Numerical simulations investigating the isotope effect in the plasma sheath of negative ion sources for fusion NBI

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NNBI FOR ITER

Needed for heating and current drive:

- Supply 16.5 MW per beamline in H and D with particle energies of 1 and 0.8 MeV
- Negative ion source is the front end of the NNBI

Goals (ITER requirements for the ion source):

Requirements	H	D
Extracted current density	329 Am^{-2}	286 Am^{-2}
Pulse Length	Several hundred s	3600s
Electron-ion ratio (j_e/j_{ex})	≤ 1	≤ 1

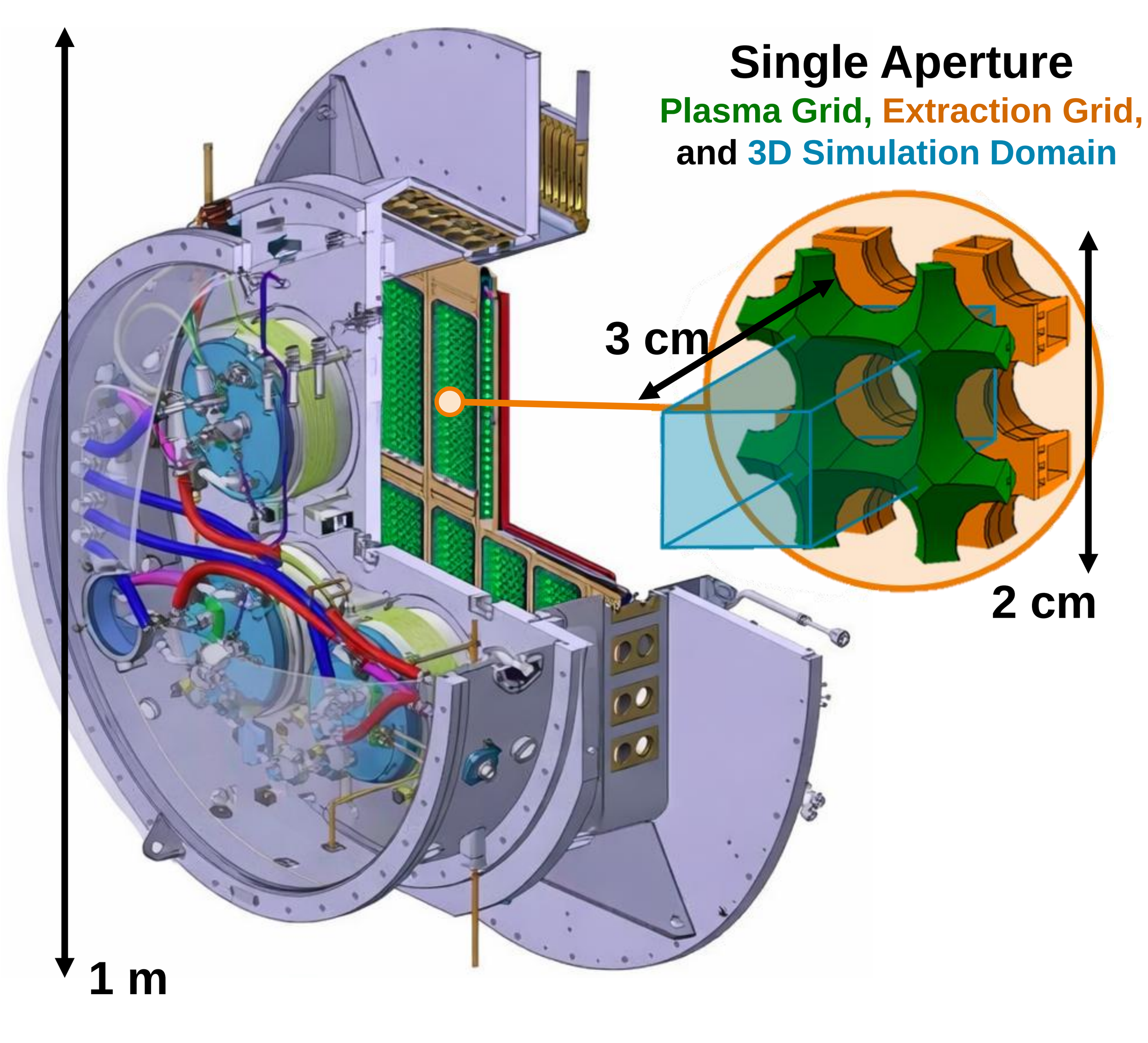
Challenges:

- Co-extracted electrons limit source performance
- Deuterium: higher co-extracted electron current which strongly increases over time

This Work:

- Model NNBI ion source extraction-region plasma to explain isotope-dependent extracted currents

ELISE ION SOURCE



NUMERICAL MODEL

Orsay Negative Ion eXtraction ONIX [1]

- **3D3V PIC-MCC** code for negative ion extraction
- Models experimentally inaccessible near-aperture plasma which directly influences beam formation and source performance
- Models single aperture, plasma density/temperature, and magnetic and electric fields at **full scale**
- Necessity to meet resolutions ($\lambda_D, 1/\omega_p$, CFL)
- **MPI-parallelized** for HPC runs of full plasma density, requires $\approx 10^6$ **core−hours**

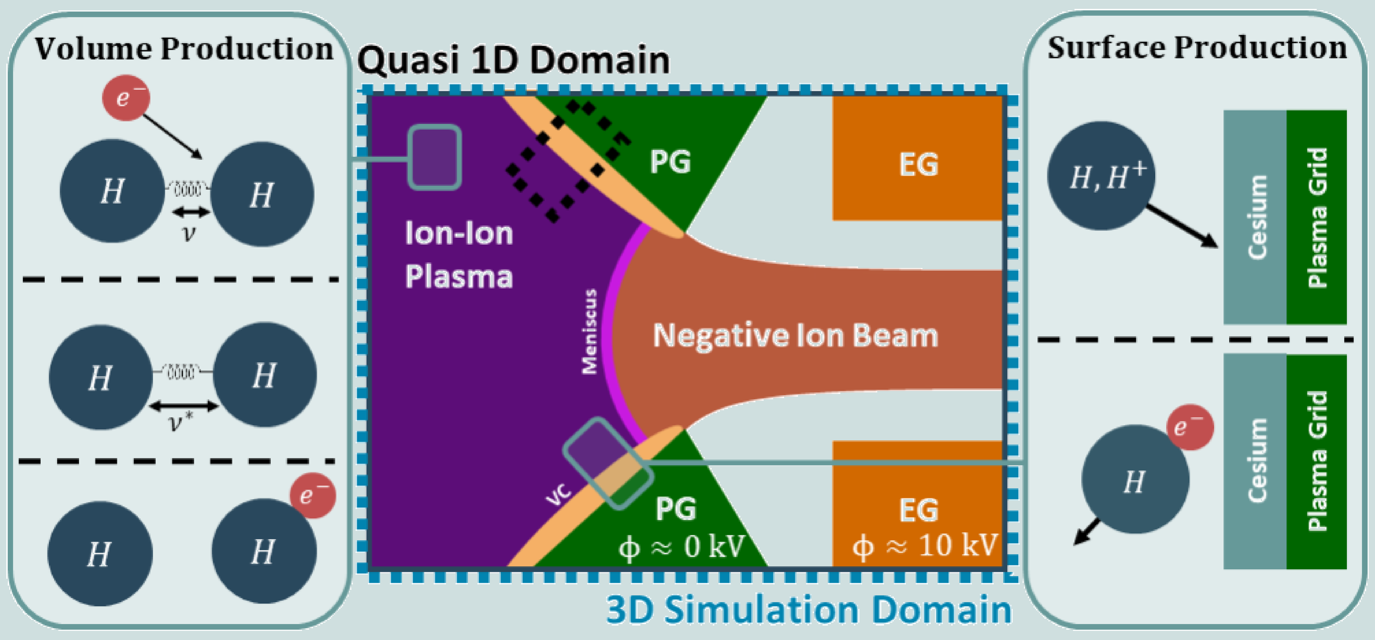
PHYSICS NEAR AN APERTURE

Meniscus

- Extraction potential penetrating into the bulk plasma, separating negative charges
- Boundary influences beam divergence

Virtual Cathode (VC)

- Negative space-charge accumulation from surface produced H^-
- **Potential well** (depth $\Delta\phi$ and width ΔX) traps/reflects emitted H^-/D^-, **limiting bulk densities**



Negative Ion Creation

Resonant Charge Transfer (SP)

