Performance Test Results of Ion Beam Transport for SST-1 Neutral Beam Injector

M. R. Jana*, S. K. Mattoo
Institute for Plasma Research
Bhat, Gandhinagar-382428, Gujarat, India

R. Uhlemann
Forschungszentrum Juelich,
Institute fur Energieforschung IEF-4, Plasmaphysik
D-52425 Juelich, Germany

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Abstract: A neutral beam injector is built at IPR to heat the plasma of SST-1 and its upgrade. It delivers a maximum beam power of 1.7 MW for 55 kV Hydrogen beam or 80 kV Deuterium beam. At lower beam voltage, the delivered power falls to 500 kW at 30 kV Hydrogen beam which is adequate to heat SST-1 plasma ions to ~1 keV. Process of acceleration of ions to the required beam voltage, conversion of ions to neutrals and removal of un-neutralized ions and the beam diagnostic systems occupy a large space. The consequence is that linear extent of the neutral beam injector is at least a few meters. Also, port access provides a very narrow duct. Even a very good injector design and fabrication practices keep beam divergence at a very low but finite value. The result is beam transport becomes an important issue. Since a wide area beam is constructed by hundreds of beam lets, it becomes essential they be focused in such a way that beam transport loss is minimized. Horizontal and vertical focal lengths are two parameters, in addition to beam divergence, which give a description of the beam transport. We have obtained these two parameters for our injector by using beam transport code; making several hundred simulation runs by varying optical parameters of the beam. The selected parameters set has been translated into the engineering features of the extractor grid set of the ion source. Aperture displacement technique is used to secure the horizontal beam focusing at 5.4 m. Combination of both aperture displacement and inclining of two grid halves to ~17 mrad are secured for vertical beam focusing at 7 m from earth grid of the ion source. The gaps between the design, engineered and performance tested values usually arise due to lack of exercising control over fabrication processes or due to inaccuracies in the assumption made in the model calculations of beam optics and beam transport. This has been the case with several injectors, notably with JET injector. To overcome this problem, we have validated and scaled our design calculations with performance parameters of the Neutral Beam Injector at IPP, Julich, Germany. The performance test of the SST-1 PINI ion source was done at MARION Test Stand at IPP, Julich. Analyses of these results indicate that the measured power profile and the optical parameters of the beam are in good agreement with the simulation results. These parameters are stable over the beam pulse of 14s with extracted beam energy of 31 MJ at 41 kV. This paper presents these results and details out future work need to be done in order to assess the steady state stability of the beam parameters.

1 E-mail: mukti@ipr.res.in (corresponding author)
1. Introduction

Steady State Superconducting Tokamak (SST-1) \[ R=1.2 \, m, \, a =0.2 \, m, \, I_p=220 \, kA, \, B_T=3T, \, n_e = 2 \times 10^{19} \, m^{-3}, \, T_e=1 \, keV \] [1-2] is equipped with neutral beam injection (NBI) system [3-6] to deliver 0.5 MW neutral hydrogen beam power at 30 kV to raise the ion temperature to \( \sim 1 \) keV. In an upgrade version of SST-1 with plasma density of \( 5 \times 10^{19} \, m^{-3} \), the required neutral beam power is 1.7 MW at 55 kV. The neutral beam shall be injected tangentially into the tokamak plasma in the direction of plasma current (co-injection) with tangency radius of 98 cm and pivot angle of 27°. The expected NB shine through is 10% and current drive efficiency is \( \sim 0.044 \, (10^{20} \, A \, W^{-1} \, m^{-2}) \).

![Fig.1 Elevation view of SST-1 NBI system](image)

The elevation view of SST-1 NBI system is depicted in fig.1. It consists of a filament based multipole bucket type positive ion source with 3-grid ion extractor system, neutralizer, a deflection magnet, ion dump and V target, housed inside a large rectangular vacuum vessel of dimension 2.9 m (W) \( \times 2.2 \, m \) (B) \( \times 3.7 \, m \) (H) to keep the ionization loss < 5%, eight cryopumps are installed with a total pumping speed of \( \sim 10^6 \, T-l/s \) to obtain beam line vacuum of \( \sim 1 \times 10^{-5} \) Torr. There are two gate valves, one is connected...
between ion source and vacuum vessel, the other to duct flange through bellows and connecting tube. The auxiliary systems (not shown here) includes power supply system, water cooling systems, diagnostic system and data acquisition and control system. Neutral beam injector consists of a single ion source with 3 multi-aperture grid extractor system. Each grid has 774 apertures, each of 8 mm diameter, distributed over rectangular extraction area – 390 cm². The rectangular shape of extractor area allows easy vertical and horizontal focusing.

