

Plasma physics in negative ion sources and challenges for MeV neutral beam injectors for fusion

5th February 2026 – Conferenza Italiana sui Plasmi

Antonio Pimazzoni on behalf of all NBTF team and international collaborators

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CONSORZIO RFX
Ricerca Formazione Innovazione



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⁸ ITER Organization (IO), Route de Vinon sur Verdon, CS 90 046, F-1, 3067 St. Paul-lez-Durance, France

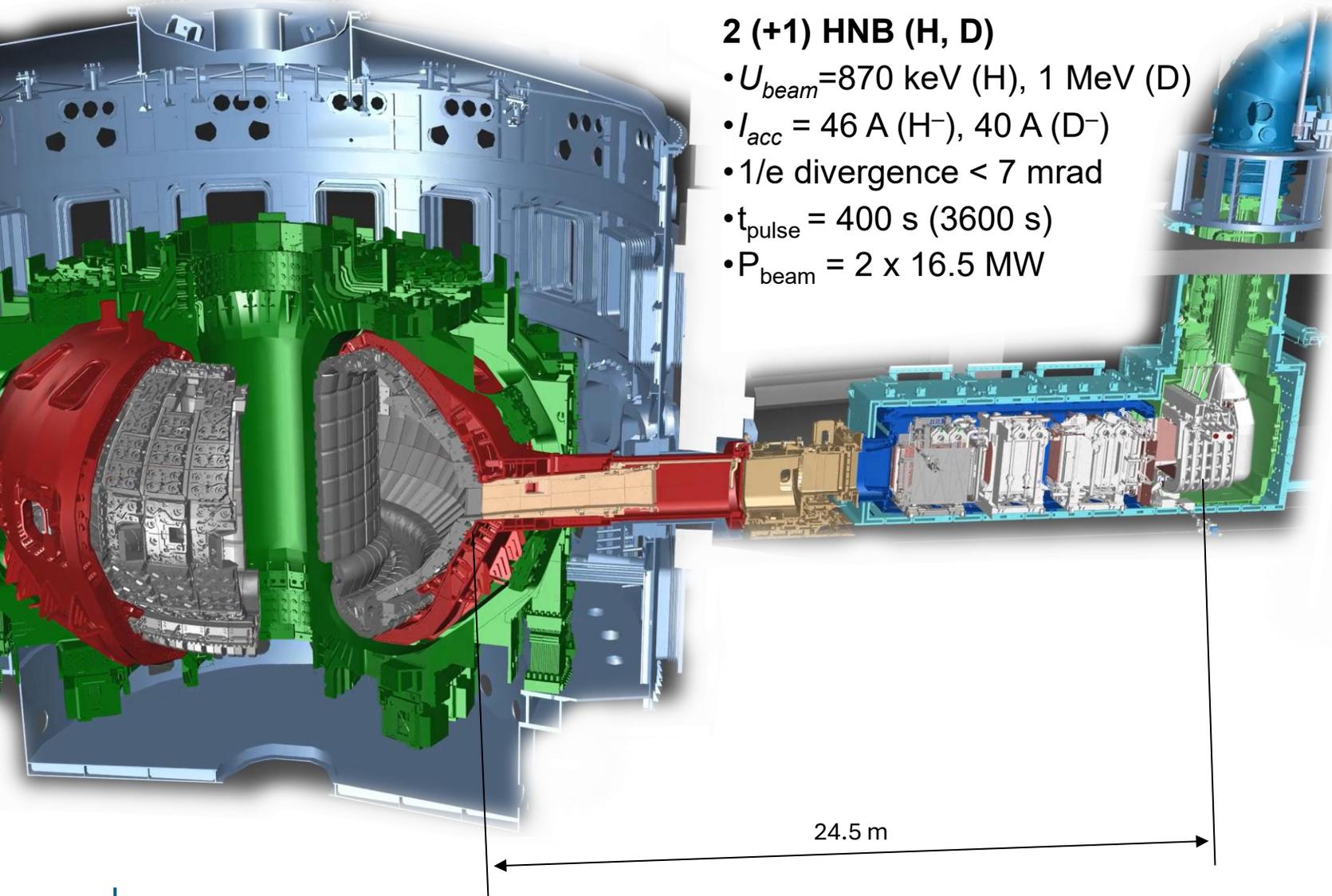
⁹ Università degli studi di Pisa, Italy

¹⁰ National Centre for Nuclear Research (NCBJ), PL-05-400 Otwock, Poland

ITER Negative-ion based heating neutral beams

2 (+1) HNB (H, D)

- $U_{beam} = 870 \text{ keV (H), 1 MeV (D)}$
- $I_{acc} = 46 \text{ A (H}^-), 40 \text{ A (D}^-)$
- $1/e \text{ divergence} < 7 \text{ mrad}$
- $t_{pulse} = 400 \text{ s (3600 s)}$
- $P_{beam} = 2 \times 16.5 \text{ MW}$



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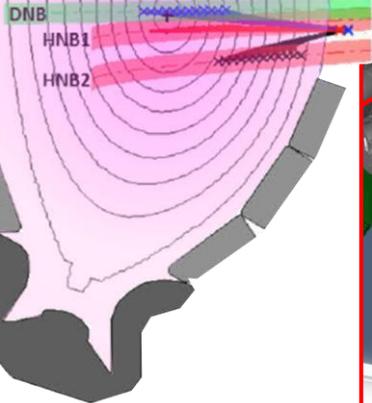
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Tokamak size &
Plasma density



Beam energy

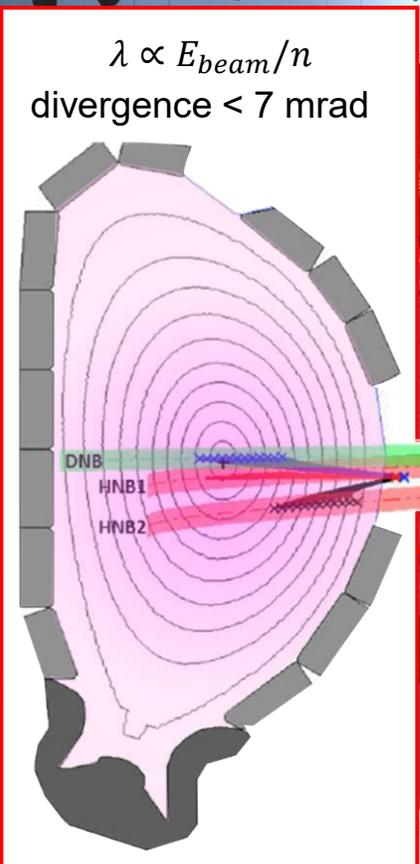
$\lambda \propto E_{beam}/n$
divergence $< 7 \text{ mrad}$



ITER Negative-ion based heating neutral beams

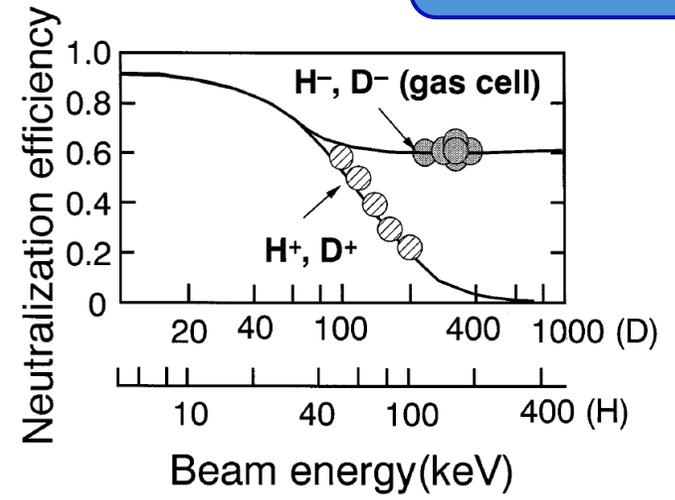
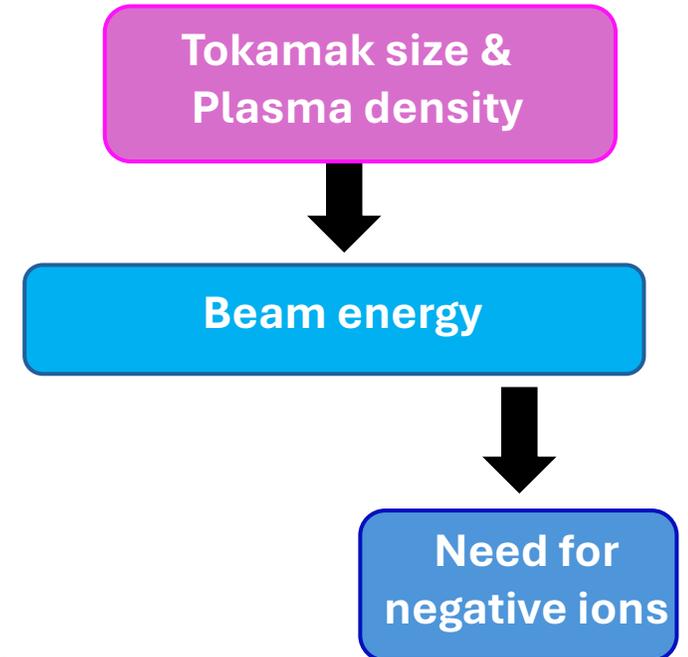
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neutralization
@ 1 MeV
 $\text{H}^- \eta \sim 60\%$
 $\text{H}^+, \text{H}_x^+ \eta \sim 0\%$

M. Kuriyama et al.
Operation of the negative-ion based NBI for JT-60U,
Fus. Eng. Des. 39-40
(1998), 115-121

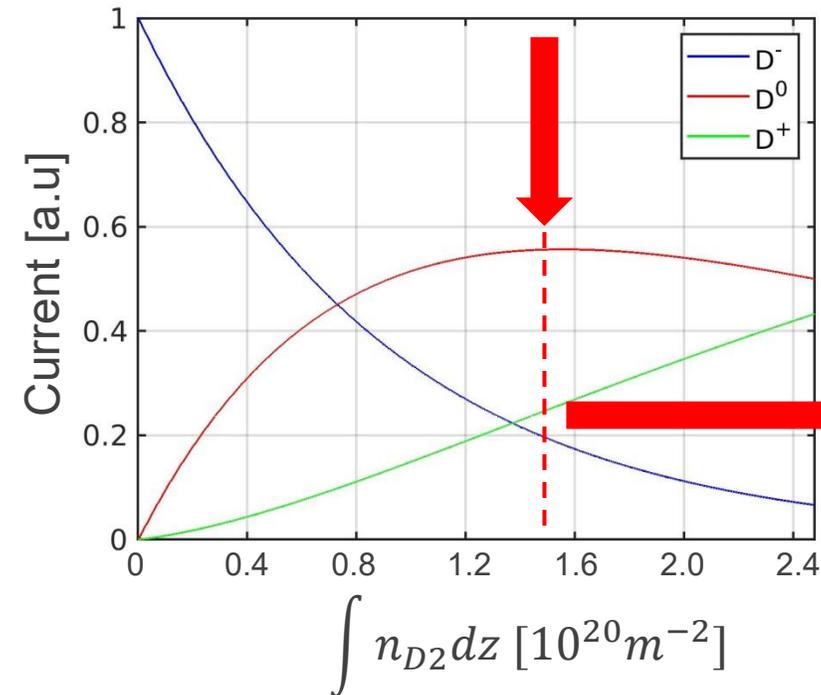


Beam neutralization: gas cell



- Tuning the gas throughput gives maximum neutralization efficiency
- Alternative concepts are under study for next generation NBIs (plasma neutralizer, photo-neutralizer)
- **Status: «Standard» component, but no neutralization of 870 keV beam so far (uncertainty on cross sections)**

$$I = I_0 e^{-\sigma(E) \int_0^L n_{D_2} dz}$$



Dumping residual ions is mandatory

Evolution of beam species inside the neutralizer (constant D_2 density)

Beam neutralization: ion dumping

- The gas cell for ITER NBIs is split in 4 channels to reduce the required gas throughput
 → Maximize beam pulse duration
- **Residual ion dump** is based on electrostatic deflection (**ERID**) : ± 25 kV biasing to remove D^+/D^- from the beam
- Concept from Kurchatov Institute (Moscow, Russia); with positive ions [1]
- Experimental verification @ ASIPP (Hefei, China) in 2024; only up to 170 keV [2]

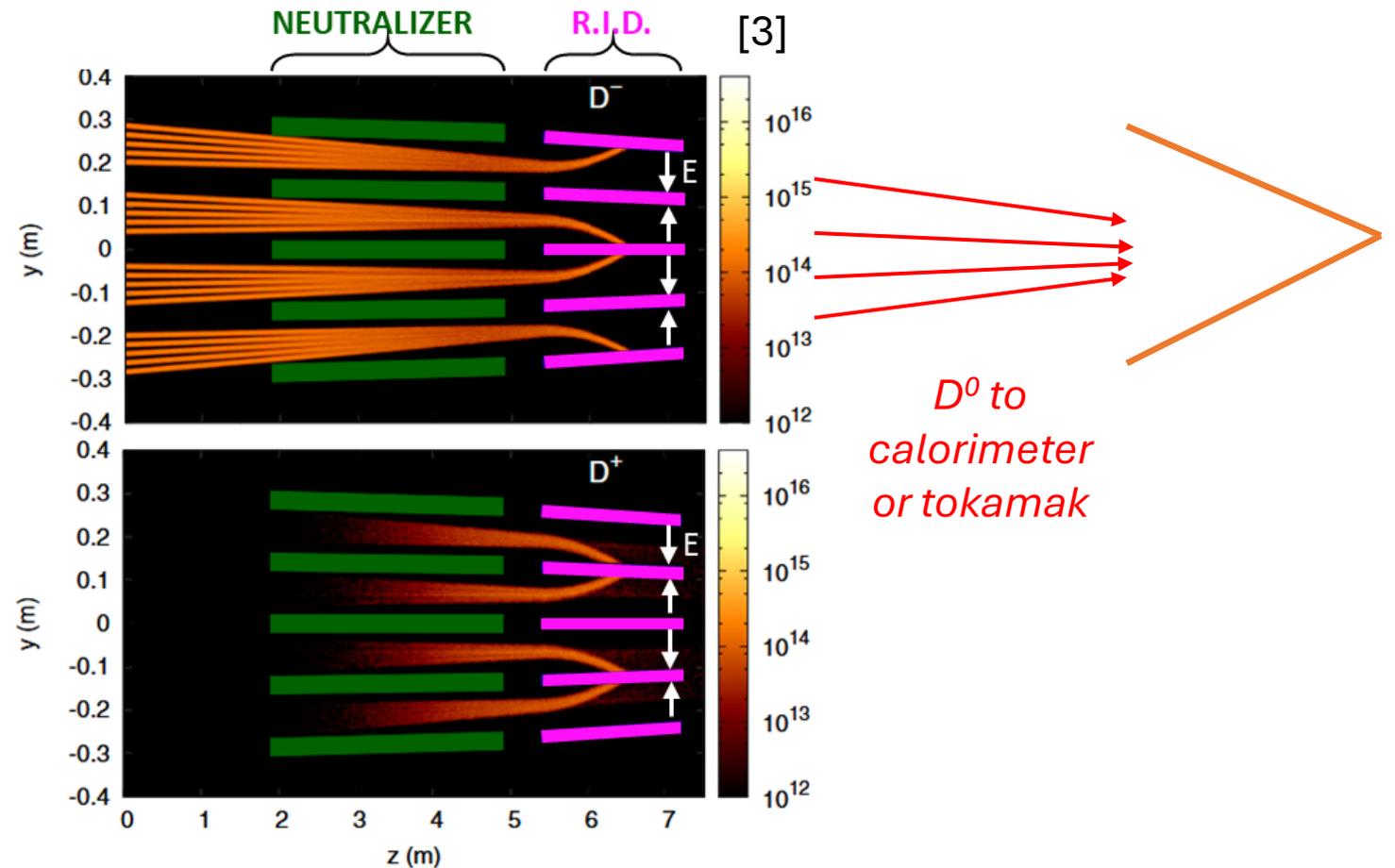


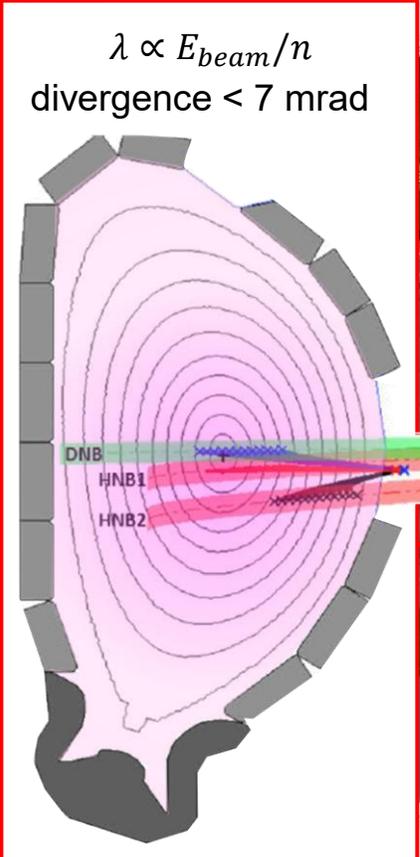
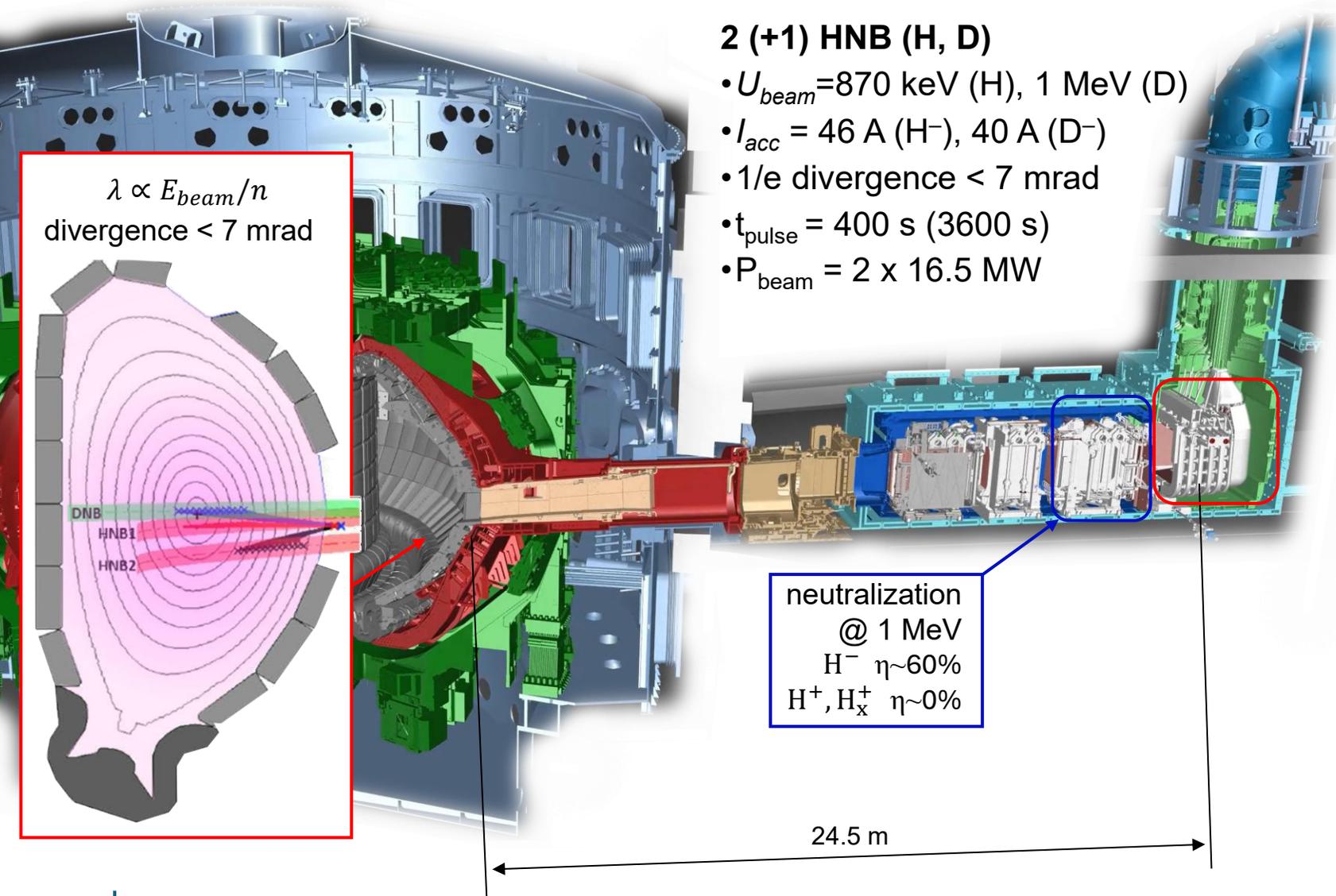
Figure 7. Spatial density distribution of the different component of the beam at $t = 15 \mu s$ at the middle plane ($x = 0$).

[1] A. A. Panasenkov, E. D. Dlougach, *AIP Conf. Proc.* 2052, 040019 (2018)

[2] J. Wei et al., *Nucl. Fusion* 66 (2026) 026020

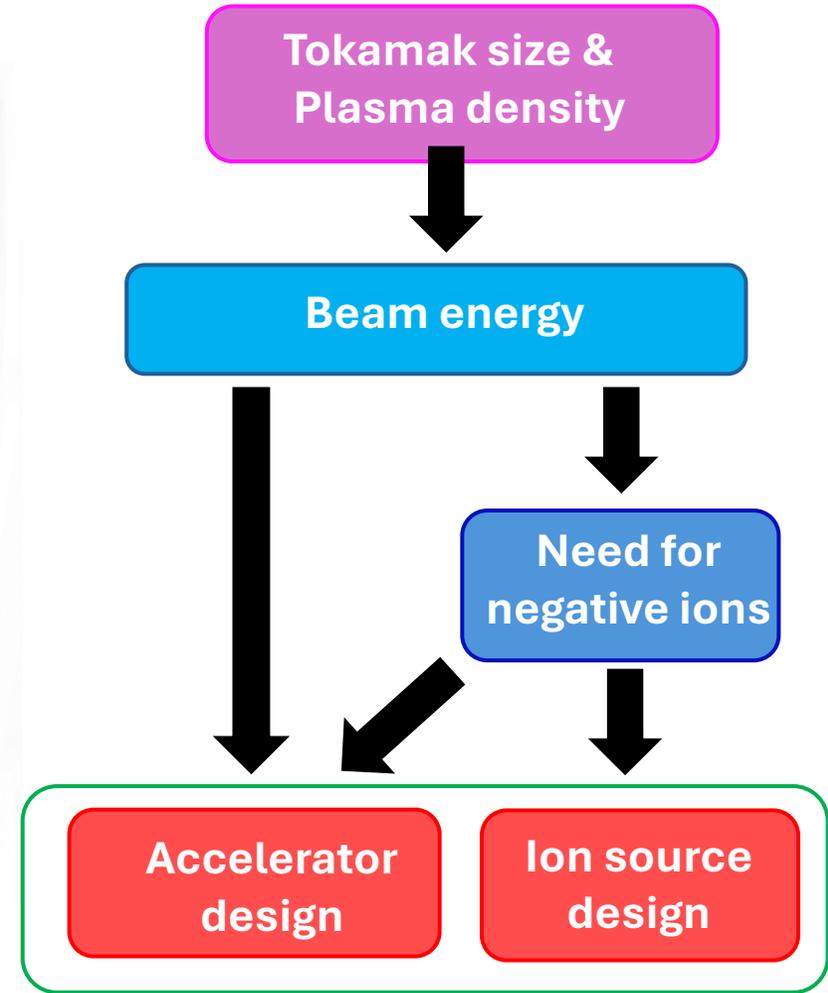
[3] A.F. Lifschitz et al. 2014 *Nucl. Fusion* 54 043020

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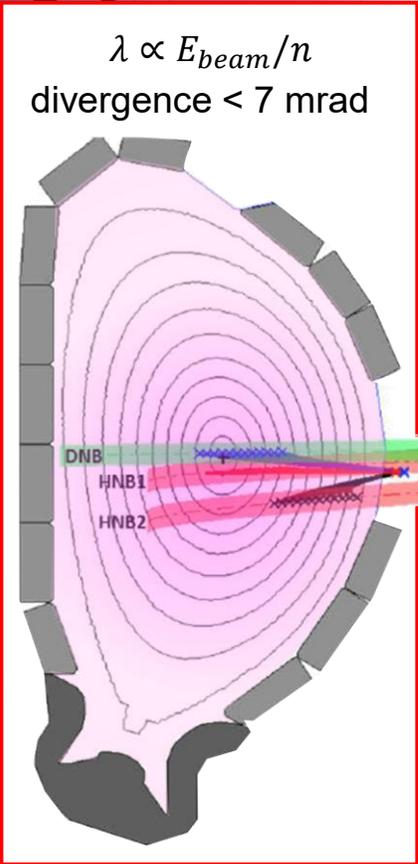
Main topic of this talk

ITER Negative-ion based heating neutral b

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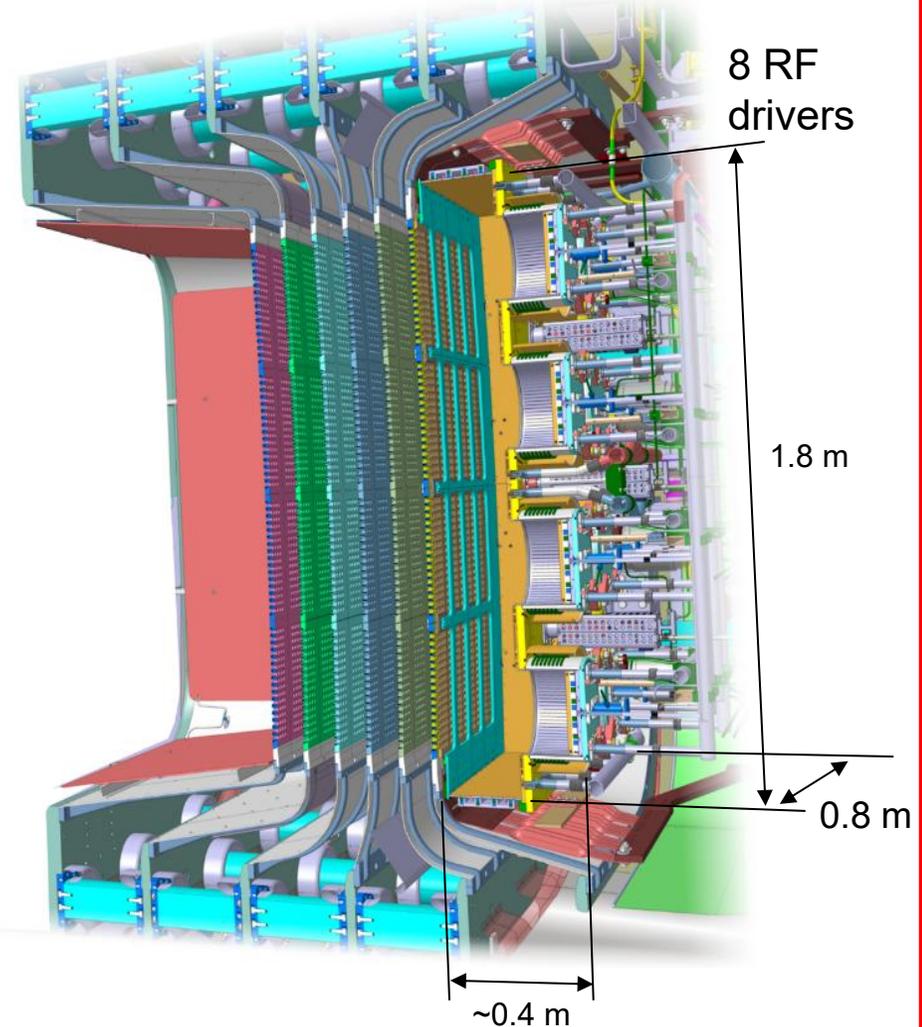


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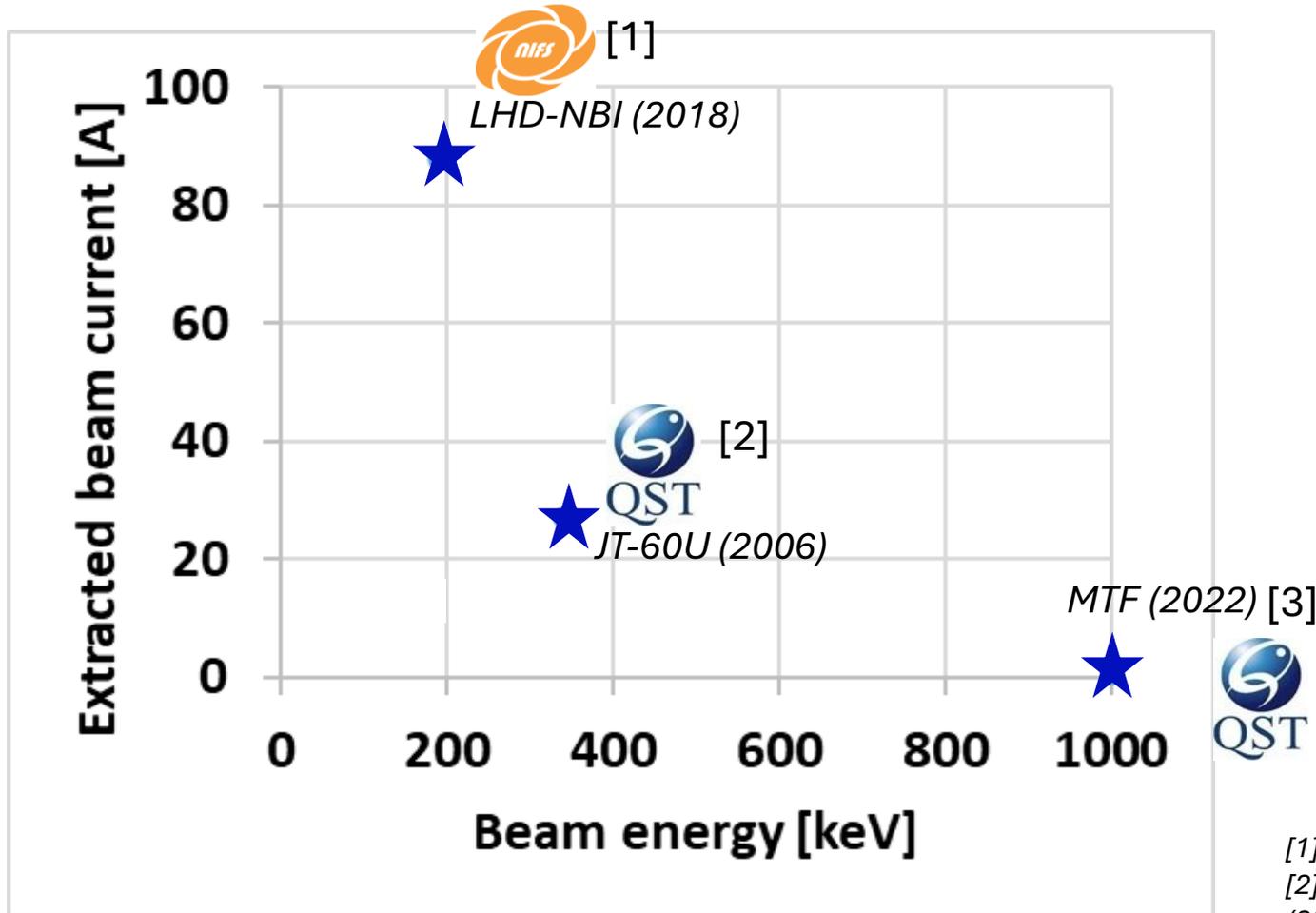
24.5 m

ITER H-/D- source

- 6 acceleration stages
- 1280 beamlets (homogeneous)
- $J_{ext} = 330 \text{ A/m}^2 \text{ (H}^-)$
- Cs-assisted plasma-surface production



Filament
arc
source



○ **QST** and **NIFS** were the first (and so far the only ones) to use NBIs from negative ions in their tokamaks or stellarators

