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A portable neutron/tunable X-ray source based on inertial electrostatic confinement

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Abstract

Portable neutron sources are of strong interest for uses such as industrial neutron activation analysis and various medical research applications. The inertial electrostatic confinement (IEC) device under development at the University of Illionis is intended for such uses and also provides a tunable X-ray source (required reverse bias and added electron emitters). The IEC operates as an accelerator plasma-target type device, and when filled with deuterium presently provides $10^7 \sim 2.5$ MeV D–D fusion neutrons/s. D–T fill gas gives 14 MeV neutrons, with rates about 100 times that of D–D, but with the added complication of handling low levels of tritium. Research on higher yield versions now under development is described. Still, in the interim, the IEC, due to its compactness, portability, simplicity and flexibility offers a unique portable neutron/X-ray source.

1. Introduction

The University of Illinois IEC uses a transparent cathode grid inside a vacuum vessel (anode) in a spherical configuration or a hollow cathode-anode configuration in cylindrical geometry [1,2]. These two geometries are illustrated in the photographs in Fig. 1. Their construction is illustrated in Fig. 2. The current spherical unit employs a single grid for simplicity, although multigrid versions offer somewhat better efficiency. Likewise, the cylindrical unit is based on the simplest electrode design and arrangement for ease of construction.

Typical operating parameters are given in Table 1. A wide range of geometric dimensions are possible. However, once the electrode spacing is selected, the voltage and pressure are fixed by the Paschen breakdown relation [3].

The spherical unit offers a "point-type" source with an off-the-shelf steady-state rate of 10^7 2.5 MeV D–D neutrons/sec (n/s) and possibly up to 10^8 D–D n/s in 50 Hz pulsed versions. The cylindrical version offers similar neutron rates, but provides a "line-like" source extending up to ~ 25 cm length. The latter configuration is most advantageous for applications requiring uniform coverage of broad surface areas, e.g. analysis of materials

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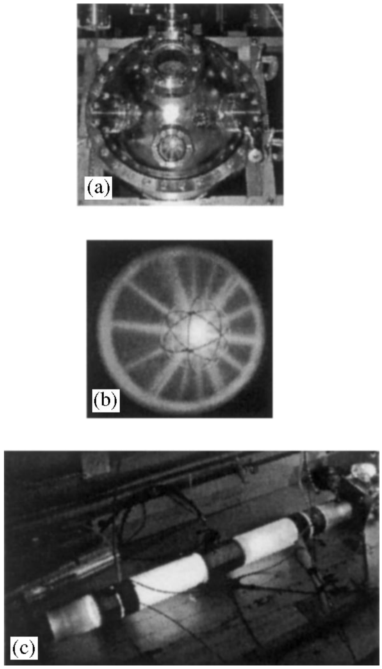

Fig. 1. (a) Photograph of a spherical unit in operation. The grid and dense core region, just visible in the port opening, is enlarged in the photograph in (b). (c) A photograph of the cylindrical IEC in operation. The dark ring structures are the electrodes.

carried on a conveyor belt. Versions of both units are now produced commercially by Daimler-Benz Aerospace Corporation (DASA) [4].

2. Tunable X-ray source

Another important advantage of the IEC, especially the smaller laboratory units, is that it can be converted to an attractive tunable X-ray source with minimum alteration of the apparatus [5]. X-ray operation involves reversing electrode polarities and adding electron emitters at the vessel ports as shown schematically in Fig. 3.

The resulting electron Bremmstrahlung radiation has a broad energy spectrum extending up to the applied voltage ($\sim$ 10–60 kV). A typical measurement corresponding to an applied voltage of 30 kV is shown in Fig. 4. A FWHM of about 15 kV is obtained with a peak intensity at about 20 kV. This makes possible some small-scale laboratory X-ray experiments that would otherwise necessitate traveling to a synchrotron-type "light" source.

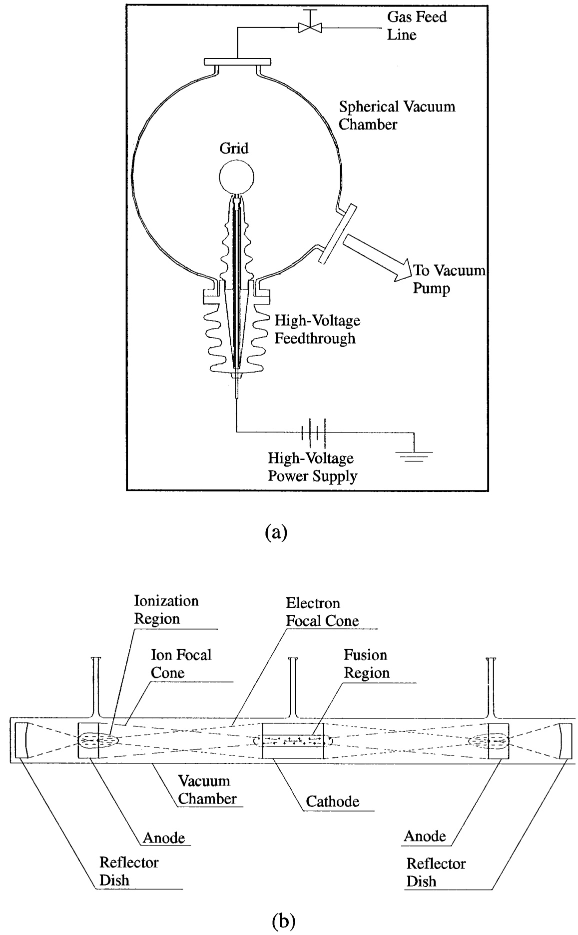

Fig. 2. Schematic of the cross section of (a) a spherical IEC unit showing the grid and high voltage insulator structure and (b) a sketch of the cylindrical device and electrode structure.

