# EVALUATION OF BEAM PROPERTIES OF A NEGATIVE HYDROGEN SOURCE BY DOPPLER SHIFT SPECTROSCOPY

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## Abstract

ROBIN (RF Operated Beam source in India for Negative Ion research) is a negative H- ion source, which is operational in IPR, Gandhinagar. For measurement of various beam parameters such as beam energy, beam divergence, beam homogeneity and the stripping losses, Doppler Shifted spectroscopy diagnostics was established on ROBIN. The beam properties are studied by varying the source pressure (0.3-0.6 Pa), RF power (30 kW-60kW), tank pressure (7 x $10^{-4}$ mbar – 5 x $10^{-5}$ mbar), the total applied voltage in the range of 7kV-24kV has been carried out. The beam divergence and stripping losses are estimated from the line profiles analysis of the observed Doppler shift spectrum. The homogeneity of the beam in the vertical direction has been evaluated by using eight lines of sight located at two symmetrical locations in the ROBIN test vessel. The effect of space charge compensation on beam divergence has also been studied by varying the test stand pressure. The observed beam divergence is found to be lower at lower applied voltages and started increasing monotonically with an increase in voltage. The beam divergence is found to be decreasing with increase in RF power. The stripping losses are higher at lower voltages and start decreasing with increase in applied voltage. The beam is more uniform in the upper portion in comparison with the lower portion. In this present work, the parametric evaluation of the beam properties is presented in detail and results are discussed.

## 1. INTRODUCTION

Neutral beam injectors are in operation for heating and diagnostics of tokamak for several years. [1]. Operation of a neutral beam injector involves plasma production, extraction of the ions and neutralization of the ions before injecting. For the ITER project, high energy neutral beams (>100keV) have to be injected for diagnostic and heating of the tokamak plasma. [2]. India is currently developing the Diagnostic Neutral Beam system for ITER in the test facility named Indian Test Facility (INTF) [3,4]. In order to gain expertise for operation of a large-scale ion source, a 1/8$^{th}$ size of the test facility, RF Operated Beam Source in India for Negative ion Research (ROBIN) is currently in operational phase. The operational experience gained on ROBIN will be used in development of ITER-DNB. The extracted negative ion beam from ROBIN is characterized by measuring beam energy, beam divergence, stripping losses, beam power density profiles using optical and calorimetric diagnostics, respectively. We have recently performed the spectroscopy based Doppler Shift Spectroscopy (DSS) for the measurement of beam divergence. The results can be found in [7]. DSS is a passive diagnostic system based on collection of emissions of the accelerated beam particles and the background gas. Due to the relative velocity of the particles emitting light, the spectrum of the emissions can be resolved using a high-resolution spectrometer. The Doppler Shift ($\Delta\lambda_D$) of emissions are given by the formula (1). Here, $\lambda_o$ is the wavelength of the background emissions, $v$ is the velocity of the accelerated particles, c is the speed of the light and $\theta$ is the angle of the observation. For obtaining a resolved signal, the beam has to viewed at an angle other than 90$^o$.

$$\Delta\lambda_D = -\lambda_o \frac{v}{c}\cos\theta \quad (1)$$

From the observed spectrum, the several beam parameters such as the beam energy, beam divergence, homogeneity and stripping loss are estimated.

