



Multi-Fidelity Simulation Approach for Negative-Ion Based NBI Development

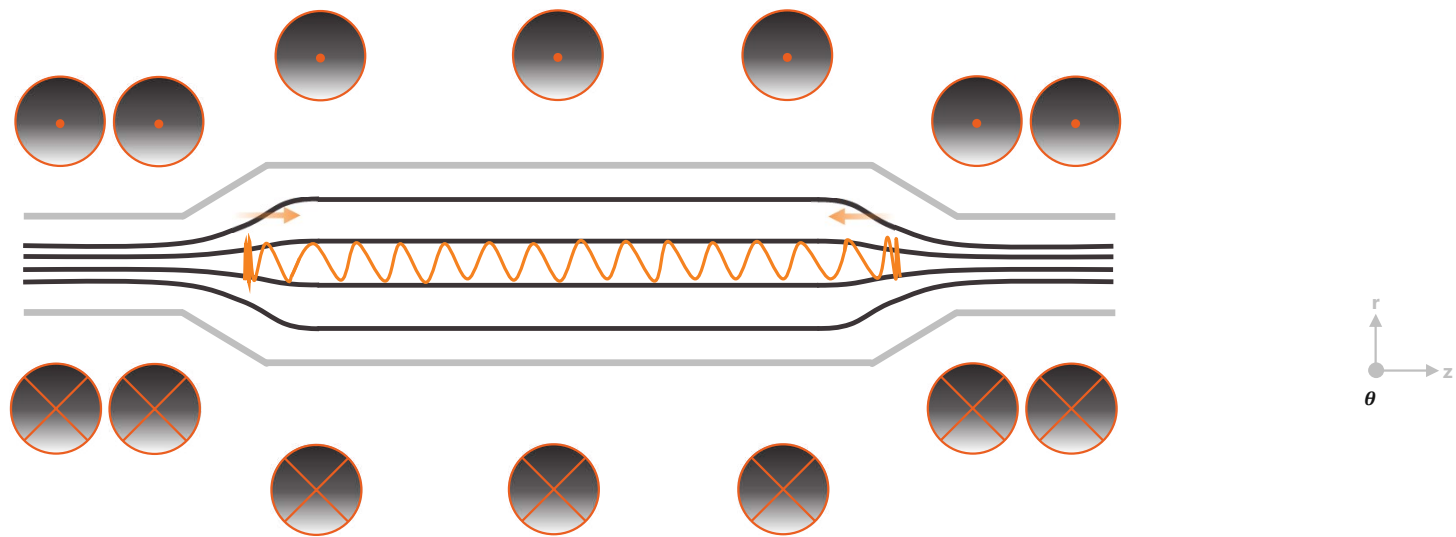
Joey Eickman, Kai Shih, Anthony Cooper, Miral Shah, Eleanor Powell, Ikhlas Addow, Roelof Groenewald

01

Magnetic Mirrors

Introduction to Magnetic Mirrors

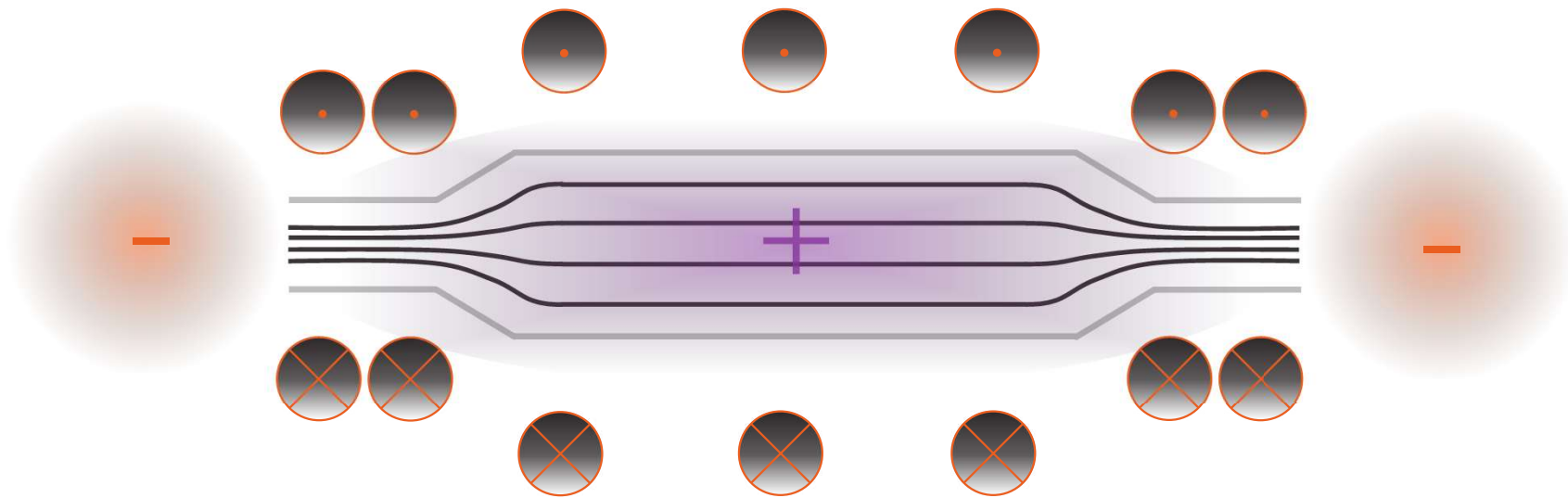
1.1 Simple Mirror



Charged particles pushed back toward center as they approach magnetic field gradient near ends

Introduction to Magnetic Mirrors

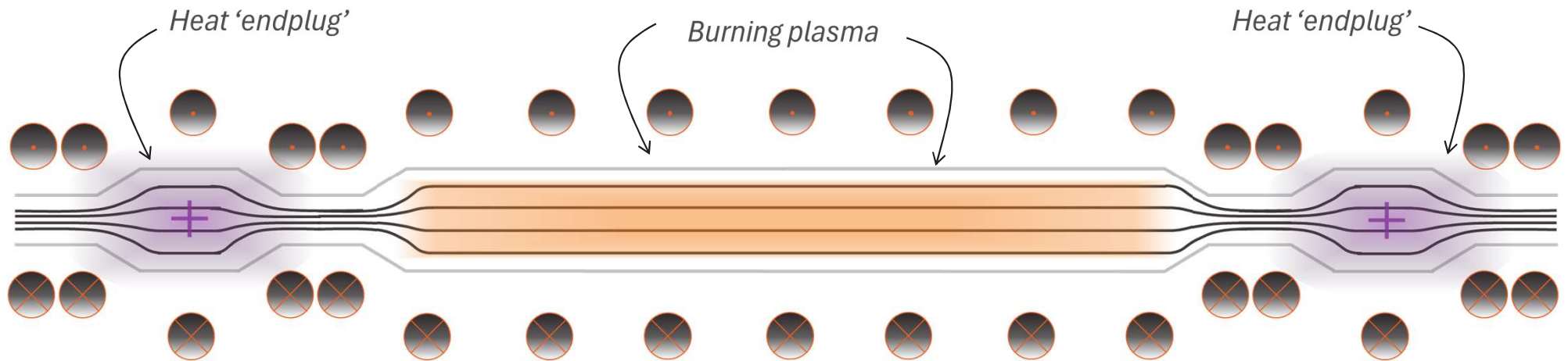
1.1 Simple Mirror



electrons are 'leakier' than ions $\Leftrightarrow$ positive potential develops in mirror

Introduction to Magnetic Mirrors

1.2 Tandem Mirror



End plug ambipolar potential

- Confines ions in the central cell
- Scales with density ratio between plugs and central cell
- Driven by neutral beam injection (NBI)

