Ion Sources for Fusion

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Ion sources in fusion devices

Ion sources are used in neutral beam injection systems (NBI)

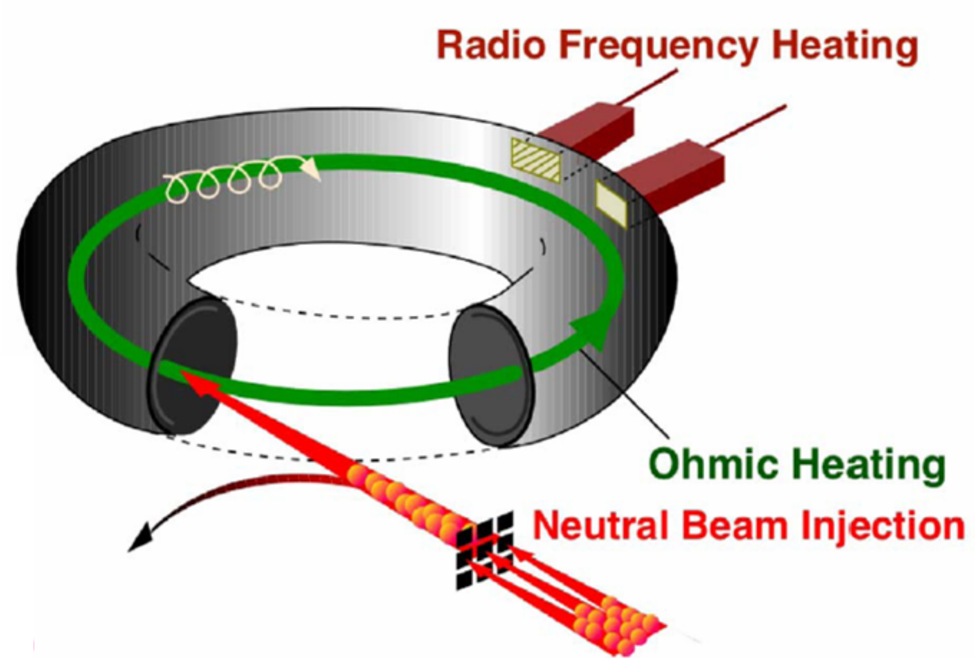
Neutral atoms can penetrate through the confining magnetic field.

Used for

Neutral beam heating

Current drive

Diagnostics beams



Outline

- **Plasma heating by neutral beam injection**
- Positive Ion sources for Neutral Beams
- Negative ion based neutral beam injection
- Beam extraction
- Production of negative ions
- Negative ion sources
- Experimental results with the RF prototype
- Giant source for ITER
- Test facilities

NBI: the work horse

NBI heating is dominant in most large past, present, and planned tokamaks

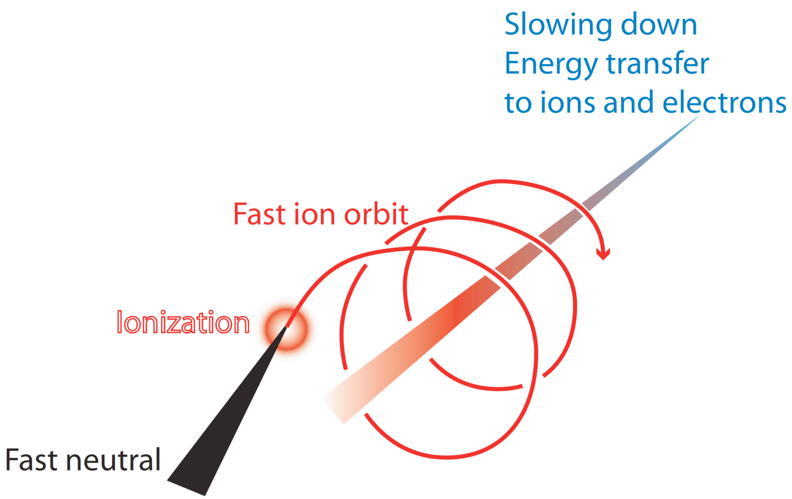
	R_0 (m)	a (m)	I_p (MA)	B_t (T)	Installed heating power (MW)				
					P-NBI	N-NBI	ECRH	ICRH	LH
ITER	**6.2**	**2.0**	**15**	**5.3**	**-**	33	**20**	**20**	**-**
JET	**2.96**	**1.25**	**4.8**	**3.45**	**34***	**-**	**-**	**10**	**7**
JT-60U	3.4	1.1	5	4.2	40	3	4	7	8
JT-60SA	**2.97**	**1.17**	**5**	**2.25**	**24**	10	**7**	**-**	**-**
TFTR	2.4	0.8	2.2	5	40	-	-	11	-
EAST	**1.7**	**0.4**	**1.0**	**3.5**	**-**	**-**	**0.5**	**3**	**4**
DIII-D	**1.67**	**0.67**		**2.1**	**20**	**-**	**5**	**4**	**-**
ASDEX Upgrade	**1.65**	**0.65**	**1.2**	**3.1**	**20**	**-**	**6**	**8**	**-**

*recently upgraded

Neutral beam heating: trapping and penetration

Interaction of fast neutrals with the plasma

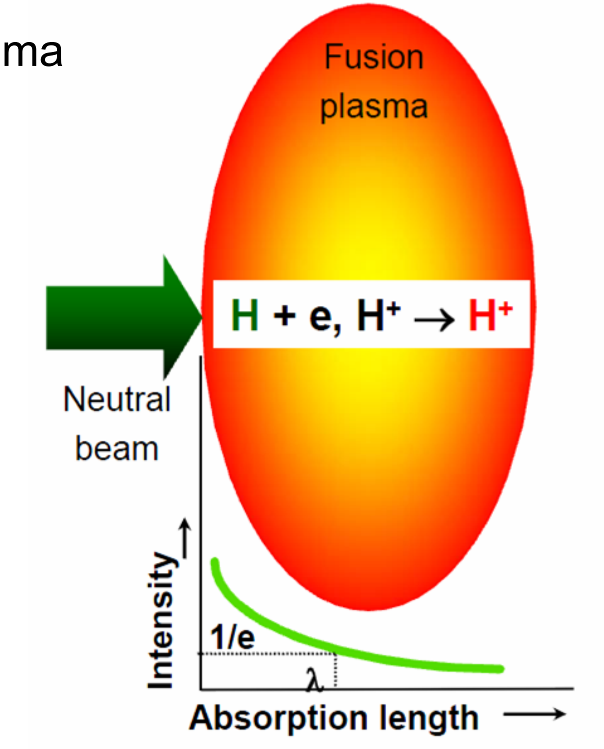
- ionisation by collisions with plasma electrons and ions
- drift of the fast ions in the magnetic field
- collisions of the fast ions with plasma ions and electrons => slow-down and scattering
- charge exchange collisions with background neutrals



Penetration depth

Attenuation of the beam in an uniform Hydrogen plasma

$$I = I_0 e^{(-x/\lambda)}$$



Approximation for the absorption length for ionisation

n in $10^{19} m^{-3}$, A in amu, E in keV

$$\lambda = \frac{E}{18 \cdot n \cdot A} [m]$$

Penetration depth depends on the energy

Example AUG: 100 keV D beam, $n_e = 5 \times 10^{19}\ m^{-3} \Rightarrow \lambda = 0.5\ m$

Fraction not absorbed by the plasma : shine-through

determines minimum plasma density

Slowing down – power to the ions and electrons

Change of energy of a fast ion

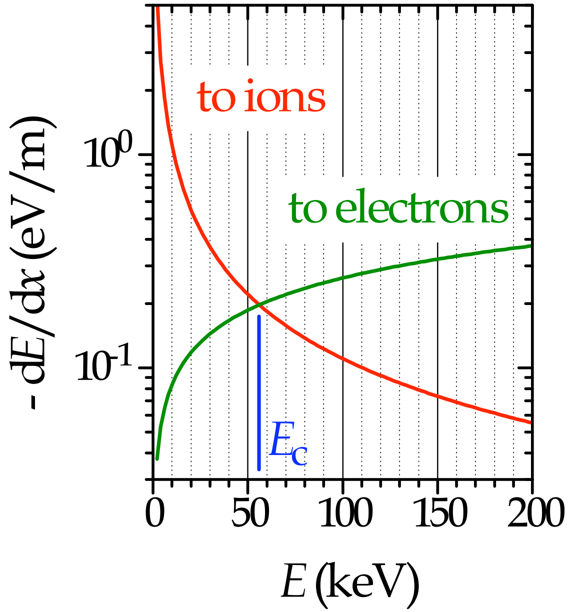
$$\frac{dE}{dx} = \underbrace{-\frac{\alpha}{E}}_{\textbf{to ions}} \underbrace{-\beta\sqrt{E}}_{\textbf{to electrons}}$$

Stopping by ions and electrons is equal at the

“Critical energy” E_c

NBI: D^0, plasma: D^+

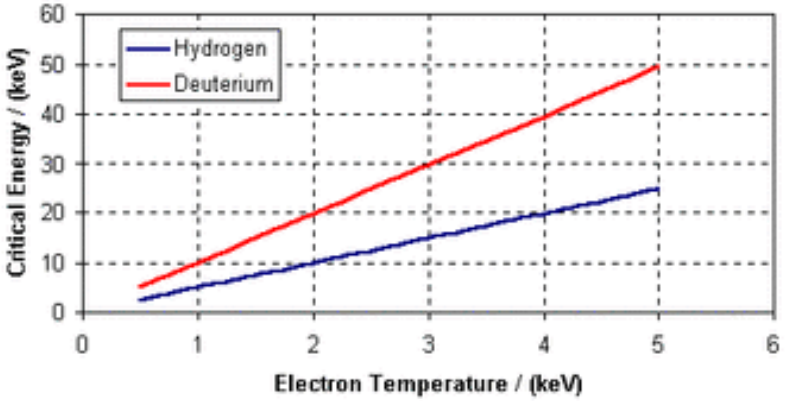
$n = 5 \times 10^{19}\,\mathrm{m}^{-3}$, $T_e = 3\,\mathrm{keV}$



E_c depends on the electron temperature

Lower energy of $E_0/2$ and $E_0/3$

=> **Ion heating dominates for E_0 < 100kV**



Neutral Beam Current Drive (NBCD)

Why Current Drive (CD) ?

- **Tokamaks:** Plasma current is driven inductively (principle: transformer).

  => pulsed operation

  ⇒ for reactor: pulsed energy production, pulsed forces and heat loads on components → reduced lifetime. Therefore aim (e.g. on ITER)

  - "stationary tokamak" - completely non-inductive CD
  - enhanced pulse length - significant part of I_p non-inductive CD

- **Local modification of plasma current profile – $j_P(r)$**

  to improve plasma confinement *(internal transport barriers, improved H-mode)* and/or plasma stability *(NTM stabilisation)*

- Each of the heating systems foreseen for ITER is able to drive plasma current

  ⇒ "Heating & Current Drive Systems"

Principle - Driving Toroidal Plasma Current by NBI

The toroidally circulating fast ions - when slowing down - represent a

- current ("fast ion current")

This fast ion current is modified by the interaction of the fast ions with the plasma, but generally some net current remains:

→ **Neutral beam driven current**

I_{NBCD}

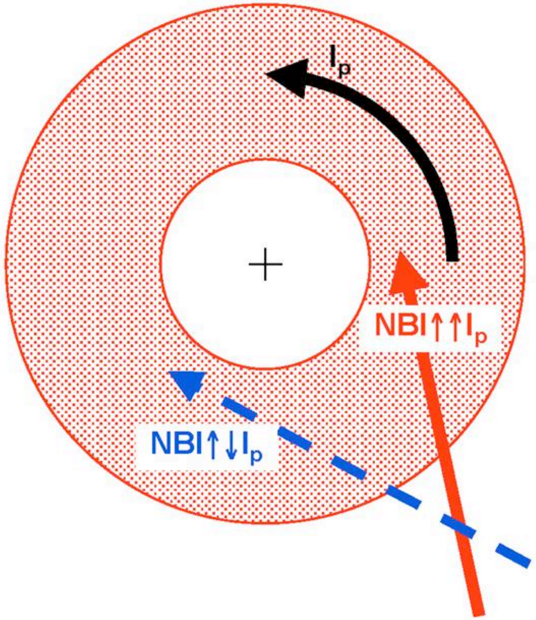
Current drive efficiency

$$\eta_{CD} = \frac{I_{NBCD} n_e R}{P_{dep}}$$

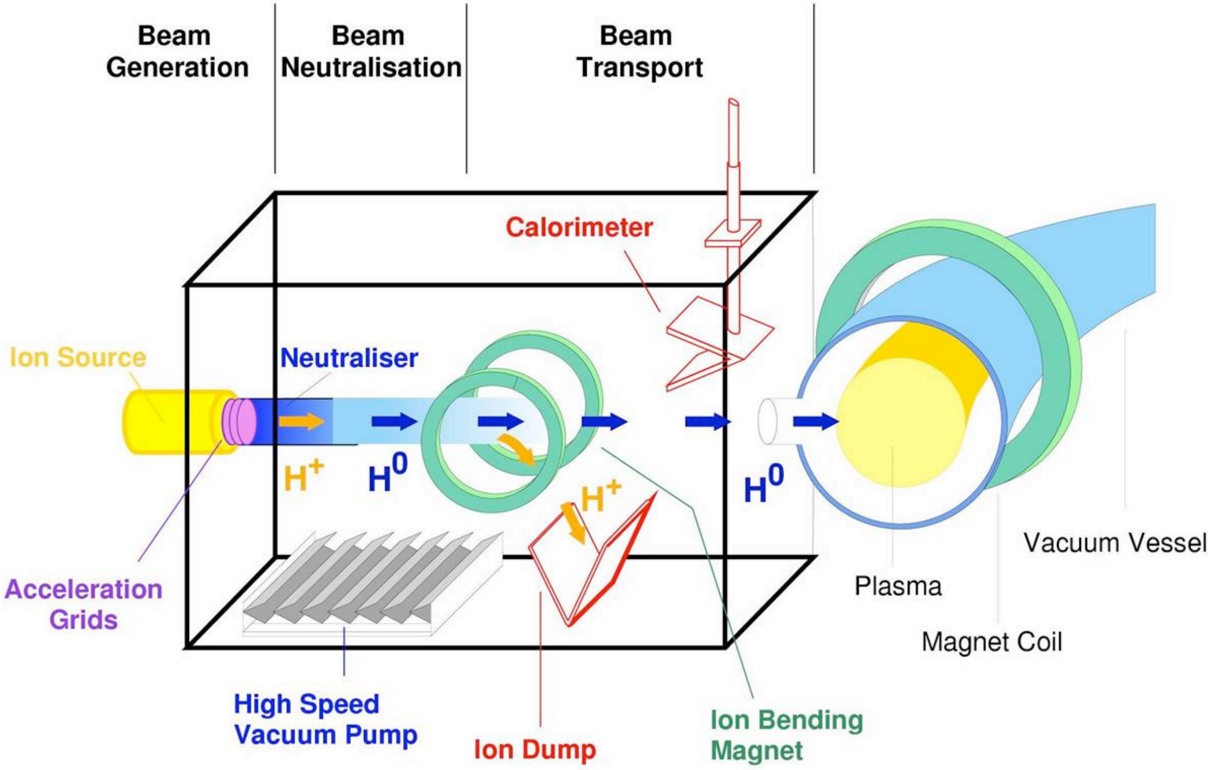
R major radius
P_{dep} deposition power

At present about 0.2 – 0.3

top view



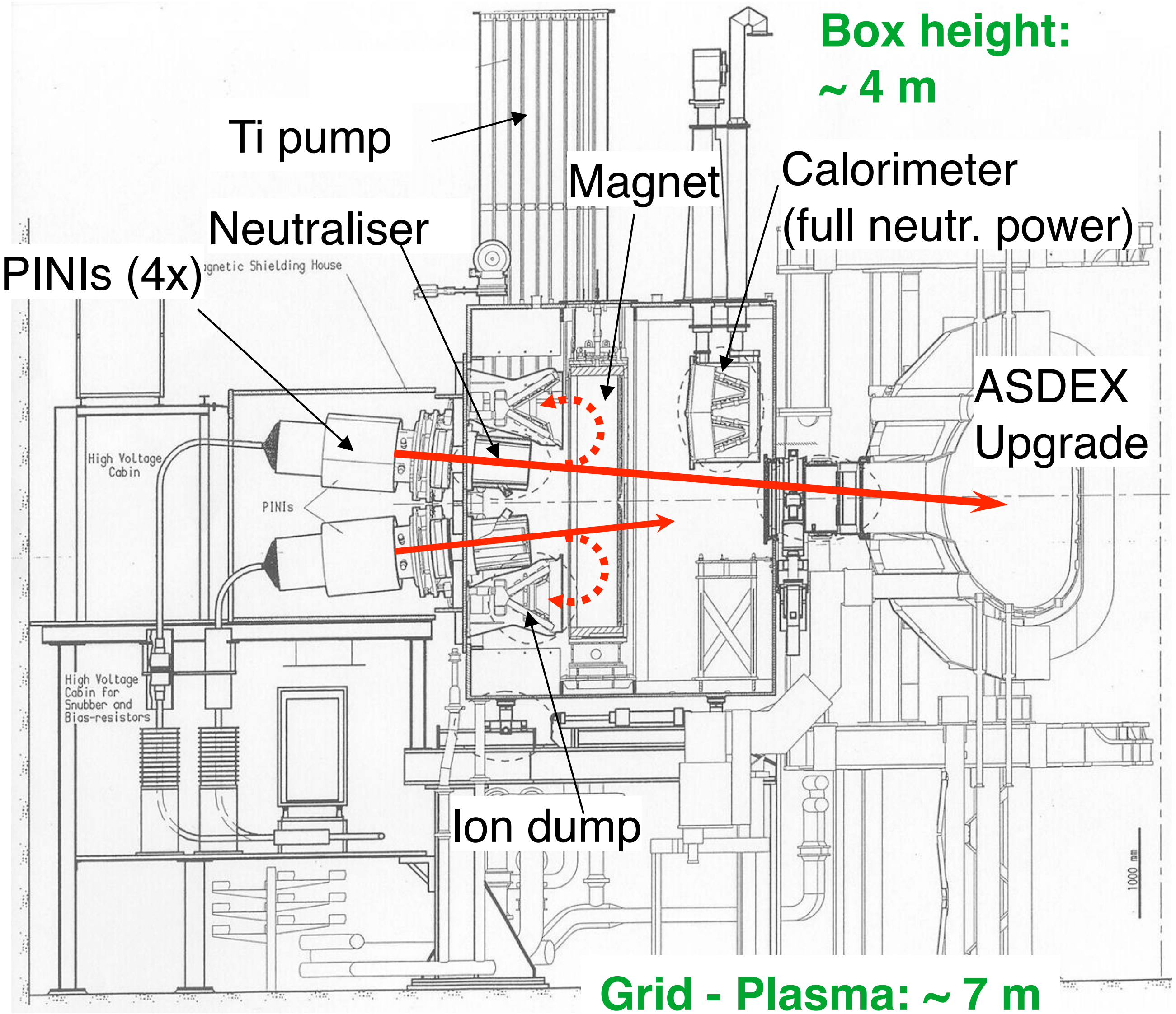
Neutral Beam Systems



Neutral beams are produced by:

- Powerful ion beam by the ion source and the extraction system
- Neutralisation by charge exchange collisions of the fast ions with the cold gas in the neutralizer
- Not neutralised part of the beam is deflected to the ion dump
- The beam power is measured by a calorimeter

The ASDEX Upgrade NBI System (Garching, Germany)



Box height: ~ 4 m

Ti pump

Magnet

Calorimeter (full neutr. power)

Neutraliser

PINIs (4x)

ASDEX Upgrade

Ion dump

Grid - Plasma: ~ 7 m

NBI system of JET (Joint European Torus, Culham, UK)

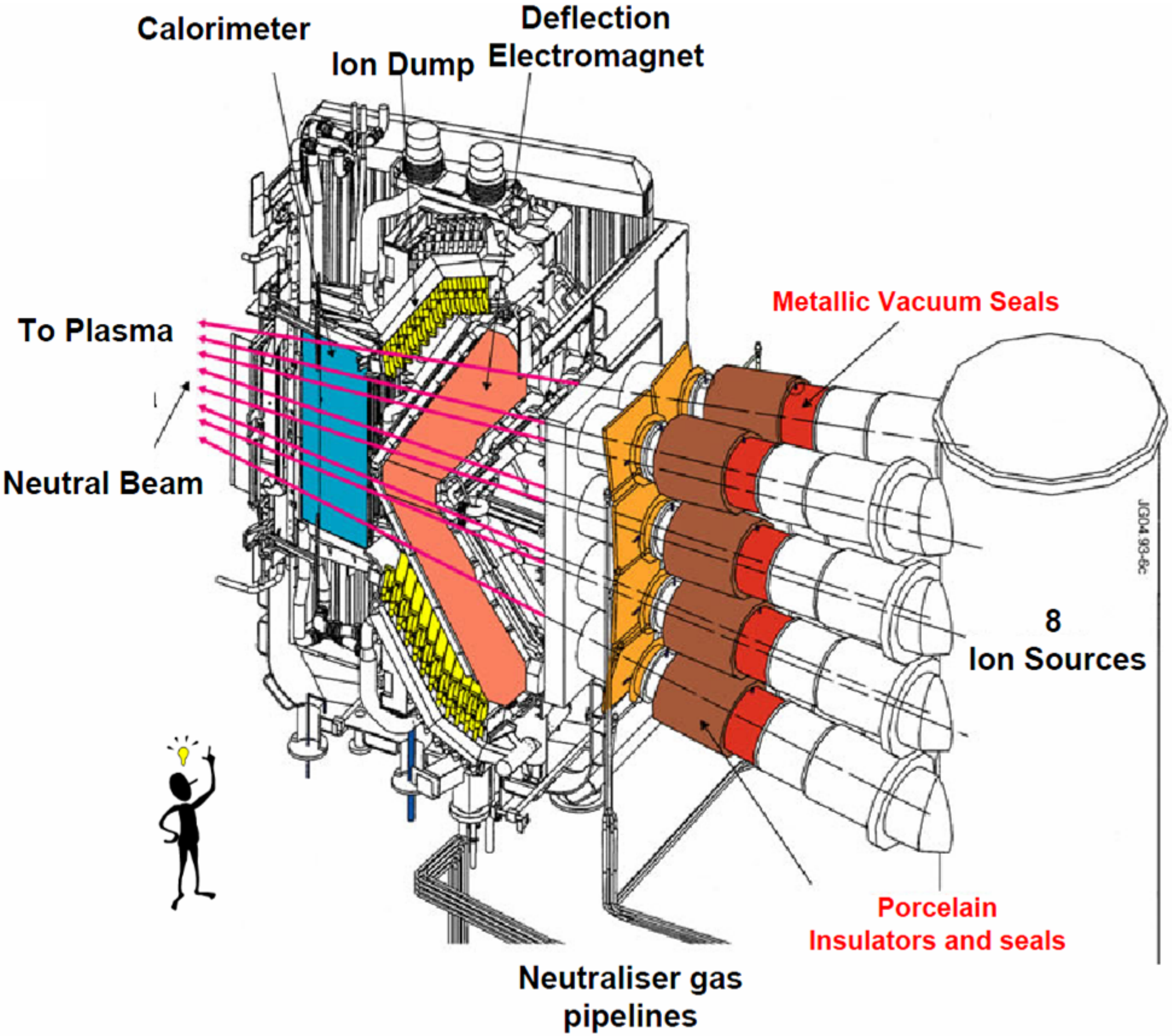
3 beamlines

with 8 sources each,

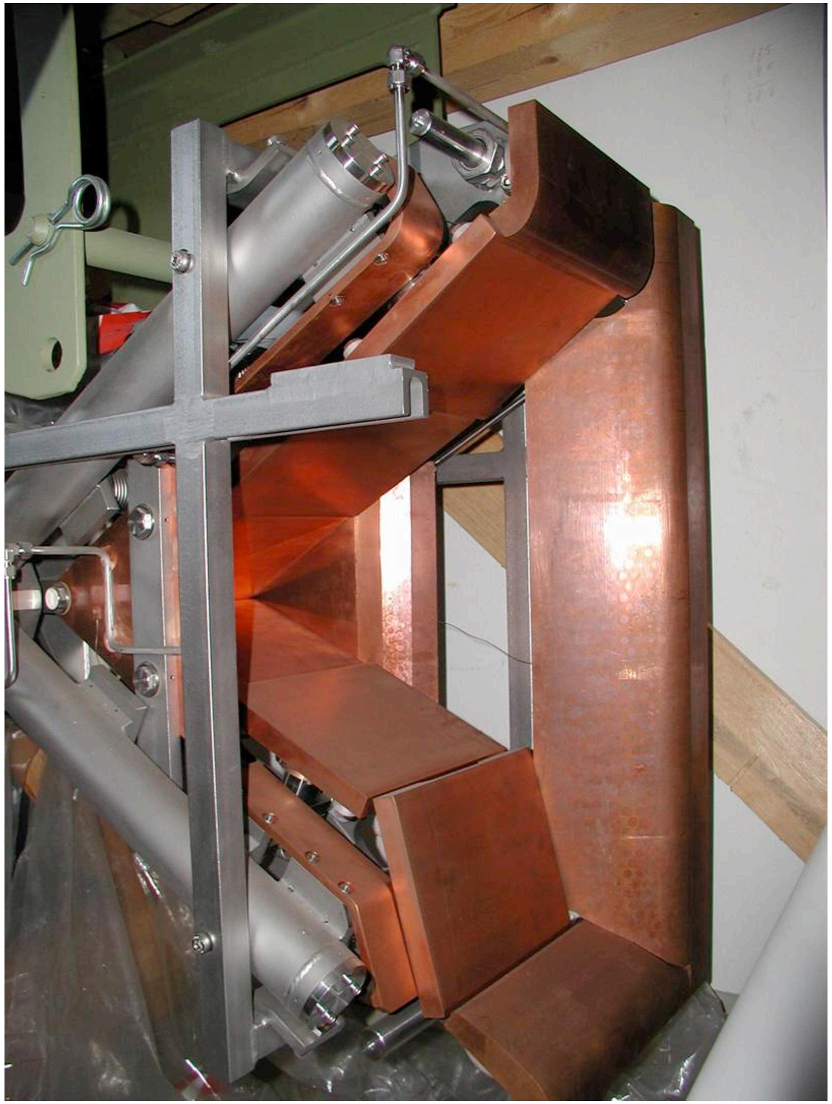
Beam energy

80 keV (H)

130 keV (D)



Residual Ion Dump of ASDEX Upgrade



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Positive ion sources

Requirements:

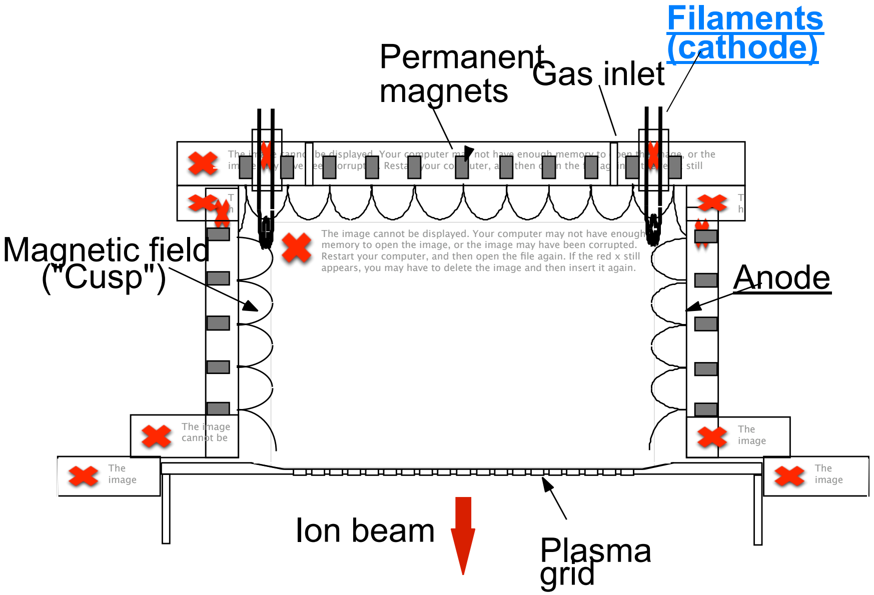
Beam species	H_n^+, D_n^+
Beam current	30 – 90 A
Current density	**230 – 300 mA/cm^2**
Beam energy	55 – 160 keV
Proton fraction (H+, D+)	70 – 90 %
Pulse duration	< 10 s
Plasma homogeneity	
on the plasma grid	< +/-10%

