Negative Hydrogen Ion Sources for Fusion
Tutorial for NIBS 2020

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on behalf of the ITER NBI contributors

ITER, France

RFX, Italy

QST, Japan

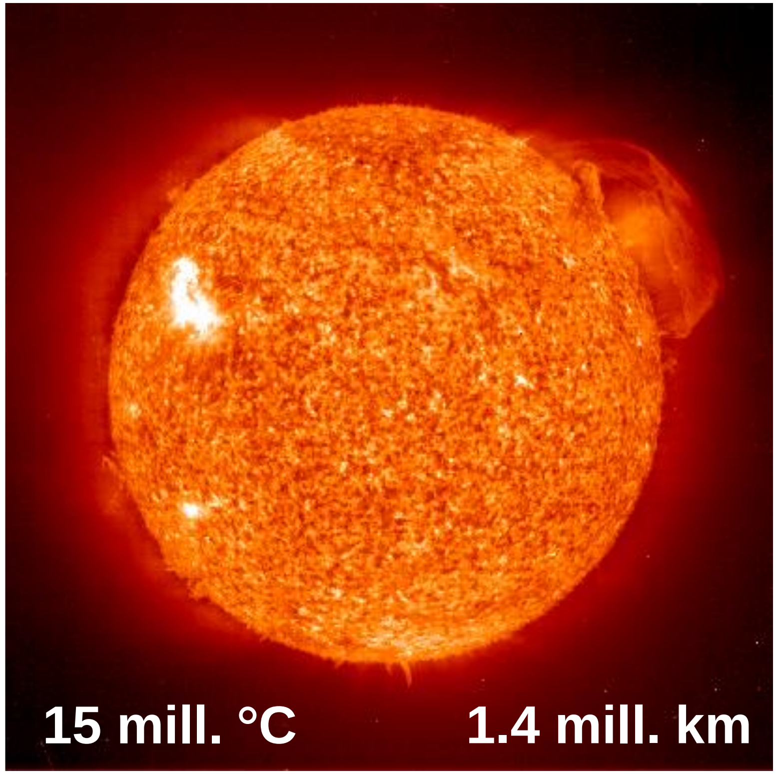
NIFS, Japan

IPR, India

IPP, Germany

Fusion – The energy source of the sun

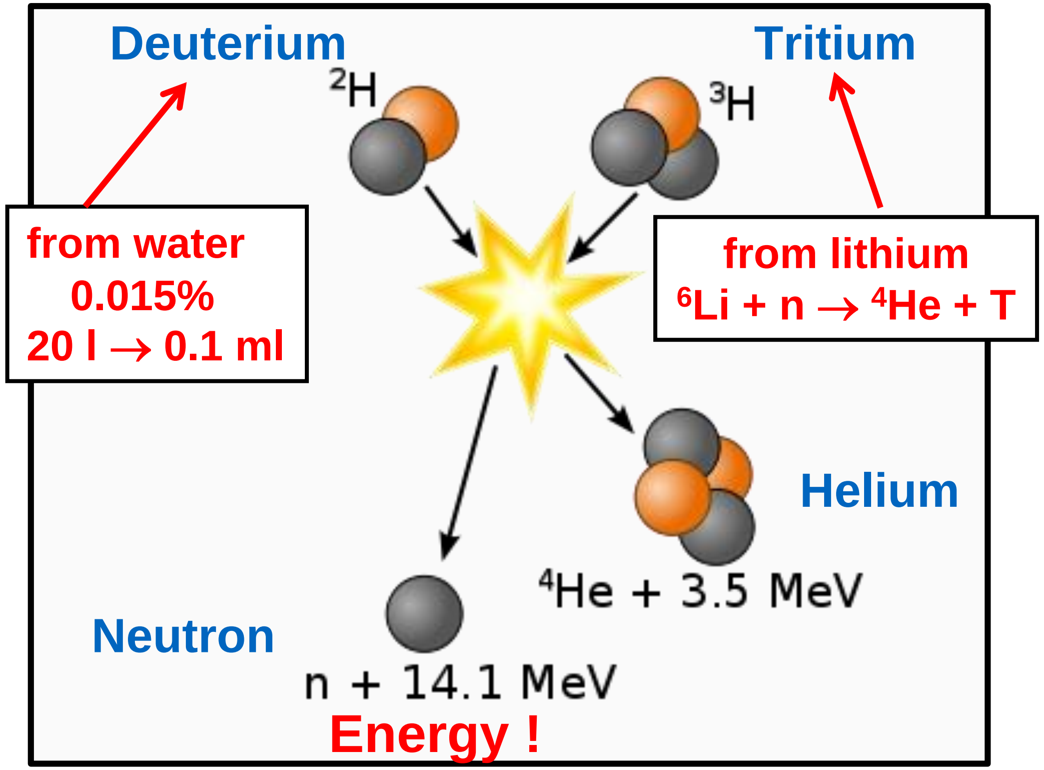
Hydrogen ⇨ Helium



$4H \rightarrow \ldots \rightarrow {}^{4}He + \ldots + 26.7$ MeV

β⁺ decay

on Earth: Hydrogen isotopes ⇨ Helium



$D + T \rightarrow {}^{4}He + n + 17.6$ MeV

Fusion on Earth needs 10 times higher temperature as in the sun!

The fusion experiment ITER

Largest multinational scientific mission.

1985: Project starts

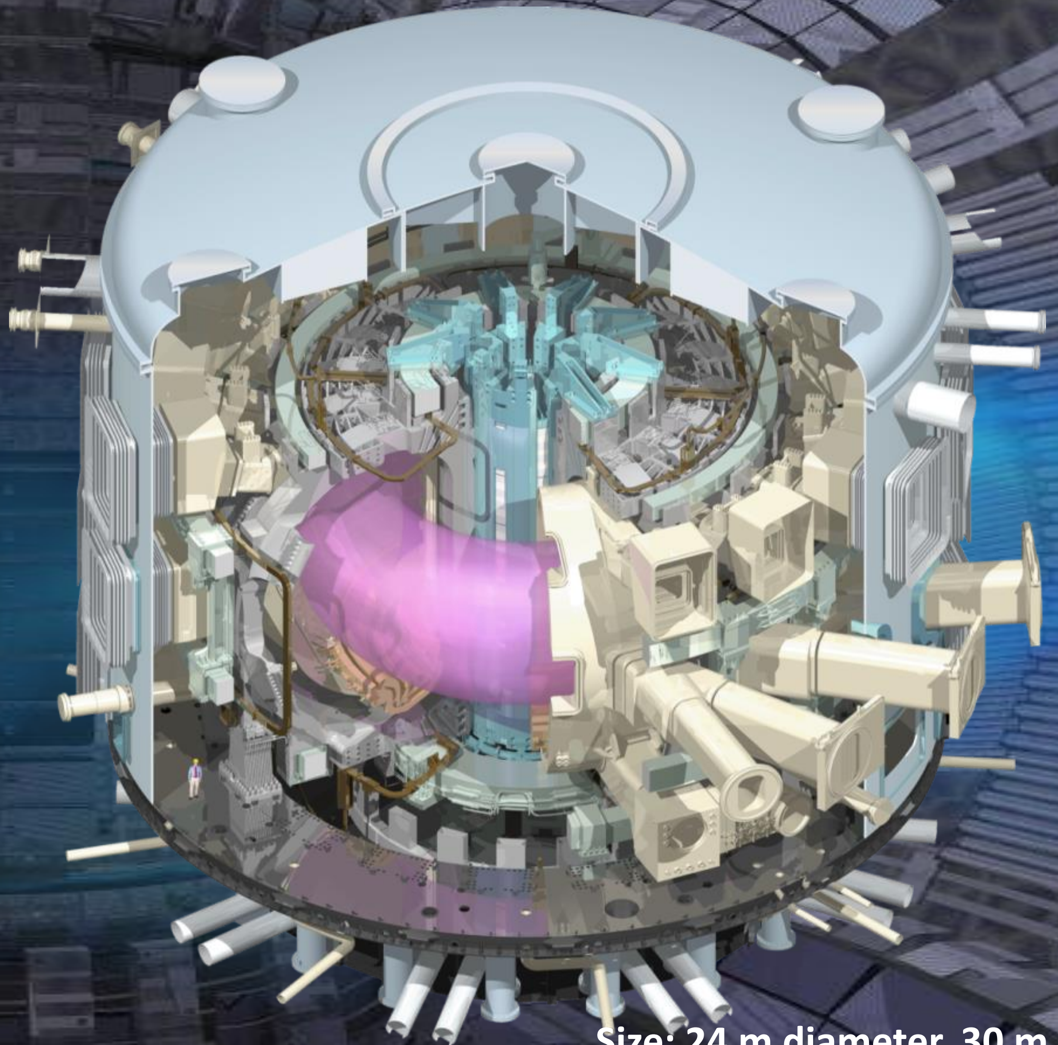
2006: ITER Agreement officially signed

2019: > 65% ready

To demonstrate the scientific and technological feasibility of fusion power for peaceful purposes.

To produce a burning plasma.

Q>10 for 400 s (Q > 5 for 3600 s)
Output (fusion power): 500 MW
Input (heating power): 50 MW



Size: 24 m diameter, 30 m height
Weight: 23 000 tons (3 x Eiffel tower)

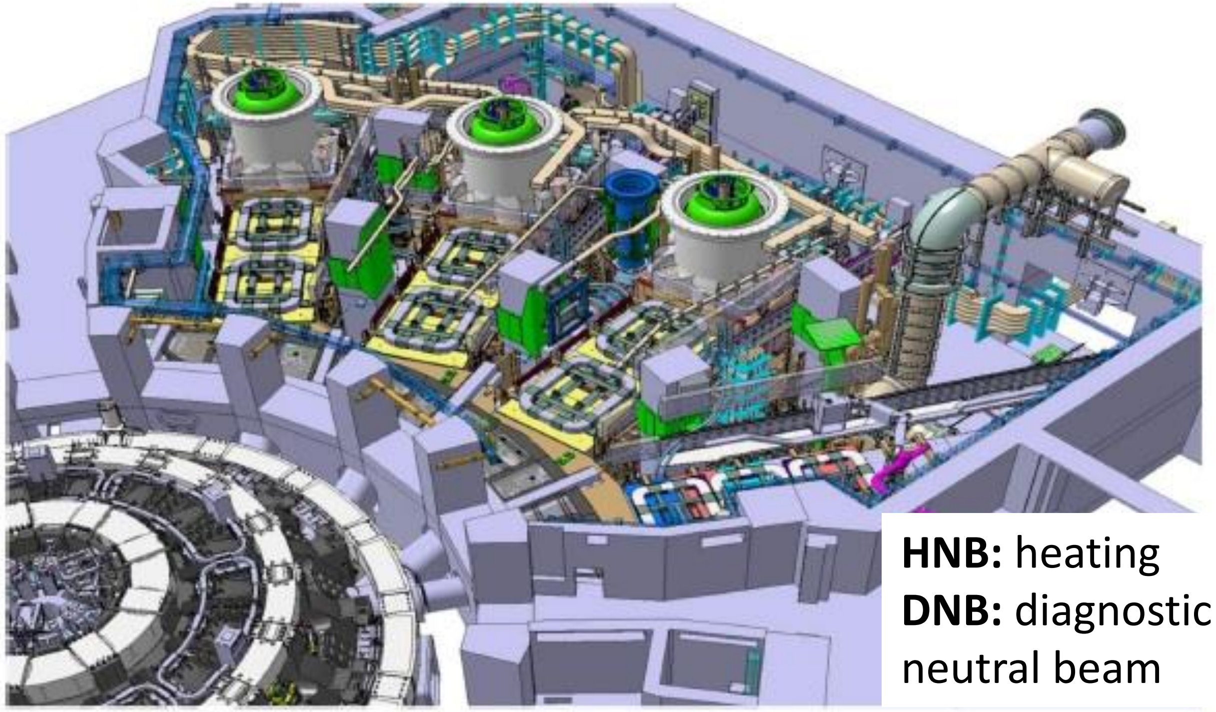
Neutral beam systems for ITER

NBI: Neutral Beam Injection of energetic neutral atoms (H or D)

To achieve with ECRH and ICRH the plasma temperatures and profiles for DT phase

↕ Electron ↕ Ion cyclotron resonance heating

Installed power
ECRH: 20 MW
ICRH: 20 MW
NBI: 33 MW



HNB: heating
DNB: diagnostic neutral beam

NBI Functions

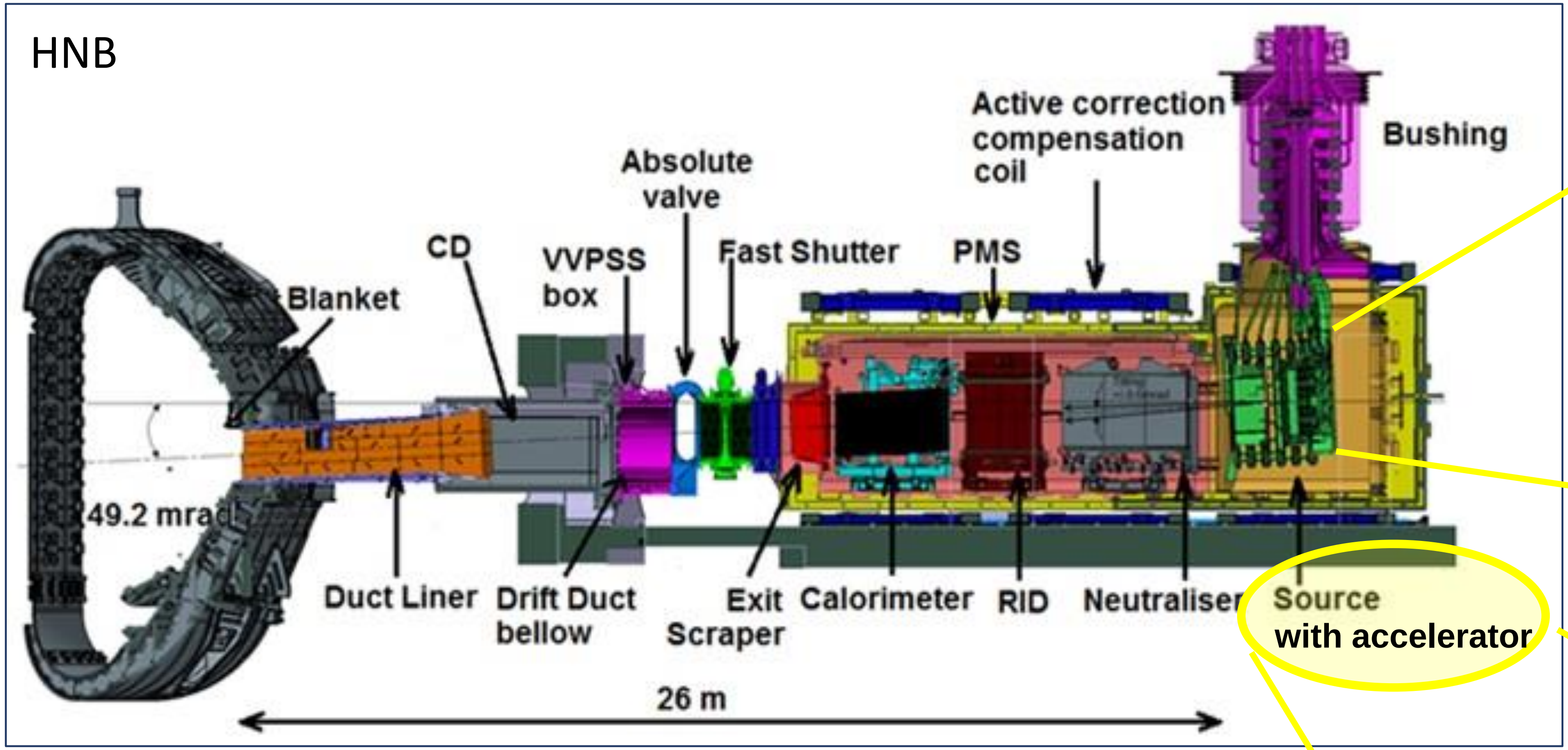
- Heating
- Current drive
- Plasma rotation
- Diagnostics

