ONIX

Orsay Negative Ion eXtraction

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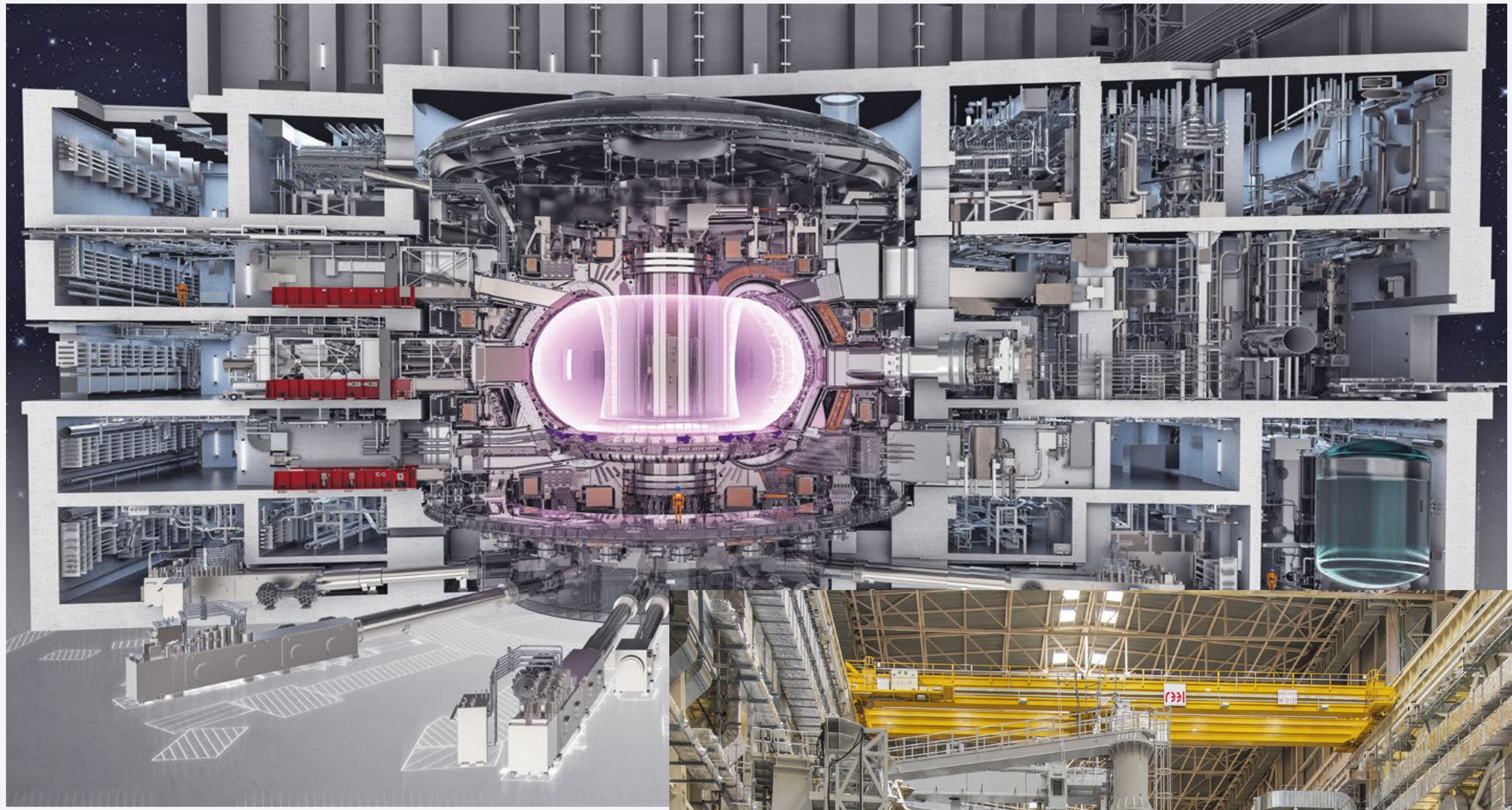
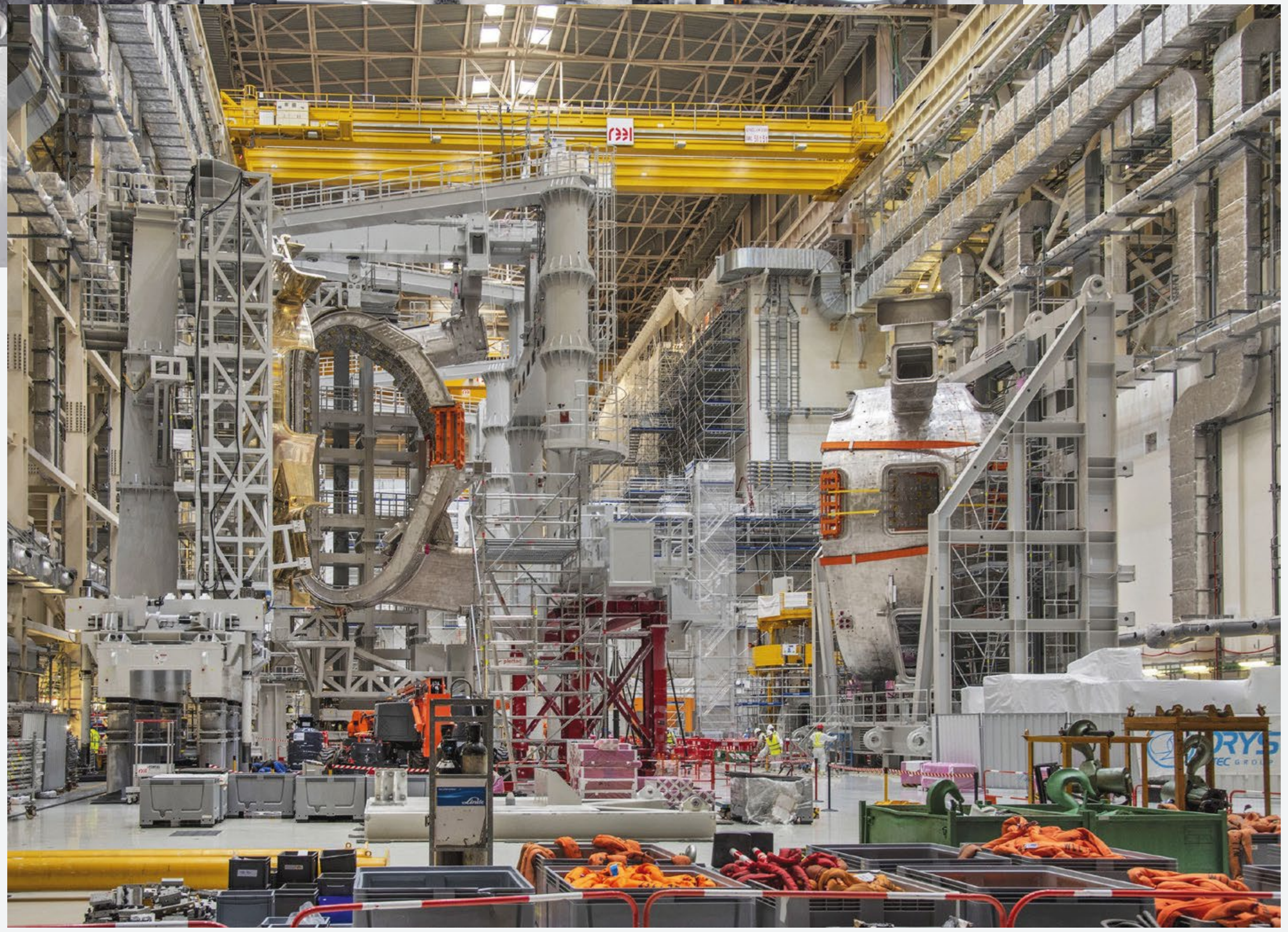
OUTLINE

ITER – International Thermonuclear Experimental Reactor





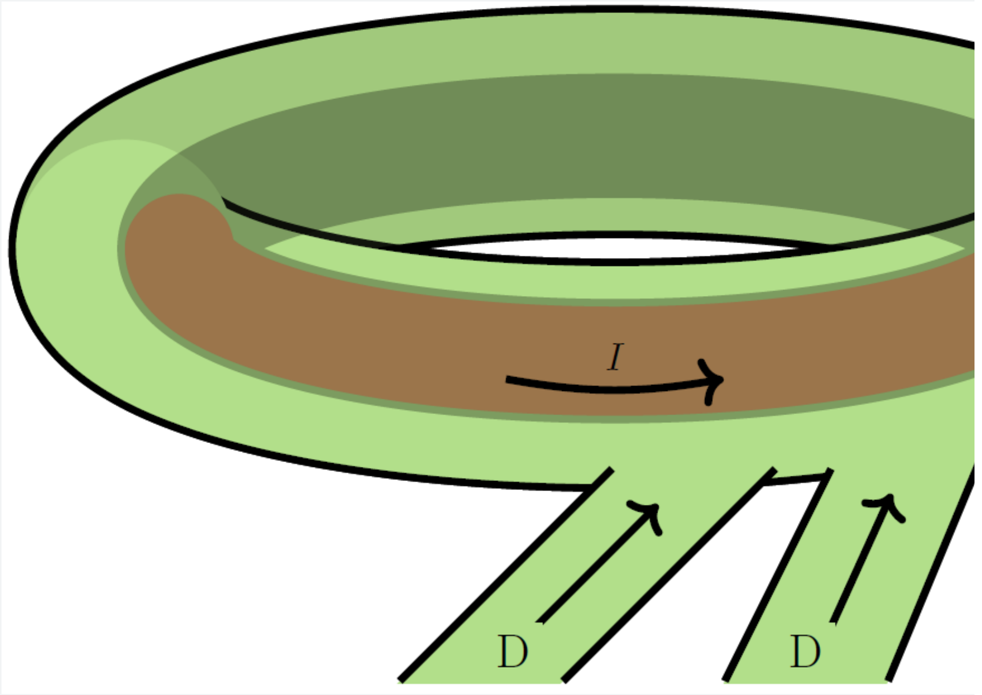
- ITER: Joint international project (China, UE, India, Japan, Korea, Russia, USA)
- 180 hectares
- Place: Saint-Paul-lez-Durance, France
- + 10 million items manufactured in the countries which are ITER members
- ITER in figures:
  - ✓ Vacuum chamber 1330 m^3 à 10^{-6} Pa ;
  - ✓ 8500 m^3 cryostat @ 10^{-4} Pa ;
  - ✓ + 200 pumps

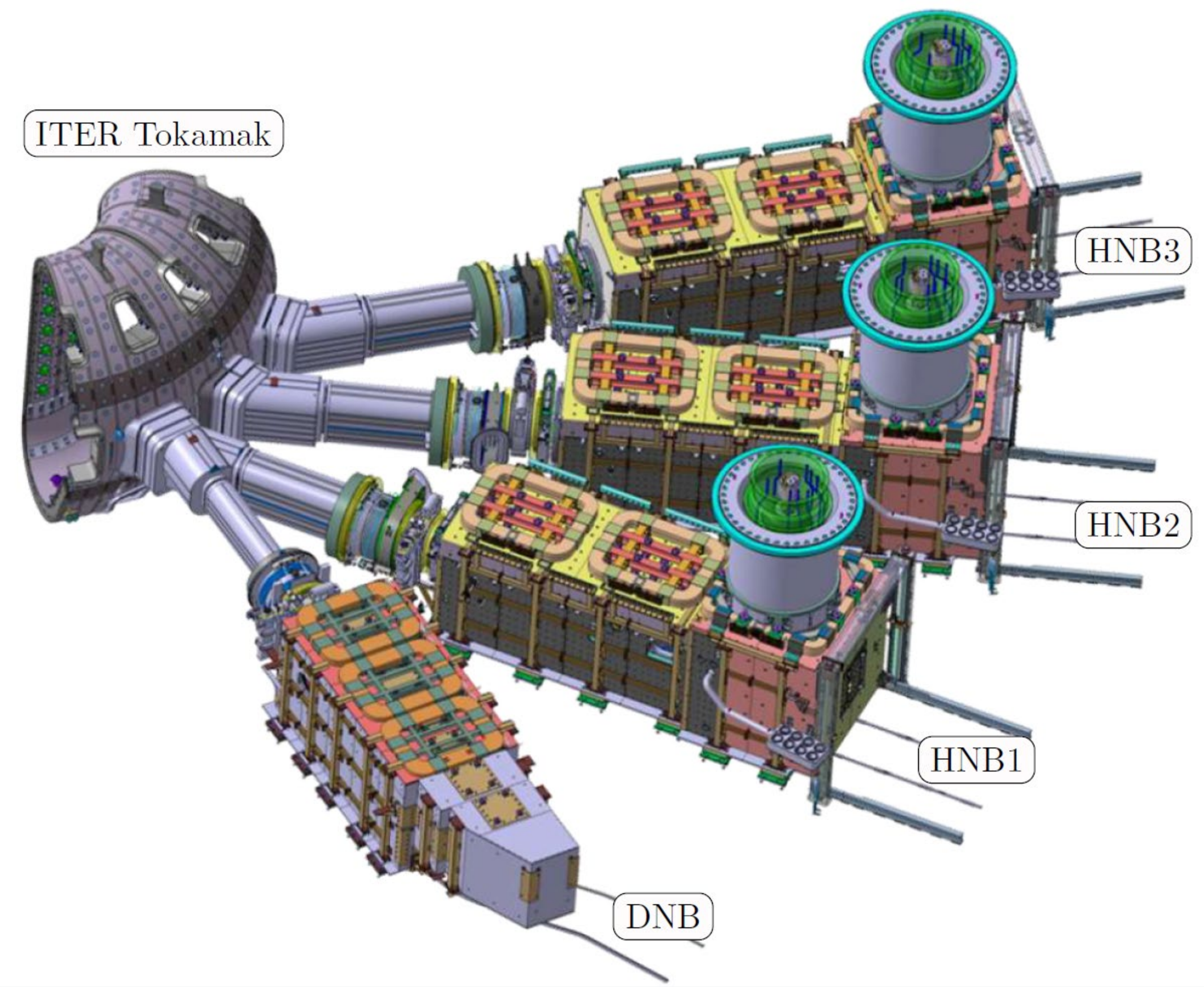
How can plasma be heated?

