MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

RF-driven ion sources for fusion
Large and powerful ion sources for H^- and D^-

A Tutorial for the NIBS 2022

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CONSORZIO RFX Ricerca Formazione Innovazione

EUROfusion

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The fusion experiment ITER

☞ www.iter.org

$$D + T \rightarrow He + n + 17.6\ MeV$$

iter

china eu india japan korea russia usa

Demonstrate the scientific and technological feasibility of fusion power.

Including the test of tritium breeding and demonstration of the safety characteristics of a fusion device.

Produce 500 MW of fusion power for pulses of 400 s.

Q > 10, Q > 5 for 3600 s

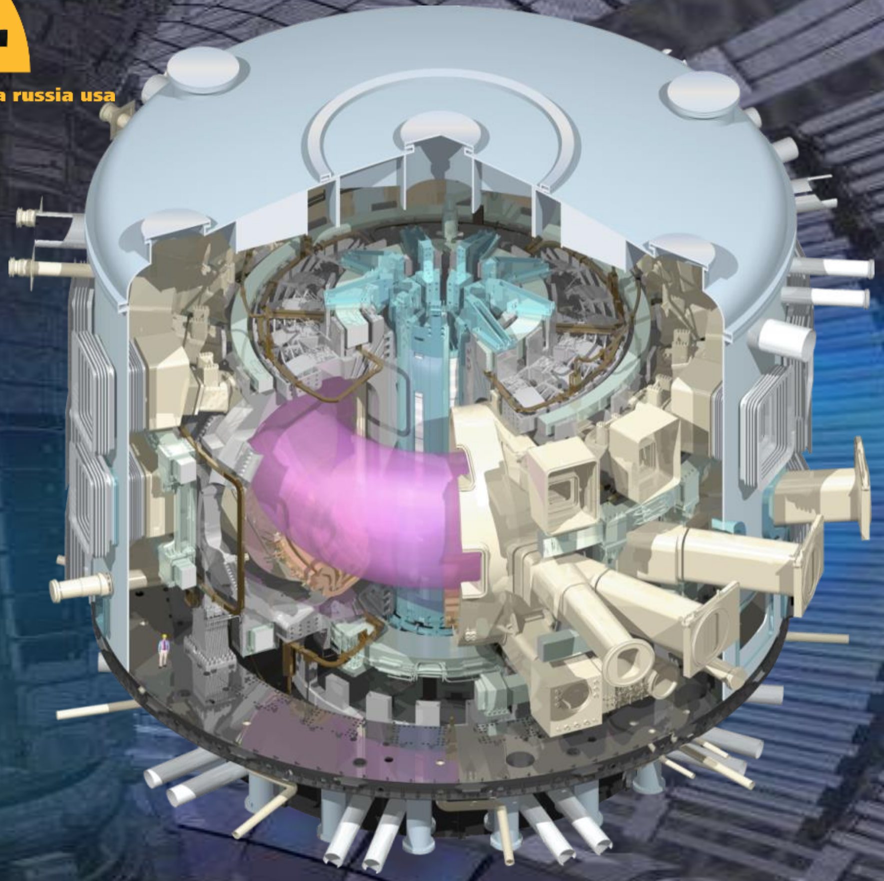
Input (heating power): 50 MW

Largest multinational scientific mission.

2006: ITER Agreement officially signed

2021: > 78% ready

2025: first plasma



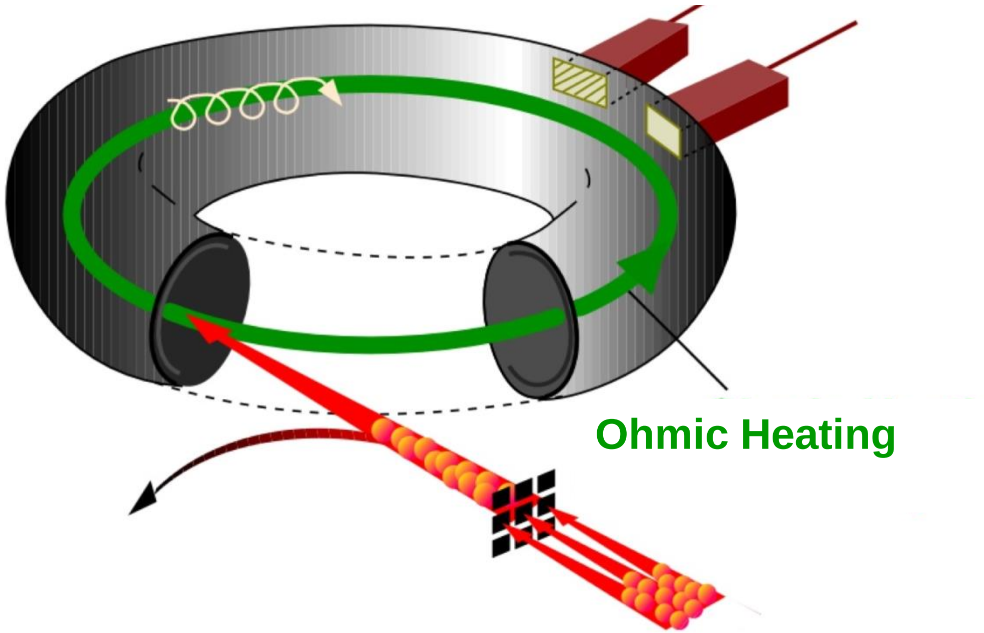
Size: 24 m diameter, 30 m height

Weight: 23 000 tons (3 x Eiffel tower)

The fusion experiment ITER
Heating systems – ECRH, ICRH and Neutral Beam systems

Installed power

ECRH: 20 MW Electron cyclotron resonance heating
ICRH: 20 MW Ion cyclotron resonance heating
Radio Frequency Heating

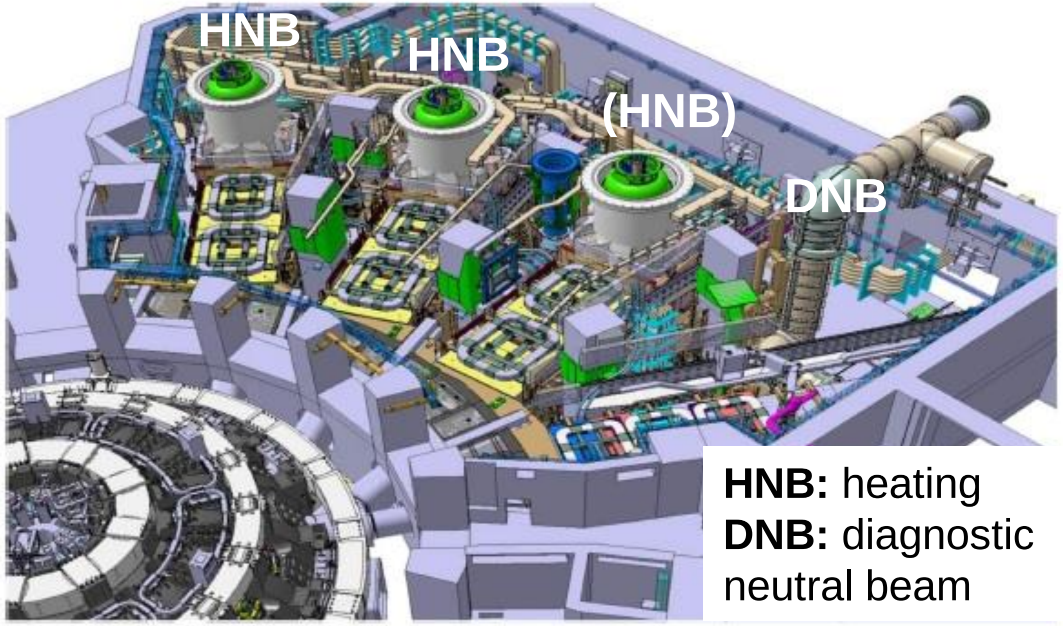


Ohmic Heating

NBI: 33 MW **Neutral Beam Injection**
Injection of energetic neutral atoms
⇨ major work horse

NBI functions

Heating | Current drive | Plasma rotation | Diagnostics



HNB: heating
DNB: diagnostic neutral beam

Hemsworth et al. 2017 *New J. Phys.* **19** 025005
Singh et al. 2017 New J. Phys. **19** *055004*

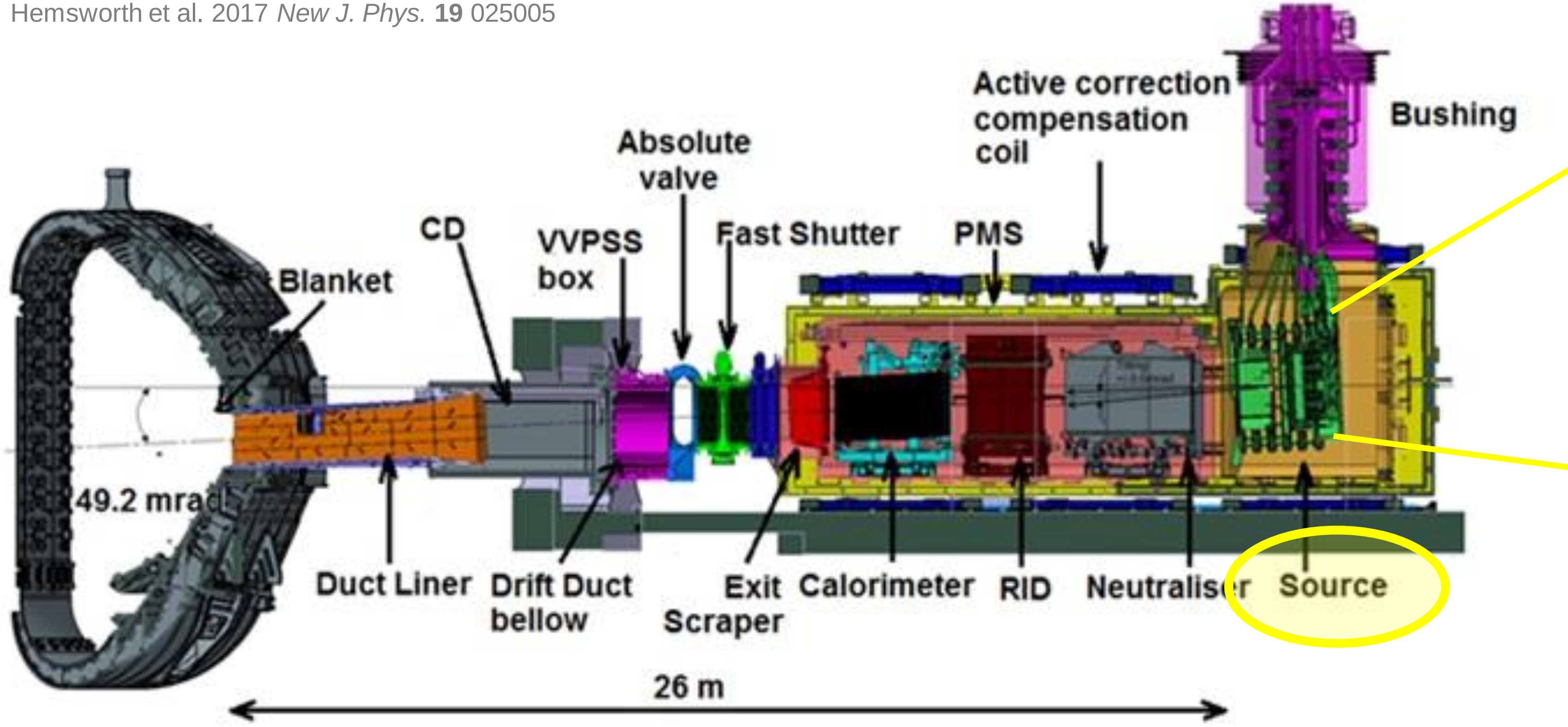
2 + 1 HNB beam lines
1 DNB beam line sharing port with HNB-1

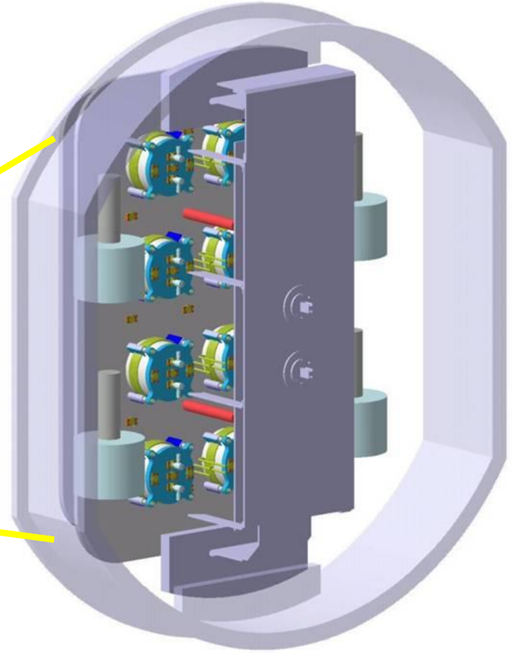
ITER NBI systems and their requirements

Heating beams **33 MW** (2 injectors) for 3600 s, **1 MeV Deuterium**, **870 keV Hydrogen**

Diagnostic beam **2.2 MW**, **100 keV Hydrogen**, 3s ON/20s OFF 5Hz

Hemsworth et al. 2017 *New J. Phys.* **19** 025005





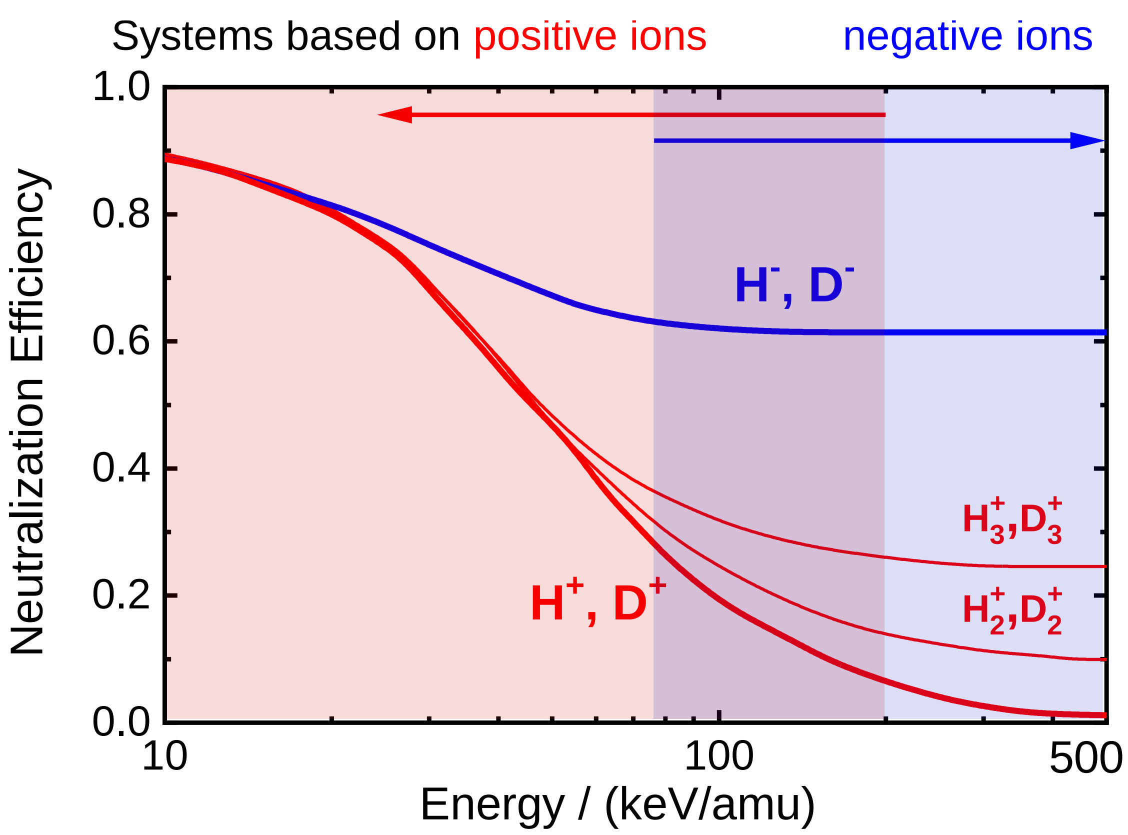
Source area: 1 m × 2 m

RF-driven ion source

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

Negative hydrogen ions for ITERs NBI systems
Neutralisation efficiency

Neutralisation efficiency at a beam energy of 1 MeV D



ITER
500 kV / amu

Neg. ions ~ 60 %
but j ≈ 200 A/m²

increase of source size

Pos. ions < 10 %
with j ≈ 2000 A/m²

Negative ion based systems make high energy range accessible

JT-60U / JT-60SA, LHD

U_{acc}>≈ 150 kV

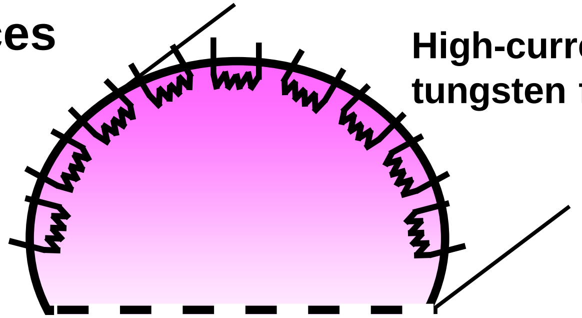
Positive ion based systems are routinely operating world wide