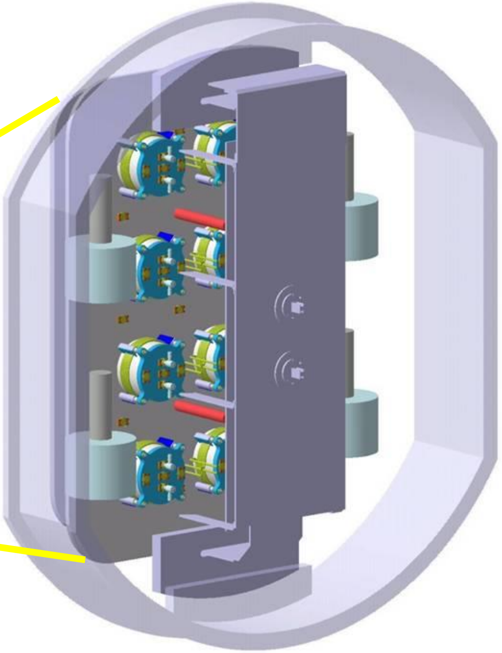
2 + 1 HNB beam lines
1 DNB beam line sharing port with HNB-1

ITER NBI systems and their requirements

Heating beams (50% EU, 50% JA) : **33 MW** (2 injectors) for 3600 s, **1 MeV Deuterium, 870 keV Hydrogen**

Diagnostic beam (100% IN): **2.2 MW, 100 keV Hydrogen**, 3s ON/20s OFF 5Hz





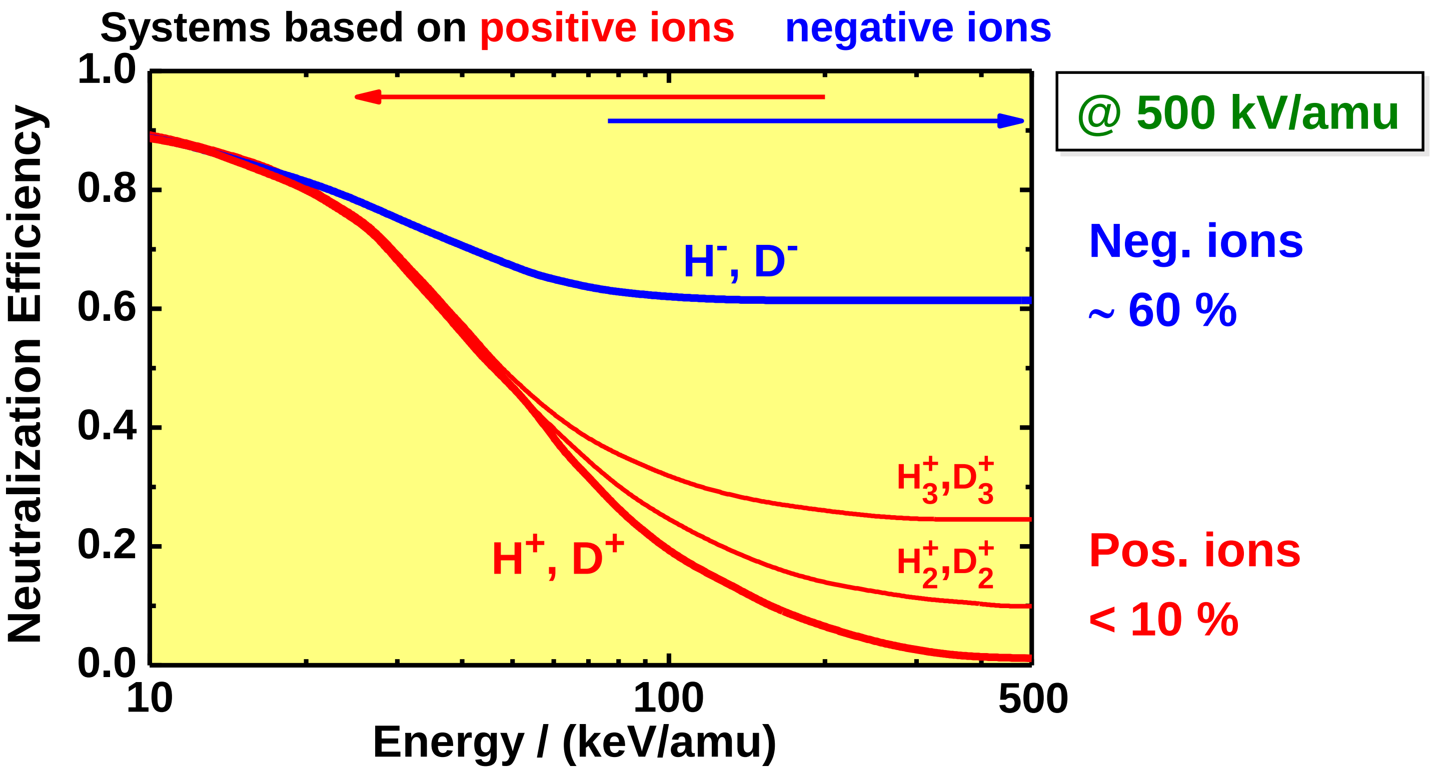
Source area: 1 m × 2 m

RF-driven ion source

Injection | Transport with 7 mrad beam divergence | Neutralization | Acceleration | Generation

Why negative hydrogen ions?

Neutralisation efficiency at a beam energy of 1 MeV D



Negative ion based systems make high energy range accessible

JT-60U / JT-60SA, LHD

U_{acc}>≈ 150 kV, j = 20 mA/cm²

increase of source size

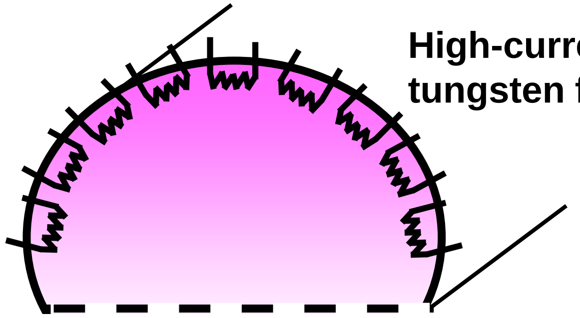
Positive ion based systems are routinely operating world wide

JET, AUG, TFTR, DIII-D, JT-60U, …

U_{acc}<≈ 100 kV, j ≈ 200 mA/cm²

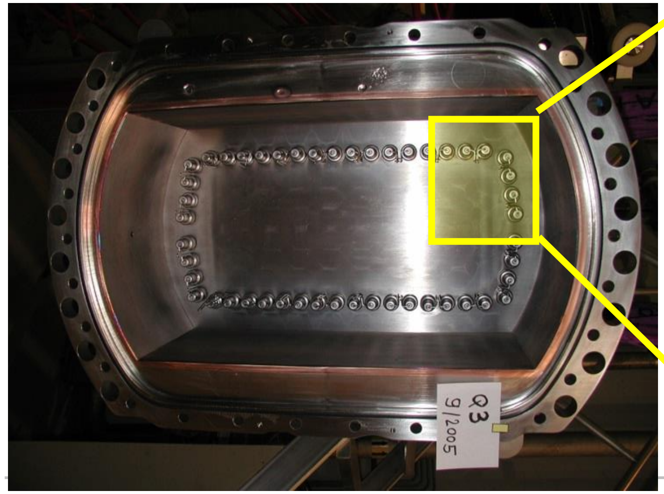
Concept of ion sources – Arc sources and RF-driven sources

Arc sources

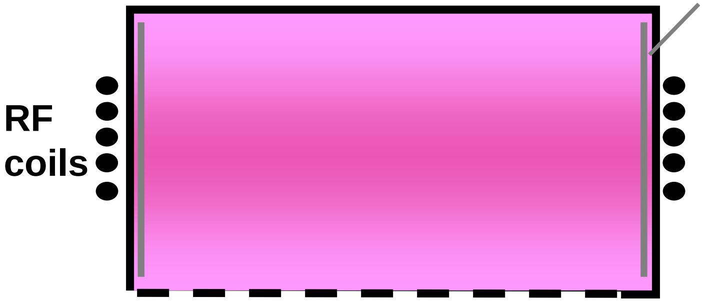


- Hot cathodes (2000 – 3000 K)
- DC voltage (≈ 100 V)
- Arc current (1000 A)

