Design of a Prototype Positive Ion Source with Slit Aperture Type Extraction System

Sanjeev K Sharma1, Prahlad Vattillil1, Bhargav Choksi1, Bharathi Punyapu1, Rambabu Sidibomma1, Sridhar Bonagiri1, Deepak Aggrawal1 and Ujjwal K Baruah1

1Institute for Plasma Research, Bhat, Gandhinagar – 382428
Email: sksharma@ipr.res.in

Abstract: The neutral beam injector group at IPR aims at developing an experimental positive ion source capable of delivering H⁺ ion beam having energy of 30 – 40 keV and carrying an ion beam current of 5 A. The slit aperture based extraction system is chosen for extracting and accelerating the ions so as to achieve low divergence of the ion beam (< 0.5°). For producing H⁺ ions a magnetic multi-pole bucket type plasma chamber is selected. We calculated the magnetic field due to cusp magnets and trajectories (orbits) of the primary electrons to investigate the two magnetic configurations i.e. line cusp and checker board. Numerical simulation is also carried out by using OPERA-3D to study the characteristic performance of the slit aperture type extraction-acceleration system. We report here the results of the studies carried out on various aspects of the design of the slit aperture type positive ion source.

1. Introduction

Neutral beam systems are demonstrated as one of the most effective techniques for heating, current drive and diagnostics in fusion related experiments. Recently, the NBI group at IPR has completed its test stand activities of the ion source PINI (plug-in neutral injector) [1] and is underway of transferring the injector system to the SST1 tokamak. The NBI group is now planning for indigenous development of a positive ion source capable of delivering H⁺ ion beam having energy of 30 – 40 keV and carrying an ion current of 5 – 10 A. The ion source will be used for basic experimental studies on the extraction system. The neutral beam ion sources consist of an arc chamber (for production of ions) and a set of electrostatic grids (electrodes) for the purpose of extraction and acceleration of the ions. Large sized ion beams are produced by superposition of many beam-lets extracted through a set of apertures distributed uniformly on the surface of electrostatic grids. The resultant ion beam current $I_p$ depends on the number of apertures, the current density $j_p$ from each aperture and aperture size or radius $r_a$ [2, 3].The arc chamber generates the required flux of H⁺ ions. Ionisation in arc chamber is caused by primary electrons emitted by the hot cathode assembly. The magnetic multipole or bucket type plasma source is one of the most prominent sources considered for the application of neutral beam systems [4]. The ion source considered here is a cylindrical shaped plasma chamber with multi-cusp magnetic configuration. In designing these sources, it is essential to optimize magnetic configuration because it has strong influence on the performance of the ion source. Uniform magnetic field (< 20 G) in the range over the whole extraction area is necessary for keeping uniform plasma densities across the whole extraction area.

In order to optimize magnetic field configuration, a computer program is developed to calculate the value of magnetic field and the trajectories (orbits) of the primary electrons to investigate the role of...
various magnetic configurations on the confinement of these electrons. An optimization is carried out for the magnetic cusp geometry to produce field free region / uniform low magnetic field over the whole extraction area. Simulation of the trajectories of the primary electrons is performed to investigate the confinement behavior of these electrons in the magnetic multi-cusp geometry. The confinement of primary electrons and plasma uniformity for different magnetic configurations is analyzed using the spatial distribution of the ionisation collision points, which is analogous to the density distribution of the plasma [5,6]. The developed ion source is planned to have low angular divergence (< 0.5°). The study on the characteristic performance of the slit aperture based extraction system is carried out by the means of numerical simulation using OPERA-3D code [7].

