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FÜR PLASMAPHYSIK

Towards long pulse operation of N-NBI ion sources

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EUROfusion

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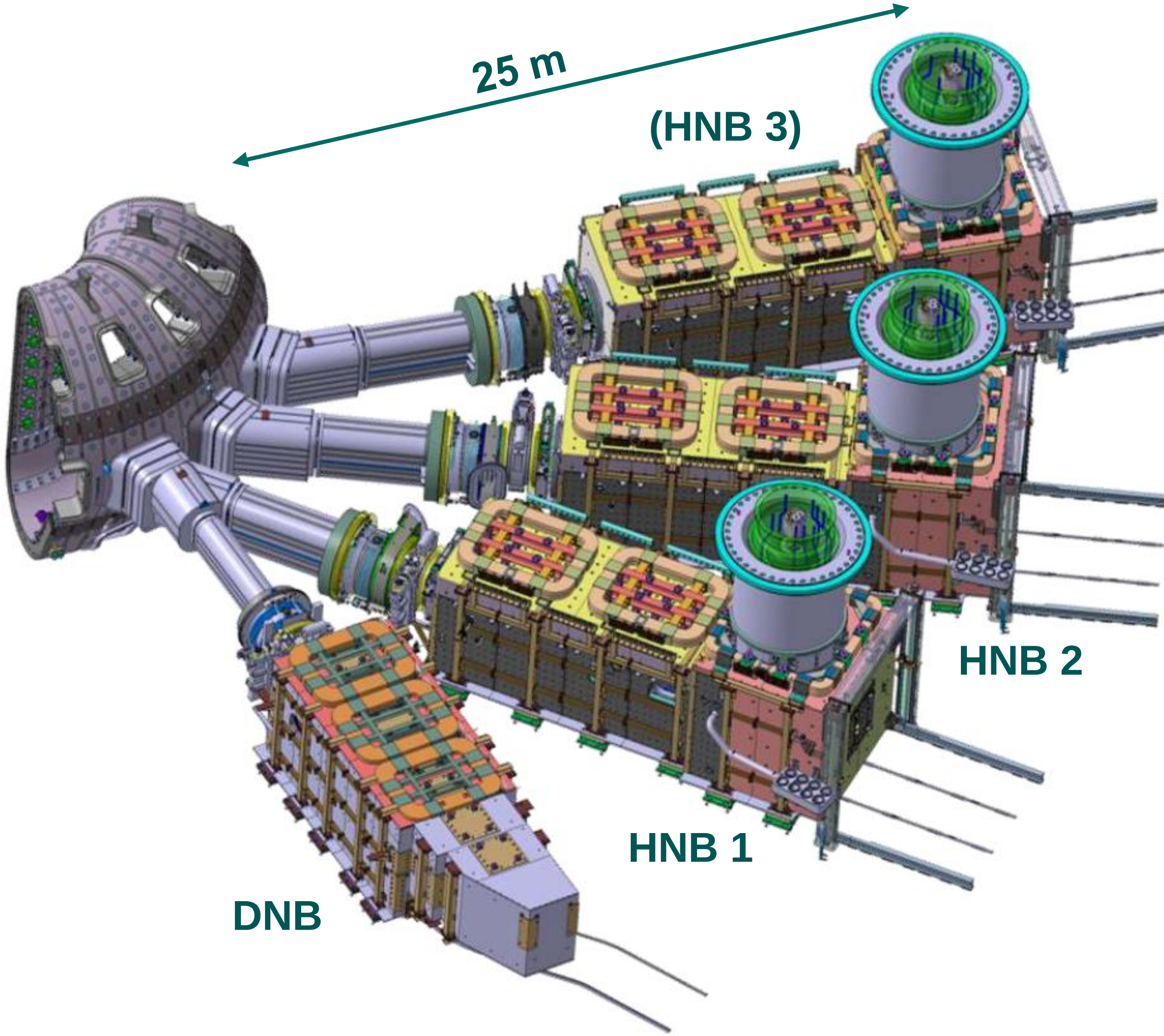
Neutral Beam Injectors for ITER

Heating neutral beam (HNB) injectors:

- 2 foreseen at the beginning
- 16.5 MW heating power each
  (fusion plasma heating & current drive)
- 1 MeV D, 870 keV H $\rightarrow$ H^- source required
  (10 kV extraction + 5 x 200 kV acceleration stages)

