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FÜR PLASMAPHYSIK

Paving the road towards ITER relevant long deuterium pulses at ELISE by investigating improved operational scenarios

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EUROfusion

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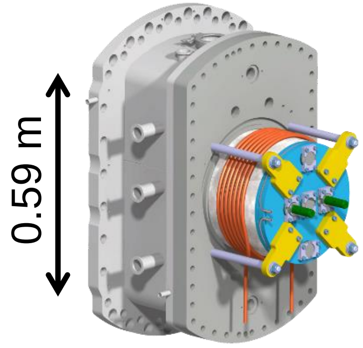
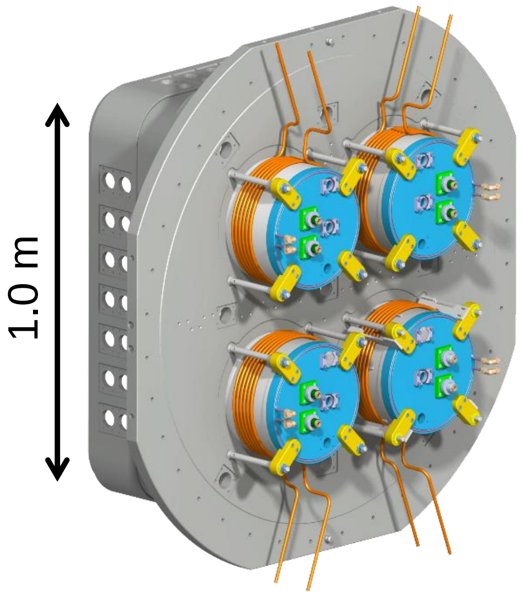
Size scaling towards the ion source for ITER NBI



IPP prototype source (59×30 cm²)

- Basic ITER requirements fulfilled. ✓
- Since 2018: BATMAN Upgrade with ITER-like extraction system.

×4



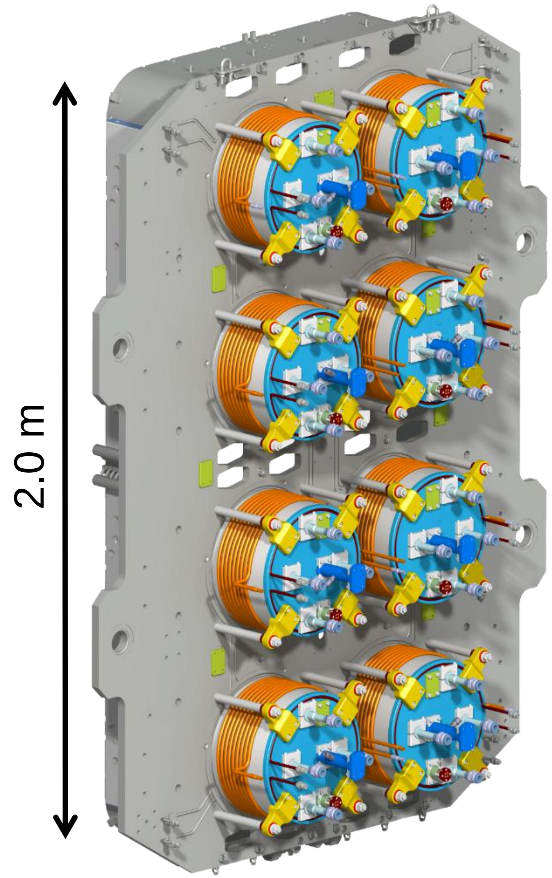
Size scaling: half ITER source size experiment (100×90 cm²)

- Test facility ELISE, in operation since 2013.
- ITER relevant short & long (t_{plasma}=1200 s) pulses in hydrogen (pulsed extraction). ✓

×2

Source for ITER NBI (200×100 cm²)

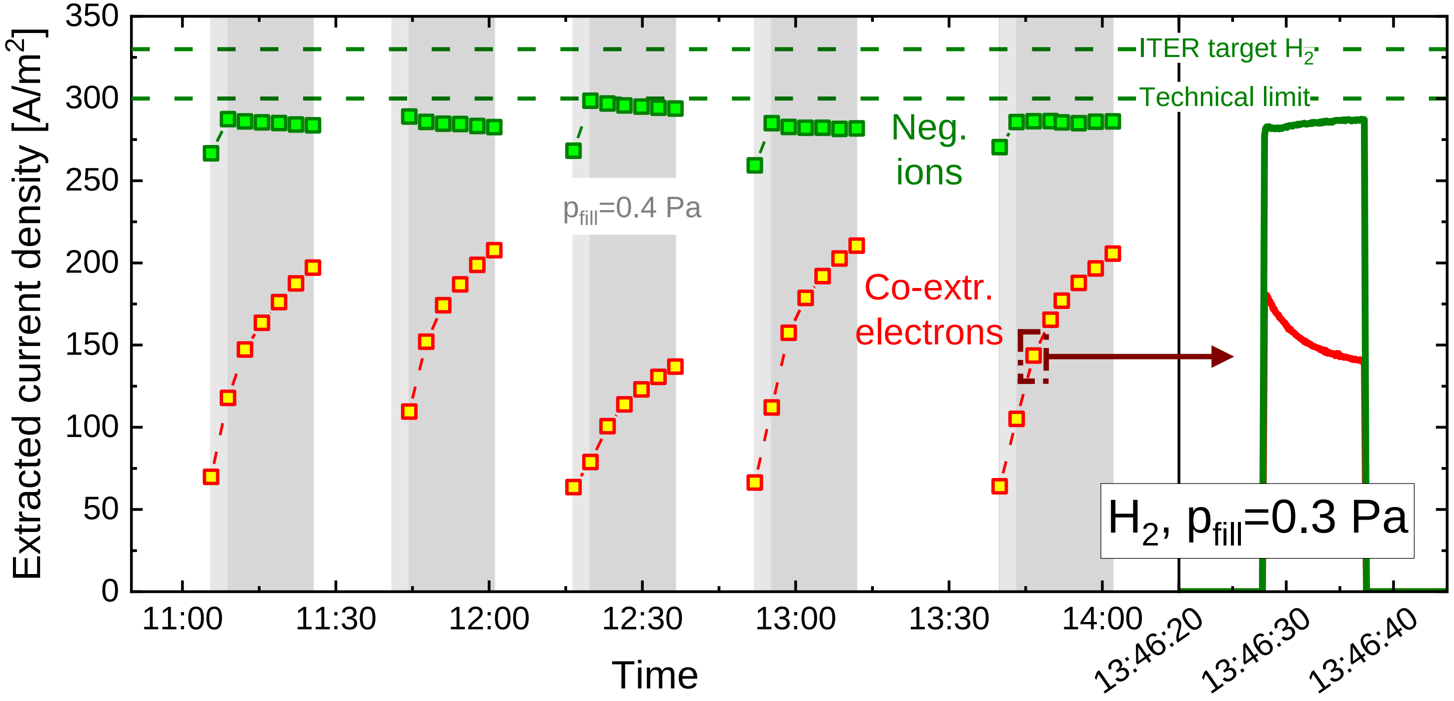
- Consorzio RFX, based on IPP design.
- SPIDER in operation since 2018.



