MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

ASDEX Upgrade

UNIVERSIDAD DE SEVILLA

PSFT Plasma Science and Fusion Technology

# First measurements and validation of the imaging heavy ion beam probe at the ASDEX Upgrade tokamak

**P. Oyola**, J. Galdon-Quiroga, G. Birkenmeier, H. Lindl, A. Rodriguez-Gonzalez, G. Anda, E. Viezzer, J.Rueda-Rueda, B. Tal, M. Garcia-Munoz, A. Herrmann, J. Kalis, K. Kaunert, T. Lunt, D. Refy, V. Rohde, M. Sochor, M. Teschke, M. Videla-Trevin, E. Wolfrum, S. Zoletnik and the ASDEX Upgrade team

High Temperature Plasma Diagnostic Conference 2024 - Asheville

# Edge dynamics determine confinement

Plasma edge is critical for plasma confinement:

- Separates confined hot plasma from the wall.
- Establishes the transport of energy and particles.

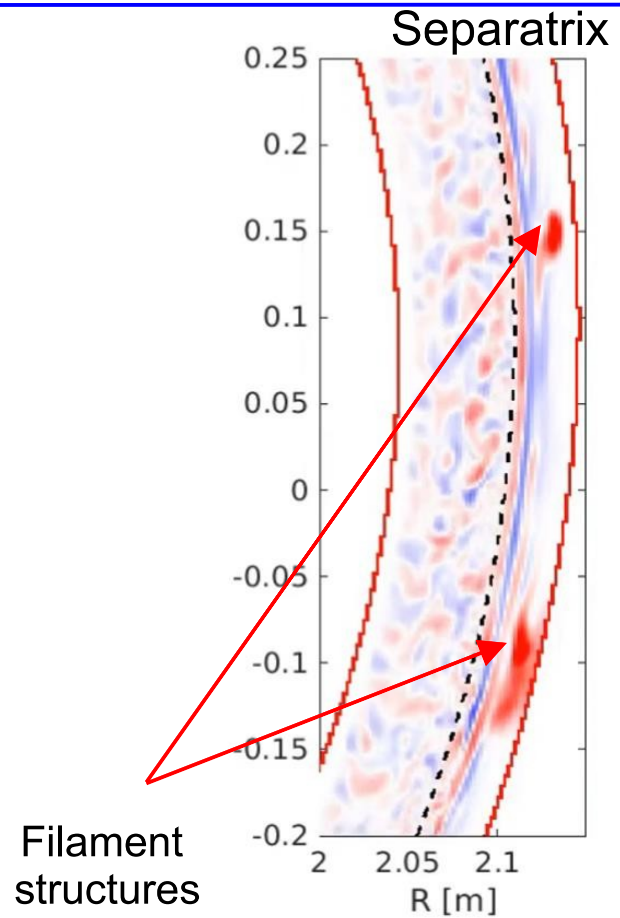



Figure from W. Zholobenko *et al.* PPCF 2021

# Edge dynamics determine confinement

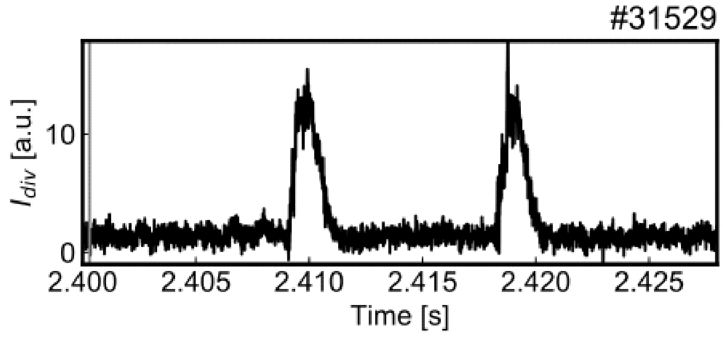
Plasma edge is critical for plasma confinement:

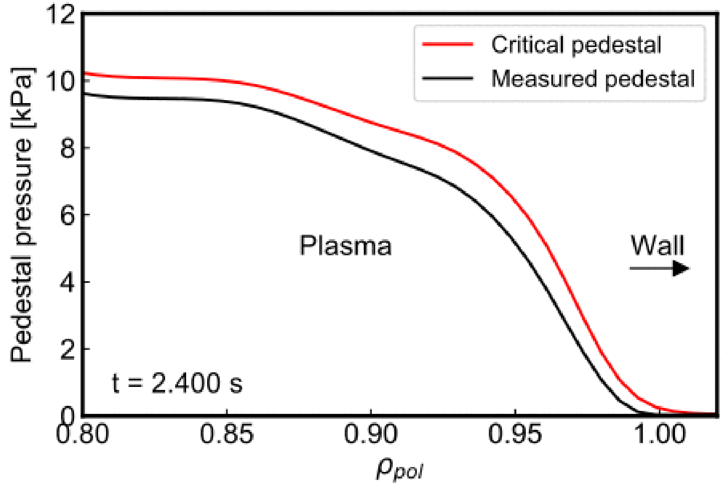
- Separates confined hot plasma from the wall.
- Establishes the transport of energy and particles.

$\nabla p$ and $j_\phi$ are a source of free energy

- ELMs can cause a drop of ~10% of energy.
- Enhances the power to the wall up to ~10MW/m$^2$

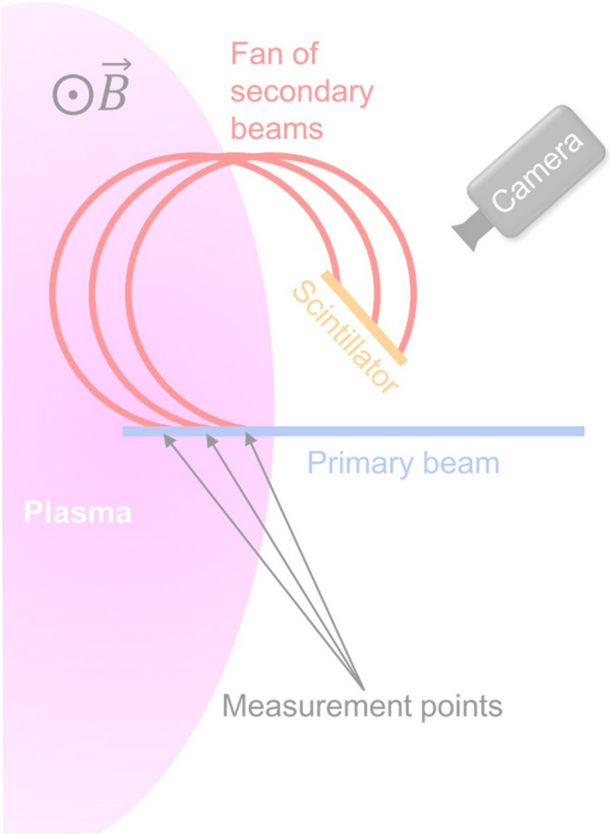
**Precise measurements of $j_\varphi$ and $n_e$ to validate models**




Courtesy of P. Cano-Megias

# Outline

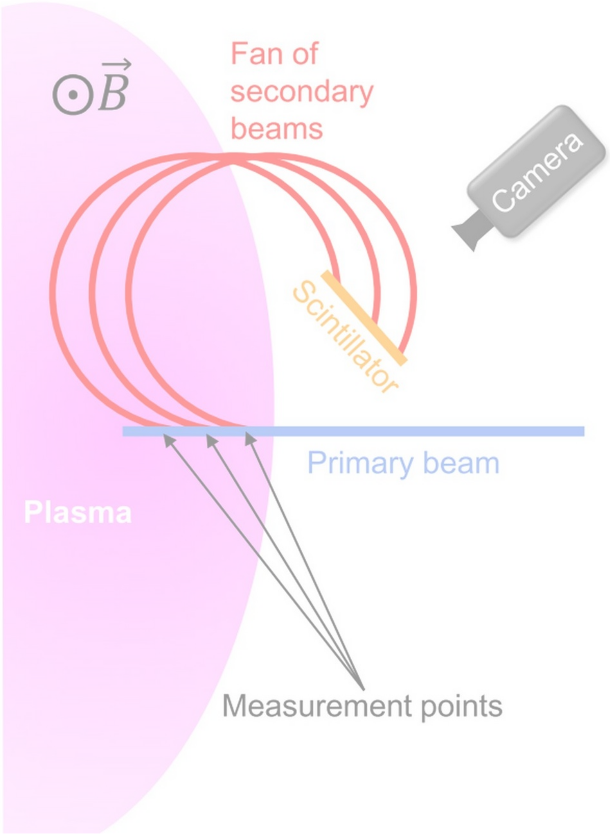



The imaging Heavy Ion Beam Probe

First measurements

Validation of *i-HIBPsim* and applications

# Outline




The imaging Heavy Ion Beam Probe

Working principle

Diagnostic setup

First measurements

Validation of *i-HIBPsim* and applications

# Working principle

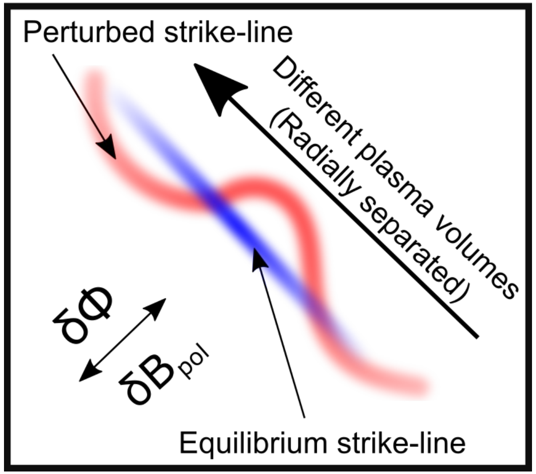
- **Primary beam**: $Cs^0$, $Rb^0$
  Ionizes around the separatrix → Measurement points

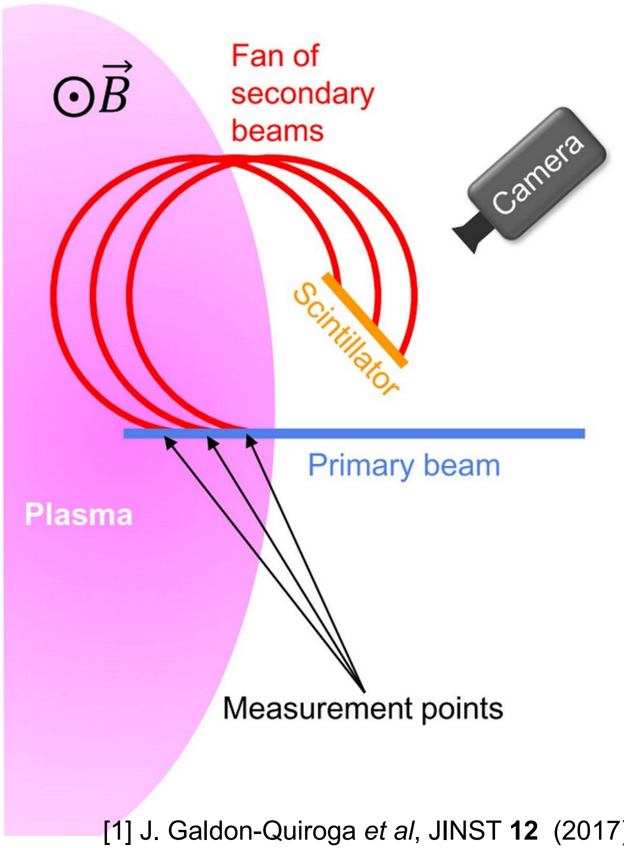
- **Secondary beam**: $Cs^+$, $Rb^+$
  Gyromotion until reaching the scintillator

Electromagnetic perturbation
($\delta B_{pol}$, $\delta\Phi$)
**Strike-line displacement**

Density perturbation ($\delta n_e$)
**Intensity variation**

CAMERA VIEW

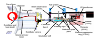




[1] J. Galdon-Quiroga *et al*, JINST **12** (2017)
[2] G. Birkenmeier *et al*, JINST ***14*** (2019)

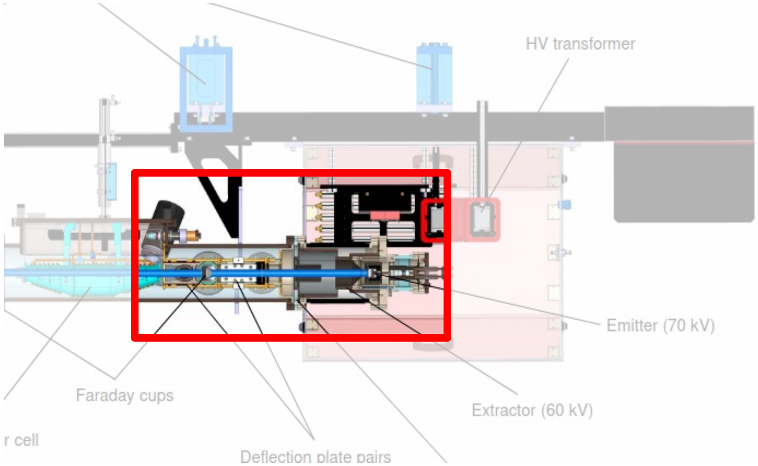
# Compact i-HIBP setup at the AUG tokamak

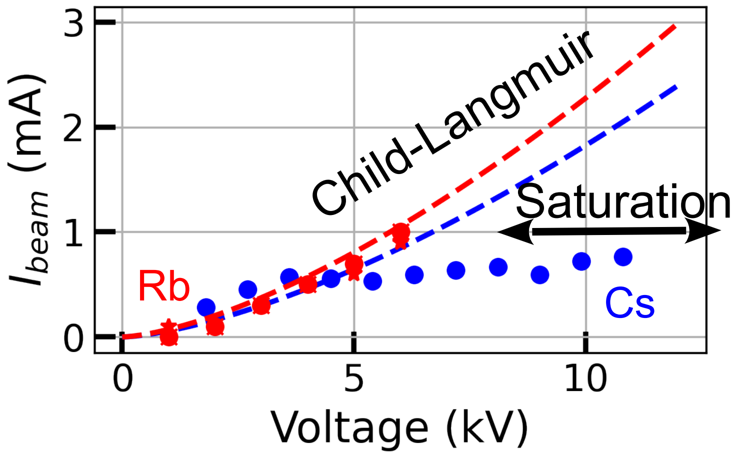


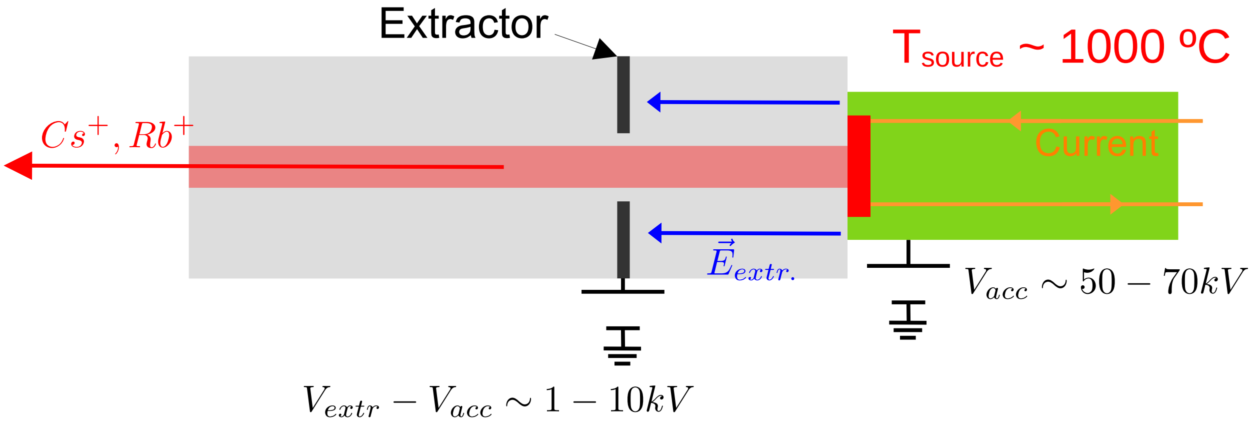
[3] G. Anda *et al*, RSI **89** (2018)

# Saturated currents with high extraction voltage

- Source heated up to ~1000 ºC.
- Extracted current measured by current sensors.
- Saturation of the current output due to:
  - Spatial charges effect.
  - Ion mobility.