In our earlier study the measurement of beam divergence is established. A formalism for estimation of beam divergence is developed and tested using the DSS data obtained in ROBIN test stand. The beam divergence measurement involves careful analysis of the line width of the observed DSS spectral corresponding to the fast hydrogen atoms, generated from the stripping of the H- ions in the drift region. The processes by which the fast hydrogen atoms are produced in the drift region are described in [7]. The observed line width is a convolution of various broadening mechanisms related to be optical measurements (broadening due to instrumental broadening and collection optics). Since the extracted beam is focused [6], the spectral line is broadened due to beam focusing in addition to the broadening caused by beam divergence. Hence the computation of the divergence is not straight forward and the propagation of error in the estimation of divergence is also needed to be estimated carefully. These details are already published in our recent publication [7]. However, these measurements were single channel measurements and yielded divergence of a portion of the beam. But, for assessing beam inhomogeneity (unequal beam divergence or beam properties) across the area of the beam. The beam emissions needed to be sampled either vertically or horizontally. The beam inhomogeneity has been studied by collecting emissions from the three ports in the vacuum vessel and estimating the beam divergence across the vertical of the beam. In the work reported here, the beam is probed with 8 line of sights and a parametric study of the negative hydrogen ion beam properties by Doppler Shift Spectroscopy is presented. The beam divergence is characterized by varying the source parameters such as the RF power, grid voltages, tank and source pressure. The inhomogeneity of the beam is studied by using a multi probe system and fraction of the stripping loss during acceleration has been evaluated.

## 2. EXPERIMENT

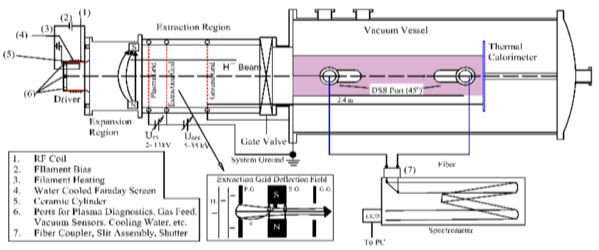


Fig. 1a. ROBIN test stand (source and vacuum vessel) with the spectrometer.

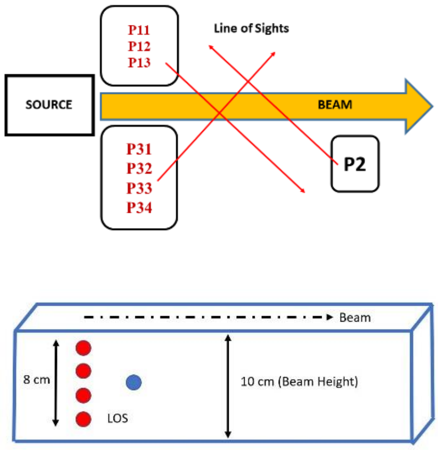


Fig. 1b. Schematic of the beam and LOS.

The ROBIN test stand has a source side and a drift side (vacuum vessel) whose length is 2.2 m. The experimental setup is shown in figure 1 (a). The source is an inductively coupled plasma source operated by a 1 MHz RF oscillator. The source is filled with hydrogen gas and the filling pressure can be varied from 0.3 to 0.6 Pa depending upon the experimental conditions. Hydrogen plasma is ignited in the driver region and the plasma expands to the expansion region. At the end of expansion region, the source has set of three of grids namely the Plasma Grid (PG), Extraction Grid (EG) and the Grounded Grid (GG). The plasma grid is cesiated by a cesium oven to facilitate the production of negative ions by the surface process. Across the grids high voltage are applied to extract the negative ions. The grids are designed on the Large Aperture Grids (LAG) design [6]. The grid originally has 776 apertures and for the present experimental campaign 146 apertures are unmasked and the remaining apertures are masked. The aperture diameter is 8 mm and the total extraction area is 73 $cm^2$.

The voltage applied between the plasma grid and the extraction grid is the extraction voltage (Uex) and the voltage applied across the extraction grid and the grounded grid is the acceleration voltage (Uacc). Two set of grids are used to produce low divergence beam. The maximum extraction voltage that can be applied is 10 kV and the maximum acceleration voltage is 25 kV. For the present experiments the extraction voltage is varied between 2-7 kV and the acceleration voltage between 7 – 15 kV to avoid excessive heat loads on the grids due to the co-extracted electrons and voltage breakdowns in the grid. The RF power is being varied in-between 30-60 kW. The source pressure for the experiment is maintained at 0.6 Pa and for the source scan experiments the pressure was varied between 0.3 to 0.6 Pa. To study the space charge compensation of the beam a dedicated hydrogen line is being installed in the tank. The pressure of the tank has been maintained between 0.02 – 0.1 Pa.