Target values and results in hydrogen

	D	H
j_{acc}	200 A/m^2 (1 MeV)	230 A/m^2 (870 keV)
j_{ex}*	286 A/m^2	329 A/m^2
j_e/j_{ex}	<1	
p_{fill}	≤0.3 Pa	
Pulse length	3600 s	1000 s
Beam homog.	>90 %	
Beamlet div.	<7 mrad	

*: assuming 30 % stripping losses as predicted for ITER

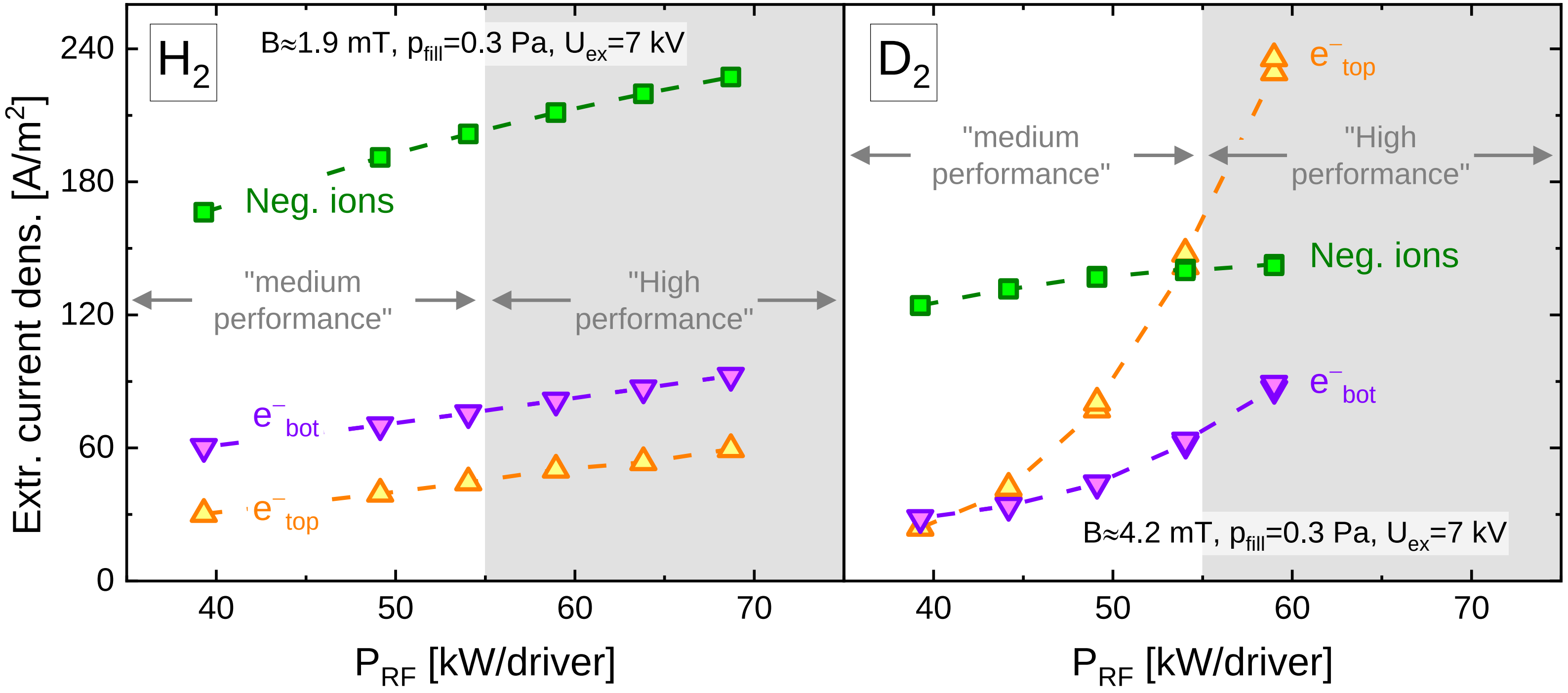


Pulsed extraction affects temporal behavior of co-extracted electrons.

Hydrogen: ITER targets can be achieved.

Series of stable and reproducible 1200 s pulses (pulsed extraction).