- Cesium **lowers work function** (WF), increasing H^- production (Γ_{H^-})
- At WF $= \mathbf{1.6}$ **eV**, $\Gamma_{H^-} \approx$ **550 A/m²**

Dissociative electron attachment (VP)

- Favors $H_2(\nu > 4)$ and $T_e = 0.1:1$eV
- Limited H^- yield at required $p_{fill} = 0.3$ Pa

MODELING THE PHYSICS NEAR AN APERTURE IN A REDUCED DOMAIN

Model Inputs/Plasma Parameters

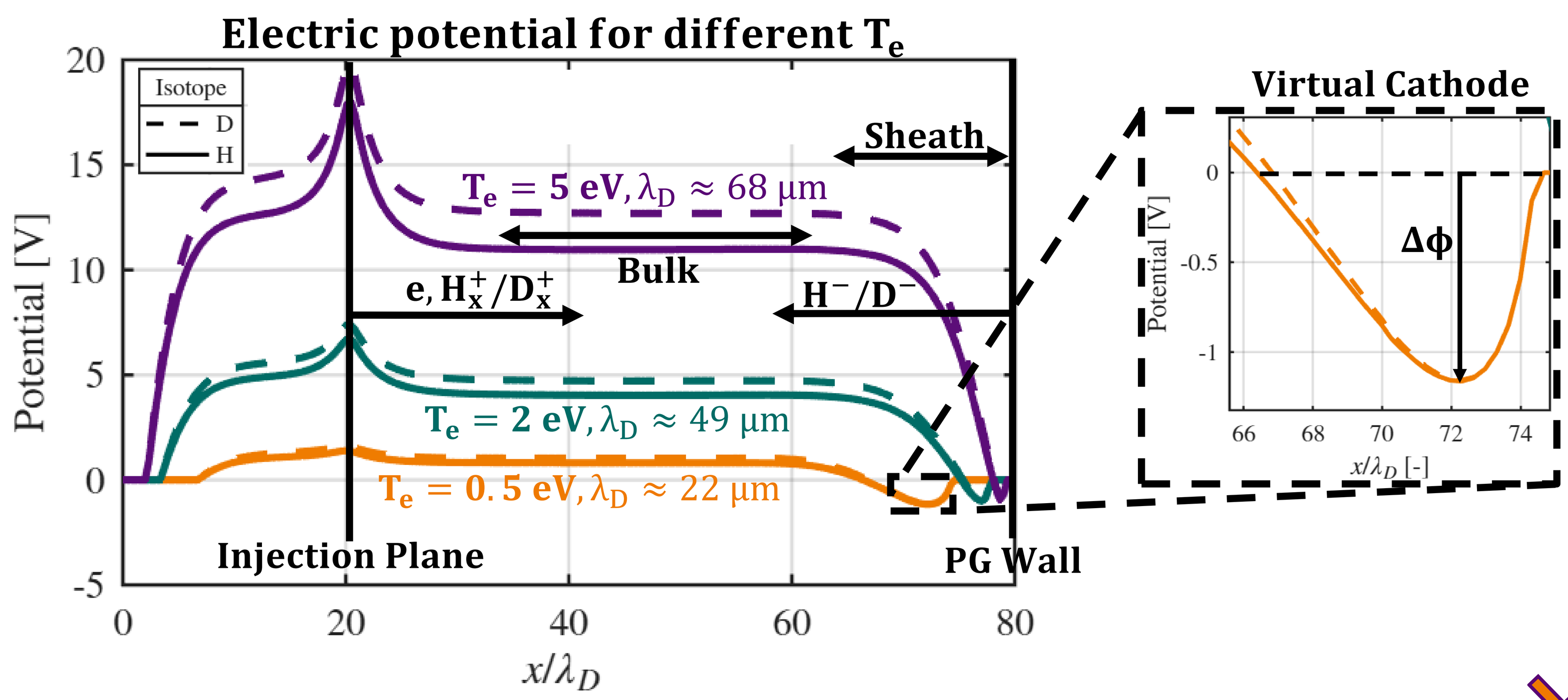
Reduced 1D domain for high-resolution parametric scans to quantify each species effect on virtual cathode (VC) behavior