Filaments require regular maintenance



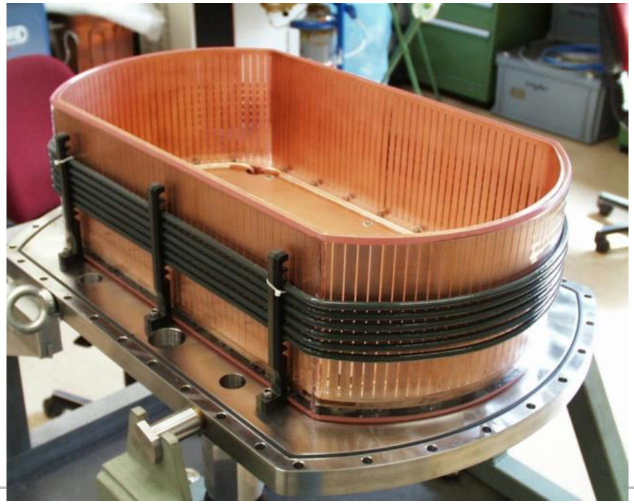
RF sources

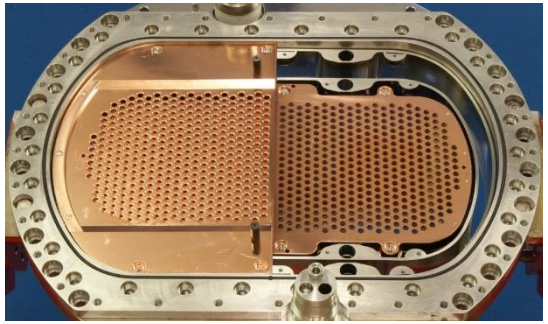


RF concept chosen by ITER in 2006

- Inductively driven source
- RF power supply (≈ 100 kW)
- RF frequency 1 MHz

Long lifetime, routine operation for positive ions at AUG

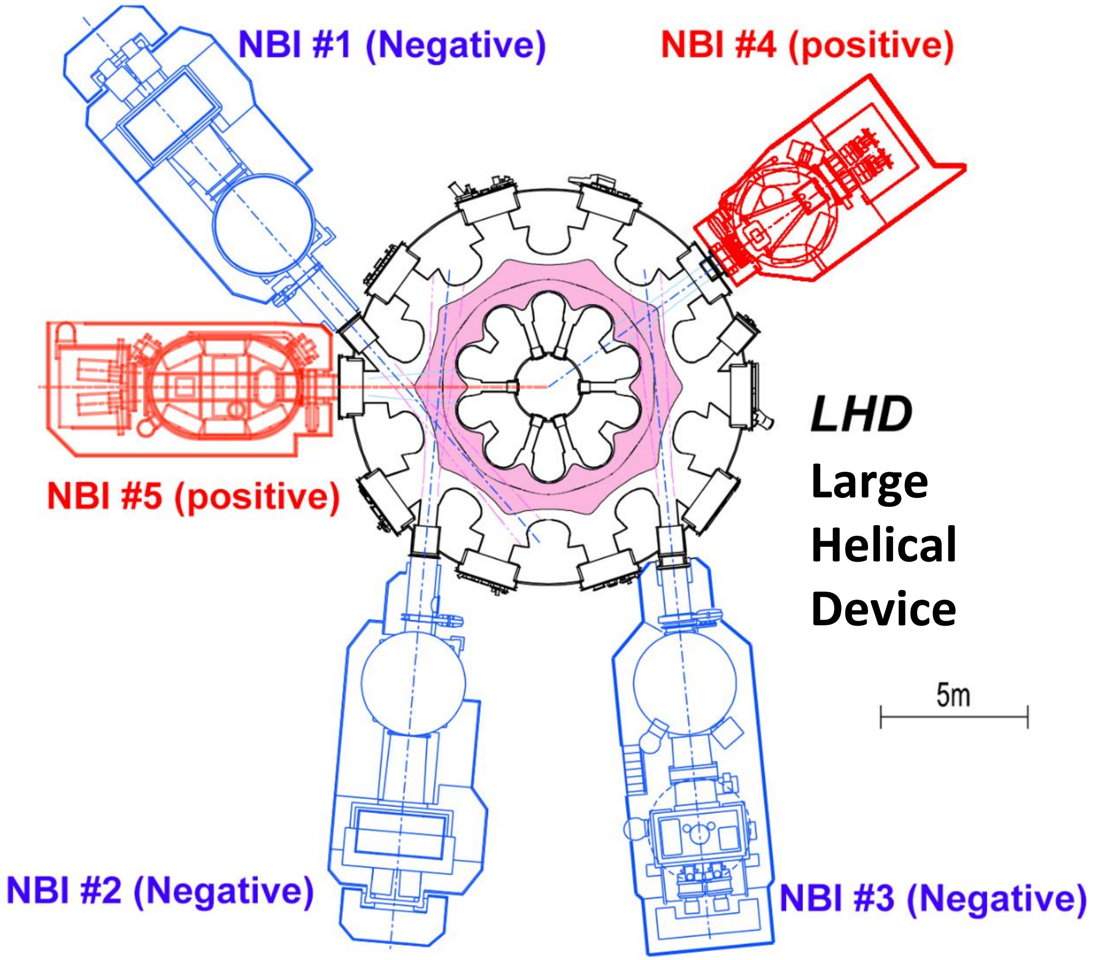




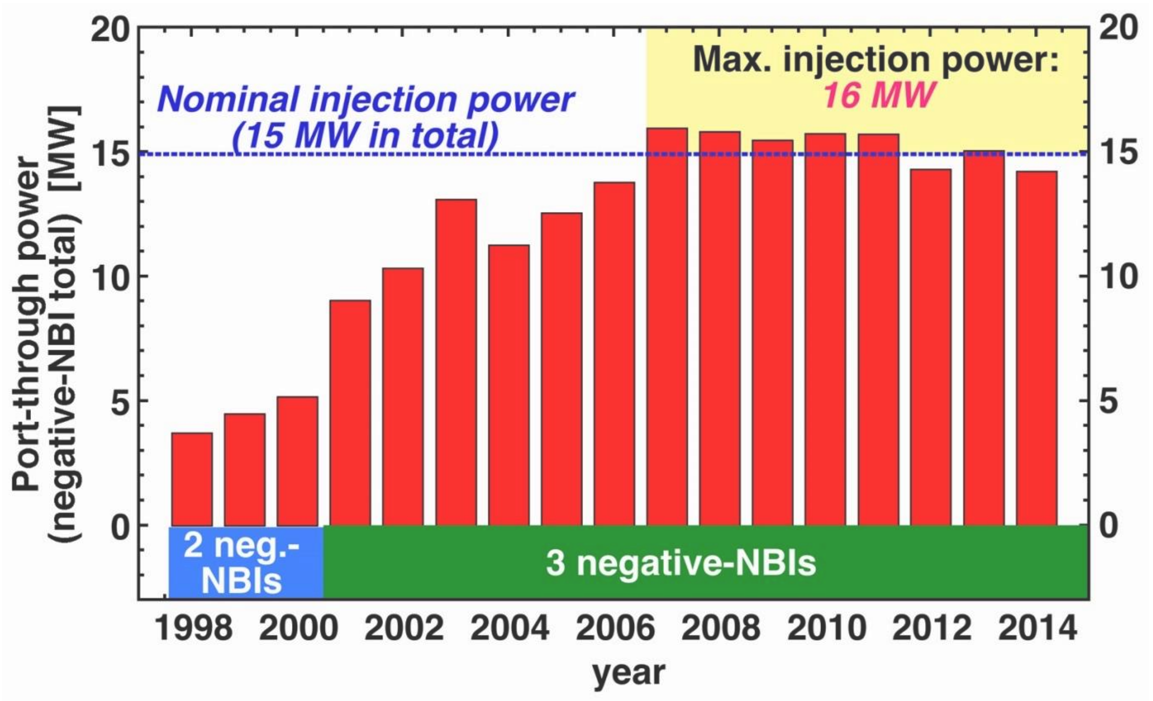
Multi-aperture grid system (AUG)

774 apertures, 8 mm in diameter
3 grids for acceleration & focussing

NBI systems at LHD at NIFS, Japan



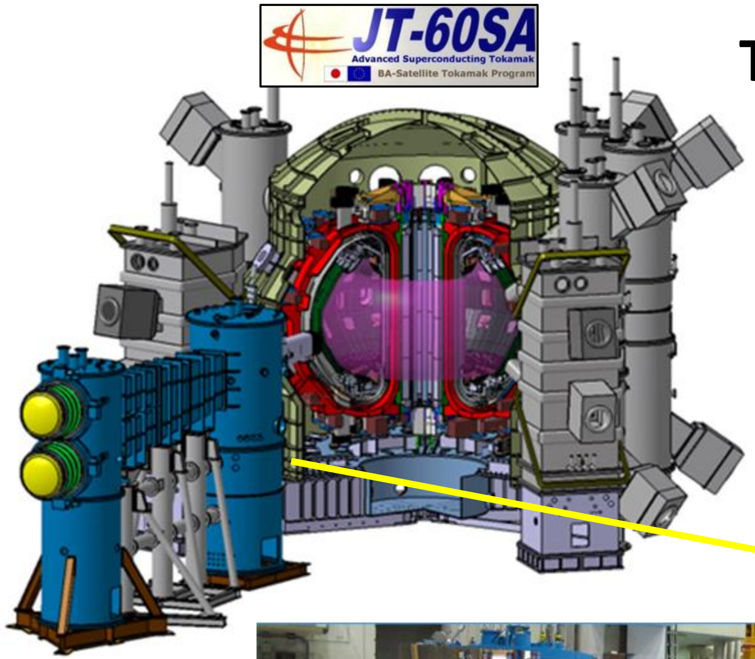
	negative	positive
Beam energy [keV]	190	80 & 90
Injection power [MW]	5.5 - 6.9	9
Pulse length [sec]	10 (max)	10 (max)
Beam divergence [mrad]	5	11



Arc sources, operation mostly in hydrogen

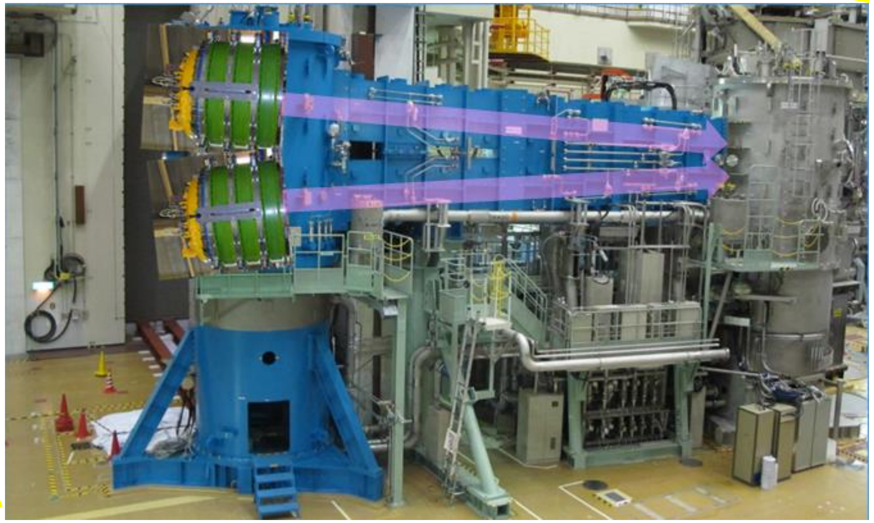
K. Tsumori, *Fusion Sci. Tech*. **58**, (2011) pp.489

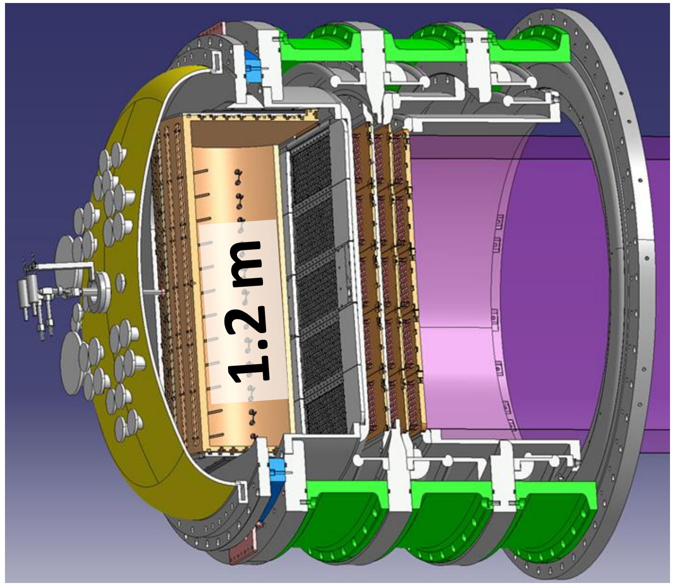
NNBI systems at JT-60U / JT-60SA at QST, Japan



Towards 100 s of H^-/D^- beams with 500 keV, 22A (130 A/m²)

Based on arc sources



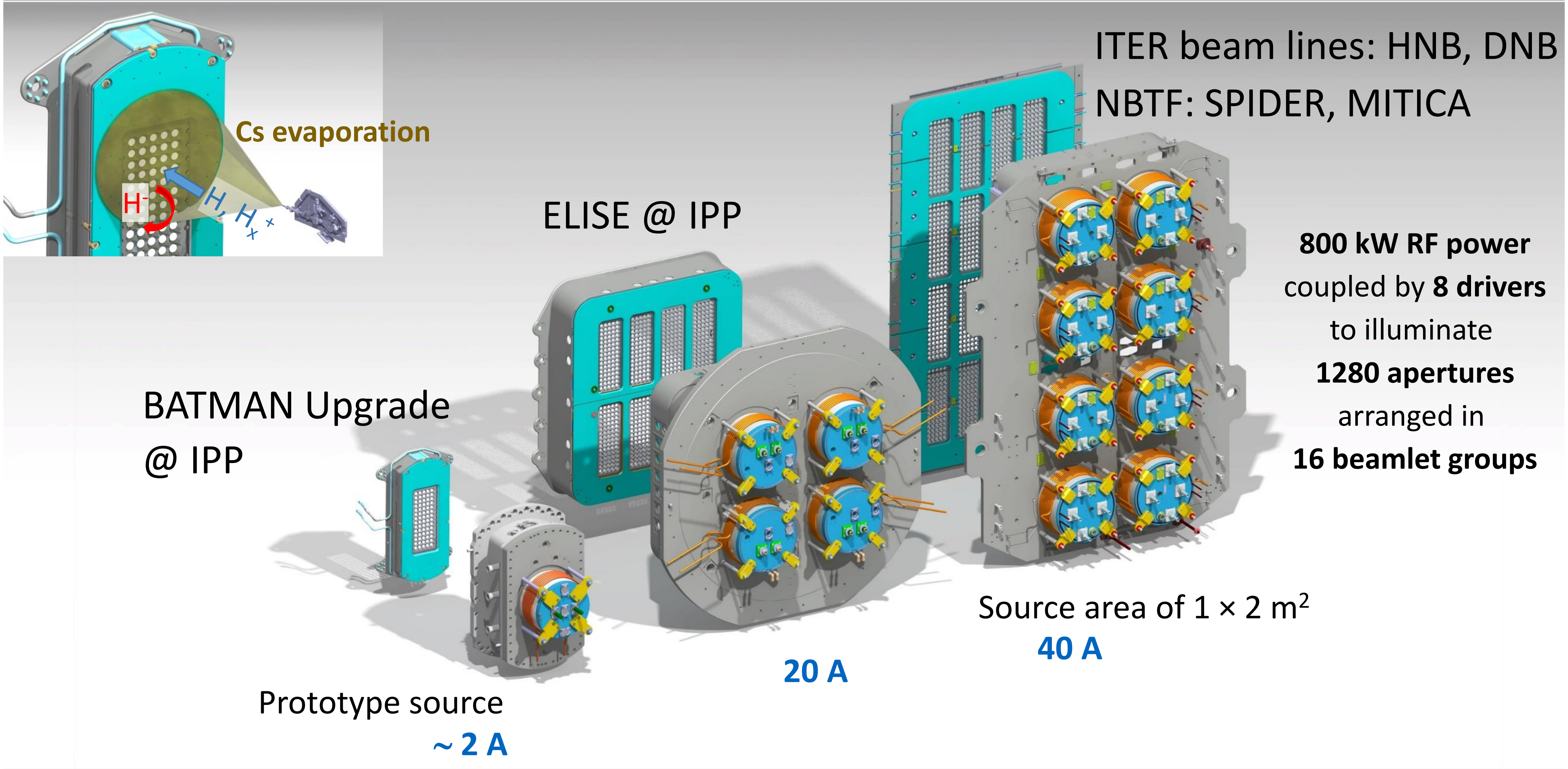


Achievement of beam acceleration
500 keV, 156A/m²,
118 s
By using 1/8 scale ion source

Achievement of H^- ion production
15 A for 100 s
→ under progress

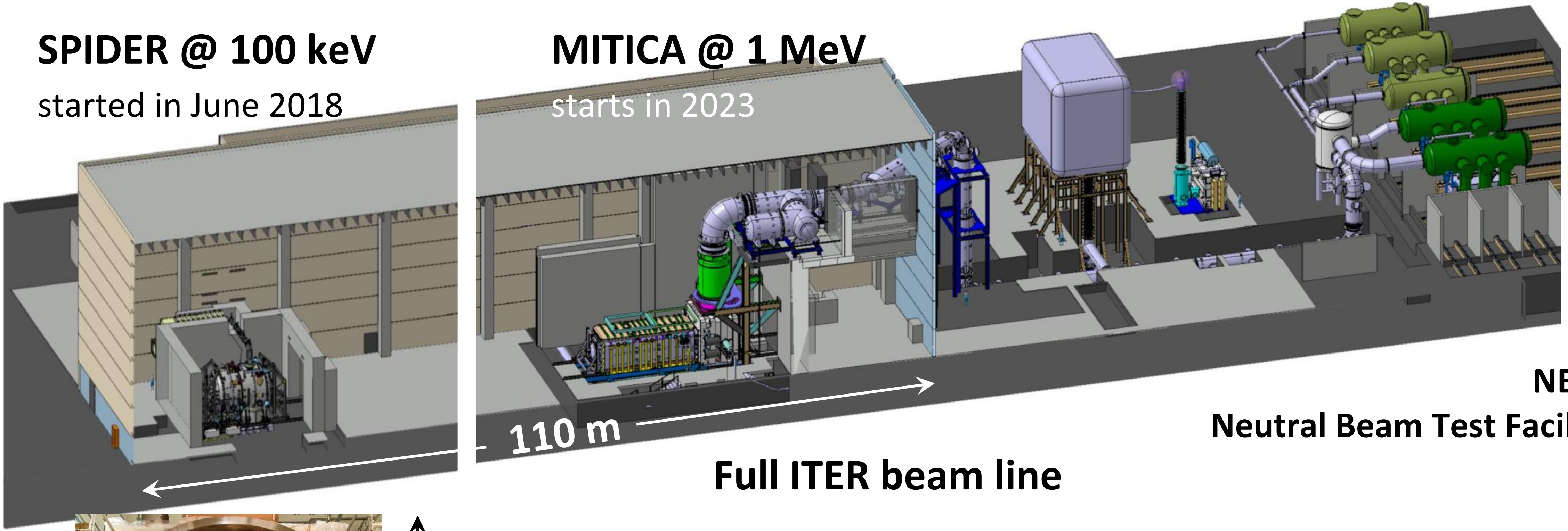
Large ion source & accelerator is combined, and starts from 2023.