➔ HV development

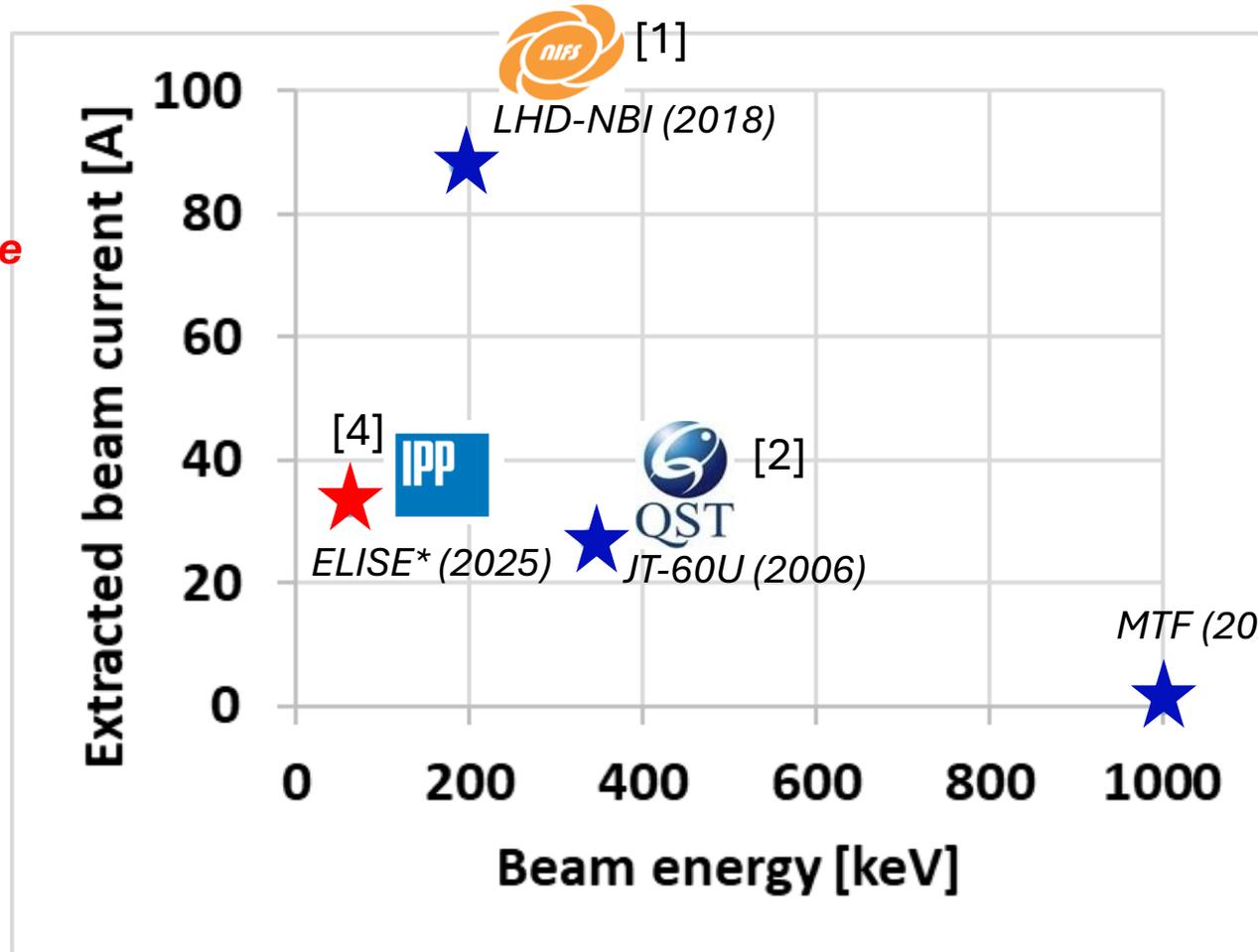
➔ Accelerator development

[1] K. Ikeda et al 2019 Nucl. Fusion 59 076009

[2] M. Hanada et al. J. Plasma Fusion Res. SERIES, Vol. 9 (2010)

[3] M. Kashiwagi et al. Rev. Sci. Instrum. 93, 053301 (2022)

RF source
 Filament
 arc
 source



***Source+Accelerator (no neutralization)**

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➔ **Main limit: replacement of filaments**

○ **IPP** developed **the RF source** selected by ITER for its HNBS and DNB

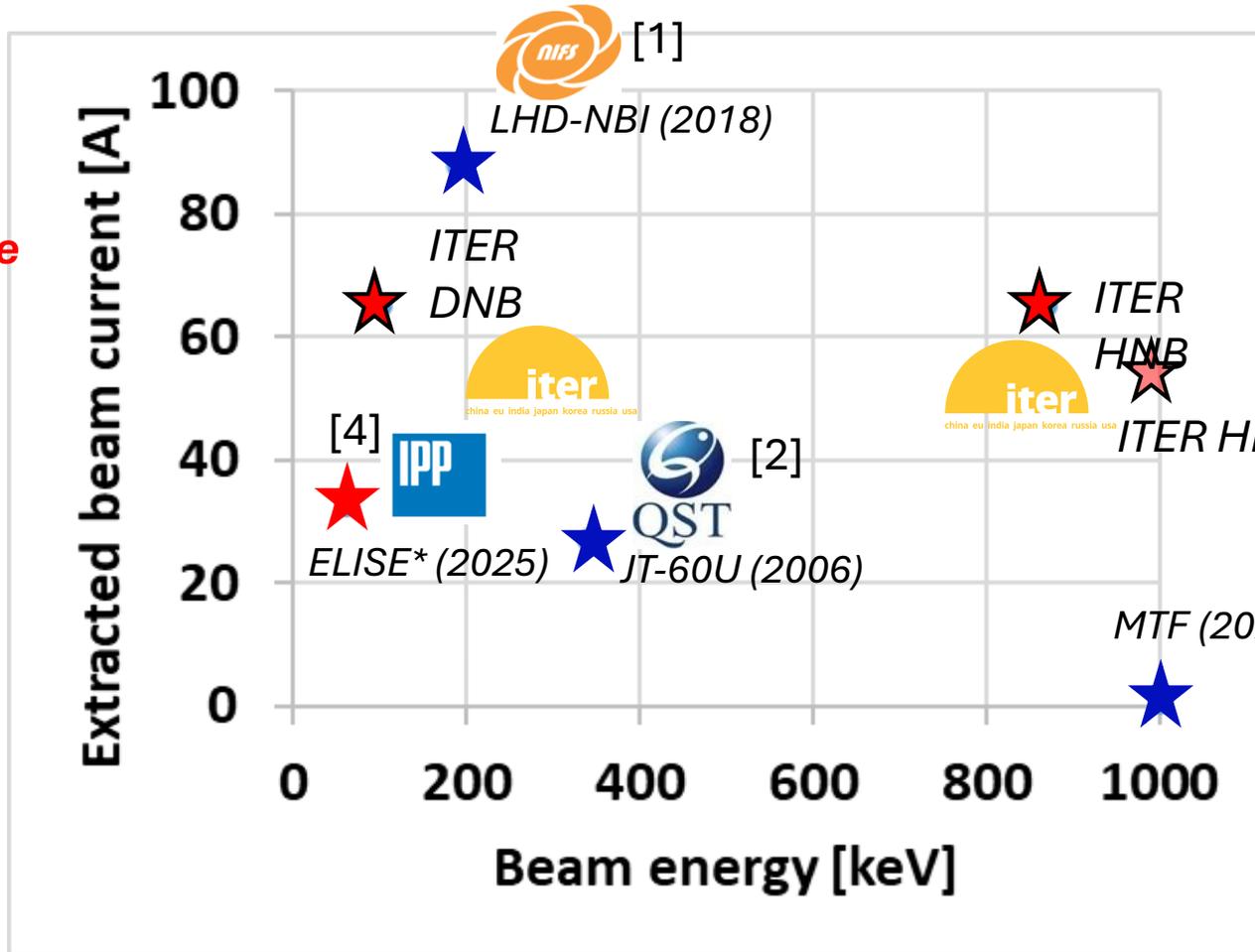
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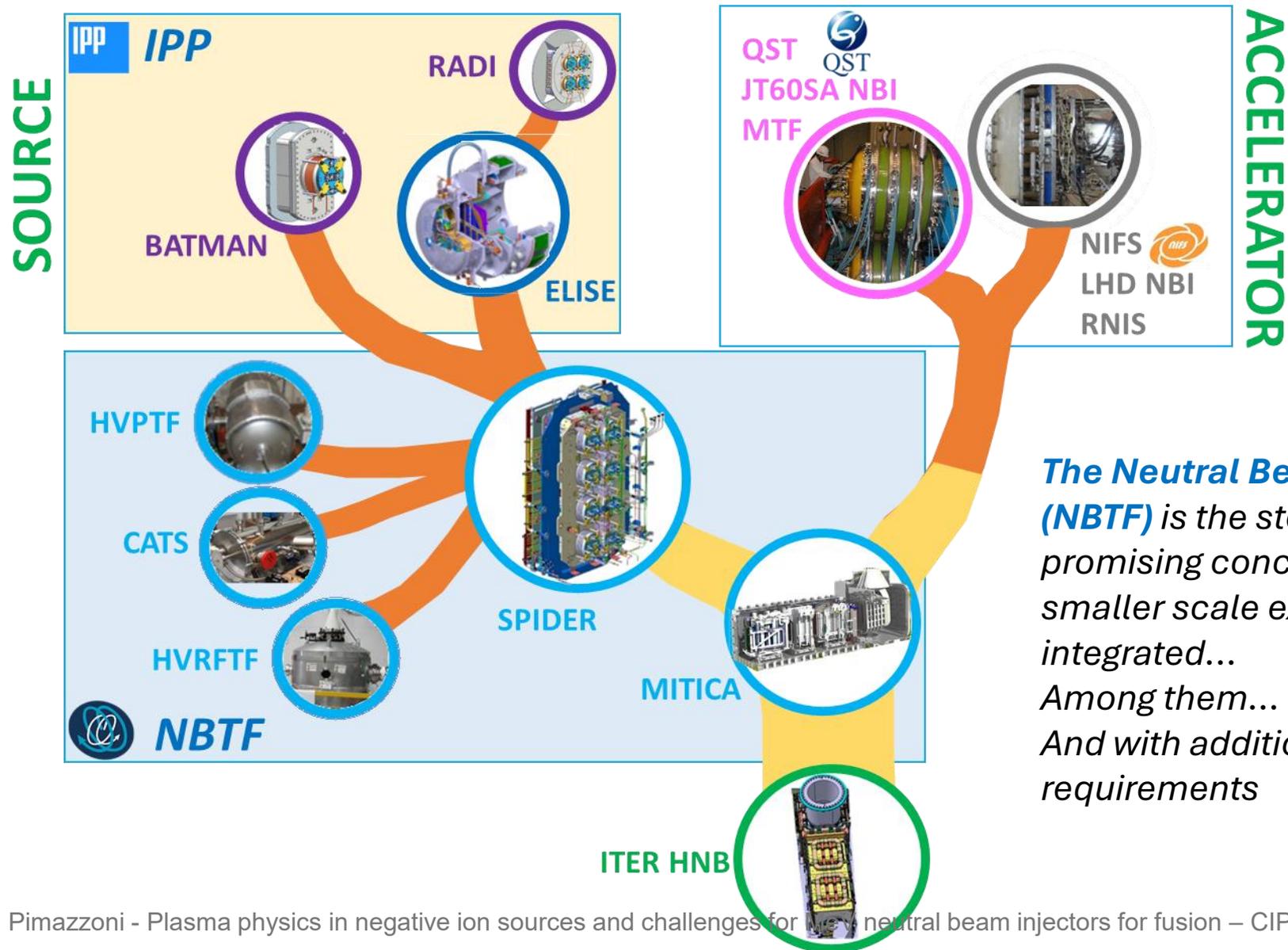
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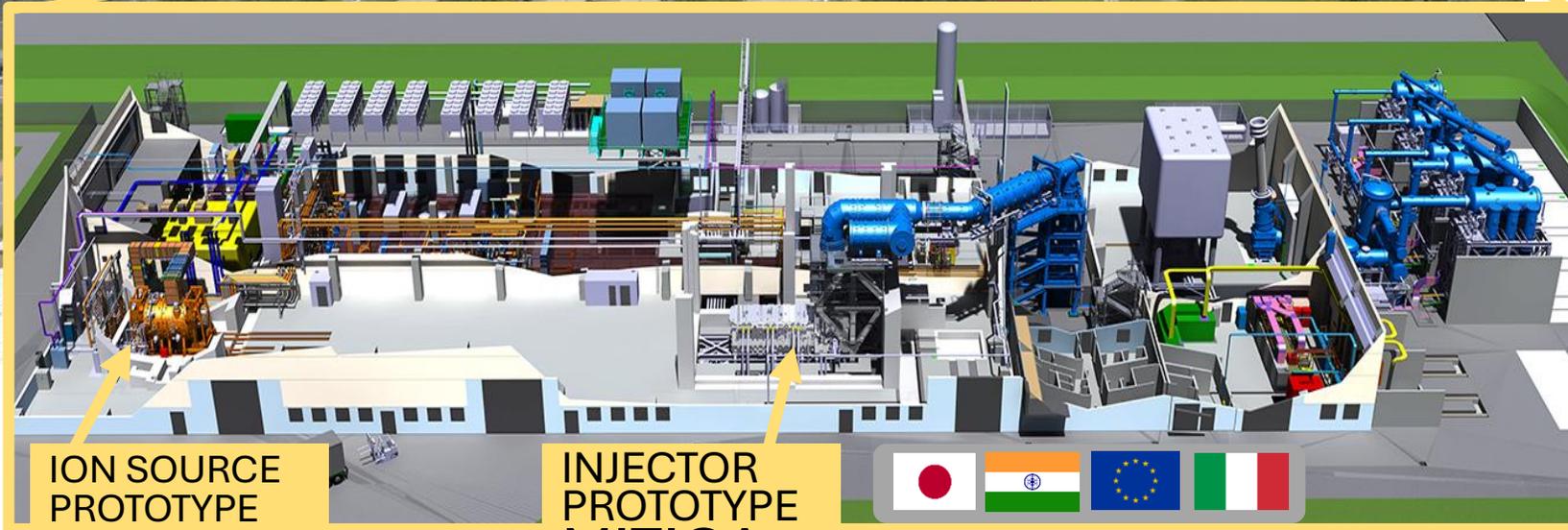
Ion source and accelerator

From the concept to the engineering design...



The Neutral Beam Test Facility (NBTF) is the step where most promising concepts developed on smaller scale experiment will be integrated... Among them... And with additional ITER requirements

ITER Neutral Beam Test Facility



ION SOURCE
PROTOTYPE
SPIDER

INJECTOR
PROTOTYPE
MITICA



P. Sonato et al. Fus. Eng. Des., 84 (2009), pp. 269-274
V. Toigo et al. New J. Phys. 19 (2017) 085004

Coordinated efforts towards ITER neutral beams with physics and technological developments
→ Community of giant NI sources for fusion
→ Neutral Beam Test Facility

- Neutral Beam Test Facility:
- High voltage components
 - Vacuum-insulated source
 - Different discharge type: RF-driven to limit maintenance
 - Steady state operation

Buildings completed 2015
SPIDER started plasma op. 2018
MITICA tests started in 2018

Outline

- Where is the NBTF now: most recent results on SPIDER and MITICA
- Physics of negative ion beam
 - ICP plasma in the driver
 - Electronegative plasma
 - Beam acceleration
 - Beam plasma
- Summary and outlook

Outline

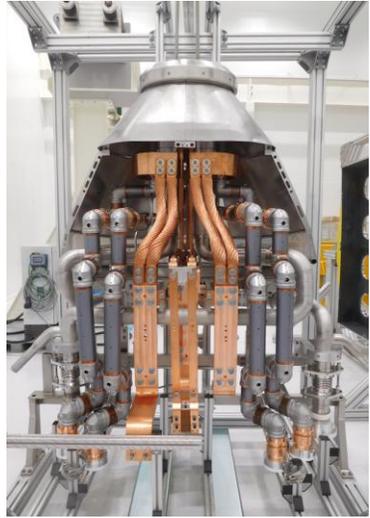
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Timeline MITICA

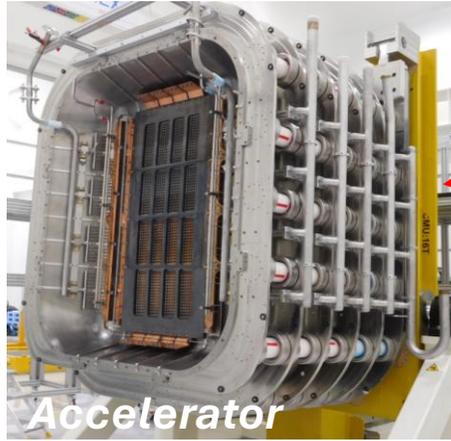
MITICA Operation – 1 (MO-1)



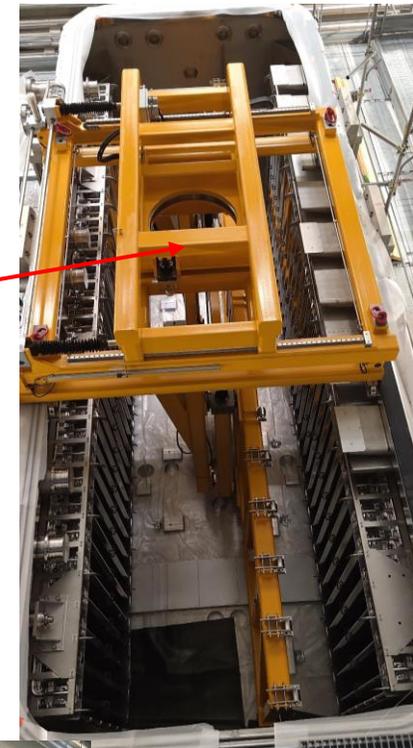
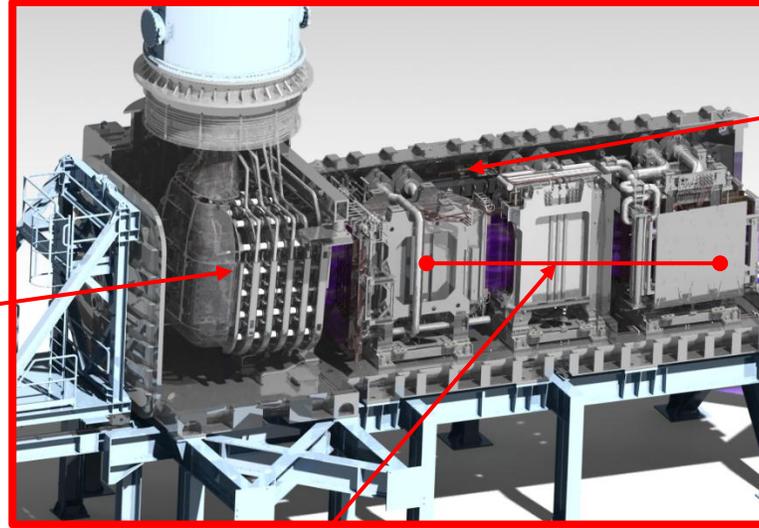
Status of MITICA components



Beam Source (Alsymex)
Delivery early 2026



Accelerator



Cryopumps
Installation tests;
verification of pumping speed

Beam Line Components
(AVS Tecnalia)



Neutralizer
Delivered on site



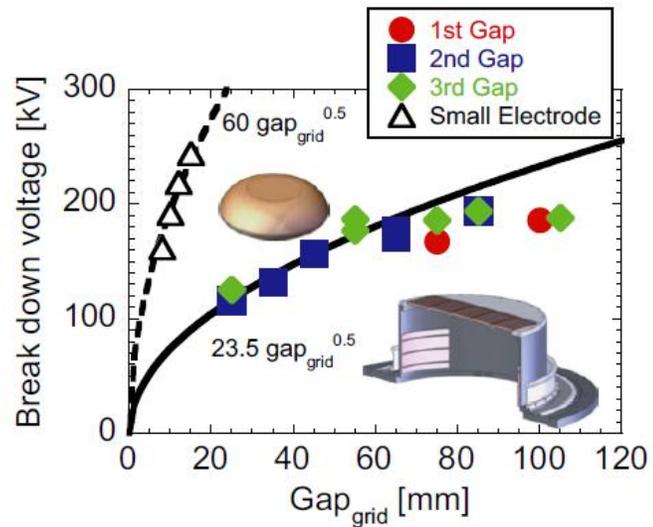
Residual ion dump
Delivered on site



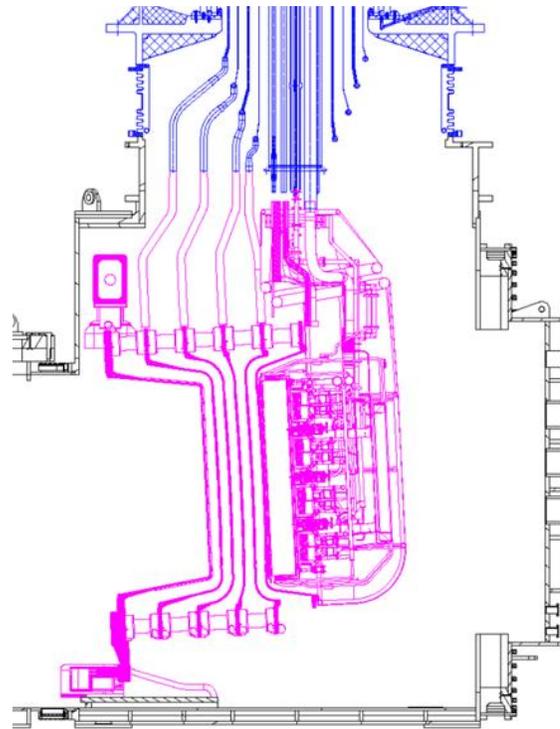
Calorimeter
Delivery early 2026

MITICA: High Voltage holding tests on source mockup

- Moving from small flat electrodes to large grid shaped electrodes the voltage holding drops



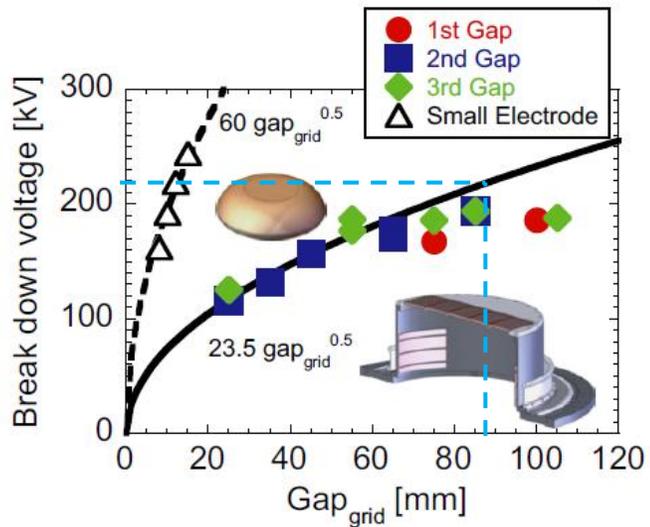
A. Kojima et al. 2011 Nucl. Fusion **51** 083049



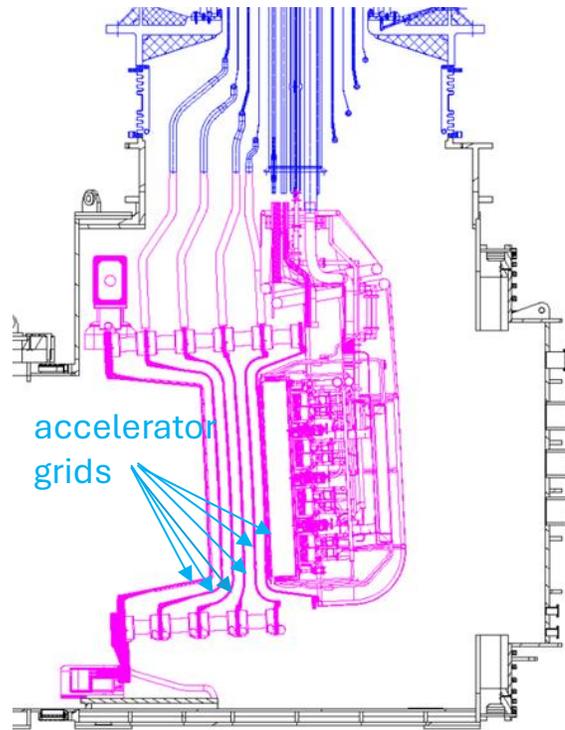
Cross section of the HNB's Beam Source inside the vacuum vessel

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- Moving from small flat electrodes to large grid shaped electrodes the voltage holding drops
- Accelerator: 200 kV gaps over 88 mm



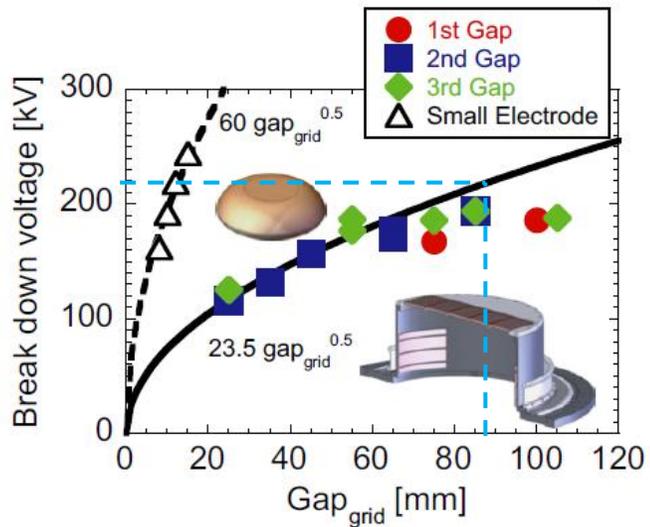
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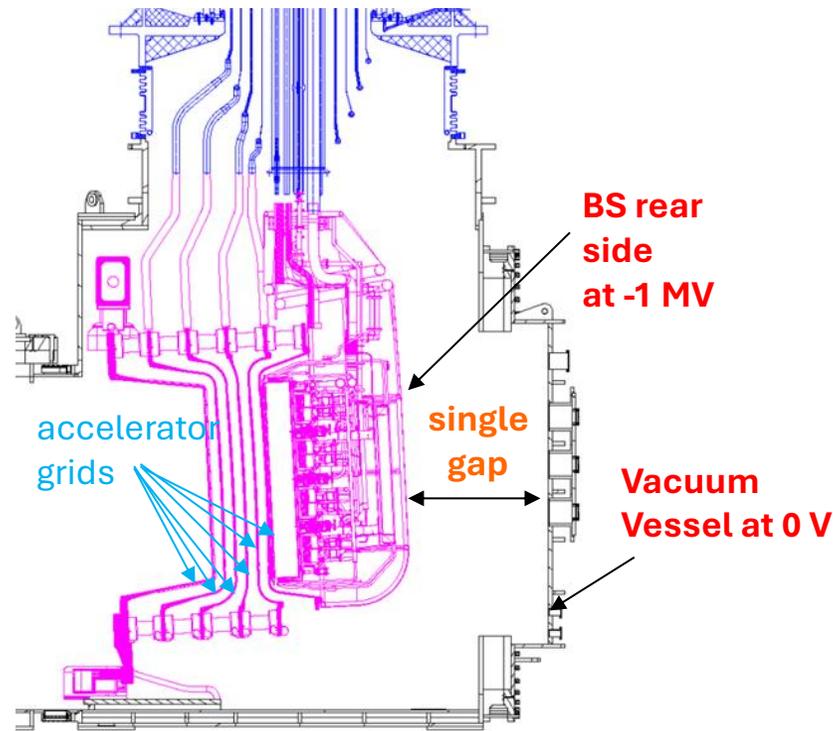
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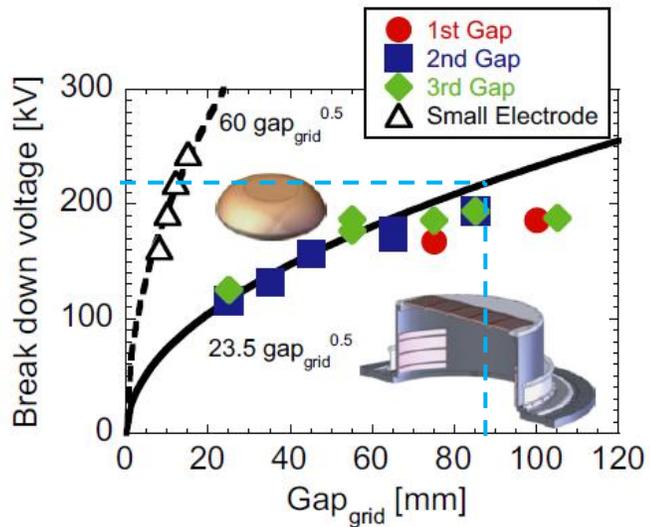
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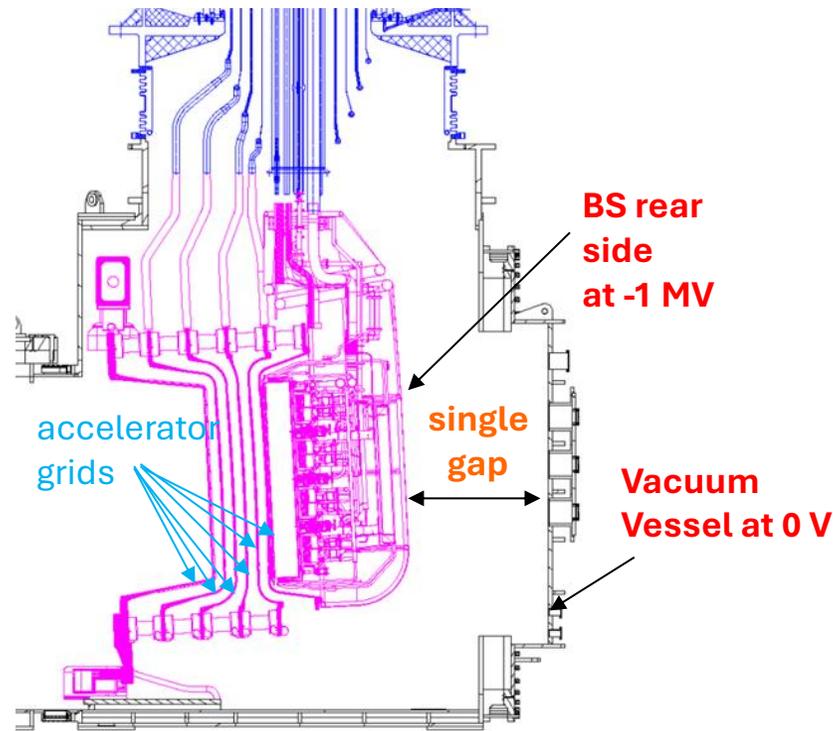
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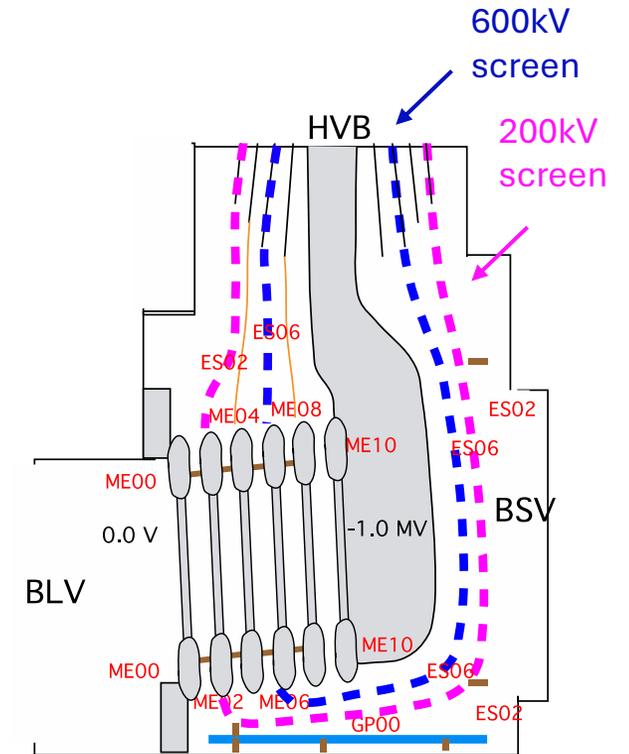
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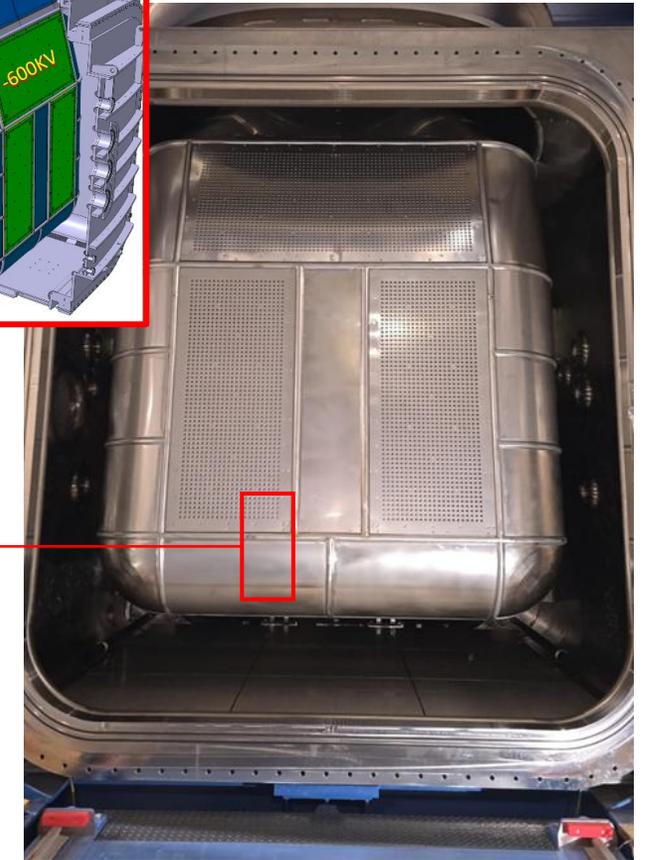
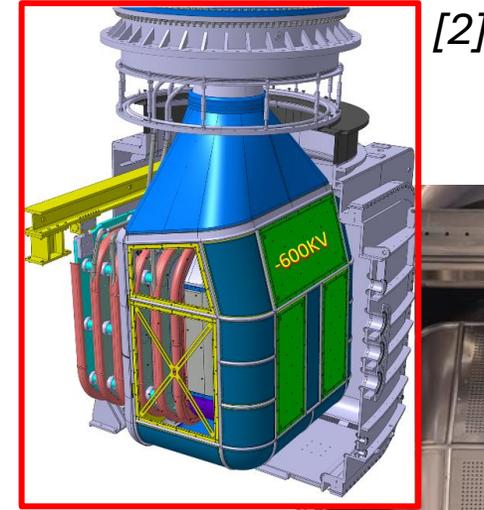
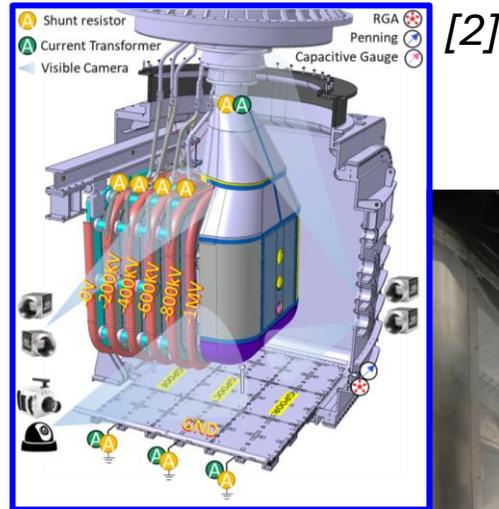
Cross section of the HNB's Beam Source inside the vacuum vessel



Do we need some electrostatic shields?