JET, AUG, DIII-D, JT-60U, …

U_{acc}<≈ 100 kV

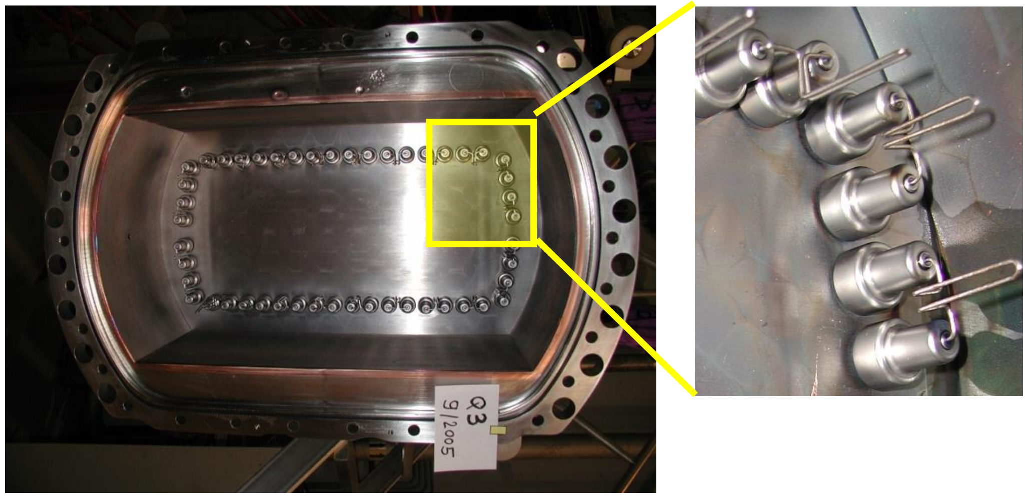
Concept of ion sources
Arc sources and RF-driven sources

Arc sources

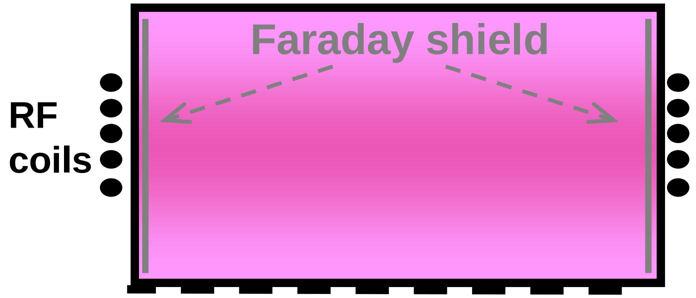


- Hot cathodes (2000 – 3000 K)
- DC voltage (≈ 100 V), Arc current (1000 A)

Filaments require regular maintenance

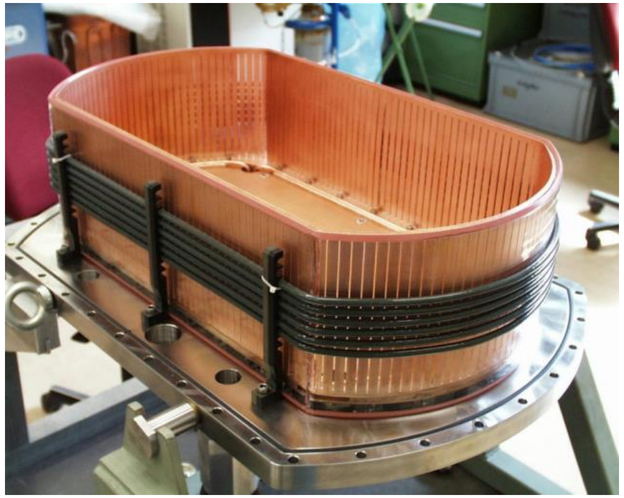


RF sources

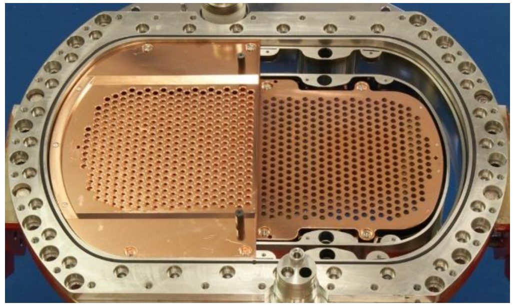


- Inductively driven source
- RF power supply (≈ 100 kW), RF frequency 1 MHz

Long lifetime → chosen by ITER in 2006

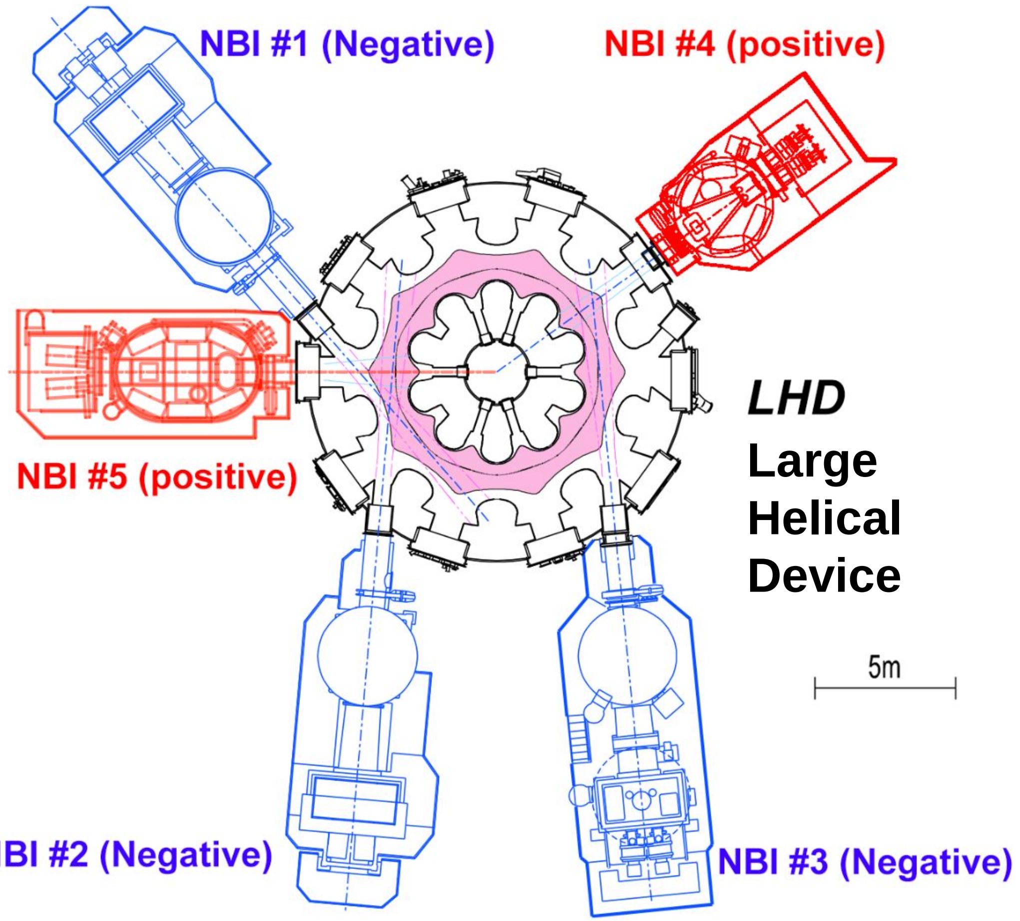


In routine operation for positive ions at AUG since more than 20 years



NBI systems at LHD at NIFS, Japan

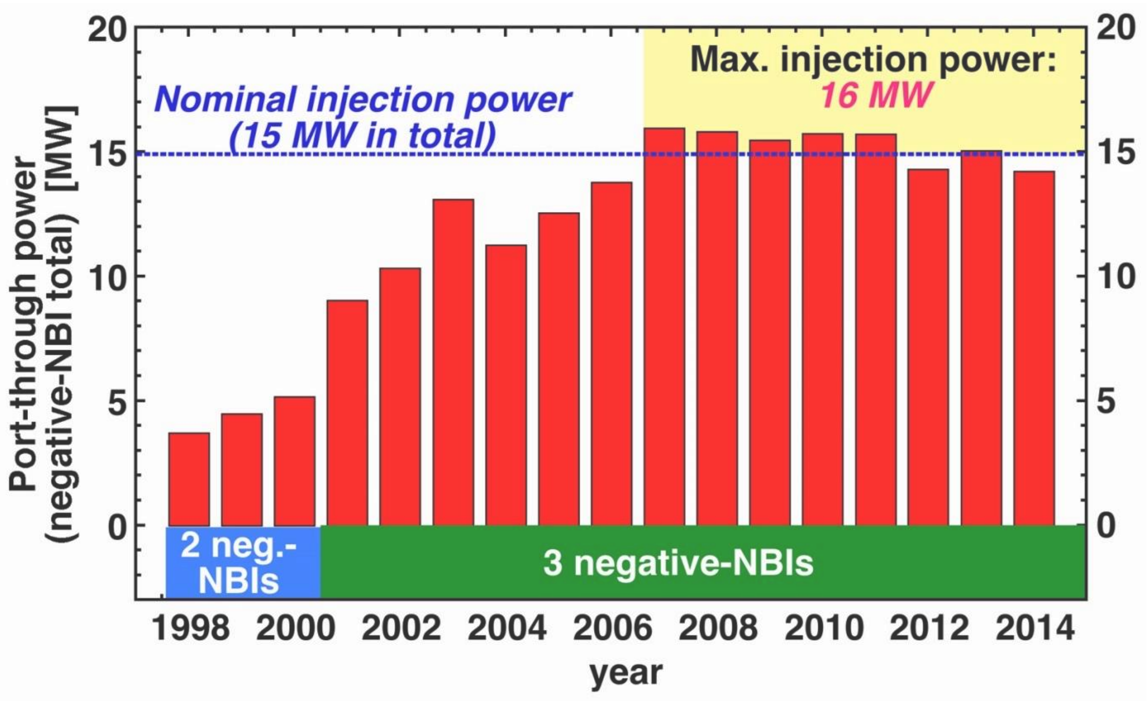
Arc sources, operation mostly in hydrogen



LHD

Large Helical Device

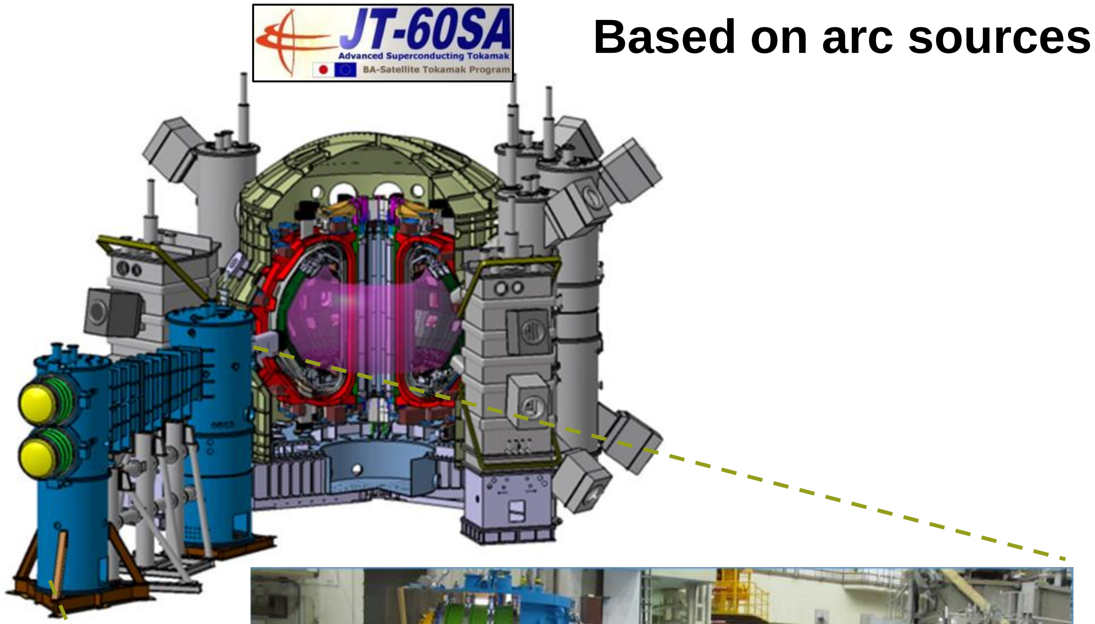
	negative	positive
Beam energy [keV]	190	80 & 90
Injection power [MW]	5.5 - 6.9	9
Pulse length [sec]	10 (max)	10 (max)
Beam divergence [mrad]	5	11

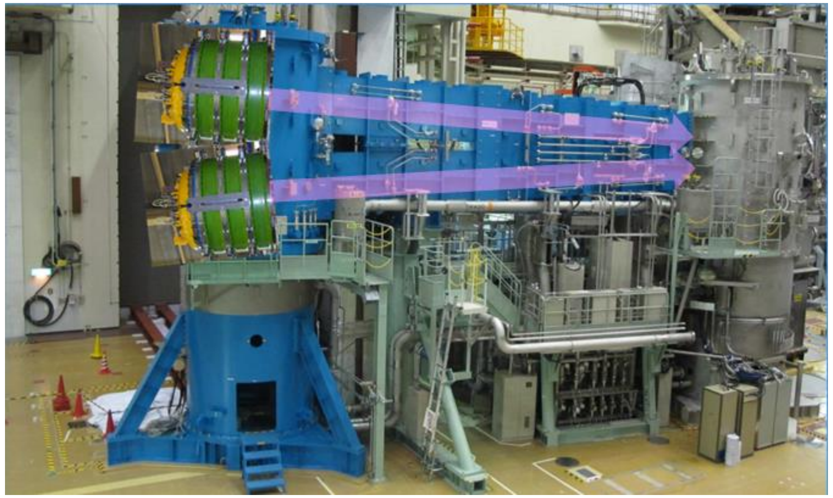


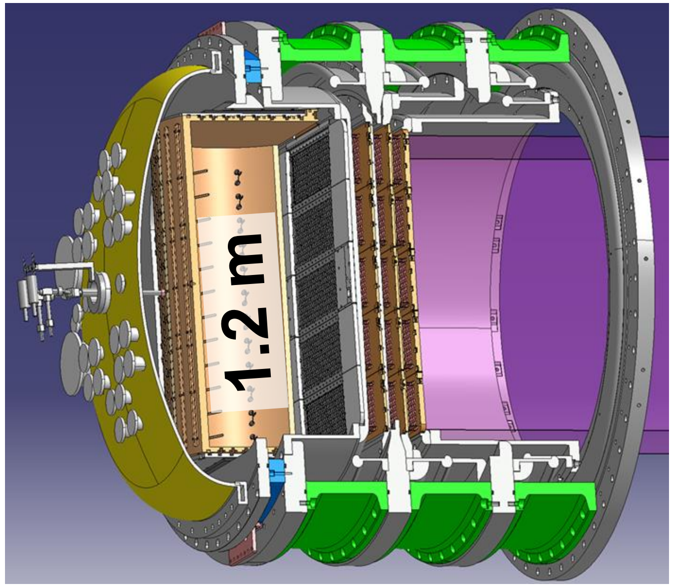
NNBI systems at JT-60U / JT-60SA at QST, Japan

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

Based on arc sources







Achievement of beam acceleration
500 keV, 156 A/m^2, 118 s
by using 1/8 scale ion source

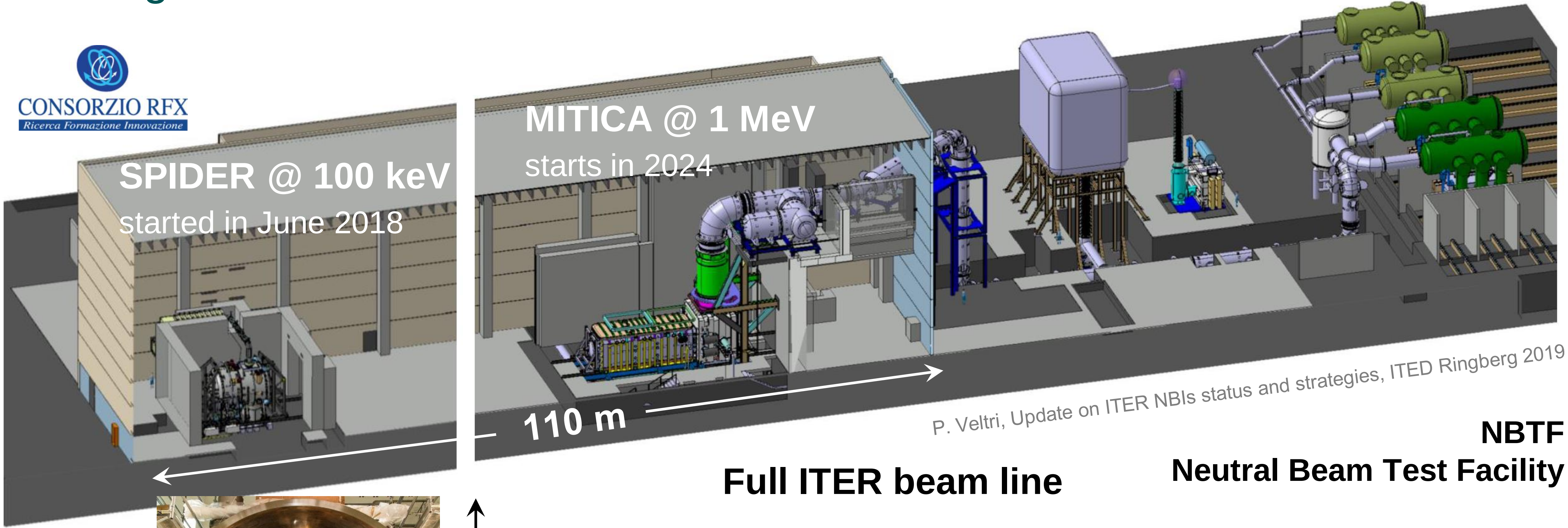
Achievement of H⁻ ion production
15 A for 100 s
→ under progress

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

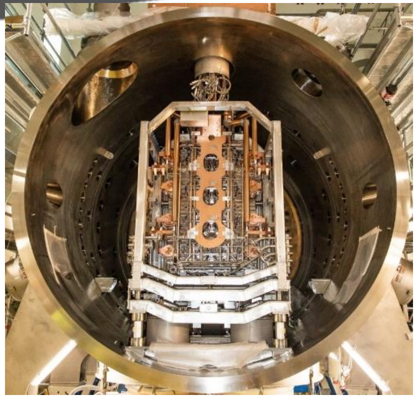
The test facility for ITER NBI at Consorzio RFX, Italy

