Highlights

Improved Understanding of Beamlet Deflection in ITER-Relevant Negative Ion Beams through Forward Modelling of Beam Emission Spectroscopy

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- BES spectra can be used to measure more than just divergence
- Additional information within spectra is best understood with forward modelling
- Horizontal deflection of beamlets affects location and width of Doppler peak
- Influence of multiple beamlet rows must be considered in analysis

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Abstract

NBI systems for the ITER tokamak will require large (1 m × 2 m cross section) and powerful negative ion beams to achieve the required 16.5 MW per beamline. Such negative ion beams can only be created from the combination of many individual beamlets - 1280 per beam in the case of the ITER Heating Neutral Beam (HNB). These beamlets are required to have a core divergence of less than 7 mrad. However in these large and powerful beams, individual beamlets cannot be measured, and divergence values can only be obtained for a mixture of multiple beamlets.

To investigate this, experiments were performed at the BATMAN Upgrade (BUG) test facility, a negative ion source roughly 1/8 the size of the ITER HNB. Through Beam Emission Spectroscopy (BES) measurements, and synthetic diagnostic results from the code BBCNI, insights into the effects of beamlet mixing on experimental observations have been obtained. For a single beamlet, it is expected that BES measurements obtain a Doppler shifted H_α peak with a roughly Gaussian profile, the width of which is related to the beamlet divergence, and the central wavelength is a function of the beamlet energy and the BES observation angle. In experiments at BUG, it was observed that the amount of Doppler shift in some BES lines of sight depended on the ratio of voltages applied to the grid system, even though the total voltage remained the same.

By combining diagnostic data from the experiment and forward modelling from BBCNI, it was found that the change in Doppler shift for the affected lines of sight was caused primarily by changes to the horizontal deflection of beamlets by uncompensated magnetic fields - termed ‘zig-zag’ deflection due to the alternating polarity by aperture row. The amount of Doppler shift was further modulated by the beamlet divergence, which affects the amount of beamlet mixing within the BES lines of sight.

Keywords:
Neutral Beam Injection, Beam Diagnostics, Beam Simulation, Synthetic Diagnostics

1. Introduction

For the ITER fusion experiment, currently under construction, two neutral beam injection (NBI) systems are foreseen to deliver a total of 33 MW of power for both heating and current drive [1]. This power will come from the neutralisation of either 46 A of 0.87 MeV H^- ions or 40 A of 1.0 MeV D^- ions, with a beam time of up to 1 hr. The H^- or D^- ions will be created in an RF driven ion source, before being extracted and accelerated by a multi-grid, multi-aperture system. The use of a gridded system means that the final ion beam will be made up of 1280 individual beamlets, in 16 rectangular groups of 80 beamlets each. To reduce transmission losses, strict requirements are placed on the divergence of the beam, namely a core with a divergence of < 7 mrad, with up to 15% of the beam power allowed in a ‘halo’ having a 15 mrad to 30 mrad divergence [1, 2]

A number of facilities exist for testing the designs and principles of RF driven ion sources. Within these devices, a hydrogen (or deuterium) plasma is generated with a power of up to 100 kW in each RF driverbefore moving into an expansion chamber. Here the electron temperature (T_e) is reduced by a magnetic filter field from $T_e \approx 10$ eV inside the driver to $T_e < 2$ eV just in front of the first grid, which reduces the electron impact destruction of negative ions; the electron density is also reduced from 10^{18} m^{-3} to 10^{17} m^{-3}, reducing the current of electrons that are inevitably co-extracted with the

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negative ions [3]. As this field is typically oriented horizontally, perpendicular to the direction of plasma expansion, a vertical drift of the plasma occurs, leading to an inhomogeneous distribution in front of the grid system [4, 5, 6]. As this field also extends beyond the grid system, beamlets are also deflected in the vertical direction. Caesium is evaporated into the source during operation and is redistributed onto surfaces by the plasma, thereby reducing the surface work function [7, 8]. This increases the surface production of negative ions on the plasma facing grid, or Plasma Grid (PG), and thereby the extracted negative ion current [9].