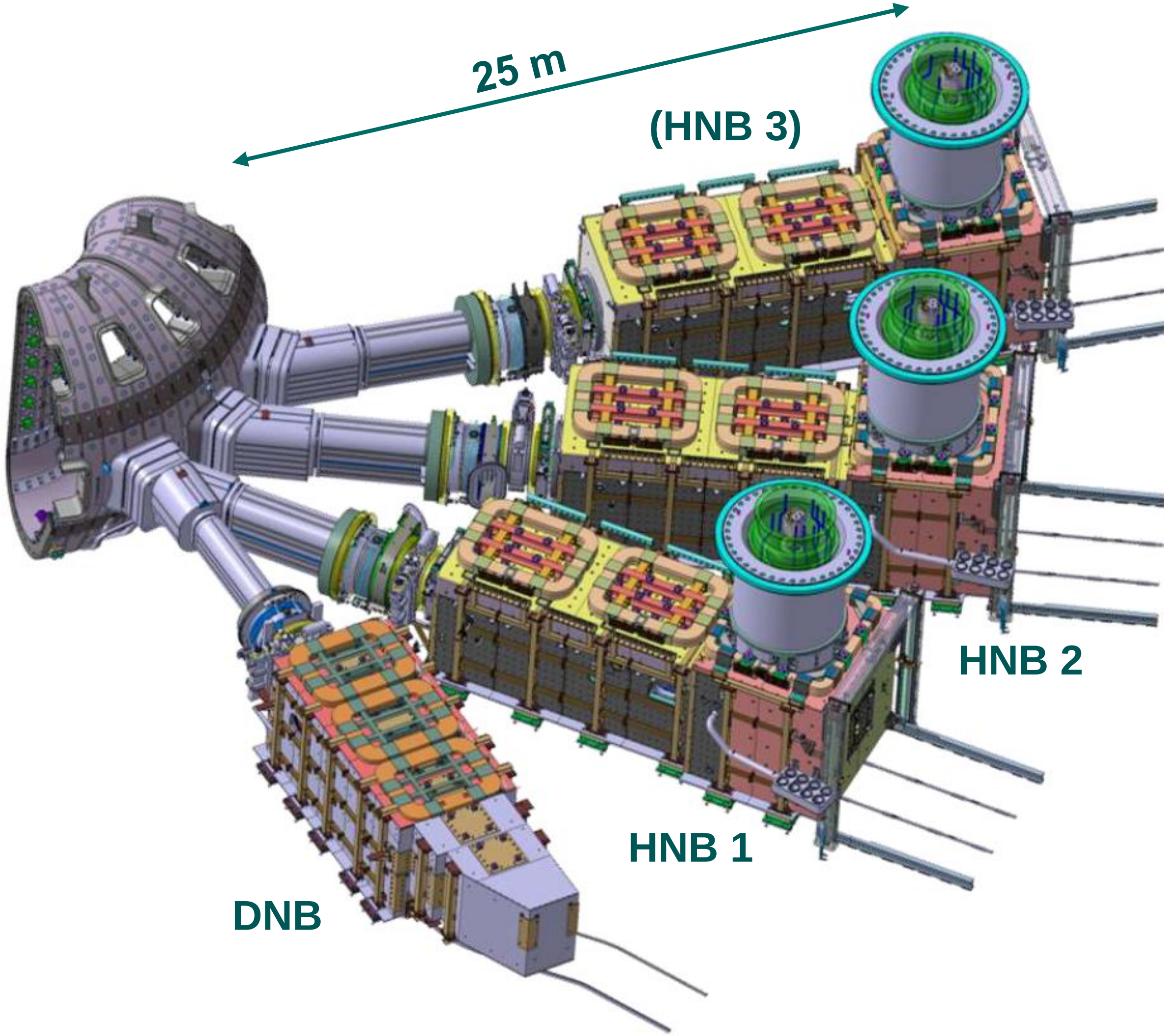
First RF ion source based N-NBI in the world!



Neutral Beam Injectors for ITER

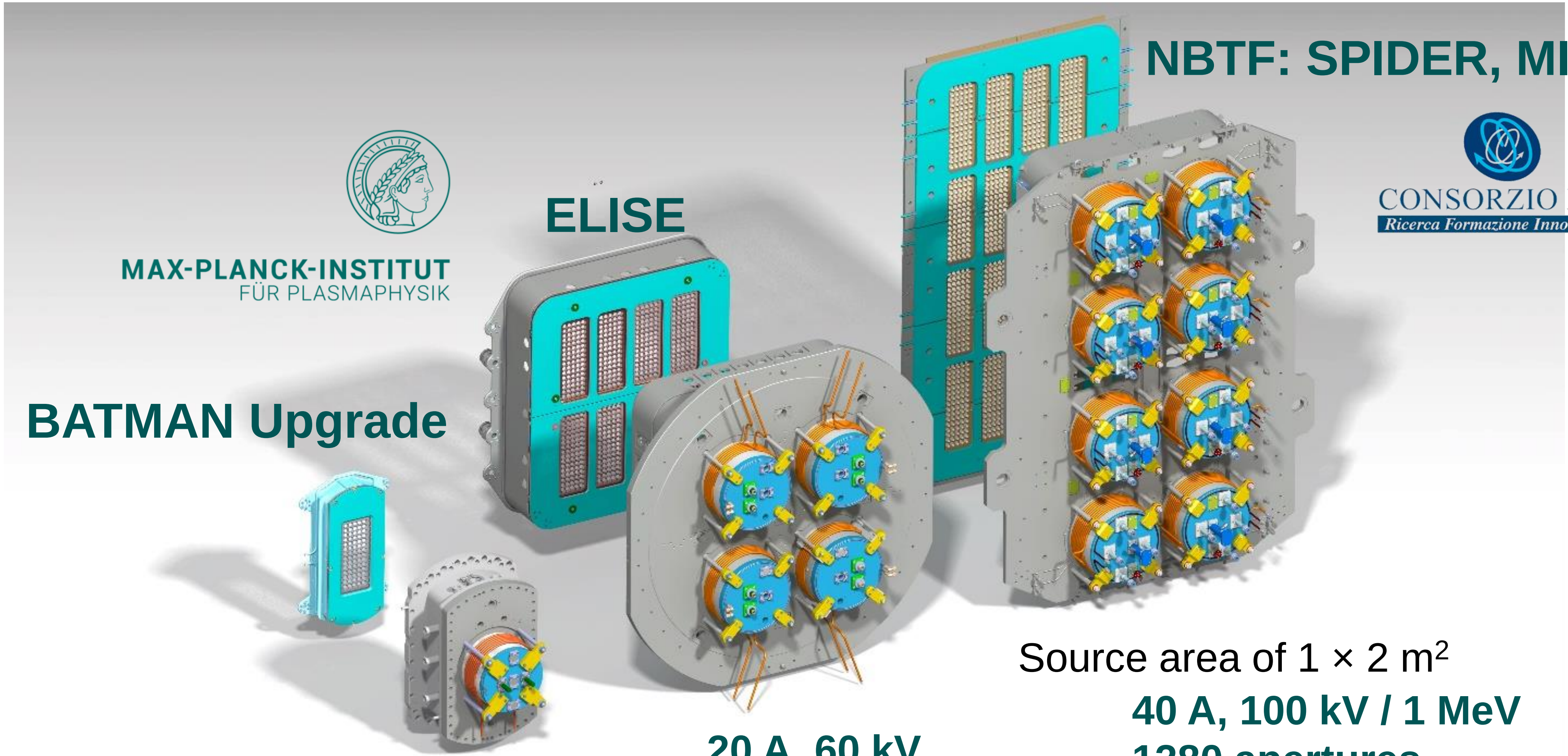
Challenging requirements for the beam source:

	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



Focus of this talk: ion source

Development program towards ITER HNB ion source



Source area of 1 × 2 m^2

40 A, 100 kV / 1 MeV
1280 apertures
(16 beamlet groups)

20 A, 60 kV
640 apertures
(8 beamlet groups)

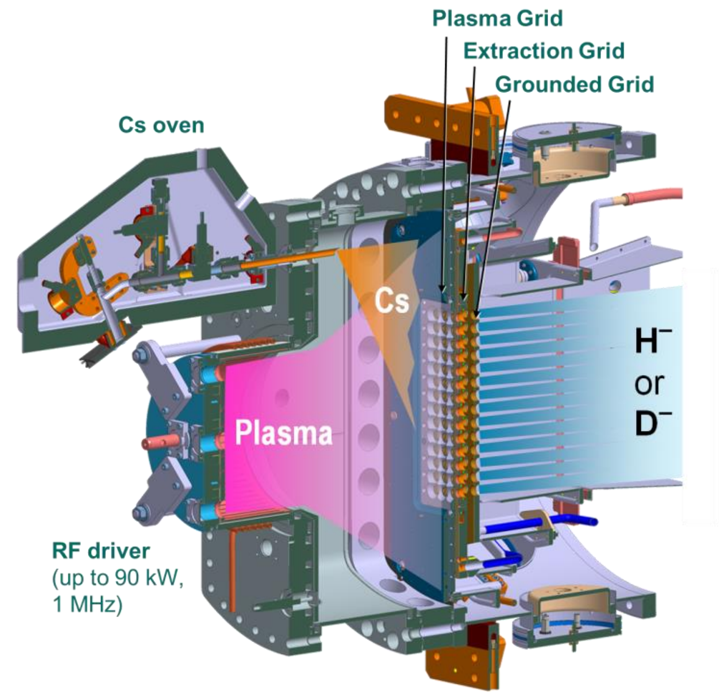
Prototype source
2 A, 45 kV, 70 apertures

Challenges for long-pulse operation

The RF source operates technically reliable!
(prototype source since late 1990s, ELISE since 2014)

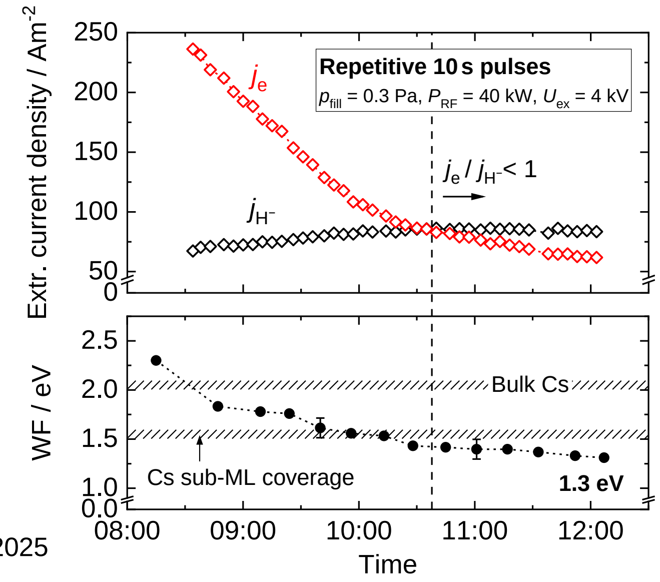
Production of negative ions:

Surface conversion of H, H_x^+ on low work-function surfaces:
Cs is continuously evaporated into source



Surface work function (WF):

- WF diagnostic indicates surface work function of 1.2-1.4 eV: probably Cesium oxide formation in non UHV-conditions
- Such low work function can hardly be maintained on a large area during plasma operation!

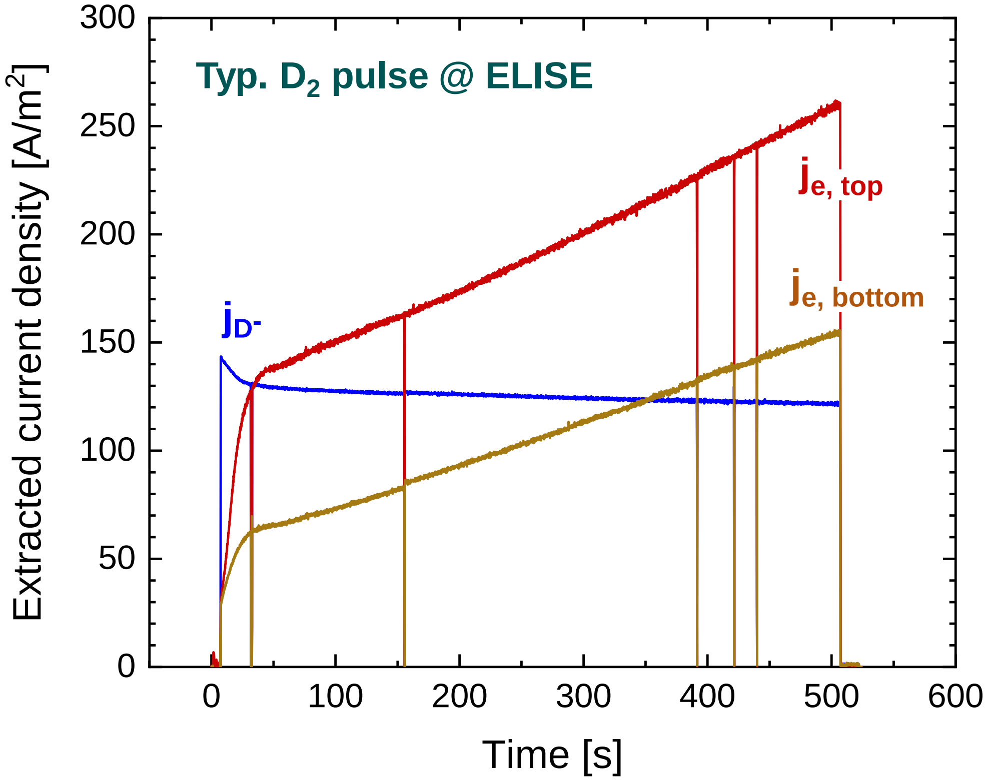


A. Heiler et al., J. Phys.: Conf. Ser. 2743, **2024**, 012025

Co-extracted electrons limit source performance

Co-extracted electrons increase in long pulses

- Electrons bent onto extraction grid
- Created heat load limits tolerable amount
- Asymmetry due do vertical plasma drifts (caused by horizontal magnetic filter field)



Degradation of Cs conditions is biggest issue for bringing H^- sources into a steady state

Measures for reducing, stabilizing and/or symmetrizing co-extracted electrons required!

