



Impact of plasma potential modifications on the performance of ITER-relevant negative hydrogen ion sources

D. Wunderlich, R. Riedl, M. Frösche, D. Mussini, E. Nanou, A. Navarro, J. Rubin,
D. Yordanov, C. Wimmer, A. Döring, U. Fantz

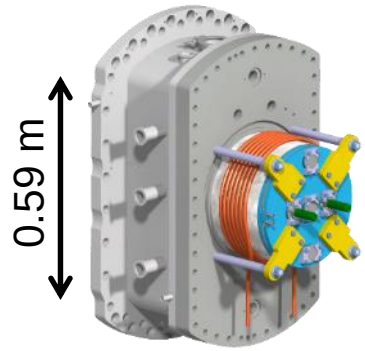
Max-Planck-Institut für Plasmaphysik, Garching, Germany



This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.



Step-ladder approach towards the ion source for ITER NBI

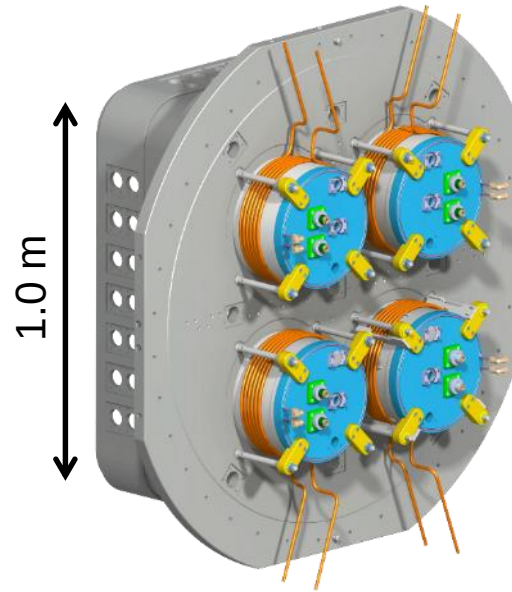


IPP prototype source
(59×30 cm²)

Used at the BATMAN
Upgrade facility

Basic ITER requirements
fulfilled. ✓

Test bed for basic
physics investigations



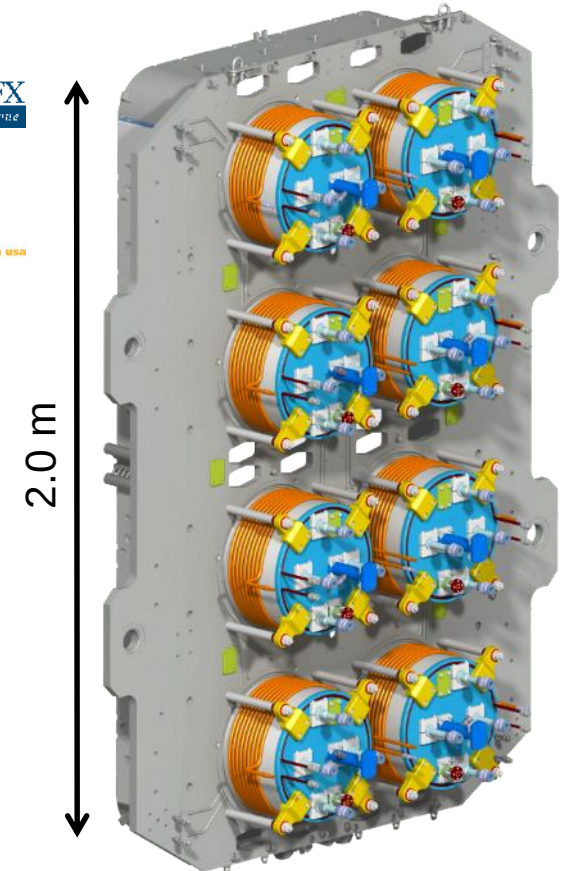
Size scaling: half ITER source size experiment
(100×90 cm²)

ELISE in operation since 2013.



Source for ITER NBI (200×100 cm²)

- SPIDER in operation since 2018.
- MITICA: commissioning ongoing.





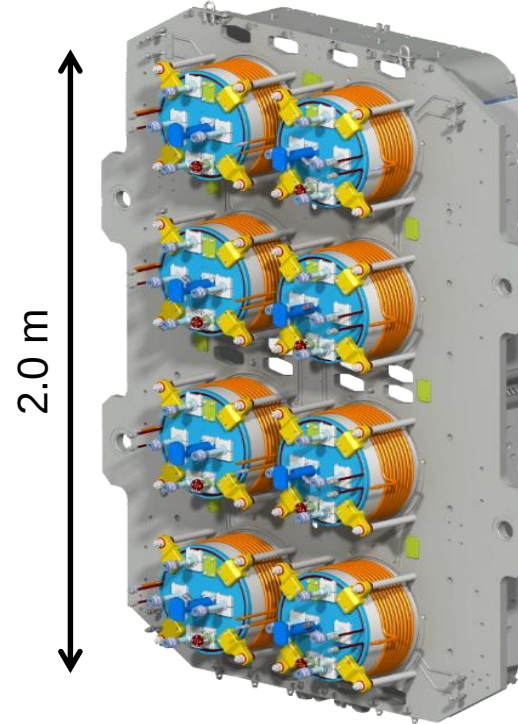
Production of negative hydrogen ions and target values

Challenge: generation of a huge and powerful negative ion beam...

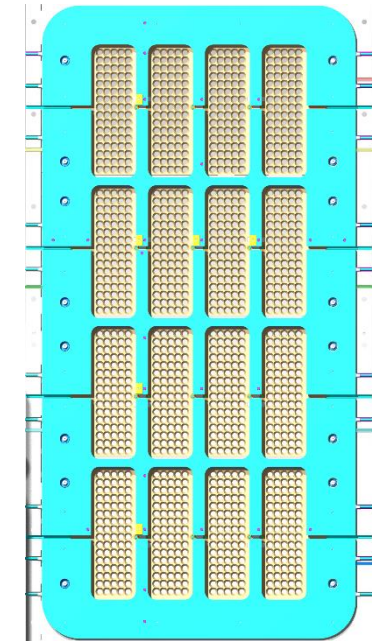
	H (DT-1)	D (DT-2)
j_{acc}^*	230 A/m ² (870 keV)	200 A/m ² (1 MeV)
j_{ex}	329 A/m ²	286 A/m ²
j_e/j_{ex}	<1	<1
p_{fill}	≤ 0.3 Pa	≤ 0.3 Pa
Pulse length	Up to several hundred seconds	Up to one hour
Beam homog.	>90 %	>90 %
Beamlet div.	<7 mrad	<7 mrad

*: The ITER 7-grid extraction system has a different stripping fraction compared to the 3-grid systems of the test facilities.