ITER Heating

- Microwave ECR ☺
- But… LH does not work for ions ☹

- Ions are heated by **Energetic Heavy** particles
- ITER also needs a Current Drive



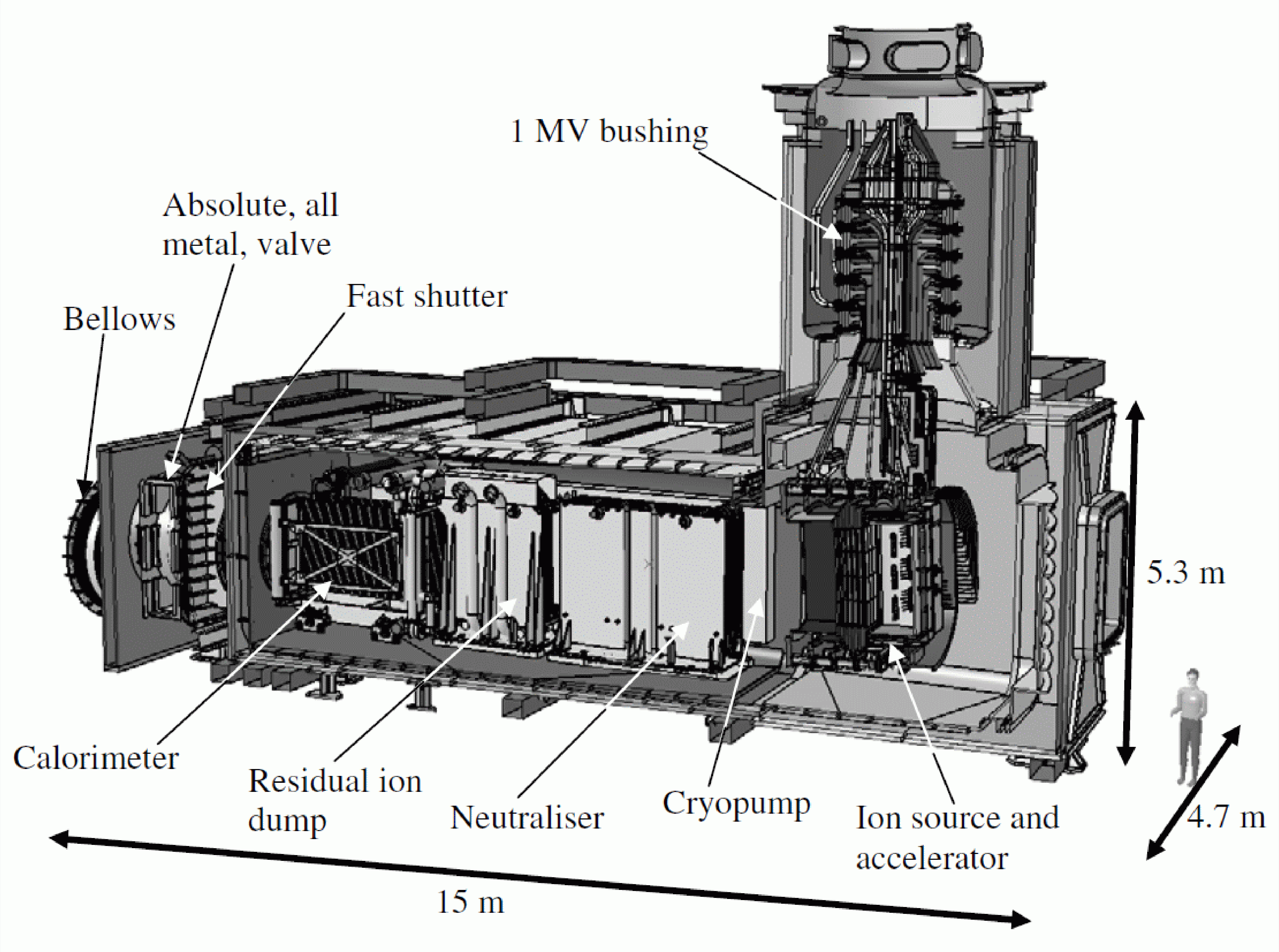


How Heavy Particles can reach the Plasma Core?

Using Energetic Neutrals!

But How???

NBI - Neutral Beam Injector

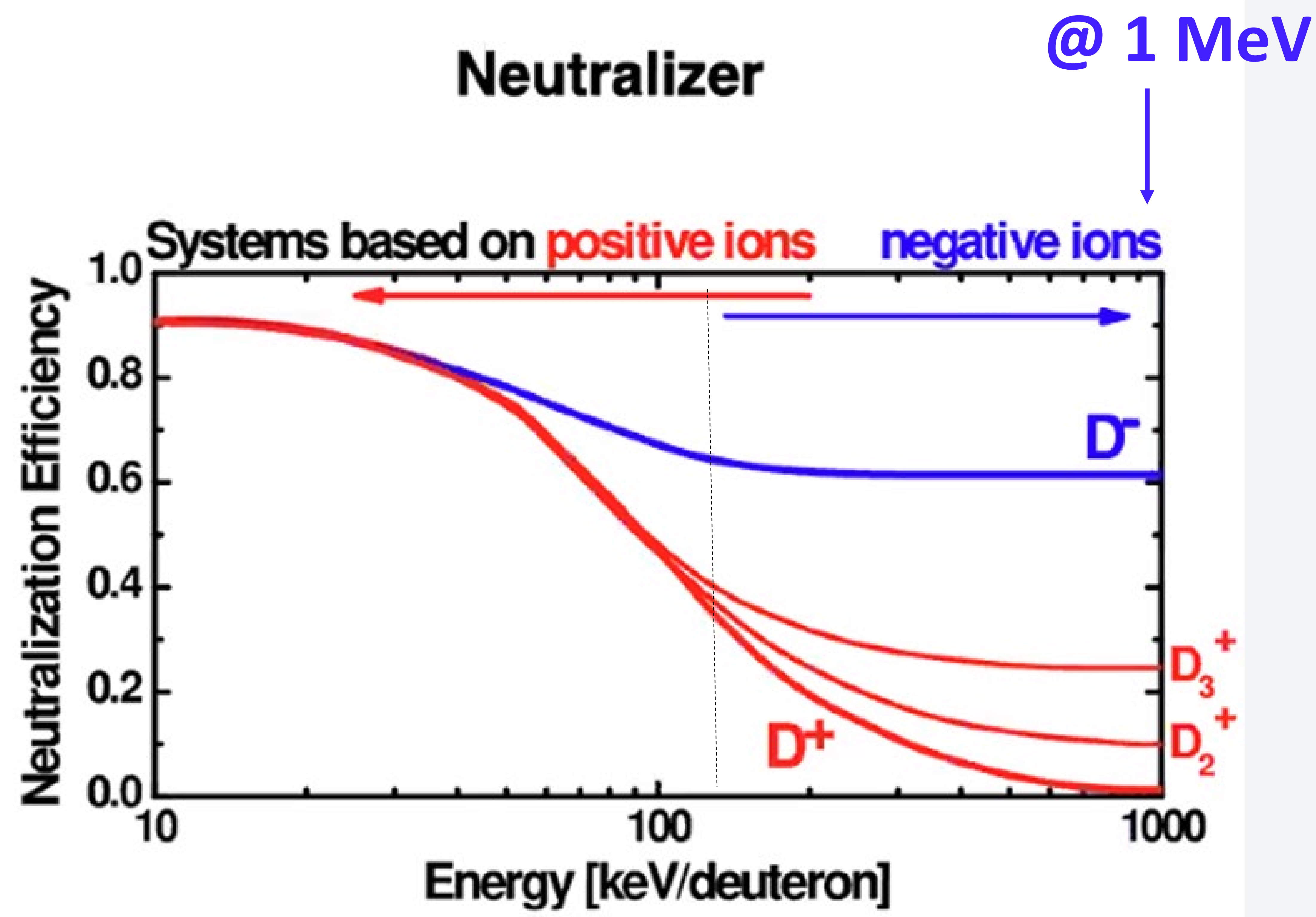


- NBI parameters:
  - 32 MW
  - 1 MeV
  - 40A / 1280 apertures

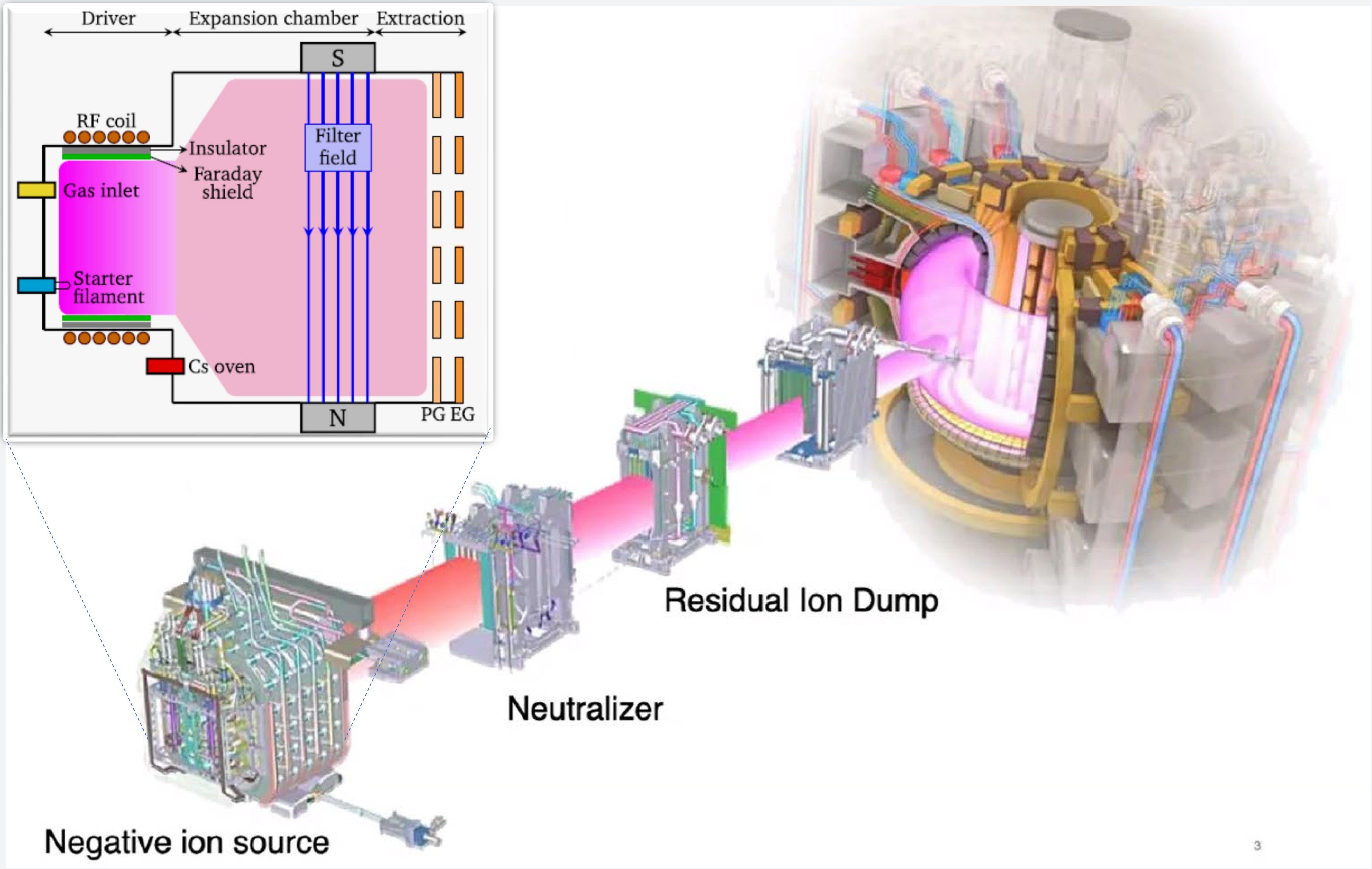
- NBI components:
  - Plasma source
  - Accelerator
  - Neutralizer
  - RID (Residual Ion Dump)

How to Neutralize Energetic Ions?
H+ or H- ??

Neutralisation efficiency



Negative Ion based Neutral Injector



Plasma Parameters:

$n_{pl}=2*10^{17}m^{-3}$

$n_e=90\text{-}50\%$; $n_{NI}=10\text{-}50\%$,

$n_{H+}=40\%$, $n_{H2+}=40\%$, $n_{H3+}=20\%$

$T_e=1$, $T_{H-}=0.8$ eV

$T_{H+}=0.8$, $T_{H2+}=0.1$, $T_{H3+}=0.1$

$j_{NI,PG}=300\text{-}600A/m^2$

$n_H=1*10^{19}m^{-3}$, $T_H=0.8eV$

$n_{H2}=4*10^{19}$, $T_{H2}=0.1eV$

Mechanisms for Negative Ion Production

- Volume NI production

  requires highly excited molecules

$$H_2(X) + e_{volume} \rightarrow H_2(v > 15) + e_{slow}$$

$$H_2(v > 15) + e_{slow} \rightarrow H^- + H$$

- Surface NI production

  or

  "Surface Ionization"

$$\gamma(H^-, H) = exp(\frac{\phi - A}{Cv_\perp})$$

$$H + e^-_{surface} \rightarrow H^-$$

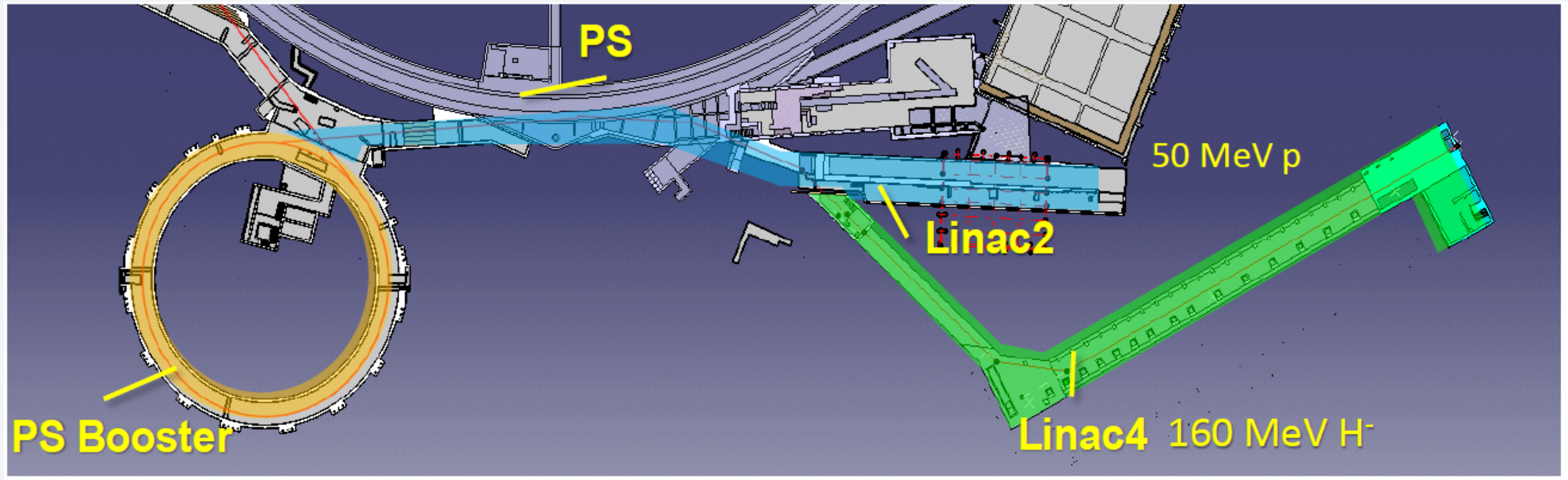
$$H^+ + e^-_{surface} \rightarrow H + e^-_{surface} \rightarrow H^-$$

ϕ = Work Function

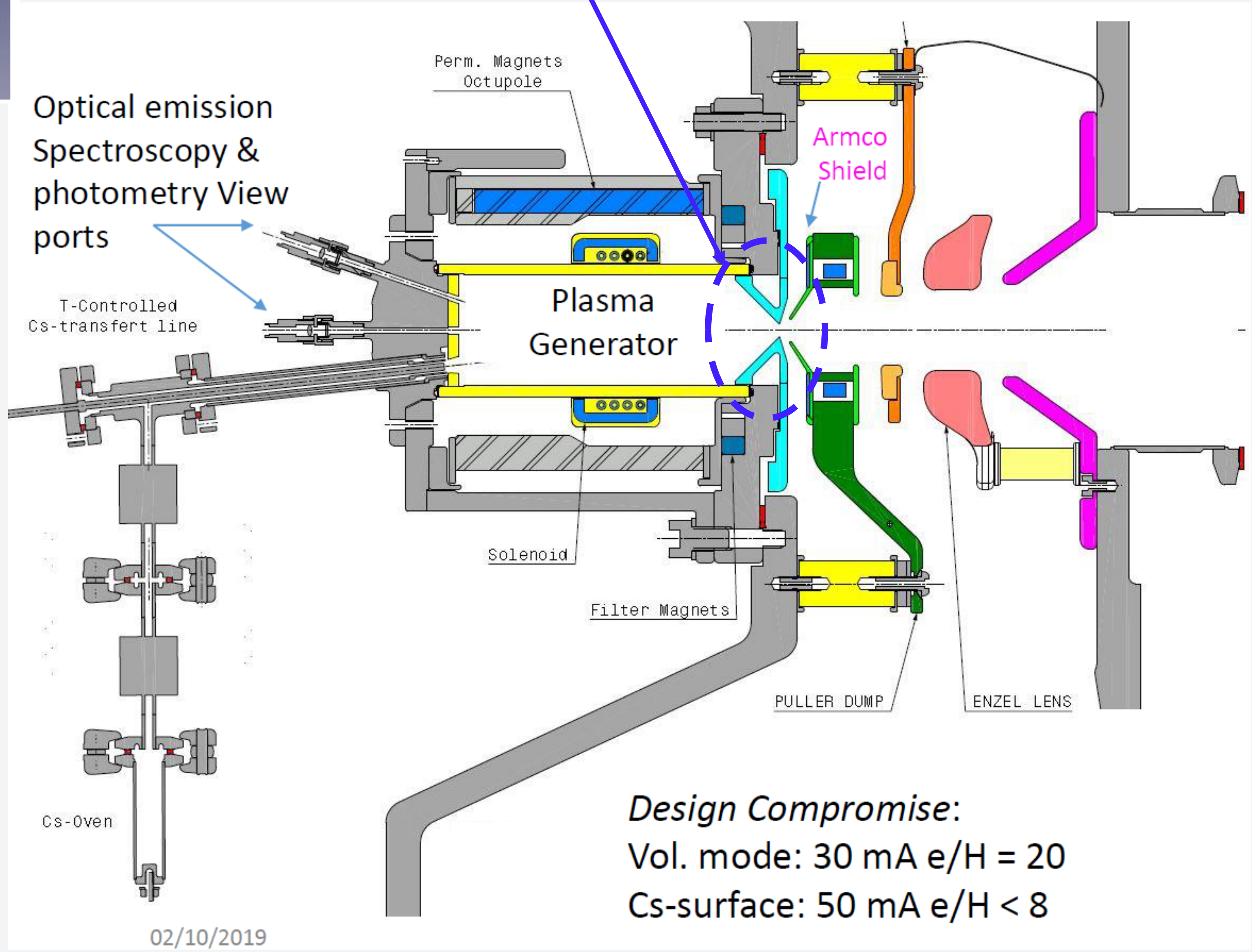
A = Electron Affinity

It works better with Cs!