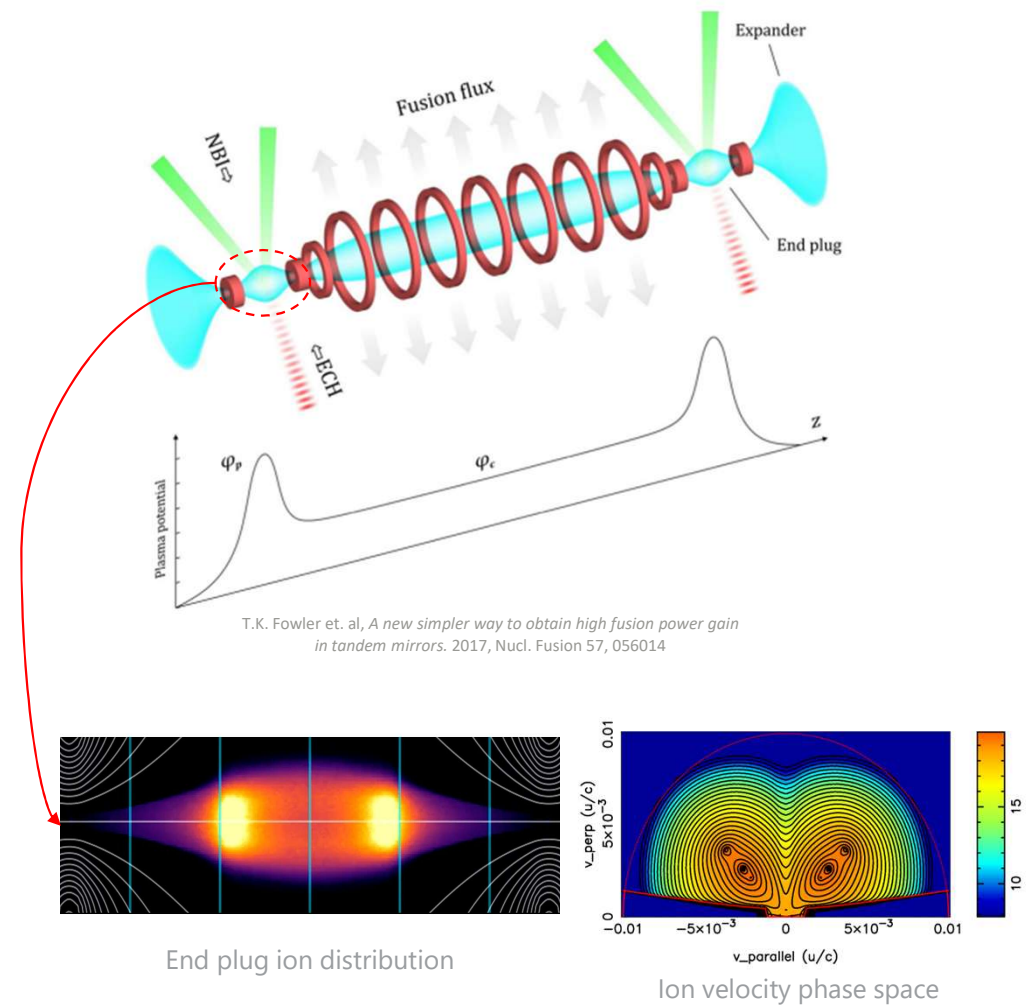
02

NBI in Tandem Mirrors

NBI in Tandem Mirrors

2.1 Confinement and Stability

- End plug ambipolar potential **requires high density, high temperature** plasma
- NBI provides a direct injection of high-energy particles
- In the magnetic mirror, confinement time scales with ion energy $\tau \propto E_i^{3/2}$
- Angled injection stabilizes plasma against Alfvén-ion cyclotron (AIC) instabilities



NBI in Tandem Mirrors

2.2 NBI Roadmap

Wisconsin HTS Axisymmetric Mirror (WHAM)

- Active fusion experiment demonstrating simple mirror

NARSIL

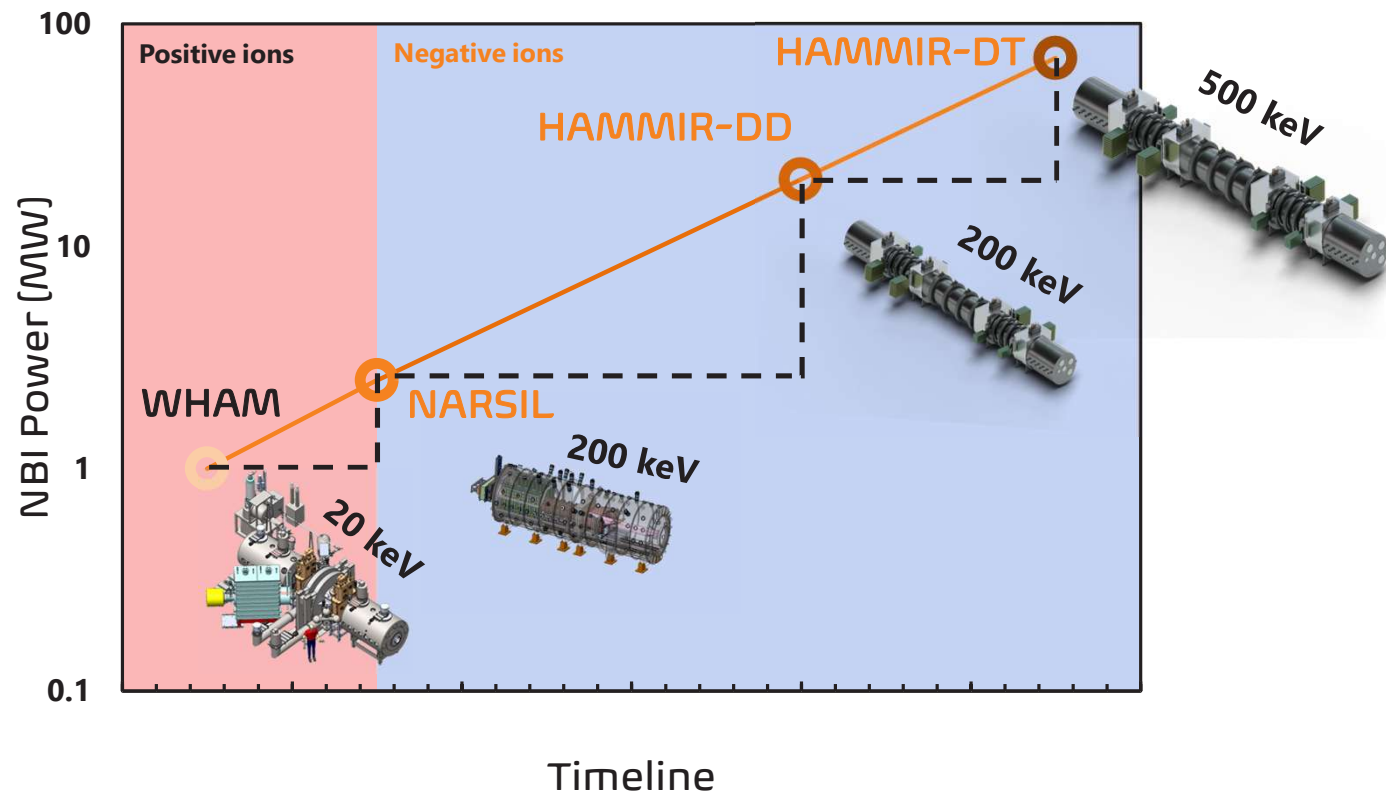
- NBI test stand

HAMMIR-DD

- Upcoming fusion experiment demonstrating tandem mirror and DD fusion

HAMMIR-DT

- First of a kind fusion power plant with DT fuel

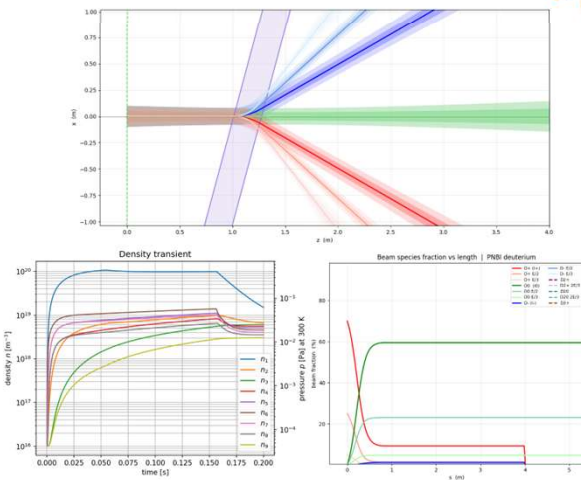


03

Multi-fidelity Modeling

Multi-fidelity Modeling

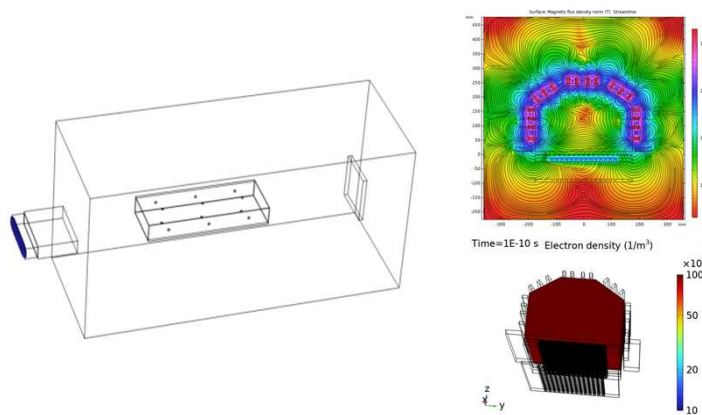
3.1 Tools Overview



Purpose: Rapid exploration of design space with key physics [Low Fidelity]

Capabilities

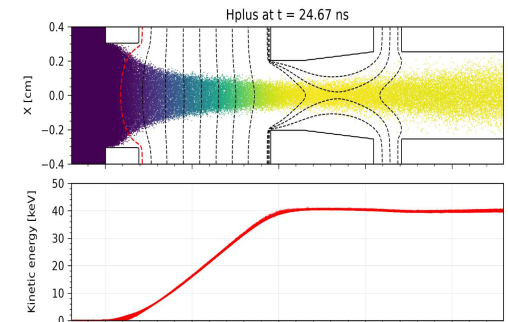
- Beam envelope and profile
- Gas density (molecular flow)
- Neutralization and reionization
- Magnetic deflection of ions
- Power deposition



Purpose: Self-consistent multiphysics simulations on detailed geometry [Medium Fidelity]