The extracted negative ions travels through the vacuum vessel interact with the background gas and neutrals are formed. The beam is dumped to a copper calorimeter located at 2.2 m from the grounded grid. During the neutralization process of the negative ions, the neutrals and the background gas goes to a higher excited state and falls back to the ground state. [7]. This transition in the state results in emission of photons during the neutralization phase. Due to the relative velocity of the neutrals and the background gas, the emitted photons are Doppler Shifted. To observe the light emissions, a spectroscopy system is being installed in the test stand. The system consists of optical probes, fiber optics and a high-resolution spectrograph. Three view ports are being used in the present experiment to observe the light emissions. In two view ports, vertical optical probe housing in being installed to observe spatially resolved emission of the beam. Two ports are in 45º and one port in 135º to the beam direction. In this present experiment a total of 8 probes are being used to collect the emissions. (fig 1b). The optical probes are plano-convex lens of focal length of 25 mm and diameter of 12.4 mm. The light collected by the optical probes are transmitted to the spectrometer by optical fiber of 600 $\mu$m. A spectrograph of 0.5 focal length which has a grating of 1800l/mm and a CCD of $1024 \times 1024$ pixels and pixel size of 13 $\mu$m is being used to resolve the Doppler shifted emissions. The setup is similar to the previous experiment conducted in the system. [7].

## 3. RESULTS and DISCUSSION

As mentioned in the previous section, to study the beam properties a multi beam probe is being installed in the view port. Fig 2a shows the spectrum for a shot of 17 kV at 0.6 Pa and 50 kW for all the LOS. In the spectrum, three peaks can be observed for each track. The peak at 656.28nm corresponds to the unshifted wavelength, the small peak in the vicinity of the un shifted peak corresponds to the emissions from the hydrogen bearing impurities present in the beam [7]. The peak around 659nm corresponds to the emission from the fast-moving beam particles i.e. the Doppler Shifted peak. Fig 2b shows the image of the spectra on the image plane of the spectrograph for visualization of the intensity obtained at different locations across the plane of the beam. An inspection of fig.2(a) &(b) clearly shows a non-uniformity in the intensities of the spectra indicating the variation of beam density (i.e. extracted current density) across the area of the beam.

From fig.2(b), it can be seen that the images corresponding to each group of atoms (as described above) are not aligned and there are some deviations in the peak positions. This is because of the fact that there may be deviation in the viewing angles (~1.5º) of the beam probes with respect to the beam axis. The exact viewing angles are estimated by using the corresponding Doppler shift values and known applied voltage [7].

The beam divergence has been estimated by measuring the 1/e width of the DSS spectrum. The broadening factors apart from the divergence and its contribution to the error in divergence estimation has been evaluated methodically. The error in estimation of the divergence is < 10%. The detailed treatment of estimating the parameters are given in ref [7]. For the parametric study of the beam divergence, the spectrum obtained from the LOS #P2 has been chosen because of its relatively high intensity. The LOS corresponding to port #P31, #P11 observe the upper portion of the beam while the #P21, #P12, #P32 observes the middle of the beam and the rest of the tracks observes the bottom portion of the beam, see fig 1b.