The second grid (Extraction Grid - EG) contains permanent magnets to create a (mostly) vertical 'deflection field', that alternates in polarity row-by-row. This field is used to deflect co-extracted electrons onto the surface of the EG and remove them from the beam; the heavier ions are also deflected slightly horizontally, but continue on through the rest of the acceleration system. After exiting from the last grid (Grounded Grid - GG) the ions have the full acceleration energy, as well as some residual sideways deflection if it is not fully compensated [10, 11]. These residual deflections not only alternate row-by-row in the horizontal direction, but may also change in magnitude across the grid system, as the magnetic fields are not perfectly uniform. This alternating horizontal or 'zig-zag' deflection, that results from the magnets in the EG, has been observed to depend on experimental parameters [12].

Measuring the divergence of these ion beams is a challenge because of their high power density, large size, and overlapping beamlets. Diagnostics for doing so at full power and duration are by necessity spatially averaged measurements: either Beam Emission Spectroscopy (BES) observing a line of sight [13]; or beam dump calorimetry, where the beam footprint can be measured with a typical resolution of several centimetres at a position several metres from the grid system [14].

BES records the Doppler shifted H_α light emitted as beam particles interact with the background gas. For a specific particle, the amount of Doppler shift observed depends on both the velocity of the particle and the angle of that velocity with respect to the collection optics. If H^- particles in the beam are assumed mono-energetic (which is true within 1%), the width of the measured Doppler peak can be related to the divergence of the particles, this being the spread in their velocity directions. The minimum divergence measurable depends on the resolution and properties of the spectrometer used, but is typically on the order of single milliradians ($\lesssim 0.1°$).

As diagnostic signals are spatially averaged, results will be a mixture of information from different beamlets, depending on the BES line of sight or calorimeter position. Diagnostic results may be affected by any differences between beamlets that occur within the measurement region. The particle tracking and ray tracing code BBCNI is able to resolve these beam and beamlet effects, by applying synthetic diagnostics to a full-beam simulation [15]. Presented in the following sections is an example of how this approach can help to analyse and understand experimental data, in this case an anomalous change in the central wavelength of the Doppler peak observed by some BES lines of sight due to zig-zag deflection at the BATMAN Upgrade test facility.

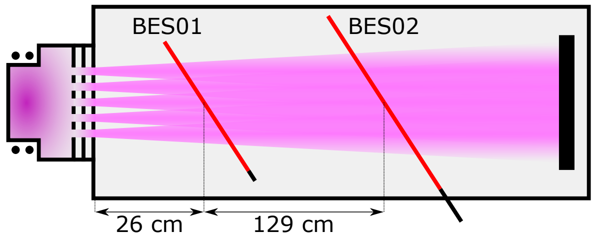

Figure 1: Sketch of the ion source and beamline at the BUG test facility, showing the BES lines of sight and their locations.

2. Experimental Data

The ion source at the BATMAN Upgrade test facility (BUG) [16] is able to accelerate negative H^- or D^- ions up to 45 kV with a 4 grid system containing 70 apertures arranges in 14 rows, with a pitch of 20 mm. This is roughly the same as one beamlet group in the foreseen ITER heating neutral beams. It is well outfitted with beam diagnostics, including two separate groups of BES lines of sight observing the beam horizontally, one crossing the beam 1.29 m from the GG, and a closer set at 26 cm from the GG [12], as shown in Fig. 1. While the complications due to beamlet mixing, as described above, certainly apply to the the further group (BES02), the closest group (BES01) may be able to detect signals from just one row of beamlets. If this is the case, then the expected broadening from zig-zag deflection may not occur, and instead the central wavelength of the Doppler peak will change according to the horizontal angle of row of the beamlets. This deflection can be up to ±0.7°, which corresponds to an additional Doppler shift of about 100 pm for a total energy of 25 kV and an observation angle of 57°.