Ion source for ITER HNB, NBTF and DNB



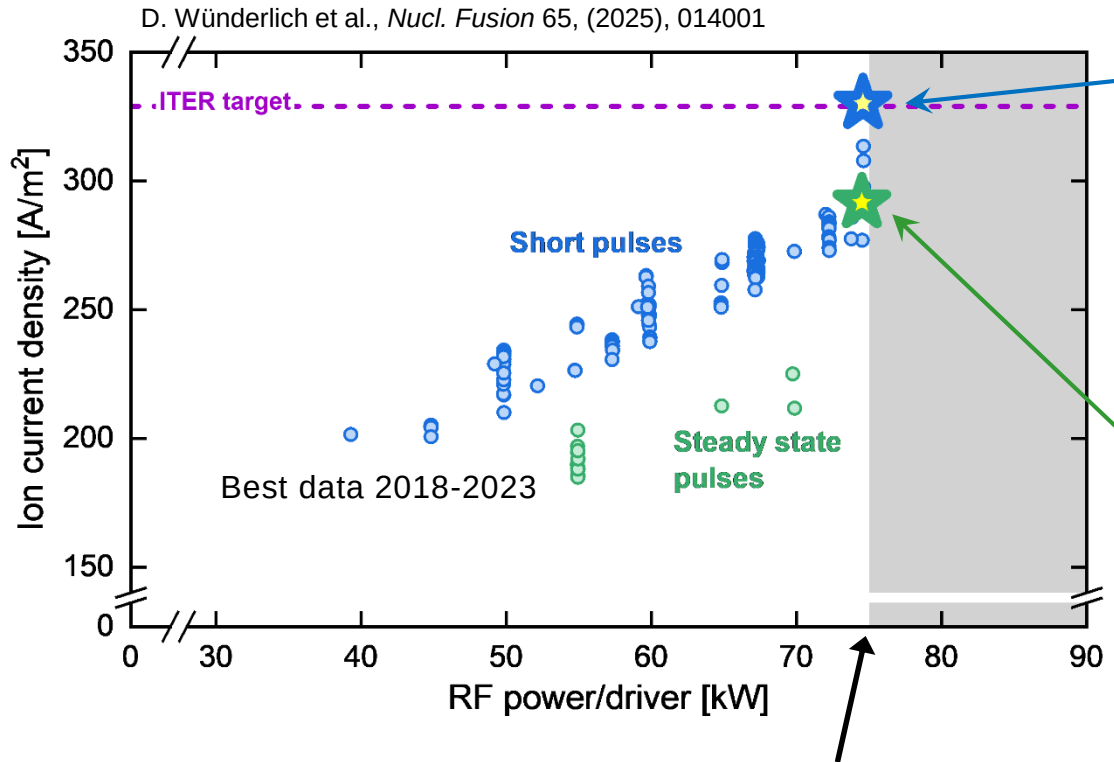
ITER grid



Main factor limiting the performance:
Amount, temporal increase and vertical non-symmetry of the co-extracted electrons.

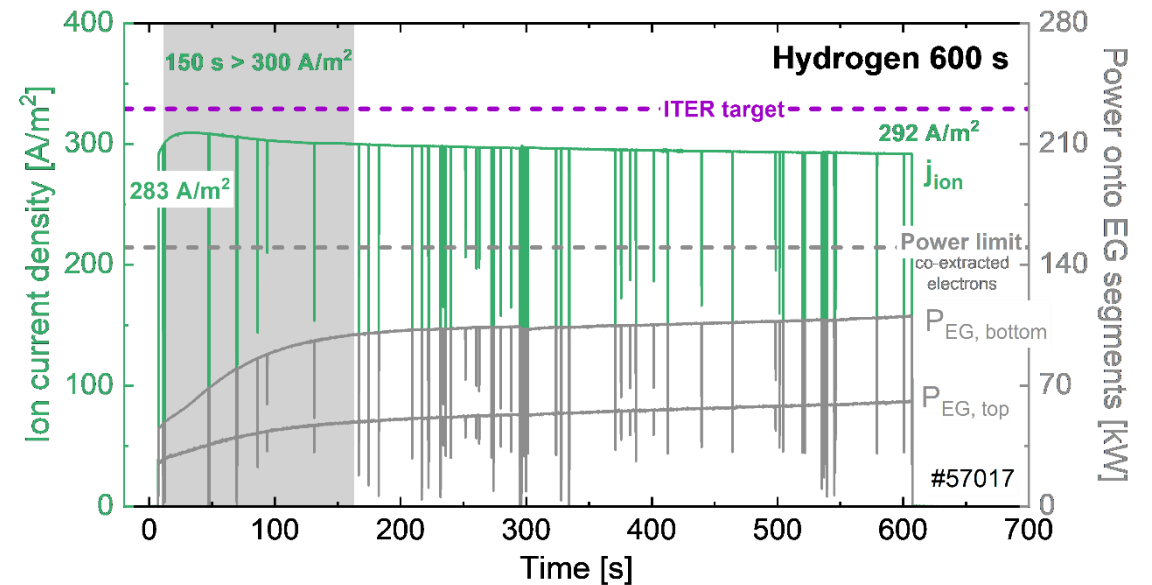
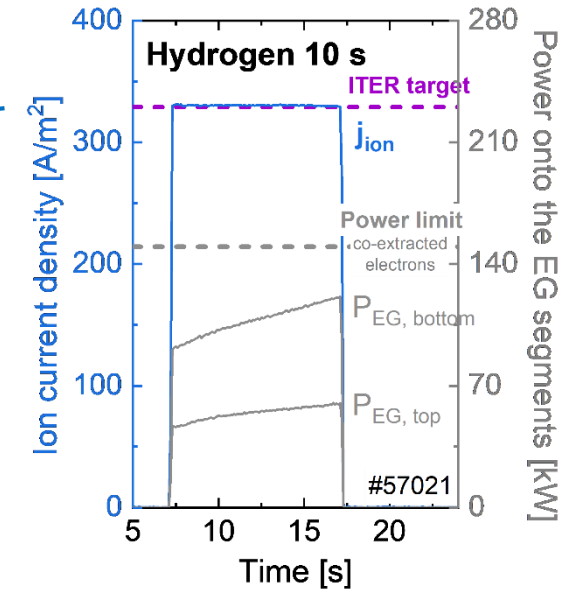


Record values obtained at ELISE in 2024



RF power at ELISE limited to 75 kW/driver.
The ITER NBI system has 100 kW/driver!