# Neutralization cell with an efficiency of ~80%

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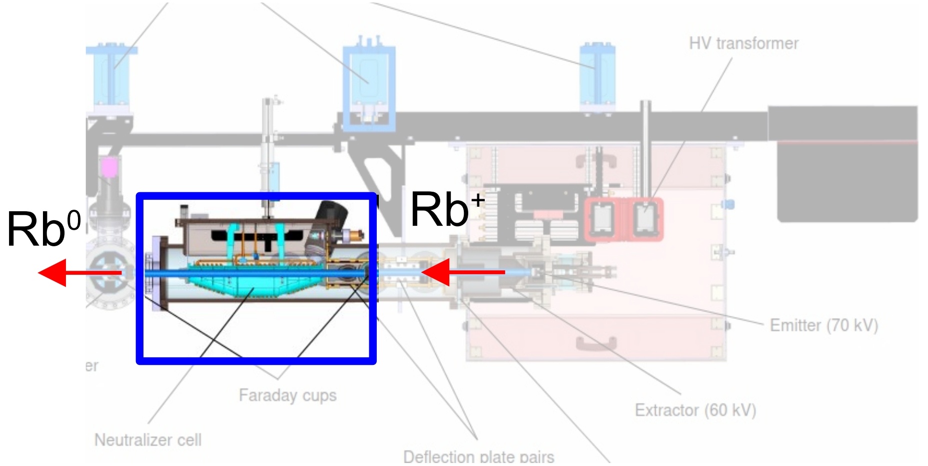
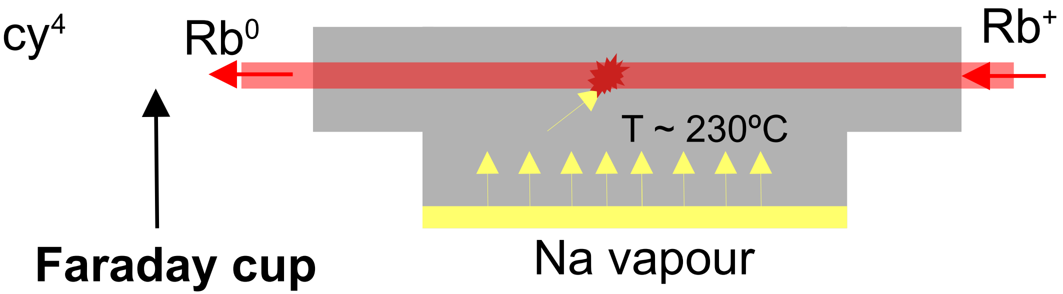
- Alkali beam is singly ionized at the exit.
- Hot sodium in the neutralizer
- Neutralizer is filled with Na
  - Alkali undergo CX reaction
- Up to an 80% of neutralization efficiency[4]




[4] J. Galdon-Quiroga *et al.*, RSI (2024)

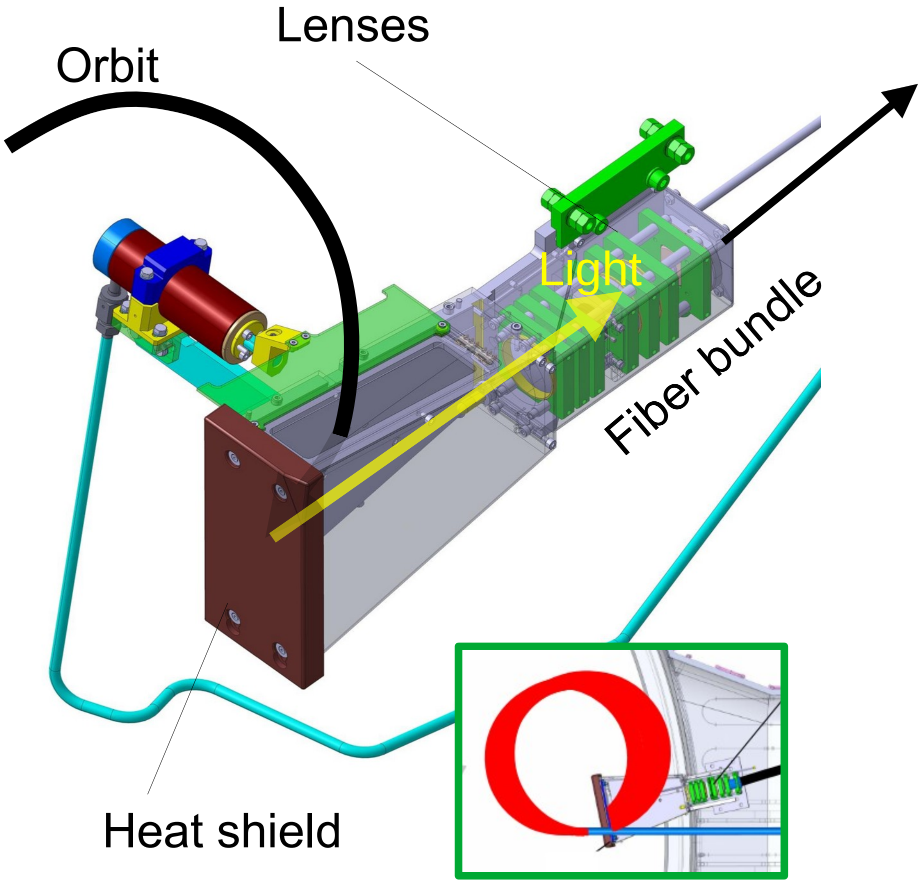
# Scintillator detector for augmented resolution

TG-Green ($SrGa_2S_4:Eu^{+2}$):

- Fast decay: 590 ns.
- Higher photon multiplication.
- Slower degradation.

Optics:

- Lenses for focalizing.
- SCHOTT image guide (1700 x 700 fibers).




[5] J.J. Toledo-Garrido *et al*, RSI (2021)
[6] M. Videla-Trevín, Msc Thesis (2021)

# Neutron flux strongly degrades the fibers

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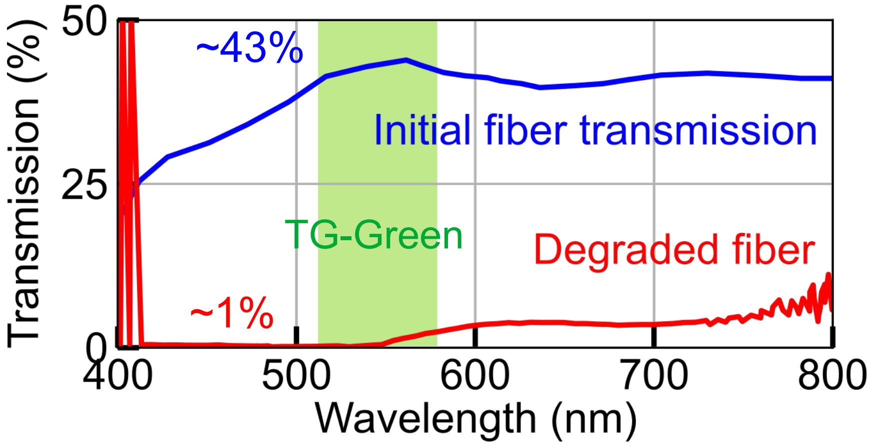
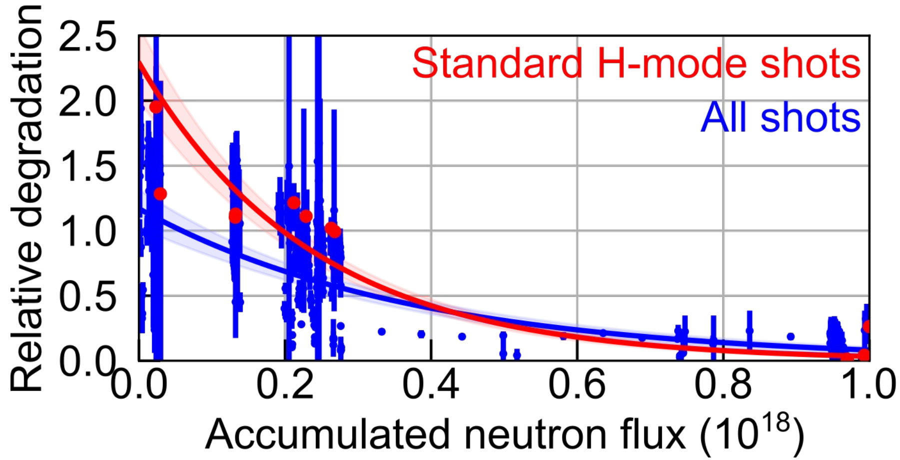
Strong neutron degradation due to the neutron flux:

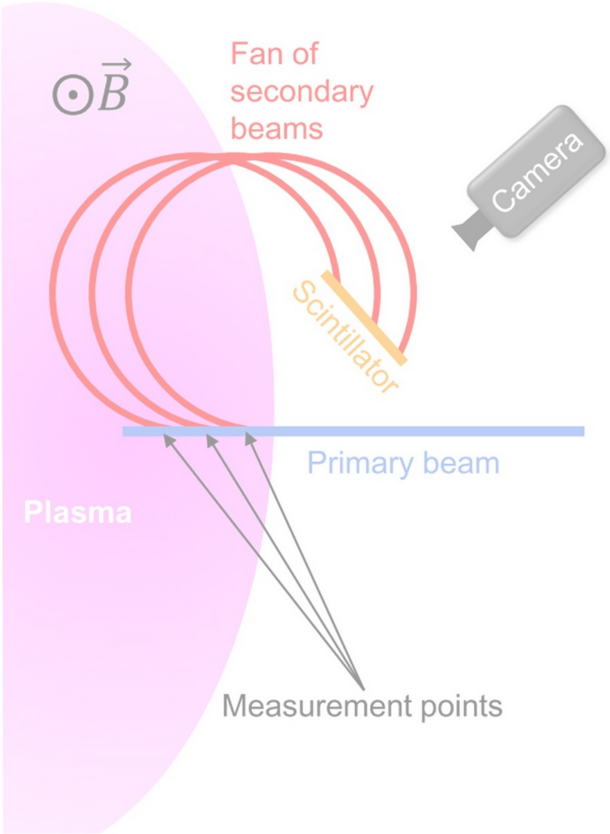
- Degradation down to ~1% after a campaign.
- Exponential degradation observed.
- Ex-vessel heating returns it back to its original transmission.
- In-vessel heating system* installed to heal the fibers up to ~25% of the original.




*Patent pending

# Outline




The imaging Heavy Ion Beam Probe

**First measurements**

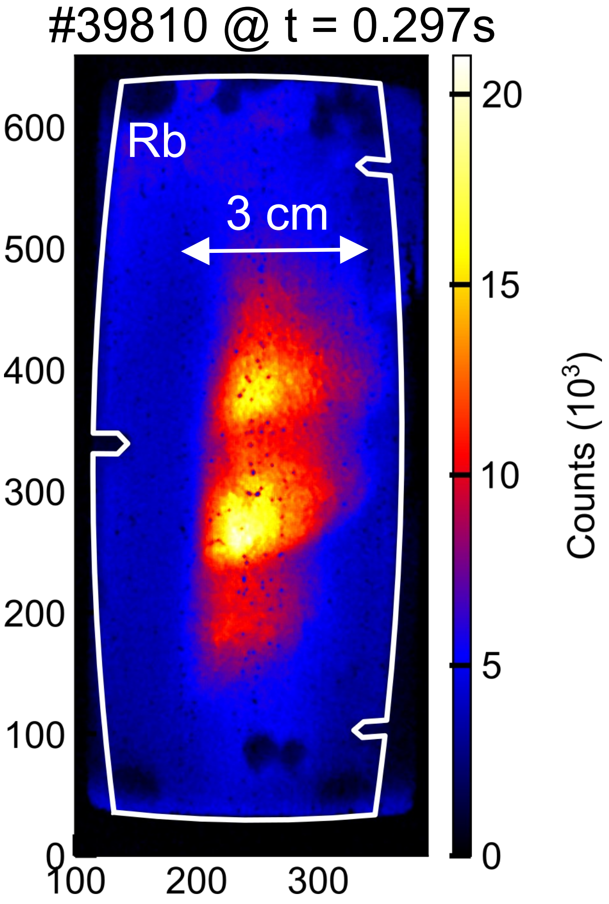
1st signals and commissioning

Operational space

Validation of *i-HIBPsim* and applications

# First scintillator images

- First scintillator images[4] obtained during the campaign 21/22:
  - Uncollimated signals with footprint of ~3 cm.

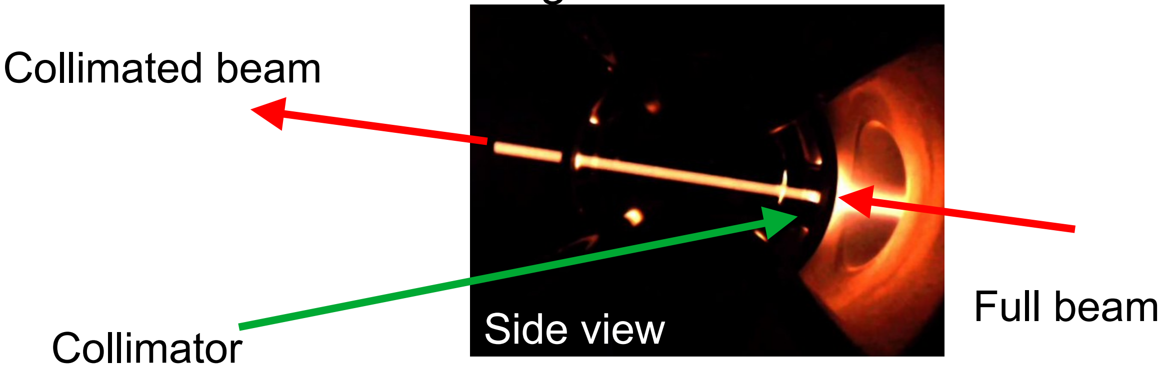



[4] J. Galdon-Quiroga *et al.*, RSI (2024)

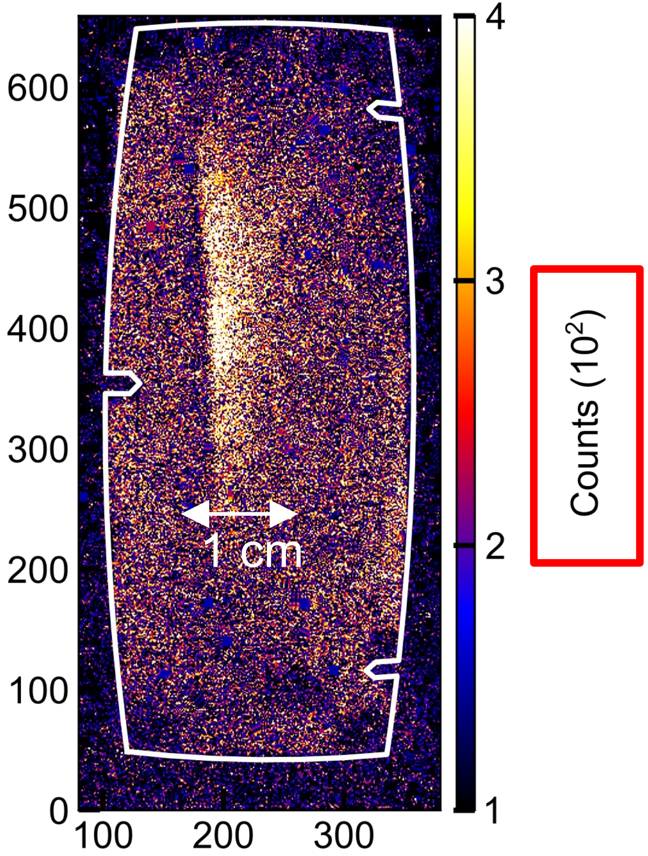
# Collimated beams are weaker

- First scintillator images obtained during the campaign 21/22:
  - Uncollimated signals with footprint of ~3 cm.
  - Collimation enhances resolution.

Diagnostic camera

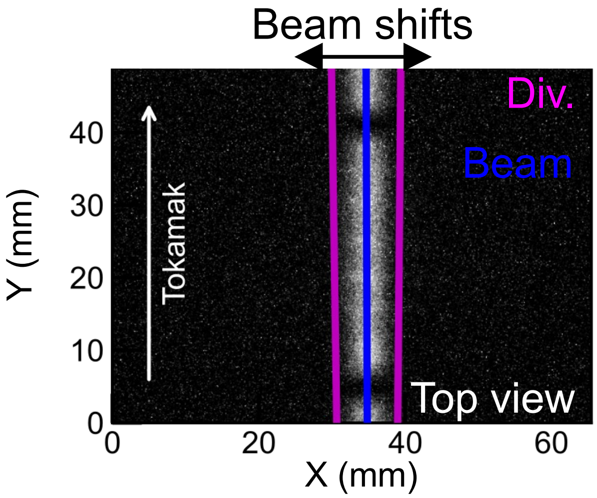


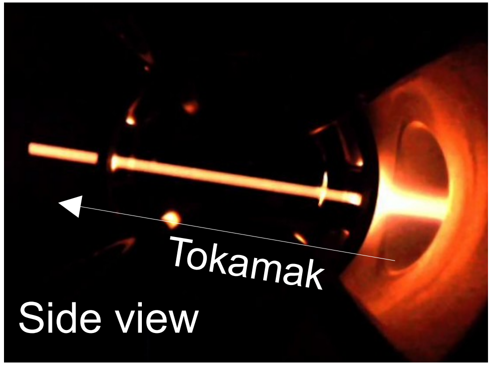

#40170 @ t = 1.96 s



# Diagnostic cameras provide accurate information on current beam location

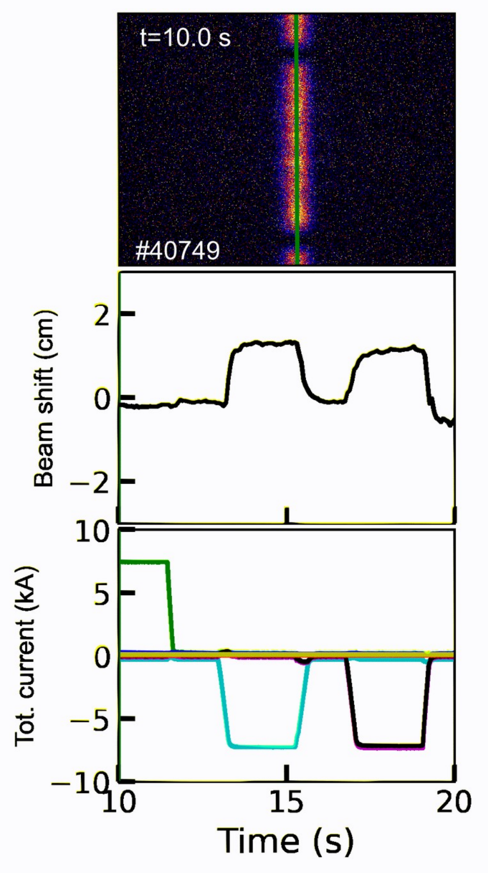
- Stray field slightly deviates the beam during ramps:
  - Beam cameras: after the neutralization.
  - Measurement of the beam deflection.