MITICA: High Voltage holding tests on source mockup

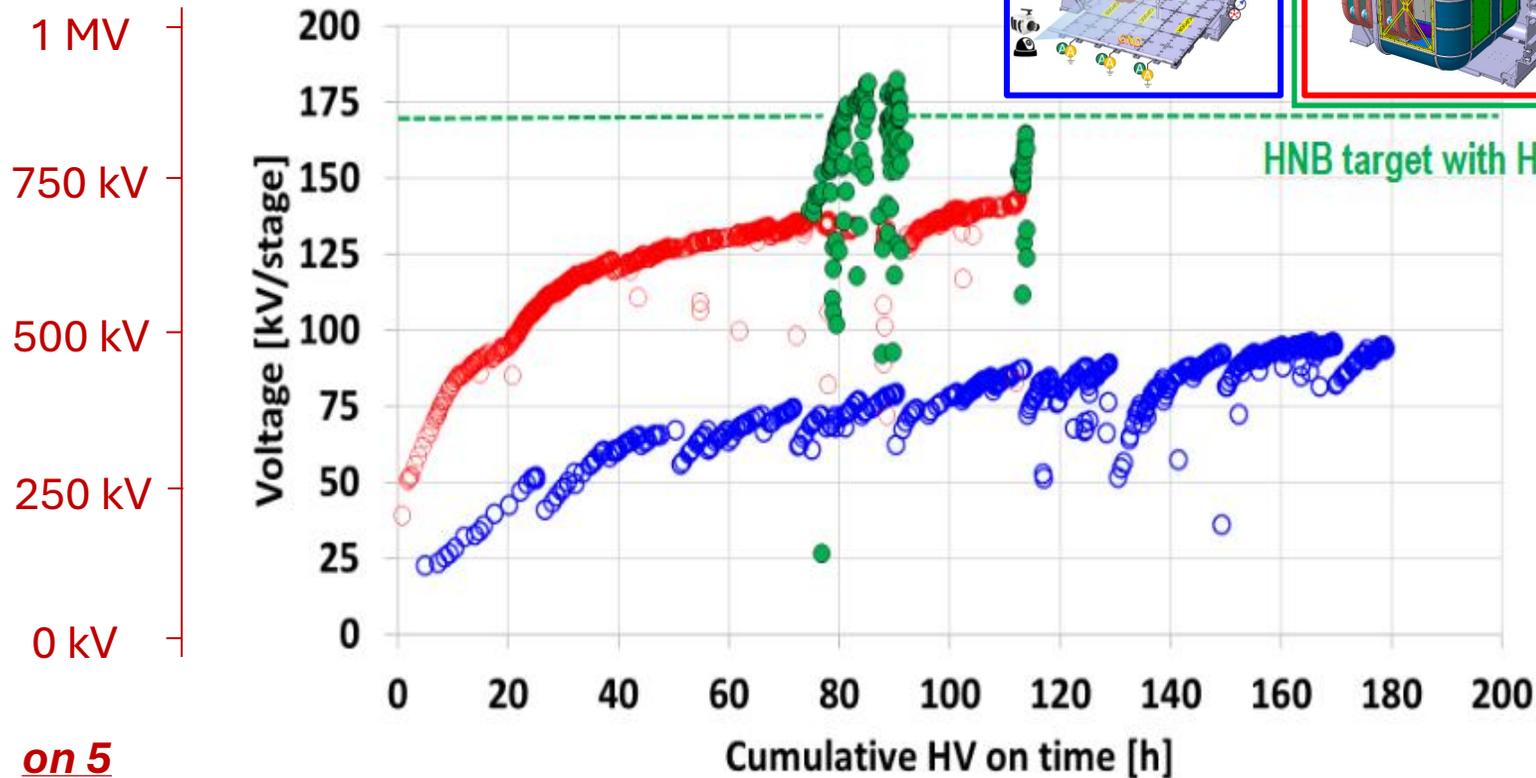
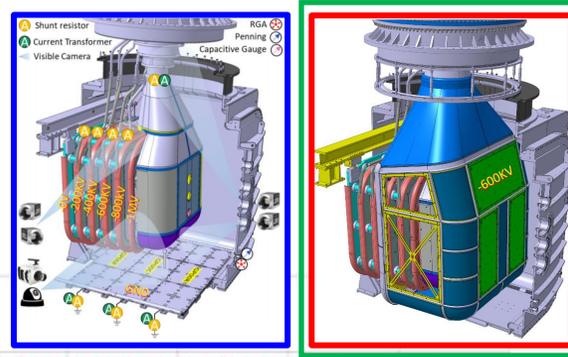
- A mock-up of the ion source was realized to assess maximum HV holding w/o screen
- A “breathable” electrostatic screen was added to quantify HV holding improvement



[1] G. Chitarin et al. 2024 JINST 19 C10001

[2] T. Patton et al. Fus. Eng. Des. 220 (2025) 115349

MITICA: High Voltage holding tests on source mockup



on 5 stages

○ w/o screen, vacuum ○ w/ screen, vacuum ● w/screen, $p > 1$ mPa

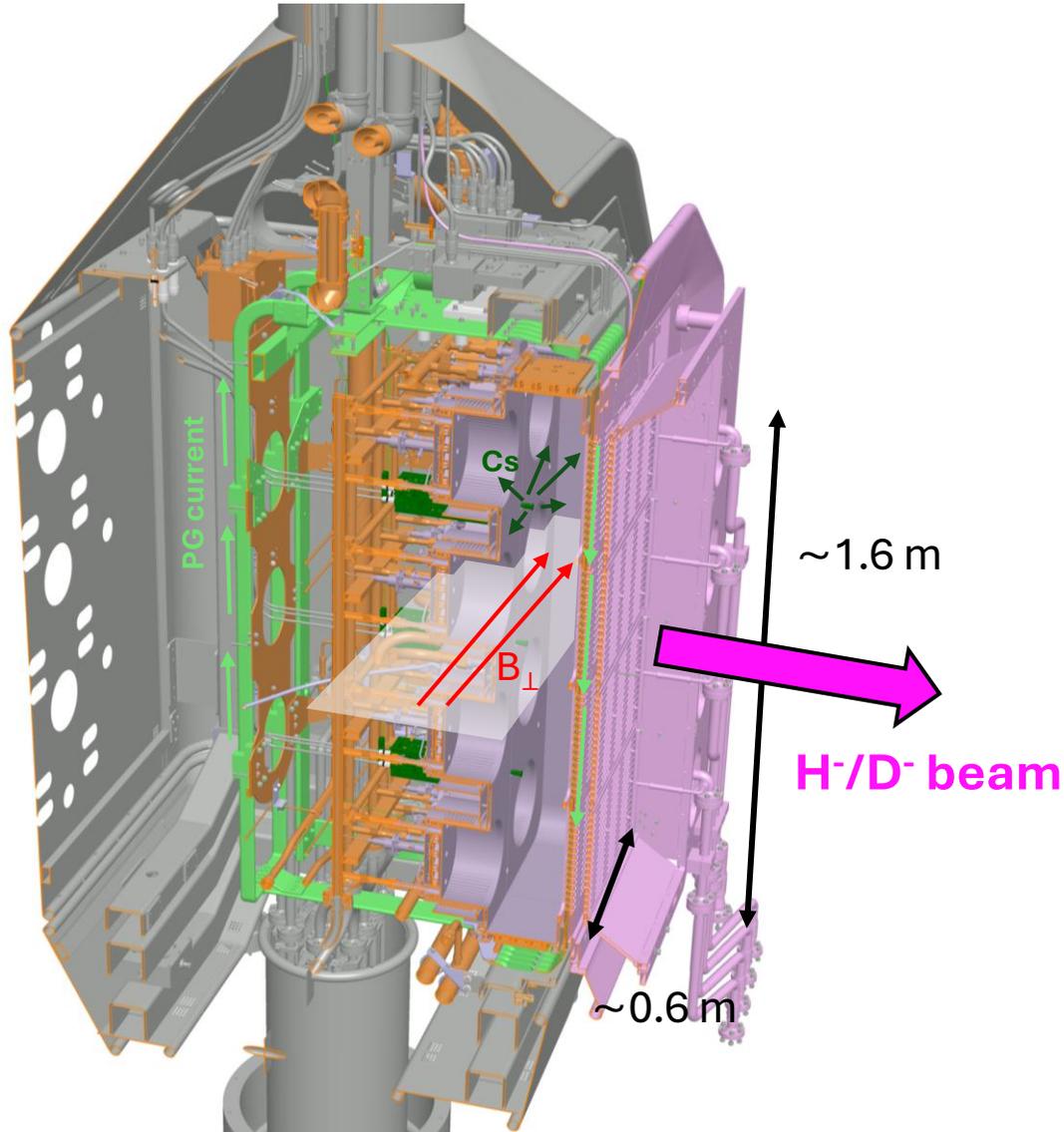
Record values (on 5 stages):
no screen: <500 kV
1 screen: 716 kV (scaled)
1 screen: 910 kV (scaled)
 $p_{\text{vessel}} \sim 30$ mPa

- Such results provide a solid ground for operation @ large beam energies
- Another campaign is planned for 2026

D. Marcuzzi et al. Achievement at the ITER Neutral Beam Test Facility and Prospects for the R&D activities within the ITER research plan, IAEA-FEC 2025, 13-18th October 2025, Chengdu (China)

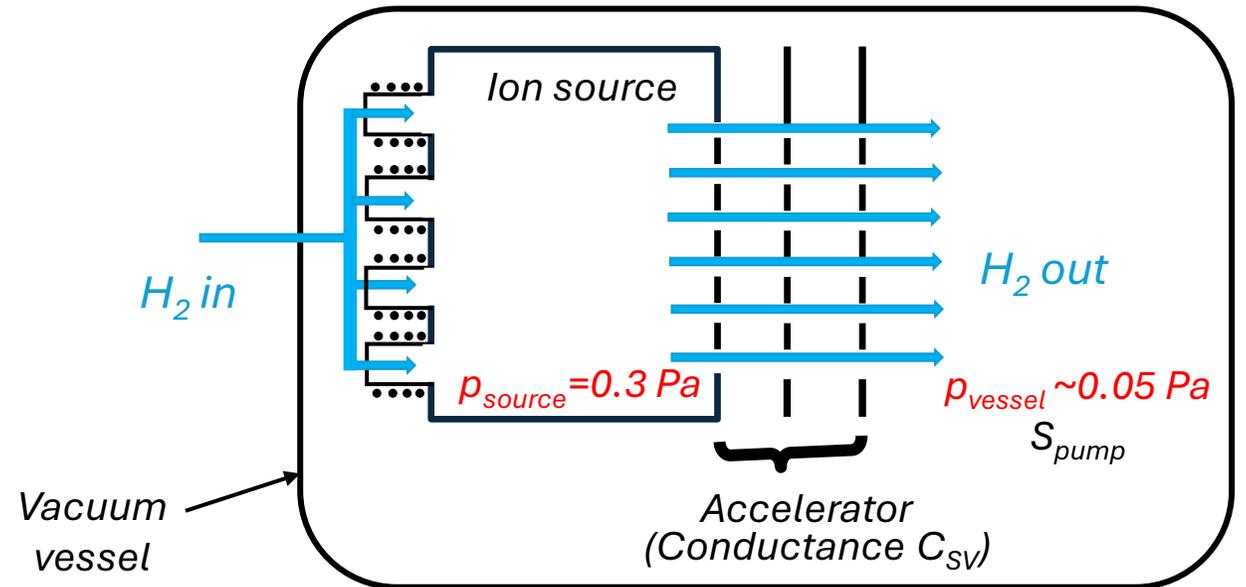


SPIDER: main features and targets

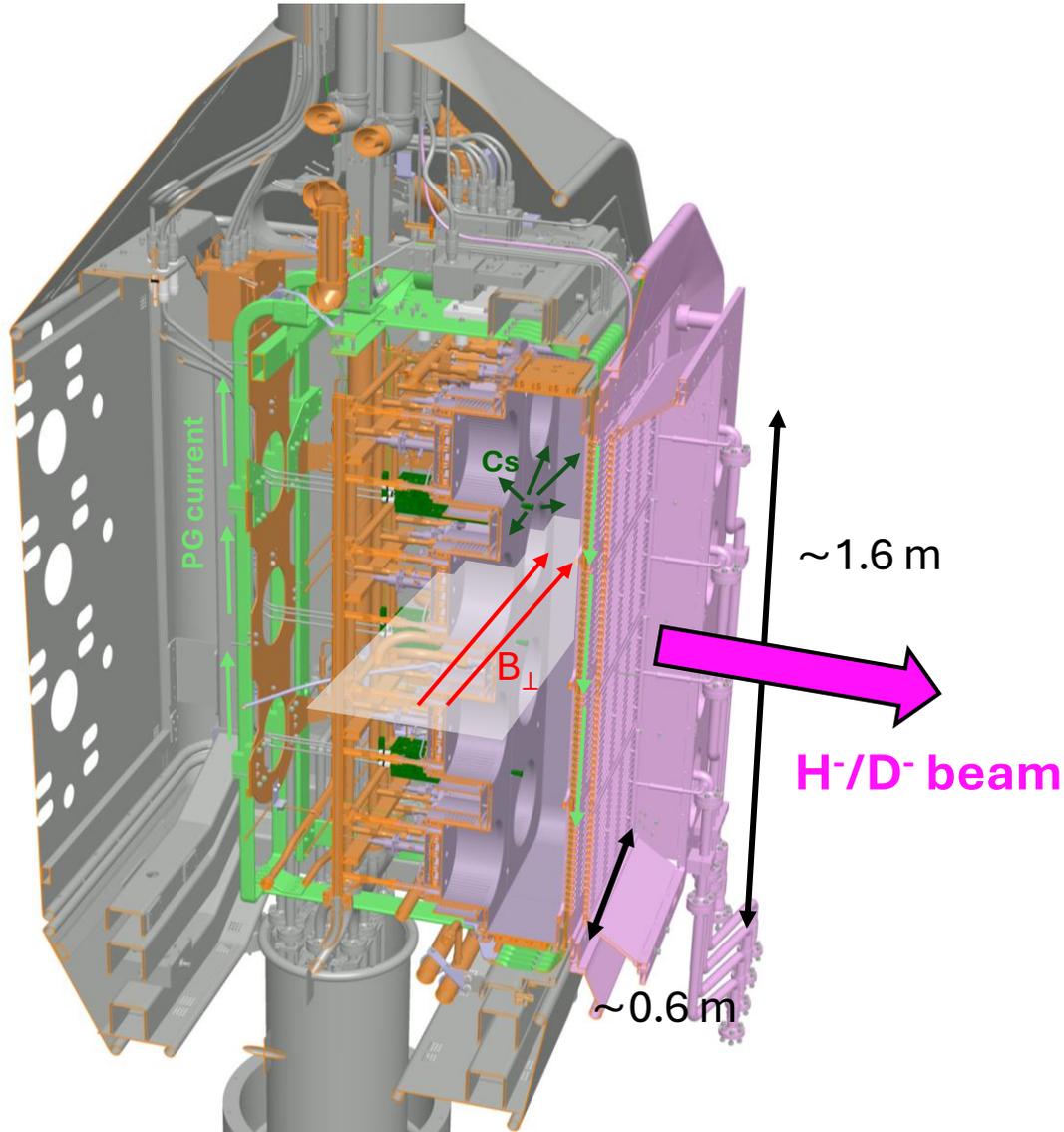


Layout

- Ion source is identical to MITICA
- A triode accelerator (100 kV) is attached to the ion source
- Ion source is fully enclosed in vacuum

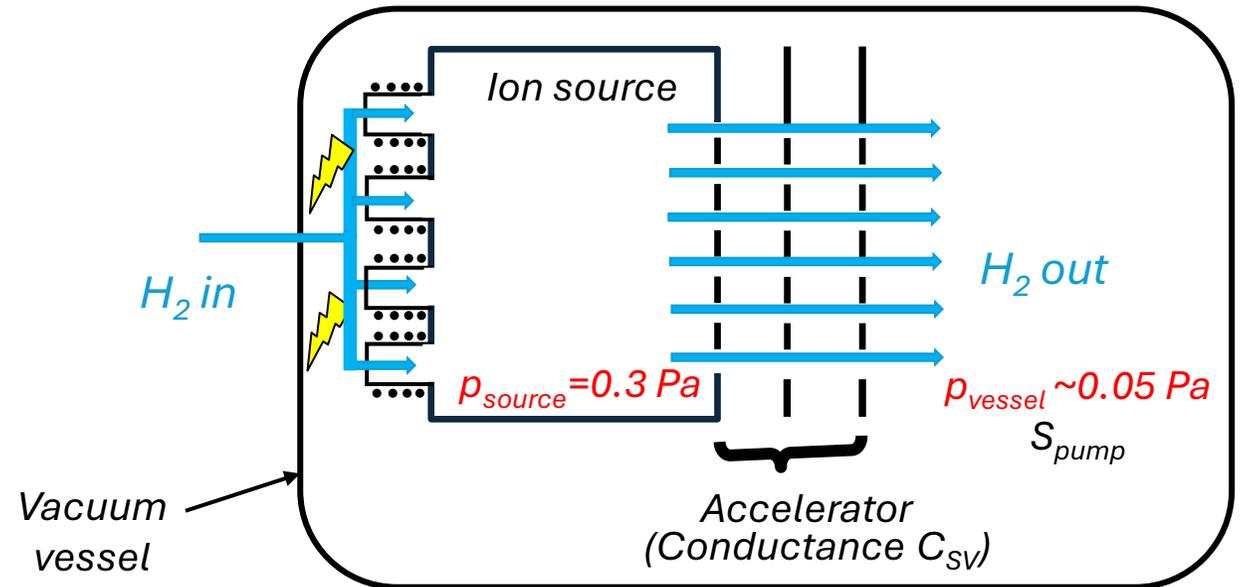


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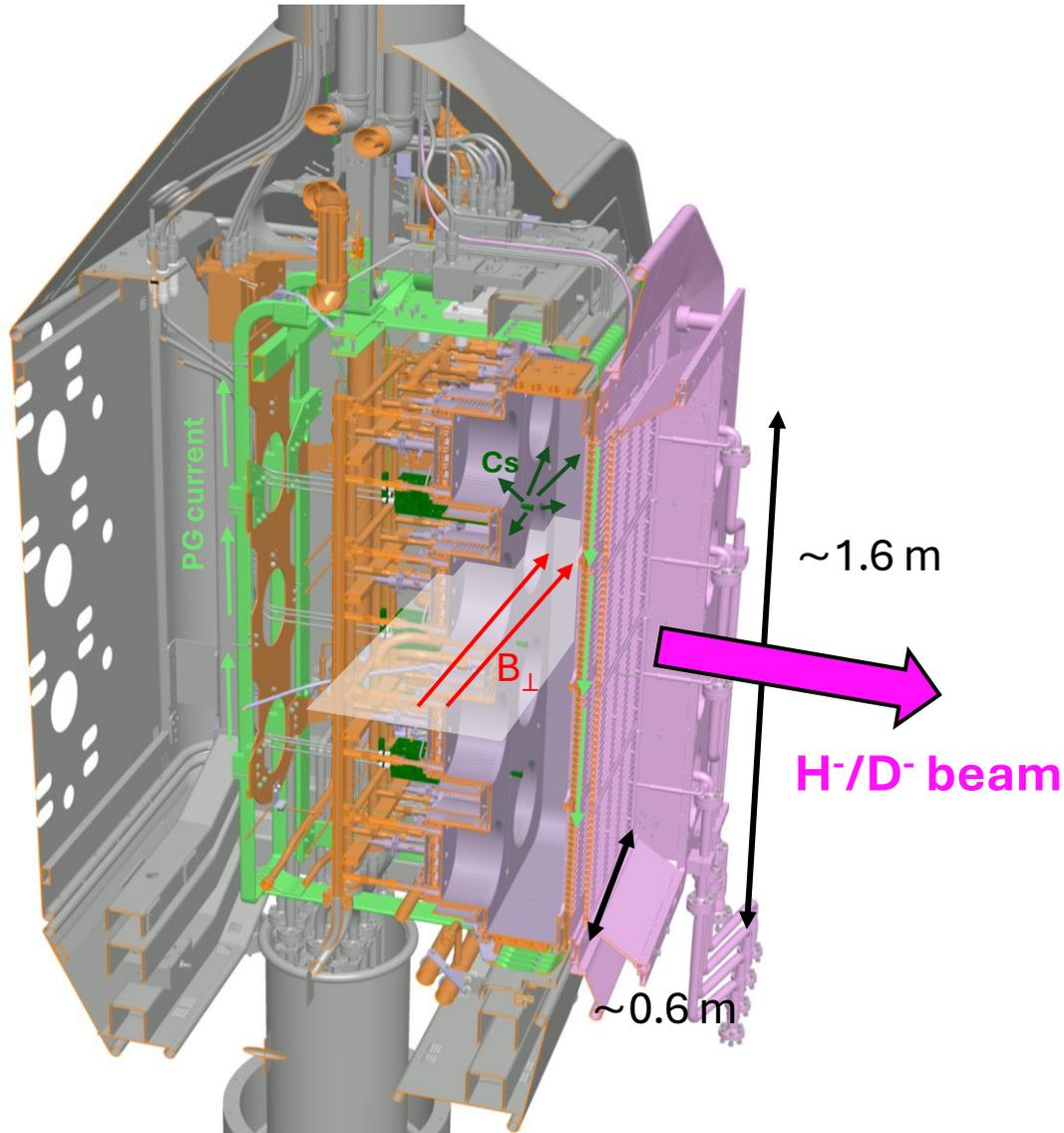


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Target parameters

- Filling pressure: 0.3 Pa
- j_{ext} : 330 A/m^2 (H^-)/ 285 A/m^2 (D^-), with $e^-/H^- < 0.5$
- Beam inhomogeneity $< \pm 10 \%$
- Beamlet divergence $\leq 7 \text{ mrad}$
- Beam duration: 1000 s (H^-)/ 3600 s (D^-)

Timeline SPIDER

Spider Operation – 1
(SO-1)

Spider Operation – 2
(SO-2)

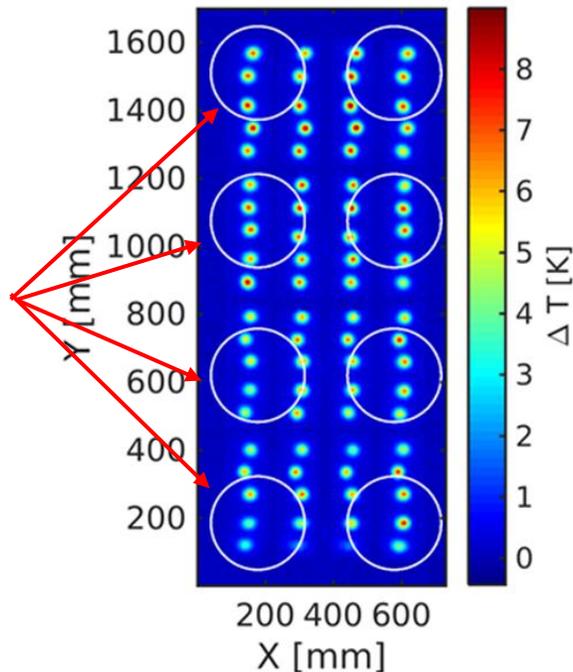
Spider Operation – 3
(SO-3)



Spider Upgrade - 1

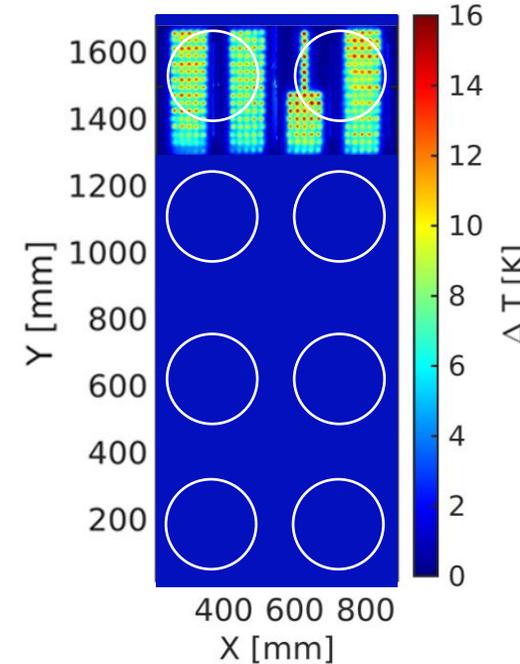
Spider Upgrade - 2

RF drivers

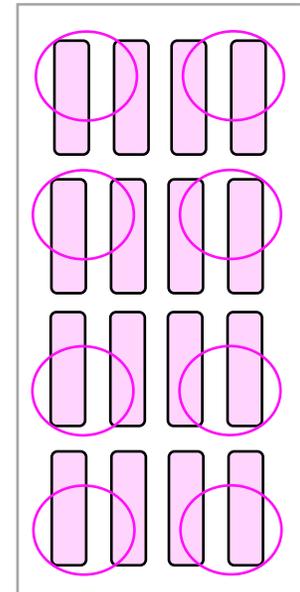


- [1] E. Sartori et al. 2022 Nucl. Fusion 62 086022
- [2] G. Serianni et al. Rev. Sci. Instrum. 93, 081101 (2022)
- [3] A. Pimazzoni et al. Rev. Sci. Instrum. 91, 033301 (2020)

Full source, isolated beamlets



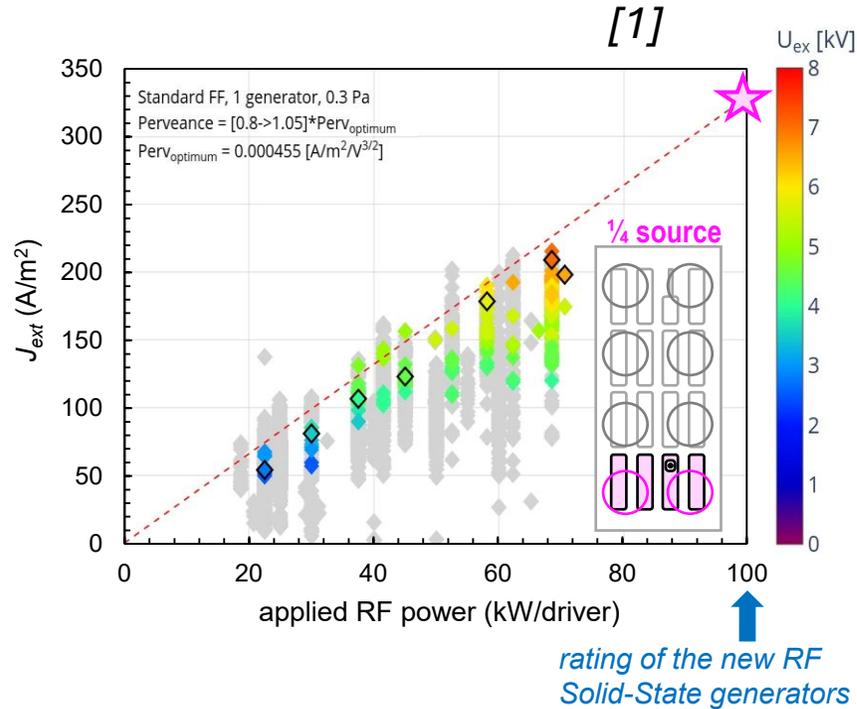
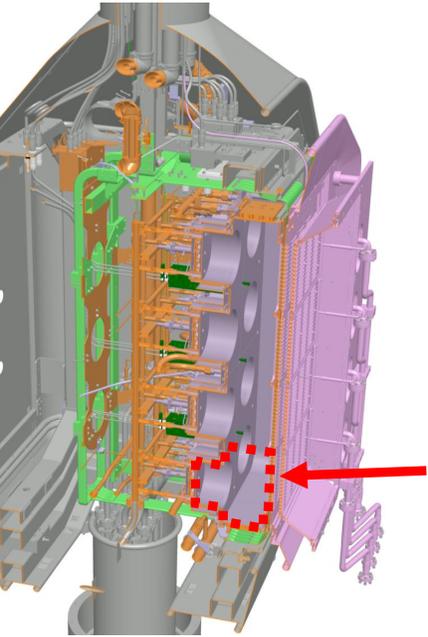
Whole single segment



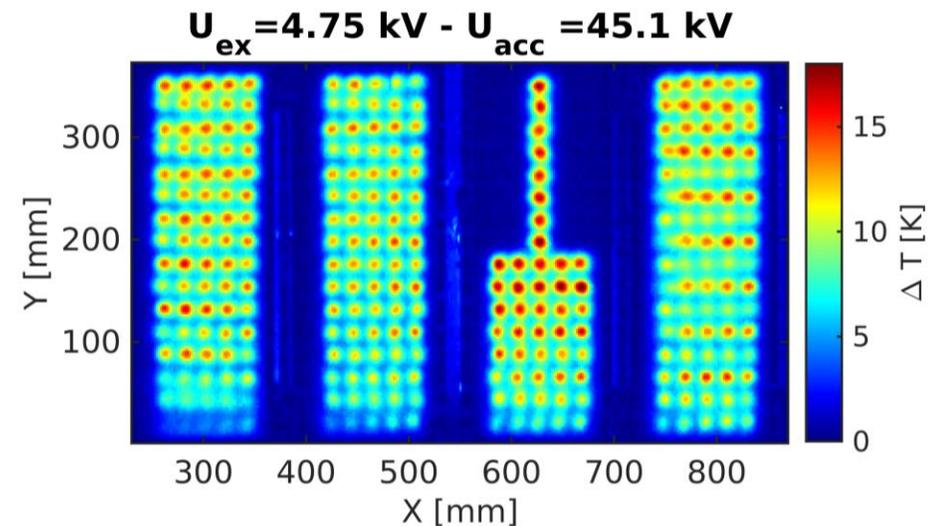
Whole source

- SPIDER ion source is fully enclosed in vacuum
- The SPIDER original pumping system proved insufficient to ensure avoidance of RF breakdowns

Recent results @ SPIDER (SO-2 campaign)



- $\frac{1}{4}$ of the ion source (present limitations of pumping system)
- Linear dependence on the applied RF power: target within specifications
- More severe condition: only two drivers, and edge segments
- Full-size ion source ($\frac{4}{4}$) and full RF power will be available in second half of 2026



