New ECR Proton Source to Produce Highly Intense Beam for ADSS

M. H. Rashid*

Variable Energy Cyclotron Centre, Sector-1, Block-AF, Bidhan Nagar, Kolkata - 700064, India
**E-mail: haroon@vecc.gov.in, DrRashidMH@gmail.com*

Abstract. Core objective of many countries is utilization of abundantly available thorium to produce nuclear energy in a sustained way with enhanced security. There is a national program on anvil in India called third-stage-nuclear-program, which is based on Thorium-Uranium-233 cycle [1]. The accelerator driven sub-critical system (ADSS) is one of the many systems to create nuclear energy with high security [2]. The system needs a highly bright proton beam of 10's of mA to be accelerated to almost one GeV to make it a powerful beam (>30 MW) to produce spallation neutrons on heavy targets like Pb, Bi etc. for compensating the deficit of neutrons in a sub-critical nuclear reactor. Some rigorous computation and magnetic field simulation has been performed for the envisaged new high current proton source. It can produce highly dense plasma in a chamber immersed in a magnetic field with camel hump shape above ECR resonance field at the chamber ends. The magnetic field can be produced and configured using either a pair of coaxial coils or three axially magnetized permanent magnet rings with proper magnetic field shielding. The Child-Langmuir theory is applicable for extracting space charge limited beam. As the beam is very intense, space charge blow-up of the beam in transverse direction takes place. Study done, for designing the proposed proton source of high intensity and containing the beam axially while transporting, is presented in the paper.

Keywords: ECR plasma heating, Intense Proton Source, Spallation Neutrons, Accelerator Driven Subcritical System
PACS: 52.50.Sw, 52.50.Qt, 28.20.Ka

INTRODUCTION

Some prototype ion sources have been constructed indigenously in India but none have crossed the target of 40 mA till now [3]. It targets to construct a source to produce intense proton beam of current ~100 mA using industrial microwave source of 2.45 GHz and power ~2 kW because emittance of the extracted beam is low at lower frequencies. An ECR ion source can run for long time at a stretch as no electrodes are used to produce electrons. It uses vacuum, magnetic field and high frequency RF field. The RF energy and material to be ionized are injected at the injection end and ions to form beam is extracted in addition to evacuation at the extraction end. The magnetic field works by transferring electromagnetic energy to electrons through ECR process, initiating more ionization and confining the electrons and ions (plasma) in the chamber to produce more protons or deuterons.

Main purpose of the highly intense proton source development is neutron production for various applications like study of fusion reaction and materials for use in such reactor. In last decade, the high flux neutrons were needed to run a sub-critical nuclear reactor, which is very safe in respect of nuclear explosion due to uncontrolled nuclear reaction as in Japan after devastating tsunami. The idea was proposed by Carlo Rubbia to produce high flux neutrons by nuclear spallation reaction for which light ion accelerator and heavy target are needed. A proton beam of 1 GeV energy and 10 mA current on the target can deposit 10 MW of power which can knock out sufficient number of fast neutrons from the heavy nucleus and they are called spallation neutrons. Almost every 600 MeV protons produce neutrons like 1 GeV protons though the number of neutrons is almost half. But the question is whether it is possible to use low energy proton beam of high intensity for an experimental or commercial subcritical reactor, ADSS. In this case the accelerator cost will reduce with slightly more investment on development of ion source to produce highly bright and intense proton beam. So, development of such source is the call of time. The extraction system of the source becomes complicated consisting of several coaxial electrodes to focus the beam properly.

The source should produce high current beam with low emittance. Some efforts in this direction have already started worldwide like construction of SILHI [4], VIS [5] and TRIPS [6]. It has been reported that some of these ion sources can produce >100 mA of proton beam. The emittance of the extracted beam is low at lower RF frequencies and magnetic field. The ECR resonance field surface is situated at both the chamber ends. The magnetic field can be produced configured and tuned using either a pair of coaxial coils or three or two axially magnetized permanent magnet (PM) rings with proper magnetic field shield so that the field is not high at the extraction region.

