Comparison of ONIX Simulation Results and Experimental Data from the BATMAN testbed for Study of Negative Ion Extraction

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Abstract

The development of negative ion (NI) sources for the ITER neutral beam injector is strongly accompanied by modelling activities. The ONIX (Orsay Negative Ion eXtraction) code simulates the formation and extraction of negative hydrogen ions and co-extracted electrons produced in caesiated sources. The 3D geometry of the BATMAN extraction system and the source characteristics such as the extraction and bias potential, 3D magnetic field were integrated in the model. Calculations were performed using plasma parameters experimentally obtained on BATMAN. Comparison of the ONIX calculated extracted NI density with experimental results suggests that predictive calculations of the extraction of negative ions are possible. The results show that for an ideal status of the Cs conditioning the extracted hydrogen NI current density could reach about ~30 mAcm^{-2} at 10 kV and about ~20 mAcm^{-2} at 5 kV extraction potential with an electron/NI current density ratio of about 1, as measured in the experiments under the same plasma and source conditions. The dependency of the extracted NI current on the negative ion density in the bulk plasma region from both the modeling and the experiment was investigated. The separate distributions composing the negative ion beam originating from the plasma bulk region and the PG surface are presented for different NI plasma volume densities and NI emission rates from the plasma grid wall respectively. The extracted current from NI produced at the Cs covered plasma grid (PG) surface, initially moving towards the bulk plasma and then being bent towards the extraction surfaces is lower compared to the extracted NI current from directly extracted surface produced ions.

1. Introduction

The future fusion experimental reactor ITER will be equipped with two neutral beam injectors (NBI) that will together deliver 33 MW of total power during the continuous pulse length of 3600 s carrying a beam energy of 1 MeV in deuterium and 870 keV in hydrogen operation [1]. At such high energies the neutralization cross-section for positive ions is negligible low. Therefore, beam lines based on the production and extraction of negative ions (NIs) have to be used. In order to achieve these beam parameters the ion source must supply 66 A (j_{H}^{-} = 33 mA/cm^2) extracted current in hydrogen and 57 A (j_{D}^{-} = 28.5 mA/cm^2) in deuterium. The area of the extraction system has to be large ($A_{extr.ITER} \approx 0.2$ m^2, composed of 1280 apertures with a diameter of 14 mm each). In order to minimize the NIs destruction in the accelerator due to collisions with the background gas, the operating pressure in the plasma source must be ≤ 0.3 Pa. Negative ion extraction implies the co-extraction of electrons, which are dumped on the second grid of the extraction system (extraction grid) by means of the magnetic field, preventing their full acceleration. Moreover, to avoid the damage of this grid, the co-extracted electron current has to be kept below or at a tolerable value, typically below the NI current ($j_e \leq j_{NI}$ for ITER).

Finding a way to reduce j_e/j_{NI} is one of the major issues for NBI that involves profound analysis of the boundary layer in the extraction region. A numerical simulation, which includes realistic plasma and source parameters, will not only help to understand formation of the meniscus (a region, where the extracted beam is separated from the plasma and the local potential is vanished, 0 V) but also will give ideas for future source optimizations by understanding the processes governing the particle transport through this area.

The radio-frequency (RF) NI source prototype for ITER NBI (Fig. 1) [2] [3] consists of three main parts: the driver, the expansion region and the extractor. A hydrogen or deuterium plasma with electron temperature T_e≈10 eV and density n_e≈10^{18} m^{-3} is generated in the driver via RF power (up to 100 kW at 1MHz). The plasma afterwards diffuses from the driver to the expansion chamber, where electrons are cooled down to the temperature ≈ 1 eV by means of a filter magnetic field in order to decrease NI volume losses via collisions with electrons. This magnetic field is produced by permanent magnets installed upstream of the plasma grid. The extractor consists of three multi-aperture grids: the plasma grid (PG), the extraction grid (EG) and the grounded grid (GG). A positive extraction potential in the range of 5-10 kV (9 kV is planned for ITER) is applied between PG and EG to attract the NIs and repel the positive ions, followed by a larger voltage of 10-20 kV between EG and GG.

The co-extracted electrons are one of the main limitations of the source operation [4]. To reduce the electron extraction a complex three-dimensional (3D) magnetic field topology is introduced in the source. Firstly the electron density in the diffusion plasma (located in the expansion chamber) is reduced by one order of magnitude to ≈ 10^{17} m^{-3} by means of the filter magnetic field. Afterwards the majority of the extracted electrons are dumped on the extraction grid by the second magnetic field called deflection field (Fig. 1, left, inset), which is perpendicular to the filter field and alternates from aperture to aperture. This magnetic field is produced by permanent magnets embedded inside the extraction grid. Further reduction of the co-extracted electrons can be obtained by a positive bias potential applied at the plasma grid against the bias plate which is connected to the source body [5]. Due to these complex inhomogeneous magnetic field configurations [3] [6] only 3D models can perform calculations representing entirely the experimental conditions.

