

Improved Neutral Beam Injection source region modelling via self-consistent Virtual Cathode evolution

G. Stathopoulos¹, M. Hasan¹

¹University of Liverpool, Liverpool, UK

Introduction - In negative ion NBI negative Hydrogen/Deuterium ions are accelerated then neutralised to form the neutral Hydrogen beam which is injected into tokamaks [1]. In future devices like ITER negative ion NBI will be used due to the ease of neutralising negative Hydrogen/Deuterium ions at high energies. [2] These negative ions are produced in the NBI source region before extraction and acceleration. The main method of production is via the conversion of Hydrogen atoms incident on the Caesiated plasma grid (PG) to negative ions [3]. So far 3D particle in cell (PIC) codes have had issues recreating the H⁻/D⁻ ion densities which reach the bulk plasma compared to experiments. In PIC codes when negative ions are emitted from a surface (simulation Dirichlet boundary) a negative space charge can form in front of that surface forming a potential minimum. This is called a virtual cathode [3]. A virtual cathode then reflects a lot of emitted negative ions back to the surface preventing them from reaching the bulk plasma. In simulations the density of H⁻/D⁻ ions which successfully reach the plasma is significantly lower than experiments.

Current Assumptions – In 3D PIC simulations up until now it is assumed that the conversion of H atoms incident on the PG to H⁻ ions occurs with a uniform conversion probability across all incident particle energies and a uniform energy reflection coefficient [3]. The incident H atom energy distribution is Maxwellian hence the emitted H⁻ ions from the PG will also have a Maxwellian energy distribution and this is how they are modelled. In some simulations H⁻ ions are emitted from the PG at the start of the simulation even if the protons from the source region haven't reached the PG yet. This will lead to an artificially deep virtual cathode forming at the initial stages of the simulation due to protons being unable to provide any compensatory positive charge for an excessive buildup of negative space charge from the H⁻ ions. This virtual cathode then stays in place and excessively hinders H⁻ ions from reaching the bulk plasma resulting in a much lower H⁻ ion density in the plasma.

Alternative Assumptions – Two alternative assumptions were tested in an alternative model. The first new assumption was the probability of an incident H atom being converted to an H⁻ ion on the PG is dependent on the incident energy of that individual atom. The dependence of

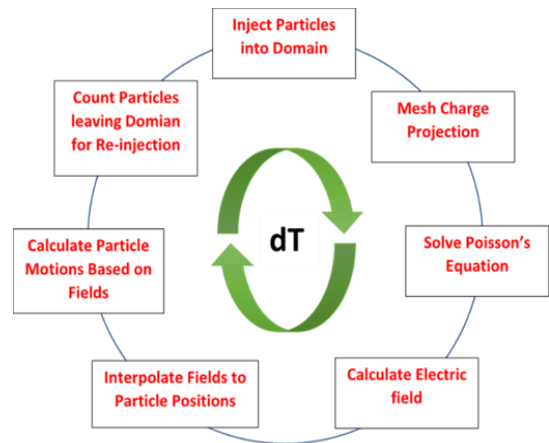


Figure 1: Schematic diagram of how a PIC code works

this conversion probability on the incident atom energy can be seen in [4]. For simplicity in this model a truncated probability distribution was adopted where under an incident energy threshold of 1.5eV the probability of H atom to H⁻ ion conversion is zero and above this energy threshold the conversion probability is 60%. This probability is applied to the atoms above the threshold with $kE > 1.5 \text{ eV}$ normal to the PG by generating a random number P between 0 and 1 ($0 \leq P < 1$) for each atom above the threshold and if $P < 0.6$ this atom will lead to the formation of an H⁻ ion but if $P \geq 0.6$ no H⁻ ion will be formed for this atom. The flux of H atoms onto the PG was determined from equation 1 for an H atom density of $1 \times 10^{19} \text{ m}^{-3}$ and an H atom temperature of 0.8eV [5]. A constant energy reflection coefficient of 0.75 was used where $kE_{Ion} = R_E \times kE_{atom}$ [3]. This led to a truncated Maxwellian distribution of energies for the emitted H⁻ ions.

$$\Gamma(H) = \frac{1}{4} \cdot \langle v(H) \rangle \cdot n(H) \quad (1)$$

The second new assumption involved implementing a proton drift velocity towards the PG to replicate the protons reaching the plasma grid before the H atoms which lead to H⁻ ion emission. This will act to provide a compensatory positive space charge to the negative space