The ion source is capable of delivering 1 MW and 5 MW positive hydrogen ion beam power at 30 kV and 55 kV respectively. The corresponding injected NB power is 0.5 MW at 30 kV and 1.7 MW at 55 kV.

Plasma is produced inside vacuum chamber by filament discharge. Positive ions are separated from plasma and accelerated to the desired energy by 3 multi-aperture grid extractor system. The accelerated ions pass through the neutralizer where they get neutralized by charge exchange process. Neutralization efficiency is about 60% at 55 kV. At the exit of the neutralizer, beam consists of accelerated ions and neutrals. The un-neutralized ions are deflected out by bending magnet and deposited on ion dump. Finally, energetic neutral beam enters into tokamak for plasma heating.

Neutral beam is injected into tokamak plasma through a narrow duct of 19 cm (W) × 40 cm (H). The beam line is optimized with PADET code [7]. It is found that, for beam transmission of > 85% through the duct, the required horizontal and vertical focal lengths are 5.4 m and 7 m respectively.

Beam optics is studied using AXCEL-INP code [8]. The horizontal beam focusing is obtained by aperture displacement and vertical focusing by a combination of both aperture displacement and by giving an inclination of 1.07° between the two grid halves. Ion source has been fabricated by M/S PVATePla AG, Germany and its performance test has been done at Marion Test Stand of IPP, Julich, Germany [9].

In this paper, we present results on beam transport derived from the measured horizontal and vertical beam power profiles. We show that the measured power profile and the optical parameters of the beam line are in good agreement with PADET code results. The paper is organized in the following way: section 2 describes the beam focusing method, section 3 deals with the results on beam transport and a comparison of the results with PADET code is made in section 4. Beam divergence is discussed in section4. Conclusion and future work is given in last section 5.

2. Method of beam focusing

Ion extractor system has been designed for a large dynamic range of beam voltage between 20 - 55 kV. The extracted ion beam current varies between 35 - 90A. Ion extractor system consists of 3 multi-aperture grids. First grid, in contact with plasma called acceleration grid, is maintained at 55 kV positive potential. It separates the ions from plasma source and extracts them for acceleration to the desired energy in the acceleration gap. The last grid at ground potential, called earth grid acts as reference of the beam line. After acceleration, ions exit the extractor system at ground potential. The second grid, called deceleration grid kept at negative potential (-2.5 kV), is placed in between acceleration grid and earth grid. This grid prevents the back-streaming electrons, generated in the neutralizer region, from damaging the ion source. After exiting from the earth grid, the multiple beamlets travel a distance of 7 m to reach the SST-1 plasma. They deposit the energy in the plasma through Coulomb collisions. These results in plasma heating. These beamlets form a combined beam having a resulting divergence which is primarily determined by the beamlets on the periphery of the total beam. To reduce the beam transport loss, beamlets are focused. Each set of corresponding apertures in 3 electrodes acts as a converging or diverging lens. Focusing is achieved by giving one or two of these electrodes a small displacement ($\Delta x$) w.r.t to the central line in the acceleration gap of the apertures. Then beam deflection occurs due to the perturbed radial electric field. Fig.2 illustrates this phenomenon.

The beam deflection angle ($\theta_s$) is given by

$$\theta_s = 22.92 \frac{\Delta x}{d}$$

(1)
The focal length of the beamlets is given by

\[ f = \frac{l}{\tan \theta_s} \tag{2} \]

where \( l \) is the distance of the aperture with respect to beam axis. Knowing the values of \( f \) and \( l \), one can calculate the required beam steering angle \( \theta_s \) from Eq. (2) and substituting this value in Eq. (1), we can estimate aperture displacement \( \Delta x \) of the particular aperture in both deceleration and earth grid w.r.t the axis of aperture in acceleration grid as shown in fig.2.

