Research and Development of a Compact Fusion Neutron Source for Humanitarian Landmine Detection

K. Yoshikawa 1), K. Masuda 1), Y. Yamamoto 1), T. Takamatsu 1), H. Toku 1), K. Nagasaki 1) , E. Hotta 2), K. Yamauchi 2), M. Ohnishi 3), H. Osawa 3)

1) Institute of Advanced Energy, Kyoto University, Uji, Kyoto, Japan
2) Tokyo Institute of Technology, Yokohama, Japan
3) Kansai University, Osaka, Japan

e-mail contact of main author: kiyoshi@iae.kyoto-u.ac.jp

Abstract. Research and development of the advanced anti-personnel landmine detection system by using a compact discharge-type D-D fusion neutron source called IECF (Inertial-Electrostatic Confinement Fusion) are described. Landmines are to be identified through increased backscattering of neutrons by the hydrogen atoms, and specific-energy capture γ-ray emission by hydrogen and nitrogen atoms with thermalized neutrons in the landmine explosives. For this purpose, improvements of the IECF device were studied for drastic enhancement of neutron production rates of more than 10^8 n/s in pulsed operation including R&D of robust power sources, as well as analyses of envisaged detection system with multi-sensors in parallel in order to show promising and practical features of this detection system for humanitarian landmine detection, particularly, in the aridic, or dry Afghanistan deserted area, where the soil moisture remains between 3-8 %, which eventually enables effectively detection of hydrogen anomaly inherent in the landmine explosives. In this paper, improvements of the IECF are focused to be described.

1. Introduction

It is reported that in the world, more than hundred of millions of landmines were abandoned in more than 60 countries due to the long years conflicts at various places. Afghanistan is one of such countries, where many citizens are still being killed or maimed by many abandoned landmines and unexploded objects (UXO). They are thus needed to be urgently cleared up for the reconstruction of the country, particularly, in the vicinity of residential areas (Fig. 1) [1].

At present most of the humanitarian demining is being done using conventional methods, such as metal detectors, and sniffing dogs, making the procedure of clearing abandoned landmines very slow and dangerous. To make matters worse, modern landmines contain very little metal of only a few grams (almost all plastic landmines) which makes detection procedure by the metal detectors extremely difficult. Therefore, innovative and efficient methods are needed to be developed as soon as possible in order to speed up the clearing.

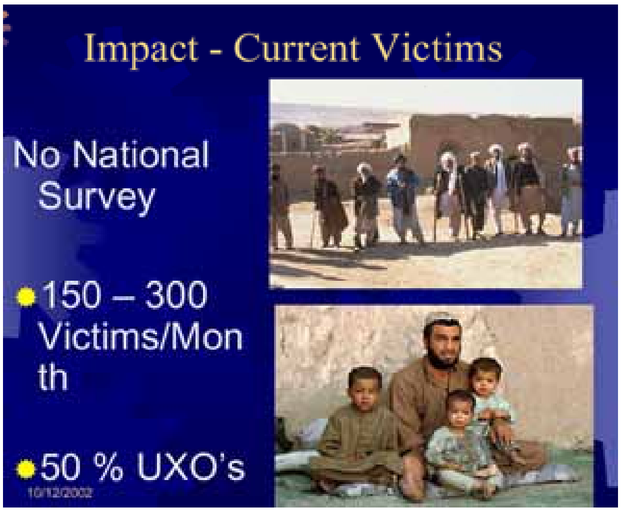


FIG. 1. Current victims in Afghanistan as of Dec., 2002 [1].

