



Stabilization of Long Beam Pulses at NNBI

IPP

Christian Wimmer, D. Wunderlich,
A. Döring, J.P. Falcao de Queiroz, T. Fellingner, M. Fröschle, D. Mussini,
E. Nanou, A. Navarro, R. Riedl, J. Rubin, D. Yordanov and U. Fantz



EUROfusion



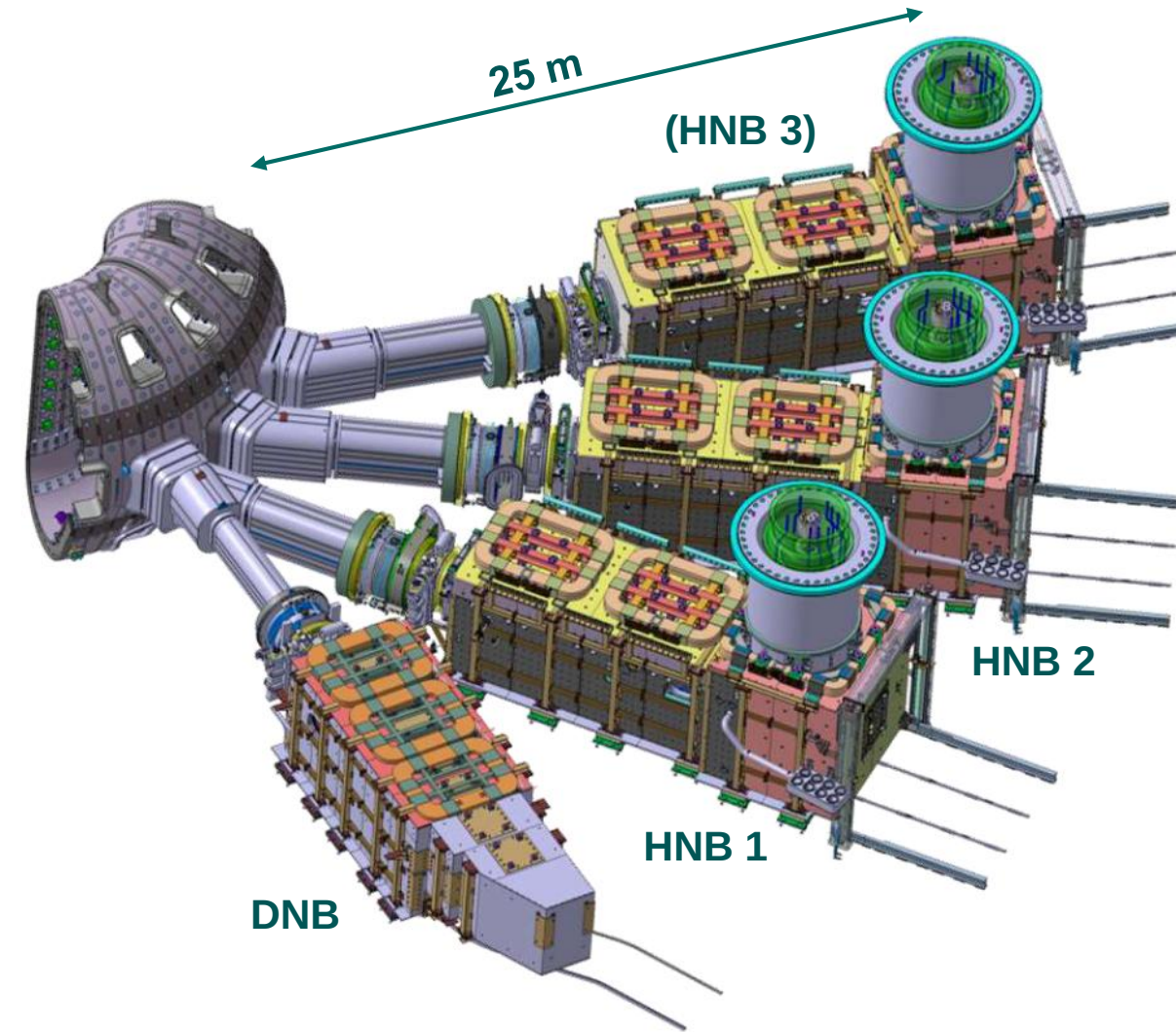
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect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

Neutral Beam Injectors for ITER

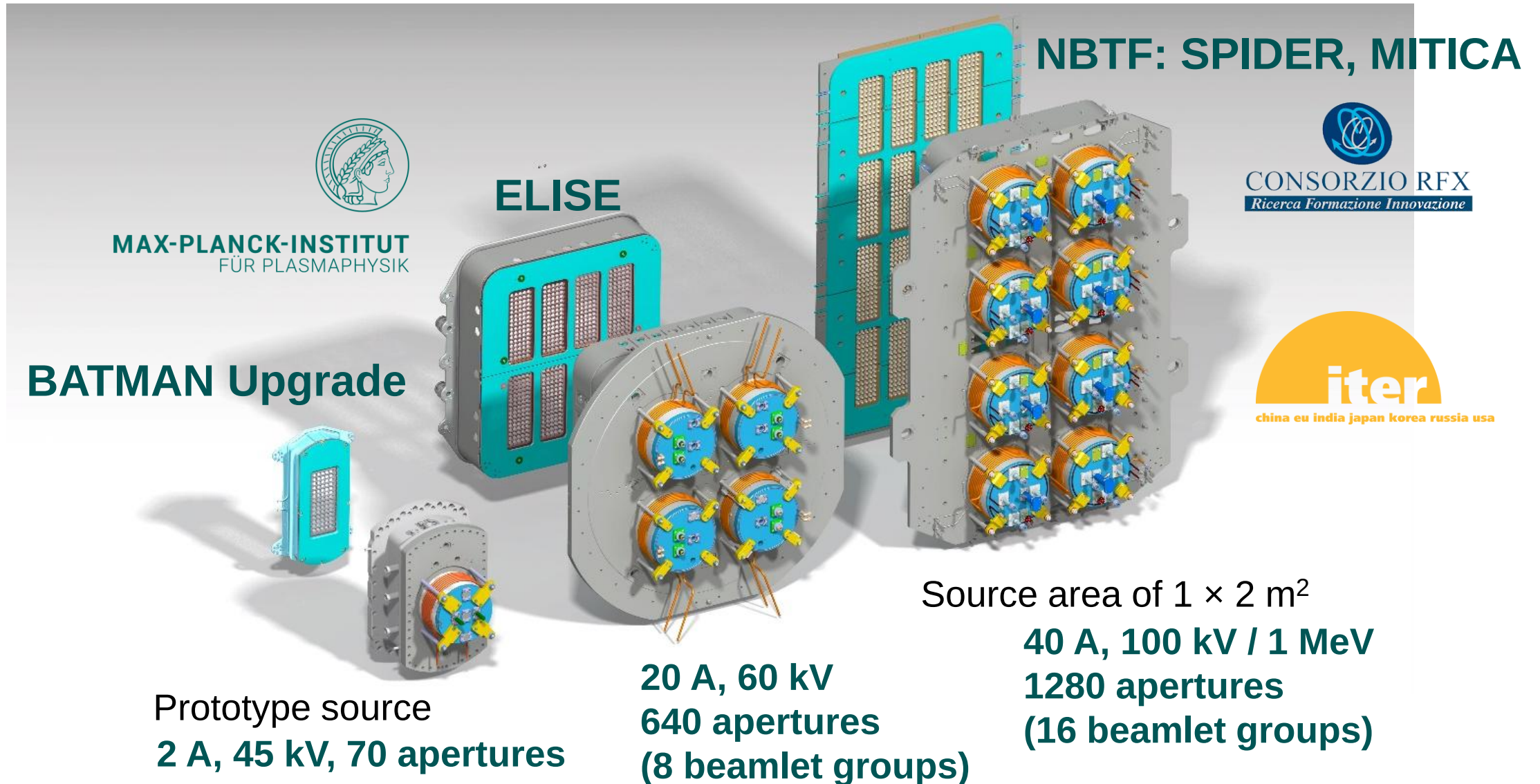
Challenging requirements for the beam source:

	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	
p_{fill}	≤ 0.3 Pa	
Pulse length	Up to several hundred seconds	Up to one hour
Beam homog.	>90 %	
Beamlet div.	<7 mrad	