Operational scenarios developed at ELISE

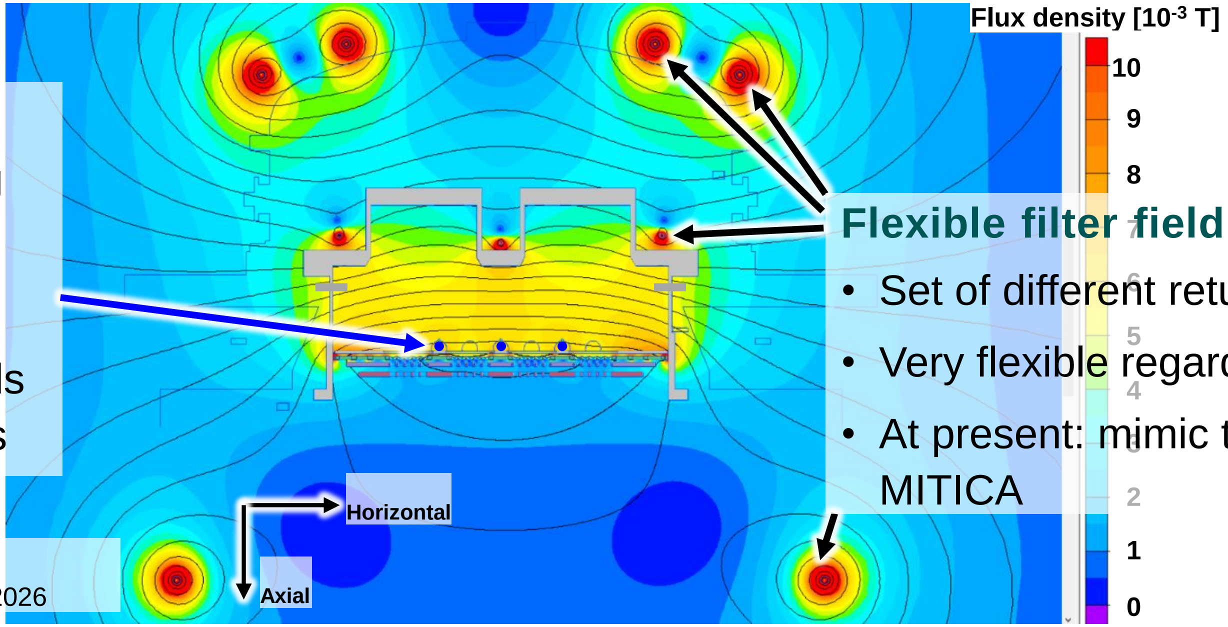
Key points for reducing, symmetrizing and stabilizing co-extracted electrons:

- Caesium conditioning
- Electrostatic potentials
- Magnetic field

Direct impact on plasma electrons and effect on plasma drift $\Rightarrow$ vertical plasma symmetry

Small potential rods:

- Vertical metal tubes traversing the plasma volume
- Affect electrostatic potential
- Follow-up to set of (larger) rods used during initial experiments

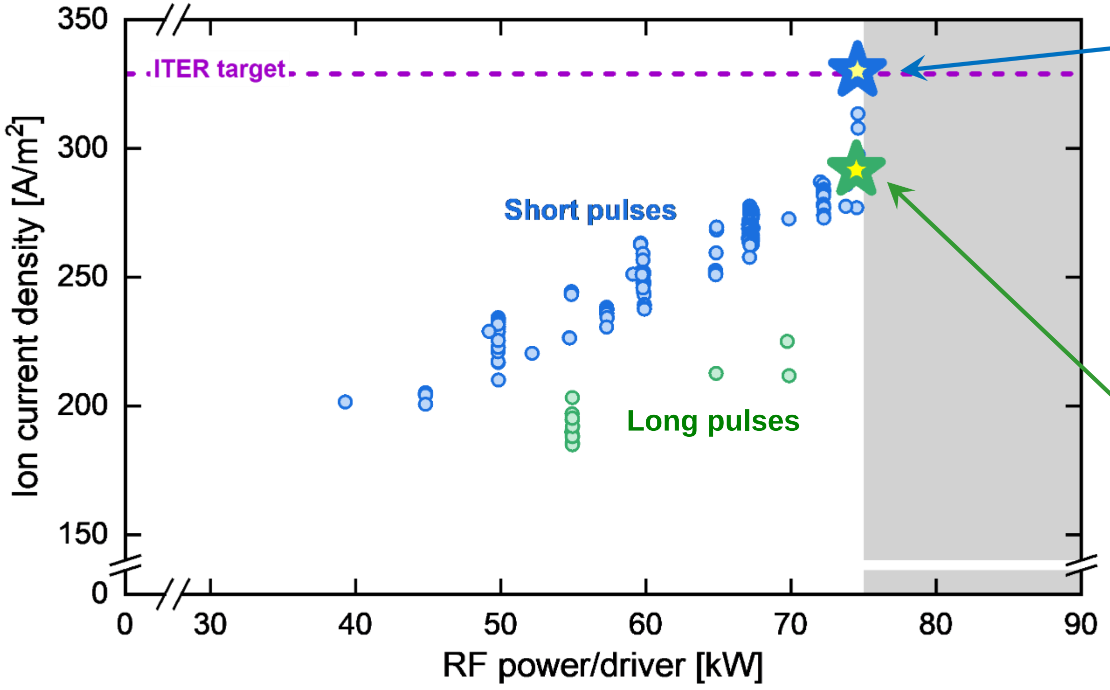


Flexible filter field setup:

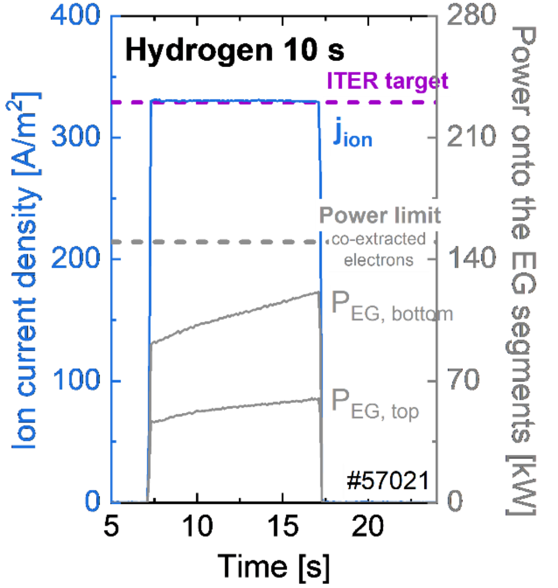
- Set of different return conductors
- Very flexible regarding the field topology
- At present: mimic the field foreseen for MITICA

W. Kraus et al., *Rev. Sci. Instrum*. 89, **2018**, 052102
D. Wünderlich et al., *J. Phys.: Conf. Ser.* 2743, **2024**, 012026

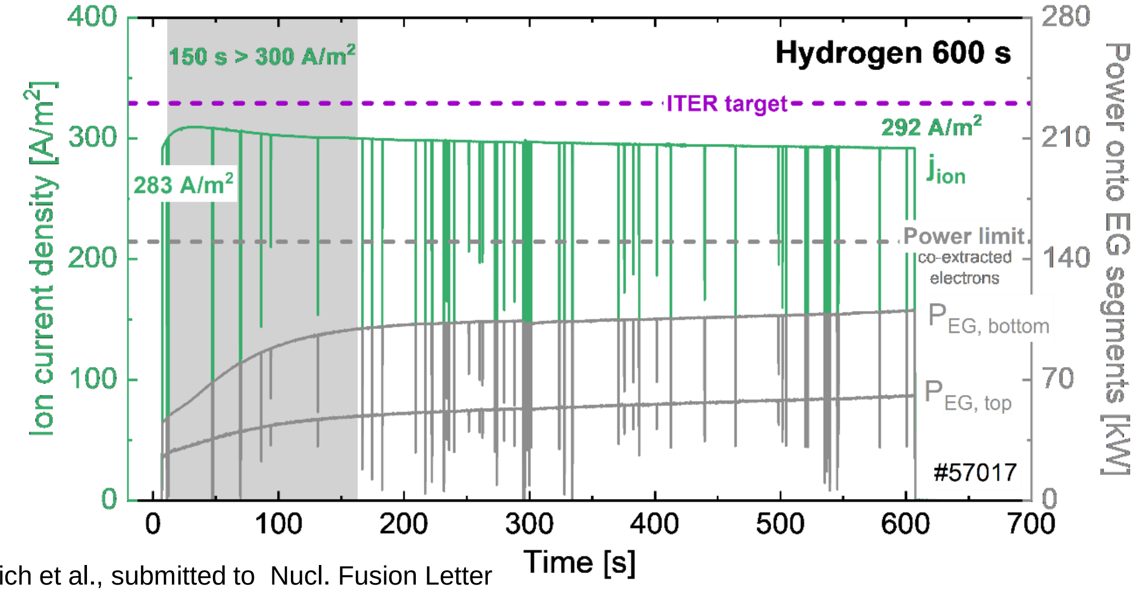
Operational scenarios for long pulses in hydrogen



Short pulse record
28.3.2024



Long pulse record
28.3.2024

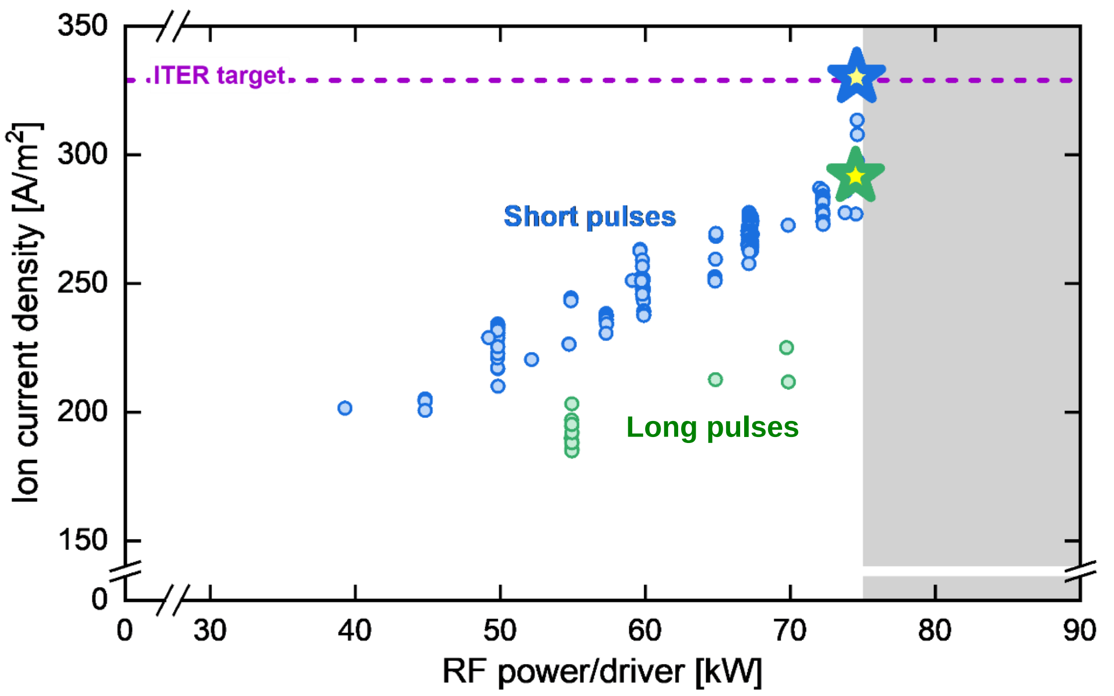


RF power at ELISE limited to 75 kW/driver.
The ITER NBI system has 100 kW/driver!

