

Analysis of isotope effects on negative ion source extraction using 3D-PIC Calculation

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Summary

Under deuterium operation, which is required for NBI systems, the relationships among **surface-produced negative ions**, the **potential structure**, and **beam focusing** are expected to differ from those under hydrogen operation. Therefore, it is important to clarify the **isotope effects** on these characteristics. In this study, simulation analyses were performed with a focus on the potential structure, particularly the **virtual cathode** formed near the surface of the **plasma grid**. The following results were obtained from the present analysis:

- **Nonuniform potential structures, including the virtual cathode, and nonuniform charged-particle density distributions** are associated with $E \times B$ drift.
- Under **deuterium conditions**, the **negative-ion density increases** and the **mean negative-ion velocity distribution becomes more nonuniform**.
- These **isotope-dependent changes may affect negative-ion beam optics**, potentially leading to **larger beam divergence in D⁻ beams**.

1. Introduction

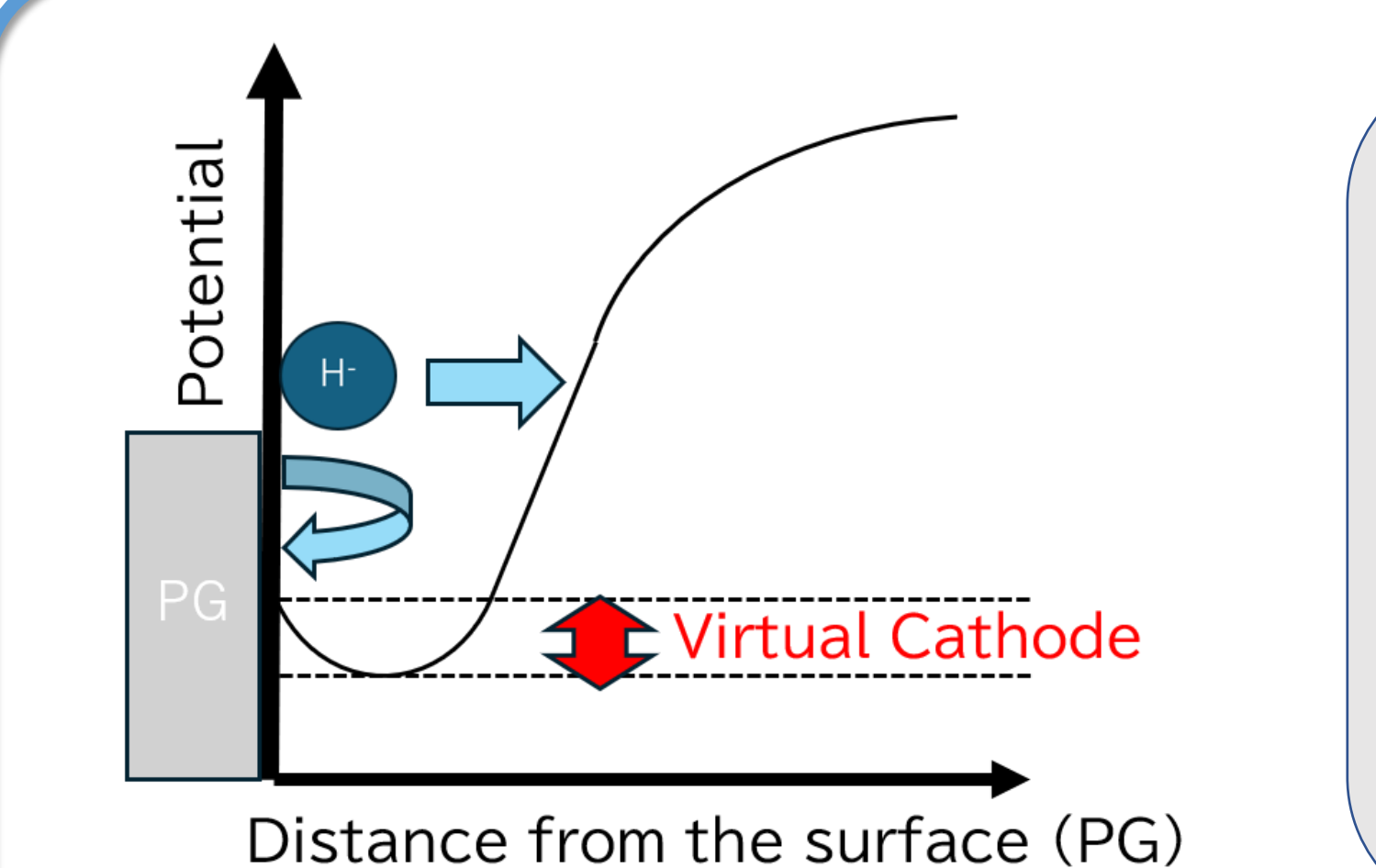


Fig. 1 The relation between virtual Cathode and surface production

Purpose of this study

Comparison of H⁻ and D⁻ extraction simulations to investigate the effects of mass-dependent differences in negative-ion behavior on extraction physics

2. Simulation Model

3D-PIC code[2,3]