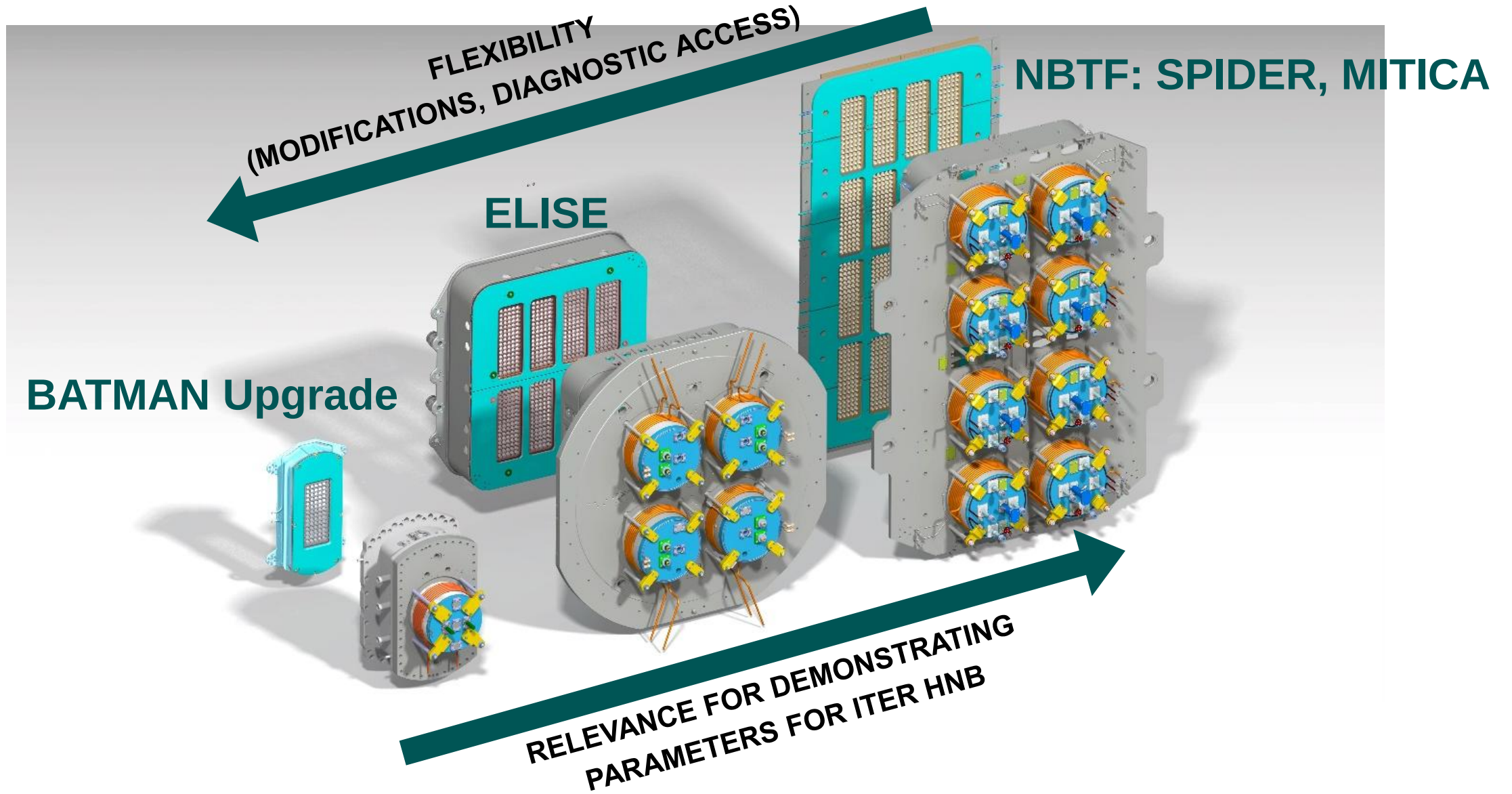
Focus of this talk:
ion source (performance in long pulses)



Development program towards ITER HNB ion source



Development program towards ITER HNB ion source



Challenges for long-pulse operation

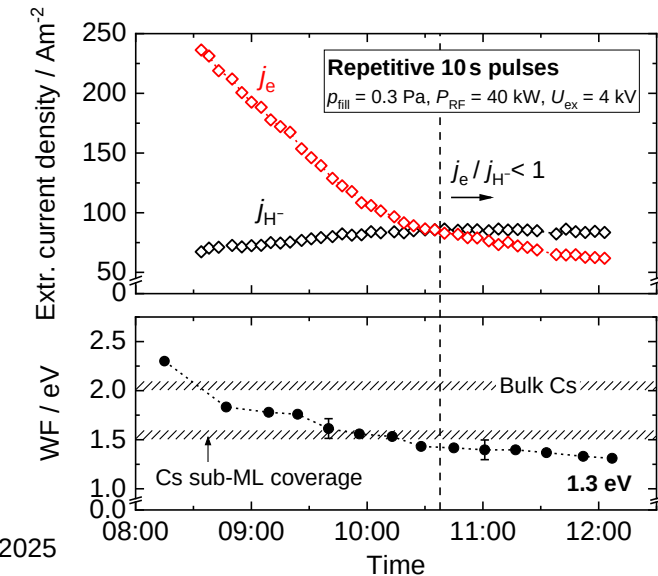
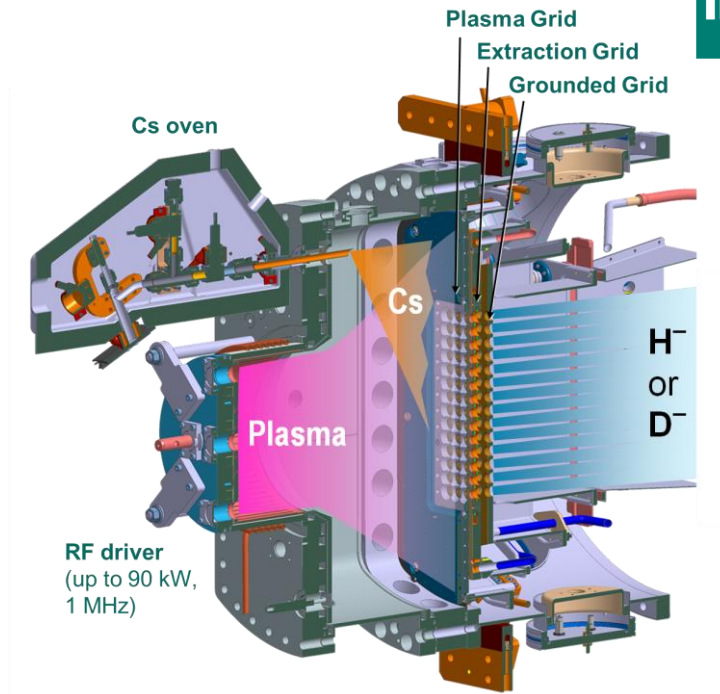
The RF source operates technically reliably!
(prototype source since late 1990s, ELISE since 2013)

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!



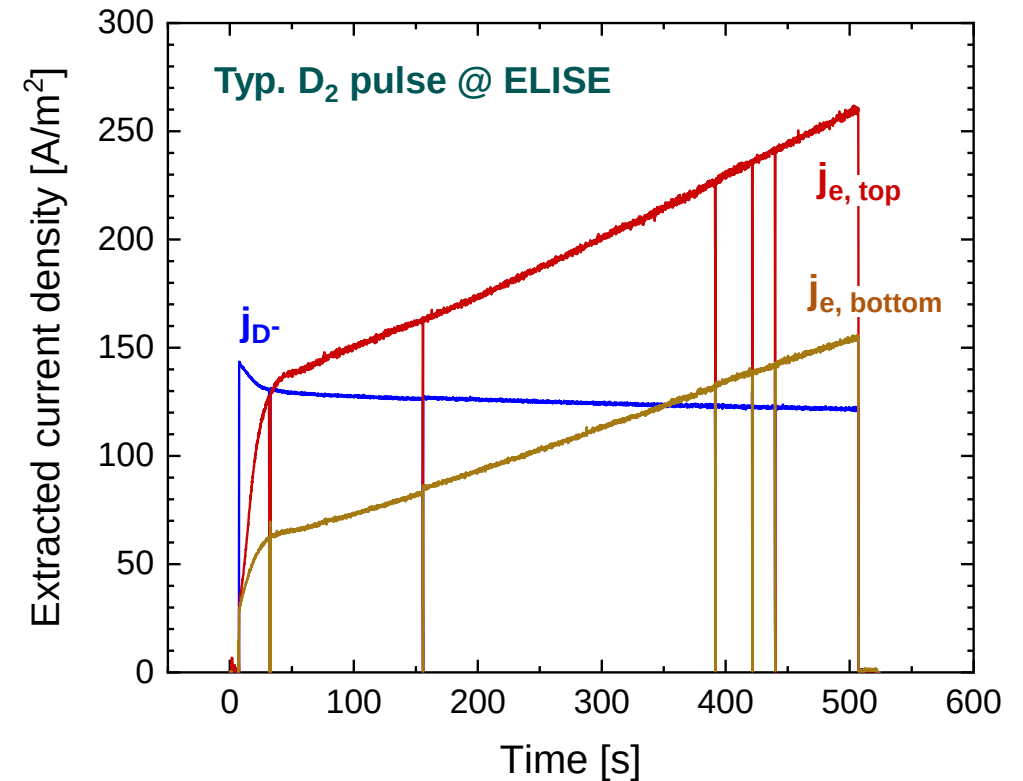
Co-extracted electrons limit source performance