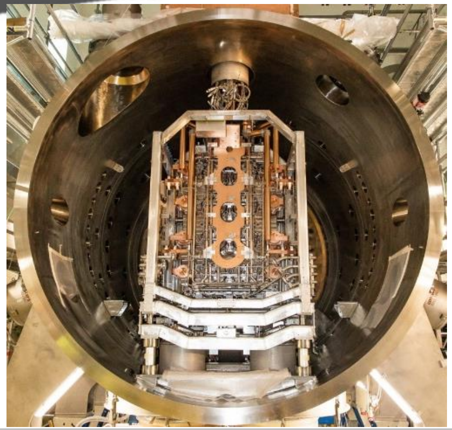
R&D for the ITER ion source – a size scaling route



The test facility for ITER NBI at Consorzio RFX, Italy

CONSORZIO RFX
Ricerca Formazione Innovazione





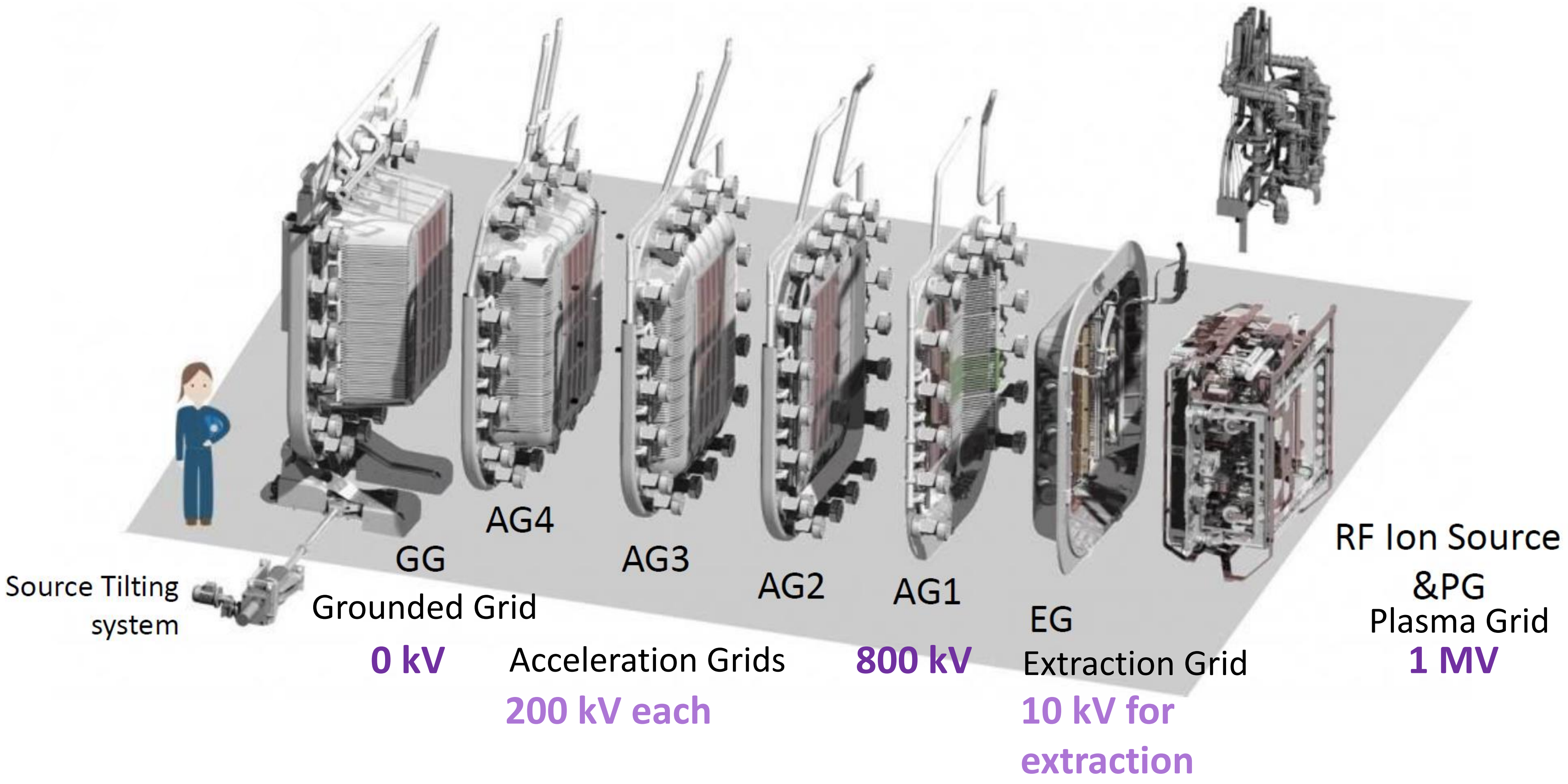
4 m

Critical challenges:

- Extraction of 40 A negative ion beam from a large-size RF source
- Acceleration 1 MeV with accurate beam optics
- Development of high-voltage, gas-insulated transmission lines
- Voltage holding (1 MV) over pulses of 3600 seconds

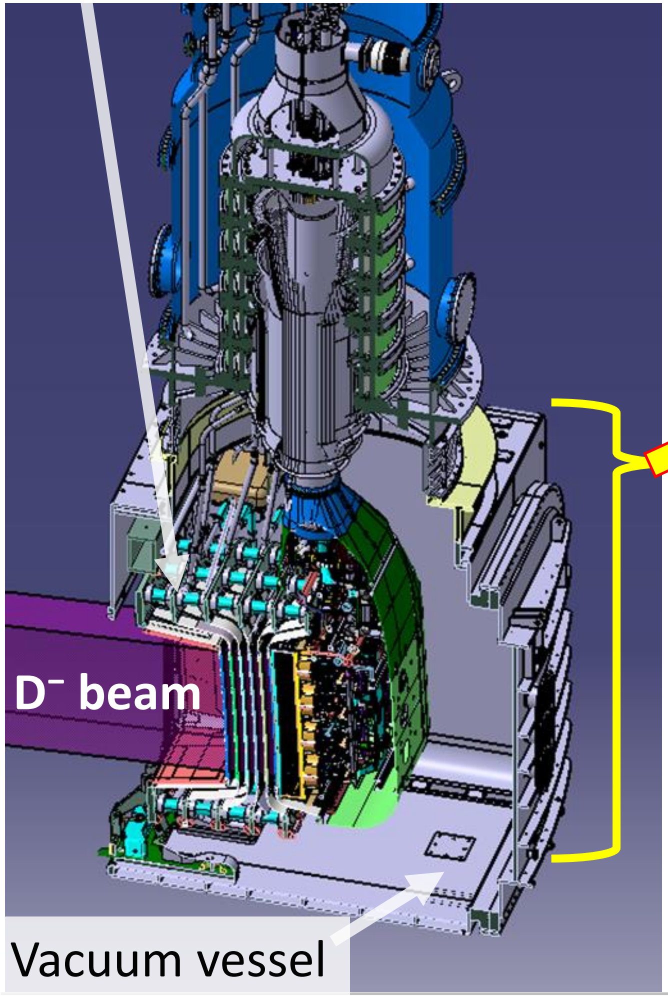
The test facility for iter NBI at Consorzio RFX, Italy

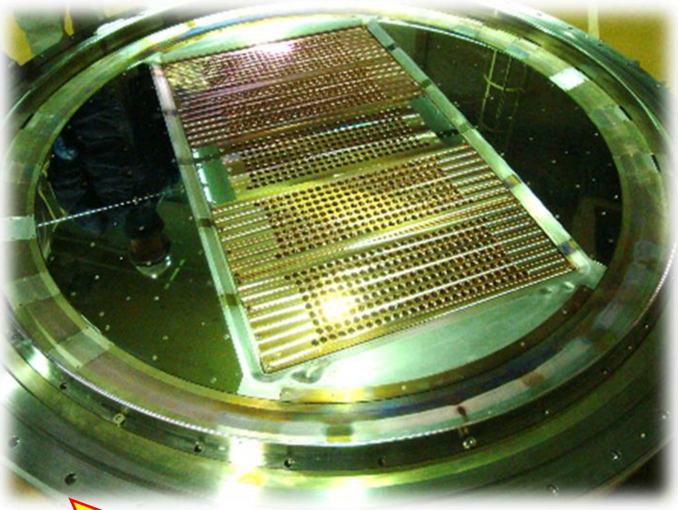
The beam source of MITICA (full size HNB prototype)

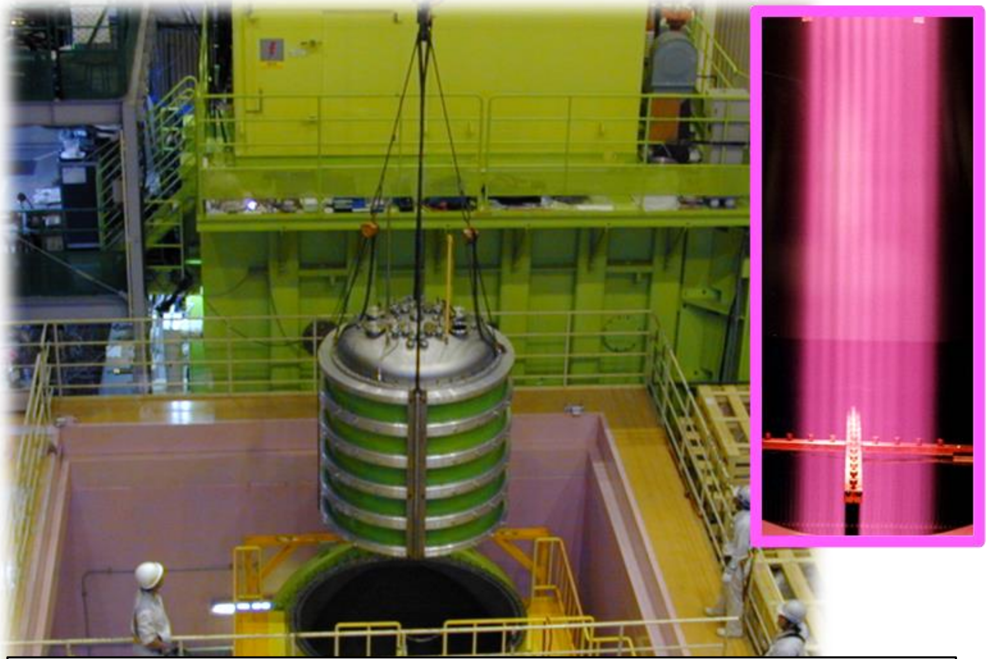


The 1 MeV acceleration R&D at QST, Japan

Vacuum-insulated beam source for ITER







Vacuum insulation design by using meter-class large grid

By using 5-stage accelerator, long pulse MeV-class beam acceleration tests over 100 s – 1000 s

Proof-of-Principle beam acceleration test to support MITICA/NBTF and the final design for ITER

ELISE – A half size ITER source

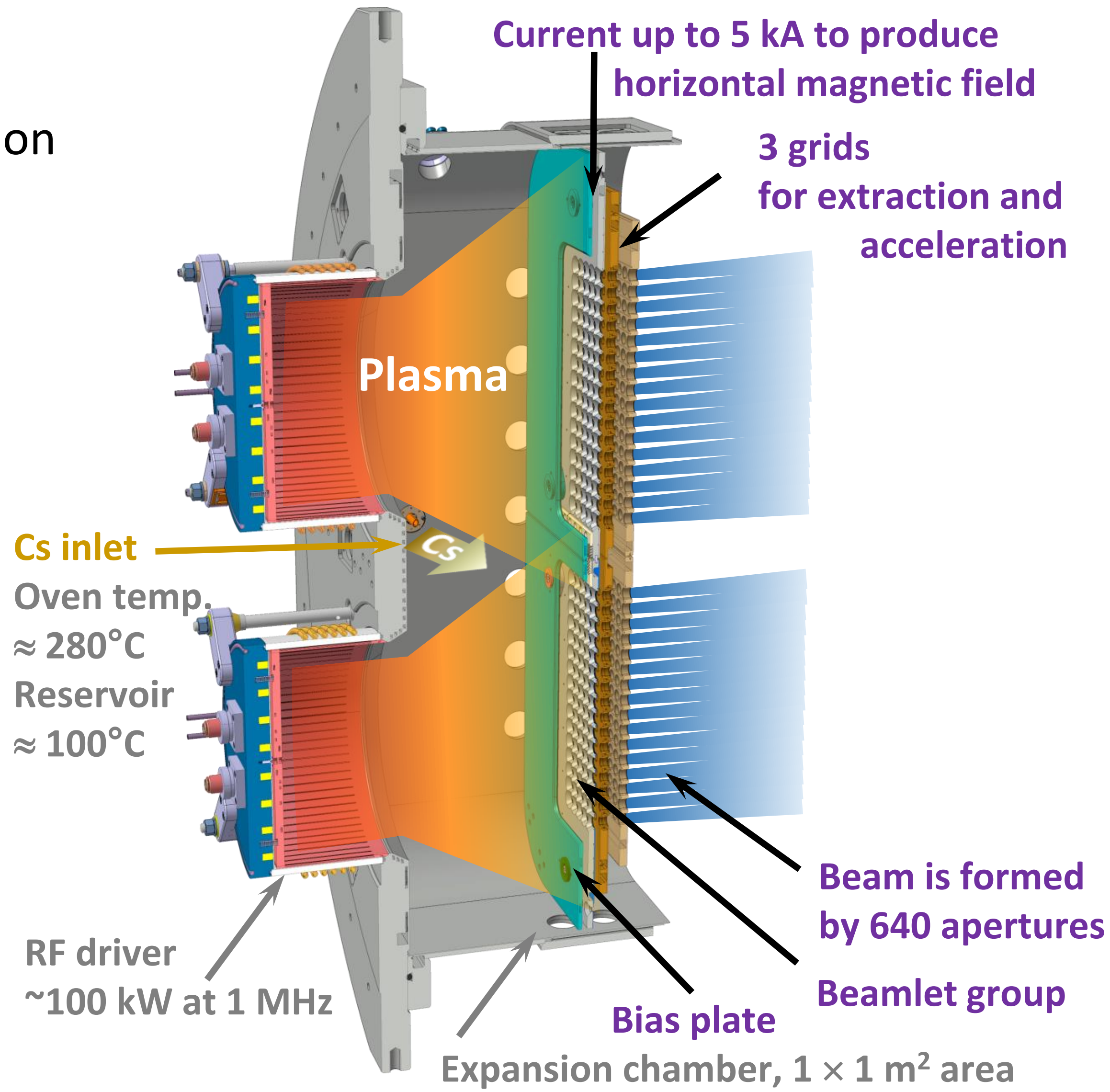
First plasma and beam: Feb. / Mar. 2013

ELISE is dedicated to

- **Provide input** for design, commissioning and operation of **ITER NBI systems**
- **Demonstrate** ITER parameters in large sources
  - **Extracted currents (ions and electrons)**
  - **Beam homogeneity**
- **Develop** most efficient source operation scenarios

