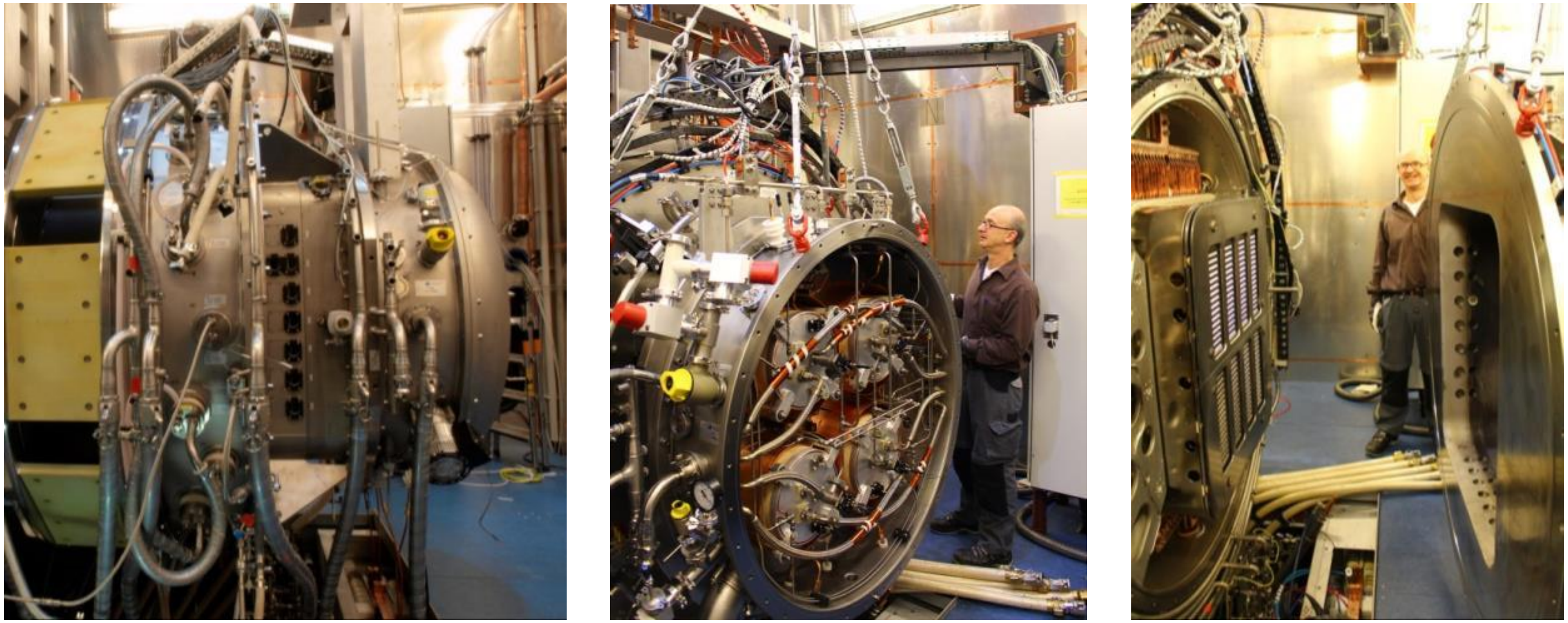
Towards 40 A Negative Hydrogen Ion Beams for Up to 1 hour

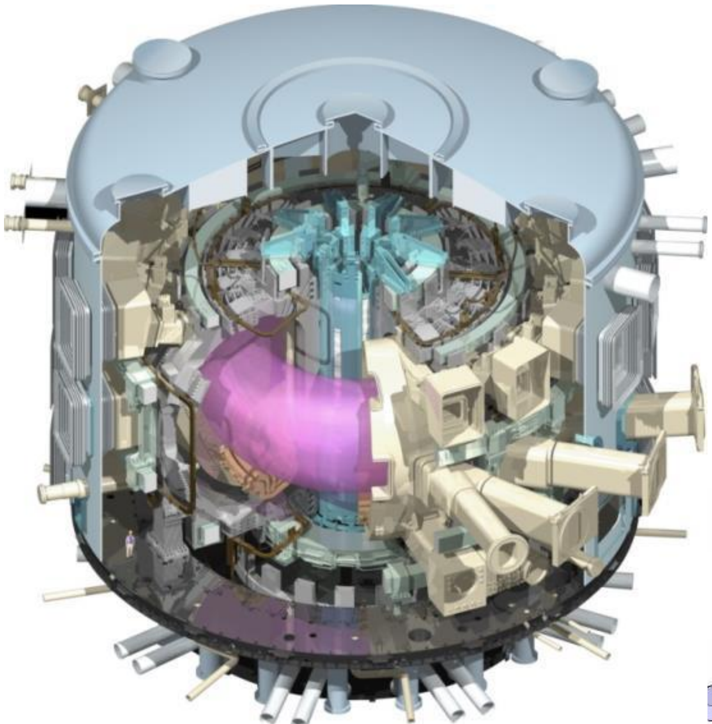
Powerful RF Ion Sources for Fusion

Ursel Fantz for the IPP-NNBI Team



The half size ITER source at the ELISE test facilty

Neutral Beam Injection (NBI) for ITER



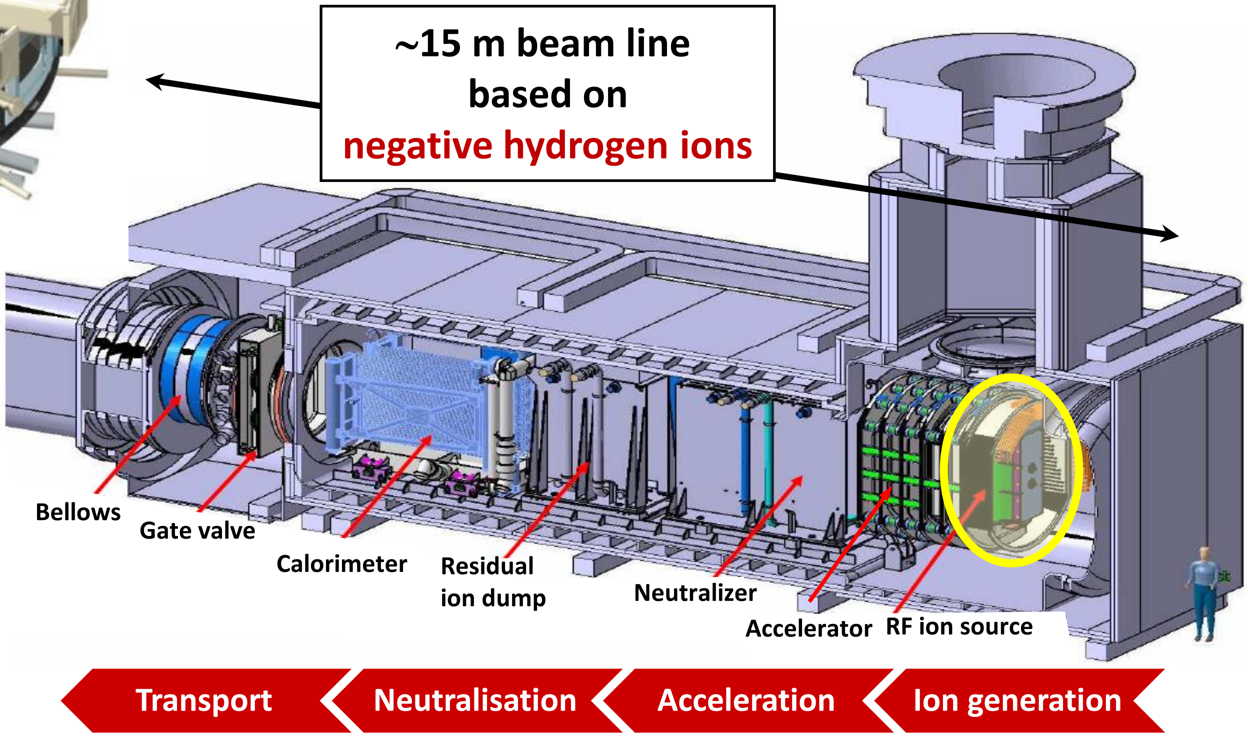
Heating beams (50% EU, 50% JA)

- **33 MW** injected power from 2 injectors
- 3600 s, **1 MeV Deuterium**

Diagnostic beam (100% IN)