Negative ions are created in such sources by two paths: volume and surface related processes. In the plasma volume NIs are produced by the dissociative electron attachment collision to hydrogen molecules in high vibrational states $(H_2(v) + e \rightarrow H + H^-, v > 5)$ [7]. However, the amount of NIs produced by this path in the ion sources for ITER NBI is relative low due to the low electron density and pressure, i.e., low density of H_2, that should be, in addition, highly vibrationally excited. Moreover, an important amount of the NIs produced in the volume are destroyed there due to a variety of loss processes [7] [8]. Therefore, the extracted NI current density from the volume produced NI is relatively low (~2-5mA/cm^2) at a source pressure of 0.3 Pa [2]. To overcome this limitation and to enhance the amount of produced and extracted NIs, caesium vapor is injected in the source [2] [9]. Cs atoms stick to the walls and they cover the inner surfaces of the source. NI are produced mainly on the surface of the PG via the surface conversion of impinging atoms ($H + e_{surface} \rightarrow H^-$) and positive ions ($H^+ + e_{surface} \rightarrow H; H + e_{surface} \rightarrow H^-$). The thickness of Cs on the plasma grid and amount of embedded impurities determine the work function, which governs the NI emission rate from the surface. Increasing the Cs amount and re-distributing it throughout in the expansion chamber by continuous evaporation is called source conditioning. A poor conditioning status (in the beginning of an experimental campaign) corresponds to a low NI emission rate from the surface reflected by a low extracted NI current density, while well conditioning represents a large negative ion emission rate and a high (expected) extracted current.

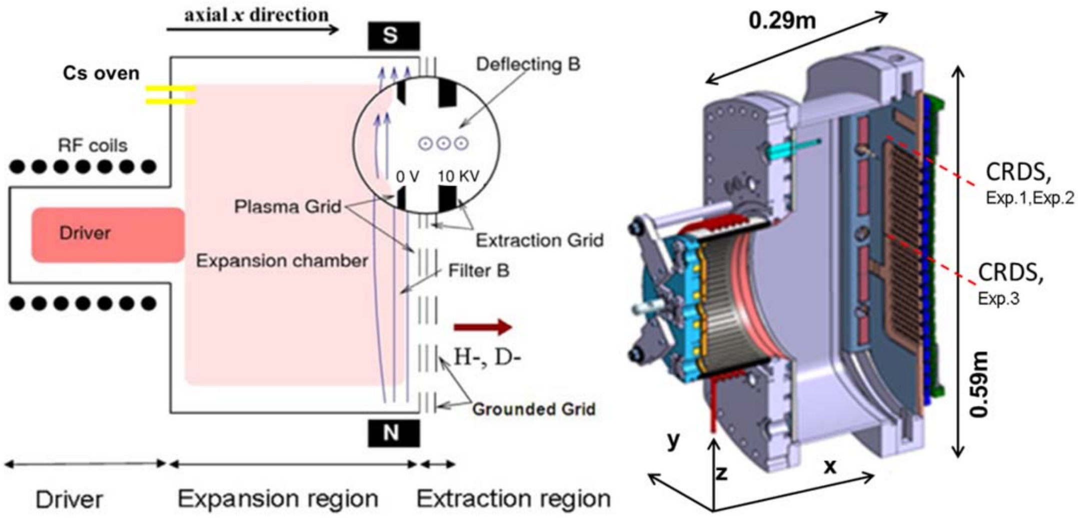

Fig. 1 Schematic views of the ITER-like 1/8 NBI NI prototype source used at BATMAN [2] [3]. *x*-axis corresponds to the beam direction while the *y* and *z* axes are in the plane of the grids.

Presently, there are two ITER-like negative ion source testbeds in operation at IPP Garching: BATMAN [2] [3] [4] and ELISE [10] [11] [12]. BATMAN is the 1/8 ITER size prototype source with small extraction area ($A_{extr.} \approx 7\times10^{-3}\ m^{-3}$), while ELISE is of half the ITER source size. A schematic view on the prototype source is shown in Fig. 1 on the right. The driver of the testbed is made by alumina cylindrically shaped of 0.14 m length and 0.245 m diameter. The RF coils around the driver are connected to an 1 MHz high power supply (<100 kW). The expansion chamber has a rectangular shape with 6 mm steel wall of 0.59 m height and 0.29 m length. The ITER requirements in terms of the extracted NI current density and electron/NI current ratio were successfully achieved in this source for both hydrogen and deuterium plasmas.

