INERTIAL-ELECTROSTATIC CONFINEMENT (IEC) OF A FUSION PLASMA WITH GRIDS

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There are two significantly different approaches to Inertial-Electrostatic Confinement (IEC) of a fusion plasma. One approach uses grids to accelerate and confine the plasma, another uses magnetic fields in conjunction with electric fields to confine a relatively high density electron cloud, that then confines a lower density ion cloud.[1,2] While the two approaches may share some physics associated with the confinement of the plasma (e.g., ability to burn advanced fuels, maintenance of a non-Maxwellian plasma, etc.), the approach to each confinement is different. This paper addresses IEC concepts utilizing grids.

Background

1) **Spherically Imploding Ion Beams:** Inertial Electrostatic Confinement (IEC) is achieved by accelerating ions into a highly transparent cathode-grid, concentrically placed inside a larger vacuum vessel of the same geometry. Typical IEC devices are usually spherical, although many cylindrical ones have also been studied. Ions generated near the wall of the vessel are accelerated into the cathode-grid, due to the strong electric field produced by the potential difference (~50 kV) placed between the cathode-grid and the grounded vessel wall. Different schemes are employed to generate the ions, e.g., glow discharge, electron-impact from a low density electron cloud that is confined near the vessel wall via an extra grid and produced from hot electron emitters, and externally mounted ion sources.
2) **Multiple Potential Well Formation:** Ion confinement time in the hot plasma can be significantly increased via the formation of a series of multiple potential wells inside the cathode-gird. These "virtual wells" appear as "virtual" anodes and cathodes to the ions, confining them but not absorbing them like the "real" cathode-grid. With this formation of wells the only loss mechanism for the ions is upscatter (an interaction in velocity space, not physical space) and fusion. These wells, modeled with computational codes and observed experimentally (described below), form due to a complex interaction between the ions circulating through the cathode-grid and electrons, emitted as secondary products from the cathode-grid when an ion is absorbed and from ionization of the background gas inside the cathode-grid.
3) **Encouraging Experimental Data:** Numerous studies, spanning almost four decades, have reported exceedingly high neutron yields, as a function of plasma density and energy, and direct measurements of potential well formation[3,4,5].[6]
4) **The Early Pioneers:** The approach to fusion using IEC was originally conceived by P. Farrnsworth[7] (inventor of electronic television in the US), and later studied experimentally by

[1] D.C. Barnes, R.A. Nebel, *Physics of Plasmas* 5, 2498 (1998).
[2] R.A. Nebel, D.C Barnes, *Fusion Technology* 38, 28 (1998).
[3] R.L. Hirsch, *J. Applied Physics*, 38, 4522 (1967).
[4] J.H. Nadler, et al., *Rev. Sci. Instruments***,** 63 (10) October 1992.
[5] Y. Gu, Ph.D. Thesis, Department of Electrical and Computer Engineering, University of Illinois (1997).
[6] This is only a partial list of references.
[7] P.T. Farnsworth, "Electric Discharge Device for Producing Interactions Between Nuclei," U.S. Patent No. 3,358,402, issued June 28, 1966, initially filed May 5, 1956, rev. Oct. 18, 1960, filed Jan. 11, 1962.

Hirsch (including neutron production, direct plasma measurements, and computational modeling)[1]. Then during the late 60's and 70's, Verdeyen conducted many experiments on the potential well depth and formation, but not neutron generation[8]. R. W. Bussard[9] and G. H. Miley[10] renewed studies in the late 80's, looking at electrical power production, space propulsion, and neutron generation.[11]

Attractiveness

1) **Non-Maxwellian Ion Energy Distribution:** Since the ions are accelerated, reaching the center of the cathode-grid with near uniform kinetic energy, the resulting plasma is non-Maxwellian. This energy distribution and consequent beam-beam type reactions, plus lack of cyclotron radiation due to the elimination of B-fields, makes the IEC attractive for burning advanced fusion fuels, like D-^{3}He and p-^{11}B.
2) **Non-Linear Scaling of Reaction Rate with Ion Current:** Computational studies have shown that potential well formation and ion confinement time is a function of ion density[12,13]. Since ion density is dependent on ion confinement time, non-linear scaling of fusion reaction rate with ion current is considered possible. Scaling on the order of current squared (or maybe even current cubed) would lead to high reactor power densities and attractive reactor efficiencies.
3) **Plasma Target Fusion:** The greatest number of fusion reactions is occurring inside and around the cathode-grid; and in most devices operating today, the majority of reactions are beam-background in nature, that is, between the fast moving ions in the plasma and the neutral background gas. Since there is no solid target upon which ions are directed there is not a solid target that will deteriorate from plasma interactions. This is advantageous for it places no upper limit on confined ion density and fusion reaction rates (beyond physical constraints of the cathode-grid).
4) **Non-Ignited Plasma:** Most IEC reactor concepts employ a direct energy conversion scheme, wherein the high energy fusion products are allowed to escape the potential well "trap" and slowed down in an external, high voltage electric field. Such a configuration does not require an "ignited" plasma where the fusion reaction products are keeping the plasma hot. Therefore, reactor sizes smaller than conventional fusion devices are possible to demonstrate reactor breakeven.
5) **Compact Size and Low Reactor Weight:** IEC devices using grids do not need magnetic fields, hence eliminating the need for large, heavy magnets. In addition, IEC devices are relatively simplistic and small, making for an easy to transport inexpensive device.