Negative Ion Beam for LINAC 4 @ CERN



Interest Region - Beam Formation



NI Beam Parameters:

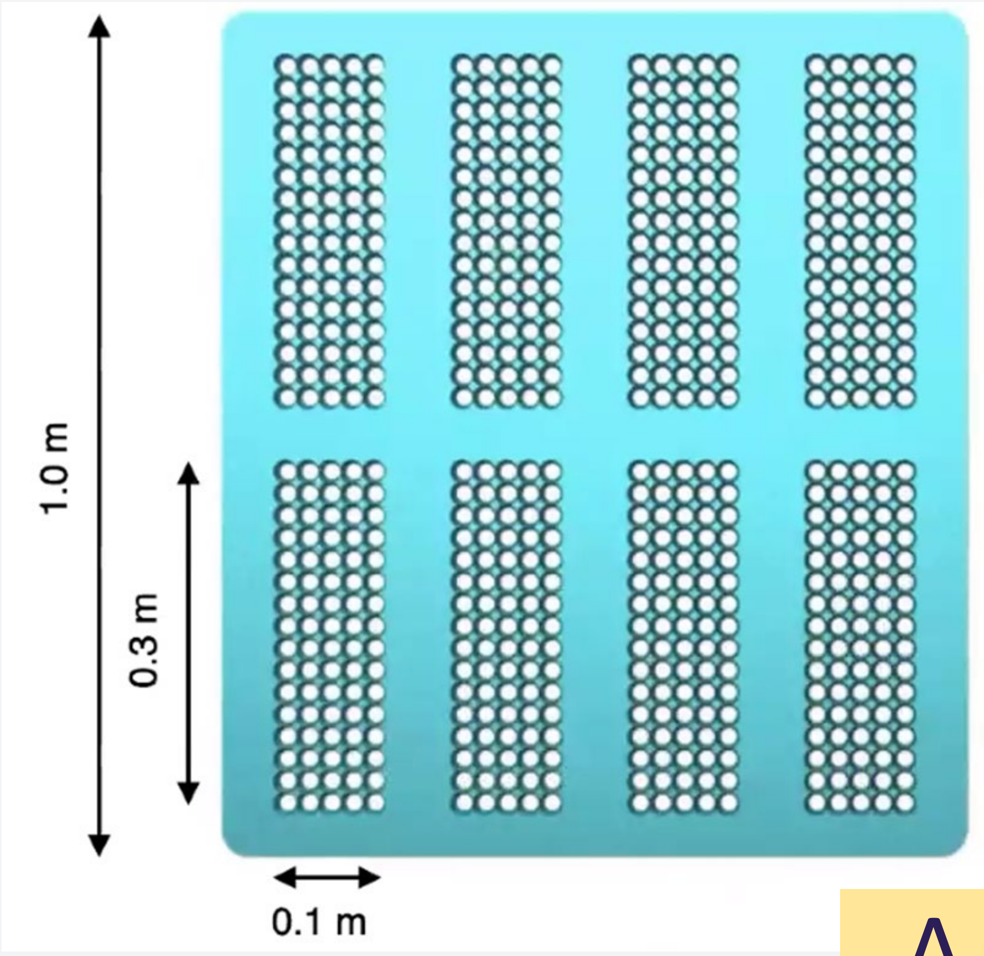
- 20 mA at the end of Linac4 to produce all 2018 CERN p-beams
- 32 mA achieved after 3MeV RFQ
- 40 mA (LS3) needed to double ISOLDE beam intensity

Simulation volume

- ½ ITER size **Plasma Grid (PG)**

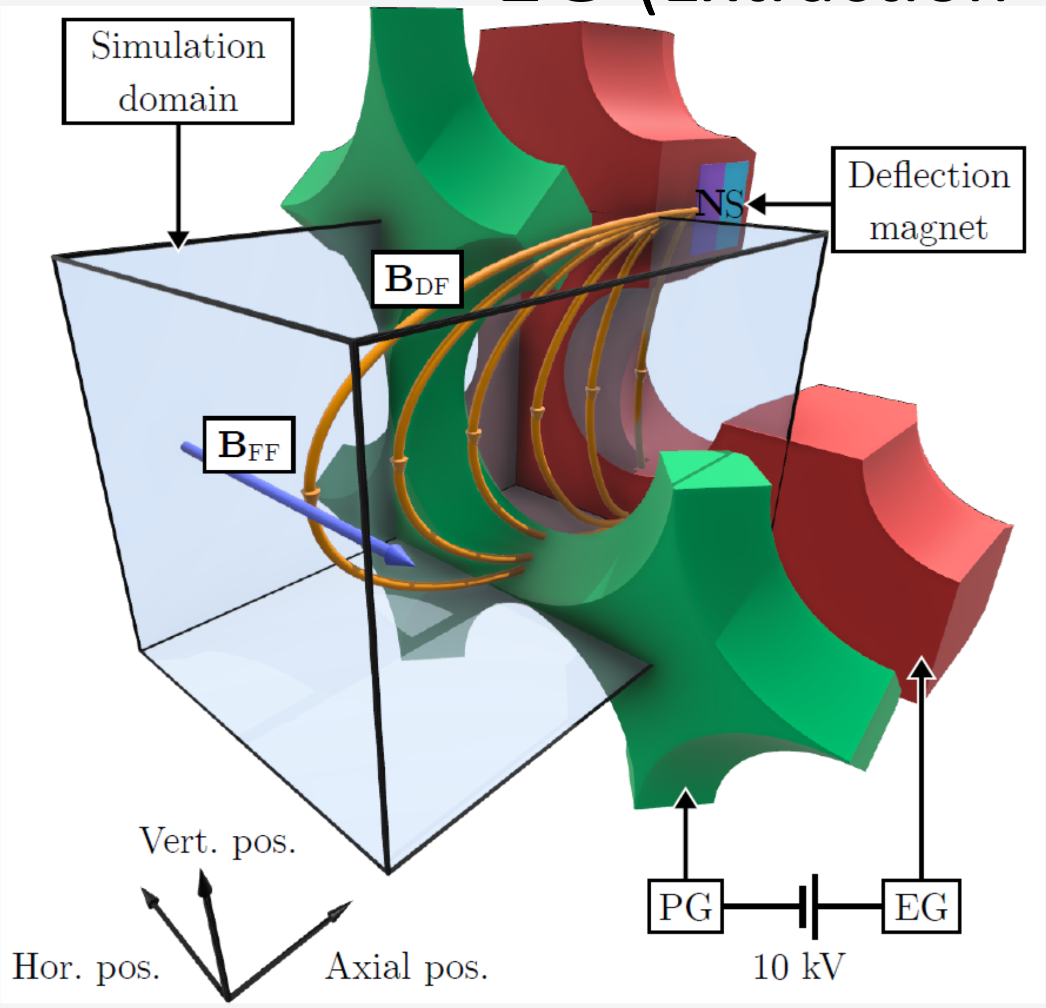
  4 x 2 segments

  5 x 16 apertures / segment



- Simulation Volume

PG EG (Extraction Grid)

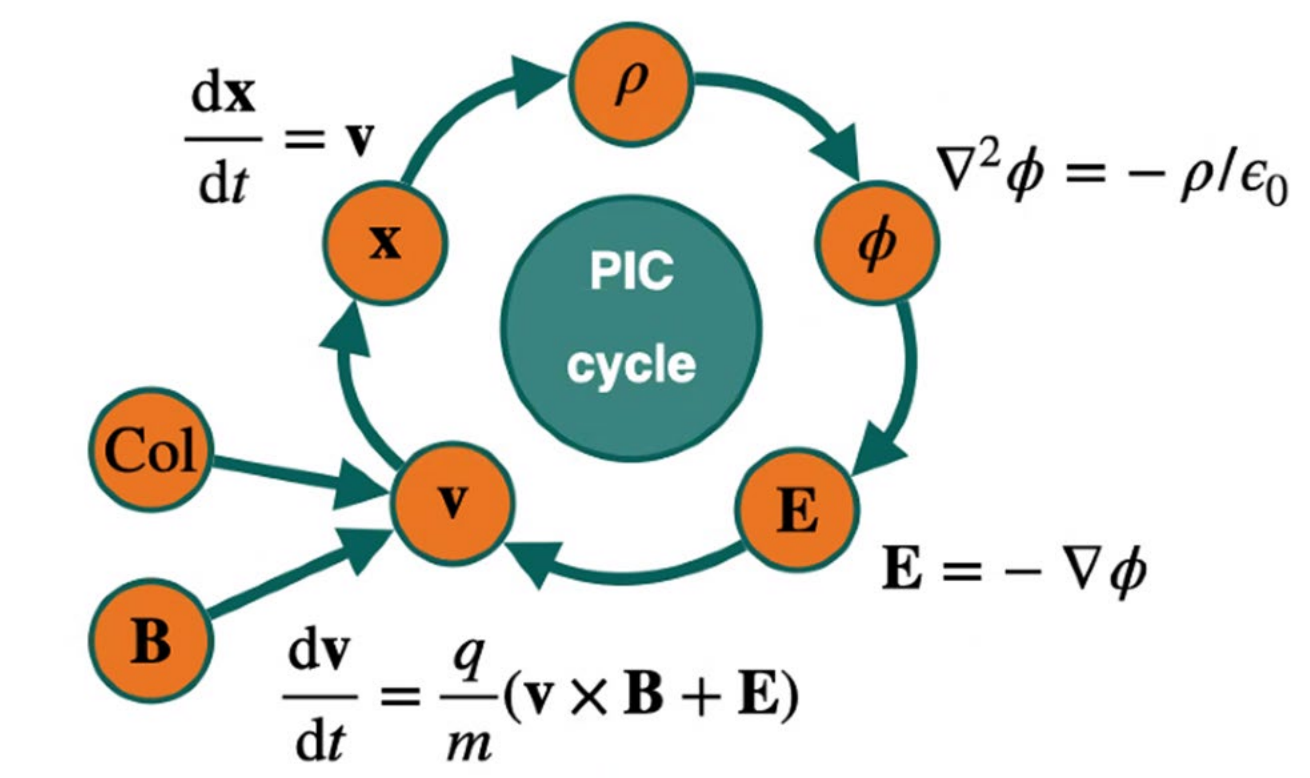


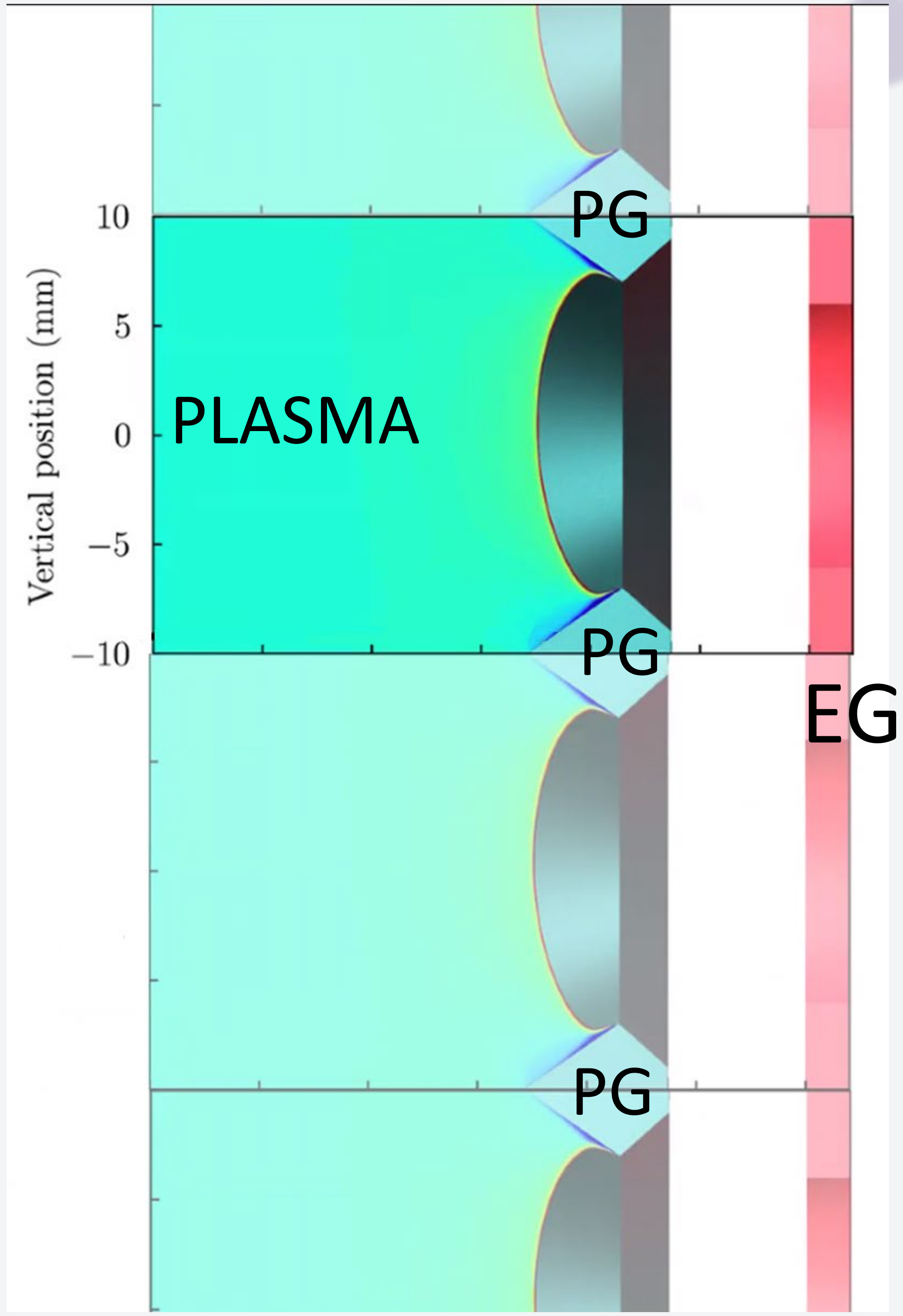
A double orthogonal Magnetic field! **3D ONLY**

ONIX
Orsay Negative Ion eXtraction

- Particle-in-Cell Monte Carlo Collisions (PIC-MCC)

  - **Poisson solver**: Preconditioned Conjugate Gradient method
  - **Equations of motion**: Boris method
  - **Charge and field projection**: Linear 64 point interpolation
  - **Neutral background**: Monte Carlo Collisions