Table 1
Typical operational parameters

Parameter	Value
Pressure	0.1–5.0 mTorr
Voltage	50–100 kV
Device diameter	5–100 cm
Input power	0.1–10 kW

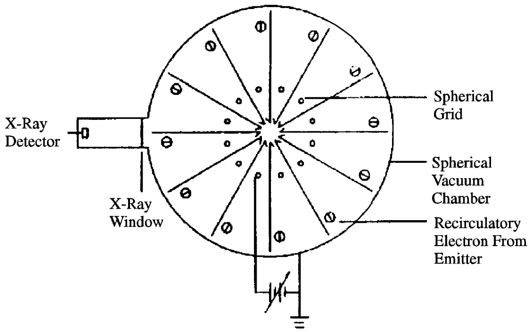

Fig. 3. Cross section of an IEC modified for X-ray production.

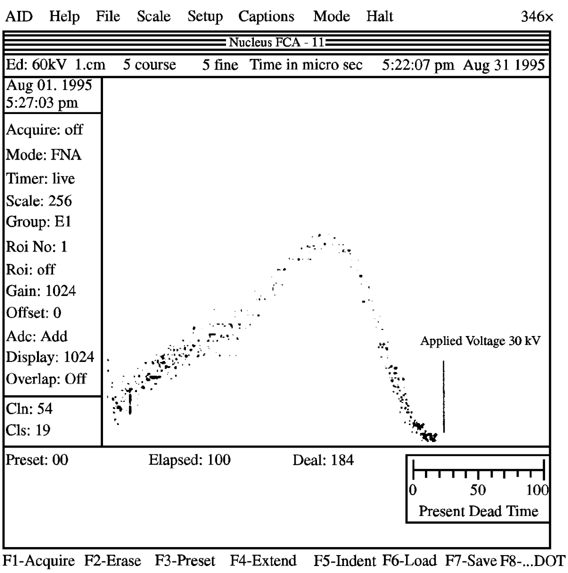

Fig. 4. Measured X-ray energy spectrum.

3. Pulsed operation

Pulsing the IEC is attractive for higher neutron yields since the neutron yield scales as the current to a power ≥ 2. Thus, high peak currents during pulsing provide efficient use of the input power and allow a compact power supply. Both the spherical and cylindrical versions have been operated with a fast switched capacitive-type pulsed power supply [6]. Pulse lengths of order of 50 μs were employed because this time exceeded the ion cathode-anode recirculation time. In this mode, time average neutron rates of $\sim 10^8$ D–D n/s are feasible at about 50 Hz while the extension to even higher yields appears possible, current research on higher yield units is focused on the RIDO concept [7] briefly described next.

4. The RIDO concept

The RIDO (resonant ion driven oscillation) concept is based on a synchronization of the natural ion recirculation frequency in the IEC system with the injection of new ions towards the inner core. Newly generated ions converge towards the center at the same instant the recirculated ions arrive at their turn-around points, superimposing particle currents towards the inner core of the device. As a consequence, very large peak densities are expected to form at the ion transit frequency ($\sim$ 1–10 MHz), providing for a high averaged fusion generation rate. Such a scheme should also reduce the level of thermalization due to the reduction in counter-streaming ion collisions (since all ions move in a spherical shell). A schematic of the experimental setup for the RIDO device employed for experiments now in progress ia shown in Fig. 5.

With this arrangement, electron emitters are added along with two guide grids such that electrons are confined to a volume near the wall, producing an intense ion source there. The inner guide grid (middle grid) serves as a gate such that when the potential on it is suddenly dropped, ions are accelerated toward the center by the cathode grid. This

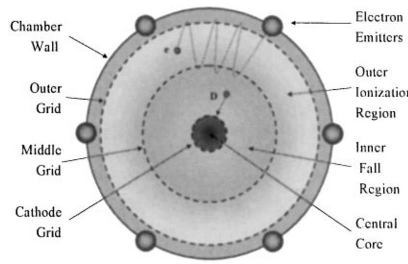

Fig. 5. Arrangement for the RIDO experiment.

gate or control grid is pulsed at the desired frequency to match the ion transit time. This provides a bunching of ions and increases the ion beam density in the center fusing core.

