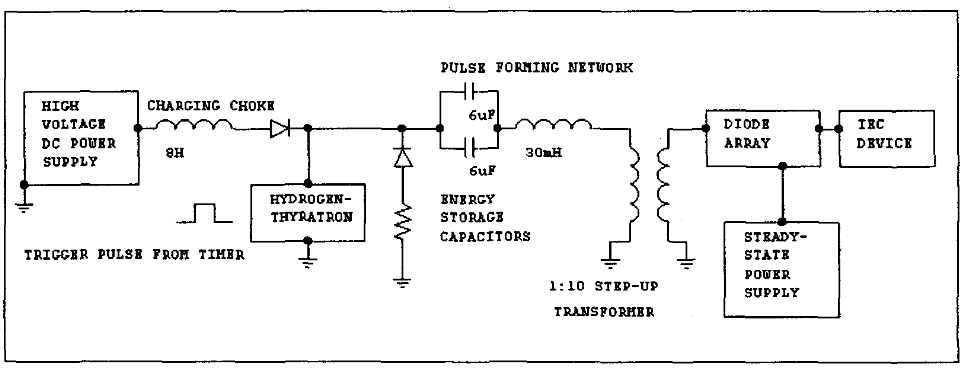

Figure 2. Electronic schematic of the pulser and IEC device.

reduces charge exchange, and hence, allows for longer ion confinement times and higher reaction rates.

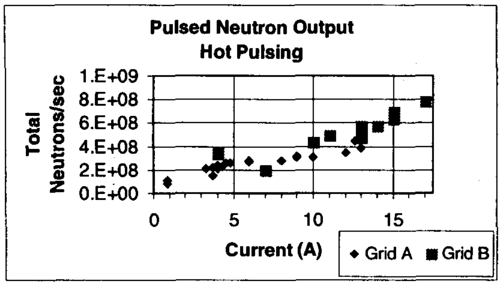

Figure 4. Pulsed neutron output at peak of pulse vs. peak cathode current for IEC Reactor Operation.

As seen in Fig. 5 (a plot of neutron production vs. peak cathode current) cold pulsing (operation in the absence of a driven ionization of the background neutral gas) behaves very similar to hot pulsing (operation during the driven ionization of the background neutral gas). Nuclear fusion reaction rates were higher for the larger Grid B (10" diameter) than they were for the smaller Grid C (8" diameter). However, cold pulsing produced a lower reaction rate than hot pulsing, where the background pressure was higher. At first inspection it may appear that this result runs counter to the argument for reduced background pressure during operation. However, it actually supports the theory: the source of ions in this configuration is the ionization of background gas, and the target for the predominantly beam-target fusion reactions in the background neutral gas. So if the background pressure is reduced the fusion reaction rate is also lowered. The goal is to increase Q, not just increase neutron production. The majority of fusion reactions are occurring in beam-background mode and not beam-background. Once a higher Q has been demonstrated in beam-beam mode, higher reaction rates can be sought. So the issue here is that there is not sufficient reduction of the background pressure, nor is there an adequate electron density for ionization. Reduced pressure and increased ion generation is a critical issue for future research and will be addressed in the next section.

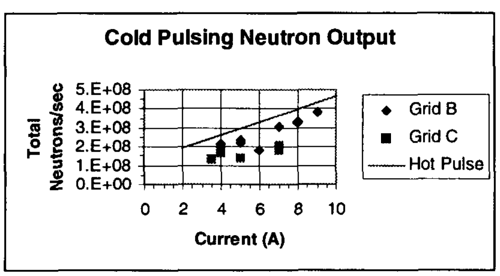

Figure 5. Cold-pulsed output at peak of pulse vs. peak cathode current for IEC reactor operation.

Cold pulsing does not produce as much "ringing" of the voltage/current trace as does hot pulsing. Also, at the end of a cold pulse, its "backlash" (cathode voltage spiking positive) is much less for a hot pulse. Minimizing ringing and backlash are two steps toward greater efficiency. The significance of the cold pulsing data is that a stable discharge can be formed, allowing a further decrease in background pressure while still increasing ion generation. The next step is to either increase the number of electron emitters around the vessel, or redesign the experiment with advanced ion sources.

ANALYSIS

One very important parameter for any fusion confinement scheme is Q, defined here as the energy produced per unit time divided by the energy consumed to operate the system per unit time. For the IEC system that can be calculated with the following equation:

$$Q\left(S_N, V, I, E\right) := \frac{S_N \cdot E}{V \cdot I}$$

where S_N is the total neutron production rate; E is the total energy released per neutron emitted; V is the cathode-grid voltage, and I is the cathode-grid current. For the given parameters of steady-state operation: 40 kV, 15 mA current, and the energy per reaction associated with D-D fusion, a Q of 7×10^{-10} is calculated. For pulsed operation at the values of current for the peak of the pulse, a Q $\sim 1 \times 10^{-9}$ is calculated.

However, this is somewhat misleading since the present devices are operating at background neutral gas pressures much higher than that expected for future power production devices and at voltages much lower. In addition D-D reactions are used to date and not the higher energy yielding D-T reactions. To account for these differences, an "effective-Q" was defined. This effective-Q accounts for the increased charge-exchange rate of the fast moving ions in the higher background pressures and the dynamic effects of the D-D reactions and lower cathode-voltages.

