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# OVERVIEW OF UNIVERSITY OF WISCONSIN INERTIAL-ELECTROSTATIC CONFINEMENT FUSION RESEARCH

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In Inertial Electrostatic Confinement (IEC) devices, a voltage difference between concentric, nearly transparent spherical grids accelerates ions to fusion-relevant velocities. The University of Wisconsin (UW) operates two IEC devices: a cylindrical aluminum chamber and a spherical, water-cooled, stainless-steel chamber, with a power supply capable of 75 mA and 200 kV. The research program aims to generate fusion reaction products for various applications, including protons for creating radioisotopes for nuclear medicine and neutrons for detecting clandestine materials. Most IEC devices worldwide, including the UW devices, presently operate primarily in a pressure range (1-10 mtorr) that allows ions to make only a few passes through the core before they charge exchange and lose substantial energy or they collide with cathode grid wires. It is believed that fusion rates can be raised by operating at a pressure where neutral gas does not impede ion flow, and a helicon ion source has been developed to explore operation at pressures of ~0.05 mtorr. The UW IEC research group uses proton detectors, neutron detectors, residual gas analyzers, and spectroscopic diagnostics. New diagnostic techniques have also been developed, including eclipse disks to localize proton production and chordwires to estimate ion fluxes using power balance.

# I. INTRODUCTION

## I.A. Principles of Gridded IEC Operation

Fusion concepts that rely on electrostatic focusing of ions into a dense core in spherical or cylindrical geometry are called *inertial-electrostatic confinement* (IEC) fusion systems.<sup>1</sup> Although the original concept relied upon beam-beam fusion reactions in the core, fusion reactions in present experiments occur mainly as beam or chargeexchange neutral interactions with background neutral gas. The limited core density stems from the finite transparency of the cathode grid and the relatively high operating pressure (1-10 mtorr) of the background gas, which lead to frequent charge-exchange reactions. The net result of these effects is that an ion makes only a few passes through the core before being lost to a chargeexchange collision with a neutral atom or an impact on the cathode grid. The ion orbits are shown schematically in Fig. 1, and the key physics effects appear in Fig. 2.

University of Wisconsin research focuses primarily on the D-<sup>3</sup>He and D-D reactions, shown in Fig. 3 with their fusion cross sections shown in Fig. 4, particularly applications of the resulting protons and neutrons. The D-T reaction is also shown, because some applications would benefit from the high energy of its neutrons or the high flux (~100 times peak D-D reaction rate) it provides due to its high cross section.



Fig. 1. Schematic view of the grid and core of a spherical IEC device, with some ion orbits shown.



Fig. 2. Dominant physics effects in present operating regimes for -80 kV cathode. Child-Langmuir electrostatic potential contours shown.

Fig. 3. Key fusion reactions for IEC applications.



Fig. 4. Fusion cross sections for the D-<sup>3</sup>He, D-D, and D-T reactions in the center-of-mass frame.

# I.B. Early IEC History

Salisbury, Farnsworth, and Hirsch invented various forms of the IEC concept many years ago.<sup>1,2,3,4</sup> Most present IEC devices remain essentially similar to the embodiment used by Hirsch, which appears in Fig. 5. In Hirsch's experiments, six symmetrically placed ion guns accelerated ions into the core.<sup>1</sup> Modern experiments replace the ion guns with a glow discharge, ionization of background gas by electrons from filaments, or a separate ion source.

#### I.C. Present Worldwide Gridded IEC Research Effort

Besides the UW work summarized in this paper, active gridded IEC research efforts are ongoing by several groups. Particularly active efforts are underway in Japan,<sup>5</sup> at Los Alamos National Laboratory,<sup>6</sup> and at the University of Illinois.<sup>7</sup> These 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 radioisotope production, neutron calibration sources, space propulsion, direct energy conversion using D-<sup>3</sup>He proton collimation by magnetic

fields, neutral beam injection for IEC fueling, an IECdriven sub-critical fission reactor, plus using D-D neutrons, D-T neutrons, and bremsstrahlung radiation to interrogate luggage and shipping cartons.



Fig. 5. IEC concept by R.L. Hirsch.<sup>4</sup>

#### I.D. Alternative IEC Concepts

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<sup>6, 8</sup> or magnetically trapped electrons as a virtual cathode. <sup>9</sup> Another interesting idea, the periodically oscillating plasma sphere (POPS), uses RF waves to create radial plasma oscillations of a Maxwellian plasma and periodically form a dense core.<sup>10</sup>

## **II. UW EXPERIMENTAL IEC FACILITIES**

One of the present Wisconsin IEC devices appears in Fig. 6, and a schematic view of it is in Fig. 7. It consists of a 91 cm diameter, 65 cm tall cylindrical aluminum vacuum chamber.<sup>11</sup> Experiments run steady-state within the limitations of chamber heating. Partly to circumvent this constraint, a spherical, stainless-steel, water-cooled chamber has recently been brought into operation.