Bias plate and plasma grid connected to each other and floating.
Potential rods floating. Flexible filter field setup.



Insight and setup before the recent campaign

Key points for reducing, symmetrizing and stabilizing co-extracted electrons:

- Caesium conditioning
 - Electrostatic potentials
 - Magnetic field
- } Direct impact on plasma electrons
and effect on plasma drift $\Rightarrow$ vertical plasma symmetry

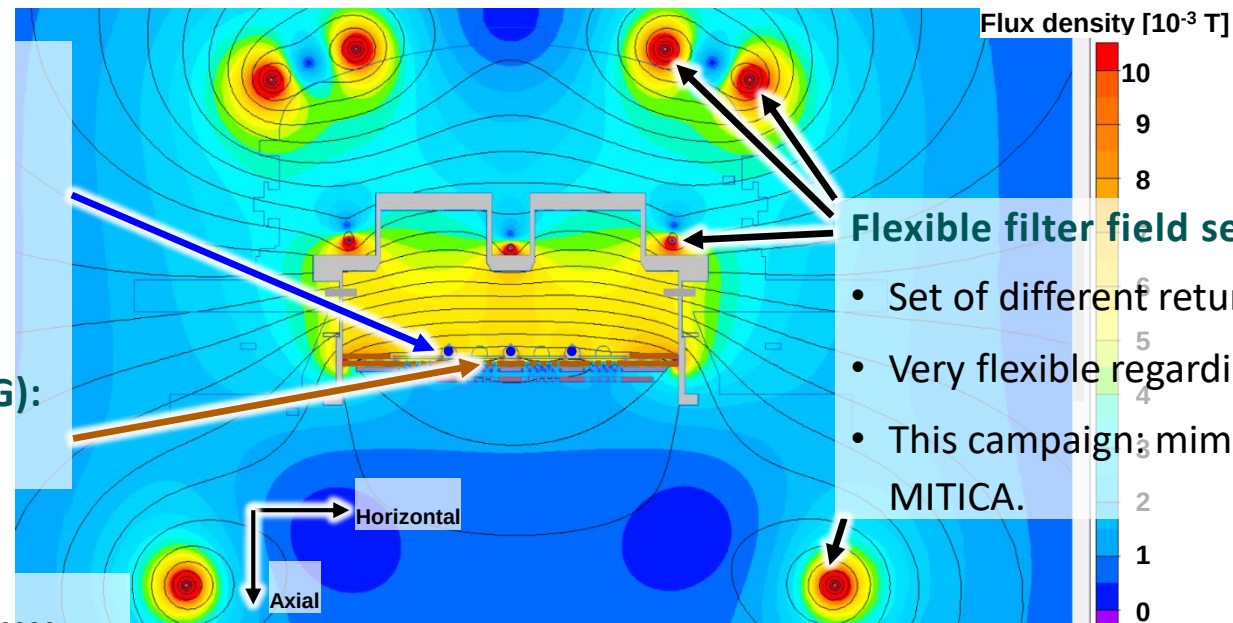
Vertically symmetric plasma $\Rightarrow$ impact on symmetry of I_e and caesium distribution. More stable long pulses

Potential rods:

- Vertical metal tubes traversing the plasma volume.
- Affect electrostatic potential.

Bias plate (BP) and plasma grid (PG):

Can be set to different potentials



Flexible filter field setup:

- Set of different return conductors
- Very flexible regarding the field topology.
- This campaign: mimic the field foreseen for MITICA.

W. Kraus et al., *Rev. Sci. Instrum.* 89, **2018**, 052102

D. Wunderlich et al., *J. Phys.: Conf. Ser.* 2743, **2024**, 012026

Insight and setup before the recent campaign

Key points for reducing, symmetrizing and stabilizing co-extracted electrons:

- Caesium conditioning
 - Electrostatic potentials
 - Magnetic field
- } Direct impact on plasma electrons and effect on plasma drift $\Rightarrow$ vertical plasma symmetry

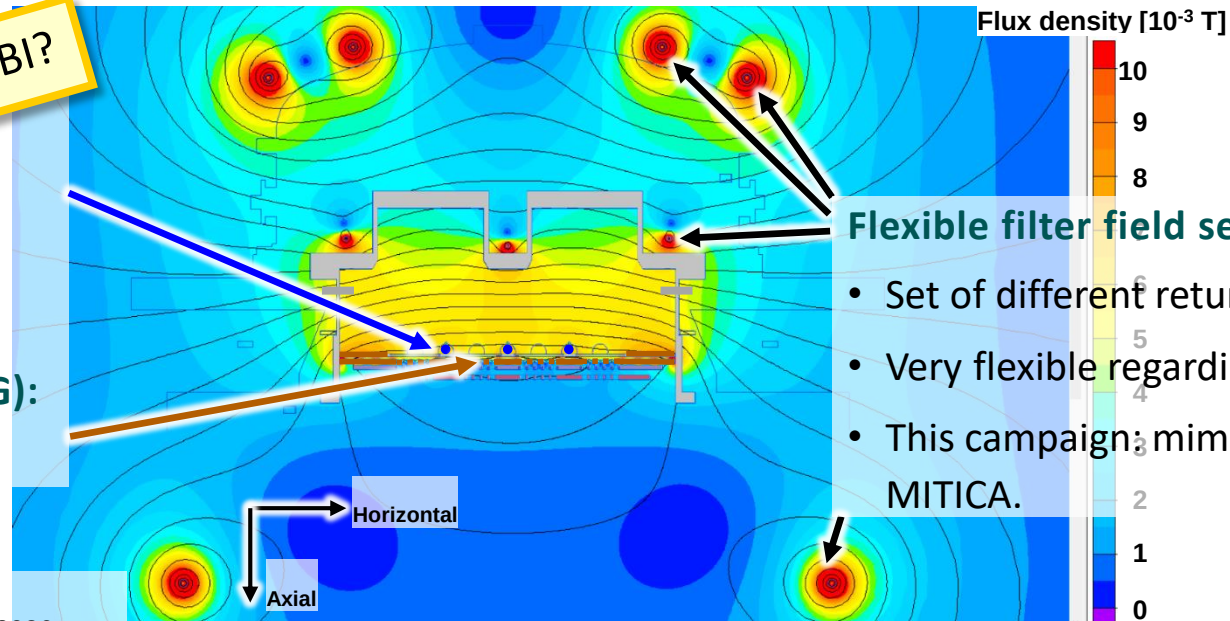
Vertically symmetric plasma $\Rightarrow$ impact on symmetry of I_e and caesium distribution. More stable long pulses

Potential rods:

- Vertical magnetic field rods
- Are the rods really needed for ITER NBI?
- Direct electrostatic potential.