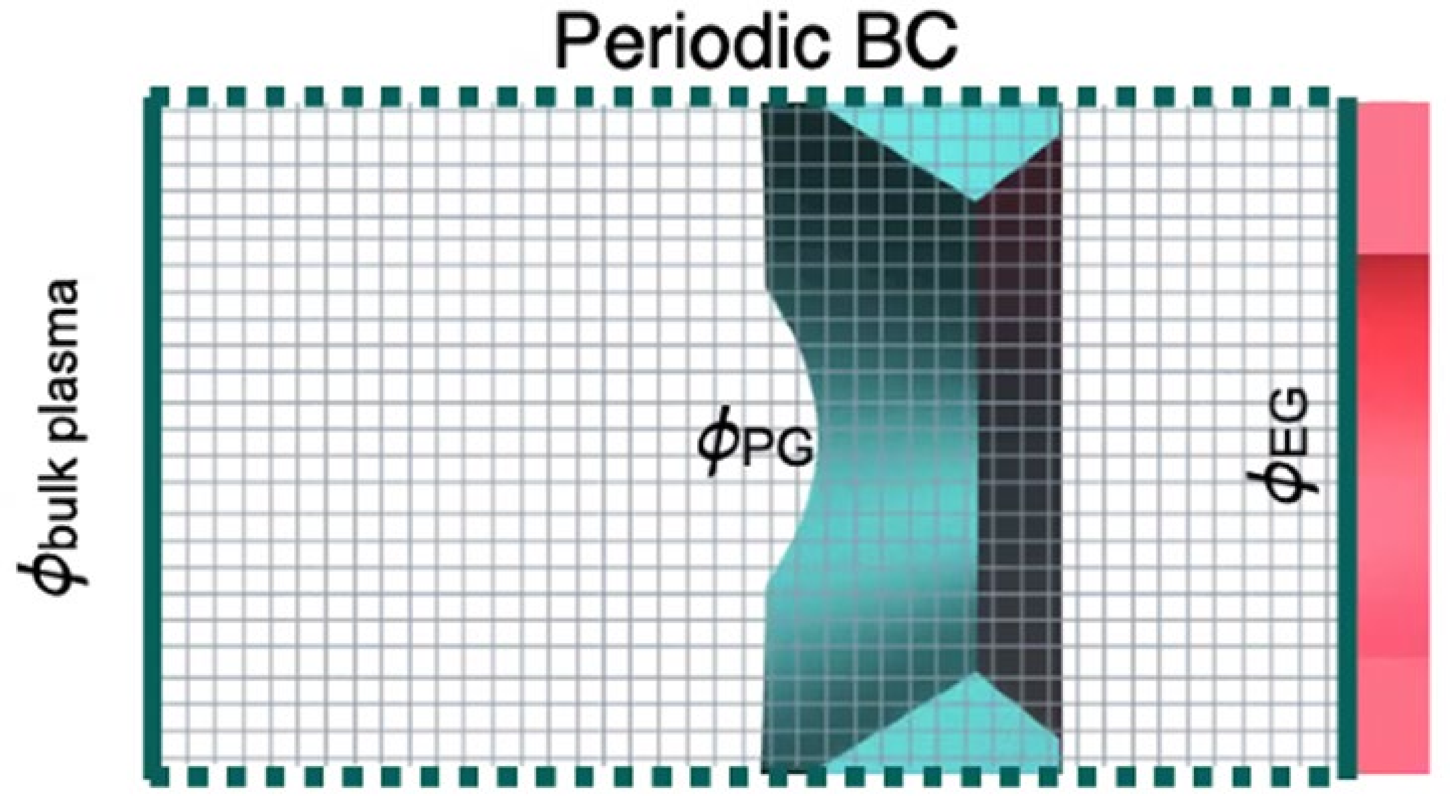


Periodic Boundary Conditions (Up/Down & Left/Right)

EG (Extraction Grid)

ONIX details

- Particle-in-Cell stability criteria
  - Plasma criteria $\lambda_{\mathrm{De}} \ll L$ $N_D \gg 1$ $\omega_{pe}\tau > 1$
  - CFL (Courant-Friedrich-Lewy) v_{MAX} dt < dx
  - Cyclotron Ω_B dt << 1



dx = dy = dz

- dt = 5 × 10^{-12} s, dx = 3.5 × 10^{-5} m (λ_{De})

ONIX Particle Injection

Pair injection

- Initial distribution of ions are injected
- Upon impact with a boundary
  - Electrons are deleted
  - NIs are re-injected
  - PIs are re-injected with an electron
- Electrons are thermalized in the injection zone

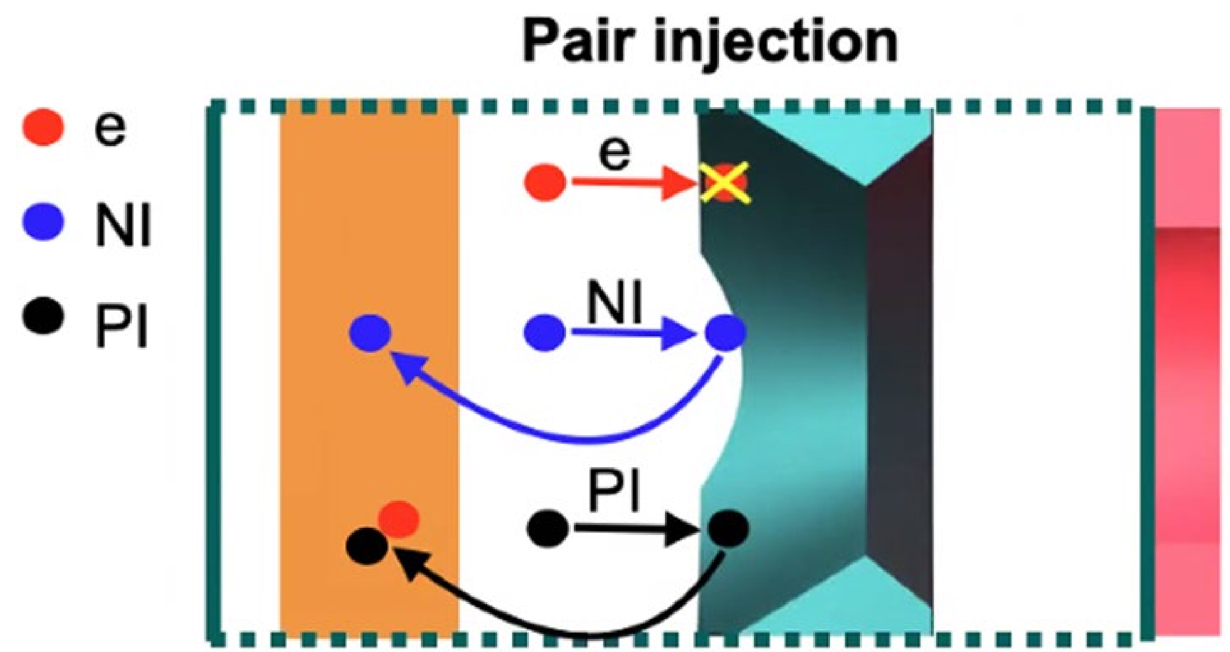
Flux injection

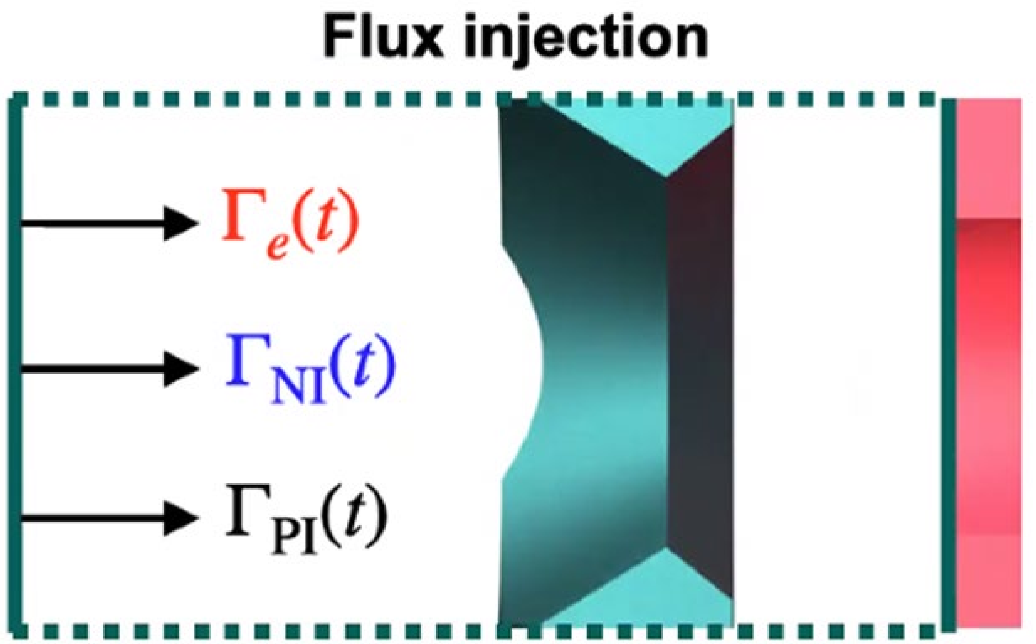
Electrons, NIs, and PIs are injected from upstream boundary

$$\Gamma_{PI}(t) = \Gamma_{NI}(t) + \Gamma_e(t)$$

$$\Gamma_{PI}(t) = P \cdot e(t) + I \cdot \int_0^t e(t)\mathrm{d}t + D \cdot \frac{\mathrm{d}}{\mathrm{d}t} e(t)$$

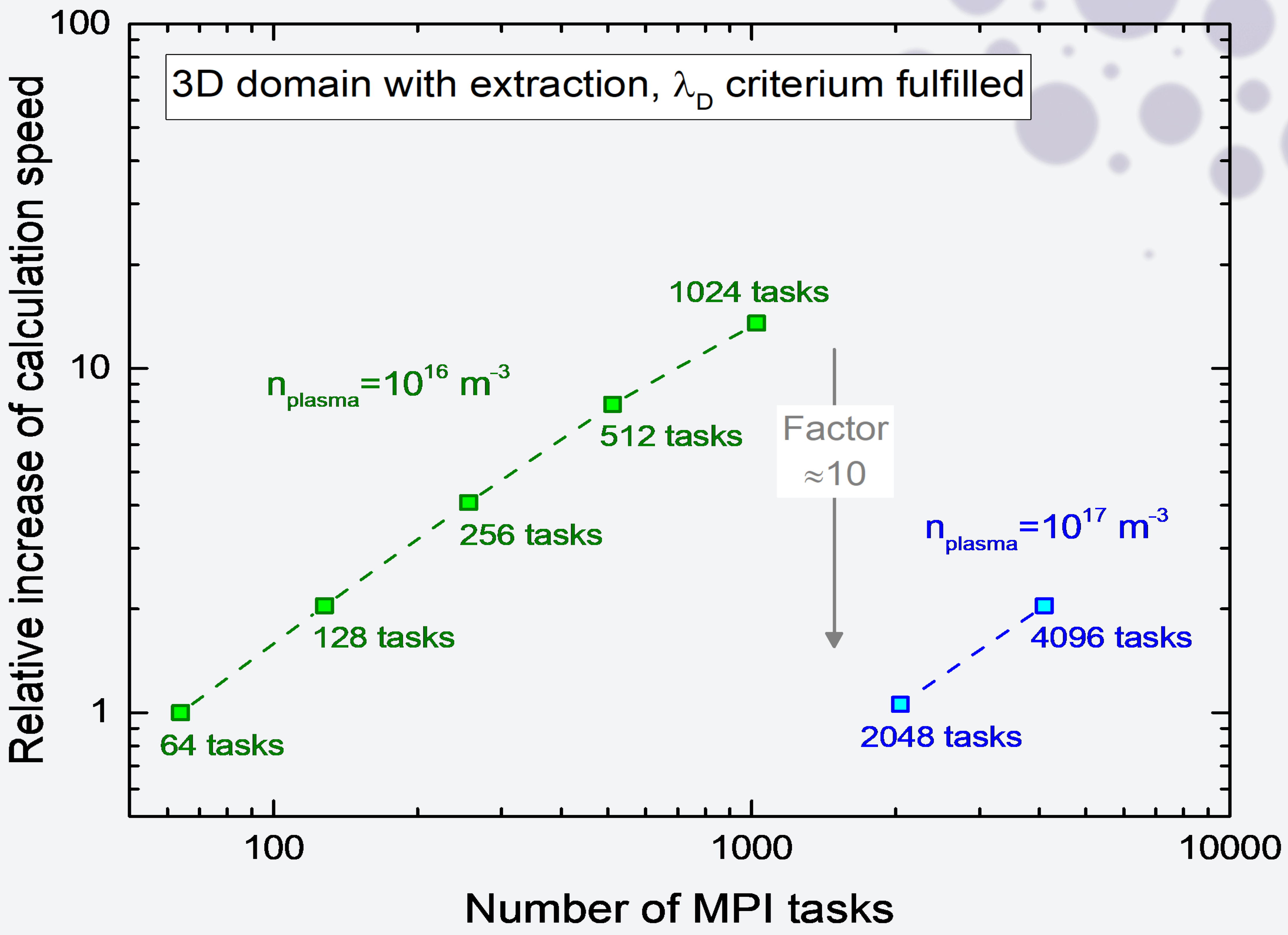
$$e(t) = n_{PI}(t) - n_{PI,steady-state}$$