In this context, in 1999 IAEA, Vienna initiated a CRP(Coordinated research program) on "Application of Nuclear Techniques to Anti-personnel Landmines Identification"

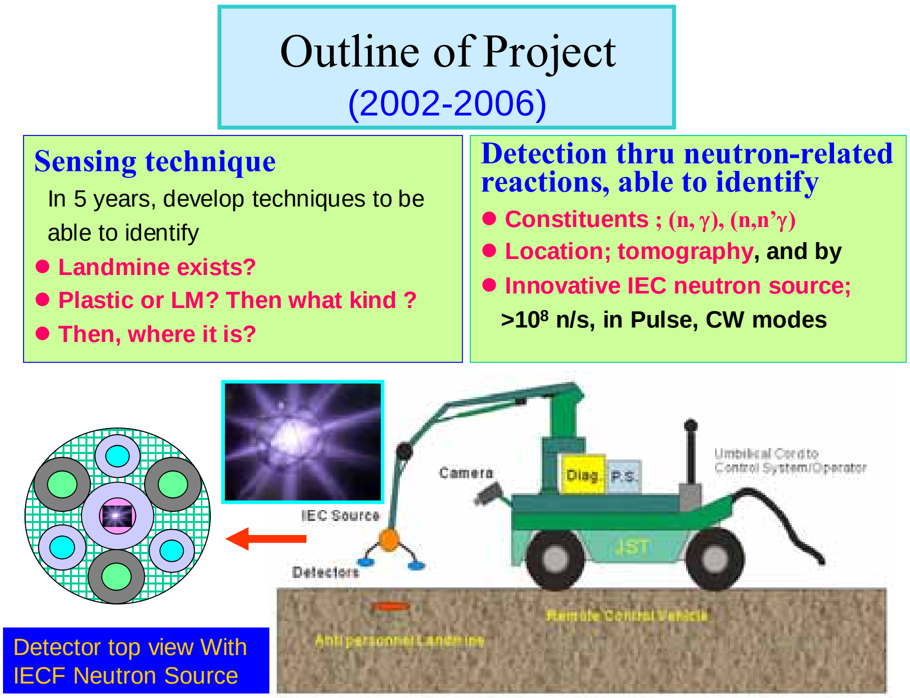


FIG. 2. Outline of project by nuclear techniques.

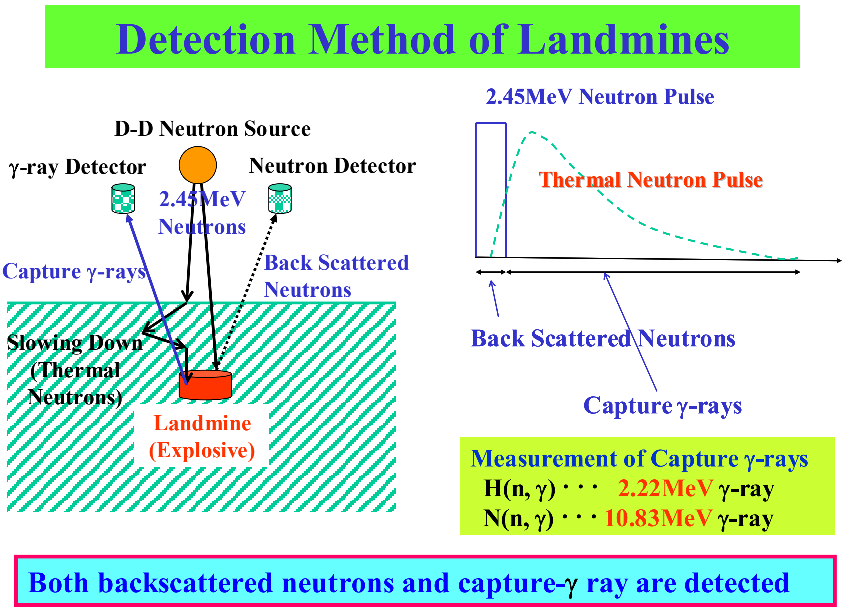


FIG. 3. Detection method of landmine by neutrons.

and ended in 2003, where two methods, i.e., (1)Methods to find buried objects (X-ray backscatter, Neutron backscatter, Positron annihilation Compton scatter imaging(PACSI)), and (2)Methods to identify composition of buried objects (Neutron-induced γ-rays, and Backscattered neutrons) were mainly studied and made preliminary experiments, with the results of making issues clear to be further studied in the future [2-4].