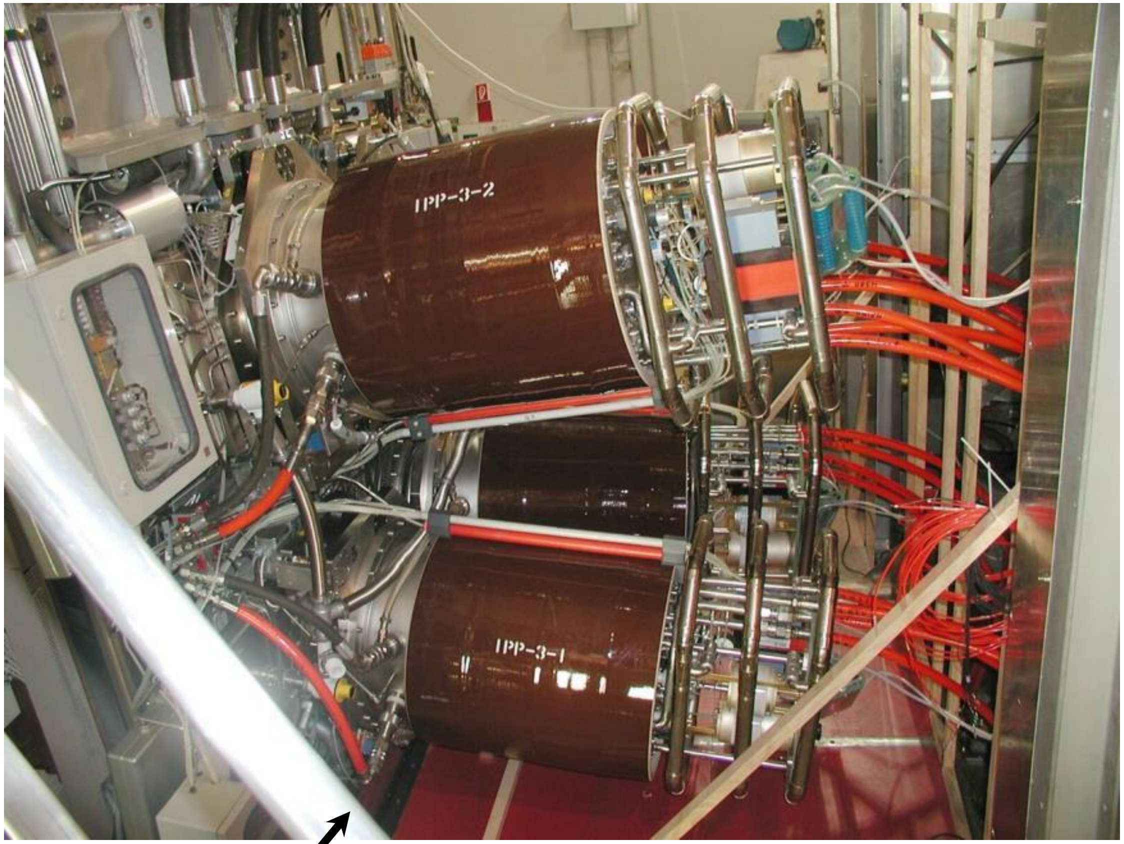
- **3 MW**
- 3 s every 20 s, **100 keV Hydrogen**

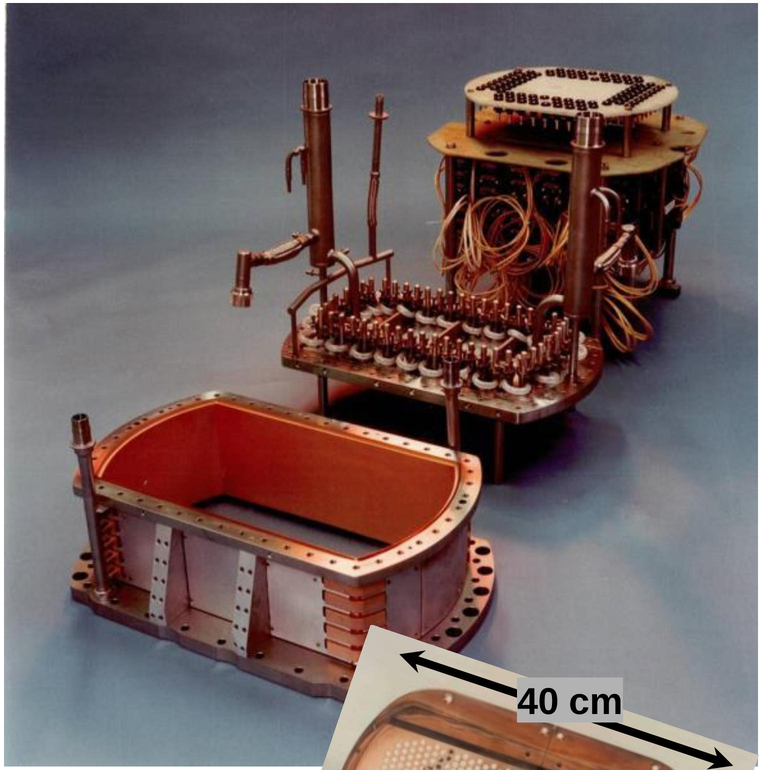
An international project that aims to demonstrate that fusion is an energy source for the future!

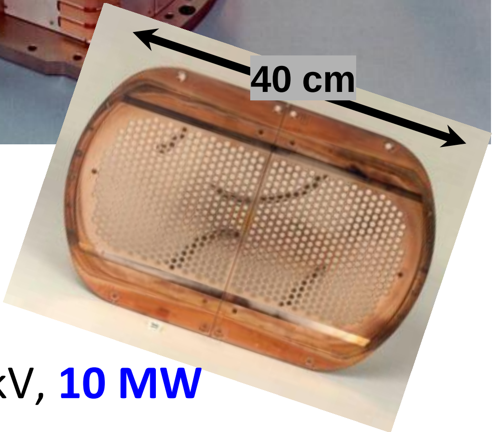


Ion sources in present NBI systems: Example ASDEX Upgrade

Sources for positive ions (> 60% H^+) at low pressure (~1 Pa) and high power (~100 kW)



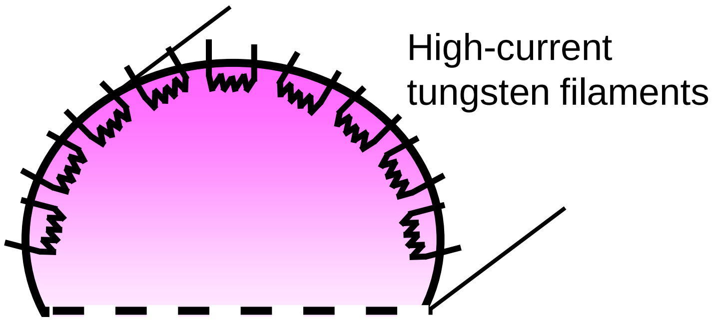




Beamline 1	**Arc sources:**	**H** 85 A, 55 kV, **7.2 MW**	**D** 75 A, 65 kV, **10 MW**
Beamline 2	**RF sources**:	**H** 62 A, 72 kV, **5.6 MW**	**D** 62 A, 93 kV, **10 MW**

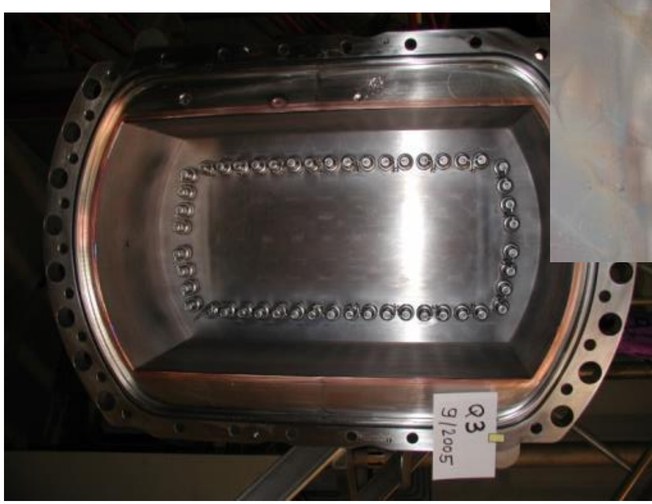
Ion sources – Two concepts

Arc sources

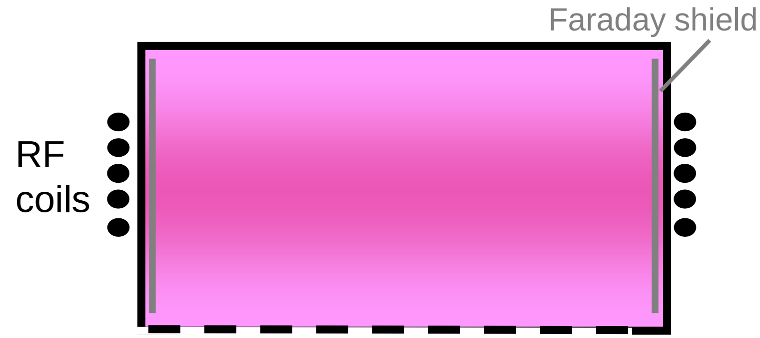


- Hot cathodes (2000 – 3000 K)
- DC voltage (≈ 100 V)
- Arc current (1000 A)