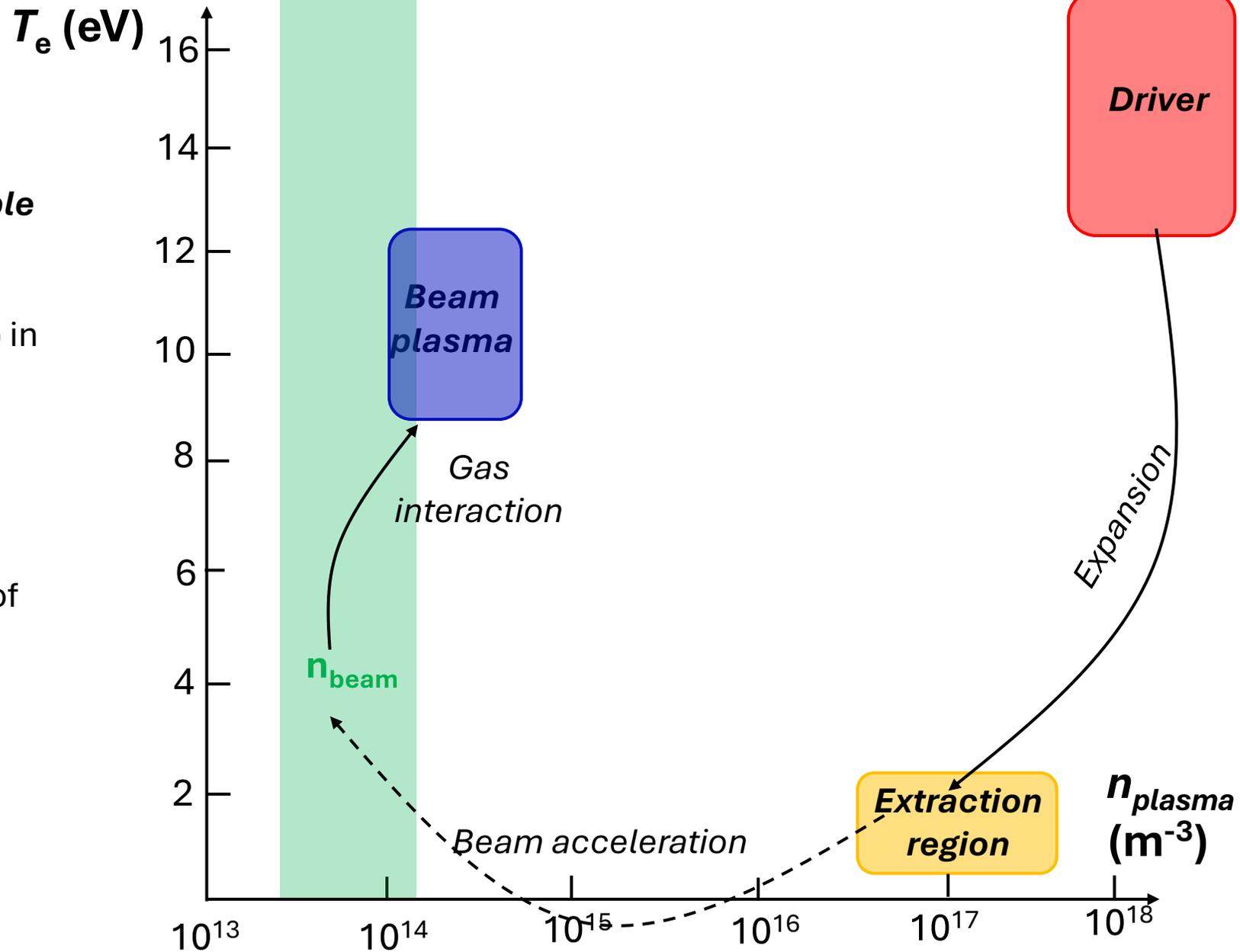
[1] E. Sartori et al. Plasma Properties in the Negative ion beam sources for fusion and recent results in view of ITER, Plasma 2025, 15-19 September 2025, Warsaw (Poland)

[2] D. Marcuzzi et al. Achievement at the ITER Neutral Beam Test Facility and Prospects for the R&D activities within the ITER research plan, IAEA-FEC 2025, 13-18th October 2025, Chengdu (China)

Plasmas for NBIs

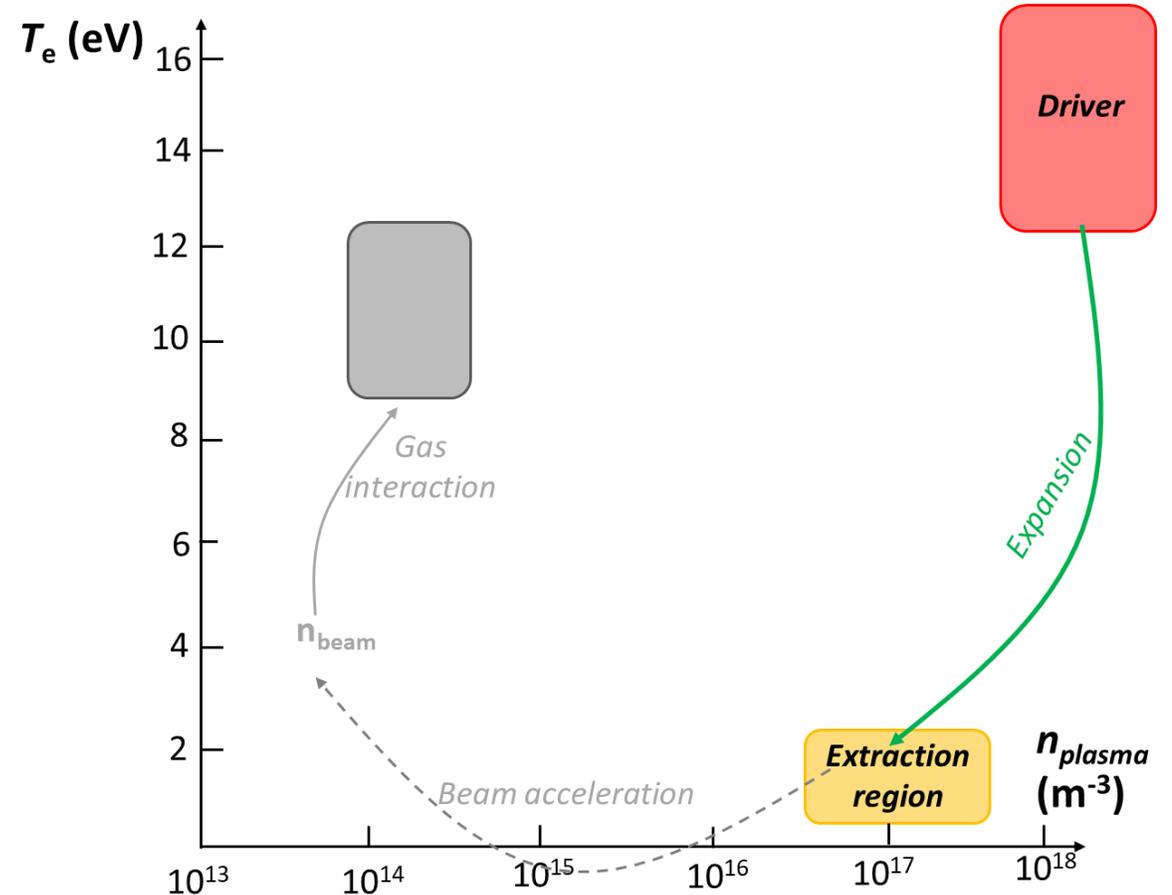
The development of neutral beam injectors for fusion relies on **an ensemble of cold plasmas**:

- An inductive coupled discharge (ICP) in the RF drivers
- An electronegative plasma in the extraction region
- A beam driven plasma downstream of the accelerator

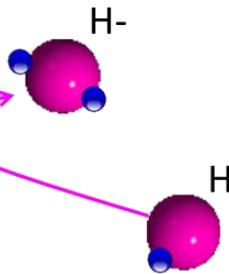
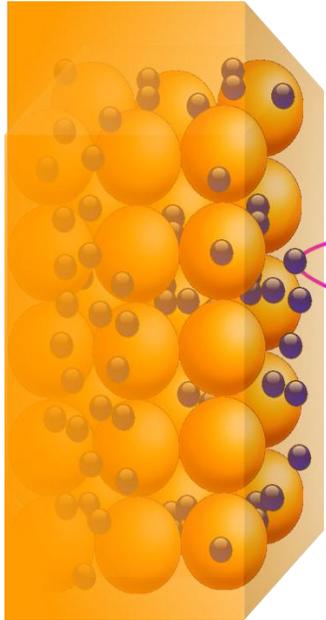


Outline

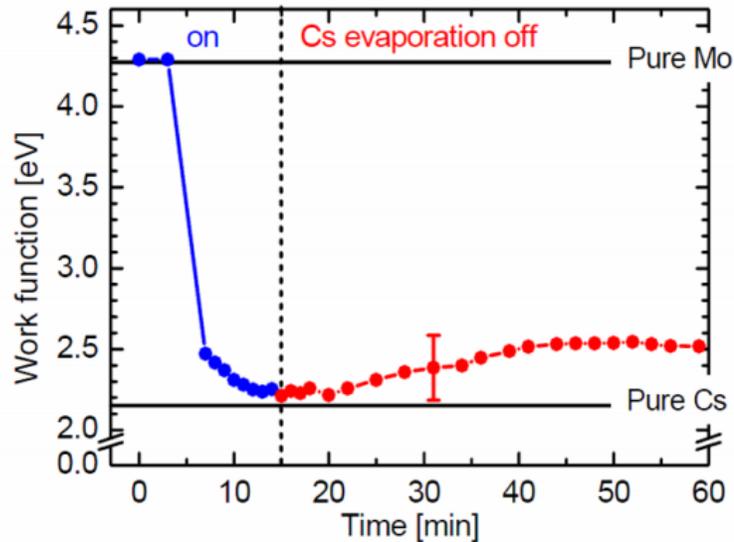
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 - Beam plasma
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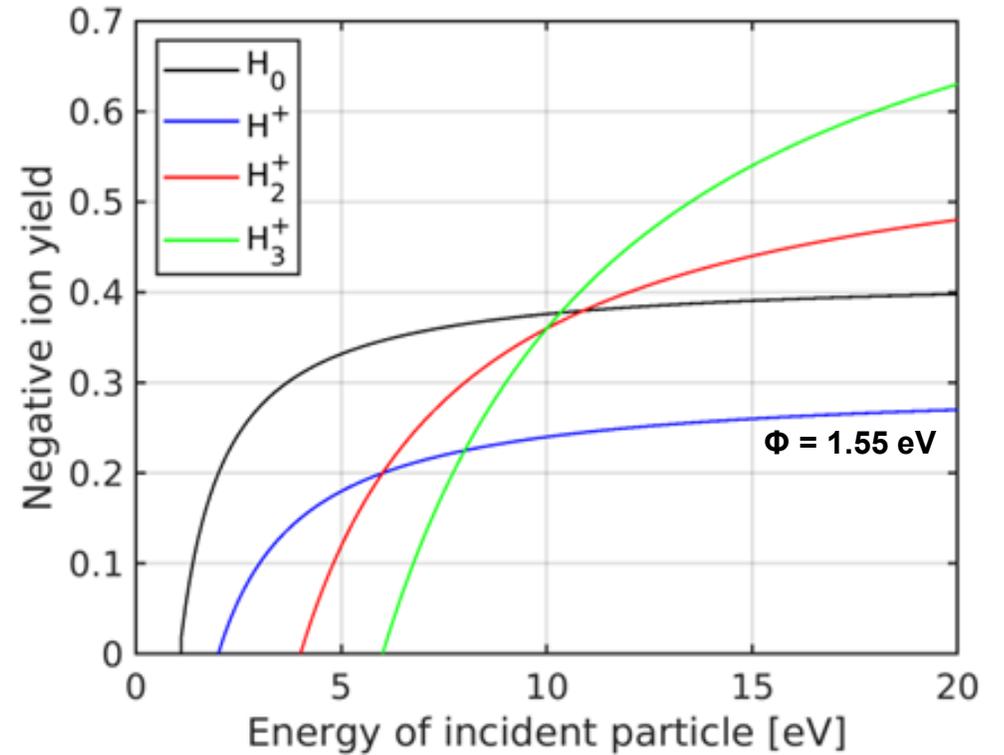
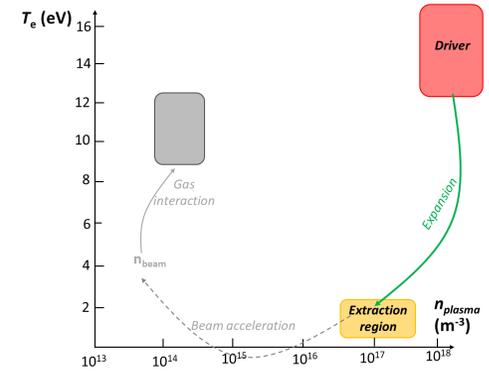
Increasing negative ion density



$$p \propto \exp\left(\frac{E_a - \phi}{v_{\perp}}\right)$$

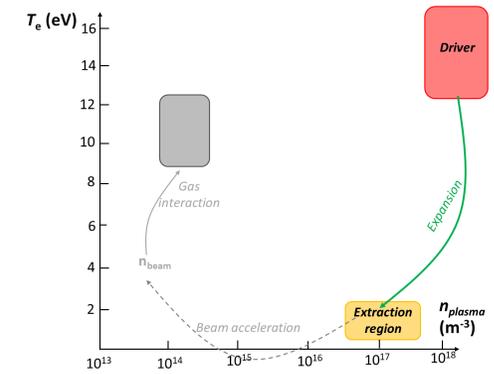
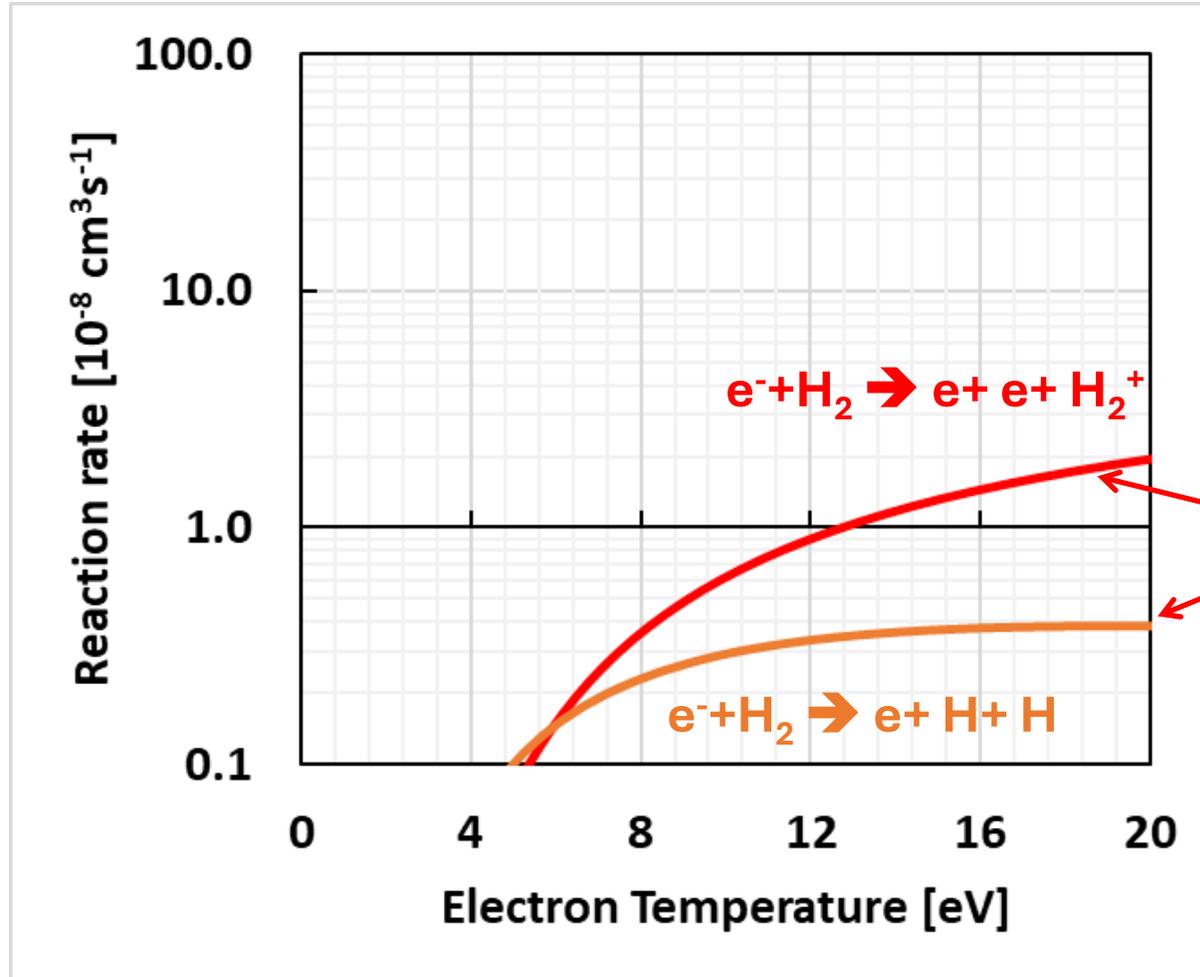


[W. Kraus, CERN Accelerator School]



Applying coefficients from:
[M. Seidl et al. Journal of Applied Physics 79, 2896 (1996)]

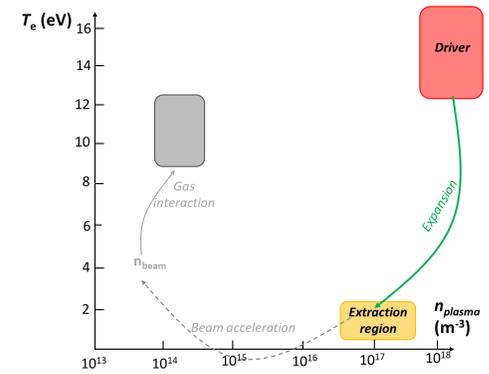
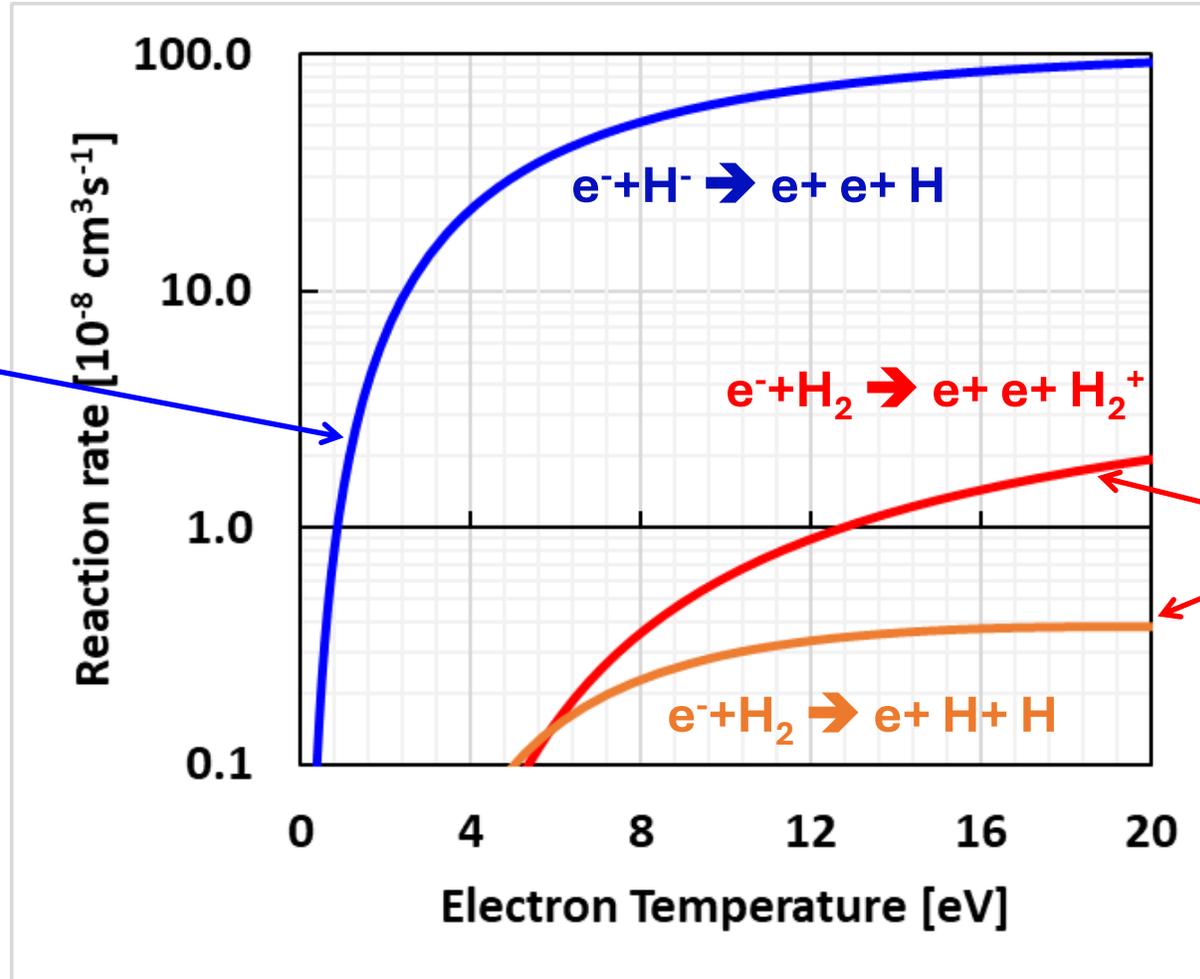
Increasing negative ion density



Hot e^- are needed to ionize and to dissociate the gas

Increasing negative ion density

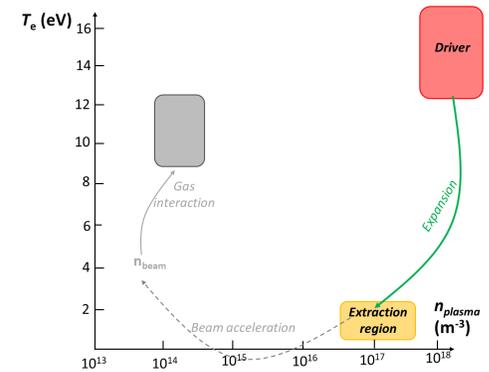
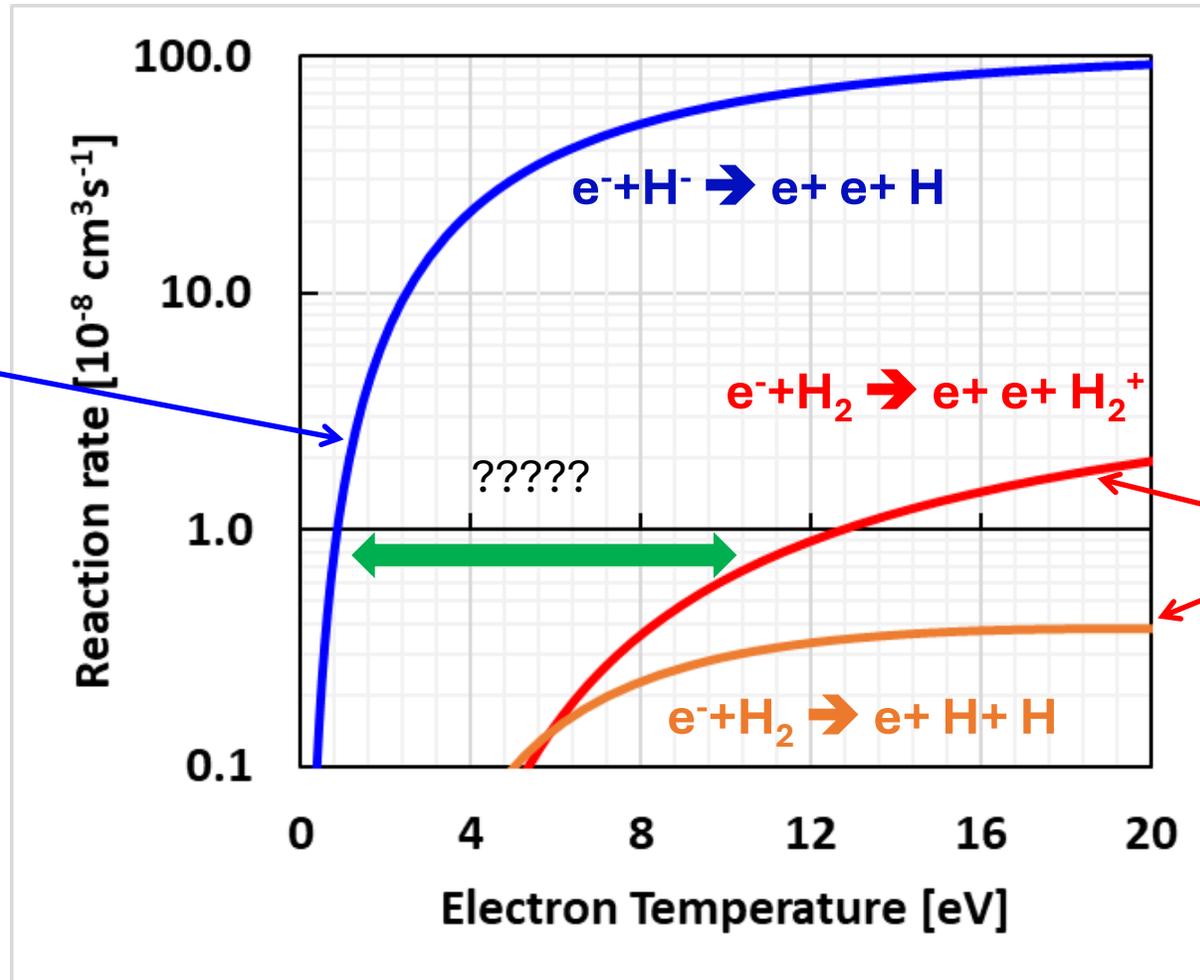
H⁻ should not encounter hot e⁻



Hot e⁻ are needed to ionize and to dissociate the gas

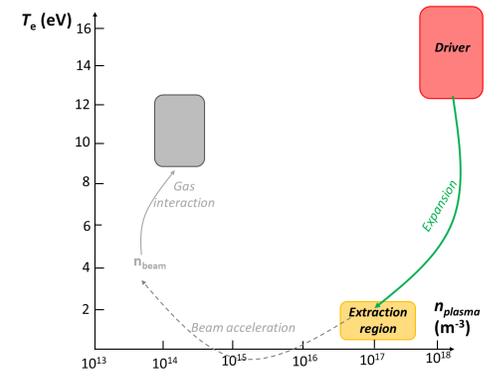
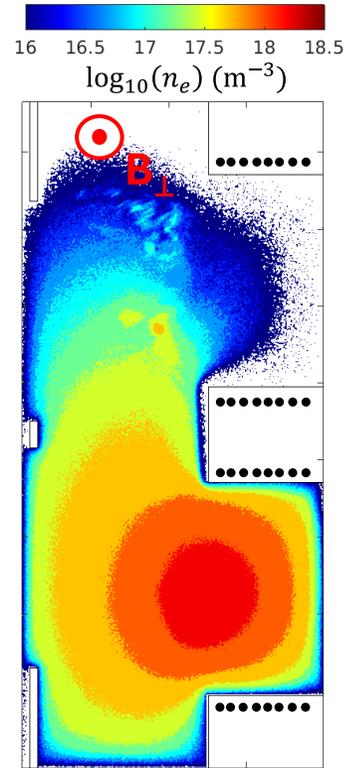
Increasing negative ion density

H⁻ should not encounter hot e⁻ (EXTRACTION REGION)

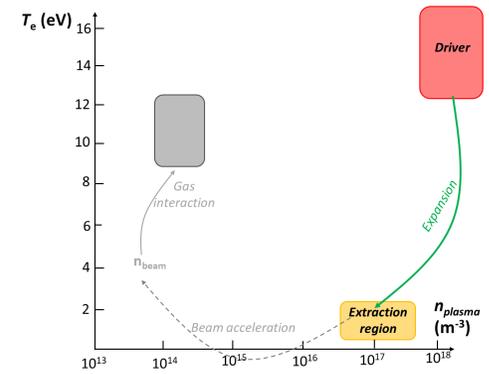
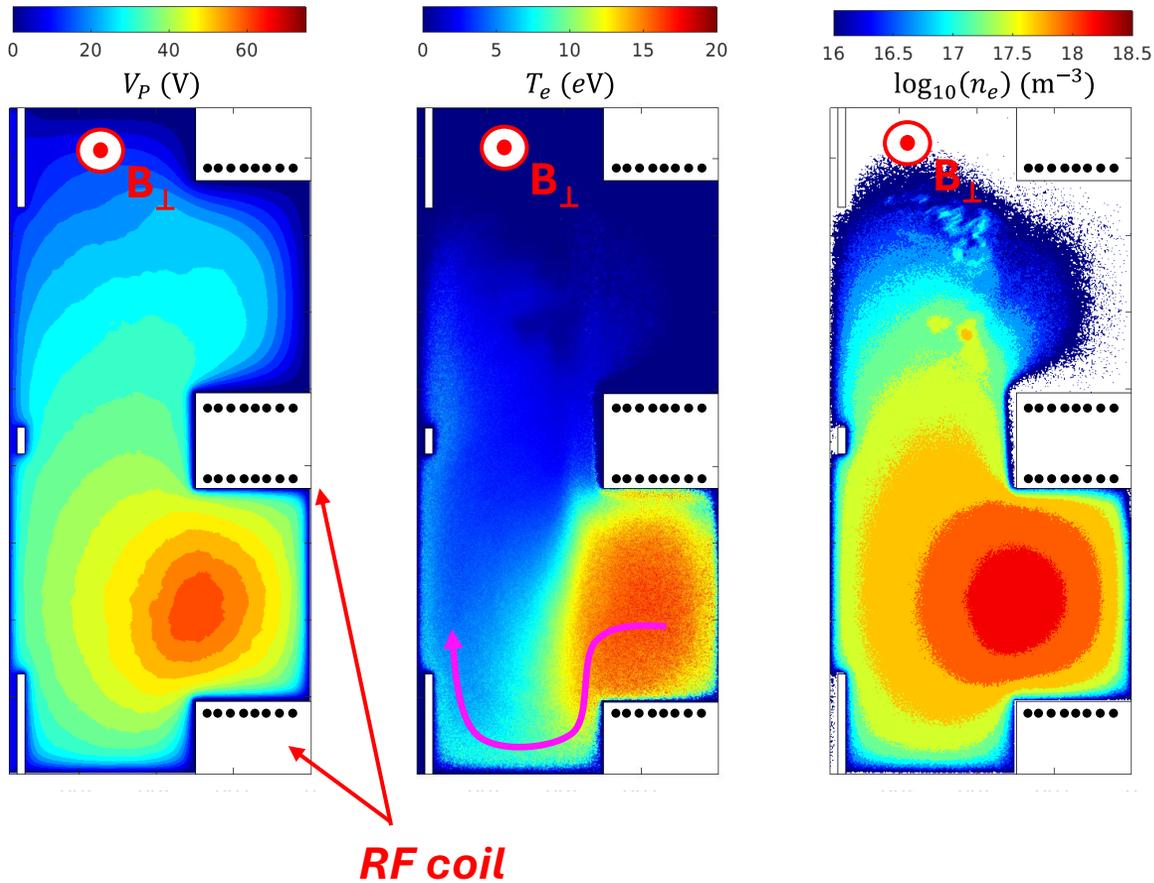


Hot e⁻ are needed to ionize and to dissociate the gas (PLASMA DRIVER)

Plasma expansion



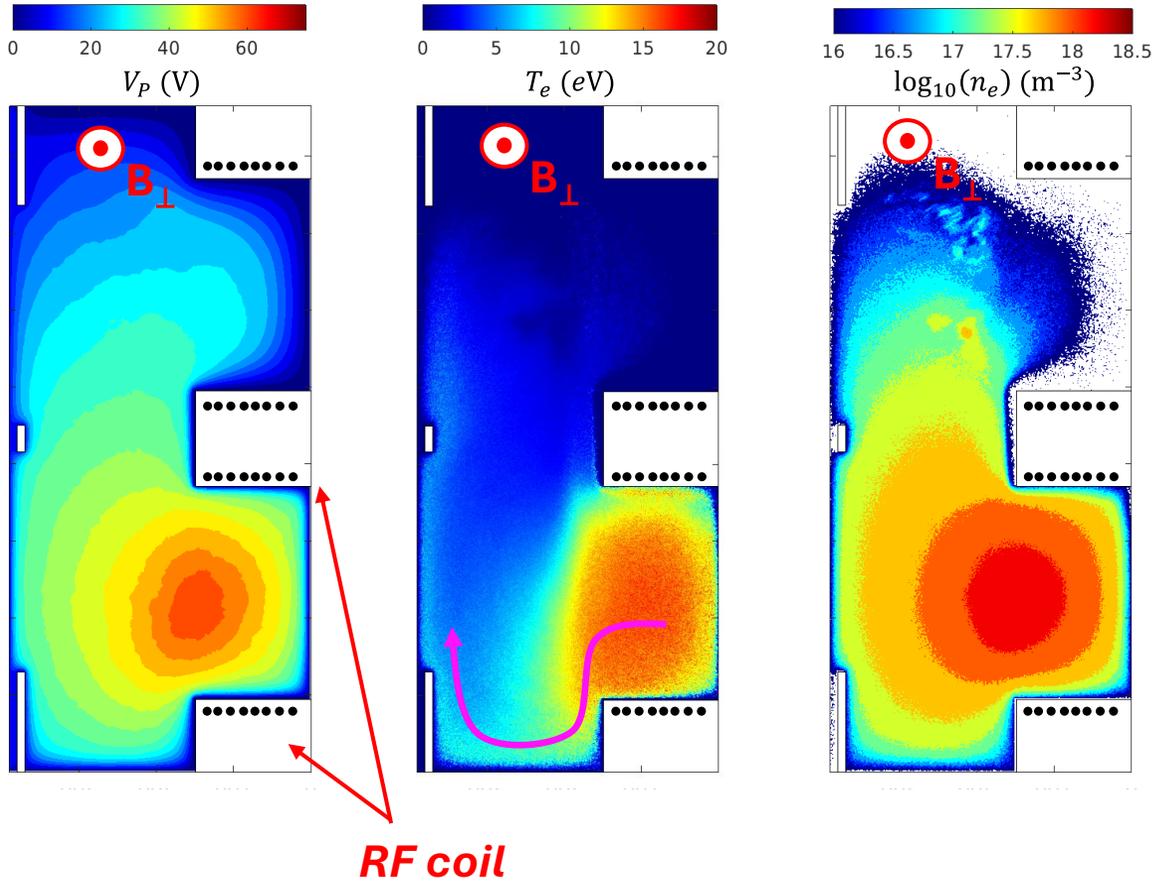
Plasma expansion



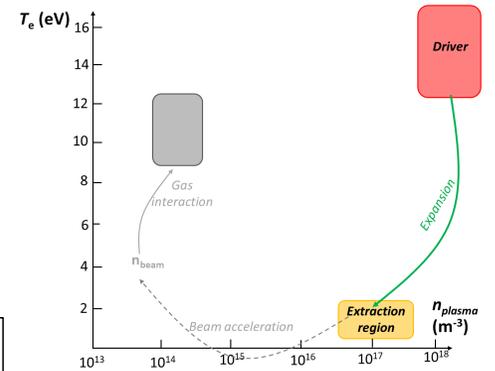
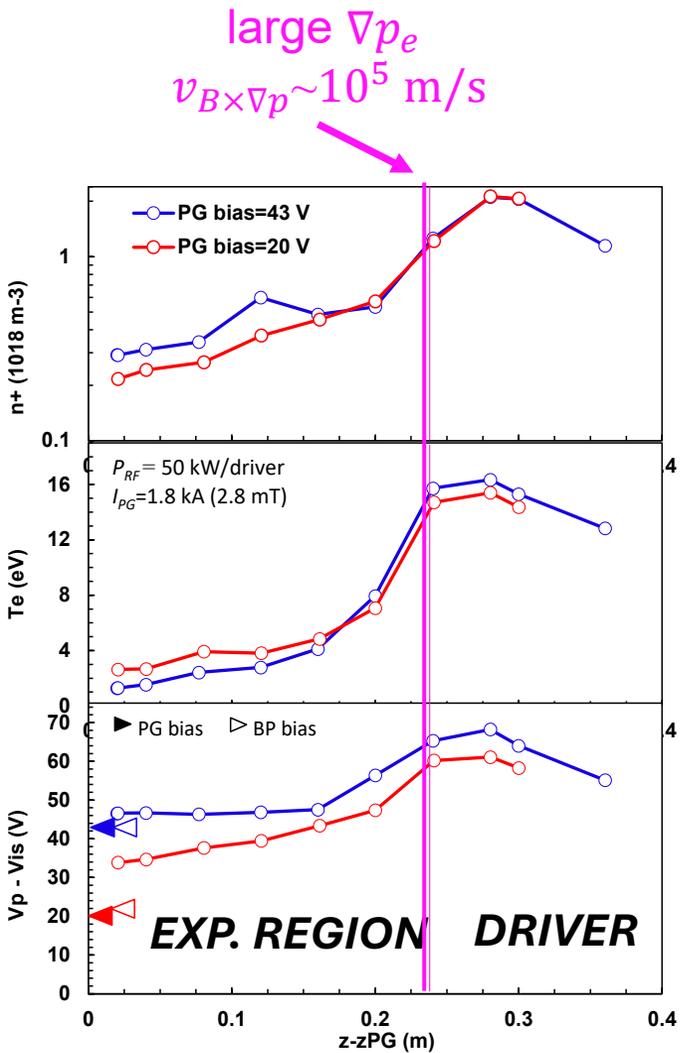
POSTER 4th February 2026
 G. Azzalin, PIC modeling of
 ICPS for the ITER NBI
 source prototype