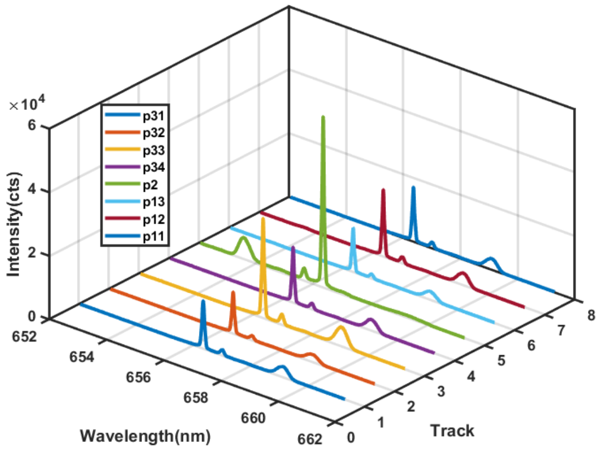


Fig. 2a. The spectrum of beam emissions observed by 8 LOS.

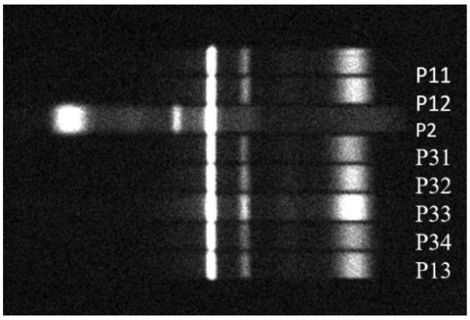


Fig. 2b. The image of the CCD showing the emissions from all the tracks

### 3.1 Parametric Study of Beam Divergence

A parametric study of the beam divergence has been performed systematically at various beam conditions. The source parameters such as RF power, grid voltages (acceleration grid, $U_{acc}$ and extraction grid, $U_{ex}$), source pressure, tank pressure are varied and corresponding spectra are recorded. The divergence evaluated for the parametric study are from the LOS #2(P2), which samples the central portion of the beam at an angle of 45°. To fix the extraction voltage for this parametric study, a perveance scan of the beam has been done. The perveance condition states that the extracted current increases following a power (3/2) law with the voltage applied across the extracted grid[8]. Another important parameter which is important for assesing the optimized beam parameter is normalised perveance. This is a ratio of the geometrical perveance to the source perveance and governs the beam optics[9]. The perveance condition decides the suitable operation regime for the ion source at which a maximum current can be extracted with minimum divergence. The divergence with normalised perveance is shown in fig (3). The divergence is minimum at the normalized perveance of 0.08. However for the present experimetns , based on our earlier operational experience, the ion source is operated in under perveant region (0.02-0.08) to minimise the co-extracted electrons[5].For this present experimental campaign, the study has been done at 5 kV extraction voltage at which the perveance of the beam is 0.03.

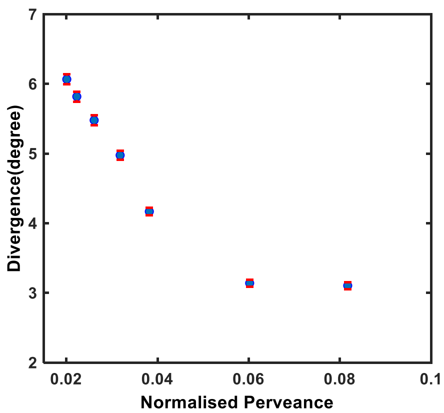


Fig.3. The normalized perveance condition of the beam at 12 kV acceleration voltage, 40 kW RF power and 0.6 Pa source pressure

The effect of the RF power coupled to the source on the beam divergence is shown in fig 4. It is observed that with increasing RF power the extracted beam current increases and beam divergence decreases. This is not surprising as the ionization efficiency of the sources is proportional to the RF power. Apparently , with increasing power, the number density of the negative ions increased thereby the extracted current also increased. According to the above stated perveance condition, at a fixed applied voltage, there exists a current value at which the beam is extracted with a minimum beam divergence. The results are shown for total voltage of 17 kV (Uex =5, Uacc = 12) at 0.6 Pa source pressure. As the primary aim of the source is to maximize the beam current, it can be said that with higher coupled RF power better divergence is observed.