A 450 l/s turbo pump pumps the chamber down to a base pressure of  $2 \times 10^{-7}$  torr. The inner tungsten-rhenium (W-Re) cathode is a 10 cm diameter coarse-grid sphere of 0.8 mm tungsten wire supported on a 200 kV vacuum feed-through. It has operated at input power levels

exceeding 8.5 kW at voltages ranging from -25 kV to -185 kV and at currents from 30-75 mA. A power supply provides up to 200 kV at 75 mA. The outer anode is typically a 50 cm diameter grid of stainless-steel wire. The wire can be biased with variable amplitude AC and DC voltages. Electronically controlled gas flow regulators adjust the fuel flow ratio and amount into the system. A remote controlled throttle on the turbo pump is used to control the operating pressure of the gas mix.



Fig. 6. The Wisconsin cylindrical IEC chamber.



Fig. 7. Schematic of the Wisconsin IEC cylindrical chamber.

The fusion reactions in the IEC chambers produce neutrons, protons, electrons, helium-4, tritium,  $\gamma$ -rays, and x-rays, depending on the fuel. The present diagnostic set detects 2.45 MeV D-D neutrons, 3.02 MeV D-D protons, and 14.7 MeV D-<sup>3</sup>He protons. The proton detector is an EG&G Ortec Ultra solid-state detector, has an active area of 1200 mm<sup>2</sup>, and has a depletion region thickness of 700 µm. This thickness allows both the 3 MeV protons and the 14.7 MeV protons to be detected simultaneously. A helium proportional counter neutron detector, placed 60 cm from the center, is used to detect the 2.45 MeV D-D neutrons. A residual gas analyzer (RGA) assesses neutral gas components.

# **III. RECENT UW RESEARCH**

#### III.A. Cathode Grid and High-Voltage Stalk

Extensive effort on the cathode grid and high-voltage stalk has allowed the UW IEC experiments to operate at voltages up to 185 kV, as shown in Fig. 8. An important feature of the design is the use of a boron-nitride (BN) stalk of 19 mm (0.75 in) diameter with a 3.18 mm (0.125 in) conducting rod (Mo) along the axis. The rod is held in place by ceramic cement filler.



Fig. 8. History of highest achieved voltage difference between the cathode and anode in the UW IEC devices.

In order to ensure uniformity of the cathode grid, several steps are followed: (1) a plastic model is created using rapid prototyping, (2) a rubber mold is made over the plastic model, (3) wax is poured into the mold, (4) W-Re wires are placed on the resulting wax form, (5) the wires are spot-welded, and (6) the wax is melted away at ~80 °C. Some of these steps are illustrated in Fig. 9.



Fig. 9. Steps in assembling the cathode grid: (a) rapid prototype model and rubber mold, (b) wires assembled on wax form created in the mold, and (c) spot-welded grid with wax melted away.

# **III.B.** Diagnostic Development

Several common plasma diagnostics are in operation on the experimental devices, as discussed in Sec. II. We have also developed a diagnostic to determine where the fusion reactions take place inside the chamber.<sup>12</sup> The diagnostic consists of three aluminum discs of different diameters, which are placed between the cathode and the proton detector. These eclipse the protons observed by the detector as shown in Fig. 10. The D-D protons get completely attenuated by the discs, while D-<sup>3</sup>He protons get shifted in energy, allowing a quantitative assessment of the number of protons passing through a disc.

Another diagnostic developed for these IEC experiments is the so-called chordwire.<sup>13</sup> An analysis of the power balance between the energetic ion flow into the chordwire or chordwires and the heat radiated allows an estimate of the flux of ions into the wire at a selected location, within limits set by heat transfer along the wire. A set of chordwires inside the IEC cathode is shown in Fig. 11.



