

# Current Status of IEC (Inertial Electrostatic Confinement) Fusion Neutron/Proton Source Study

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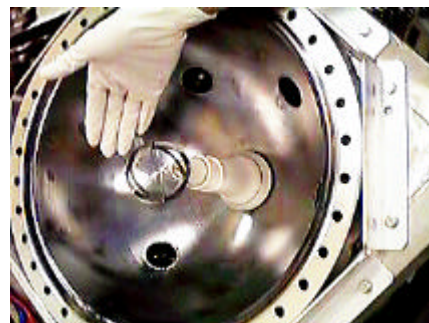
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**Abstract:** A compact fusion neutron/proton source, i.e., IEC (Inertial Electrostatic Confinement) fusion device is introduced with its principle, function, application and research history.

## 1. What is IEC?

An IECF (Inertial-Electrostatic Confinement fusion) device is an extremely compact, and simple configuration device as is shown in Fig. 1, running by electrical discharge on D-D/D-T/D-<sup>3</sup>He fuel gases. It basically consists of a hollow cathode at the center of a spherical vacuum chamber (serves as anode) filled with a fuel gas, and glow discharge takes place between them, thereby, produced ions are accelerated toward the cathode, and most of them penetrating the hollow cathode wire undergo fusion reactions through beam-beam collisions (see Figs. 2 and 3).

Actually, by this very simple device, as is shown in Table 1,  $5 \times 10^7$  neutrons/sec on D-D, and  $3 \times 10^7$  protons/sec on D-<sup>3</sup>He both in CW mode were achieved at University of Wisconsin [1,2], as well as much higher neutron production of  $7 \times 10^8$  neutrons/sec during peak of each pulse operated in the large-current (17 Amps, 100  $\mu$ sec, 10 Hz)



vacuum chamber : inner dia. = 340mm  
cathode grid (Ta) : inner dia. = 50mm  
outer dia. = 60mm  
thickness = 0.3mm

**Figure 1.** An IECF device, with a spherical hollow cathode in a spherical vacuum chamber as an anode

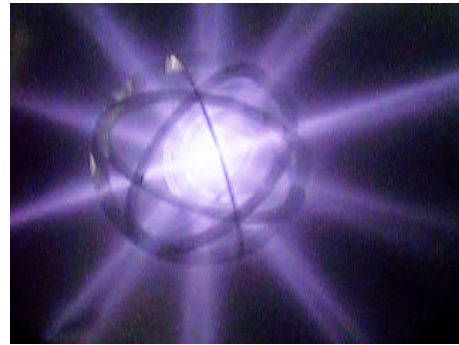
pulse mode achieved at UIUC [3].

It is to be noted that a fusion power station of 1 GW output power requires the fusion reaction rate as high as  $10^{21}$  neutrons/sec, and, on the other hand, an IEC produces only  $\mu$  watt ( $10^{-6}$  W) fusion power for  $10^6$  neutrons/sec D-D reaction rate.

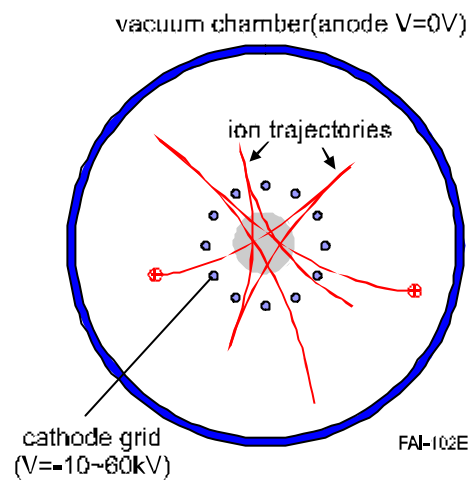
## 2. History

This concept of a fusion plasma was first proposed in 1950's aiming at the future fusion power plant, which is basically a beam-beam colliding fusion device with an extremely compact and simple configuration. Working with Fransworth, an inventor of the US, at ITT laboratories, Hirsch obtained record neutron output of approximately  $10^8$  neutrons/sec, and  $10^{10}$  neutrons/sec for D-D, and D-T, respectively, in 1967 from a gridded IECF device driven by six ion guns [4].