- hot electrons drifting downward -> Hall current of hot electrons towards the extraction region
- Vertical profile of plasma density at PG moves upwards

Plasma expansion

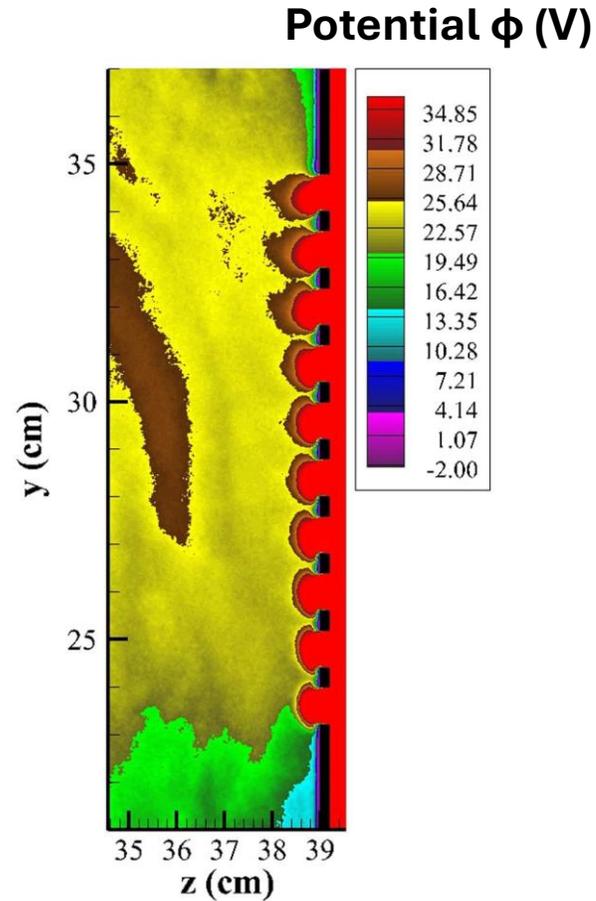


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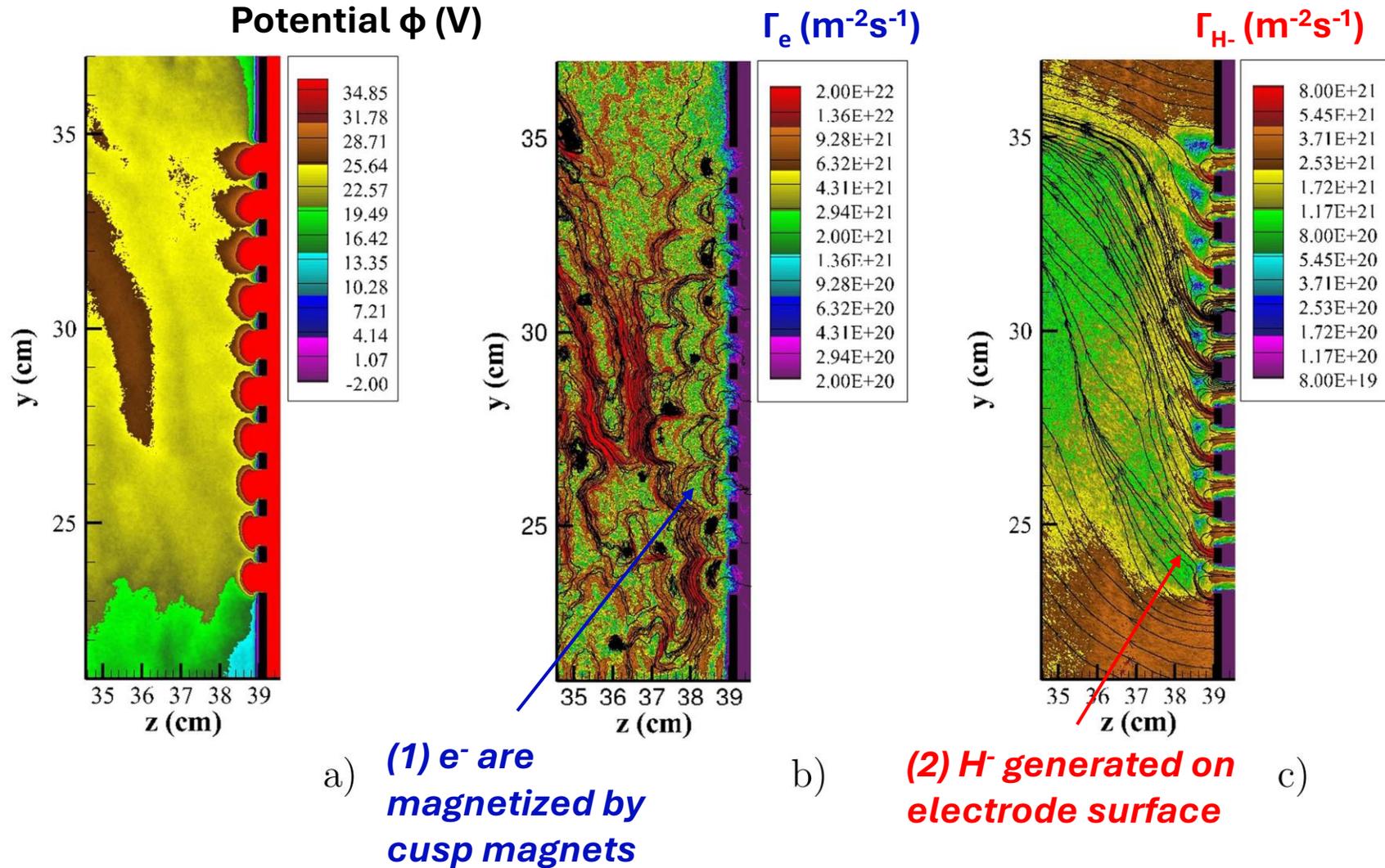
Plasma
characterization by
axial Langmuir probe

The extraction region: electronegative plasma



*F. Taccogna and P. Minelli 2017 New J. Phys. **19** 015012
PIC modeling of negative ion sources for fusion*

The extraction region: electronegative plasma

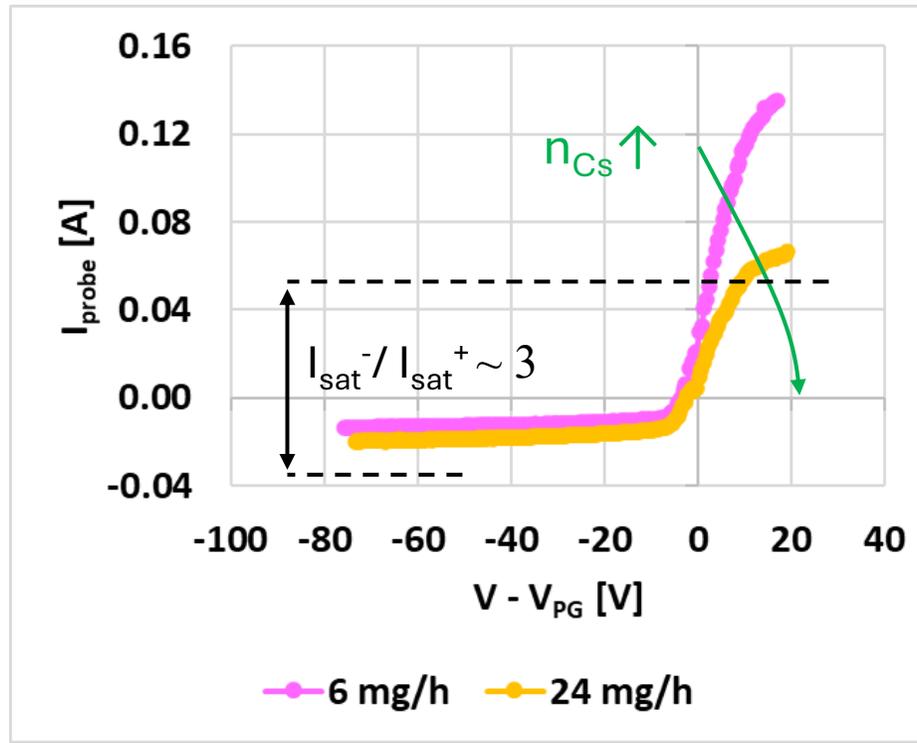
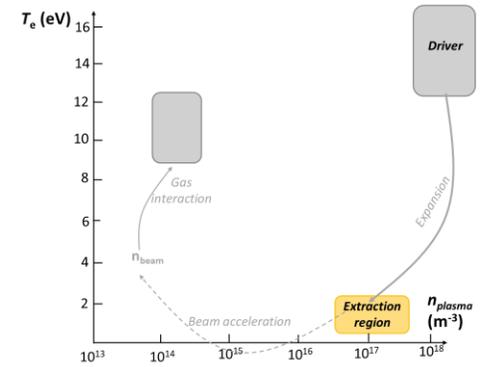
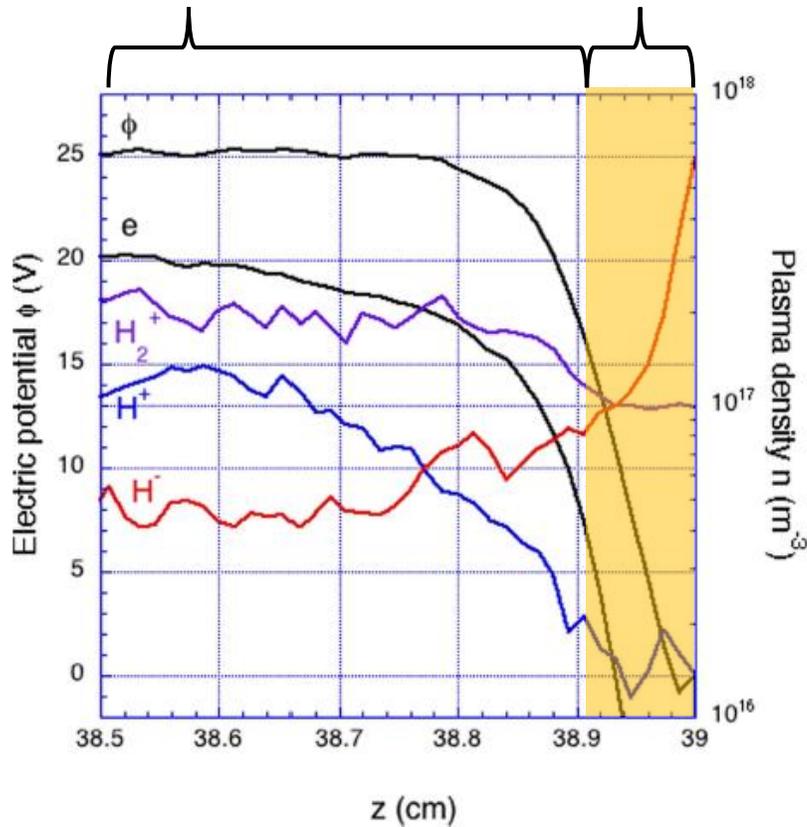


*F. Taccogna and P. Minelli 2017 New J. Phys. **19** 015012
PIC modeling of negative ion sources for fusion*

The extraction region: electronegative plasma

$n_e \sim n^+$ & $n_{H^-} \sim 0$
Electro-positive plasma

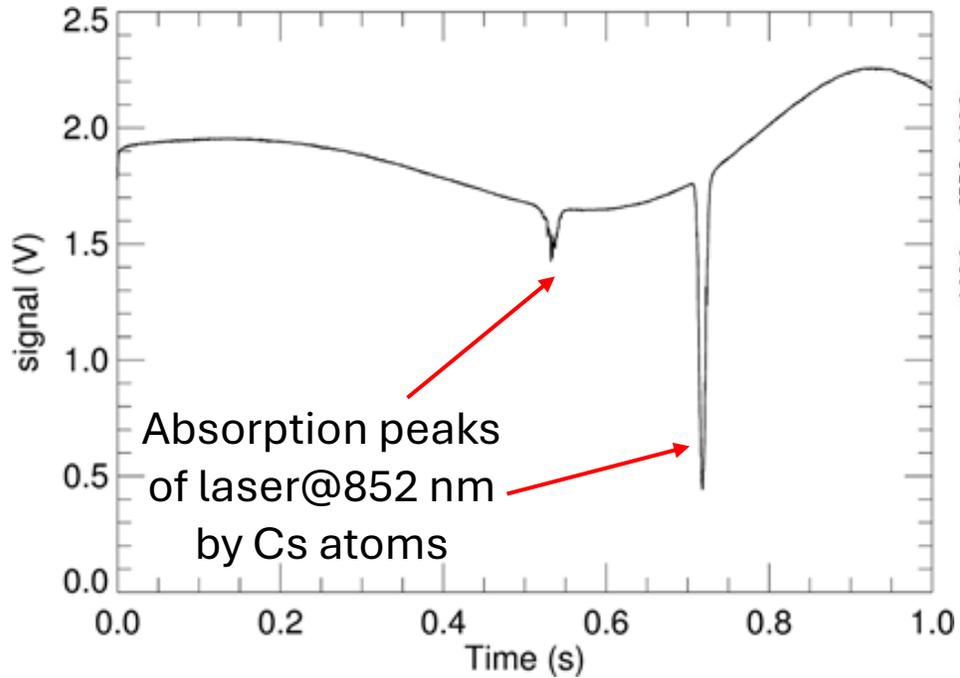
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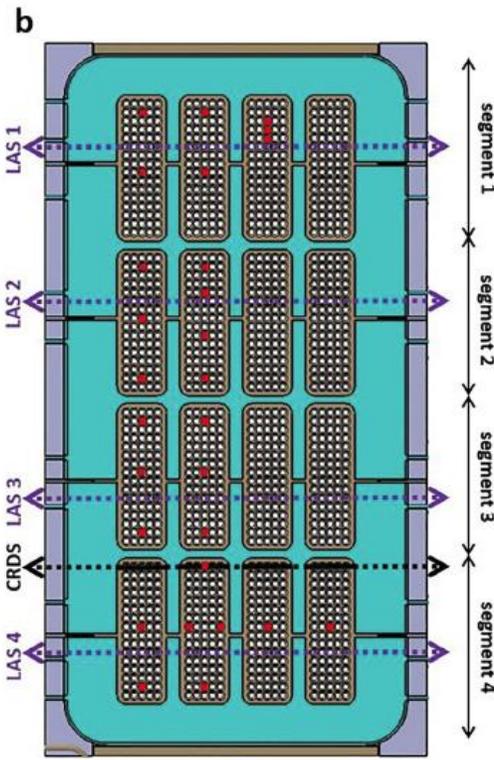
*F. Taccogna and P. Minelli 2017 New J. Phys. 19 015012
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Measuring Cs density

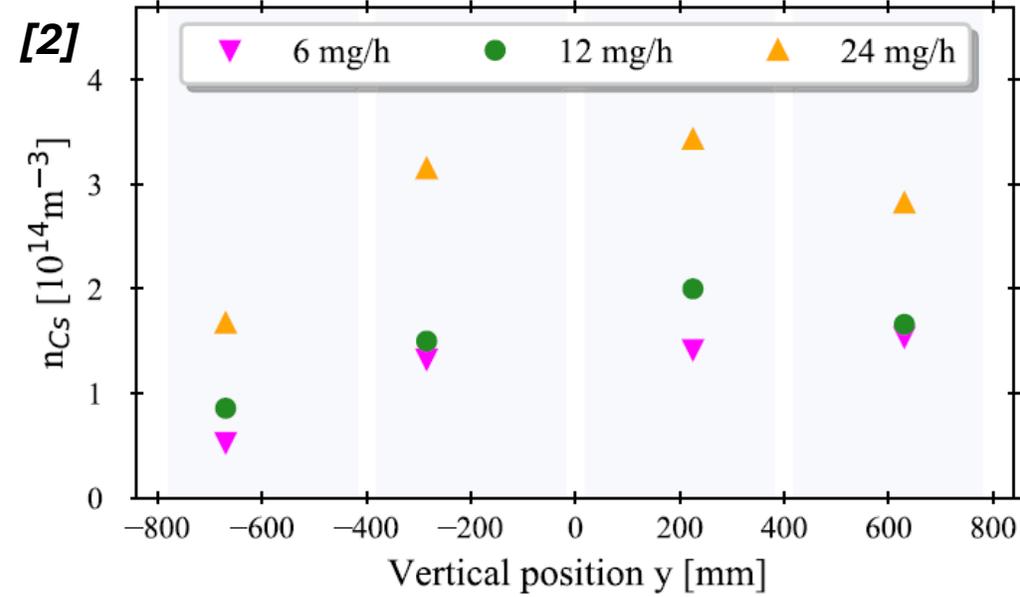
A line average of n_{Cs} can be estimated by **Laser Absorption Spectroscopy (LAS)**



[1]



[1]

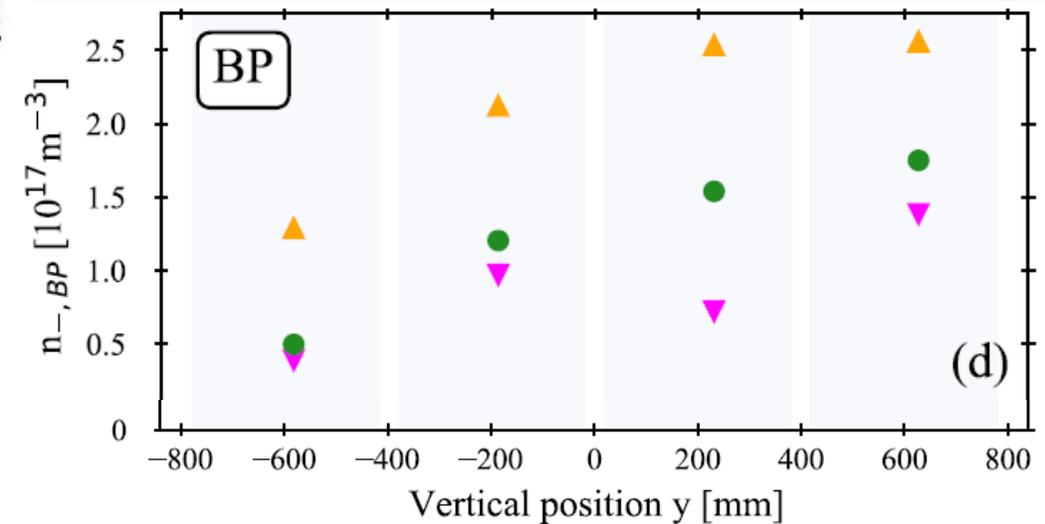
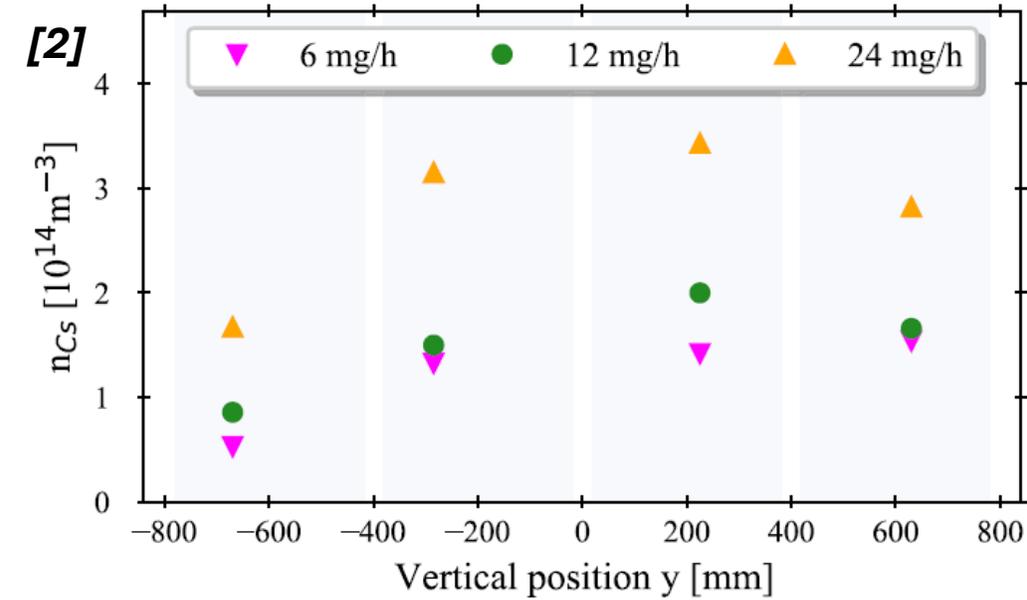
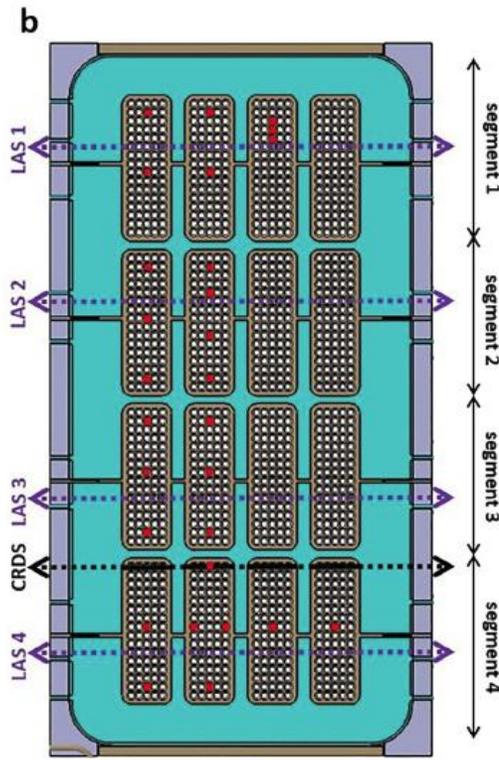
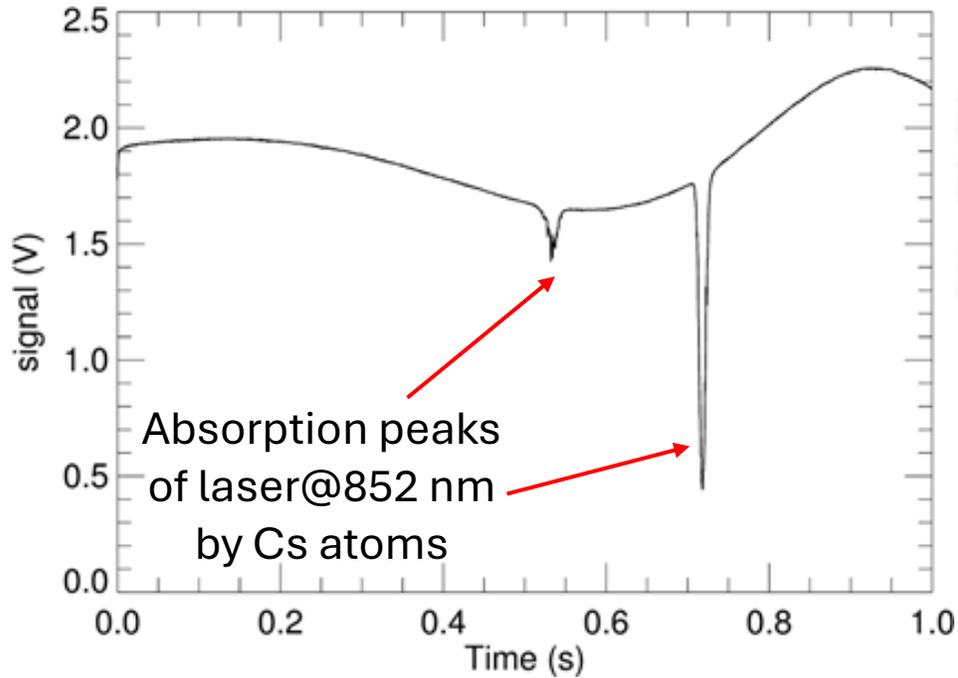


[1] M. Barbisan et al. *Fus. Eng. Des.* 146 (2019) 2707–2711

[2] G. Serianni et al. *Rev. Sci. Instrum.* 93, 081101 (2022)

Measuring Cs density

A line average of n_{Cs} can be estimated by **Laser Absorption Spectroscopy (LAS)**

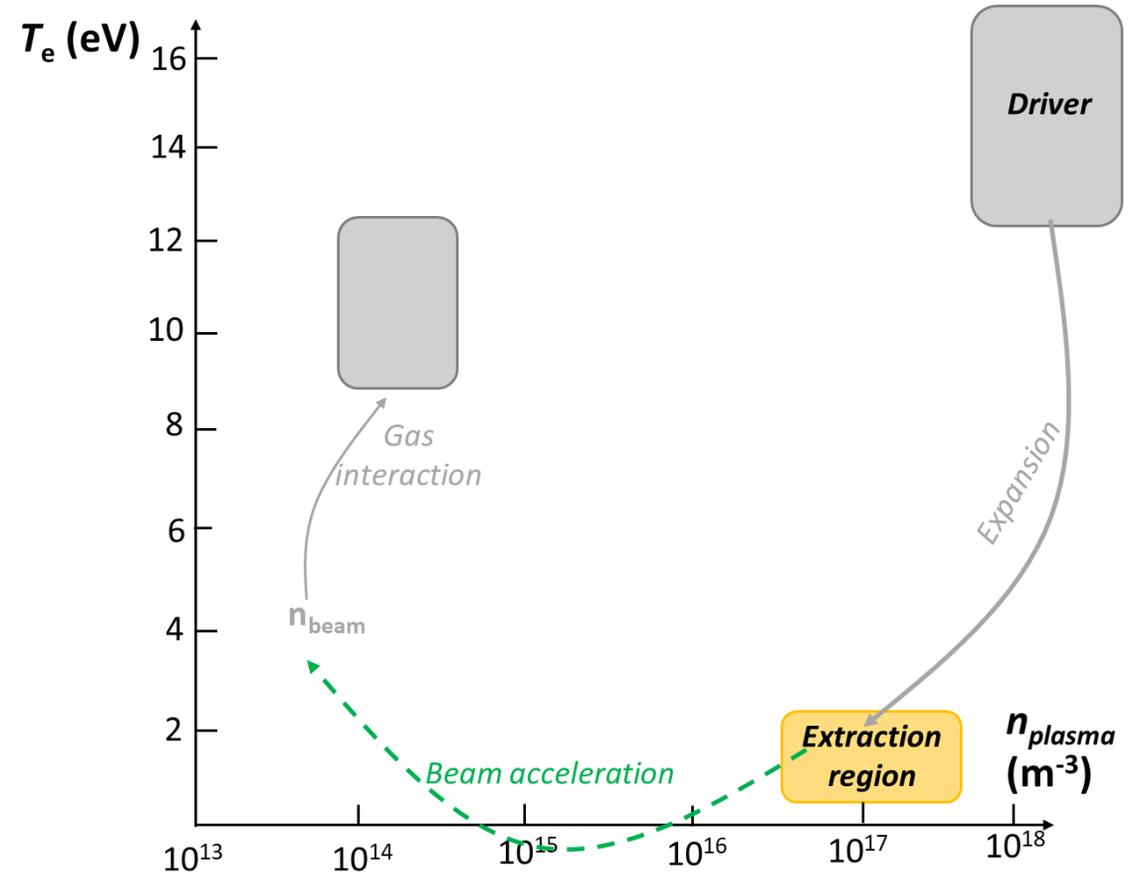


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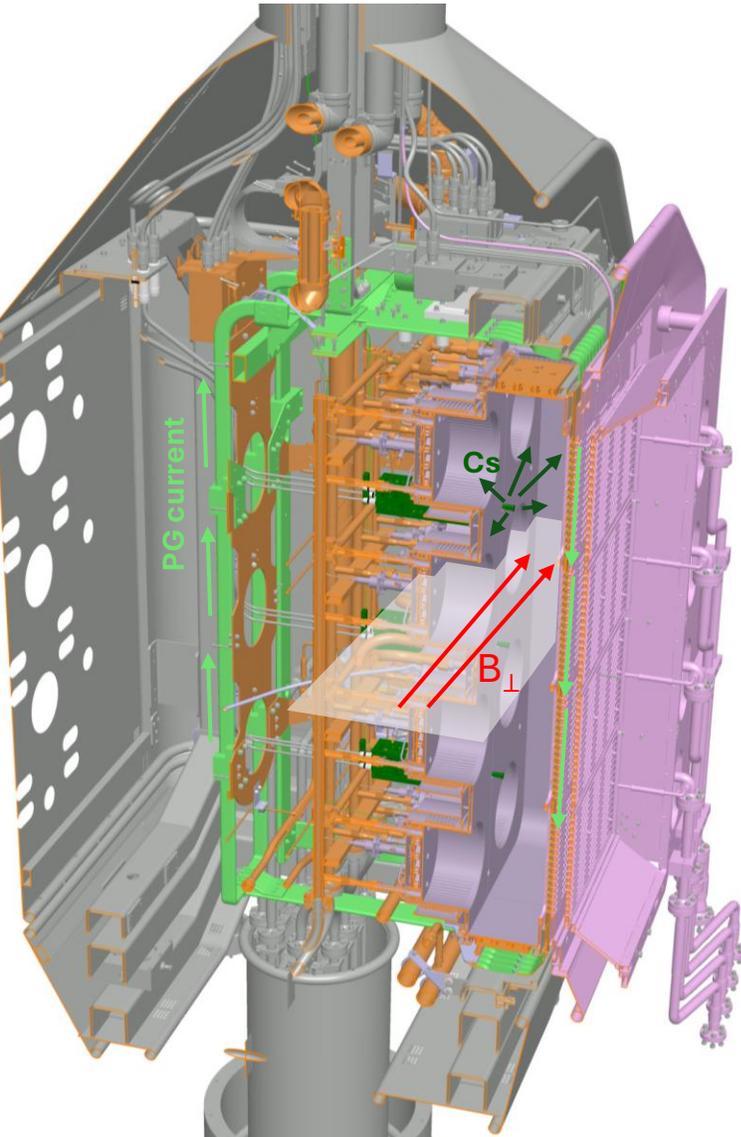
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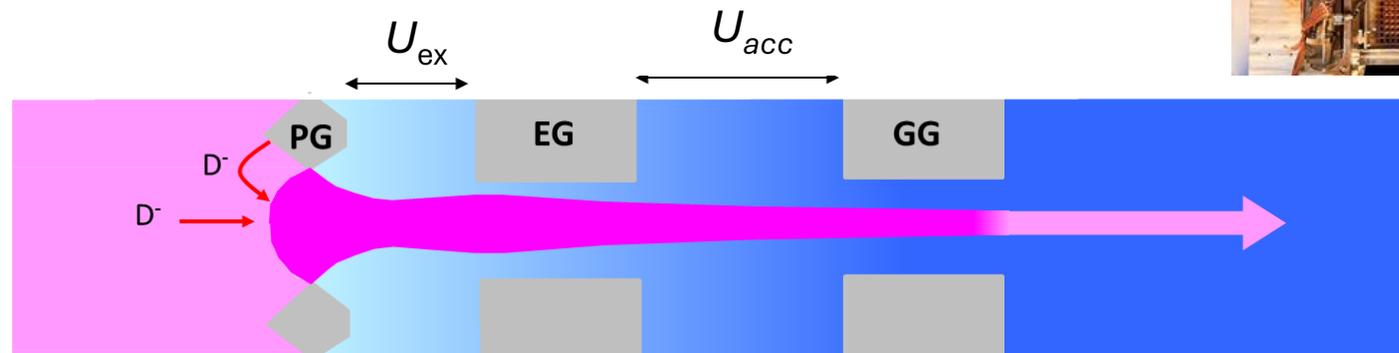
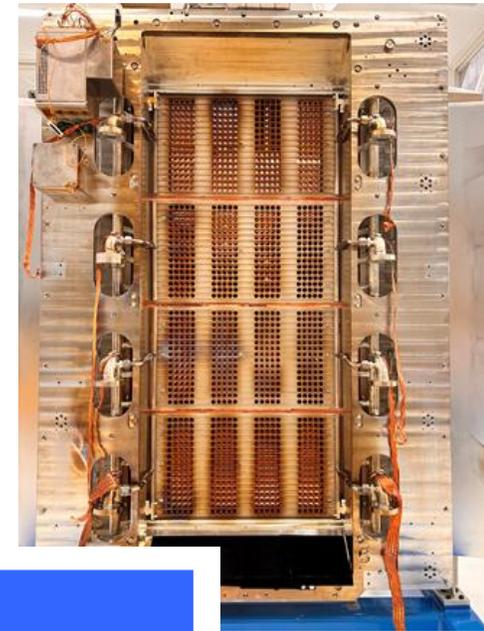
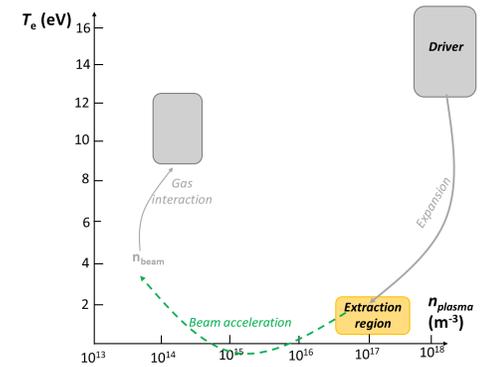
Beam extraction and acceleration



