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October 1999

UWFDM-1119

Presented at the 18th Symposium on Fusion Engineering, Albuquerque NM,
25-29 October 1999.

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ABSTRACT

Advanced fusion fuels, D and ³He, have been successfully fused in an Inertial Electrostatic Confinement device at the University of Wisconsin. It is thought that this is the first known fusion of helium-3 with deuterium on a steady state basis. The detection of 14.7 MeV protons has confirmed the reaction of D-³He fusion, and has produced a continuous, charged particle flux in excess of 1.4×10^5 protons/s. Using the same device with D-D fuel a neutron rate of 2.2×10^7 was achieved. Operating parameters that affect the reaction rate are discussed.

INTRODUCTION

In the 1950's, research began on one form of purely electrostatic confinement, in which a voltage difference on concentric grids focuses charged particles [1-3]. This causes the ions to accelerate down the electrostatic potential configuration in spherical geometry, where geometrical convergence at the origin gives high density. The basic geometry is shown in Figure 1, which depicts a gridded inner cathode surrounded by a larger anode grid.

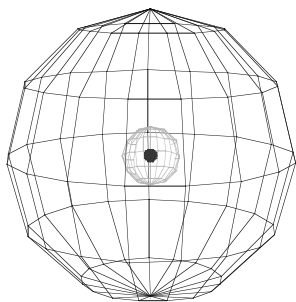


Figure 1. Core and cutaway view of the grids of the simplest IEC configuration.

The gridded IEC approach possesses the significant advantage that ions can be continuously accelerated to high fusion relevant energy (tens of keV) with relative ease. A key feature of IEC devices is that they allow the steady state burning of advanced fusion fuels, such as D-³He and potentially including even ³He-³He and p-¹¹B. Applications include medical isotope production, neutron activation, direct conversion electricity production, and ion propulsion for space flight [4]. The IEC device does not require any magnetic coils for plasma confinement, allowing it to be lightweight and portable. Since IEC configurations are not restricted to D-T fusion, there is also much less of a problem of neutron activation of the reactor structure. Other research groups in the U.S., Germany, and Japan are also working in this area [5].

THE WISCONSIN IEC EXPERIMENTAL FACILITY

The facility, Figure 2, consists of a 91 cm diameter cylindrical aluminum vacuum chamber, which is 65 cm tall. This is basically the same chamber used by T. Thorson et al. in earlier work [6-7].

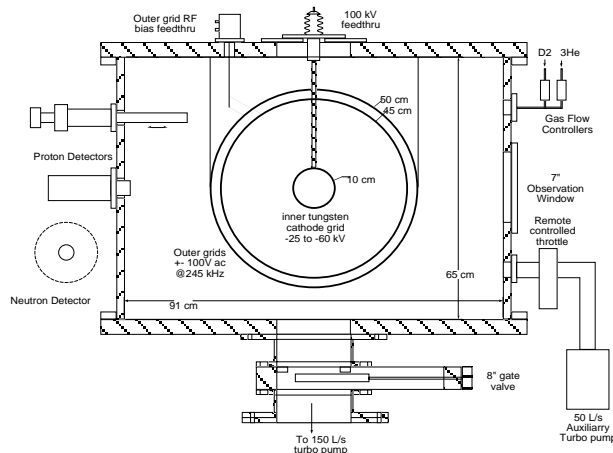


Figure 2. The Wisconsin IEC chamber.

A 150 l/s turbo pump pumps the chamber down to a base pressure of 2×10^{-6} torr. The inner cathode is a 10 cm diameter coarse grid sphere of 0.8 mm tungsten wire supported on a 100 kV vacuum feed-through. The tungsten construction of the inner grid has allowed operation at input power levels exceeding 8.5 kW without failure. Normal operating voltages range from -25 kV to -55 kV, 30-150 mA. Typical γ -ray radiation levels of 1 rem/hr have been measured at the tank boundary during higher power level runs. The power supply is capable of 75 kV at 330 mA. The outer anode grid is actually a pair of concentric grids 45 cm and 50 cm in diameter made of stainless steel wire. The outer grids are biased with variable amplitude AC voltage at 245 kHz through a vacuum feed-through. The variable AC bias is used to control the ionization of the fuel gas, which in turn controls the current to the cathode grid. This allows far better control of the ion current and produces a more uniform, higher level of ionization compared to previously used filament ion sources [6-7]. 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.