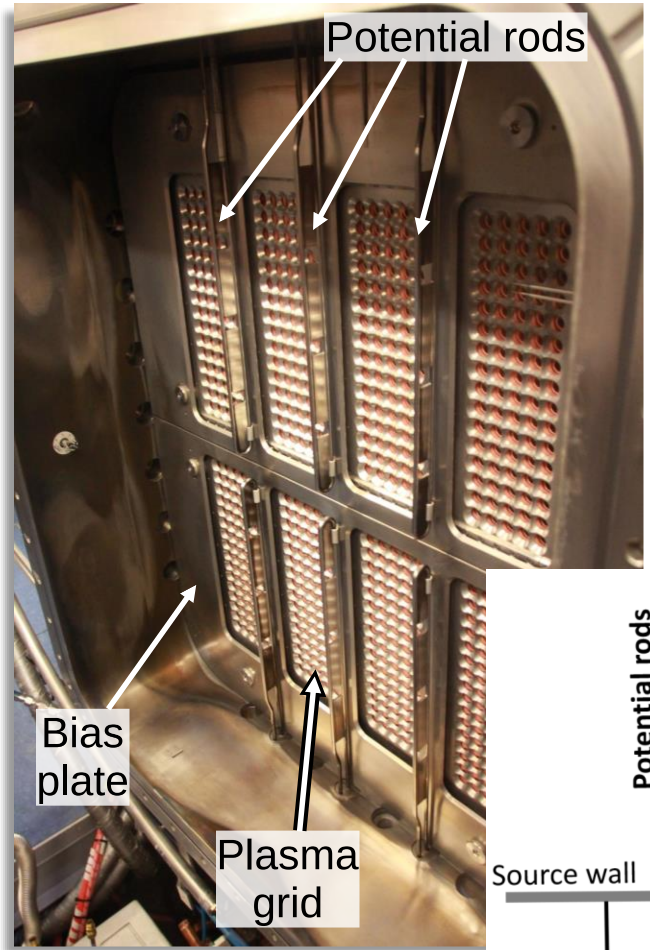
Isotope effect hydrogen ↔ deuterium (short pulses)

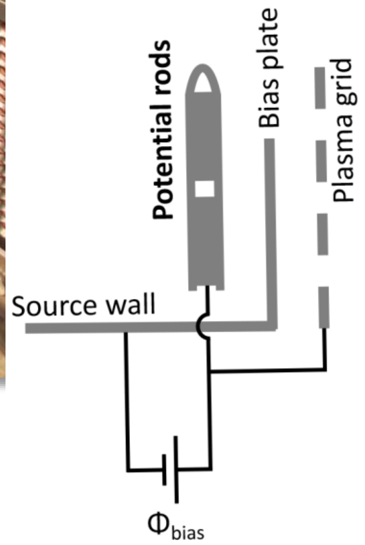


Strongly pronounced isotope effect:

- Amount of co-extracted electron and their temporal instability
  (can be counteracted by a stronger filter field, resulting in reduced ion current).
- Symmetry of the co-extracted electrons (strongly depends on RF power!), effect of vertical plasma drift.

Potential rods for symmetrizing the co-extracted electrons





Potential rods introduced to ELISE in 2017:

- Reduction and symmetrization of co-extracted electrons.
- Prerequisite for demonstrating ITER-relevant long pulses in H_2 (pulsed extraction) and 66 % of the target for D_2.

Lesson learnt

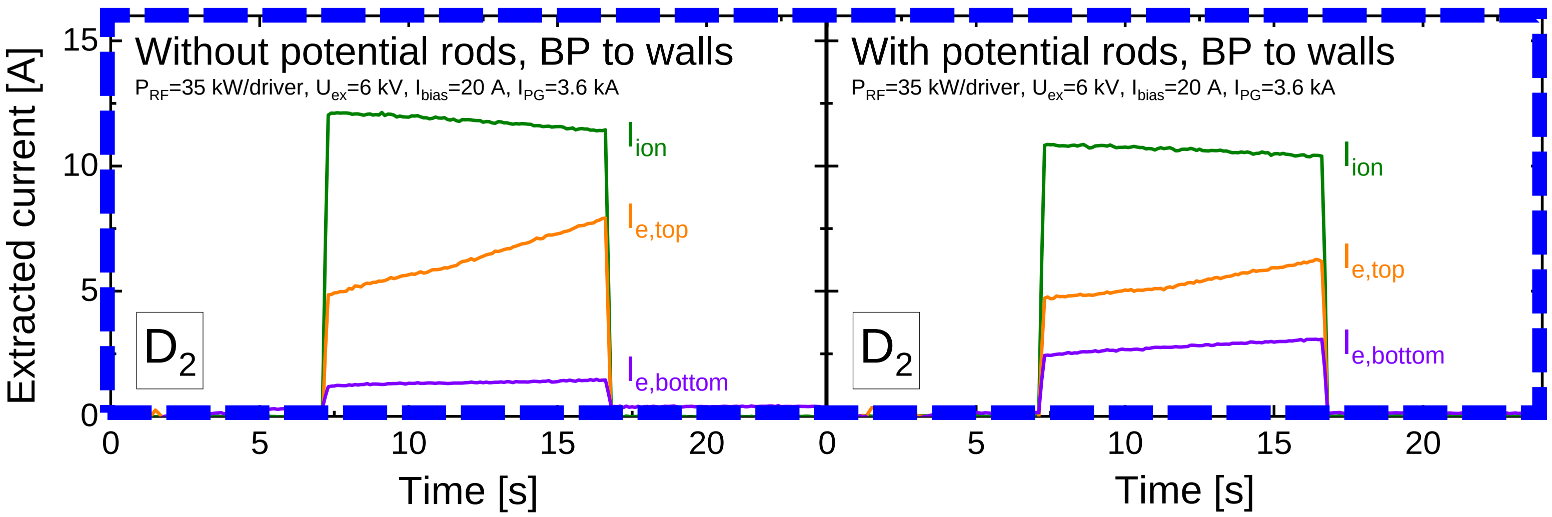
Beneficial effect of removing the electrons (partially) from the plasma upstream the plasma grid by means of the rods.