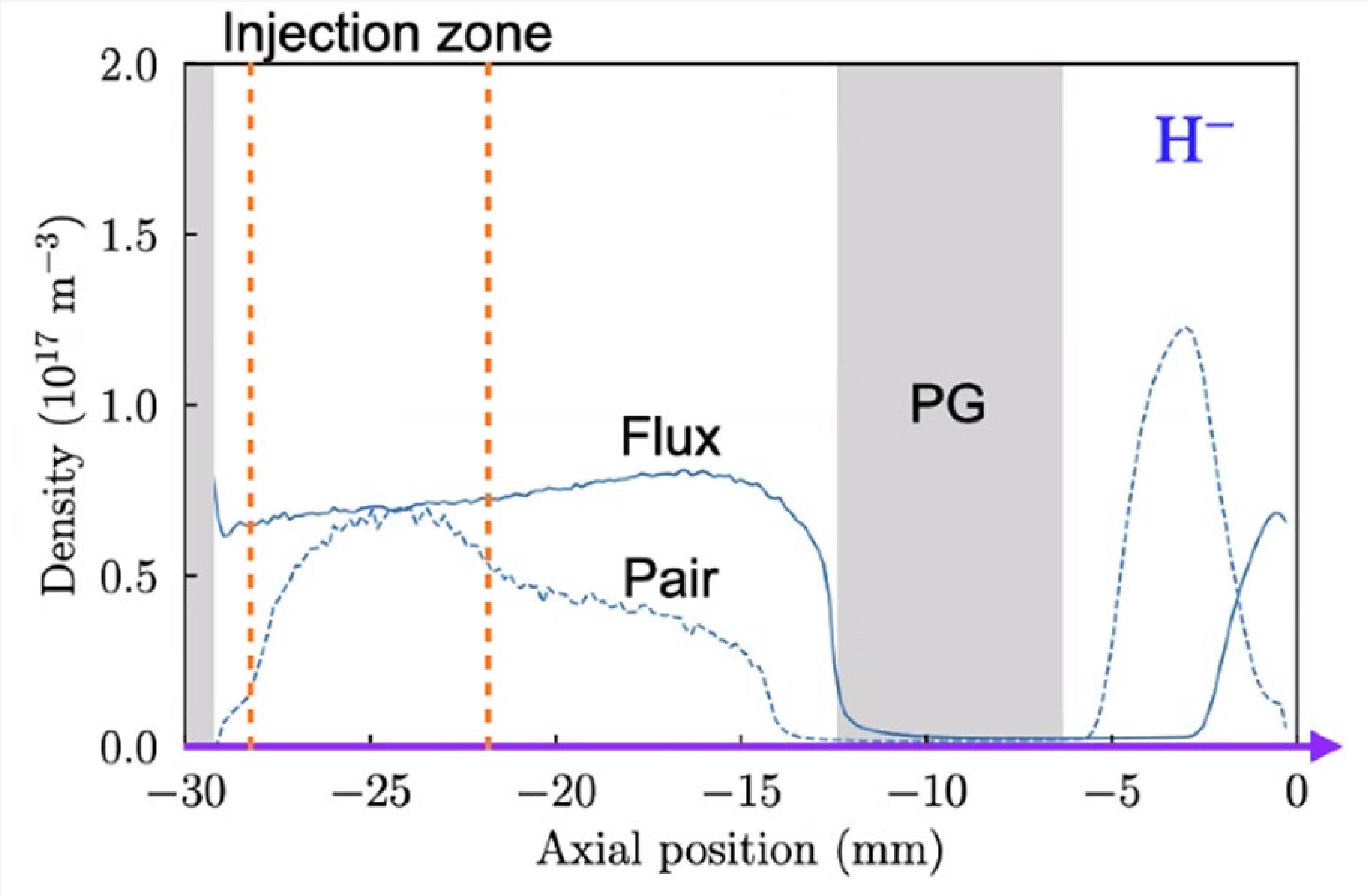
ONIX efficiency

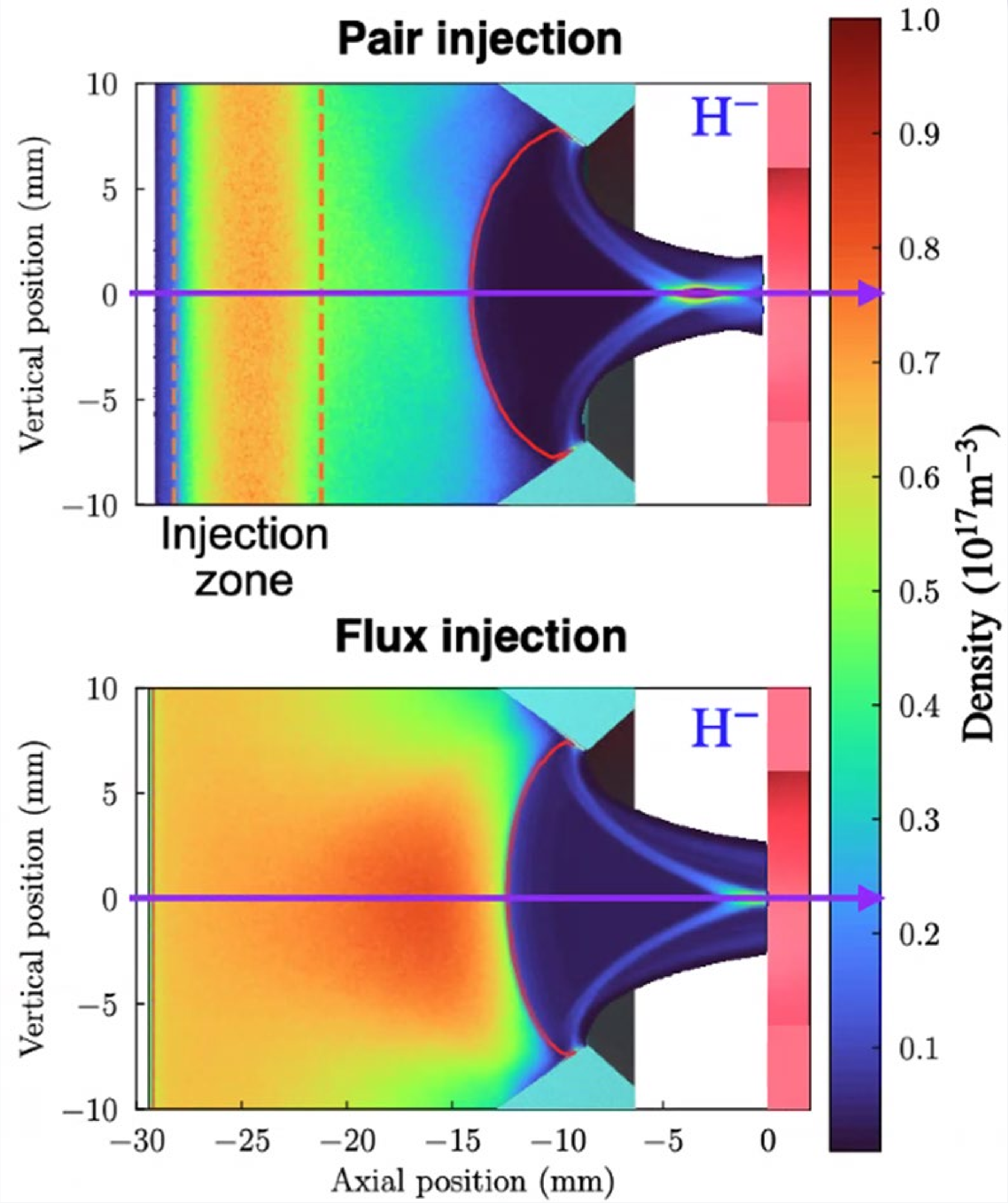
- Parallel
  - MPI – Message Passing Interface
  - Multi-domains
  - Flexible boundary domains (edges, round objects)
- Computational cost
  - N° macroparticles ~10^6
  - Mesh nodes
  - 3 days / µs on 4096 CPUs



NI beam formation

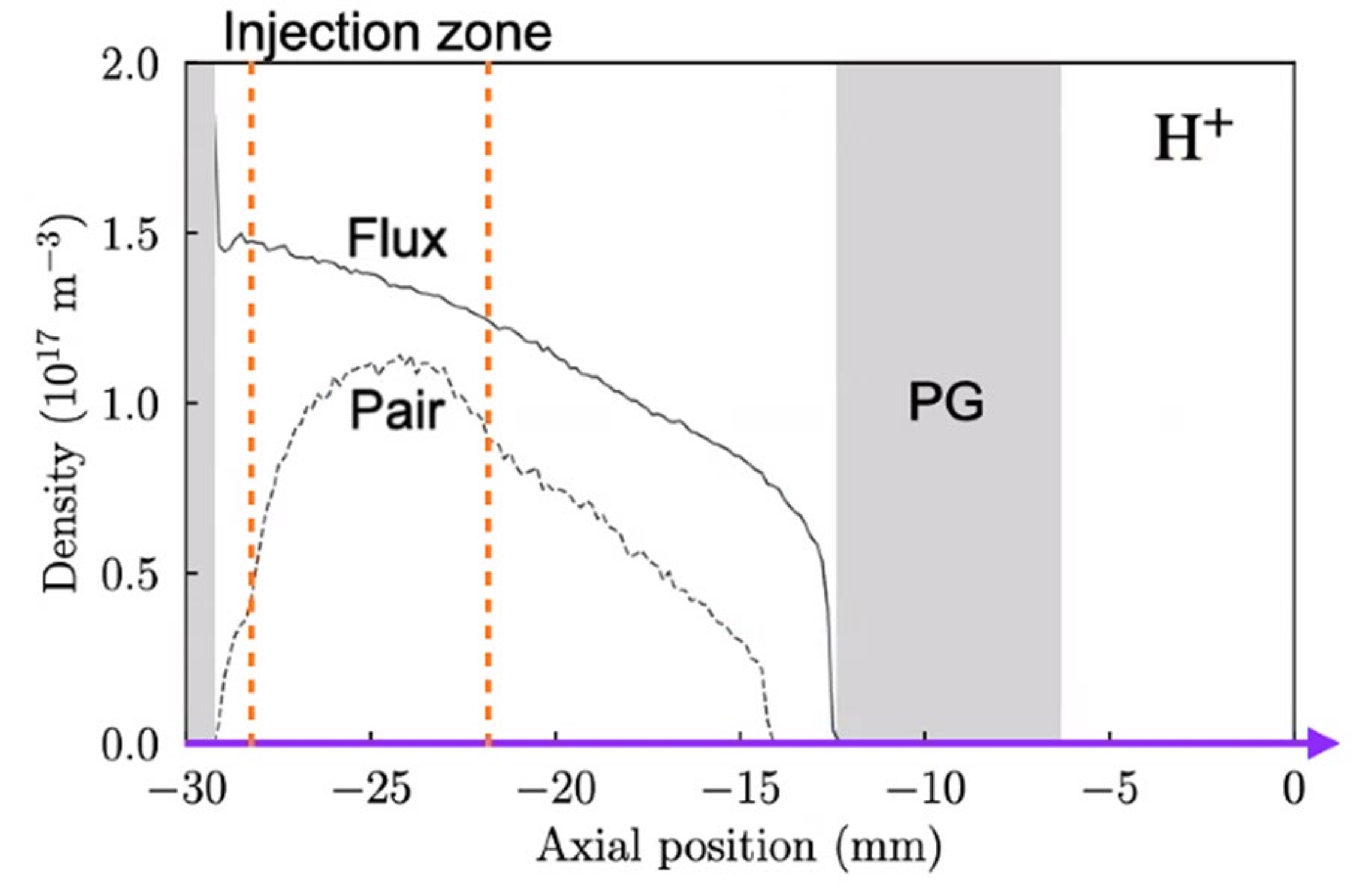
- Meniscus penetration depends on the extraction field and plasma screening
  - Flat meniscus = well focused
  - Curved meniscus = over focused
- NI are guided by the meniscus

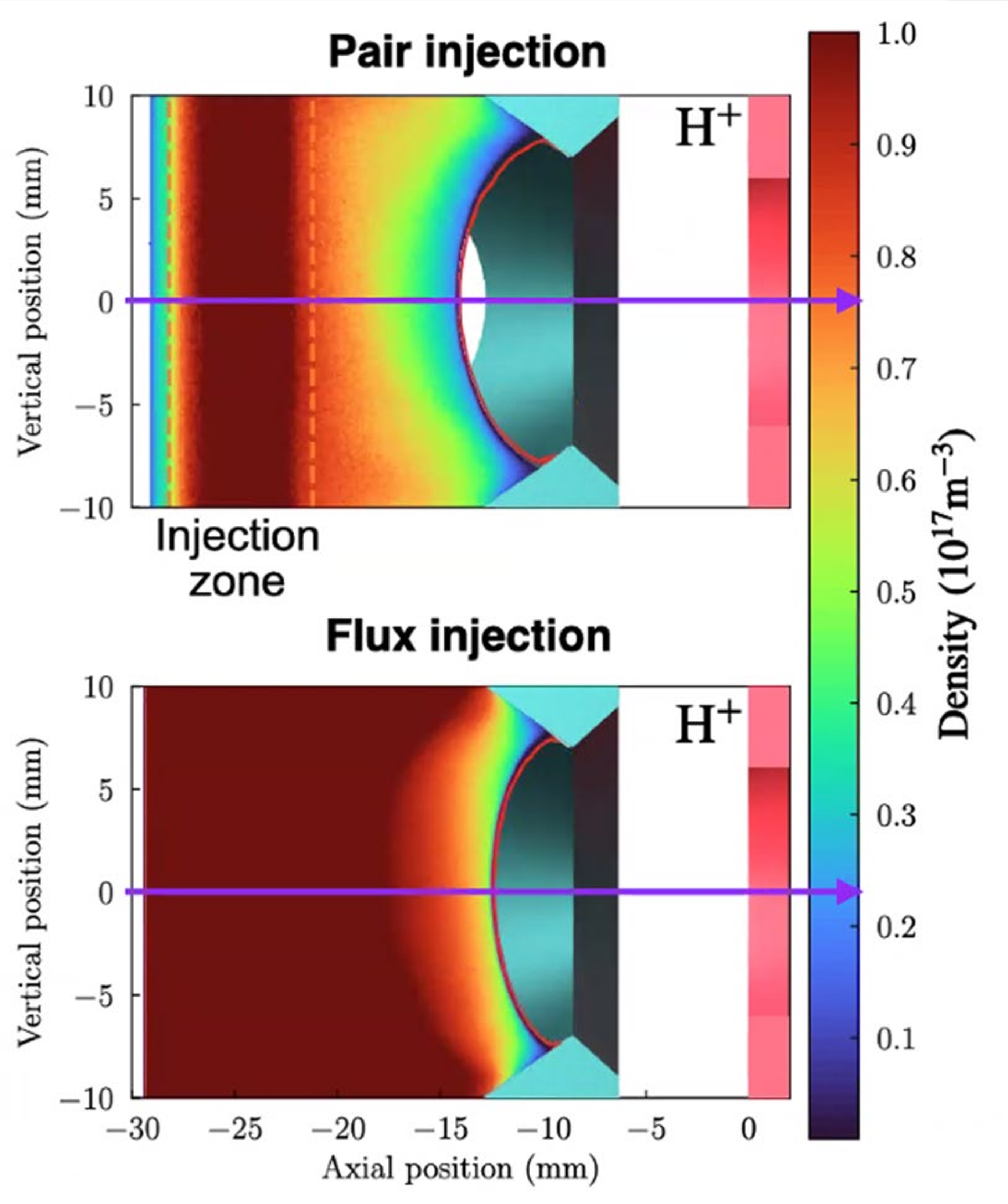




PI in the extraction region

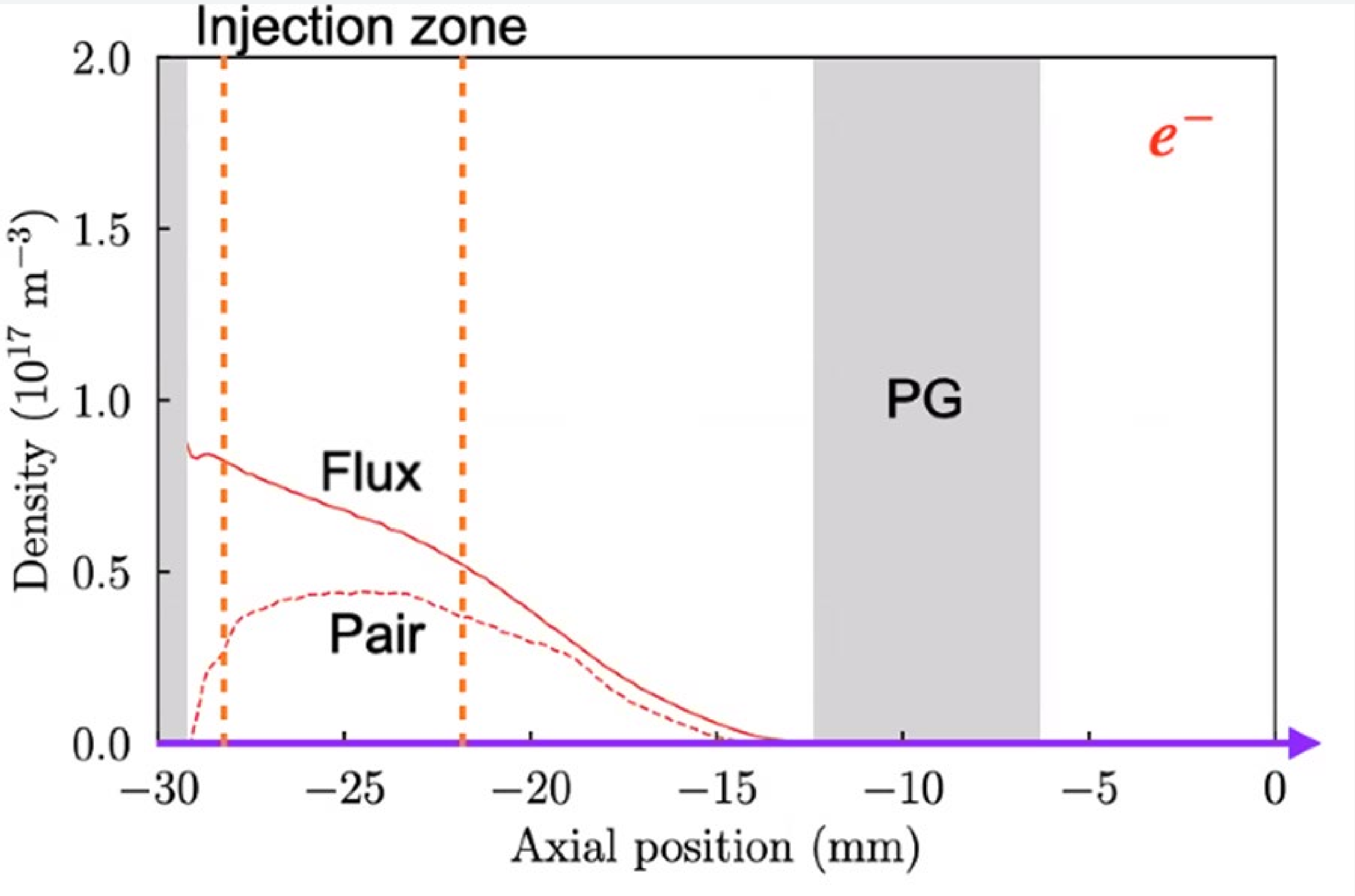
- Plasma density in front of the meniscus is very sensitive to the injection scheme
- PI behave different following the injection scheme