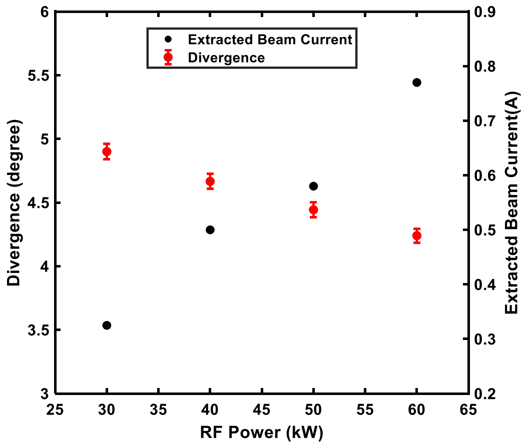


Fig. 4. The divergence and the extracted beam current variation with the RF at 17 kV total applied voltage in the grid.

The effect on the divergence due to the variation of the source pressure and the tank pressure has been studied. Increasing the filling pressure of the source leads to higher number density of the ions and so it is expected to have increased extracted current density with lower beam divergence. The source pressure is varied from 0.3 Pa to 0.6Pa and the divergence has been estimated, fig 5a. The decrease in the divergence is not drastic. The effect of space charge compensation due to the background gas is also investigated by using a separate gas feed line in the tank to inject $H_2$ gas independently. For a set a tank pressure (0.04 -0.1 Pa) there is no change in the divergence, as shown in figure 5b. The phenomena of space charge compensation need further investigation in the future experiments by increasing the tank pressure further more. The above space charge study has been done at 50 KW RF power and 17 kV total grid voltage (5kV in extraction gap and 12kV in acceleration gap).

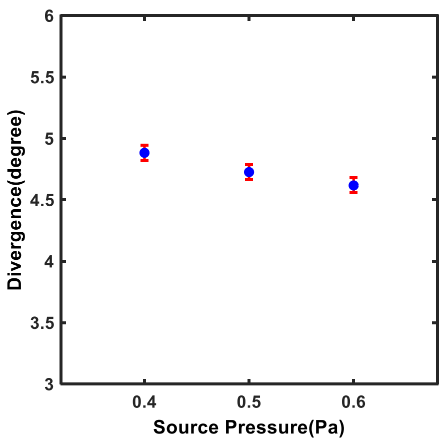


Fig. 5a. The effect of source filling pressure on the beam divergence.

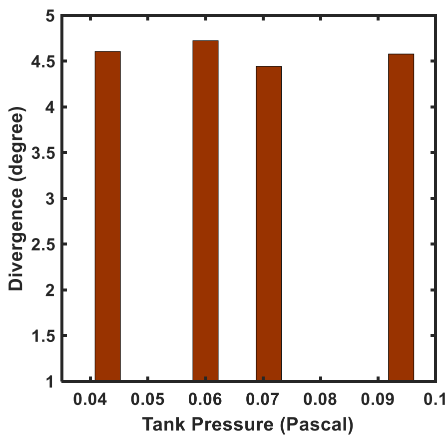


Fig. 5b. The effect of tank pressure on the beam divergence.

The effect of the voltage applied across the grids (Uex and Uacc) on the divergence has been studied. From fig 6a, it is observed that with increasing extraction voltage from 2kV to 7kV, the divergence of the beam increases . As the extraction voltage increases probably the beam is over focussed which leads to the increasing divergence. The optimum extraction voltage seems to be 2-5 kV, figure (6a). The study of the effect of the acceleration voltage on the beam divergence is shown in figure (6b). The variation of the beam divergence due to the acceleration voltage is about 20% for Uacc = 7 to 15 kV. This shows the effect of the acceleration voltage on the beam divergence is comparatively less as in case of the extraction voltage. Therefore, it can be stated that the beam optics primarily controlled by extraction voltage, which influence the plasma meniscus of the beam extraction surface at the beam origin plane. The minimum beam divergence has been estimated to be ~ 2.5 degree at 2 kV extraction voltage( Total applied voltage: 14kV).