In the past, different numerical models [13] [14] [15] [16] [17] for simulating the plasma behavior and negative ion extraction from different RF sources were developed and exploited. However, a direct cross-checked analysis with experimental results using the same input plasma parameters, source conditions and 3D source geometry was not performed yet. Most of these models were developed and used independently of the experimental testbeds or are not able to fully reproduce experimental conditions. Therefore, the 3D particle-in-cell (PIC) Monte Carlo Collisional (MCC) code ONIX was applied in order to describe the BATMAN testbed and to implement a cross-checked benchmark. The extracted NI and the co-extracted electron current were compared at different plasma and source parameters. ONIX can track the origin of the extracted particles and show the importance of each NI production and extraction channels: *volume* extraction, *direct* surface extraction, *in-direct* surface extraction as will be explained below.

The structure of this paper is as follows: section 2 details the numerical features of the ONIX code. The obtained results is presented and discussed in section 3. The last section summarizes the conclusions of this work and describes the possibilities for future work.

2. Simulation model

The ONIX code was developed in order to simulate the particle transport in the negatively charged plasma in vicinity to the plasma grid of an ITER-like NI source extraction system [18] [19]. The code was adapted later to simulate the boundary layer of the BATMAN NI source testbed with the realistic magnetic field configuration, the bias potential and Cs^+ ions in the bulk plasma region. Furthermore, ONIX was validated against other codes and experimental results [6] [20]. A detailed description of ONIX can be found in [6] [20], the version of the code used for this study is the one used in [20]. Therefore, the main features of the code are introduced only briefly here.

The simulation domain includes one central aperture of the plasma grid with some region downstream and upstream it (Fig. 2, left). The extraction system used at BATMAN is the LAG (Large Area Grid) with 8 mm diameter (14 mm is planned for ITER) and 45° chamfered angle from both sides [3]. In such configuration one can distinguish flat and conical surfaces of the plasma grid. These different types of surfaces are depicted in Fig. 2, left. The positive extraction potential is applied between the plasma grid and the extraction grid V_{ext}=5-10kV (up to 10kV is foreseen for ITER) in order to extract negative ions.

Negative ions can be extracted via three different channels (Fig. 2, right): the *volume* extraction, *direct* surface extraction, *in-direct* surface extraction. *Volume* extraction refers to the NI produced in the bulk plasma region via electron dissociative attachment collision to hydrogen molecules in high vibrational states, as described in previous section, and crossing the meniscus (blue trajectories). *Direct* surface extraction refers to NIs produced at the Cs covered conical surface of the plasma grid downstream from the meniscus, which move directly towards to the extraction grid without crossing the plasma bulk. Finally, in the *in-direct* surface extraction negative ions produced at both the conical and/or the flat surface of the plasma grid (upstream of the meniscus) move first towards the bulk plasma region and then their trajectories are bent back towards the extraction apertures. The ONIX code can determine the origin of the extracted negative ions distinguishing between these channels.

The NI production at the caesium covered plasma grid surface is simulated in the model as the NI emission flux from 5 to 60 mA/cm^{-2} representing different Cs conditioning states in the source. The maximum rate was estimated for the 1D PIC code BACON [13] using NI conversion yield from the literature [21] and an atomic flux to the plasma grid wall calculated for the parameters of BATMAN. The produced NI is randomly distributed along the whole plasma grid surface at the plasma side inside the simulation domain (upstream from the center of the plasma grid). This distribution is based on the assumption of a homogeneous Cs covering of this surface and homogeneous neutral flux towards this surface.

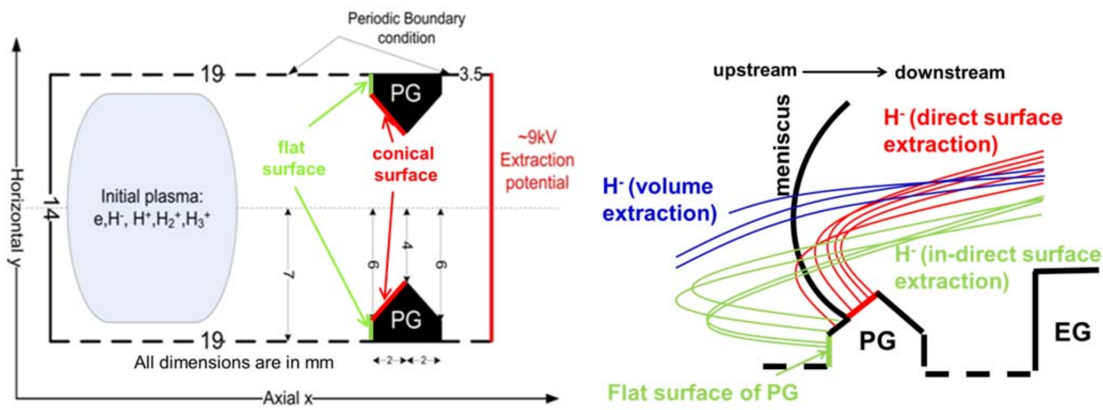

Fig. 2 Schematic view of the simulation domain used in ONIX – left. Sketch of different NI extraction channels – right.