Hosting SPIDER and MITICA

CONSORZIO RFX
Ricerca Formazione Innovazione



P. Veltri, Update on ITER NBIs status and strategies, ITED Ringberg 2019



4 m

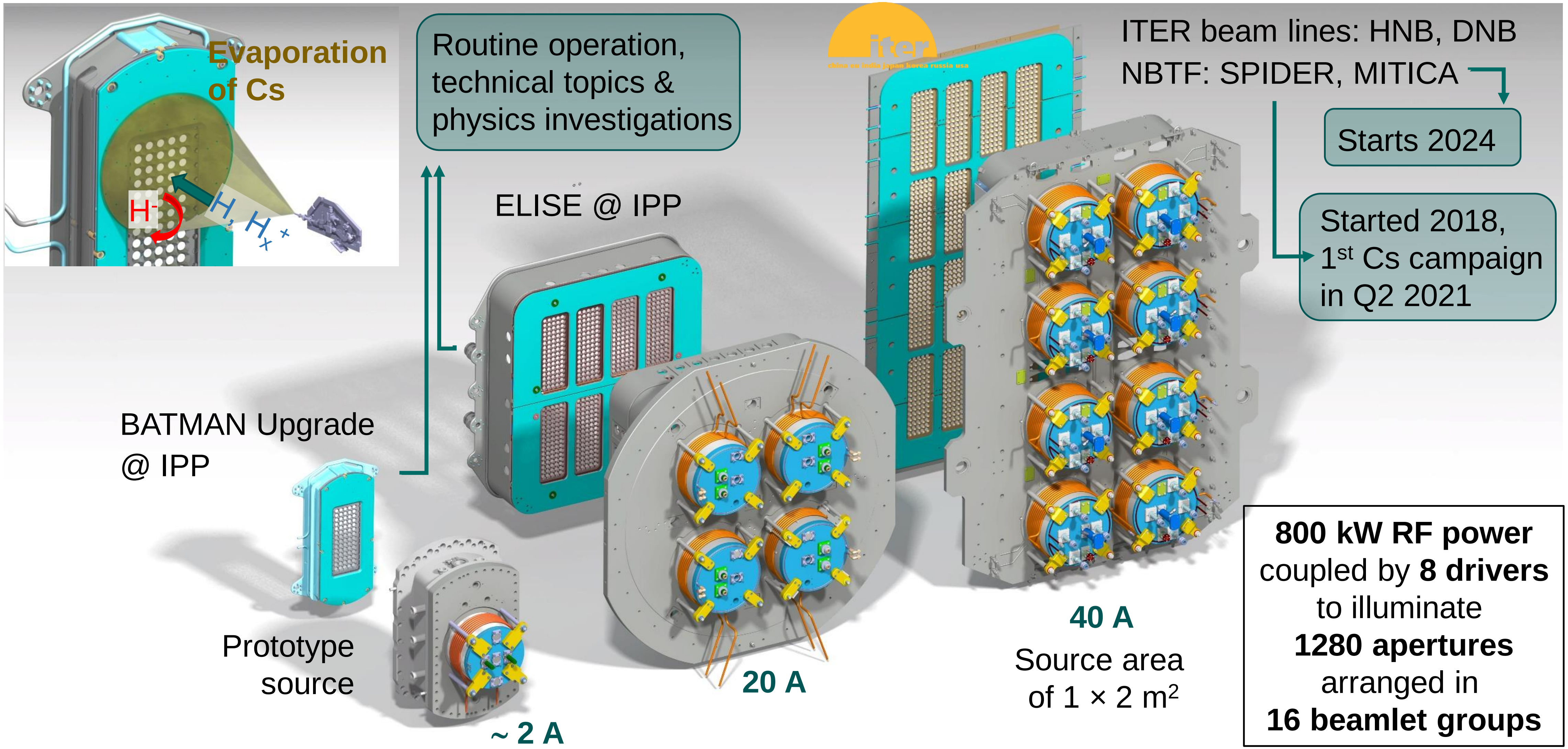
Chitarin et al., AIP Conf. Proc. 2052 (2018) 030001

Critical challenges:

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

Negative ion sources (H^-, D^-) for ITER

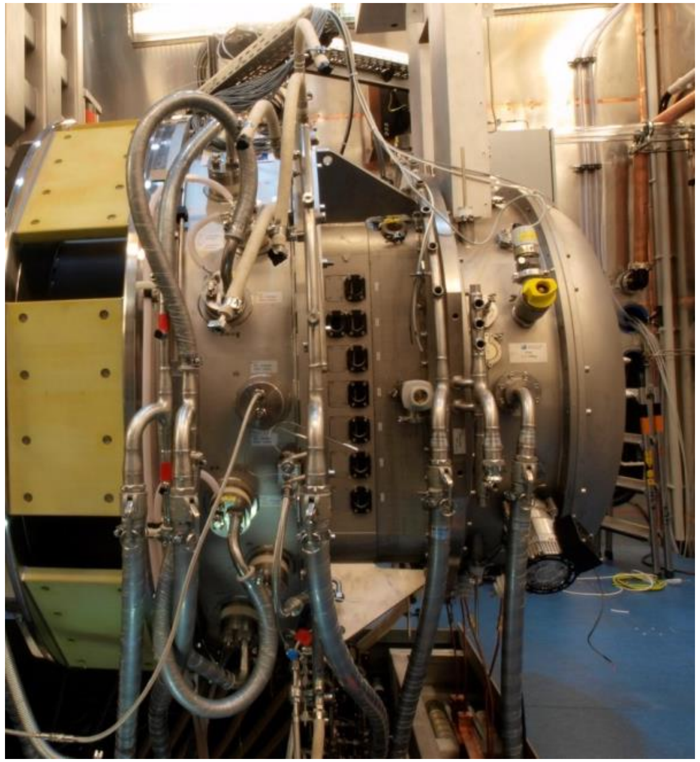
The size scaling route



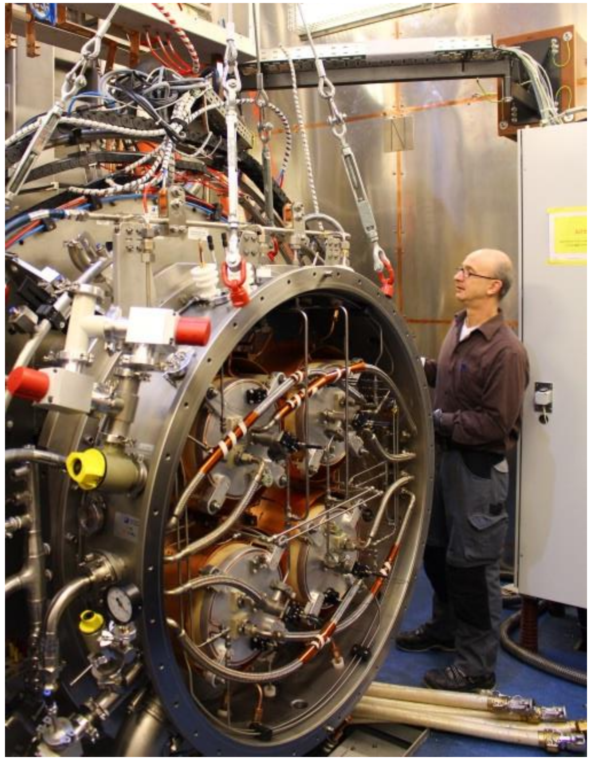
800 kW RF power coupled by **8 drivers** to illuminate **1280 apertures** arranged in **16 beamlet groups**

A half size ITER source
ELISE (Extraction from a Large Ion Source Experiment)

Construction and assembly in house (3 years)



Ion source with dome

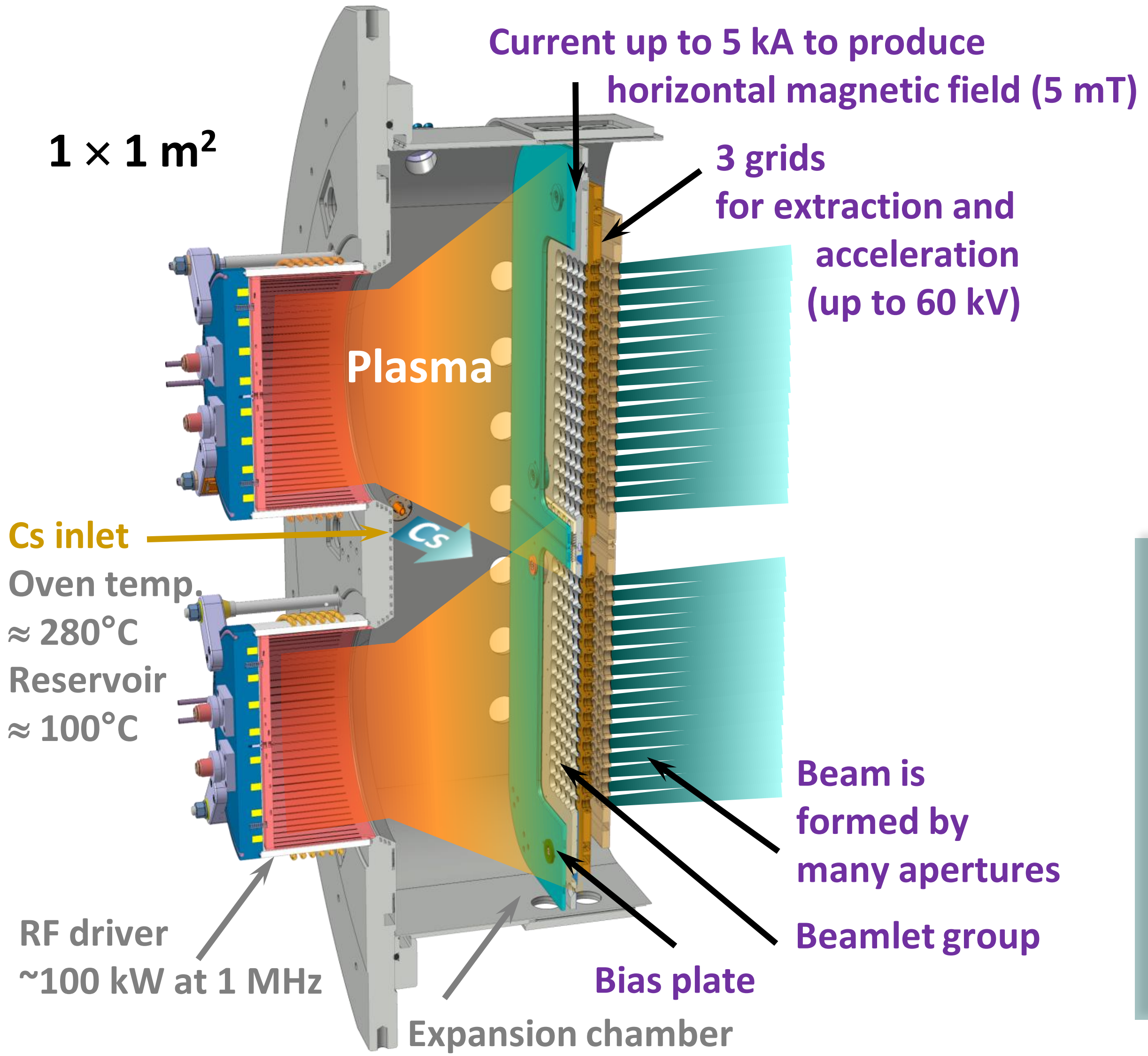


RF drivers in the dome

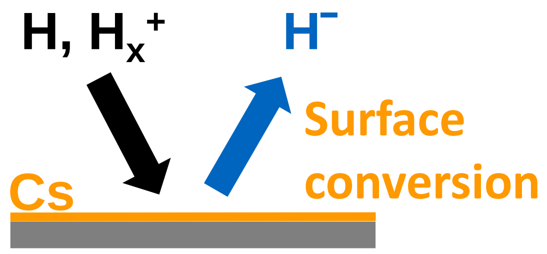
Open source with grid system

First plasma and beam: Feb. / Mar. 2013

The concept of the RF driven negative ion source



Negative ions via surface conversion



effective at low work function

ITER requirements for D (H)

- Extracted ion current density j_{ex} **= 286 (329) A/m²** at $p_{fill} \leq 0.3$ Pa, Accelerated current **I = 40 A (46 A, 60 A DNB)**
- Co-extracted electrons: $\mathbf{j_e/j_{ex} \leq 1}$
- Beam homogeneity > 90 %, divergence < 0.4°

stable for 1 h (1000 s)

Formation of negative hydrogen ions
at low pressure (0.3 Pa)

Volume process dissociative attachment

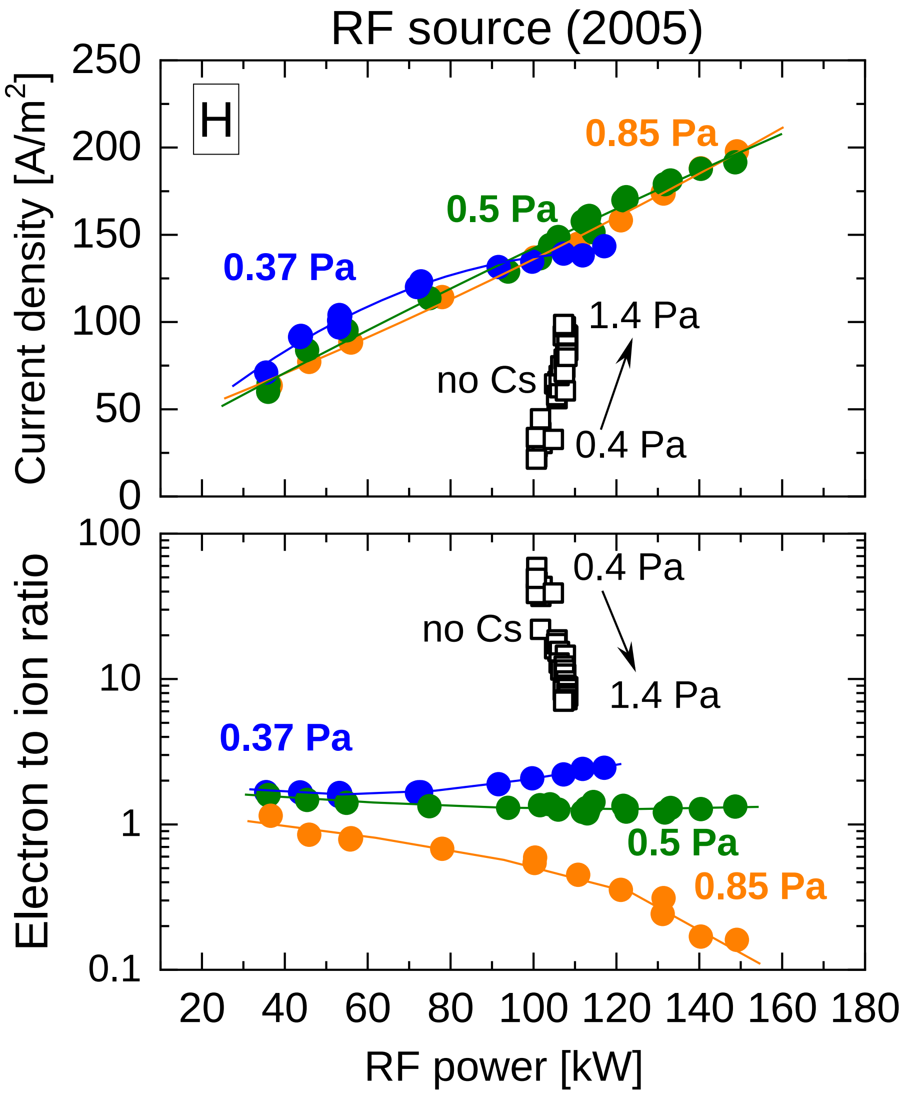
$e^- + H_2(v) \rightarrow H^- + H$ j_{H^-} ≈ **20 A/m²**
j_e/j_{H^-} **> 30**

Surface process

H, H_x^+ + surface $e^- \rightarrow H^-$ **Cs evaporation**
Cs layer **much higher j_{H^-}**
low work function **much lower j_e/j_{H^-}**

Destruction: volume processes

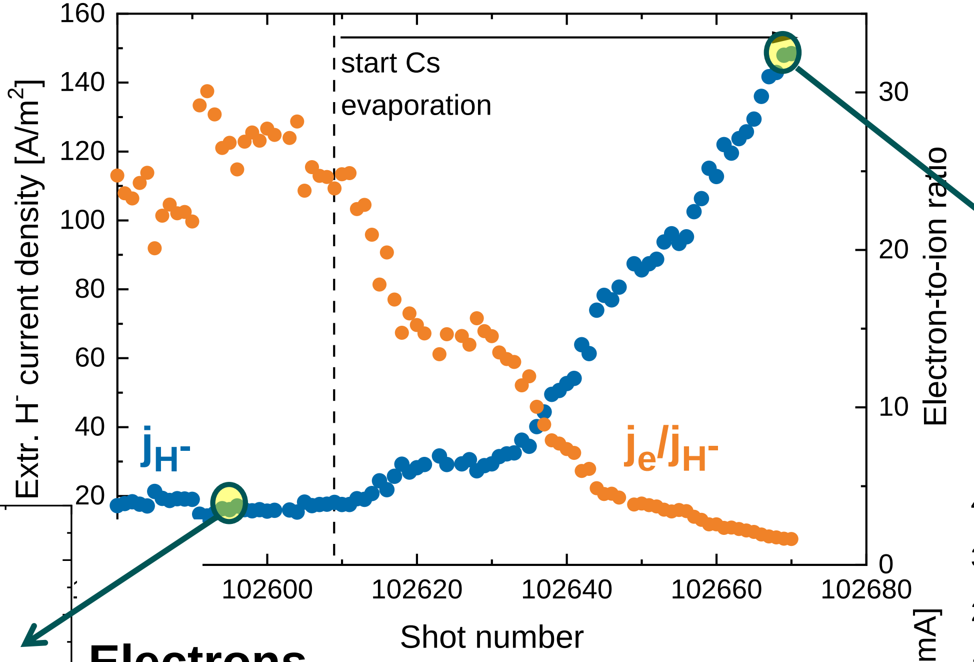
$H^- + e^- \rightarrow H + 2e^-$	Electron stripping
$H^- + H^+ \rightarrow H + H$	Mutual neutralisation
$H^- + H \rightarrow H_2 + e^-$	Associative detachment
$\rightarrow H + H + e^-$	(non-associative)



