Direct Comparison of H^- and D^- Single Beamlet Divergence in View of ITER's NBI System

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Introduction

The ITER Neutral Beam Injection (NBI) system will have strict requirements on the beam optics: a maximum divergence of 7 mrad for the beamlet core (85%) and up to 30 mrad for the halo (15%), and a beam uniformity of ≥ 90 %, at a source filling pressure of 0.3 Pa for both hydrogen and deuterium operation [1]. Negative ion test facilities such as SPIDER (full sized ITER source, 1280 beamlets), ELISE (1/2 sized source, 640 beamlets), and BATMAN Upgrade (BUG) (1/8 size source, 70 apertures) are developing the RF ion sources to meet ITER's ion source criteria. Positive ion NBI sources have been in routine operation for many years, and the beam optics observed in these sources is typically the same. However, ITER's negative ion sources will use magnetic filter fields and directly extract ions produced on surfaces, and so a change of isotope may affect the final beamlet divergence.

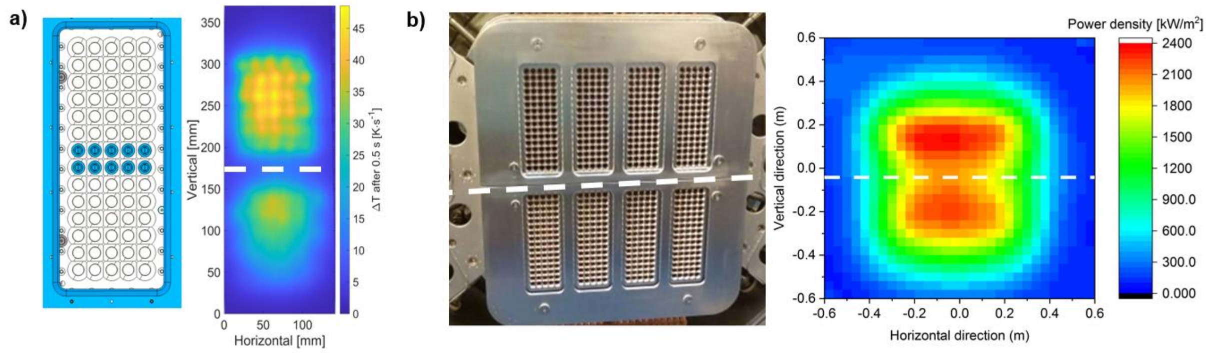

Figure 1: Grid system and calorimetric beam measurements at a) BUG and b) ELISE test stands [2]. The ELISE calorimeter in this example uses square copper blocks, which have a lower resolution than the CFC tile used at BUG. The BUG beam can be seen to have a greater top-bottom asymmetry in the extracted ion current.

The BATMAN Upgrade [3] test stand is well suited for studies of beam optics in hydrogen and deuterium. It utilises a magnetic filter field (generated by passing a current through the plasma grid (PG)) to reduce the electron temperature and decrease negative ion losses. The filter field causes ×B drifts in the source which results in a plasma density asymmetry in front of the PG [4], which can be seen in figure 1 a). This drift is more pronounced in smaller ion sources like BUG when compared to larger sources, such as ELISE (figure 1 b)). The acceleration system of BUG is composed of the plasma grid, extraction grid (EG), and grounded grid (GG), which accelerate the extracted negative ions with a typical extraction potential (U_{ex}) of 5kV (for the best beam optics) and a maximum beam energy of 45keV.

A retractable high resolution (~0.6 mm) 1D CFC tile (dimensions 376x142x20 mm) is positioned 851 mm from the GG which measures spatially resolved thermal images of the ion beam [5]. The PG of BUG can be masked to isolate a single extraction aperture in the upper half of the grid, allowing measurement of the single beamlet divergence using the CFC, as shown in figure 2. The e-folding width of a 2D rotatable Gaussian fit is then used to calculate the divergence of the beamlet core and halo by assuming the beamlet has a size of 0 mm at the exit of the GG aperture.

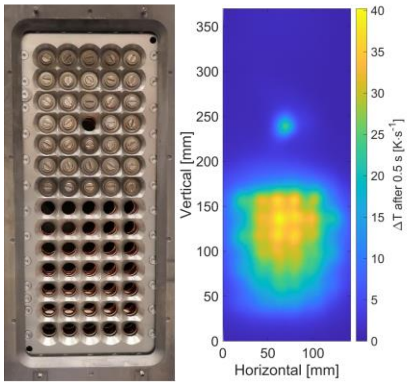

Figure 2: Masking scheme of the BUG Plasma Grid, and the resulting image of the CFC, with the isolated beamlet in the upper half.

After Caesium conditioning [4], 2D parameter scans were performed: one source parameter (e.g. filling pressure, filter field strength, PG bias current, etc) is varied whilst scanning the RF power. Scanning the RF power typically increases the extracted current, which allows comparison between scans using the normalised perveance, P/P0, which is a measure of the beam optics. Here the extracted negative ion current is normalised with respect to the theoretical maximum extractable space charge limited current given by

$$I_{max} = \frac{4}{9}\pi\varepsilon_0\sqrt{\frac{2e}{m}}\left(\frac{r}{d}\right)^2 U_{ex}^{\frac{3}{2}}, \qquad \frac{P}{P_0} = \frac{I_{ex}}{I_{max}}$$

where m is the ion mass, r is the extraction aperture radius, d is the PG to EG separation distance, U_{ex} is the extraction potential between the PG and EG, and I_{ex} is the *average* extracted ion current across the whole grid. As a current measurement of the single beamlet is not available, it was assumed that the current extracted through the isolated aperture was equal to the averaged ion current, and therefore had the same normalised perveance as the value calculated from this average.