Bias plate (BP) and plasma grid (PG):

Can be set to different potentials



Flexible filter field setup:

- Set of different return conductors
- Very flexible regarding the field topology.
- This campaign: mimic the field foreseen for MITICA.

W. Kraus et al., *Rev. Sci. Instrum.* 89, **2018**, 052102

D. Wunderlich et al., *J. Phys.: Conf. Ser.* 2743, **2024**, 012026



Insight and setup before the recent campaign

Key points for reducing, symmetrizing and stabilizing co-extracted electrons:

- Caesium conditioning
 - Electrostatic potentials
 - Magnetic field
- } Direct impact on plasma electrons
and effect on plasma drift $\Rightarrow$ vertical plasma symmetry

Vertically symmetric plasma $\Rightarrow$ impact on symmetry of I_e and caesium distribution. More stable long pulses

Potential rods:

- Vertical magnetic field
- Are the rods really needed for ITER NBI?
- Direct electrostatic potential

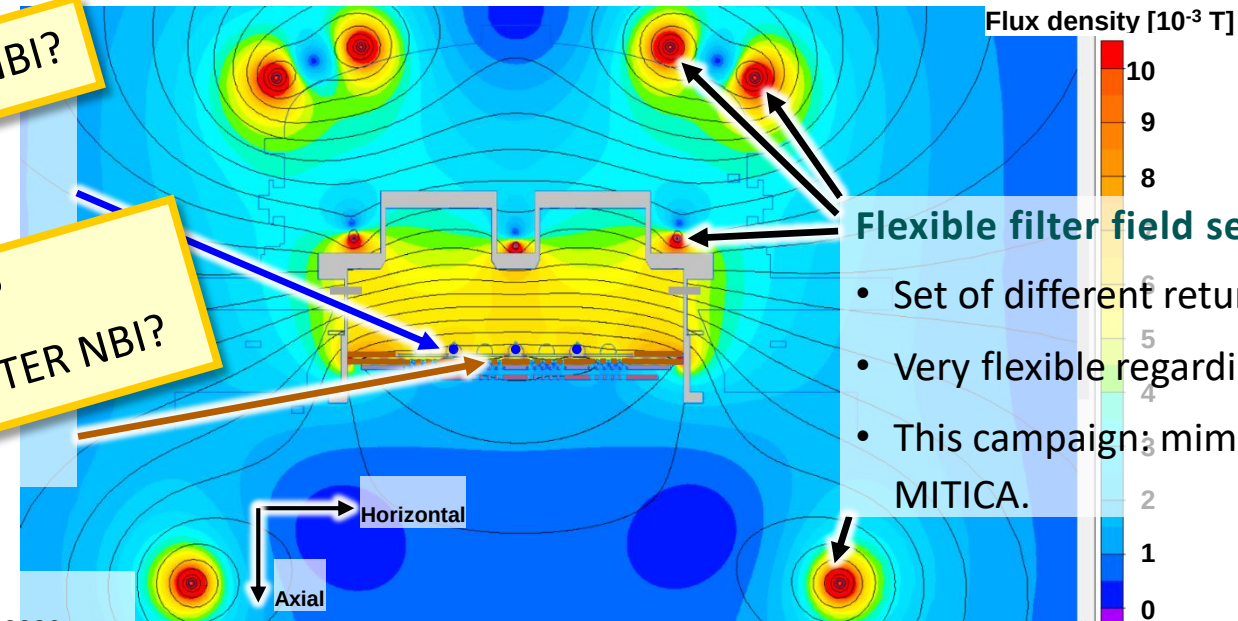
Bias plate

Optimum potential settings?

Is the bias plate really needed for ITER NBI?

Wunderlich et al., *Rev. Sci. Instrum.* 89, **2018**, 052102

D. Wunderlich et al., *J. Phys.: Conf. Ser.* 2743, **2024**, 012026



Flexible filter field setup:

- Set of different return conductors
- Very flexible regarding the field topology.
- This campaign: mimic the field foreseen for MITICA.



Plasma potential in negative hydrogen ion sources

- Are the potential rods needed for ITER NBI?
- Optimum potential settings for the BP and the PG?
Is the BP needed for ITER NBI?



