ANL/RE/CP-100670

An Innovative Accelerator-Driven Inertial Electrostatic Confinement Device Using Converging Ion Beams *

Submitted to Eighth International Conference on Nuclear Engineering – ICONE-8
Track 8.09

By
T. H. Bauer[1] and R. A. Wigeland[2]

Reactor Engineering[1] and Reactor Analysis[2] Divisions
Argonne National Laboratory
Argonne, IL 60439

Abstract

Fundamental physics issues facing development of fusion power on a small-scale are assessed with emphasis on the idea of Inertial Electrostatic Confinement (IEC). We propose a new concept of accelerator-driven IEC fusion, termed Converging Beam Inertial Electrostatic Confinement (CB-IEC). CB-IEC offers a number of innovative features that make it an attractive pathway toward resolving fundamental physics issues and assessing the ultimate viability of the IEC concept for power generation.

Small-Scale Fusion

It was recognized early on that achieving fusion power without the need for plasmas at exotically high temperatures requires some form of colliding and recirculating ion beams. A solid target is not useful since the beam loses energy too quickly, resulting in no energy gain, i.e. reaction energy out << energy into beam. Colliding beams offer at least the theoretical possibility of a favorable energy balance. Still, a colliding beam approach faces two rather imposing physics and engineering obstacles. (1) Due to the large ratio of the scattering cross section versus the reaction cross section, beams must be re-circulated many times in order to achieve a net energy gain. (2) A high density of ions in the collision volume, while needed for a high fusion reaction rate, leads to undesirable space charge effects tending to disperse the beams.

If these obstacles can be overcome, the "upside" is considerable. Beam energies necessary for the fusion reaction are readily accessible at small-scale using conventional high-voltage or other acceleration techniques. Moreover, because the range of achievable energies is quite wide, the beam approach is suitable for a much wider variety of fusion reactions than ever could be achieved by thermonuclear ignition. For example, it is widely acknowledged that $p + {}^{11}B \rightarrow 3\,\alpha$ represents an ideal nuclear reaction for energy production. First, the fuels are both plentiful and cheap. Second, no radioactive products are directly involved, and only a small amount of radioactivity is generated by a side reaction. Finally, since all of the reaction products are charged, direct energy conversion techniques are available to convert particle kinetic energy directly to electricity. While overcoming the energy threshold for a nuclear reaction is just one

DISCLAIMER

of many technical barriers, we note that the threshold energy needed for the p-^{11}B reaction is far too high for thermonuclear ignition but readily achievable with beams.

Inertial Electrostatic Confinement

In the 1960's, P. Farnsworth (inventor of electronic television) invented a beam approach known as Inertial Electrostatic Confinement (IEC) and developed the first concepts (Farnsworth, 1966; Hirsch, 1967). Basically, the IEC concept uses electrostatic fields to inject multiple ion beams toward a central spot in a background plasma. Spherical symmetry allowed and encouraged ion recirculation. Electrons were introduced near the central spot to neutralize positive space charge and permitted ion densities high enough to achieve significant fusion rates.

However, beyond simple cancellation of space charge, Farnsworth also asserted that the convergence of ion beams and electrons toward a central spot could create not only a high-density interaction zone but an ion trap as well. Solving the coupled Vlasov-Poisson equations to account for particle inertia as well as space charge, he deduced that converging electrons and ions would not simply neutralize one another but would, instead, form multiple layers of alternating charge as the central focus is approached. Farnsworth associated these charged layers with configurations of potential "wells" that would be deep enough to trap high densities of energetic ions. Such a configuration would significantly amplify an ion's probability of undergoing fusion before succumbing to parasitic loss and ultimately lead to energy out > energy into beam.

The existence of these predicted deep potential wells is arguably the single key physics question that determines the long-term viability of the IEC concept. Demonstrating that such potential wells actually form near the focus of a spherical device and uncovering scaling laws governing their properties are needed to validate any IEC concept with potential for scale-up to power generation. Features of the highly non-equilibrium, non-neutral, high ion-current plasma created near the central focus of an IEC device are doubtless more complex than described by Farnsworth's initial analyses. (For instance, two-body scatterings tending to drive particle beams into Maxwellian velocity distributions were ignored.) However, as long as postulated charge-separation between ions and electrons is significant, Farnsworth's approach is self-consistent and remains highly plausible. Significant improvements to understanding arguably require input from experimental studies.