Capabilities

- Monte-Carlo particle transport
- Beam envelope and profile
- Gas density (3D molecular flow)
- Neutralization and reionization (secondary particles)
- Magnetic field solver and ion deflection
- Power deposition and heat transfer
- Ion source plasma dynamics



Purpose: Detailed physics simulations of key phenomena [High Fidelity]

Capabilities

- Monte-Carlo particle transport
- Beamlet extraction and acceleration
- Space charge effects
- Neutralization and reionization (secondary particles)
- Magnetic field solver and ion deflection
- Ion source plasma dynamics
- All of physical reality (given enough GPUs)

03.2

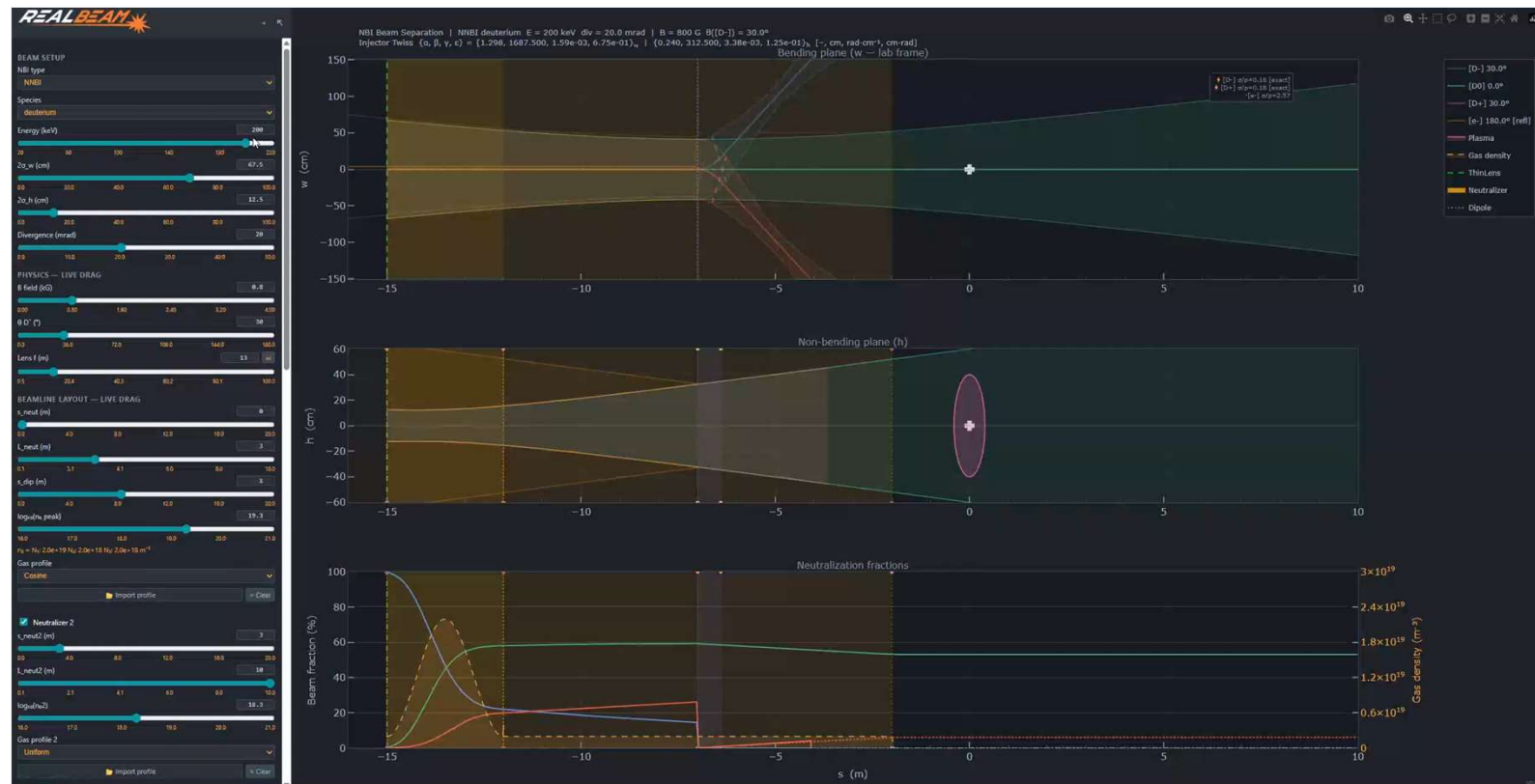


In-house interactive tool for beam dynamics modeling

Multi-fidelity Modeling

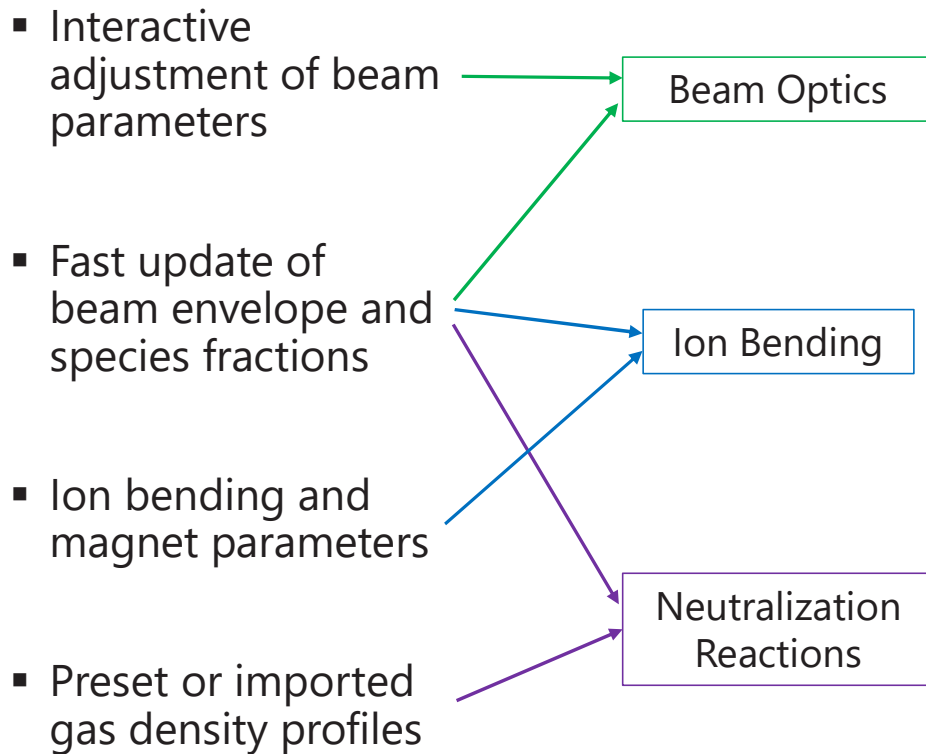
3.2 RealBeam

- Interactive adjustment of beam parameters
- Fast update of beam envelope and species fractions
- Ion bending and magnet parameters
- Preset or imported gas density profiles



Multi-fidelity Modeling

3.2 RealBeam - Equations



$$\psi(s) = M(s|s_0)\psi(s_0)$$

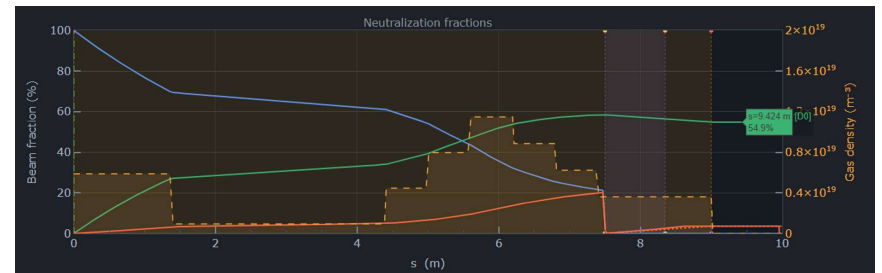
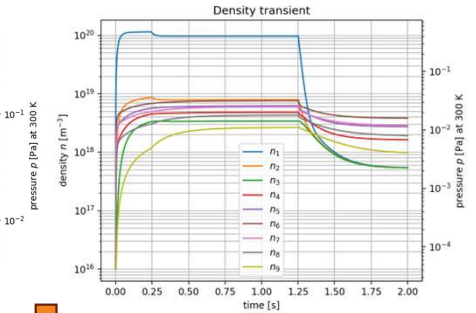
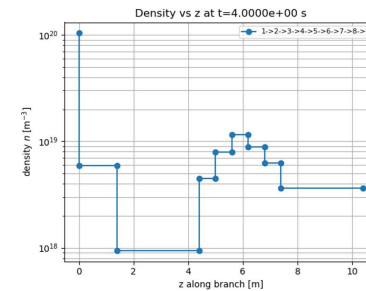
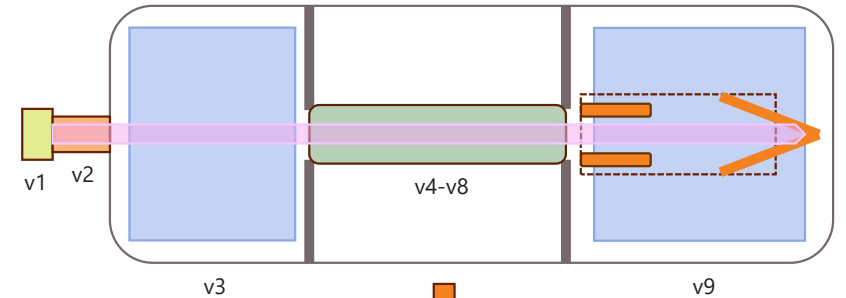
$$\theta = \frac{L}{\rho} \quad \rho = \frac{\sqrt{2mT}}{Bq}$$

$$\frac{d\Gamma^0}{ds} = \Gamma^- \sum_k \sigma_{-10}^k n_k + \Gamma^+ \sum_k \sigma_{10}^k n_k - \Gamma^0 \sum_k \sigma_{01}^k n_k$$