It should be noted that this kind of focusing has advantages over magnetic focusing. In the latter case, the beam line length is increased and so also the pumping region. Further, stray magnetic field affects the ion extraction from plasma. By employing a programmed aperture displacement to oppose beam divergence, the neutral beam power transmission is increased by \( \sim 40\% \) in ORMAK [10] plasma. A similar improvement in beam transmission by programmed aperture displacement method was reported by Berkeley group [11].

2.1 Scheme for horizontal focusing (by aperture displacement)

It is implemented on the small side of the grid since steering distance is not large even for the outermost apertures. Further, the smaller side of the grid is oriented parallel to the horizontal direction of the injection port. Extraction area is 23 cm (W) \( \times \) 48 cm (H) for our extractor. Hence horizontal focusing is implemented on the side having width of 23 cm by displacement of the apertures. Normally, beam steering distance should not exceed 5\% of acceleration gap length. The minimum and maximum aperture...
displacement are 21 µm (first aperture from mid plane of the grid) and 400 µm (outermost aperture) respectively. The corresponding beam steering angles are shown in fig.3 to obtain the horizontal focal length of 5.4 m.

2.2 Scheme for Vertical focusing (combination of both aperture displacement and inclination between two halves)

Vertical beam focusing is implemented on larger side of the grid, oriented towards vertical direction of the duct. Outermost apertures lie on vertical direction of the grid which is about double the distance of horizontal direction. They need larger displacement as expressed in Eq. (1). Larger displacements of the aperture deflect the beam trajectories more severely. They are intercepted by other grids causing increase in heat loading. To counter this effect, a small inclination (θ) in given to two grid halves along with aperture displacements, keeping displacement in the same range as given for horizontal direction. Inclination angle (θ) of 1.07° is obtained from Eq. (2) for the distance (l) of central aperture (indicated by zero on horizontal axis in fig.4) is of ~ 133.08 mm and vertical focal length of 7 m. It is to be noted that inclination angle is obtained from Eq. (2) by replacing θ by θ. This does not have any offset i.e., Δx=0. For this aperture, no beam steering is required (θ=0). The beamlets lying above this central aperture are steered in the direction of the beam deflection caused by inclining grid halves. The beamlets lying below the central aperture are steered in the direction opposite to the beam deflection. If θ is the beam steering angle and θ is the inclination of grid halves, the net beam steering θ = θ + θ. The value of θ is adjusted according to the distance of aperture from the central aperture. The opposite is true for the apertures lying below the central aperture, the beam steering angle in this case is given by θ = θ − θ. The positive and negative values of θ is obtained by the direction of displacement of apertures in the deceleration and earth grids with respect to axis of the corresponding aperture in the acceleration grid. Vertical beam steering angles and the corresponding net beam deflection angle, including inclination angle of 1.07°, for various aperture offsets is shown in fig.4 for vertical focal length of 7 m. Fig.5 shows schematic 3D view of both the horizontal and vertical focusing scheme.
Fig. 4 Variation of vertical beam deflection angle with aperture offset.

Fig. 5 Three dimensional view of focusing of ion beam emitting from two grid halves.
3. Results

The performance test of PINI ion source has been carried out at MARION Test Stand of IPP, Julich, Germany [12]. Schematic of MARION Test Stand is shown fig.3. It is a multi-megawatt beamline test bed. It consists of a main vacuum tank with the ion source mounted on one end. Bending magnet and 6 cryopumps are installed inside. A smaller target tank, following the main tank, contains V-target, differential calorimeter and diagnostics equipment, Pb-target and an array of Faraday cups. As bending magnet is not activated during performance test, the beam consists of ion and neutrals. Scrapers are used to limit the beam to the apertures of the V-target and differential calorimeter which measure the vertical and horizontal beam profile calorimetrically.

3.1 Vertical beam profile

Vertical beam power profile is measured by V-target. It is water cooled copper structure and performs as a calorimeter. It consists of 6 upper and 6 lower plates with optimized cooling channels symmetrically are placed to the beam axis [13]. Each plate is made of CuCrZr alloy of size 22 cm × 15 cm × 2.2 cm which can take a maximum heat load of 450 kW with water flow rate of 2.8 kg/s at a working pressure of 15 bar and a pressure drop of 6.6 bar between inlet and outlet.