However:

Potential rods not foreseen for ITER NBI.

Develop improved operational scenarios w/o the potential rods

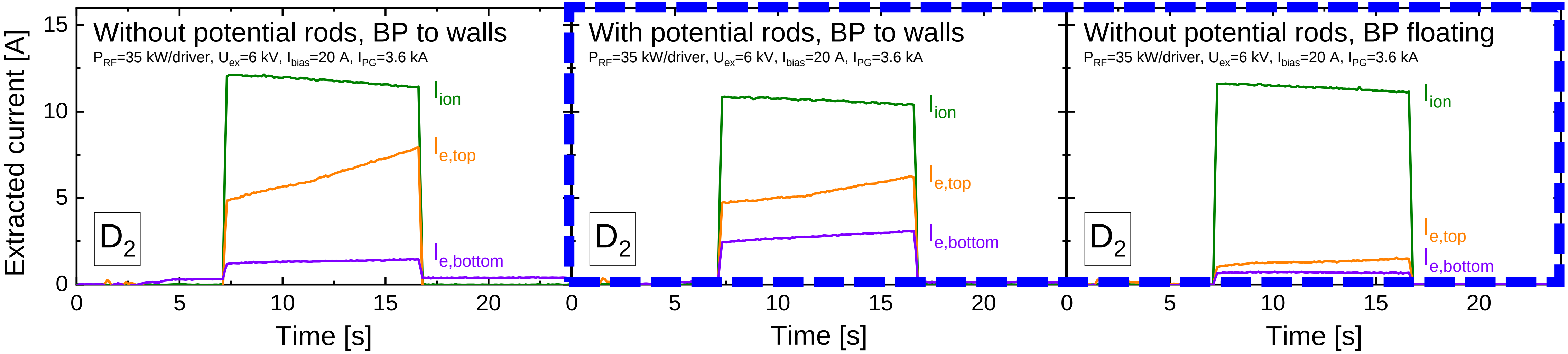
Replace the potential rods: biasing the bias plate I



Add potential rods to the standard ITER setup:

- Co-extracted electron current more symmetrical.
- Reduced extracted ion current (geometrical effect).

Replace the potential rods: biasing the bias plate I



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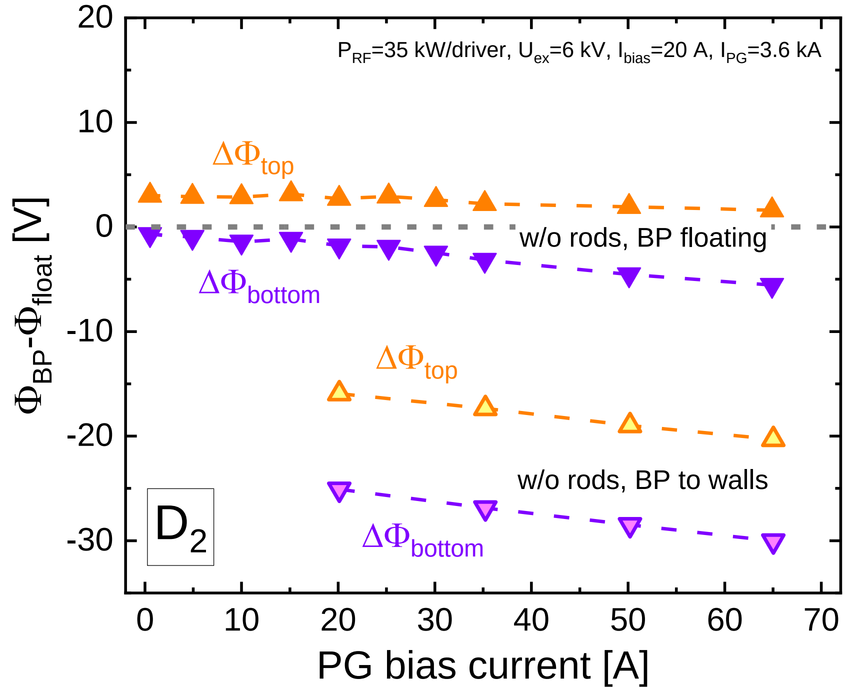
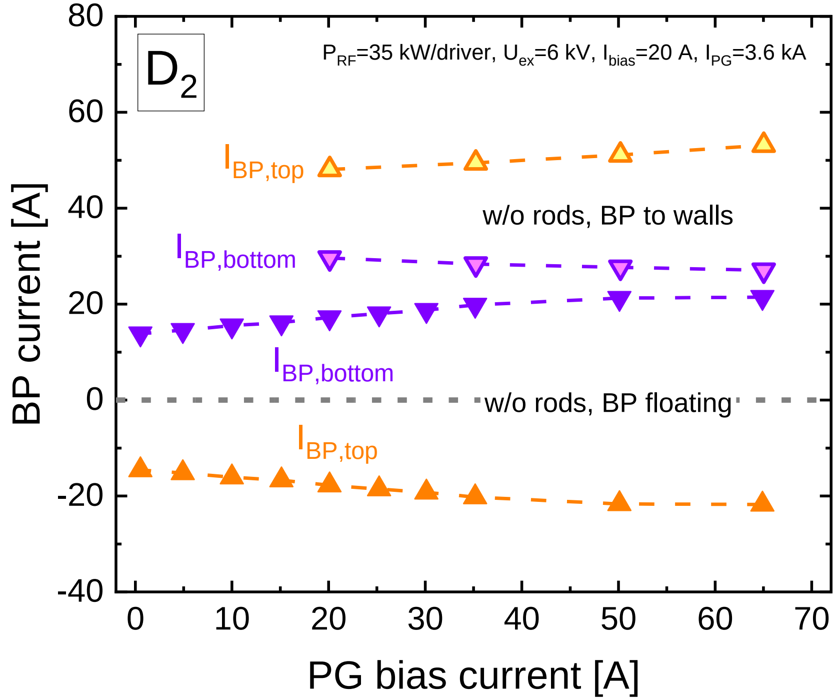
- Co-extracted electron current more symmetrical.
- Reduced extracted ion current (geometrical effect).