Steady state in reach for long hydrogen pulses! ✓

D. Wünderlich et al., submitted to Nucl. Fusion Letter

Operational scenarios for long pulses in hydrogen



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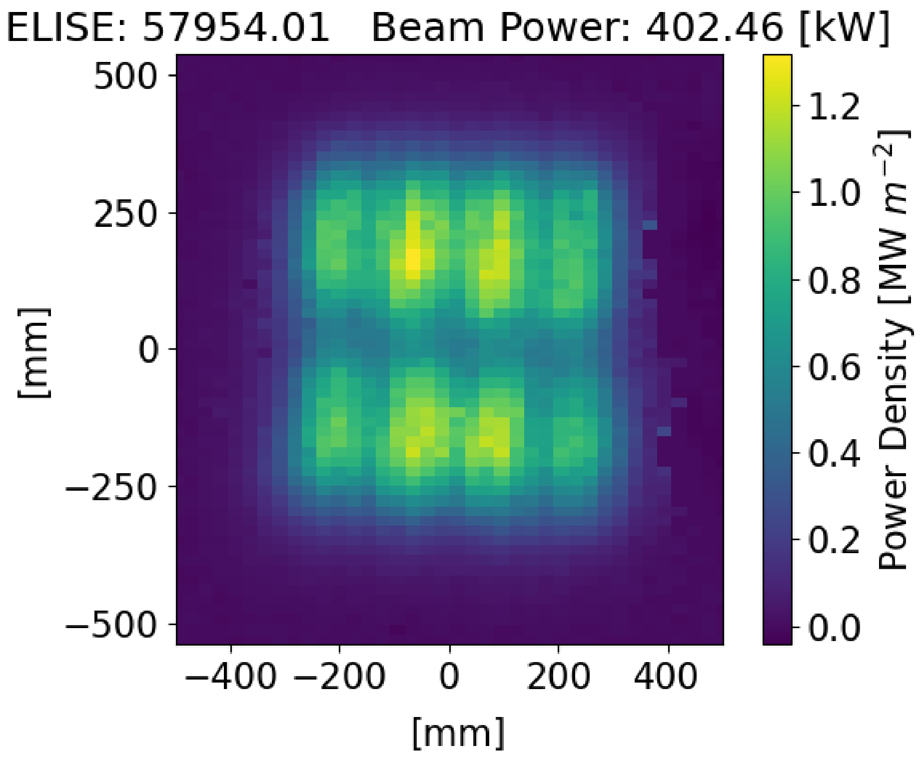
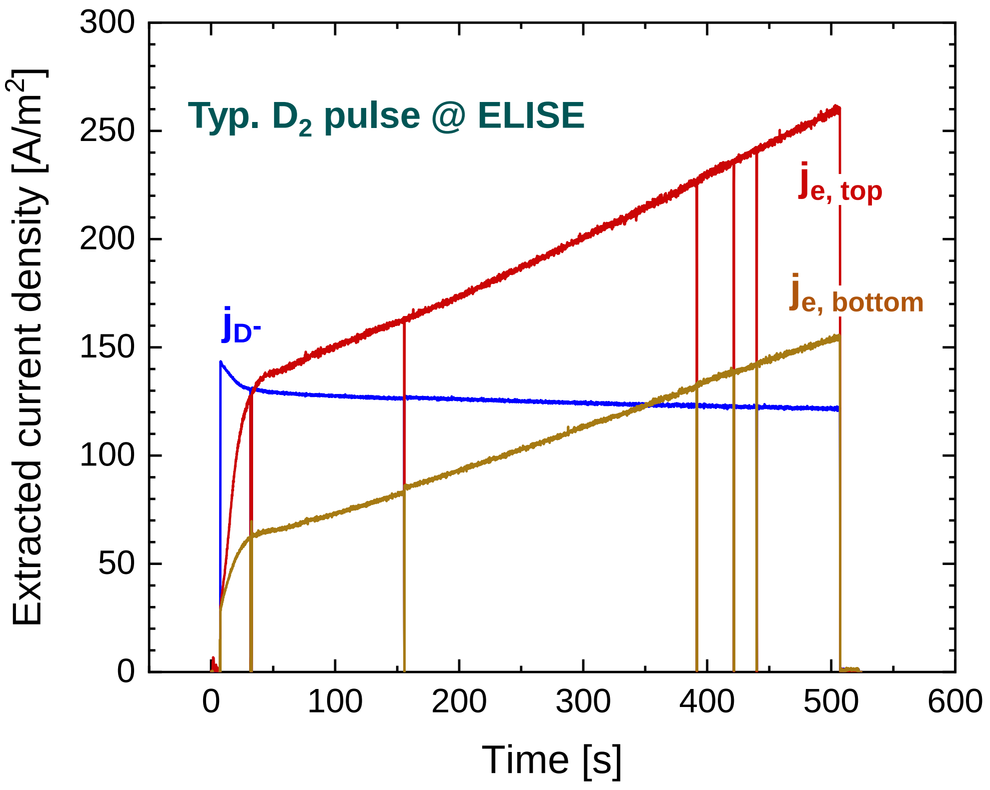


Homogeneous beams
achieved at ELISE!