Multi-fidelity Modeling

3.2 RealBeam – Molecular Flow

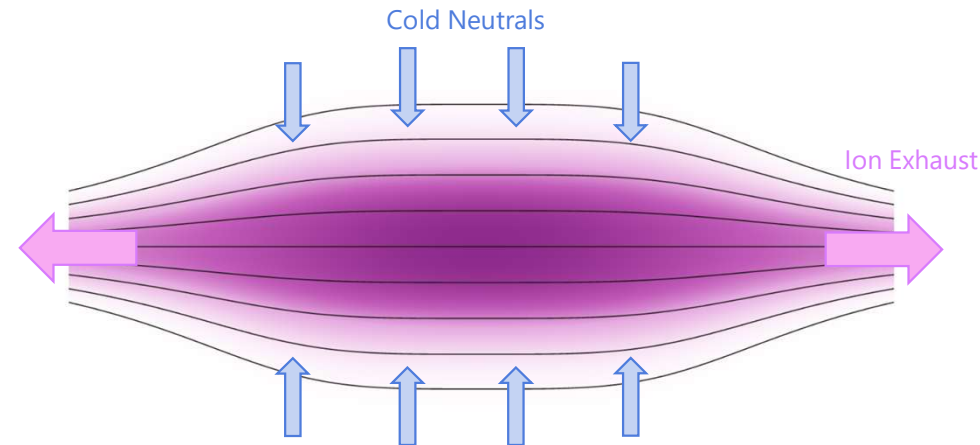
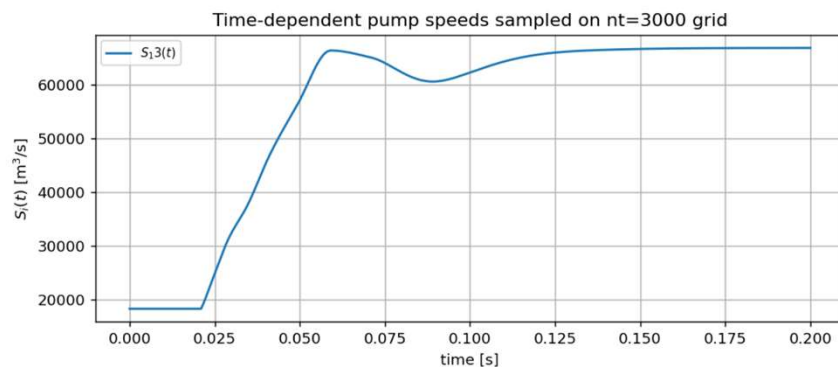
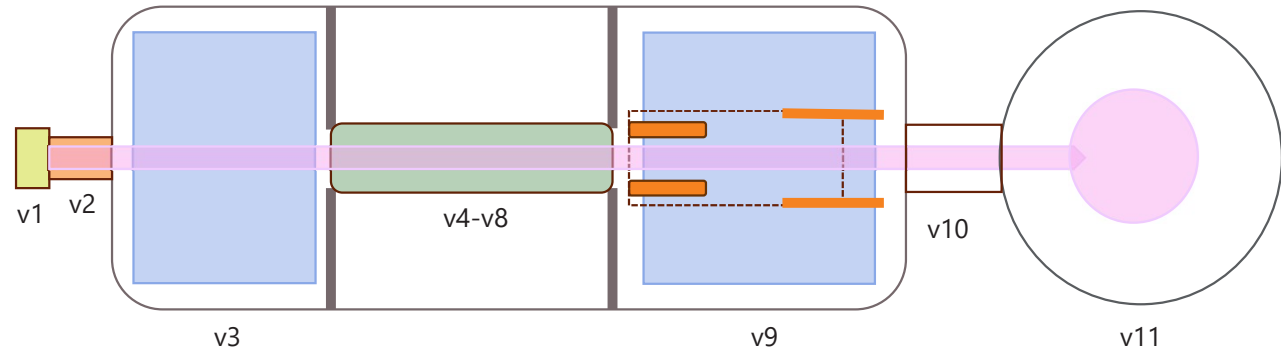
1. Discretize volumes
2. Calculate conductances
3. Add sources and sinks
4. Solve gas density profile (transient)
5. Use profile to calculate neutralization



Multi-fidelity Modeling

3.2 RealBeam – Molecular Flow

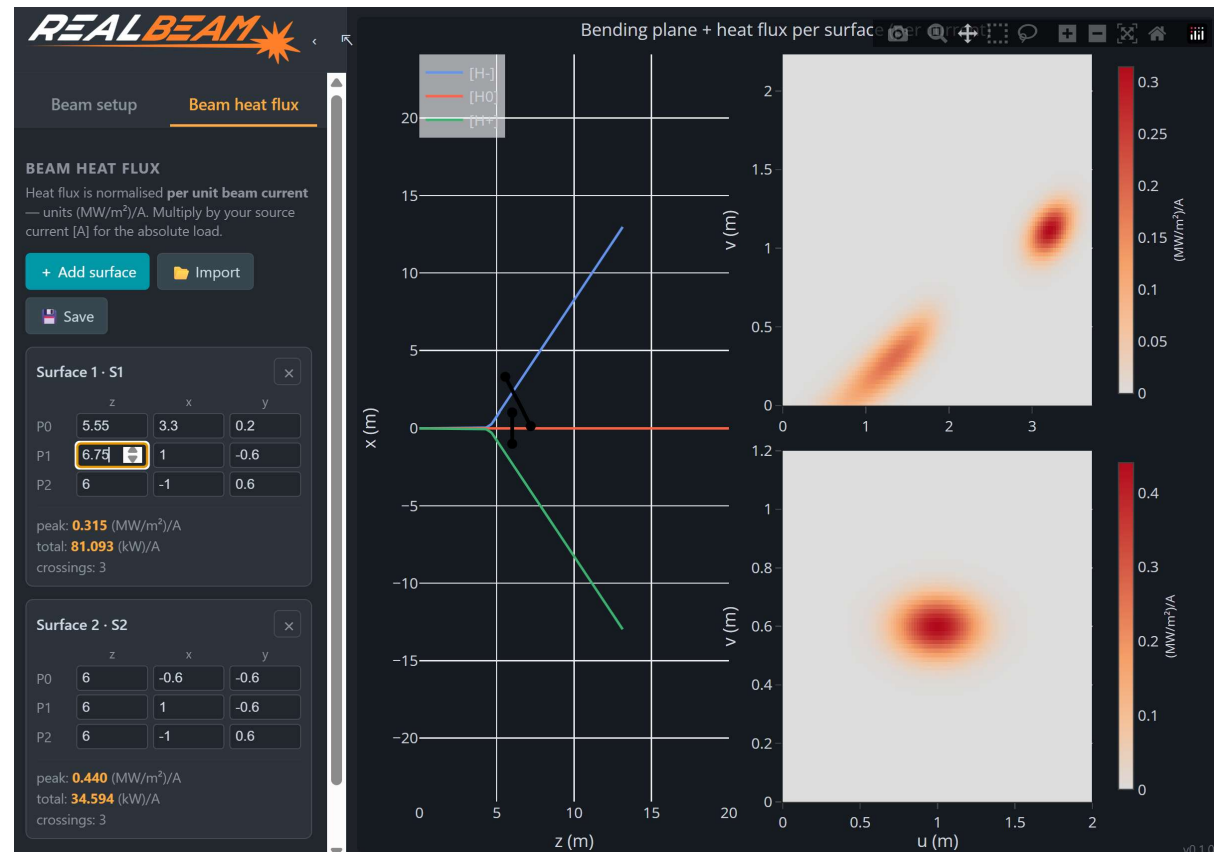
- NBI must maintain a vacuum environment which can sustain the plasma
- Gas migration from the NBI beamline into the mirror plasma can be evaluated
- Time-dependent “plasma-pumping” speed can also be modeled