Remove the rods and let the BP float:

- Strong reduction of co-extracted electrons.
- Extracted ion current higher than with the rods.

Replace the potential rods: biasing the bias plate II

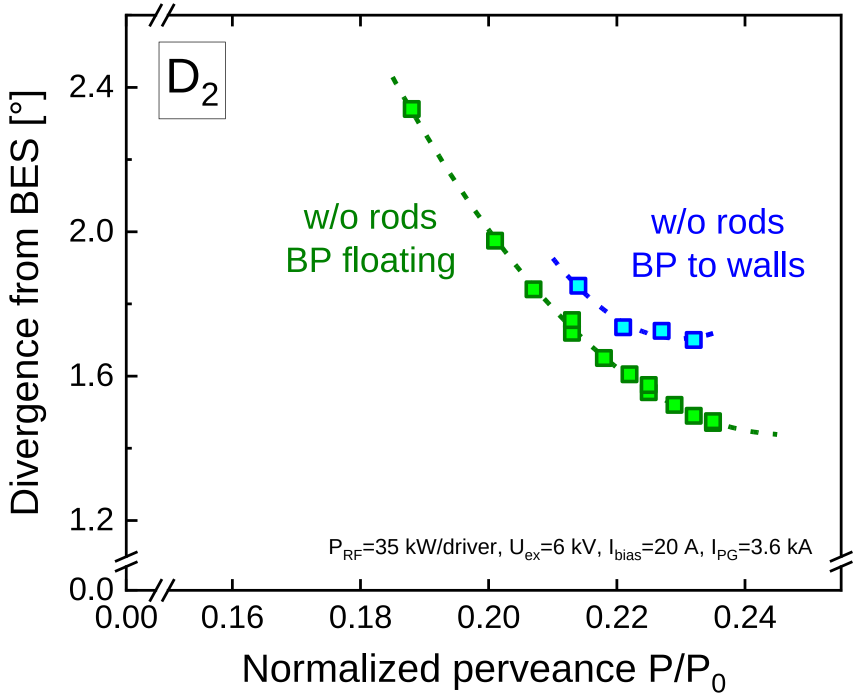




Compare the standard ITER setup (w/o rods) with floating BP (w/o rods):

- Floating BP: Plasma potential shifted upwards by a few Volts (not shown here).
- Sheath drop at BP much smaller, U_{BP}-U_{float} gets positive for the top segment
  $\Rightarrow$ Increased flux of electrons onto the BP and the observed reduction in I_e, in particular for the top segment.

Replace the potential rods: biasing the bias plate II



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- Modified 3D potential structure $\Rightarrow$ H^- trajectories $\Rightarrow$ Beamlet divergence

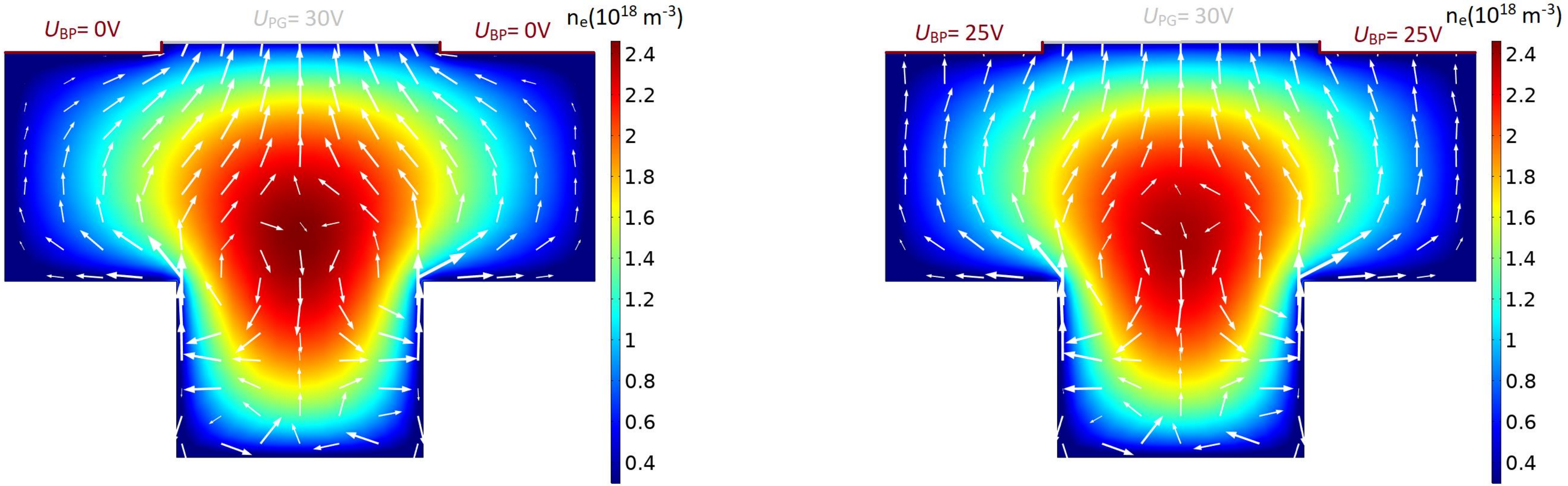
Impact of biasing surfaces on the electron flux I

Calculations using a 2D fluid code (based on Comsol):