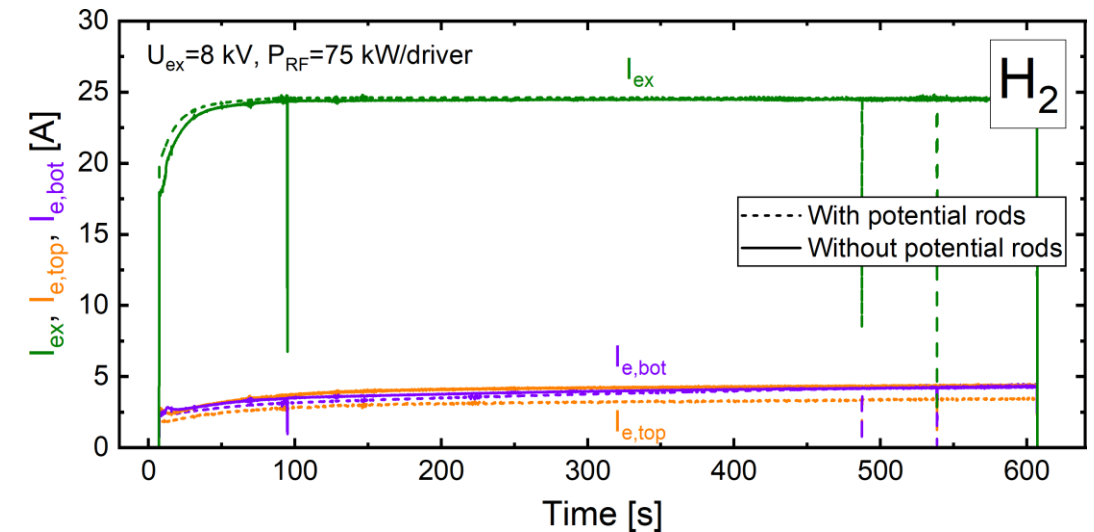
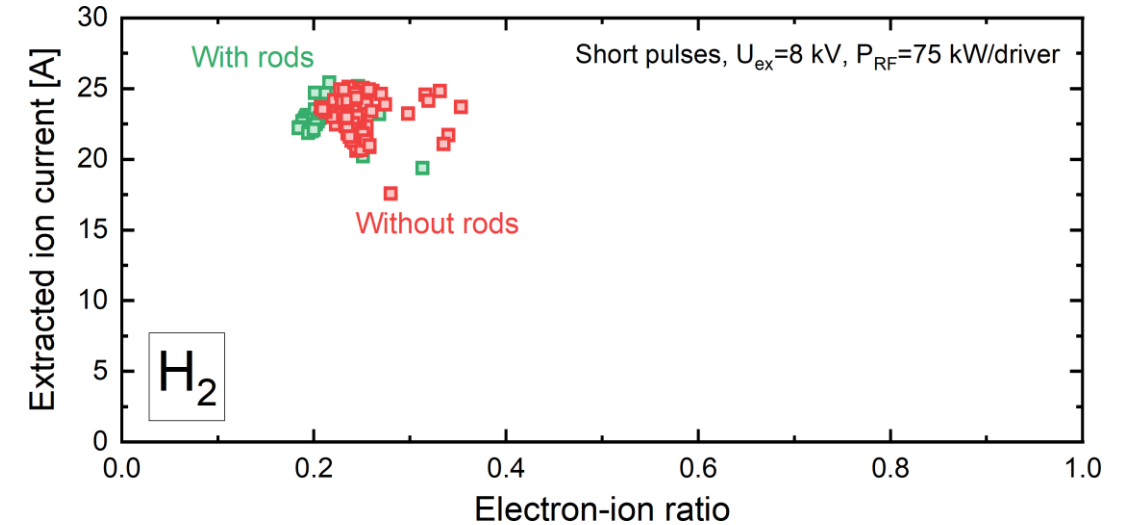
Removing the potential rods in H₂ and D₂

Experiments done in H₂ and D₂:

Use the flexible filter field setup. Take out the rods and compare the achievable performance before and after.

Results:

- Operating with and without the rods yields comparable results in short and long pulses
- Differences in long pulses caused by slight differences in the caesium conditioning status.





Removing the potential rods in H₂ and D₂

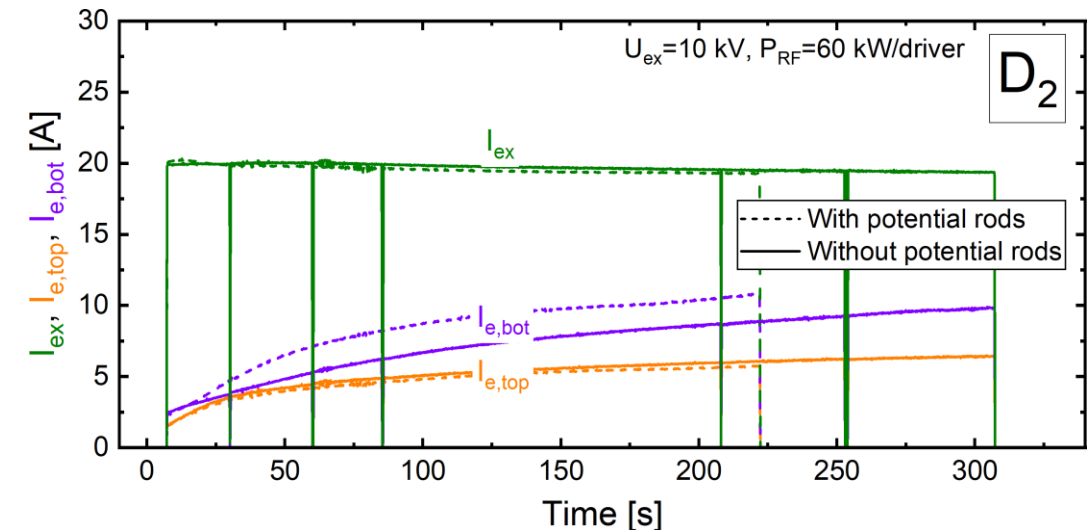
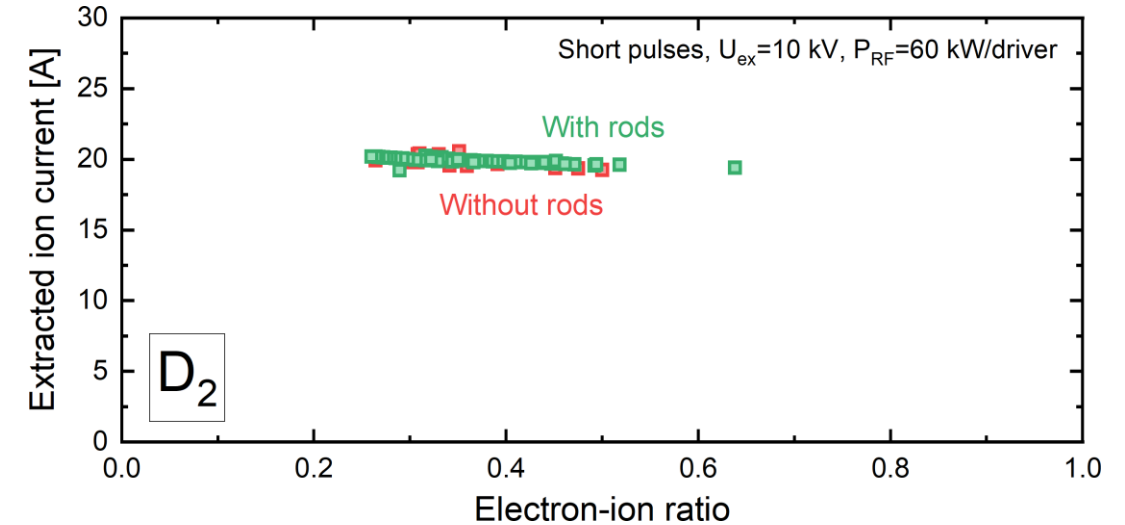
Experiments done in D₂ and H₂:

Use the flexible filter field setup. Take out the rods and compare the achievable performance before and after.