After a long pause of the research, a new concept came out at UIUC early in 1990's, primary involving use of a single wire-cathode grid and discovery of a new discharge mode without complicated ion guns, resulting in an potentially promising compact neutron source for the versatile industrial applications as is shown in Fig. 4. Since then, IECF researches based on this concept were carried out widely at various institutions in the world (see Table 1), leading to the current highest neutron yield as was already stated.



**Figure 2** An IEC plasma within the hollow cathode



**Figure 3.** Schematics of IECF

**Table 1** Present neutron and proton outputs by IECFs (as of March, 2001)

Intensity (n/s)	Institution
$5 \times 10^6$ (CW)	Kyoto University
$3 \times 10^5$ (CW)	Idaho Nuclear Engineering Lab.
$5 \times 10^6$ (CW)	Daimler Benz Aerospace-Space
$1 \times 10^7$ (pulse)	
$2 \times 10^6$ (CW)	University of Illinois
$7 \times 10^8$ (pulse)	
$5 \times 10^7$ (CW)	University of Wisconsin
$3 \times 10^7$ (CW, D- <sup>3</sup> He)	
$1 \times 10^6$ (CW)	Los Alamos National Laboratory
$6 \times 10^7$ (CW)	Hitachi

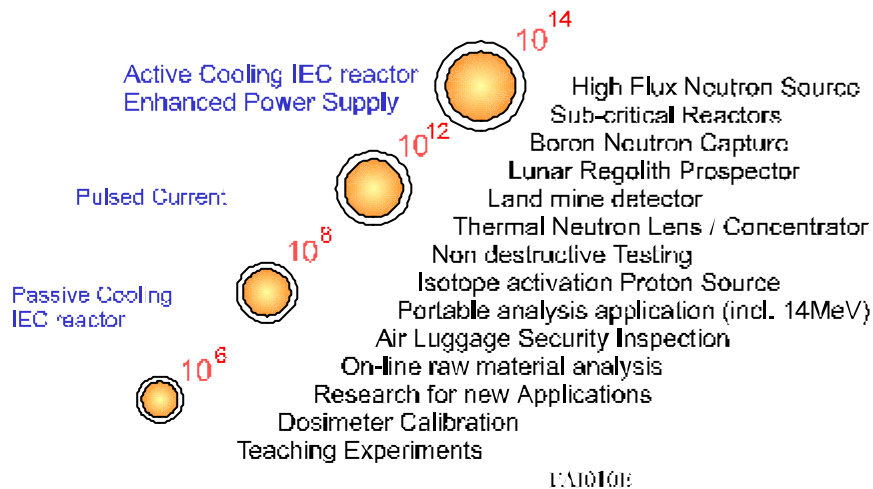
### 3. What are IECF applications?

An IECF device can provide versatile applications as is shown in Fig. 4, depending on the fusion reaction rate and mode (CW or pulse). Among major requirements of compact neutron/proton sources, positron emitter production for cancer detection, boron neutron capture therapy (BNCT) for cancer treatment, and anti-personnel landmine identification would be three urgent issues.

The first is the production of positron emitter of  $^{11}\text{C}$  (half life time of 20 min), and/or  $^{18}\text{F}$  (half life time of 110 min), both having so short half life time, they need to be produced in-situ in or very near the hospital where cancer detection is to be made. At present, relatively large, expensive proton accelerators are necessary for production of positron emitters, and thus, largely limiting the number of opportunities for cancer detection.

In the second BNCT, the nuclear reaction between  $^{10}\text{B}$  and neutron yields energetic alpha particles ( $>1.47\text{ MeV}$ ) and lithium, and thereby, alpha particle provides enormous energies in the very vicinity of the cancer, eventually to kill, as some special chemicals including boron tend to be concentrated in the local cancer regime.