# Beam moves during current ramp phases

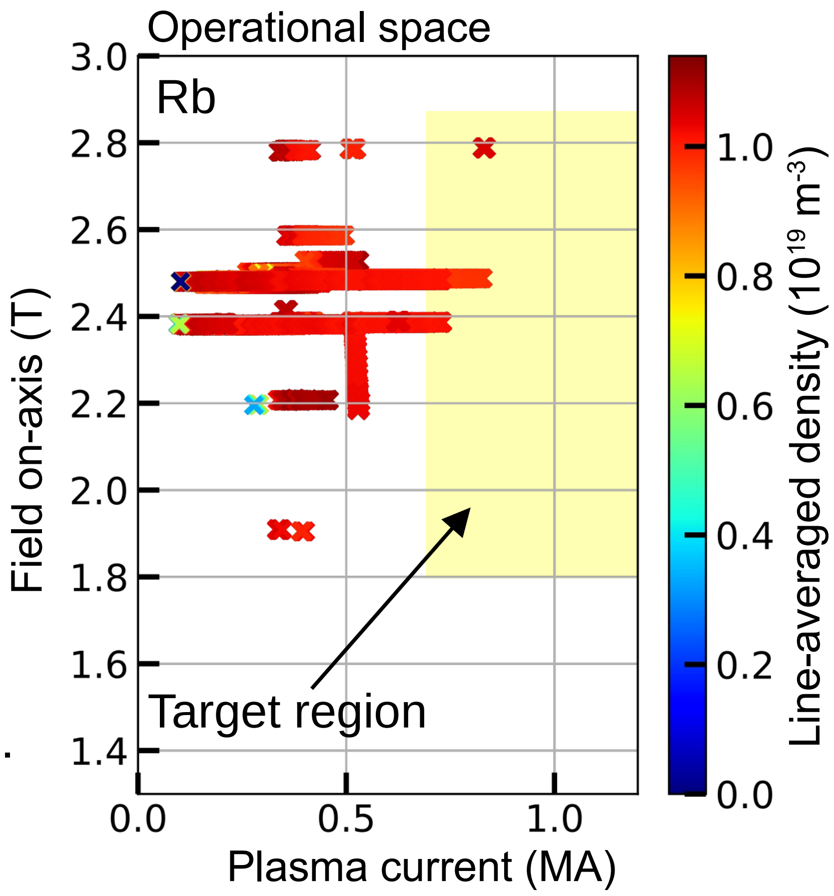
- Stray field slightly deviates the beam during ramps:
  - Beam cameras: after the neutralization.
  - Measurement of the beam deflection.
  - RT observation of the beam motion within the beam line.



# Beam signal obtained with low-density quiescient L-modes

Operational space:

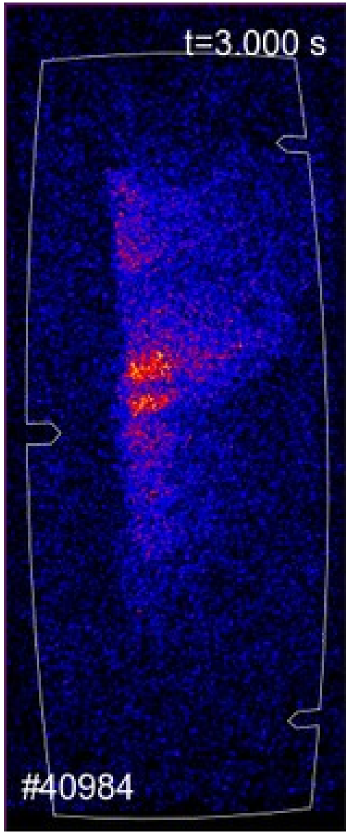
- First measurements span over large operational space.
- Low-density L-mode plasmas.
  - Large secondary-ionization.
  - Background light.
- Improvements to reach the target region in progress.



# Filamentary-like dynamics in the signal

Interesting dynamics observed in the i-HIBP signals:

- Dynamics where perturbation seems to propagate outwards (to the SOL):
  - Filamentary-like transport.

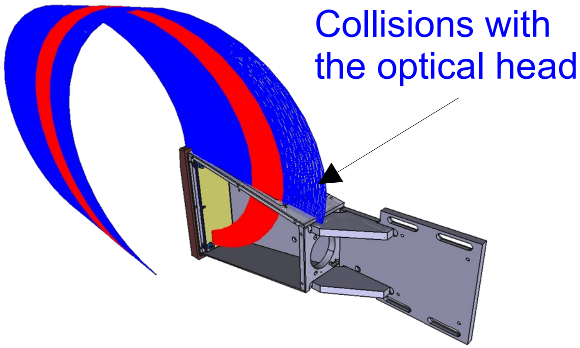


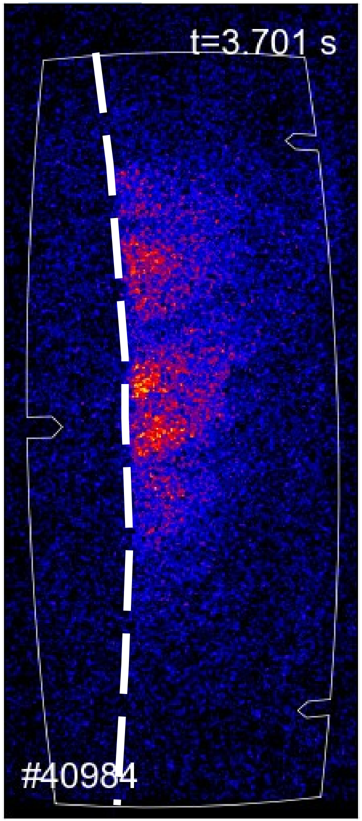
# Strong cut-off on the signal

Interesting dynamics observed in the i-HIBP signals:

- Dynamics where perturbation seems to propagate outwards (to the SOL):

- Cut-off observed in the signal.
  - Shadowing from the optical head.

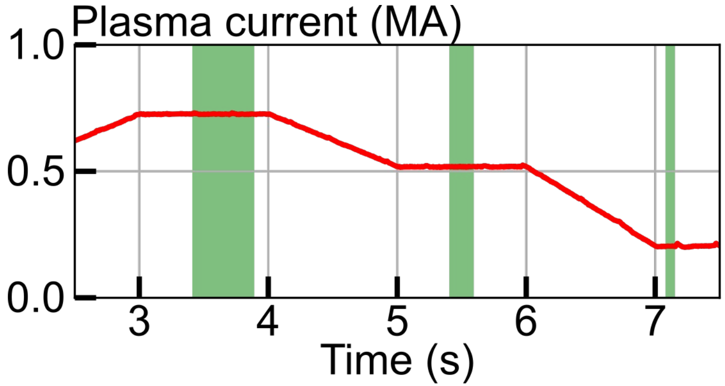


# Plasma current dependence of the cut-off

Interesting dynamics observed in the i-HIBP signals:

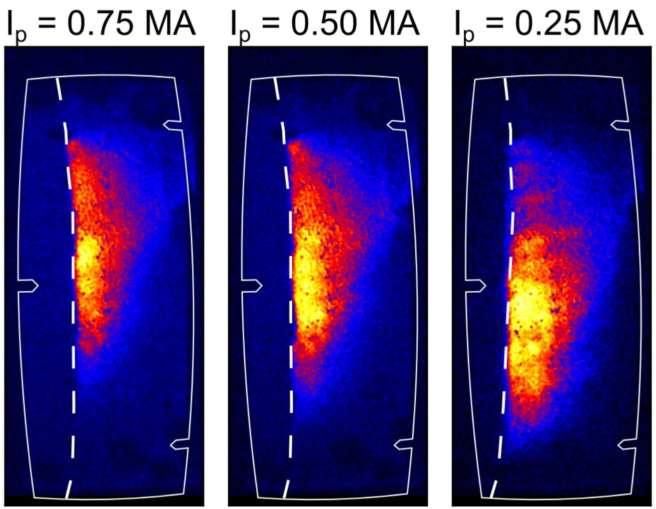
- Dynamics where perturbation seems to propagate outwards (to the SOL):




- Cut-off observed in the signal.

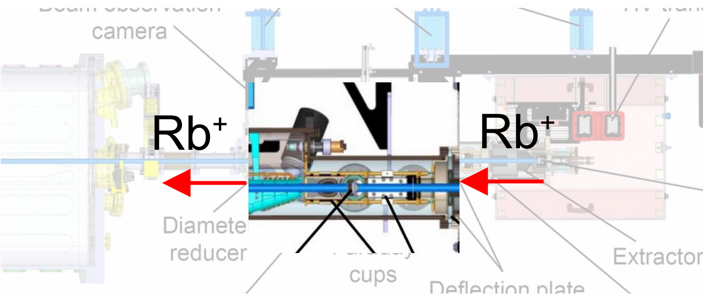
- Cut-off positions depends on the plasma current
  - Enables future magnetic field measurements!

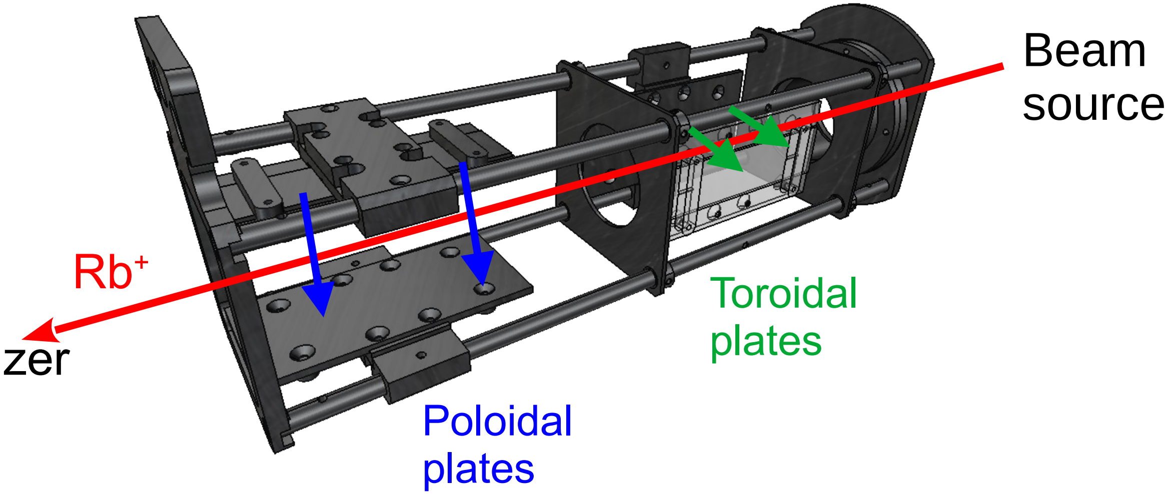
$$\frac{\Delta p_x}{\Delta I_p} \sim 1.1 \text{ cm/MA}$$ ⟷ Spatial resolution = 0.2 mm



# Beam chopper and deflection plates

- Beam chopper installed prior to neutralization
  - Electric field to slightly change the beam trajectory
  - Chopping to allow for background subtraction.



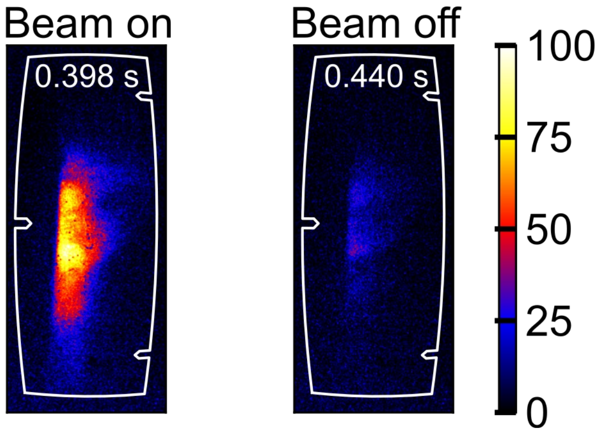



# Beam chopper correlates with signals at the scintillator



Beam chopper installed prior to neutralization:

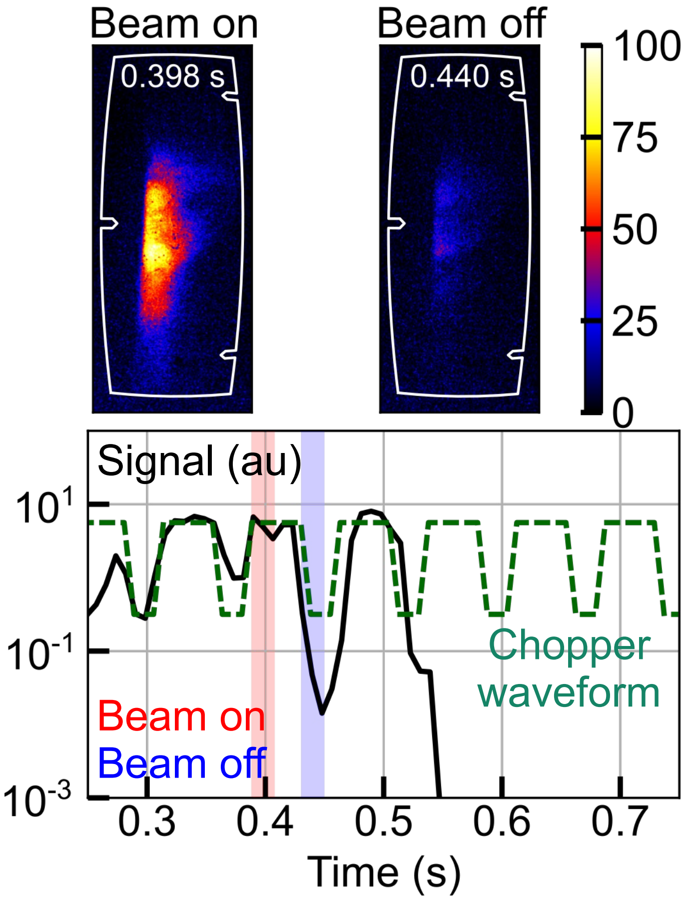
- Electric field to slightly change the beam trajectory.
- Chopping to allow for background subtraction.
- Chopper used during some discharges.
- Observable differences.



