WARPX SIMULATION OF THE PLASMA MENISCUS EFFECT IN A NEUTRAL BEAM INJECTION SYSTEM

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Abstract

The US Department of Energy INFUSE collaboration between Realta Fusion and Lawrence Berkeley National Laboratory (LBNL) aims to extend WarpX towards high fidelity modeling of neutral beam injection (NBI) systems [1]. WarpX is a parallel, open source, and portable particle-in-cell (PIC) code with an active developer community and demonstrated scalability [2]. In this work, we implement and validate the plasma meniscus modeling for a positive ion source using first principle PIC simulations. These simulations are performed in the electrostatic mode with extraction electrodes represented as embedded boundaries. The upstream plasma reservoir is modeled using a thermal injection scheme with real electron mass to capture the correct sheath physics. These results and validations form a crucial basis for future extensions to negative ion sources and photoneutralization, enabling start to end NBI modeling within WarpX.

INTRODUCTION

Realta Fusion is a startup based in Madison, Wisconsin, working on the magnetic mirror fusion concept [3, 4]. The Wisconsin High-temperature superconductor Axisymmetric Mirror (WHAM) is a high-field platform for prototyping this technology, where plasma heating is achieved through neutral beam injection (NBI) and electron cyclotron heating (ECH) [5]. Among different NBI approaches, positive-ion beam systems are the most mature and well-studied [6]: ions are extracted from a plasma source, accelerated through a multi-electrode structure, and neutralized by a background gas to form a high-energy neutral beam. Reliable modeling of such systems is therefore crucial for optimizing plasma power balance and overall machine performance.

Traditionally, ion-optics codes such as PBGUNS and IBSimu are used to model NBI devices [7,8]. These approaches assume steady-state beam transport and treat space-charge compensation using ad hoc neutralization factors, which is generally sufficient for engineering studies of conventional positive- and negative-ion NBI systems. However, more advanced concepts such as photoneutralization require self-consistent treatment of space-charge effects and transient particle dynamics [9]. The particle-in-cell (PIC) method provides a natural framework to capture these effects [10].

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Under funding by the US Department of Energy INFUSE program, Realta Fusion and LBNL are extending the capabilities of the WarpX PIC code for high-fidelity modeling of NBI systems [11]. WarpX is an open-source, massively parallel PIC code designed to run efficiently on both GPU and CPU architectures [2, 12]. It has demonstrated strong scalability on modern high-performance computing platforms and has been applied to a wide range of problems, including laser–plasma interactions, accelerator, and beam physics [13–15].

In this paper, we implement and validate plasma meniscus modeling in WarpX for a positive-ion NBI system, benchmarking against published PBGUNS results for the WHAM-relevant NBI settings [16]. This work establishes a foundation for future studies of more advanced NBI designs and their coupling to mirror plasma simulations.

SIMULATION SET-UP

Simulations are performed using the WarpX PIC code in the electrostatic mode with the default energy-conserving option. The set-up follows the extraction of a single 40 keV H^+ beamlet from the WHAM-relevant NBI system as described by Sorokin *et al.* [16].

The electrodes are implemented through the embedded boundary capabilities in WarpX. As shown in Fig. 1, the simulation domain is fully three-dimensional with the longitudinal direction along z, with dimensions $L_x = L_y = 0.8$ cm and $L_z = 2.7$ cm. Through a convergence study, the resolution parameters are chosen to be $(n_x, n_y, n_z) = 128 \times 128 \times 256$ with $\Delta t = 1.8\omega_{pe}^{-1}$, where ω_{pe} is the electron plasma frequency. Note that ω_{pe} does not need to be explicitly resolved when using the energy-conserving option. However, if the chosen timestep is too large, significant current oscillations can occur during the transient phase of the simulation.

Particles are subject to absorbing boundary conditions at the domain boundaries and embedded electrode surfaces. For the field solver, Neumann boundary conditions are applied on all boundaries except at the negative z boundary, where a Dirichlet condition $\phi = 0$ kV is imposed. The electrode potentials are specified such that the second electrode is at -41 kV and the final electrode at -40 kV.