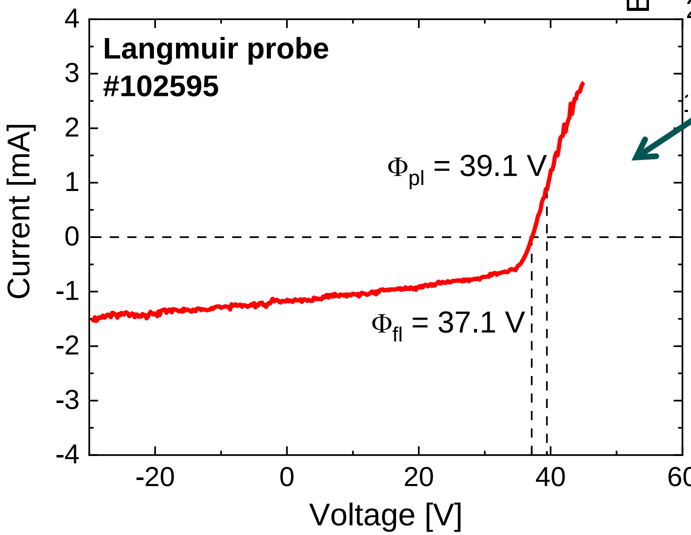
Speth et al. 2006 *Nucl. Fusion* **46** S220

Transition to an ion-ion plasma during the Cs conditioning

Langmuir probe measurements

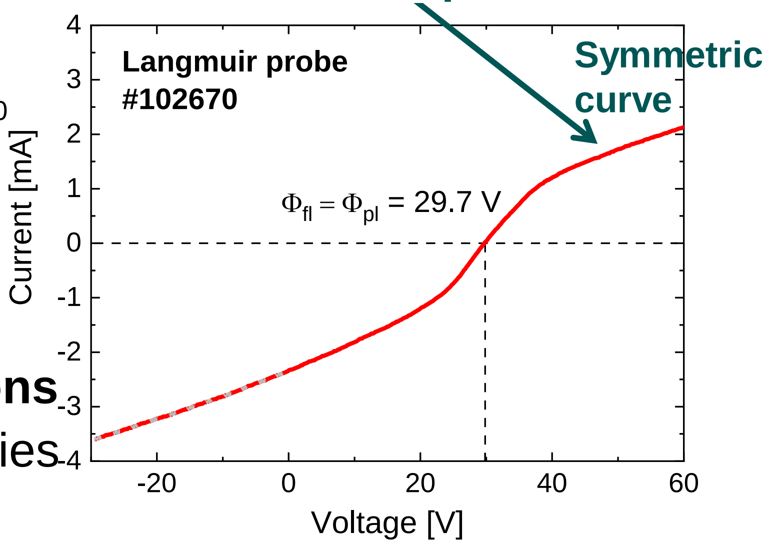


Volume process



Electrons
as dominant negative species

Surface process

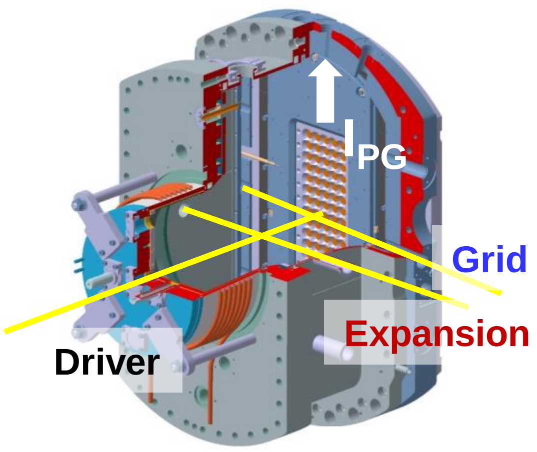


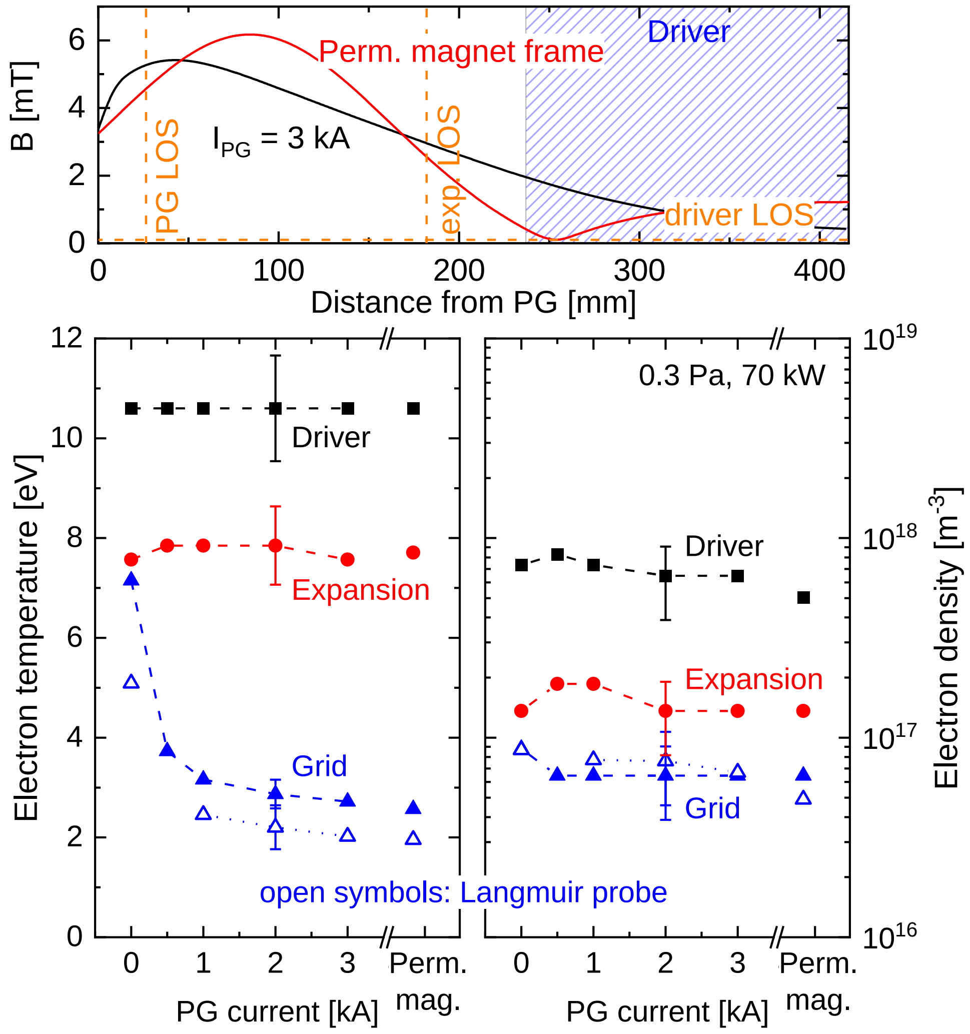
Negative hydrogen ions
as dominant neg. species

Heinemann et al. 2017 *New J. Phys.* **19** 015001

Plasma parameters by OES, Langmuir probes, …

Ionising and recombing plasma regions & ion-ion plasma





	OES Method	Results
T_{gas}	H_2 Fulcher	630 K
T_{vib}	H_2 Fulcher	3000 K
T_H	H_{γ} 2^{nd} order	2200 K & 2.5 eV
n_H / n_{H_2}	$H_{\gamma} / H_{2,\,Fulcher}$	0.3 ± 0.1

	Method	Results
$n(H^-)$	CRDS	10^{17} m^{-3}
n(Cs)	TDLAS	10^{15} m^{-3}
$n(Cs^+)$ / n(Cs)	Simu.	~70%
n(Cs) vacuum	TDLAS	5×10^{14} m^{-3}

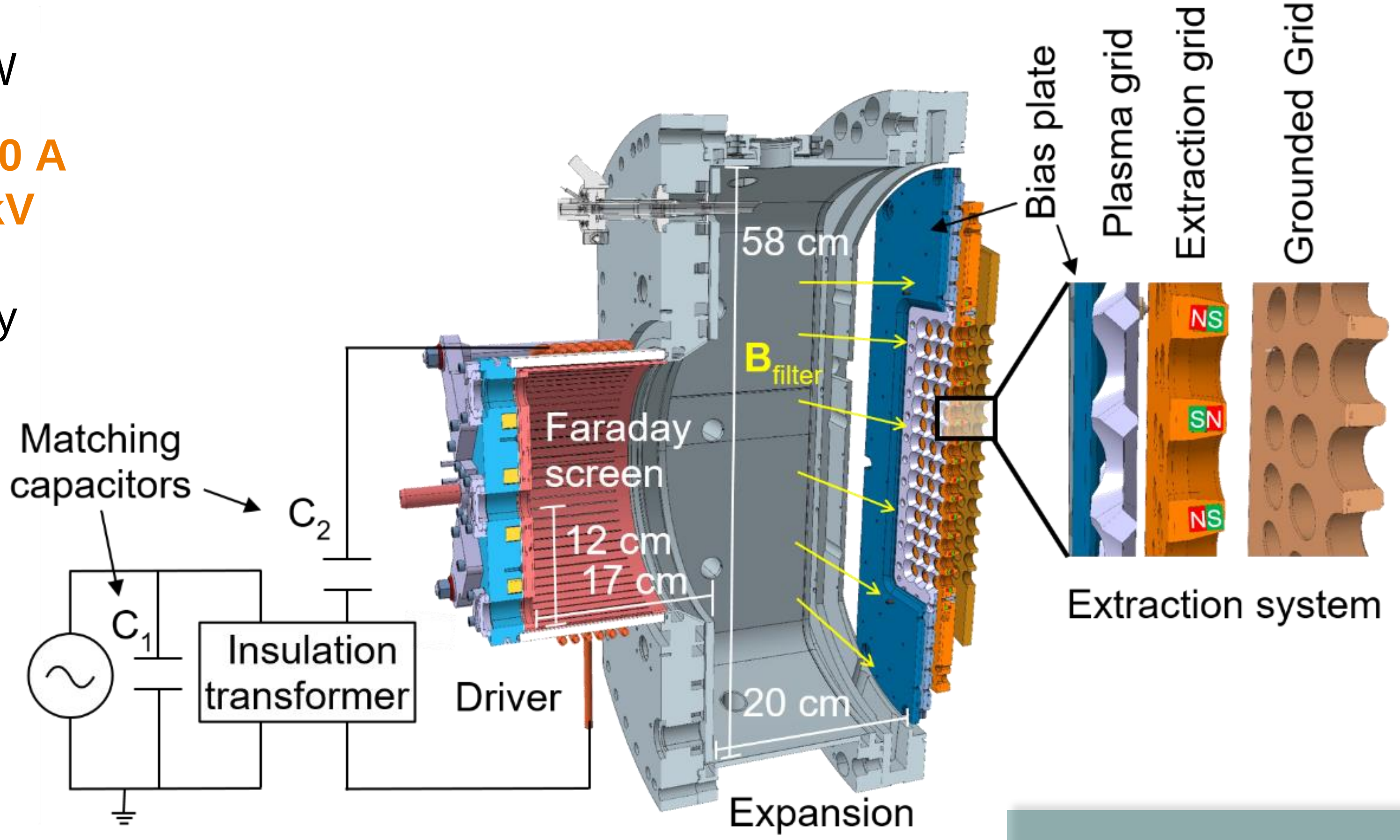
Briefi et al. 2018 *AIP Conf. Proc.* **2052**, 040005

RF power coupling in high power ICPs at low frequency

f = 1 MHz, $P_{RF} \leq 100$ kW

High coil current I ~100 A and high voltage U ~ kV

→ **arcing** at coil can limit source reliability



Power losses due to

→ ohmic resistance of conductors

→ **eddy currents** in metallic components

Driver plasma:

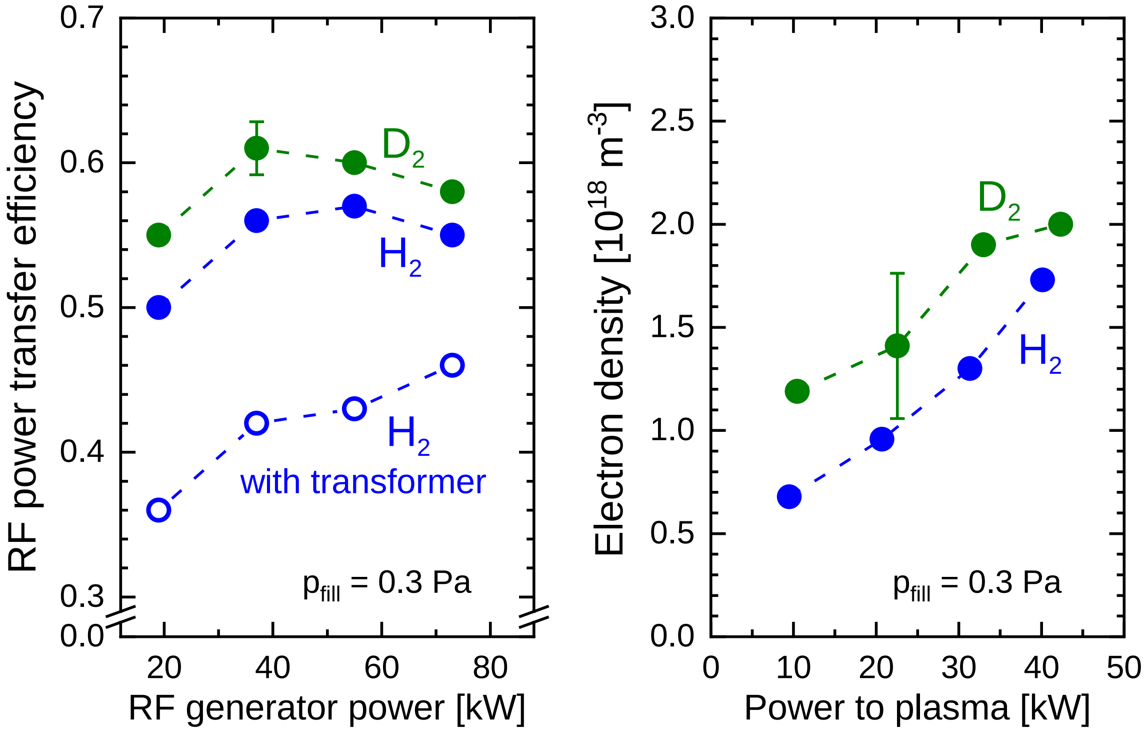
Relevance of RF Lorenz force and neutral depletion

RF power transfer efficiency

$$\eta = \frac{P_{plasma}}{P_{RF}} = \frac{R_{plasma}}{R_{network}+R_{plasma}}$$

Measurements at prototype source

Zielke et al. 2021 J. Phys. D. ***54*** *155202*

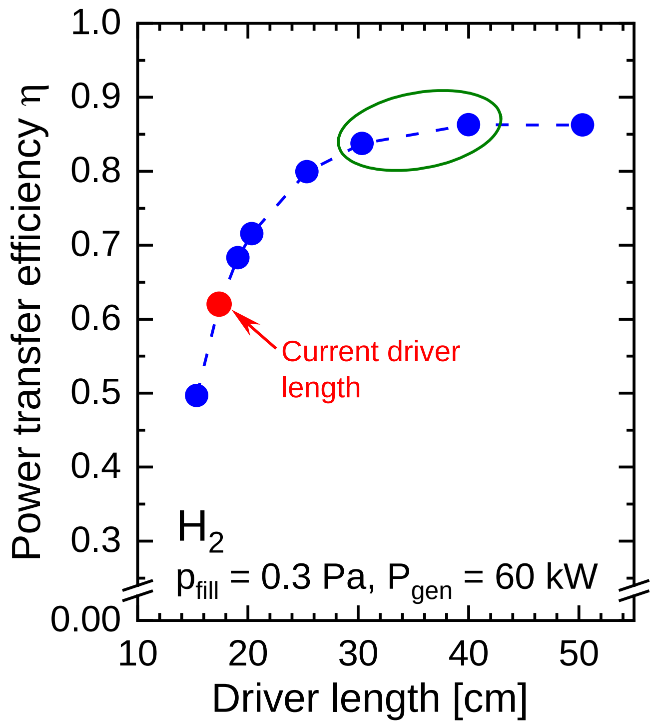


- ➢ Better coupling for D_2
- ➢ Efficiencies below 65%

Modelling using a 2D fluid code

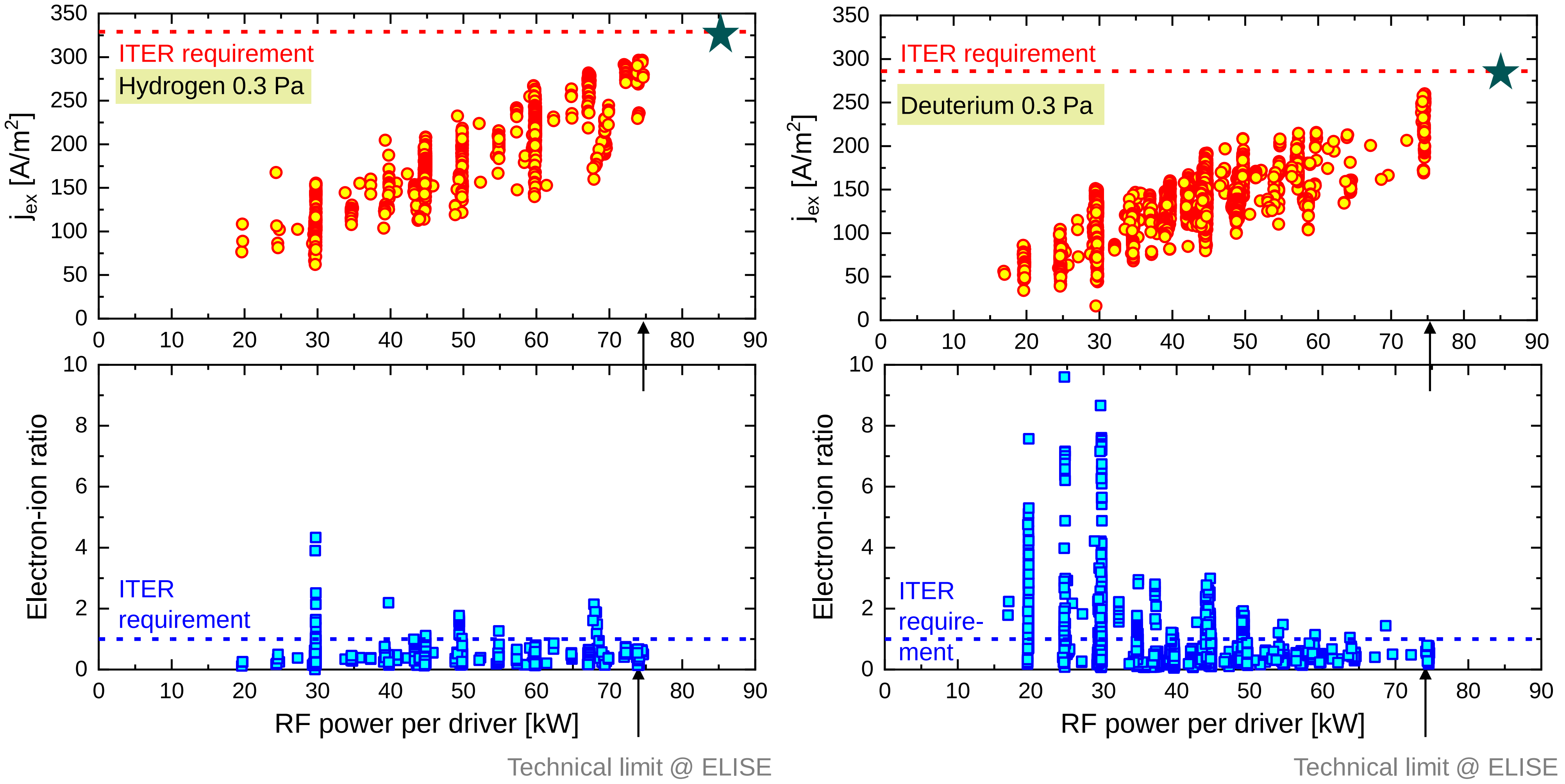
- Self consistent calculation of coil current and plasma resistance
- RF Lorenz force, electron viscosity, neutral depletion
- Benchmarked at BUG
- Optimization: driver length & RF frequency