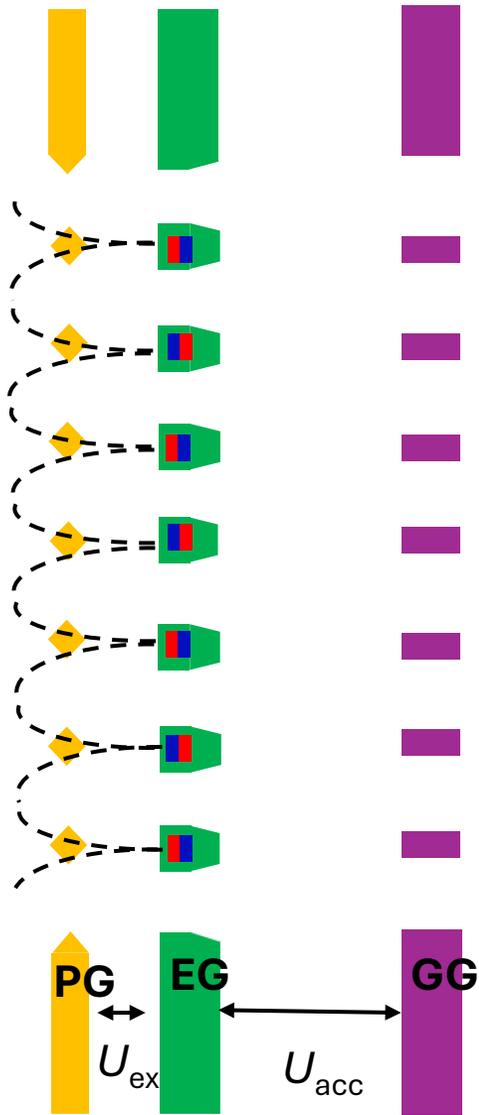
Aim 1: Dump co-extracted e^- before full acceleration

Solution

- Split accelerator in 2+ gaps
- Apply $U_{ex} \ll (U_{ex} + U_{acc}) = U_{tot} = E_{beam}/e$ in first gap
- Split beam in beamlets \rightarrow Grid shaped electrodes



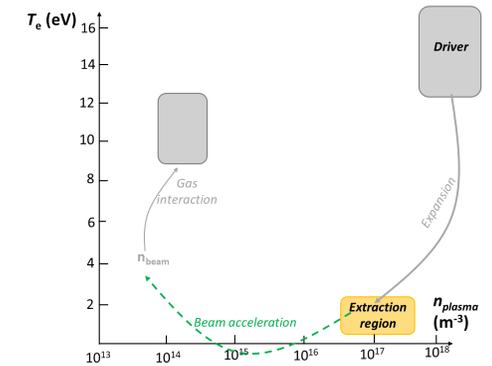
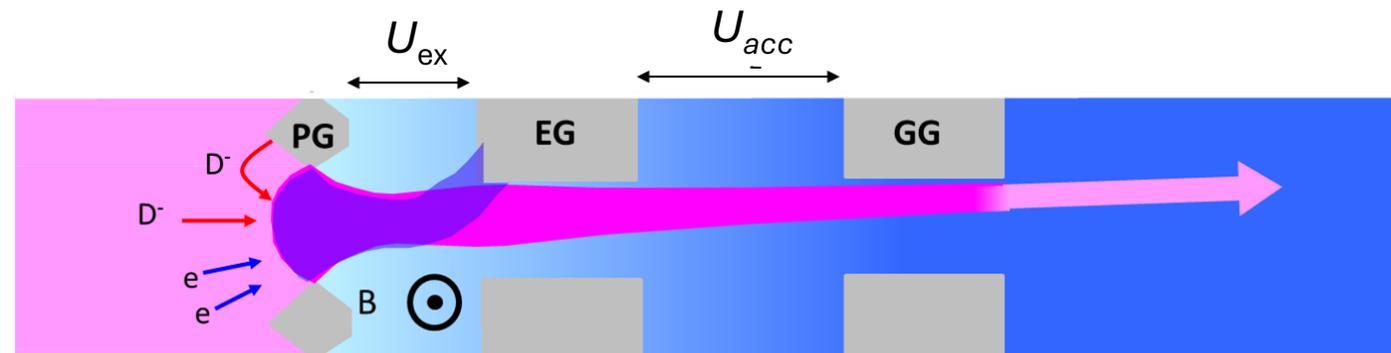
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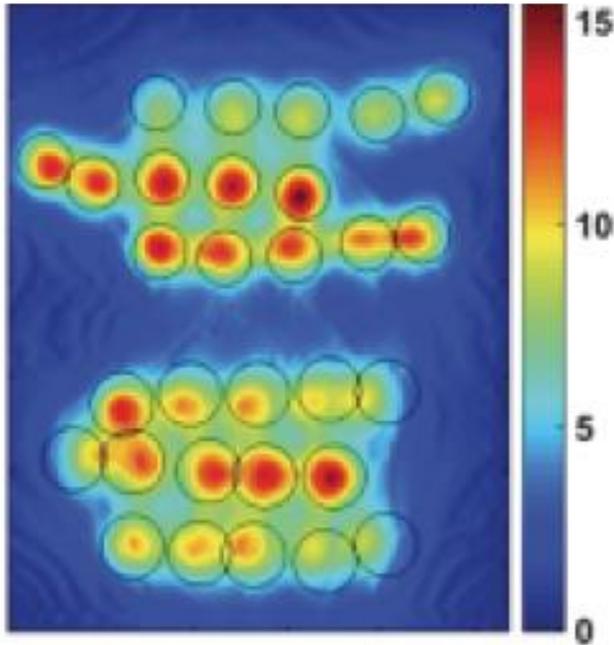
- Split accelerator in 2+ gaps
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- Split beam in beamlets \rightarrow Grid shaped electrodes
- Embed permanent magnets in first electrode



Beam acceleration

G. Chitarin et al., AIP Conf. Proc. **1869**, 030026 (2017)

Uncompensated beam

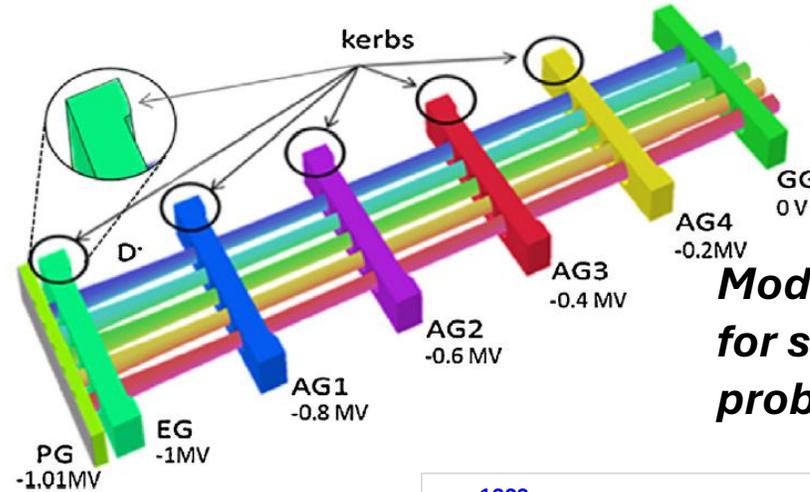


Almost Compensated beam

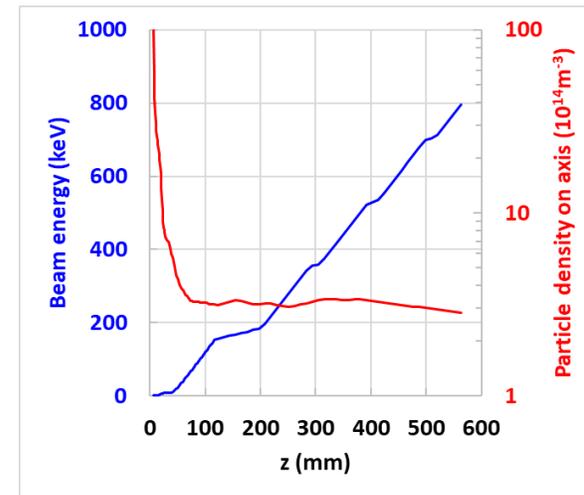
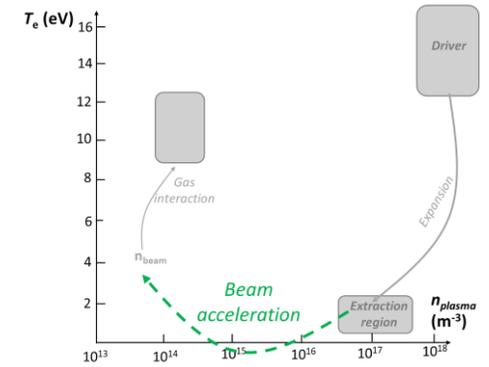
Magnetic deflection + Coulomb repulsion on a small scale experiment ($E_{beam} \sim 30 \text{ keV}$)

Beam footprint @ distance $\sim 0.8 \text{ m}$

P. Veltri et al., Fus. Eng. Des. **107**, 64-69 (2016)



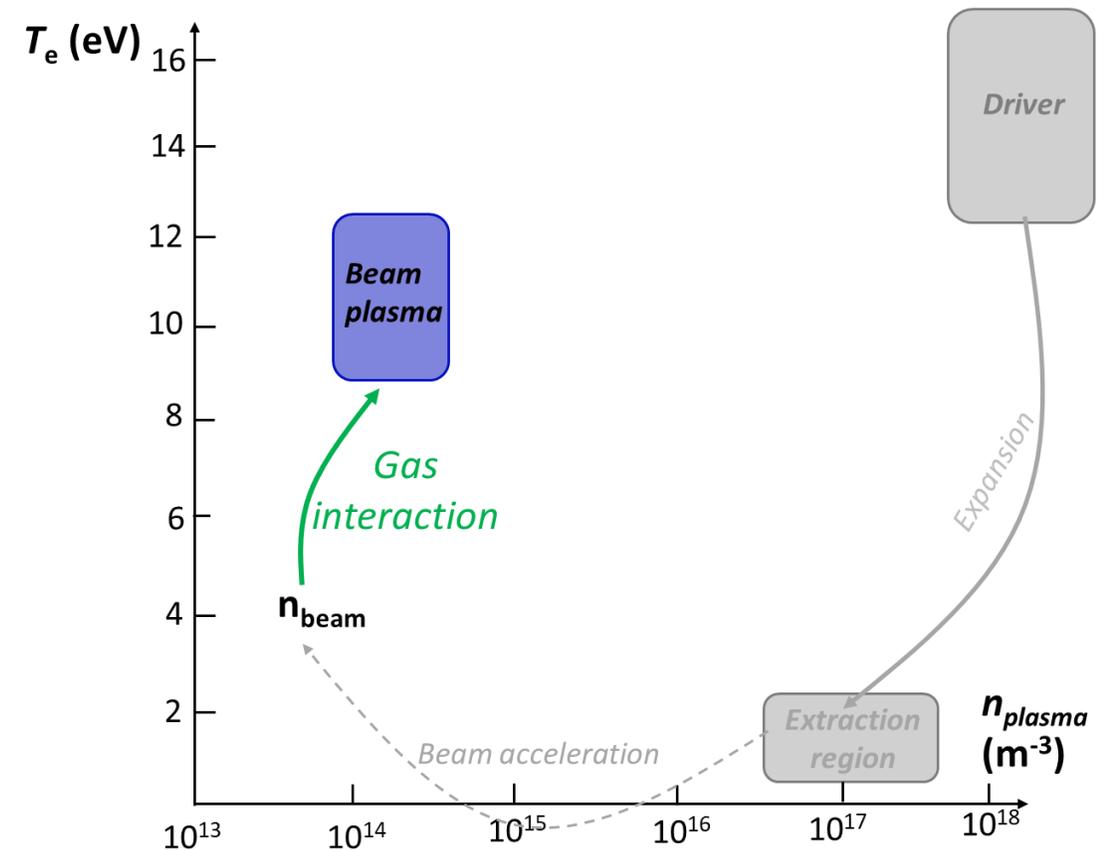
Models require good meshing for small details; but size of the problem is huge



$$I_{beamlet} = A_{beamlet} n_{beamlet} v_{beamlet}$$

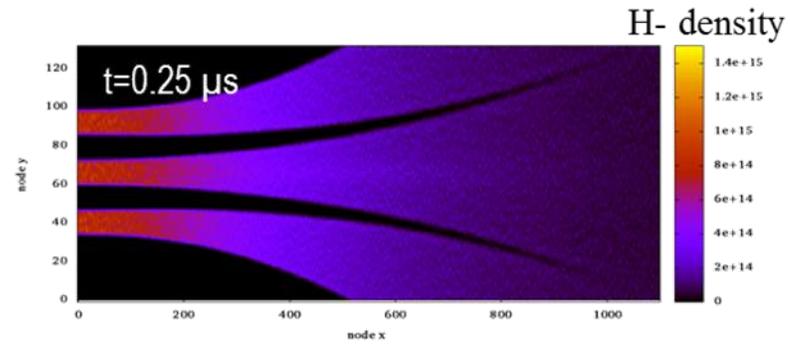
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Beam-plasma

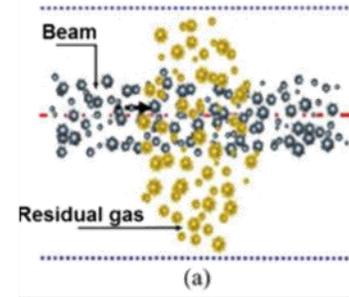
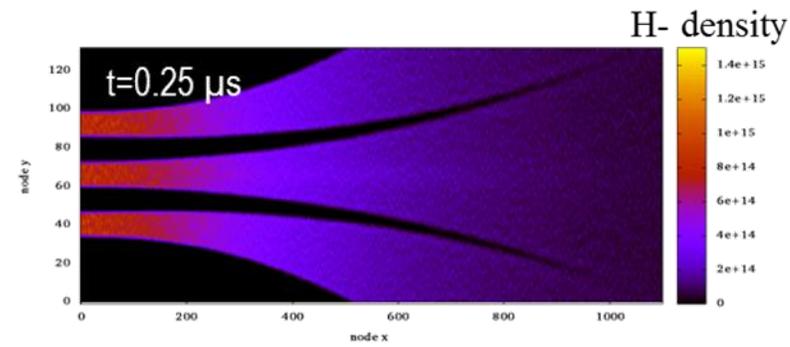
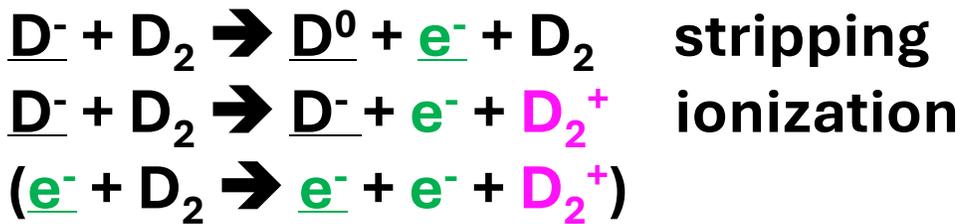
- Downstream of the accelerator, we have no electric field
- Beam space charge can cause a potential well increasing the beam divergence (Coulomb repulsion):
terrible beam transport!



E. Sartori et al. Rev. Sci. Instrum. 87, 02B917 (2016)

Beam-plasma

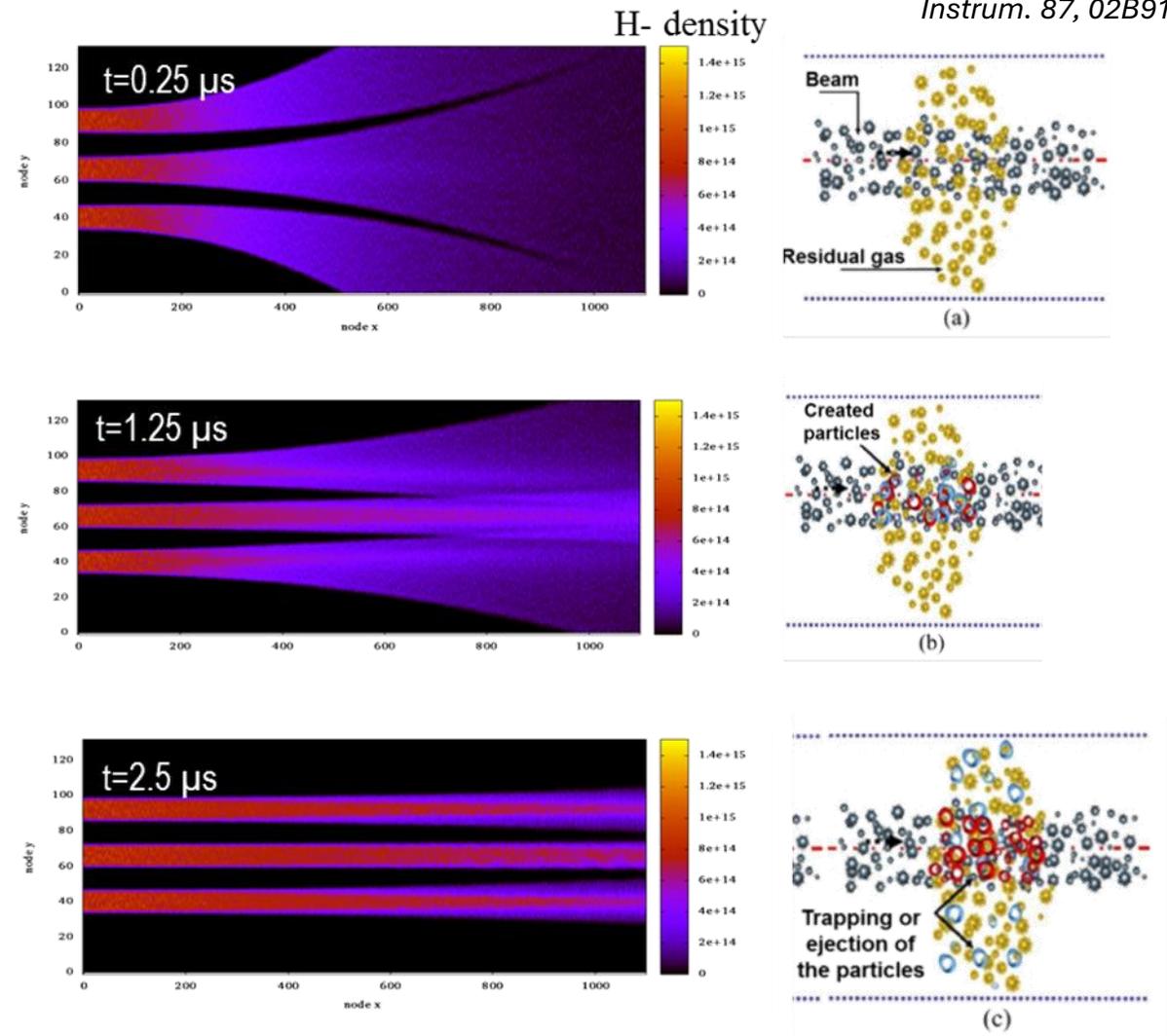
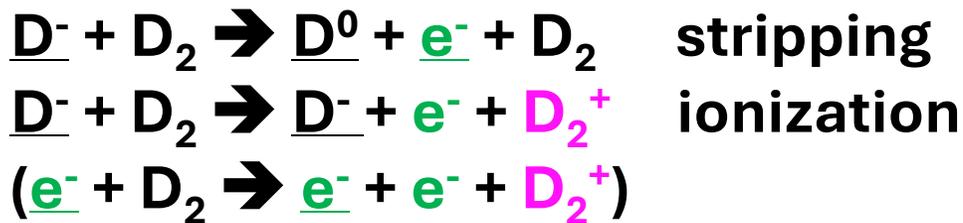
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- Beam-gas interaction leads to gas ionization



E. Sartori et al. Rev. Sci. Instrum. 87, 02B917 (2016)

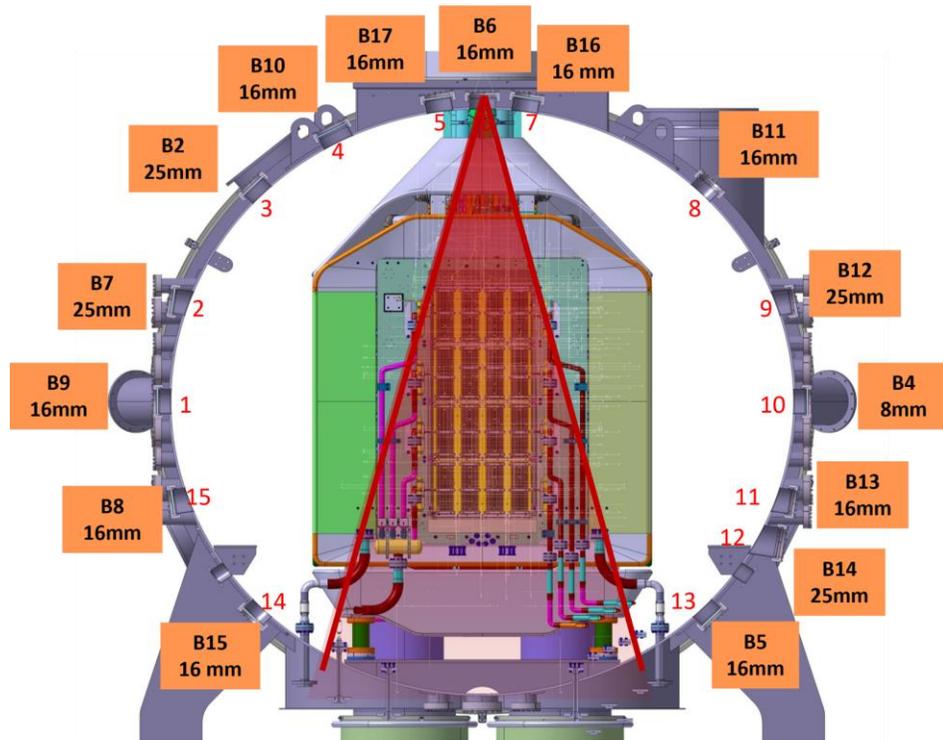
Beam-plasma

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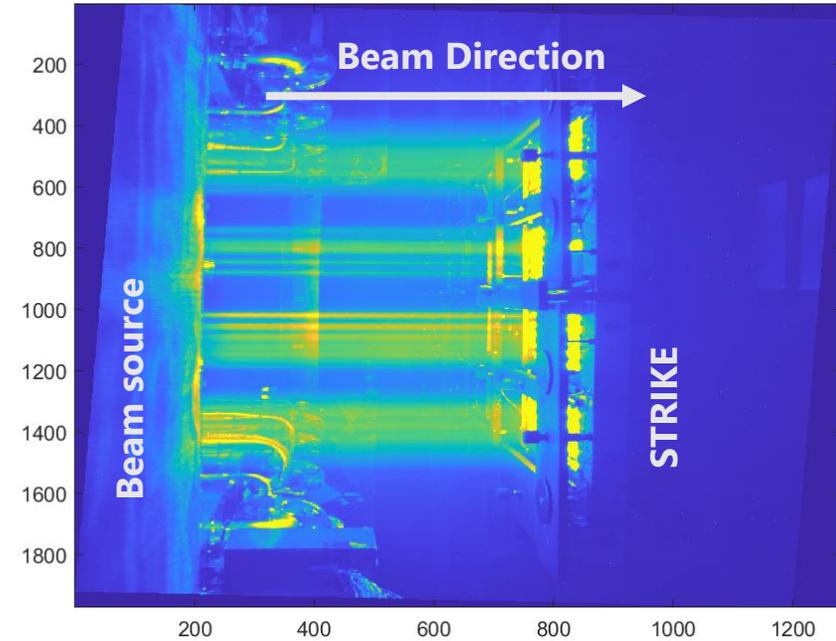
The formation of a beam-plasma shields the beam space charge and restores the beam optics

Beam-plasma

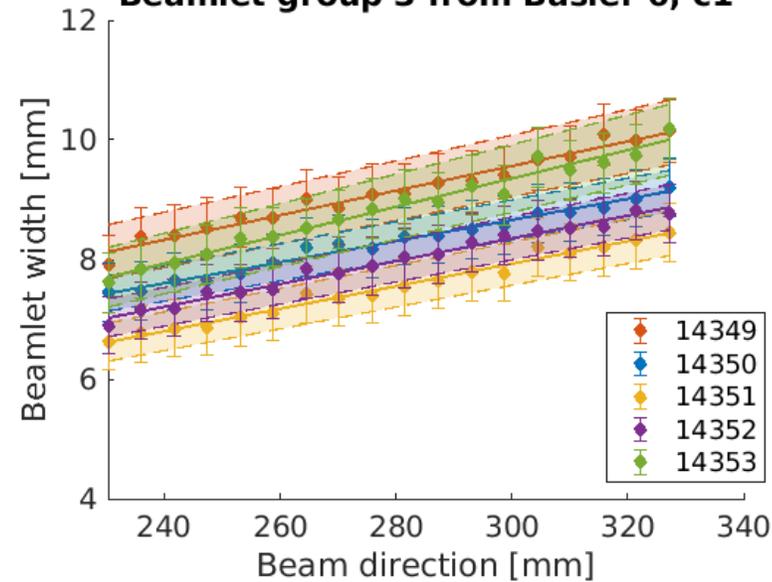


G. Emma et al. Beam optics analysis by visible cameras applied for the first time to a large-scale multi-beamlet configuration in the ITER prototype source, 21st International Conference on Ion Sources, 8th-12th September 2025, Oxford (UK)

#Pulse 15436. Top view from camera Basler 6



Beamlet group 3 from Basler 6, c1



Linear trend of beamlet column width confirms space charge compensation

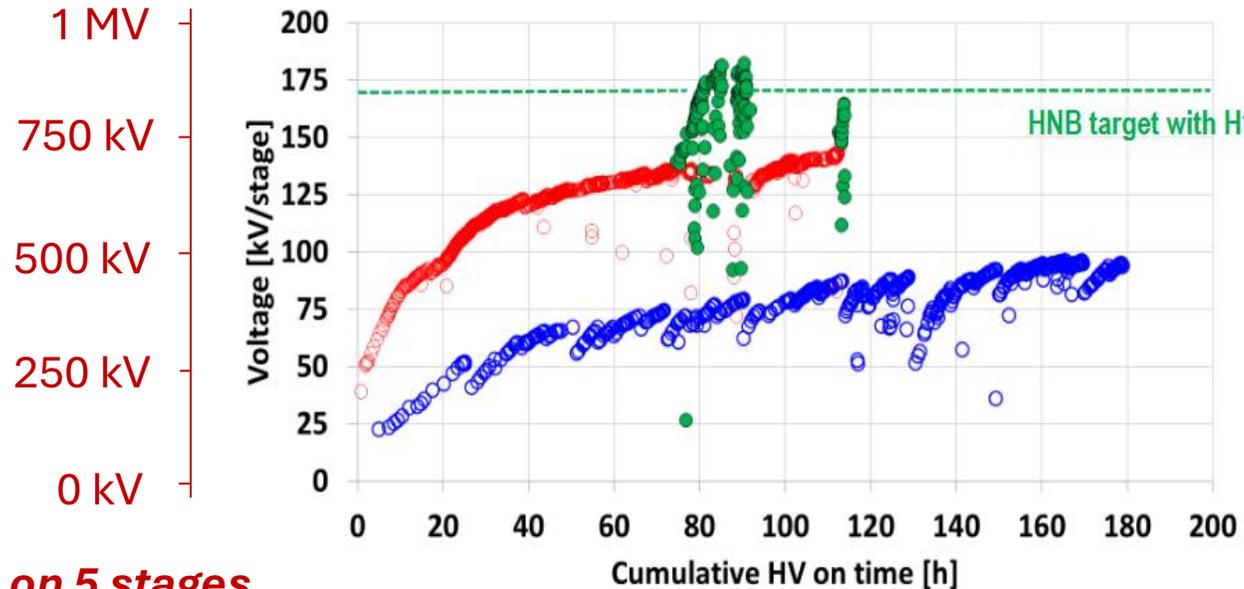
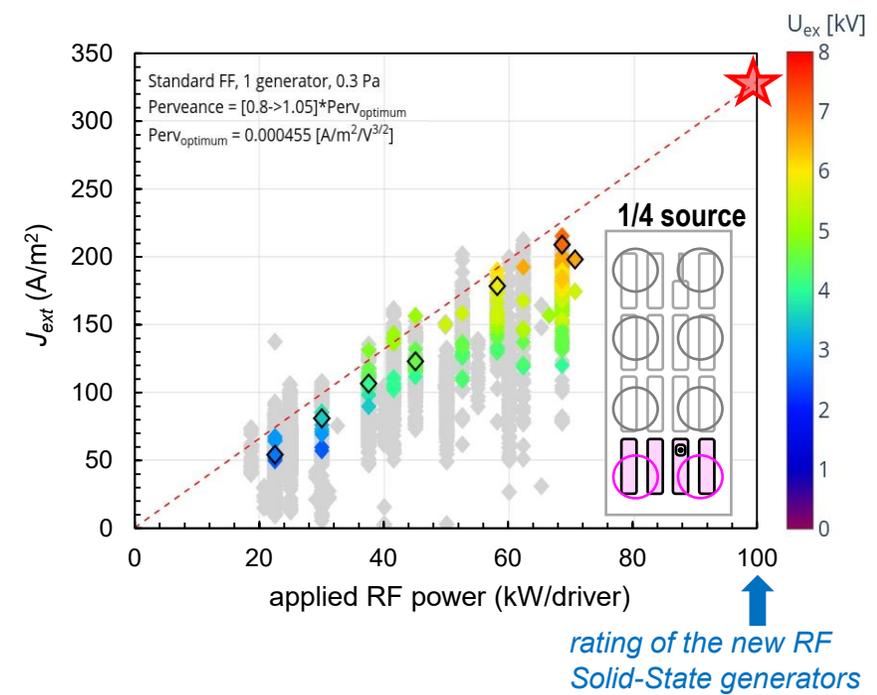
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Summary and outlook

At the NBTF, **SPIDER** is running:

- First campaigns of SPIDER **confirmed expected scaling of beam current density** with RF power



on 5 stages

○ w/o screen, vacuum ○ w/ screen, vacuum ● w/screen, p>1 mPa

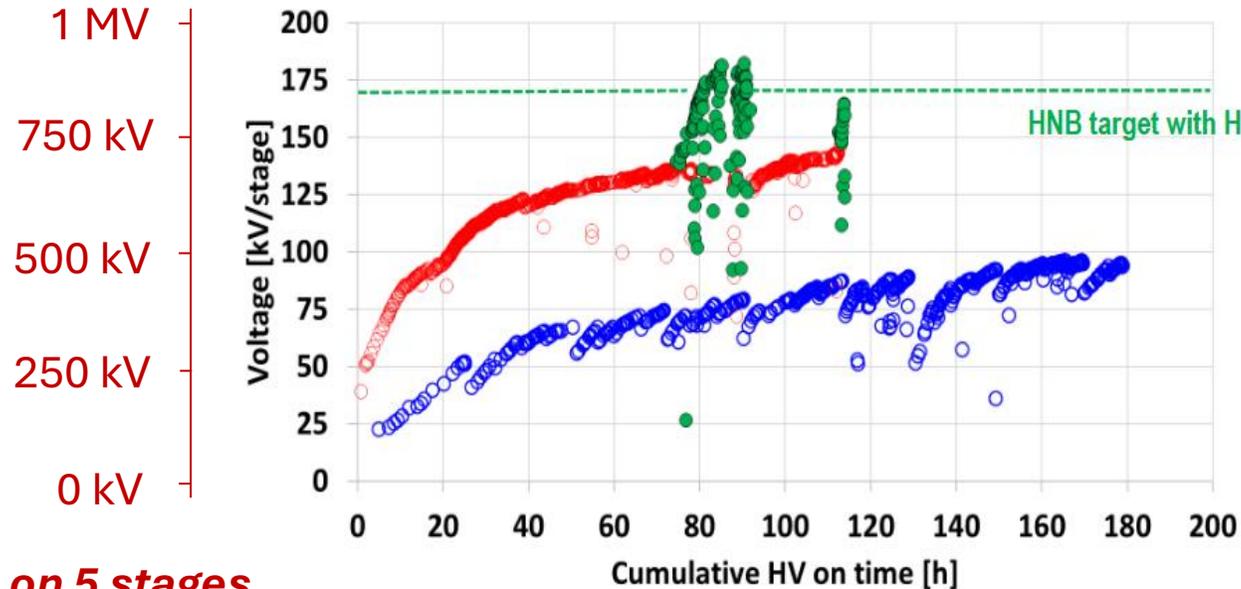
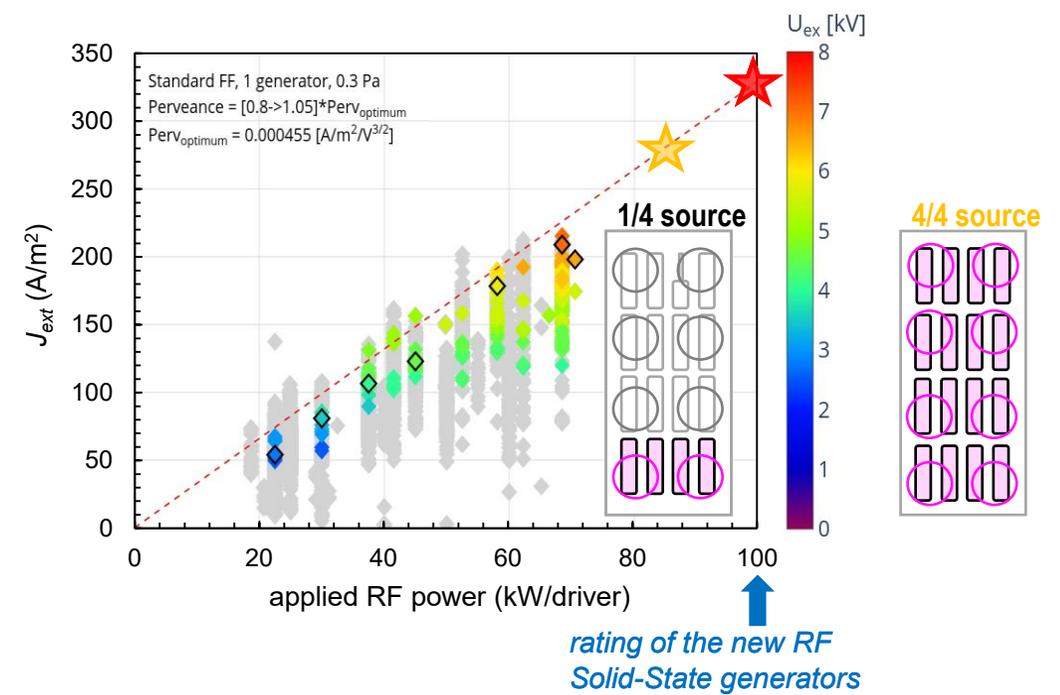
and **MITICA** is on its way:

- HV holding @ MITICA was tested with a mock-up of the ion source: **ITER-grade beam energies are attainable!**

Summary and outlook

At the NBTF, **SPIDER** is running:

- First campaigns of SPIDER **confirmed expected scaling of beam current density** with RF power
- Start operation with new RF generators and getter pumping system: **increasing beam current** and its homogeneity



○ w/o screen, vacuum ○ w/ screen, vacuum ● w/screen, p>1 mPa

on 5 stages

and **MITICA** is on its way:

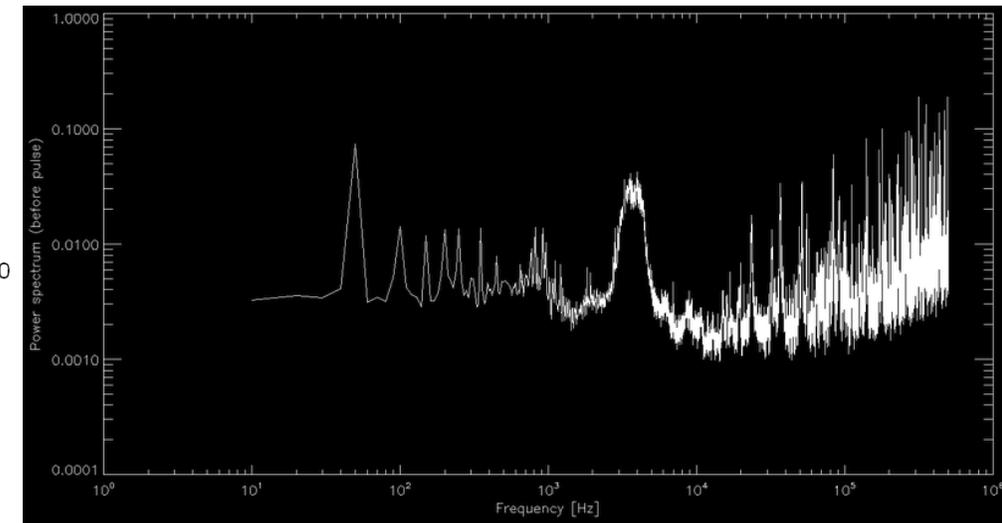
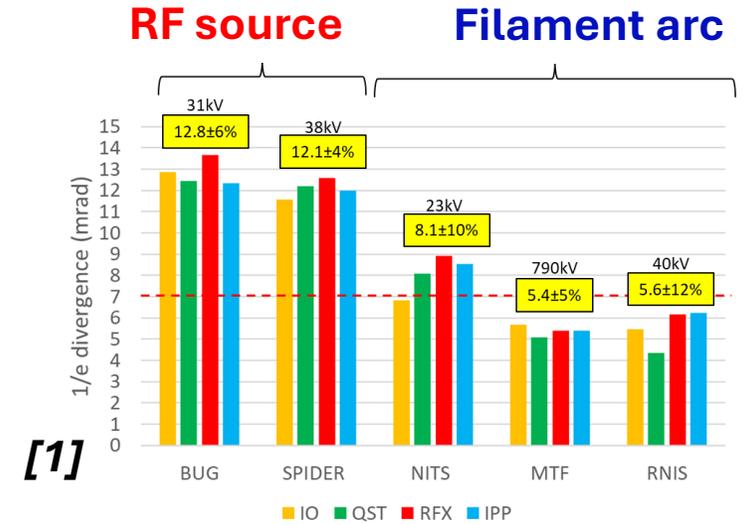
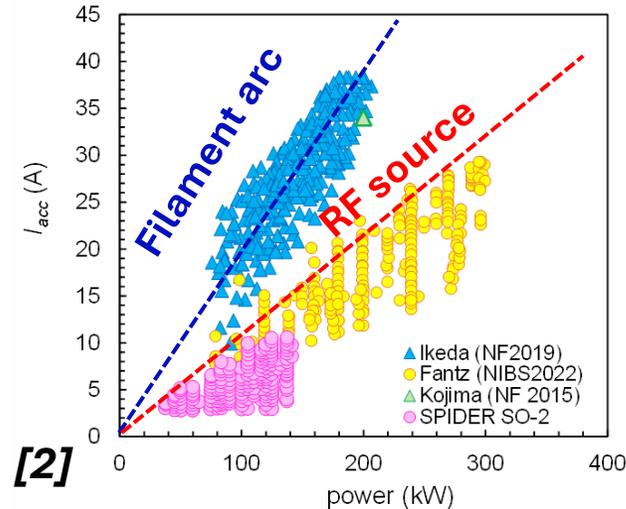
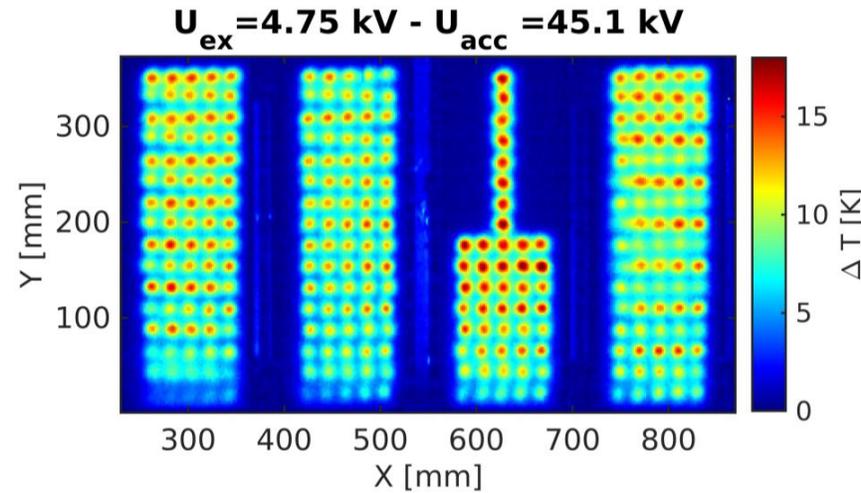
- HV holding @ MITICA was tested with a mock-up of the ion source: **ITER-grade beam energies are attainable!**
- Assembly and installation ongoing
- Beam operation expected in 2027

Outlook

Plant upgrades at SPIDER should allow reliable full source operation

Physics topics ahead

- Beam homogeneity
- Beam divergence
- RF coupling ($P_{\text{plasma}}/P_{\text{RF}} \leq 0.5$)
- High frequency: does the beam suffer for MHz range plasma oscillations?



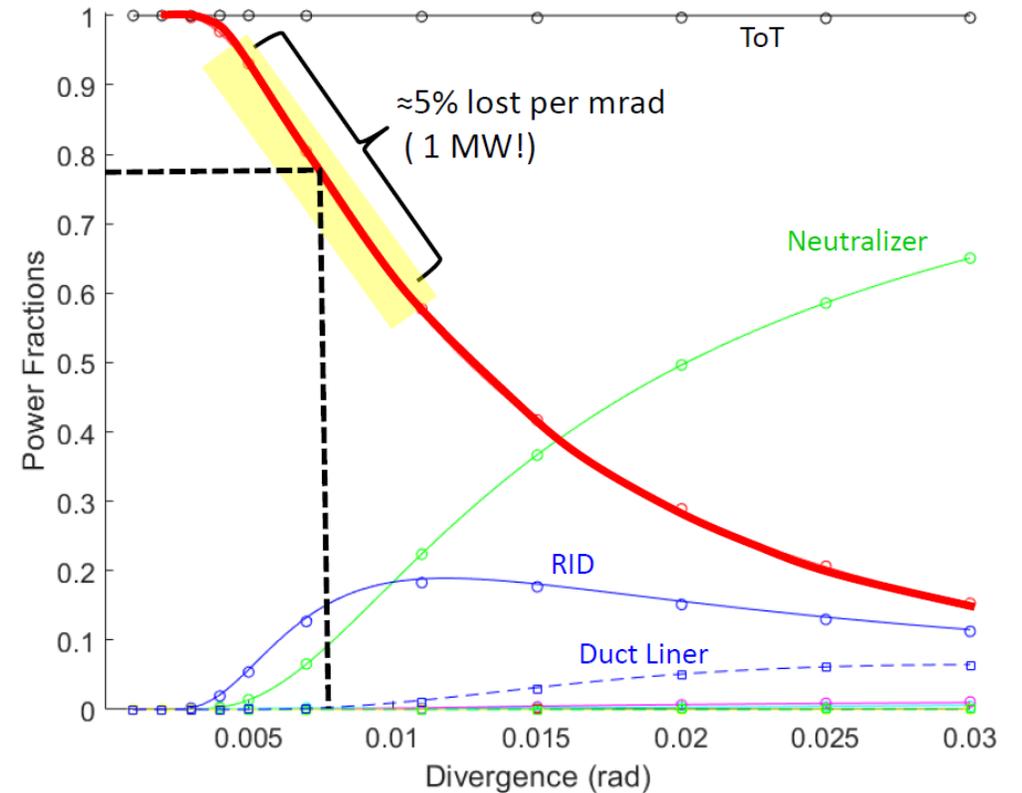
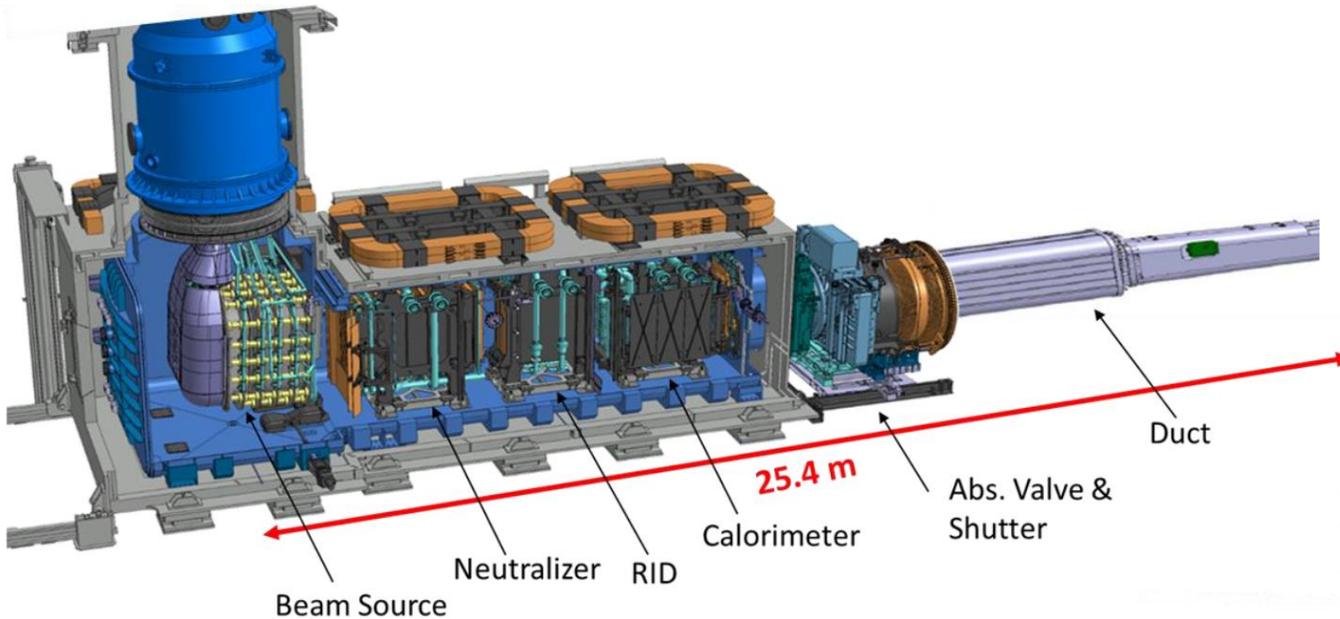
[1] P. Veltri et al. 8th International symposium on Negative Ions, Beams and Sources Padova, Italy, Oct. 2-7, 2022

[2] E. Sartori et al. Plasma Properties in the Negative ion beam sources for fusion and recent results in view of ITER, Plasma 2025, 15-19 September 2025, Warsaw (Poland)

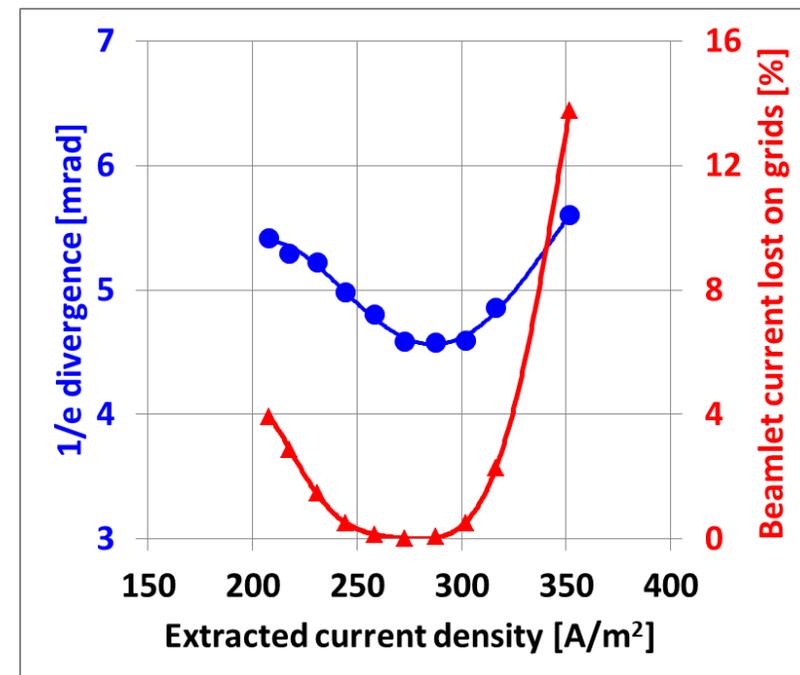
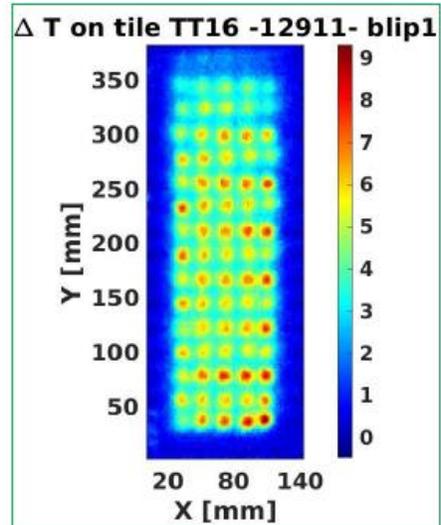
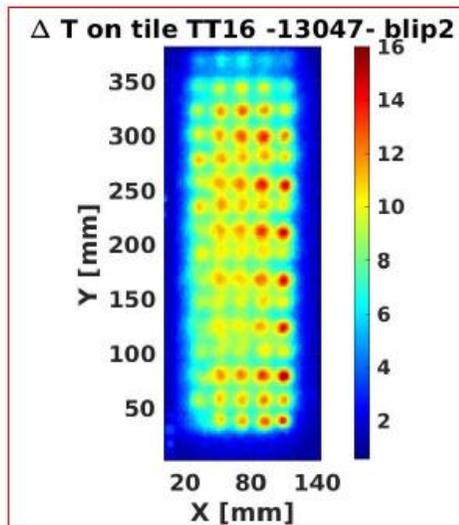
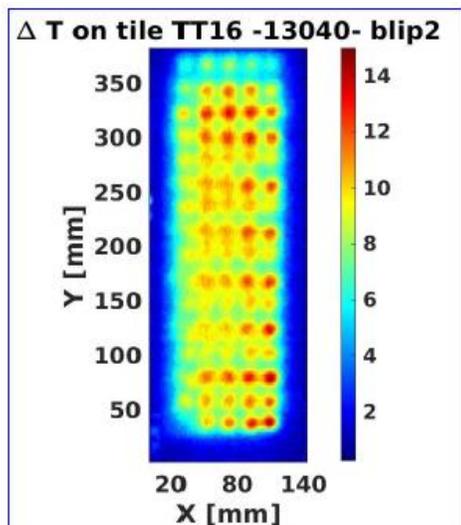
THANK YOU FOR YOUR ATTENTION !

Features of the ITER HNB accelerator

Parameter		
Species	H ⁻	D ⁻
Beam energy [MeV]	0.87	1
Beamlet divergence [mrad]	<7	<7
Beamlet aiming [mrad]	-2< β <2	-2< β <2



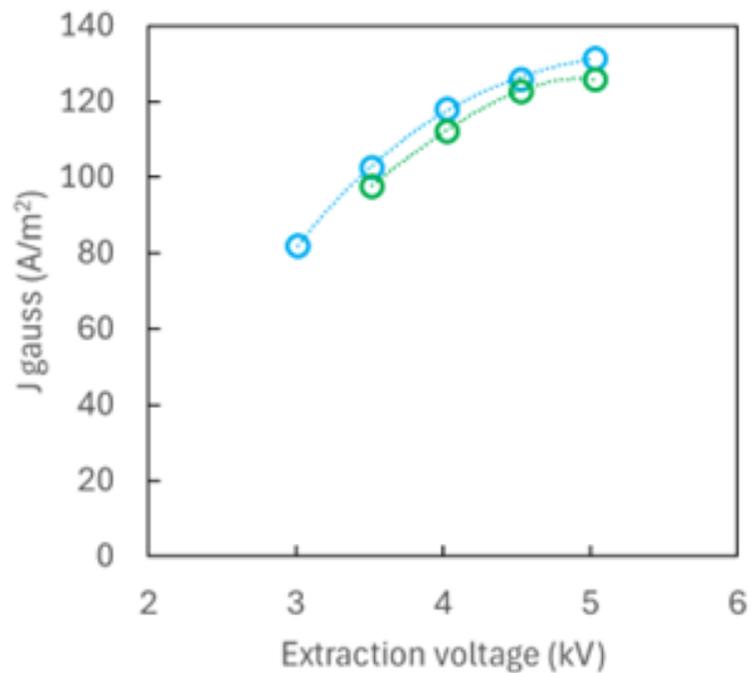
P. Veltri et al., 8th International symposium on Negative Ions, Beams and Sources Padova, Italy, Oct. 2-7, 2022



Single beamlet optics simulation for MITICA.
 $U_{ex}=9\text{ kV} - U_{acc}=5\times 200\text{ kV}$

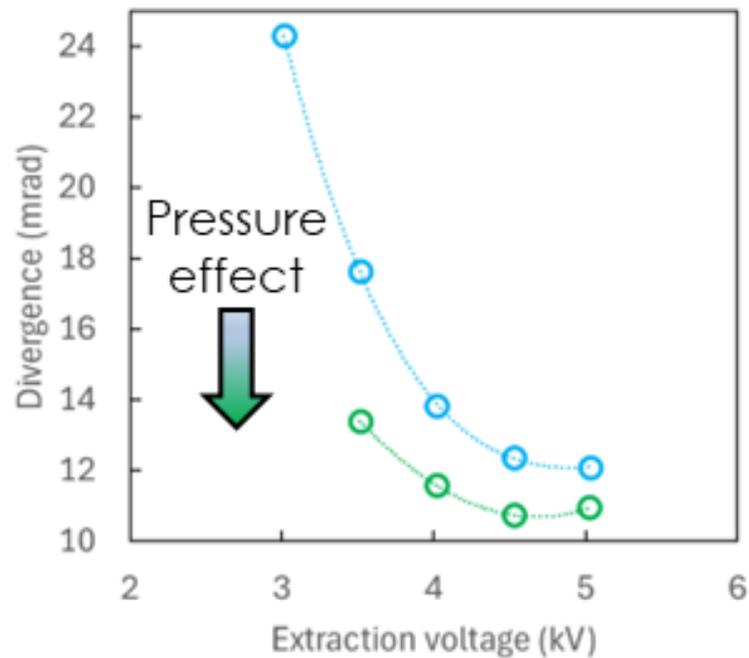
G. Q. Saquilayan et al. *J. Phys.: Conf. Ser.* **2244**
012091
Presented at ICIS conference 2021

Current density



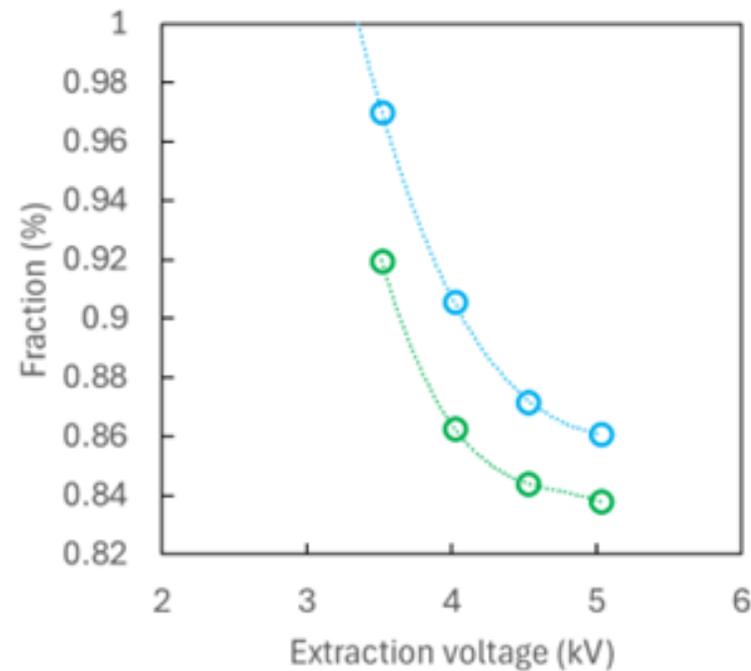
○ 0.3Pa ○ 0.42Pa

Divergence



○ 0.3Pa ○ 0.42Pa

Gaussian fraction



○ 100/120 ○ 0.42Pa

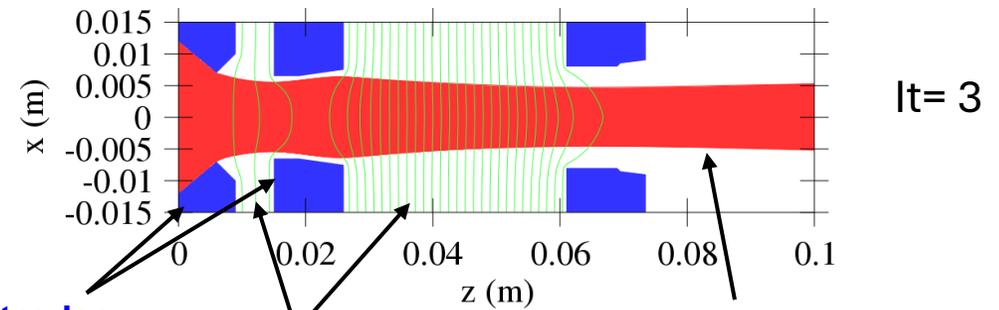
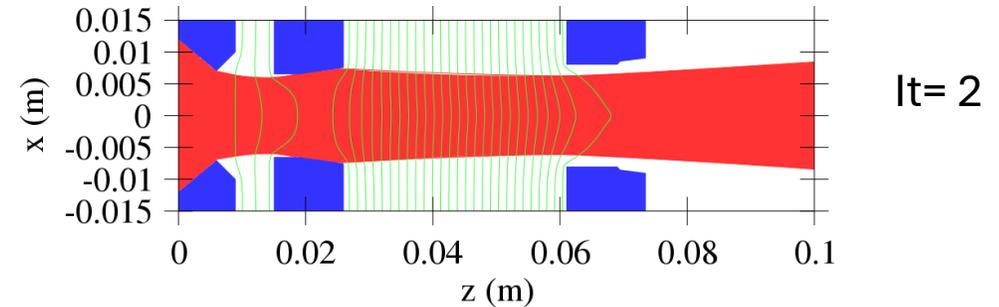
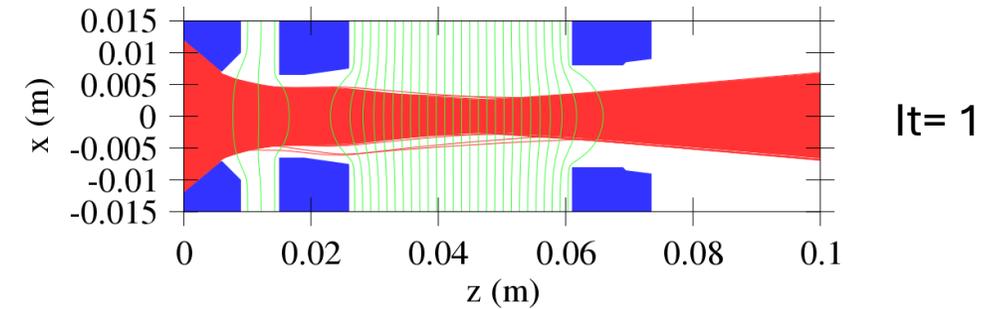
SPIDER SO-2 results [2]

Ray-tracing simulations

- Boundary conditions: grid potential $\rightarrow \nabla^2 V = 0 \rightarrow V(x,y,z)$
- Particles tracing in electro-magnetic fields
- Space charge deposition on mesh nodes $\rightarrow n(x,y,z)$
- Solve Poisson equation $\nabla^2 V = -\frac{\rho}{\epsilon_0} = -n \frac{e}{\epsilon_0} \rightarrow V(x,y,z)$
- Repeat up to numerical convergence

IBSimu

<https://ibsimu.sourceforge.net/>



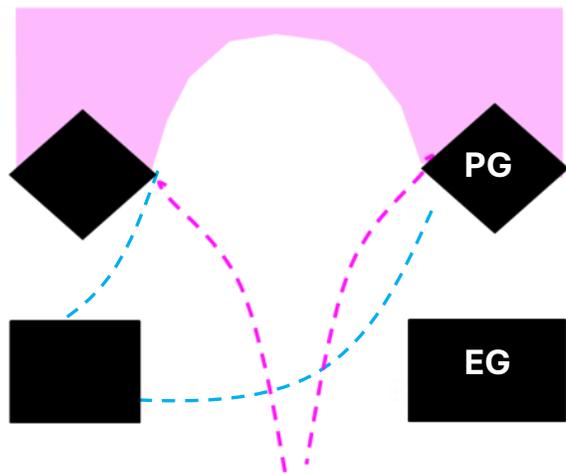
Electrodes

Equipotential surfaces

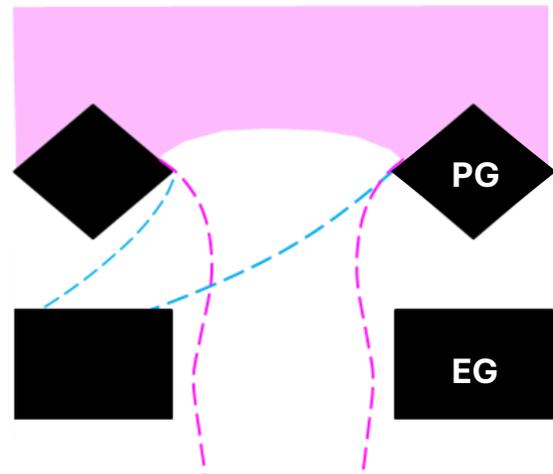
Particle trajectories

Beamlet perveance

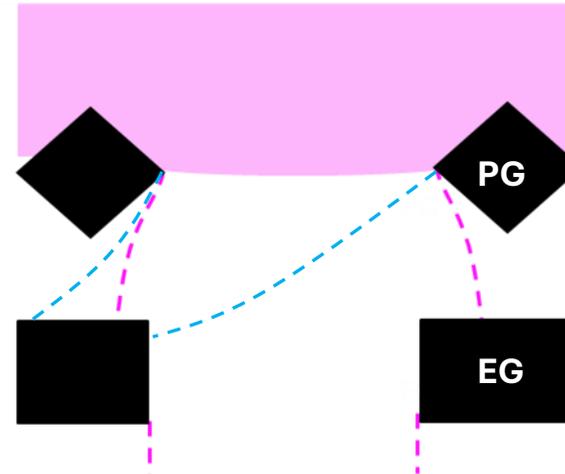
- Beamlet particles experience a force that is perpendicular to the **equipotential surfaces**
- The most important equipotential surface is the plasma **meniscus**; i.e. the surface separating plasma and beam
- The meniscus shape depends on the **space charge**; which is described by the so-called **perveance**