ECR ION SOURCE REQUIREMENTS

There are many benefits of ADS like radioactive wastes incineration, impossibility of nuclear explosion, breeding of thorium (Th^{232}) and uranium (U^{238}), less fuel enrichment cost, less sophisticated control system and above all caping of enriched nuclear fuel proliferation. Number of neutrons produced is expressed as, Nn = Ip*Mn, where Ip and Mn are particle beam current and neutron multiplicity respectively. The total Nn produced by a proton beam of 100 mA, 0.600 GeV than a proton beam of 10 mA, 1 GeV is about 4.7 times more. The table 1 shows the Nn at different current, Ip and multiplicity, Mn. Thus, more powerful ADSS with high gain is envisaged.

TABLE 1. Total Spallation neutrons produced (Nn) as a result of proton bombardment on Pb target.

Ip	Mn=11.6 at 0.6 GeV	14.5 at 0.8 GeV	24.6 at 1.0 GeV
6.25×10^{14}	7.25×10^{15}	9.06×10^{15}	1.53×10^{16}
6.25×10^{15}	7.25×10^{16}	9.06×10^{16}	1.53×10^{17}
6.25×10^{16}	7.25×10^{17}	9.06×10^{17}	1.53×10^{18}

Magnetic field rises at the centre of the chamber above the resonance field at the ends by ~1.3 times. This principle is based on the experience of achieving high beam current by Tailor [7]. The mode of the injected RF may be TE01, which is distributed in the metallic multimode cavity, the plasma chamber. Some energy is carried by the right hand (RH) mode of the RF wave, which propagates easily without suffering any cutoff in the field higher than ECR field region because of positive plasma dielectric constant. The electrostatic Bernstein waves (EBW) are excited by the electron cyclotron motion of electrons in the magnetic field when the wavelength of the wave is comparable with the gyro-radius of electrons. A periodic space charge distribution of electrons is produced with maxima and minima perpendicular to the magnetic lines of force because of difference in gyro-phase of electrons. Electrons are capable of moving in phase with the wave and gaining energy from it. One very important feature of the EBW is that it can propagate easily within the over-dense plasma without facing any cutoff and cannot propagate outside plasma because of electrostatic nature.

MAGNETIC FIELD COMPUTATION

Magnetic field is very important to increase the path length of the electrons as they gyrate about the lines of force and sufficiently increases the confinement time of electrons and consequently of ions created after plasma discharge. Since the ionization time of the H atom is very less than the confinement time of the electrons and ions, further confinement of ions employing the mirror configuration of minimum-B field is not needed essentially. The required field can be generated either using coils or sufficiently strong PM rings. The most prevalent, successful and tested configuration of the field is creation of ECR field (B_{ECR}) inside the chamber at the vicinity of the RF injection and beam extraction holes on the central axis. A rising field pattern is achieved towards the centre with maximum field having value ~$1.3 \mathrm{x} B_{ECR}$. It is achieved using a pair of co-axial coils with carrying electric current in the same direction. It is achieved by using three PM, having remnant field and coercive force 8.5kG and 8.5 kOe respectively, rings also with magnetization along the axis.

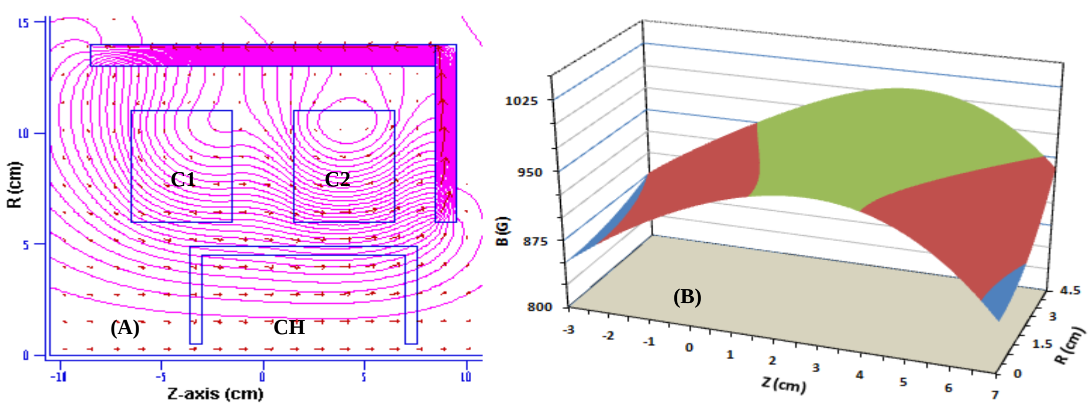

FIGURE 1. (A): The geometry and MLF plot, coils (C1 & C2), plasma chamber (CH) and the iron yoke shield; (B): 3D field plot in inside the chamber with B_{ECR} at the ends.