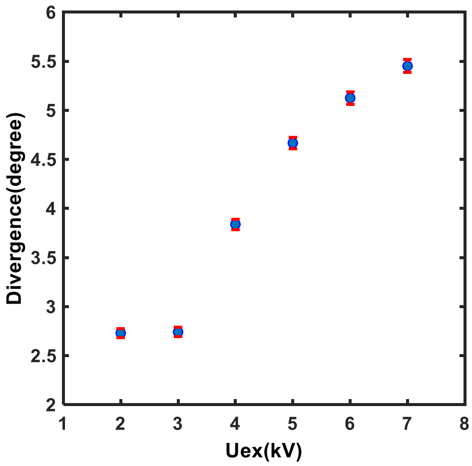


Fig. 6a. The variation of the divergence with the voltage applied across the extraction grid ($U_{ex}$) at $U_{acc}$ = 12 kV, RF Power = 40 kW and source pressure = 0.6 Pa.

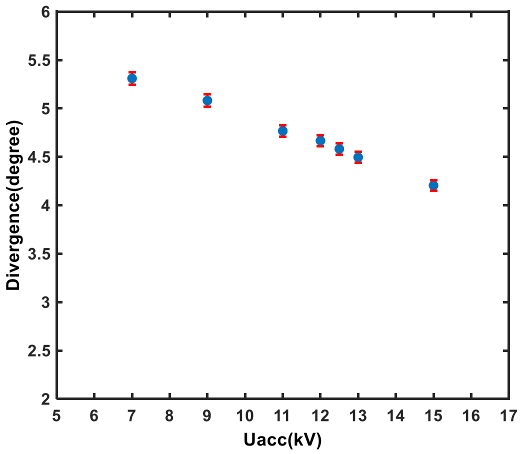


Fig. 6b. The variation of the divergence with the voltage applied across the extraction grid ($U_{ex}$) at $U_{acc}$ = 12 kV, RF Power = 40 kW and source pressure = 0.6 Pa.

### 3.2 Beam Inhomogeneity

As discussed in section.1, the beam inhomogeneity is studied by collecting emissions from the beam using a vertical probe arrangement. The probes installed in the vacuum vessel observe the beam at the upper plane (UP), midplane (MP), below midplane (BMP) and lower plane (LP). Fig 7a shows the divergence of the beam along the vertical direction of the beam (10 cm height) and the variation in the divergence is about 10%. As the beam divergence depends on the extracted current density. It can be said that, an inhomogeneous extracted current density of the beam across the grid may result in the variation of the beam divergence. The low variation in the divergence shows that the extracted current density is nearly uniform across the beam plane. The area under the curve of the Doppler Shifted peak is shown in fig 7b. The beam emissions from the midplane is comparatively higher than the bottom and the upper plane although total emissions are approximately same. Hence, it can be inferred that that beam inhomogeneity is less than 10 %.

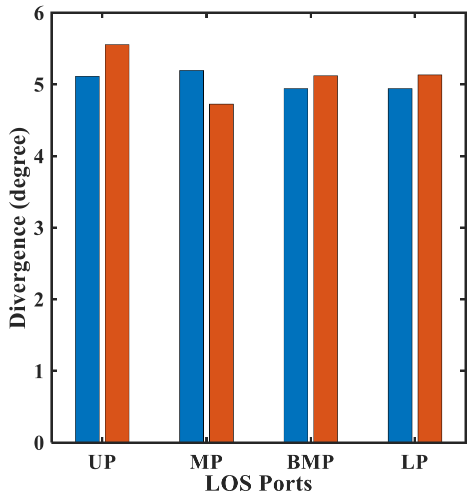


Fig. 7a. The divergence of the beam grouped for the probes installed at the opposite ports.