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

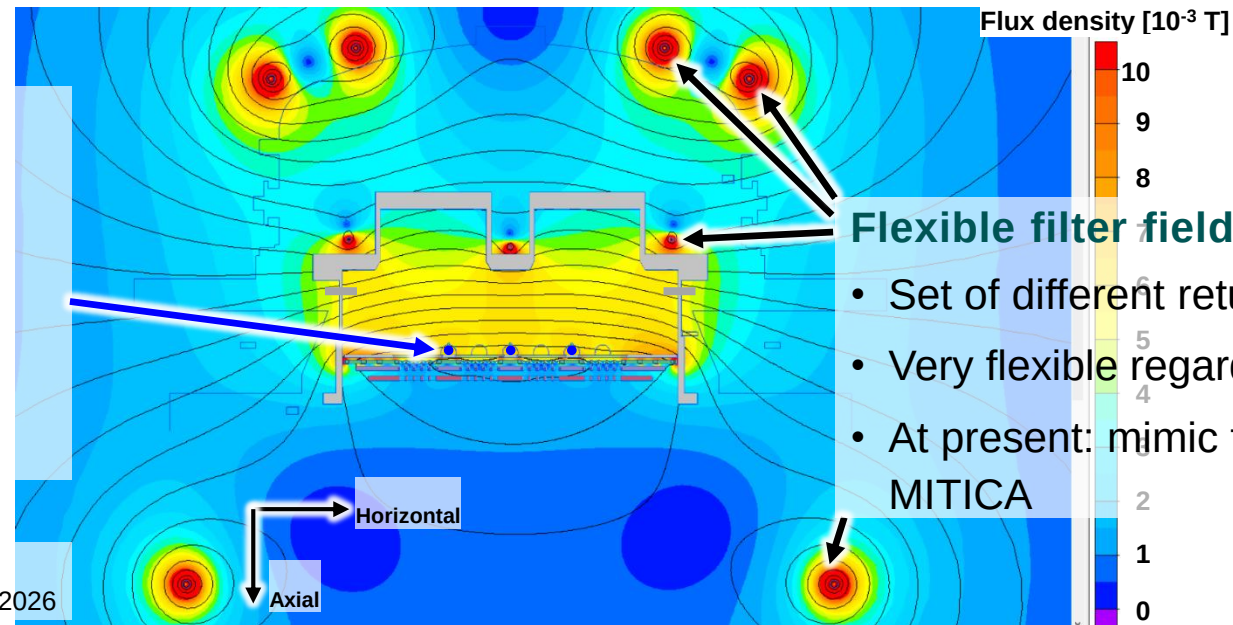
Talk by D. Wunderlich
Tuesday

Optimizing potentials:

- Plasma Grid
 - Bias Plate
 - Potential Rods
- } needed?

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

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

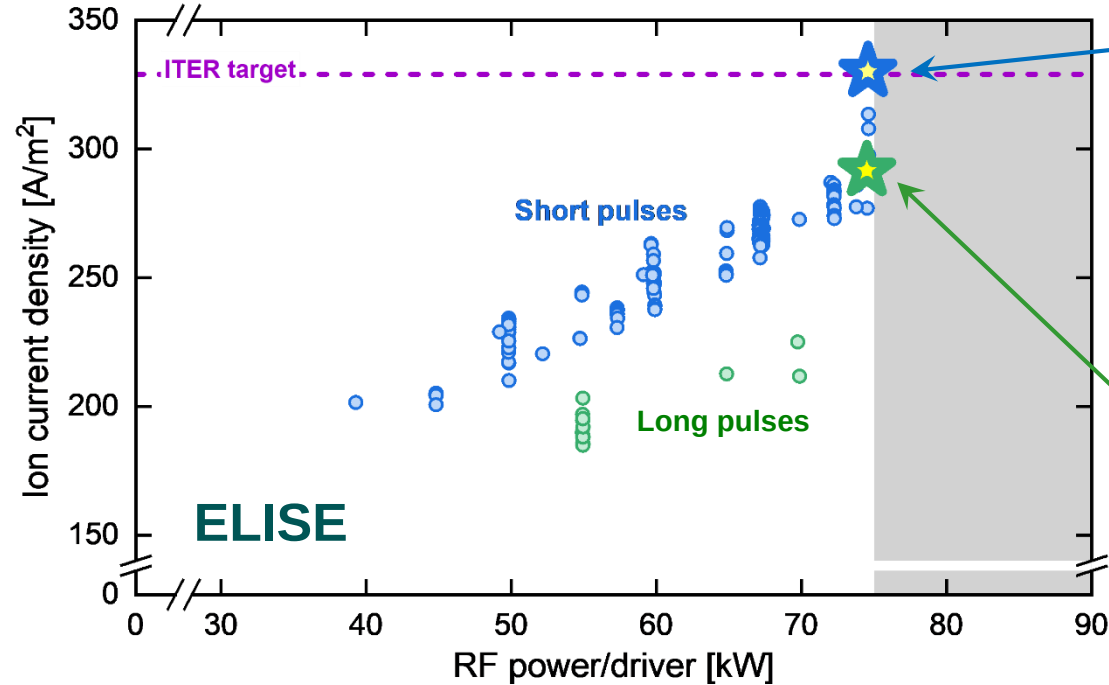


Flexible filter field setup:

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

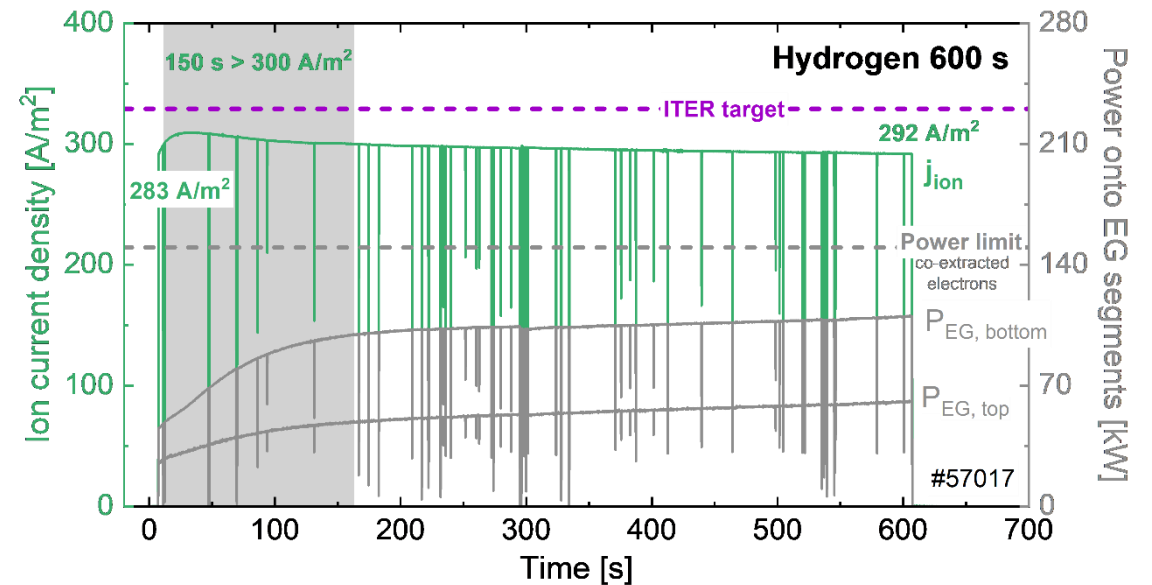
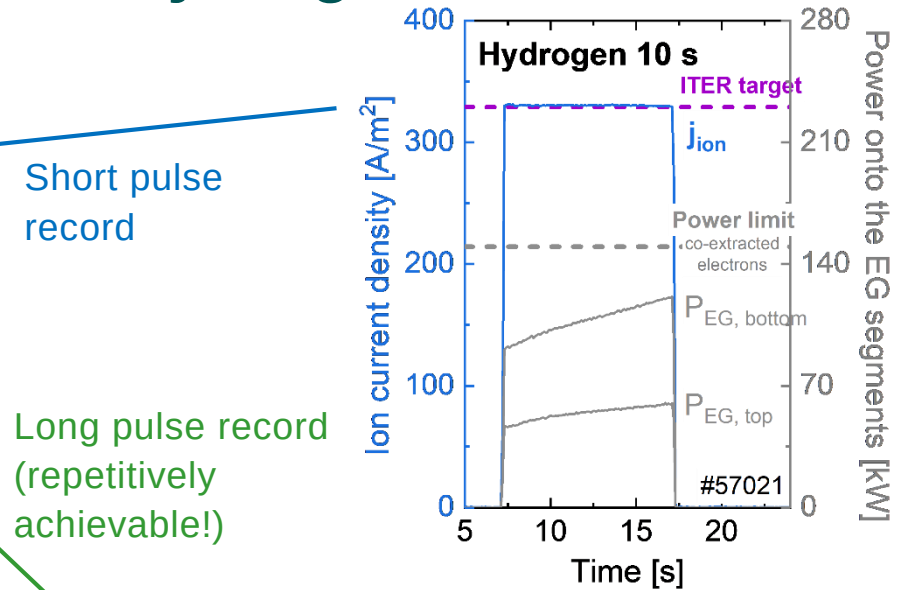
Operational scenarios for long pulses in hydrogen

D. Wunderlich et al., *Nucl. Fusion* 65, 2025, 014001



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!