Experimental confirmation of the predicted deep potential wells has been encouraging but not definitive. R Hirsch (1968), working with Farnsworth, performed experiments with an ion-gun-injected IEC device and reported measurements of fusion reaction products emerging from a potential well in the center of the IEC sphere. By the late '60s, after Farnsworth's death, the IEC approach was generally abandoned by the fusion community in favor of much larger-scale thermonuclear projects, such as tokamaks. As hopes for quick technical success of large-scale fusion gradually faded, interest in the IEC approach revived. However, fundamental experimental work was not resumed until the 1990's when collimated proton measurements from a low-intensity IEC neutron source performed at UIUC confirmed the early Hirsch results (Gu and Miley, 1997 and Gu et al., 1997).

Long range thinking on IEC devices still focuses on prospects for power generation. (However, the revival of interest in IEC devices in the 1990's includes some innovative, near-term practical applications, such as low-intensity neutron sources, e.g. Miley and Sved, 1996 and Sved, 2000.) To date, IEC devices have successfully operated with deuterium (D) and tritium (T) generating nuclear reactions from D-D (Hirsch and UIUC) and D-T (Hirsch). Other reactions, such as D-^{3}He, have also been proposed by UIUC for investigation in the near term.

The New CB-IEC Concept

While acknowledging the significant contributions from previous work, in both technique and promise, practical hardware considerations kept ion beam intensities achievable in the early and current IEC devices to below what was needed to either fully investigate underlying physics or fully exploit the formation of potential wells. First, they employ electrode hardware concentrically positioned in ways that partially block ion trajectories. The unavoidable structural damage and potential for overheating force significant limits on ion flux in the central focal region and operating power. Second, they rely on spherical symmetry alone to produce converging beams. Angular momentum, added by the cumulative effect of a number of small scatterings and/or perturbations, may make it difficult to assure strictly convergent beams after multiple passes through the center. Finally, the needed injection of electrons from the cathode to the ion beams depends on parasitic ion collisions with the cathode grid and is essentially uncontrolled.

The Converging Beam Inertial Electrostatic Confinement (CB-IEC) concept proposed here introduces a new type of IEC device. A preliminary concept of a small (≤ 1 m) device is shown in Fig. 1. As in all earlier IEC concepts, electrostatic fields are used to accelerate ions toward a central focus. What is new, however, is that the CB-IEC abandons strict, overall spherical symmetry in favor of conical confinement volumes contained within a cylindrical high-vacuum chamber. The fundamental innovation is the introduction of two opposed converging accelerators to exert more extensive control over the ion beam dynamics. The electric fields within these accelerator sections serve to confine the ion beams within two facing conical volumes, induce recirculation, and maintain a strong focus on a central spot at the cones' common apex. In turn, the accelerating electrodes bounding the conical confinement volume permit control of the electric fields without imposing grids or other hardware directly in the paths of recirculating ions. To enable conditions favorable to the creation of deep potential wells, low voltage electrodes are located near the central spot for controlled injection of electrons into the converging ion beam by field emission. The conical geometry allows electron-emitting electrodes to be removed from substantial direct contact with recirculating ions and permits diagnostic instrumentation to be located much closer to the focal point (central spot) than is possible with any other existing IEC device.

Uses of the CB-IEC

The CB-IEC concept readily lends itself to progressive step-wise development. Initially proposed CB-IEC configurations are small-scale devices intended to confirm the existence of the predicted potential wells, study the laws governing their formation, and determine their effects on fusion reaction characteristics. Later on, more advanced configurations may be optimized for fusion rate and perhaps ultimately power generation. The initial example shown in Fig. 1

functionally illustrates the reaction-generating part of what could be an actual power-generating unit, contained within a vacuum chamber and outfitted as a physics experiment.

For overall flexibility, CB-IEC hardware is modular in construction and will support multiple design options as a test bed for investigating fundamental physics, computer code benchmarking, and exploring the potential for power generation. The range of accelerating voltages can be sufficiently broad as to permit fusion studies with multiple ion types. For example, initial experiments could employ deuterium and/or tritium ion beams to minimize voltage requirements. More advanced fuels such as ^{3}He, protons (p), and or ^{11}B could be introduced later in the same or, if needed, a more advanced device. Due to the modular design, capability for implementing direct energy conversion (as appropriate for a power-producing device) can be included as a subsequent step in development.