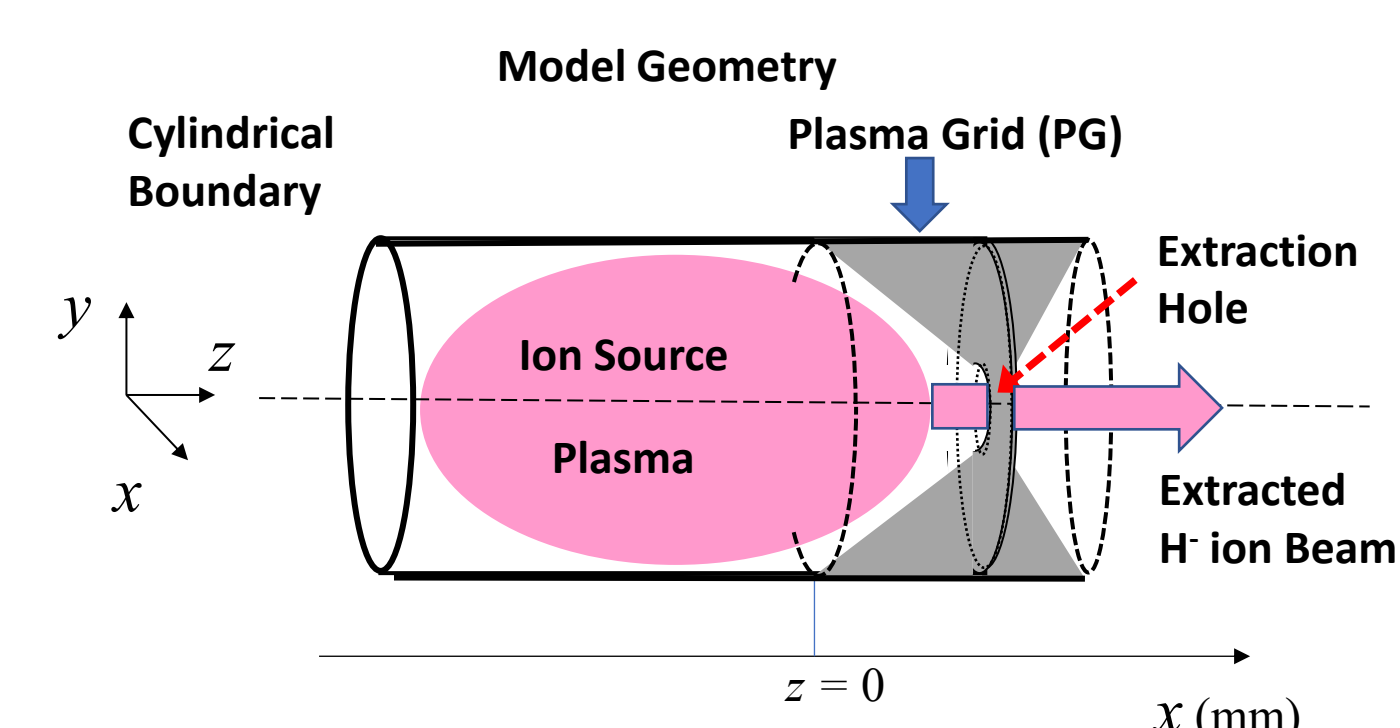


Fig. 2 The geometry in 3D code

Basic Equation of 3D ES PIC

Eq. of Motion

$$m_j \frac{dv_j}{dt} = e_j [E + (v_j \times B)] + \text{Monte-Carlo Collision}$$

($j = H^+, H^-, \text{electron}$)

Poisson's Eq.

$$\nabla^2 \phi = -\frac{\rho}{\epsilon_0}$$

$$\rho = \sum_j e_j n_j$$

Table. 1 The plasma parameter in the simulation[4]

Parameters	Values
e ⁻ density	$1.8 \times 10^{17} \text{ m}^{-3}$
e ⁻ temperature	0.8 eV
H ⁺ temperature	0.3 eV
H ⁻ temperature	0.1 eV (Volume) 1 eV (Surface)
H ₂ density (background)	$1.88 \times 10^{19} \text{ m}^{-3}$
H density (background)	0.1 eV