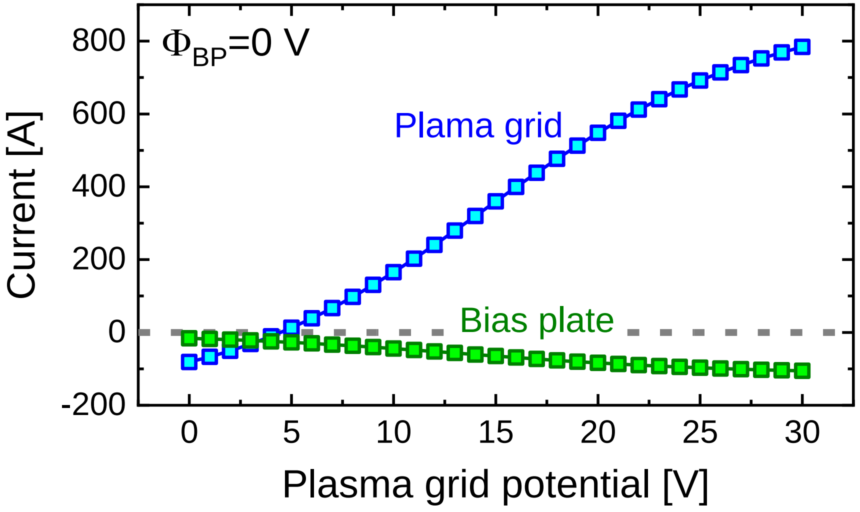
- Taking into account the equations for continuity, momentum balance, energy transport and Poisson's equation.

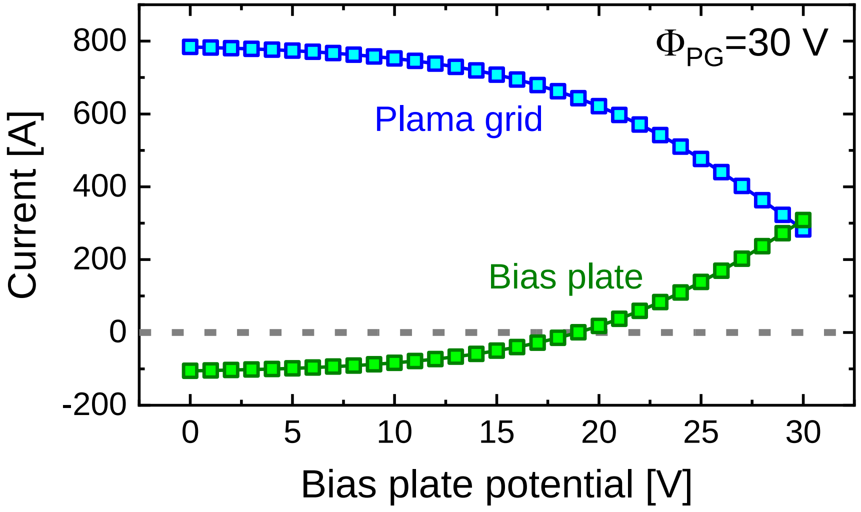
Two cases, w/o magnetic filter field: basing only the PG vs. biasing the PG and the BP:

- The BP bias strongly increases the electron fluxes towards the BP
  $\Rightarrow$ in agreement with the experiment.



Impact of biasing surfaces on the electron flux II





Current onto plasma grid and bias plate predicted by the fluid code:

- Plasma grid biasing can be (partially) replaced by bias plate biasing.

Further investigations should aim at defining operational scenarios that …

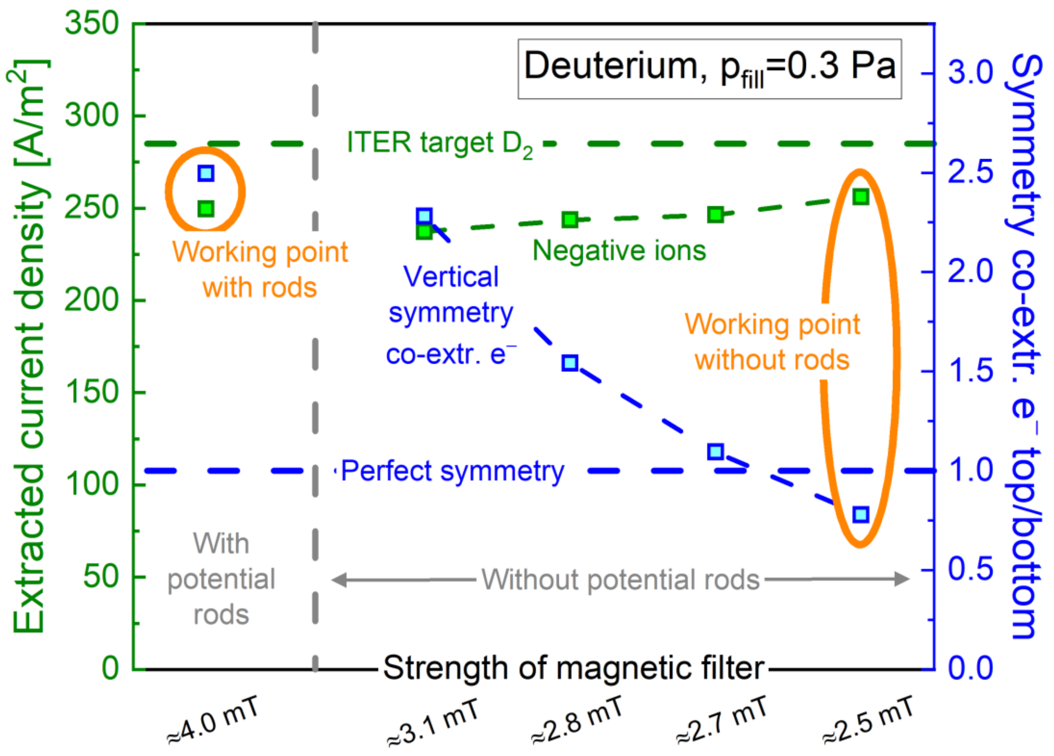
- Effectively reduce and/or stabilize the co-extracted electrons.
- Do not cause a strong top-bottom asymmetry of the co-extracted electrons.
- Do not reduce significantly the extracted ion current.