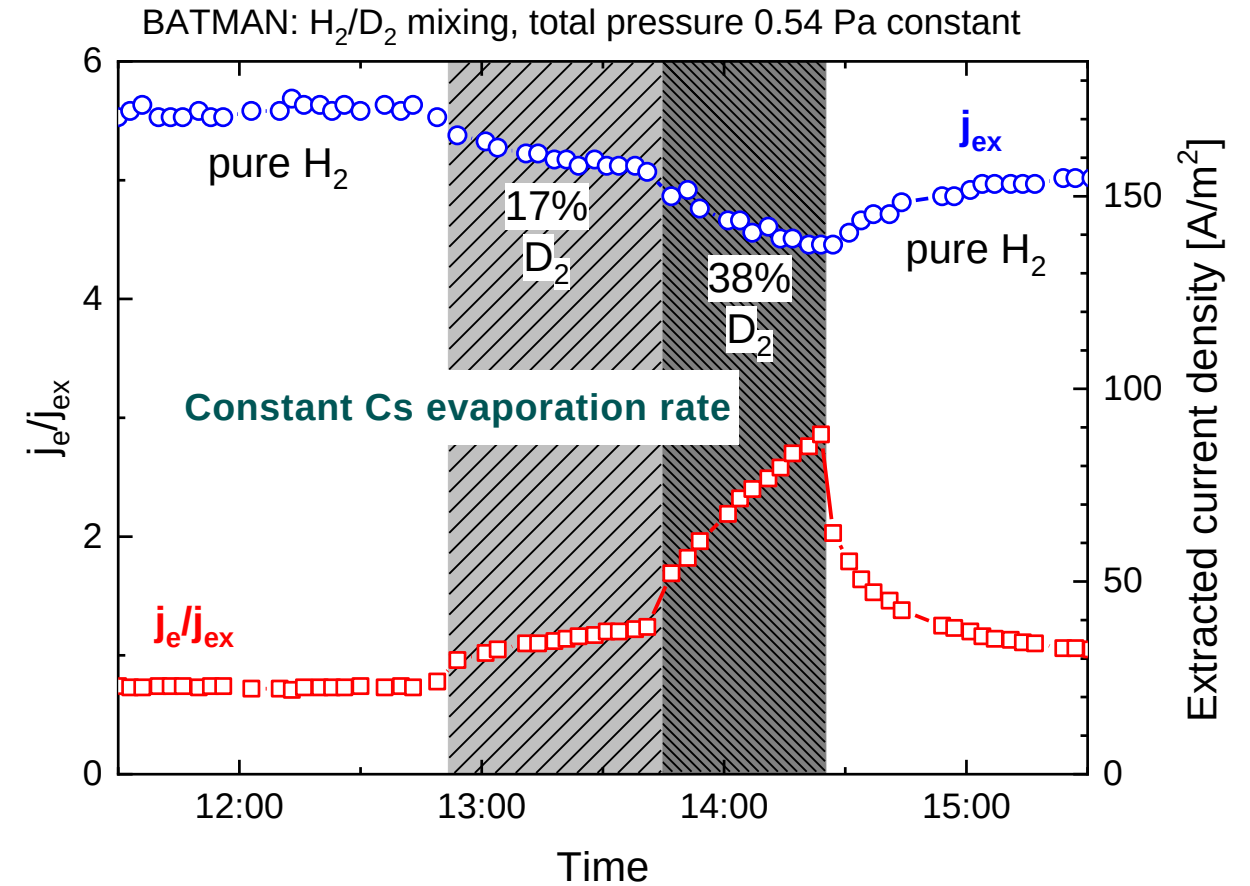
Talk by D. Wunderlich
Tuesday

Challenges in deuterium

H_2/D_2 gas mixing (short pulses):

Dynamic de-conditioning pulse to pulse!
(more pronounced at higher D_2 content)

→ **Higher Cs evaporation rate required**

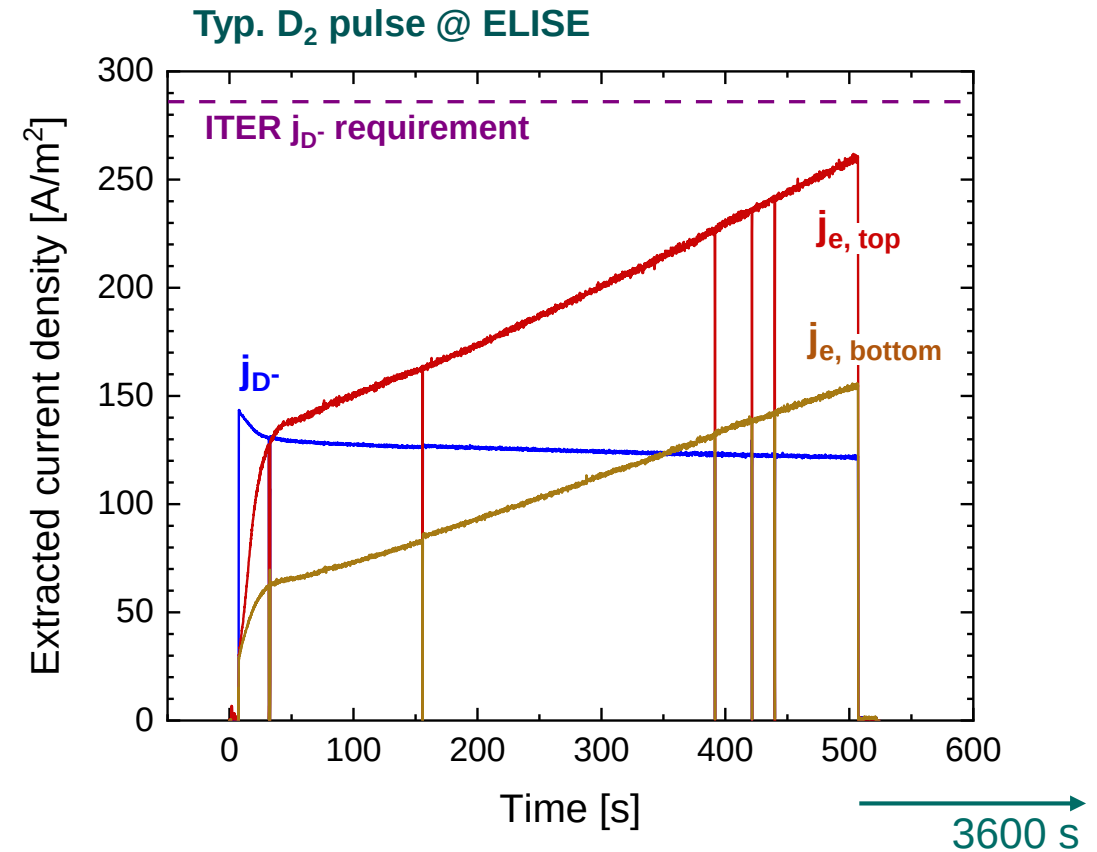


Challenges in deuterium

Even after adapting to optimum Cs evaporation rate for deuterium:

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

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



7x longer pulses at 2x higher extracted current density seems to be far out of reach for classic concept!