Results and Discussion

A comparison of the single beamlet CFC divergence from a selection of different scans in both deuterium and hydrogen are shown in figure 3. When operating in deuterium, the coextracted electron current is higher compared to hydrogen, and so the filter field strength used is typically greater for deuterium plasmas. Figure 3 shows the divergence of the deuterium beamlets is found to be lower than that measured for hydrogen by up to 20% at the ITER filling pressure of 0.3 Pa for the equivalent normalised perveance. The deuterium beamlets also appear to become overperveant: the divergence decreases until some optimum P/P_0 has been reached, where the divergence then starts to increase as the perveance is further increased. For similar scans in hydrogen, it can be seen that the optimum normalised perveance was not reached (as the divergence continues to decrease). The minimum divergence measured for deuterium beamlets was 13-14 mrad, higher than the ITER required 7 mrad. A higher divergence is expected due to operating at a much lower beam energy than the planned ITER NBI energy, as divergence is expected to decrease at higher acceleration potentials (BUG typically uses extraction voltages of 5 kV and beam energy of 37.5 keV, compared to ITER's 10 kV and 1 MeV).

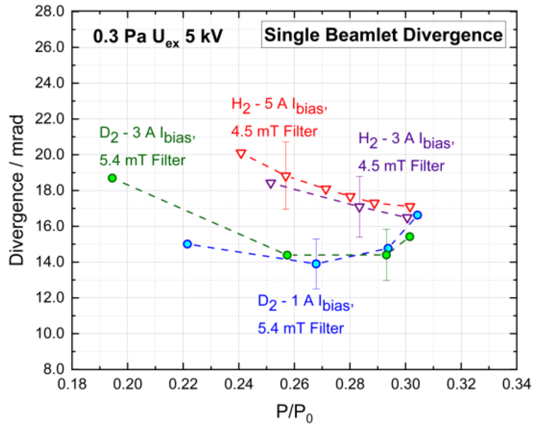

Figure 3: Measured single beamlet divergence for perveance scans of hydrogen and deuterium at different PG bias current (I_{bias}) and filter field strengths. In addition to the filter field, I_{bias} also affects plasma uniformity in front of the PG.

The optimum normalised perveance should be the same for both isotopes when using identical extraction and acceleration grid potentials, hence the indicated difference of 20% is not expected. This difference is also not observed in larger ion sources such as the half-sized source ELISE [2]. This indicates that the uniformity of deuterium plasmas is different than for hydrogen (caused by the increased filter field) with the consequence that the average current density is not representative for the isolated beamlet. It should be highlighted, there may be a genuine difference in the minimum divergence between the two isotopes, due to a difference in perpendicular temperature, or other effects cause by the grid system. As previously discussed above and shown in figure 1, BUG has a more pronounced top-bottom beam asymmetry than a larger ion source such as ELISE. The asymmetry in the extracted beam current is caused by an asymmetry in the plasma density in front of the PG. A asymmetric flux of positive ions to the surface results in a nonuniform H^-/D^- production and

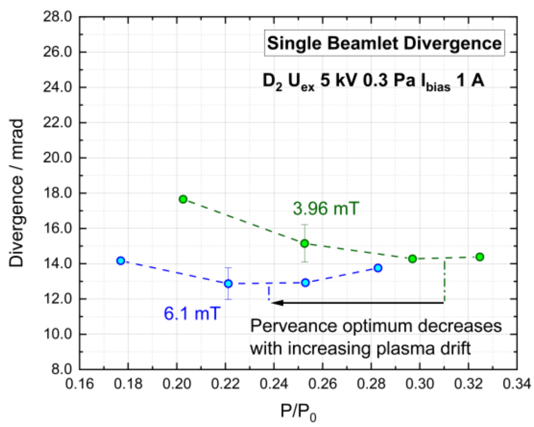

Figure 4: Deuterium perveance scans using different PG filter field strengths. As filter field strength is increased, the perveance optimum decreases due to the plasma drift in front of the PG.

neutralisation of negative space charge build up in front of the PG surface, leading to an asymmetry in the extracted current. If the local beamlet current density is larger than the globally measured average, then the local isolated beamlet perveance will be larger than the calculated average normalised perveance. If this ratio between the current extracted from the single beamlet aperture and the globally measured average changes between isotopes, then the extracted current densities will not be the same at some equivalent global normalised perveance, as shown by the different perveance optima in figure 3. As a result, the observed 20% difference in divergence (or at least part of it) is likely to be a consequence of different local beamlet current density. As the plasma drift is enhanced by increasing filter field strength, the deuterium perveance optimum will shift to a lower value, as the ratio of the local beamlet perveance to global average perveance increases. Figure 4 shows that increasing the strength of the magnetic filter field moves the perveance optimum from between 0.3 and 0.32 to between 0.22 and 0.24. This is also supported by the consistent minimum divergence at the perveance optimum for the various filter field strengths shown in figures 3 and 4.

Conclusion

A 20% difference in the minimum single beamlet divergence was observed between hydrogen and deuterium at BUG for comparable source parameters and average normalised perveance. This difference is not likely to be a genuine isotopic effect, but due to different local beamlet perveance relative to the globally measured perveance. The CFC measurements have shown that in order to make ITER relevant single beamlet optics comparisons between hydrogen and deuterium in smaller ion sources such as BUG, care must be taken to ensure that the local beamlet perveance is the same for both isotopes. This can be done either by directly measuring the extracted current density of the isolated beamlet using a beamlet current monitor or by changing the filter field strength and topology to attain the same plasma symmetry in front of the grid system for both isotopes to achieve the same local beamlet perveance.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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