D. Zielke, PhD thesis 2021, University Augsburg



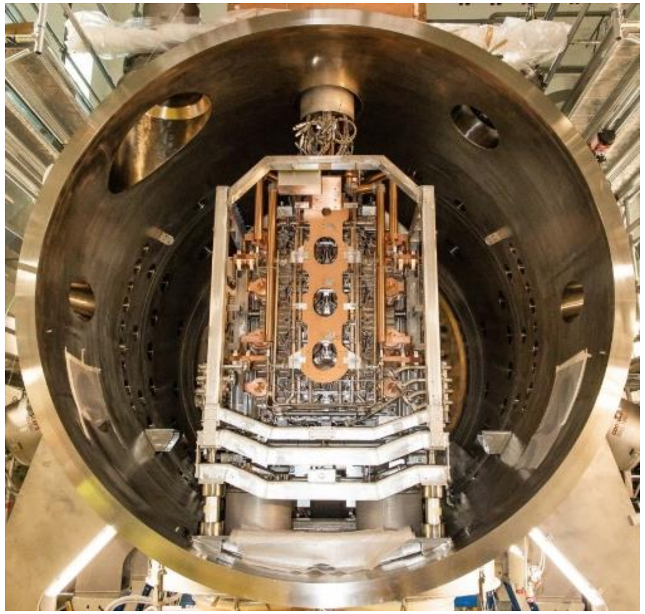
Performance of the ½ size ITER source ELISE

Short pulses (20 s plasma, 10 s beam)

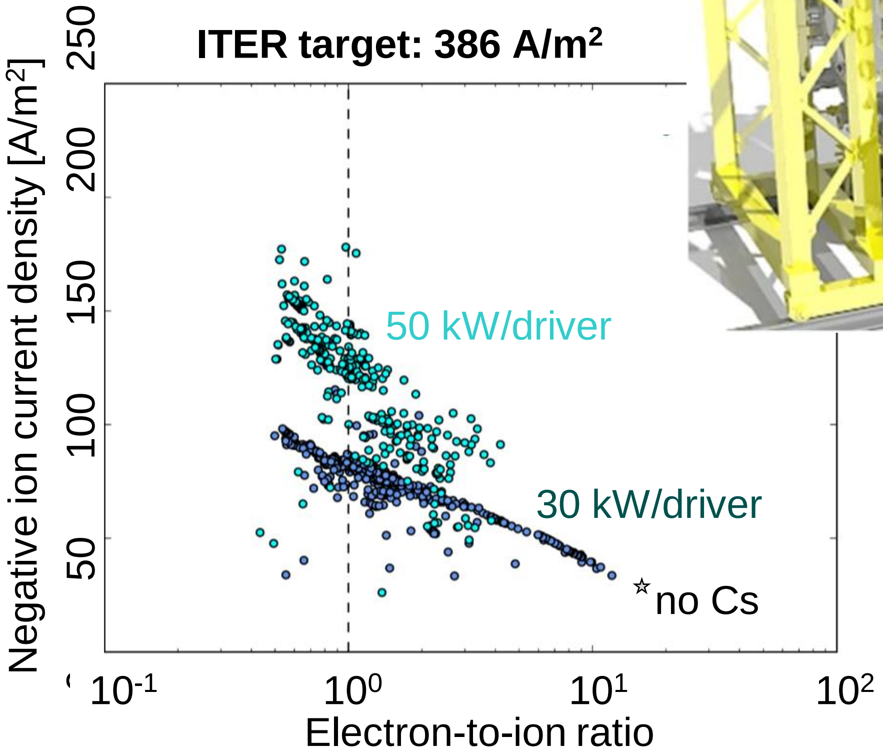


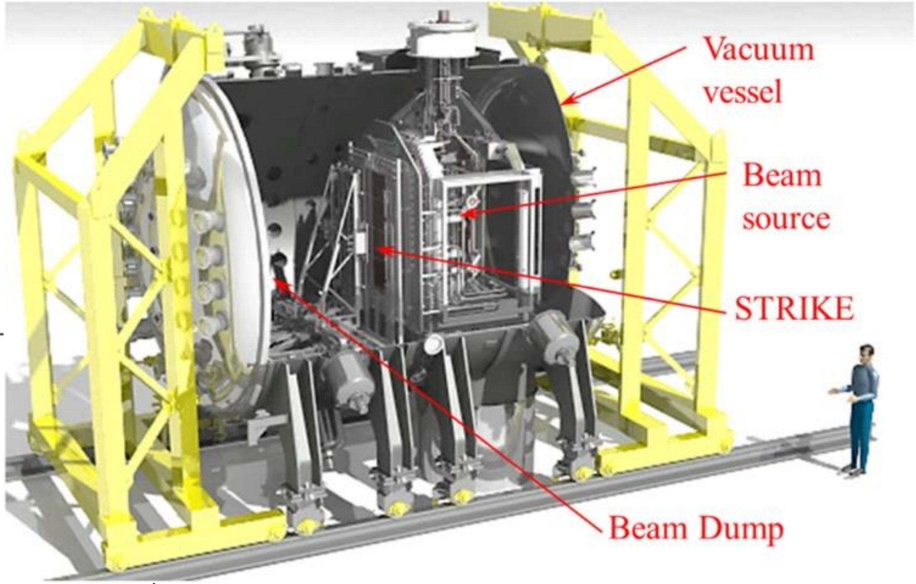
Results from the NBTF – Full size ion source SPIDER

First campaign with caesium in 2021



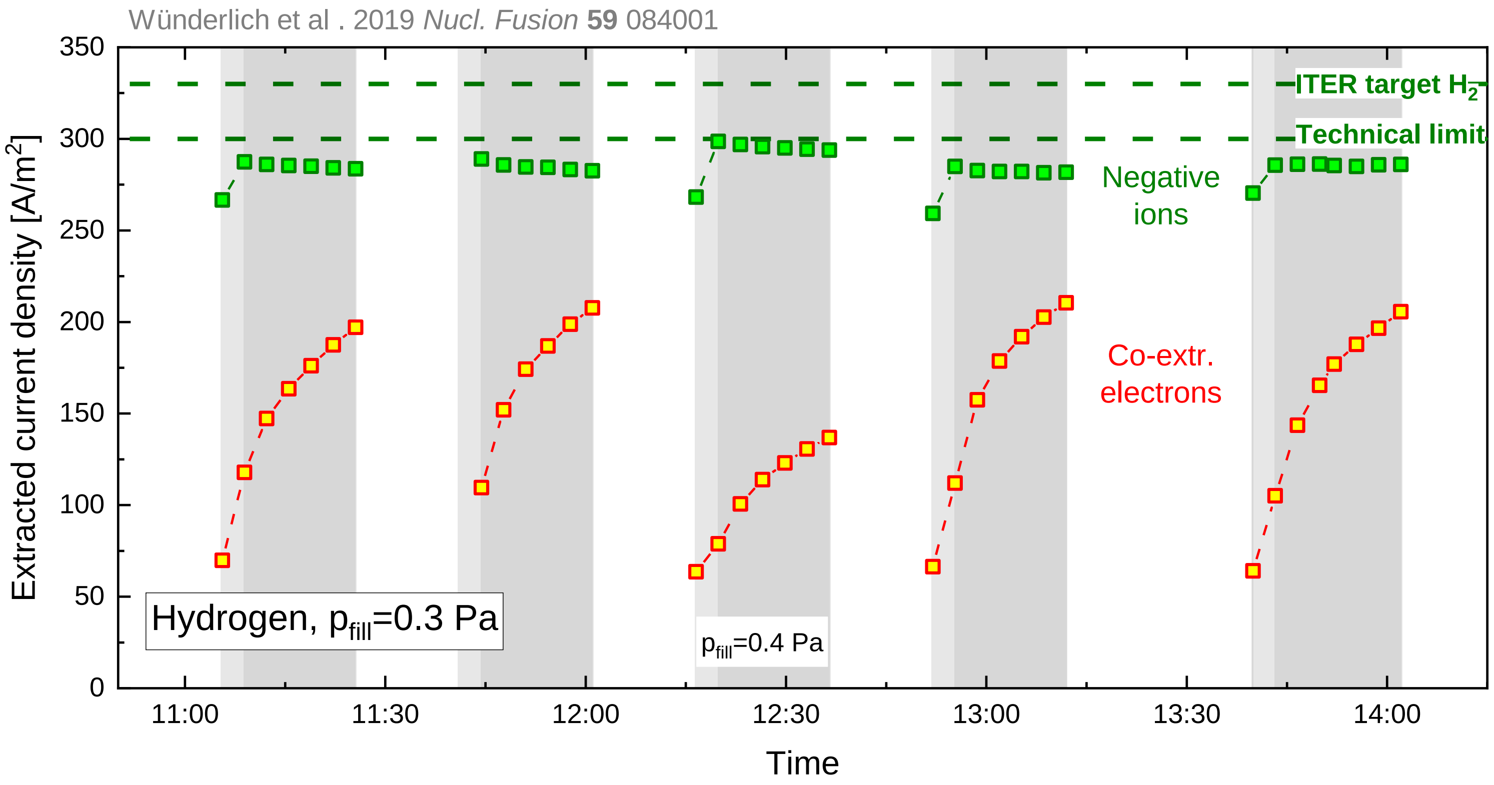
Chitarin et al., AIP Conf. Proc. 2052 (2018) 030001





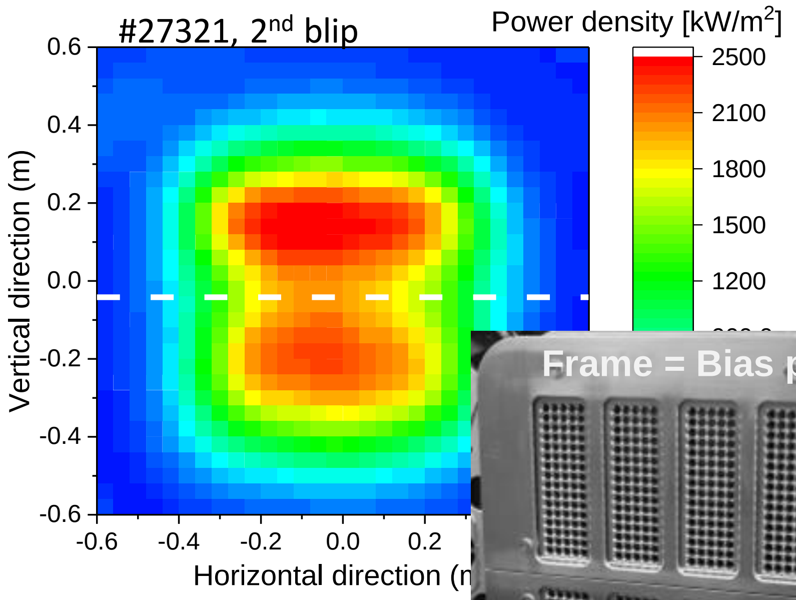
V Toigo et al 2017 New J. Phys. 19 085004

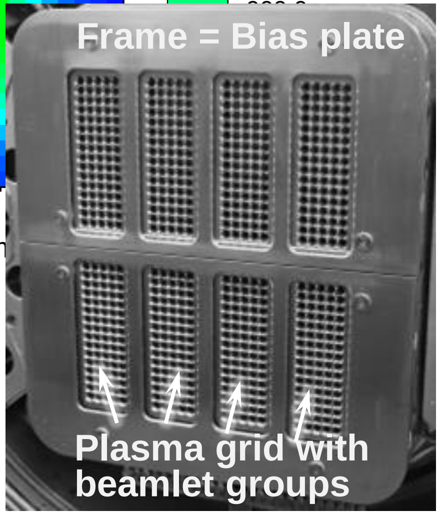
Performance of the ½ size ITER source ELISE
Long pulses in hydrogen (beam blips of 10 s / 3 min)



Limited by available HV power supply & by RF generators

Footprint of beam at calorimeter





ITER parameters for hydrogen (almost*) achieved during consecutive long pulses

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

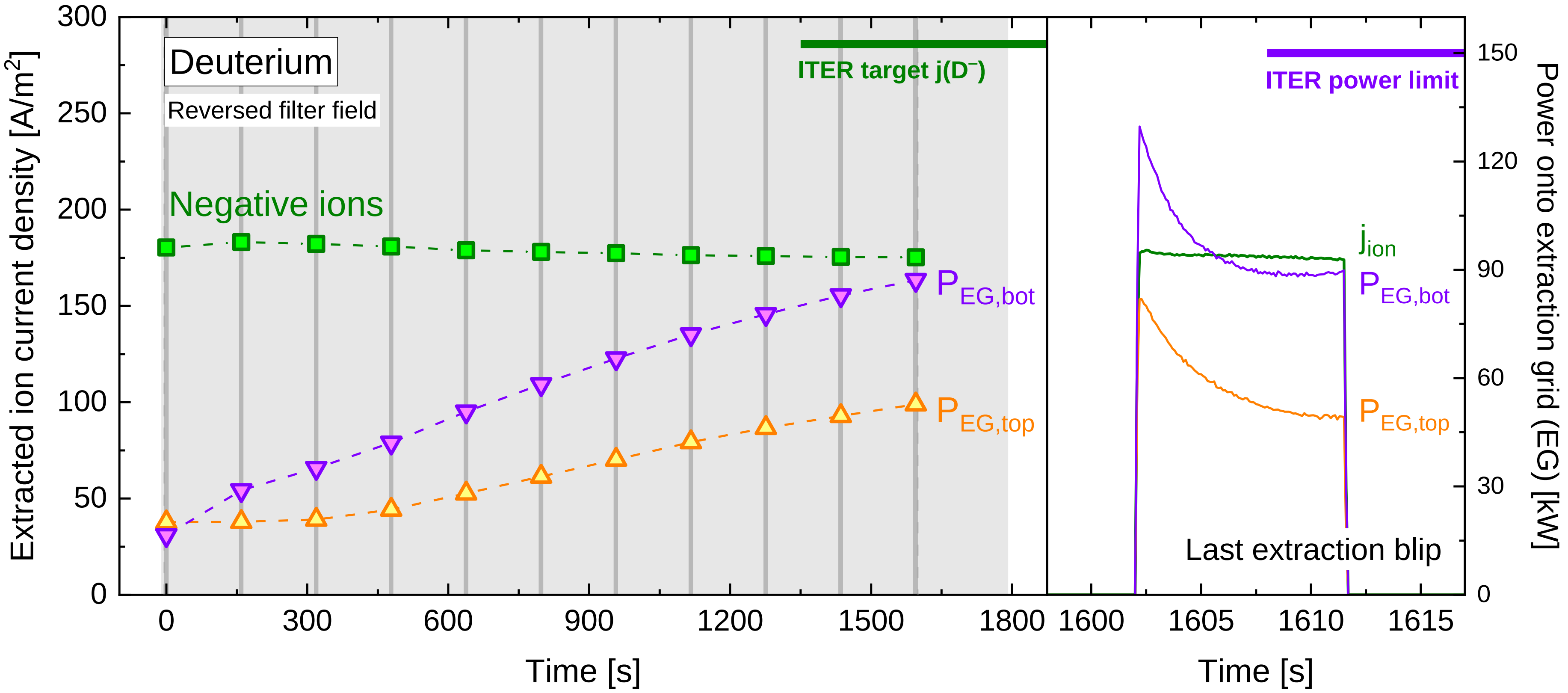
***Limited by available HV power supply & RF generators**

Performance of the ½ size ITER source ELISE

Long pulses in deuterium (beam blips of 10 s / 3 min)

Achievements:
Hydrogen > 90% long & short pulses
Deuterium > 60% long pulses > 90% short pulses

Wünderlich et al. 2021 *Nucl. Fus.* **69** 096023



Stable ion current but **strong temporal behavior** and vertical asymmetry **of co-extracted electrons**