The various fusion reactions in the IEC device (D-D and D-³He) produce a steady stream of neutrons, protons, electrons, helium-4, tritium, gamma and x-rays. The diagnostics currently in use detect the 2.45 MeV neutron from the D-D reaction, and the 14.7 MeV proton from the D-³He reaction. The ratio of these detected particles can be used to characterize the ratios of the two fusion reactions. The proton detector used is a Canberra Passivated Implanted Planar Silicon (PIPS) Detector. It is mounted inside the chamber 46 cm from the center, on a water-cooled mount (Figure 3). This solid state silicon detector has an active area of 1200 mm² and a depletion region thickness of 700 μm. This thickness allows both the 3 MeV proton and the 14.7 MeV proton to be detected at the same time. A lead foil of thickness 236 μm and a 32 μm thick Al foil is placed in front of the detector to block the x-rays, which create noise in the detector. This procedure precluded the simultaneous measurement of both proton energies. A helium proportional counter neutron detector, placed 60 cm from the center, is used to detect the low energy neutrons from the D-D reaction. It is mounted outside the chamber in a container of polyethylene to thermalize the neutrons.

The neutron detector was calibrated by placing a Pu-Be source of 2.18 x 10⁶ n/s inside the chamber, and noting the activity on the counter. The proton detector was calibrated using a ²⁴¹Am alpha source to determine its efficiency and energy peak location. Both of these detectors, with their associated signal conditioners, provide a continuous readout of the count rate during the steady state operation.

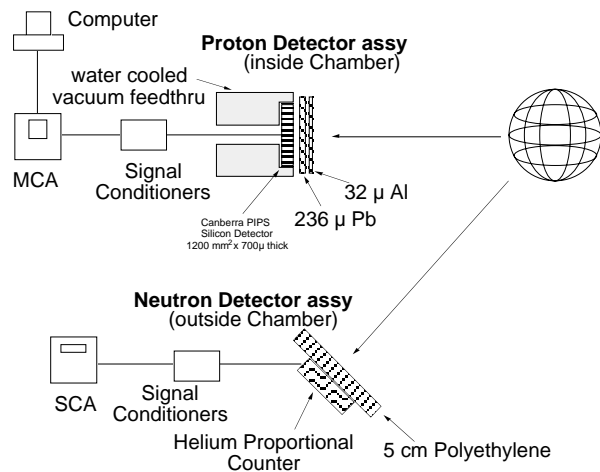


Figure 3. The proton and neutron detector systems.

Figure 4 shows the proton rate measured as a function of grid voltage, while holding the pressure and current constant. The rate increases with increasing voltage, as expected. Also apparent is the effect of the total fuel flow rate on the proton rate. Figure 5 shows the D-D neutron rate compared with the D-³He proton rate.

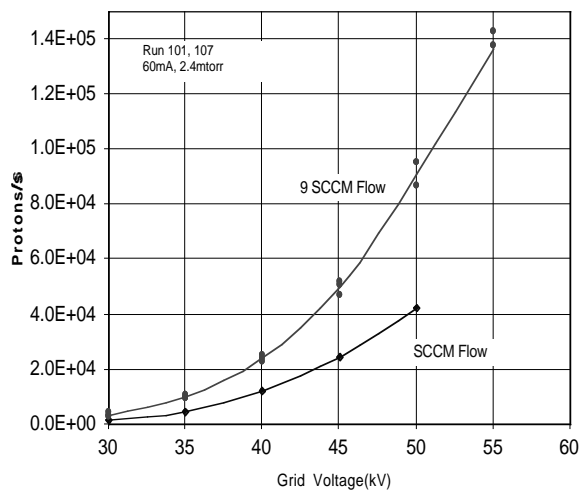


Figure 4. Proton production rates increase with grid voltage and fuel flow rate (SCCM = standard cubic centimeters per minute).

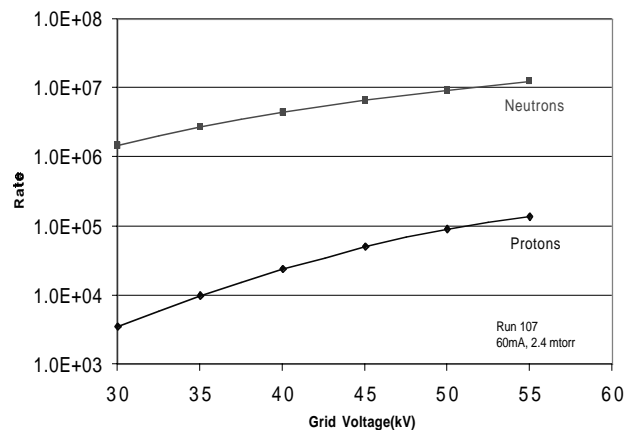


Figure 5. In the 30-55 kV range and with fuel densities of 2.4 mtorr, the neutrons from the D-D reaction exceed the protons from the D-³He reaction.