The simulations were performed as close as possible to the experimental conditions using measured data as input parameters for the code (Table 1). Most of these quantities were measured by optical emission spectroscopy or Langmuir probes [3] [22] [23] installed in BATMAN close to the extraction region.

The initial bulk plasma covers the first ~10 mm of the simulation domain and it consists of H^+, H_2^+, H_3^+, Cs^+, H^- and electrons. The plasma neutrality is maintained in this region by re-injection of the same particle species if one leaves (destroyed or extracted) the simulation domain. As it was described in the previous paper [20] the code cannot self-consistently reproduce the negative ion density in the bulk plasma region for NI created at the plasma grid surface. Therefore, the negative ion density in the plasma volume was used as an input parameter taken from the experimental measurements (Table 1). These negative ions are treated in the simulations in the same way as other charged species.

A full 3D realistic magnetic field distribution, calculated by an external code namely PerMag [24] was implemented to ONIX [6]. This field was obtained by taking into account both the filter and the electron deflecting field. The bias potential was also implemented in the code as the potential difference between the PG wall and the plasma [20].

Densities of different plasma species [m^{-3}]	
n_e+n_{H-}	2.0 ×10^{17}
n_e	1.0-1.8 ×10^{17}
$n_{H-(in\ bulk\ plasma)}$	0.2-1.0 ×10^{17}
$n_{H+}+n_{H2+}+n_{H3+}+n_{Cs+}$	2.0 ×10^{17}
n_{H+}	0.8 ×10^{17}
n_{H2+}	0.8 ×10^{17}
n_{H3+}	0.3 ×10^{17}
n_{Cs+}	0.1 ×10^{17}
n_H	1 ×10^{19}
n_{H2}	4 ×10^{19}
Temperatures of different plasma species [eV]	
T_e	2.0
$T_{H-(volume)}$	0.8
$T_{H-(surface)}$	1.0
T_{H+}	0.8
T_{H2+}	0.1
T_{H3+}	0.1
T_{Cs+}	0.8
T_H	0.8
T_{H2}	0.1
Extraction potential	5 or 10 kV
H^- emission rate from Cs covered PG surface	from 5 mA/cm^2 to 60 mA/cm^2

Table 1 Main input plasma parameters for ONIX simulation based on the experimental measurements from BATMAN testbed.

In order to speedup the simulation the code is parallelized via the Message Passing Interface (MPI) using full domain and particle decomposition techniques. Typical runs with 10^6 macro particles, each representing 5×10^4 real particles take from 4 to 7 days on 20 CPUs.

The charge of the macro particles is linearly interpolated and distributed onto the PIC nodes (186×70×70 in axial *x*, horizontal *y* and vertical *z* direction respectively) with the following dimensions of the mesh: Δx=0.15 mm, Δy=Δz=0.2 mm. Stable plasma PIC simulation requires few calculation conditions. The chosen time step must be smaller than the inverse plasma frequency $\Delta t=3\times10^{-12}$ s < $1/\omega_p=3.97\times10^{-11}$ s. The simulation PIC mesh size should be in a range (or smaller) than the Debye length. In our model the mesh size (Δx=0.15 mm) is larger than the Debye length ($\lambda_D\approx0.026$ mm) in the bulk plasma but only for the denser plasma region. However, the plasma density drastically drops close to the PG and Debye length condition ($\lambda_D\approx0.15$ mm) is completely fulfilled in the region of interest (~1 cm from the PG wall), namely the sheath including the meniscus. The last and the most important criterion for the stable PIC simulation is the Courant–Friedrichs–Lewy (CFL) condition [25]. Under this requirement the particles with the maximum possible energy must not “jump” over one PIC cell during one time step. For the chosen time step and size of the PIC mesh this criterion is strictly fulfilled in all the volume.

3. Results and discussion

ONIX can easily track the extracted negative ion current created by different atomic processes (surface and volume production), but it can also memorize the place where these negative ions have been born (flat or conical surface of the plasma grid, Fig. 2, right). Fig. 3 shows the time evolution of the extracted negative ion current densities from different production channels. All currents are evaluated at the exit plane of the simulation domain 3.5 mm from the plasma grid back plane (Fig. 2, left). In this simulation an extraction potential of 5 kV was used. The other plasma parameters were taken from Table 1 with equal density of H^- and electrons $n_{H-}=n_e=10^{17}$ m^{-3} in the bulk plasma region representing a well Cs conditioned source with high NI production rate at the plasma grid surface of 60 mA/cm^2 according to the flux density of the surface impinging particles (H and H^+) and their conversion yield [13]. As it was shown in a previous paper [20] the code could self-consistently reach only $n_{H-}=10^{15}$ m^{-3} in the bulk plasma region from the surface production channel. This low negative ion density does not agree with experimental results (measured in the bulk plasma region of BATMAN have been $n_{H-}=10^{17}$ m^{-3} for a well-conditioned source, i.e. cesiated surface production dominates. This mismatch between code and experiment can be explained by two reasons: firstly, the depth of the negative potential well in the front of the plasma grid plays a crucial role for the H^- dynamics. Different models predict different potential well from more than 30 V [26] to less then 1 V in [13]. Therefore, the depth of the potential well remains an open question. The calculated potential well in ONIX (~5V) repels most of the surface produced negative ions (with an average energy of equal or below 1 eV) back towards the wall where they are destroyed [20]. Secondly, negative ions produced at the large flat surface above the plasma grid or the surface of the bias plate are not considered in the model. Due to the absence of the extraction potential in this region the density of the positive ions can be much higher in vicinity to the large flat area of the plasma grid (or the bias plate) in comparison to the aperture area. These positive ions will efficiently compensate negative charge from the potential well allowing more NI escape from the surface. In order to overcome the observed inconsistency, the NI density measured in BATMAN was used as input parameter for the code.