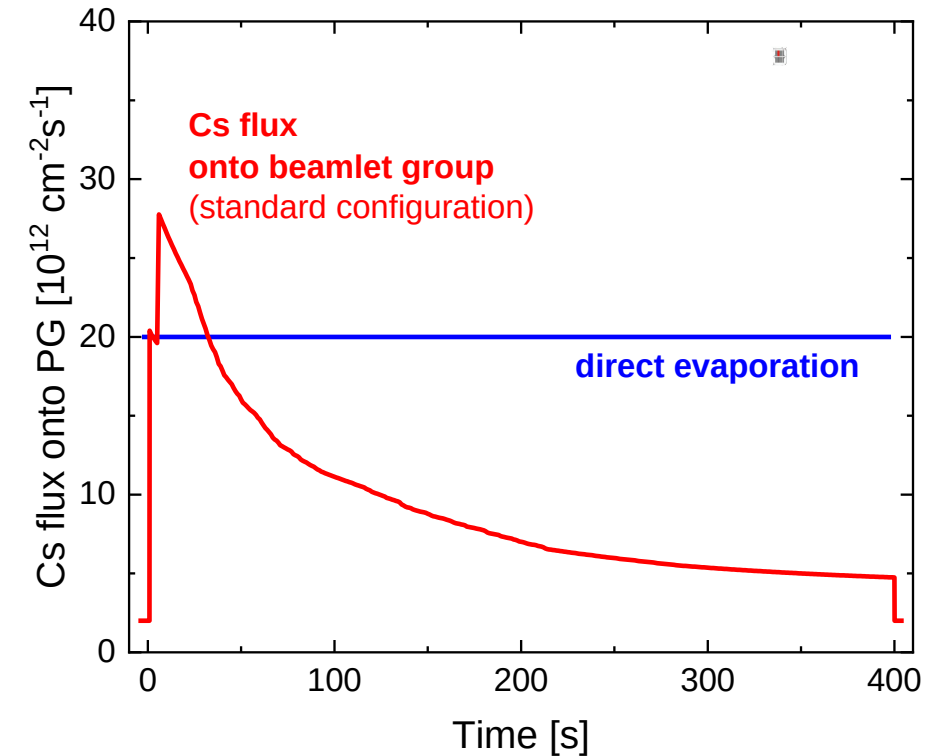
Modeling Cs dynamics

Standard Cs scenario:

- Steady evaporation of Cs from oven(s) into ion source (typ. 1–5 mg/h)
- Redistribution of Cs during plasma pulses: large fraction of Cs towards PG 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

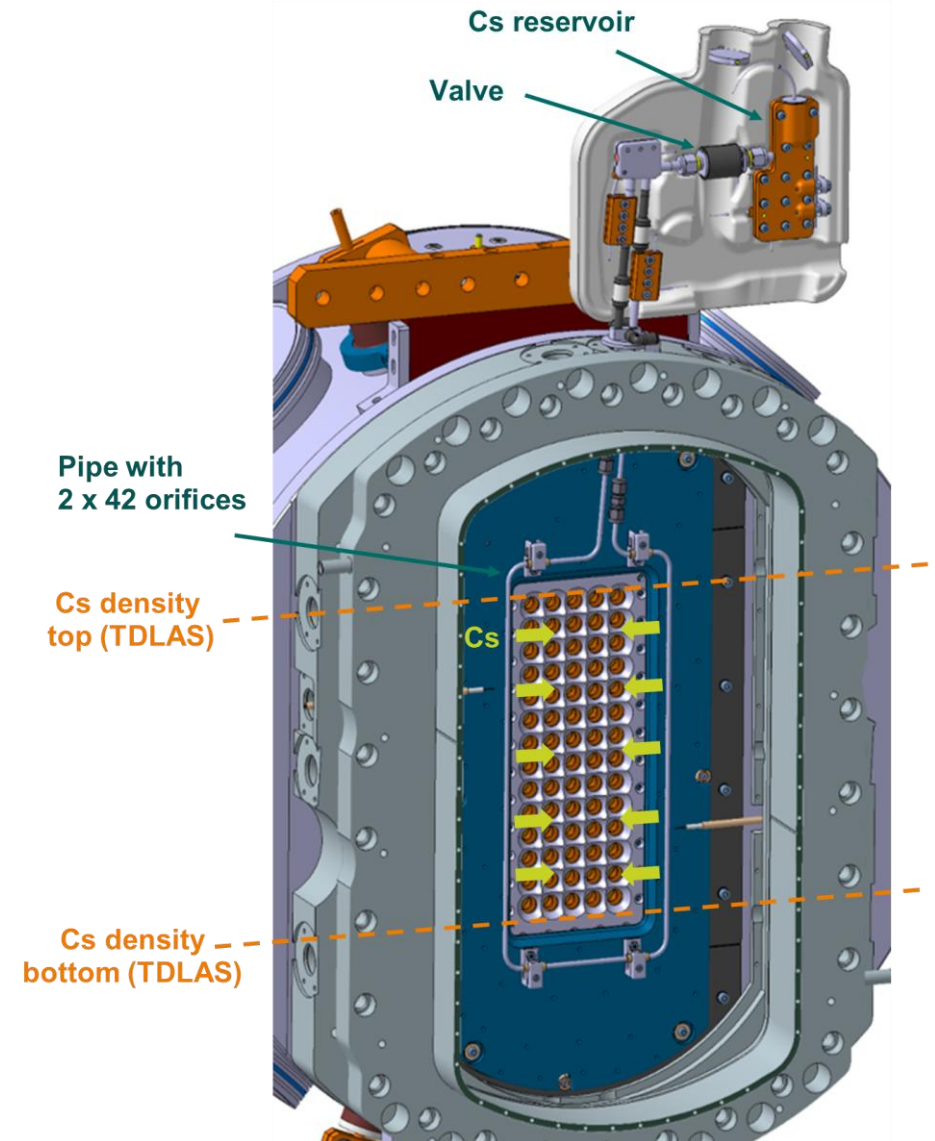


A. Mimo et al., *AIP Conf. Proc.* 2052, **2018**, 040009

Challenges in deuterium: Cs shower concept

Cs shower at BATMAN Upgrade:

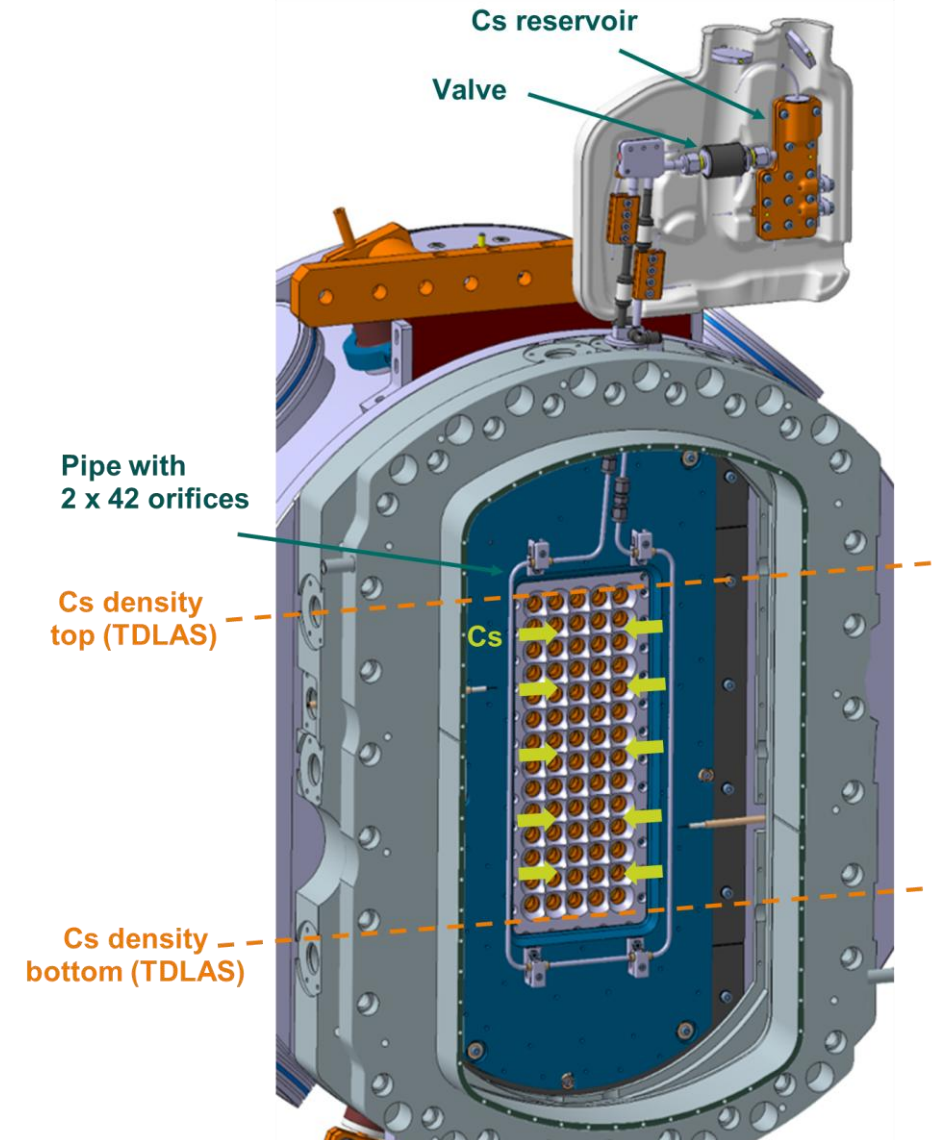
- Additional evaporation of Cs close to PG, only during beam pulses
- Tube ohmically heated to 300 °C
- Magnetic valve at Cs reservoir allows quickly turning on/off Cs evaporation
- Higher Cs leakage to extraction system expected: problems with HV breakdowns?



