Comment on ‘Issues in the understanding of negative ion extraction for fusion’

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Abstract. The discussed paper strongly criticizes the capability of 3D PIC codes for describing the extraction physics of negative hydrogen ions generated via the surface conversion process using caesium. A strong disagreement of the obtained results with the experimental results is pointed out as well. On the other hand, the capability for experimental validation of the 2D PIC used by the authors is highlighted. This comment is dedicated to put one of codes, namely, the ONIX code in perspective concerning assumptions made and results obtained in correlation with the experiments and on the other hand to comment on the assumptions and observations made with the 2D PIC model.

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The paper [1] summarizes issues in the PIC modelling of the negative ion extraction for ion sources relevant to fusion. Thereby, 3D PIC models used around the world [2-5], [6,7] and [8] are strongly criticized and the capabilities of the 2D PIC code developed within the LAPLACE group are highlighted. One of the 3D models is the ONIX code [2-5] and the developers and users of the code would like to take the opportunity to comment on the issues raised in connection to this code. It is also claimed that the ONX results are far from experimental observations. Thus the experimental observations will be addressed as well. Furthermore, critical issues seen in the introduced 2D PIC modelling are pointed out, in particular those being connected with experimental observations. The reference experiment is the ITER prototype ion source developed by the Max-Planck-Institut für Plasmaphysik (IPP), Garching, being in operation at the BATMAN test facility [9-11].

Comments on the ONIX code concerning:

- Debye length and mesh size
  The ONIX code [2-5] as the other 3D PIC models [6-7] uses realistic plasma and source parameters. The electron density higher than 10^{17} m^{-3} poses particularly the challenge to fulfil the criteria of having a mesh site smaller than the Debye length. The chosen mesh size in the ONIX code is a compromise between the available computing time and accuracy. For low electron densities the mesh size can be chosen such that the Debye length criterion is easily fulfilled. Results for a variation of the mesh size at a factor of ten lower electron density, covering the range from being much smaller than the Debye length to be by the factor of about 4 higher (as it is for the higher electron density) are underway. They will allow for accessing the uncertainty of ONIX results with respect to extracted electron and ion densities. A thorough discussion in a regular paper will follow. However, in spite of the large mesh size (compared to Debye length), the plasma bulk

and extraction of the ONIX code has been successfully benchmarked for positive ion extraction against the commercial KOBRA3D [12] code. A very good agreement has been found for not only the extracted current but also the meniscus position [3].

- Injection scheme
  There are at least three different plasma injection schemes in the community: (i) the re-injection of each particle that is lost [2,7]; the re-injection of electron-positive ions pairs for each positive ion that is lost [1,8] and a constant particle influx for each species [13]. As stated in the discussed paper [1], the re-injection of each particle (i) will not be able to model the plasma sheath in a system without the extraction because the same amount of electrons and positive ions is always maintained. However, it also unproven if any of the three injection schemes is able to properly model the plasma sheath under the presence of an extraction aperture and the extraction potential. In order to study systematically the impact of the injection schemes on the model results, an analysis of all plasma injection methods and its influence on the sheath and negative ions extraction has been started using a mesh size lower than the Debye length. It is expected that all three schemes give the same results for the extraction of negative ions as the physics needs to be correctly represented.

- Simulation time
  The paper [1] points out the difference of the converging time between the ONIX simulations and the 2D PIC code. This difference comes from different approaches of the initial plasma conditions. In the ONIX code the initial bulk plasma is injected from the very beginning of the simulation using the plasma parameters from the experimental measurements. Therefore, the steady values of the extracted particle currents are approached relatively fast (a few µs) and do only slightly evolve for longer computation times. In the code reported in [1] the initial plasma is without negative ions. Hence this model requires much longer simulation time in order to allow negative ions produced from the plasma grid surface to reach the left border of the simulation domain and to build up H^+, H^-, e^- plasma moving afterwards back towards the extraction aperture.

- Flat grid
  The relatively low extracted ion current (< $2mA/cm^2$) from the negative ions produced at a flat area of the plasma grid in the ONIX simulation comes from the relative low negative ion density in the bulk plasma region that by turn depends on the deepness of the virtual cathode (see below: potential well). The latter is most probably linked to the mesh size being larger than the Debye length and will be verified soon.

- Realistic plasma and source conditions
  The ONIX code uses realistic plasma and source conditions. Among them are the source geometry, the plasma density and the particle temperatures, the external applied 3D magnetic field topology and the extraction potential. It needs to be stated, that no parameter is object to be scaled.

- Potential well
  The paper under discussion [1] criticises strongly that the potential well in the ONIX simulation is -20 V. Such high values, however, were obtained in the very first simulations only that used a non-realistic emission rate for the negative ions from the plasma grid surface (2000 A/m^2 [2]). Publications later on, report on a potential well of order of -6 V to -7 V [3,4] by using the realistic emission rate of 600 A/m^2 and introducing in the simulation Cs^+ ions. Very recent simulations with improved grid treatment (a slight underestimation of the electric field close to the grid was removed by correcting the distance of the closest PIC node to the plasma grid) show even a value of -3 V [15].

- Ion-ion plasma
  In order to simulate the contribution from the volume to the extracted current, the negative ion density in the bulk plasma region was introduced artificially as background by using data obtained from the experiments. As a consequence an ion-ion plasma is achieved and furthermore the impact on the co-extracted electrons could be tested [5].