The extracted NI current density and co-extracted electron current density are calculated in the model as the extracted current divided by the plasma grid aperture area with diameter 8 mm (Fig. 2). The particles are considered to be extracted when they cross the right hand side boundary of the simulation domain. As shown in Fig. 3 first the NI current density from the volume production grows very fast. Reason is that the extraction potential is not screened in the beginning of the calculation and thus penetrating deeply in the expansion chamber. This increase lasts up to 0.15 μs. After this transitory phase the extracted current stabilizes and the system reaches a quasi steady state.

The amount of NIs produced at the conical surface of the PG that first move to the bulk plasma and afterwards are extracted (*in-direct* extraction) crossing the plasma at the meniscus edges is relative low (<5%) in comparison to the *direct* surface extraction (Fig. 2, on the right). Therefore, we assume that all extracted negative ions that were produced at the conical part of the plasma grid aperture contribute to the *direct* NI extraction keeping in mind that less than 5 percent of this current is given by the *in-direct* surface extraction. The extracted NI current density from this production channel is ~12 mA/cm^2 (Fig. 3). The extracted NI current density from NIs initially located in the bulk plasma ($n_{H-}=10^{17}$ m^{-3}) corresponds to a half, namely ~6 mA/cm^2. Finally, the *in-direct* negative ion surface extraction, from NI produced at the flat PG surface accounts for ~0.5 mA/cm^2.

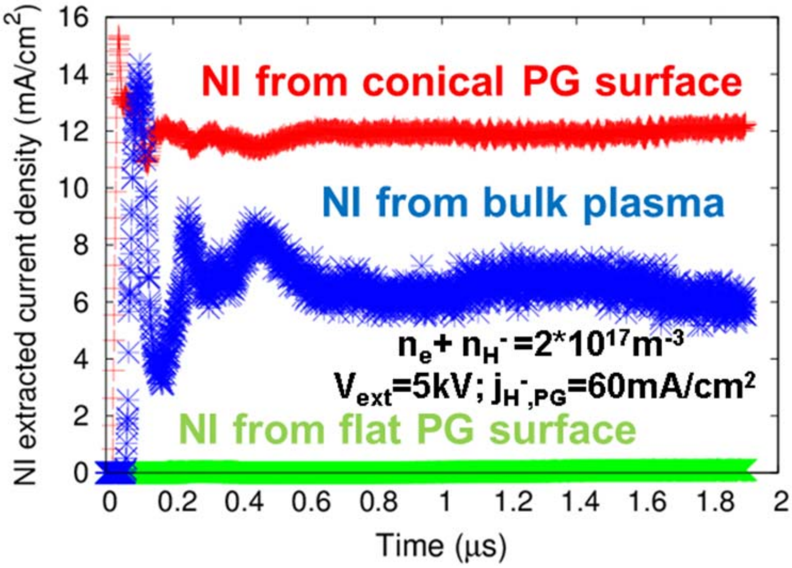

Fig. **3** Time evolution of the extracted NI current density from different production channels. The extracted potential of 5 kV and 60 mA/cm^2 NI emission rate were used in the simulation with the plasma parameters from Table 1 and equal density of H^- and electrons $n_{H-}=n_e=10^{17}$ m^{-3}.

Summarizing all NI current densities from Fig. 3 a total current density of ~18.5 mA/cm^2 is obtained (Fig. 4), which is in good agreement with experimental measurements at BATMAN for the same source and plasma conditions and a good status of the Cs conditioning. The co-extracted electron current density is fluctuating during whole simulation. However, the average value can be estimated to ~20 mA/cm^2, i.e., $j_e \approx j_{H-}$ which is also in agreement with the experiment for a well Cs conditioned source. Modelling of a poor Cs conditioning with n_{H-} = 3*10^{16} m^{-3} and n_e= 17*10^{16} m^{-3} in the bulk plasma region and correspondingly using a low negative ion emission rate of 5 mA/cm^2 shows that the co-extracted electron current increases to ~37 mA/cm^2 with j_e/j_{H-} ~4. Such trend is also in agreement with experimental measurements for a poor Cs conditioning.