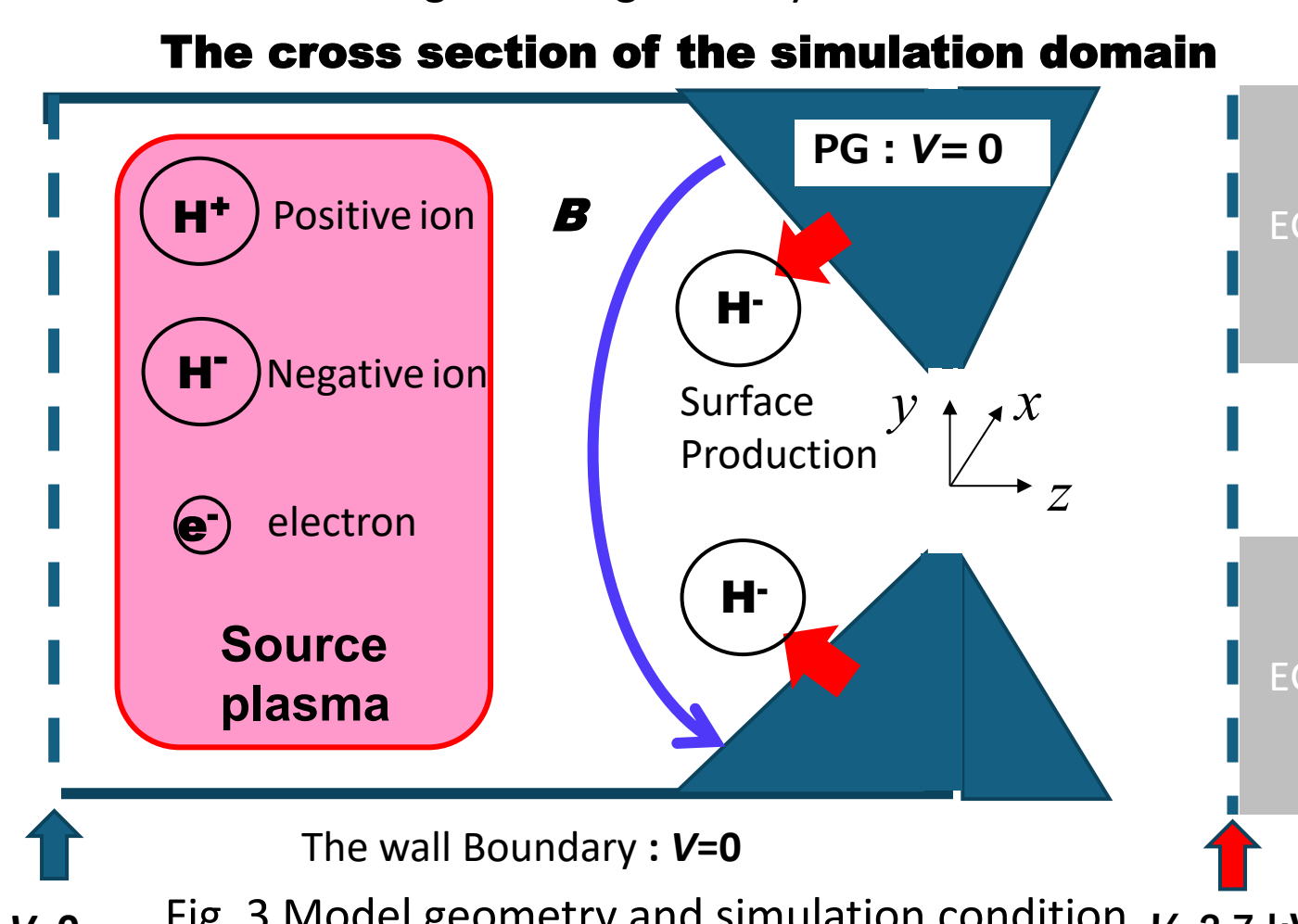


Fig. 3 Model geometry and simulation condition

Model geometry and plasma parameters are based on a single aperture of the NIFS-RNIS negative ion source.