Depending on the outcome of experimental studies, the CB-IEC concept may itself present a pathway to practical IEC devices. A CB-IEC physics experiment that succeeds in generating deep potential wells may be readily adapted to a practical fusion-generating device, since high fusion rates follow as a consequence. Compared to spherical devices, CB-IEC cylindrical geometry is usable in a much wider range of engineering configurations and is capable of much more efficient waste heat rejection. The advanced neutron source described in Miley et al. (2000) is an example of one such application. As a final illustration of long term possibility, Fig. 2 shows a schematic "cartoon" of a CB-IEC power generating device utilizing the $p + {}^{11}B \rightarrow 3\,\alpha$ reaction and employing direct conversion of charged particle kinetic energy into electricity.

Conclusions

The predicted existence of deep potential wells as beams of ions and electrons converge on a central focus has been singled out as a key physics question that may determine the long-term prospects of achieving practical fusion power on a small scale. First proposed by Farnsworth in the 1960's, the existence of these "ion traps" have not been definitively confirmed or refuted.

The proposed CB-IEC concept offers a low-cost, low-risk technical development opportunity to initially explore basic physics issues and ultimately develop a wide range of engineering techniques associated with IEC-based nuclear fusion of light nuclei. While confirming new physics is at the core of the effort, technical risk for the investment of time and money is small. Even a negative result showing such devices have little potential for power generation is valuable for orienting future CB-IEC efforts toward other applications. On the other hand, a near-term CB-IEC device, such as proposed here, may well be capable of successfully demonstrating feasibility of the IEC concept as a power generator. In this case, opportunities to explore completely different approaches to nuclear power generation will abound.

References

1. Farnsworth, P. "Electric Discharge Device for producing Interactions Between Nuclei," U.S. patent 3,258,402, June 28, 1966.

2. Gu, Y. and Miley, G. H. "Overview of IEC Research," DOE Workshop on Innovative Confinement Concepts, UCLA, March 4-6, 1997.

3. Gu, Y., Miley, G. H., Ohinishi M., et al., "Potential Well Structure and Scaling Studies for the IEC," International Sherwood Fusion Theory Meeting, Wisconsin, Madison, April 27-30, 1997.

4. Hirsch, R. L. "Inertial-Electrostatic Confinement of Ionized Fusion Gases," J. App. Phys. *38*, pp. 4522-4534 (1967).

5. Hirsch, R. L. "Experimental Studies Of A Deep Negative Electrostatic Potential Well In Spherical Geometry", Phys. of Fluids, Vol. 11, Number 11, pp. 2486-2490, (1968).

6. Miley G. H and Sved, J. "The IEC, a Plasma-Target-Based Neutron Source," Invited Paper, International Conference on Radiation and Radioisotope Measurements and Applications '96, Raleigh, NC, 6-9 Oct 1996.

7. Miley G. H., et al., "Converging Beam Neutron Source for Driving a Subcritical Fission Reactor", This Conference, 2000.

8. Sved, J. "Evolution Of IEC Fusion Via Commercial Fusionstar Opportunities", This Conference, 2000.

* This work was performed under the auspices of the U. S. Department of Energy, Office of Technology Support Programs, under Contract No. W-31-109-ENG-38