Results:

- Operating with and without the rods yields comparable results in short and long pulses
- Differences in long pulses caused by slight differences in the caesium conditioning status.

For a very good status of the caesium conditioning the potential rods work in interplay with the flexible filter field setup and are not needed.





Plasma parameters with and w/o the rods

No impact of removing rods on most plasma parameters, except of:

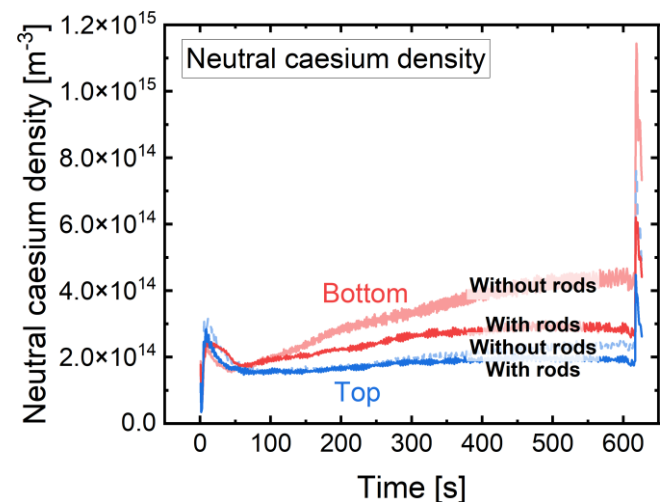
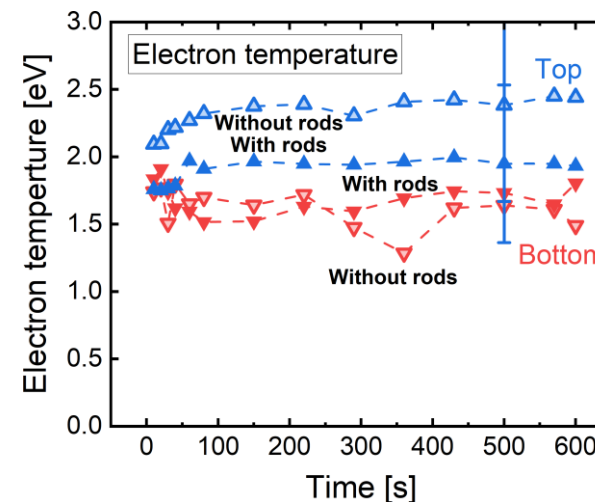
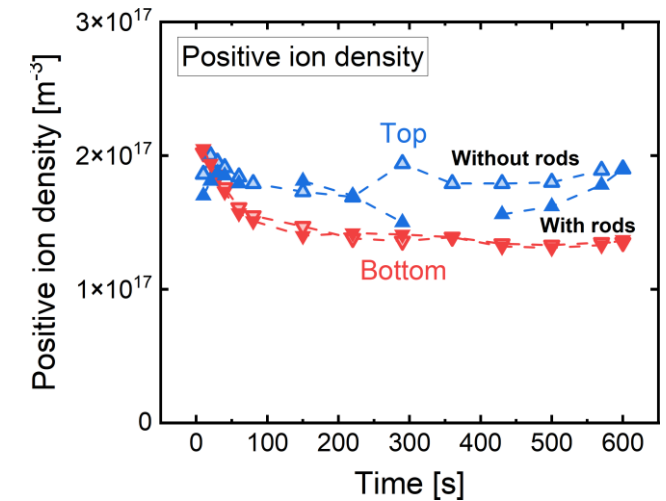
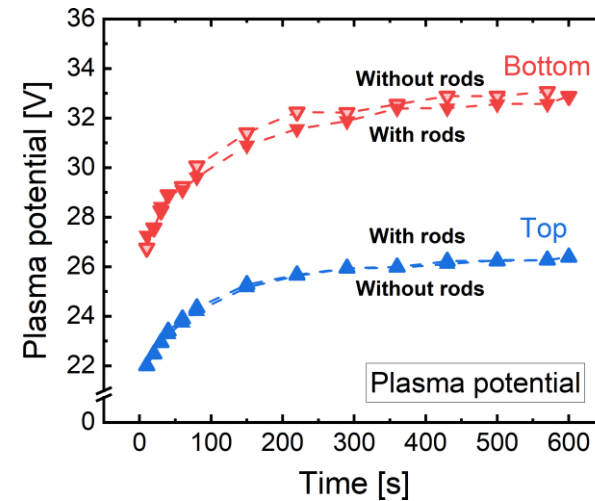
- Electron temperature in the top.
- Neutral caesium density.

Both do not affect, however, I_{ex} and I_e . One possible reason: axial distance (≈ 2 cm) between Langmuir probe/LOS used by TDLAS and meniscus.

High relevance of measurements very close to the meniscus.

Planned: ELISE operation w/o bias plate during the next campaign $\Rightarrow$ it is possible to shift diagnostics closer to meniscus.

H_2 , $U_{ex}=8$ kV, $P_{RF}=75$ kW/driver





Plasma potential in negative hydrogen ion sources

- Are the potential rods needed for ITER NBI?
- Optimum potential settings for the BP and the PG?
Is the BP needed for ITER NBI?