Parameter and targets

Isotope D^- (H^-)
RF power = 2 x 150 kW in 4 drivers
A_{ex} = 1000 cm^2, **uniformity > 90%**
$I_{ion,ex}$ = 29 (33) A, I_e/I_{ion} < 1 at 0.3 Pa
U_{tot} = 60 kV, U_{ex} < 12 kV
Plasma: 3600 s Beam: 10 s every ~150 s (HV supply)



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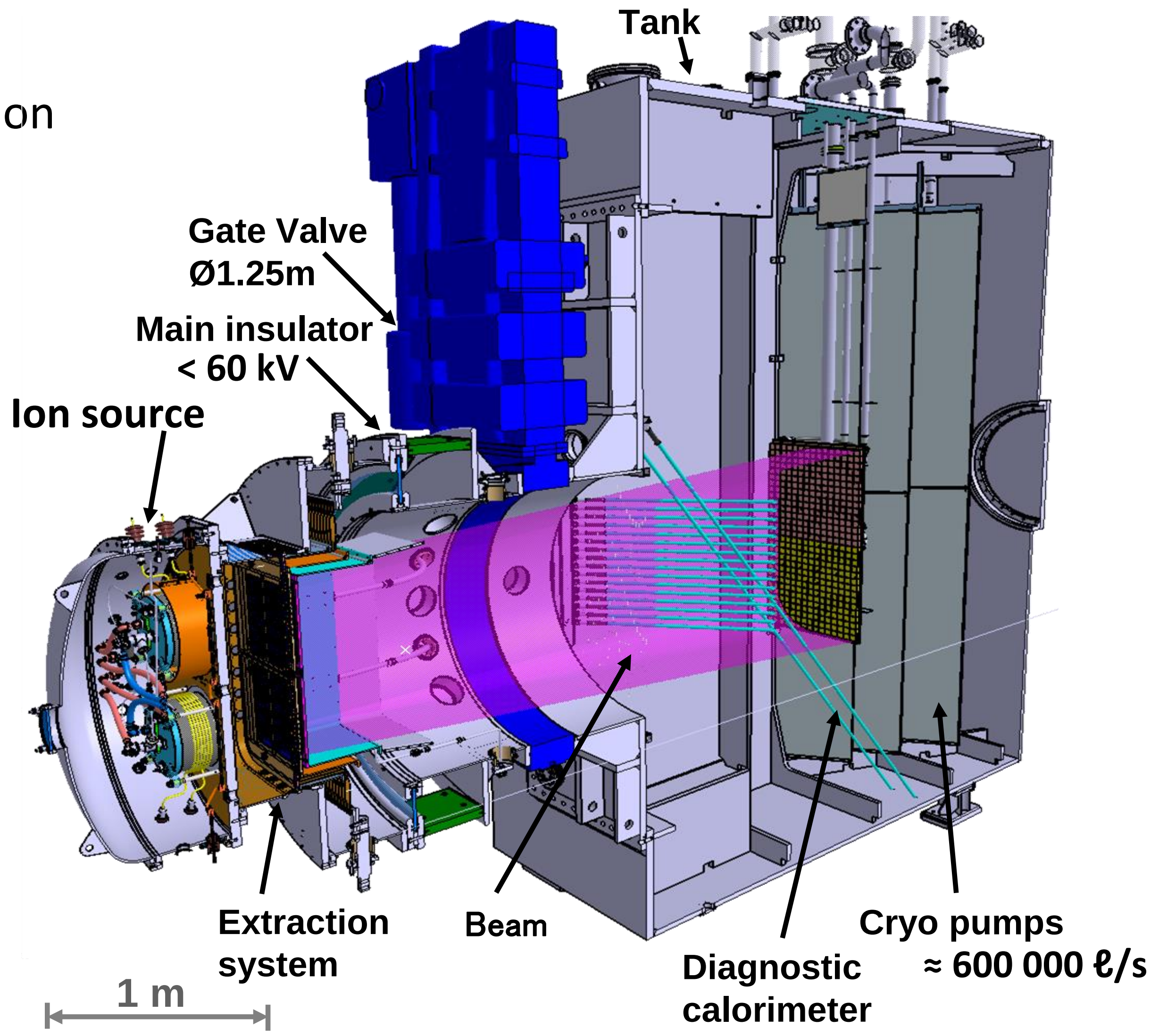
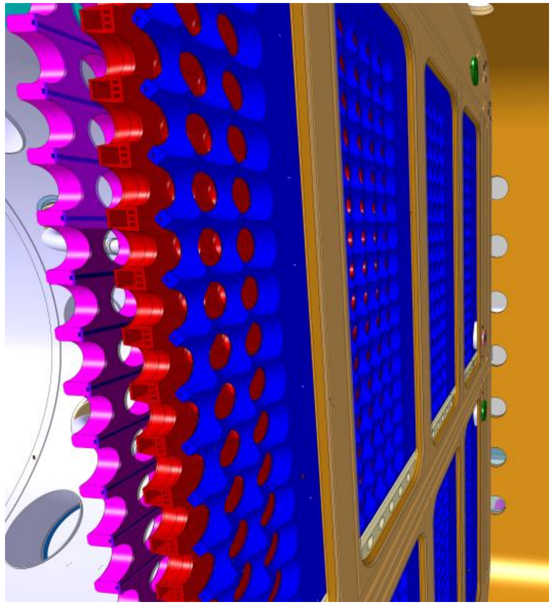


The grid system

Three grids



GG EG PG BP

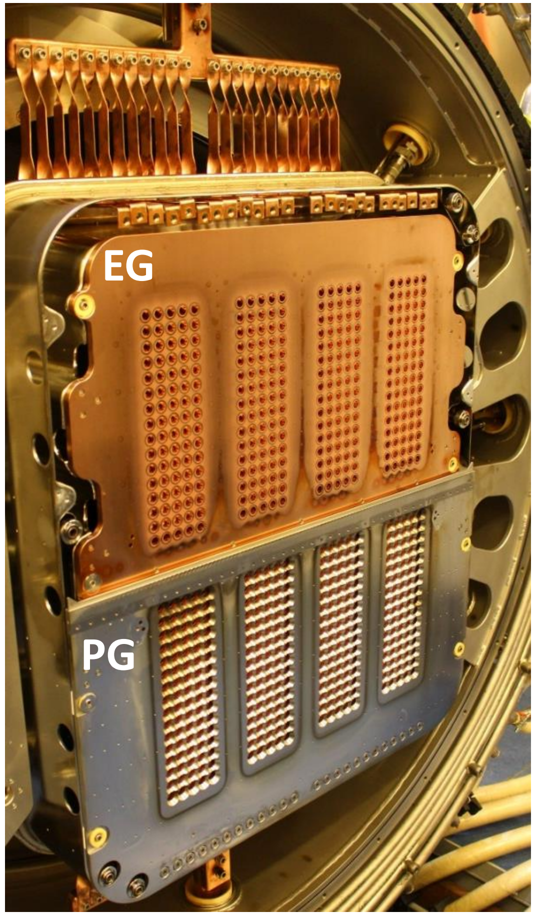
Bias Plate

Plasma

Extraction

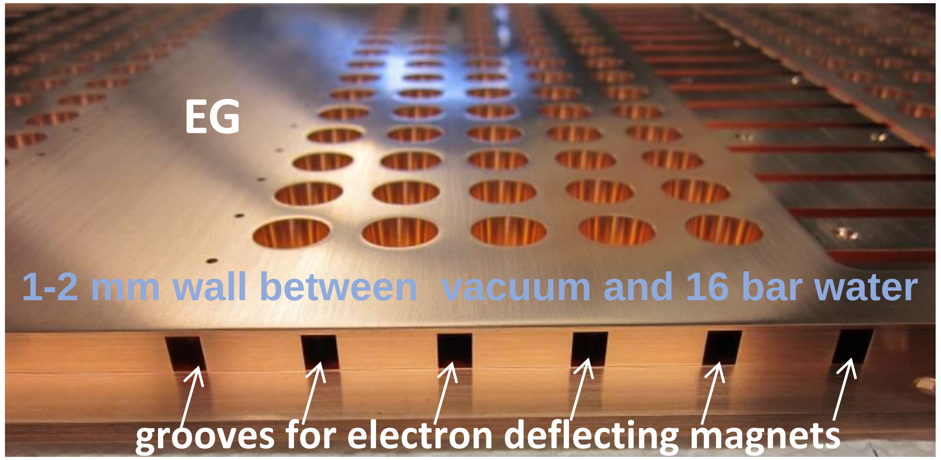
Grounded Grid

Two segments

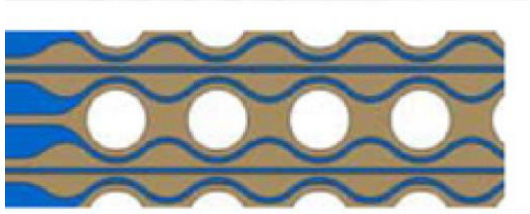


PG and inner surfaces of the ion source are coated with molybdenum to avoid Cs interaction with Cu.

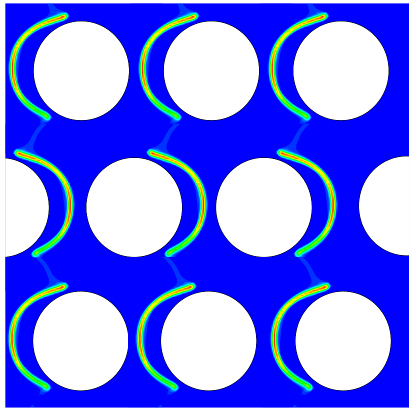
Extraction grid



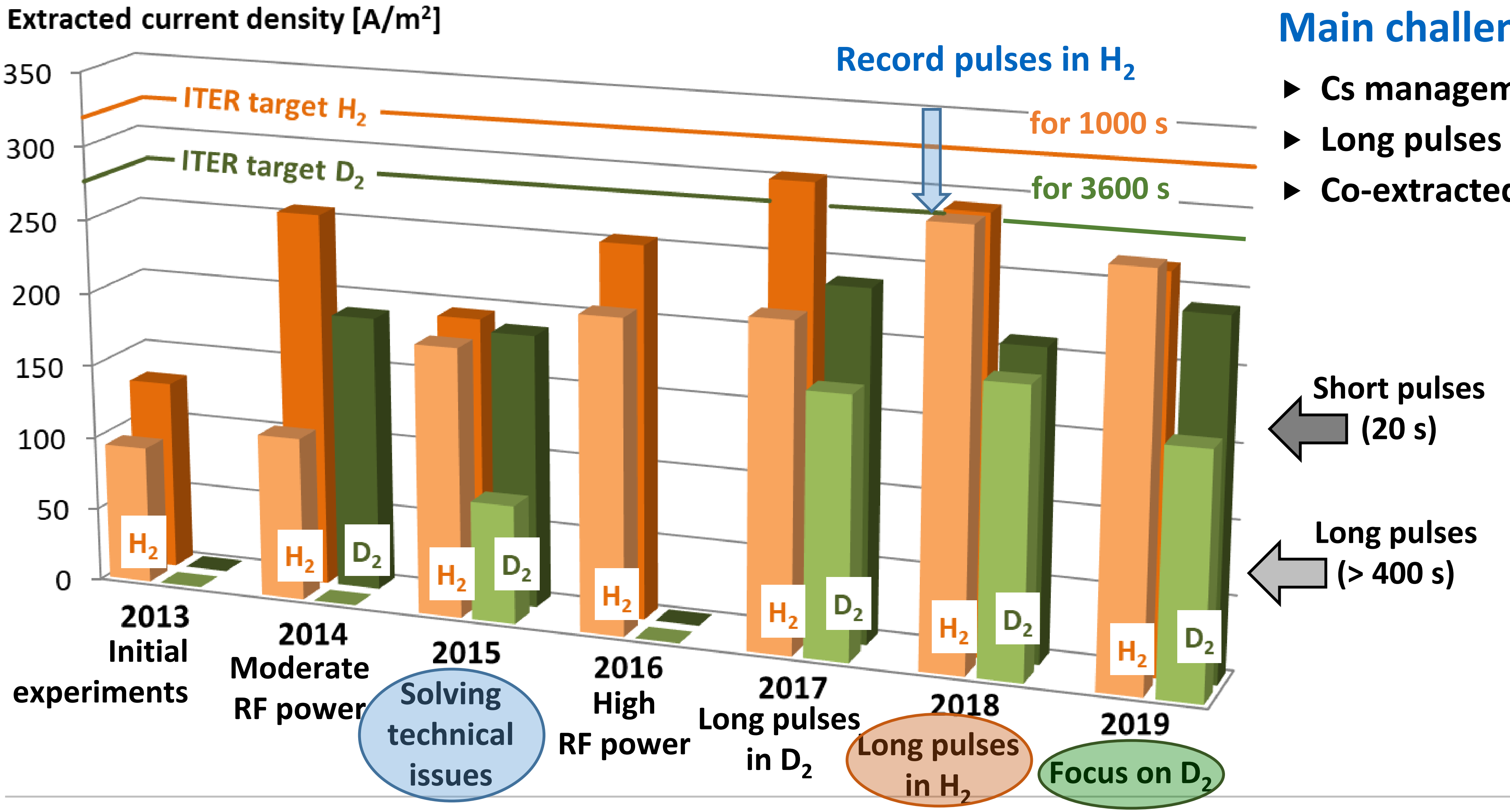
altering direction from row to row



Power density of
32 MW/m^2 by
co-extracted electrons



Present status – Source performance



Main challenges

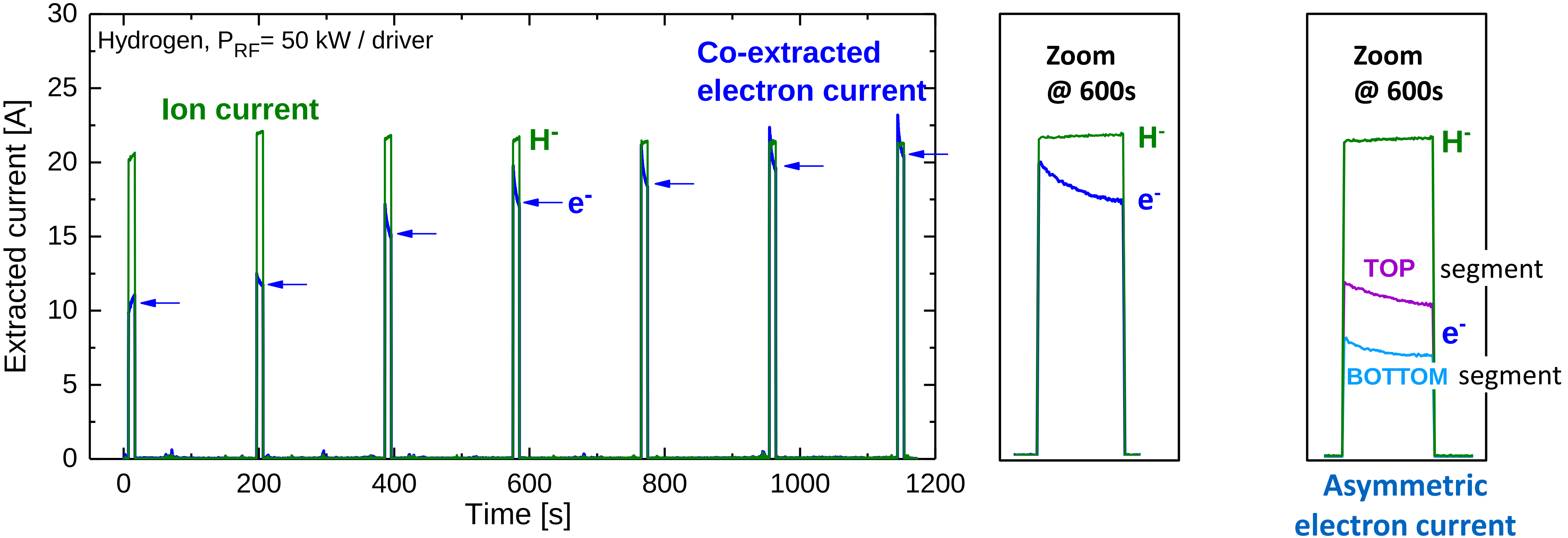
- Cs management
- Long pulses
- Co-extracted electrons