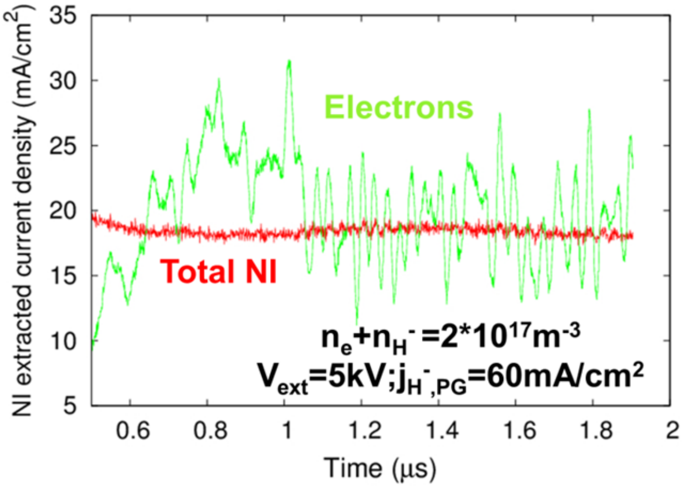

Fig. 4 Time evolution of the total extracted NI (red line) and the co-extracted electron (green line) current density. An extraction potential of 5 KV and 60 mA/cm^2 NI emission rate were used in the simulation with the plasma parameters from Table 1 and equal density of H- and electrons $n_{H-}=n_e=10^{17}$ m^{-3}.

An additional simulation was performed with identical parameters presented above but with an extraction potential of 10 kV. When the steady-state is attained, the total extracted NI current density reaches in this case a value of ~30 mA/cm^2 with $j_e \approx j_{H-}$ that is again in good agreement with the BATMAN experimental results.

A similar benchmark presented above for the well Cs conditioned source was performed in a previous work [20] but for slightly different source parameters with again good agreement between experiments and simulations. The next step is to compare the results from ONIX calculations with measurements performed on BATMAN during the Cs conditioning phase. Such benchmark should validate again the ONIX code if it will be able to reproduce experimental results for different source conditions stages, changing not only the extraction potential but also the NI emission rate and the plasma densities. Having the full set of measured data we tried to find out what value of NI emission rate corresponds to the particular measurements.

Fig. 5 shows the dependency of the negative ion density in the bulk plasma region versus the total extracted NI current from different experimental campaigns and simulations. This plot represents the Cs conditioning in BATMAN from a poor status with a low NI density ($n_{H-} \leq 4\times10^{16}$ m^{-3}) and a small extracted current densities ($j_{H-} \leq 15$ mA/cm^2) to a well Cs conditioned source with a high NI density ($n_{H-} \approx 10^{17}$ m^{-3}) and extracted current ($j_{H-} > 22$ mA/cm^2). The experimental results, which are shown in Fig. 5 were obtained from two different source setups. In the first case the negative ion density in the bulk plasma region was measured by means of a cavity ring-down spectroscopy (CRDS) diagnostic that was installed above the upper part of the bias plate and a few cm downstream from its surface (for more details refer in [27]). The measurement results from this arrangement (Fig. 1, right) are marked in Fig. 5 as *Exp.1*, red line for the source pressure 0.5 Pa and *Exp. 2*, light-blue line for the pressure 0.4 Pa. In the second case the negative ion density in the bulk plasma region was measured with the same diagnostic (cavity ring-down spectroscopy) but it was installed above the center of the plasma grid again a few cm downstream from its surface - Fig. 1, right (more details can be found in [28]). The measurements corresponding to this configuration are shown in Fig. 5 as *Exp. 3*, green crosses for the source pressure 0.5 Pa.

Two experimental measurements from different setups described above were reproduced by ONIX simulations (*Exp. 1* and *Exp. 3*) and shown in Fig. 5 *ONIX fit 1* - pink and *ONIX fit 2* - dark-blue lines respectively. In ONIX simulation the NI density in the bulk plasma region was set to the value measured in experiment (Fig. 5, *y* axis). A parametric study of the negative ion emission rate was then performed in order to determine if the code is able to reproduce the experimental results with the emission rate not higher than its estimated theoretical maximum. Afterwards the code should be able to provide the values of this NI emission rate for different Cs conditioning stages. The NI emission rates used as input parameters to fit experimental results are indicated also in the figure.

The modelling results are in good agreement with experimental measurements. The NI emission rates used in all simulations are in a realistic range with a maximal value of 55 mA/cm^2. At poor Cs conditioning the NI emission rate is relatively low ~14-15 mA/cm^2, corresponding to a low NI density in the bulk plasma (~4×10^{16} m^{-3}) region and relatively low total extracted NI current densities (13-15 mA/cm^2). In the well conditioned source the extracted NI current densities increase to 20-25 mA/cm^2, corresponding to a NI emission rate of 30-55 mA/cm^2. Such benchmark between simulation and experiment validate again the ONIX code and show the accuracy of numerical estimations of the NI emission rate for different Cs conditioning stages.