Regular maintenance

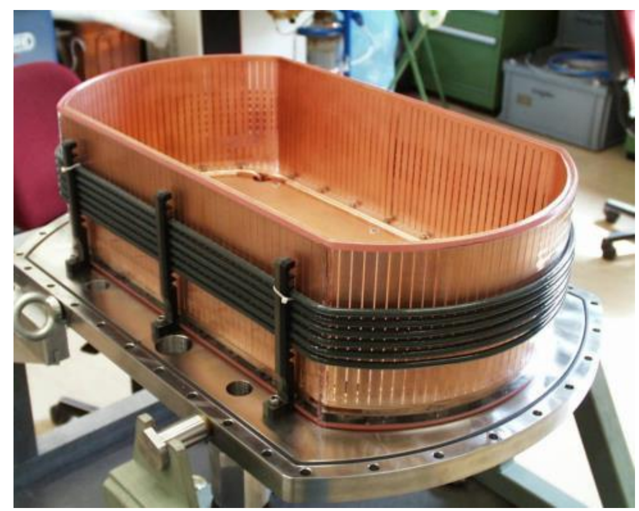


RF sources



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

Long lifetime

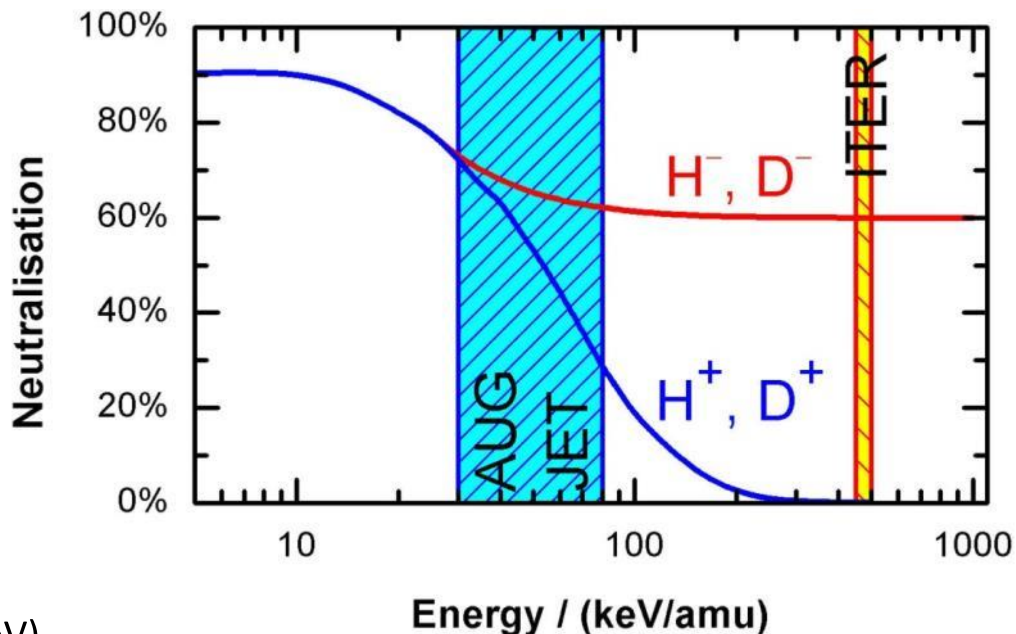


AUG sources

Positive or negative hydrogen ions?

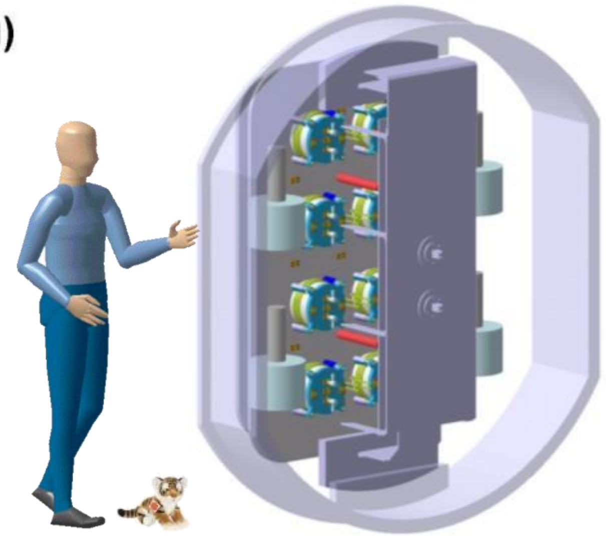
Question answered by requirements on beam energy needed for heating and current drive

ITER: 1 MeV (D)
for substantial CD



Negative ions

- **Fragile objects**
  (binding energy: 0.75 eV)
- **Co-extracted electrons** **ITER: electrons / ions < 1**
  Accelerated electrons damage electrodes !
  Deflection of electrons by a magnetic field in the 2nd grid, the extraction grid, keeps heat load below tolerable amount.
- **Low current densities** **ITER: 40 A D^-** **Large sources**
  $j(H^-) \approx 0.1 \times j(H_x^+)$ for 16.5 MW power →



How to create negative hydrogen ions?

- **Volume process**

$$e^- + H_2 \rightarrow H_2(B,C) + e^- \rightarrow H_2(v) + e^- + h\nu$$

hot electrons **Vibrational excitation**

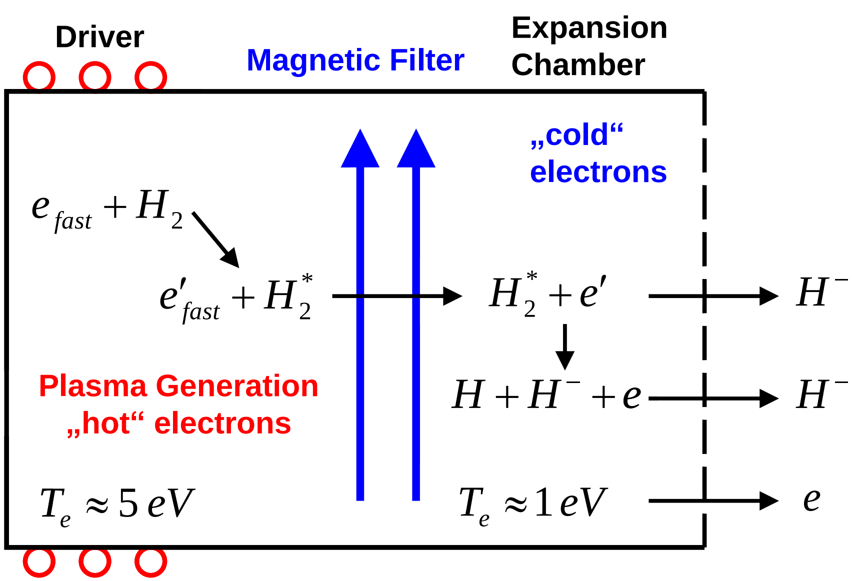
cold electrons

$$e^- + H_2(v) \rightarrow H^- + H$$

Dissociative attachment

High electron density and high pressure

Concept of a tandem source



Problems:

- **High co-extracted electron current**
- Pressure and thus

  Stripping losses in accelerator

  $$H^- + H_2 \rightarrow H + H_2 + e$$

  ITER: **p ≈ 0.3 Pa** ⇨ 30% losses
- **Low ion current at low pressure**

How to create sufficient negative hydrogen ions at 0.3 Pa?

- **Volume process** dissociative attachment

  $e^- + H_2(v) \rightarrow H^- + H$ $j_{H^-} \approx 4\ mA/cm^2$
  $j_e/j_{H^-} > 30$

- **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**

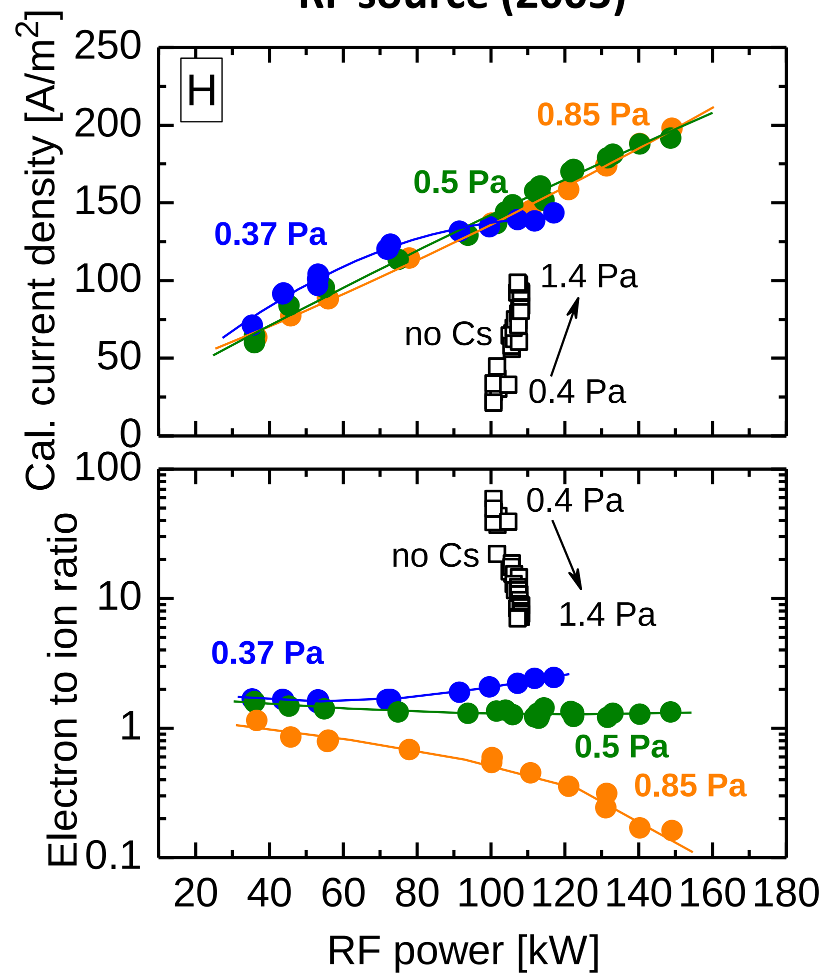
  $H^- + e^- \rightarrow H + 2e^-$ Electron stripping