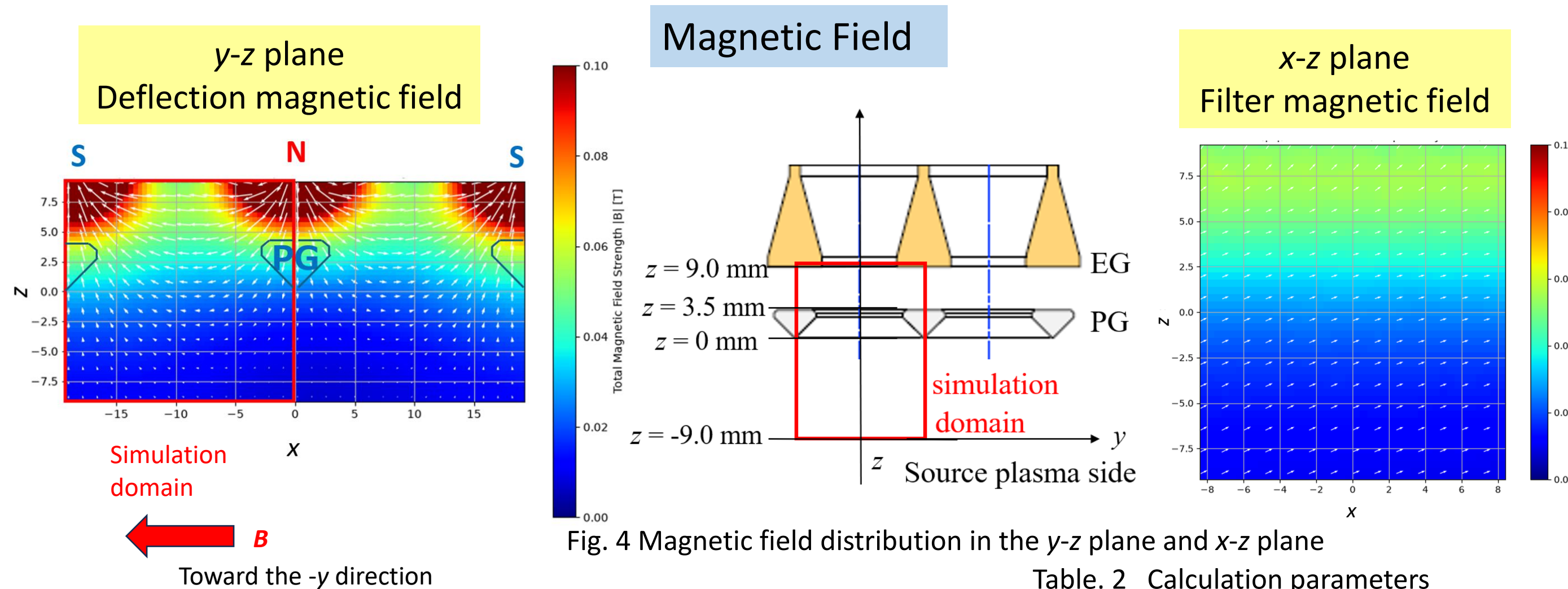


Fig. 4 Magnetic field distribution in the y-z plane and x-z plane

Table. 2 Calculation parameters

Parameters	Values
Number of super particle	19,200,000
Mesh	$178 \times 164 \times 164$
Mesh size	$7.83 \times 10^{-6} \text{ m}$ ($0.5\lambda_{DE}$)
Time step	$1.67 \times 10^{-11} \text{ s}$ ($0.4/\omega_p$)
Scaling factor	0.0783

Isotope Effects of Negative Ions Considered in the Model

- Reaction rates between negatively charged particles and background neutral particles (dissociative attachment, electron detachment and associative detachment)
 - D⁻ Surface production rate is reduced to 0.24 times the H⁻ value, based on survival probability β^- reported by Rasser et al. [5]
- $$\beta^- \propto \exp\left(-\frac{1}{v_{\perp}}\right)$$

Comparison of H⁻ and D⁻ extraction simulations to investigate isotope effects

Reference

- [1] MacAdams et al., Review of Scientific Instruments, **83**, 02B109(2012).
- [2] S. Nishioka et al., J. Appl. Phys. **119**, 023302(2016).
- [3] M. Lyndqvist et al., J. Appl. Phys. **126**, 123303(2019).
- [4] K. Miyamoto et al., JINST **18**, C06014(2023).
- [5] B. Rasser, J.N.M. van Wunnik, J. Los, Surf. Sci. **118**, 697 (1982).