Typical long pulse behaviour

Source performance is probed by short pulse extraction of 10 s every 3 min

- **Stable** negative ion current density (within 10%)
- Strong **temporal dynamics** of co-extracted electrons

Interlock of extraction grid is set to 125 kW/segment although designed for 200 kW (ITER: 600 kW for all 4 segments)

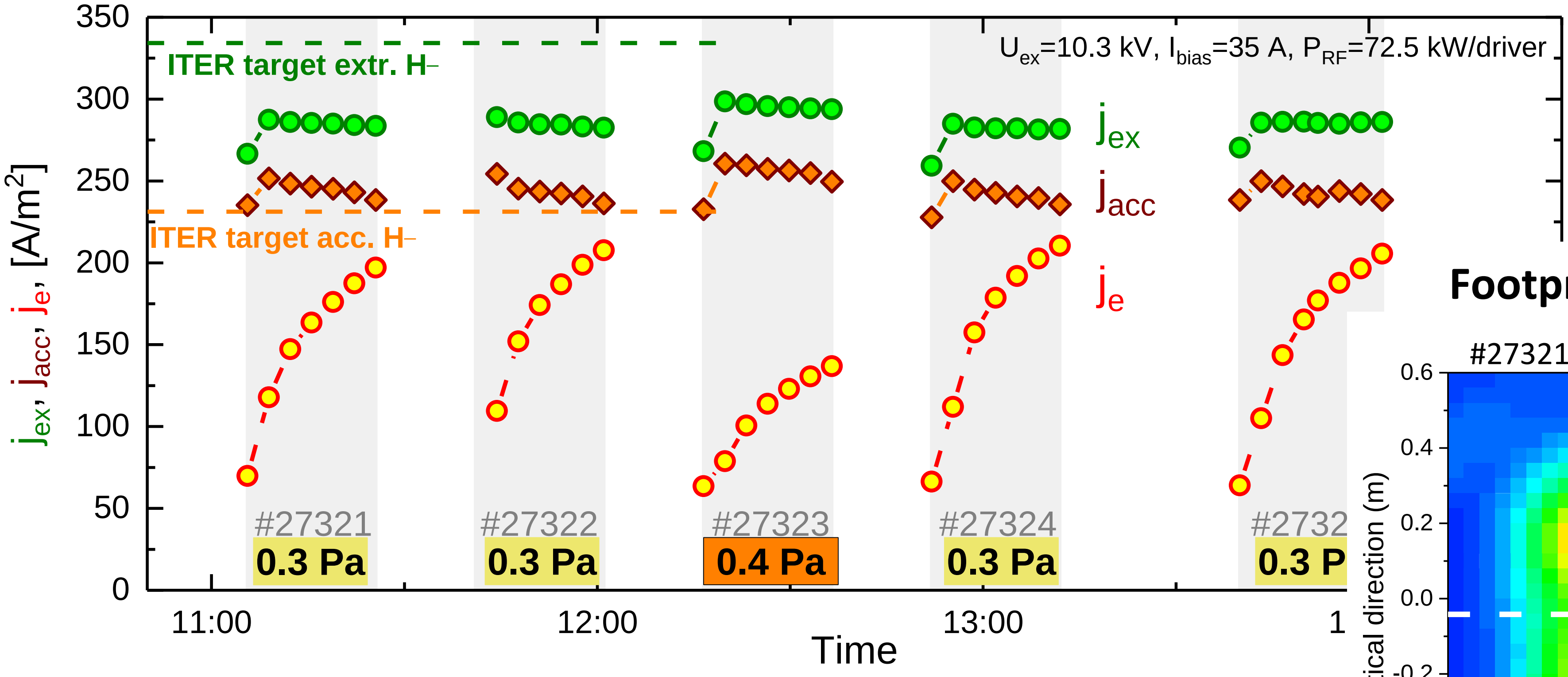


Asymmetric electron current

Requires careful Cs conditioning and measures to suppress co-extracted electrons

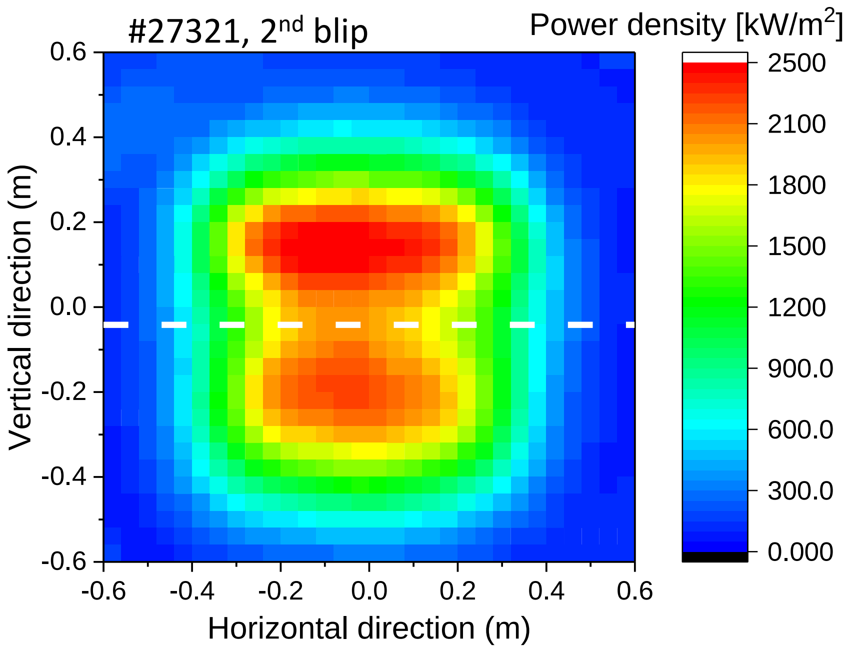
Achievements of ELISE in 2018 – Towards ITER targets

Parameter for hydrogen (almost*) achieved in consecutive pulses



* due to technical limitations (HV power supply & RF generators)

Footprint of beam at calorimeter



Demonstration of first operational phase at ITER (up to 2035)

Deuterium operation – Achievement so far: 200 A/m^2 (67%) for almost 1 h

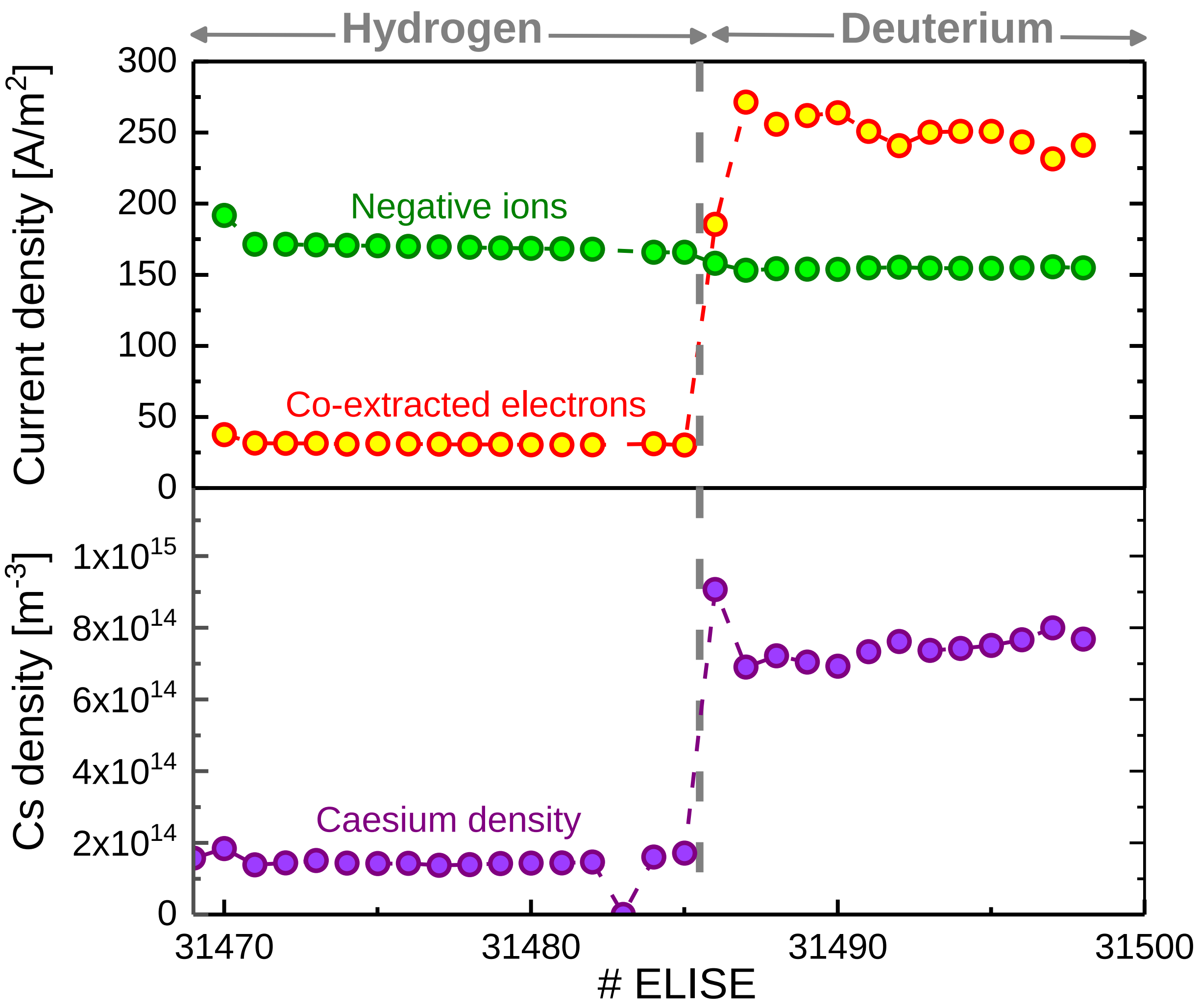
IPP

Strong isotope effect in terms of co-extracted electrons

Transition from hydrogen to deuterium at identical source parameters

- Drastic increase of co-extracted electrons
- Strong increase of Cs density close to plasma grid

at almost the same ion current density



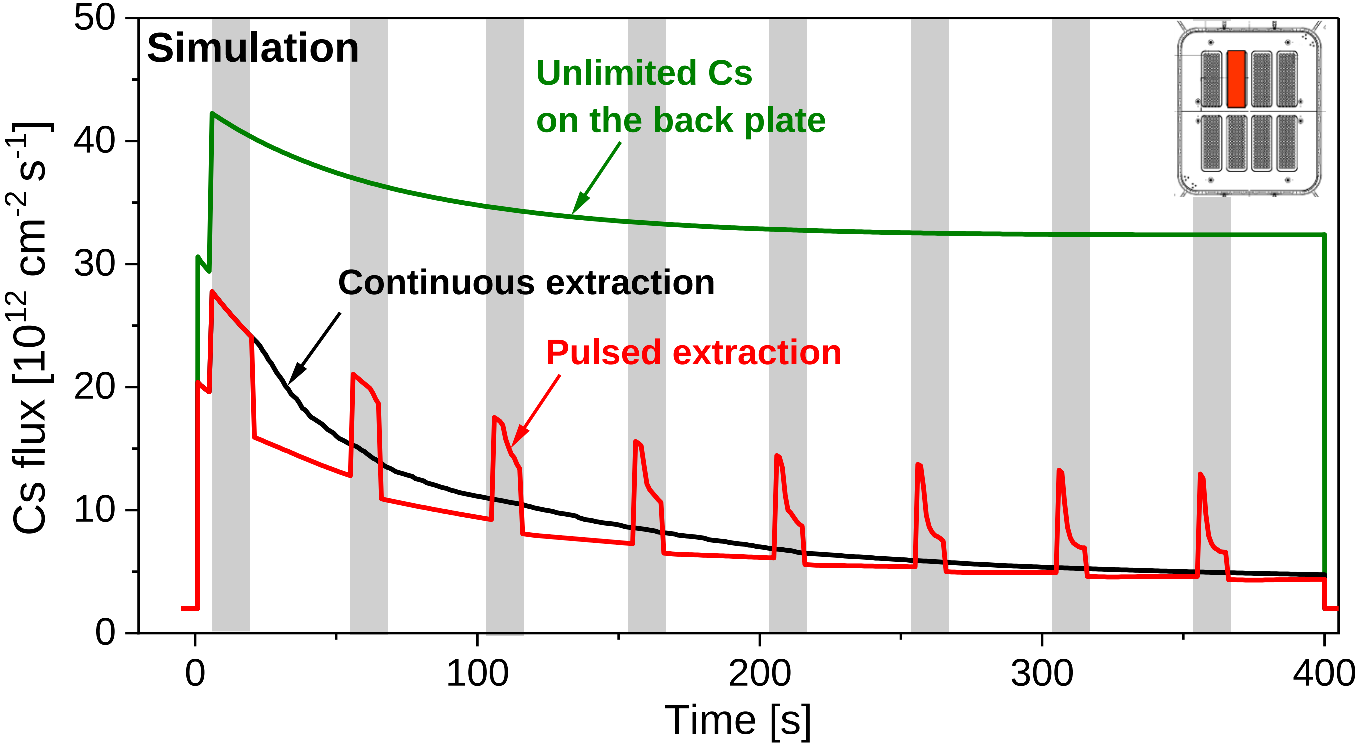
In general: co-extracted electrons

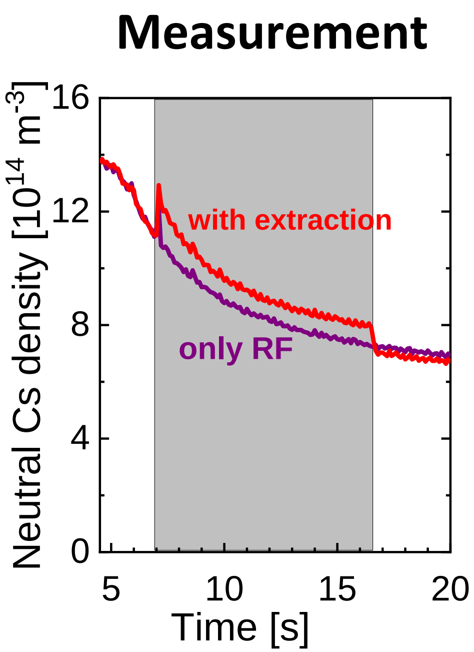
- are factor 2 – 4 higher in D
- **limit the source performance**
- require more Cs (~ factor 2)

