Particle Tracking and Beam Line Diagnostic Reconstruction for Applications in Large Negative Ion Sources for NBI.

A. Navarro, M. Barnes, N. den Harder, D. Wünderlich, C. Wimmer, R. Nocentini,
B. Heinemann, U. Fantz
[1] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*

Introduction

To provide an overall heating power of 33.3 MW, two Neutral Beam Injection (NBI) lines are foreseen for the upcoming ITER fusion device [1]. The beams are required to have an energy up to 1 MeV for D and 870 keV for H. The target values of the extracted ion current density for H^- and D^- are 330 Am^{-2} and 285 Am^{-2} respectively, assuming negative ion losses of 30% by the background gas during acceleration. Strict requirements are also placed on the beam divergence (<7 mrad) and beam homogeneity (>90%). BATMAN Upgrade (BUG) and ELISE are two ion source test facilities operating at IPP Garching [2].

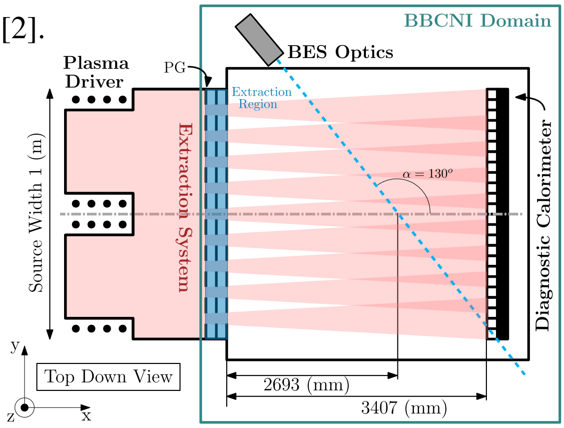

Figure 1: Schematic representation of ELISE ion source and beam diagnostics. Also shown is the simulation domain of BBCNI.

The operational limit, for the source filling pressure (p_{fill}) of the ITER NBI sources has been set to 0.3 Pa. This limit is directly related to the 30% stripping loss assumption. The stripping losses highly depend on the density profile of the background gas, and thus on its conductance and temperature profiles along the acceleration system. It has been shown that having higher filling pressures might be beneficial, as they can stabilize the current of co-extracted electrons [3] and reduce the beam divergence [4]. In this contribution, we show experimental and simulated values of the stripping losses for ELISE, as a function of the filling pressure, for both H and D. The Bavarian Code for Negative Ions (BBCNI) has been used for the simulations [5]. BBCNI is a full 3D particle tracking code. It has two main functionalities: particle tracking (full 3D) and synthetic diagnostic evaluation (Beam Emission Spectroscopy (BES), calorimetry). BBCNI allows to study the effects of the residual gas particle temperature on the stripping losses. It also provides information on the location of the stripping losses generation and its impact on the total stripping value calculation.

BES spectra evaluation

Figure 2 shows a comparison between a BBCNI-simulated BES spectrum and the experimental one measured at ELISE. The spectrum shows a peak at the D_α emission wavelength ($D_\alpha = 656.106$ nm) and a Doppler-shifted peak due to fully accelerated radiating particles centered at the total potential (U_{HV}). A pronounced stripping peak appears at a wavelength of 657.19 nm. This corresponds to particles accelerated to the extraction potential (U_{ex}), which in this case was 6.1 kV. Due to the higher gas density in the first accelerator gap, the majority of the losses are expected to occur in the region between the PG and the EG resulting in a non-uniform energy spread of neutral particles.