Calculations of ion dynamics indicate that as many as 50 passes could be possible in future devices, instead of the likely 1 to 2 passes in present high-pressure experiments[8]. The number of passes is estimated from the mean free path for charge exchange, which at present pressures is on the order of the vessel diameter, that is, 50 cm.

In order to assess the attractiveness of IEC for controlled fusion, it is beneficial to estimate the currents at which we would expect to achieve a

[8] J.M. DeMora, "Cathode Grid Optimization for the Spherical Inertial-Electrostatic Confinement Device," MS Thesis, Nuclear Engineering Department, University of Illinois, 1999.

breakeven of Q = 1. Figure 6 (derivation of which follows below) shows a projection of Q with current (I) for both I-squared and I-cubed scaling. Linear scaling with current will not change the operating Q-value since the doubling of the fusion reaction rates would be canceled by the doubling of input power. Current squared scaling, on the other hand, would result in linear scaling of Q-values with increasing current; and, current cubed scaling would yield a second order quadratic increase in Q-value with current.

Ion recirculation current and cathode current are not identical in these devices. Ion density inside the cathode-grid varies with the spherical radius, r, as:

$$n_i(r) = \frac{I \cdot \gamma}{2 \cdot \pi \cdot r^2 \cdot v(r) \cdot e}$$

Here I is the cathode current, γ is the number of passes an ion makes across the cathode-grid, and v is the velocity at the point r. The density of a spherically reflexing ion beam will increase with decreasing r up to some point, R, where the potential-well structure flattens. For an IEC device such as those used in this study, that point is on the order of a centimeter. So the total fusion rate for beam-beam reaction, where V is the total volume of the plasma core, would be:

$$\text{Total Reaction Rate} = \left(\frac{I \cdot \gamma}{2 \cdot \pi \cdot r^2 \cdot v(R) \cdot e}\right)^2 < \sigma v(r) > V$$

Current squared scaling of the total reaction rate is the first order scaling expected for beam-beam fusion,

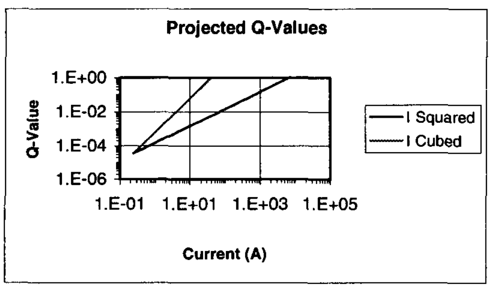

Figure 6. Projected Q-values vs. cathode current for a scaled-up IEC reactor.

since the reactant densities that appear are squared in the reaction rate equation. However, the effects of total reactor volume and the number of ion passes (i.e., confinement time) must be considered for higher order scaling. Non-linear scaling effects have been predicted in the literature[9,10], and can be explained conceptually by considering that the multiple potential well structure inside the IEC core will grow with increasing ion recirculation current. This in turn leads to an increased γ (number of ion passes) and V (volume) in the equation above. Plus, the ion acoustic waves formed in the plasma during compression will support higher ion densities. So, increased confinement time along with increased reactant density can easily result in I-cubed scaling.

The scaling in Fig. 6, then, is based on two data points. The first corresponds to the experimental measurements and calculations of potential well formation for a similar IEC core[11]. Gu proposed a perveance relationship between applied cathode voltage and current for which multiple potential wells would form. For an operating voltage of 80 kV, Gu's work predicts multiple potential well formation at 240 mA. The second data point, the effective-Q of 6 x 10^{-5} found above for IEC pulsed operation is then used as a foundation point for I^2 and I^3 scaling projections.

CONCULSIONS

Based on these results, it is found that breakeven could be achieved at as low of an ion current as 40-A if I-cubed scaling is observed, but 6.7 kA if the more conservative I-squared scaling occurs. It is important to summarize here the assumptions that went into this projection:

1. Operation at a cathode voltage > 80 kV.
2. Low-pressure operation is achieved where charge exchange is not a significant process.
3. Deuterium-tritium operation
4. Nonlinear scaling of fusion reaction rate with current.

IEC fusion offers a substantially different approach to controlled fusion. The relatively simplistic nature and the inexpensive develop costs associated with IEC devices make them attractive as an alternative concept for controlled nuclear fusion.

ACKNOWLEDGEMENTS

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[9] R.W. Bussard, et al., "Ion-Acoustic Waves and Ion Wave Group Trapping in IEC Systems," *Bulletin of the American Physical Society,* 37, 6, 1582 (1992).

[10] I.V. Tzonev, "Effect of Large Ion Angular Momentum Spread and High Current on IEC Potential Structures," M.S. Thesis, Nuclear Engineering Department, University of Illinois, 1996.

[11] G.H Miley and Y.B. Gu, "IEC Neutron Source Development and Potential Well Measurements," *Current Trends in Fusion Research -- Proceedings of the Second Symposium*, Ed. E. Panarella. NRC Research Press, National Research Council of Canada, Ottawa, ON K1A 0R6, Canada, 1999.