Comments on the results of the ONIX code compared to experimental results and results from other models:

- Extracted ion currents (and meniscus)
  The extracted negative ion current and the amount of the co-extracted electrons agree with experimental measurements for different source conditions (for example at the different extraction potential 5 kV and 10 kV reported in [5]). The negative ion extraction probability (about 35% from conical plasma grid surface) is also in the same range with the simulation made by Gutser [16] (~30%). The meniscus shape and its position calculated by the ONIX code for positive ion extraction is also in agreement with commercial code KOBRA3D [12]. Unfortunately, there is no experimental data to compare with the meniscus position in the negative ion extraction sources. Recent measurements performed in an arc source [17] show that at the distance of as close as 4 mm from the plasma grid surface there is still a quasineutral plasma. Therefore the ONIX code, where the deepest meniscus point is located at the distance ~2.5 [3] mm from the plasma grid, also agrees with this measurement.

- Co-extracted electrons
  ONIX is the only code aiming to calculate and predict the co-extracted electron current. A dedicated benchmark shows good agreement for different extraction potentials and source conditioning [5]. As pointed out several times, the 3D topology of the magnetic field, in particular the deflection field in the extraction grid, plays a crucial role for such simulations. Small changes in the magnetic field strength and its topology change drastically the extracted electron current. This highlights the relevance of 3D simulations where the correct topology on the magnetic field can be implemented only.

- Variation with extraction voltage
  The results of a parametric study of the extraction potential performed by the ONIX code is also in agreement with the experimental measurements [5]. An increase of the currents (H- and e) with extraction voltage is obtained in both the simulation and the experiments.

- Variation with Cs conditioning
  The Cs conditioning from experiments was modelled in ONIX by variation of the emission rate of negative ions from the plasma grid surface. It was found that the simulations were able to reproduce experimental results [5] by using the emission rate in the realistic range (50-550 A/m^2).

Comments on the 2D PIC code in connection with the experimental setup and results:

- Debye length criterion near the PG
  The authors of the discussed paper [1] state that the Debye length criterion should always be fulfilled in PIC modelling and show how it affects the results especially in terms of the beam profile. However, the simulations presented do not satisfy this criterion near the plasma grid. In the caption of Figure 5, the density of negative ions has a maximum value of 2×10^{16} m^{-3} this results together with the temperature of negative ion coming from the plasma grid surface of 1 eV in a Debye length of 52 µm while the mesh size is 100 µm.

- Negative potential at the left border
  The code presented in the paper [1] applied a negative potential at the left hand side border of the simulation domain describing that a similar condition is present in the experiment. As a result of this negative left hand boundary negative ions present in the volume cannot be lost through that boundary and are reflected into the calculation domain of the 2D code. As shown in Fig. 10 [1] a reasonable number of negative ions is achieved in the 2D PIC code only with the negative potential; contrary without negative potential the negative ion density in the volume is as low as in the 3D PIC codes. The existence of such a negative left hand boundary is completely in disagreement with the situation in the experiments: axial potential profiles measured by Langmuir probes [18] show a steady increase of the plasma potential in the ion sources from the plasma grid towards the driver volume. Additionally, the mean free path of the negative hydrogen ions – although it is in the range of several tens of cm close to the PG [19] – decreases drastically towards the driver due to increasing T_e and n_e. Even if some negative ions reach a side or back wall and are reflected into the bulk plasma the probability for these negative ions to return to the extended boundary layer close to the PG is negligibly small. Concluding, the introduction of the negative left hand boundary is completely artificial.

- Extraction voltage and beam profile
  The extraction voltage is much too low as already stated in [1]. It is the result of a scaling procedure, assuming a "usual collisionless space charge limited situation". The applicability of this scaling procedure to the negative hydrogen ion sources under investigations is highly questionable since – as stated above – experimental results indicate that extraction in these sources is not space charge limited and the extracted currents do not follow the Child-Langmuir law. The performed scaling of the extraction voltage may result in a non-realistic shape and position of the meniscus that directly depends on the extraction voltage and thus a non-realistic description of the beam optics and beam physics. The latter may be a reason for the beam asymmetry shown in [1] for 700 V extraction potential.

- Co-extracted electrons
  It is stated that the co-extracted electron current is negligible compared to the negative ion current. This contradicts completely the experimental evidence: the co-extracted electrons are in the same range as the negative ion current and often limit the source performance. Moreover, the magnetic field used in [1] is with 40 mT at the origin not a realistic value. It is at least twice lower than the magnetic field strength in the experiments (110 mT). If the electron current is negligible at 40 mT it will be even lower at 110 mT. Furthermore, in all the sources the negative ion density and the co-extracted electrons scale with the extraction voltage. As stated above the dependence on the extraction voltage is much higher than for the negative ions.

- Magnetic field topology
  In a 2D code the 3D magnetic field topology, being of importance for describing the deflection field, cannot be matched and the circular aperture is approximated by a slit. As mentioned in the preceding paragraph, the deflection field defined as 40 mT in the zero point (figure 3) is strongly underestimated as it is about 110 mT at this point in the experiment. Beside the underestimation of the deflection of negative ions in the beam, this has also consequences of the co-extracted electrons and also on the plasma parameters close and in the plasma sheath as the deflection field dominates about 5 to 6 mm in front of the plasma grid over the magnetic filter field. Additionally the relevance of flat grids in 2D representing an infinitive slit needs to be questioned as well before comparing to experimental values.

Finally we would like to state that in general all codes use assumptions and simplifications to be capable to target a problem. We completely agree with the authors of the paper that a complete full 3D modelling of the ion source under realistic parameters is out of the computer capabilities. Results of any modelling presented are interesting and relevant physics issues under the corresponding constrains. As long as they are mentioned in the respective papers it is to be seen as a contribution to the community worth to be published.

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