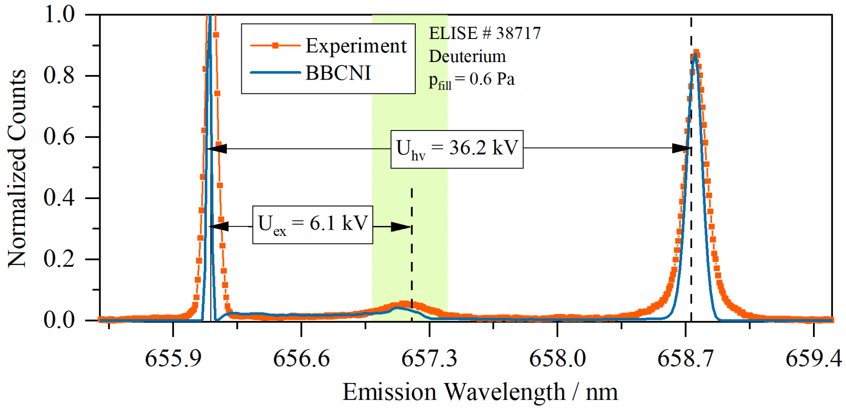

Figure 2: Measured and synthetic BES spectrum from ELISE for deuterium. $U_{ext} = 6.1$ kV, $U_{HV} = 36.2$ kV and $p_{fill} = 0.6$ Pa.

The stripping fraction in this region is commonly calculated by integrating an area of ±0.25 nm around the extraction voltage wavelength (indicated in green in figure 2). For an extraction voltage of 6.1 kV only particles accelerated between 2.6 kV to 7.1 kV are considered. These losses are often referred to as first gap losses or PG-EG losses. The total, stripping fraction (f_s), is quantified by the fraction of neutral atoms in the beam with less than the full energy.

Even though the majority of stripping losses occur in the PG-EG gap, ignoring losses generated in other parts of the acceleration system or in the tank, underestimates the total amount of stripped particles. An experimental approach faces several challenges [6] as the signal to noise ratio in the area between the stripping peak and the Doppler peak is very high. In addition, the method how to separate the contribution of the stripping from that of the fully accelerated beam in the Doppler peak is questionable. Both aspects however are accessible by the unique capability of BBCNI to generate synthetic spectra.

Discussion

Figure 3 shows the measured stripping fraction referring to the PG-EG gap, for both hydrogen (left) and deuterium (right) at ELISE. The BBCNI simulation for the same gap is also shown.

Here, the gas temperature (T_{gas}), i.e. the temperature of the particles in the plasma close to the PG, is varied and all of them use a minimum temperature of 300 K in the tank. The tank pressure (p_{tank}) linearly increased with the filling pressure reaching a maximum of $7 \cdot 10^{-4}$ Pa for 0.8 Pa. For the stripping losses of the ITER NBI, about 10% are attributed to the stripping in the first accelerator stage [8]. This is indicated as ITER reference in figure 3. Theoretical calculations performed for SPIDER predict this value to be 7.5 %, with an additional 8 % of neutralization occurring between the GG exit and the location of the LOS [6]. These differences are attributed to the dependency of the stripping losses on the gas conductance along the acceleration system.

In general, a linear increase of the stripping losses with the filling pressure is obtained. Experimental stripping loss values are 1.9 % and 2.7 % at 0.3 Pa for H and D respectively. BBCNI shows a better agreement with the experimental results when a temperature of $T_{gas} \sim 600$ K is considered. This matches the optical emission spectroscopy measurements performed at BUG [7]. Deuterium shows for both, the measurements and simulation, systematically, a higher stripping fraction. From BBCNI it can be obtained that, due to its higher mass, deuterium has a higher residence time than hydrogen in the extraction system. It should be noted, that due to a lack of data, the same emission crosssections for H-H_2 and H^--H_2 collisions are used also for deuterium.