  $H^- + H^+ \rightarrow H + H$ Mutual neutralisation

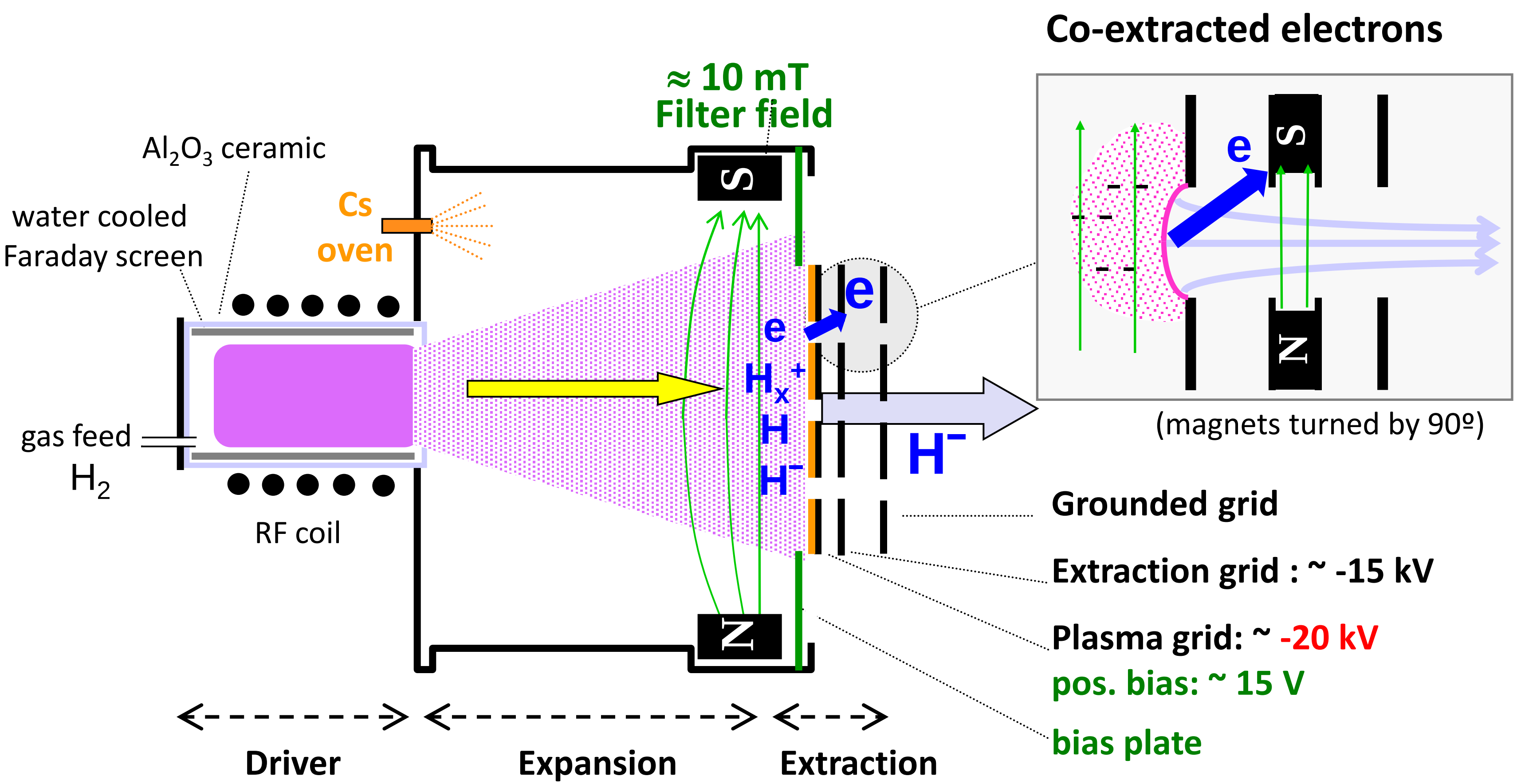
  $H^- + H \rightarrow H_2 + e^-$ Associative detachmen
  or $H + H + e^-$ (non-associative)

Survival length of H^- ≈ few cm

RF source (2005)



The RF ion source concept for negative hydrogen ions



Source on high potential

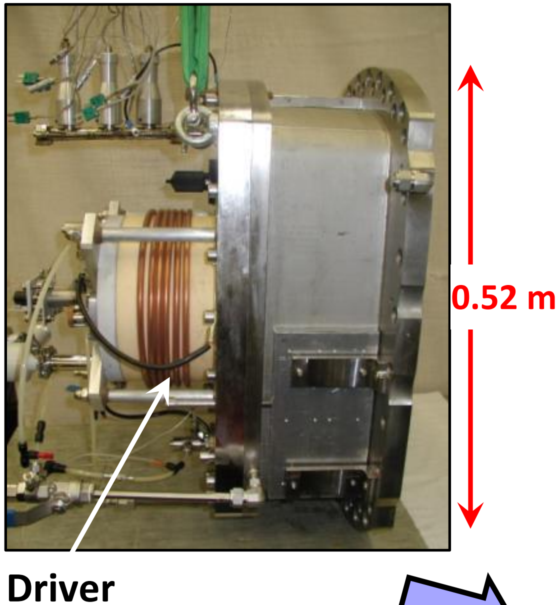
Current density measurements

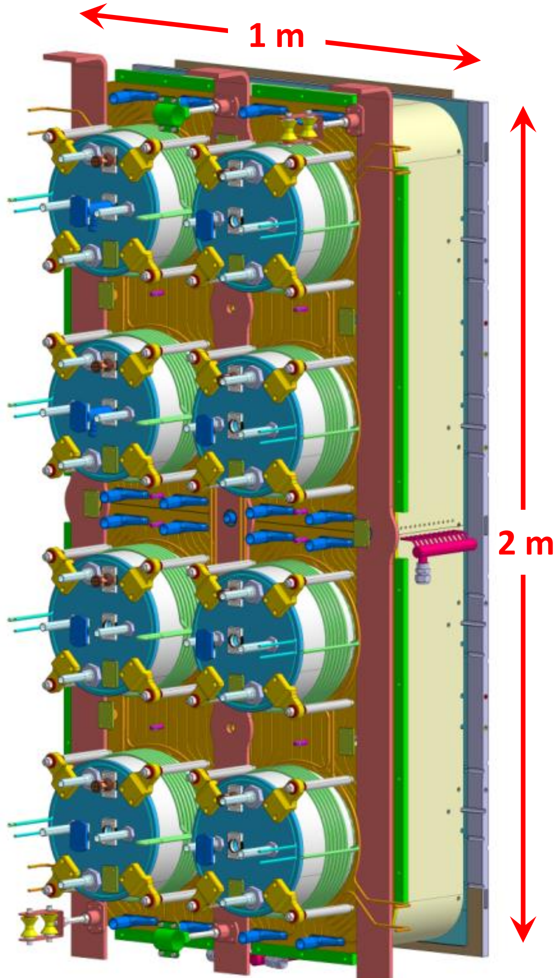
- Electrical: j_e, j_{ion}
- Calorimeter: j_{ion}, beam profile

In 2007 chosen as ITER NBI reference source.

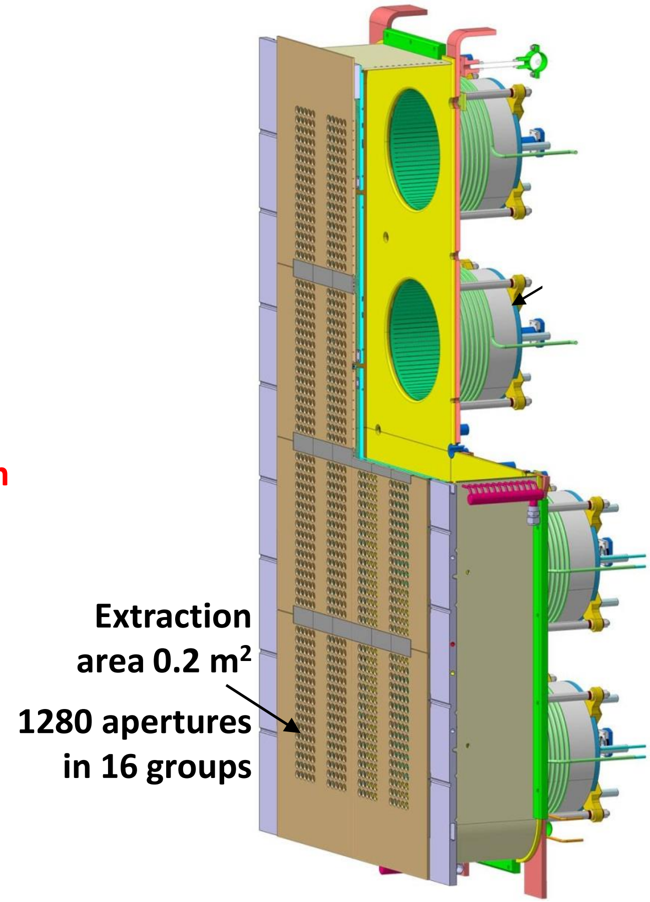
The RF ion source for ITER NBI

Prototype source





8 RF drivers with
4 RF generators of
180 kW power each



Requirements

- I_{ex} = 57 A (D^-), I_{ex} = 66 A (H^-)
- **j_D > 28 mA/cm²**, j_{H^-} > 32 mA/cm²
- **j_e/j_{D^-} < 1** (co-extracted electrons)
- Stable for **1 hour**
- **Uniform** (δ<10%)
- **p ≤ 0.3 Pa**

Achievements at test facilities: Status 2011

* stopped operation in 2011

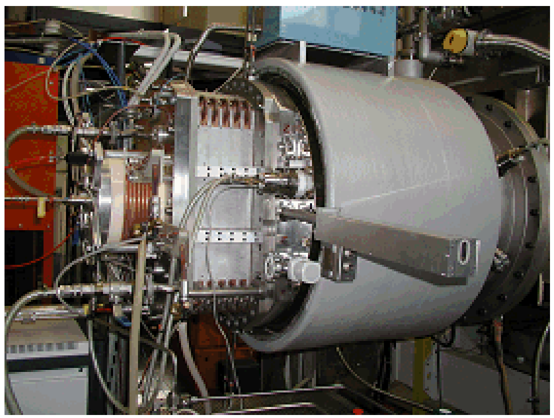
BATMAN

BAvarian Test MAchine for Negative Ions

Physical parameters

- j_{H^-} > 30 mA/cm²
- j_{D^-} > 20 mA/cm²
- j_e/j_{D^-} < 1
- 0.3 Pa

✓(4 s)