Types:

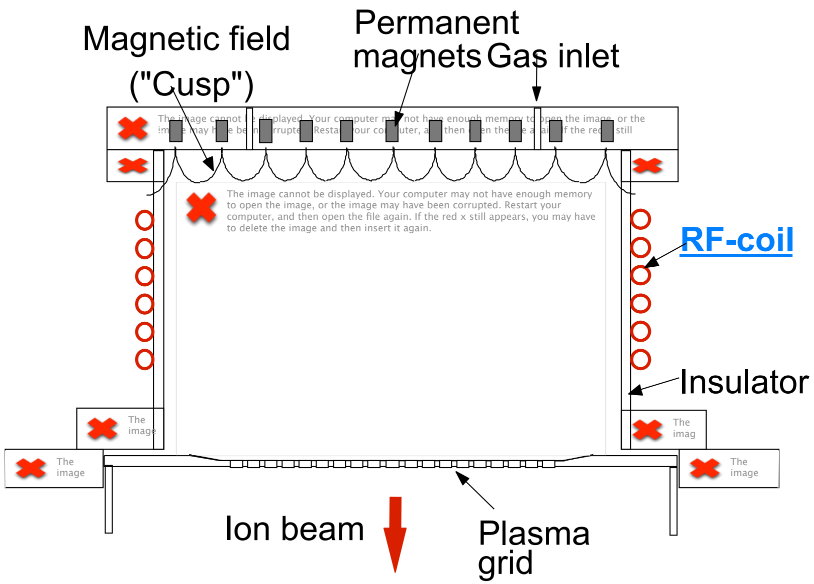
- **Arc sources**, filament based
  - Periplasmatron,
  - magnetic multipole ion source, “bucket source”
- **RF source**

Arc and RF sources

Arc source



RF source



Advantages of the RF source

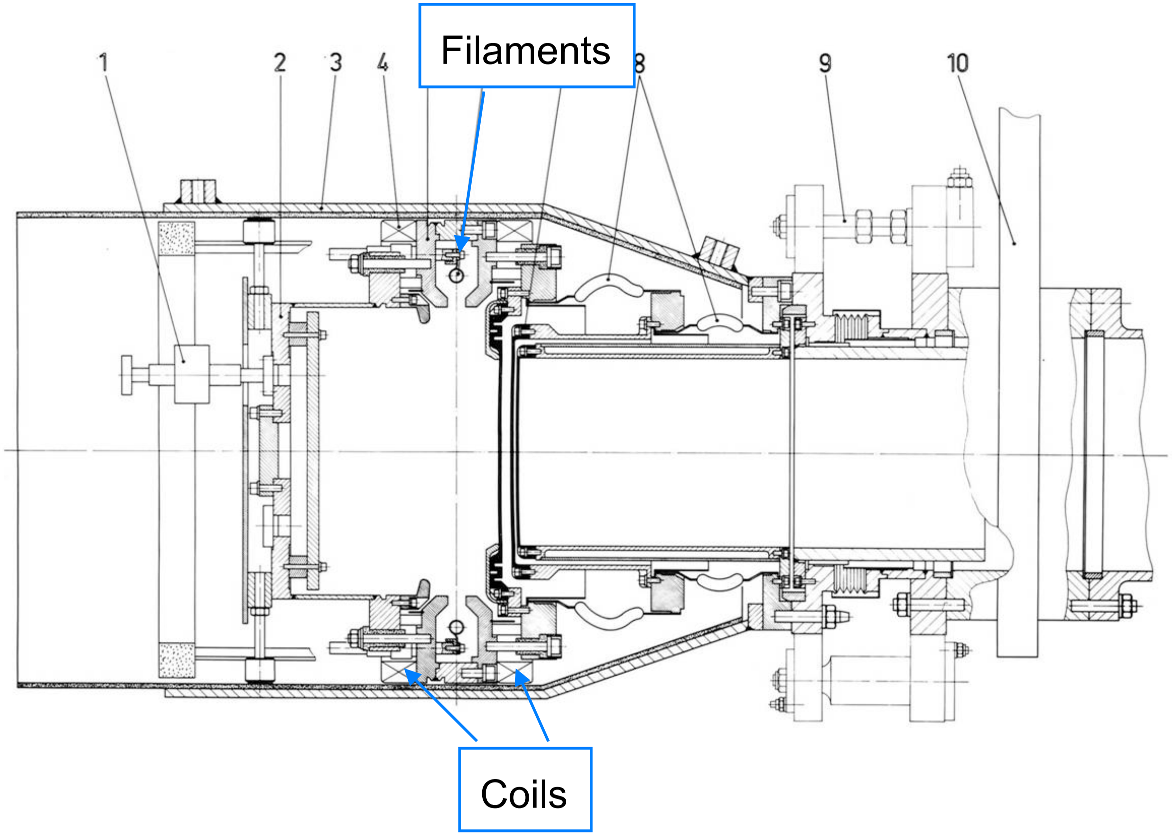
- No filaments => no lifetime limitations
- Cost saving due to the cheaper power supply
- Power supply on ground potential (separation by a transformer)

=> RF sources used in the second injector of ASDEX-Upgrade since 1997

Arc sources: Periplasmatron ion source (Fontenay-aux-Roses)

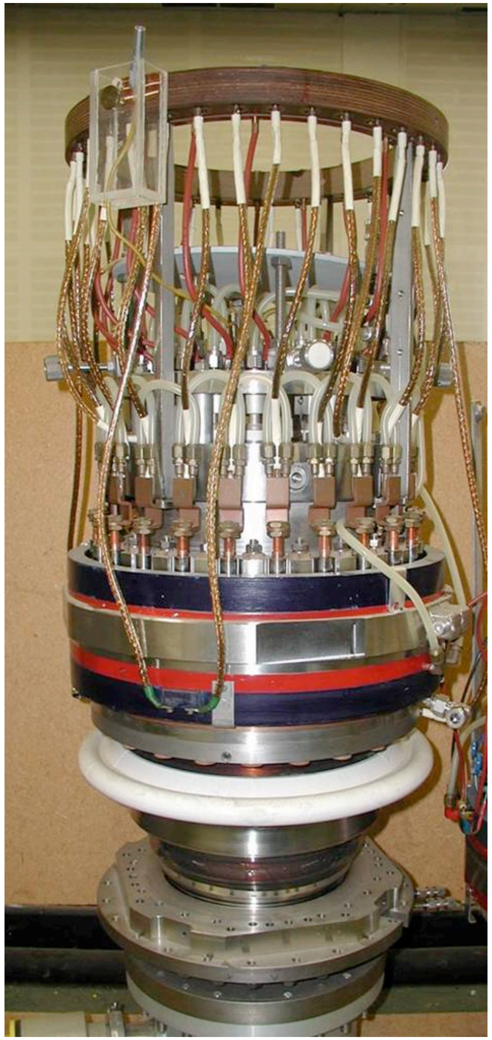
Used on **ASDEX** (20 A, 55 keV)

- Close to the extraction system radially arranged filaments
- Source back plate as anode
- Cusp field by two coils around the cathode to compensate stray fields and for confinement of the electrons

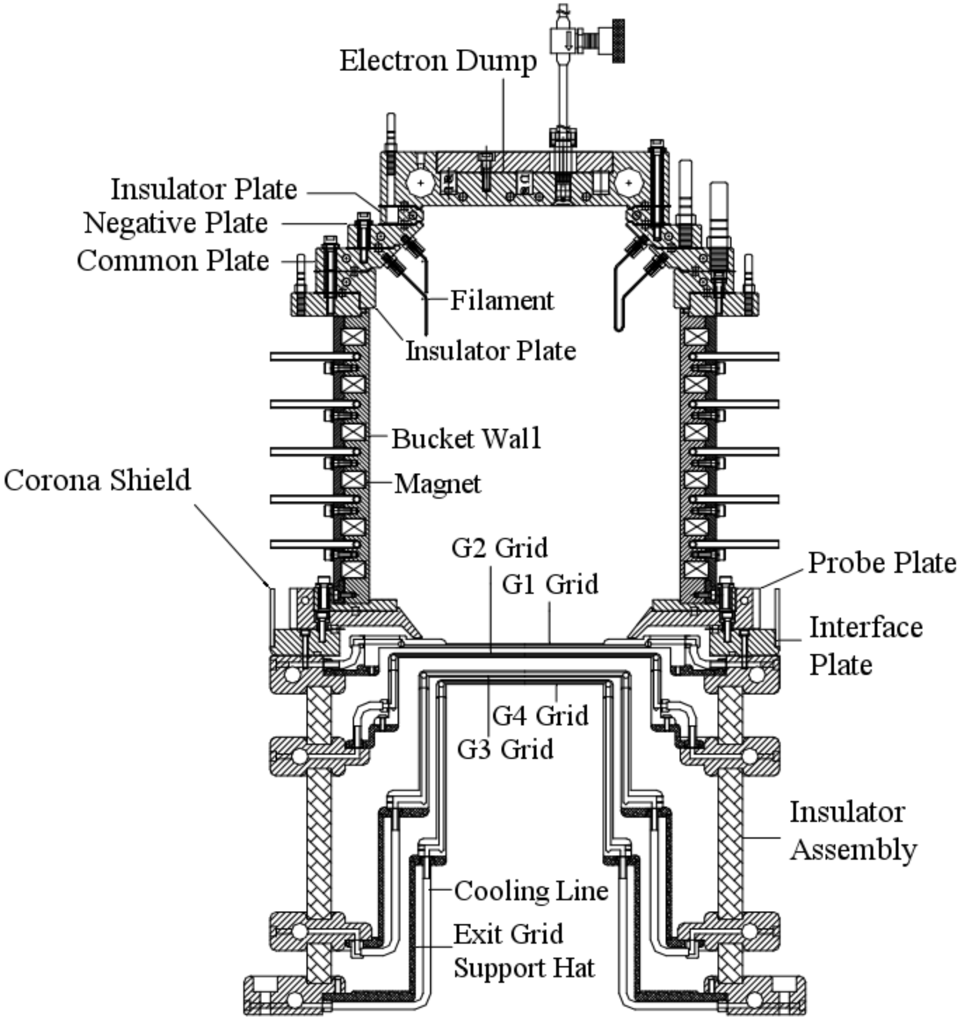


Filaments

Coils



Arc sources: TFTR source



Upgraded version used at KSTAR (Korea)

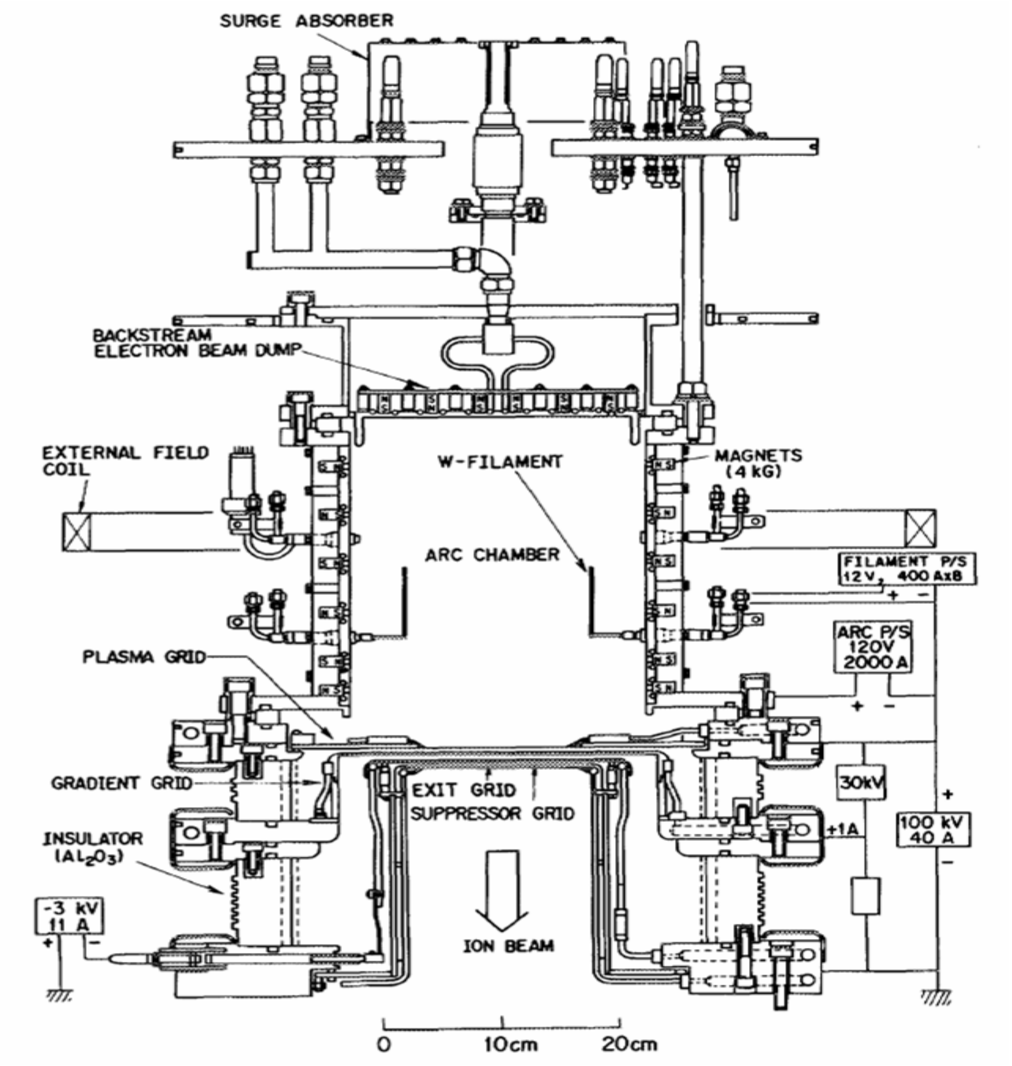
Accelerator Part : Circular Aperture Grids

- Designed Energy	100 keV (H)
- Designed Current	55 A (H)
- Pulse Length	300 s
- Aperture Size	7.6 mm
- Extraction Hole No.	562
- Beam Size	12.5 x 45 cm^2
- Transparency	49 %
- Beam Divergence	1 deg

Plasma Chamber : Cusp Bucket

- Current Density	> 210 mA/cm^2
- Plasma Volume	26 x 64 x 32 cm^3
- Hydrogen Ion Ratio	> 80 % (H^+)
- Filaments (1.2 mm W)	32
- Max. Arc Power	120 kW

Arc sources: JT-60-NBI positive ion source



Beam energy : 100keV

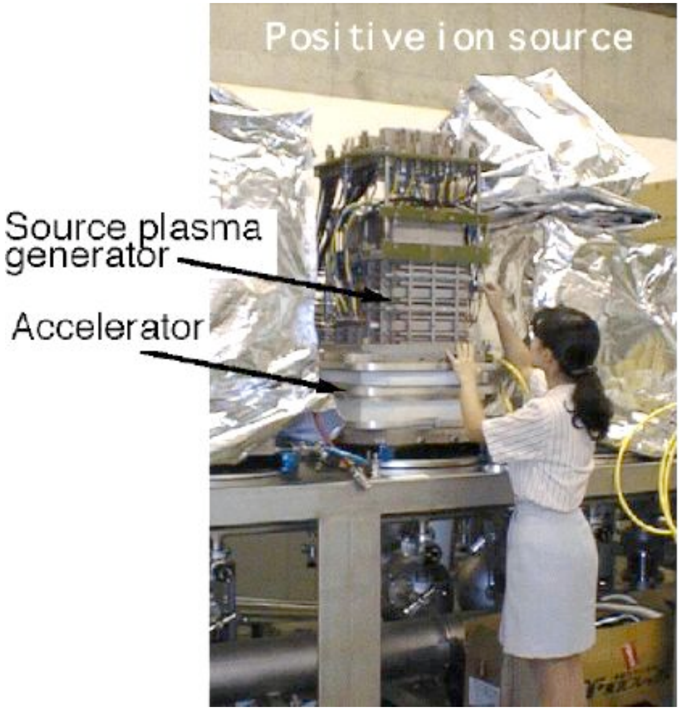
Beam current : 40A

Beam species : D/H/3He/4He

Extraction area : 12 × 27 cm^2

D+ : D2+ : D3+ = 90 : 7 : 3

No of ion sources : 28

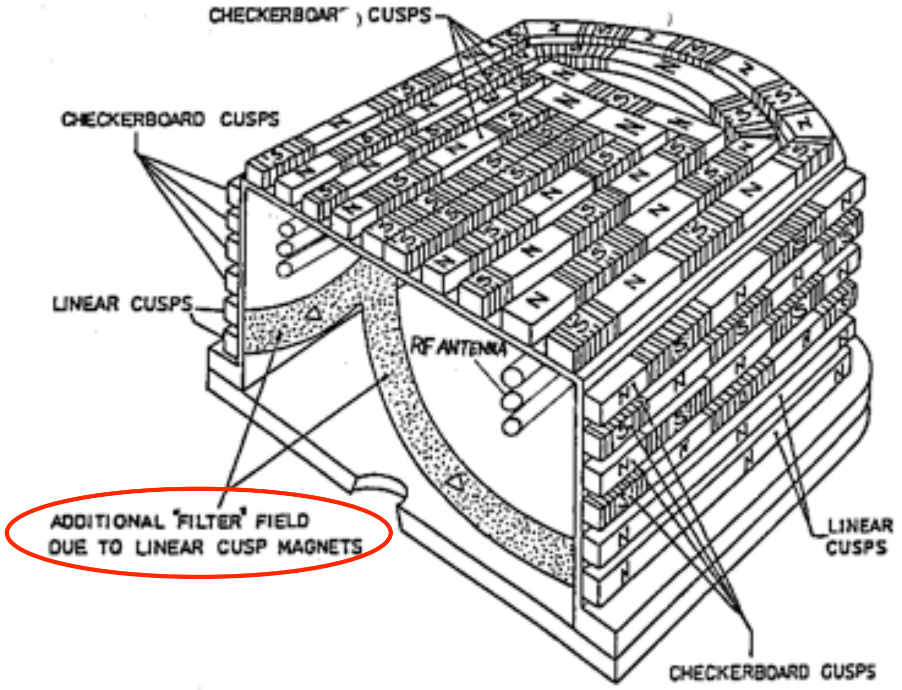


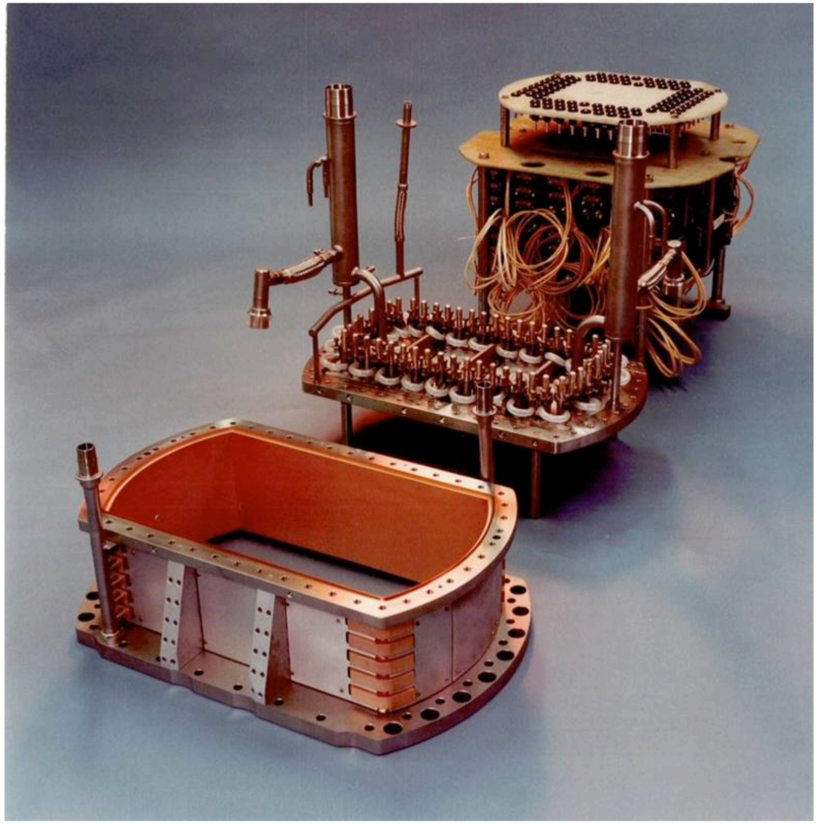
Arc sources: “Bucket” source

Used at **ASDEX-Upgrade, Textor, JET**

$I_{ARC} \leq 1000$ A, $U_{ARC} \sim 120$ V

- 24 filaments
- Water-cooled Copper chamber with confinement magnets
- B x L x H = 30 x 60 x 19 cm^2
- Arc power 120 kW





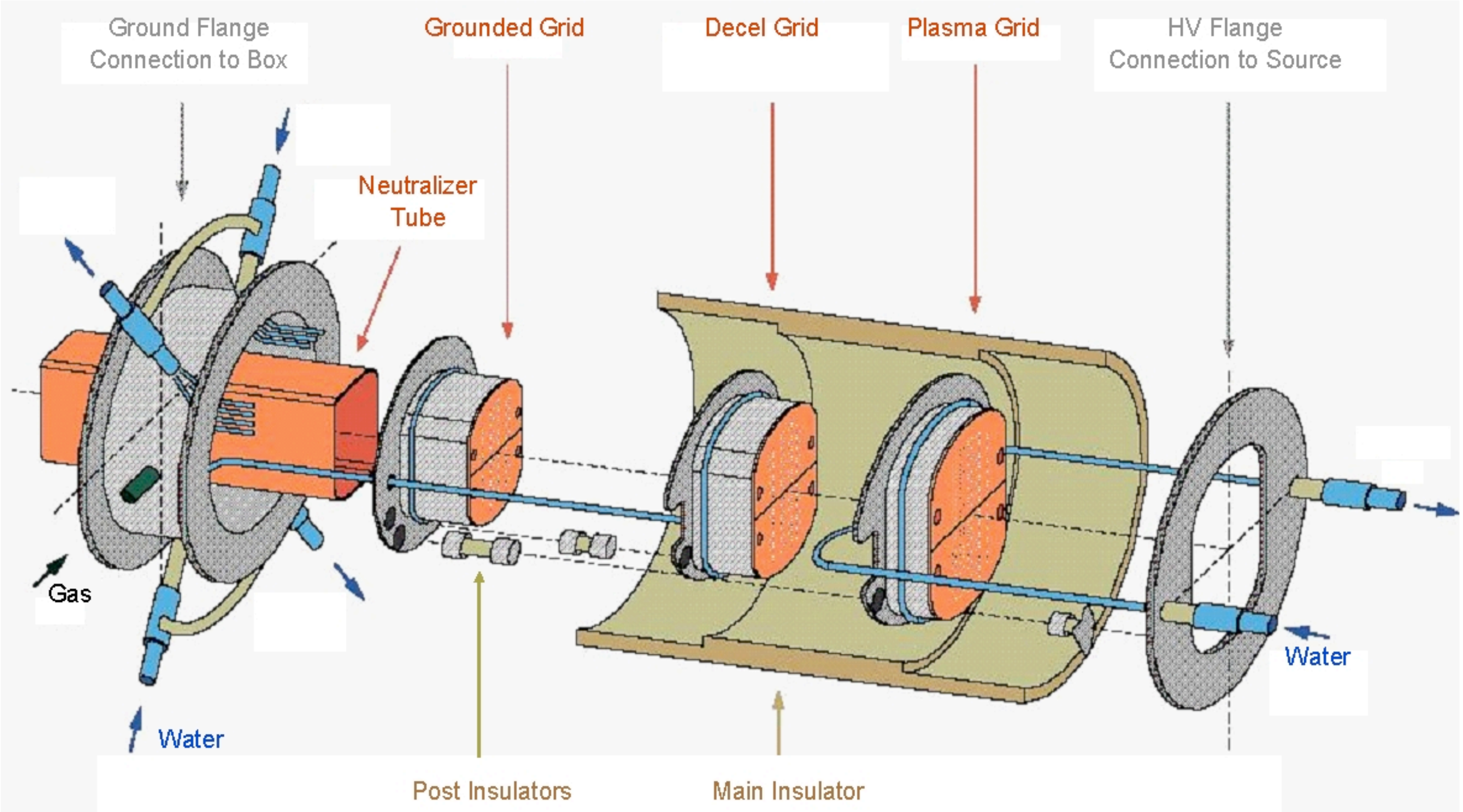
“Tent” filter

to reduce the electron temperature

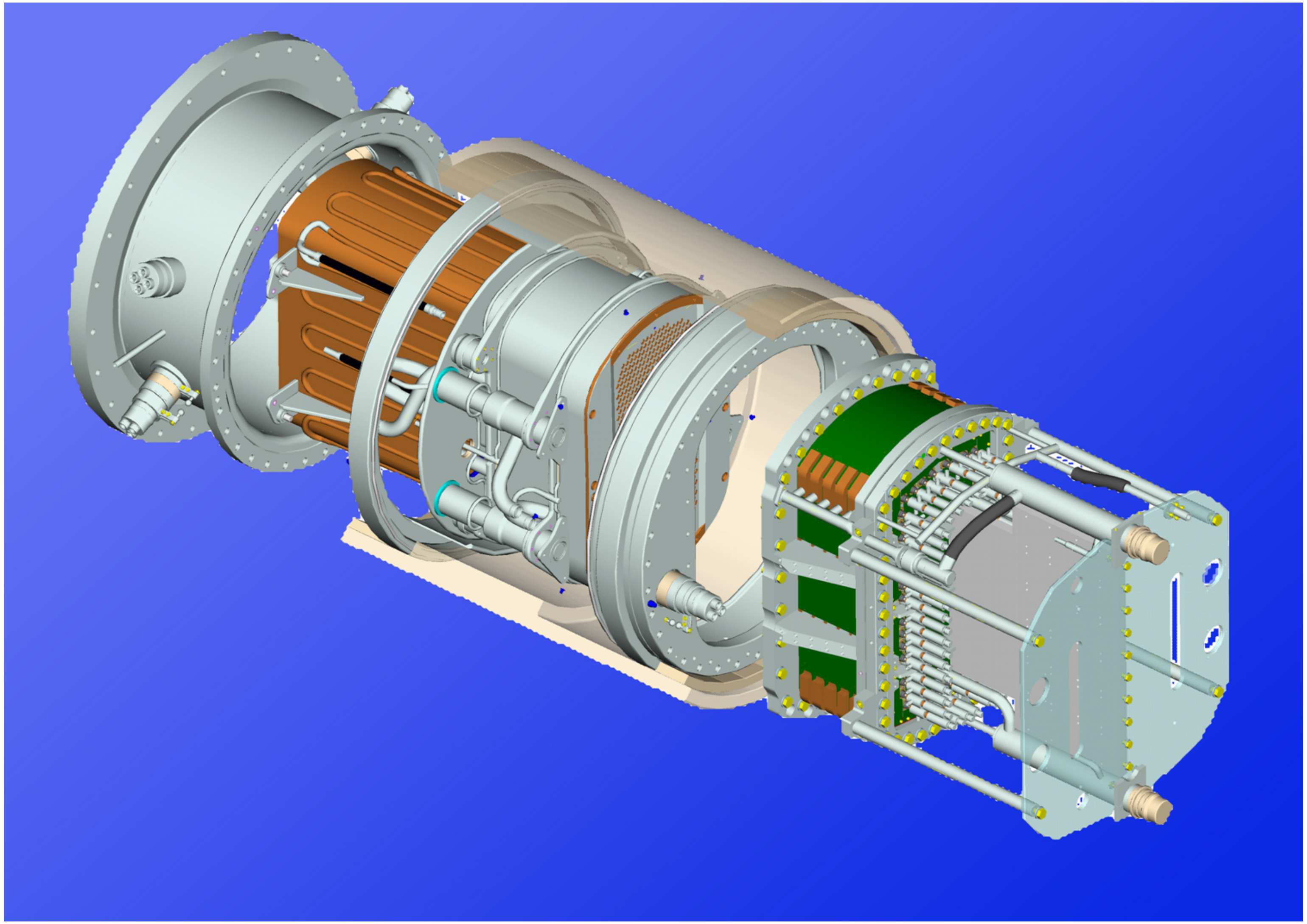
=> H^+/D^+ fraction

PINI extraction system (Plug In Neutral Injector)