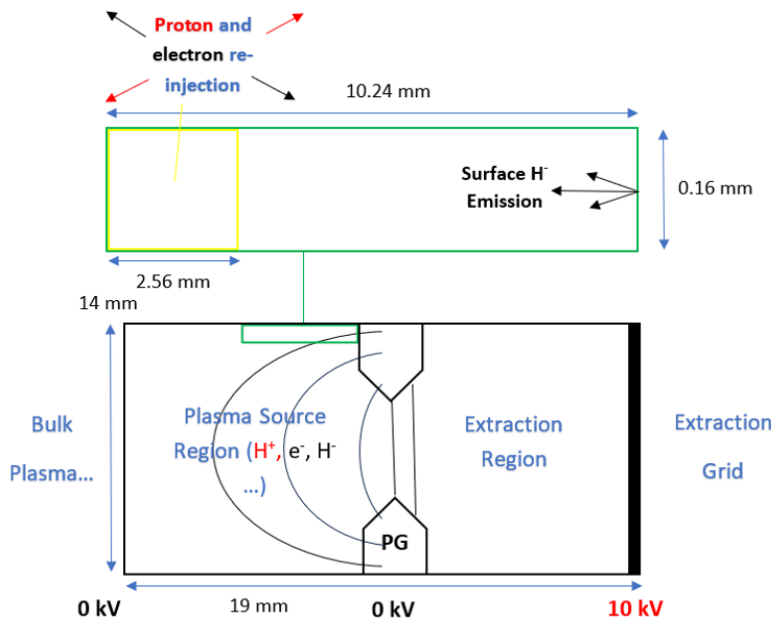


Figure 2: Used domain in green. Cell size was $1 \times 10^{-5} \text{ m}^3$ and timestep was $1 \times 10^{-12} \text{ s}$. Upstream boundary and PG were modelled as Dirichlet boundaries and all other boundaries were periodic.

charge buildup from H⁻ ion emission which should reduce the depth of the evolved virtual cathode allowing more H⁻ ions to reach the bulk plasma resulting in a higher H⁻ ion density. The value of this proton drift is taken from the Bohm criteria at the sheath edge which can be seen in equation 2 from [6] for the case of H⁻ ion emission from the PG and H⁻ ions present in the plasma volume (in this case 0 since no volume production of H⁻ ions is simulated). Here V_0 is the initial energy of protons at the PG

sheath edge towards the PG, n_{io} , n_{eo} and n_{no} are the plasma proton, electron and H⁻ ion densities respectively where in this case initial n_{no} will just be set to 0 for convenience. T_e and T_n are the electron and H⁻ ion temperatures respectively, j_b is the resultant current flux of emitted H⁻ ions and M_b is just the mass of a proton. V_c is the value of the plasma sheath at the PG and U_b is the energy of the emitted H⁻ ions. e is just the unit charge. From this a proton drift

of $\sim 13000 \text{ ms}^{-1}$ towards the PG is calculated and implemented.

$$V_0 = \frac{n_{i0}}{2 \left(\frac{n_{e0}}{T_e} + \frac{n_{n0}}{T_n} - \frac{j_b}{e} \left(\frac{M_b}{e} \right)^{\frac{1}{2}} (2V_C + 2U_b)^{-\frac{3}{2}} \right)} \quad (2)$$

No Proton Drift

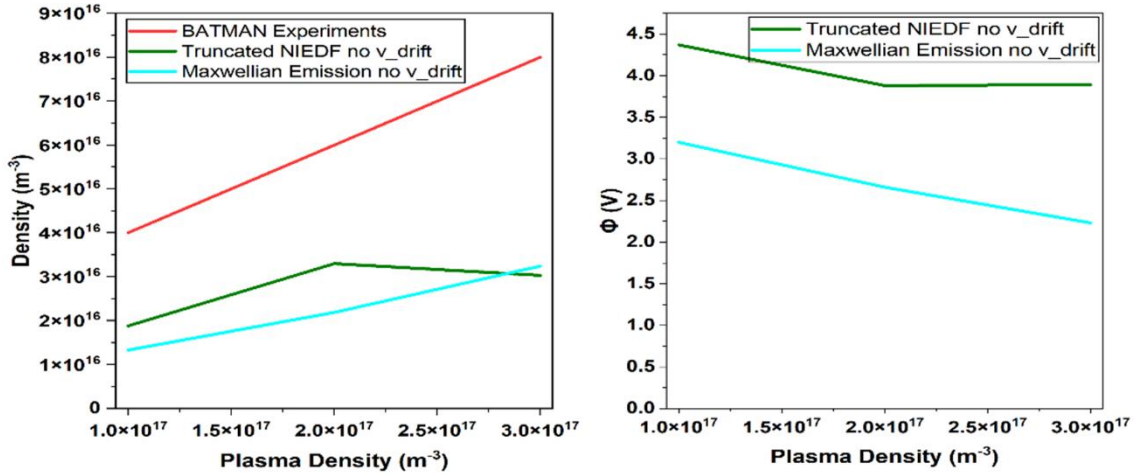


Figure 3: H⁻ ion density in plasma (left) and virtual cathode depth (right)