1/8 area of ITER source, 1 driver, body 32×59 cm²

MANITU*

Multi Ampere Negative Ion Test Unit

Long pulse extraction

- 3600 s ✓ (H^-)
- D^- operation ✓

at reduced parameters

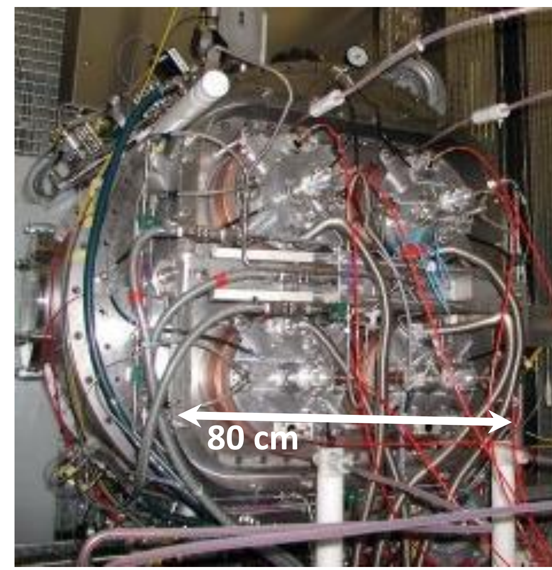
RADI*

Former RADIal Injector of W7-AS

Size scaling

- Scalability ✓
- Plasma uniformity ✓

okay



1/2 area ITER source, 4 drivers
body 76×80 cm²

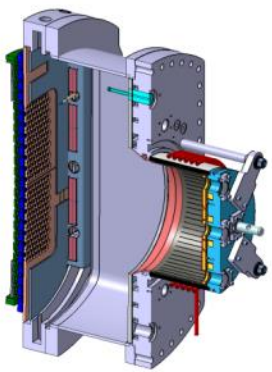
Tasks achieved BUT NOT SIMULTANEOUSLY IN ONE LARGE SOURCE

→ Task of ELISE within the F4E roadmap towards ITER NBI

The intermediate step: ELISE

Extrapolation to large ITER source within the F4E roadmap towards ITER NBI

1 driver, 100 kW
0.52 x 0.26 m²

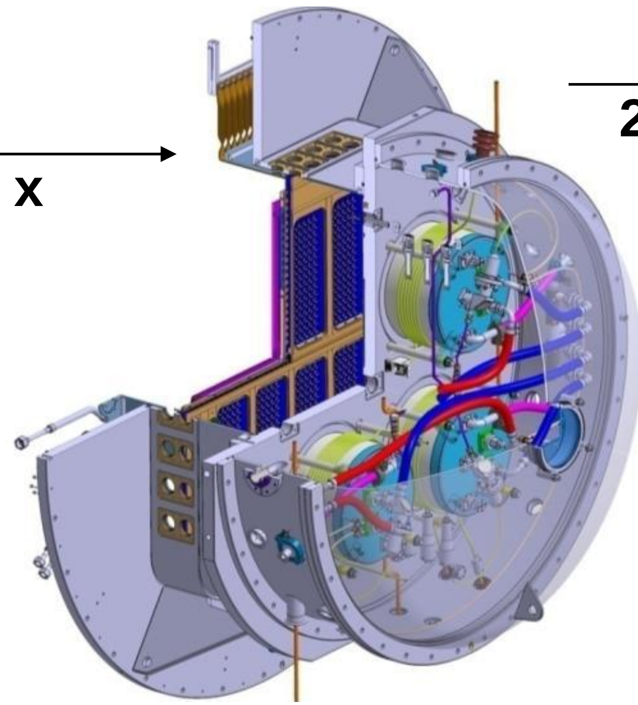


IPP prototype source

ITER reference source since 2007

4 x

4 driver, 360 kW
1.0 x 0.9 m²

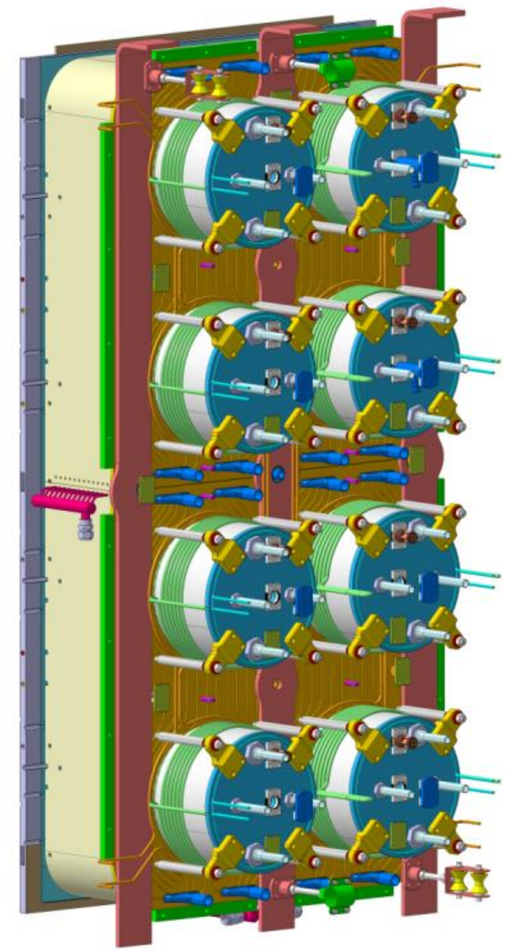


Intermediate step: ELISE

Extraction from a **L**arge **I**on **S**ource **E**xperiment

2 x

8 driver, 800 kW
1.9 x 0.9 m²



Heating & Diagnostic beam

European NBTF (Italy)

Neutral **B**eam **T**est **F**acilities

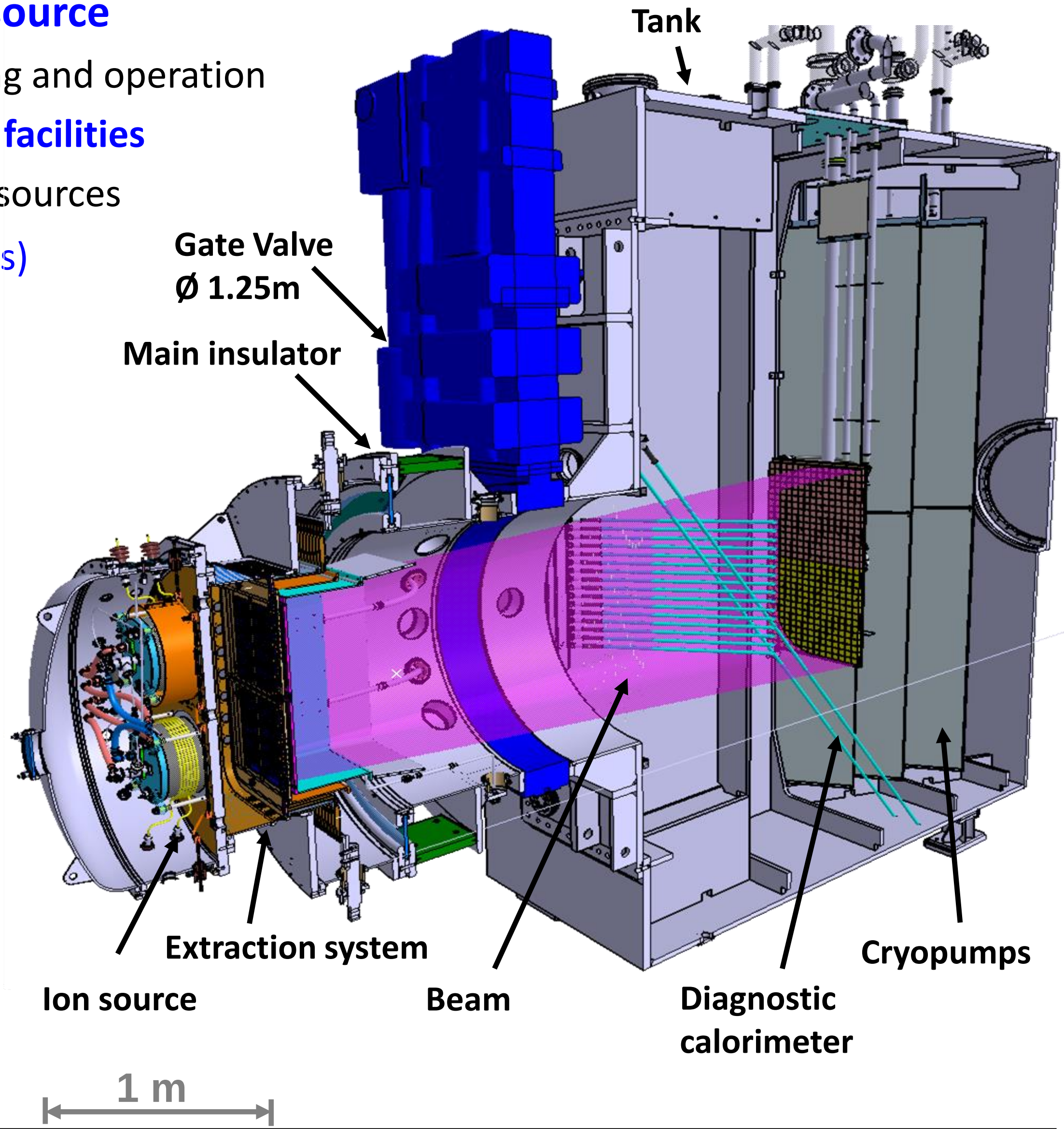
The ELISE test facility

ELISE test facility with a ½-size ITER source

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

Parameter and targets

Isotope H⁻, D⁻
RF power = 2 x 180 kW in 4 drivers
A_{ex} = 1000 cm², **uniformity > 90%**
$I_{ion,acc}$ = 20 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 120 - 150 s (HV)