Used with the bucket source



Bucket source on the PINI extraction system



RF driven positive ion sources in the NBI of ASDEX-Upgrade

Dimensions

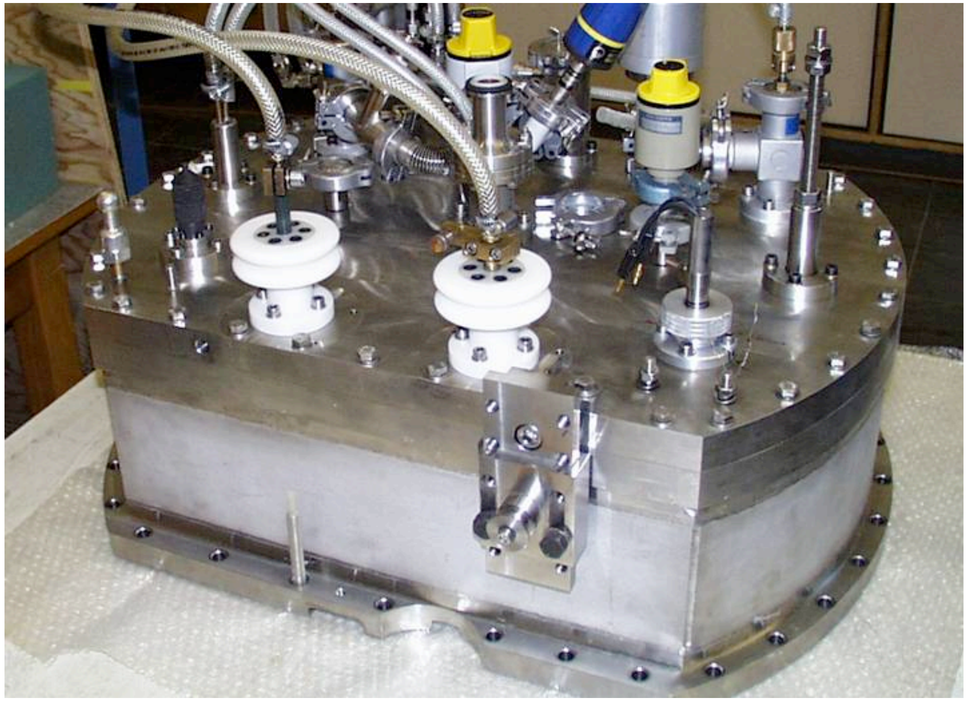
B x H x L = 32 x 19 x 59 cm^3
(=Bucket source)

Beams

Hydrogen: 90 A / 100 kW / 55 kV

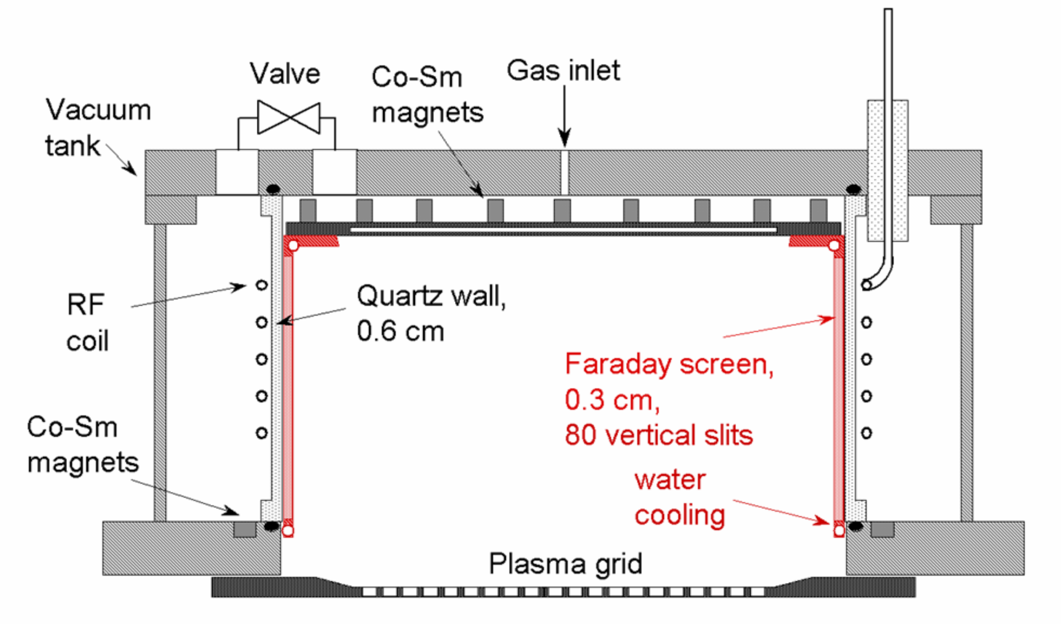
Deuterium: 65 A / 80 kW / 93 kV

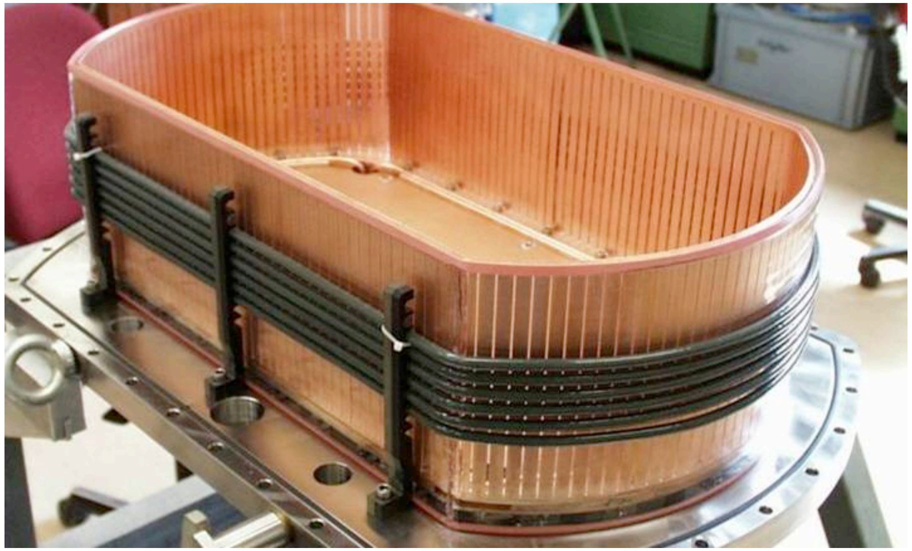
Pulse duration < 10 s



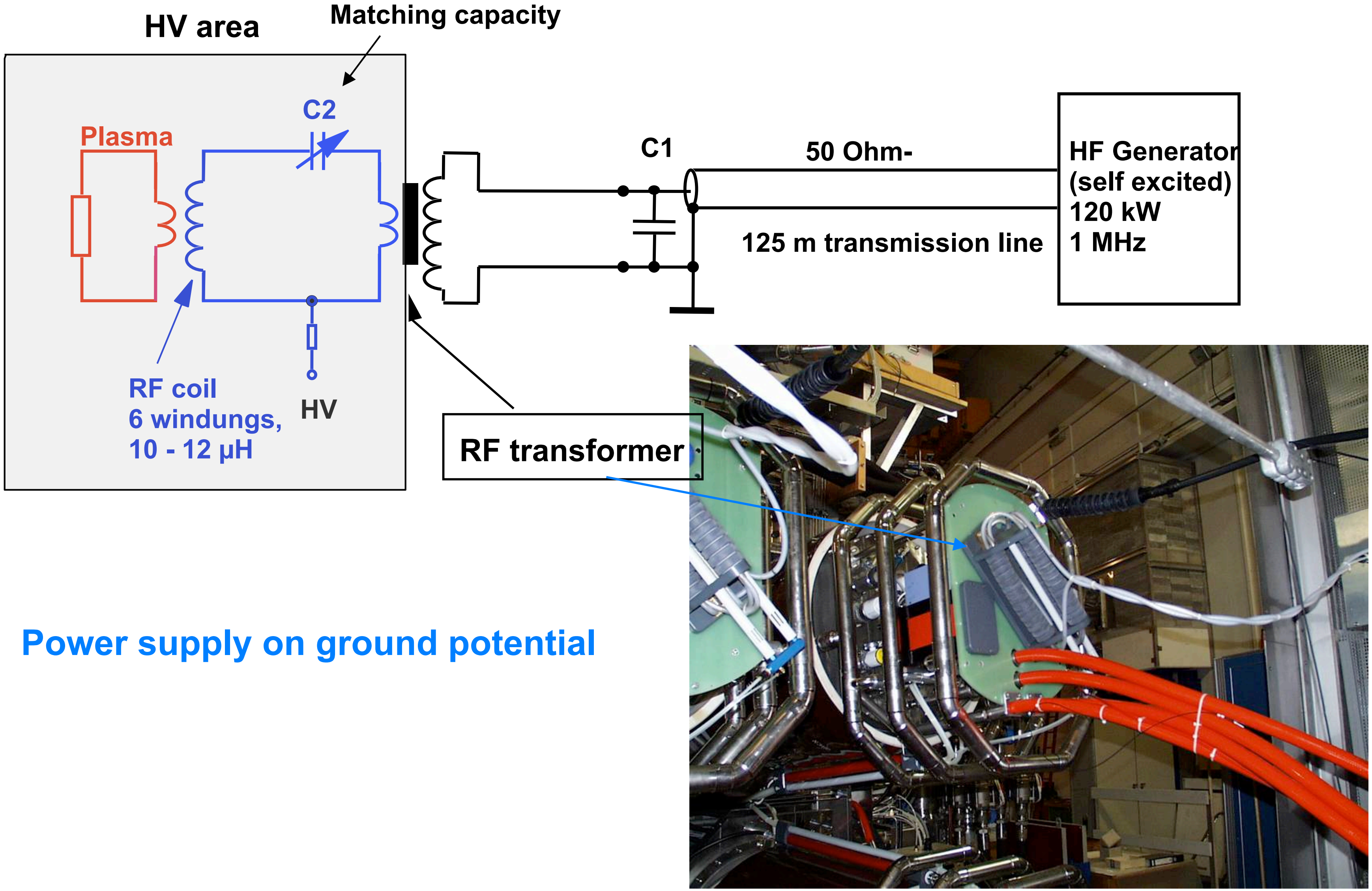
Design of the AUG RF source

- Water cooled **Faraday shield** to protect the insulator from physical and chemical sputtering
- Power supply 1 MHz/120 kW
- Quartz insulator in a vacuum tank
- Confinement magnets on the source back plate
- Compatible with the PINI extraction system



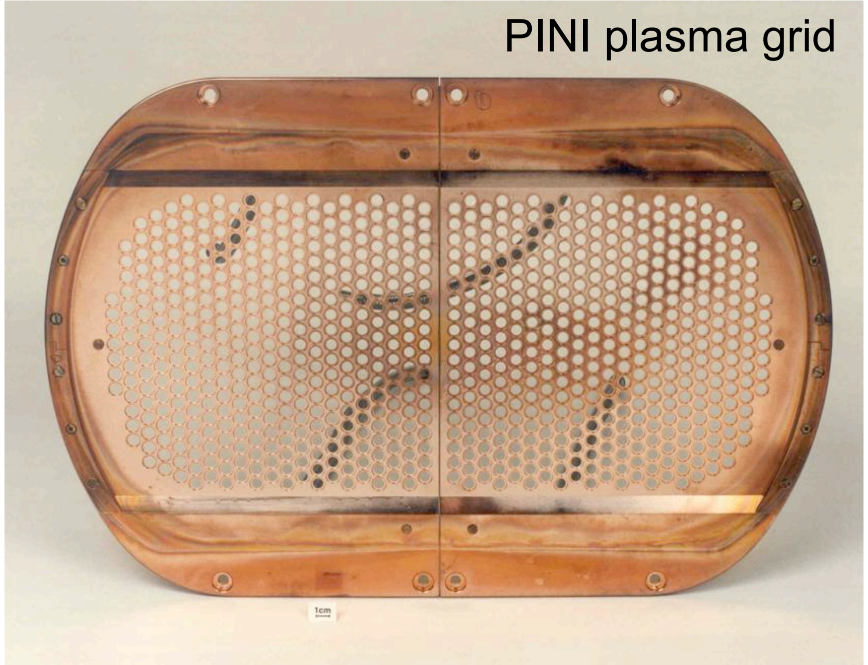


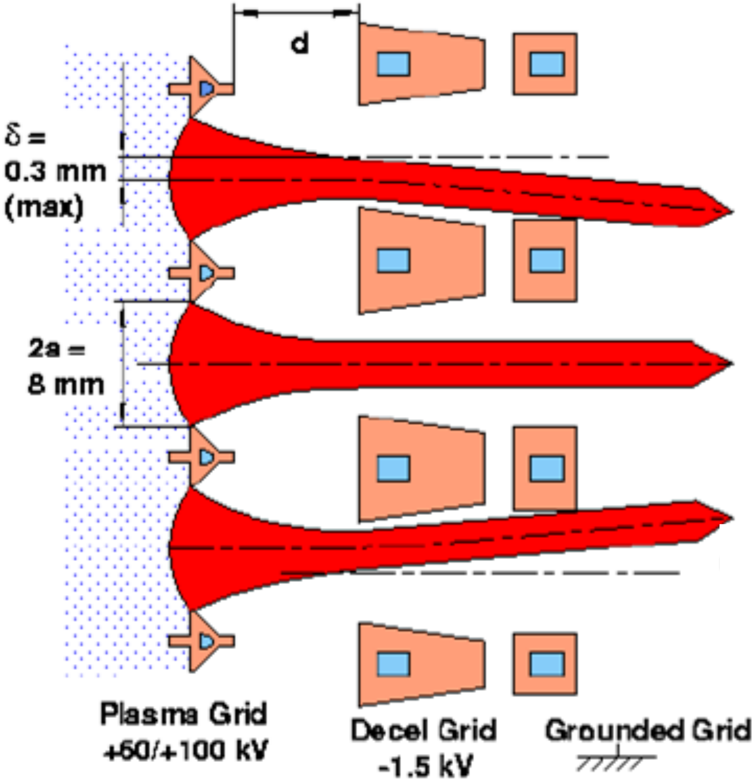
RF matching



Power supply on ground potential

Beam extraction


PINI plasma grid



- Three electrodes
- AUG: 774 apertures, 8 mm diameter
- Extraction area 390 cm^2 in 50.66 x 22.8 cm^2
- Negative decel voltage reflects electrons from the neutralizer

Child-Langmuir law

=> Maximal extractable current

$$I = C x V^{3/2} \sqrt{\frac{Z}{M}} \left(\frac{a}{d + x} \right)^2$$

2nd injector of ASDEX-Upgrade

Proof of reliability:

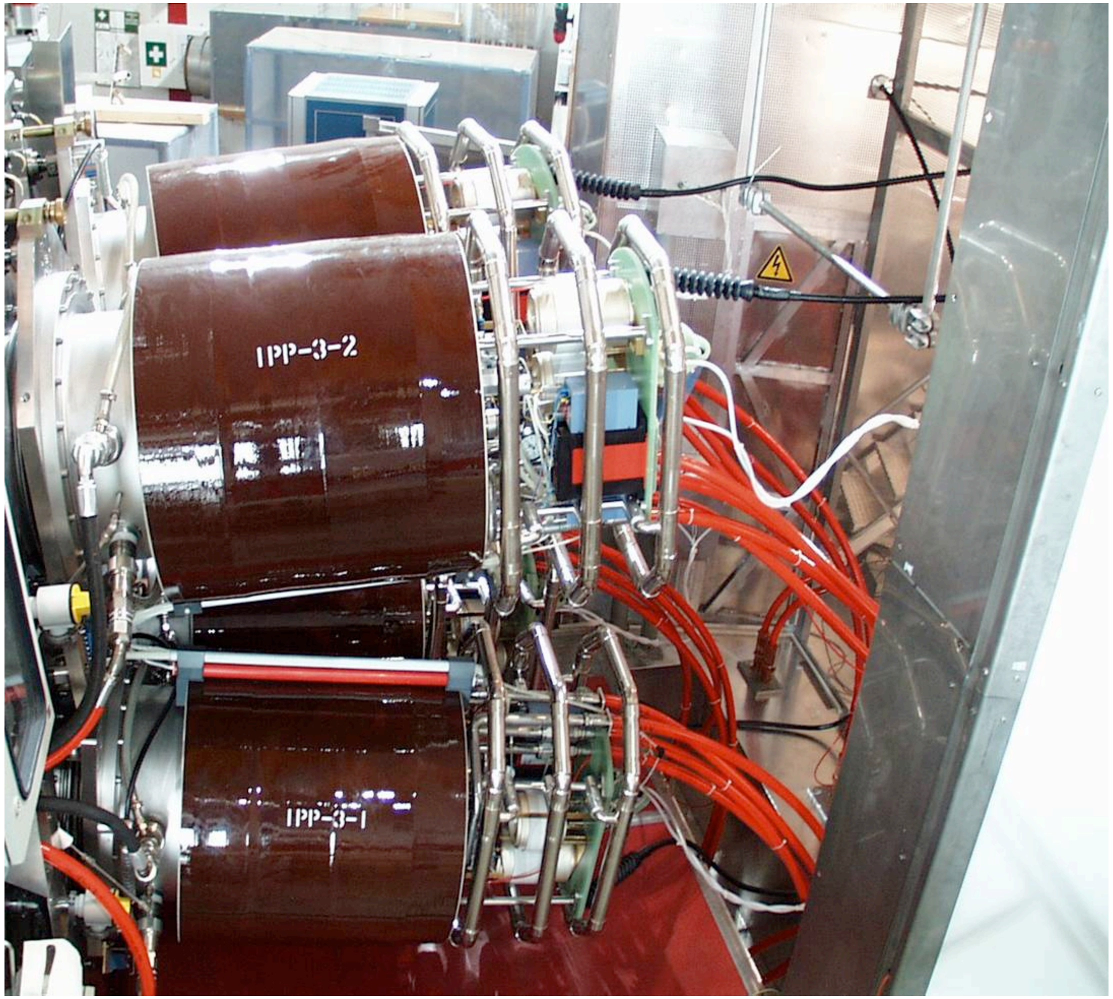
4 RF sources are used

in the NBI of the

ASDEX-Upgrade-

Tokamak since 1997

- no maintainance
- no malfunction



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Beam neutralization

Neutralization efficiency depends on energy and ion species

Positive ions

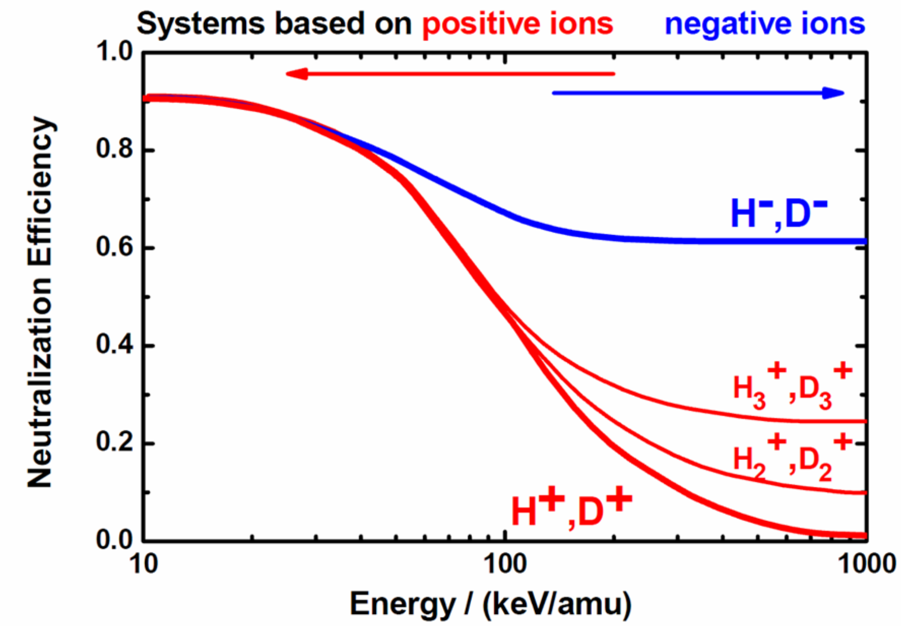
Low neutralization efficiency at high beam energy,

Different for molecular ions

Negative ions

Electron weakly bound (0.75 eV)

=> High neutralization efficiency at high beam energy



Large machines require high energies to achieve the penetration depth,

Current drive more efficient at high beam energy

⇒ up to 1 MeV

⇒NBI based on negative ions

“NNBI”

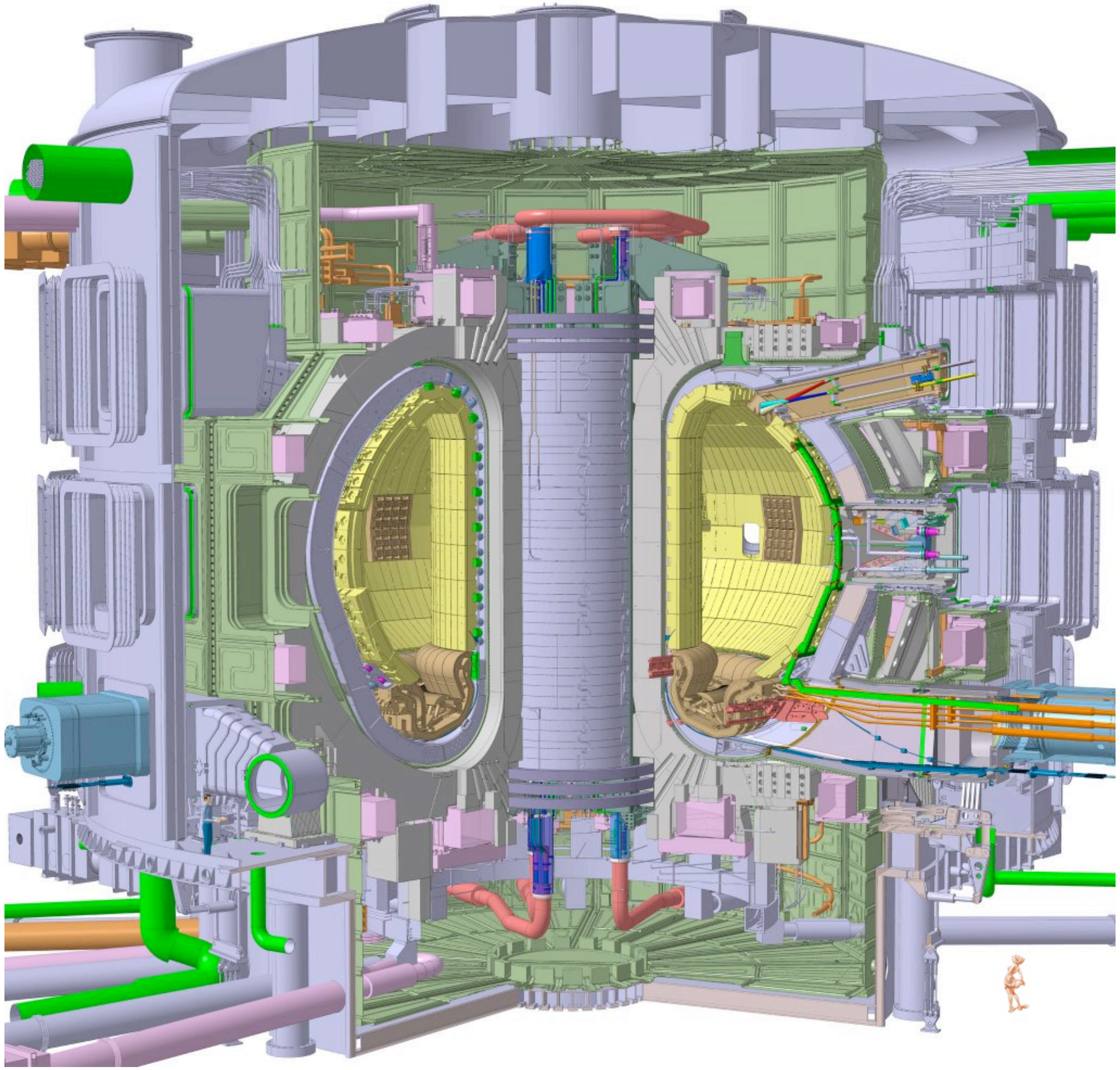
The ITER Tokamak

International Thermonuclear Experimental Reactor

R_{major}	6.2 m
R_{minor}	2.0 m
V_{plasma}	840 m^3
I_{plasma}	15 MA
B_{Tor}	5.3 T
P_{fusion}	500 MW
NBI:	**33 MW**
ICRF	20 MW
ECRH	20 MW