Potential Applications

1) **Terrestrial Power Source:** Several approaches are under consideration for earth-based power production: Q >1 fusion reactor, employing direct energy conversion; and a fusion-fission hybrid with a Q < 1 IEC reactor and a $k_{eff} < 1$ fission assembly.
2) **Deep Space Power and Propulsion:** IEC is presently being investigated for use in deep space power and propulsion. The low weight, compact nature of the IEC makes it attractive for use in propulsion and remote site power production.

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[8] B.E. Cherrington, J.T. Verdeyen, et al., *Annals of New York Academy of Sciences*, 139-150 (1973).
[9] Bussard, R. W., *Fusion Technology*, Vol. 19, No. 2, p. 273-293 (1991).
[10] Miley, G.H., *1991 U.S.-Japan Workshop on Nuclear Fusion in Dense Plasmas*, Austin, TX, (Oct. 7-9, 1991).
[11] J.H. Nadler, G.H. Miley, Y. Gu, T. Hochberg, "Characterization of an Inertial-Electrostatic Confinement Glow Discharge (IECGD) Neutron Generator," *Fusion Technology*, 21, 1639 (1992).
[12] R.W. Bussard, et al., *Bulletin of the American Physical Society*, 37, 6, 1582 (1992).
[13] I.V. Tzonev, M.S. Thesis, Nuclear Engineering Department, University of Illinois, 1996.

3) **Radioisotope Production:** A Q < 1 IEC device producing either high energy neutrons or protons, would be ideal for producing radioisotopes for everything from industrial uses to medical diagnostics and therapy.
4) **Medical Therapy:** A high output IEC device has been considered in therapies involving neutrons such as Boron Neutron Capture Therapy.
5) **Nondestructive Evaluation/Neutron Activation Analysis:** Thermalizing neutrons from an IEC device, or using 14-MeV neutrons from D-T fusion in an IEC, is advantageous, considering the attractive attributes considered above, i.e., low weight, compact nature, and most importantly, plasma target. Indeed, Daimler-Chrysler has commercialized IEC technology for small, compact neutron generators (this is the first commercial application of a confined, fusing plasma!)[14].

Key Issues

1) **Multiple Potential Well Formation:** Further study is required to understand potential well formation and the scaling of such formation with ion current, energy, etc. This is the central key to developing IEC technology for advanced applications beyond that of small scale neutron activation analysis.
2) **Ion Thermalization:** Recent calculations have indicated that the ion thermalization time in an IEC will be much shorter than the ion fusion time.[15] If true, then an IEC reactor will be forced to spend far more energy maintaining a non-Maxwellian distribution then it will produce. Given the inherently complex nature of the problem, the assumptions that must be made in order to carry out this kind of a calculation, and the fact that collisions at the center of the core (where the ion density is the highest) may not affect the ion energy distribution, it is believed that an experiment to address these issues might help shed some light on the problem.
3) **Charge Exchange:** Operation of IEC devices in the glow discharge mode, with background pressures in the mTorr region, is charge-exchange dominated. Some researchers have thought that the high neutron production rates observed to date have come primarily from fusion reactions inside the cathode-grid, while others are of the opinion that the fusion reactions are mostly occurring in the inter-electrode region (that is, the region between the cathode-grid and the anode-wall).
4) **Scaling of Reactor-Power with Current:** Operation with present IEC devices is in the mode of linear scaling of neutron output with cathode-grid current. It is believed that too high of a background operating pressure is truncating ion confinement, preventing the formation of deep, multiple potential wells. Construction of next-generation IEC devices are needed to reduce background neutral gas pressure, increase ion injection currents, so as to measure reaction rates as a function of cathode-grid current.
5) **Power Conversion:** Given the advantage and possible use of advanced fuels, such as D-^{3}He and p-^{11}B, research is needed to develop a conversion scheme that will allow for high efficiency extraction of useful energy from the IEC device.
6) **Cathode Grid Life Expectancy and Efficiency:** It is unlikely that present-day cathode-grid technology is sufficient to make a grid that can contain a Q > 1 IEC plasma. Investigation is needed to optimize grid design and the materials with which they are made.

Conclusions:

Inertial-Electrostatic Confinement offers several possible advantages for the confinement of a Q > 1 fusion plasma. Numerous past experiments have produced data that warrants further

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[14] Sved, J., "The Commercial IEC Portable Neutron Source," *Trans. of the ANS*, 77, 504, (1997).
[15] W.M. Nevins, "Can inertial-electrostatic confinement work beyond the ion-ion collisional time scale?" Phys. Plasmas 2, 10 October 1995.

investigation by the fusion community. Due to the simplistic nature, and relatively small physical scale of an IEC device, it is possible to explore the potential of IEC concepts without spending large sums of money. A modest experimental program, conducted at two or three laboratories, could conduct a small number of experiments that could either put the relevant issues to rest, or give the community reason to support further research and development.

Acknowledgements:
This work was supported in part by the Propulsion Research Center, Marshall Space Flight Center, NASA. The encouragement and support of Drs. George Schmidt, Francis Thio, and Ivana Hrbud are greatly appreciated. Additional technical discussions with Dr. George Miley were also invaluable.