The inlet temperature is 25°C and outlet temperature is kept below 98°C. Local nucleate boiling is allowed. The V-target can take maximum beam power density (i.e, ions plus neutrals) of 15 kW/cm² on its axis. The plates have optimized tilt angles between 11° on beam axis and 23° at the entrance aperture so that the values for the maximum power density on the plates are not exceeding 2.9 kW/cm² (burnout power density is 4.1 kW/cm²). The difference of temperature between inlet and outlet of each plate and the total water flow rate are measured. These two parameters determine calorimetric value for the total beam power transmitted to V-target. This gives 12-point on beam power density profile. They are obtained from the measured thermal plate loads across the total vertical entrance aperture of ±19.7 cm with a vertical spatial resolution of ~3 cm. This profile is used to calculate physical parameters such as the total beam power transmission, the neutral beam power transmission to the V-target when the deflection magnet is charged, neutralization efficiency, vertical beam position etc. The accuracy of the calorimetric measurement is ±7%.
Vertical beam power profile is shown in fig.7. It is measured at a distance $z = 450$ cm from earth grid, 54 kV, 83 A hydrogen beam. The measured peak power density is 8.3 kW/cm$^2$ and $1/e$ width is $\sim 20.7$ cm. The asymmetry of the peak power position is due to the misalignment of ion source with MARION Test Stand vacuum vessel. The accuracy of vertical position, i.e., the center of the plate, is not better than $\pm 0.5$ cm for the full width half maxima (FWHM) of the beam profile [12]. The absolute value of the peak power density of the beam is found by calorimetrically measured value of power of each plate divided by the vertical projected area of the beam axis. The solid lines represent the Gaussian fits curve from which values of peak power density, $1/e$ width and vertical beam divergence are estimated. The asymmetry of peak power position is due to error in the alignment of the PINI ion source with test stand vacuum vessel. $1/e$ width estimated from measured horizontal and vertical beam power profiles at different acceleration voltage is plotted in fig.8. Pulse duration of these beam profiles is 1 s except 14 s at 31 kV and 0.5 s at 34 kV. We note that the beam width remain nearly same for both short and long pulse lengths. This indicates grids are thermally stabilized for extracted beam power of $\sim 1.3$ MW in time $< 0.5$s and that of 1 MW in time 14 s.
3.2 Horizontal beam profile

The horizontal beam profile is measured by differential calorimeter consists of an array of 38 V-shaped actively cooled copper blocks placed closely behind V-target on horizontal direction as shown in fig.6. Each copper block is 59.2 mm of height, 10 mm of thickness and maximum width of 52 mm. It intercepts beam shining through the end of the V-target on horizontal direction is opened to ~3 mm. The horizontal power density distribution is fitted with Gaussian curve. The peak power density ($P_o$), the horizontal position of the beam ($x_o$) and the divergence ($\theta$) are calculated from the fitted curve. The divergence is evaluated from the expression

$$\theta = \tan^{-1}\left( \frac{1}{2z} \frac{1}{\text{width}} \right) \text{ (deg)}$$

(3)

Where $z (=650 \text{ cm})$ is the distance from the earth grid.
Typical horizontal beam power density profiles of hydrogen ion beam at 54 kV, 83A is illustrated in fig.9. The peak power density is 8.2 kW/cm² and 1/e width of 21.6 cm. It may be noted that peak power density measured by differential calorimeter is in agreement with the value of the same parameter measured by V-target. The estimated beam divergence is 0.97°. Solid circles represent the experimentally measured points. The asymmetry of the peak power position is due to error in the alignment of the PINI ion source with MARION Test Stand vacuum vessel. It is to be noted that 1/e width estimated from horizontal beam profiles at different acceleration voltage ranging from 20 kV to 54 kV does not show any significant or systematic variation. Beam width which is 22 cm which is 3 cm more than width of the duct (19 cm). However, power in the wings is low. It would be intercepted by the actively cooled duct. Central portion of the beam can pass through the duct before it enters tokamak plasma.