Challenges in deuterium: Cs shower concept

Evolution of Cs shower:

- **1st version: 2x27 0.4 mm orifices (2021)**
significant pulse stabilization (max. 100 s pulses possible during that time), but **strong vertical evaporation asymmetry** (< 10 times less at the bottom): insufficient vacuum pumping (high sticking) or high pressure drop along tube?
- **2nd version: 2x42 0.5 mm orifices (2023/2024)**
Cs evaporation **asymmetry increased even more**, but **steady-state reached** in 1000 s deuterium pulse (at reduced source parameters)



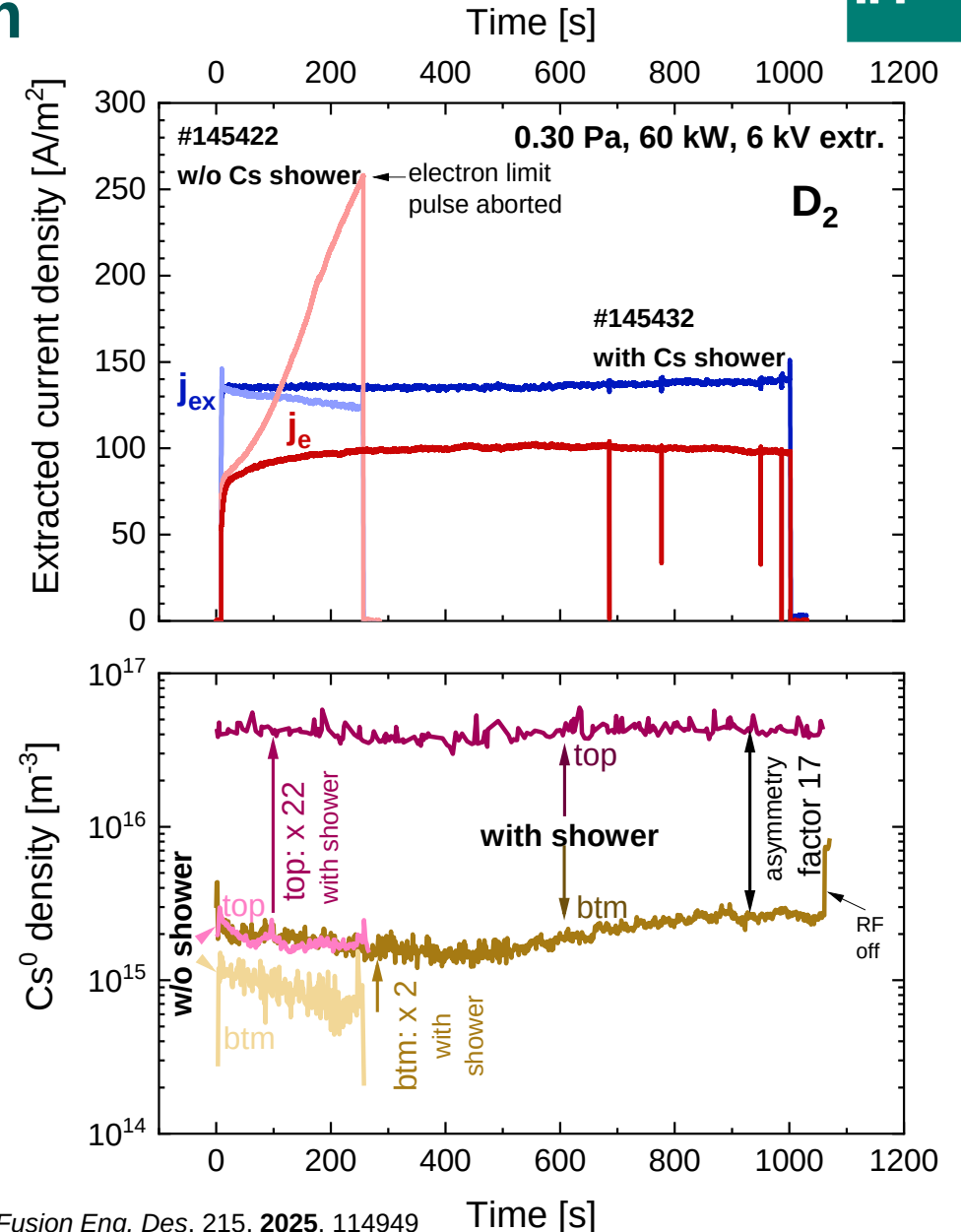
Results with 2nd Cs shower in deuterium



With Cs shower:

- Initial e⁻ increase not suppressed, but good stabilization after 200 s at manageable level
- 50% of required current density reached
- Pulse could have been run for longer (cw)
- No significant problems with HV breakdowns
- But: strong evaporation asymmetry requires huge evaporation rate!

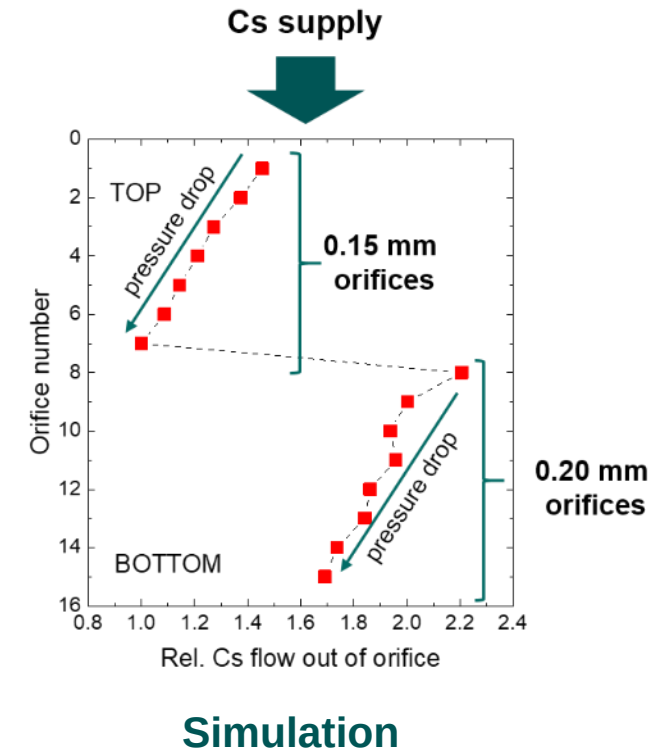
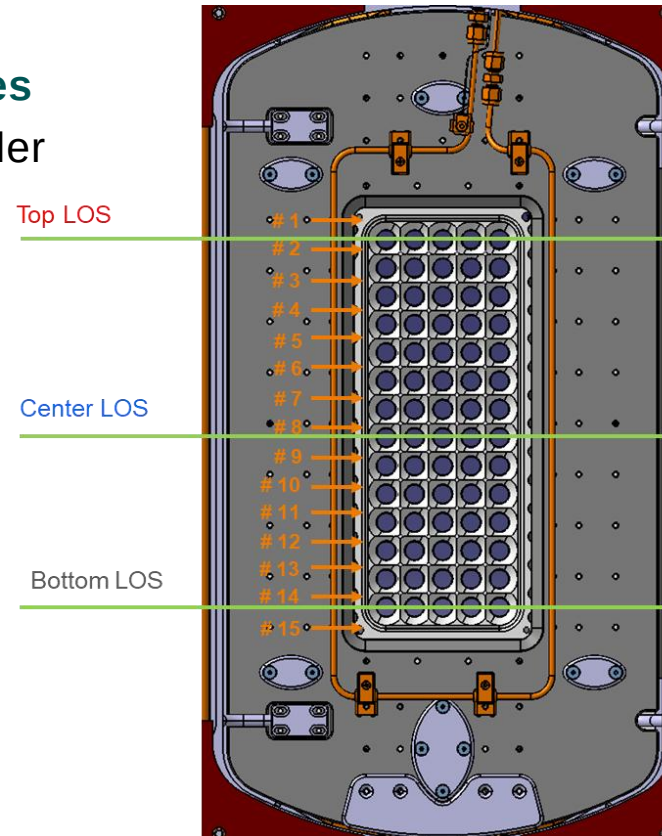
For the first time: steady state reached
in a long deuterium pulse!