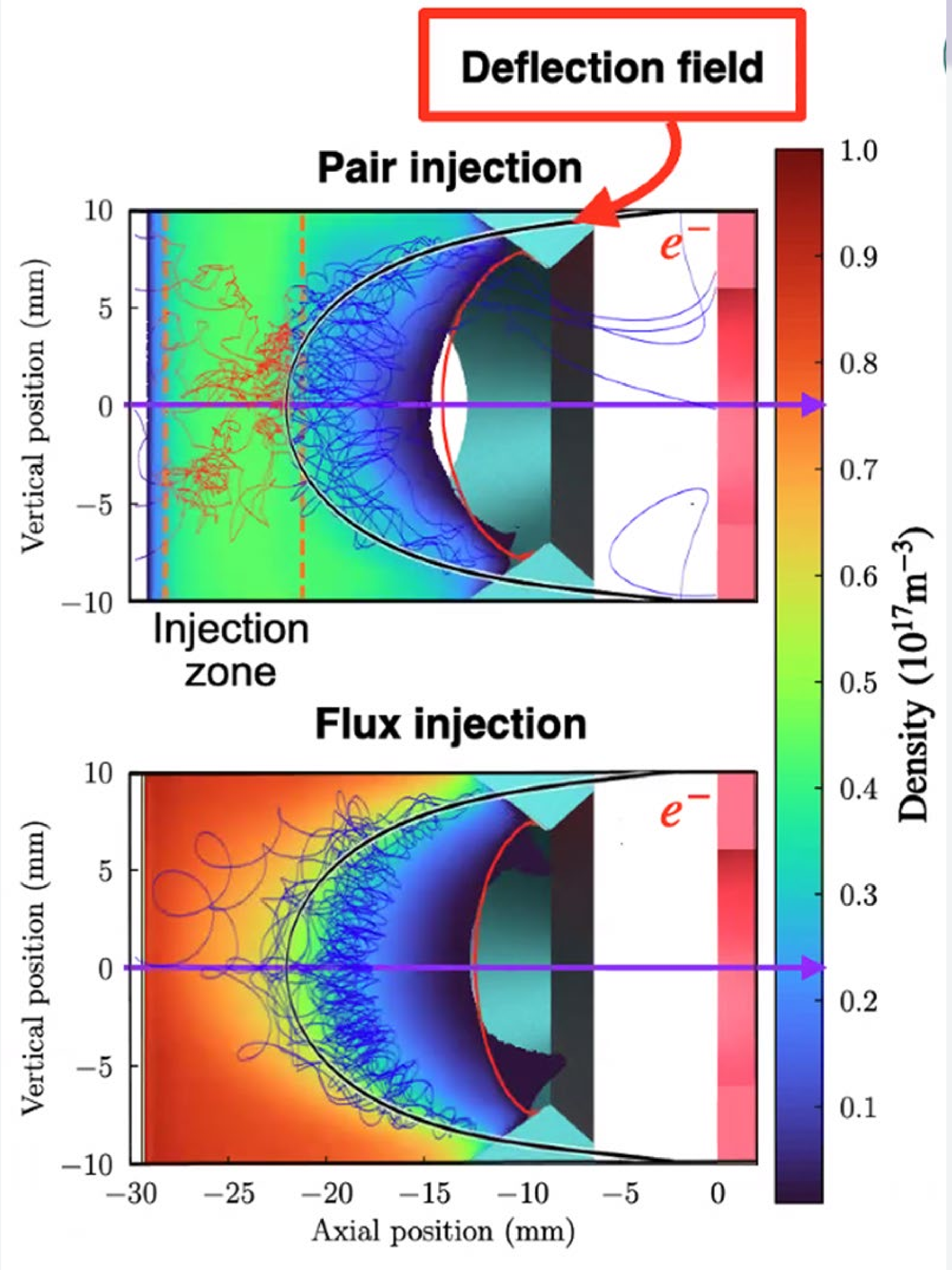




Electron co-extraction

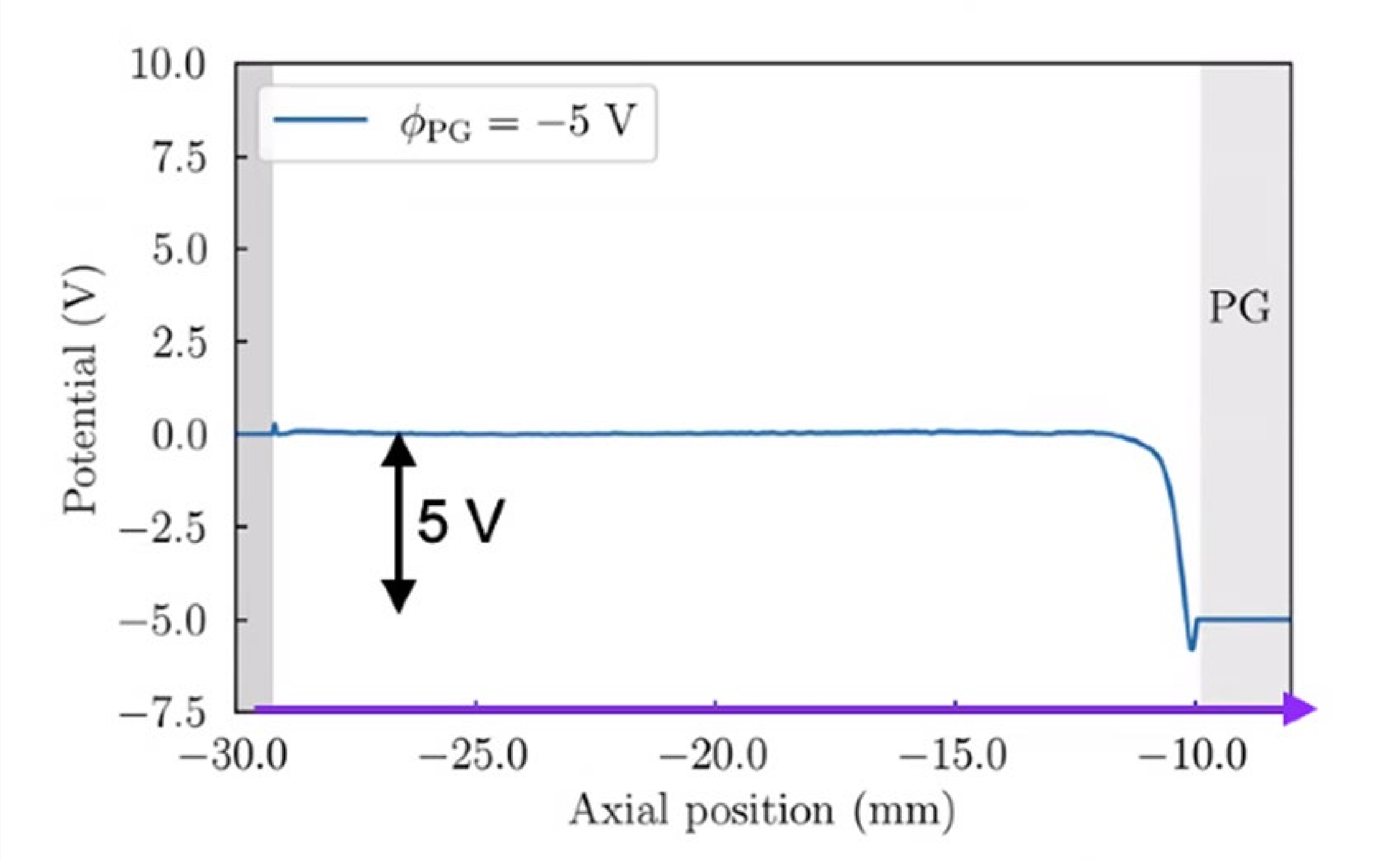
- ➢ Electrons intercept the injection region in the pair-injection scheme
- ➢ Electrons follow the magnetic field lines in the extraction region

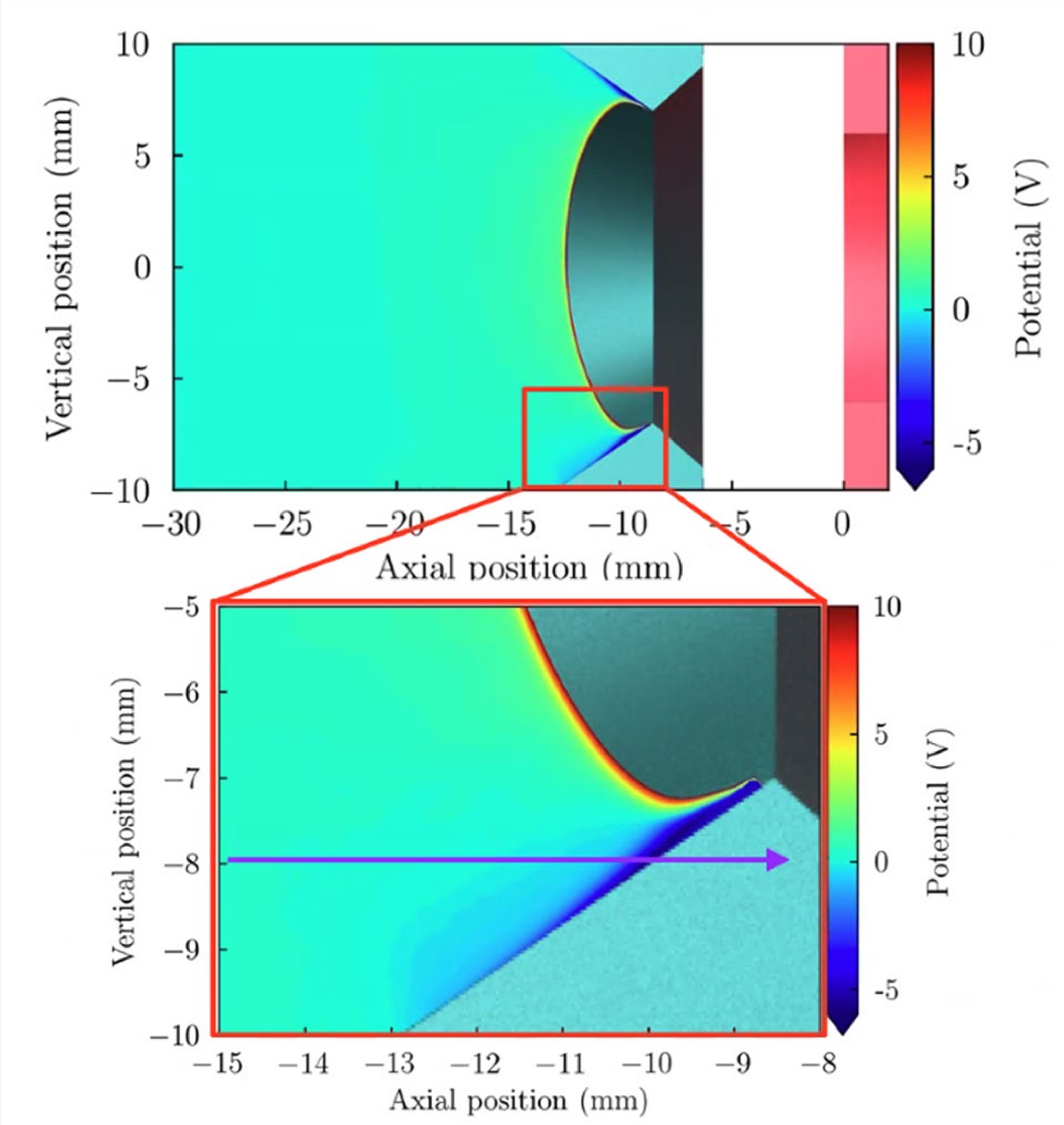




Sheath Formation and Virtual Cathode

- Close to the PG surface a sheath is formed
- Electrons are repelled inside the plasma
- NI can hardly reach the plasma due to the Virtual Cathode formation