Deuterium operation
Strong isotope effect in terms of co-extracted electrons

Transition from hydrogen to deuterium at identical source parameters

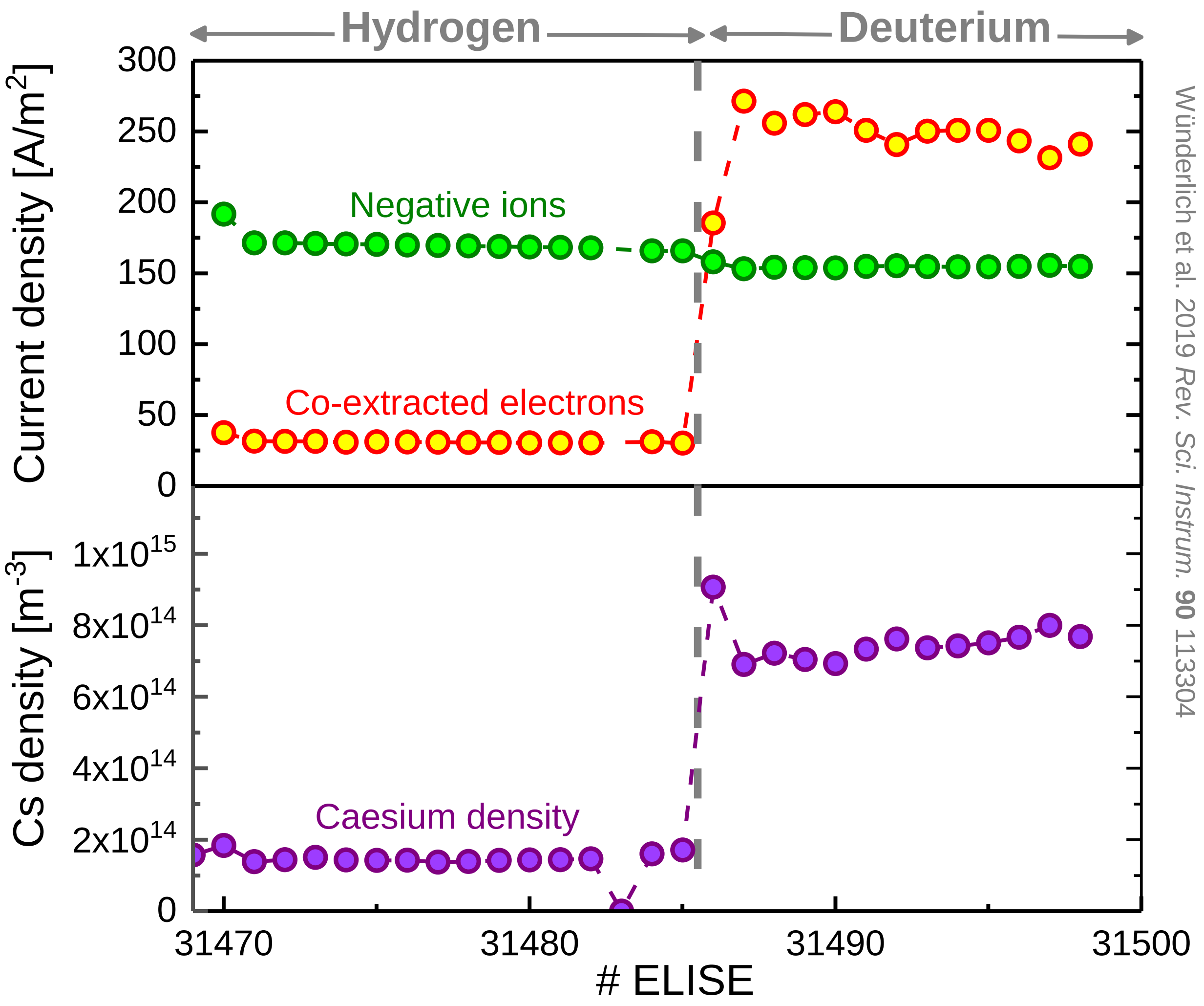
- Drastic increase of co-extracted electrons
- Strong increase of Cs density close to plasma grid

at almost the same ion current density

In general: co-extracted electrons

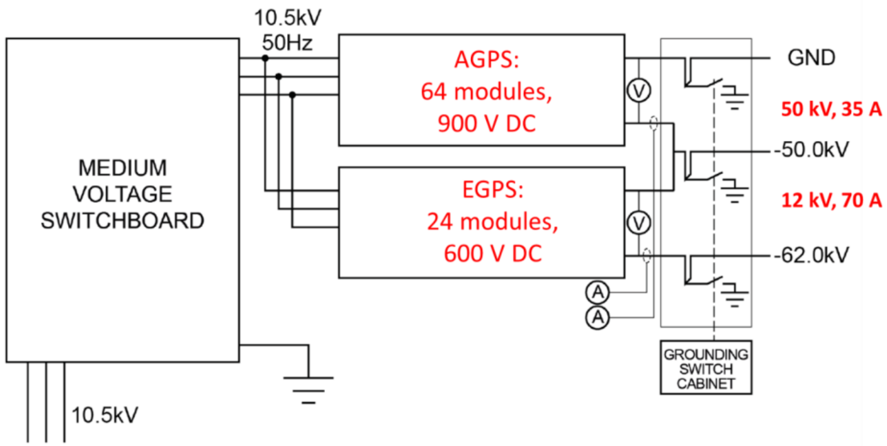
- are factor 2 – 4 higher in D
- **limit the source performance**

→ challenge for 1 hour pulse in D



Wünderlich et al. 2019 *Rev. Sci. Instrum.* **90** 113304

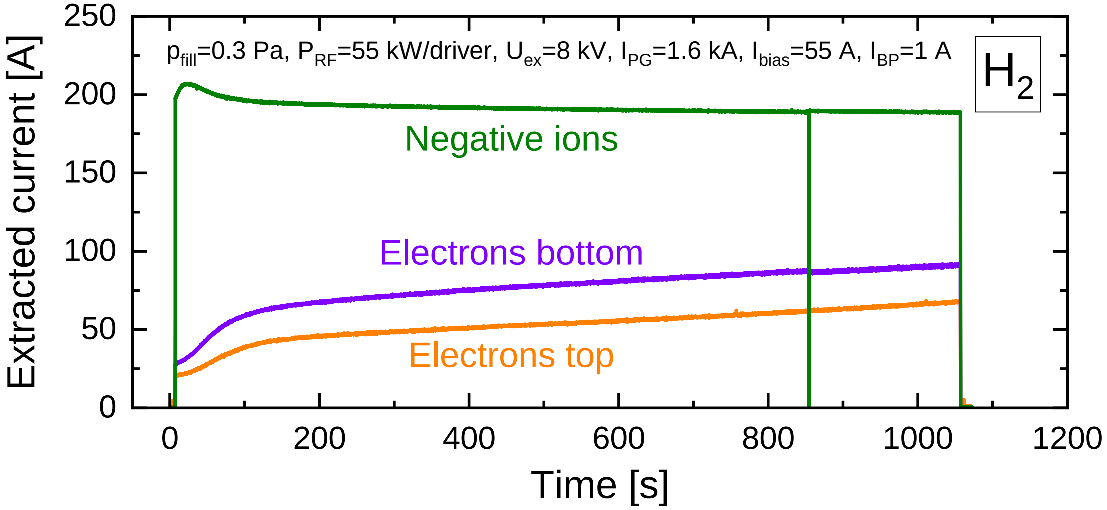
Steady state extraction at the ½ size ITER source ELISE
Upgrade of power supply and first results

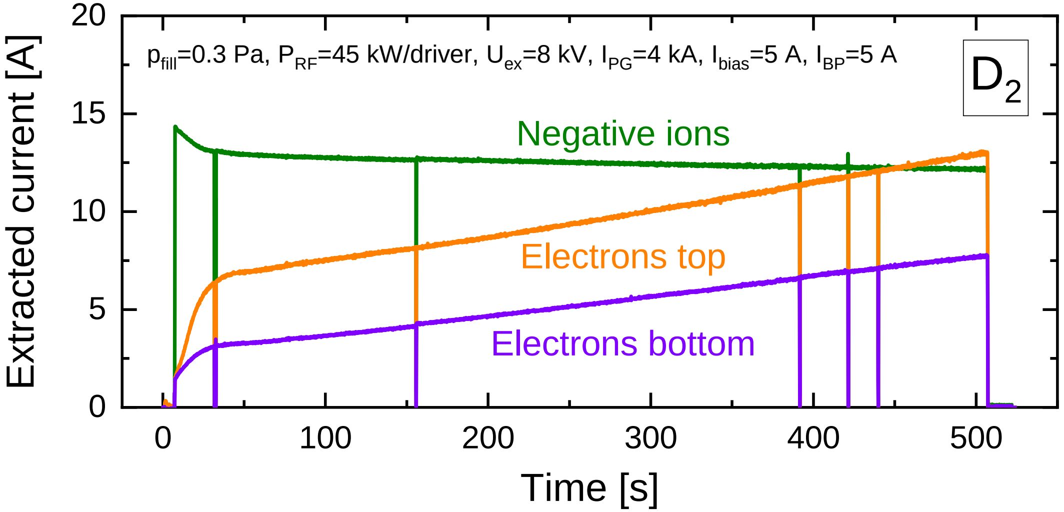


CW power supply (2.6 MW) supported by

EUROfusion

Commissioning started in 2021





Beam characterisation
Diagnostics for beam divergence and homogeneity

Arrangements of apertures

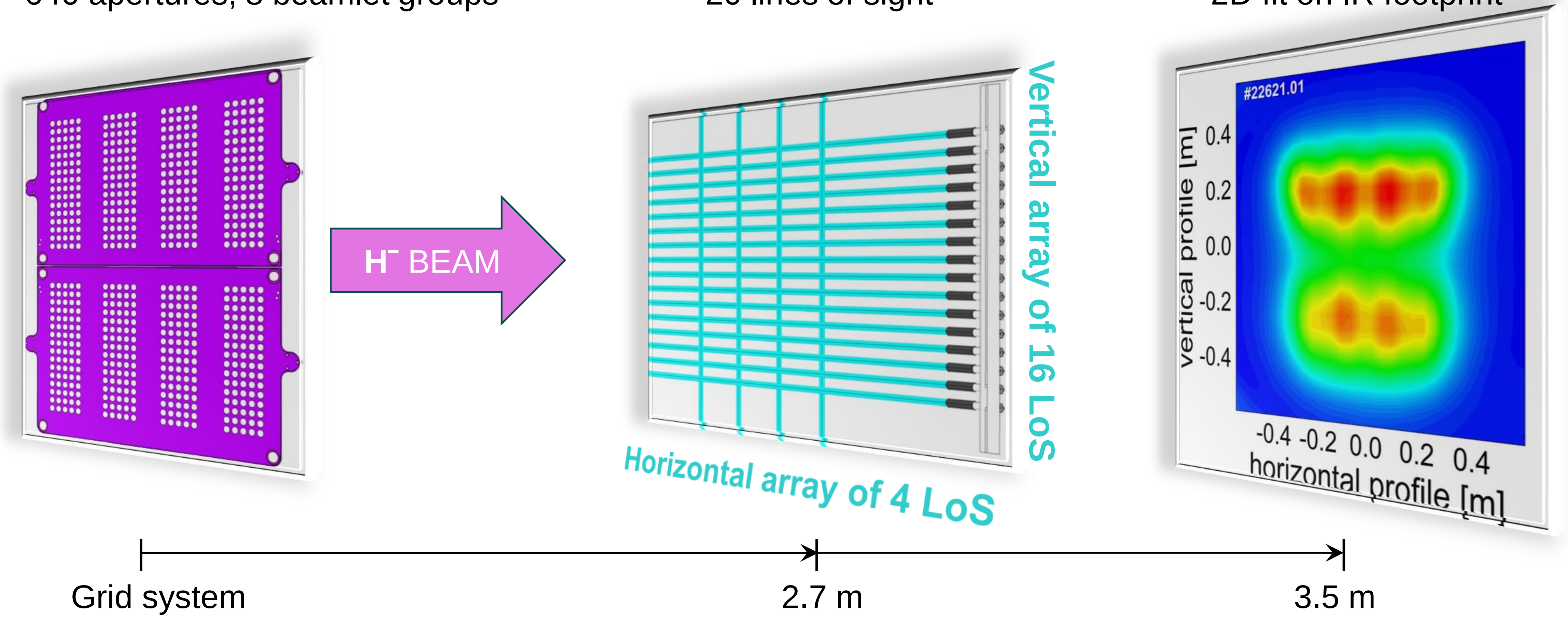
640 apertures, 8 beamlet groups

Beam emission spectroscopy

20 lines of sight

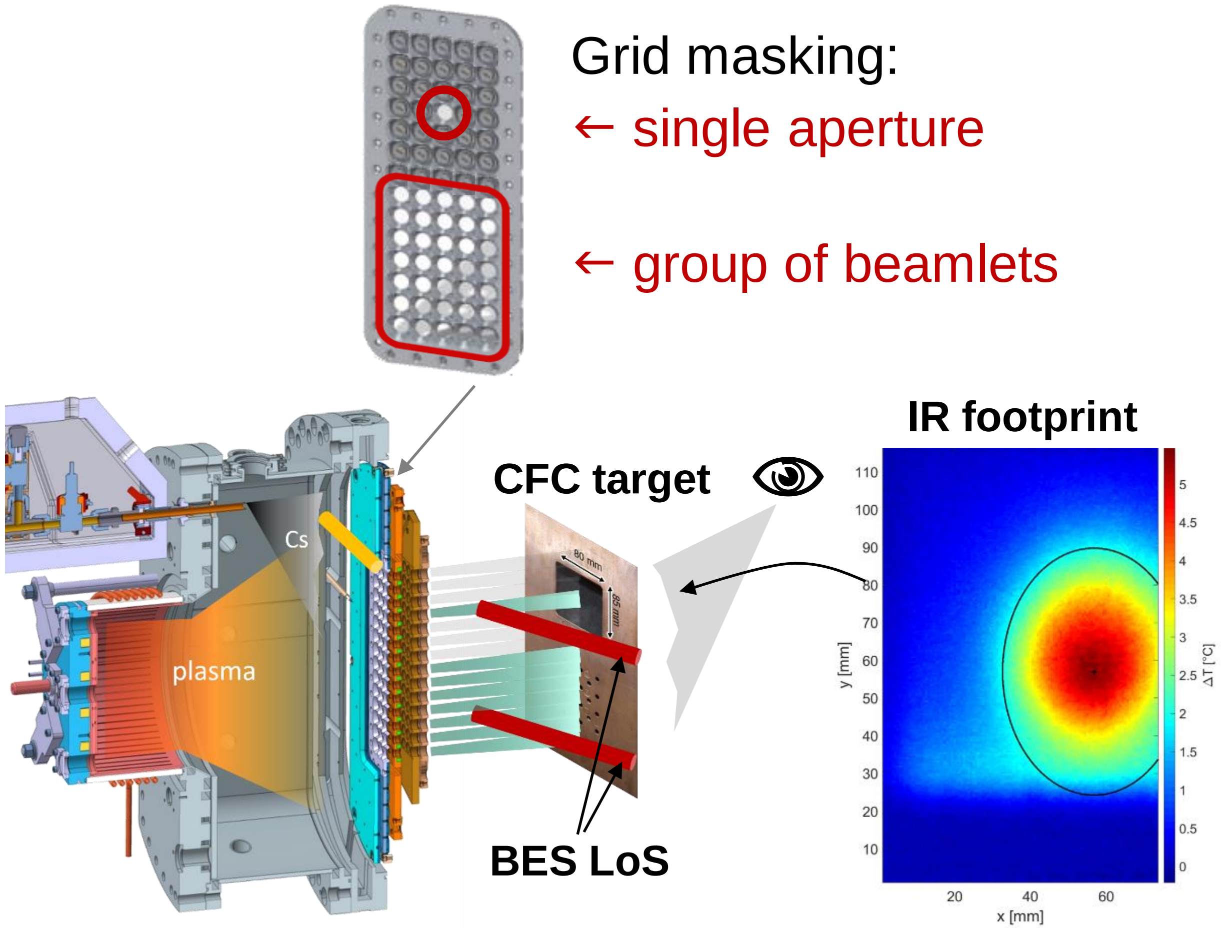
IR calorimetry

2D fit on IR footprint



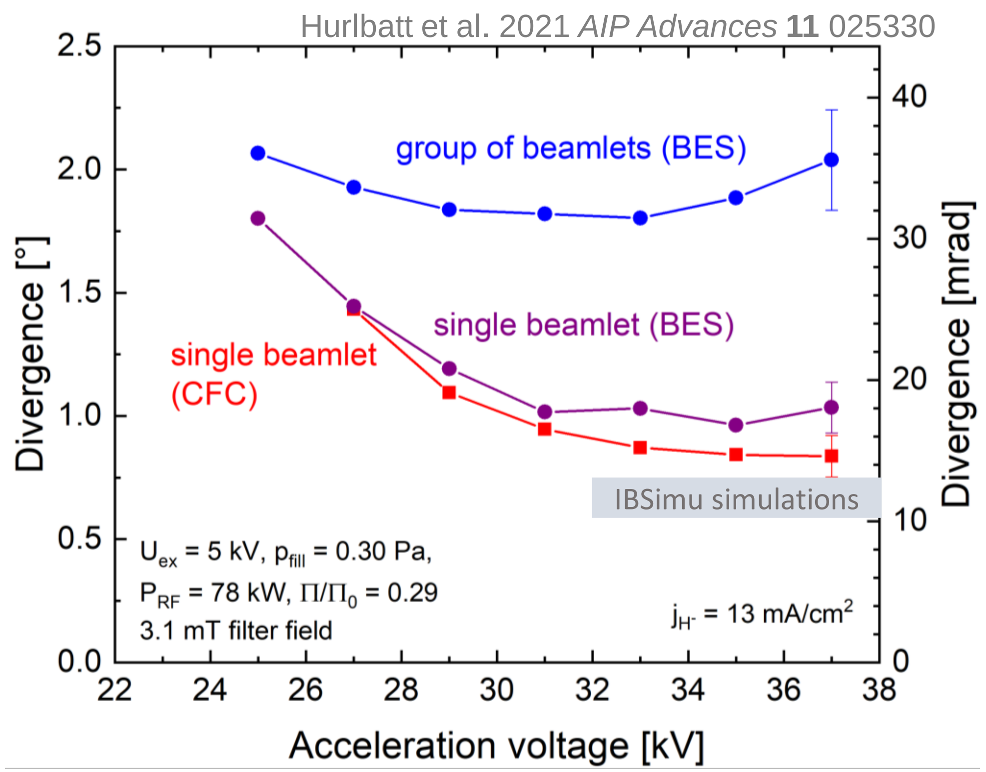
Prototype source at BUG for studies on beam optics