Multi-fidelity Modeling

3.2 RealBeam – Power Deposition

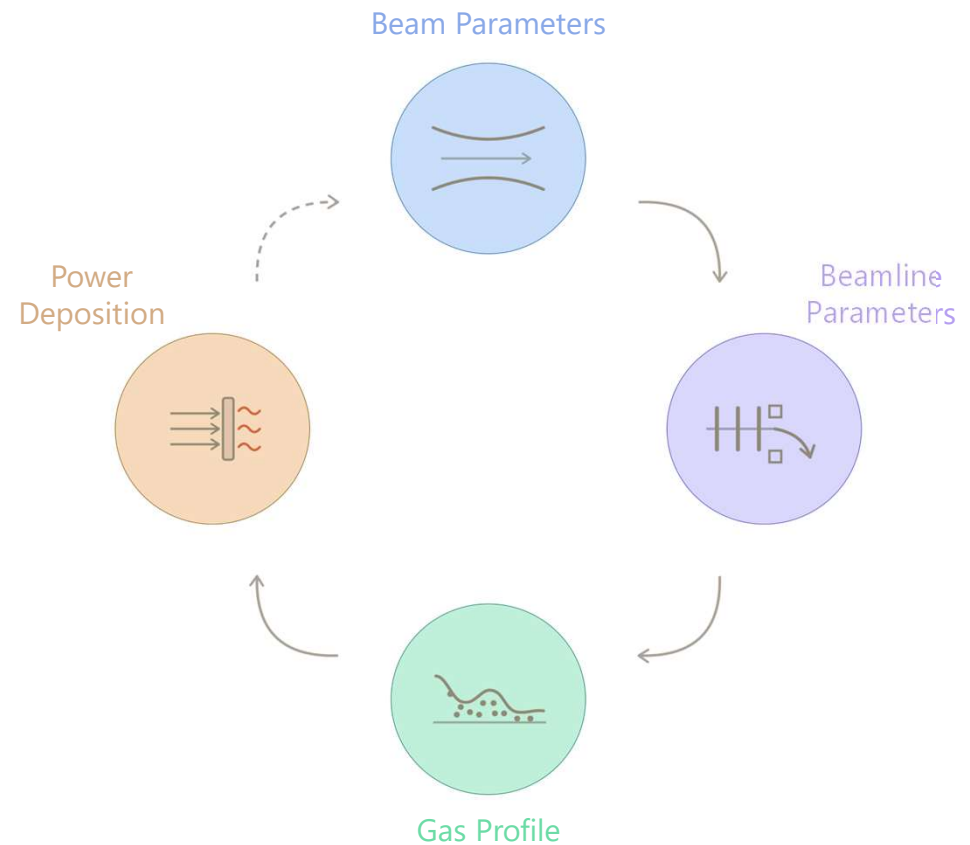
- Arbitrary planes represent beamline geometry
 - (ion dumps, calorimeter, drift tube, etc.)
- Beam profile assumed or calculated analytically
- Power deposition calculated on surfaces
- Provides first estimate of heat flux on beam-facing components



Multi-fidelity Modeling

3.2 RealBeam – Workflow

- Interactivity of RealBeam enables rapid iteration
- Primary physics and their interactions captured with analytical models
- Exploration of a large design space allows many configurations to be evaluated
- Complete workflow establishes baseline design for higher fidelity tools



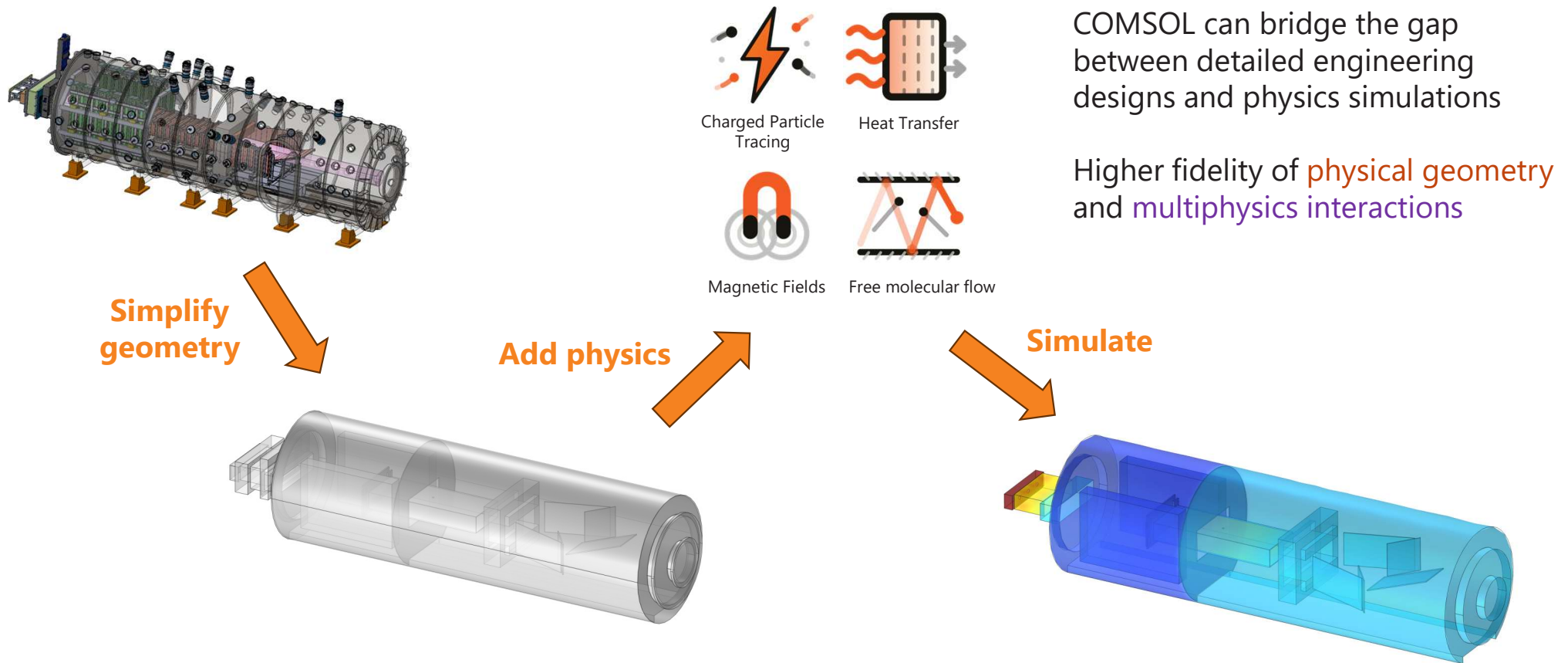
03.3



Commercial multiphysics software for integrated simulations on CAD geometry

Multi-fidelity Modeling

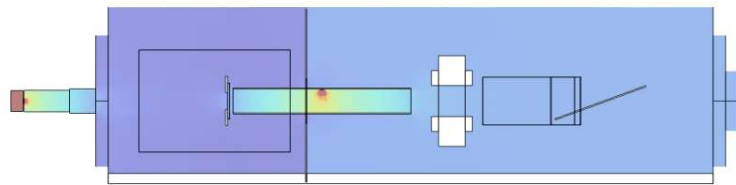
3.3 COMSOL - Workflow



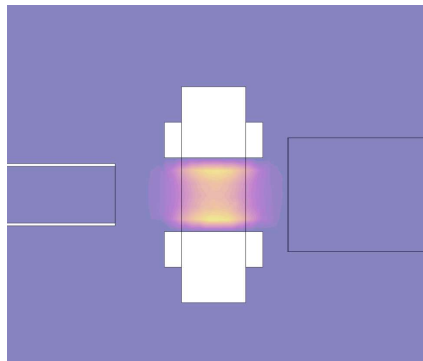
Multi-fidelity Modeling Approach

3.3 COMSOL - Simulation

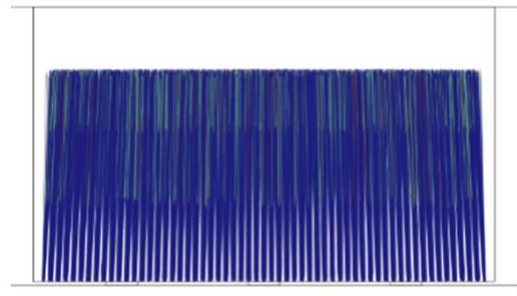
Comprehensive multiphysics environment + CAD geometry