Fig. 10. By placing solid discs between the cathode and proton detector, the location of D-<sup>3</sup>He and D-D reactions can be determined.<sup>12</sup>



Fig. 11. Planar set of chordwires inside the UW IEC device cathode.<sup>13</sup>

# III.C. Production of <sup>13</sup>N

Radioisotopes useful for nuclear medicine can be made with neutrons or protons. UW IEC experiments have focused on short half-life isotopes for positron emission tomography (PET) scans, particularly <sup>13</sup>N (10 min. half-life).<sup>14,15,16,17</sup> The <sup>13</sup>N is produced by protons from the D-<sup>3</sup>He reaction (see Fig. 3) via the reaction <sup>16</sup>O(p, $\alpha$ )<sup>13</sup>N. This is a variation of an idea initially suggested by Dawson.<sup>18</sup> Experiments in the UW IEC cylindrical device have produced proof-of-principle amounts of <sup>13</sup>N using water as a target in either a tube bank outside of the anode<sup>16</sup> or a stainless-steel tube serving as the cathode.<sup>17</sup> The radiator target appears in Fig. 12.



Fig. 12. Tube bank target for production of <sup>13</sup>N using 14.7 MeV, D-<sup>3</sup>He protons.<sup>16</sup>

# III.D. Hydrogen and Helium Implantation into Fusion Reactor First-Wall Materials

A critical issue for the development of inertial fusion power plants is the survival of the reactor first wall under radiation and particle bombardment from the fusion blast.<sup>19</sup> By replacing the cathode with a conducting sample target, the UW IEC device is used to study the effect of relevant H (D) and He fluences on W, HfC foam, and TaC foam.<sup>20,21</sup> The UW experiments investigate the effects of fluence and target temperature on steady-state implantation. As illustrated in Fig. 13, deuterium implantation has little effect beyond some grain growth due to heating, but helium implantation can form a high density of small holes and greatly modify a surface.<sup>21</sup>



Fig. 13. Left: D-implanted, W-plated TaC foam (830 °C, 6x10<sup>17</sup> cm<sup>-2</sup>); right: <sup>3</sup>He-implanted W-plated HfC foam (775 °C, 6x10<sup>17</sup> cm<sup>-2</sup>).<sup>21</sup> Similar results were obtained with polycrystalline W.<sup>20</sup>

# **III.E. Optimizing D-D Neutron Production**

A key goal of all IEC research groups is to increase neutron and proton production, which allows faster production of radioisotopes or better detection of clandestine materials. The history of neutron production in the UW IEC experiments is shown in Fig. 14. Recent UW efforts in this direction have included varying cathode size and geometry, cathode material, and the current in D-D plasmas.<sup>22</sup> The immediate goal of this optimization is the proof-of-principle detection of explosives using 2.45 MeV D-D neutrons.<sup>22</sup>

The anode-cathode voltage difference has a large impact on the fusion reaction rate, because the fusion cross sections are a strong function of energy in the 10-100 keV range as shown in Fig. 4. The fusion rate scales approximately linearly with current, indicating that beam-background and charge-exchange neutralbackground fusion reactions dominate, rather than the beam-beam reactions in a dense core that motivated the original IEC research.<sup>1</sup> The cathode size, geometry, and material had little effect. To make significant improvement in fusion reaction rates, therefore, it will probably be necessary to change the mode of operation from the present, relatively high-pressure regime to the low-pressure regime that requires a separate ion source.



Fig. 14. History of neutron production in the UW IEC cylindrical device.

#### **III.F.** Ion Source Development

The new UW spherical IEC chamber has recently begun operation and will be used initially for pure <sup>3</sup>He operation in conjunction with the independent ion source discussed in Ref. 23. This chamber appears in Fig. 15 along with the helicon ion source that will allow low-pressure operation. Challenging issues include the efficient extraction of ions from the helicon source plasma. Present UW IEC experiments run steady-state within the limitations of chamber heating. One use of the ion source will be in conjunction with pulsed operation to increase the ion current and explore core convergence issues.



Fig. 15. UW spherical IEC chamber with helicon ion source operating.<sup>23</sup>

# **IV. SUMMARY**

The University of Wisconsin inertial-electrostatic confinement fusion experiments presently focus on

- production of D-D neutrons for detecting clandestine materials,
- production of D-<sup>3</sup>He protons for creating radioisotopes for nuclear medicine,
- ion implantation for investigation of candidate fusion reactor first wall materials,
- invention of IEC plasma diagnostics, and
- development of an ion source for use in extending the operating regimes to low pressure for exploration of converged-core operation.

Recent achievements of the UW IEC experiments include

- operation at up to 185 kV, using a power supply capable of 75 mA and 200 kV,
- D-D neutron production at a rate of  $1.8 \times 10^8 \text{ s}^{-1}$ ,
- invention of the eclipse-disc and chordwire diagnostics,
- production of proof-of-principle amounts of <sup>13</sup>N,
- implantation of D and He into W, HfC, and TaC samples, and
- construction of a helicon He-ion source.

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