Comparison of different diagnostic techniques in collaboration with Consorzio RFX



ITER requirement

Beamlet core divergence ≤ 7 mrad

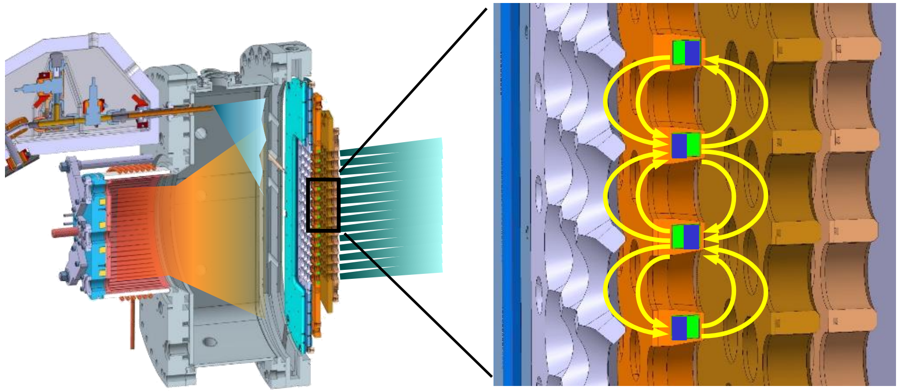


Reduced divergence (from 32 to 14 mrad) for single beamlet measurement

Beam optic studies: BUG-MLE

MITICA-like Extraction system

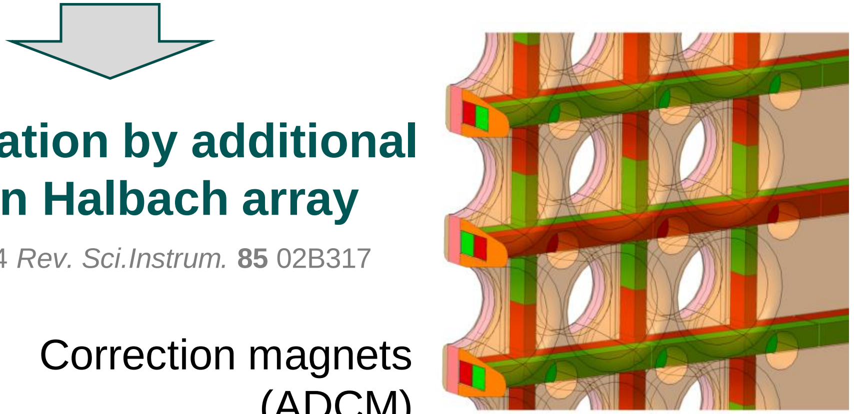
Zig-zag deflection caused by alternating electron suppression magnets in EG



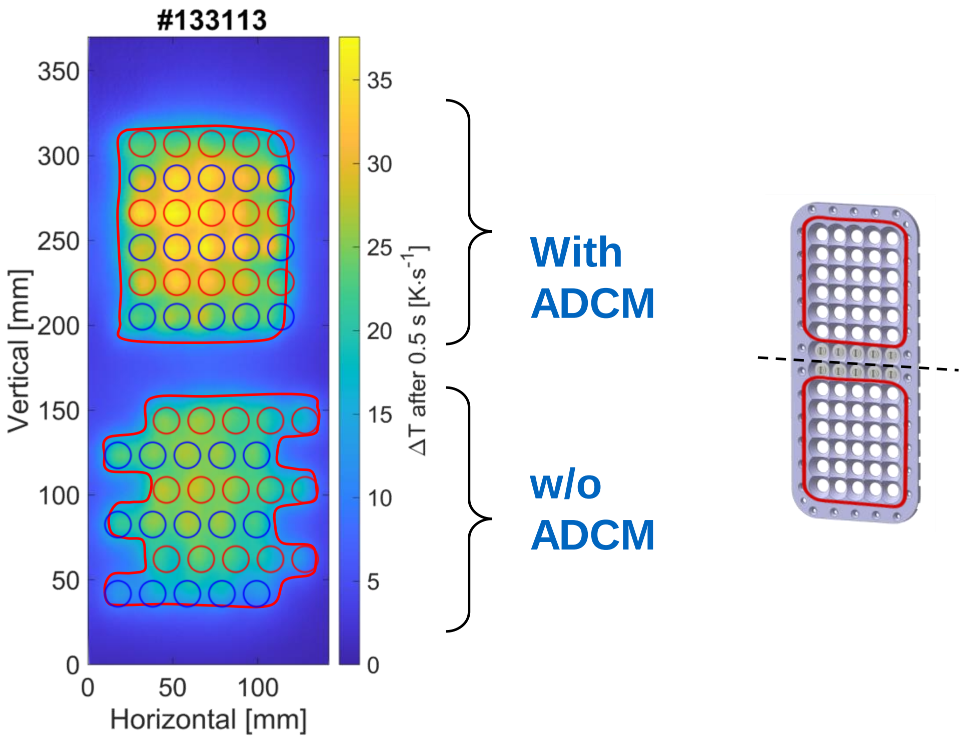
Compensation by additional magnets in Halbach array

Chitarin et al. 2014 *Rev. Sci.Instrum.* **85** 02B317

Correction magnets (ADCM)



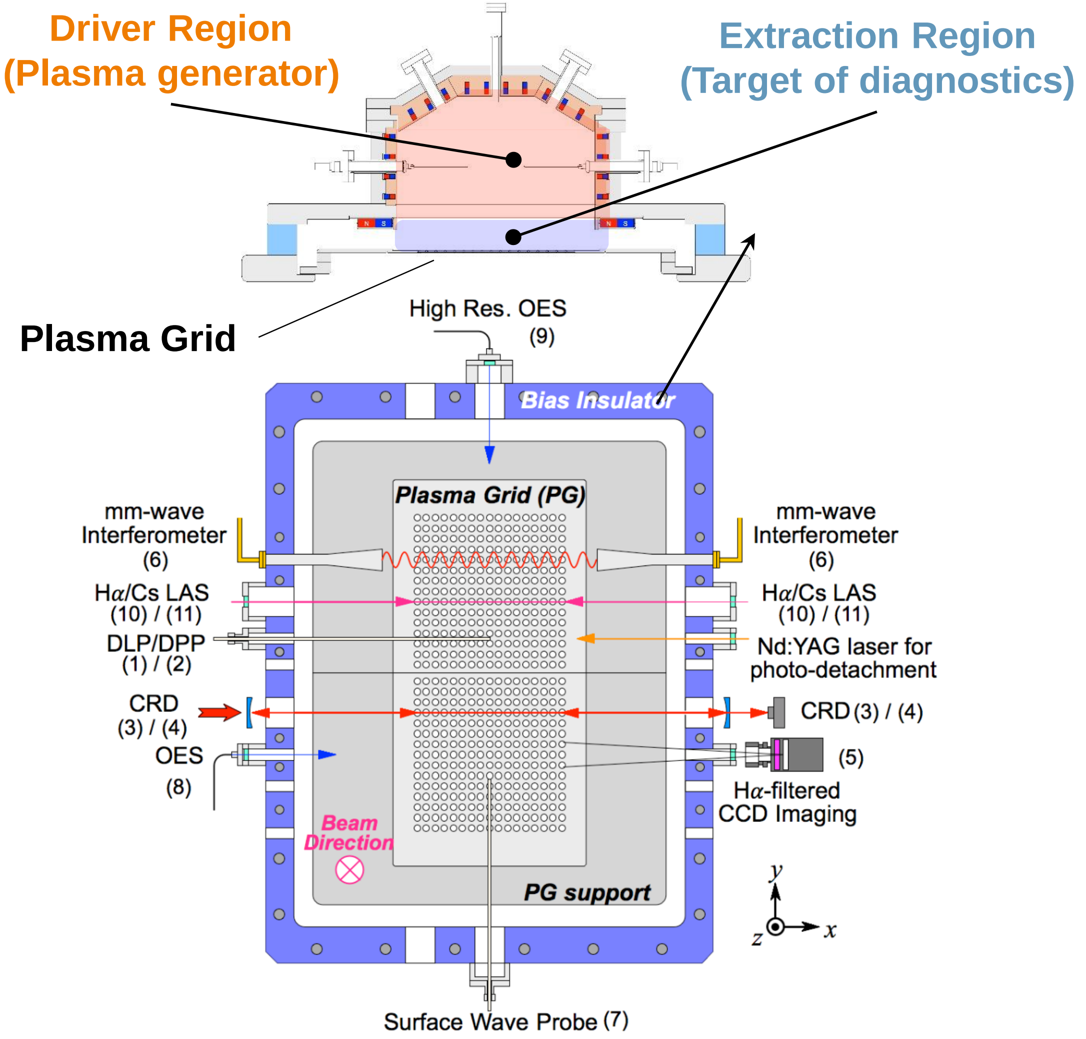
Compensation of zig-zag deflection
→ Successful in a wide operational regime



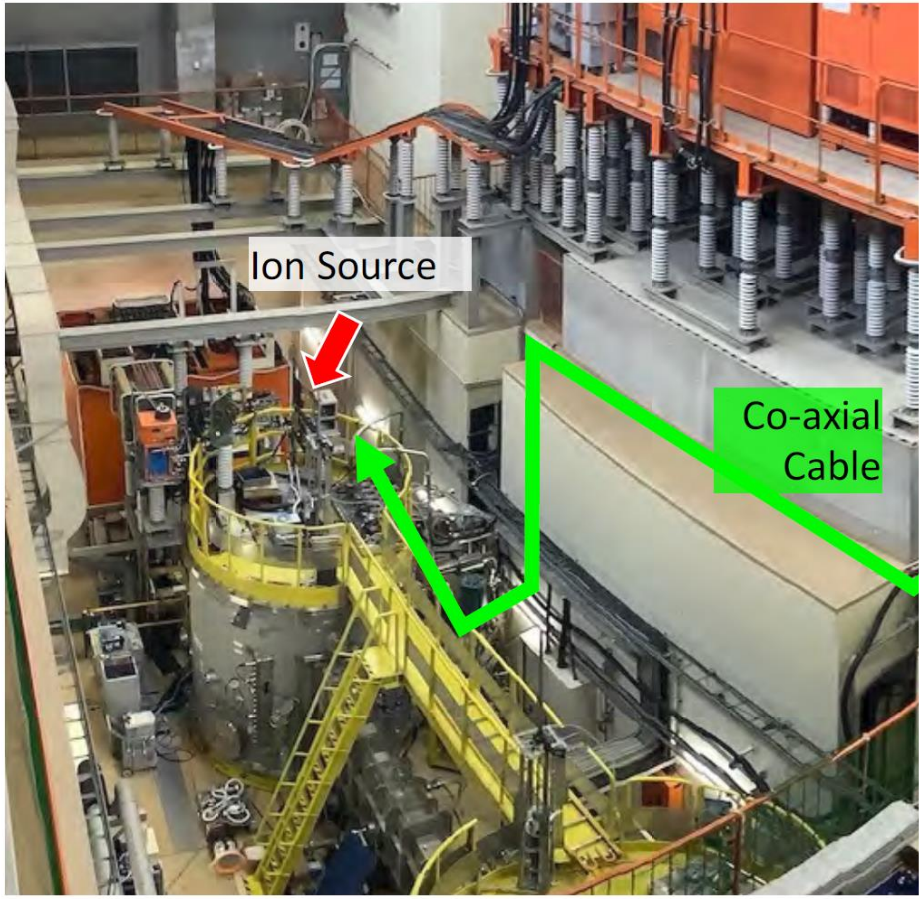
Wimmer et al. 2022 *J. Phys.: Conf. Ser.* **2244** 012051
den Harder et al. 2022 *J. Phys.: Conf. Ser.* **2244** 012053

R&D at dedicated test facility at NIFS, Japan

Versatile diagnostics of plasma and beam for fundamental understanding

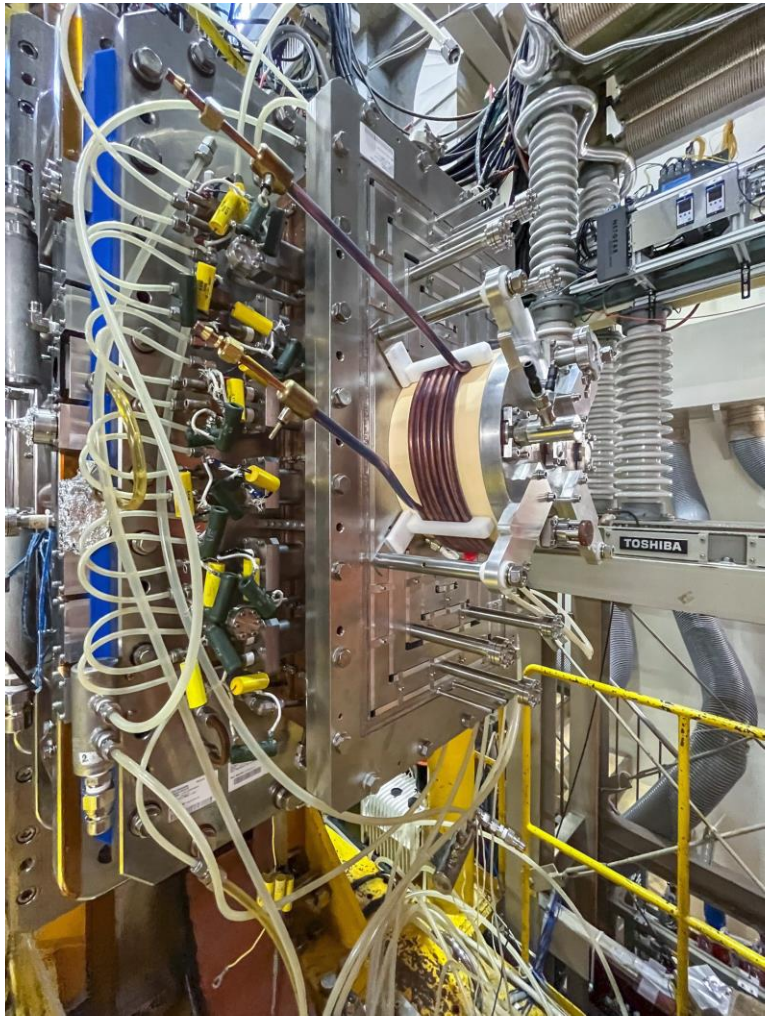


The test facility - ready for a hybrid source



R&D at dedicated test facility at NIFS, Japan

A test facility for a hybrid source



The RF ion source with the back plate attached to the NIFS NB Test Stand beamline – August 2022.

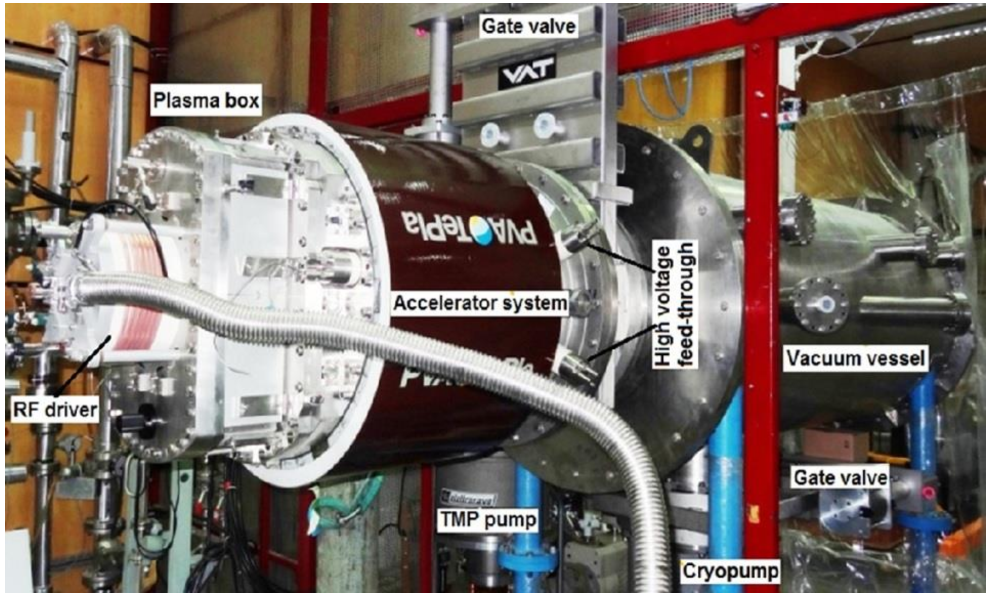
Back plate exchangeable to arc source.

Unique possibility to investigate plasma and beam with same diagnostics.