Under construction

In Cadarache, France

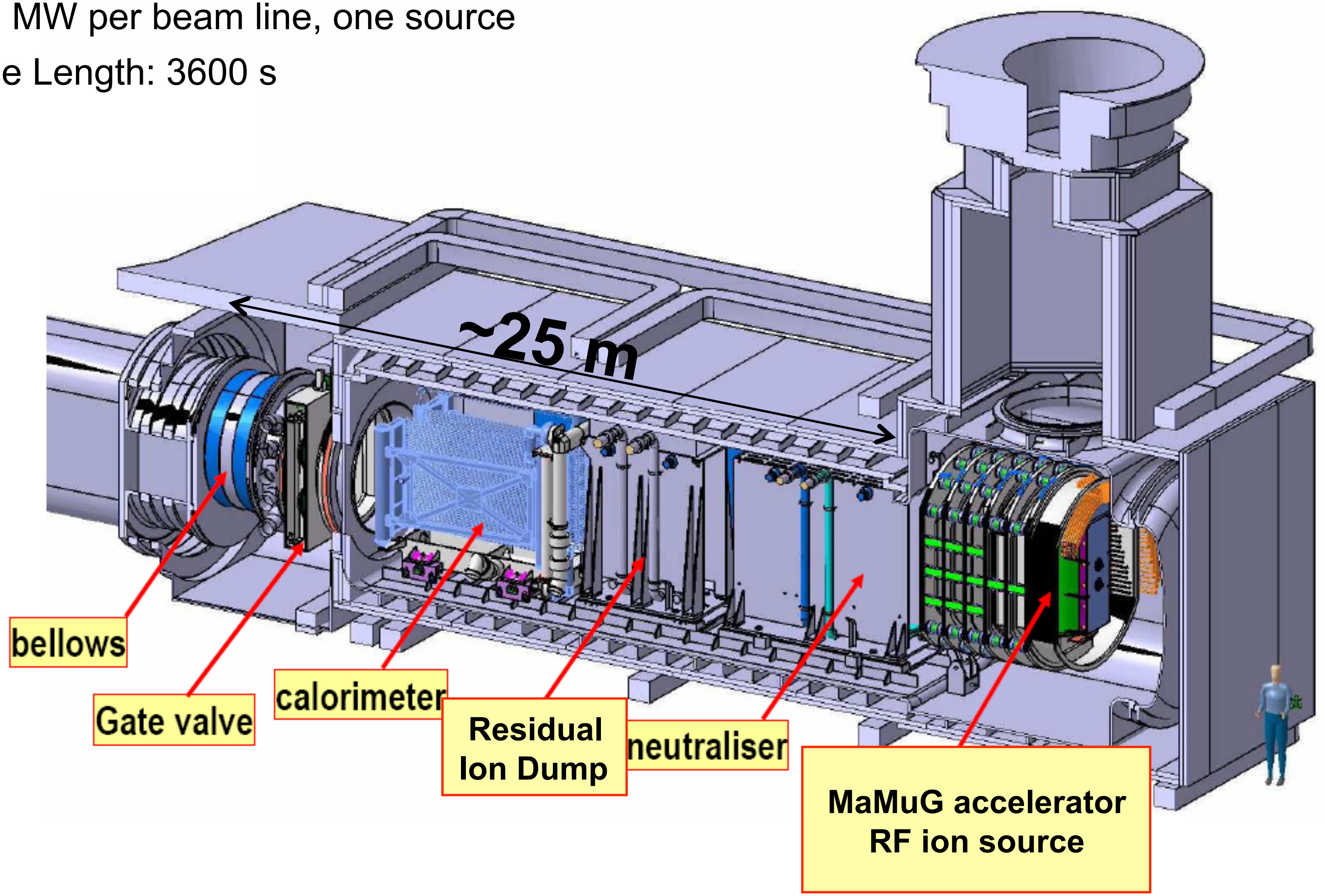


ITER Negative Neutral Beam Heating Injector

Two beam lines

16.7 MW per beam line, one source

Pulse Length: 3600 s



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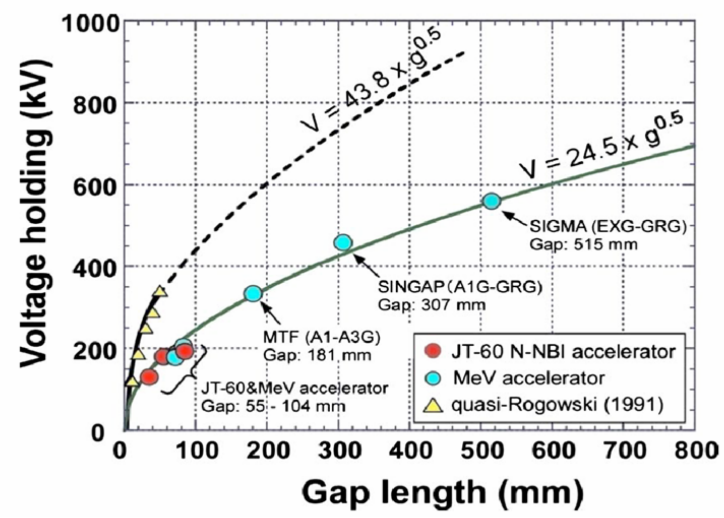
ITER acceleration system



Breakdown voltage ~ (gap length)$^{1/2}$

⇒ Multistage acceleration is shorter

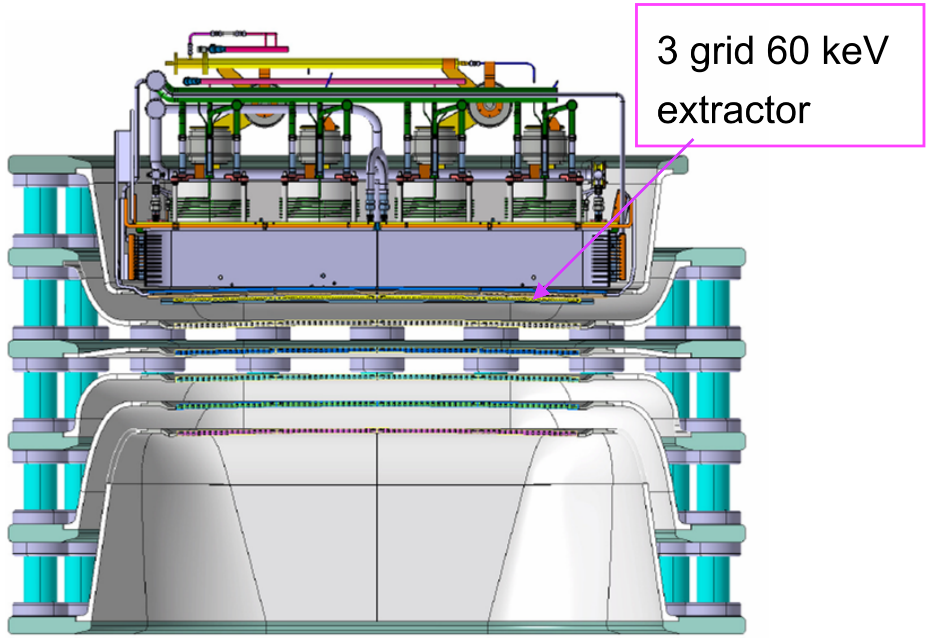
⇒ for ITER

1 MeV in five 200 keV stages

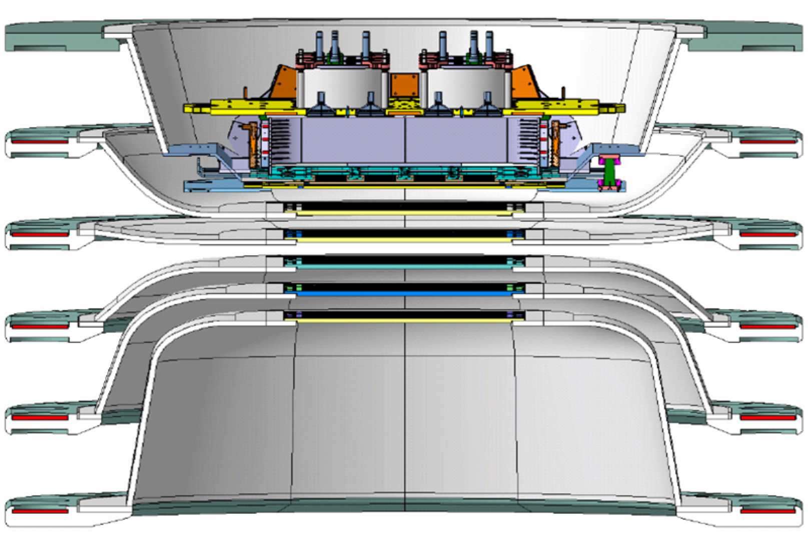
MAMuG

(Multi-aperture and multi-grid)

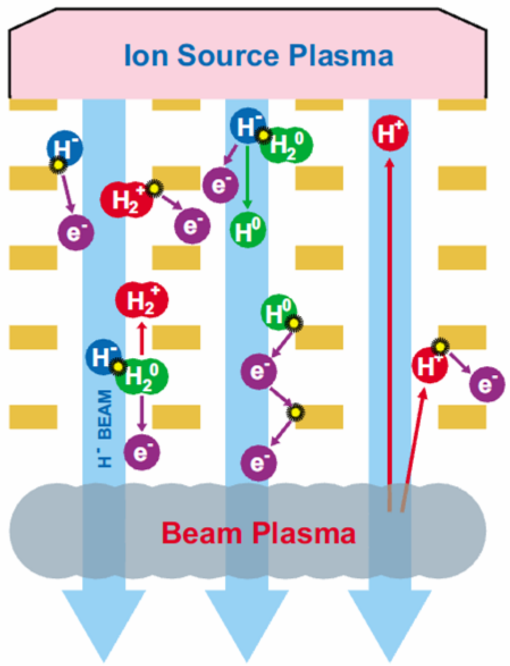
0.33 A (14.4 mA/cm^2 H$^-$) at 937 keV have already been demonstrated at JAEA for 2 s



3 grid 60 keV extractor



Secondary particle generation during the acceleration



(Takeiri, 2010)

Stripping

Negative ions destroyed by collisions
with the back ground gas
⇒ Power loss

Stripped electrons and **secondary electrons**
are accelerated
⇒ High power load on the grids

Backstreaming (positive) ions

Produced by collisions of electrons and negative ions
with the back ground gas
=> High power load on the source back plate

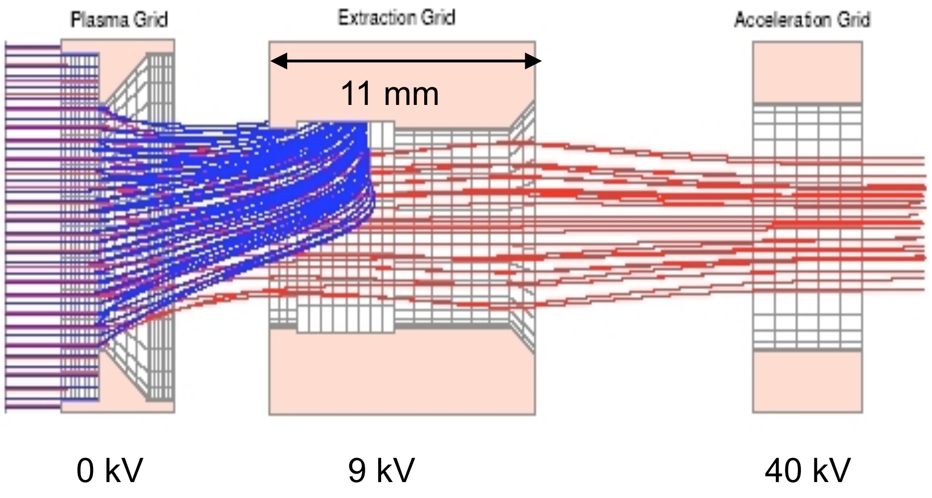
=> Limitation of the source pressure

$$\mathbf{p = 0.3\ Pa \rightarrow f_s = 25\%}$$

Negative Ion Extraction

Co-extraction of electrons

Electrons are deflected by small permanent magnets to the extraction grid



To limit the power load on the grid

=> Limitation of the current of co-extracted electrons

$$j_e/j_{D^-} \leq 1$$

Giant ion sources for the NNBI

Achieved negative ion current densities:

$j = 200\ A/m^2\ D^-$

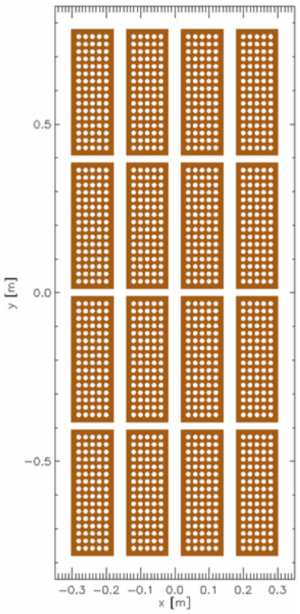
(~1/10 of positive ion systems)

ITER: Required for 16.7 MW at 1 MeV

$40\ A\ D^-$

$\Rightarrow$ **extraction area $2000\ cm^2$**

$\Rightarrow$ **Giant sources**



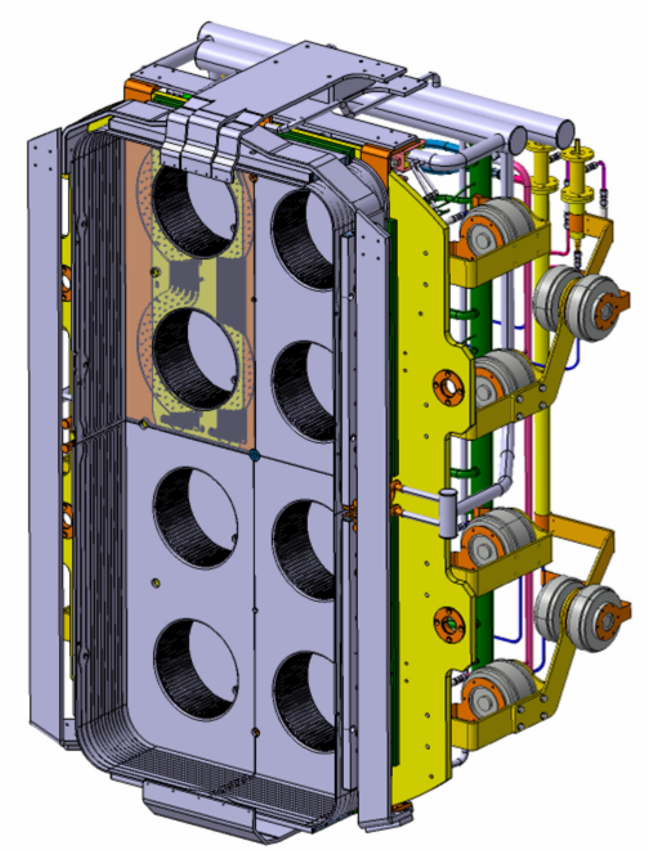
1.5m

1280 apertures

0.6 m

ITER source

$1.9 \times 0.9\ m^2$



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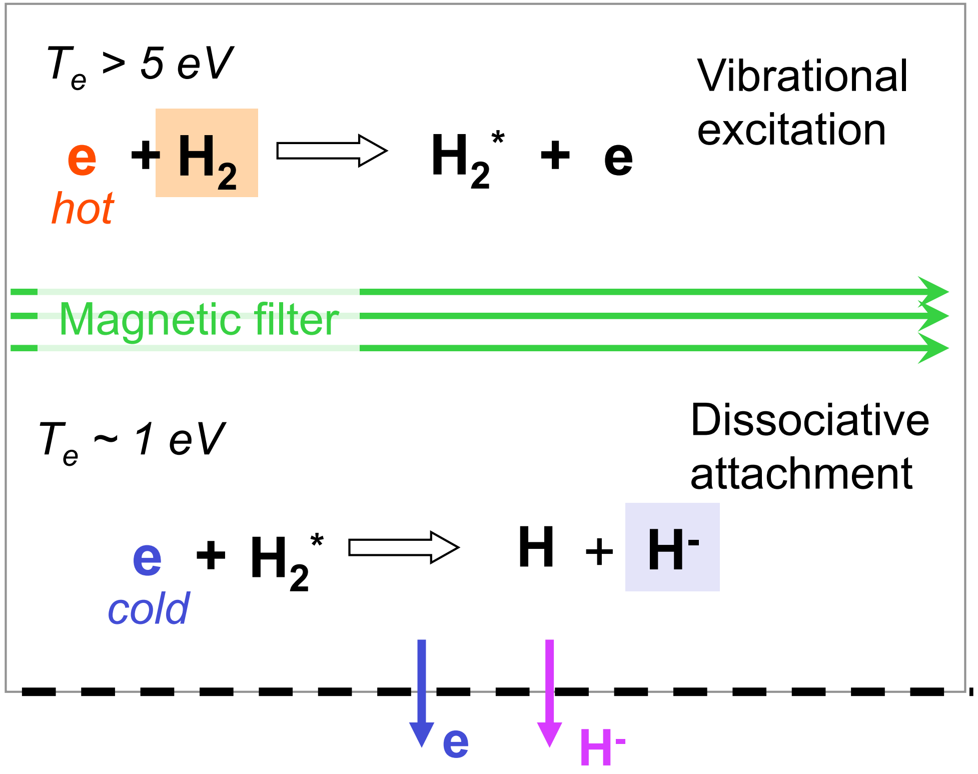
Volume production of negative ions



$T_e > 5$ eV

$e_{hot} + H_2 \Rightarrow H_2^* + e$

Vibrational excitation

$T_e \sim 1$ eV

$e_{cold} + H_2^* \Rightarrow H + H^-$

Dissociative attachment

Problems

- Low ion currents < 5 mA/cm^2
- High source pressure > 0,6 Pa => high stripping losses
- High current of co-extracted electrons

=> **not applicable for the NNBI**

Surface production of negative ions

H^0, H_n^+ + surface-e ⟹ H^-

- Conversion rate high at low work function Φ
- Φ can be reduced by coating with alkali metals

	Φ [eV]
Cs	1.9
Rb	2.08
K	2.24
Na	2.28
Li	2.42

- Φ of Cs on Mo is minimal 1,6 eV at **0.6 mono layer**

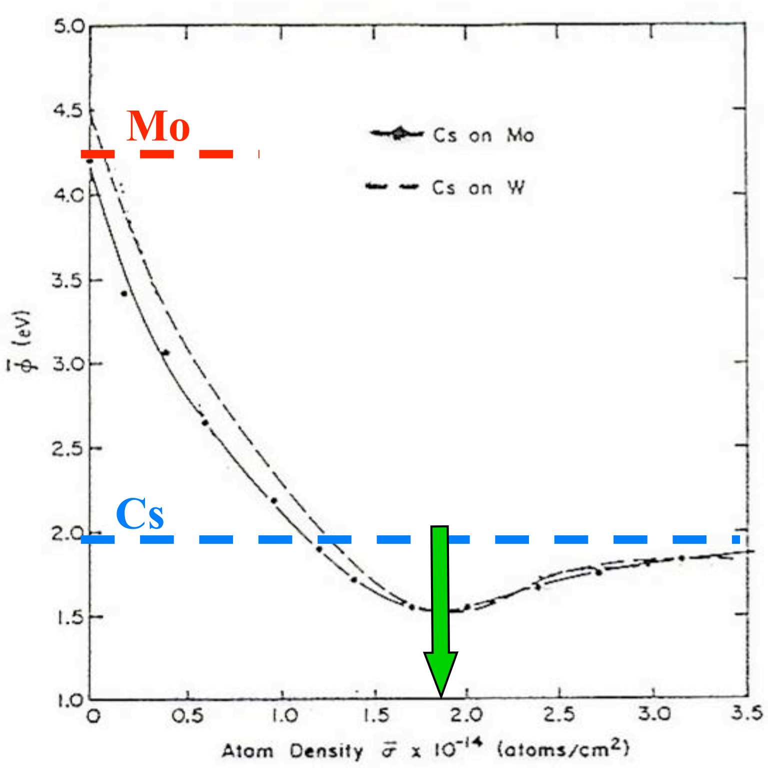
Cs coating by Cs evaporation into the source

⇒ **- Much higher H^- current,**

- Much lower current of co-extracted electrons

- lower pressure possible

(Swanson 1968)



Destruction of the negative ions

Negative ions are fragile, binding energy of the electron is 0,75 eV

$H^- + e \rightarrow H + 2e$ *electron detachment*

for ***hot electrons*** *with* $T_e > 2$ *eV*

$H^- + H_i^+ \rightarrow$ neutrals *mutual neutralisation*

$H^- + H \rightarrow H + H + e$ *associative detachment*

or $H_2 + e$

Survival length of H^- only a few cm

⇒ **Only negative ions produced on the plasma grid can be extracted**

⇒ **divide source by a magnetic filter field in ‘hot’ plasma and ‘cold’ extraction zone**

Modelling results of the negative ion production

- Production by surface conversion of H^0 atoms greater than of H_n^+ ions

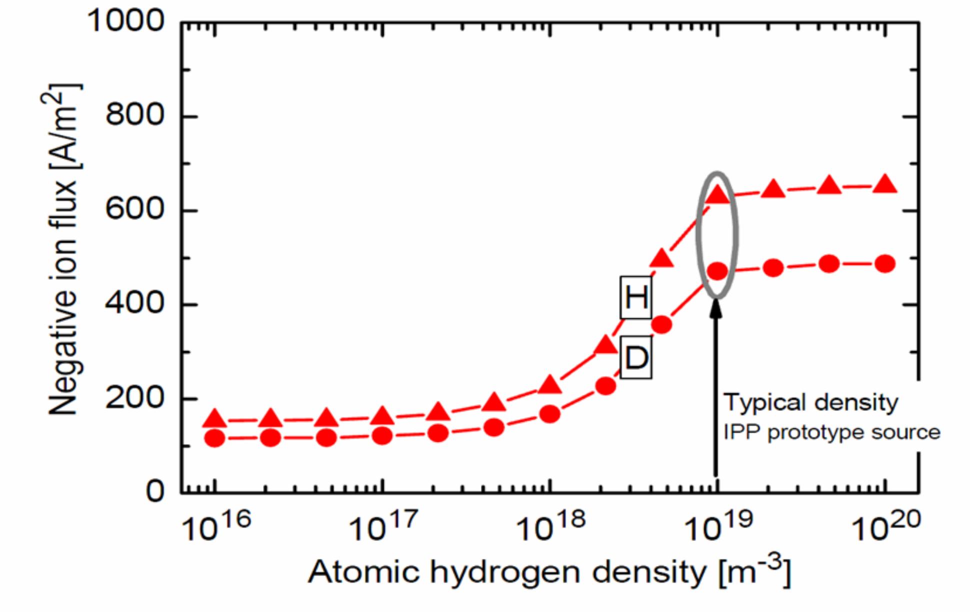
- Negative ion flux from the PG saturates at high atomic density due to space charge limitation

  => plasma needed

- Flux of D^- ions lower than of H^- ions under the same plasma conditions

- Extraction probability of D^- ions lower than of H^- ions under the same plasma Conditions

  => lower D^- current



Outline

- Plasma heating by neutral beam injection
- Positive Ion sources for Neutral Beams
- Negative ion based neutral beam injection
- Beam extraction
- Production of negative ions
- **Negative ion sources**
- Experimental results with the RF prototype
- Giant source for ITER
- Test facilities

NNBI systems

Operating NNBI systems

Japan

JT-60 U, JAEA (Japan Atomic Energy Agency)

LHD, (Large helical device), NIFS (Nat. Inst. For Fusion Science)

Europe

IPP Garching, Germany

Future

RFX, Padua

ITER, Cadarache

Kamaboko source (Japan)

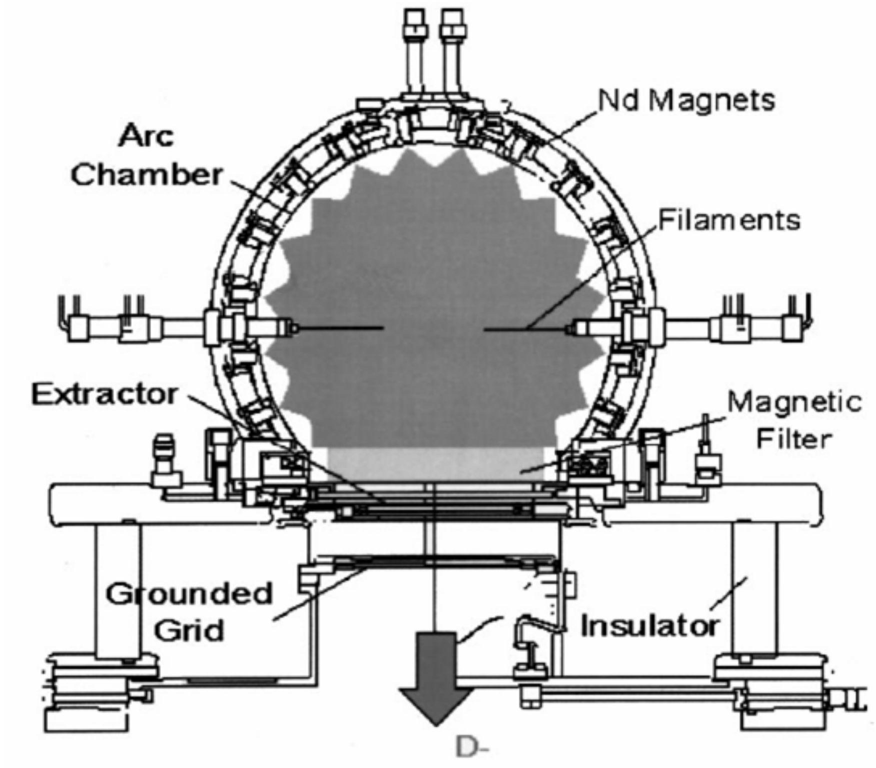
Initially part of the reference design of ITER

Semicylindical chamber shape

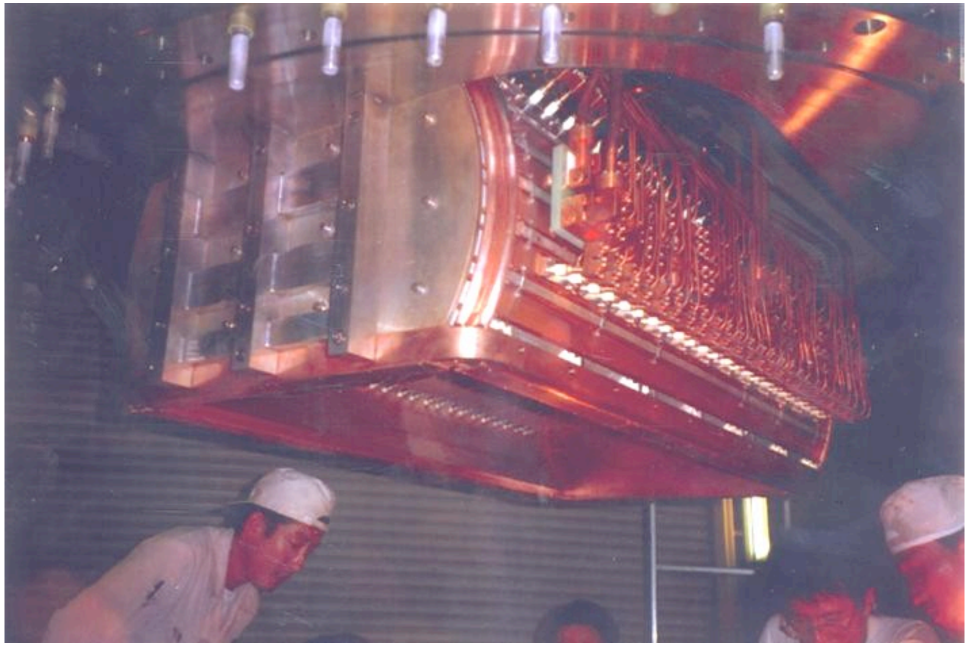
⇒ To minimize plasma loss area

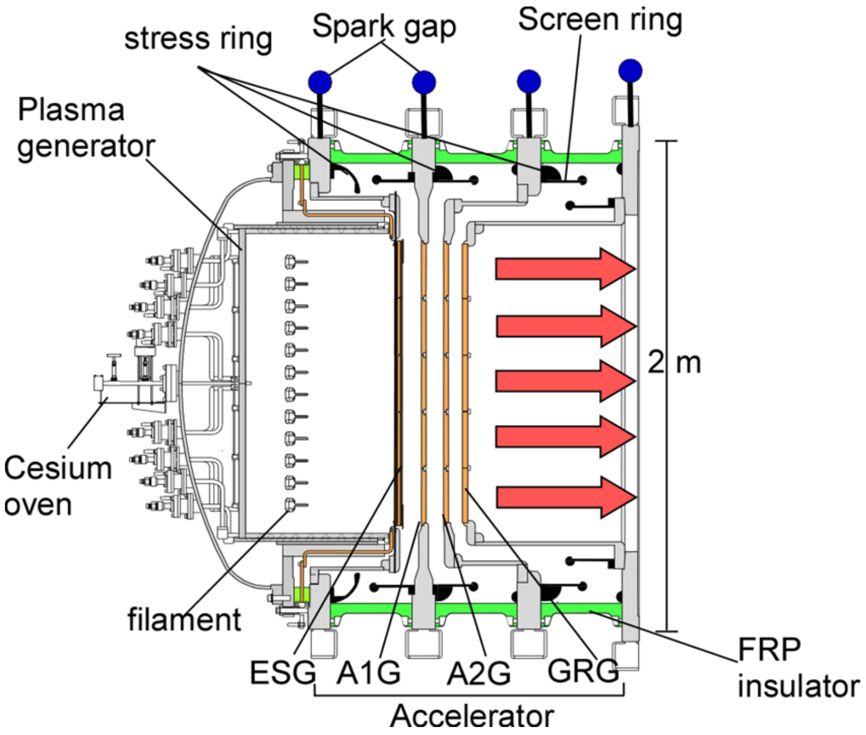
⇒ High negative ion production efficiency at low pressure was expected