Proton Drift

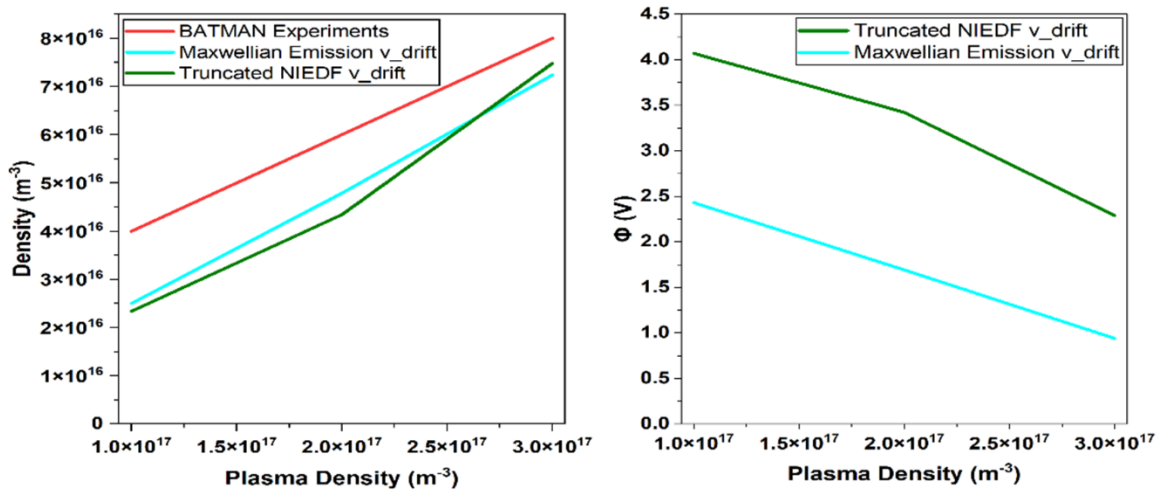


Figure 4: H⁻ ion density in plasma (left) and virtual cathode depth (right)

Discussion – For the case of no proton drift it can be seen that the H⁻ ion density in the plasma from both the Maxwellian emission and truncated NIEDF (Negative Ion Energy Distribution Function) emission is roughly similar. The virtual cathode depth though for the truncated NIEDF emission is significantly higher than that of the Maxwellian emission for all plasma densities. For the case where there is a net proton drift towards the PG the H⁻ ion density reaching the plasma from both the Maxwellian emission and truncated NIEDF emission again is roughly similar. Compared to the case with no proton drift though both models show a significantly higher H⁻ ion density in the bulk plasma. For the combination of the truncated

NIEDF and proton drift the H^- ion density in the bulk plasma is 89% higher compared to that of the Maxwellian NIEDF with no proton drift. Similar to the no proton drift case the virtual cathode depths of the truncated NIEDF emission model for all plasma densities are significantly higher than those of the Maxwellian emission model. Virtual Cathode depths for both models are lower when there is a proton drift vs no proton drift.

These results show that the implementation of the proton drift provides a compensatory positive space charge for the negative space charge accumulation from the H^- ion emission reducing the virtual cathode depth allowing more H^- ions to surpass the virtual cathode and reach the bulk plasma. This made a considerably larger difference than the H^- ion emission energy distribution function. For both cases of proton drift and no proton drift the virtual cathode depths were higher for the truncated NIEDF. This is because without the compensatory positive space charge there is a given space charge limit to the negative space charge buildup and in the truncated NIEDF the average emission energy is higher. Since this is the case a deeper virtual cathode forms to suppress the more energetic H^- ions from reaching the bulk plasma as well.

Conclusion – This work shows how important factoring in the effect of a net proton drift towards the PG really is and how important it is to investigate experimental values of this drift. This demonstrates how there is still a lot of work to be done in understanding space charge effects when it comes to surface emission of negative (and even positive) ions in simulations. It is seen that the virtual cathode and resultant ion density in the plasma are extremely sensitive to initial simulation parameters and this is worth further investigation so the simulation model can be refined further with its effects on the whole source region and H^- ion beamlet extraction factored in. Consideration of these factors is important for self-consistent NBI source region modelling, understanding and development.

References

- [1] Wunderlich D, Mochalsky S, Montellano IM, Revel A. Review of Scientific Instruments. 2018 May 1;89(5).
- [2] Fantz U, Franzen P, Kraus W, Berger M, Christ-Koch S, Frösche M, Gutser R, Heinemann B, Martens C, McNeely P, Riedl R. Plasma Physics and Controlled Fusion. 2007 Nov 20;49(12B):B563.
- [3] Montellano IM, Wunderlich D, Mochalsky S, Fantz U. Journal of Physics D: Applied Physics. 2019 Mar 28;52(23):235202.
- [4] Cui HL. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films. 1991 May 1;9(3):1823-7.
- [5] Wunderlich D, Gutser R and Fantz U 2009 Sci. Technol. 18 045031.
- [6] McAdams R, Holmes AJ, King DB, Surrey E. Plasma Sources Science and Technology. 2011 May 19;20(3):035023.