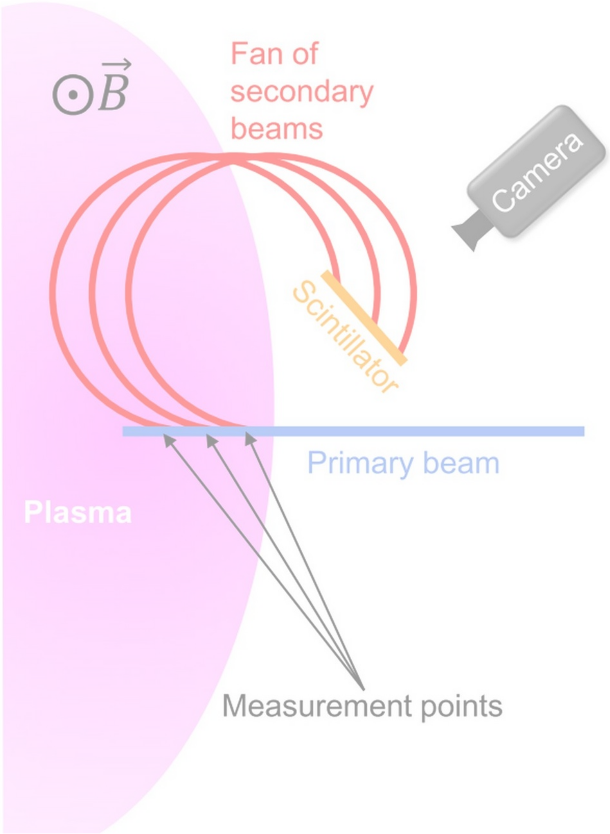
# Beam chopper correlates with signals at the scintillator

Beam chopper installed prior to neutralization

- Electric field to slightly change the beam trajectory.
- Chopping to allow for background subtraction.
- Chopper used during some discharges.
- Observable differences.
- **Good agreement between signal and chopper.**



# Outline




The imaging Heavy Ion Beam Probe

First measurements

Validation of *i-HIBPsim* and applications

Synthetic diagnostic

Density reconstruction

# The simulation framework: i-HIBPsim

Equilibrium

Density & Temperature

Beam geometry

→

**Kinetic module**

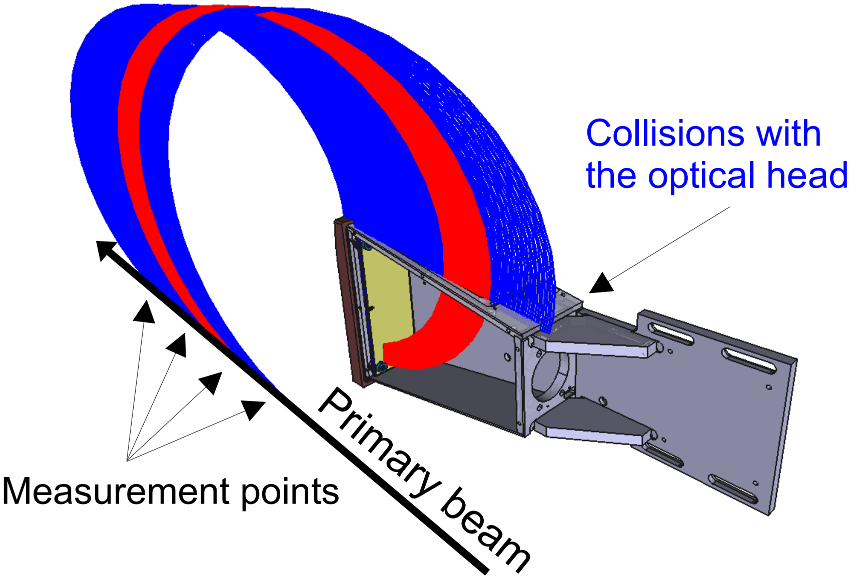
Generation of the secondary beam → Secondary followed until scintillator

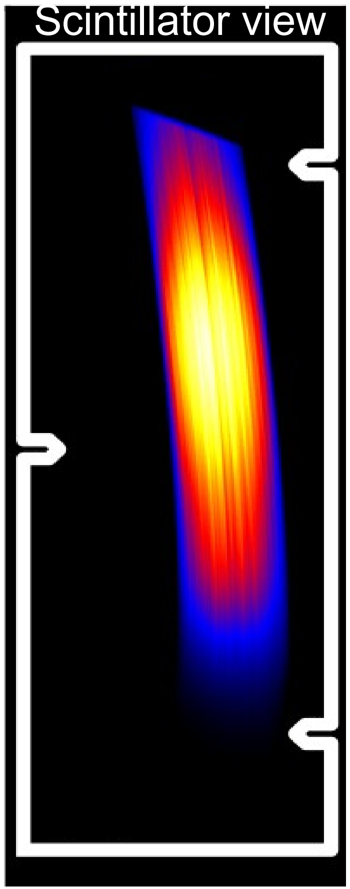
$$Rb^0 + D^+ \rightarrow Rb^+ + D^0$$

$$Rb^0 + e^- \rightarrow Rb^+ + 2e^-$$

$$Rb^+ + e^- \rightarrow Rb^+ + (N+1)e^-$$

Simplectic integrator




[8] P. Oyola *et al.*, in preparation

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Equilibrium

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Secondary followed until scintillator

$Rb^+ + e^- \rightarrow Rb^+ + (N+1)e^-$

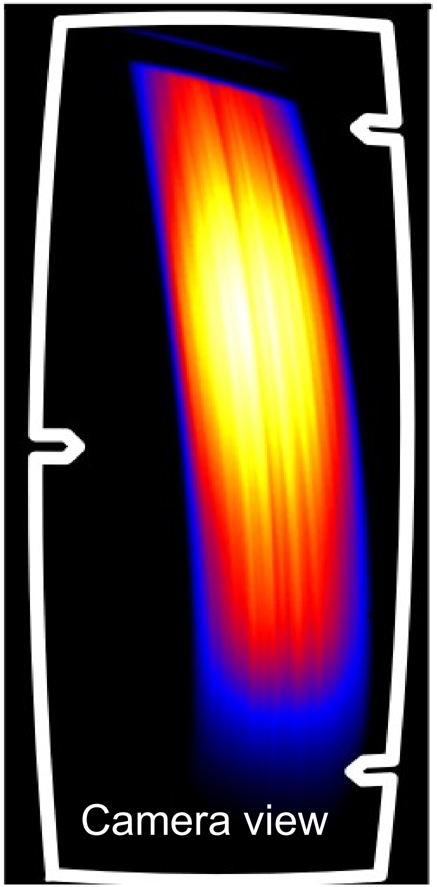
Simplectic integrator

**Optical module**

- Distortion
- Magnification
- Absolute calibration

i-HIBPsim

**Synthetic signal**



# Validation of the experimental shape

### Realistic 3D modeling of the beam

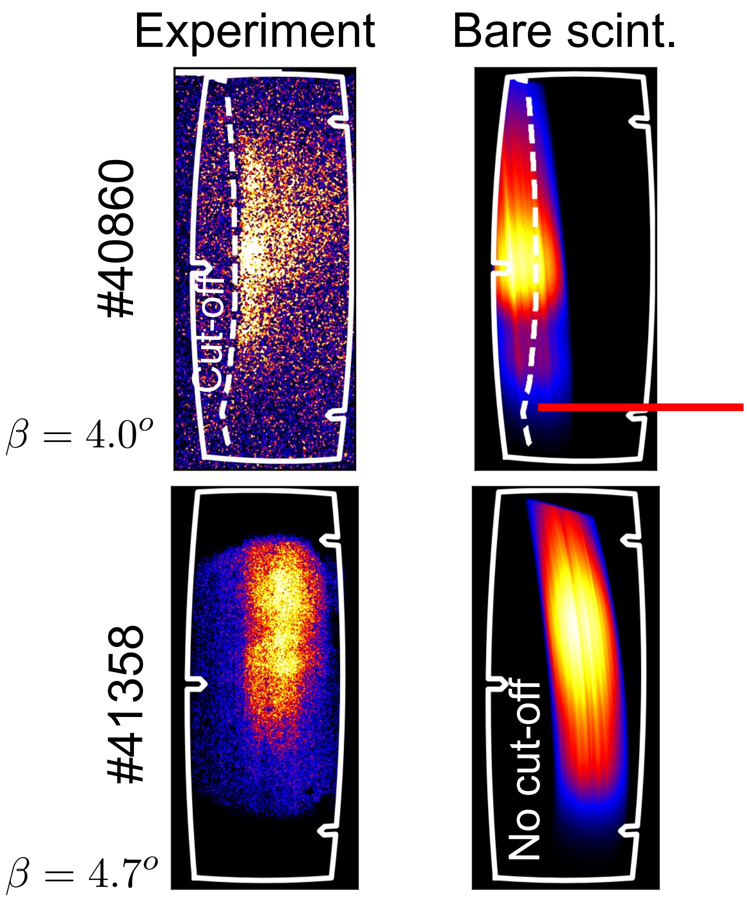
- Gaussian beam divergence ($\alpha_{div}$ ~ 0.4º).
- Finite beam width ($R_{beam}$ = 7 mm)

### Full optical model implemented

- Strong distortion
- Periodic calibrations
- Realistic synthetic images and comparisons

### Real 3D model of the i-HIBP optical head

- Cutting edges in experiments reproduced by the synthetic model





[8] P. Oyola *et al.*, in preparation
[9] H. Lindl *et al.*, DPG SmuK (2023)

# Beam current profile depends on the beam radial coordinate

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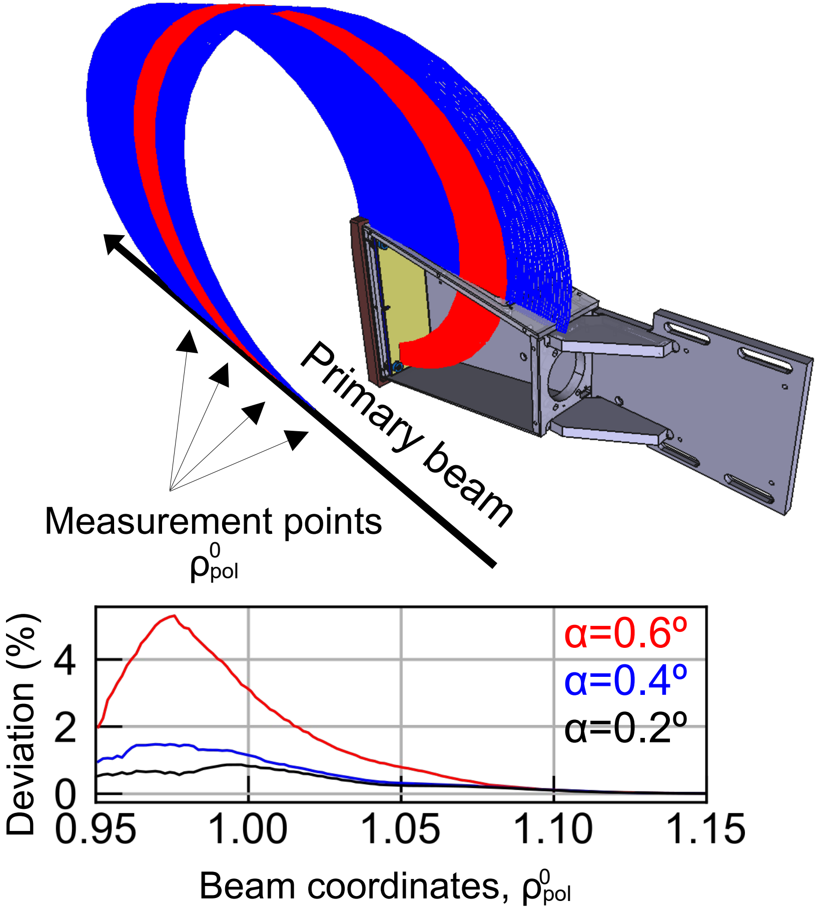
In principle, the beam attenuation depends on all the 3D beam parameters:

- Beam finite width.
- Beam divergence.

**Attenuation** of the particles only depends on:

- Injection angles (fixed)
- Magnetic configuration (fixed)
- Initial position of the particles in $\rho_{pol}$

$$I_{\text{beam}} \approx I_{\text{beam}}\left(\rho^0_{\text{pol}}\right)$$



# Detector 2D mapping

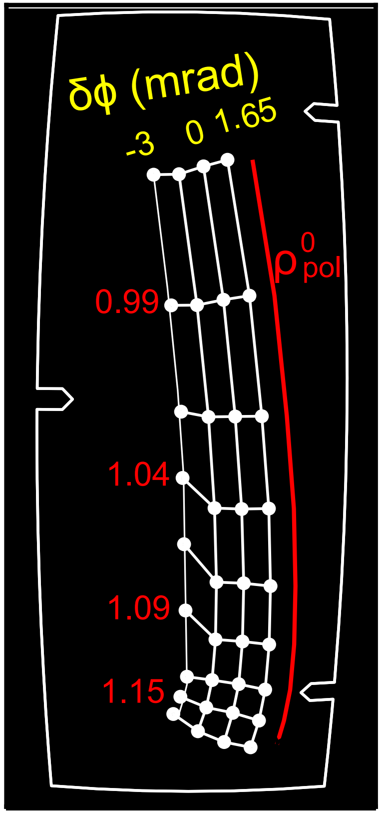
In a 2D symmetric large aspect-ratio equilibrium:

- $(P_\phi, \delta\phi) \sim (\rho_{pol}, \delta\phi)$ can be used to map the scintillator.
- Translation to more physically relevant variables.

$\rho_{pol}$ → Location along the beam in magnetic coordinates

$\delta\phi$ → Toroidal deviation from the center of the beam, same $\rho_{pol}$

E = 70 keV
#41358



# Little stop here: apparent, real and scintillator spaces

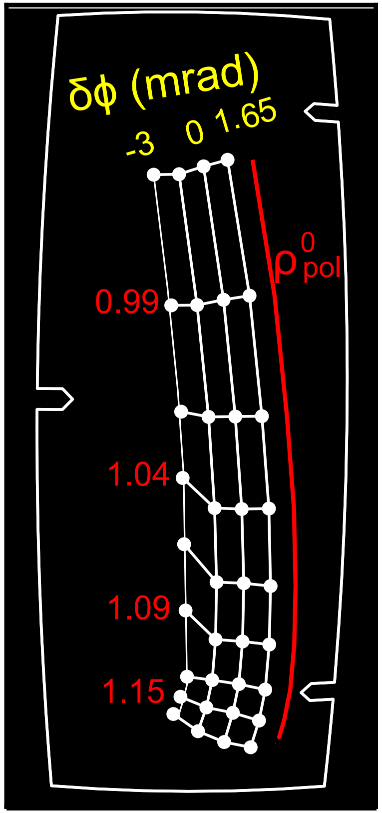
**Scintillator space**:
- Signal space
- Poor physical understanding

**Apparent space**:
- First step of treatment.
- Larger insight
- Ignoring resolution

**Real space**:
- Tomographic inversion.
- Full reconstruction.
- Takes resolution into account

$$\rho_{pol} = \rho_{pol}(x_1, x_2)$$
$$\delta\phi = \delta\phi(x_1, x_2)$$


E = 70 keV
#41358



# Remapping to physical coordinates: the apparent space

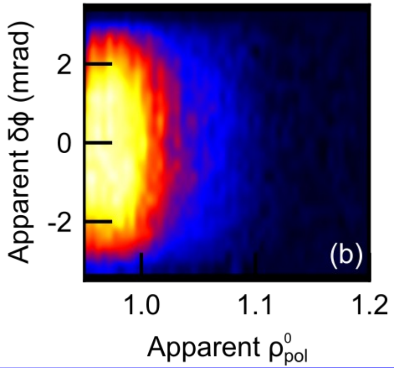


In a 2D symmetric large aspect-ratio equilibrium:

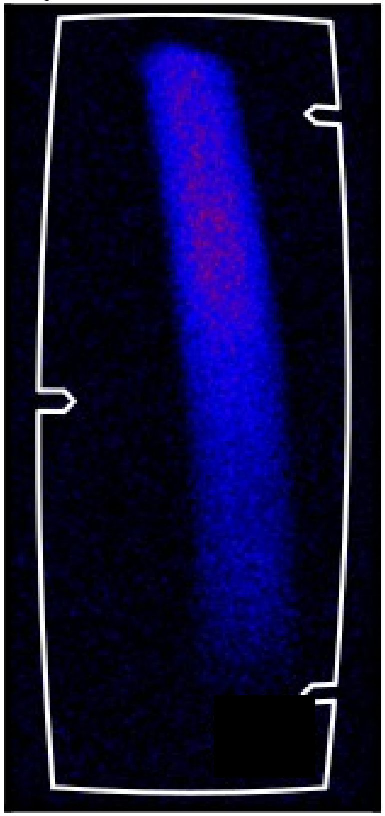
- $(P_\phi, \delta\phi) \sim (\rho_{pol}, \delta\phi)$ can be used to map the scintillator.
- Translation to more physically relevant variables.