As part of the experimental campaign investigating ion optics at BUG, a scan was performed in the ratio between acceleration voltage, U_{acc}, and extraction voltage,

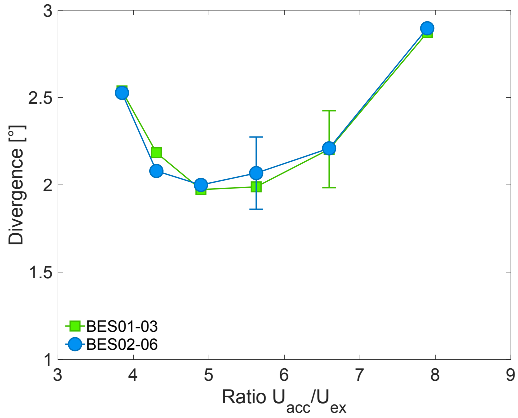

Figure 2: Beam divergence as a function of voltage ratio, for $U_{HV} = 25.5$ kV and $P/P_0 = 0.22$. Measurements are taken from two vertically centred BES lines of sight at 26 cm from the GG (BES01-03) and 1.29 m from the GG (BES02-06).

U_{ex}, these being the voltages in the second and first grid gaps, respectively. Other experimental parameters were kept constant. The total voltage was $U_{HV} = 25.5$ kV, and a source filling pressure of 0.36 Pa was used, close to the ITER target value of 0.3 Pa. A magnetic filter field was generated by driving 1.5 kA vertically through the PG to give a field strength of roughly 3.15 mT in front of the PG; higher field strengths start to detrimentally affect the extracted ion current. The RF power was changed between 25 kW and 65 kW to keep the normalised perveance constant at 0.22 as U_{ex} varied, with normalised perveance being defined as the perveance $\Pi = I_{ex}/U_{ext}^{3/2}$ normalised to the space-charge limited maximum possible perveance for planar grid surfaces [17]. The divergence is high for this experiment due to the suboptimal perveance used for this scan - this grid system shows a minimum divergence of around 11 mrad to 14 mrad (0.6° to 0.8°) at a normalised perveance of around 0.28 [18, 19].

Divergence measurements from two of the BES lines of sight are plotted in Fig. 2, where results are given from the vertically centred lines of sight from the first and second arrays of BES, these being BES01-03 and BES02-06. It can be seen that the measured divergence is similar for both sets of BES, with a minimum of around 2° at a ratio between 5 and 6.

The results in Fig. 2 are expected as, at a constant total U_{HV}, the ratio of U_{acc} to U_{ex} affects the electrostatic lenses in the grid system, causing a change in the beamlet focussing and therefore divergence. However, the analysis of the central Doppler wavelength for different lines of sight in Fig. 3 shows a more complex behaviour. Plotted here is the Doppler shift anomaly - the difference between the expected 2.643 nm of Doppler shift due to the total high voltage and the angle of the BES lines of sight (57°), and the actual Doppler shift measured by the BES. Along with the trends, discussed below, there is a clear systematic error in this data. Contributions to this could come from either the measurement of the high voltage or the positioning on the BES optical collection heads. The high voltage measurement has an estimated uncertainty of ±500 V, which corresponds in this case to ±26 pm of Doppler shift. If the BES optical heads are misaligned by ±1° this would contribute up to ±70 pm of offset in the Doppler peak central wavelength. The observed offset of 30 pm to 50 pm is likely to come from a combination of these two effects, but the actual contributions are not currently discernable. Despite this, it can be seen that there is a dependence of the observed Doppler shift for BES01 on the ratio U_{acc}/U_{ex}.

As the behaviour is so different between lines of sight, this can only be due to local changes in the horizontal angle of the section of beam that is sampled by the lines of sight. The appearance of a variation in BES01, but not in BES02, fits with the previous hypothesis that BES01 may detect light only from a single row of beamlets, whereas beamlet rows have merged by the time they get to BES02. As the magnets causing zig-zag deflection are embedded in the EG, a change in the grid voltages will change the trajectories of the ions as they pass through this field, thereby changing their deflection. The beamlet rows observed by the BES01 lines of sight at ±6 cm have a different polarity of deflection field to those at 0 cm or ±12 cm, which is why the Doppler shift moves in the opposite direction.