5. Plasma structure and scale-up issues

An understanding of the underlying plasma-electrodynamic physics of the IEC is needed to evaluate its potential for scale up to higher neutron rates. The spherical version will be used here to explain the basic phenomena. In it, the cathode grid extracts and accelerates ions created in a plasma discharge created between it and the anode (vacuum vessel wall). As these ions converge in a small volume around the center of the sphere, a virtual anode is created which accelerates and focuses electrons into a yet smaller concentric volume.

Consequently, as illustrated conceptually in Fig. 6, these converging electrons develop a negative potential well within the positive "hill," which traps ions, greatly reducing energetic ion leakage and creating an intense region of beam–beam fusion reactions. A number of attempts to measure this potential structure had been tried earlier by various researchers without success. However, Gu recently achieved a measurement using a collimated proton detector to observe the source rate profile of D–D protons across the central core region [8]. Some of his results are shown in Fig. 7. A triple peak profile, indicative of a potential "double well" such as shown in Fig. 7, is observed to occur at higher currents ($\geq$ 40 mA). The ability to scale-up to yet higher neutron fluxes requires generating a larger and deeper ion trap, which in turn involves controlling ion energies and angular momentum while increasing ion currents. The possibility of instabilities disrupting the trap is one of the key issues to be studied. Since the scale-up involves a velocity-space phenomena, from a fundamental physics point of view, higher neutron rates do not require larger unit sizes. However, a modest size increase of the total system dimensions is required to accommodate increased cooling and radiation shielding requirements.

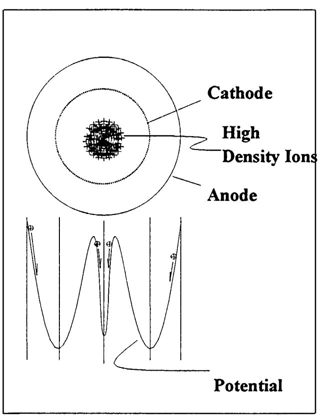

Fig. 6. Schematic illustration of the potential well structure created in the IEC by convergence of the ion beams to form a dense central core which in turn accelerates and focuses electrons creating a "double-well" structure.

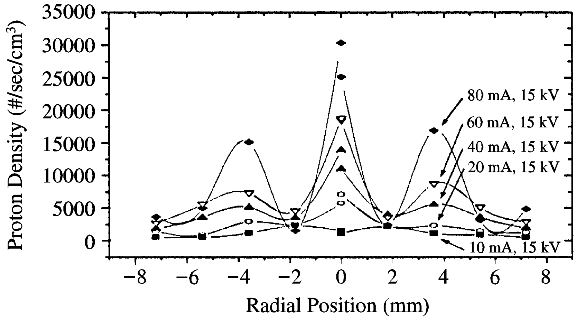

Fig. 7. Measurement of the potential-well structure using a collimated D–D proton detector.

6. Conclusions

The IEC devices described here represent a new class of neutron sources based on ion-beam–plasma-target fusion. Both employ special configurations to create a dense fusing region by focusing or concentrating the beam ions. In addition, energy efficiency is achieved by used of a potential structure such that ions are trapped and recirculated. These features are similar to those incorporated in fusion power experimental units, but the IEC is unique in using electrostatic fields alone without the complication of magnetic fields. The configurations use ion dynamics, i.e., ion inertia, to obtain confinement without violating limits imposed by Earnshaw's theorem [9]. Key benefits of this approach in the present devices include simplicity, compactness and long lifetime. Since these represent "first generation" designs, further improvements can be expected as research progresses.

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References

[1] G.H. Miley, J. Javedani, R. Nebel, J. Nadler, Y. Gu, A. Satsangi, P. Heck, An Inertial Electrostatic Confinement Neutron/Proton Source, in: Malcolm Haines, Andrew Knight (Eds.), 3rd Int. Conf. on Dense Z-pinches AIP Conf. Proc., vol. 299, AIP Press, New York, 1994, pp. 675–689.

[2] G.H. Miley, J. Brachytherapy Int. 1 (1) (1997) 111.

[3] G. Miley et al., IEEE Trans. Plasma Sci. 25 (4) (1997) 733.

[4] J. Sved, Trans. ANS 77 (1997) 504.

[5] Y. Gu, G.H. Miley, Bult. APS 11 (1995) 1851.

[6] Y. Gu, P. Heck, G. Miley, 1995 IEEE Int. Conf. on Plasma Sci., IEEE Conf. Rec. 95CH35796, 1995, pp. 266–267.

[7] B. Jurczyk, Y. Gu, G. Miley, Proc. 39th Annual Meeting Division of Plasma Physics, Pittsburgh, PA vol. 42 (10) November 17–21, 1997, p. 1818.

[8] G.H. Miley, Y. Gu, M. Ohnishi, Y. Yamamoto, M. Hasegawa, K. Yoshikawa, Potential Well Structure and Scaling studies for the IEC. Int. Sherwood Fusion Theory Conf. Madison, Wisconsin, April 23–26, 1997.

[9] S. Glasstone, R. Lovberg, Controlled Thermonuclear Reactions: An Introduction to Theory and Experiment, D. Van Nostrand, New York, 1960, p. 47.