$\rho_{pol} \rightarrow$ Location along the beam in magnetic coordinates

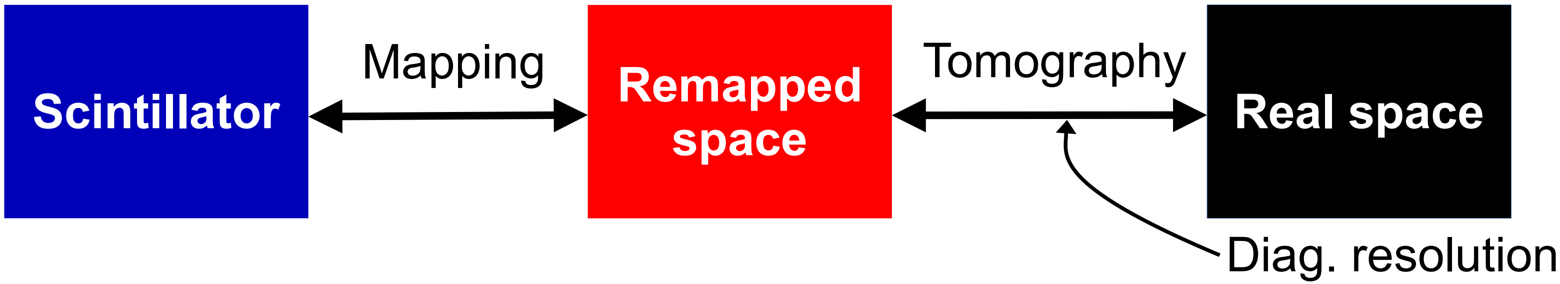
$\delta\phi \rightarrow$ Toroidal deviation from the center of the beam, same $\rho_{pol}$

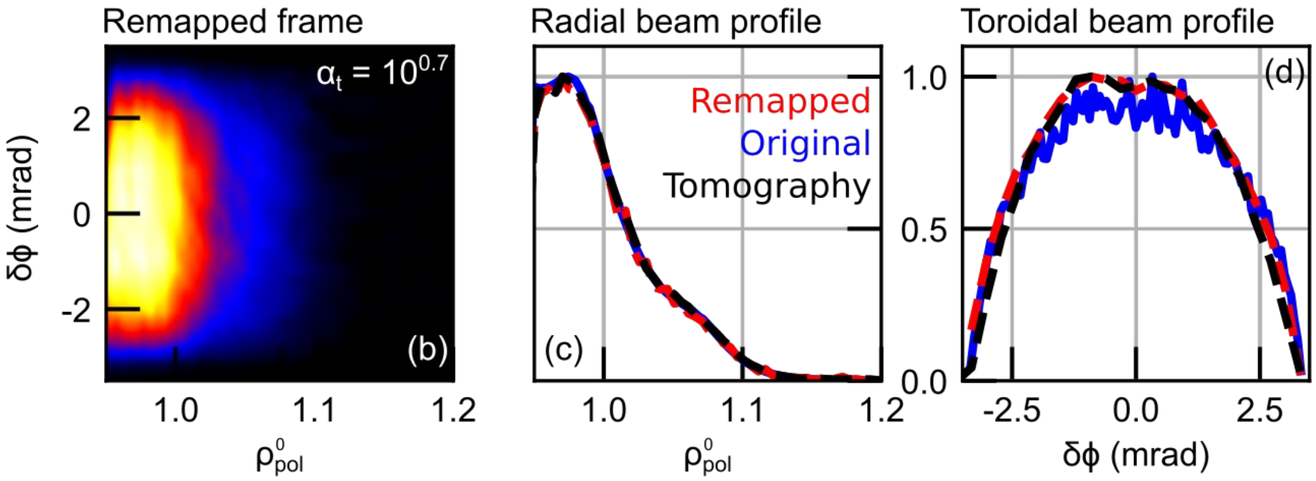



Synthetic frame



# Tomography: recovering the real space

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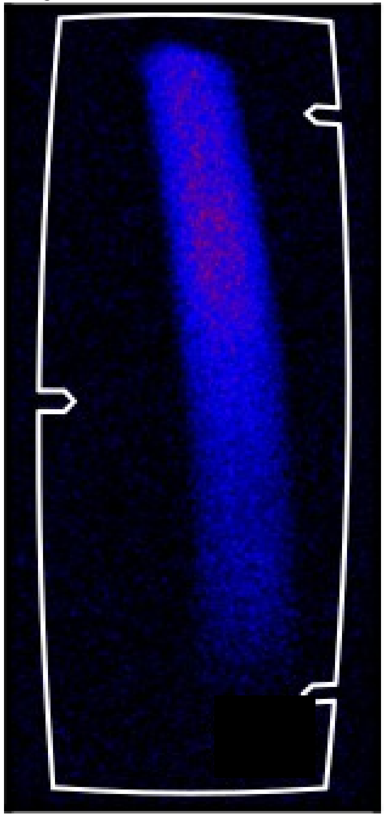
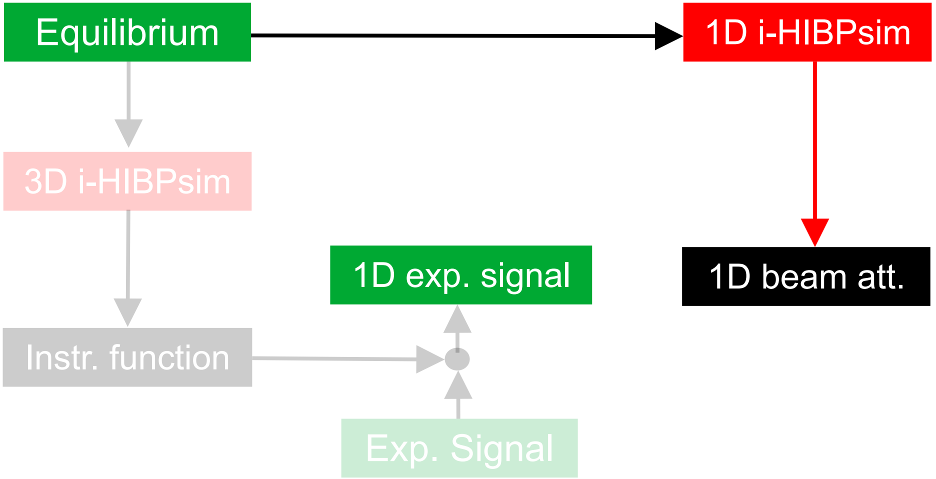


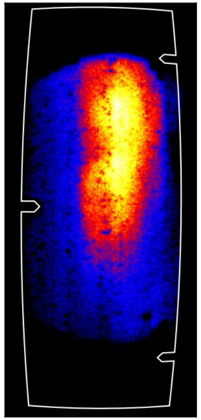
# Synthetic reconstruction matches qualitatively and allows reconstruction

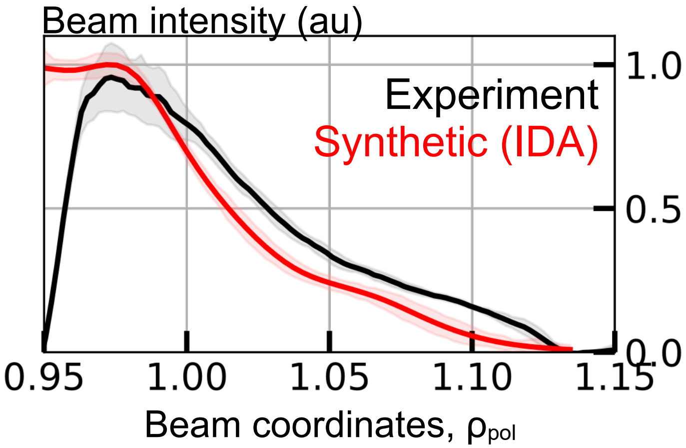
Calculation of pure synthetic signal in 1D:

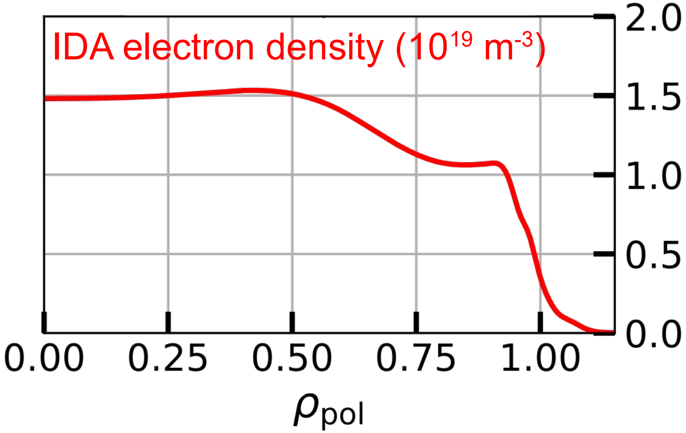
- IDA[10] profiles: qualitative agreement.
- Different in the SOL → Higher i-HIBP sensitivity.




#41358






[10] R. Fischer *et al.*, Fus. Sci. and Tech. **58** (2010)

# Synthetic reconstruction matches qualitatively and allows reconstruction

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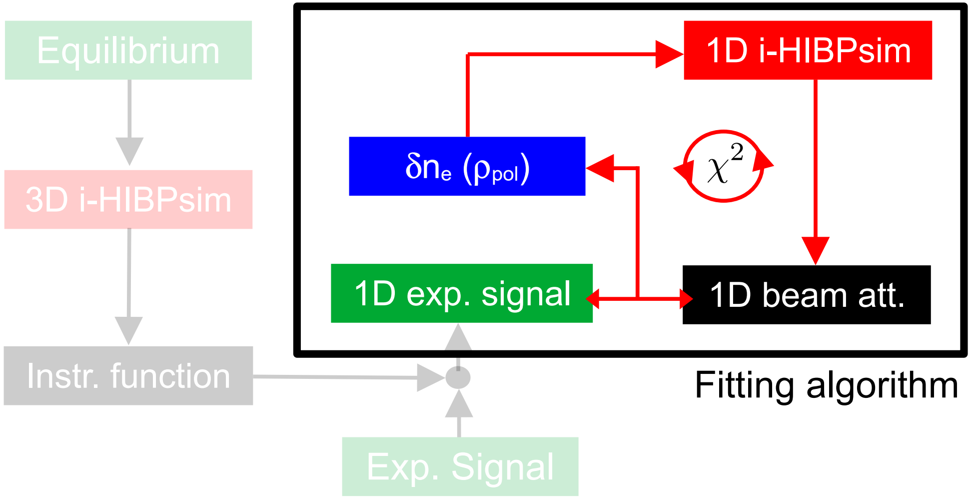
Calculation of pure synthetic signal in 1D:

- IDA profiles: qualitative agreement.
- Different in the SOL → Higher i-HIBP sensitivity.

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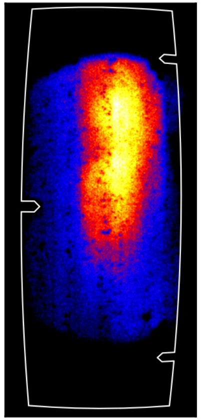

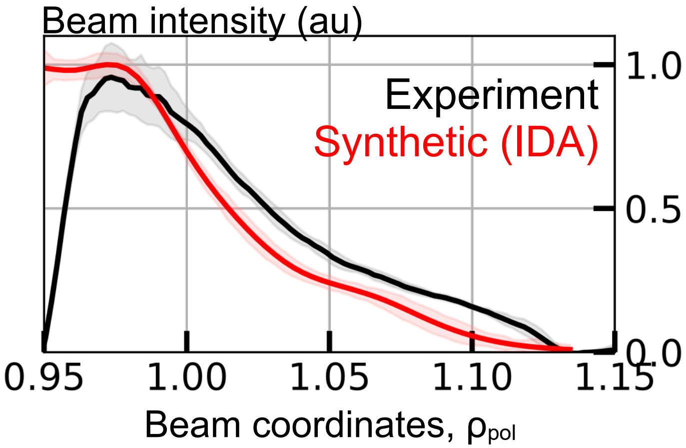


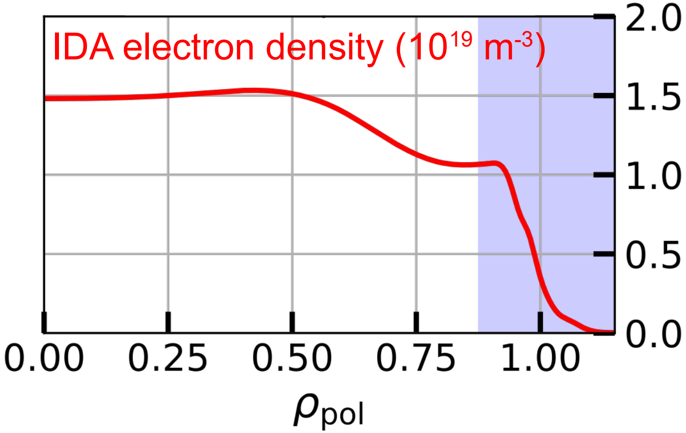

# Synthetic reconstruction matches qualitatively and allows reconstruction

- Started fitting from IDA profile.
- Signal is extremely sensitive to perturbations on the Scrape-off Layer.
- First density profiles reconstructions with i-HIBP.

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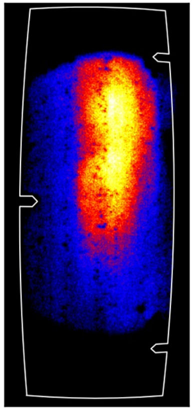

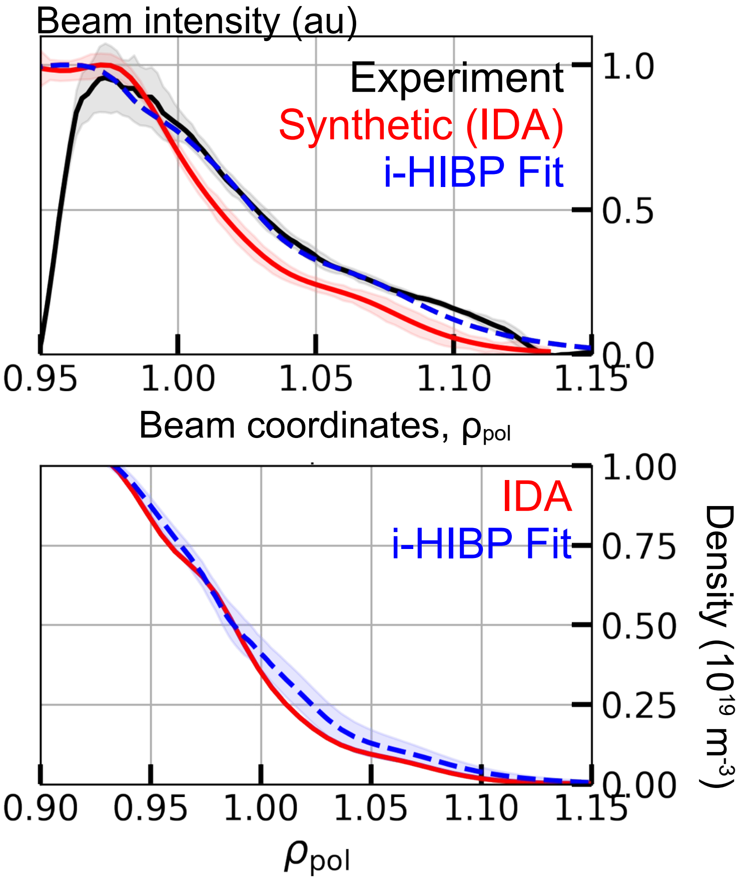

# Large detector resolution in the radial coordinate

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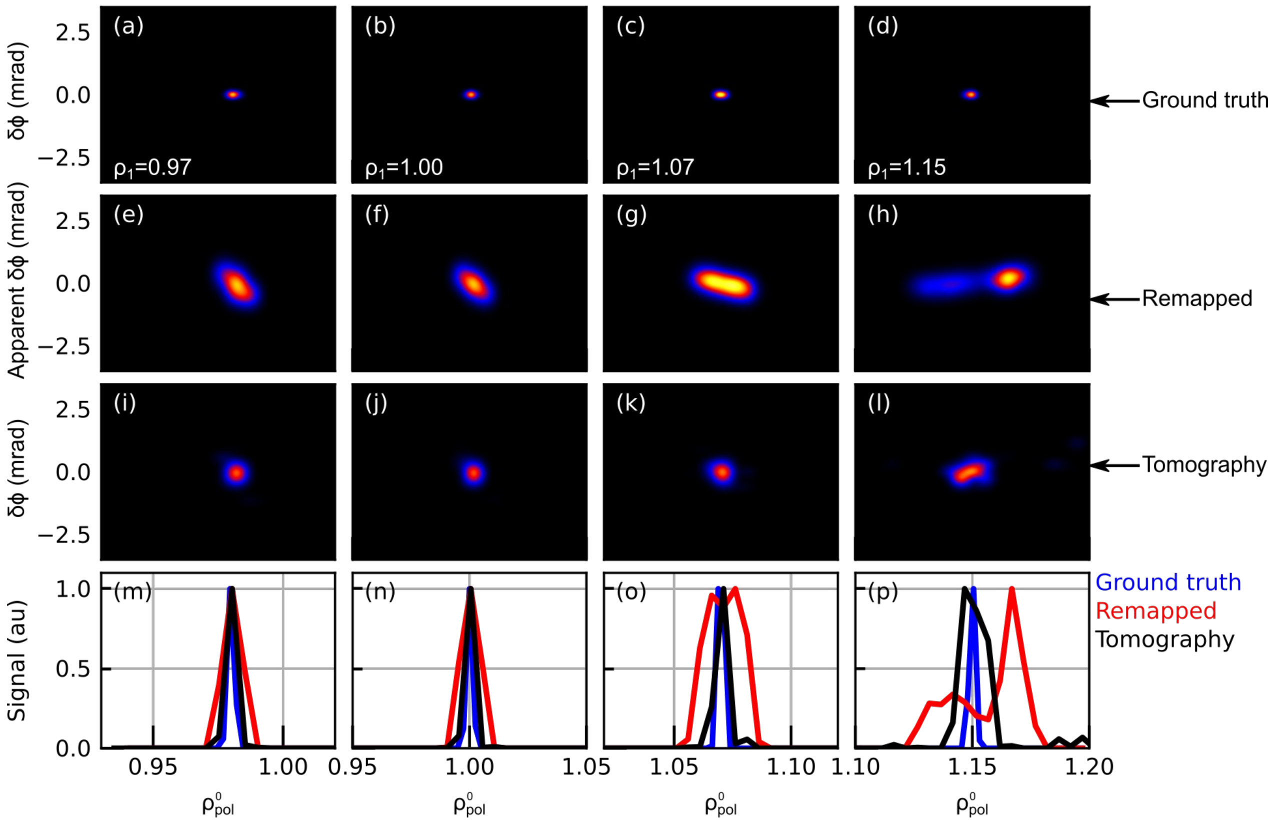
Large detector resolution:

- On the pedestal top.
  - Pixel ↔ $\rho_{pol}$

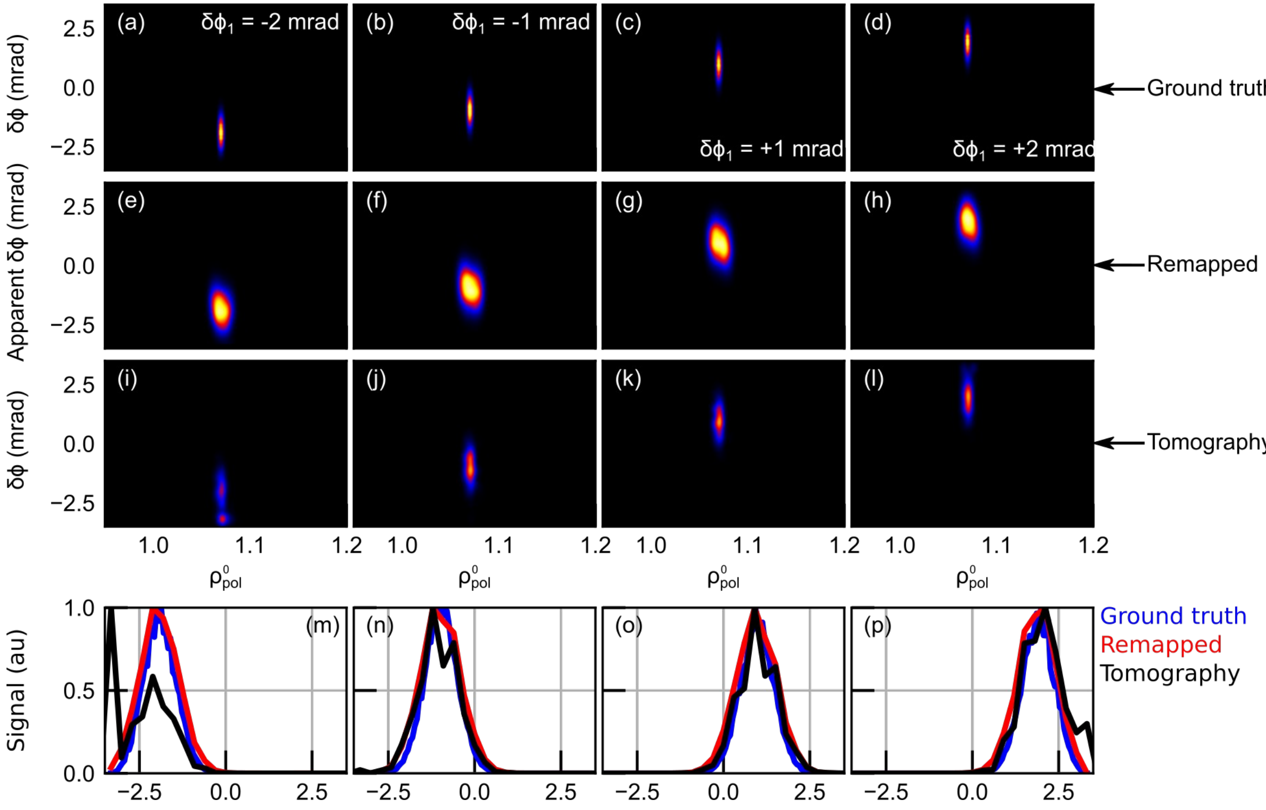
- On the far-SOL, peaky structures are convoluted with the larger pixel numbers:
  - Requires from tomography.



# Larger spread in the toroidal direction

The toroidal distribution of the particles:

- Nicely reproduced by the remap.
- Tomography also does a good job.
- Larger spread in the remap than tomograpy.
- Tomography recovers 2D more accurately.



# Conclusions and prospects

- Commissioning of the main components of the system was successful.
- First signals of the i-HIBP diagnostic obtained at the AUG tokamak.
- Operational regime established:
  - Low-density L-mode
- First density profiles reconstructions with the i-HIBP.

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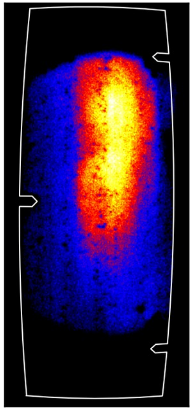
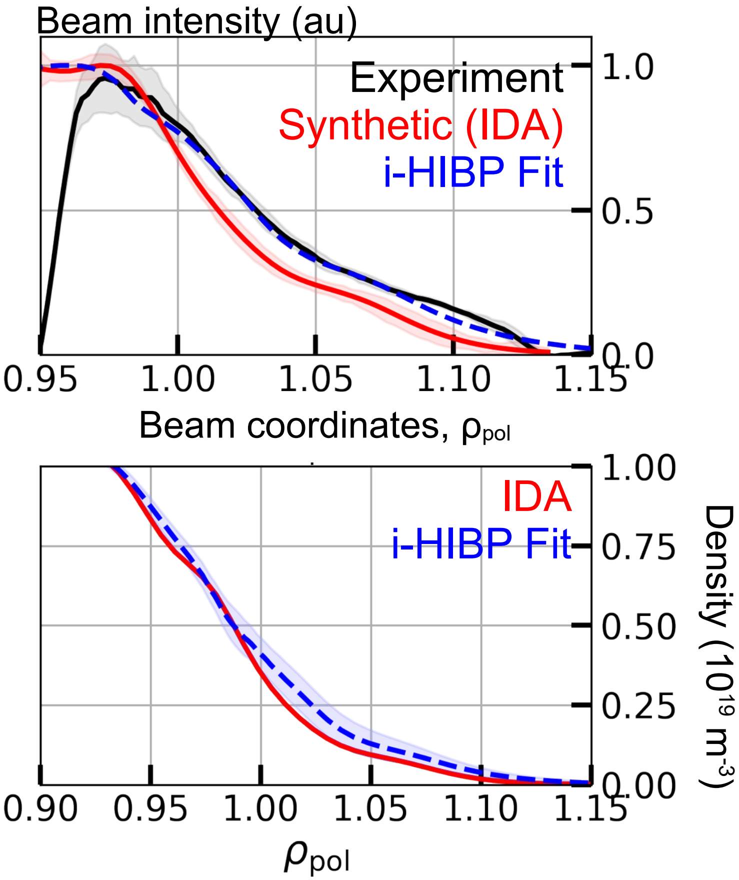
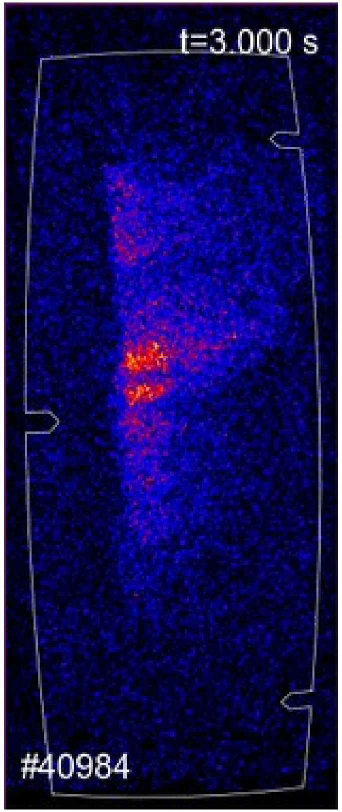
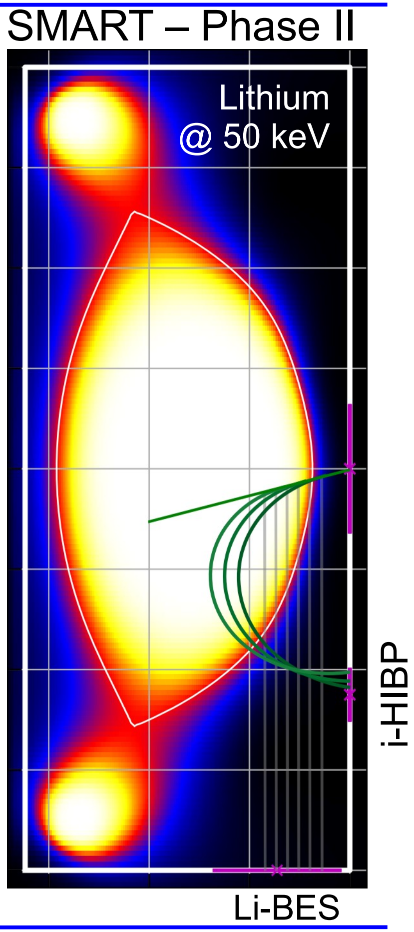




# Conclusions and prospects

- Higher ion currents expected for lower-mass alkali, like potassium:
  - Lower secondary attenuation.
  - Larger expected scintillator response.
- Measurements of filamentary phenomena.
- Working principle is expected to work better for smaller machines:
  - Feasibility study of combined LiBES + i-HIBP in the SMART tokamak.



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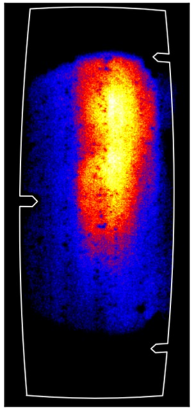
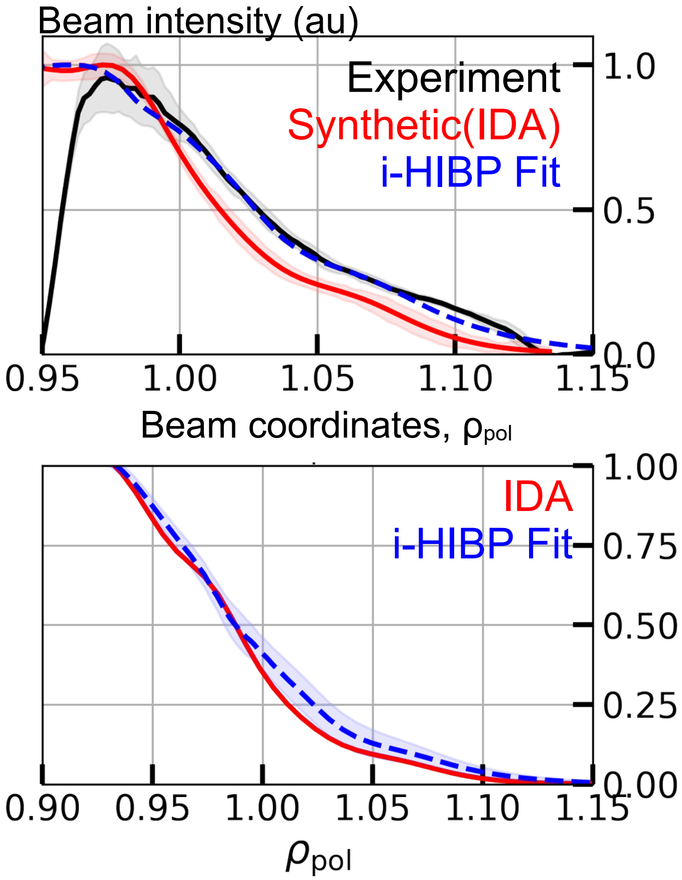




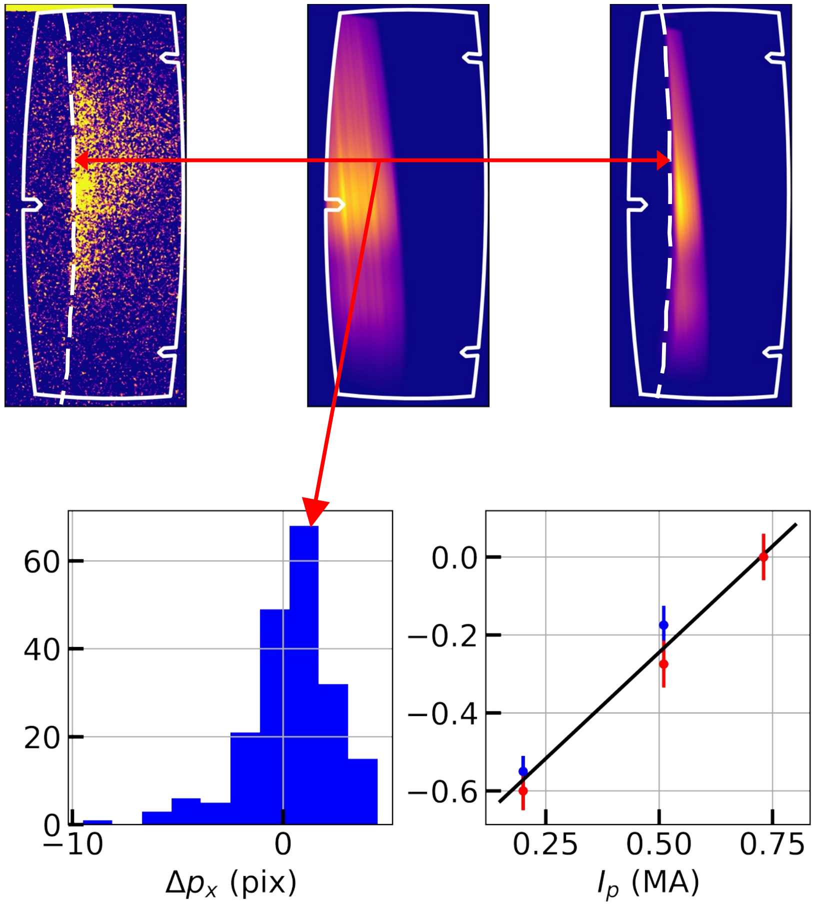
# First measurements and validation of the imaging Heavy Ion Beam Probe at the ASDEX Upgrade tokamak

Backup slides

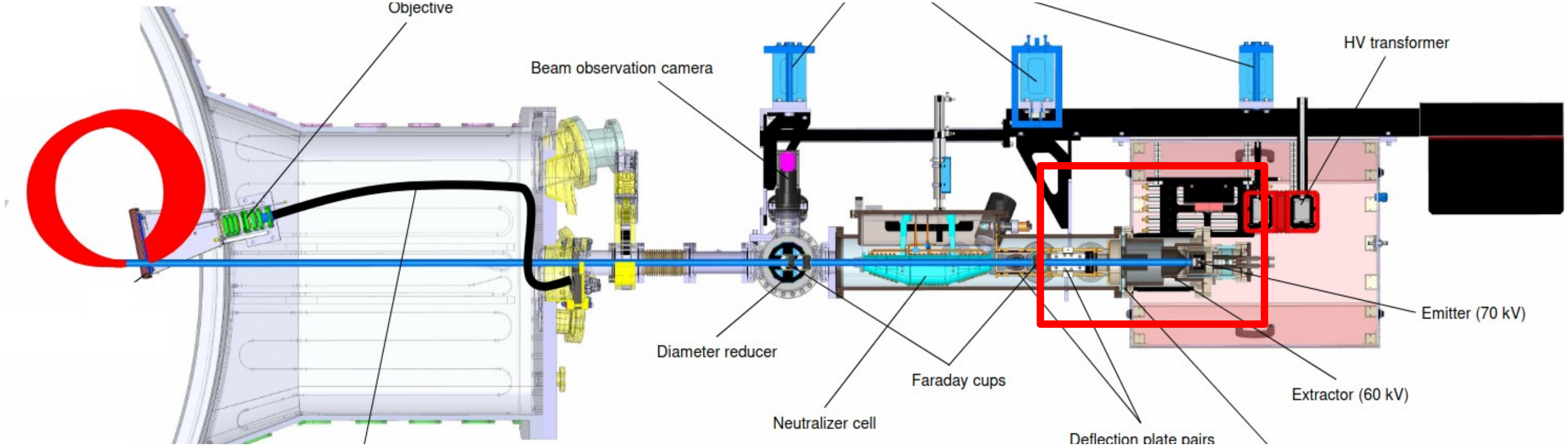
High Temperature Plasma Diagnostic Conference 2024 - Asheville

# Summary & Outlook

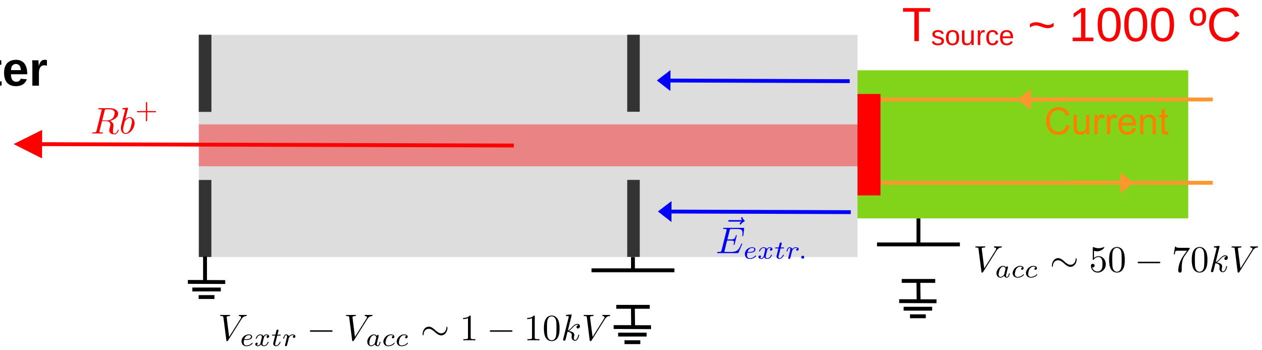
- Complete synthetic diagnostic for the i-HIBP diagnostic implemented
- Validation across of different plasma pulses, including the optical and 3D modeling.
- Despite the issues, first measurements were obtained for the plasma density.
- Current density measurements may be also possible when including the cutting edge.