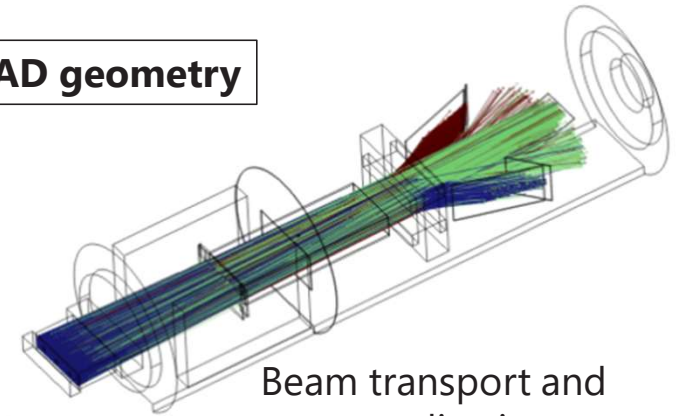
Gas density profile



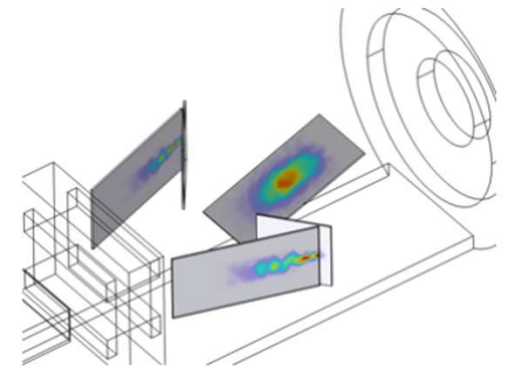
3D magnetic field



Initial particle distribution



Beam transport and neutralization



Heat deposition

Multi-fidelity Modeling

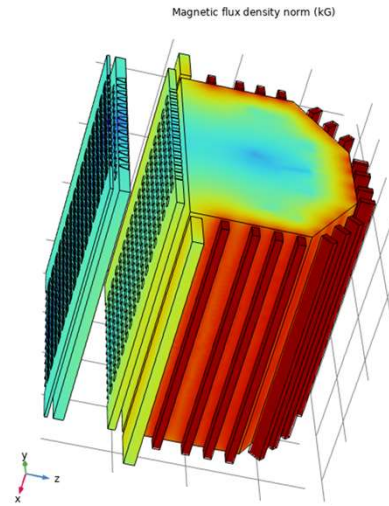
3.3 COMSOL

3D Ion source plasma dynamics

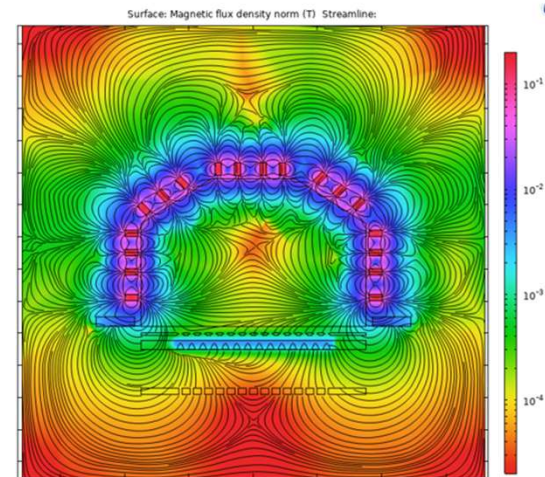
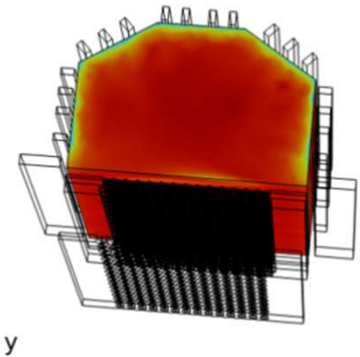
- Electron density
- Magnetic flux
- Negative ion production



Initial plasma distribution for
extraction and acceleration
simulations



Time=1E-8 s Electron density ($1/m^3$)



03.4



Particle-in-cell code for high fidelity physics modeling

Multi-fidelity Modeling

3.4 WarpX

Advanced Particle-In-Cell (PIC) code

Geometries, models, & physics

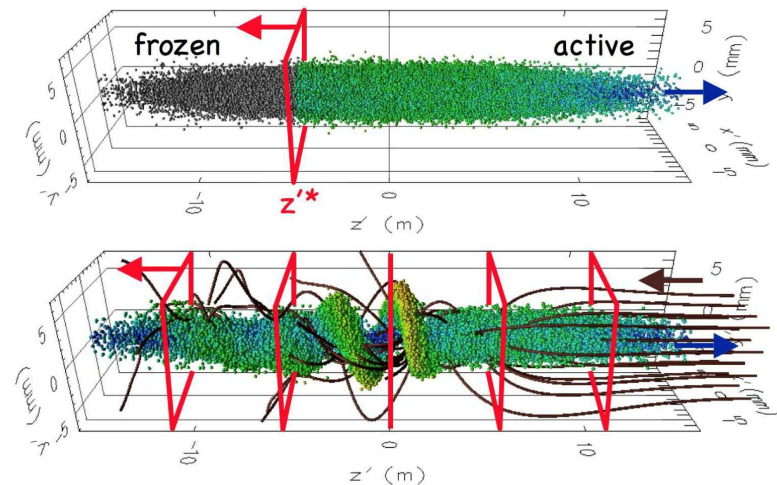
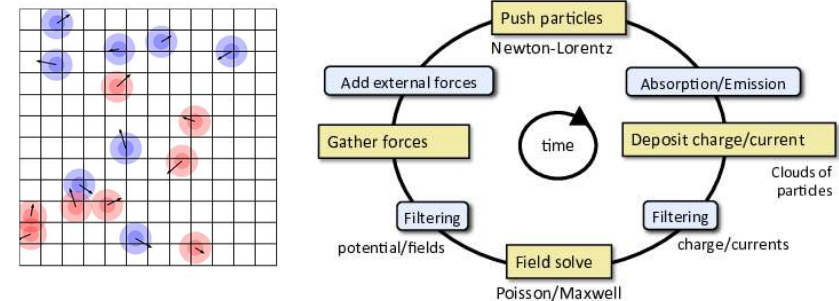
- 1D/2D/3D Cartesian, cylindrical, spherical
- electromagnetic, electrostatic, magnetostatic
- ionization, atomic, fusion and collisional physics, QED

Advanced numerical methods

- boosted frame
- mesh refinement
- explicit, implicit, pseudo-spectral solvers
- embedded boundaries (via STL files)

High-performance computing

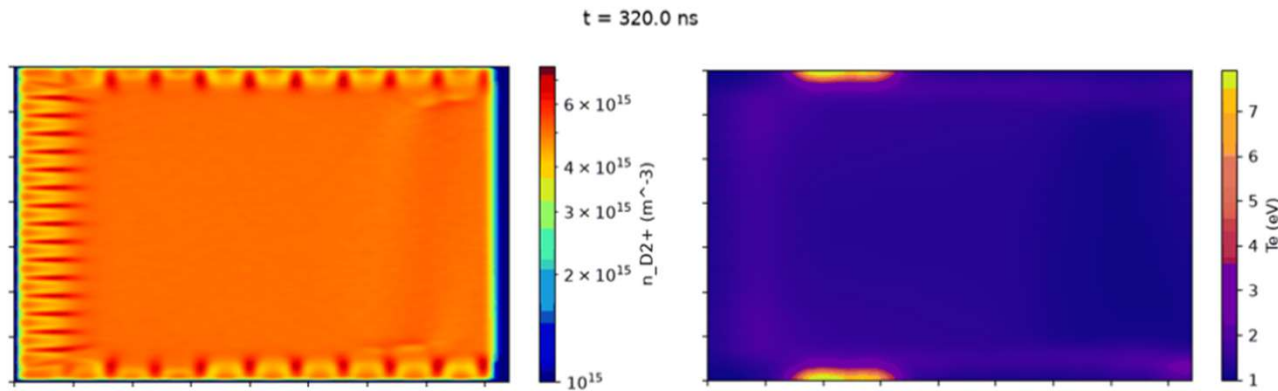
- from laptops to supercomputers
- CPUs and GPUs
- interactive python interface



<https://warpX.readthedocs.io/en/latest/index.html>

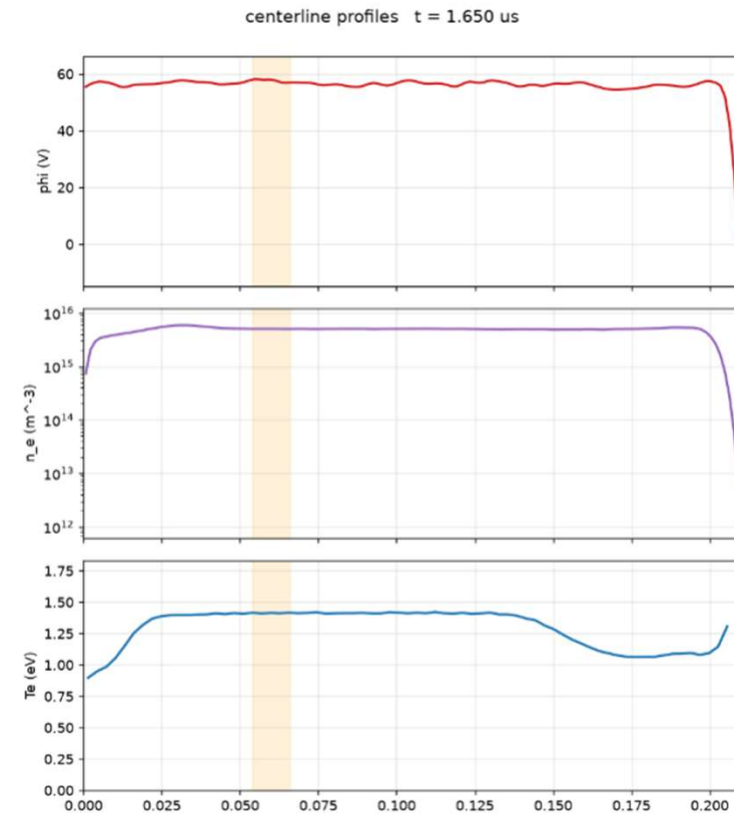
Multi-fidelity Modeling

3.4 WarpX – Ion Source Plasma Dynamics



3D PIC simulations provide **high fidelity** results for ion source plasma

- Charged particle density profiles (e^- , D^+ , D_2^+ , D_3^+ , D^-)
- Magnetic field and electric potential distributions
- Non-uniformities from magnetic filter field (ExB drift)
- Cesium dynamics
- Surface and volume production of negative ions