2. Plasma Source and extraction-acceleration system
A magnetic multipole plasma source consists of an anode chamber equipped with several columns of permanent magnets on its outer surfaces and tungsten filaments kept at the potentials of the cathode. The energetic primary electrons emitted by the hot tungsten filaments are used to ionize the background gas to generate dense hydrogen plasma. The primary electrons are confined mainly in the magnetic field produced by the permanent magnets (SmCo, surface field ~ 4 kG). A numerical code (in MATLAB) was written to calculate the magnetic field and the particle trajectories of the primary electrons. The equation of motion for a primary electron with collision term (equation (1)) is solved to trace the particle trajectory and the collision points.

\[
\frac{mdv}{dt} = q(E + v \times B) + F_{coll}
\]

(1)

where \(m, q, v, t\) are mass, charge, velocity of the primary electron, and time, respectively. \(E\) and \(B\) are electric and magnetic fields respectively. \(F_{coll}\) is the ionisation collision term. For the simplicity other types of collisions are not considered. The initial energy of the primary electron is considered as 80 eV as the electron gains energy from the acceleration caused by the sheath potential at the filament surface, which is equal to the applied discharge voltage. An electron emitted from each filament is traced only until the electron causes its first ionisation or it is lost to the wall. The considered physical model assumes that the sheath thickness is thin enough and that a primary electron is traced only after the acceleration by the sheath field. In this simulation, the potential gradient in the plasma is also neglected for the simplicity. The magnetic field due to the current in filaments and due to permanent magnets is calculated by using Biot–Savart’s law and the formulation as discussed by Y. Ohara et al [6], respectively. The magnetic field is first calculated for each magnet in their respective coordinate systems, and then transformed into the coordinate system of the ion source.

**Figure 1(a).** Schematic diagram of the two magnetic configurations: line cusp and checkerboard, (b) vector plot showing the magnetic cusps near the extraction plane. The size of a typical magnet is (9 mm x 13 mm x 40 mm) and the size of plasma chamber is 20 cm (diameter) and 20 cm (depth).
The considered extraction-acceleration system is a three grid system (triode type). The first grid is called the ‘plasma grid’ or extraction grid. The positive voltage, $V_{pg}$, required for accelerating the ions is applied to this grid. The second grid is called the ‘suppressor grid’. A small -ve voltage is applied to this grid to prevent the back streaming of secondary electrons (produced due to interaction of ion beam with residual gas) from reaching the arc chamber. The second grid, which causes a small deceleration to the beam, is also known as the ‘deceleration grid’. The third grid is at zero potential ($V_g = 0$) and therefore is known as ground grid. The considered width and length of the slits are 8 mm and 100 mm, respectively. The shapes/contours of the slit grids are considered as similar to those of PINI [1]. The gap between the plasma-deceleration grids and deceleration-ground grids are 8 mm and 2 mm respectively.

3. **Optimization of magnetic geometry**

The plasma chamber is equipped with an arrangement of permanent magnets on its outer surface to form the required magnetic configuration. There are two types of magnetic configurations commonly used in multi-cusp ion sources, namely, line cusp and checkerboard. They can be further classified into continuous and broken ones. The calculations are carried out for the continuous line-cusp and continuous checkerboard configurations. The two types of magnetic configuration are depicted in figure 1(a). In the continuous line-cusp configuration, columns of permanent magnets having north and south poles facing alternatively inward are placed on the outer surfaces of the ion source. The magnetic cusps are formed perpendicular to these magnetic columns as shown in figure 1(b). In the checkerboard configuration, each magnetic column has several magnets, facing their north and south poles alternatively inward in such a way that the magnetic cusps are formed along both parallel and perpendicular to the magnetic columns. In both the configurations, magnetic columns are parallel to the source axis i.e. along the longitudinal direction.