Tested and operational at CEA (Cadarche) and JT-60



JT60 source





(Hanada, 2006)

Kamaboko type

2/3 of ITER source size

In operation since 1996

~50 high-current filaments

- limited lifetime (100 h)
- frequent remote maintenance, every 2-3 months

Design: two sources

22 A, 500 keV, 10 s D^- ion beams

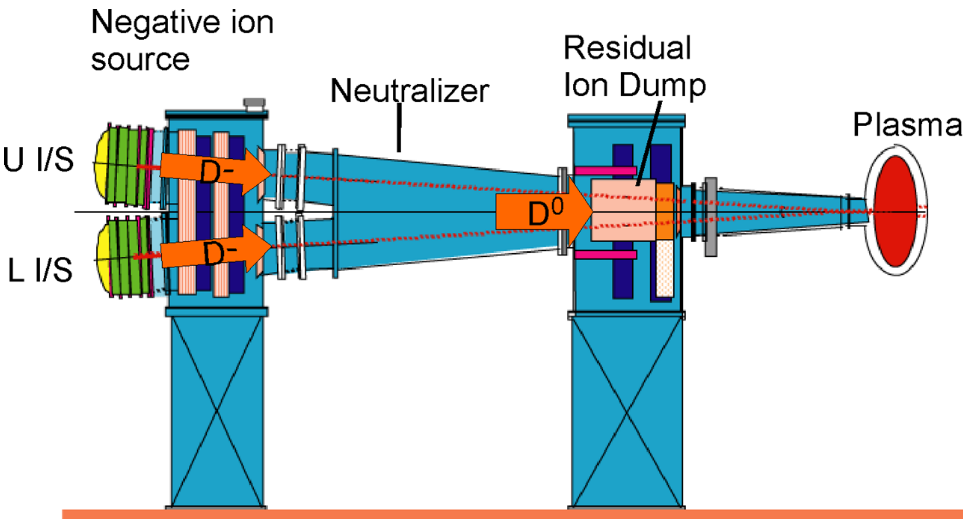
Achieved (2010):

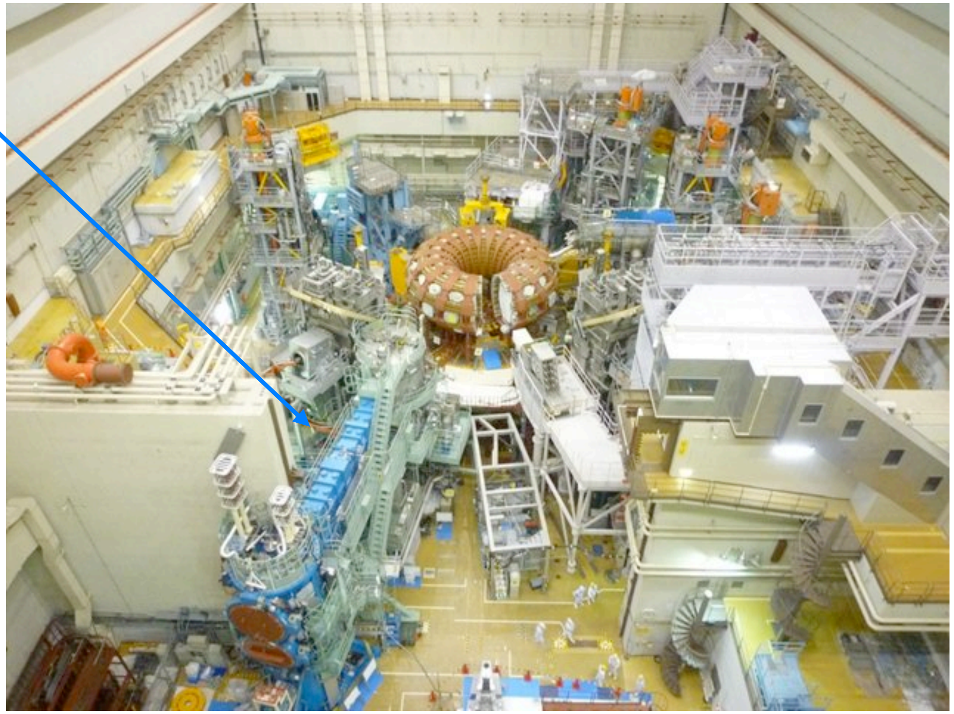
17.4 A or 13 mA/cm^2, 400 keV, 0.7 s

10 A, 360 keV, 25 s

Problem: voltage holding

JT-60 negative ion beam line

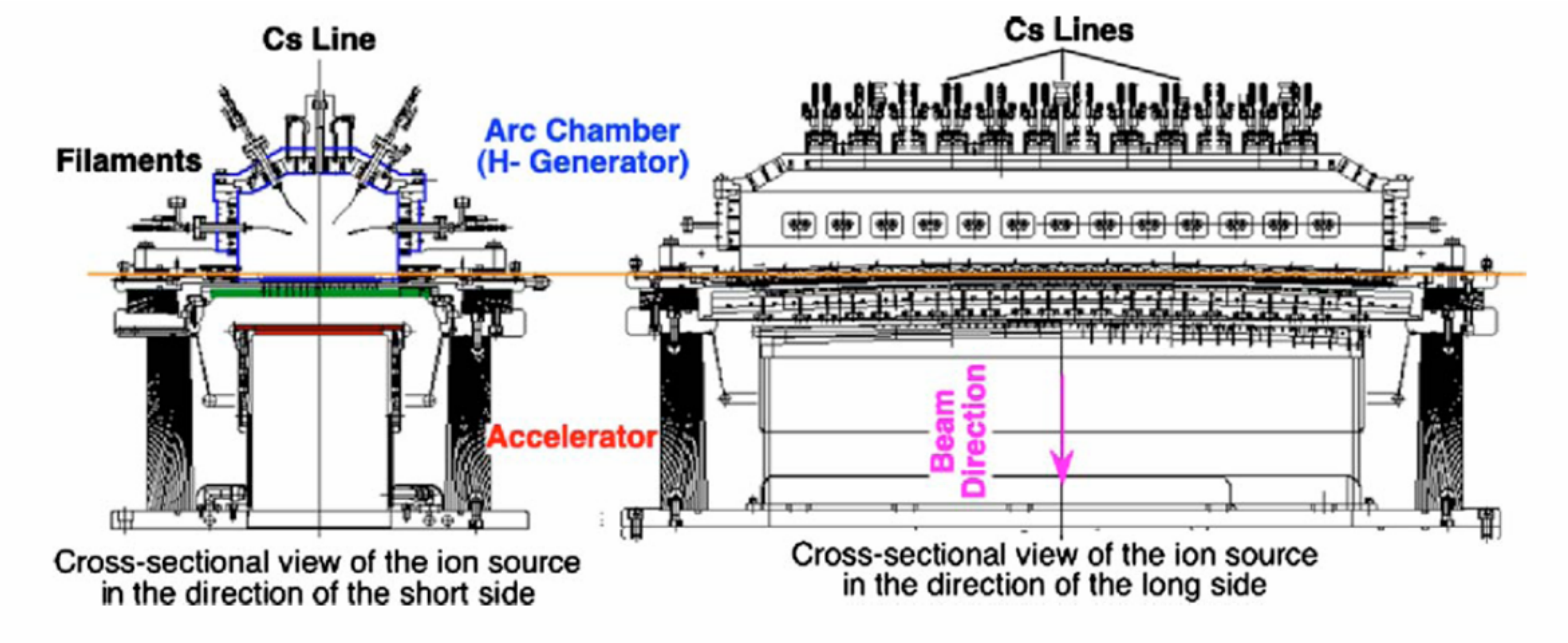




Construction of JT-60SA,

first plasma in March 2019

LHD negative ion source



Cross-sectional view of the ion source in the direction of the short side

Cross-sectional view of the ion source in the direction of the long side

(Takeiri, 2010)

Three injectors with two sources each

Operating since 1998

Design: 30 A, 180 keV, 1 s (one source)

Achieved: 37 A or 340 mA/cm^2, 190 keV, 1.6 s

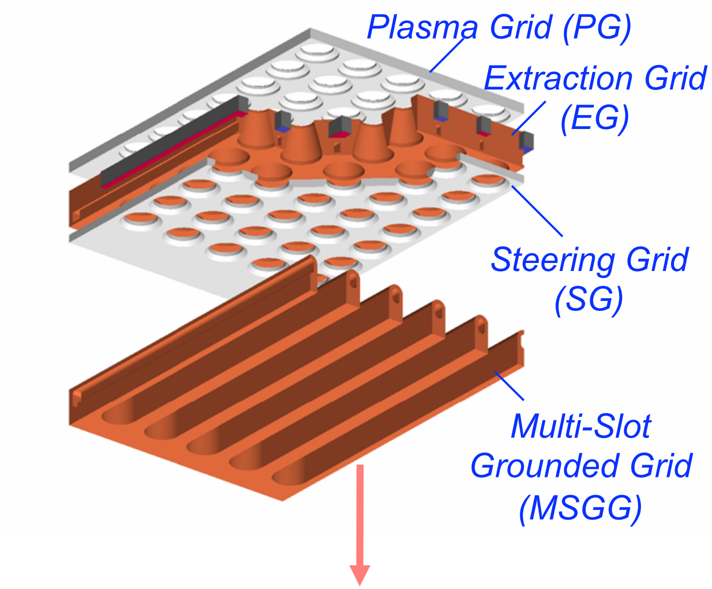
LHD negative ion source

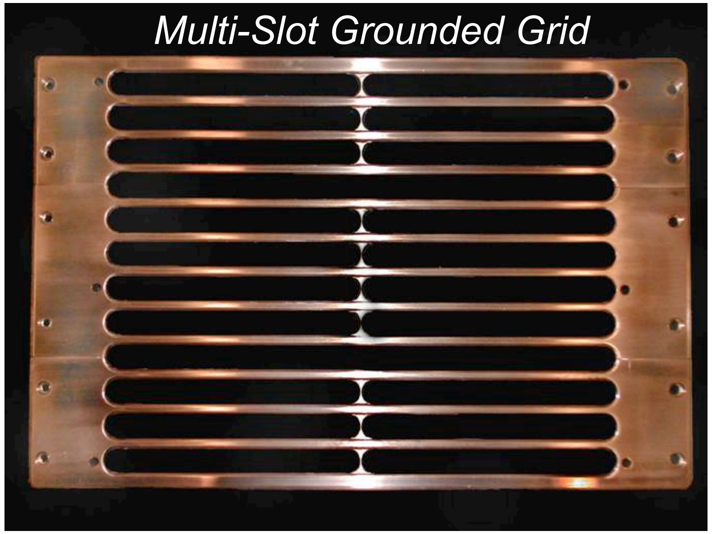
Problem:

High power load on the grounded grid

Solution

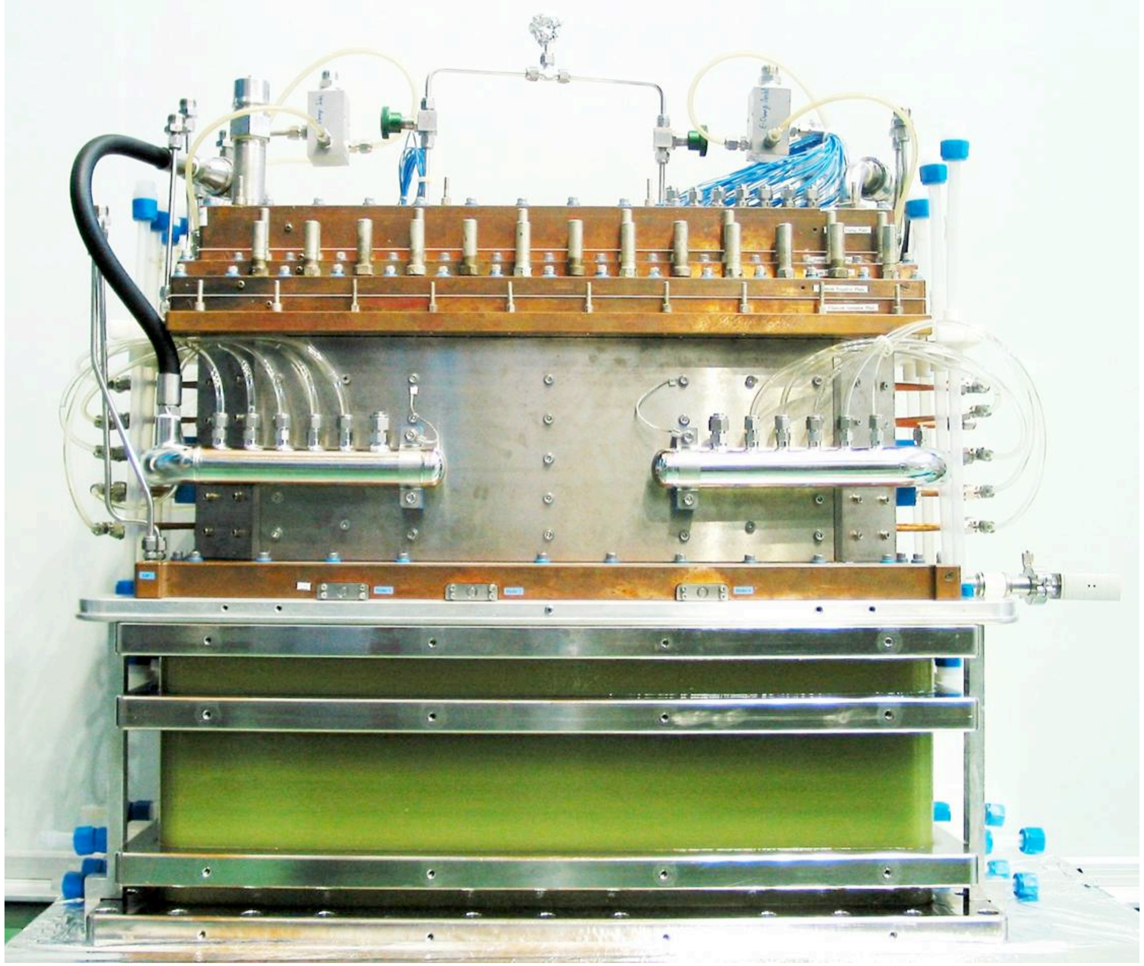
Slots instead of apertures in the grounded grid

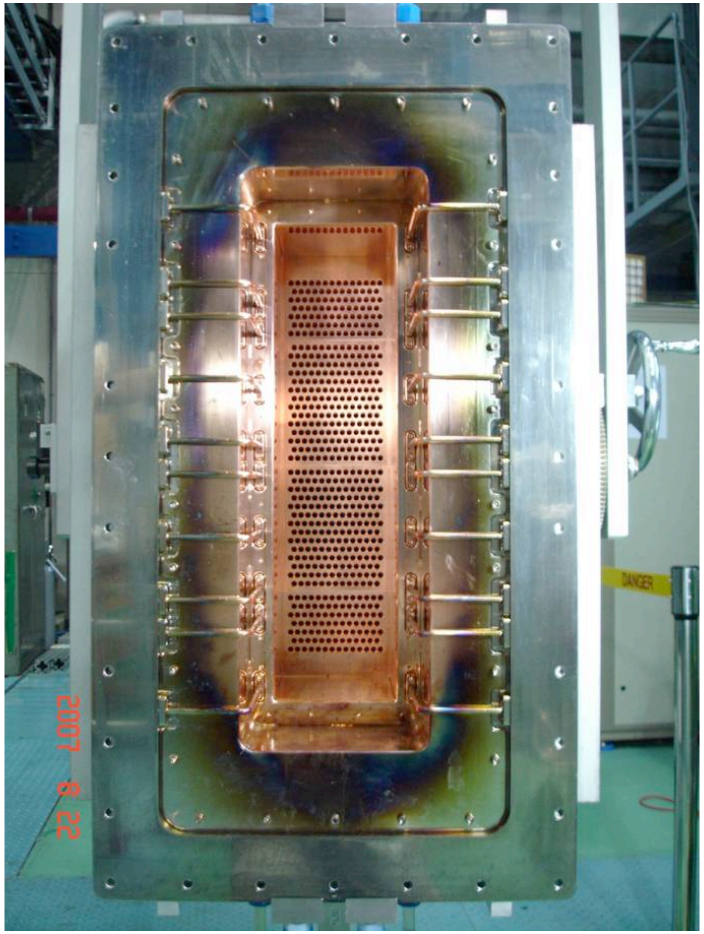



Multi-Slot Grounded Grid

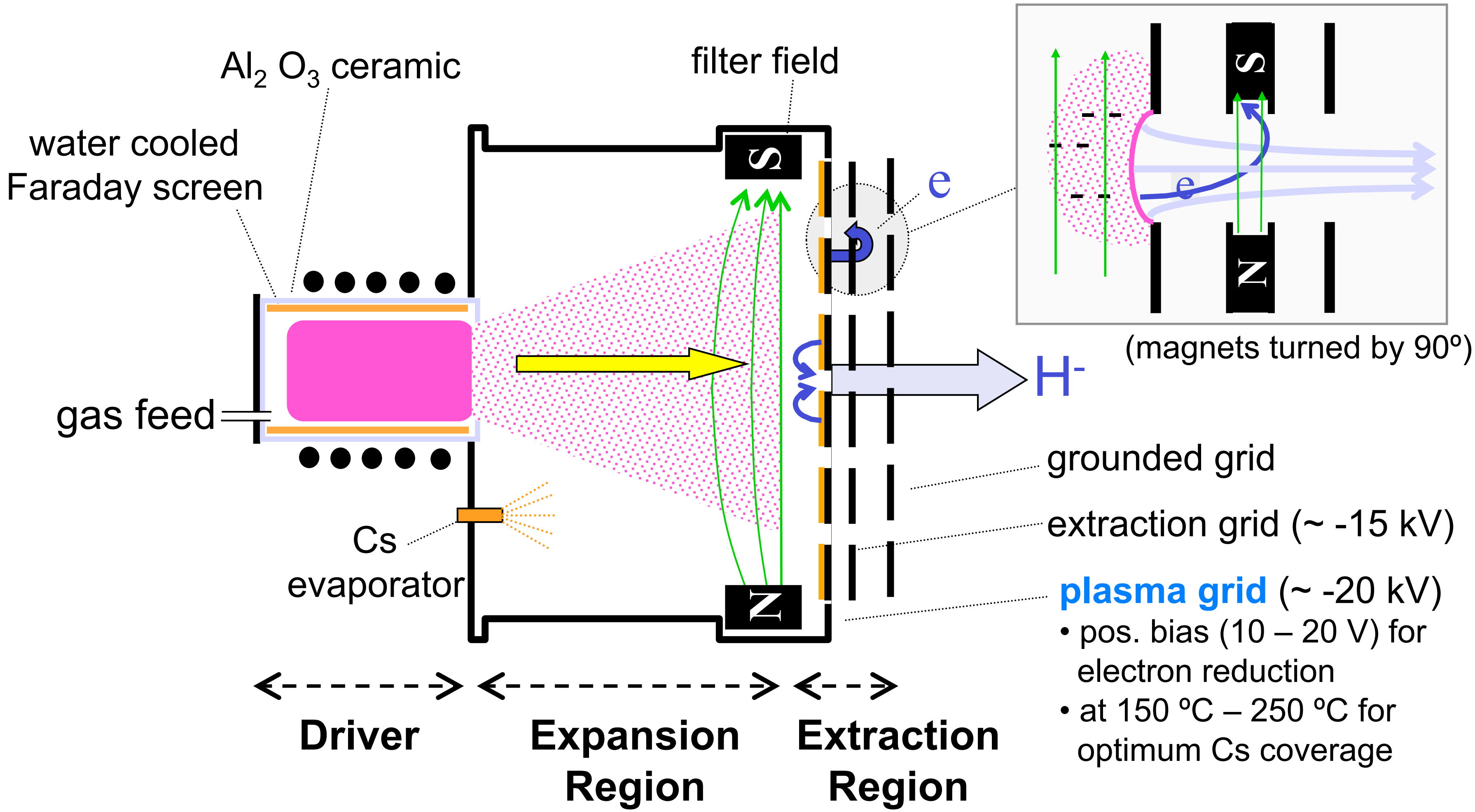
(Tsumori, 2009)

Photos of the Constructed LHD Ion Source





IPP RF Source: Working principle

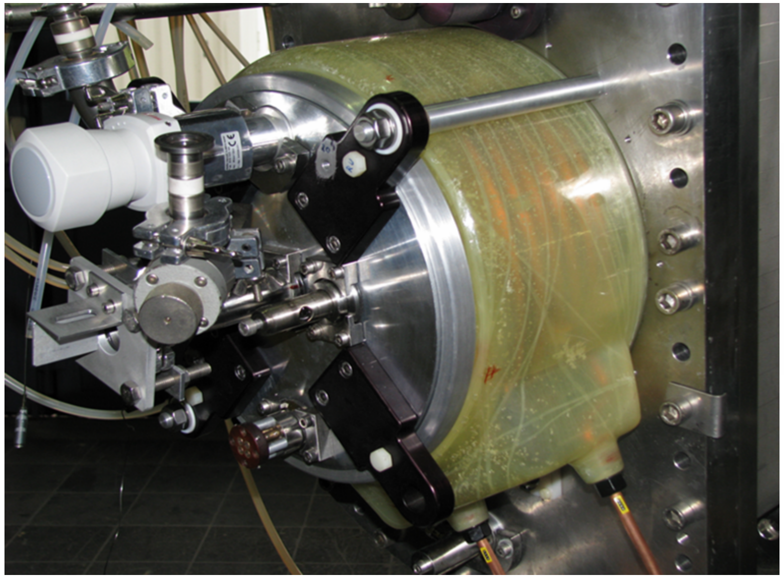


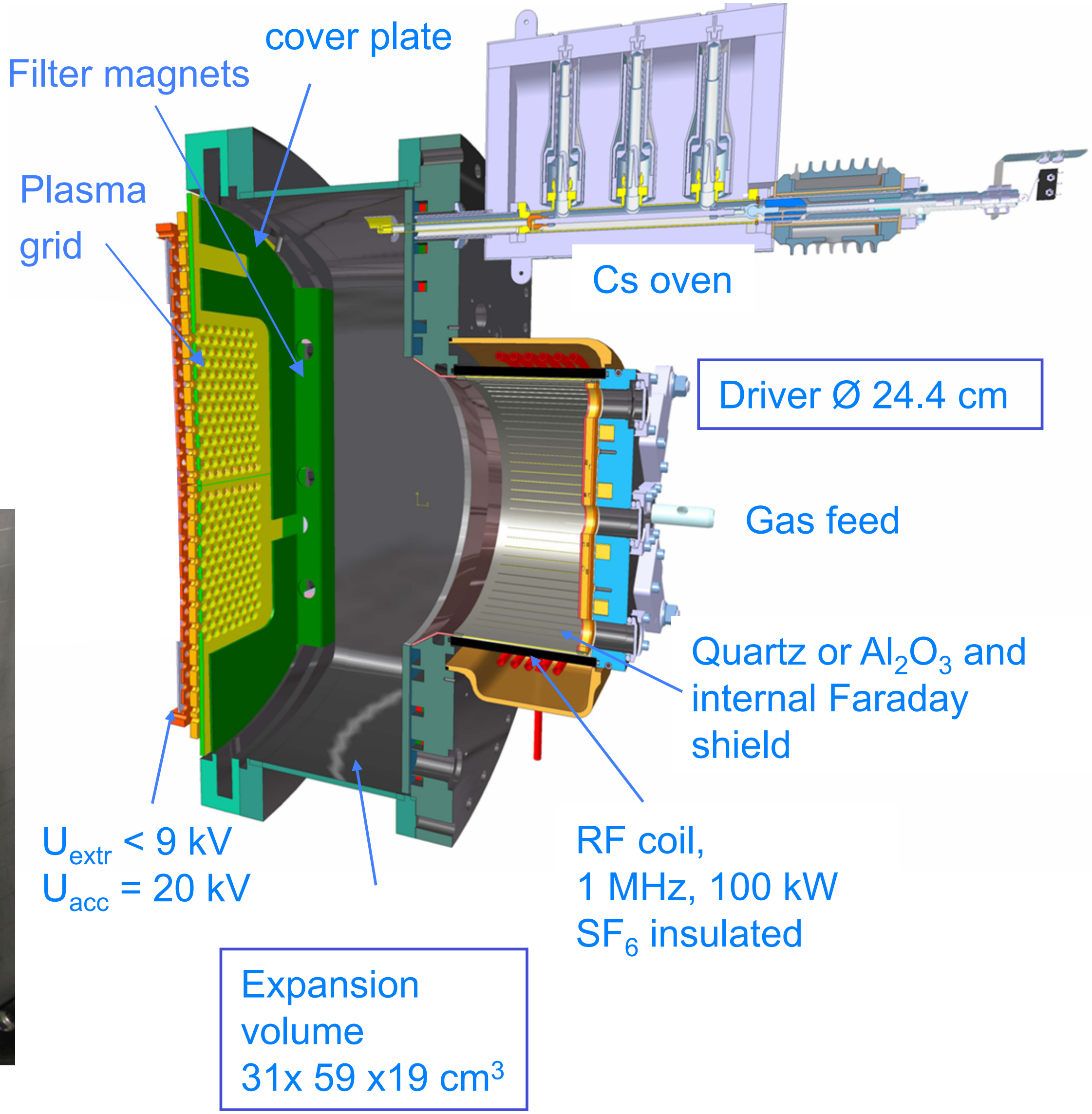
plasma grid (~ -20 kV)

- pos. bias (10 – 20 V) for electron reduction
- at 150 ºC – 250 ºC for optimum Cs coverage

Design of the IPP prototype RF source

Operated on the long pulse testbed **MANITU** and the short pulse testbeds **Batman (< 5s) and Robin**, IPR, India