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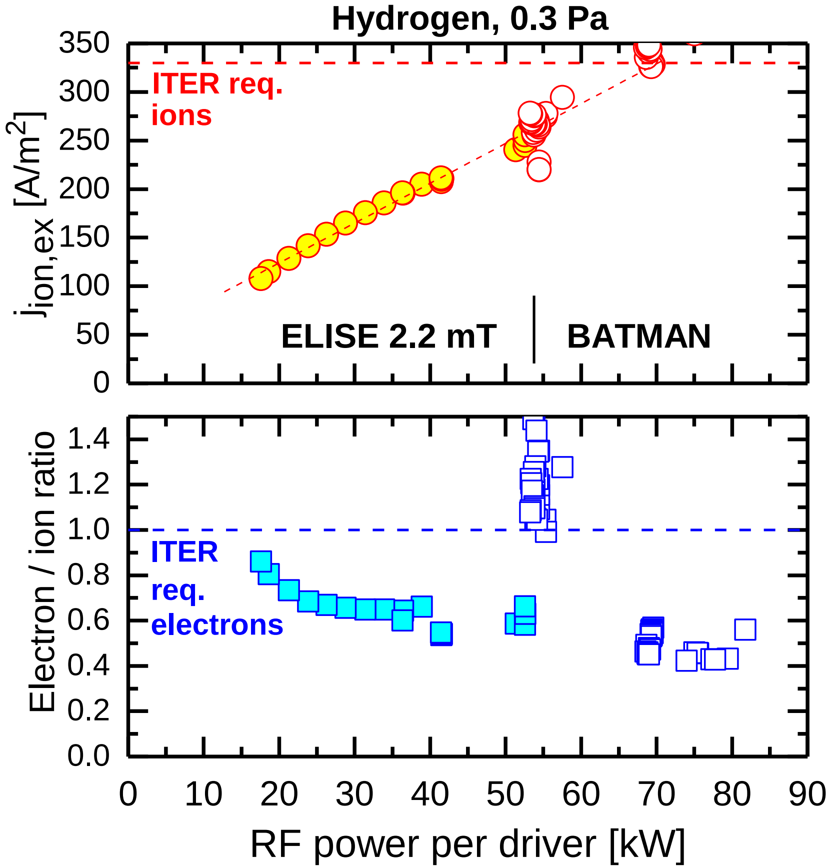
Plasma: 3600 s Beam : 10 s every 120 - 150 s (HV)

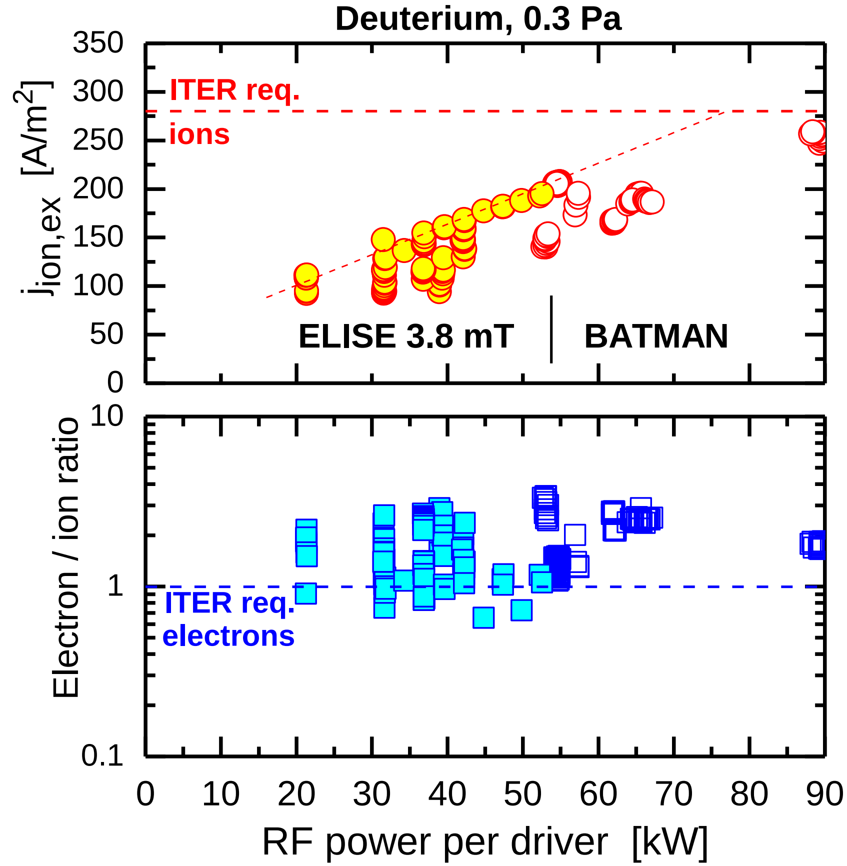
Source opening after 2 years of experimental phase