Approaching the ITER targets in deuterium (short pulses)

Strong reduction of co-extracted electrons caused by biased BP:

- Allows to reduce the filter field strength
  ⇒ almost perfect top-bottom symmetry of co-extracted electrons even at high P_{RF}.
- New best deuterium pulse:

> 90 % of ITER target at almost perfect vertical symmetry of the co-extracted electrons.



But:

Does it also work for long pulses?

Overcome restriction to pulsed extraction I

New CW HV power supply (OCEM), supported by EUROfusion

- Technical specs comparable to old PS.
- One 12 kV module and one 50 kV module, each consisting of several power modules in series.
- No tube-based HV modulators needed.
- Commissioning: end of 2021. ✓

CW beam calorimeter (IPP design)

Commissioning: beginning of 2022. ✓

CW beam extraction now routinely done at ELISE

12 kV PS module

12 kV PS transformer

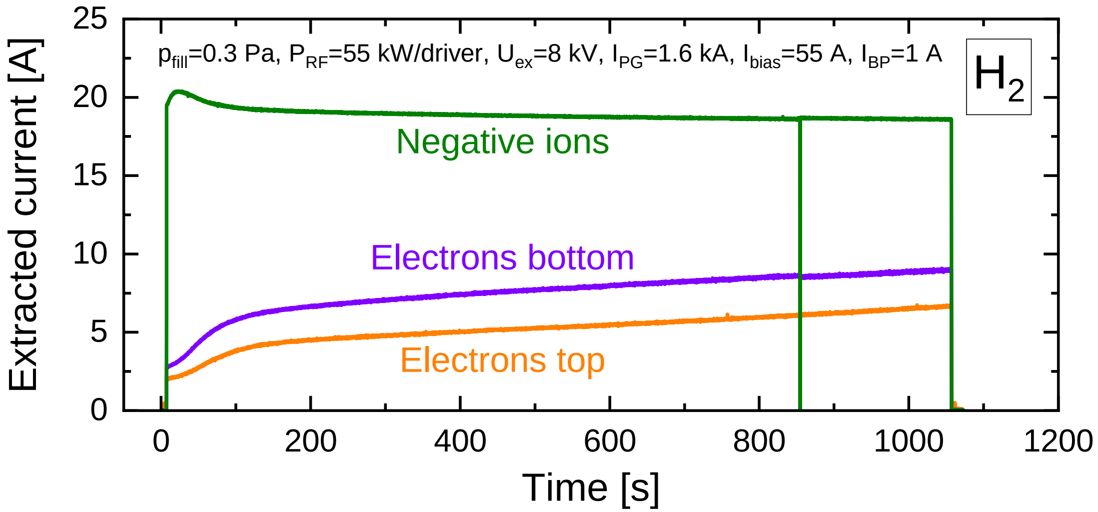
CW extraction: first results

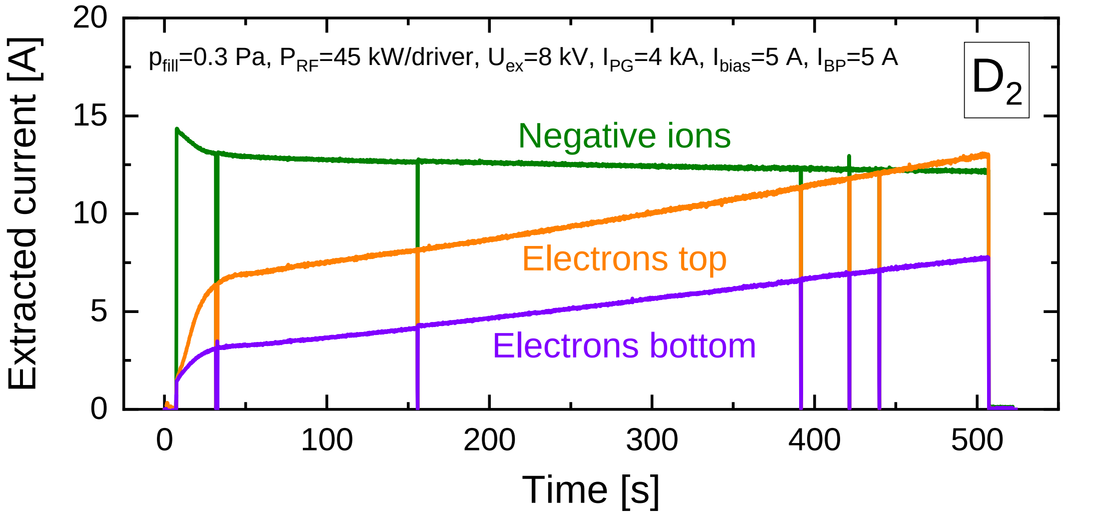
Very first campaign in H_2 and D_2

- Biased bias plate without potential rods
- Only a short campaign

  ⇒ No perfect caesium conditioning status reached, i.e. no final statement possible on temporal stability in this setup.

ITER target for the extracted negative ion density:
≈60 % reached for hydrogen,
≈ 40 % for deuterium.





Summary and outlook

ELISE is now a CW machine, focus on D_2

- CW HV power supply.
- CW calorimeter.
- Improved beam diagnostics

→ Very promising first results both in hydrogen and deuterium

Improved operational scenarios

- Removing the potential rods.
- Replace by biasing the bias plate.
- Symmetrize electrons by reducing the filter field strength.