Under-perveance



Perveance match

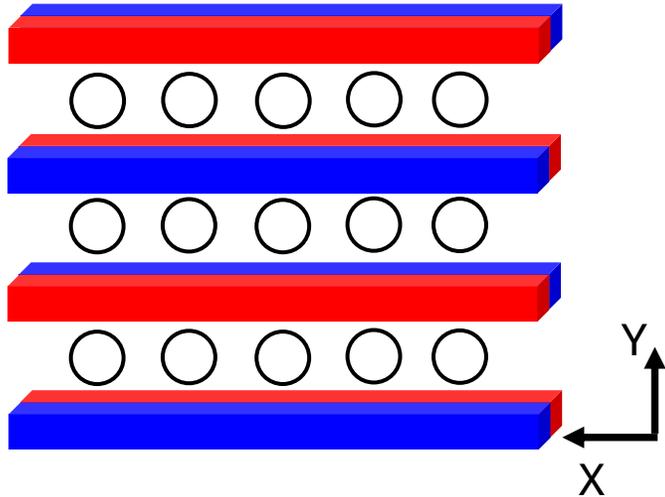


Over-perveance

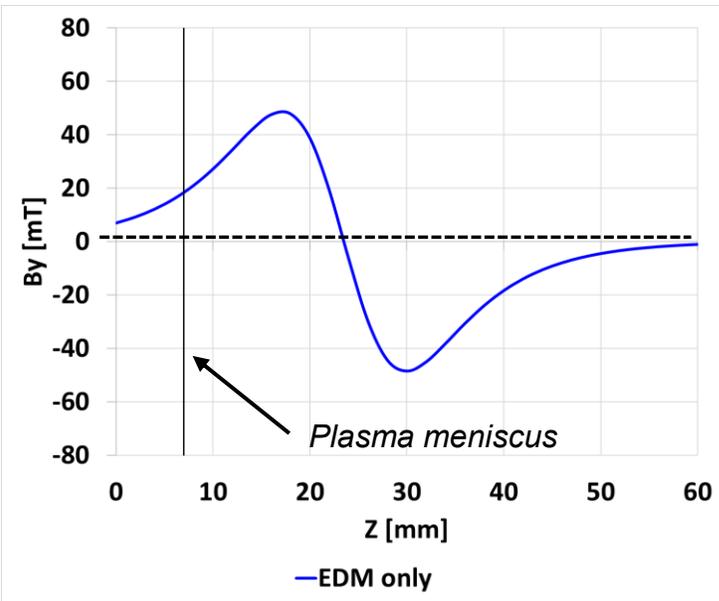
$$\Pi = \frac{j_{ex}}{U_{ex}^{3/2}}$$

$$1 \mu\text{Perv} = 10^{-6} \text{ Am}^{-2}\text{V}^{-3/2}$$

Sources for beam aberrations: magnetic field

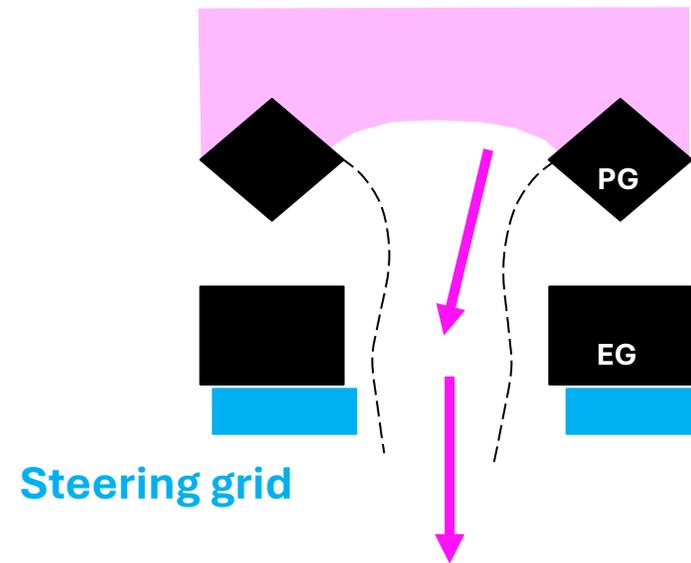


- Cusp magnets embedded in the EG to dump electrons
- Effective line integral is from the plasma meniscus at $z=z_{men}$
 - a net deflection β is induced
 - Such deflection depends on perveance $\beta = \beta(\Pi, \dots)$



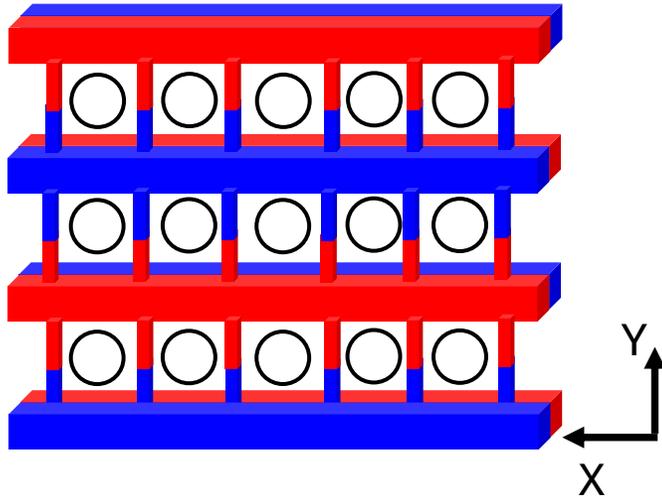
$$\beta \sim \int_{-\infty}^{+\infty} B_y dz = 0$$

$$\beta \sim \int_{z_{men}}^{+\infty} B_y dz \neq 0$$

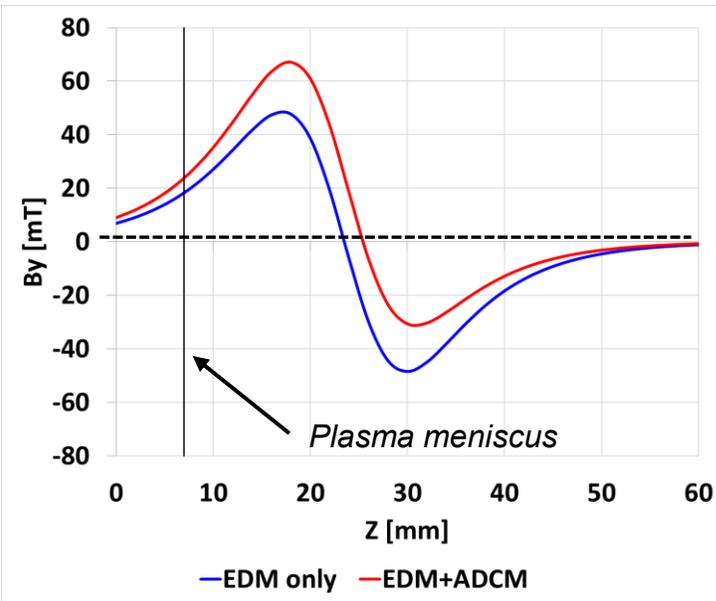


Standard method:
Electrostatic steering by aperture offset

Sources for beam aberrations: magnetic field



- Cusp magnets embedded in the EG to dump electrons
- Effective line integral is from the plasma meniscus at $z=z_{men}$
 - a net deflection β is induced
 - Such deflection depends on perveance $\beta = \beta(\Pi, \dots)$
- Another possible solution is to tune the magnetic field profile by the so-called ADCM (Asymmetric Deflection compensation magnets)



$$\beta \sim \int_{-\infty}^{+\infty} B_y dz = 0$$

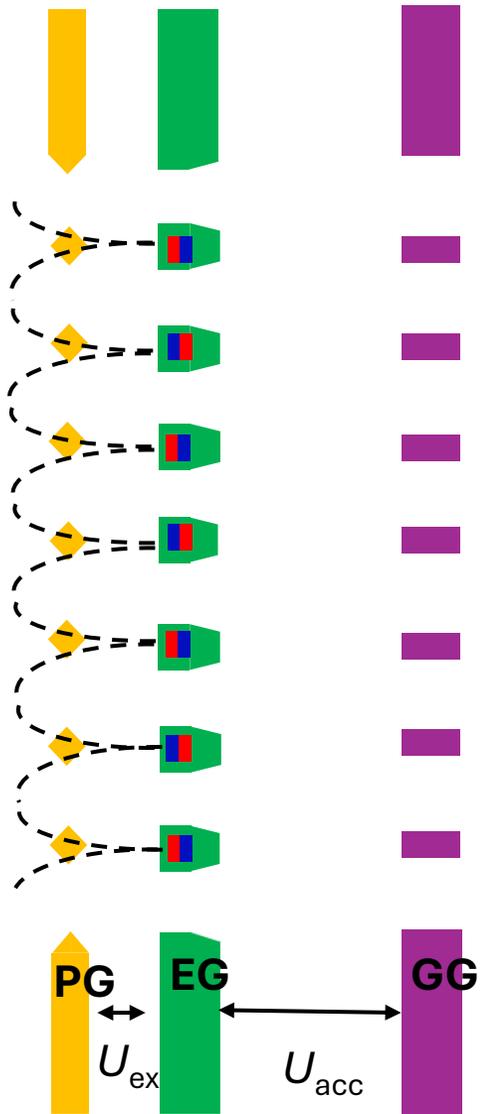
$$\beta \sim \int_{z_{men}}^{+\infty} B_y dz \neq 0$$

$$\beta \sim \int_{z_{men}}^{+\infty} B_y dz = 0$$

Pro: Compensation is energy independent

Con: Slight aberration of beamlet divergence along Y

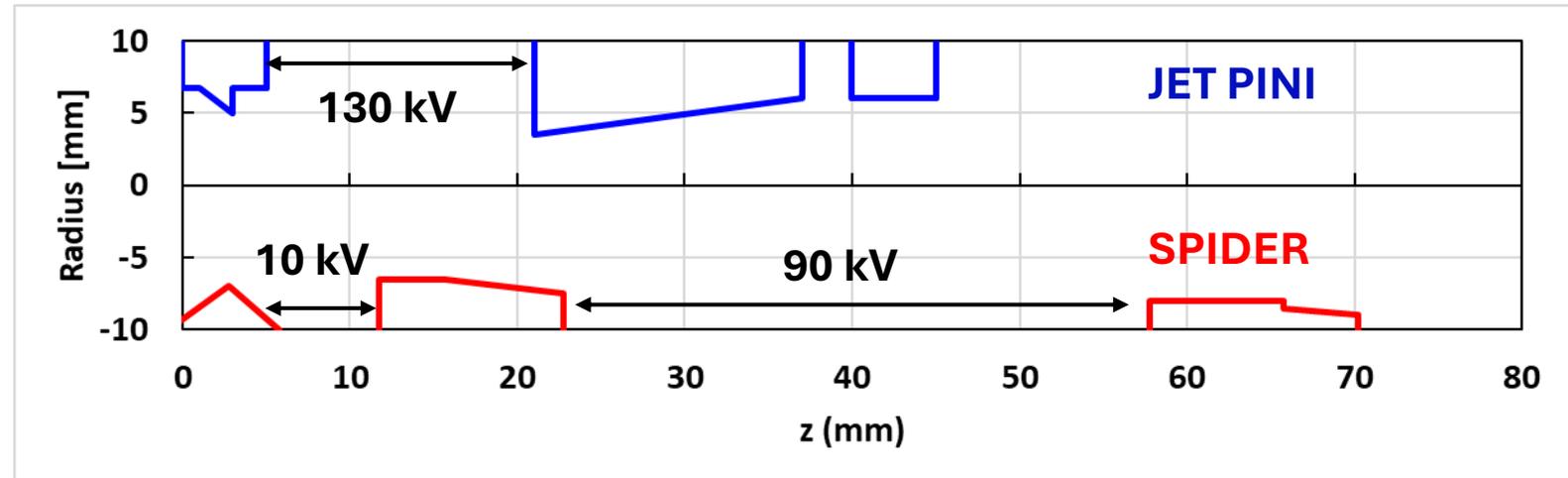
How does the beam source work?

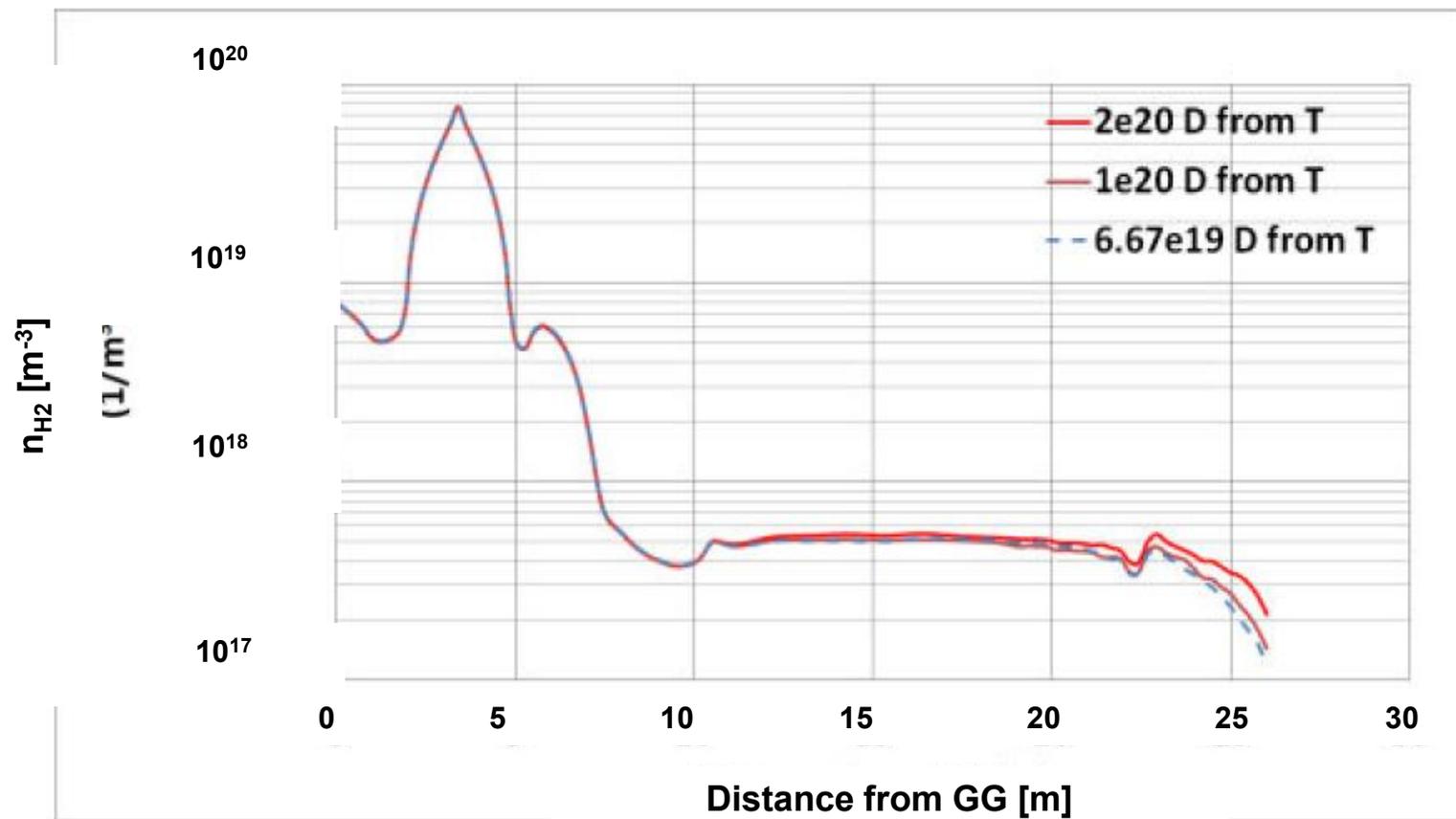


Aim 1: Dump co-extracted e^- before full acceleration

Solution

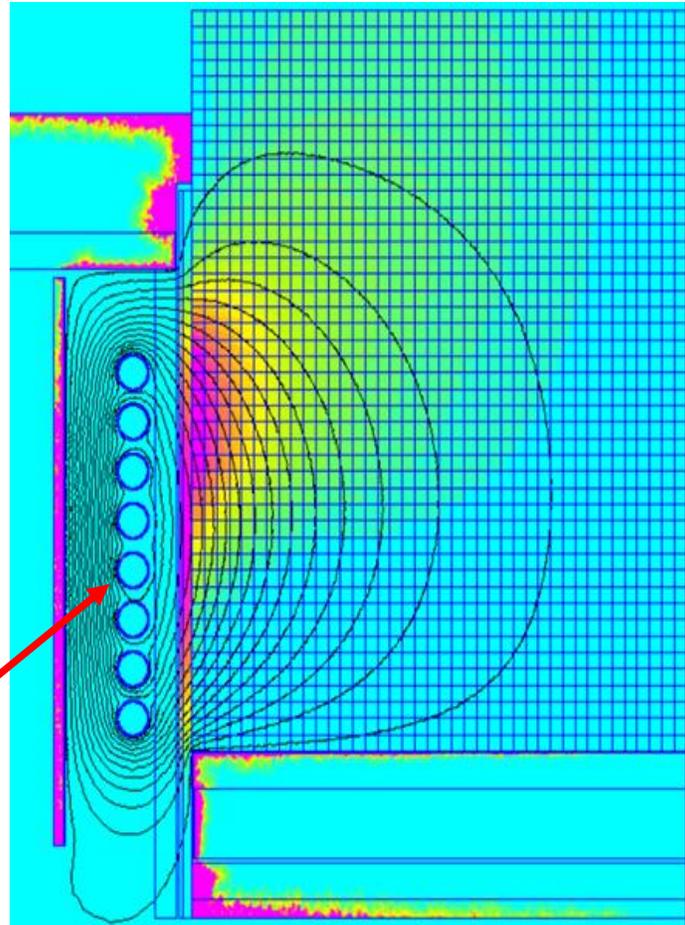
- Split accelerator in 2+ gaps
- Apply $U_{ex} \ll (U_{ex} + U_{acc}) = U_{tot} = E_{beam}/e$ in first gap
- Split beam in beamlets \rightarrow Grid shaped electrodes
- Embed permanent magnets in first electrode





Adapted from: M. J. Singh et al. AIP Conf. Proc. **1655**, 050011 (2015);

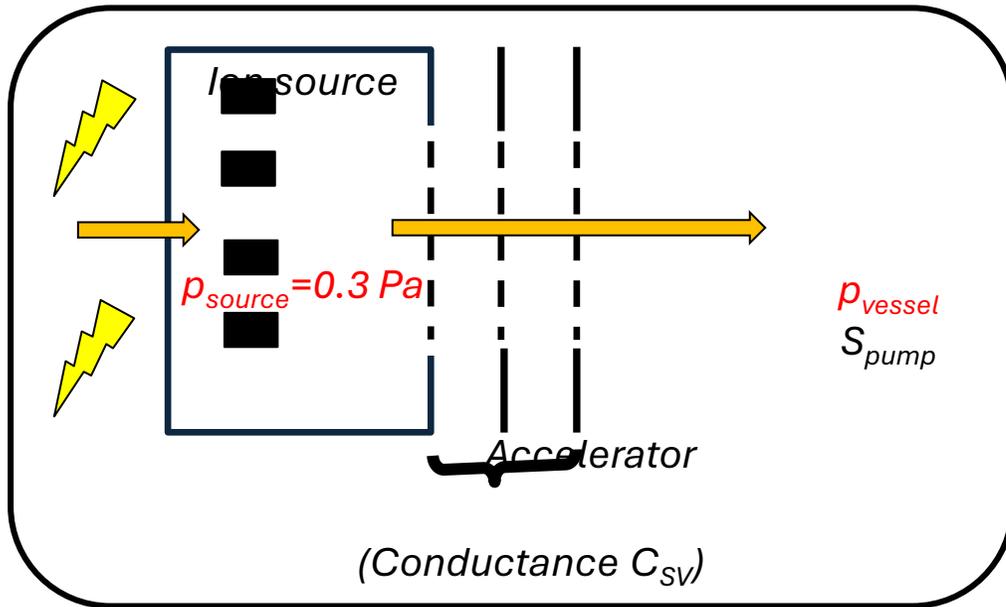
MINION (Magnetized ICP for Negative Ion Operation in NBI)



FEMM e.m. simulation



Plasma expansion in magnetic field



RF discharges at the back of the source

Operation with all of the 8 drivers was possible only for

$$p_{\text{vessel}} < 40 \text{ mPa}$$

$$q [\text{Pa} \cdot \text{m}^3/\text{s}] = S_{\text{pump}} [\text{m}^3/\text{s}] p_{\text{vessel}} [\text{Pa}] = C_{\text{sv}} (p_{\text{source}} - p_{\text{vessel}})$$

→ Long term: Vacuum enhancement module (VEM)

→ Short term: Reduce C_{sv} → Aperture masking

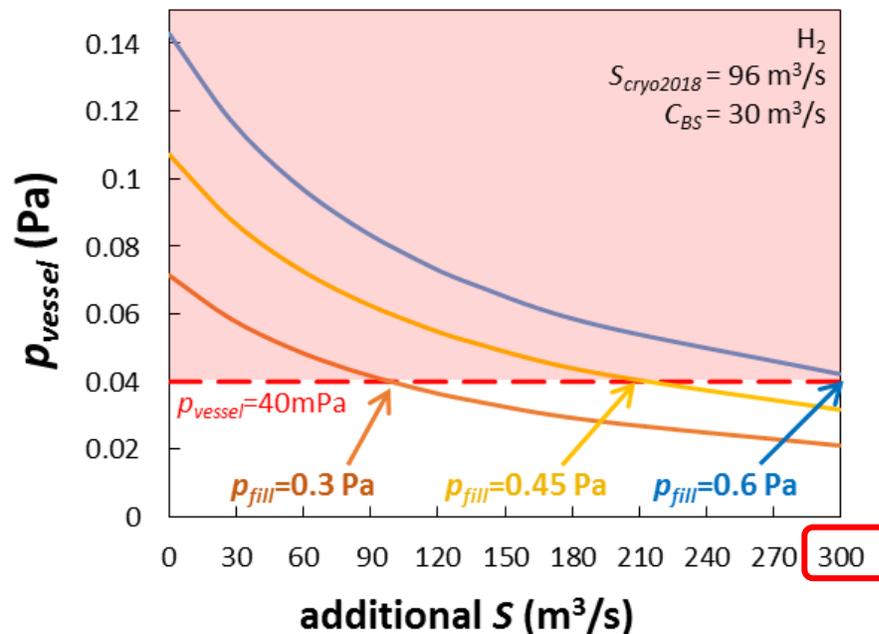
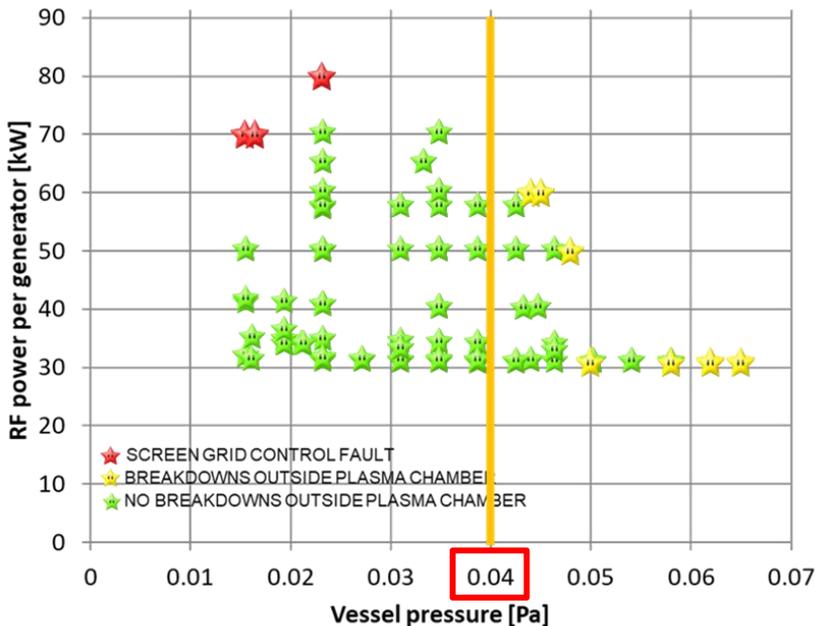
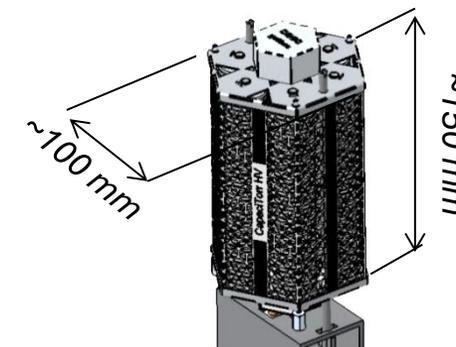
Background

A series of concurrent factors resulted in a vacuum system not powerful enough:

- design range of pressure/conductance vs actual operation
- commercial cryopump performances
- **RF discharges in vacuum**

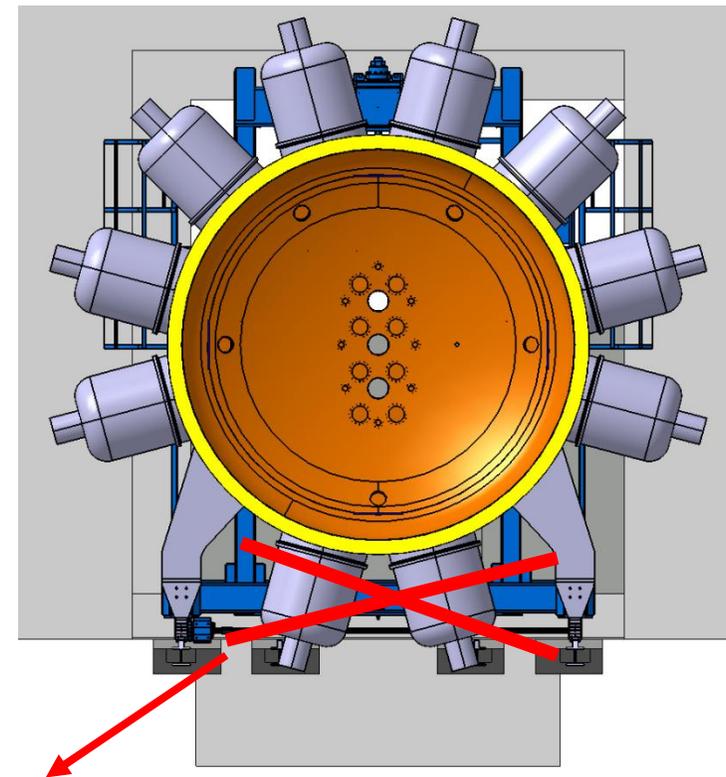
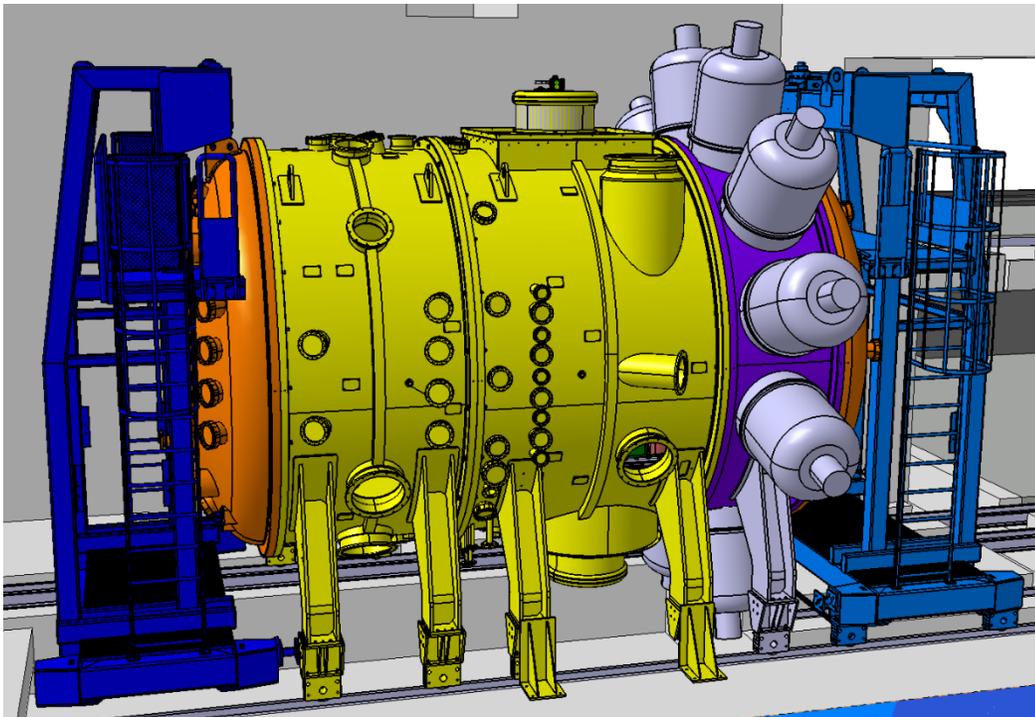
- The base unit of the pump is the **Non Evaporable Getter** cartridge
- **2 x 192 NEG cartridges** have a pumping speed for H₂ of about **300 m³/s**
- **H₂ Capacity** for 2 x 192 NEG cartridges = **440000 Pa*m³**
- **Heaters** needed for the regeneration with dedicated power supply and control unit

NEG Cartridge (saes)



A preliminary assessment compared possible solutions (commercial cryopumps, custom cryopumps and NEG pumps), leading to the final choice

- Installation of a **new vessel module of ~1.2 m**
- 10 COOLVAC 30000 iCL cryopumps (Leybold) ($S=30\text{m}^3/\text{s}$, Capacity= $10000\text{ Pa}\cdot\text{m}^3$)

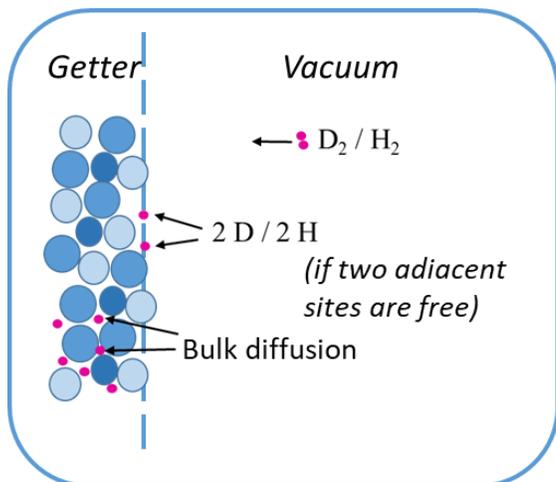


- SPIDER Lower side not available → **only 8 pumps could be installed**

(without considering buckling due to high ratio $\frac{\text{holes surface}}{\text{ring vessel surface}}$)

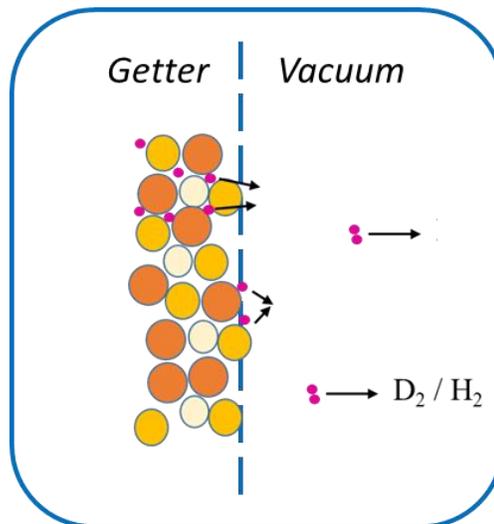
Sorption

RT < NEG Temperature < 150 °C



Regeneration

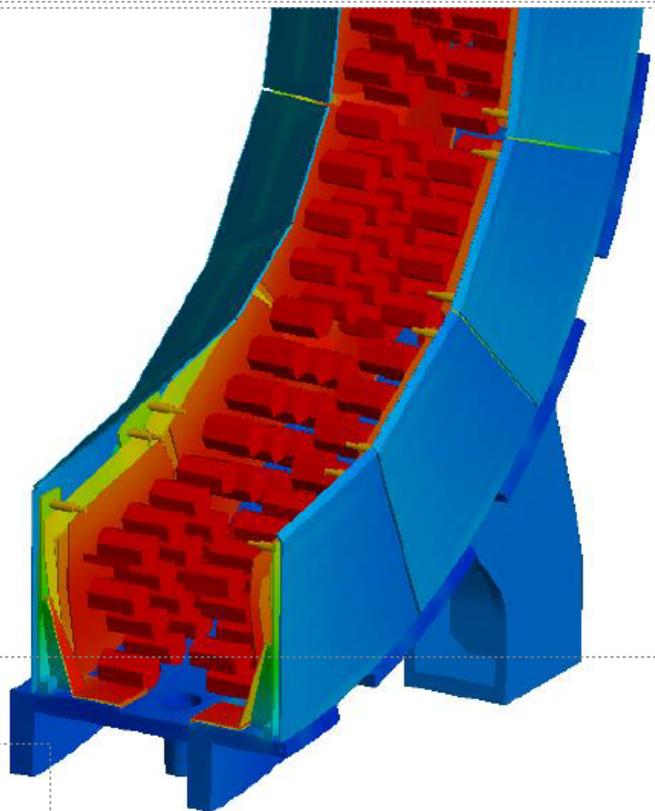
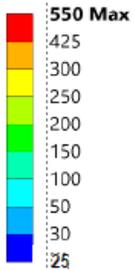
NEG Temperature > 450 °C



Mechanisms

- Metals suitable as NEG material belong to group 4 of the periodic table (Zr, Ti)
- CO, CO₂, O₂, N₂ produce carbides, oxides, and nitrides layers on the NEG surface followed by diffusion into bulk by heating
- **H₂** and its isotopes **dissolve in the bulk** forming solid solution (sorption), by heating the process is reverted and H₂ is **desorbed** (regeneration) → **REVERSIBLE**

Type: Temperature
 Unit: °C
 Time: 75600
 06/05/2022 09:56



- Long regeneration during weeknds: 550°C maintained during 20h. Risk of overheating delicate parts of the beam source (e.g. diagnostics)
- effective emissivity of the cartridges tuned at steady-state on the basis of mockup pump tests
- Total heating power 111 kW (20h)
- At present, focus on the optimization of the cooling down phase: target is allow regeneration every night, reaching $\leq 80^\circ\text{C}$ of NEG cartridges for the beam source operation in a relatively short t_{cooldown}