The magnet structures in the two cases are shown in Fig. 1(A) and 2(A) respectively. Figures depict the geometry and plot of magnetic lines of force (MLF). The filed produced in the case of coils and PM's correspond to Figs. 1(B) and 2(B). Proper shielding of the magnetic field was provided at the extraction end using highly permeable MS disk, which reduce the emittance of the extracted proton beam. The field generated by PM rings also has ~$1.3 \mathrm{x} B_{ECR}$ at the centre. It is stretched some length and falls at the two ends such that the ECR surfaces are close to them. Another configuration of the magnetic field is suggested here for confining plasma in zero-B field (spindle cusp field) at the centre.

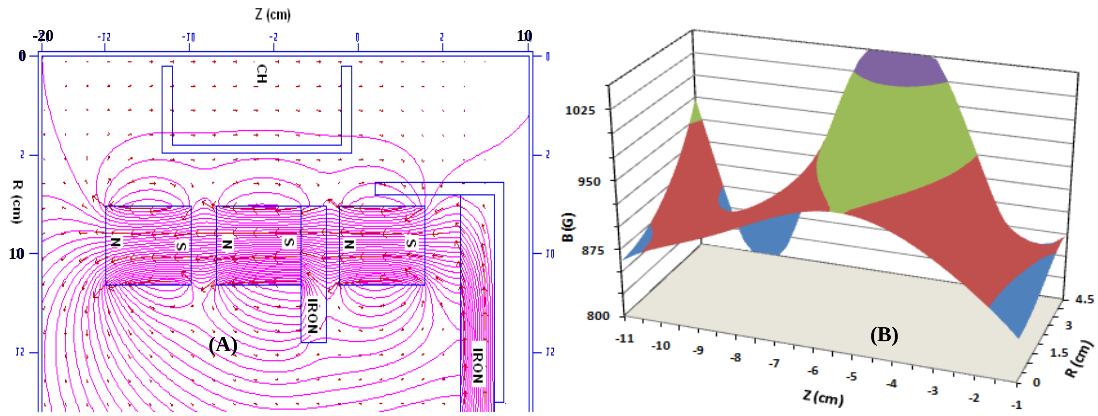

FIGURE 2. (A): The geometry with PM structure and MLF plot in the chamber (CH), N-S represent PM blocks with poles and IRON the shield; (B): 3D magnetic field plot with B_{ECR} at the ends.

EXTRACTION ANALYSIS

Extraction of the proton beam is one of the complex problems as high current beam is affected violently by the space charge. The pentode extraction system gives immediate and more control on the space charge containment. Some study was done for proper design of such extraction system with 8 mm diameter extraction hole and electrostatic einzel lens configuration to control the space charge of 40 mA proton beam. Further extraction analysis continues. Recent studies to focus the beam while transporting in the LEBT has shown that the lens aberrations are less for a pair of Glaser lens in anti-solenoid mode which is termed as magnetic einzel lens also.

CONCLUSIONS

Magnetic field simulation was done for high current proton beam (~100mA) for accelerating to 0.6 MeV possibly by RFQ>DTL >LOW BETA LINAC, which will reduce the cost of the accelerator designed for high current beam. It is proposed that lower energy and higher current of the beam has capability of running a high gain sub-critical reactor. More study should be done for space charge compensation of the high current beam by production of tenuous plasma in the low energy beam transport line.

REFERENCES

1. Nuclear India, Vol : 39 / No.9-10 / Mar.-Apr. 2006, p. 6; ***Website :*** [***www.dae.gov.in***](http://www.dae.gov.in)
2. Jos´e Rubens Maiorino, Adimir dos Santos, et al., Brazilian J. Phys. **33**, (2003).
3. P. Roychowdhury et al.,Proc. InPAC-11, IUAC, N. Delhi, 2011, paper-141,149; V.S. Pandit (p-231).
4. S. Gammino, L. Celona et al., Review Sc. Instrum. **81**, 02B313 (2010).
5. F. Maimone, G. Ciavola et al., Proc. EPAC08, Genoa, Italy (2008) p. 430.
6. G. Ciavola, L.Celona et al., Proc. Part. Accel. Conf., Chicago (2001) p. 2406.
7. T. Tailor and J.S.C. Wills, Nucl. Instrum. and Meth. **A309** (1991) 37.