Species	n $[m^{-3}]$	T [eV]
Electrons (e)	4×10^{16}	2
Negative Ions (H^-/D^-)	2×10^{16}	0.6
Monoatomic Positive Ions (H^+/D^+)	2.4×10^{16}	0.8
Diatomic Positive Ions (H_2^+/D_2^+)	2.4×10^{16}	0.1
Triatomic Positive Ions (H_3^+/D_3^+)	1.2×10^{16}	0.1

*True ion source conditions have slight H/D variations

Experimentally relevant conditions in H/D*: $\Gamma_{H^-} = 550\ A/m^2$, $\Gamma_{D^-} = 390\ A/m^2$

Parametric Scans



→ Plasma potential (ϕ_{Bulk}) is consistently higher in D and increases with T_e ✓

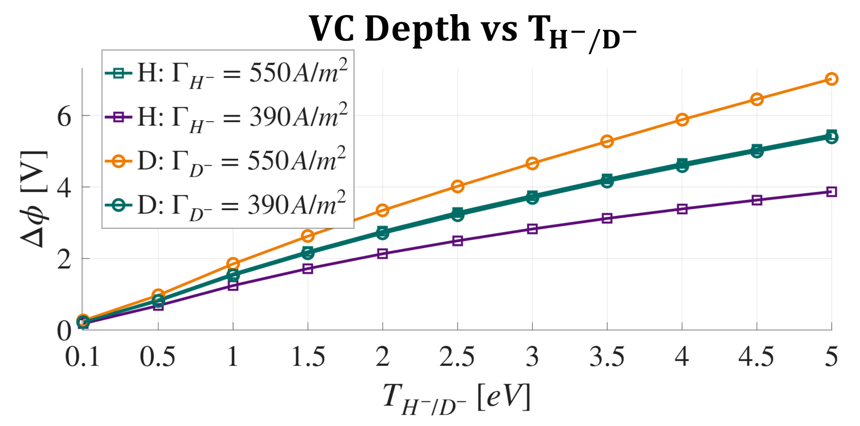
Ambipolar diffusion drives plasma potential: heavier/hotter plasmas need higher potentials to balance ion and electron wall fluxes

Mass Dependence Isolation

To match H/D densities at fixed $T_{H^-/D^-} \rightarrow \Gamma_{H^-} = \sqrt{2}\Gamma_{D^-}$, $\left(v_{th} \propto \frac{1}{\sqrt{m}}\right)$

If $\mathbf{\Gamma_{H^-} = \Gamma_{D^-}} \rightarrow \mathbf{\Delta\phi_D > \Delta\phi_H}$

If $\mathbf{\Gamma_{H^-} = \sqrt{2}\Gamma_{D^-}} \rightarrow \mathbf{\Delta\phi_H \gtrsim \Delta\phi_D}$



→ No significant mass effects in VC for equal density plasmas

At a fixed T_{H^-/D^-}, more H^- must be emitted to match space charge densities; $\Delta\phi_H \gtrsim \Delta\phi_D$ due to enhanced D^- transport ($\phi_{Bulk.H} < \phi_{Bulk.D}$)