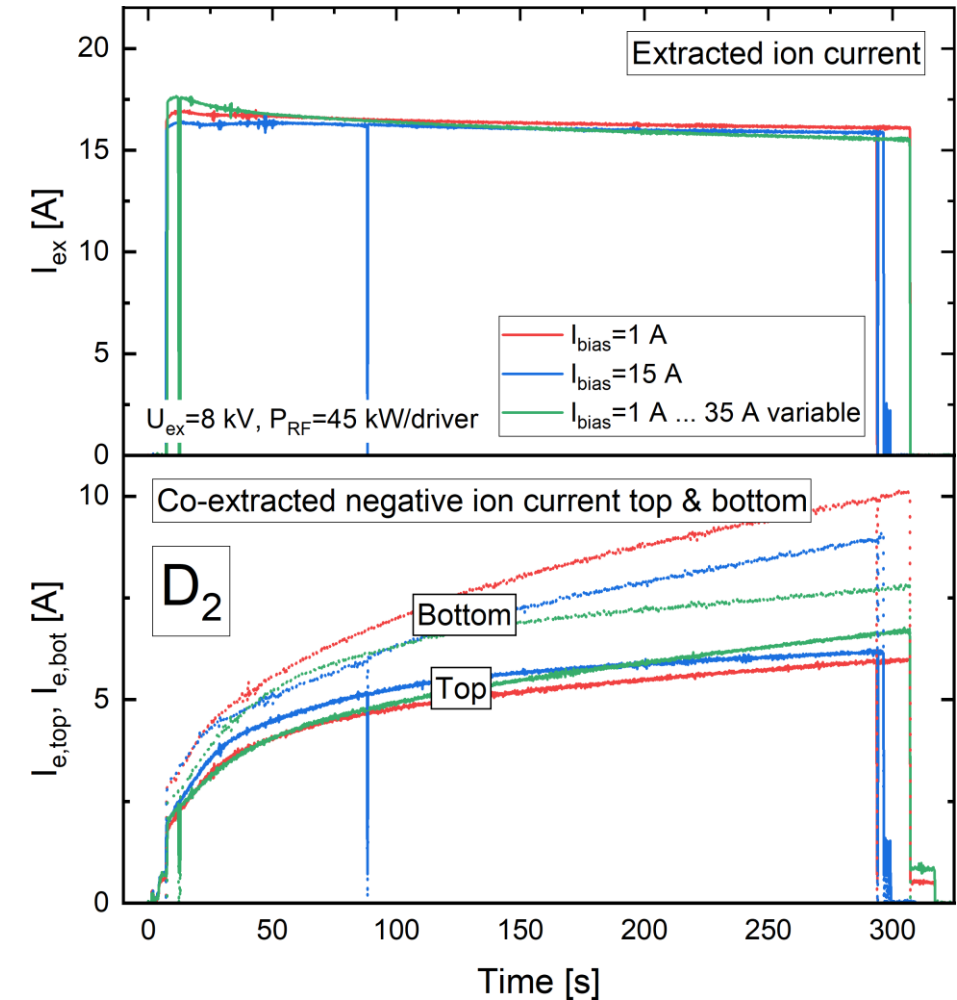


Long pulses with different PG bias (w/o rods)

Effect of the PG bias for floating BP and a very well conditioned source

- Well-known effect during short pulses: PG bias reduces the co-extracted electron current.
This effect vanishes for a very good caesium conditioning status.
- Experiments done in D_2 and without the rods
⇒ PG bias still has an effect on the long pulse stability and the vertical symmetry of the co-extracted electrons.
- Slight effect on I_{ex} .
- Keep in mind uncertainty caused by the Cs conditioning
⇒ one pulse with increasing bias (1 A ... 35 A) over the full pulse length as cross check.

Adjusting the PG bias during long pulses can be a valuable tool for affecting the co-extracted electrons





Role of the bias plate (with rods)

Initial motivation for introducing the BP:

Prevent potential locking, i.e. the positive PG bias shifts the plasma potential to higher values.

⇒ Standard configuration up to 2021:

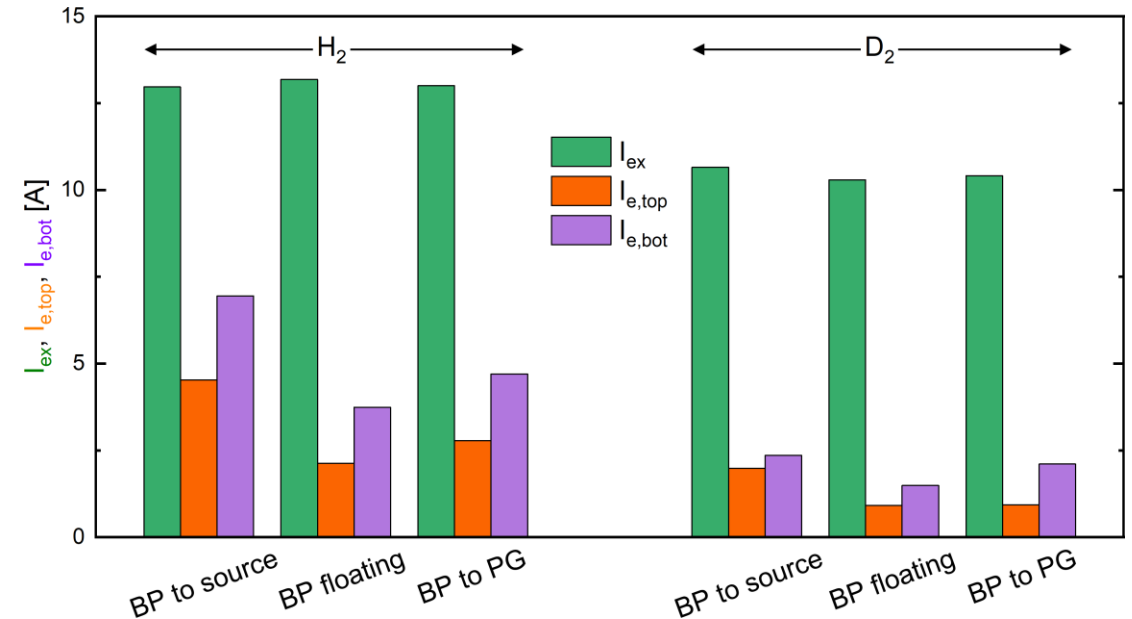
BP connected to the (grounded) source walls

Systematic experiments (short pulses):

- BP connected to source walls.
- BP plate floating.
- BP connected to PG.

Results:

- No significant effect on the extracted negative ions
- BP connected to source walls is the worst setup regarding amount of co-extracted electrons.
- BP floating is the best setup, BP connected to PG slightly worse.