The upstream plasma reservoir occupies the region -0.2 cm $\leq z \leq 0$ cm and consists of H^+ ions and electrons with density n_p and temperature T_p. Here, real electron mass is used in order to capture the correct sheath physics of the meniscus. Since the physical plasma reservoir is much

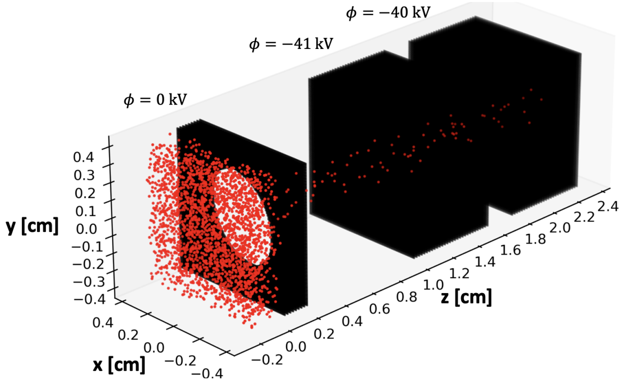

Figure 1: Three-dimensional visualization of H^+ ion extraction. The plasma reservoir region is $z < 0$ electrons not shown. The electrode geometry is shown in black, while H^+ macroparticles are shown in red. Note that only a small fraction of the macroparticles ($\sim 10^{-3}$) are shown to avoid visual clutter.

larger than the simulated region, it is approximated with a self-replenishing thermal injection scheme. Without continuous particle injection, the source plasma would be depleted over time, leading to unphysical oscillations in the extracted current.

Plasma particles are therefore continuously injected through five faces of the reservoir with flux

$$\Gamma = \frac{n_p v_{\mathrm{th},j}}{\sqrt{2\pi}}, \tag{1}$$

where the thermal velocity is $v_{\mathrm{th},j} = (k_B T_p / m_j)^{1/2}$ for species $j \in \{H^+, e^-\}$, k_B is the Boltzmann constant, and m_j is the particle mass.

RESULTS

Reproducing WHAM-relevant Operating Point

In their simulation, Sorokin *et al.* consider an extracted H^+ current of $I_0 \sim 0.066$ A [16]. To reproduce this operating point, the plasma temperature is fixed at $T_p = 10$ eV while the plasma density is varied until the steady-state current approaches I_0. This condition is obtained for $n_p = 1.2 \times 10^{18}$ m^{-3}. The extracted current trace is shown in Fig. 2. After an initial transient, the current reaches a constant value of ~ 0.064 A at $t \sim 40$ ns.

Figure 3(a) depicts the steady-state slice at $y = 0$, where the first electrode provides focusing. Further downstream, space charge effect dominates, causing H^+ particles to diverge and the beam radius to increase. Figure 3(b) shows the kinetic energy profile as a function of z, where the acceleration follows the electrode potentials as expected.

Numerical Validation

Having reproduced the WHAM-relevant operating point, we examine three cases that fail to reach steady state, highlighting the importance of the plasma reservoir, thermal injection and timestep choice. The extracted current traces for all three cases are shown in Fig. 4.

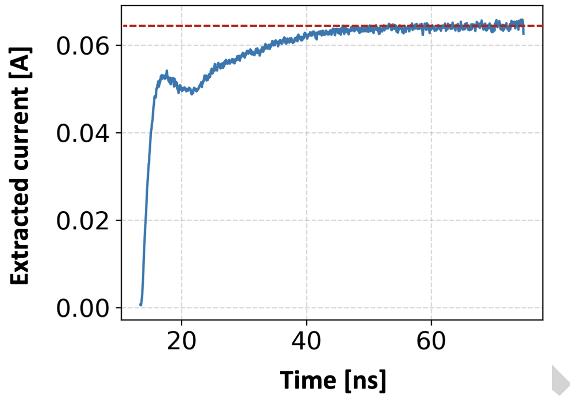

Figure 2: Extracted H^+ current trace measured at the positive z boundary as a function of time. The current reaches a steady-state value of ~ 0.064 A after ~ 40 ns. The current is computed by tracking H^+ ions absorbed by the $+z$ boundary.