# Hardware setup[3]




**Source and emitter**




[3] G. Anda *et al*, RSI **89** (2018)

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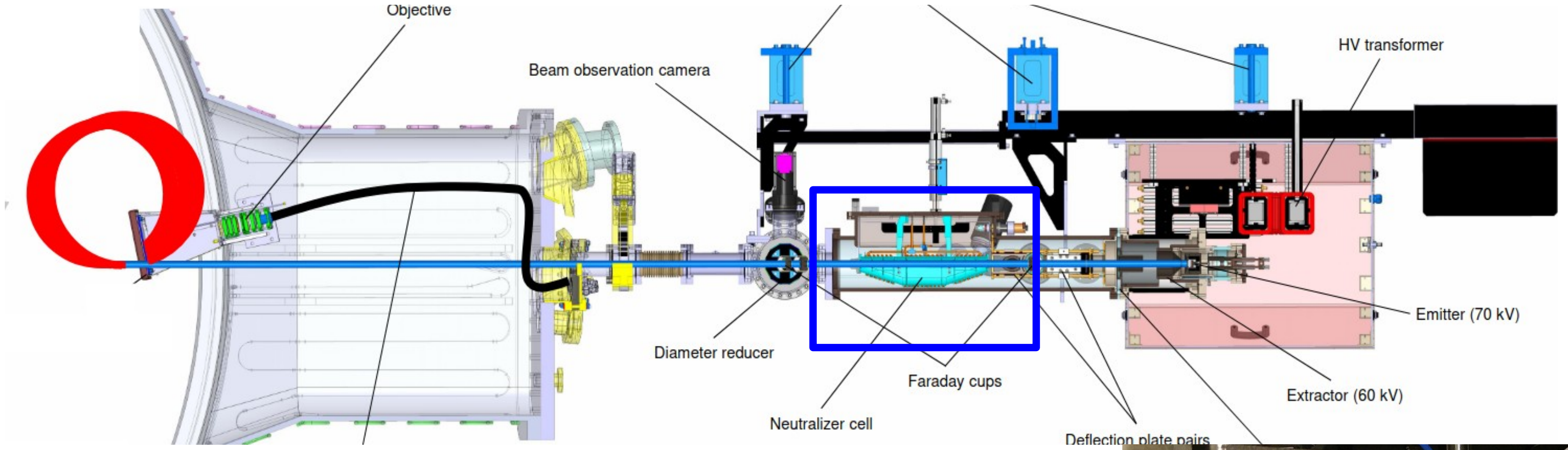


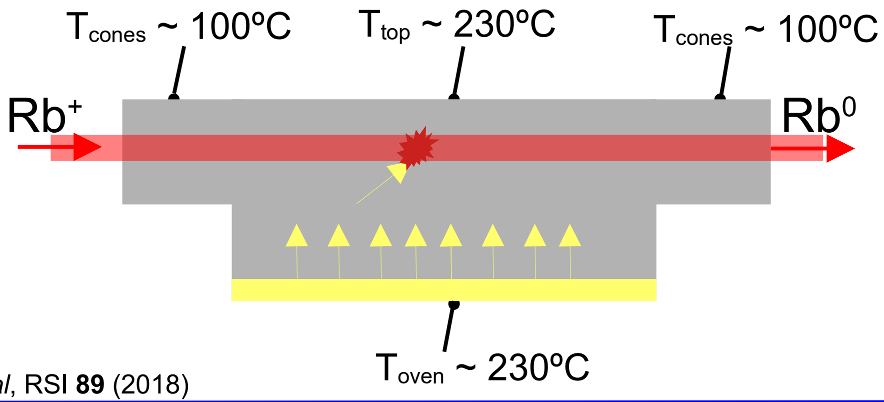


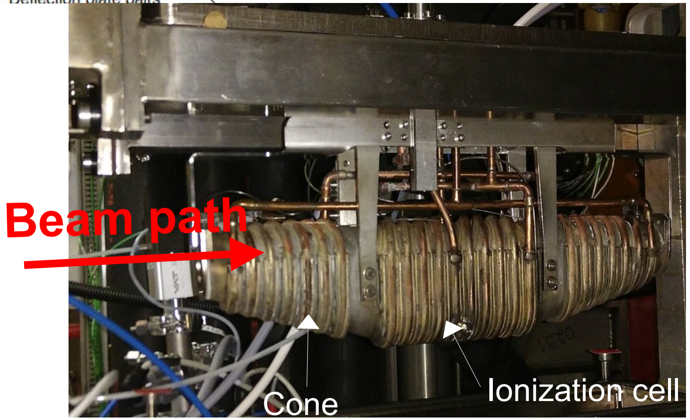


[3] G. Anda *et al*, RSI **89** (2018)

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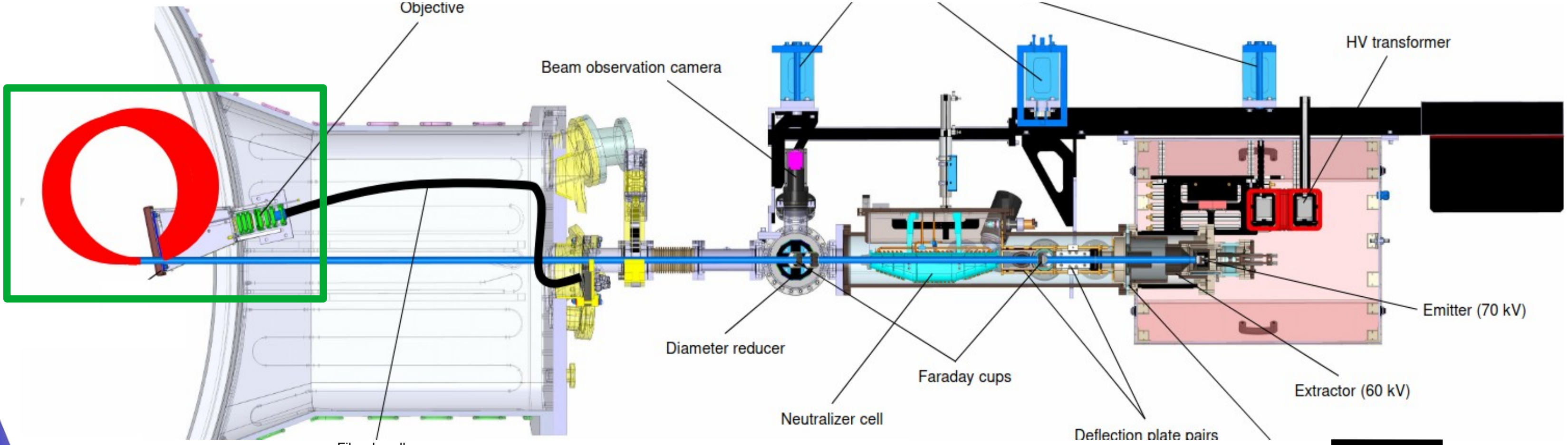
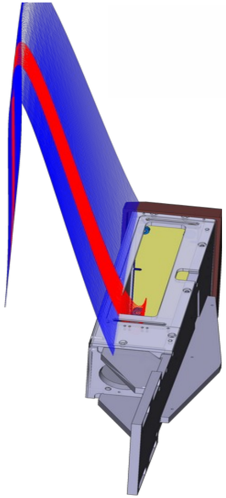
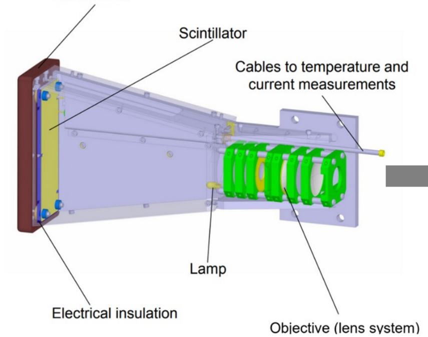


Light emission




Optical system
Magnification & distortion

Fiber bundle

Camera

[3] G. Anda *et al*, RSI **89** (2018)

# The simulation framework: i-HIBPsim[4]

Equilibrium

Density & Temperature

Beam geometry

Generation of the secondary beam

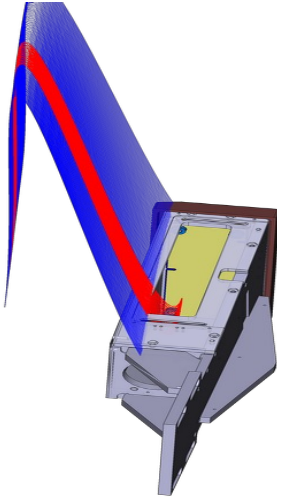
$$Rb^0 + D^+ \rightarrow Rb^+ + D^0$$
$$Rb^0 + e^- \rightarrow Rb^+ + 2e^-$$

Secondary followed until scintillator

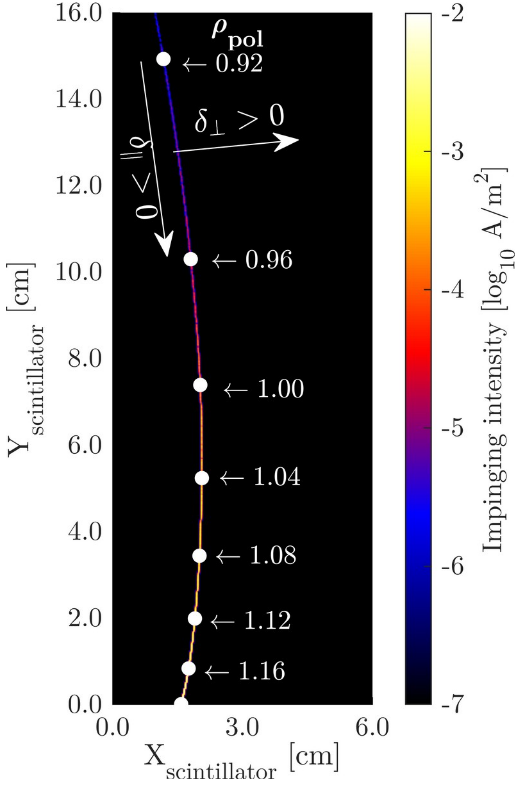
$$Rb^+ + e^- \rightarrow Rb^+ + (N+1)e^-$$

Simpletic integrator

Kinetic module



Thin-beam approximation

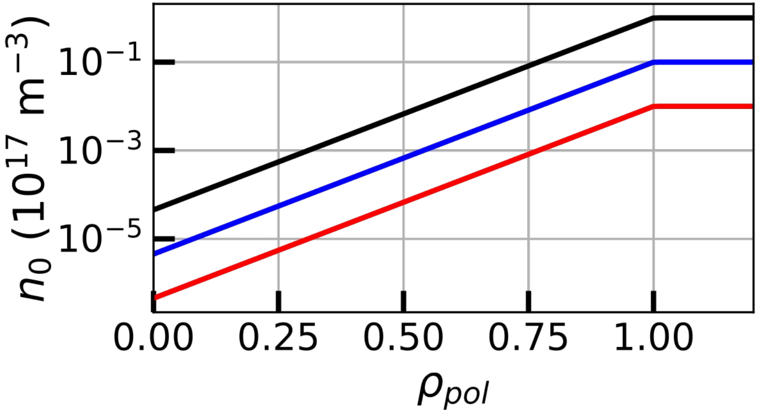


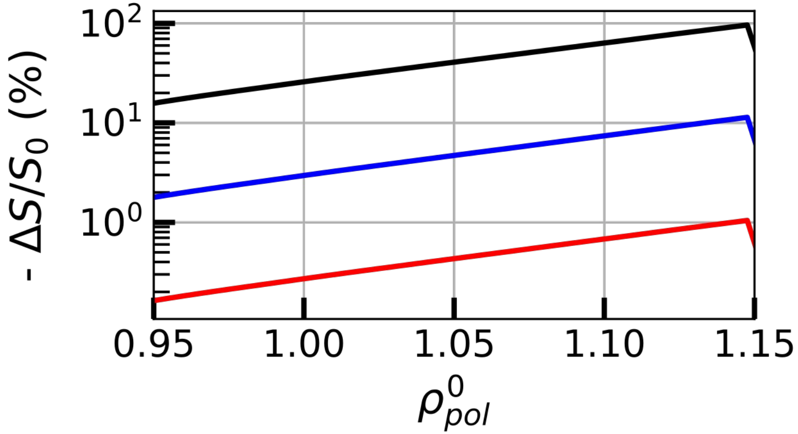

[4] P. Oyola *et al*, RSI **92** 043558 (2021)

# Impact of the neutral density is negligible

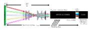
For realistic values of the neutral density:

- Decrease in the full signal is observed, correlated with the total density.
- For realistic value of $n_0 \sim 10^{16}$ $m^{-3}$, there is a reduction of ~1-5% in the signal.
- Experiments are carried out with low levels of gas puff injection.



# Optical calibration in detail



# TG-Green emission projected to Rb

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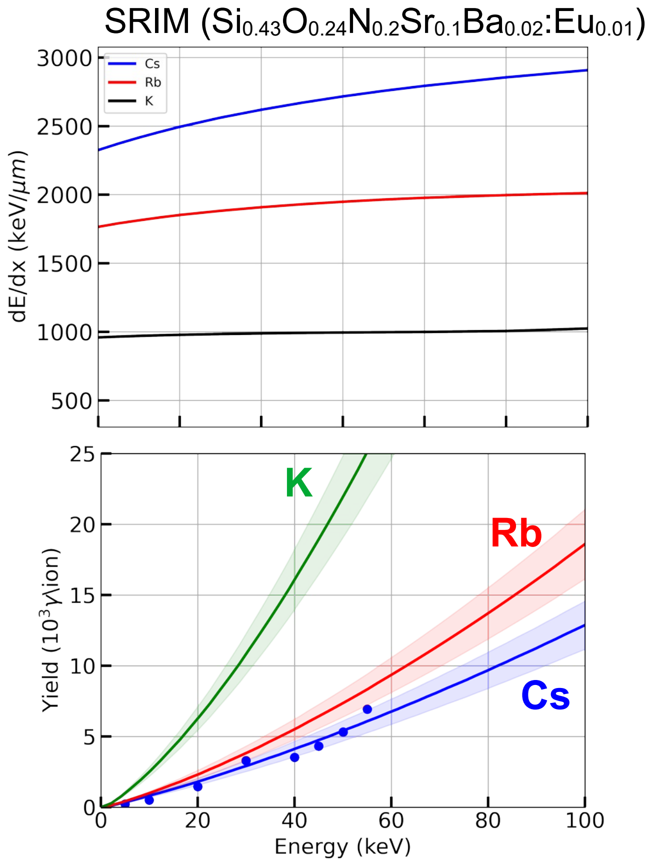
Experimental measurements are only taken for $^{133}$Cs:

- Properties of the TG-Green vary depending on the scintillator.
- No experimental measurements for the $^{85}$Rb species.

*Ad-hoc* approximation to the ϒ(E) for the Rb and K can be done via the Birk's law.

$$\Upsilon_s = \mathcal{S}\int_0^R \frac{\left(\frac{dE}{dx}\right)_s}{1+\alpha_B\left(\frac{dE}{dx}\right)_s}$$

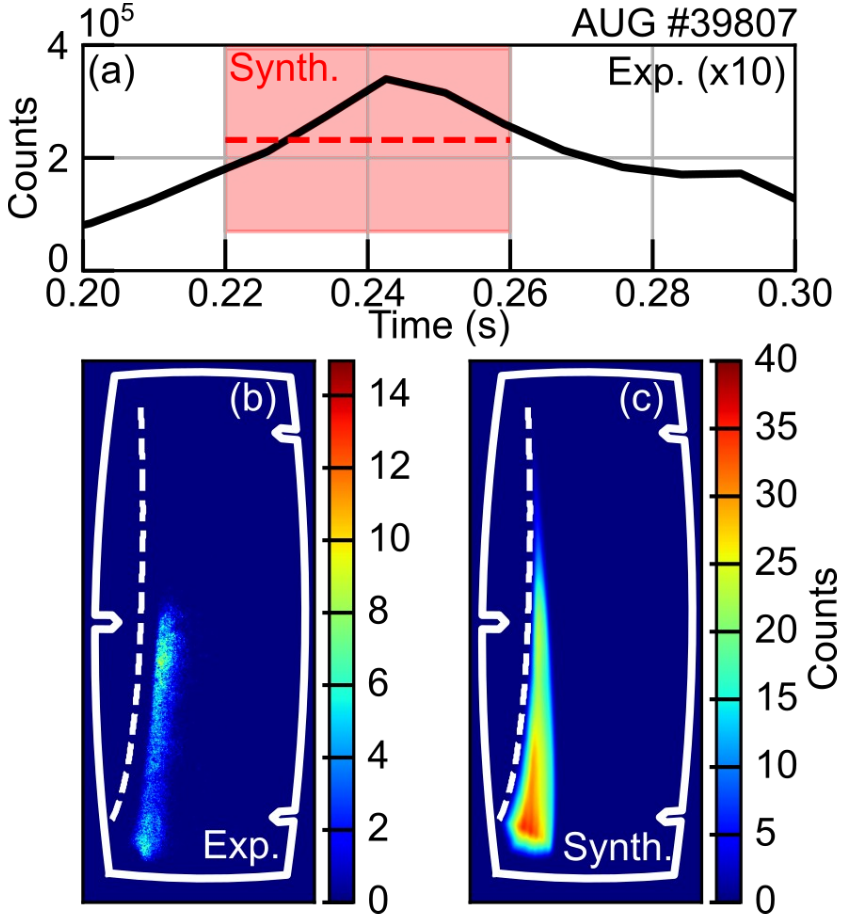
For E = 70 keV
→ Cs: U = 10·10$^3$ γ/ion
→ Rb: U = 12·10$^3$ γ/ion
→ K: U = 25·10$^3$ γ/ion