With respect to the anti-personnel landmine identification, it is reported that the underground mines of more than 60 millions were buried in 62 countries, lethal remnants of armed conflicts over the past century, and abandoned landmines were/are killing or maiming about 26000 people every year. At present most of the humanitarian demining is done using conventional methods, such as metal detectors, podders, and sniffer dogs, making the procedure of destroying 60 million abandoned anti-personnel landmines (APL) very slow and dangerous. Innovative methods are thus needed in order



**Figure 4.** Applications of IECF devices as neutron and proton sources

to speed up the process [5].

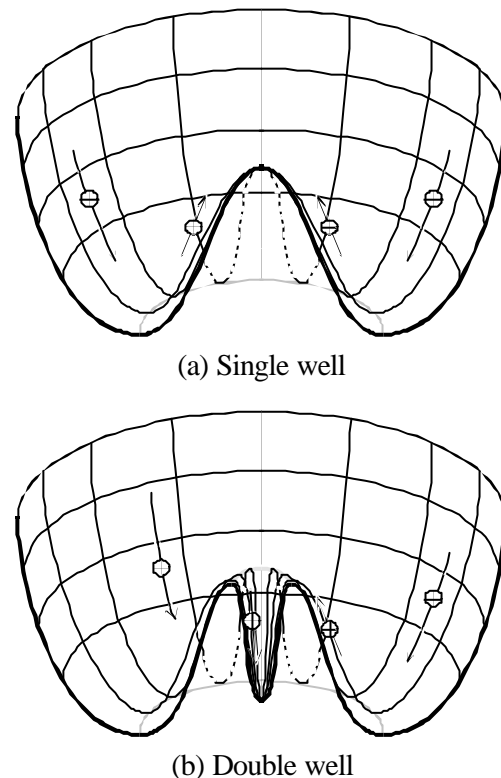
Since explosives of landmines include such as C, N, O, and Cl in specific fraction, interaction with neutrons, such as, neutron backscatter, and neutron-induced gamma rays could be made use of as innovative methods for identification. At present testing, a neutron emitter such as  $^{252}\text{Cf}$ , or AmBe of the intensity on the order of  $10^5$  neutrons/sec, or a D-T tube, i.e., a small accelerator-driven fusion device, are being used for neutron emitters.

Isotopes or tritium-included devices are, however, regarded not to be favorable from viewpoint of radioactive material diffusion, as well as the operation mode, i.e., pulse neutron irradiation mode.

From this viewpoint, an IECF device could be an ideal neutron source both from viewpoint of safety and pulse mode operation. Development of neutron yield improvement and also of diagnostics technique to identify landmines are the issues to be studied in the very near future.

#### 4. Research issues to be resolved

For further drastic improvement of the fusion reaction rate, however, it is essential to clarify the mechanism of potential well formation (see Fig. 5) predicted to develop in the central plasma core within the cathode, since potential well formation due to space charge associated with spherically converging ion beams plays a key and essential role in the beam-beam colliding fusion, i.e., the major mechanism of the IECF devices. Actually, this has been the central key issue for IECF researchers for the past 30 years, until the first successful direct measurement of the double-well potential profile in the IECF device through the laser-induced fluorescence (LIF) method at Kyoto University [6] in 1999 with an approximately 200 V dip at the center in the helium plasma core as will be described below.



**Figure 5.** Potential well formation in IECF device due to space charge associated with spherically converging ion beams

Many theoretical results so far predicted strongly localized potential well formation, and actually for the past 30 years, many experiments were dedicated to clarify this mechanism using, such as, electron beam reflection method [7], spatially collimated neutrons [4] or proton [8,9] profile measurements, or an emissive probe [10], as is seen in Table 2, but, neither seems to be perfectly conclusive in convincing that well does form.