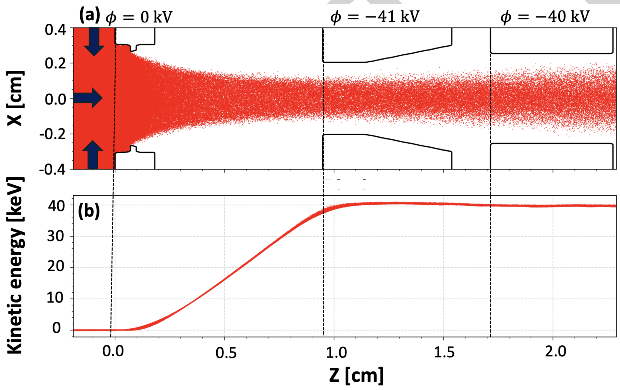

Figure 3: (a) Slice at $y = 0$ at steady state showing the H^+ macroparticles and the electrode geometry. The arrows denote the thermal particle injection used to maintain the plasma reservoir (two additional injection in the $\pm y$ direction are not shown). (b) Kinetic energy of the individual H^+ macroparticles as a function of z, showing the expected energy gain from the applied electrode potentials.

The first case removes the plasma reservoir entirely, and instead injects slow H^+ ions (kinetic energy $\ll 40$ keV) directly from the $z = 0$ plane. While this is tempting in practice as it avoids the need to resolve electron motion and allows for a larger timestep, the plasma meniscus cannot form self-consistently without a reservoir. The current therefore exhibits persistent oscillations without converging to a steady state.

The second case retains the plasma reservoir with thermal injection omitted. The reservoir therefore depletes over time, leading to initial oscillations in the current which subsequently decays and never reaches steady state.

The third case retains thermal injection with a coarser timestep ($dt = 3\omega_{pe}^{-1}$), violating the plasma frequency condition ($dt \leq 2\omega_{pe}^{-1}$). Similar initial oscillations are observed. However, the simulation eventually develops a numerical instability, manifesting as an unphysical growth in the extracted current.

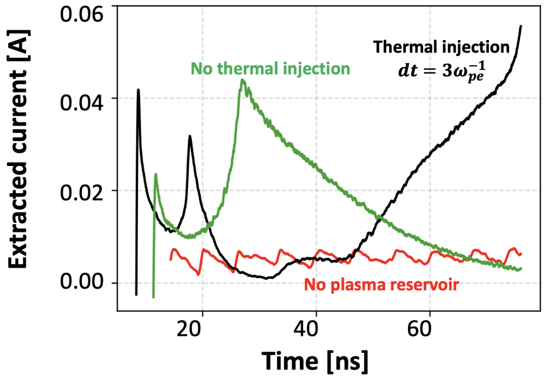

Figure 4: Extracted H^+ current as a function of time for three cases that fail to reach steady-state: (1) no plasma reservoir (red), (2) plasma reservoir without thermal injection (green), (3) thermal injection with a coarse timestep $dt = 3\omega_{pe}^{-1}$ (black).

CONCLUSION

In this paper, plasma meniscus formation and beam extraction for a positive-ion neutral beam injector were modeled using the PIC code WarpX. The simulations were performed in electrostatic mode with the electrode geometry represented using embedded boundary capabilities. The upstream plasma reservoir was modeled using a thermal particle injection scheme with real electron mass in order to capture the correct sheath physics at the extraction aperture.

This study demonstrates that WarpX can model ion source extraction physics with self consistent space charge effects within an open source framework. The results highlight the importance of a self consistently modeled plasma reservoir, a physically motivated thermal injection scheme, and adequate resolution of plasma timescales to capture meaningful beam extraction dynamics. This work opens the capability for incorporating full space charge effects in NBI simulations within a flexible and extensible PIC framework. The approach is readily extendable to more advanced NBI concepts, including negative ion extraction and photoneutralization [11].

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