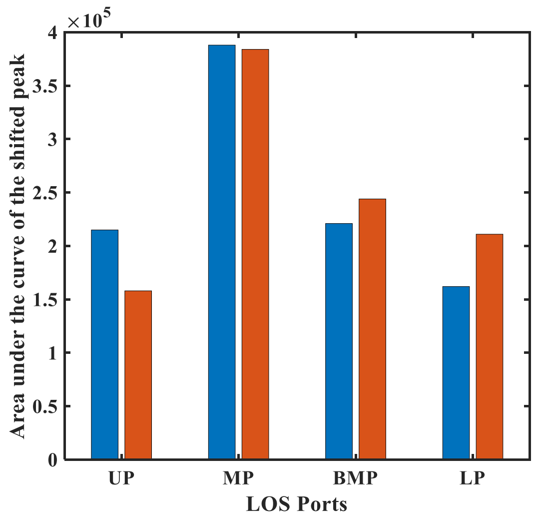


Fig. 7b. The area under the curve of the emissions collected by the probes.

### 3.3 Stripping Loss

The stripping loss of the beam can be quantified by analyzing the stripping peak of the spectra which corresponds to the emissions from the beam particles which are not fully accelerated in the accelerator system. The stripping loss has to be analyzed by comparing the ratio of the stripping peak and the full energy peak. It is known that with higher source filling pressure stripping increases due to more available molecules in the grids for stripping. To understand the effect of stripping, the source has been operated at three pressure configurations i.e. 0.4 Pa, 0.5 Pa and 0.6 Pa. In fig 8a, the spectrum of the beam for the three pressure configurations has been shown. The area under the curve of the stripping peaks has been shown in figure 8b. With decrease in the pressure of the source, the stripping reduces significantly, about ~ 25% due to the reduction of pressure from 0.6pa to 0.4pa. This shows that to maintain a low stripping fraction in the accelerated negative ion beam, it is necessary to operate the source at a lower pressure. The effect of the voltage on the stripping loss shall be reported on future publication.

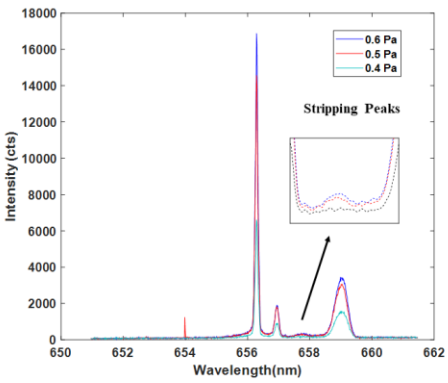


Fig. 8a. The spectrum for shots at three different pressures (0.6, 0.5, 0.4 Pa) showing the stripping peaks

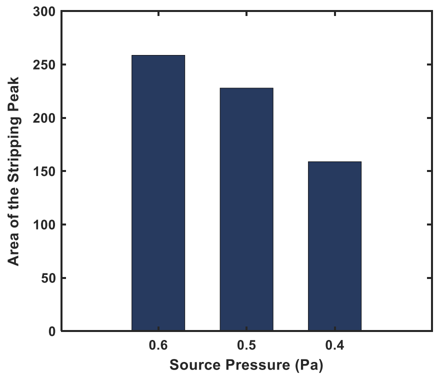


Fig. 8b. The area under curve of the stripping peak at 17 kV total grid voltage at 40 kW RF power.

## 4. SUMMARY

By Doppler Shift Spectroscopy the beam divergence of a negative ion source has been estimated for various source conditions. It has been found that the beam divergence primarily depends on the extraction voltage which decides the beam optics by influencing the meniscus of the beam emission surface in the plasma near plasma grid aperture location. The inhomogeneity of the beam has been evaluated by a multiple probe system and the effect of the source pressure on the stripping has been studied. The beam uniformity is nearly within ~ 90% and stripping reduces significantly ~ 25% due to reduction of pressure from 0.6pa to 0.4pa.

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