Progress in Inertial-Electrostatic Confinement Fusion

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A small, but active, worldwide research effort exists on inertial-electrostatic confinement (IEC) fusion. The potential for even small (< 0.5 m^3) IEC devices to produce high-energy (multi-MeV) neutrons and protons or electromagnetic radiation at levels useful for medical, environmental, and industrial applications motivates the research [1,2]. Active gridded IEC fusion research groups exist in the U.S. at the University of Illinois, the University of Wisconsin, Los Alamos National Laboratory, Marshall Space Flight Center, and Greatbatch, Ltd. In Japan, gridded IEC research takes place at Kyoto University, Kansai University, Tokyo Institute of Technology, Kyushu University, and Hitachi, Ltd. The University of Sydney conducts Australian IEC research. This article will primarily discuss U.S. IEC research, but will briefly cover the Japanese and Australian programs. Five U.S.-Japan IEC Workshops have been held at intervals of roughly one year. The two most recent were held at Kyoto University in March, 2002 and at the University of Wisconsin in October, 2002.

In gridded IEC fusion, which originated in the 1950's [3-5] and is the main subject of this article, a voltage difference on concentric, nearly transparent grids focuses charged particles radially in either spherical or cylindrical geometry. Ions accelerate down the electrostatic potential hill and convergence at the origin creates a high-density fusion core. IEC fusion possesses the key advantage that high voltages (50-200 kV) and, therefore, high ion energies can be achieved with relative ease. This facilitates advanced-fuel fusion, using pure deuterium or mixed deuterium/helium-3 fuel, for example, with reactions $D(d,n)^3He$, $D(d,p)T$, and $^3He(d,p)^4He$. In the ideal IEC operating mode, multiple passes of ions through the core enhance the effective ion current and the core density, increasing the fusion reaction rate. At the relatively high-pressures (2-10 mtorr) of most present IEC experiments, however, the bulk of the neutron and proton production stems from fusion reactions of streaming ions or charge-exchange neutrals with background gas and fusion of ions impacting ions embedded in the grid wires. Typical neutron and proton production rates are 10^7-10^8 s^{-1}. Table 1 gives approximate operating regimes for present U.S. devices.

Table 1: Operating Regimes for Present U.S. Gridded IEC Devices.

	Fuel	Upper Voltage (kV)	Typical Current (mA)	Typical Pressure (mtorr)
University of Illinois	D-D	80	10-100	1-10
Los Alamos National Laboratory	D-D	75	50	~10
Marshall Space Flight Center	D-D	80	30-50	5-10
University of Wisconsin	D-D D-^{3}He	160	30-60	0.5-3

The Fusion Studies Laboratory at the University of Illinois possesses the largest U.S. IEC research program, led by Prof. George H. Miley. The program operates three IEC devices, two spherical and one cylindrical, using D-D fuel. Experimental investigations focus on core convergence, multiple potential wells, pulsed operation, grid geometry, "star-mode" operation (ions and electrons flowing in spokes through the grid openings), and radio-frequency (RF) ion sources. Applications being studied conceptually include neutron calibration sources, space propulsion, direct energy conversion using D-^{3}He proton collimation by magnetic fields, neutral beam injection for IEC fueling, an IEC-driven sub-critical fission reactor, plus using D-D neutrons, D-T neutrons, and bremsstrahlung radiation to interrogate luggage and shipping cartons. Modeling tools include a Monte Carlo particle code (MCP) for cylindrical IEC devices and a Fokker-Planck code to explore core convergence.