One of the key elements – The Cs dynamics

Simulation of the average Cs flux

Three phases: vacuum, plasma, extraction





- **Back streaming** pos. ions sputter Cs and provide additional Cs
- **Continuous extraction** ⇨ still not sufficient to stabilize Cs flux
- **Unlimited Cs reservoirs** in the back-plate: higher and stable flux

Insights by CW extraction at SPIDER (soon at ELISE)

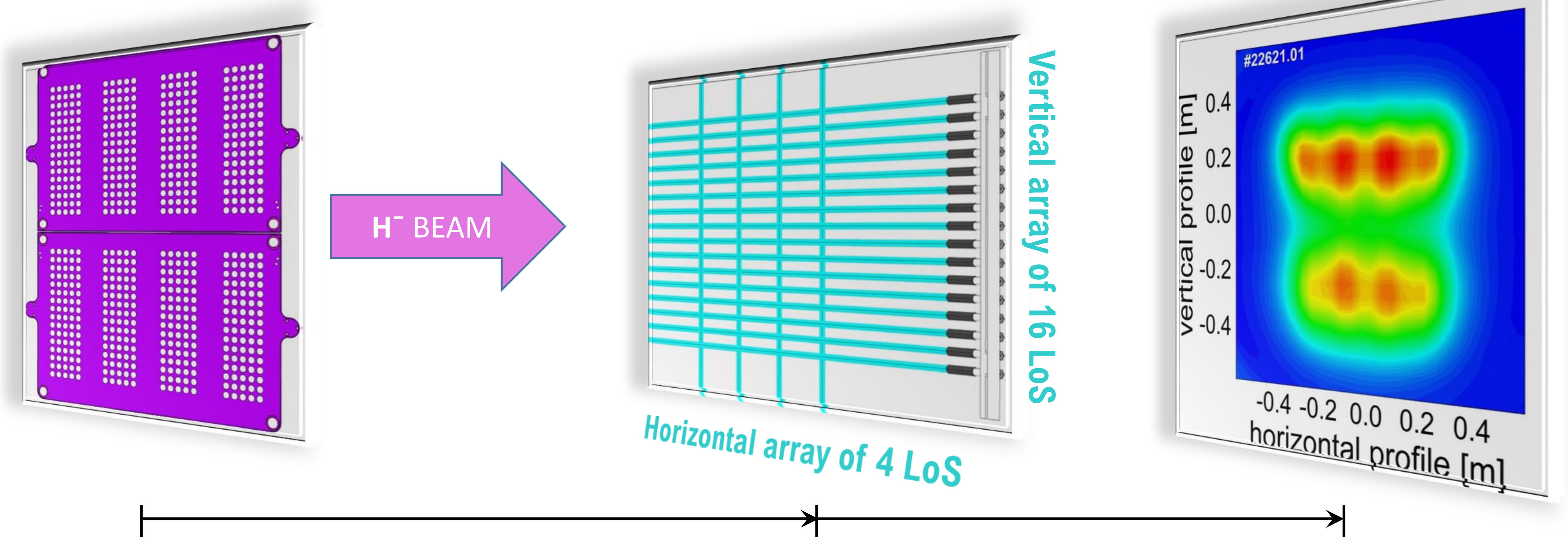
Beam characterisation

Diagnostics for beam divergence and homogeneity

Arrangements of apertures
640 apertures, 8 beamlet groups

Beam emission spectroscopy
20 lines of sight

IR calorimetry
2D fit on IR footprint

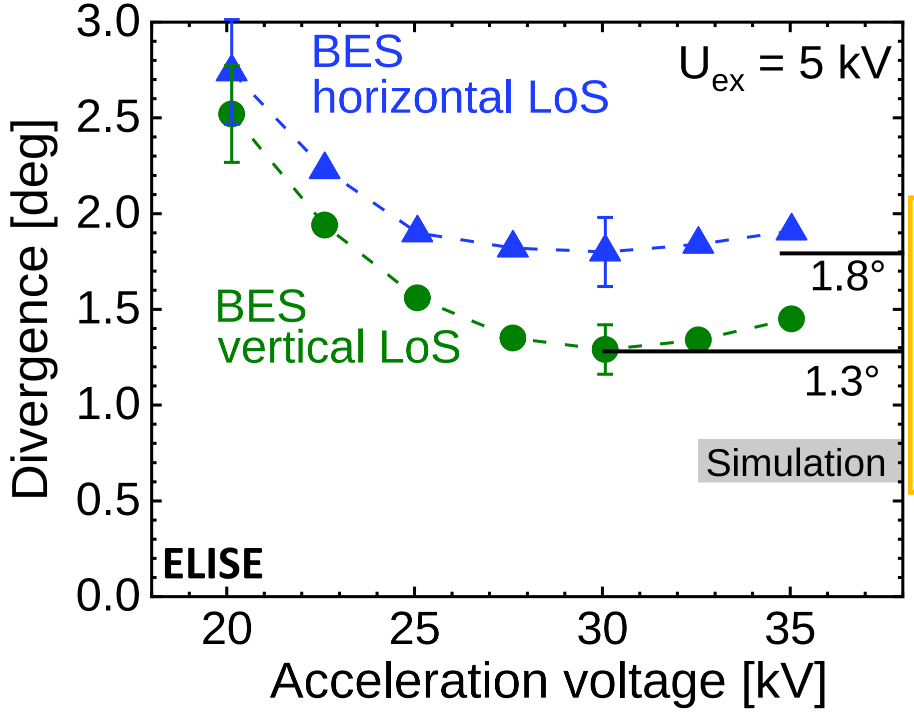


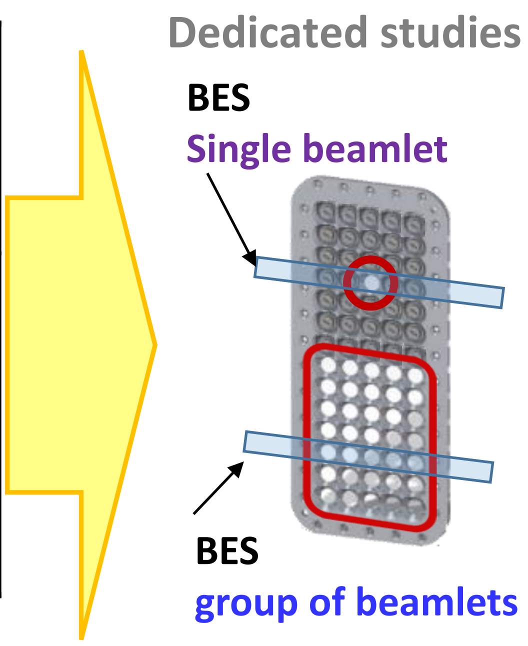
Grid system *2.7 m* *3.5 m*

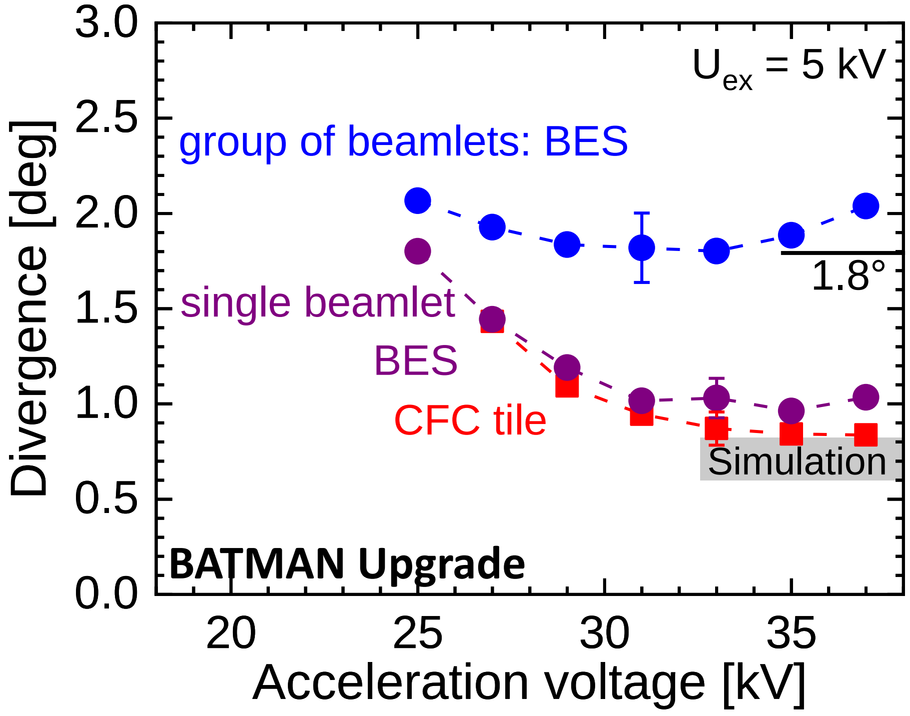
Beam characterisation: group of beamlets - single beamlet

ITER requires a divergence of < 7 mrad (0.4°) in the core of a single beamlet

ELISE grid system: simulation give a divergence of 0.6 -0.8° (3 grids with max. 60 kV acceleration)



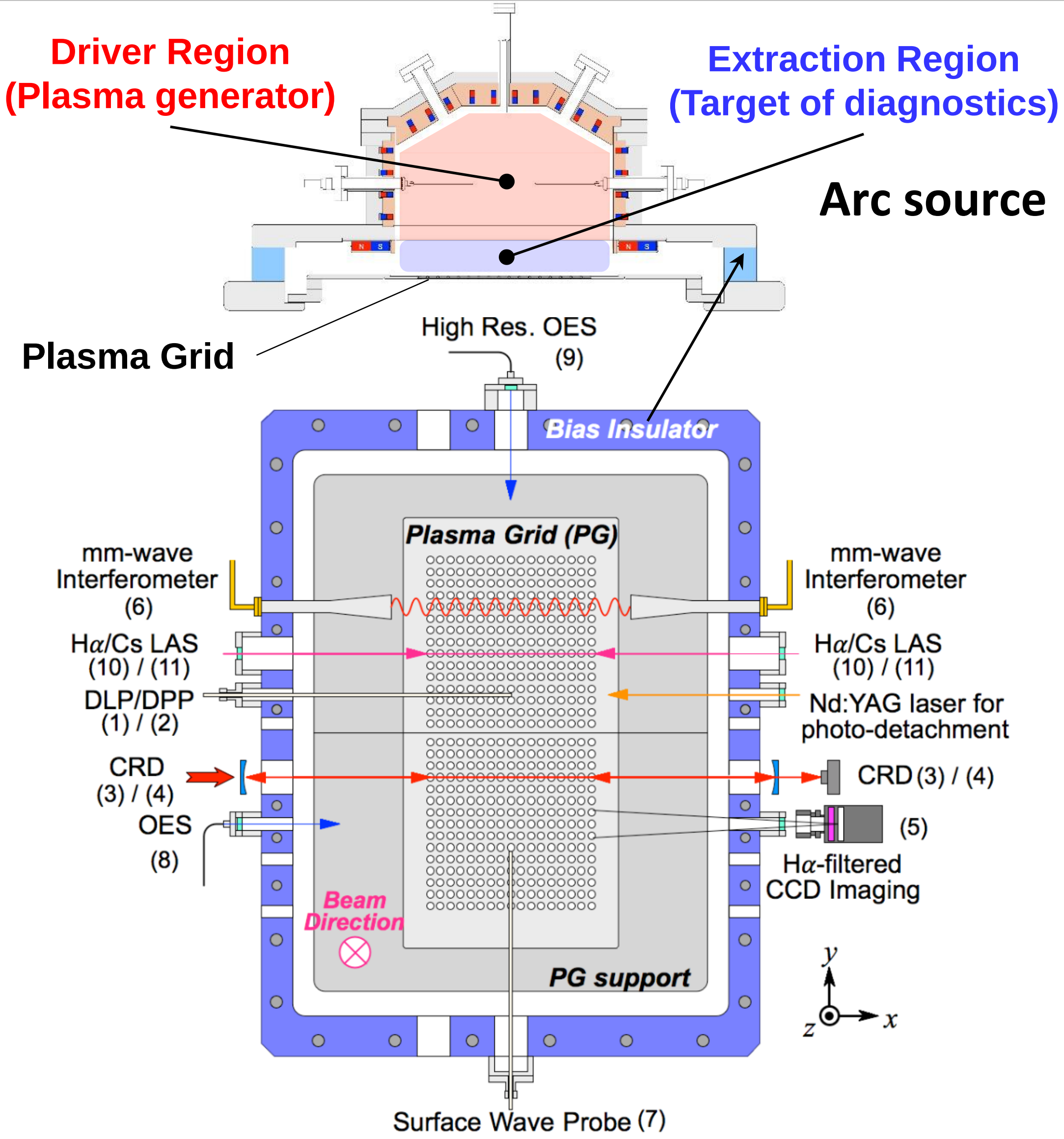




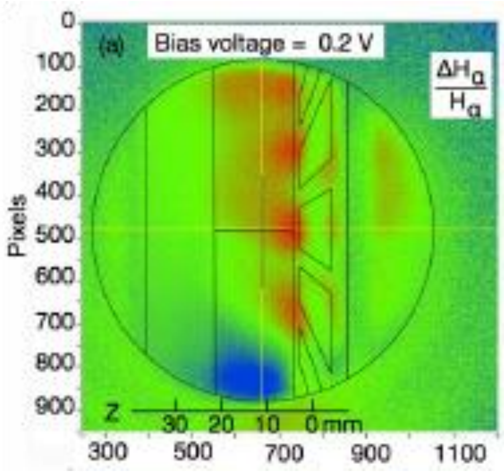
Horizontal LoS sees **zig-zag deflection** caused by deflection field (EG magnets)