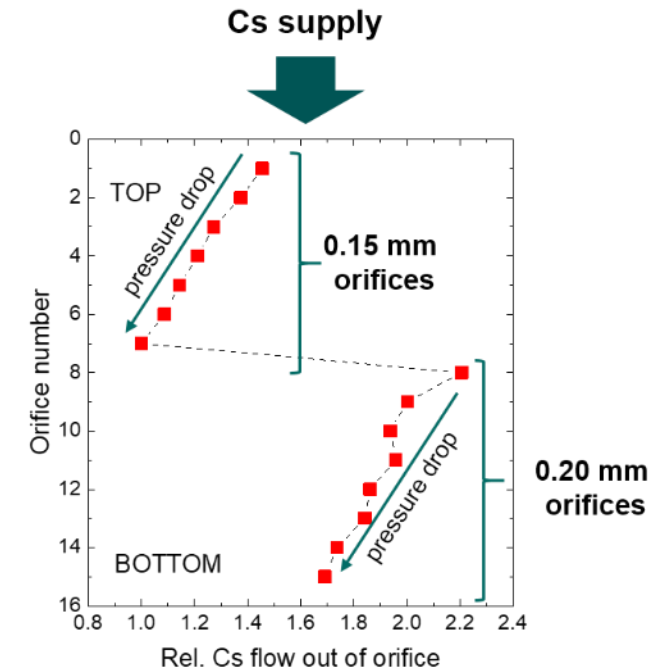
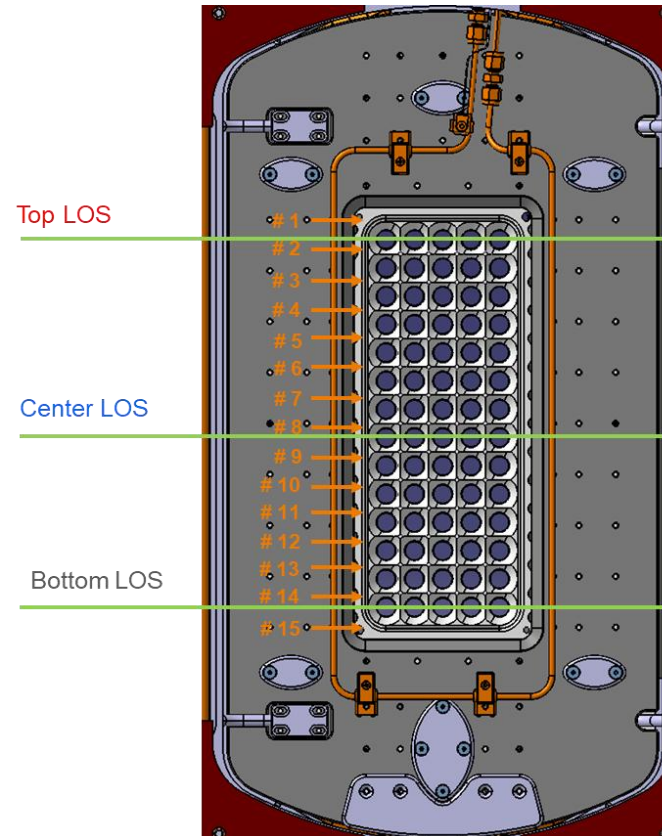
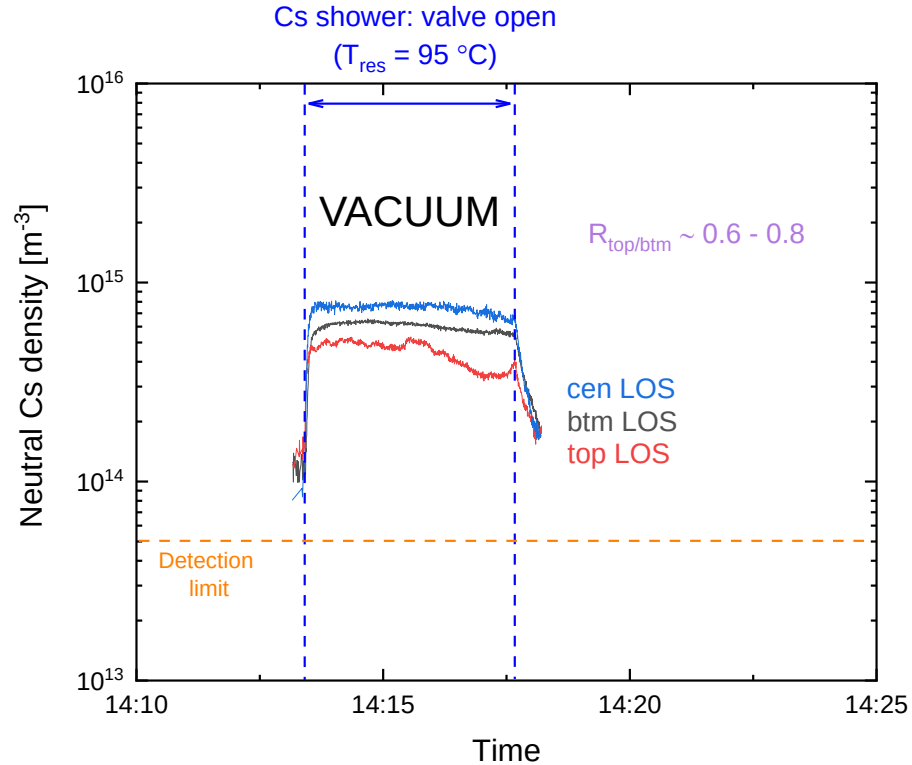
Evolution of the Cs shower

Optimization carried out with Molflow+:
3rd version: 2x15 0.15 mm & 0.20 mm orifices
Pressure drop along tube is minimized by smaller orifices and (over)compensated by increased orifice diameters in bottom half

3 TDLAS (Tunable Diode Laser Absorption Spectroscopy) **lines of sight** to measure **Cs distribution vertically resolved**



Evolution of the Cs shower



Simulation

Overcompensation proven by TDLAS!

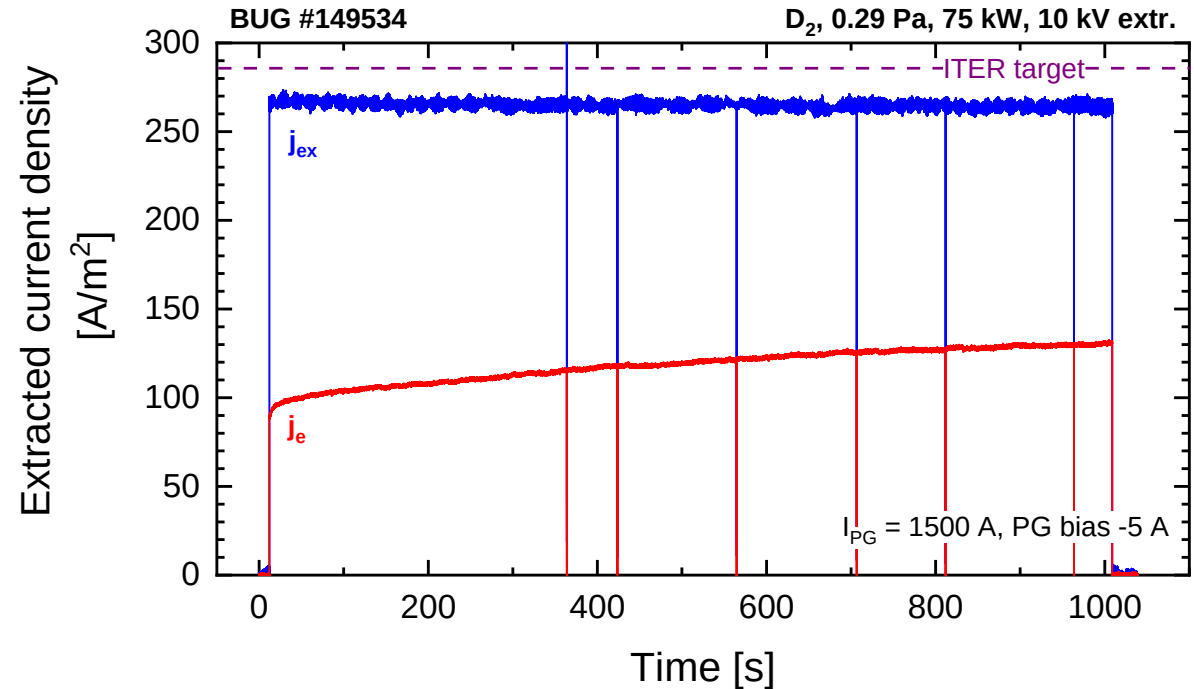
(central LOS has highest density due to more neighboring orifices)