Figure 2(a). Radial profile of magnetic field, $B_{abs}$, (b) Field free region for various number of longitudinal line cusps, N.
A uniform plasma density over the whole extraction region is the basic necessity of the multi-cusp ion sources. Another important requirement is the achievement of maximum discharge efficiency. The uniform plasma is mainly produced in the field free region which has nearly uniform magnetic field (< 20 G). Figure 2(a) shows a magnetic field free region over ~ 10 cm for $N = 12$. $N$ is the numbers of magnetic columns /cusps lines. In figure 2(b), the extent of field free regions is plotted as a function of number of cusps, $N$. It is evident that as the number of magnetic cusps increases, the field free region increases. More number of cusps causes strong magnetic field between the regions of the two cusps. When the number of cusps increases, the loss of the primary electrons also decreases due to the reduction in the cross field diffusion ($\propto 1/B$) of the plasma particles. The reduced loss of the primary electrons causes an increase in the discharge efficiency [8, 9]. It is also observed from figure 2(b) that the 24 magnetic cusps provide the maximum field free region of ~ 12 cm. It is however impractical to incorporate 24 magnetic columns on the periphery of the ion source having a diameter of 20 cm. The increment in the field free region from 12 cusps to 24 cusps is merely ~ 20 %. The numbers of magnetic cusps (or magnetic columns) are therefore chosen as $N = 12$. It is also observed that the field free region is increased by about 30 % for the checkerboard-configuration. The magnetic field at the inner surface of the ion source is reduced by 50 %, which cause a rise in the cusp loss area i.e a decline in the discharge efficiency.

4. Particle orbit simulation
A three dimensional particle orbit simulation is carried out to analyse the particle confinement in the continuous line-cusp and checkerboard configurations. Figure 3(a) shows trajectories of about 1000 primary electrons (80 eV), projected over a transverse plane. The starting positions of the primary electrons are randomly chosen near the filaments (outside sheath). These trajectories are calculated for the continuous line cusp configuration. It can be seen that the electrons are well trapped by the cusp magnetic field produced by the permanent magnets.
5. Spatial distribution of ionisation collision points

The spatial distribution of ionisation collision points (electron-neutral collision points) inside the plasma source is calculated using particle orbit simulation for continuous line cusp and continuous checkerboard configurations. The distribution of these collision points basically represents the pattern of ion birth locations. The primary electrons emitted from the filaments are traced inside the plasma source until they are lost due to the ionisation of hydrogen neutrals. The event of ionisation is decided by the completion of their ionisation mean free path, which is 38.2 cm for 5 mTorr hydrogen gas pressure and the primary electrons with 80 eV energy [8]. These positions are recorded for several electrons and used for calculating spatial distribution of the ionisation collision points. The distribution of ionisation collision points for the continuous line cusp configuration as shown in figure 3(b) suggests that the ionisation occurs mainly in the magnetic field free region. Figure 4(a) shows the radial density profile of these ionisation collision points. The curve with inverted triangles shows the density of these collision points for the case when plasma grid is biased at a fixed negative potential as similar to that of cathode i.e – 80 V. The curve with open circles shows this density for the unbiased plasma grid. It suggests that the density of the collision points (\( \propto \) plasma density) would be higher for the biased plasma grid case. This is due to the increased confinement of the primary electrons caused by the reflection from the negatively biased plasma grid. Similarly the density of the ionisation collision points for the checkerboard configuration is calculated for both the biased and unbiased plasma grids as depicted in figure 4(b). It is seen that the ionisation occurs over a large region in case of checkerboard as compared to the line cusp. The density of the ionisation collision points is reduced significantly for the checkerboard configuration. Also an unbiased plasma grid further reduces the density of the ionisation collision points.

![Figure 4](image.png)

**Figure 4.** Radial density profile of the ionisation collision points of the primary electrons for (a) continuous line cusp, (b) continuous checkerboard cusps for two cases namely, with grid biasing (inverted triangle and diamond) and without grid biasing (circle and squares).

![Figure 5](image.png)

**Figure 5.** Emittance plots for the ion trajectories (a) along the width of slit (X) and (b) along the slit (Y). The emittance plots were obtained at a distance \( z = 29.2 \) mm from the surface of the emitter.
6. Simulation of ion beam trajectory
A multi aperture extraction-acceleration system can be described as superposition of several individual apertures. Hence the analysis of a single aperture of the extraction-acceleration system is adequate for understanding the performance of the complete extraction-acceleration system. Simulation of ion trajectories for the slit shaped apertures is performed by the OPERA code. The emittance calculations for the ion trajectories were performed at a distance \( z = 29.2 \text{ mm} \) from the extraction plane. Slit aperture of widths 8 mm was considered for the simulation.