Single beamlet lower than group of beamlets
Agreement with simulation

ITER R&D at dedicated test facility at NIFS, Japan

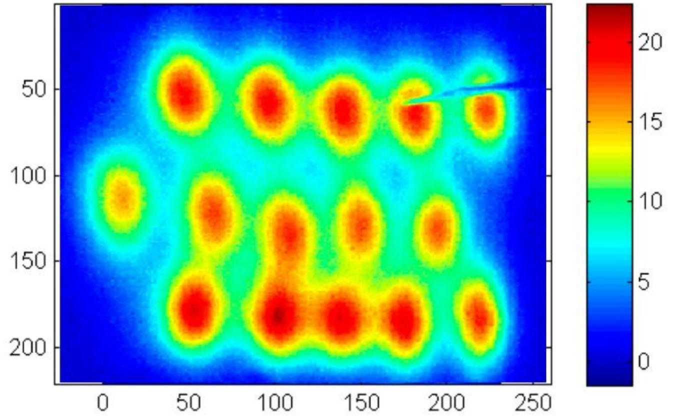


Versatile diagnostics of plasma and beam for fundamental understanding



H_α image of
H^- extracted distribution

5 x 3 beamlet pattern
on a CFC tile
monitored with infrared camera



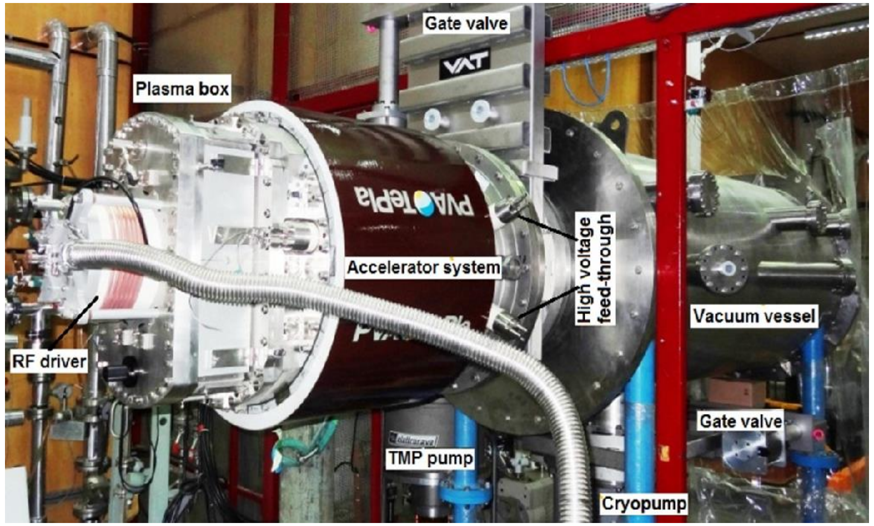
K. Ikeda *et. al.*, *New J. Phys.* **15** (2013) 103026
S. Geng *et. al.*, *Fusion Eng. Des.* **121** (2017) 481

ITER R&D at IPR, India

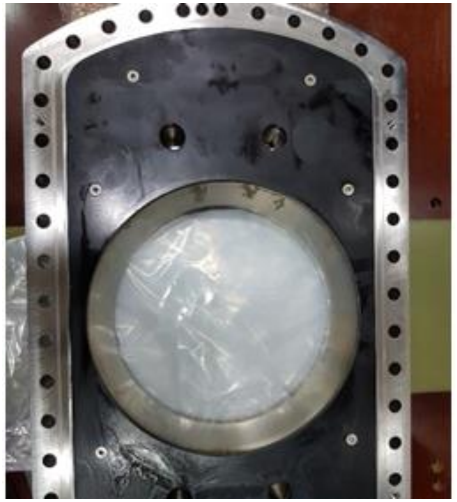
Roadmap : Beam (operational experience) and technology development in parallel

Learning curve on 3 test beds : ROBIN, TWIN, INTF

ROBIN TEST BED

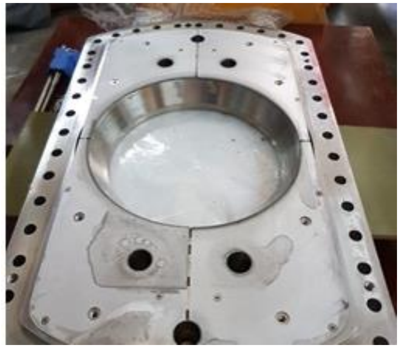


- 27 mA/cm^2 H^- beams @ 25 keV
- High Cs consumption (impurity control)
- e^-/H^- > 1
- Experiments restarted after cesiated source cleaning

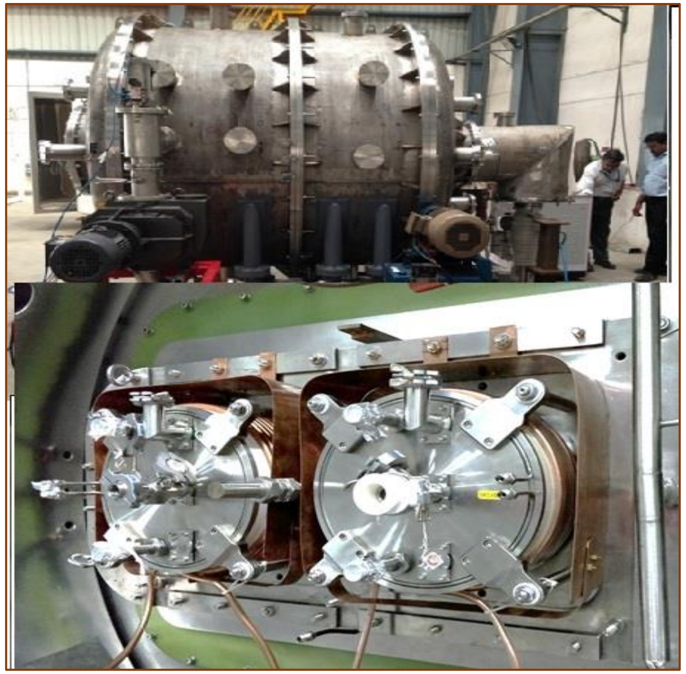


before and

after Cs cleaning

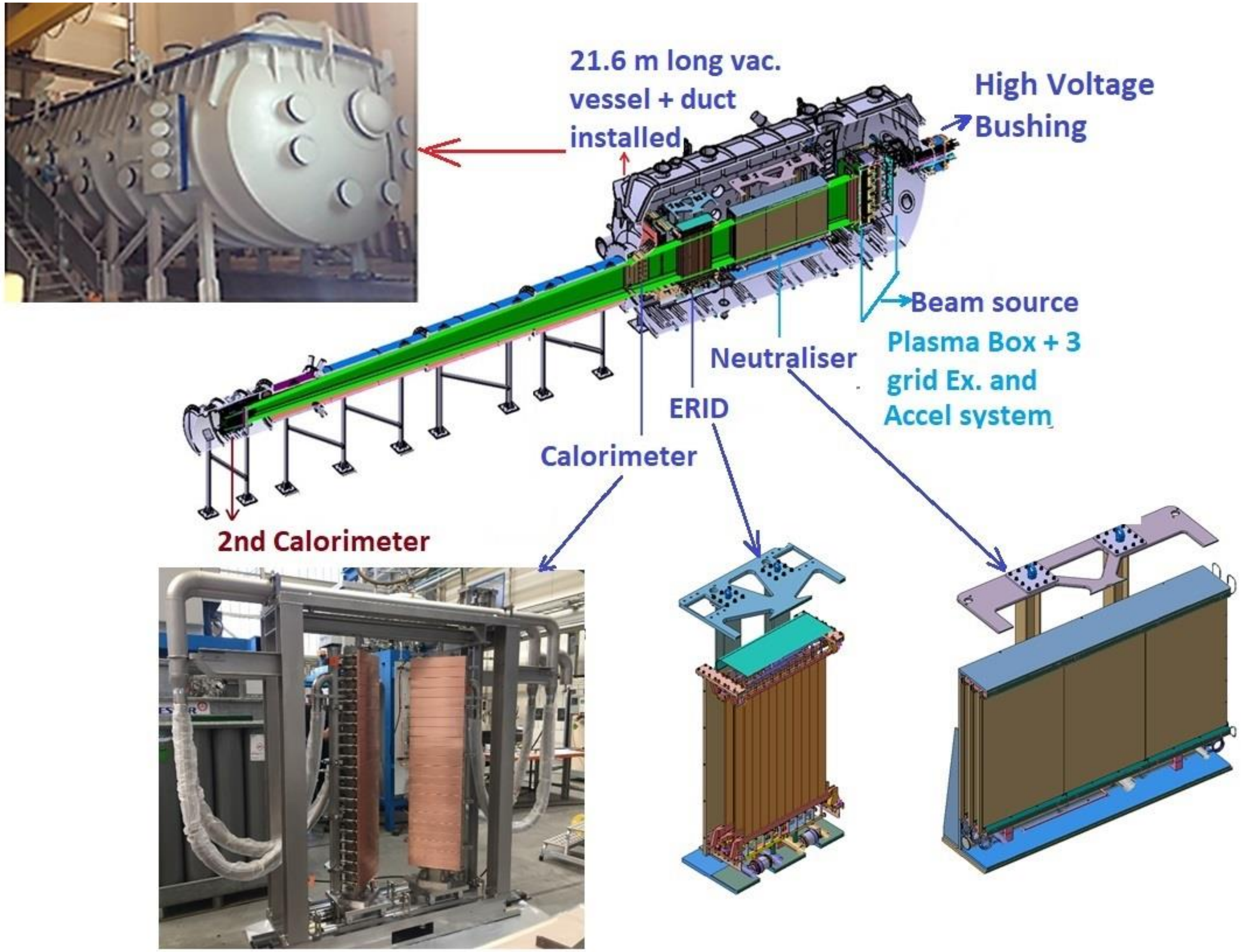


TWIN TEST BED



- Plasma production exp. initiated (50 kW two drivers)
- RF generator problems
- Accelerator system under proc.

ITER diagnostic beam developed at IPR, India



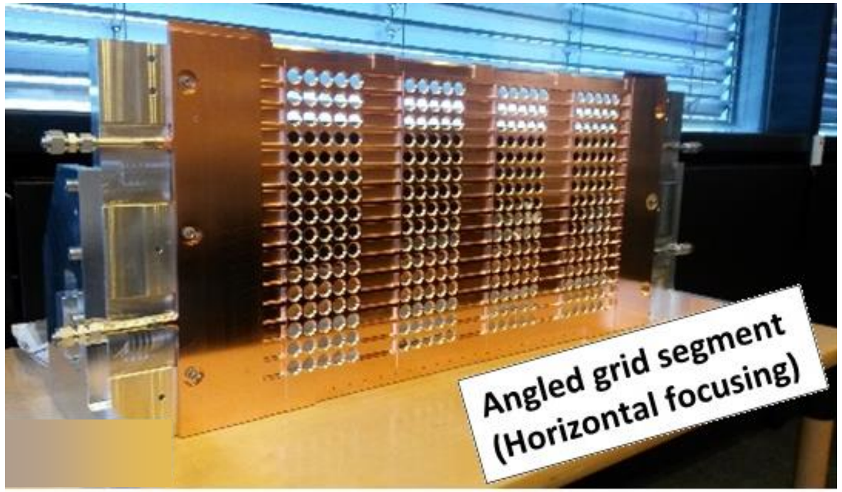
INTF @ ITER-India lab

Protoype DNB beam line

Unique 21.6 m path length to establish beam parameters and transport

- **Several technologies developed enroute**
- **Components (DNB) under fabrication**

Integration and commissioning : Q3 2021



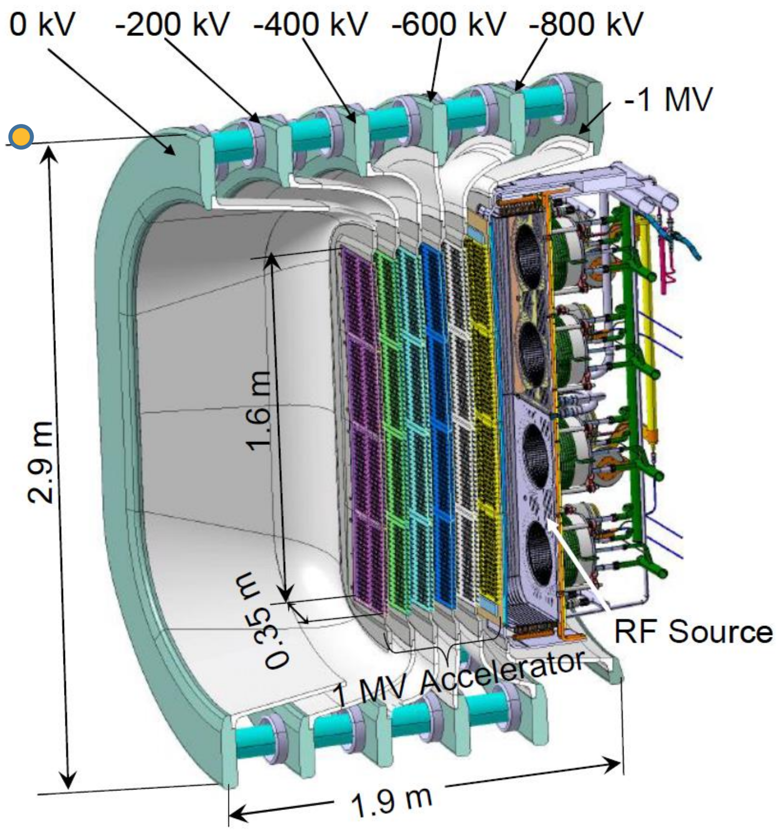
Ion sources for fusion – Take-Home message

- Strong activities for ITER to make it a success!
- International coordination, only feasible with high commitment of participating institutes to ITER.
- Cutting edge physics and technology.
- We are on a good path with many contributions with distributed responsibilities and know-how.
- ITER is prepared with the NBI R&D activities worldwide. In fact, NBTF is the first ITER facility in operation.
- **Still huge challenges in front of us**
  - Achievement of Deuterium target values
  - Co-extracted electrons limiting the source performance
  - Cs management for large sources
  - 1 MeV holding and beam acceleration with accurate optics
  - Reproducibility and reliability

Think Big !

Fact Sheet

40 A, 1 MeV D^- for 1 h
46 A, 0.87 MeV H^-
60 A, 100 keV H^- for DNB
800 kW RF (8 drivers), 0.3 Pa
7 Electrodes
15 beamlet groups
1280 beamlets



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