J.J. Toledo-Garrido *et al*, JINST **17** P02026 (2022)
http://www.srim.org/
Done with pysrim package: https://gitlab.com/costrouc/pysrim (v0.5.10)

# Absolute calibration

- With the absolute calibration, the synthetic signal only fails with a factor ~6:
  - Uncertainty in scintillator emission for Rb.
  - Uncertainty in the fiber bundle degradation.
  - The beam moves during the ramp-up phase,
    - Uncertain beam geometry



# Neutralization cell with an efficiency of ~80%

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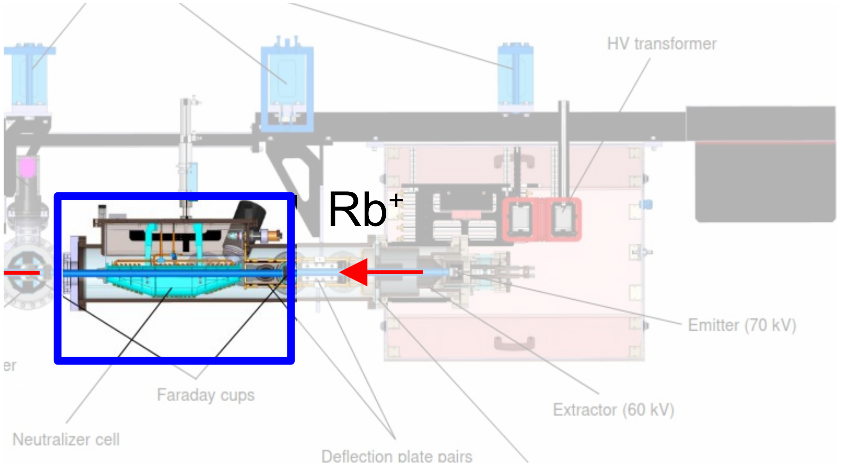
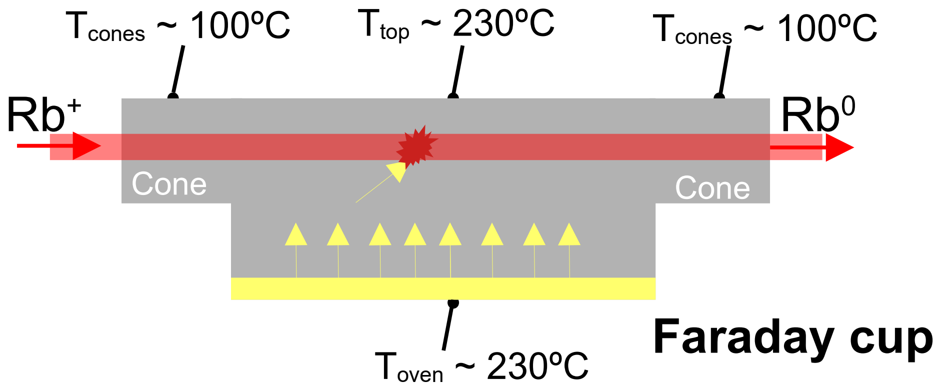
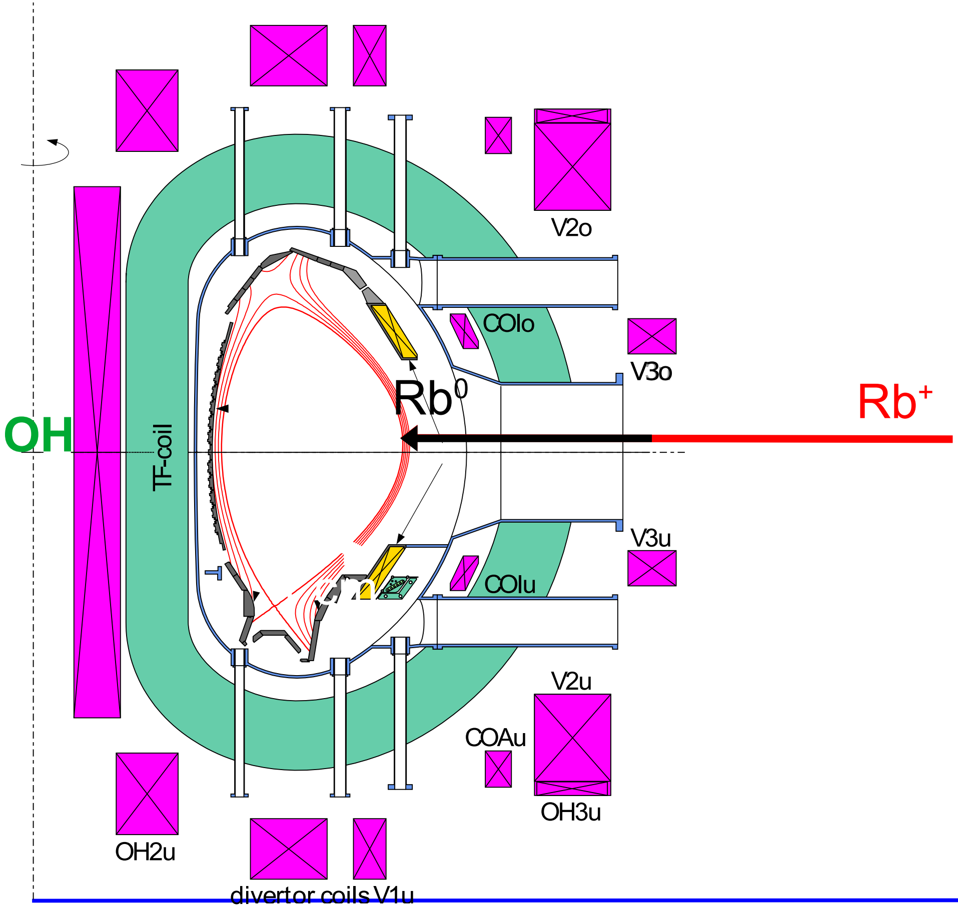
- Alkali beam is singly ionized at the exit.
- Hot sodium in the neutralizer
- Neutralizer is filled with Na
  - Alkali undergo CX reaction
- Up to an 80% of neutralization efficiency[4]




[4] J. Galdon-Quiroga *et al.*, RSI (2024)

# Beam shifts by the magnetic field[7]




Before neutralization: Singly ionized beam

[7] B. Tal *et al.*, E2-E2M Seminar (2023)

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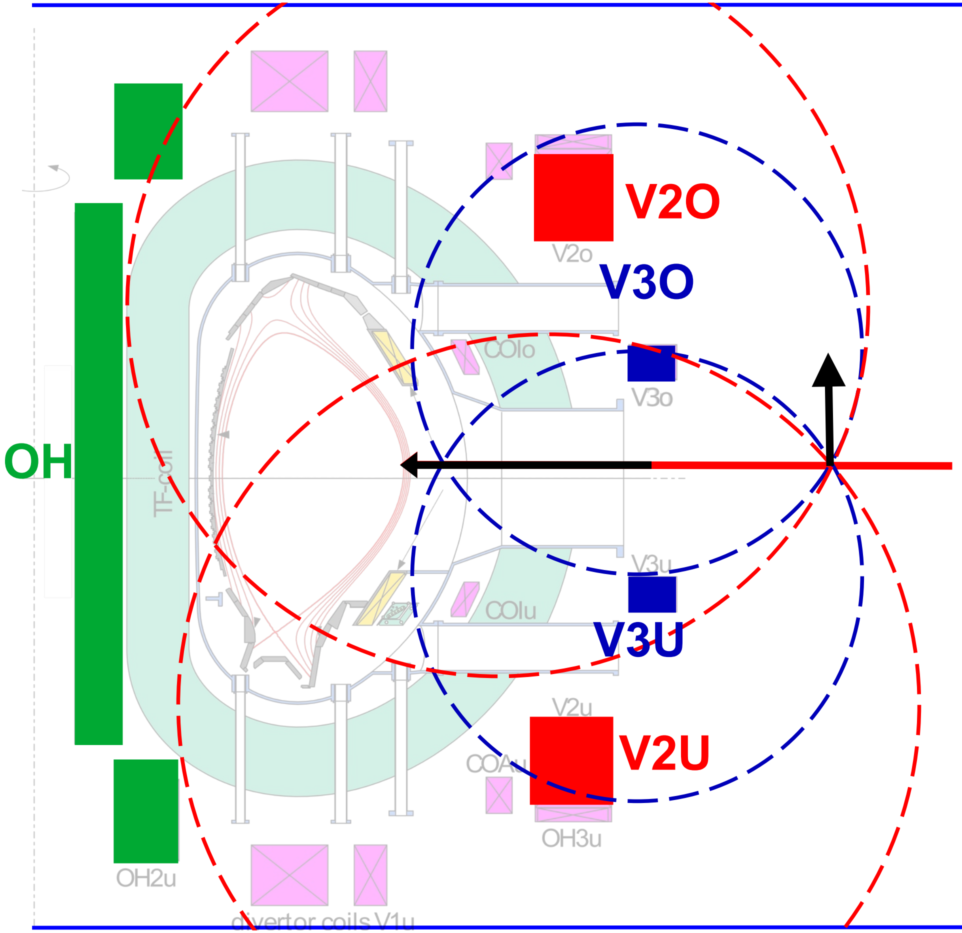


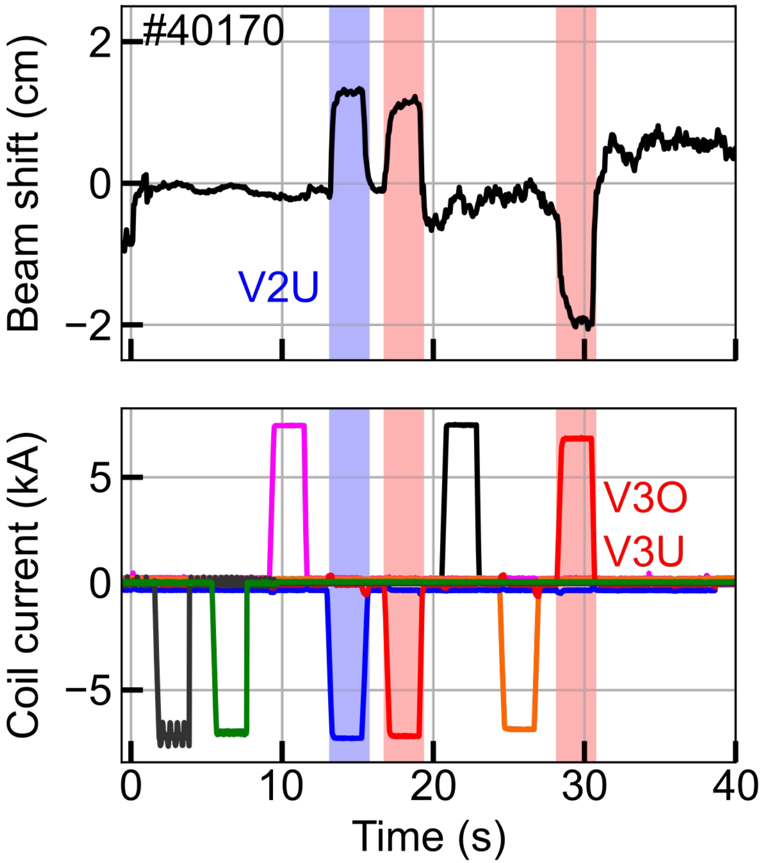

Before neutralization: Singly ionized beam

- Subject to stray magnetic field.
- Beam path deviation from the beam center.
- Plasma current also contributes to the beam deflection.

[7] B. Tal *et al.*, E2-E2M Seminar (2023)

# Magnetic fields penetrate the beam line

- Stray field slightly deviates the beam during ramps:
  - Beam cameras: after the neutralization.
  - Measurement of the beam deflection.
  - Coils close to the beam cause a significant displacement.
  - Design scenarios with low $I_p$.

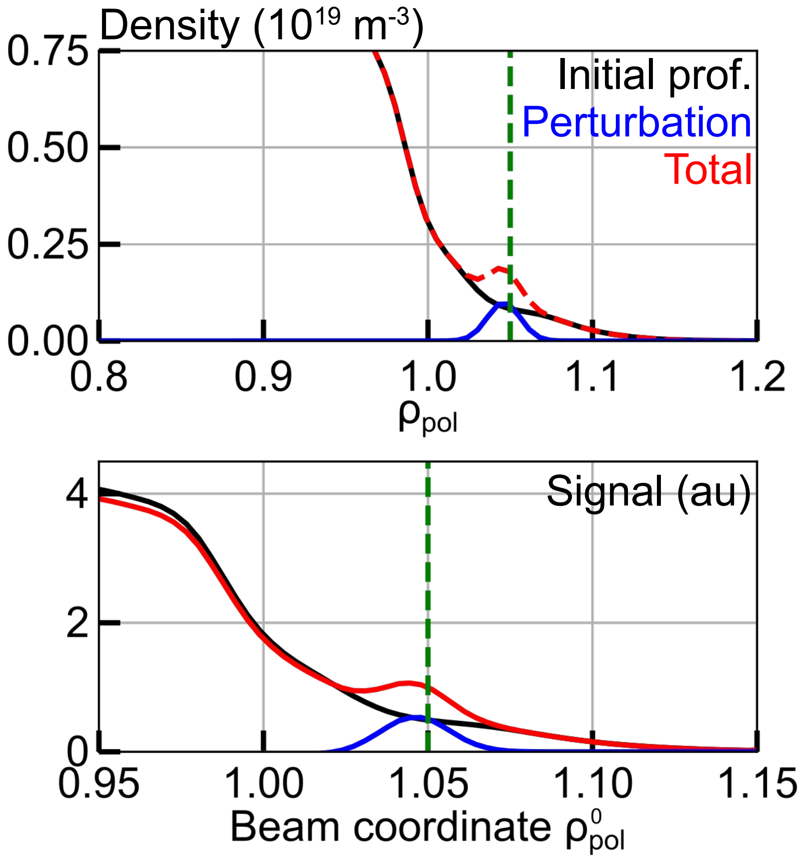


# High sensitivity to the SOL perturbations

Systematic study of the perturbed signal:

- Perturb the original profiles locally:
  - Proxy: the total signal variation.

$$\frac{\Delta S}{S_0} = \int \frac{S(\text{perturb}) - S(\text{original})}{S(\text{original})}$$



# High sensitivity to the SOL perturbations

Systematic study of the perturbed signal:

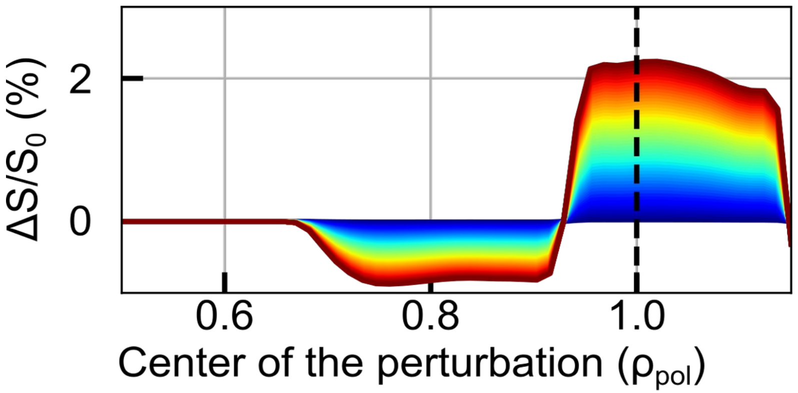
- Perturb the original profiles locally.

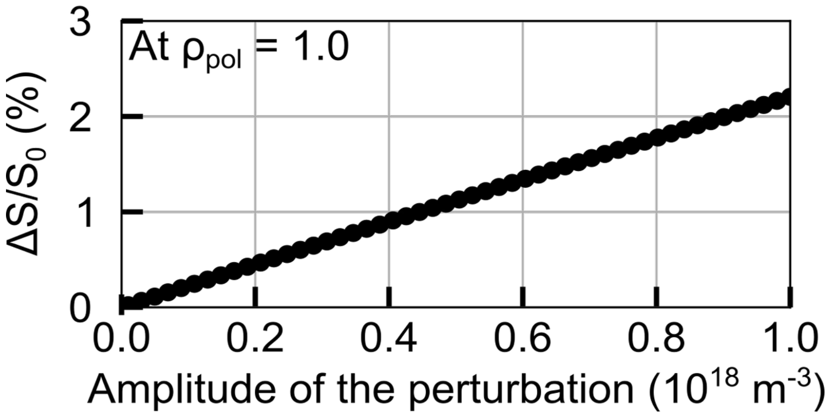
- Large sensitivity at the SOL when perturbing the density.

- Almost linear dependence of signal with perturbation.

$$\frac{\Delta S}{S_0} \propto \delta n_e \quad \text{for small perturbations}$$

- For $\delta T_e \sim 100$ eV at the SOL, signal is barely affected.



# Transforming the 2D scintillator images into 1D profiles

**Direct mapping between pixel and birth position:**

- Vertical → Magnetic radial coordinate

- Single $\rho_{pol}$ per pixel → We can map the signal to $\rho_{pol}$ from 2D signals