Figure 5(a) and (b) shows the emittance plots along the width of slit (8 mm) and along the slit. The abscissa represents the radial location (X or Y) of the individual ion from the beam axis (Z-axis). The parameter in the ordinate of the emittance plot denotes the transverse angles \( \Omega_x \) and \( \Omega_y \) subtended by the velocity of individual ion with beam axis in the \( X-Z \) and \( Y-Z \) planes respectively. Ellipses drawn over the emittance plots depict the spread of particles in phase space. The area of ellipse represents the geometrical emittance of the beam. The major and minor axes of the ellipses generally represent the spread in space and transverse angles. The rotation angle, \( \theta \) of the ellipses, is estimated from \( \tan(2\theta) = 2X\Omega_y/(X^2 - \Omega_y^2) \). This angle is \( +ve \) for convergent (\( -ve \) for divergent) beam. It may be noted that particles lying outside the ellipse have abnormally large transverse angles. The above behaviour can be explained by the fact that the trajectories lying outside the ellipse represent those particles that have originated from the edges of the slit aperture. As expected for slit aperture, the emittance in X-direction (along width of the slit) is entirely different from that of the Y-direction (along the slit). The small expansion of beam observed at the ends is due to the presence of large transverse electric fields at such locations. This expansion is more prominent in case of the slits with larger width. Transverse angles in the direction along the slit (i.e. along Y-axis) are nearly zero. Along the width of the slit (i.e. X-axis) the transverse angles vary from +/- 1° to +/- 1.6°. The minimum divergences along x-axis for 8 mm slit shaped apertures is 1.8° which correspond to ion emission current densities 160 mA/cm² respectively. The divergences along the slit (i.e. Y-axis) are very small (< 0.2°) and nearly constant for all the current densities.

Slits having widths of 8 mm are selected for developing the extraction system of the ion source. Figure 6(a) shows 3-D model of plasma slit grid. Figure 6 (b) shows the beam power profile calculated using bi-Gaussian beam profiles having angular beam divergences 1.8° and 0.2° (along width of the slit and along the slits, respectively) at 1 m distance from the extraction plane.
the extraction system is not considered because beam focussing is not found helpful in reducing the size of the beam for such smaller sized grids.

7. Summary and conclusion
The neutral beam injector group is engaged in the indigenous development of an experimental ion source capable of delivering H⁺ ion beam having energies of 30 – 40 keV and carrying an ion beam current of 5 – 10 A. Studies have been carried out on various aspects of the design of the slit aperture type positive ion source. The three dimensional particle orbit simulation is carried out to analyse the confinement of primary electrons to understand the performance of the plasma generation in the magnetic multi-cusp geometry. First, the number of magnetic cusps (or magnet columns) to produce the uniform magnetic field is optimised as 12 for the ion source of the diameter 20 cm. Next the cusp geometries for the line cusp and checkerboard configurations are compared for the same number of magnetic columns. The densities of the electron-neutral (ionisation) collision points (i.e. the ion birth locations) calculated using the particle orbit simulation for continuous line cusp and continuous checkerboard configuration are compared.

For achieving the maximum density, the line cusp with the negatively biased plasma grid is found an optimum solution for higher discharge efficiency. However the checkerboard configuration with negatively biased plasma grid would be the optimum solution when a uniform density over a large extraction area would be required. Ion beam extraction and acceleration have also been studied by means of numerical simulation using OPERA-3D code. For Extraction system with slit apertures, the angular divergence along the slit is negligible (<0.2°), while the divergence along the width of the slit is ~2°. Slit based extraction-acceleration system with size 8 mm (width) is considered for developing this ion source. The beam focussing in the extraction system is not considered.

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