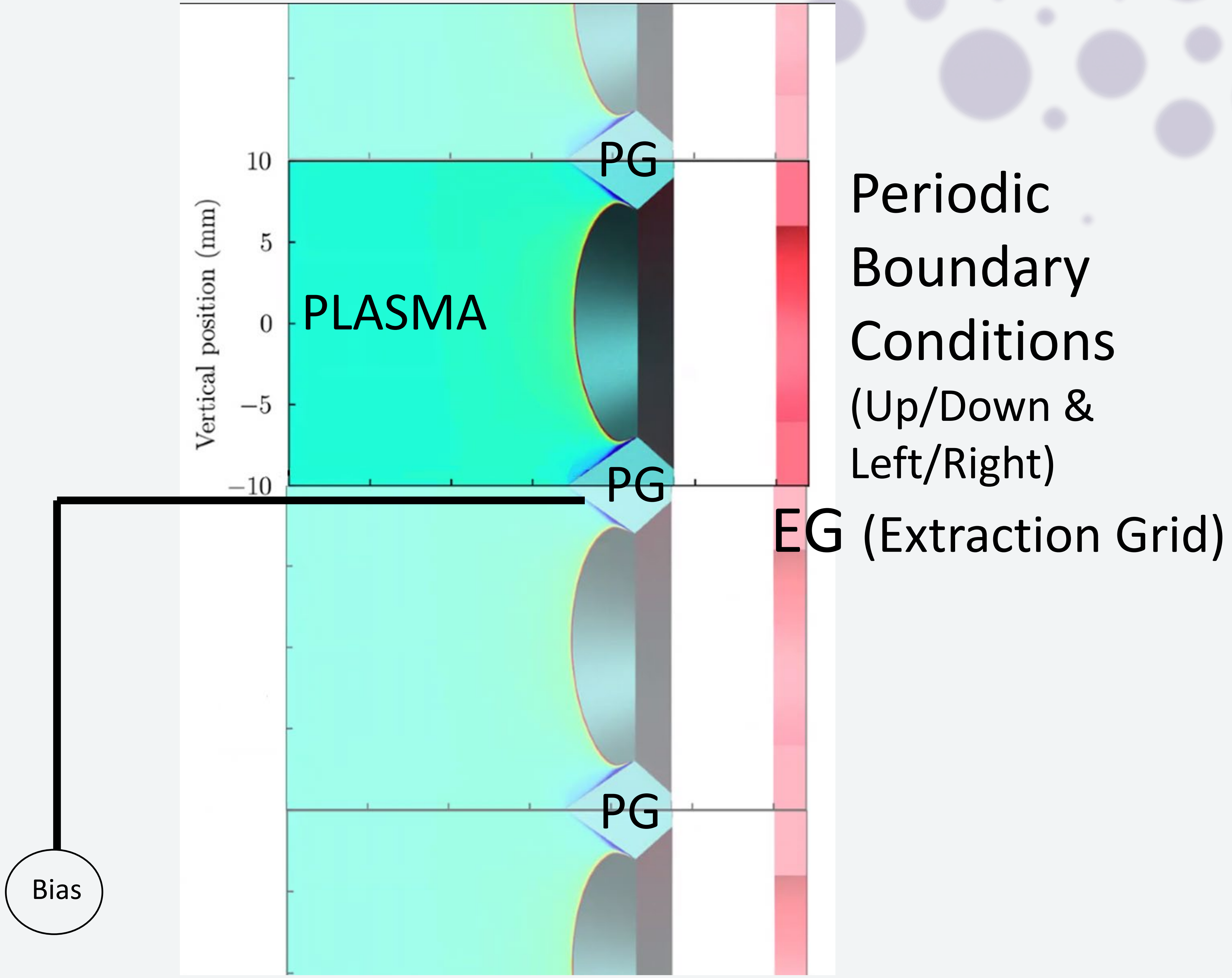




Plasma Grid Bias Effect

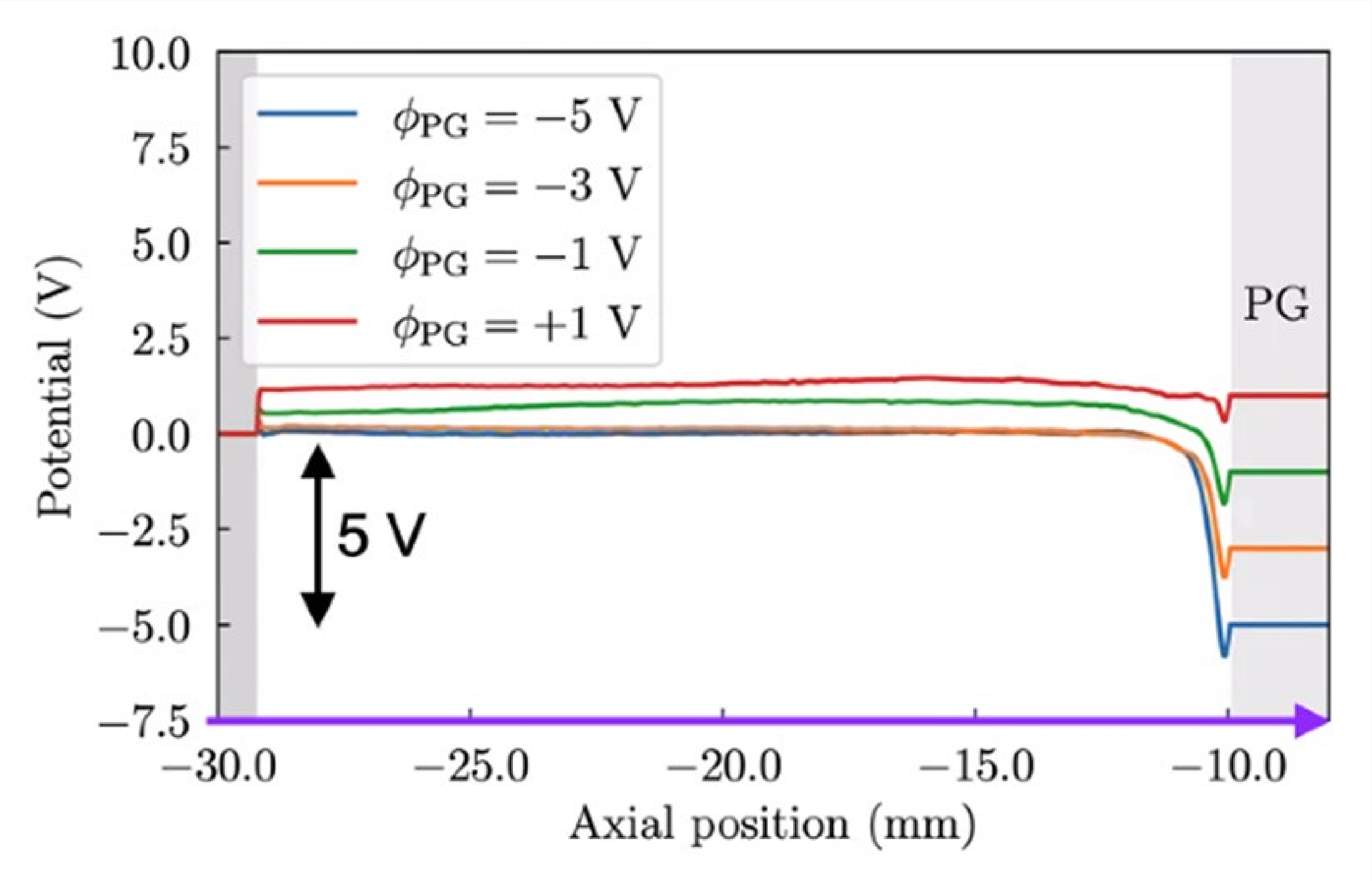
- How to reduce the electron extraction?

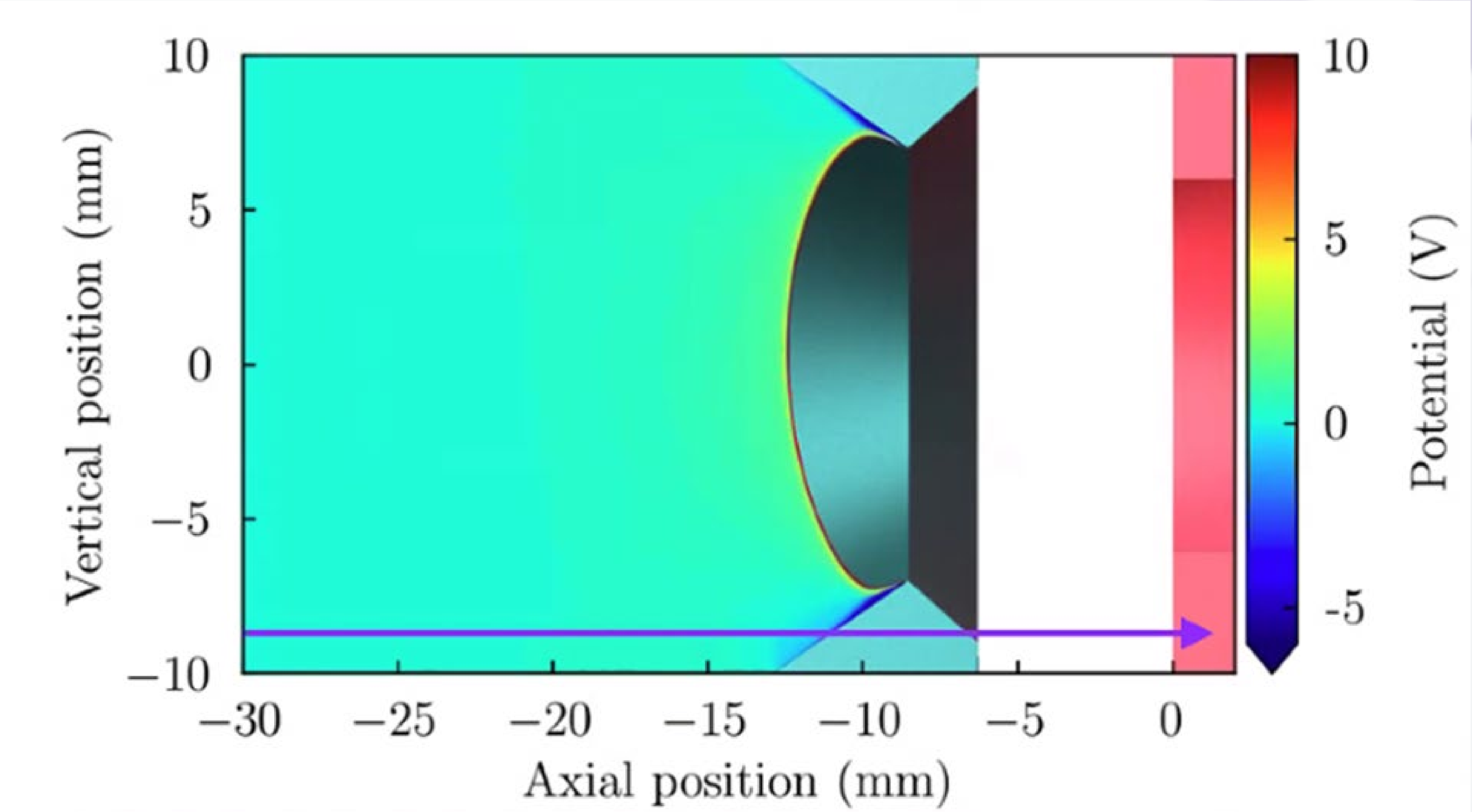
Biasing the PG electrons can reach it.

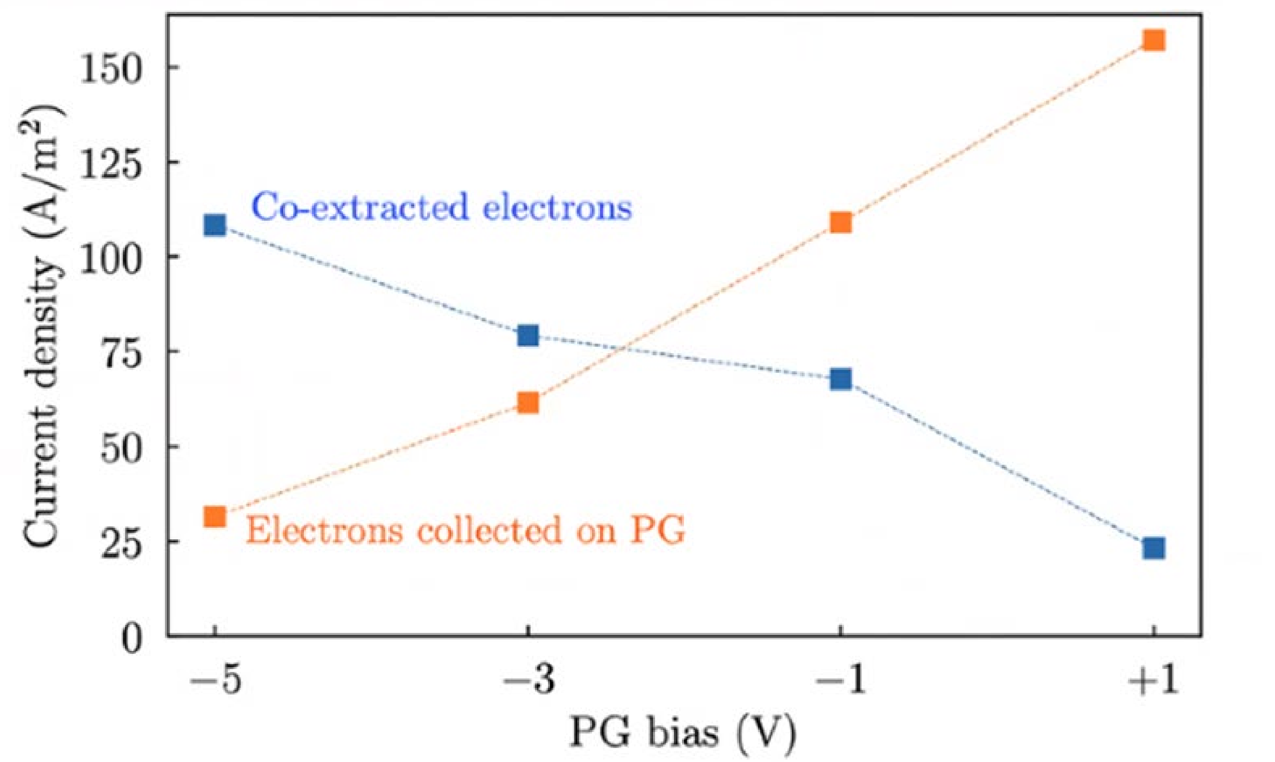


Bias effect on Plasma Electrons

- The Virtual Cathode is always present, but the sheath is hardly affected
- Electrons are collected by the PG





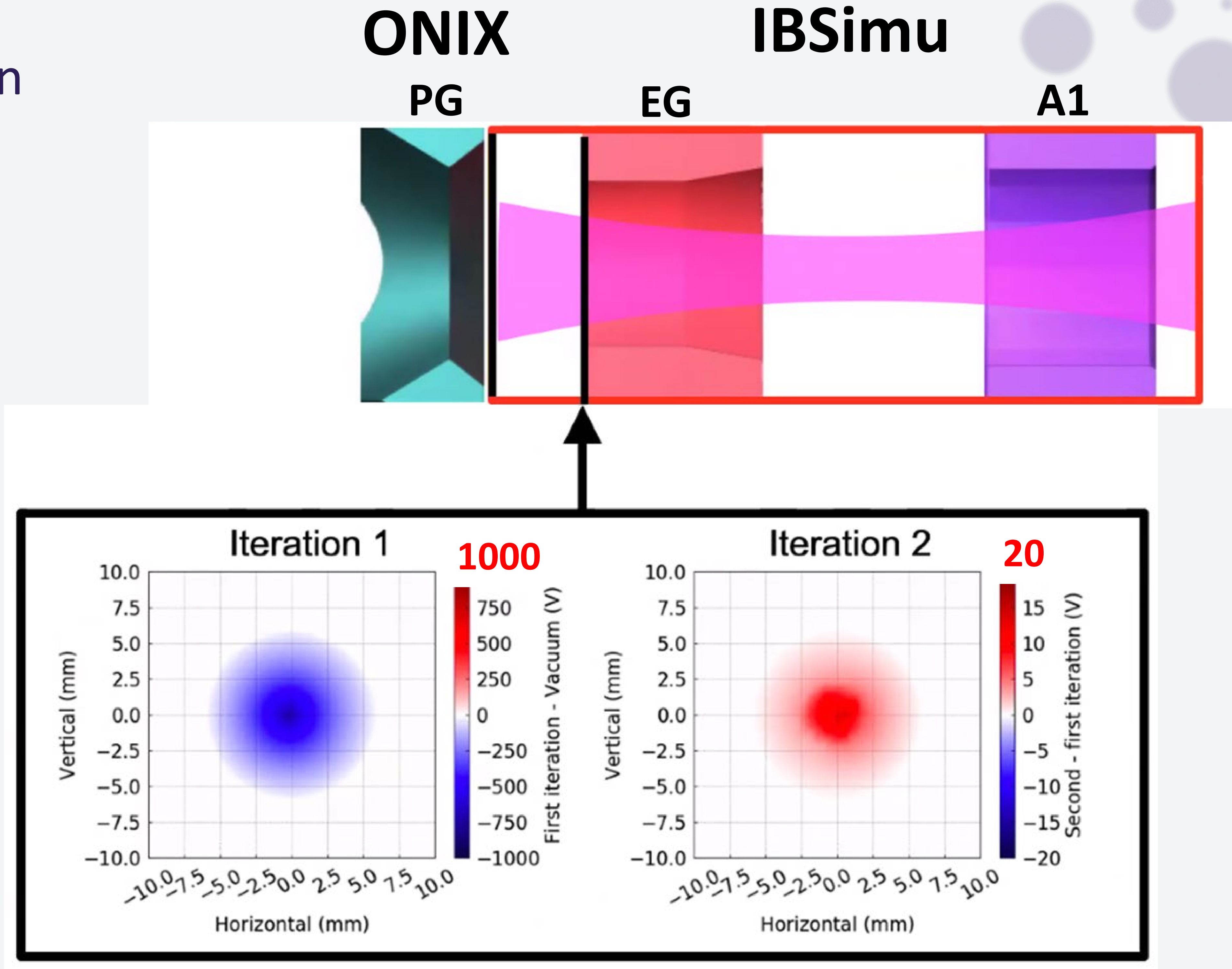


ONIX – IBSimu / ONAC coupling

- ONIX simulates the extraction region in a plasma source close to PG
- Several models simulate beam propagation: IBSimu, SIMION, …