DISCUSSION

The operation of IEC devices can be separated into the two broad categories of long and short mean free paths (λ) with respect to charge exchange. If $\lambda \gg (r_o - r_i)$, where r_o is the outer grid's radius and r_i is the inner grid's radius, the average ion coming from the source region will reach the origin of the spherical grids at the energy of the potential well depth. The dominant physics in this regime will be the convergent-core mode originally postulated for IEC devices [1-3]. The reacting ions will have acquired nearly all of the voltage difference between the inner and outer grids, and the relevant fusion reaction rates are those of a spherically symmetric velocity-space distribution, labeled " $D^{+1} + D^{+1}$ " and " $D^{+1} + {}^3He^{+1}$ " in Figure 6.

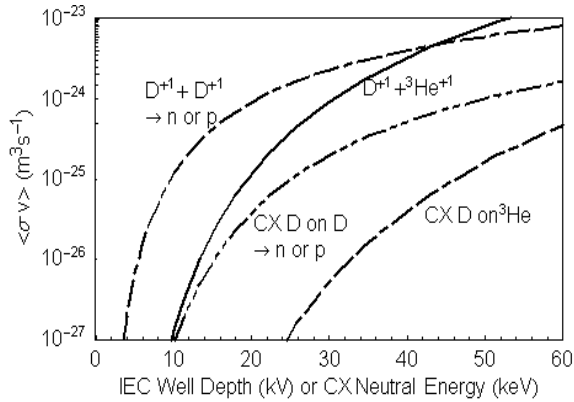


Figure 6. Fusion reactions in the Wisconsin IEC experiment.

If $\lambda \ll (r_o - r_i)$, the average ion will charge exchange after picking up only part of the voltage difference between the inner and outer grids, and the resulting neutral will collide with a very low energy background neutral at a much lower center-of-mass energy than in the convergent-core case. The fusion reaction rates in the charge-exchange mode are given by the curves labeled "CX D on D" and "CX D on 3He " in Figure 6. The curves show that in the 30-50 kV range, the convergent-core mode should give nearly equal D-D neutron and D- 3He proton production rates, while in the same energy range, the charge-exchange-dominated mode should give ~100 times higher neutron production than proton production. It is apparent from Figure 5 that, in the present mode of operation, the Wisconsin IEC device is charge-exchange dominated. Note, however, that calculating the total fusion-product reaction rate, Γ , requires weighting the fusion reaction rates by the appropriate densities throughout the chamber volume,

$$\Gamma = \int n_1 n_2 \langle \sigma v \rangle dV,$$

and the charge-exchange-dominated mode may thus produce more fusion products because of the large background density and chamber volume.

An experiment was conducted to determine the effect of the D- 3He flow ratio on the proton production rate. One might expect that a higher percentage of 3He would increase the proton production rate, but such was not the case as shown in Figure 7. Since the $D \rightarrow$ neutral 3He charge exchange cross

section is lower than for $D \rightarrow$ neutral D (Figure 6), the excess 3He should lower the overall proton production rate. When the flow ratio is $\ll 1$, the dearth of 3He atoms could account for the lower proton production rate.

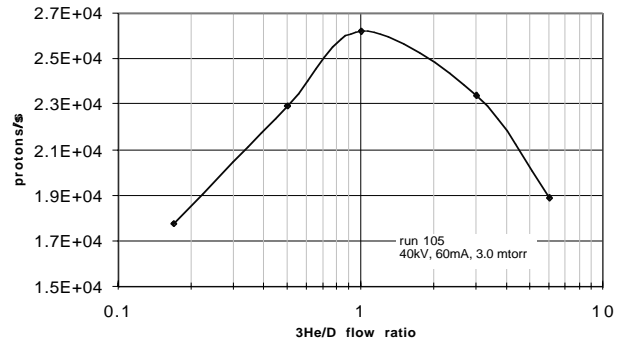


Figure 7. The maximum proton production rate occurs near the D to 3He flow ratio of 1.

SUMMARY

The University of Wisconsin's IEC facility at the Fusion Technology Institute has been successful at producing a steady state fusion reaction of D- 3He . This resulted in a production of 1.5×10^5 protons/s. Steady state D-D fusion resulted in a production rate of 2.2×10^7 neutrons/s. A number of experimental results have confirmed the dominance of charge-exchange ion flow conditions, characterized the optimal conditions of D- 3He fusion, and raised new issues to be studied.

ACKNOWLEDGEMENTS

The authors would like to acknowledge that this work was funded by the FINDS foundation, Dr. Walt Anderson, and the Grainger Foundation. The authors would also like to acknowledge discussions and advice from Dr. Tim Thorson and Professor Raymond Fonck, both from the University of Wisconsin-Madison.

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