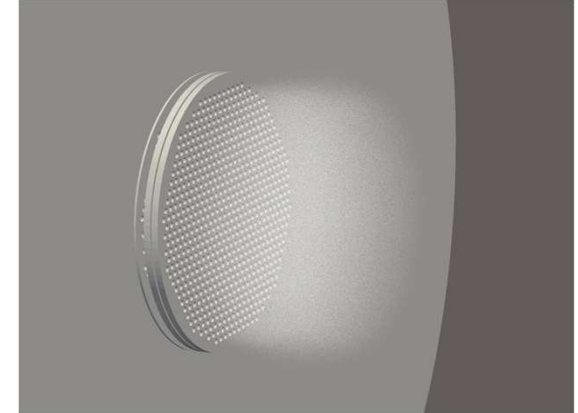
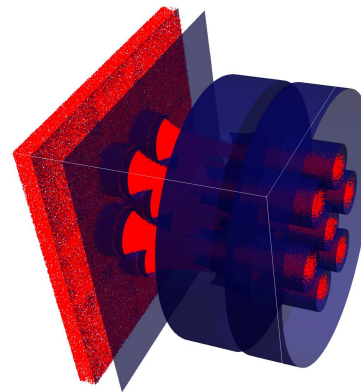
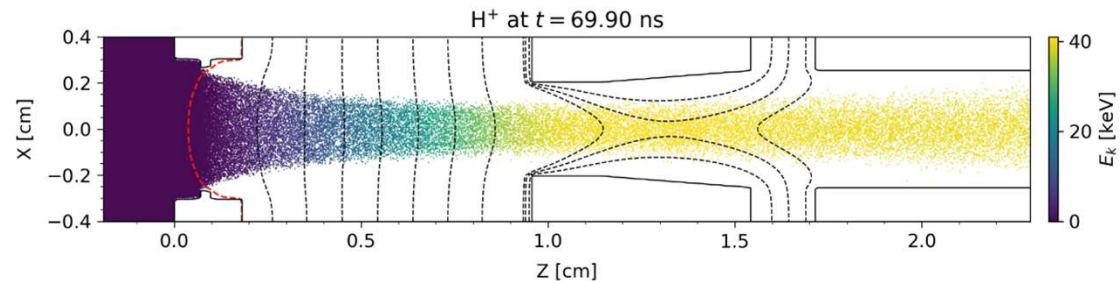


Multi-fidelity Modeling Approach

3.4 WarpX – Extraction & Acceleration

Grid simulations on multiple scales:

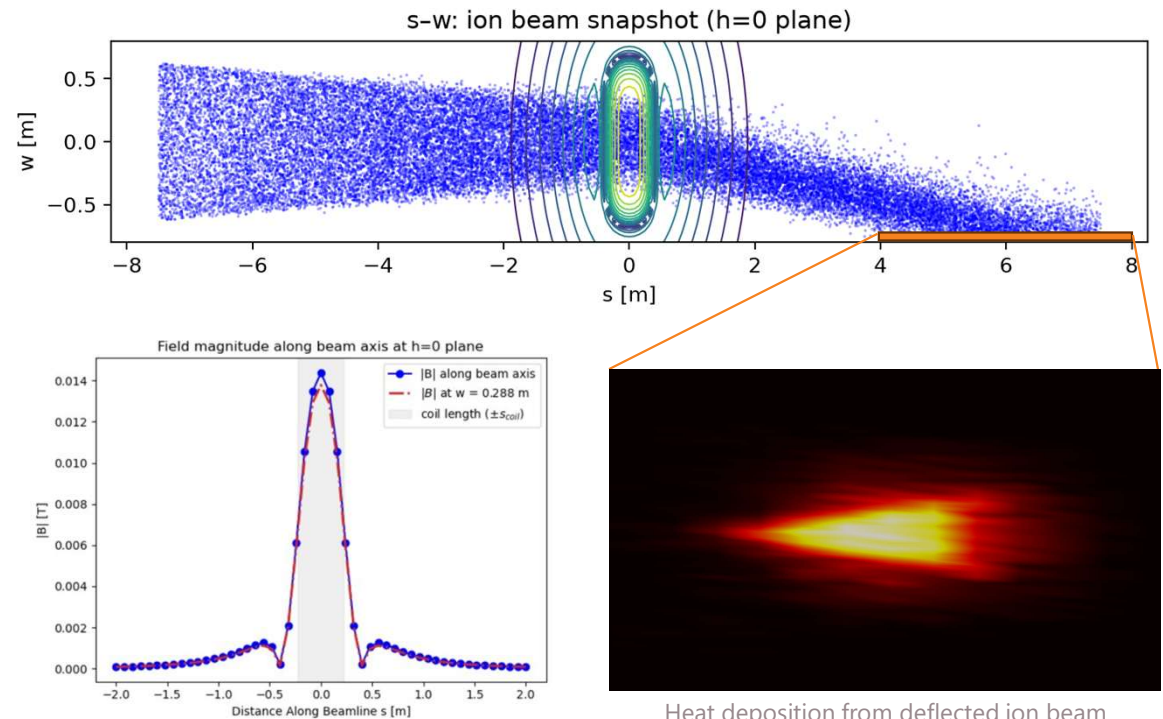
- **Single beamlet simulation**
 - validate beam current, beam size, and divergence
- **7 beamlet simulation**
 - Quantify multi-beamlet interactions and solve over STL geometry
- **~700 beamlet simulation**
 - Full-scale simulation of entire grid geometry
 - Accurate space charge representation for entire beam



Multi-fidelity Modeling Approach

3.4 WarpX – Ion Bending

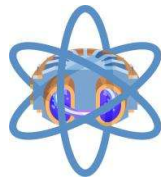
- Bending magnet designs evaluated with B-field calculator
- Weak focusing and edge focusing effects of dipole captured
- Detailed beam profile and heat deposition used for ion dump design



Multi-fidelity Modeling Approach

3.4 WarpX – Awards and Collaborations

Awards



INFUSE | Innovation Network
for Fusion Energy

Work supported by the INFUSE program under **CRADA No. FP00019597**. Simulations performed on NERSC under Contract No. DE-AC02-05CH11231 using NERSC award **FES-ERCAP0026655**.

Energy Department announces first Genesis Mission projects to accelerate new era of AI-driven scientific discovery

Announcement Number: DE-FOA-0003612

List Posted: 7/22/2026

<https://science.osti.gov/-/media/funding/pdf/Awards-Lists/2026/GM-RFA-Awards-List.pdf>

Collaborators



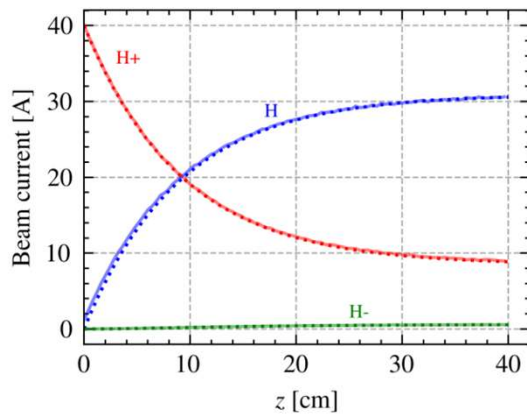
WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON



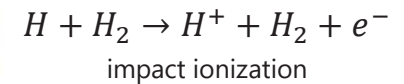
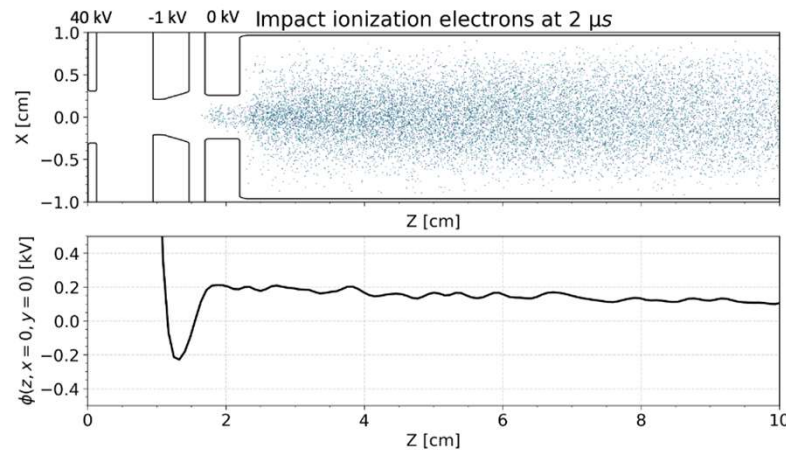
LBNL Collaborators: Remi Lehe, Olga Shapoval, Arun Persaud, Arianna Formenti

Multi-fidelity Modeling

3.4 WarpX – INFUSE Award



- Collisions with neutral gas alter the beam species fractions
- WarpX model matches analytical calculations