**Table 2.** Chronological History of Potential Structure Research in Spherical Inertial Electrostatic Plasma Confinement

1930-1950	Inventions regarding electron focusing in cylindrical and spherical vacuum tubes.
1950-1960	Consideration of concentric spherical grids for production of nuclear fusion reactions by Lavrent'ev(Kharkov); Fransworth(ITT); Elmore, Tuck, & Watson(LANL).
1967	Hirsch's experiment predicting two or more virtual anodes(ITT).
1973	Potential well measurement by electron beam probe (Swanson, Univ. of Illinois).
1974	Measuring potential profile with radioactive electron source (Black, Pennsylvania State University).
1974	Theoretical predictions of potential and density distributions for realistic distribution functions (Klevans, Hu & Black, Pennsylvania State University; Cherrington et al, Univ. of Illinois).
1976	Studies of charged-particle distributions by microwave cavity technique (Gardner, Brigham Young).
1992	Potential well measurement via a collimated proton detector (Nadler, Univ. of Illinois).
1995	Light intensity measurement of IEC core size (Satsangi, Univ. of Illinois).
1995*	Theoretical prediction of transition from single to multiple potential wells (Ohnishi et al, Kyoto University).
1996	Ion flow and fusion reactivity characterization (Thorson, Univ. of Wisconsin).
1999*	Potential well measurement via collimated proton detector as a function of beam perveance (Miley & Gu, Univ. of Illinois).
1999*	Double well potential measurement by laser-induced fluorescence method (Yoshikawa et al, Kyoto University).
Conclusion	<p><b>Potential evidence for multiple potential wells:</b> 1)Neutron yield(Hirsch), 2)Spatial gamma &amp; neutron emission(Hirsch), 3) Theoretical predictions (Cherrington), 4) E-beam probe studies (Swanson), 5) Light intensity measurement (Satsangi), 6)Collimated proton yield (Miley &amp; Gu). <b><u>None of them produced definitive evidence, however.</u></b></p> <p><b>* But, finally,</b> 7)First and straightforward double well measurements by laser-induced fluorescence method through Stark effects (Yoshikawa et al, Kyoto University, 1999).</p>

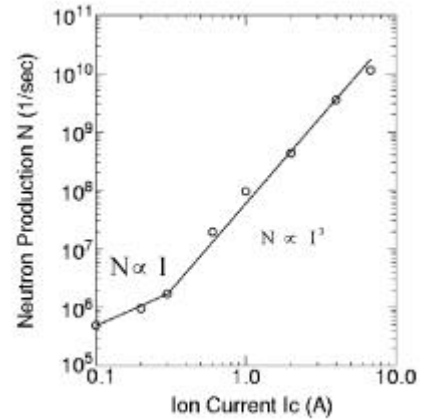
\* updated after Miley's original by Yoshikawa, Kyoto University, Jan., 2000

Recently some theoretical results predicting very promising new nonlinear regime for drastically enhanced fusion reaction rates in a relatively large current (perveance) region [11] (see Fig. 6) urgently call for diagnostics with higher degree of temporal and spatial resolution for verification, which was, unfortunately, not fulfilled by the conventional methods made so far.

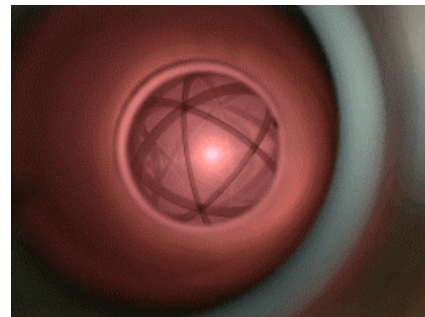
In order to cope with this urgent issue, we have adopted optical diagnostics by using the Stark effects, sensitive to the local electric fields, to the IECF device with a hollow cathode. Also to enhance S/N (signal to noise) ratio as well as to specify radial potential profile, we introduced the LIF method.

Consequently, we could have finally measured the double-well potential profile (see Fig. 11) with an approximately 200 V dip at the center for the first time in the helium plasma core (Fig. 7) in the IECF device.