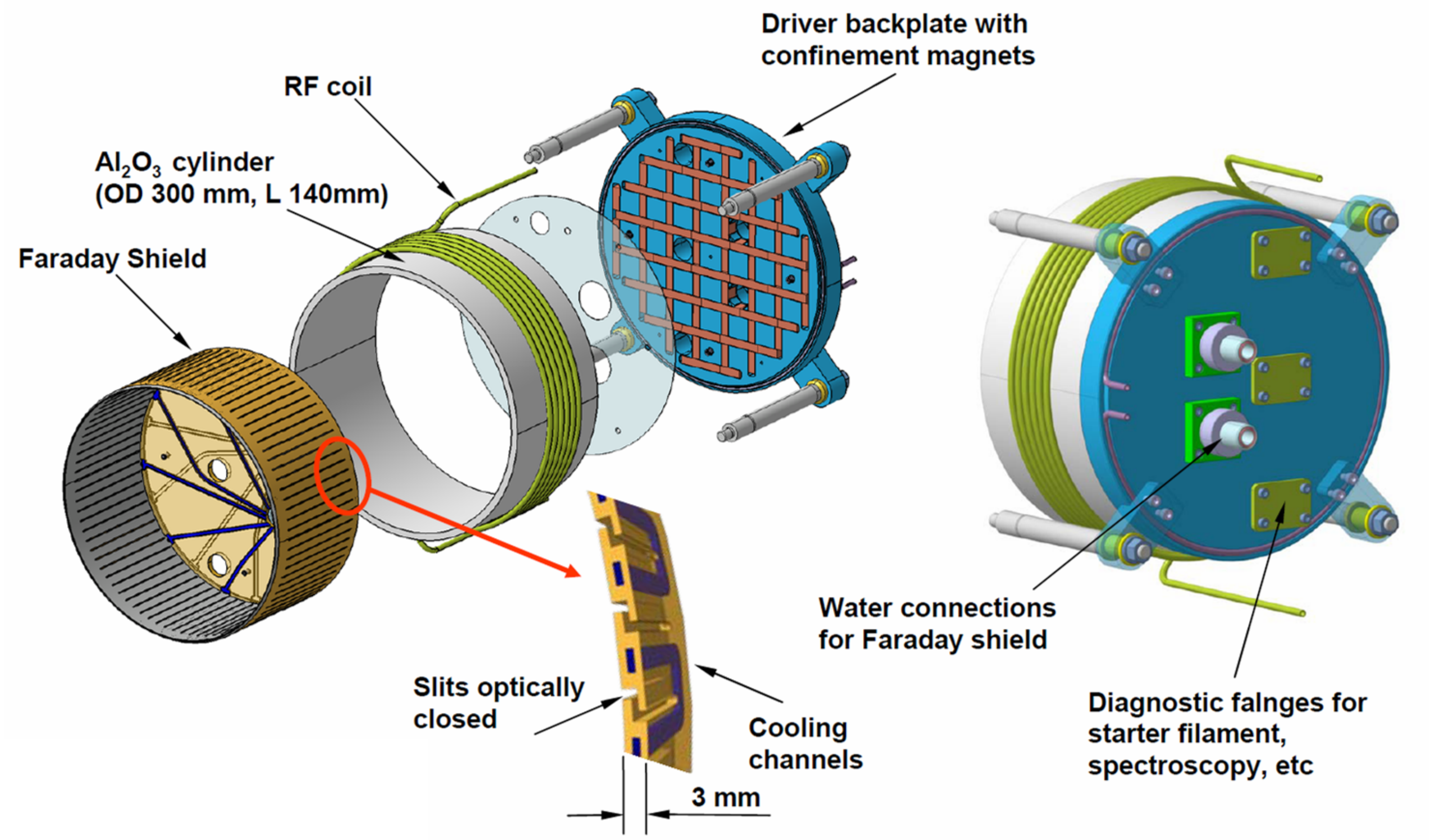
Driver Ø 24.4 cm

Expansion volume
31x 59 x19 cm^3

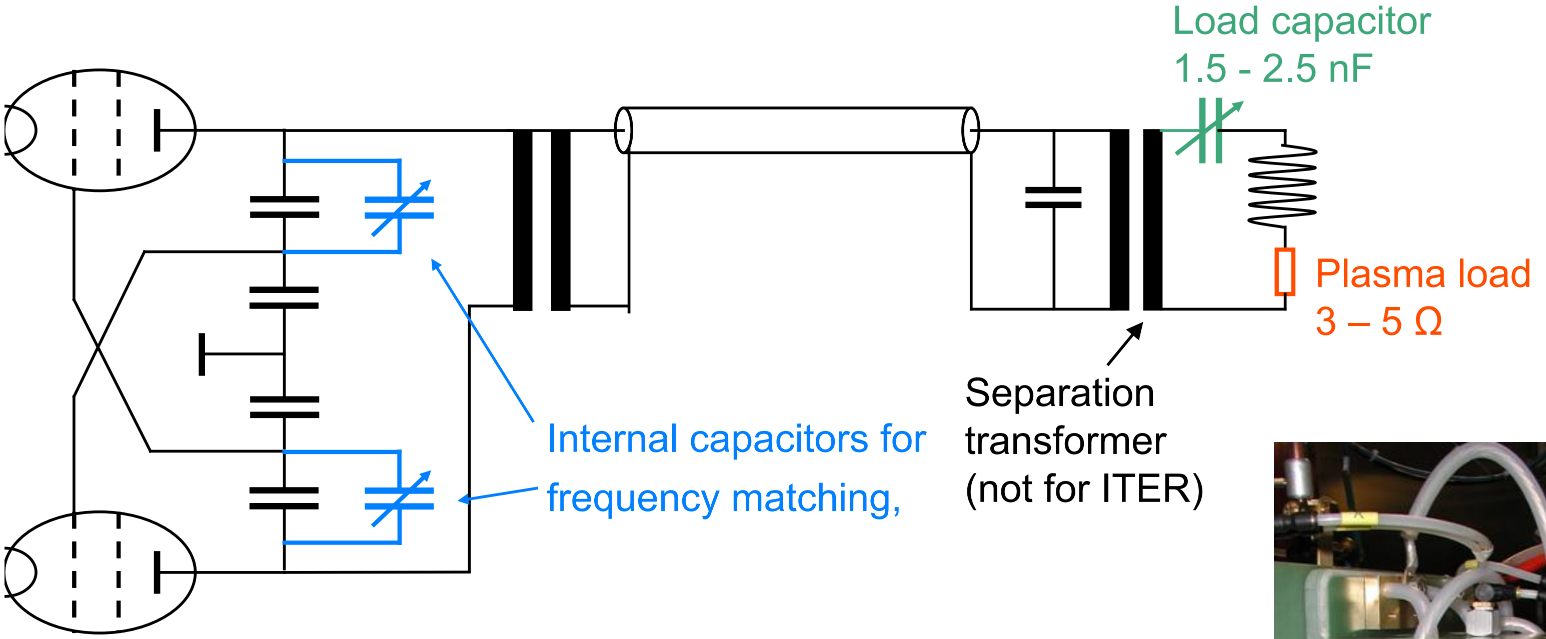
Driver design

Used in all NNBI RF sources

High power density $P_{RF}/V \sim 10 - 15$ kW/l



RF matching



Self-excited 1 MHz oscillator

+ Frequency matching possible

=> no remote controlled capacitors at the source

- Limited frequency stability

Filter field concepts

Small sources

Filter field generated by permanent magnets
close to the PG

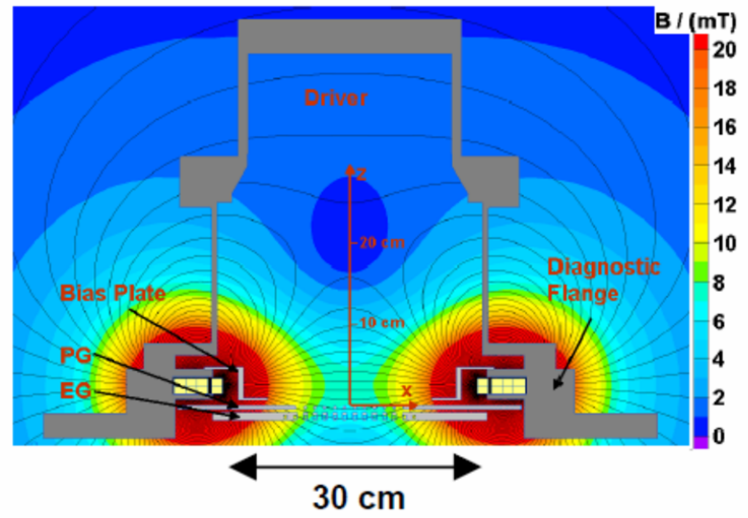
Large sources

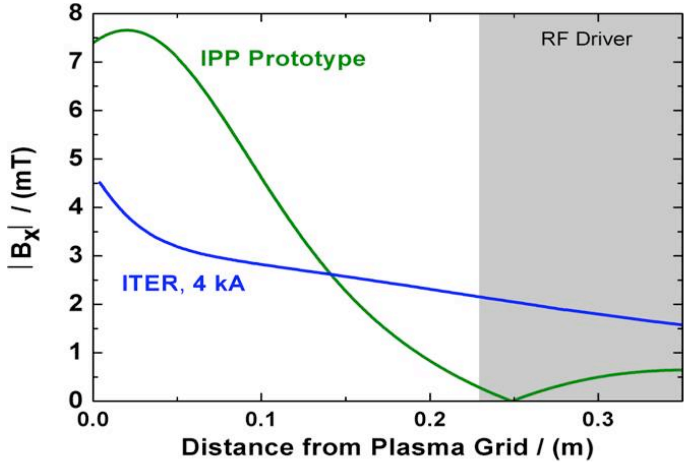
ITER: Current through the plasma grid (4kA)
“PG Filter”

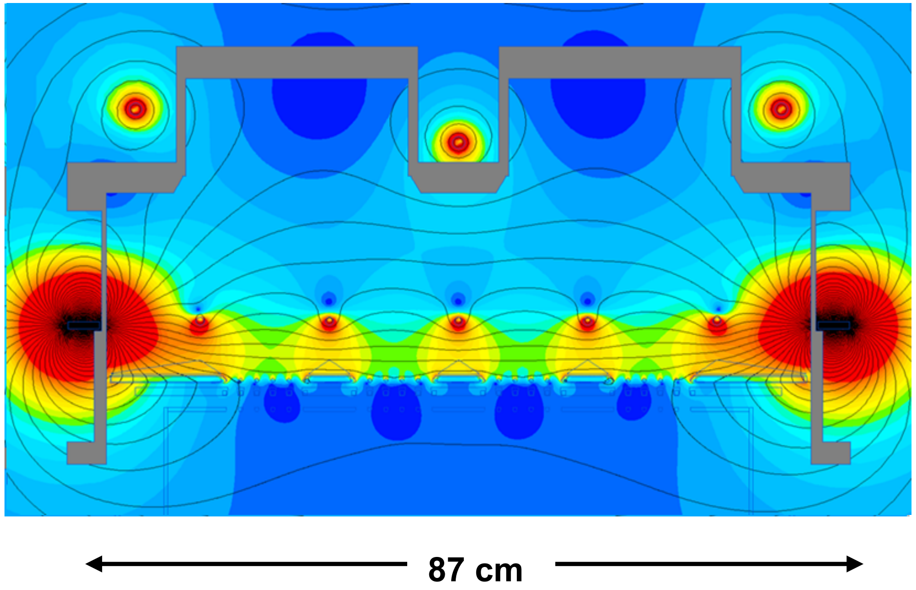
=> lower field close to the PG,
larger range

=> **new concepts to be tested**

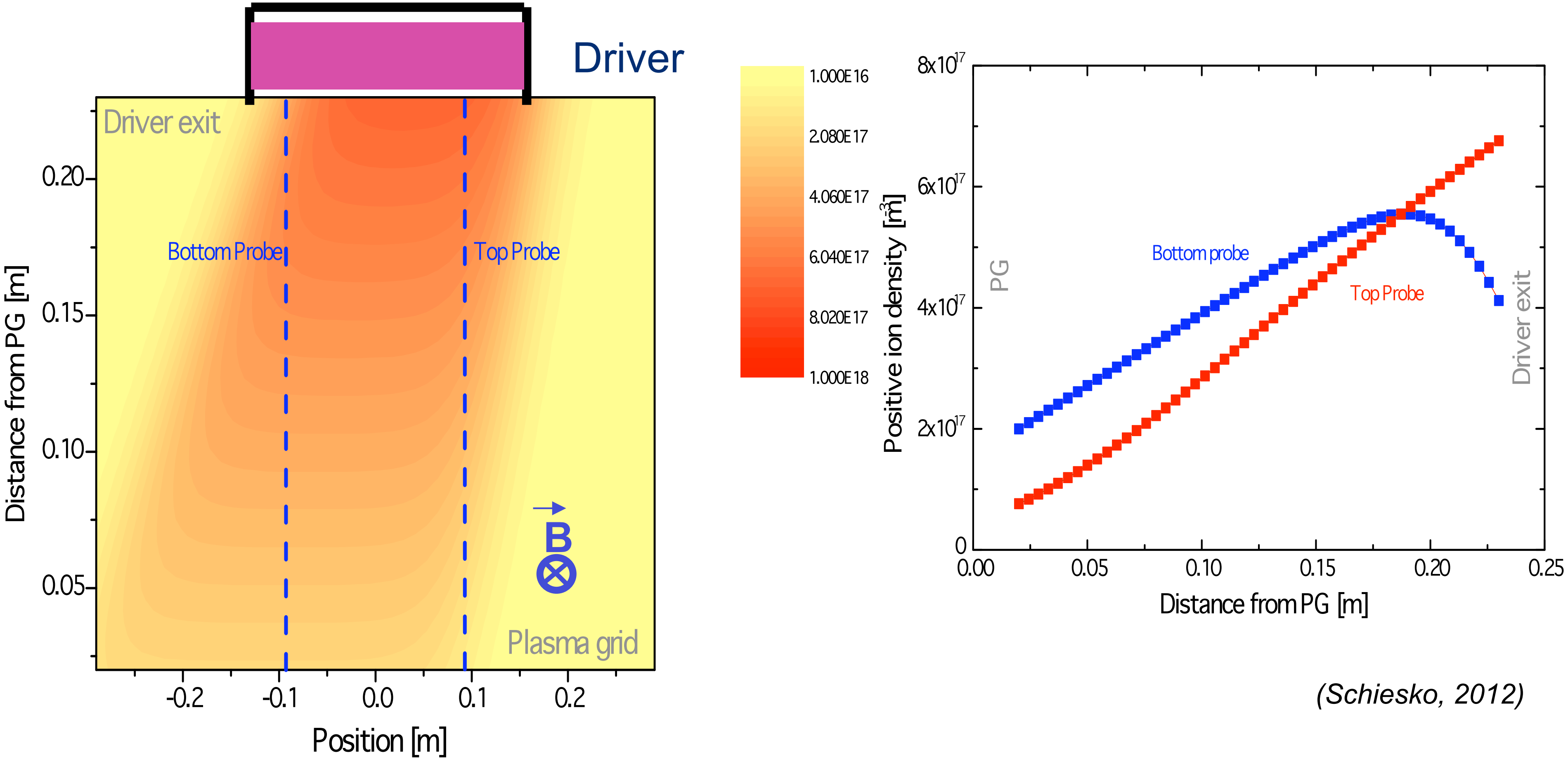
IPP Source







Drifting plasma in presence of a perpendicular magnetic field



(Schiesko, 2012)

Plasma drifting downwards (or upwards)

Combination of several cross B drifts

⇒ Inhomogeneous plasma density close to the plasma grid

Plasma drift in the RADI RF source

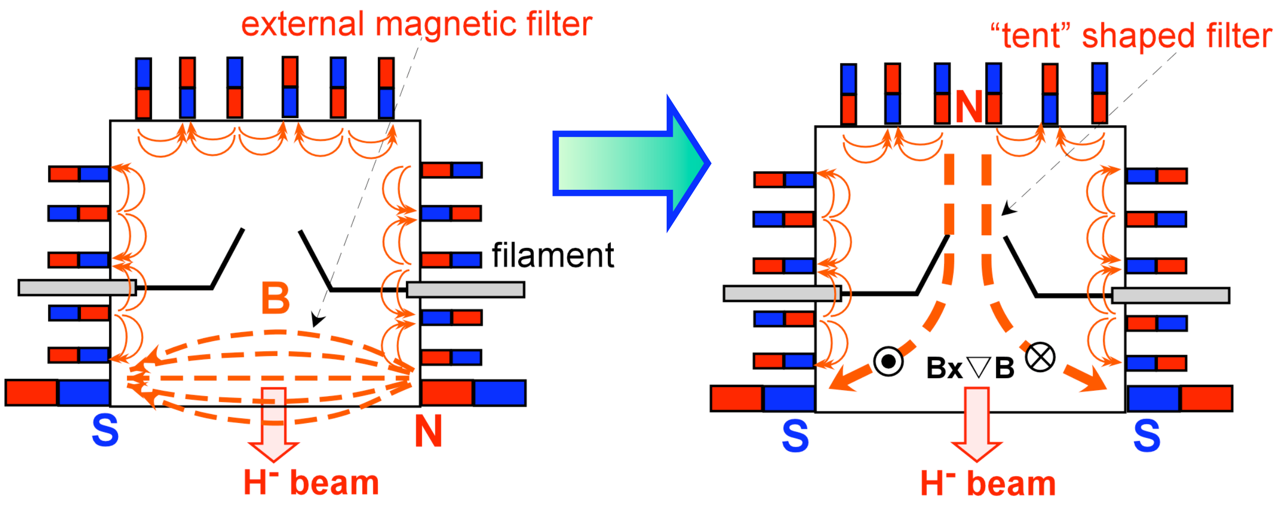
Without magnetic filter

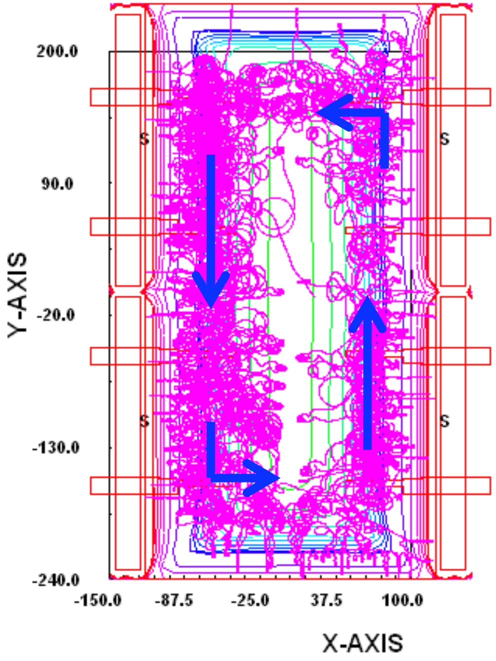
With 5 kA PG filter

Compensation of the plasma drift in arc sources

- Individual control of the arc and filament voltages according to the intensity of local arc discharges (LHD)
- Tent filter configuration (JT60)

  => Drift is closed azimuthally





(Inue, 2007)

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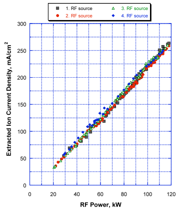
Cs dynamics: Reproducibility of beam currents

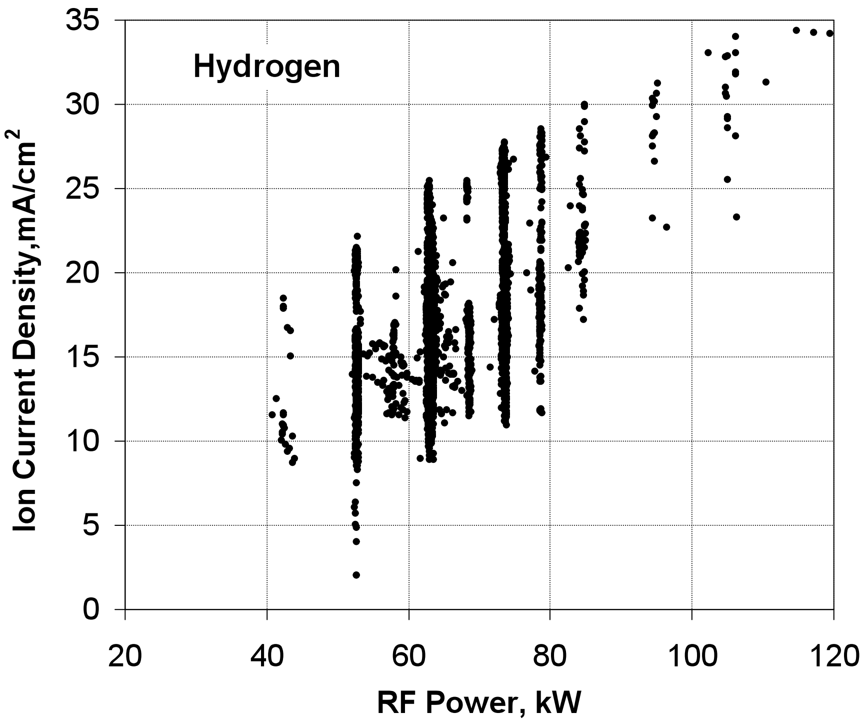
Volume production of **positive** Hydrogen ions



4 positive ion sources of the AUG NBI, max. current 100 A

Reproducibility very good

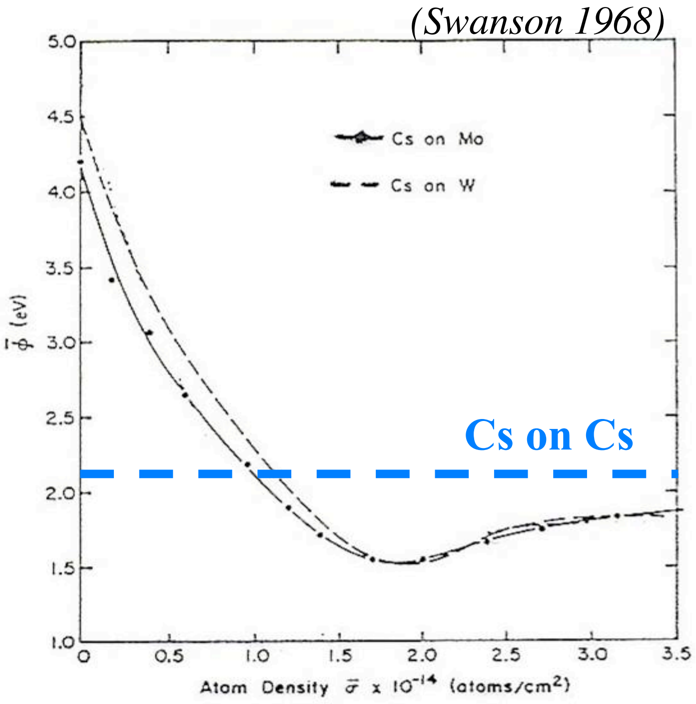
Surface production of **negative** Hydrogen ions

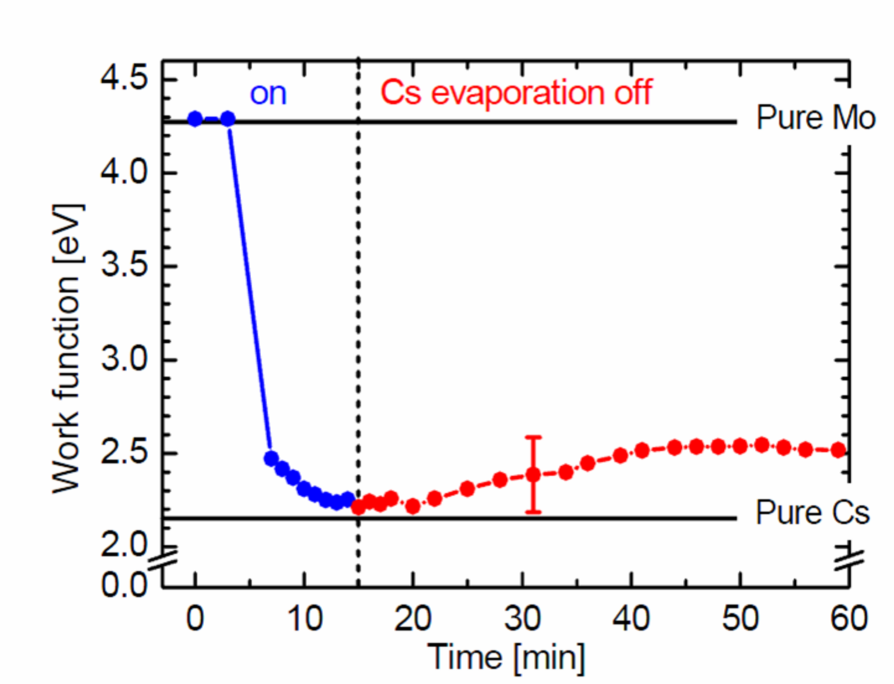


Two months experimental campaign with the negative ion prototype source, max. current 4 A

Poor reproducibility

Cs dynamics: Work function measurements





Minimum at 0.6 mono layer **not** achievable under vacuum conditions of the source (10^{-6} mbar)

=> **WF of Cs bulk material 2.14 eV**

WF degrades under after stop of the evaporation

=> **Detoriation by impurities** in the background gas (Cu, O_2, H_2O, …)

=> Constant Cs evaporation required

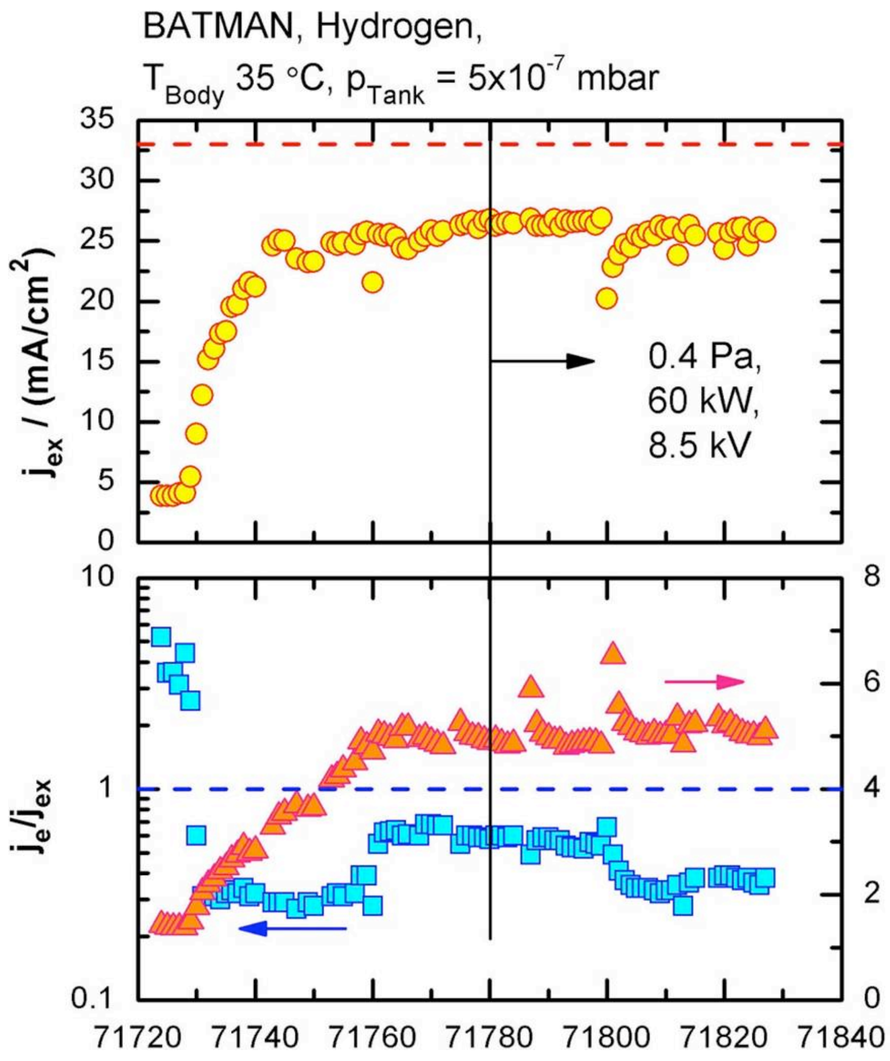
CS handling: Source conditioning at BATMAN (short pulses)

Conditioning procedure:

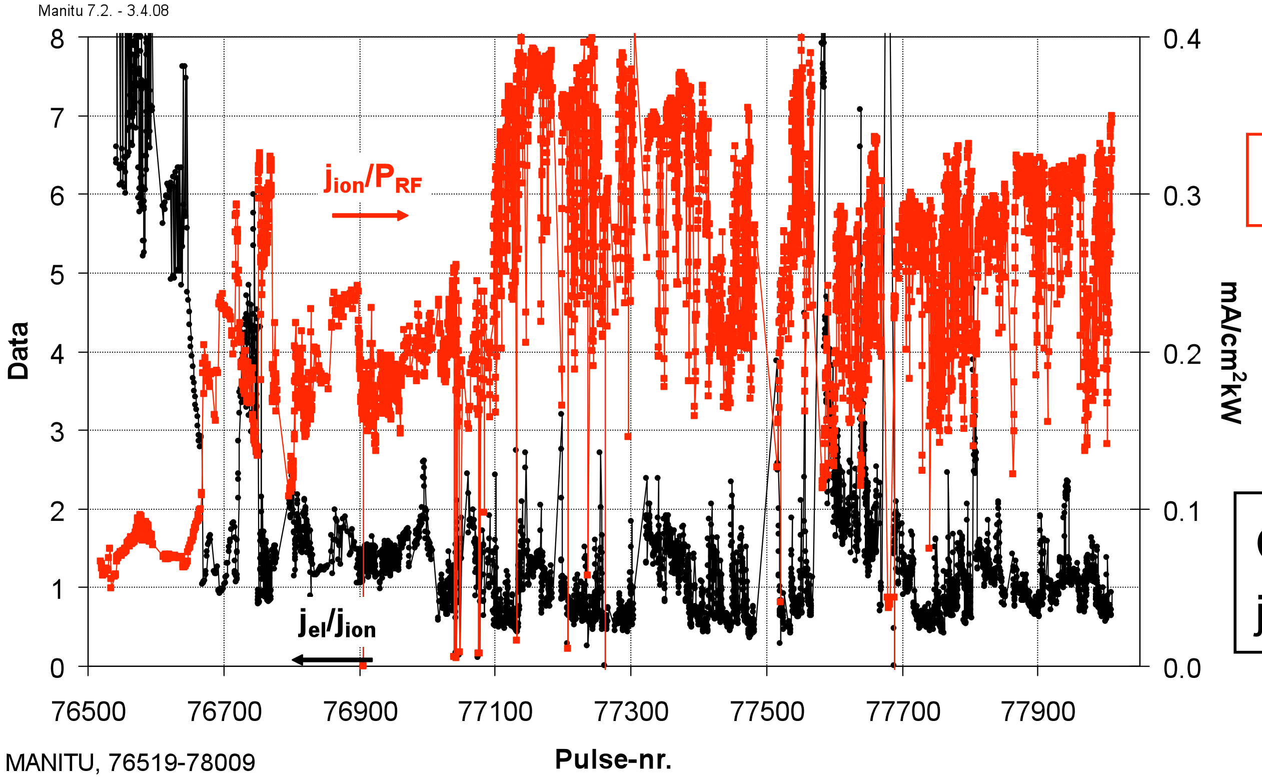
Optimize t_{Pulse}, t_{Pause}, Cs evaporation rate

=> reduction of electron current,
increasing ion current

- Faster conditioning
  at low background pressure
- Plasma grid temperature >140°
- Source body temperature 35° to
  avoid trapping of Cs on the walls



Long pulse conditioning at MANITU



Efficiency $j(H^-)/P_{RF}$

Co-extracted electrons $j_{el}/j(H^-)$

- Large variation of the currents at the same parameters
- Long-term degradation by impurities

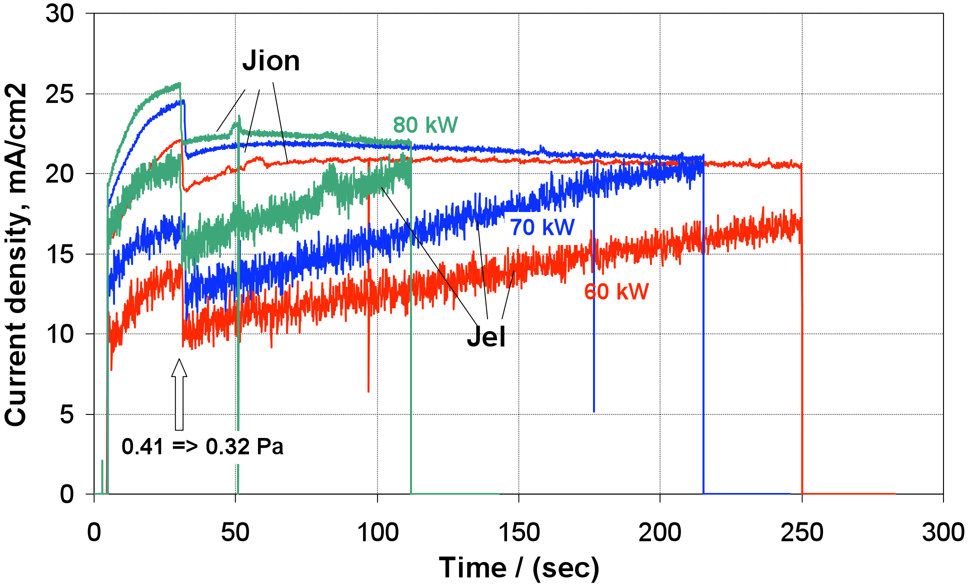
Electron currents in long pulses

- Ion currents more stable than electron currents,
- but saturate at high power
- Electron currents increase steeper at high power

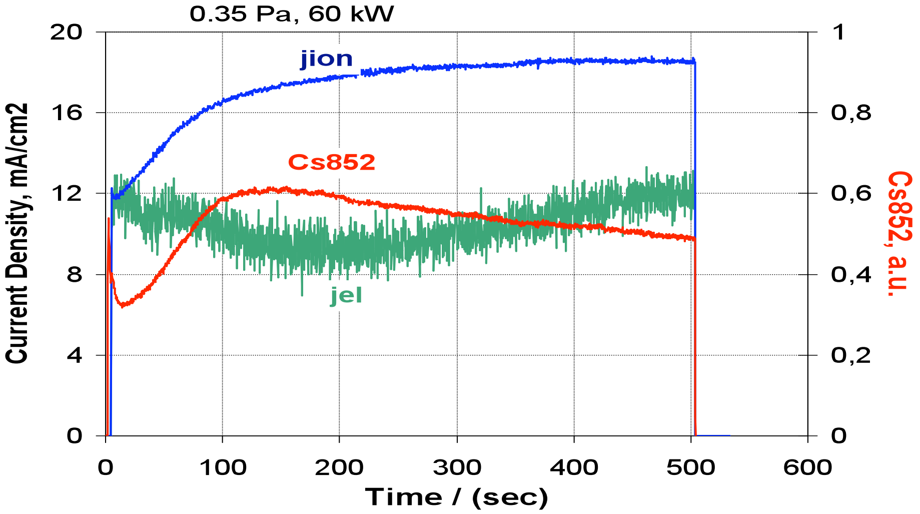
⇒ In long pulses high load on the extraction grid

⇒ Reduction of the power

⇒ Lower ion currents



Electron current in long pulses correlated to Cs dynamics (Cs released from inner surfaces of the source)



Minimizing the current of co-extracted electrons

1. Conditioning

Plasma cleaning of the plasma grid surface

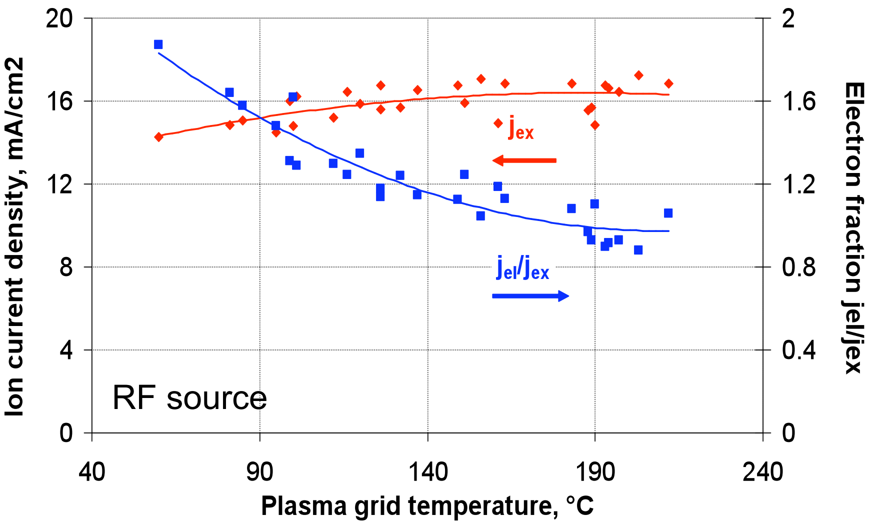
+ Cs evaporation

2. **Plasma grid temperature**

RF source: Minimum temperature > 150°(**?**),

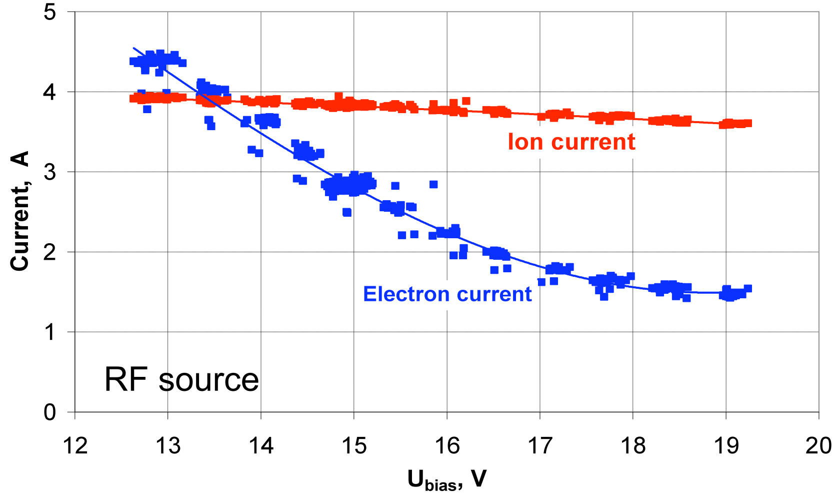
- up to 220° no significant change,
- in arc sources much higher plasma grid temperature required > 250°

=> Effect of tungsten coating ?



3. **Positive biasing** the plasma grid with respect to the source

- Electron current more sensitive
- Dependence on the bias voltage is different according to the Cs conditions



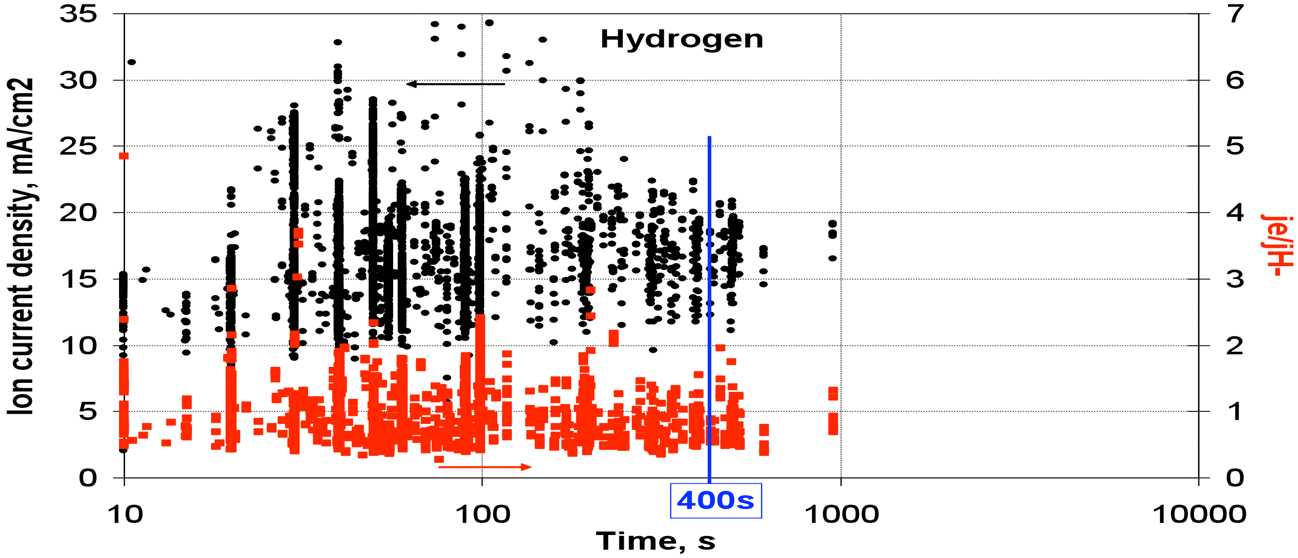
Long pulse performance of one experimental campaign

Hydrogen:

20 - 30 mA/cm^2

Pulse length ITER

400s



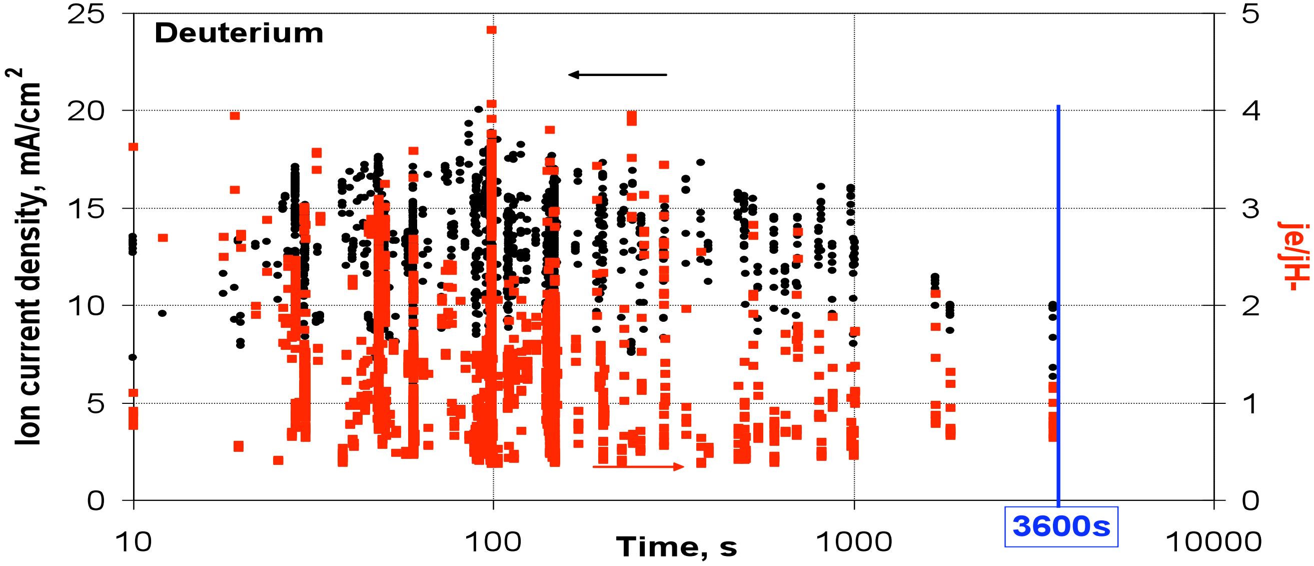
Deuterium:

10 - 20 mA/cm^2

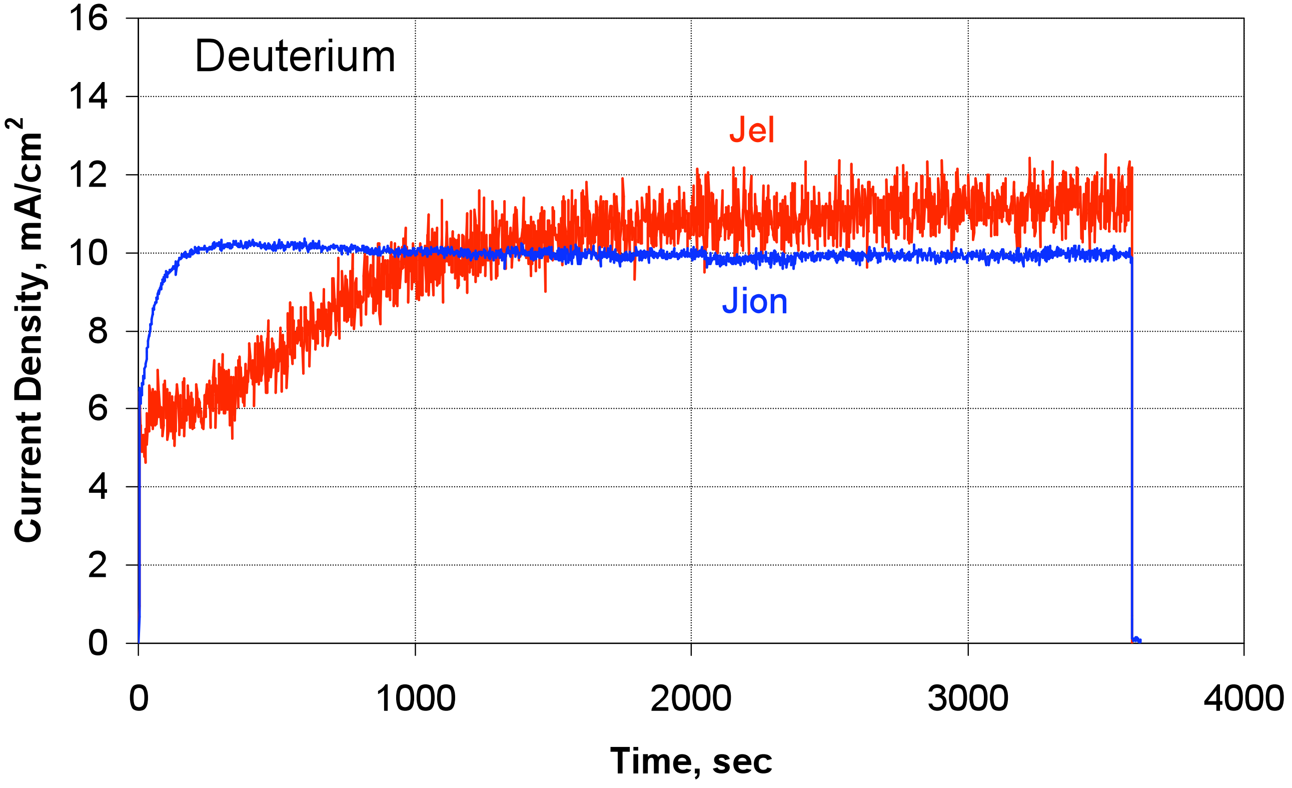
Pulse length ITER

3600s

Higher electron current(?)



One hour pulse in Deuterium



0.3 Pa, 45 kW, J_{ion}= 10 mA/cm^2

Stable long pulses at reduced power

Outline

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- Negative ion based neutral beam injection
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- **Giant source for ITER**
- Test facilities

Requirements for the ITER NBI

Heating beams HNB

33 MW injected power

2 (later 3) tangential injectors

1 MeV

3600 s

I(D$^-$)= 40 A (one beamline)

Diagnostic beam DNB by IPR, India

3 MW, 100 keV, negative ions!

I(H$^-$) = 60 A, same source type

Requirements for the HNB ion sources

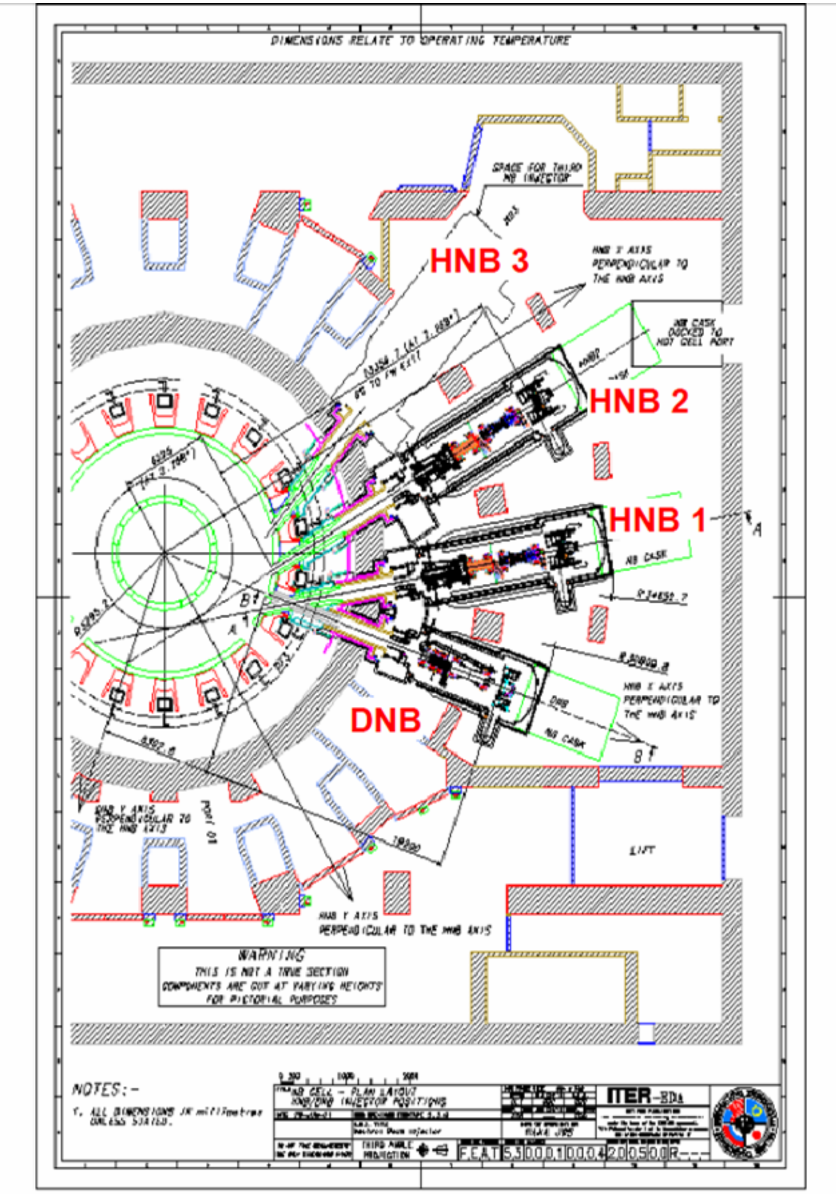
Accelerated current density

20 mA/cm^2 (D$^-$)

24 mA/cm^2 (H$^-$)

j_{el}/j_{ion} <1, at 0.3 Pa

Durations: 3600s (D$^-$), 400s (H$^-$)



In 2007 RF Source was chosen for the reference design of ITER

Reasons for the decision:

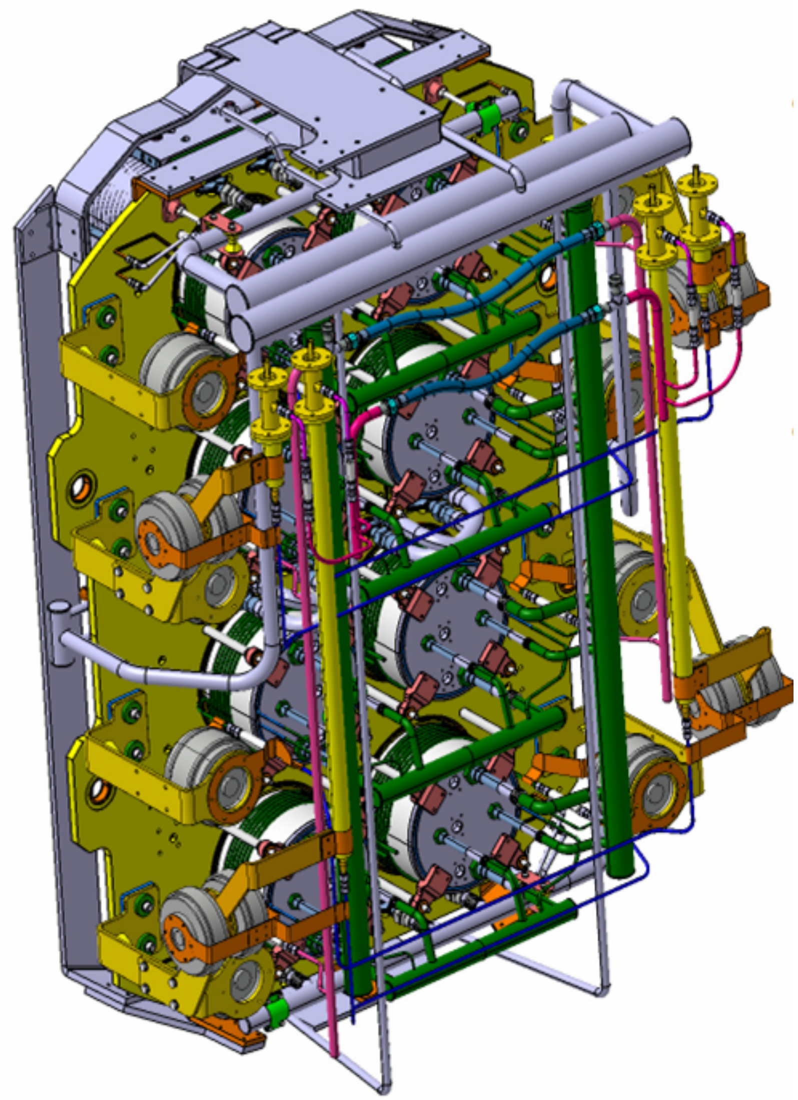
- No regular maintenance intervals necessary

  Important in the radioactive environment

- Simpler and possibly cheaper
  - much fewer components on HV
  - much fewer vacuum feedthroughs
- **No tungsten** coating of the walls

  => Lower Cs consumption

- **Proof of reliability** by 10 years operation of RF sources in the positive ion based NBI of the AUG tokamak
- Required **H^-/D^- current densities** have been achieved with a small scale prototype at low source pressure (<0.3 Pa) in short pulses (> 4s) on the test facility BATMAN (IPP)



Design of the ITER RF source

Development of large RF sources

Test of

- the modular concept: multi driver – large expansion volume,
- RF power supply with two drivers in series,
- new filter field concepts,
- optimized extraction system

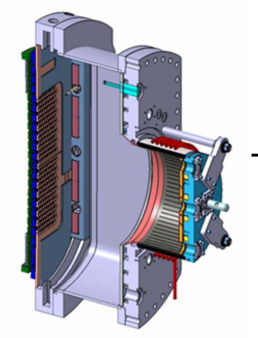
Benefits of large sources

- Larger driver diameter reduces neutral depletion,
- Expanding plasmas of the multi drivers overlap