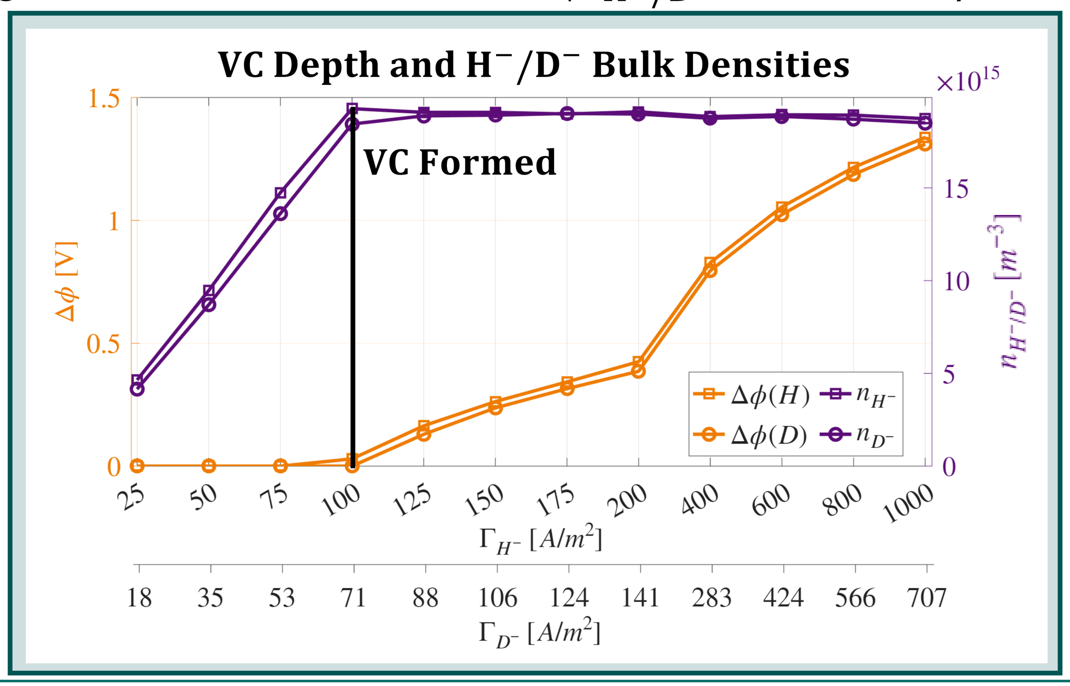
Scans Summary

Electrons: $\uparrow T_e$ (0.5: 5 eV) → ↓VC(20%) | Enhanced H^-/D^- transport ($\uparrow\phi_{Bulk}$)

Positive Ions: $\uparrow T_{H_x^+/D_x^+}$ (0.1: 5 eV) → no effect | Unchanged H^-/D^- transport

Negative Ions: Order of magnitude increase in VC as $\uparrow\Gamma_{H^-/D^-}$ (25: 1000A/m²) or $\uparrow T_{H^-/D^-}$ (0.1: 5 eV)

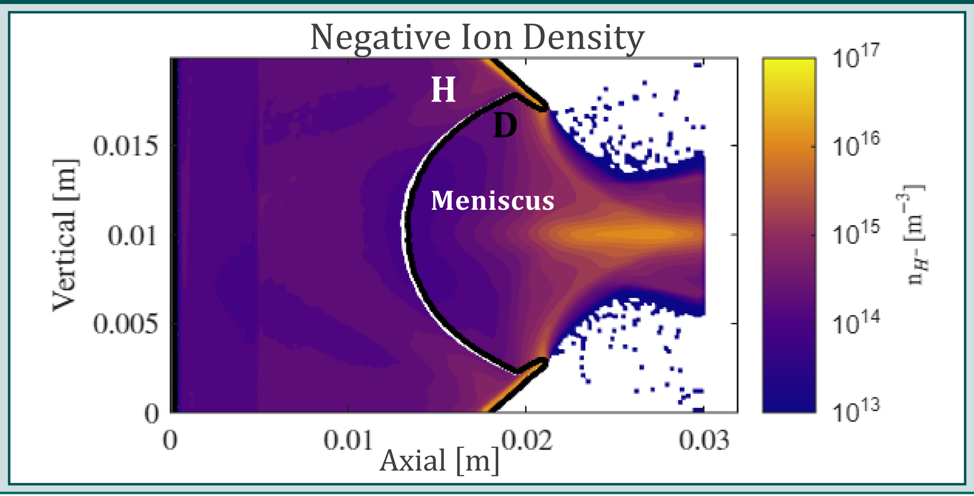
- $\uparrow\Gamma_{H^-/D^-}$ or $\uparrow T_{H^-/D^-}$ increases negative ion current
  → VC deepens in response
- Effect more pronounced with $\uparrow T_{H^-/D^-}$
  → Current scales strongly with T_{H^-/D^-}



CONCLUSION

- **Virtual cathodes** arise from surface production and **restrict negative ion bulk densities**
- Scans show **negative ion** emission rate and temperature **drive VC behavior**, while increasing T_e can reduce VCs and increasing $T_{H_x^+/D_x^+}$ has no effect
- **Hydrogen and deuterium** plasmas form **similar VC** and respond similarly across all parametric scans

NEXT STEPS



- Further development of **self-consistent negative ion production**
- Perform similar **3D** parametric scans to **quantify meniscus** sensitivity to species and isotope

(1) Lindqvist, M., et al. "Particle injection methods in 3D-PIC MCC simulations applied to plasma grid biasing." Physics of Plasmas 31.3 (2024).

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