R&D at IPR, India

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

H- beams from a caesiated ROBIN



- RF powers up to 80 kW coupled
- > 300 A/m² H- beam @ 40 keV
- Cs consumption ~ 10 – 12 mg/hr
- Extracted current ratio $e^-/H^- \leq 1$

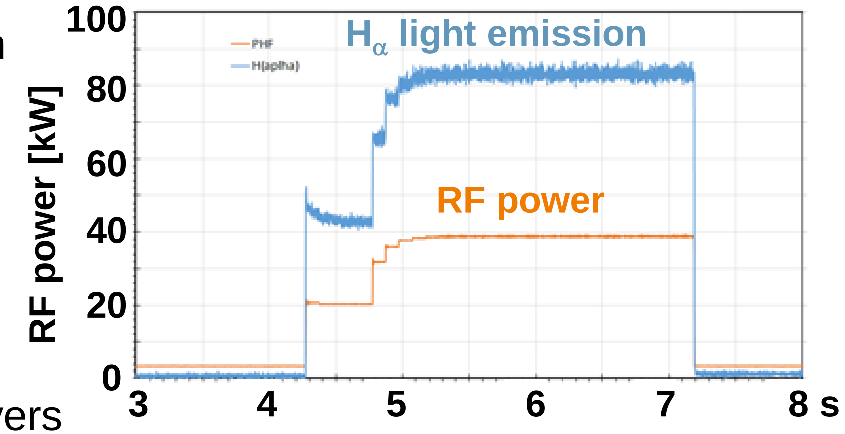
TWIN SOURCE test bed

Future plans

- Tests with full turn coils
- Coupling of 150 kW
- H- beams on TWIN

Development of an 40 kW solid state RF generator

38 kW RF power coupled to two drivers

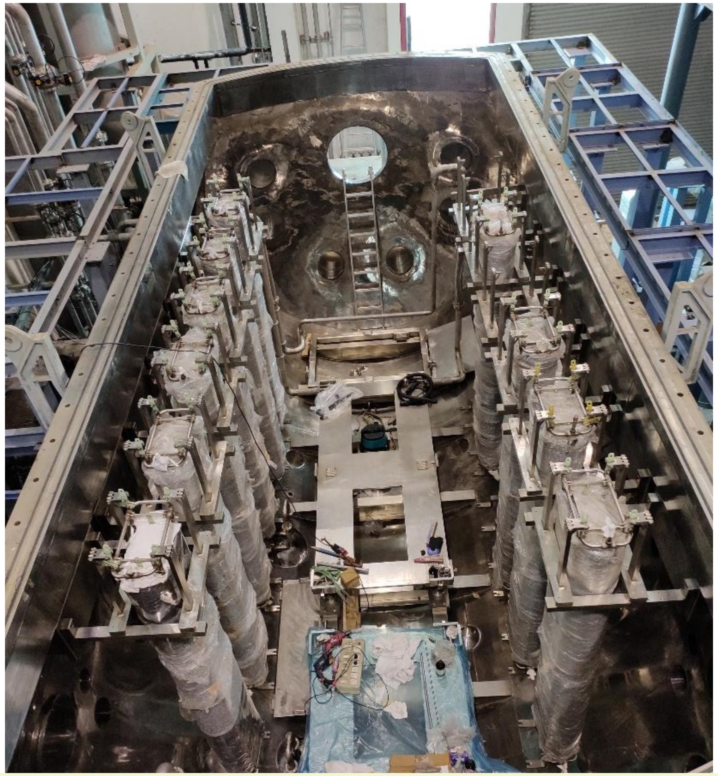


R&D at IPR, India

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

INTF @ ITER – India lab is the prototype DNB beam line

A unique 21.6 m path length to characterize focused H^0 beams



Cryopanel installation in progress inside INTF vacuum vessel

Preparations underway towards installation and commissioning

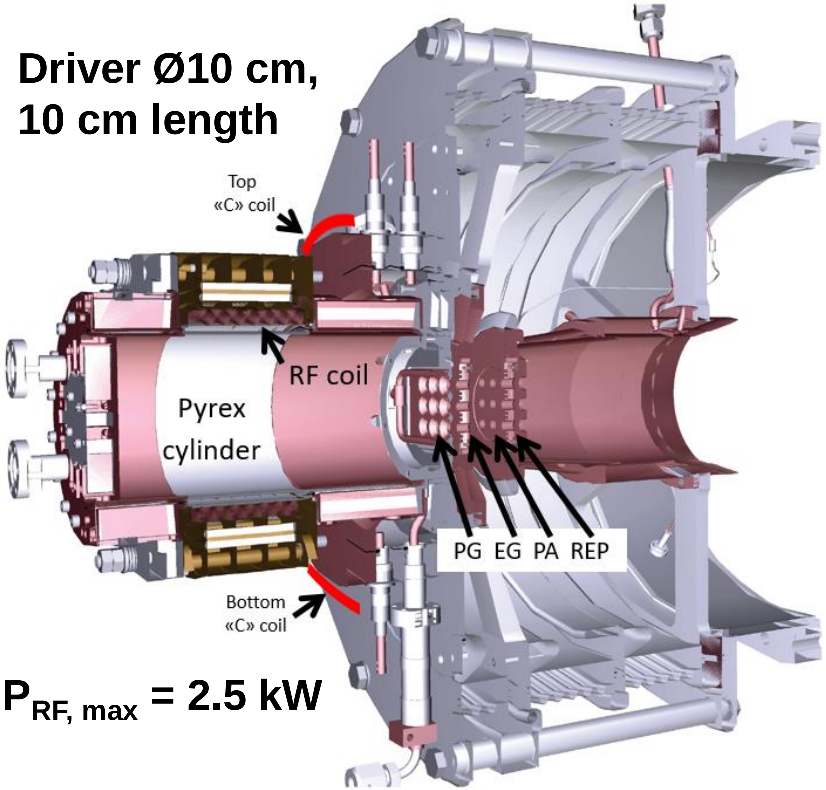
Beam line components: Neutraliser, ERID, calorimeter expected in Dec 2022

Source expected in October 2023
Modifications from SPIDER learnings incorporated

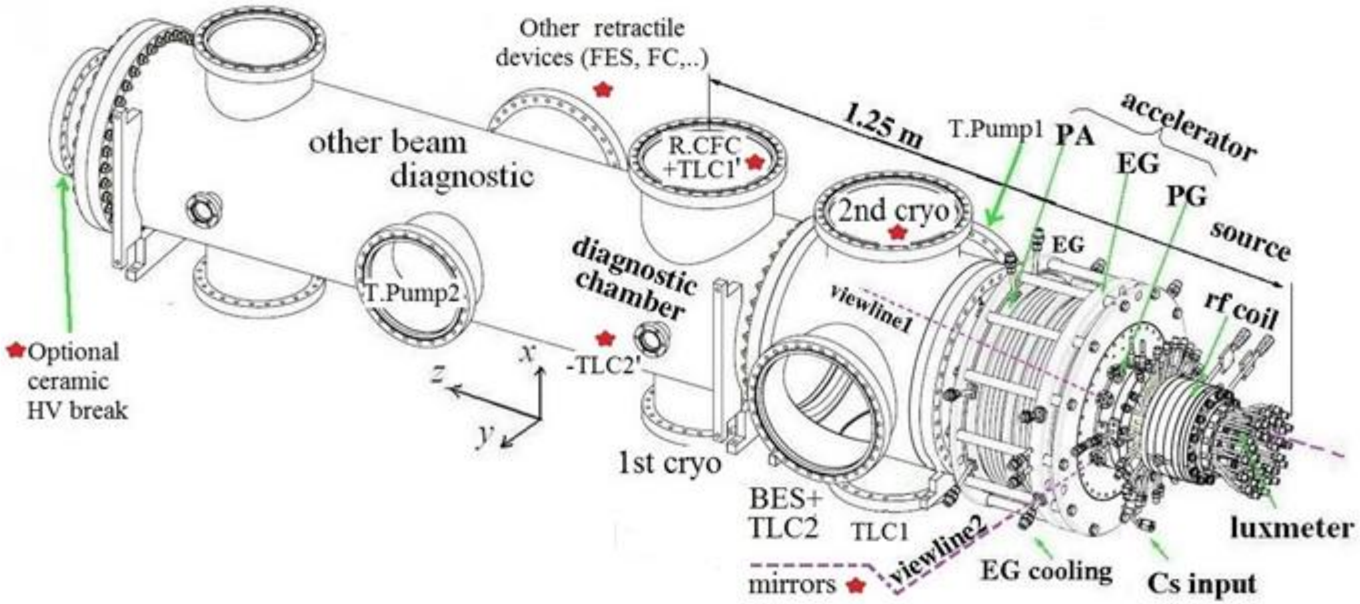
Progress of components & assembly

R&D at Consorzio RFX, Italy
The compact RF ion source NIO1

Driver Ø10 cm, 10 cm length



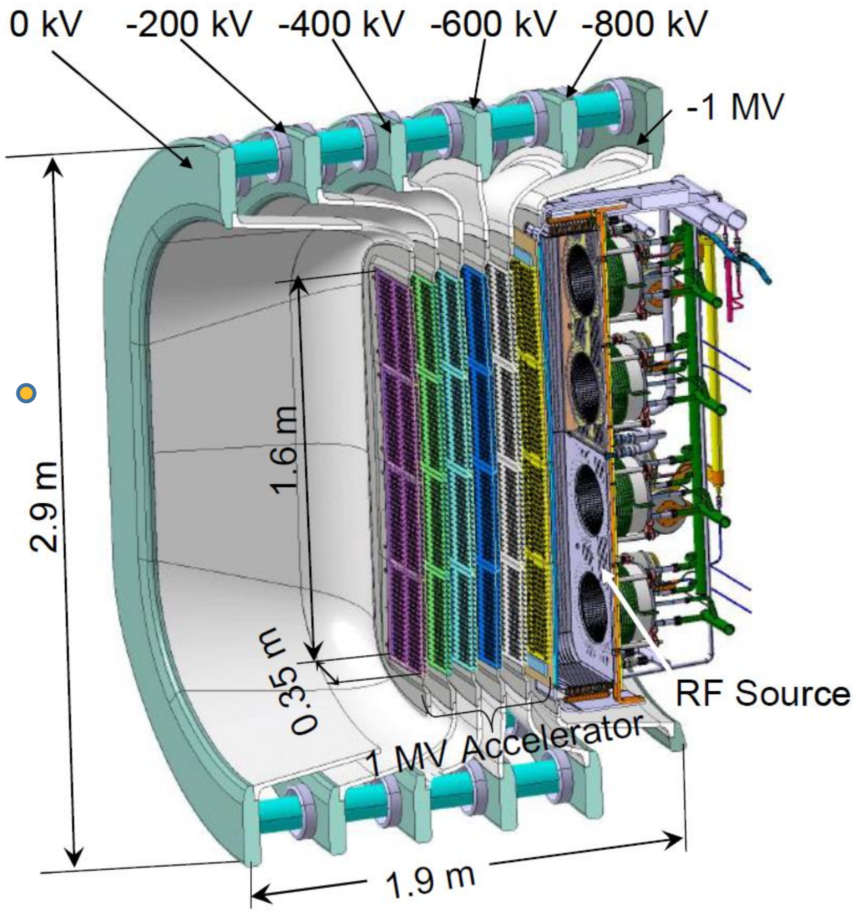
$P_{RF,\ max}$ = 2.5 kW



Steady state operation

- Beam extraction and acceleration provided by 3 grids + repeller.
- Design beam ratings: 130 mA, 60 keV max.
- **Several diagnostics: OES, TDLAS, CRDS, BES, beam tomography, etc.**

RF Ion sources for fusion
Take-Home message



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, 0.3 Pa

7 Electrodes

16 beamlet groups

1280 beamlets

NNBI R&D activities worldwide to make HNB and DNB at ITER a success!

Cutting edge physics & technology.

Still huge challenges

- 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

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Katsuyoshi Tsumori

NNBI group

and the respective teams

for providing valuable input to this contribution!

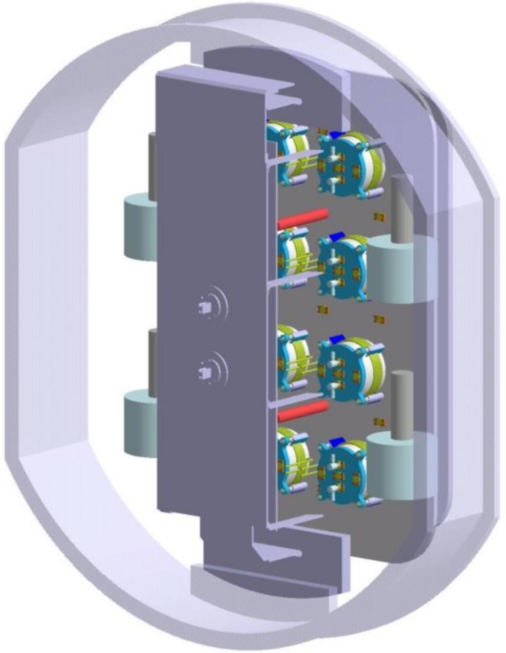
Backup slides

Negative hydrogen ion sources for ITER’s NBI – Summary
A low temperature plasma to heat the fusion plasma

High power plasma sources
for negative hydrogen ions (H^-, D^-)

T < 10 eV

Source area: 1 m × 2 m



Acceleration to
1 MV

40 A D^- for 1 hour

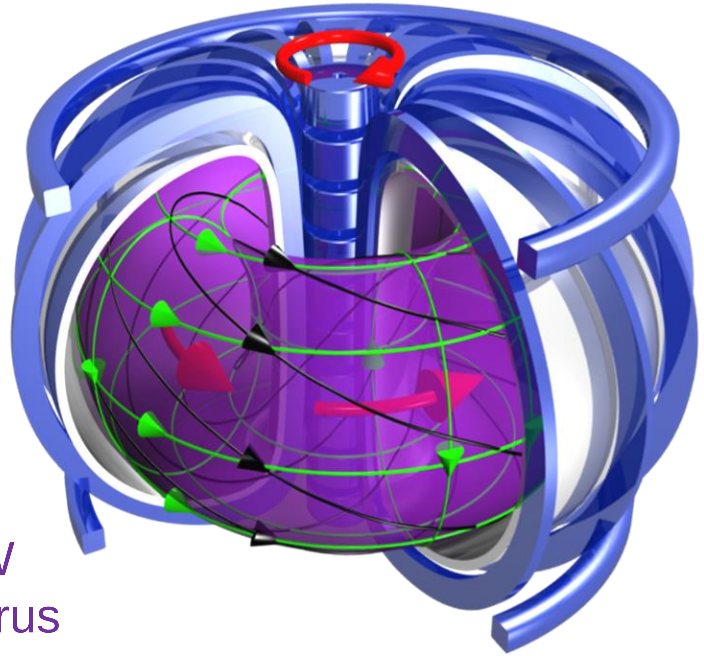
40 MW
generated

17 MW
to the torus

Fusion plasma

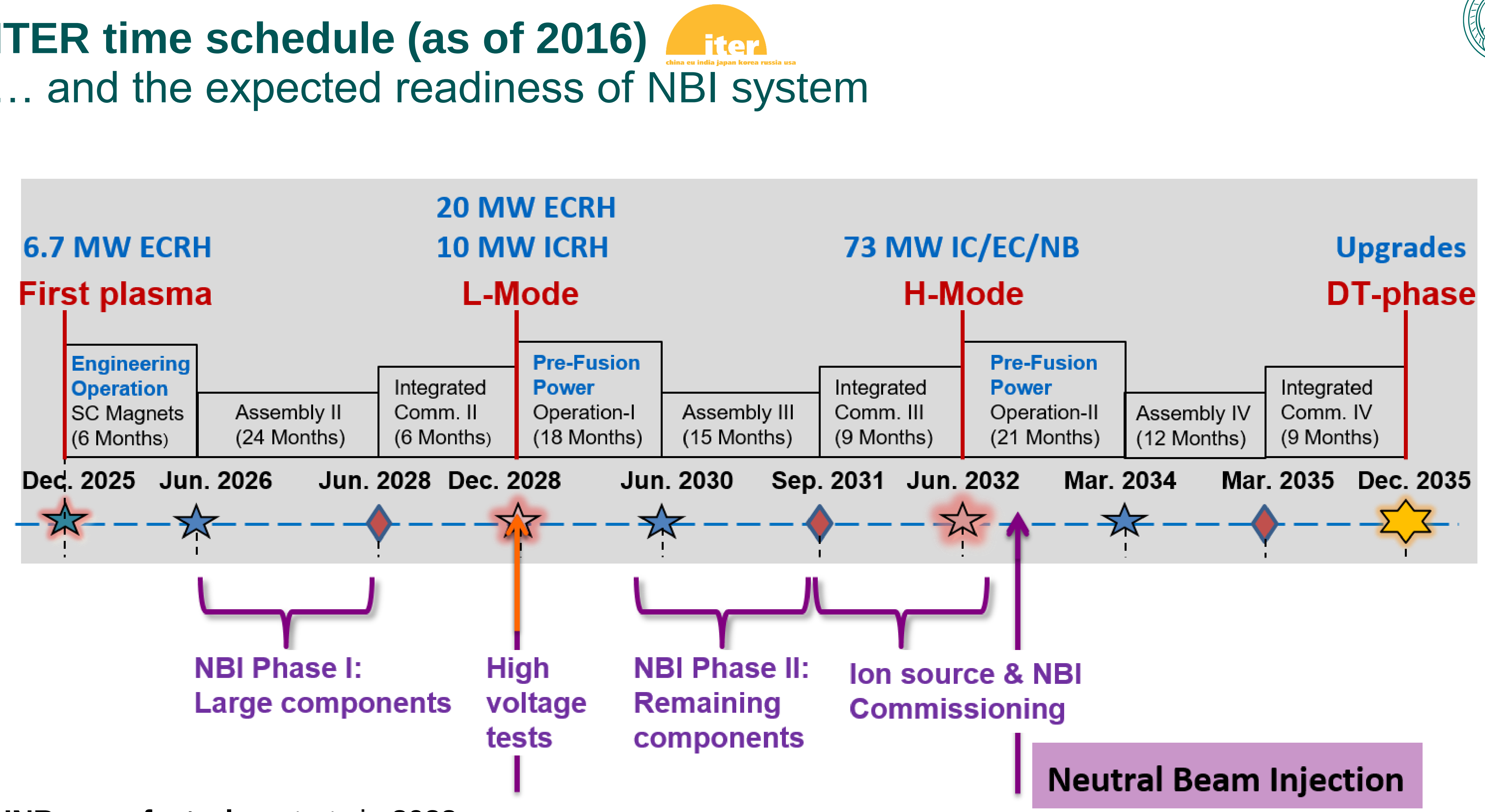
$D + T \rightarrow {}^4He + n + 17{,}6$ MeV

T > 10 keV



ITER time schedule (as of 2016)

… and the expected readiness of NBI system



HNB manufacturing starts in **2022**

The test facility for iter NBI at Consorzio RFX, Italy

The beam source of MITICA (full size HNB prototype)