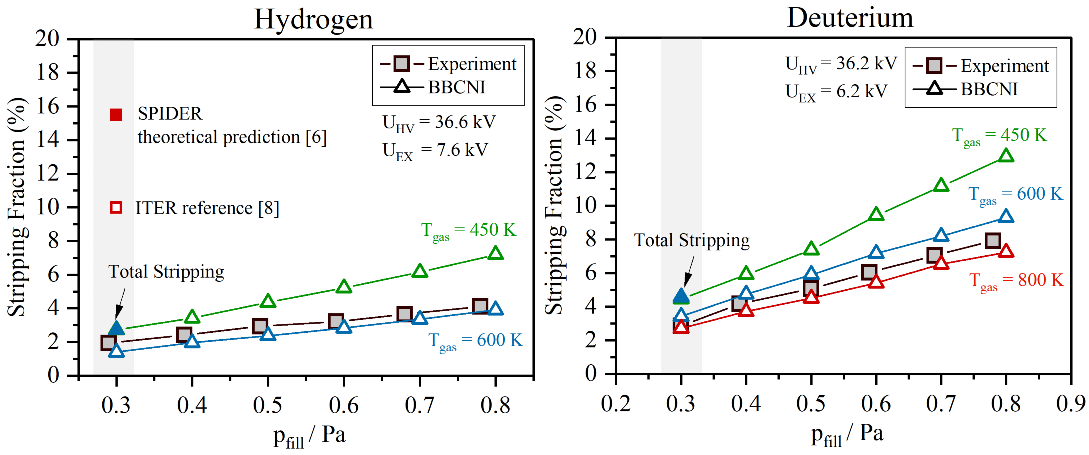

Figure 3: Comparison between experimental stripping fraction values and BBCNI simulations (left: hydrogen, right: deuterium). Shaded in gray is the currently planned filling pressure $p_{fill} = 0.3$ Pa. Total stripping losses were calculated for this pressure and $T_{gas} = 600$ K.

As mentioned before, the total amount of stripping losses can be calculated with BBCNI. This has been done for the 0.3 Pa case and is shown in figure 3. BBCNI predicts the simulated losses increase by a factor 1.9 for H and by a factor 1.3 for D, resulting in 2.6 %, 4.4 % respectively. Both are well below the ITER reference value of 15.5 %. This indicates, that increasing the filling pressure to 0.4 Pa is a viable option. This would improve strongly the performance of the negative ion sources for ITER concerning co-extracted electrons and long pulse stability, uniformity and beam divergence [4][3]. Nonetheless, further detailed investigations are needed, in particular, the comparison with BBCNI results from [8] and for the case of deuterium.

Conclusions

Stripping losses are a decisive parameter for the selection of the operating filling pressure in the ITER NBI systems, which has been set to 0.3 Pa, limited by the 30% stripping losses assumption in the 5 stage-accelerator (7 grid system). The prediction for a 3-grid system like it is installed in SPIDER, ELISE and BUG is about 15.5 % at 0.3 Pa (ITER reference case). The experimental and simulated BES spectra show a pronounced stripping peak around the extraction voltage. This peak shows a linear increase in pressure and the comparison with the experimental data reveals that the gas temperature of 600 K is to be used. This is higher than the value used for the ITER reference case (300 K) such as the neutral density and thus calculated values for the stripping in the PG-EG gap are reduced. The total stripping fraction, taking into account the full accelerated particles and the losses in the tank, is accessible with the BBCNI code, revealing 2.6 %, 4.4 % for H and D at 0.3 Pa, respectively. As these values are well below the ITER reference case for the 3-grid accelerator the usage of the filling pressure of 0.4 Pa might be a viable option. Further detailed investigations are needed, in particular the comparisons with BBCNI with the results from [8], the interpretation of experimental data [6] and isotope difference.

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.

References

[1] Hemsworth R.S.et al 2017, New J. Phys.19025005.
[2] Fantz, U., et al. Frontiers in Physics 9 (2021): 709651.
[3] Franzen, P., et al. Nuclear Fusion 55.5 (2015): 053005.
[4] Bonomo, F., et al. AIP Conference Proceedings. Vol. 1655. No. 1. AIP Publishing, 2015.
[5] Hurlbatt, A., et al. Plasma Physics and Controlled Fusion 61.10 (2019): 105012.
[6] Agnello, R., et al. Fusion Engineering and Design 186 (2023): 113350.
[7] Briefi, S. et al. AIP Conference Proceedings. Vol. 2052. No. 1. AIP Publishing LLC, 2018.
[8] Krylov, A. et. al. Fusion engineering and design 81.19 (2006): 2239-2248.