As changes to the beamlet trajectory should be monotonic with the change in voltage ratio, so too should be the change in Doppler shift due to the zig-zag deflection. As this is contrary to what is observed, further investigation is required. In the next section, the code BBCNI is used to recreate the experimental data to determine why such an effect is seen.

3. BBCNI Results

BBCNI simulations were performed using the same parameters as the experimental data from Section 2, with homogeneous extraction. The simulations ran with 10^5 initial particles per aperture, with an initial energy of 3 eV and a perpendicular temperature of 1 eV. Individual electric fields are provided for each aperture from IBSimu calculations [20], and magnetic fields are given for the whole domain using magnetostatic calculations

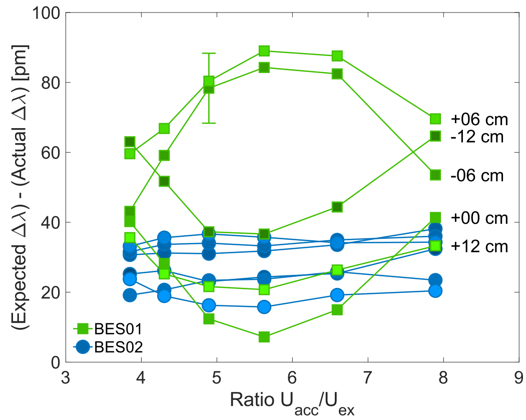

Figure 3: Doppler shift anomaly as a function of voltage ratio as measured by selected BES lines of sight from BES01 and BES02 in the experiment. Distance labels on the curves for BES01 correspond to the vertical distance of the line of sight from the horizontal centre line of the grid system. The Doppler shift anomaly is constant for BES02, so no distance labels are given.

for the deflection field and ANSYS® Workbench™ for fields generated by the current flowing through the PG.

Figure 4 shows the anomalous Doppler shift as measured by BES01 in the BBCNI results. It can be seen that at low U_{acc}/U_{ex} the simulated behaviour matches that seen in the experiment, even though the systematic offset is very different; the reason for this is currently unclear. In the synthetic data, there are still minima and maxima in the Doppler shift anomaly, but the reversal at high voltage ratios is not as extreme as seen in the experiment.

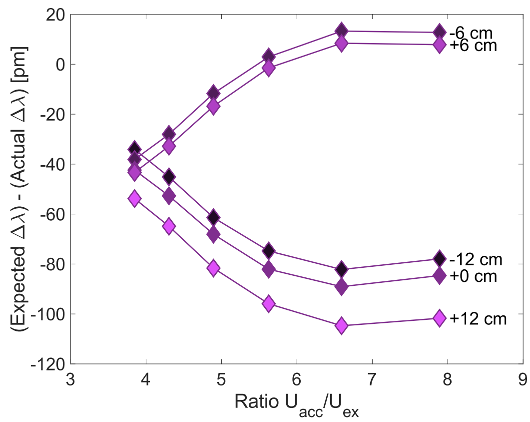

Figure 4: Doppler shift anomaly as a function of voltage ratio, as measured by BES01 in the BBCNI simulation.

The beamlet horizontal angles for the central column of 14 beamlets as they exit the GG in BBCNI is plotted against the voltage ratio in Fig. 5. The alternating zig-zag deflection can be seen as the two populations of positive and negative angles. A small spread within each population can also be seen, which indicates that there are differences in the magnet field experienced by each beamlet. The beamlet angles show the aforementioned monotonic behaviour, in contradiction with the experimental and simulated BES results in Fig. 3 and Fig. 4.

The relative contribution of beamlet row 8, the row of beamlets contributing most to the vertically centred line of sight BES01-03, is calculated from the individual spectra from each aperture, which are available in BBCNI. This data is shown along with the experimental and synthetic divergence measurements in Fig. 6. As the measured divergence changes, so too does the contribution of the central row to the light seen by BES01-03. Contributions to the recorded spectrum from neighbouring rows will have the Doppler peak at a slightly different wavelength, due to the alternating deflection field and resulting zig-zag effect, as discussed.