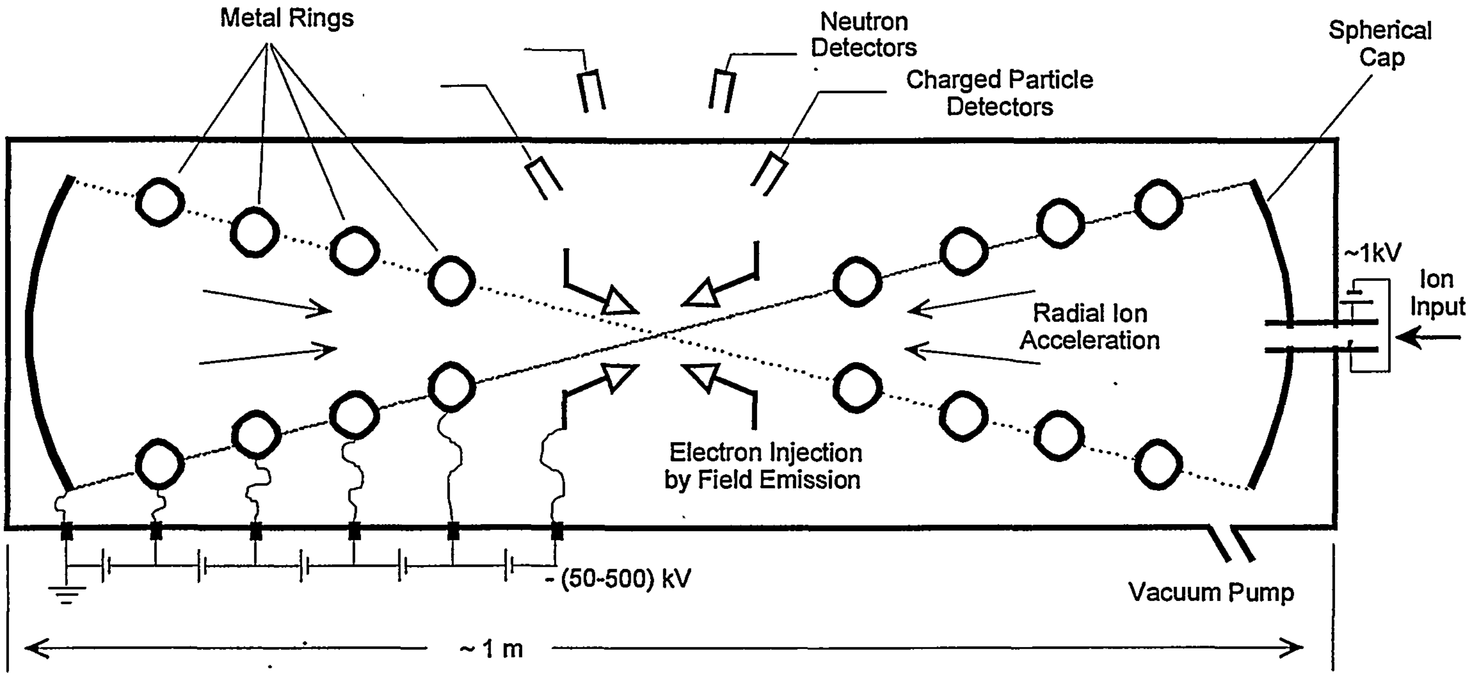

Fig. 1 Conceptual Design of a Cylindrical CB-IEC Test-Bed Device to Study the Physics of Fusion Generation

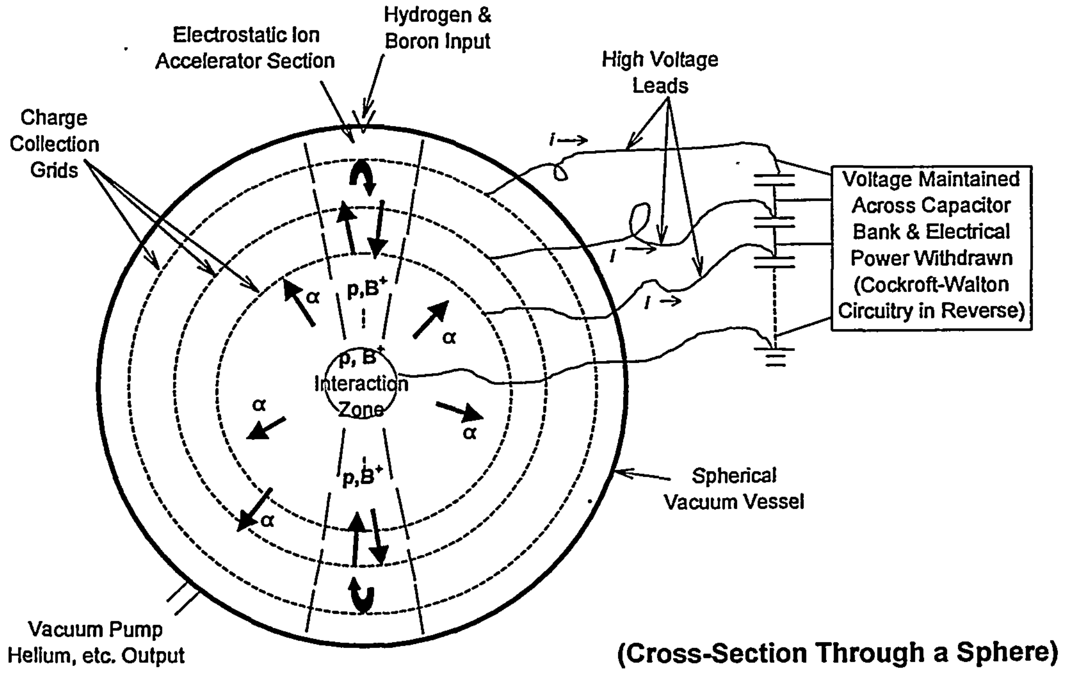

Fig. 2 Schematic of a Hydrogen-Boron CB-IEC Power Generator With Direct Energy Conversion