Due to the detection limit of the cavity ring-down spectroscopy setup for the experimental campaigns presented in Fig. 5 it was not possible to measure NI densities below 10^{16} m^{-3} in the bulk plasma region. However, the ONIX simulations could predict the extracted NI current densities if the NI emission rate continuously decreases to 0 mA/cm^2 (Fig. 5 pink line). One can see that without NI production from the plasma grid surface and with the negative ions produced only in the volume with the density $n_{H-}\approx1.5\times10^{16}$ m^{-3} the extracted negative ion current density will be 2-3 mA/cm^2. This value is also in agreement with measurements at BATMAN in the Cs free regime [2]. The next step will be to complete the missing experiments with a new diagnostic set up and compare the results with predicted simulation results from ONIX. The detailed analysis of the spatial distribution of the co-extracted electrons is out of the scope of the present work and will be further communicated.

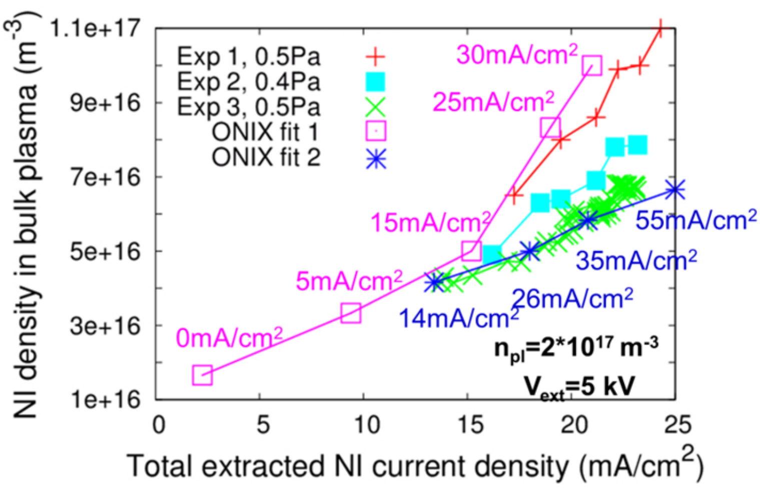

Fig. 5 Comparison of the extracted NI current densities from experimental measurements at BATMAN and ONIX simulations for different plasma conditions. Red and light-blue lines represent the experimental measurements taken from [27]; green crosses shows the experimental data from BATMAN setup described in [28]; pink and dark-blue lines correspond to ONIX calculations.

Indications by the number close to the points/dots are the NI emission rate used in ONIX. An extraction potential of 5 kV was used for all results.

A deep analysis of the relevance of different NI extraction channels described in section 2 on the extracted NI current density presented in Fig. 5 was performed. The calculated total NI extracted current density was separated into three parts: *volume* extraction, *direct* extraction and *in-direct* extraction. The dependence of the former on the NI density in the bulk plasma is shown in Fig. 6. For the low NI density 1.7×10^{16} m^{-3} the extracted current density is about 2.2 mA/cm^2. With increasing NI density in the plasma bulk the extracted current also increases with almost linear dependency. However, only a relatively low value of 6.2 mA/cm^2 can be reached with NI density of 10^{17} m^{-3} i.e. maximum NI density measured in the experiment. This means that the contribution of this type of extracted current to the total one is between 20-30 percent.

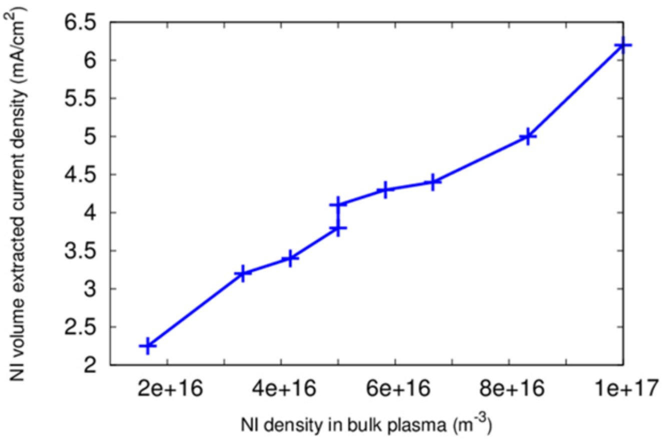

Fig. 6 Negative ion extracted current density from the *volume* production channel versus the NI density in the bulk plasma region.