One of the critical issues is the development of the high performance D-D neutron source which can produce neutrons of more than 10^8 n/s in pulsed operation to provide substantial nuclear reactions with explosive components under the ground in the compact, simple configuration with almost free maintenance in the deserted area of Afghanistan where the operation environment is very severe. In 2002, Japan made promise to help Afghanistan resume its old peaceful country from various aspects, and humanitarian landmine detection and clearance is one of such programs. Accordingly, we started research and development of the landmine detection system through the nuclear techniques for sensing and identifying the explosives of the buried landmines applicable to the very dry Afghanistan deserted area (Fig. 2) while taking into consideration of the IAEA activities, and BNCT (Boron neutron capture therapy) techniques being developed at Kyoto University for cancer treatment (Fig. 3).

2. Current Status of IECF Research

An Inertial-Electrostatic Confinement Fusion (IECF) neutron/proton source is an extremely compact device of simple configuration as is shown in Figs. 4 and 5. It basically consists of a transparent hollow cathode at the center of a spherical vacuum chamber (serves as an anode) filled with a D_2 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 or beam-background gas collisions.

Due to advantages of its compactness and robustness, the IECF device can provide versatile applications, including anti-personnel landmine detection. The IECF device could be an ideal neutron source for this application from the viewpoint of both safety and long lifetime, compared with conventional neutron emitters, such as radioactive isotopes ^{252}Cf, and a D-T tube, i.e., a small accelerator-driven fusion device.

Taking again into consideration of the Afghanistan environment, we have developed an extremely compact IECF device (Fig. 5, 200 mm in diameter) with a titanium getter pump as a main exhaust pump and D_2 gas feed to endure the vibration when it is installed on the remote-controlled vehicle [5]. Also, a high voltage power supply system was developed [6].

By this very simple device based on the glow discharge, we achieved neutron production rate (NPR) of 2.0×10^8 neutrons/sec on D-D for –51 kV, 7.3 A in a pulsed operation as shown in Fig. 6 in 2003 [6], which

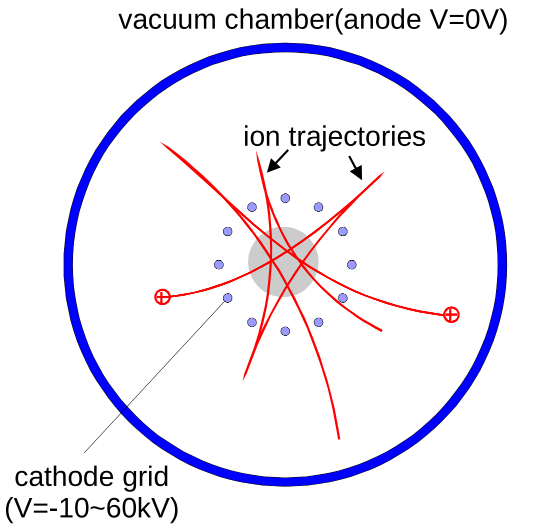


FIG. 4. An IECF configuration with a hollow cathode.

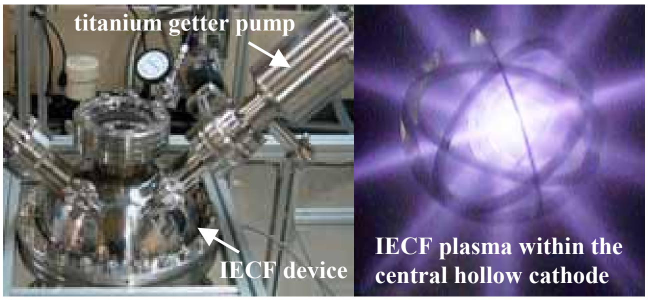


FIG. 5. An IECF neutron source, and a plasma within the central hollow cathode (star mode).

was the original target value for –90kV, 10 A to be achieved in FY2004 we set at the initiation of this project. In order to make efficient landmine detection, however, it is essential to enhance the NPR as high as possible to shorten the detection time.