4. Beam divergence

The measured value of beam width is used to calculate beam divergence with the help of Eq. (3). Beam divergence at different beam voltages in vertical (θv) and horizontal (θh) directions are plotted in fig.10. It is clear that vertical beam divergence at all beam voltages is consistently higher than the same in the horizontal direction. θv is 1.3°–1.5° and θh is 0.97°. Since divergence in two directions is measured with diagnostics set ups with different spatial resolution, it is not clear whether the beam has asymmetrical beam divergence. More probable reason is that beam has two divergence components. As a consequence, the measured vertical divergence is obtained by considerably poorer spatial resolution of the V-target. Another feature to note is that although beam voltage varies between 20 and 55 kV, the beam divergence shows relatively lower variation, with in ±0.05°, with beam voltage and is not simply vary with $1/\sqrt{B}$ . This indicates that divergence is largely determined by field distribution within the acceleration gap of the extractor than by ion temperature in the plasma box.
5. Verification of design value of horizontal focal length \( (f_h=5.4 \, m) \) and vertical focal length \( (f_v=7\, m) \) by PADET code.

MARION Test Stand has facility of measurement of vertical beam profile at a distance of 4.50 m and horizontal beam profile at 6.50 m from earth grid. Due to this limitation we did not have any provision of beam profile measurement at 7 m (vertical focal length). Verification of focal lengths is done in the following way: A Gaussian fit is made to horizontal power beam profile; experimentally measured by 38 thermocouples. From the Gaussian fit we calculate \( \text{1/e} \) width and this value is used to calculate beam divergence using equation (3). This estimated value of beam divergence and arbitrary values of horizontal focal length \( (f_h) \) and vertical focal length \( (f_v) \) are entered in PADET code [13] for plotting of power beam profile at the same distance. Comparison of experimentally measured beam power profile with the same predicted by PADET code is used to determine the best value of horizontal and vertical focal lengths. For example we have chosen horizontal power beam profile from the ion source performance test data for shot # 14316 with the following beam parameters: beam energy of 41.8 kV, extracted beam current of 61.3A, pulse duration of 1 sec, extracted ion beam power of 2.5 MW, \( \text{1/e} \) width of 21.73 cm and estimated beam divergence of 0.97°. Experimentally measured data is represented by blue circles and Gaussian fit curve is depicted in blue line in fig.11. The beam divergence of 0.97°, different values of \( f_h \) and \( f_v \) are entered into the input file of PADET code. Power density profile at a same distance of 6.5 m from earth grid is calculated. Fig.11 shows that closed fit to the experimentally measured power density profile is obtained for \( f_h = 5.4 \, m \) and \( f_v = 7 \, m \) as indicated by red line with red solid circle. These two power density profiles are in very good agreement which indicated that during ion source performance test at 41.8 kV, 61.3A \( H^+ \) beam generated from three grid accel-decel extractor system has \( f_h \sim 5.4 \, m \) and \( f_v \sim 7 \, m \) which meets the SST-1 NBI design value.
6. Conclusion

SST-1 plasma demands 0.5 MW neutral hydrogen beam power at 30 kV and 1.7 MW at 55 kV for SST-1 upgrade to raise plasma ion temperature of 1 keV. Therefore the ion extractor system is designed to have a large dynamic range long pulse operation capability. To meet this requirement ion extractor system has been designed with 3 multi-aperture grid system capable of extract 1 MW positive hydrogen ion beam power at 30 kV and 5 MW at 55 kV. In this paper, we have shown how use of numerical beam transport code can be effectively used to supplement experimental measurements to obtain useful information on the beam characteristics. We have demonstrated it by obtaining values of focal lengths in the vertical and horizontal directions from the measured beam widths at an arbitrary distance from the source. This procedure has an obvious advantage of obviating the need of test stand of length greater than the larger focal length of the beam. It is important to investigate the limits of this procedure in set up where benchmarking of results obtained by numerical modeling can be done by actual measurements. In NBI system to be used for large focal length like ITER, it may be worth investigating whether there would be an actual need of test stand having a physical length ~ 20 m to measure parameters of focal length.
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