Challenges in deuterium

Pulses decondition much more in deuterium (& j_e generally higher)!

As result: deuterium performance at ELISE is far from ITER requirements (j_{ex} = 286 A/m^2 for 1 h)



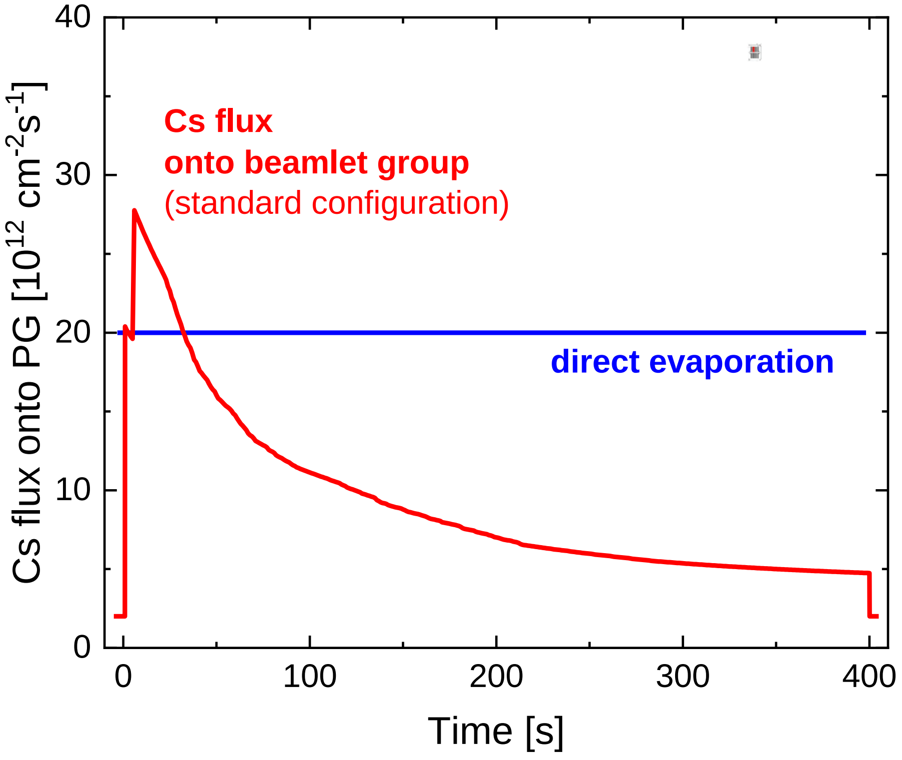
Modeling Cs dynamics

Standard Cs scenario:

- Steady evaporation of Cs from oven into ion source (typ. 1–5 mg/h)
- Redistribution of Cs during plasma pulses: large fraction of Cs ionized (70%), limited flux reaching positively biased PG

CsFlow3D: models Cs transport in ion source (plasma & vacuum phases)

- Strong decrease of Cs flux onto plasma grid during long pulses (depletion of Cs reservoirs)
- Direct evaporation of Cs close to plasma grid could stabilize Cs flux