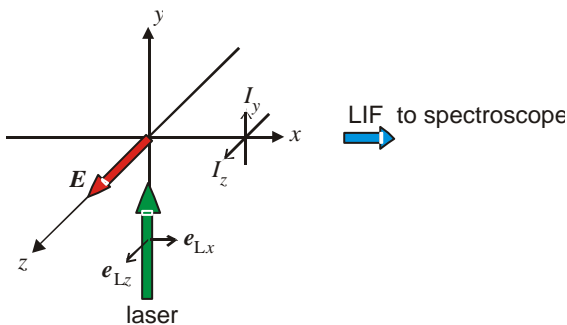
The LIF system consists of a Nd:YAG laser, a dye laser to produce 504.2 nm to cause forbidden transition through Stark and quadrapole transitions from  $2^1S$  atoms to  $3^1D$  states of HeI (see Figs. 8 and 9). The LIF (667.8 nm) is then observed (Fig. 10) to provide peak spatial profiles to result in the profiles of degree of polarization, from which spatial electric field, thus potential, can be obtained. The operation conditions were chosen as; He pressure of



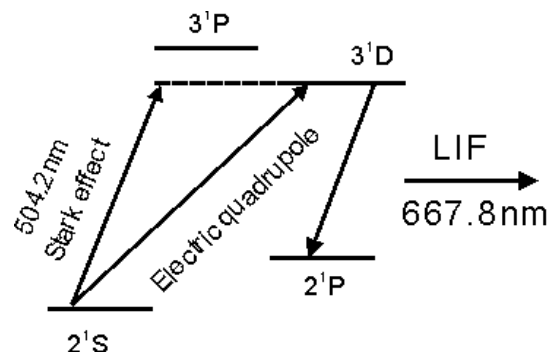
**Figure 6.** Neutron production rate as a function of ion current by numerical simulation



**Figure 7.** An helium IEC plasma core at the center of the hollow cathode for scanning



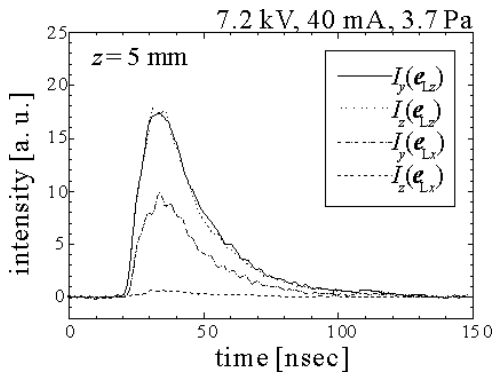
**Figure 8** Observation geometry for the LIF method



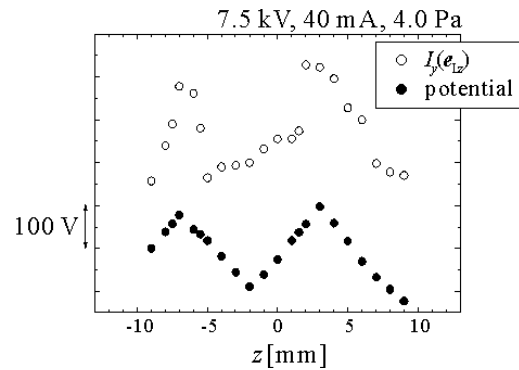
**Figure 9.** Energy diagram for the LIF process of HeI.

20-30 mTorr, cathode voltage of 7-11 kV, cathode current of 30-40 mA (regulated) to enhance the beam perveance.

With consideration of the sign of electric fields, and symmetry, the potential profile is calculated by integrating electric fields and is shown in Fig. 11 together with the representative QDP (quadrupole) component  $I_y(e_{Lz})$ . It is seen that the double well potential forms with an approximately 200 V dip in the potential profile. Also it clearly shows peak correspondence with the QDP spatial intensity, since the peaks in the QDP profile are thought to be due to the convergence of electrons with higher energy, i.e., corresponding to the potential peaks.



**Figure 10.** Time evolutions of the LIF polarization components at  $z = 5$  mm.



**Figure 11.** Potentail (black dots) and LIF QDP peak intensity (white dots) profiles along  $z$ -axis

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