The Fusion Technology Institute at the University of Wisconsin, led by Prof. Gerald L. Kulcinski, performs IEC experiments using D-D or D-^{3}He fuel, with the key objective of operating at high voltage and using D-^{3}He protons (~14.7 MeV) to produce radioisotopes for nuclear medicine. The initial focus centers on short half-life isotopes (2-20 minutes; ^{11}C, ^{13}N, and ^{15}O) for positron emission tomography (PET) scans. Present experiments use spherical grids in a cylindrical aluminum chamber. A photo of the plasma core appears in Figure 1. A water-cooled, stainless-steel, spherical chamber has just begun operation. Modeling is accomplished using MIEC, a 1-D Mathematica™ code that follows atomic physics effects for several generations of ion and electron current. A helicon ion source, under construction, will be used to explore low-pressure, converged-core operation.

The Los Alamos National Laboratory effort, led by Dr. Richard A. Nebel, explores a unique mode of IEC operation, the periodically oscillating plasma sphere (POPS) [6]. In the POPS mode, properly tuned radio-frequency waves would cause a Maxwellian plasma to oscillate radially, increasing the density in the core while maintaining a Maxwellian distribution. The present LANL effort explores instabilities for converging electrons in a gridded IEC device at very low pressure (10^{-5}-10^{-6} torr). Earlier LANL experiments explored ion-IEC operation.

The Marshall Space Flight Center IEC research program, led by Dr. Ivana Hrbud, has begun operation of a spherical IEC device that will investigate the potential of IEC fusion space propulsion. Another U.S. IEC experiment, at Greatbatch, Ltd., has just begun operation in a very large chamber (radius~1 m), and will explore direct electrostatic conversion in IEC devices.

In Japan, Prof. K. Yoshikawa of Kyoto University coordinates a large effort on IEC neutron sources for landmine detection. The research groups mentioned earlier all play a role; their leaders include Profs. E. Hotta, H. Matsuura, M. Ohnishi, and T. Tadokoro. The University of Sydney, Australia, led by Prof. J. Khachan, also participates in this research. Typical operation of the IEC experiments occurs at pressures of 2-10 mtorr in deuterium plasmas.

Alternative IEC concepts exist that aim to overcome the disadvantage of finite grid transparency, which leads to excessive grid heating at high power densities. These utilize either Penning-trap geometry [7] or magnetically trapped electrons as a virtual cathode [8].

In summary, U.S. IEC research programs explore neutron and proton production for detecting clandestine materials and generating radioisotopes, with longer range goals of electricity production and space propulsion. The Japanese and Australian IEC efforts primarily focus on neutron production for landmine detection. All groups use D-D fuel at voltages up to 80 kV for neutron production. The University of Wisconsin also uses voltages up to 170 kV to produce D-^{3}He protons. The Los Alamos National Laboratory effort explores the periodically oscillating plasma sphere mode of IEC operation. Researchers have made considerable improvement in IEC parameters during the past few years, and experiments presently hover at the edge of economic attractiveness.

References:

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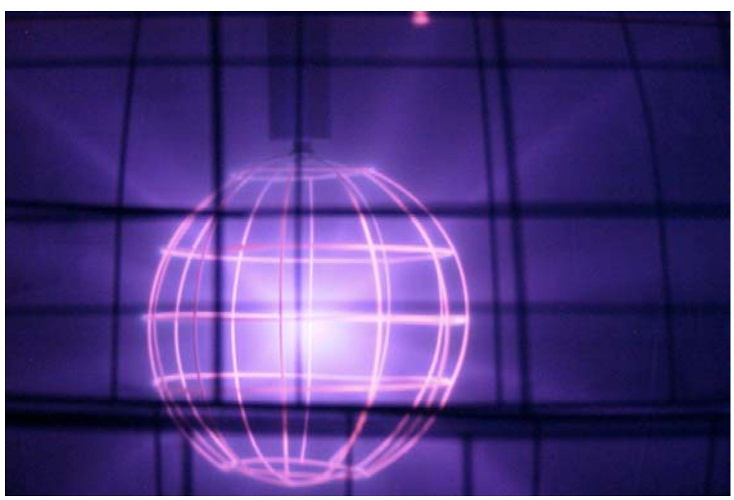

Figure 1: Plasma Core of the UW IEC Experiment.