Recent experiments for identifying ion energy distribution by making use of the Doppler shift spectra from charge-exchanged energetic hydrogen atoms clearly show the existence of large fraction of low energy components, which is inherent in the ion production by the glow discharge as is seen in Fig. 7 [7, 8]. In order to improve the NPR drastically, it is essential to produce ions in the very vicinity of the anode, i.e., vacuum chamber to provide full energies to the ions. It is to be noted that the fusion cross section for the head-on collision in the IECF

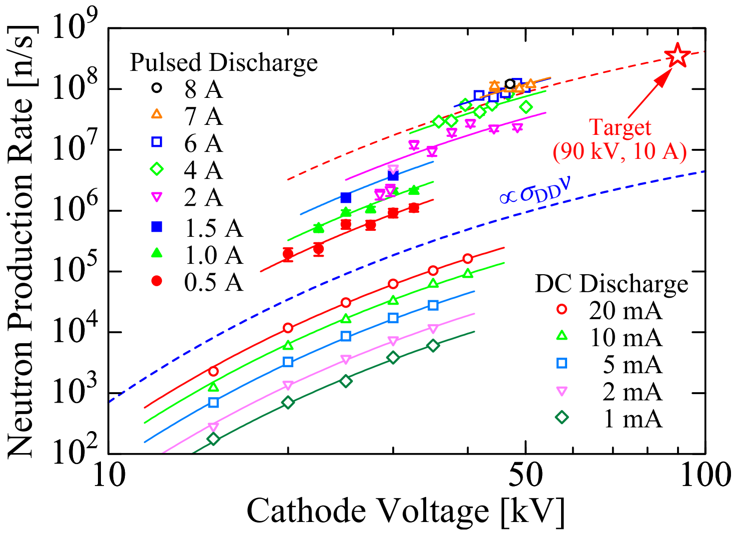


FIG. 6. Relationship between neutron production rate and cathode voltage at constant current.

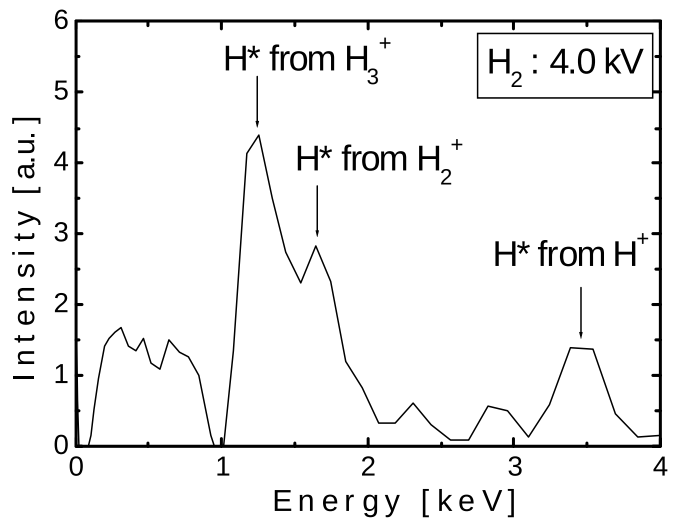


FIG. 7. Energy spectrum of fast neutral hydrogen for 4.0 kV, 40 mA, 2.7 Pa.

device for the acceleration voltage of –90 kV ions is equivalent to the 360 kV acceleration in the D-T tube, where the D^+ ions are accelerated and bombarded onto the tritium-sintered titanium target to occur fusion.

To achieve this, and considering the application in the Afghanistan, we have chosen a magnetron-discharge ion source (MIS) as a compact and simple ion source to develop.

3. Ion Production by Magnetron Ion Source (MIS) [9]

In order to provide full energy to the ions possibly undergoing maximal fusion reaction, it is also essential to produce ions under low pressure to reduce charge-exchange processes. Compared with rather complicated conventional external ion sources, magnetron discharge scheme needs only several permanent magnets of the simple geometry, and the electrodes nearby, which confines electrons by crossed electric and magnetic fields to consequently extend their trajectory length to great extent increasing subsequently ionization efficiency (Fig. 8). Also it is essential to produce such ions in the negative potential region with respect to the anode, i.e.,