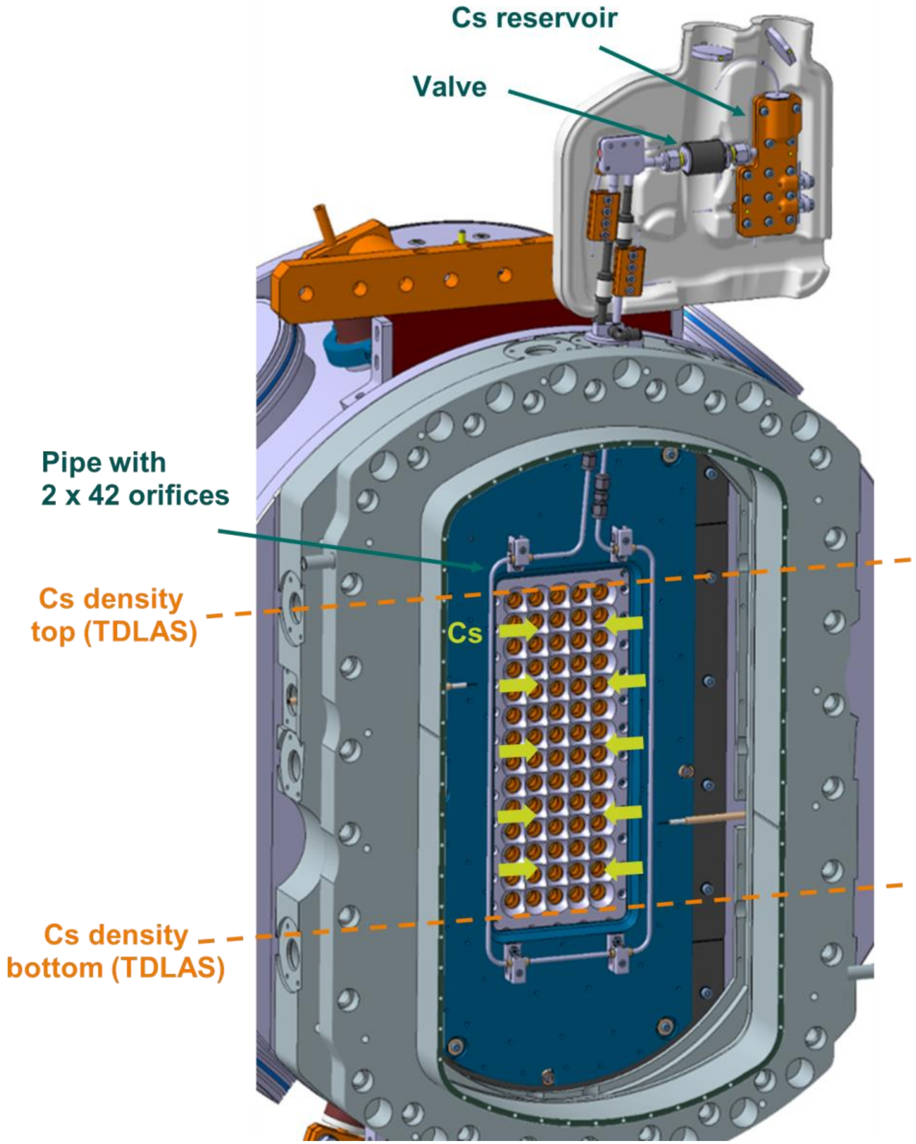


A. Mimo et al., *AIP Conf. Proc.* 2052, **2018**, 040009

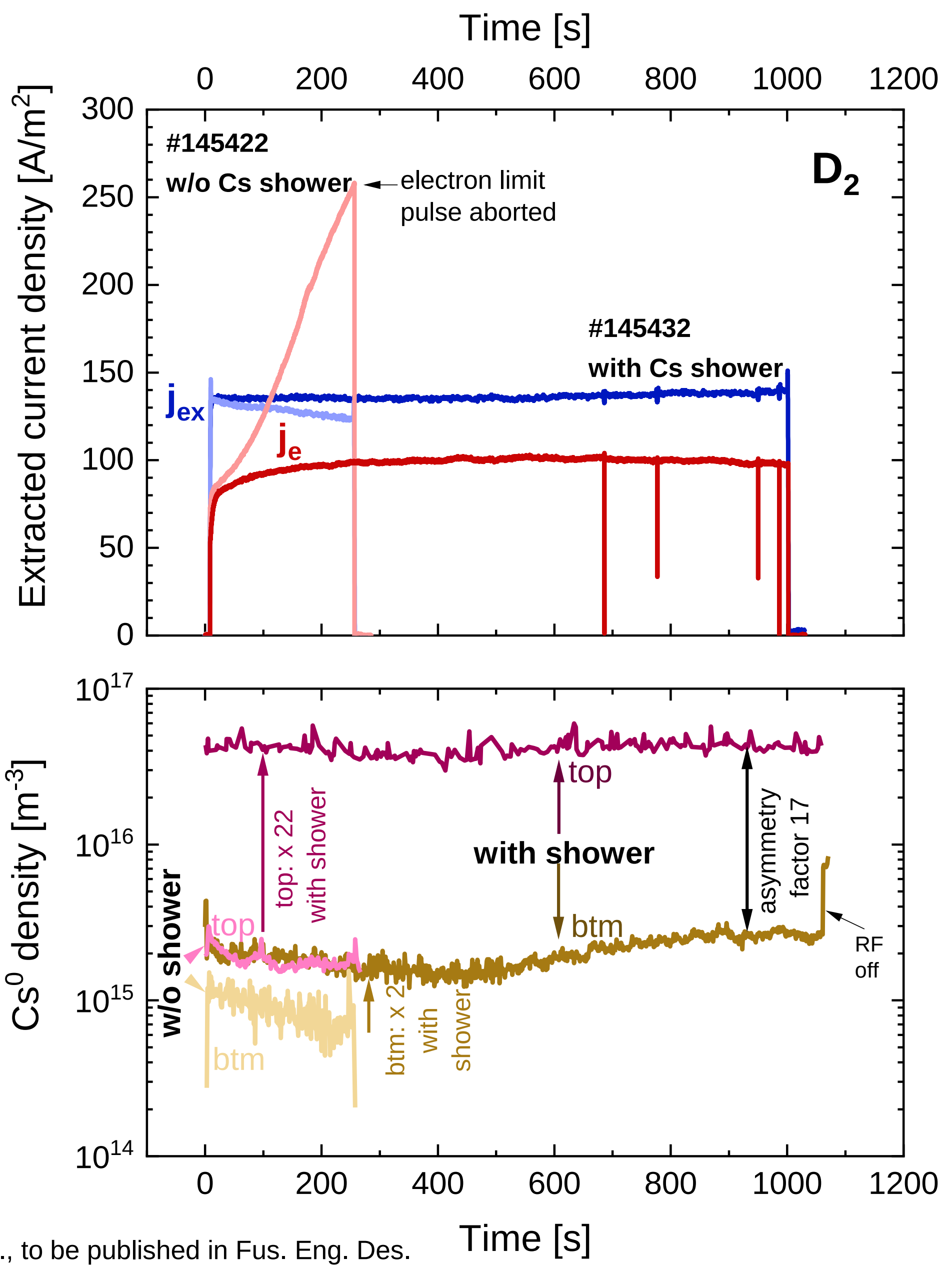
Challenges in deuterium: Cs shower concept

Cs shower at BATMAN Upgrade:

- Additional evaporation of Cs close to PG, only during plasma pulses
- 4 mm Ø tube containing 2 x 42 orifices (0.5 mm Ø), vertical spacing varies from 10 mm (top) to 5 mm (bottom) to counteract Cs supply only from upper side
- Tube ohmically heated to 300 °C
- Magnetic valve at Cs reservoir allows quickly turning on/off Cs evaporation
- Higher Cs leakage to extraction system expected: problems with HV breakdowns?



Results with Cs shower in deuterium



With Cs shower:

- Initial e⁻ increase not suppressed, but good stabilization after 200 s at manageable level
- Pulse could have been run for longer (cw)
- No significant problems with HV breakdowns
- But: strong evaporation asymmetry requires huge evaporation rate!

For the first time: steady state reached in a long deuterium pulse!

C. Wimmer et al., to be published in Fus. Eng. Des.

Conclusion

RF H^-/D^- source:

- Operates technically reliable
- In principle capable of running continuously
  (RF plasma generation, RF coupling, high voltage for extraction and acceleration, cooling etc.)
- Main limit: deconditioning during long pulses

- **Stable long pulses in hydrogen at high performance**
  after optimizing the filter field and introducing additional biased surfaces
- **Deuterium is more problematic: strong deconditioning**
- **Possible solution found: direct evaporation of Cs onto the convertor surfaces**

- **We are on a good way bringing large negative hydrogen ion sources into a steady state!**
- Further technology aspects: see following talk by Ch. Hopf