=> Higher plasma density in the expansion chamber

=> higher efficiency

Extrapolation to the ITER Source

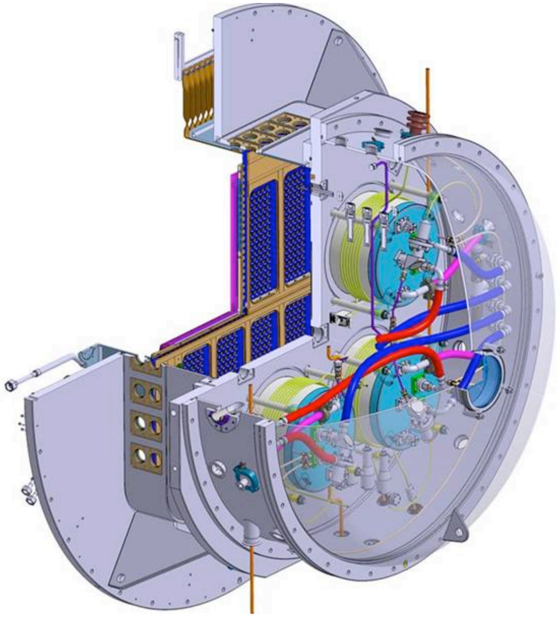


1 Driver

0.59 x 0.31 m^2

4 x →

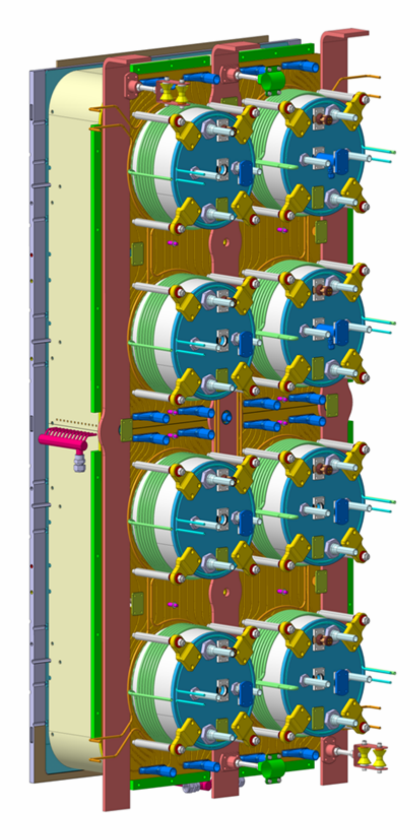
Intermediate step at IPP



4 Drivers

1.0 x 0.9 m^2

2 x →



8 Drivers

1.9 x 0.9 m^2

Batman 5s

Manitu cw

Robin 5s, IPR

Radi without extraction

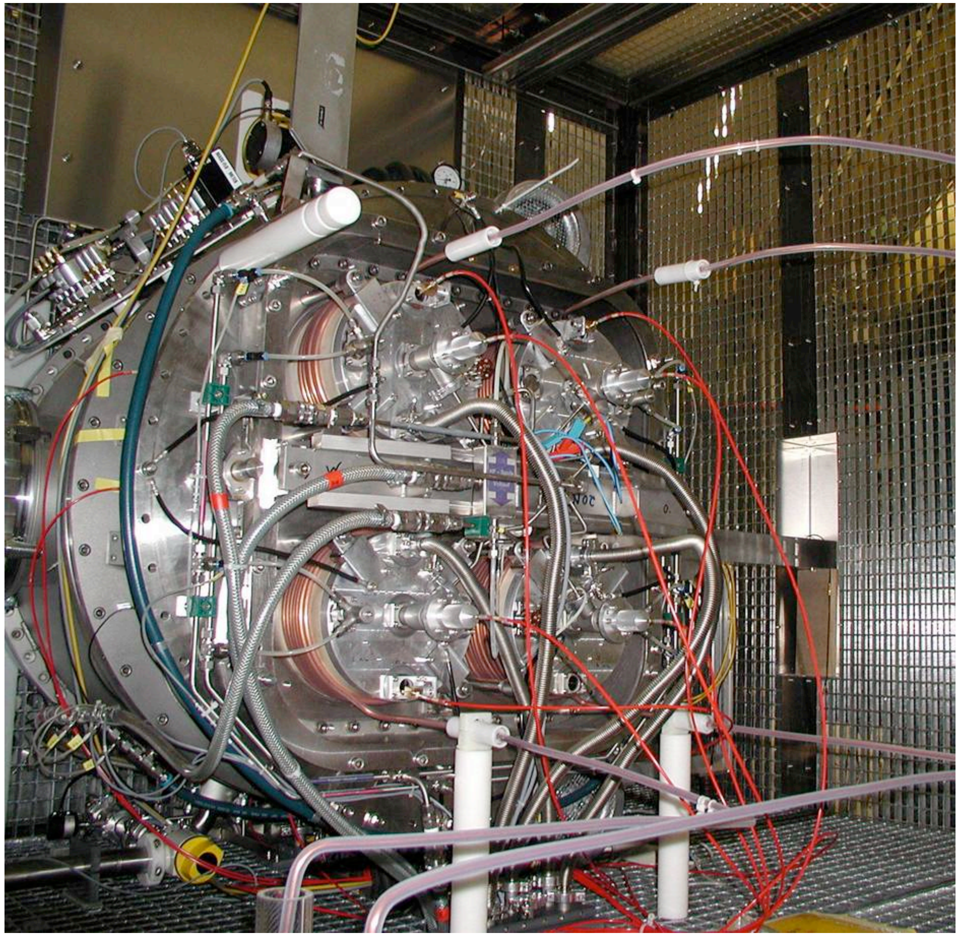
ELISE

HNB (RFX, Italy), 58 A D^-

DNB (IPR, India), 70 A H^-

RADI source

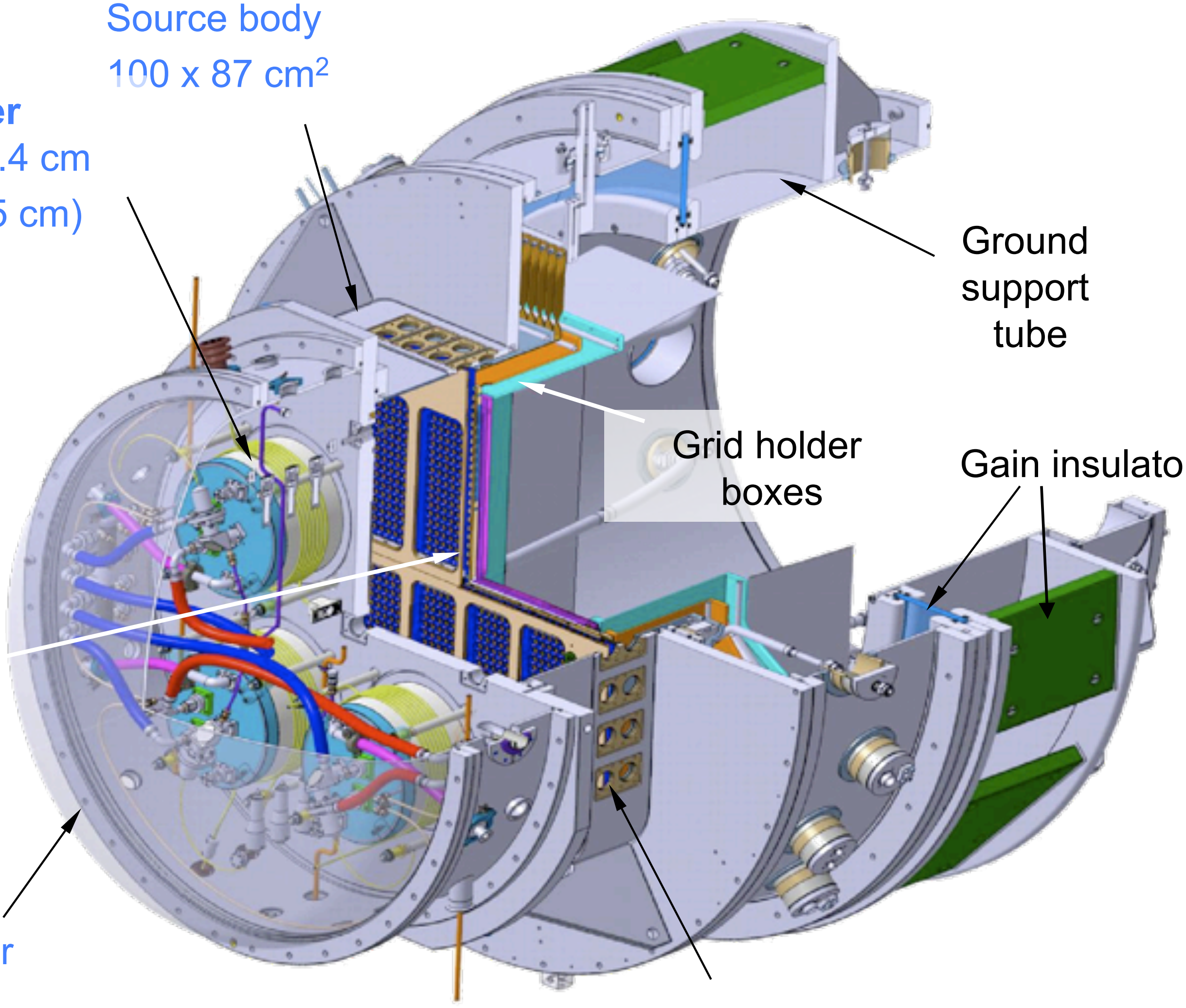
- About full width and half the height of ITER source (0.76 x 0.8 m^2)
- Two drivers in series supplied by one 1MHz/180kW RF generator
- **No Cs evaporation**
- **No beam extraction**



Achieved

- 2 x 130 kW operation
- Homogenous plasma density
- Low pressure operation 0.2 - 0.3 Pa

ELISE ion source
(Extraction from a Large Ion Source Experiment)



Source body
100 x 87 cm^2

Larger driver diameter 28.4 cm
(Type 6: 24.5 cm)

Ground support tube

Grid holder boxes

Gain insulator

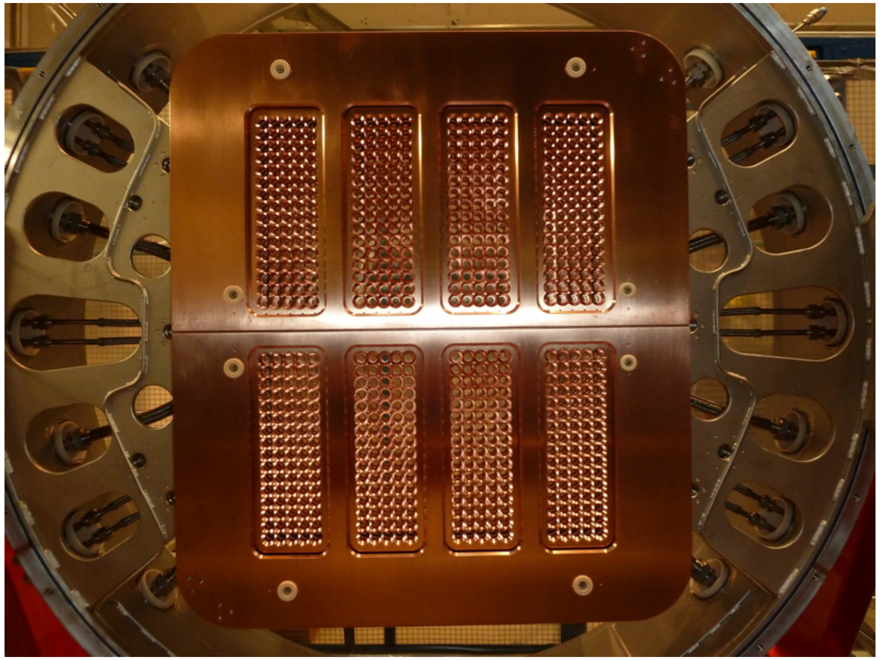
Extraction system

Driver dome for **operation in vacuum**

Diagnostics ports near PG

ELISE extraction system

4 beamlet groups

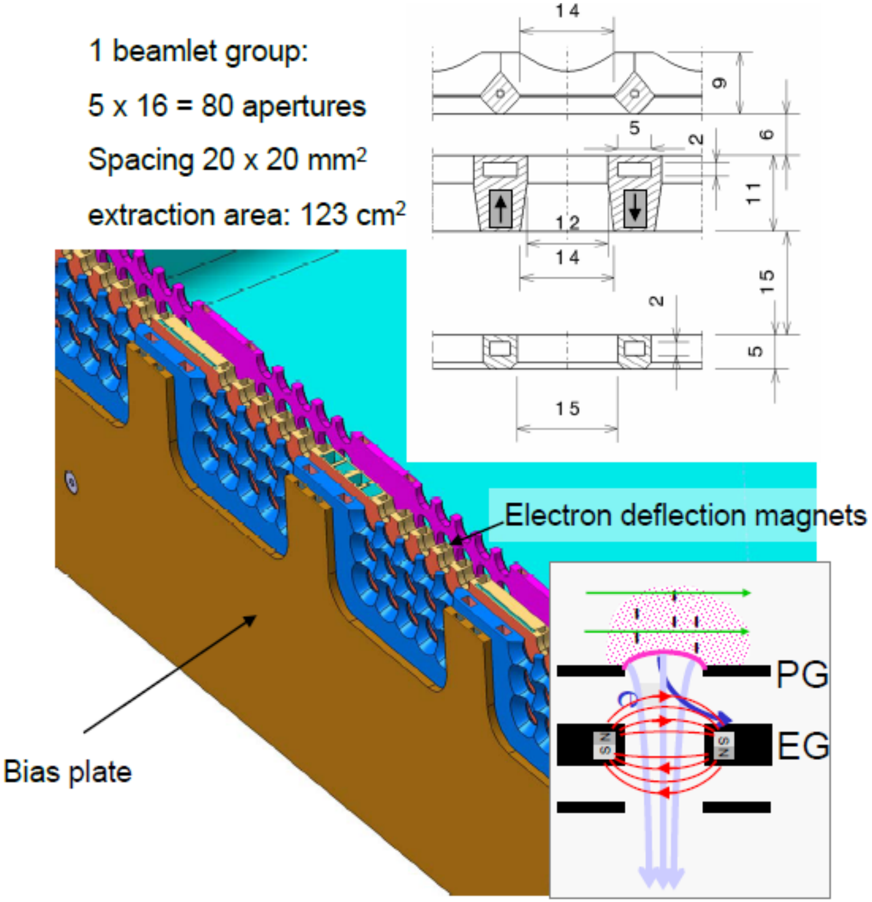


1 beamlet group:

5 x 16 = 80 apertures

Spacing 20 x 20 mm²

extraction area: 123 cm²

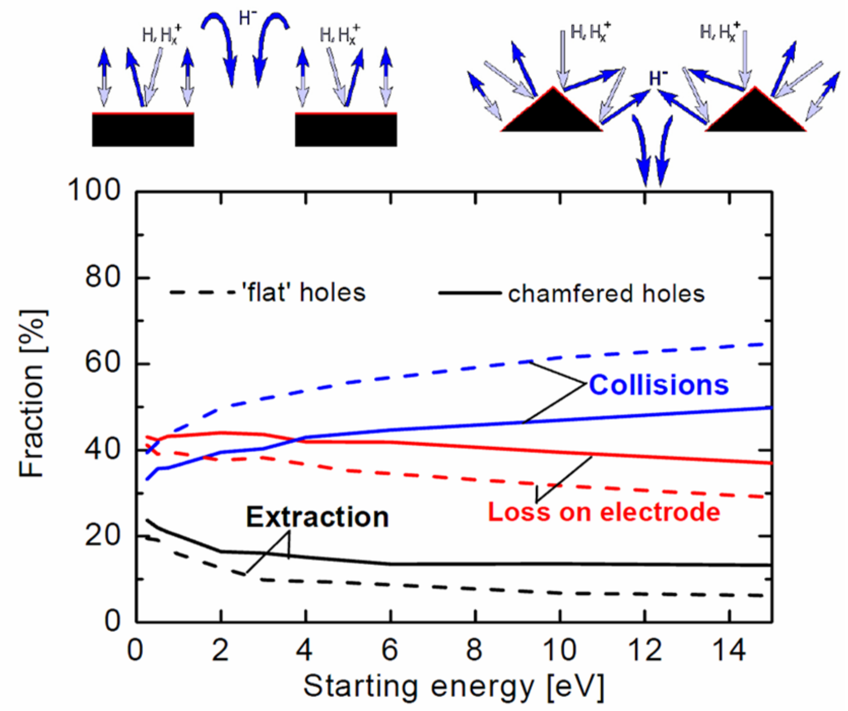


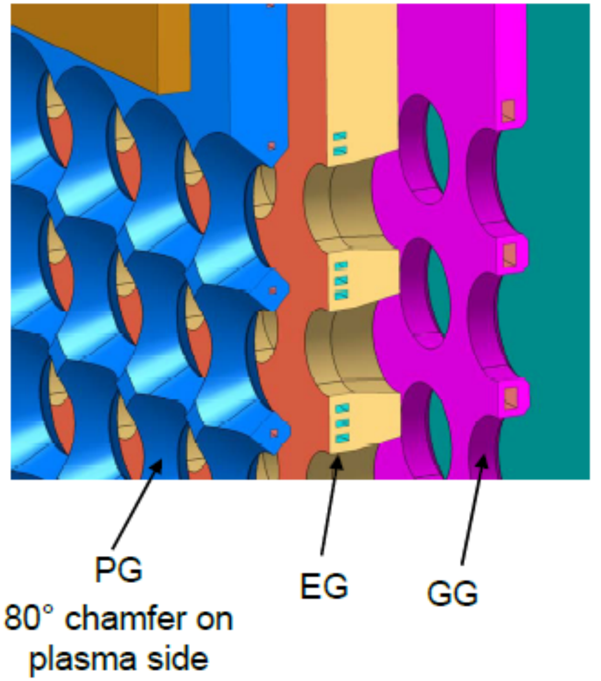
ELISE: Shape of plasma grid apertures

Chamfered apertures

- Less collisions with particles
- Less losses on the electrode

=> **Higher extraction probability**



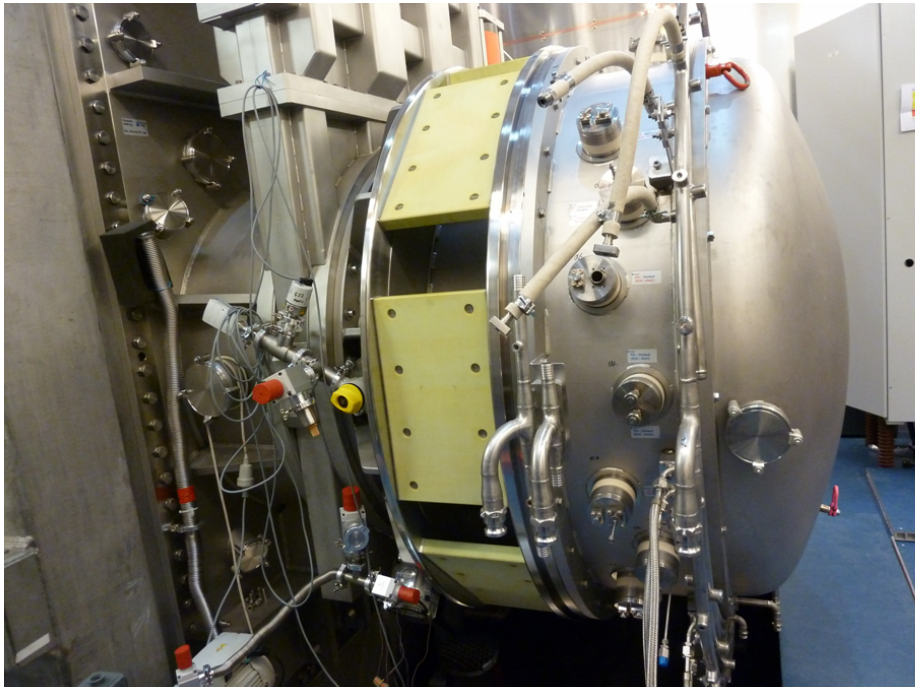


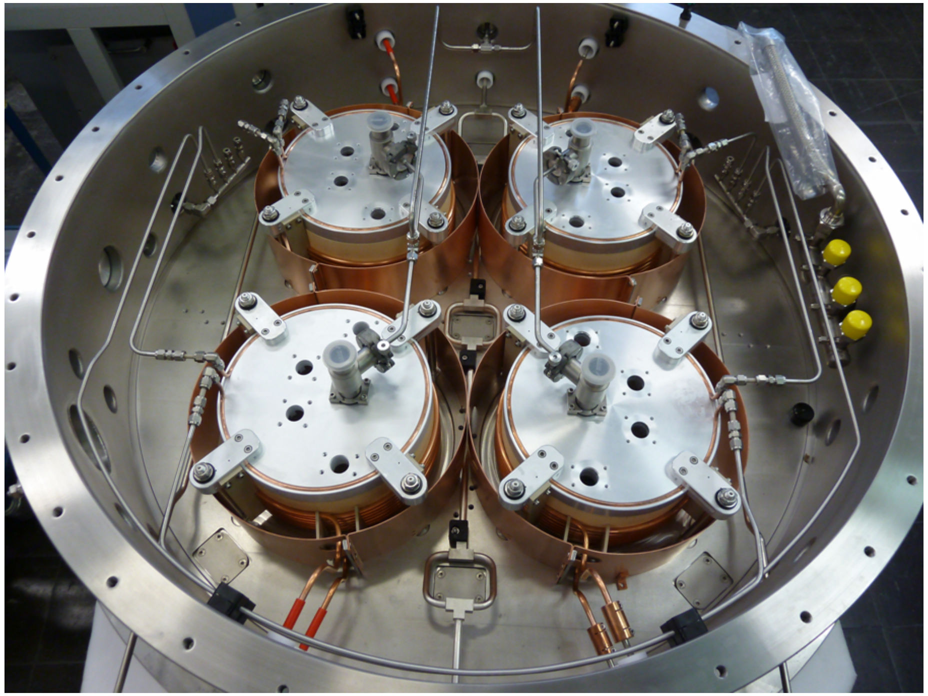
80° chamfer on plasma side

Assembly of the ELISE source

Commissioning in June 2012

RADI and MANITU shut down in August 2011





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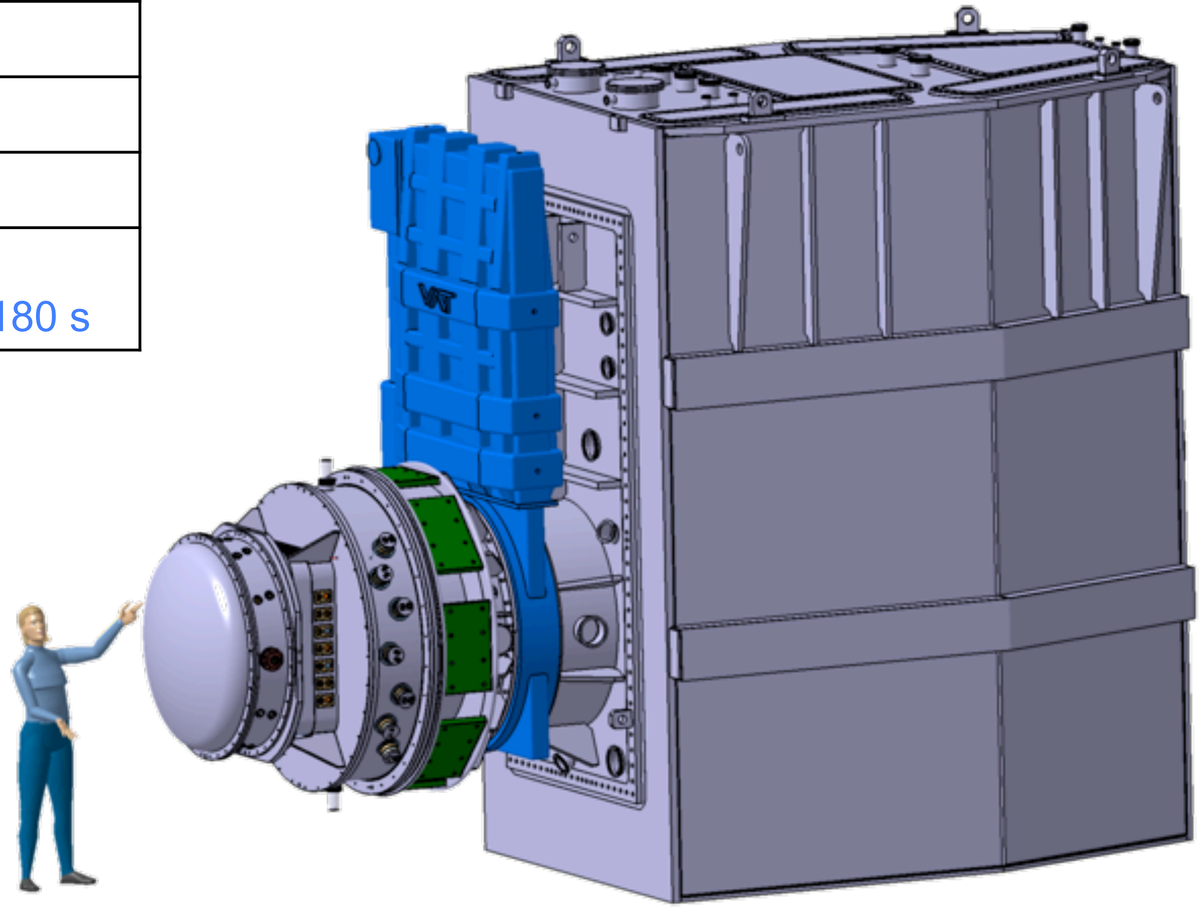
- Plasma heating by neutral beam injection
- Positive Ion sources for Neutral Beams
- Negative ion based neutral beam injection
- Beam extraction
- Production of negative ions
- Negative ion sources
- Experimental results with the RF prototype
- Giant source for ITER
- **Test facilities**

NNBI test facilities

		ITER (rf)	LHD (arc)	JAEA JT60U (arc)		JAEA MV TF (arc)	IPP (rf source)	
Species		D^-	H^-	D^-	H^-	H^-	H^-	D^-
Energy	**MeV**	1000	**180**	**400**		**937**		
Voltage holding	**MV**	1000	**190**	**500**		1000		
Source height	**m**	1.95	**1.45**	**1.22**			**0.59**	
Source width	**m**	1.55	**0.35**	**0.64**			**0.3**	
No. of apertures		1280	**770**	**1080**				
Accelerated current	**A**	40	**30**	**17**		**0.33**	**1.4**	
Source power	**kW**	800	**180**	**350**			**100**	
Extracted current density	**A/m^2**	285	**250**			**144**		280
Pulse length	**s**	3600	**2**	**2**		**2**	3600	**4**

ELISE testbed

Extraction area	1000 cm^2
Acceleration voltage	60 kV
Extraction voltage	<12 kV
Ion current	20 A
RF power	2 x 180 kW
Plasma on time Beam extraction	3600 s 10 s every 180 s



Gate valve

=> no deterioration of Cs
during cryo regeneration

ITER beam test facilities

- ELISE (IPP Garching): Half-size ITER-type source in cw operation with 60 kV/10s beam extraction.

  → to assess spatial uniformity of negative ion flux, validate or alter source concept
- SPIDER (RFX, Padua): Full size ITER source with full extraction voltage 100 keV, 3600s → to validate or alter source and extractor
- MITICA (RFX, Padua): Full size ITER source, 1 MeV, 3600s

  → to validate or alter accelerator and beamline components
- DNB source test facility (Ghandinagar, India), Full size ITER source, 100 keV, 3600s

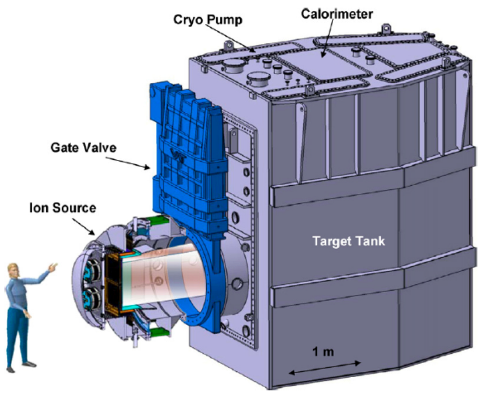
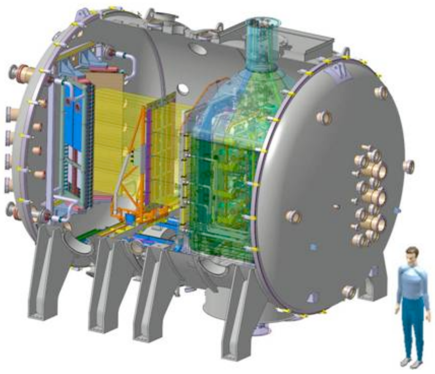
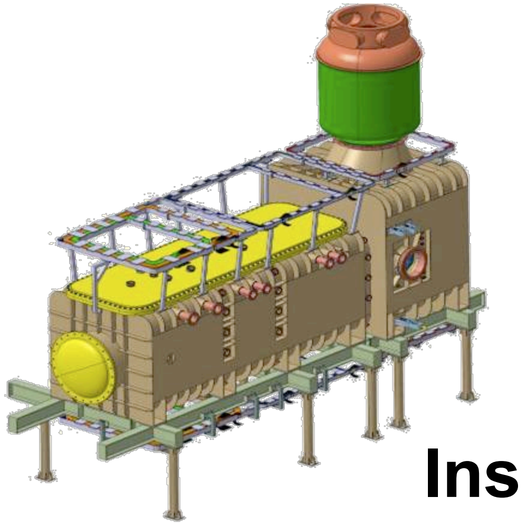


Fig. 1. Overview of ELISE test facility.





Installation at ITER

ELISE 2012 → **SPIDER** 2015 → **MITICA** 2017 → **Installation at ITER** 2018

Summary

- Positive ion sources have reached a high degree of performance and reliability.
- Future fusion reactors require giant high power ion sources in which the negative ions are produced on Cs-adsorbed surfaces with low work function.
- The present development concentrates on the ITER NBI source which will produce 40A /1MeV beams for 3600s. The RF source was chosen for the ITER reference design due to the maintenance free operation and because the individual target values have been achieved with a small prototype.
- The further development of sources of ITER relevant size will be carried out in the next years on new large testbeds at IPP Garching and RFX Padua.