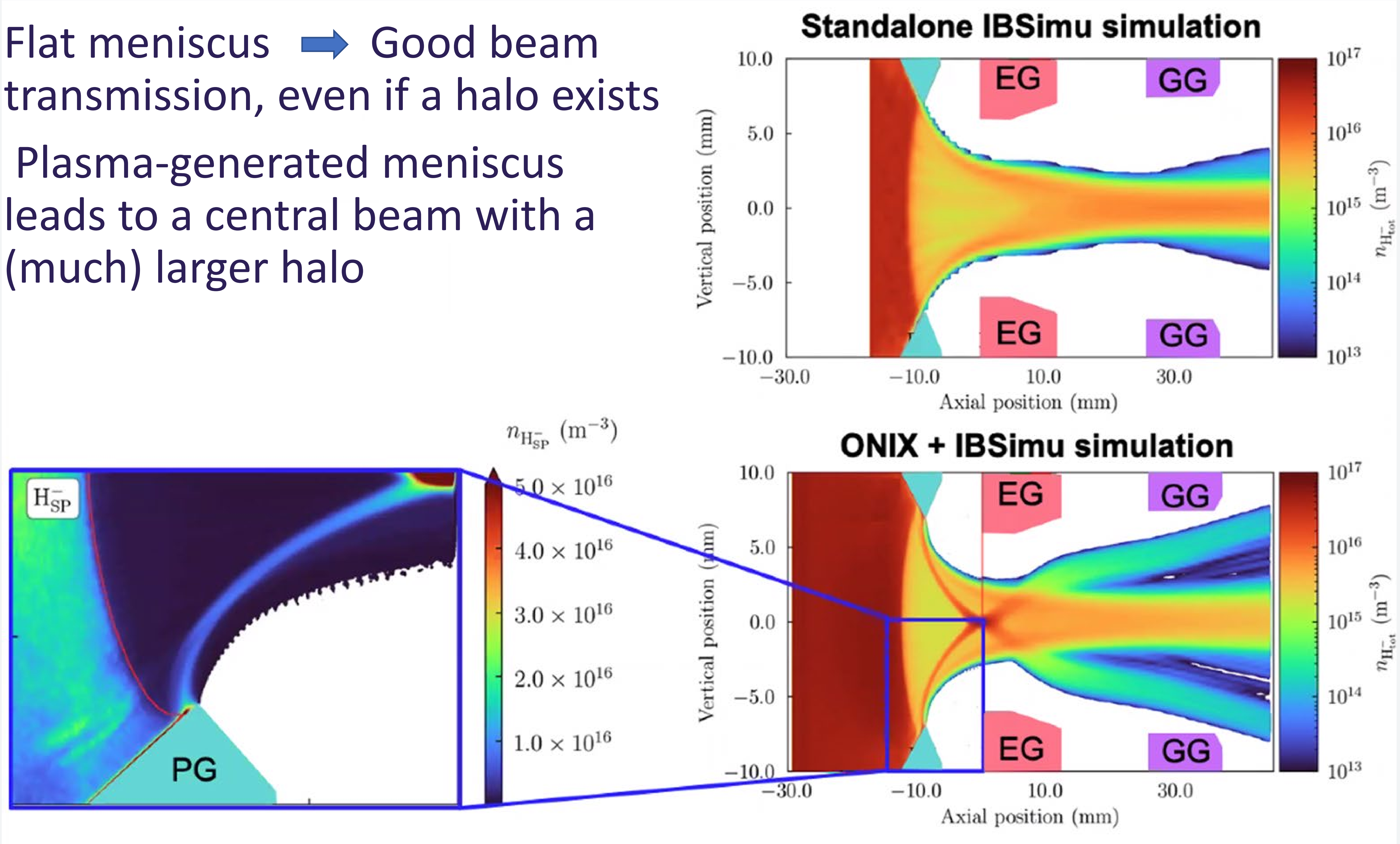
Condition: Potential Continuity

- **ONAC** : Orsay Negative Ion ACceleration was developed for
  - ➢ Solves Poisson Equation
  - ➢ Includes particle interaction with the residual gas (MCC)
  - ➢ Parallelized using MPI
  - ➢ Fully compatible with ONIX



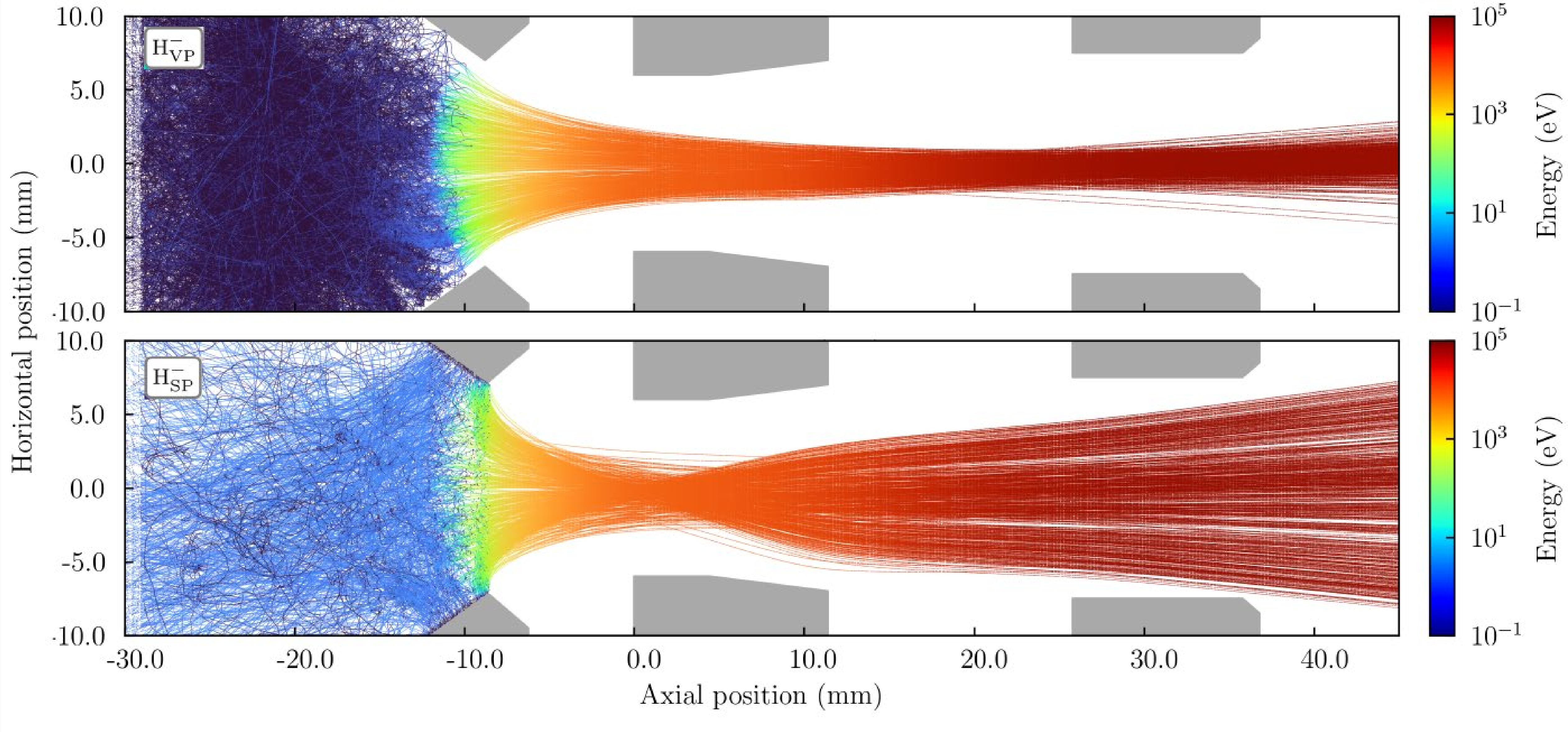
Meniscus Effect on the Beam Shape

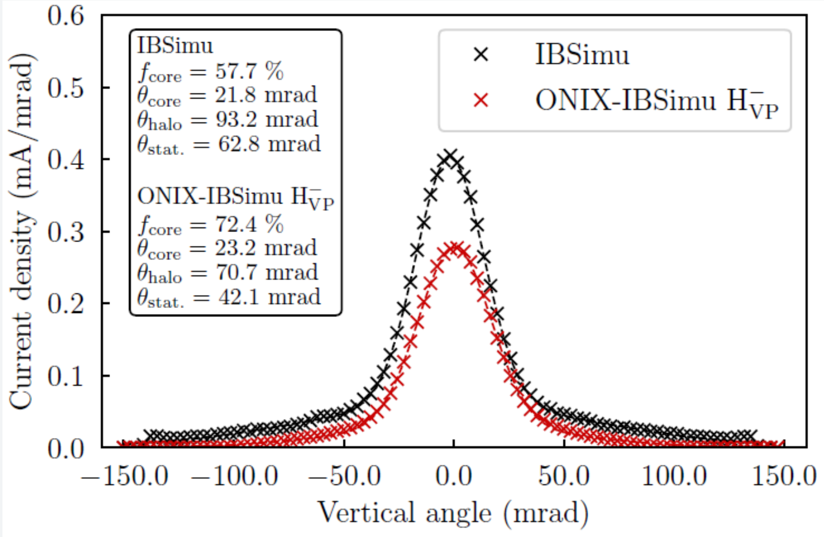
- Flat meniscus ➡ Good beam transmission, even if a halo exists
- Plasma-generated meniscus leads to a central beam with a (much) larger halo

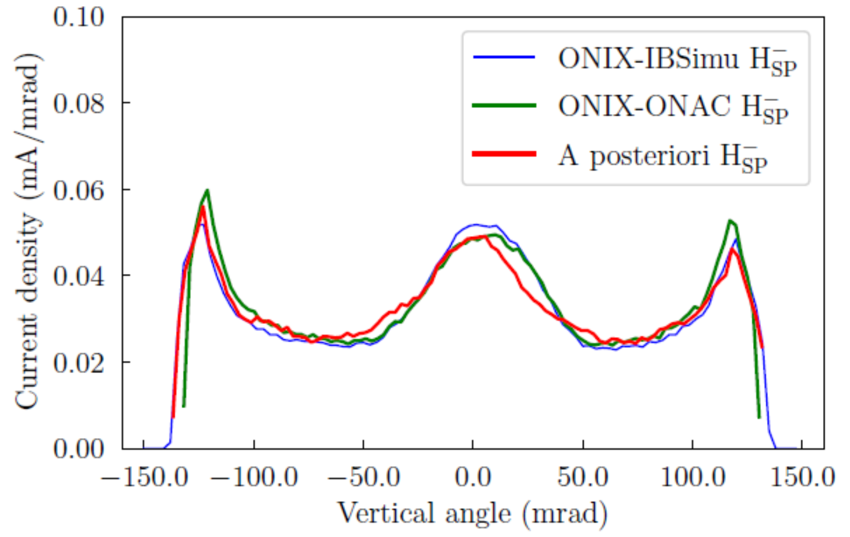


Beam Spread Related to Particle Origin

- Volume originating NI



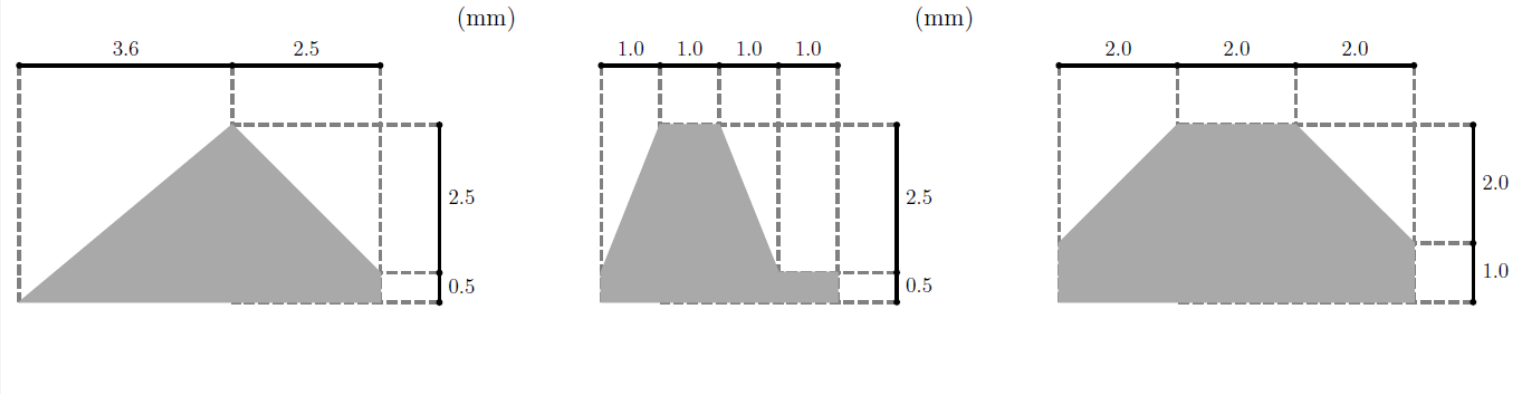




- Surface originating NI

PG Geometry Effect

- Three Grid Chamfrain Geometries

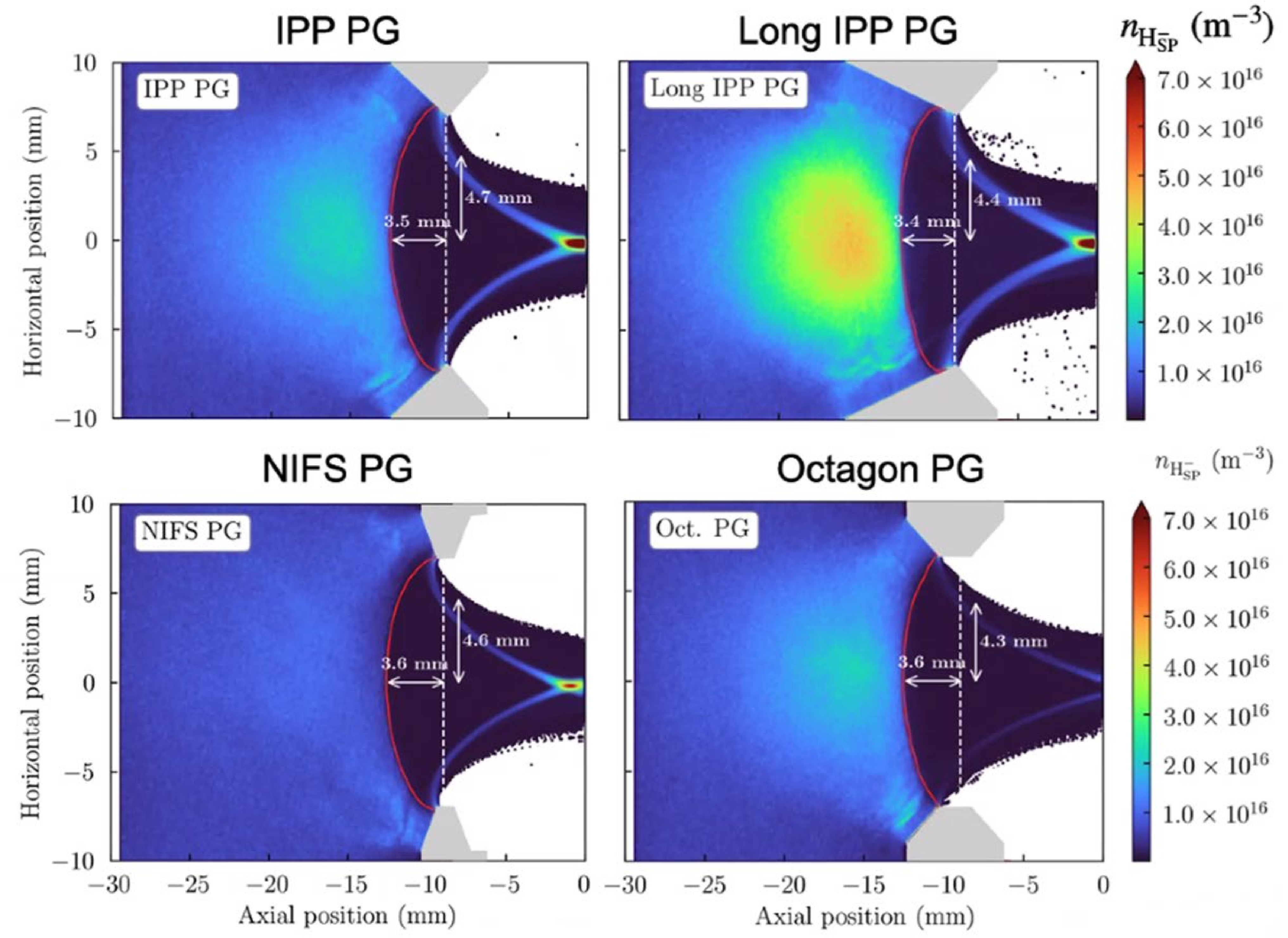


(a) *IPP PG* (b) *NIFS PG* (c) *Oct. PG*

- Extracted current

	Indirect	$j_{H_{SP}^-}$	j_e
	%	A/m²	A/m²
IPP PG	38	57	108
Long IPP PG	44	81	102
NIFS PG	49	26	118
Octagon PG	64	17	125

- Similar co-extracted e-current
- Plasma-facing angle limits surface extracted NI



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Conclusions & Perspectives

- ✓ ONIX is a powerful model to simulate the self-consistent meniscus formation for a given plasma facing the Plasma Grid and a given extraction electric field
- ✓ Kinetic of species in the gas phase is included
- ✓ External bias of the PG (or another wall) can be simulated
- ✓ ONIX can give valuable hints for the grid design
- ✓ ONIX can be coupled with ONAC or any other accelerator simulator

TO DO

- ✓ Transport of NI from the surface to the plasma volume must be improved
- ✓ Deuterium plasma and isotopic effect to be developed
- ✓ Explore the role of Cs^{+} ions

MERCI