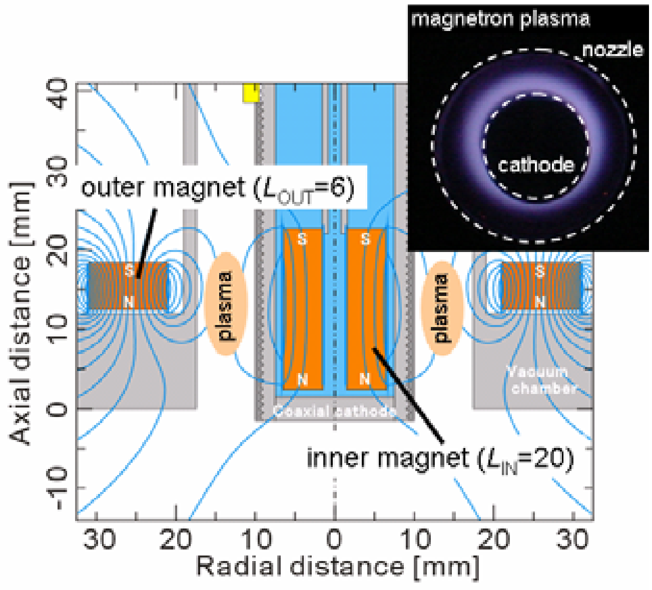


FIG. 8. Magnetron discharge type ion source with calculated flux lines and observed magnetron plasma.

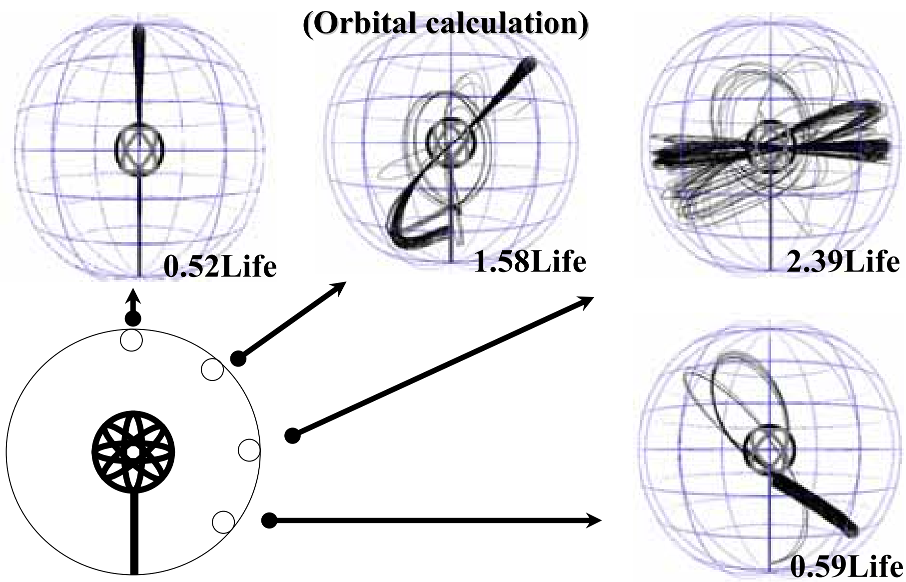


FIG. 9. Dependence of injection location of the ion source on the ion life time.

vacuum chamber, to prevent ions hitting the opposite wall, and elongate their life time, i.e., improve the ion recirculation. Simulation results in Fig. 9 indicate the longest life of ions when injected horizontally with respect to the cathode feedthrough [10].

To achieve this target, we applied the inner coaxial electrode with an inner permanent magnet at a negative high voltage based on the numerical analyses. The refined magnetron-type ion source consists of an anode port (ICF70 of 35 mmϕ inner diameter) at grounded potential, and a coaxial inner cathode (20 mmϕ diameter) at a negative potential (<–3 kV) inside which a