ELISE test facility – Short pulse operation

Size scaling: ELISE source performance compared to prototype source at BATMAN

20 s plasma, 10 s beam

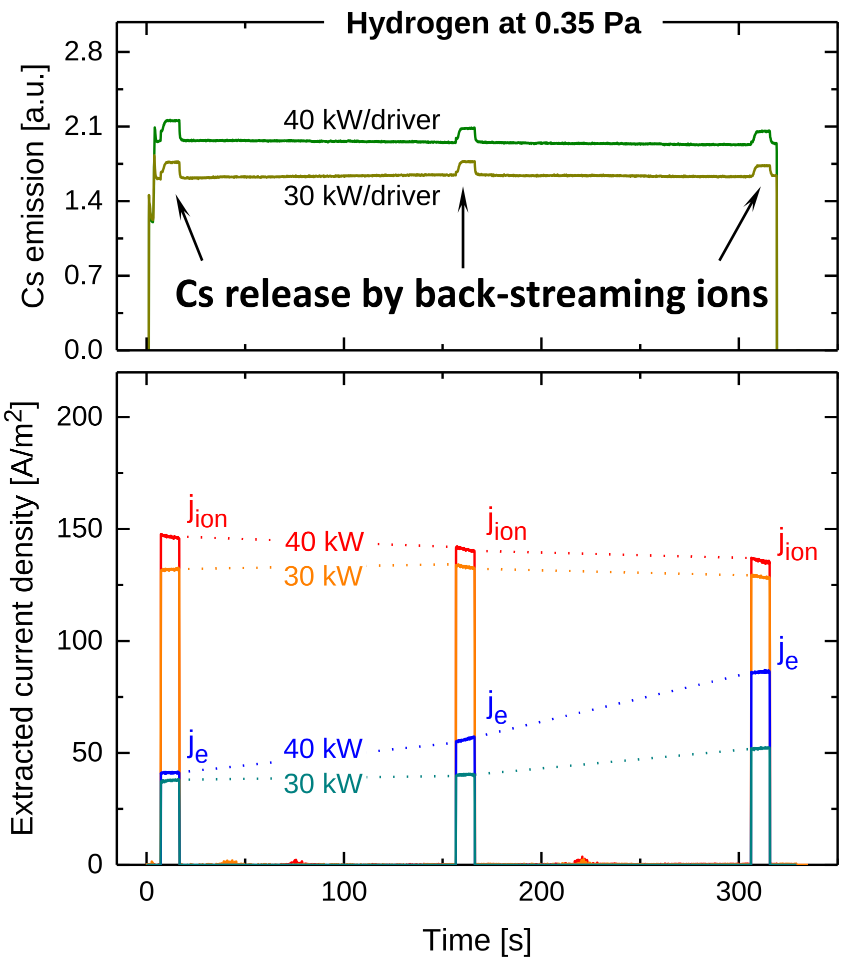


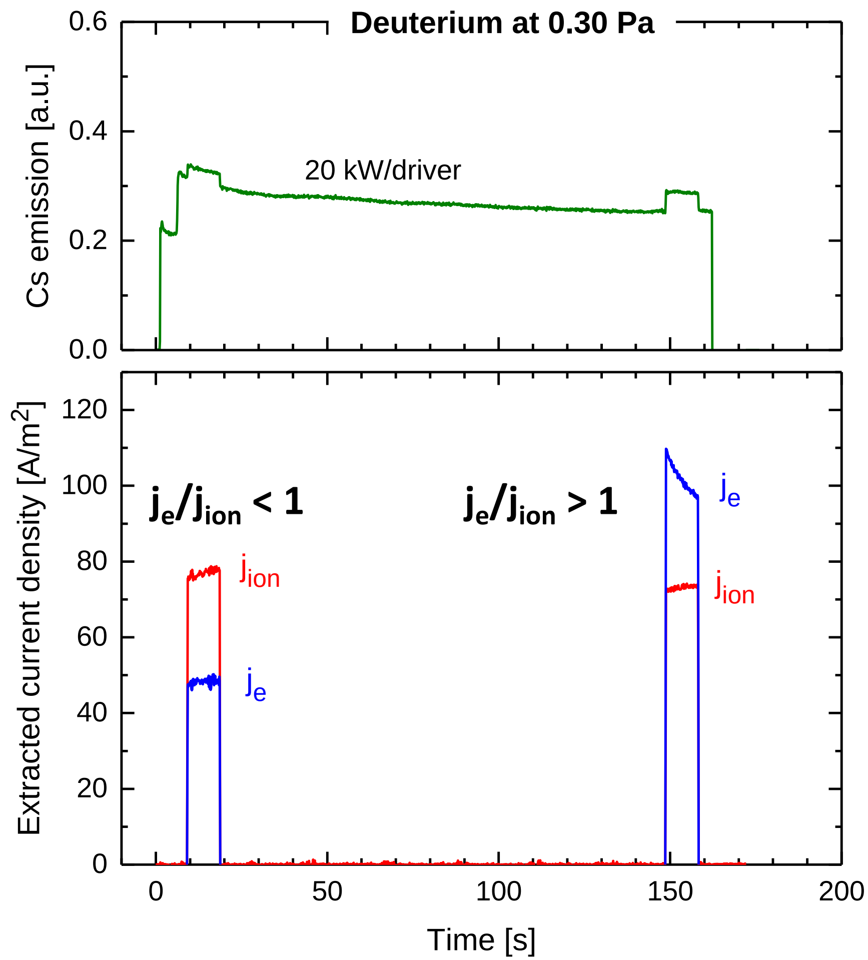


- Similar dependencies
- Lower Cs consumption than expected
- Less magnetic filter field needed
- 80 kW/driver should be sufficient

ELISE test facility – Towards long pulses

Stable ion currents (within 5%) but high dynamics of co-extracted electrons





Co-extracted electrons limit source performance, in particular in deuterium !

ELISE test facility – Towards long pulses

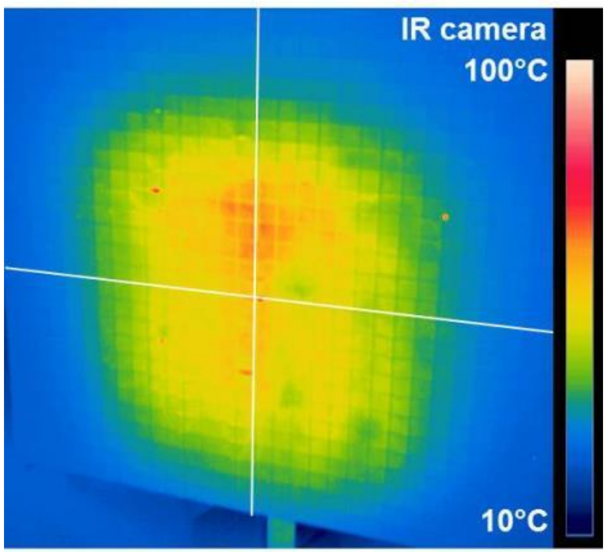
Record-setting one hour pulse at 0.3 Pa in hydrogen

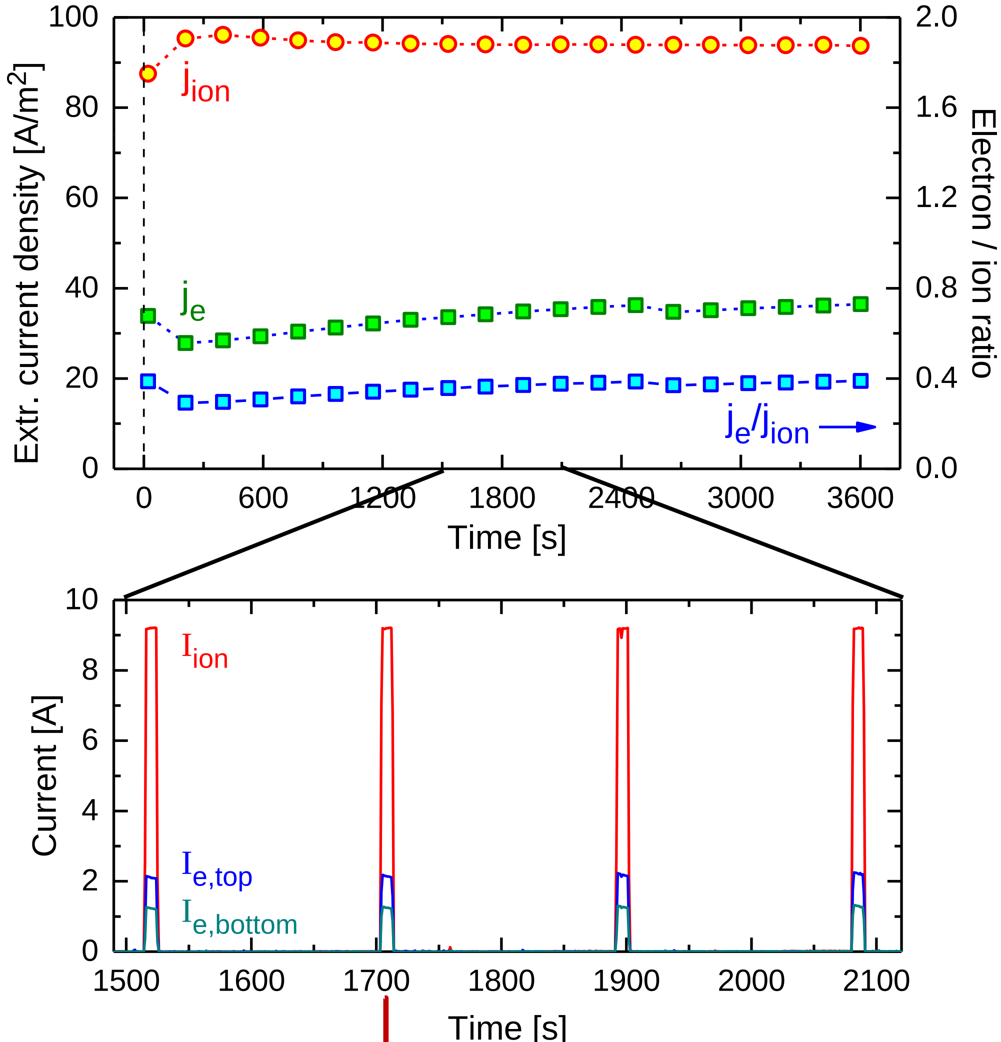
Best 3600 s pulse up to now

I_{ion} = 9.3 A, j_e/j_{ion} < 0.4

(20 kW/driver)