Record long pulse in deuterium

3rd version of Cs shower at
BATMAN Upgrade:

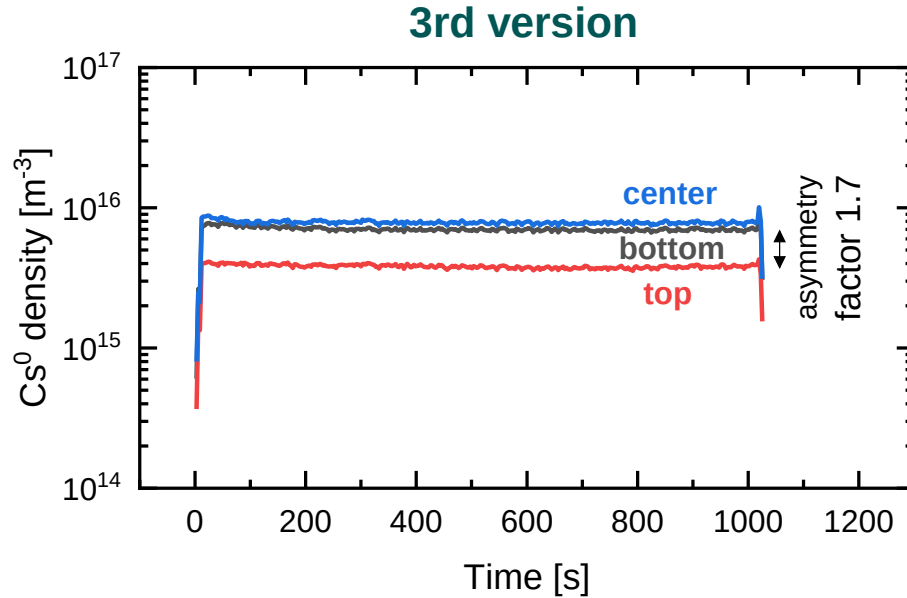
> 90% of required D⁻ current density
demonstrated at BATMAN Upgrade for
1000 s!

- Pulse duration limited by radiation safety
- Max. RF power available at BATMAN Upgrade:
75 kW, i.e. 75% of RF power / driver available
at ITER sources

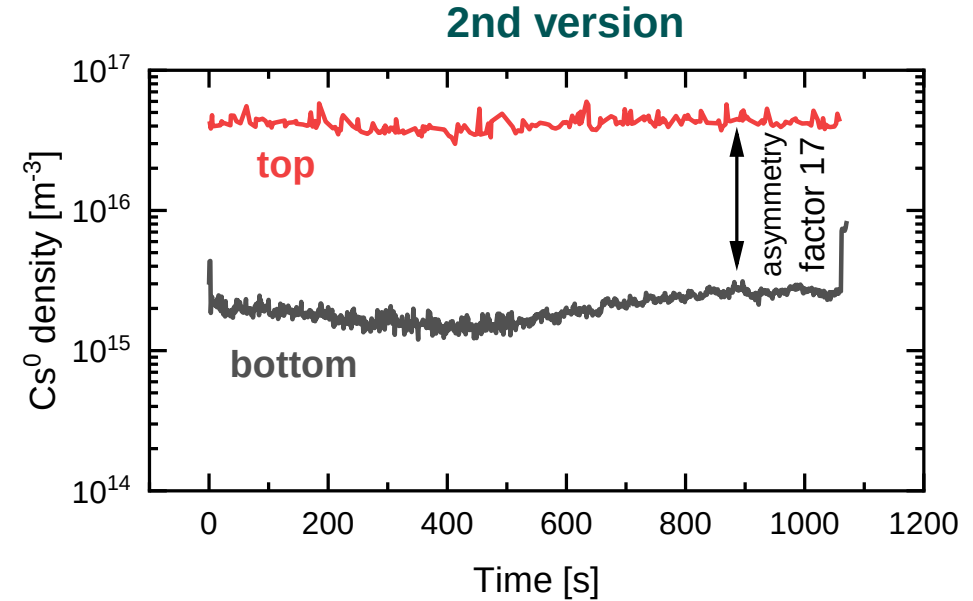


Proof:
Higher Cs flux onto PG required in
deuterium during beam pulses
to stabilize performance!

Record long pulse in deuterium



3rd version of Cs shower at
BATMAN Upgrade:



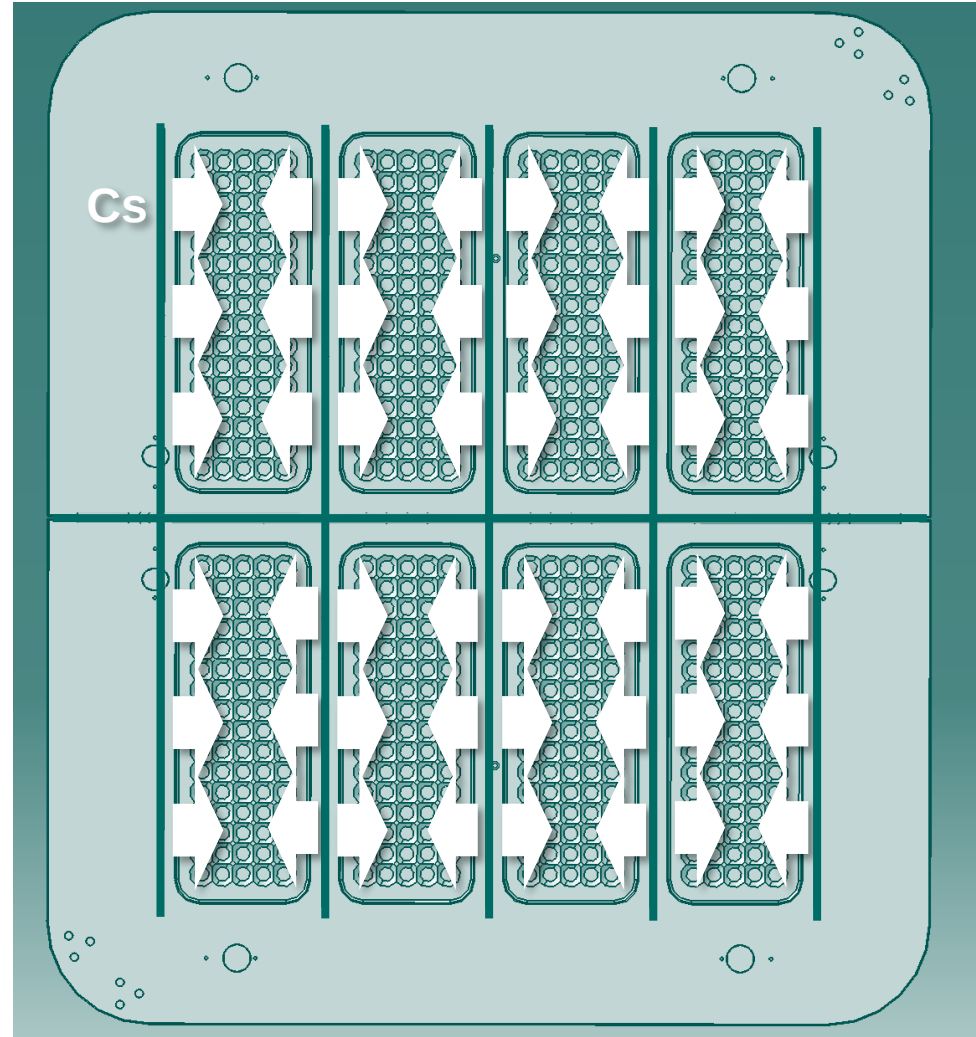
- Cs asymmetry decreased from 2nd to 3rd version: 17 → 1.7
- Max. Cs⁰ density less extreme: $5 \times 10^{16} \text{ m}^{-3} \rightarrow 1 \times 10^{16} \text{ m}^{-3}$

Cs shower: roll-out to ELISE

Next step:

Test Cs shower @ ELISE

**Stabilization of long
deuterium pulses!**



RF H⁻/D⁻ source for NBI:

- Operates technically reliably
 - In principle capable of running continuously (RF plasma generation, RF coupling, high voltage for extraction and acceleration, cooling etc.)
 - Main limit: Cs deconditioning during long pulses
-
- **Stable long pulses in hydrogen at high performance**
after optimizing the filter field, biases and Cs conditioning procedures
 - **Deuterium is more challenging:**
strong Cs deconditioning, Cs flux onto PG is too low in classic concept
 - **Possible solution: direct evaporation of Cs onto the convertor surfaces during beam pulses**
-
- **Well on the way to bringing large negative deuterium ion sources into a steady state!**

Long deuterium pulses

Deuterium operation:

- Cs shower shows nice stabilization of co-extracted electrons at increased evaporation rates!
- No increase of HV breakdowns detected at higher evaporation rates