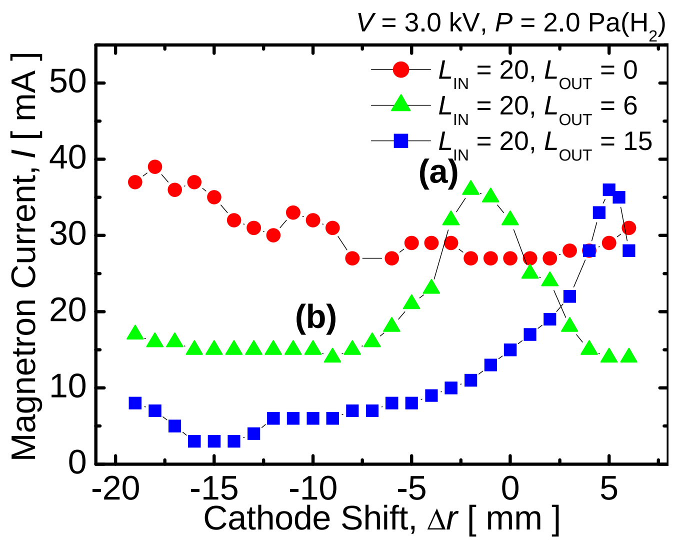
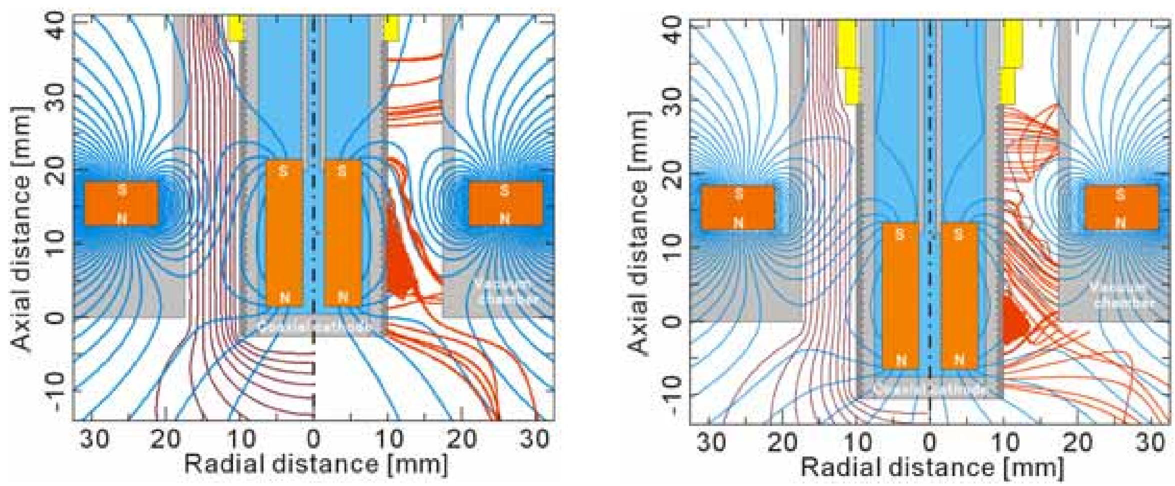


FIG. 10. Typical MIS performance characteristics for L_{in} = 20 mm, B_{in} = 0.45 T, B_{out} = 0.32 T, and L_{out} = 0, 6, 15 mm.



(a) Δ*r* = -2 mm (b) Δ*r* = -10 mm

FIG. 11. Electron trajectories for L_{in} = 20 mm, B_{in} = 0.45 T, B_{out} = 0.32 T, L_{out} = 6 mm, comparing cases for two different shift lengths of the inner cathode, Δr's, indicated in Fig. 10.

cylindrical water-cooled permanent magnet (Nd-Fe: 0.45 T) is installed as shown in Fig. 8 with a typical discharge photo.

This magnetron-type ion source shows a good performance, showing discharge current as high as 60 mA at a cathode voltage below –3 kV under H_2 gas pressure of 2.0-3.0 Pa, and a typical performance characteristics of the MIS is shown in Fig. 10 (–3.0 kV, 2.0 Pa (H_2)) for three sets of inner and outer magnet combinations, where Δr is the shift length of the inner electrode surface with respect to the vacuum chamber surface, and positive means outward shift. It is clear that the MIS current depends on the combination as well as the shift length, indicating strongly the existence of optimal condition.