→ Interplay of electrostatic potentials with the magnetic fields plays a critical role.

First steps towards improved operational scenarios in deuterium have been done.

$\Rightarrow$ Further improve physics insight by means of experimental and theoretical investigations.

The 2D fluid model

Equation system:

Continuity equation:

$$\frac{\partial n_\alpha}{\partial t} + \nabla . n_\alpha \boldsymbol{u}_\alpha = \frac{\delta n_\alpha}{\delta t}$$

α = e, H^+, H_2^+, H_3^+

Momentum equation:

$$n_\alpha m_\alpha \left(\frac{\partial \boldsymbol{u}_\alpha}{\partial t} + (\boldsymbol{u}_\alpha . \nabla) \boldsymbol{u}_\alpha \right) = Z_\alpha e n_\alpha \mathbf{E} - \nabla p_\alpha - \mu_{\alpha n} n_\alpha \nu_\alpha \upsilon_\alpha - m_\alpha n_\alpha \frac{\delta n_\alpha}{\delta t}$$

E – field force

Friction force:
elastic collusions with neutrals

Inertia term
- negligible for electrons
- important for ions at low pressure

Pressure force

Change of the velocity,
due to non elastic collusions

Electron energy transport equation:

$$\frac{3}{2} \frac{\partial (n_e T_e)}{\partial t} + \nabla . \mathbf{J}_e = Q - P_{coll}$$

$$\mathbf{J}_e = -\chi_e \nabla T_e + \frac{5}{2} T_e \boldsymbol{\Gamma}_e$$

Poisson's equation:

$$\Delta \Phi = -\frac{e}{\varepsilon_0} \left(\sum_{i=1}^{3} n_i - n_e \right)$$

The 2D fluid model

Boundary conditions:

Charged particle fluxes towards the walls

- $\mathbf{\Gamma}_e^{\mathrm{wall}} = \frac{1}{4} n_e u_{e,\mathrm{th}}$
- $\mathbf{\Gamma}_i^{\mathrm{wall}} = n_i u_{i,\mathrm{eff}}\left(u_{i,\perp}, u_{i,p}\right)$

Electron energy fluxes towards the walls

- $\mathbf{J}_e^{\mathrm{wall}} = \frac{5}{2} T_e \mathbf{\Gamma}_e$

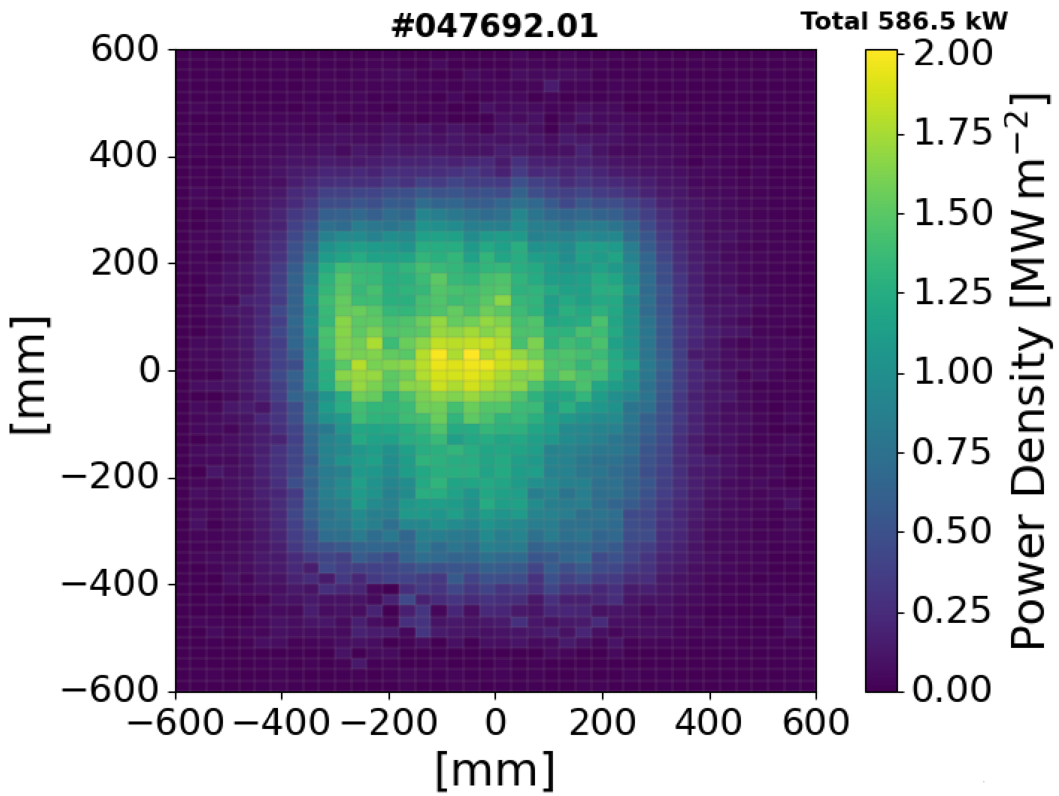
Set potentials for the walls (Dirichlet BC)

- $\Phi_{\mathrm{wall}} = 0(\mathrm{V})$
- $\Phi_{\mathrm{PG}} = U_{PG}(\mathrm{V})$
- $\Phi_{\mathrm{BP}} = U_{BP}(\mathrm{V})$

Overcome restriction to pulsed extraction II

CW beam calorimeter (IPP design)

- Active cooling needed
  (max. power load: 4.5 MW/m², max. power: 1.8 MW).
- Modular design: 3 horizontal plates, water cooled.
- Beam profile diagnosed by IR camera:
  - Calorimeter back side blackened.
  - Resolution: 20 × 40 mm.
- Commissioning: beginning of 2022. ✓



CW beam extraction now routinely done at ELISE