If the difference in angle between left and right deflected beamlets is smaller than the divergence, then the two Doppler peaks will not be distinguishable, as the difference in central wavelength will be smaller than the width of each peak. Therefore the encroachment of spectra from the neighbouring rows will be visible as a skewing and broadening of the observed Doppler peak. The Doppler shift anomaly in both experimental and synthetic data reduces slightly above a U_{acc}/U_{ex} ratio of around 6 as the beamlets from the neighbouring rows start to impinge on the lines of sight. This is despite the beamlet angles continuing to increase with the voltage ratio, as shown in Fig. 5.

It should be noted that U_{acc}/U_{ex} is just one example of a parameter that can change what is seen by a spatially averaging beam diagnostic. Changes to the magnetic fields, including the long range filter field, or particle energies, will change the horizontal or vertical position of the beam, and therefore which parts are observed by diagnostics. Any other parameter that has an impact on the divergence will cause beamlets to merge at different distances from the GG.

4. Conclusions

Existing and future negative ion beam facilities need to be well diagnosed and understood so that the strict requirements placed on NBI systems for ITER can be met. The example presented in this work shows the effects beamlet mixing can have on experimental results

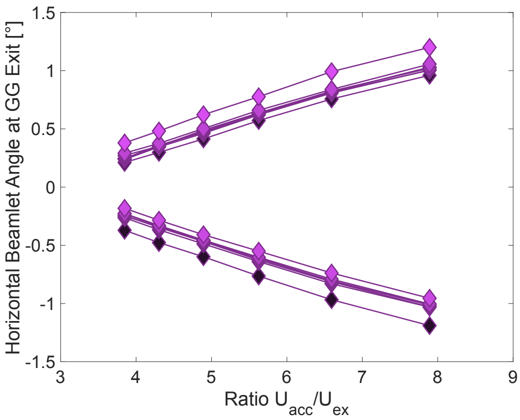

Figure 5: Beamlet angles for the central column of 14 apertures as calculated by BBCNI. The beamlet angle is defined as the mean angle of all ions comprising that beamlet.

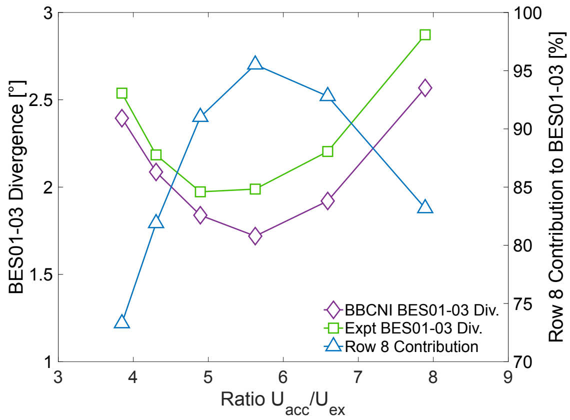

Figure 6: Beam divergence as measured by the vertically centred line of sight in BES01 from the experiment (squares) and the simulation (diamonds). The contribution of the 8th beamlet row (counted upward) to BES01-03 (triangles) is shown to depend on the measured divergence.

of large negative ion beams, which are necessarily composed of many individual beamlets. The importance of diagnostic forward modelling is also shown, as is how a better description of the beam behaviour can be obtained by combining simulations and experiment than with experimental data alone.

Changes in any experimental parameter that causes differences in the horizontal or vertical deflection, or in the divergence of beamlets, will impact the results of spatially averaging diagnostics. The precise impact of beam mixing effects will depend on the beam properties, the nature of the diagnostic being used, and the location at which the beam is being diagnosed.

The present investigation shows just one example of this, whereby variations in the uncompensated zig-zag deflection can cause an anomaly in the measured Doppler shift of light emitted from beam particles. It was further shown how this effect is modulated by the beam divergence, causing unexpected non-monoticities in the data due to a variation in the amount of beamlet mixing that occurs. This means that even if the zig-zag deflection were to be fully compensated, as foreseen for ITER, beamlet mixing can still impact experimental results. By using the forward modelling and long range beam transport capabilities of BBCNI, the effects of beamlet mixing on a large variety of diagnostic systems can be resolved.

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