3. Results and Discussion

Results : Potential Profile

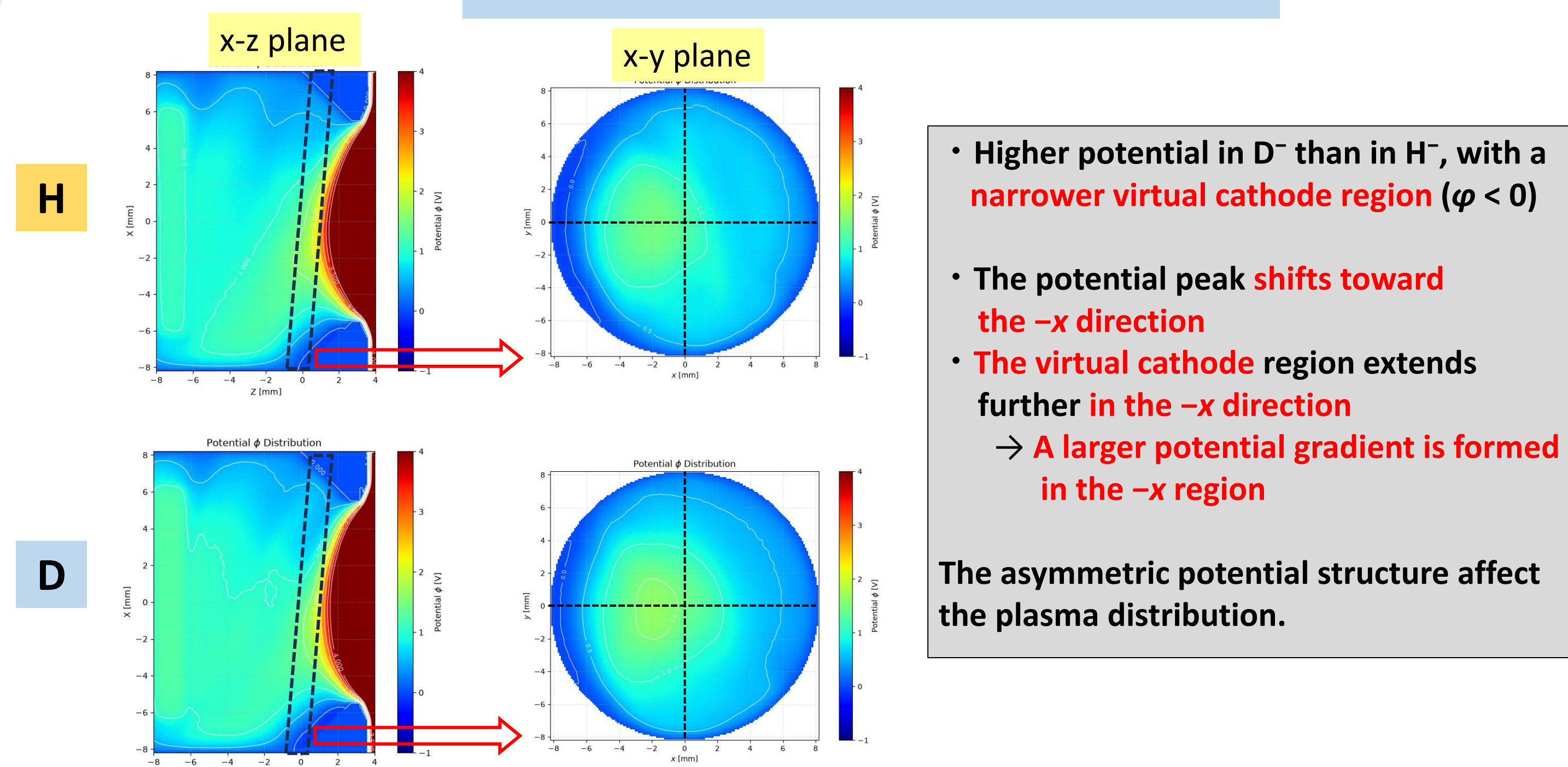


Fig. 5 Potential distributions in the x-z plane (left) and the x-y plane at $z = 0$ (right).