The extracted negative ion current density from the surface produced NI (*direct* extraction) versus the NI emission rate from the plasma grid surface is shown in Fig. 7. One can see that even for a low emission rate (<10 mA/cm^2) the extracted NI current density is in the same range than the one extracted from the plasma volume with a negative ion density of 10^{17} m^{-3}. With increasing the negative ion emission rate the extracted current density also continuously grows but not linearly as it was for the volume production channel. Using a low NI emission rate (<10 mA/cm^2) all produced NI are extracted. Increasing the NI emission rate the produced negative ions will create the well-known double layer [6] [13] in the font of the plasma grid surface, which repels a significant amount of NIs back to the plasma grid where they are destroyed. The depth of the potential well is not homogeneous, it is high (about 5 V) in front of the flat surface of the PG (Fig. 2) and along the first few mm of the conical surface. Almost no NIs are able to overcome this negative sheath. The depth of the potential well decreases along the conical surface due to the compensation from the positive extraction potential [6]. Therefore, using a NI emission rate of 55 mA/cm^2 only less than 40 percent of NIs are extracted via this channel with the current density of about 20 mA/cm^2. Fig. 6 and Fig. 7 also demonstrate the relative importance of the *direct* NI extraction in the source, which is in ~3 times higher than one extracted from the bulk plasma region and is about 70-80 percent of the total extracted current density.

Due to the low amount (in the simulations [20]) of surface produced NIs, which are able to overcome the negative potential sheath described above (5 V) in vicinity to the plasma grid flat part (Fig. 2) the *in-direct* NI extracted current is very low. It contributes less than 2 percent to the total extracted negative ion current density. Much higher total NI current density from both volume and surface production channels (34 mA/cm^2) was measured for very high arc power and short pulse at the NIFS NI source [29], where the plasma grid has a flat structure. However, the plasma parameters (density, temperature, atomic hydrogen density, NI emission rate from PG surface, amount of impurities, meniscus position, etc.) are very different at NIFS from the one in the IPP sources for which the simulations presented in the current paper were performed. Therefore, the ONIX results presented here can not be easily transformed for NIFS source. Nevertheless, in future, simulations without conical aperture, i.e. only the flat surface, are planned in order to check a behavior of the potential well and NI production. In addition, the parametric study of the positive ion density in this region will be done to show how the virtual cathode reacts on the higher positive charge.

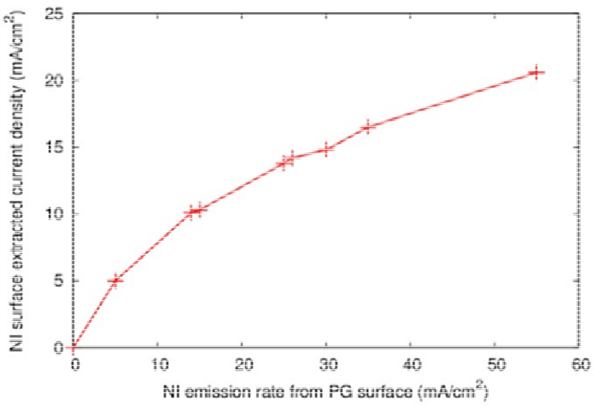

Fig. 7 Negative ion extracted current density from the surface production channel versus the NI emission rate from the plasma grid surface.

Conclusions

A benchmark of the simulations results in terms of the extracted negative ion and co-extracted electron current with experimental measurements at the BATMAN testbed is performed using experimental data and 3D geometry. Results from ONIX simulations are in good agreement with experimental measurements for two extraction voltages ($V_{ext.}$= 5 kV, $V_{ext.}$= 10 kV) in terms of the extracted NI and co-extracted electron current.

Further code benchmark was done by reproducing the experimental results of the Cs conditioning phase in the simulation. These calculations show that using a realistic range of NI emission rate (<60 mA/cm^2) from the plasma grid surface ONIX is able to reach the experimentally obtained NI extracted current density at BATMAN for all plasma and source conditions. The NI emission rate at different Cs conditioning statuses was also determined by the code. The simulations predict also the NI extracted current for low NI densities in the bulk plasma region. Measurements of this quantity were not accessible due to the detection limits of the diagnostic technique and they are planned to be done in a new experimental campaign aiming to confirm the ability of ONIX to predict experimental results.

The total extracted NI current densities were separated on three parts: extraction of the NI in the bulk plasma region (*volume* extraction), extraction of NIs born at the plasma grid surface (*direct* extraction) and extraction of NIs born at the plasma grid surface but directed towards the plasma and after bending their trajectory towards the aperture (*in-direct* extraction). It was determined that the *direct* extraction is dominant in all simulations and it accounts for about 70 percent of the total extracted NI current densities. The extraction from the bulk plasma NI contributes of ~30 percent to the total current density and the *in-direct* NI extraction is less than 2 percent. However, this value of the extracted NI current for the *in-direct* extraction is valid only for the physics implemented into the model without bias plate, considering only one aperture and with the negative potential well in front of the plasma grid of ~5V.

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