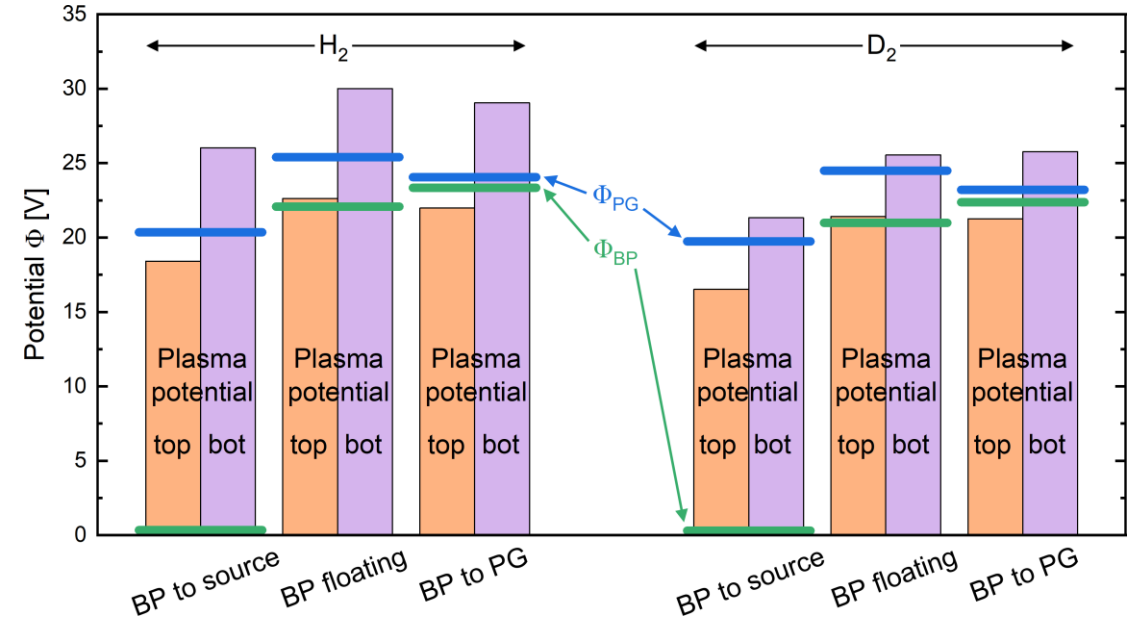
Role of the bias plate (with rods)

Investigate role of potential differences:

- BP connected to the source walls:
 $\Phi_{\text{Plasma}} - \Phi_{\text{BP}} > 17 \text{ V}$
 $\Rightarrow$ BP does not act as electron loss area.
- BP floating *or* connected to PG:
 $\Phi_{\text{Plasma}} - \Phi_{\text{BP}}$ significantly reduced
 $\Rightarrow$ BP does act as electron loss area.

Increase of plasma potential caused by potential locking.

Partially compensated for by increase of PG potential (resulting from constant PG bias current)
 $\Rightarrow$ PG still (locally) acts as electron loss area.



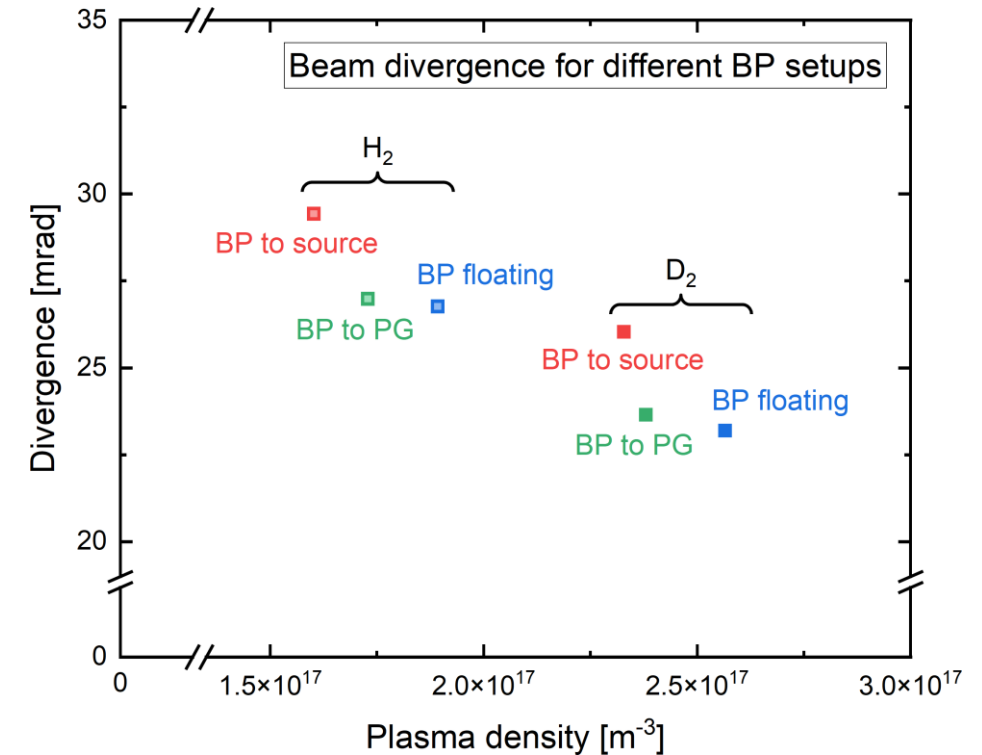
Crucial role of potential differences for transport of electrons towards surfaces $\Rightarrow$ reduction of co-extracted electron current.



Role of the bias plate (with rods)

Impact on beam divergence:

- BP connected to the source walls again is the worst configuration. BP floating *or* connected to PG show similar results
- Divergences in deuterium in general lower than in hydrogen.
- Differences in the beam divergence correlate to plasma density at the meniscus
⇒ Deeper penetrating meniscus for lower plasma density is a possible explanation.
However, no significant effect on extracted ion current!
Other possible explanations: geometrical effects, different plasma drift, different electron temperature, ...





Summary, conclusions and outlook

ELISE and BATMAN Upgrade play a leading role in defining operational setups and scenarios for ITER NBI:

1) Potential rods not needed.

Effectivity of measures for reducing and stabilizing the co-extracted electrons can strongly depend on the Cs conditioning status and interplay with other measures.

2) Very good Cs conditioning: PG bias does not affect short pulse performance but the long pulse stability.

Long pulse experiments mandatory for optimizing long pulse operation.

3) Connecting BP and PG is a good setup regarding the co-extracted electrons

Re-start of ELISE after the maintenance phase 2026 w/o BP upon request from ITER.