H^- beam on the calorimeter



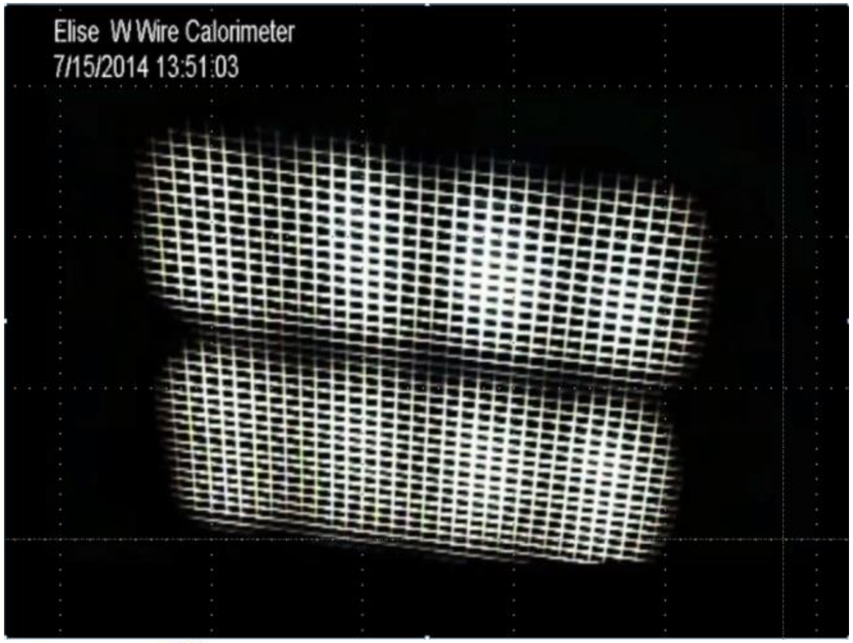


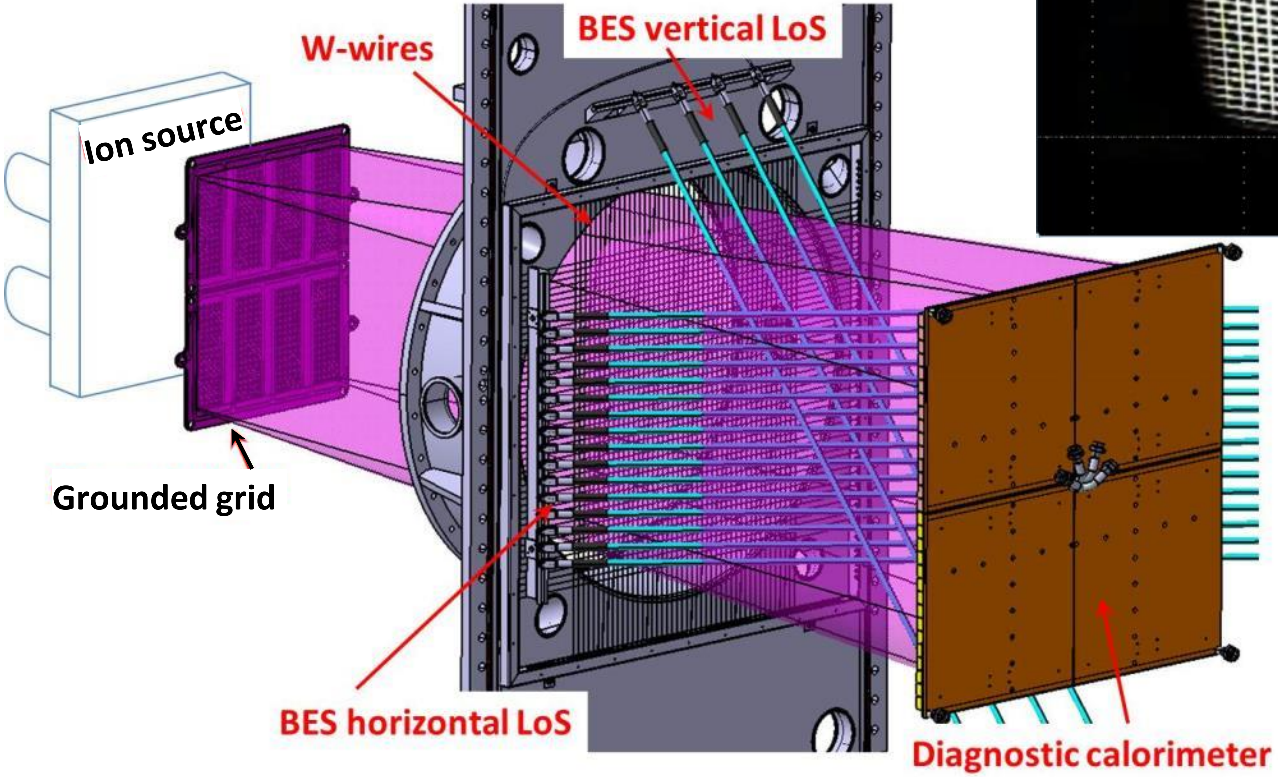
ELISE test facility – Beam diagnostics

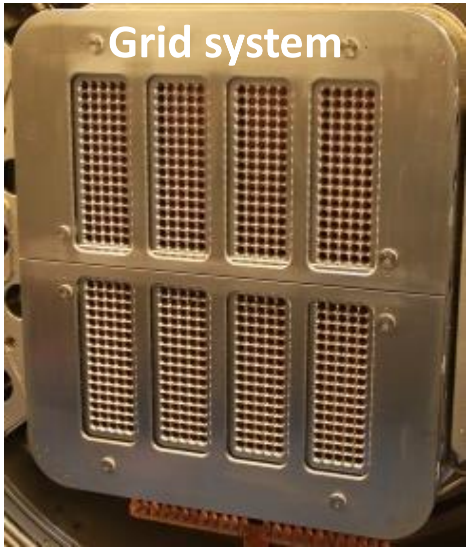
Advanced beam diagnostics

To determine beam divergence and beam homogeneity

- **Diagnostic calorimeter** with thermocouples, water calorimetry and IR data analysis
- Beam Emission Spectroscopy (**BES** with 20 LoS)
- **Tungsten wire** calorimeter







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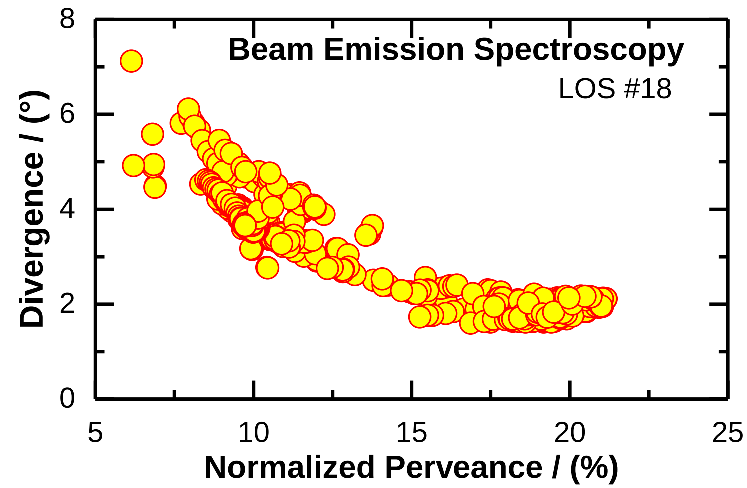
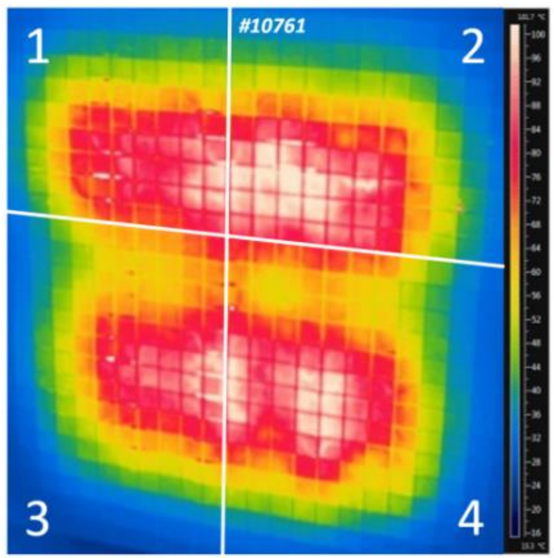
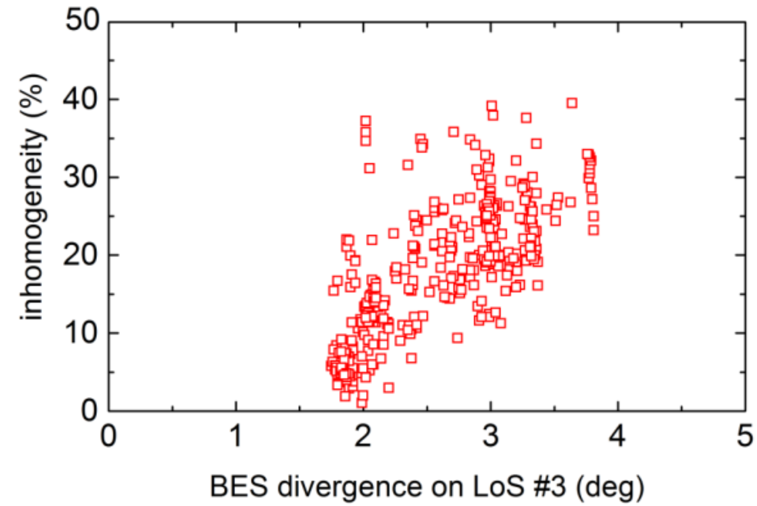






In perveance optimum: divergence between 1° and 2° and homogeneity better than 90 %

Towards 20 A Negative Hydrogen Ion Beams for Up to 1 hour

Achievements of the ELISE Test Facility

Experience in operation of large RF beam sources

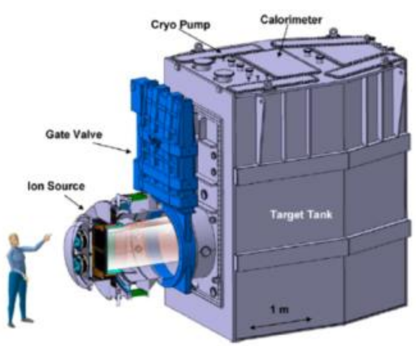
- 2½ years of successful operation
- Inspection and maintenance ✓
- **Similar dependencies as in prototype source**
- **Less Cs consumption** as expected
- **Lower magnetic filter field** needed
- **80 kW/ driver** should be sufficient
- Beam homogeneity better than 90% ✓

$I_{ion,ex}$	Pulse	Power/driver
25.5 A	20 s	52 kW
18.3 A	400 s	45 kW
9.3 A	1 h	20 kW

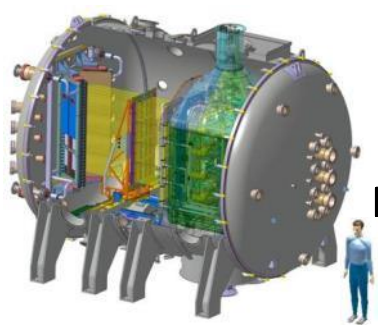
Hydrogen, 0.3 Pa, e/ion < 1

Co-extracted electrons limit source performance, in particular in deuterium !

Important step within the European roadmap for ITER NBI

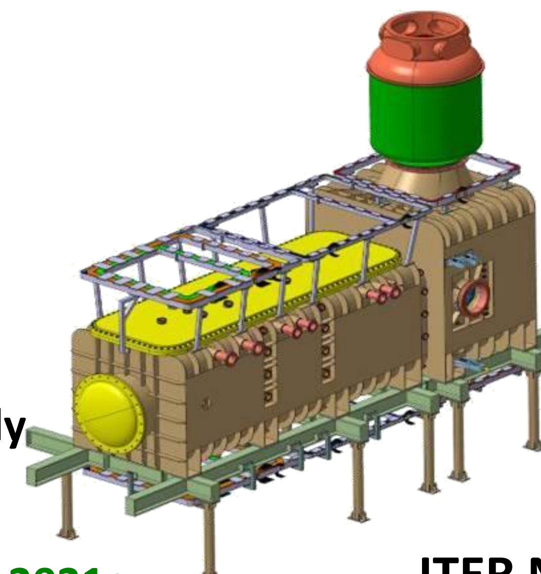


ELISE, 2012+



SPIDER, 2017+

NBTF in Padua, Italy



MITICA, 2021+

ITER NBI