Results : Density Profile

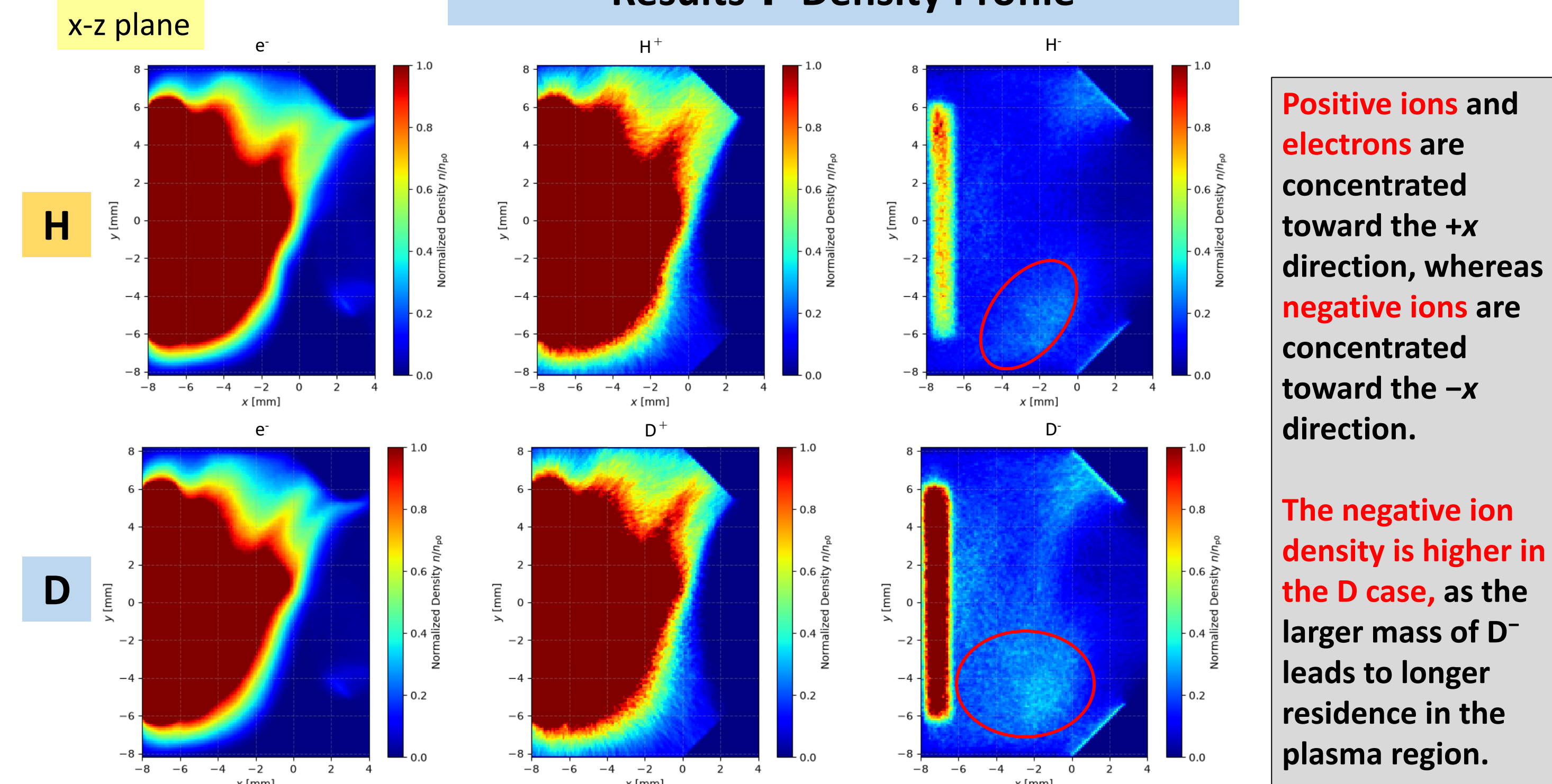


Fig. 6 2D Distributions of Charged Particles in the x-z Plane

Discussion: $E \times B$ drift & mean velocity

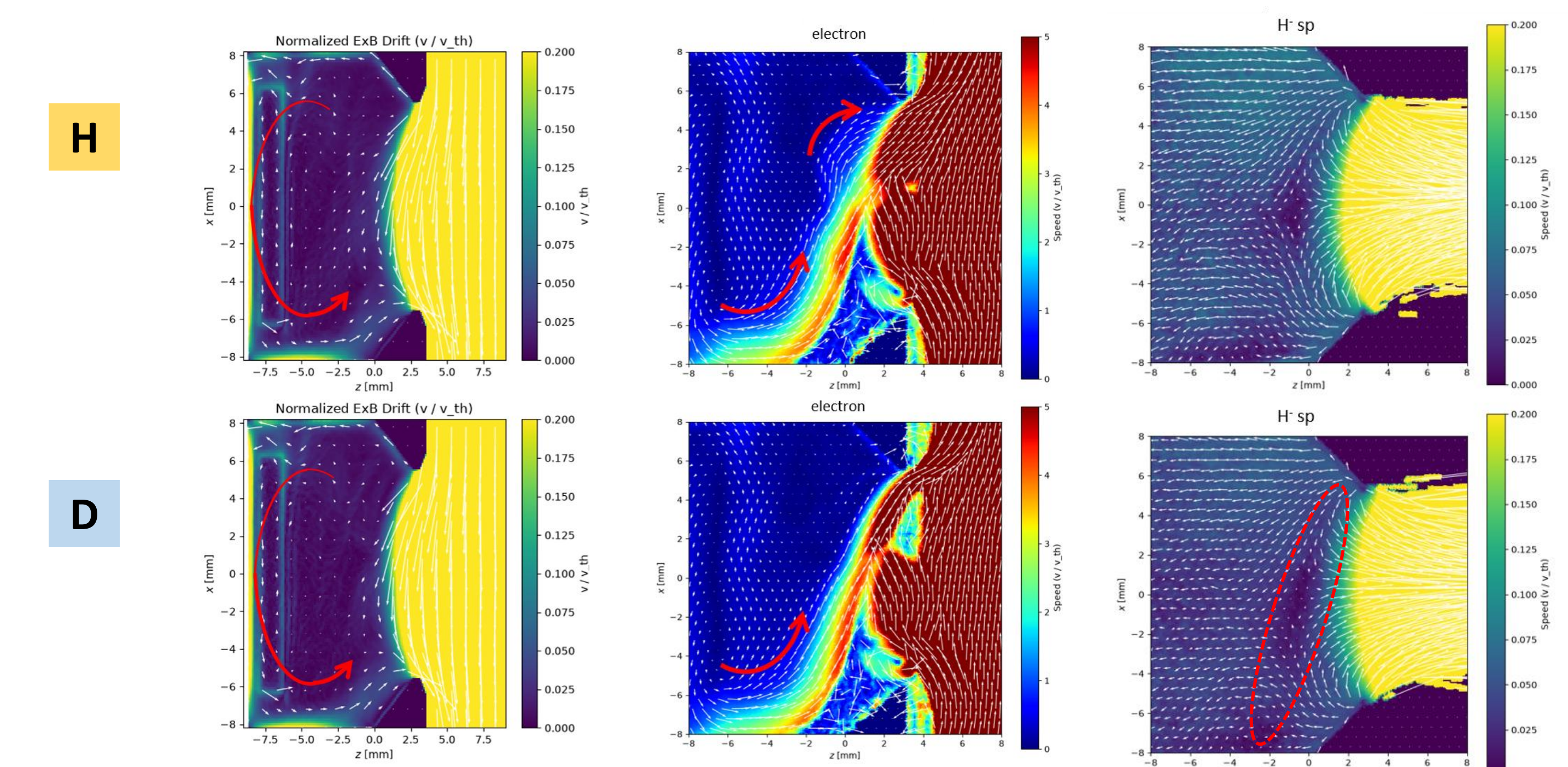


Fig. 7 $E \times B$ Drift and Mean Velocity Distributions of Electrons and Negative Ions in the x-z Plane
From left to right: $E \times B$ drift velocity, mean electron velocity, and mean negative-ion velocity.

The enhanced potential gradient leads to a stronger $E \times B$ drift in the $-x$ region

The mean electron velocity is directed along the $E \times B$ drift

The negative-ion flow becomes more nonuniform in the D case

Both the $E \times B$ drift induced by the nonuniform virtual cathode and isotope-dependent changes in the negative-ion distribution may affect beam optics. (The more nonuniform D⁻ distribution may lead to increased beam divergence.)

4. Future Work

- ① Inclusion of Coulomb collisions affecting the trajectories of surface-produced negative ions
- ② Investigation of the survival probability of surface-produced D⁻ ions
- ③ Comparison using experimentally measured deuterium plasma parameters (3 times higher plasma density)