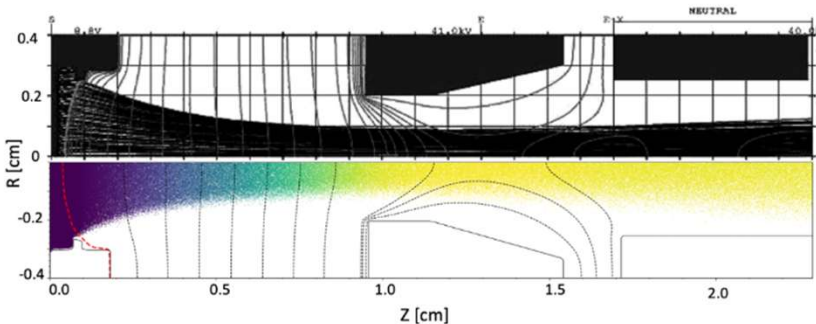
~80% space charge compensation from secondary electrons

- Secondary electron production is tracked
- Electrons compensate the space charge for PNBI

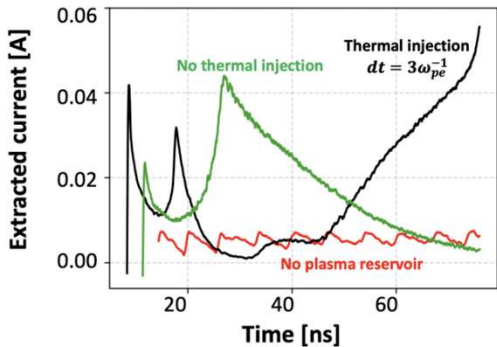
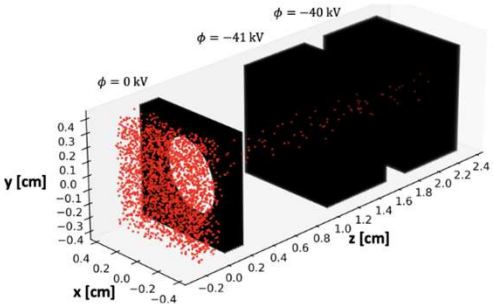
Framework being adapted for **NNBI space charge compensation** and **photo-neutralization**

Multi-fidelity Modeling

3.4 WarpX – INFUSE Award



Quantity	Reference	WarpX
Extracted current [A]	0.0658	0.0640
Beam radius [cm]	0.13	0.16
Neutral divergence [mrad]	20	19
Transmitted neutral current [A]	24	14



17th International Particle Accelerator Conference (IPAC), Deauville, France

17th International Particle Accelerator Conference, Deauville, France
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WARPX SIMULATION OF THE PLASMA MENISCUS EFFECT IN A NEUTRAL BEAM INJECTION SYSTEM

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C. M. Jacobson¹, A. Latrille¹, A. Persaud³, D. A. Sutherland¹, J.-L. Vay³

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³Lawrence Berkeley National Laboratory, Berkeley, United States

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 [10]. WarpX is an open-source, massively parallel PIC code designed to run efficiently on both GPU and CPU architectures [11, 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 PBUNTS 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_z, n_z, n_z) = (128 × 128 × 256 with Δt = 1.8ω_{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 φ = 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 ≤ z ≤ 0 cm and consists of H⁺ ions and electrons with density n₀ and temperature T₀. Here, real electron mass is used in order to capture the correct sheath physics of the simulation.

For reference, the idealized neutralization model is described by the evolution of a beam species fraction vector, $\mathbf{F} = [f_e, f_n, f_p, f_i]^T$, where f_e, f_n, f_p, and f_i represent the positive-ion, neutral, and negative-ion fractions. For a beam passing through a prescribed neutral gas target, the charge-state evolution can be written as

$$\mathbf{F}(s) = \exp \left[\mathbf{M} \int_0^s n_{\text{gas}}(s') ds' \right] \mathbf{F}(0), \quad (1)$$

where n_{gas} is the background gas density and **M** is a reaction matrix containing the relevant charge-changing and ionization cross sections [7]. This matrix model provides

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SELF-CONSISTENT WARPX MODELING OF SPACE-CHARGE NEUTRALIZATION IN WHAM-RELEVANT NEUTRAL BEAMS

K. Shih¹, B. Nguyen^{1,2}, R. Lehe³, O. Shapoval³, A. C. Cooper¹, J. Eickman¹, A. Formenti³,
C. M. Jacobson¹, A. Latrille¹, A. Persaud³, D. A. Sutherland¹, J.-L. Vay³

¹Realta Fusion, Madison, Wisconsin, United States
²Imperial College London, London, United Kingdom
³Lawrence Berkeley National Laboratory, Berkeley, United States

Abstract

This work presents Particle-in-Cell (PIC) simulations using WarpX [1] to study neutral beam injection (NBI) [2] physics in Wisconsin HTS Axisymmetric Mirror (WHAM) [3]-class beamlines as part of a DOE INFUSE collaboration between Realta Fusion and Lawrence Berkeley National Laboratory. The goal is to develop a self-consistent model that couples beam extraction, gas neutralization, re-ionization, and space-charge compensation. The neutralization model is verified against an analytic matrix formulation for charge-state evolution, and the accelerator model is benchmarked against a published WHAM-relevant positive-ion NBI configuration. WarpX reproduces the single-aperture extracted current and captures the reference downstream beam divergence. The coupled simulation further shows that primary electrons generated by impact ionization reduce the beam potential by about 80%, identifying the dominant space-charge neutralization mechanism. These results establish a benchmarked positive-ion NBI modeling workflow for future multi-aperture WHAM simulations and advanced negative-ion or photo-neutralized beam concepts.

INTRODUCTION

Neutral beam injection (NBI) is a mature and widely used technique for plasma heating in magnetic confinement fusion devices [4]. However, predictive modeling of NBI systems remains challenging because beam extraction, neutralization, and space-charge compensation are strongly coupled. In particular, downstream transport is not determined only by accelerator optics or gas neutralization efficiency, but also by the charged-particle population created by beam-gas interactions.

This work was performed as part of a U.S. DOE INFUSE collaboration between Realta Fusion and Lawrence Berkeley National Laboratory to develop a self-consistent WarpX modeling capability for Wisconsin HTS Axisymmetric Mirror (WHAM)-class neutral beam systems. The immediate objective is to benchmark WarpX against a positive-ion neutral beam configuration relevant to the WHAM NBI system. The broader motivation is to establish a validated simulation framework for future negative-ion and photo-neutralized NBI concepts [5, 6], where space-charge effects are expected to play a central role.

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TUP-Poster session
MCA2B: Applications: Industrial Accelerators

TUP3068
2305

<https://www.ipac26.org/prepress/doi/jacow-ipac2026-tup3068/index.html>

<https://www.ipac26.org/prepress/doi/jacow-ipac2026-tup8301/index.html>

Multi-fidelity Modeling

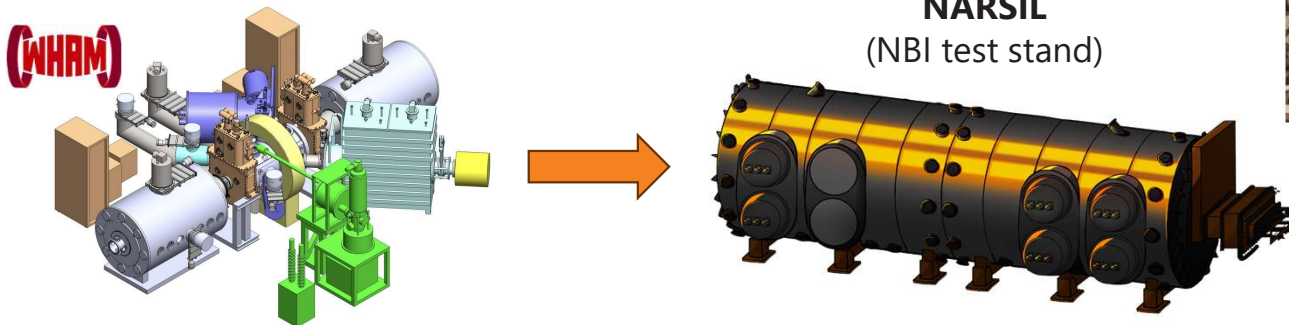
3.5 Genesis Mission

NBI operation is challenging due to the tightly coupled and non-linear nature of the system

This high-dimensional control space requires **extensive experimental iteration** and **long operational timescales**

Machine learning + **Multi-fidelity toolkit** -> **NBI digital twin**

Digital twin will enable near-real-time human-in-loop optimization and control



PI: Dr. Kai Shih

04

Conclusion

Conclusion

4.1 Advantages to the Multi-fidelity approach

Appropriate tool can be chosen for each stage of design

- **RealBeam** – scoping and first approximations
- **COMSOL** – integrated multiphysics and engineering design
- **WarpX** – detailed validation and physics investigations

Overlaps in capability allow us to check our results under different physics models

Assumptions can be validated with higher fidelity tools then applied to lower fidelity simulations

- Paraxial ray approximation
- Space charge compensation
- Beam profile



***REALITY
FUSION***

Thank you for your attention!

(WHAM)



NBI shot seen through the central cell