To better understand the cases "(a)" and "(b)" in Fig. 10 (L_{in} = 20 mm, B_{in} = 0.45 T, B_{out} = 0.32 T, L_{out} = 6 mm), numerical calculations of the electron trajectories are made by a 2-dimensional code [11], and results as well as the magnetic flux and equi-potential lines are shown in Figs. 11(a) and (b).

It is qualitatively seen that the substantial number of electrons emitted from the inner cathode are trapped in the crossed electric and magnetic fields region in Fig. 11(a). In contrast, in Fig. 11(b), most of the electrons are seen running toward the outer anode along the magnetic fulx lines, and thus less number of electrons are trapped between the cathode and anode.

For further enhancement of discharge current, particularly from view point of ion supply to the transparent hollow cathode at the spherical center of the IECF neutron source, it is very important to study the MIS behaviour under the conditions with the hollow cathode at a negative high potential to find the optimal MIS configurations and conditions.

Also the pulse-mode operation required for neutron-induced γ-ray measurements is made in the experiments, and found that excellent controllability of neutron production in hybrid mode, i.e., ion production by the glow discharge and MIS, can be made by the pulsed operation of the magnetron-type ion sources.

4. Conclusions

For further drastic improvements of NPR applicable to anti-personnel landmine detection by the present compact IECF device, it is essential to produce ample fraction of full energy ions under considerably low deuterium gas pressure. Also, it is essential to make system simple and robust enough to accommodate use in Afghanistan. The magnetron-type ion source is eventually found to meet these requirements very efficiently, and being expected as high as 10^9 n/sec NPR by the optimized D-D IECF devices.

Acknowledgements

This work has been supported by JST (Japan Science and Technology Agency).

References

[1] KELLY, D., "Briefing on research and development technology to support humanitarian demining", Tokyo, Dec.2, 2002.

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, "Application of Nuclear Techniques to Anti-personnel Landmines Identification", Report of the First Research Co-ordination Meeting, Zagreb, Croatia, IAEA/PS/RC-799, Nov. 23-26, 1999.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, "Application of Nuclear Techniques to Anti-personnel Landmines Identification", Report of the Second Research Co-ordination Meeting, Saint Petersburg, Russia, IAEA/PS/RC-799-2, Sept. 11-14, 2001.

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, "Application of Nuclear Techniques to Anti-personnel Landmines Identification", Third Research Co-ordination Meeting, IAEA HQ, Vienna, Austria, May 19-23, 2003.

[5] YOSHIKAWA, K., et al., "Research and development of landmine detection system by a compact fusion neutron source", 16^{th} Topical Meeting on Fusion Energy, Madison, WI, USA, O-I-6.4 (2004).

[6] YAMAUCHI, K., et. al., "Pulsed Operation of a Compact Fusion Neutron Source Using a High-Voltage Pulse Generator Developed for Landmine Detection", 16^{th} Topical Meeting on Fusion Energy, Madison, WI, USA, P-II-23 (2004).

[7] MIZUTANI, T., "Study on Energy Distributions of Fast Neutral Atoms in an Inertial Electrostatic Confinement Fusion Device", BS thesis, Department of Engineering, Kyoto Univ., March, 2001 (in Japanese).

[8] MASUDA, K., et al., "Measurement of the Energy Distribution of Fast Excited Atoms by Doppler Shift Spectroscopy in an Inertial-Electrostatic Confinement Fusion Device", Proc. of the 19^{th} IEEE/NPSS Symposium on Fusion Engineering, Atlantic City, NJ, USA (2002) 434-437.

[9] TAKAMATSU, T., et. al., "Improvement of an Inertial Electrostatic Confinement Device", 16^{th} Topical Meeting on Fusion Energy, Madison, WI, USA, P-II-16 (2004).

[10] OSAWA, H., et al. "Optimal Position of Ion Source for High Performance of IEC", 16^{th} Topical Meeting on Fusion Energy, Madison, WI, USA, P-II-17 (2004).

[11] MASUDA, K., "Development of Numerical Codes and Application to Klystron Efficiency Enhancement", Ph.D. thesis, Department of Electrical Engineering, Kyoto University, March, 1997.