Ion Sources for Fusion

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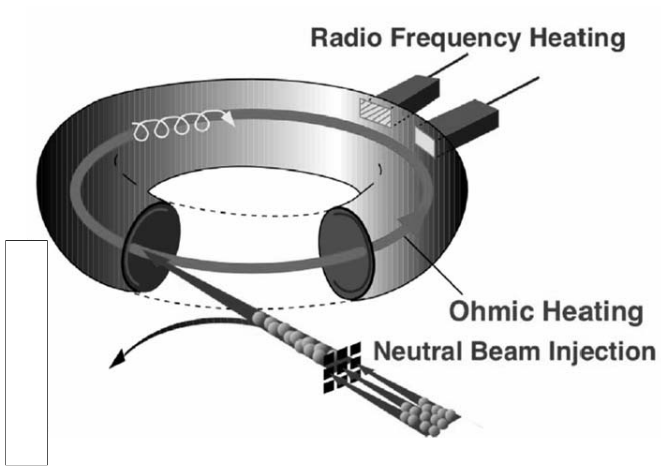
Ion sources in fusion devices

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
- Surface 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

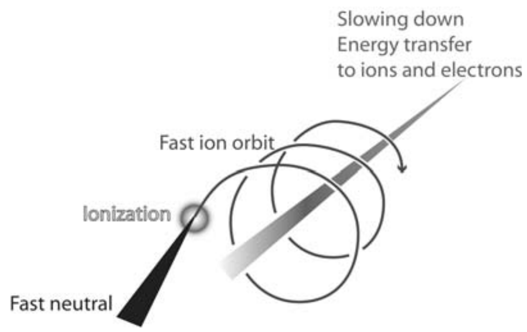
	R_0 (m)	a (m)	I_p (MA)	B_t (T)	Installed heating power (MW)				
					P-NBI	N-NBI	ECRH	ICRH	LH
ITER	6.2	2.0	15	5.3	-	33	20	20	-
JET	2.96	1.25	4.8	3.45	34*	-	-	10	7
JT-60U	3.4	1.1	5	4.2	40	3	4	7	8
JT-60SA	2.97	1.17	5	2.25	24	10	7	-	-
TFTR	2.4	0.8	2.2	5	40	-	-	11	-
EAST	1.7	0.4	1.0	3.5	-	-	0.5	3	4
DIII-D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



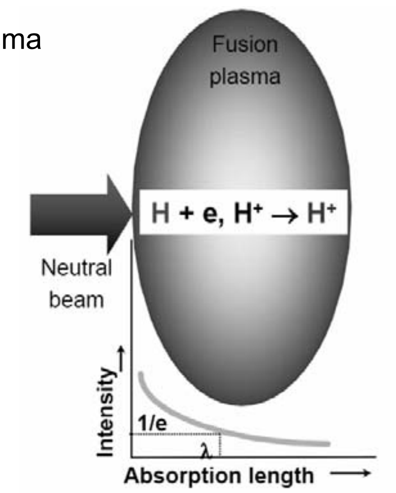
Penetration depth

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 = 5x10^{19} m^{-3} => λ = 0.5 m

Fraction not absorbed by the plasma : shine-through
determines minimum plasma density

Slowing down – power to the ions and electrons

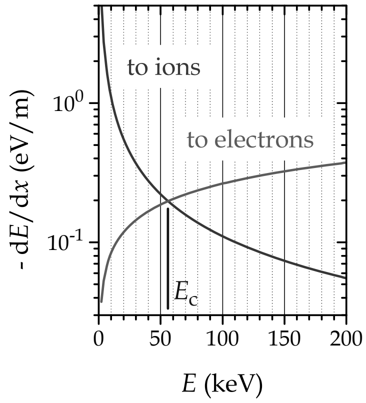
Change of energy of a fast ion

$$\frac{dE}{dx} = -\frac{\alpha}{E} - \beta\sqrt{E}$$

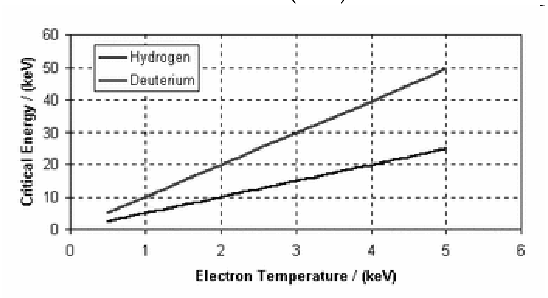
to ions | to electrons

Stopping by ions and electrons is equal at the
“Critical energy” E_c

NBI: D^0, plasma: D^+
$n = 5 \times 10^{19}$ m^{-3}, $T_e = 3$ 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) ?

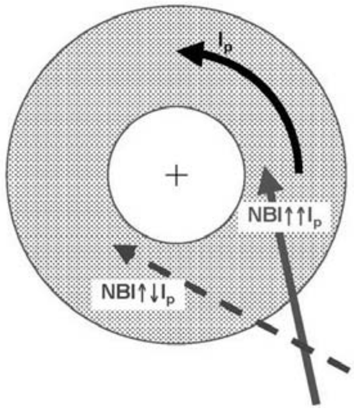
- **Tokamaks:** Plasma current is driven inductively (principle: transformer).
  => pulsed operation

  ⇒ 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

top view



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}

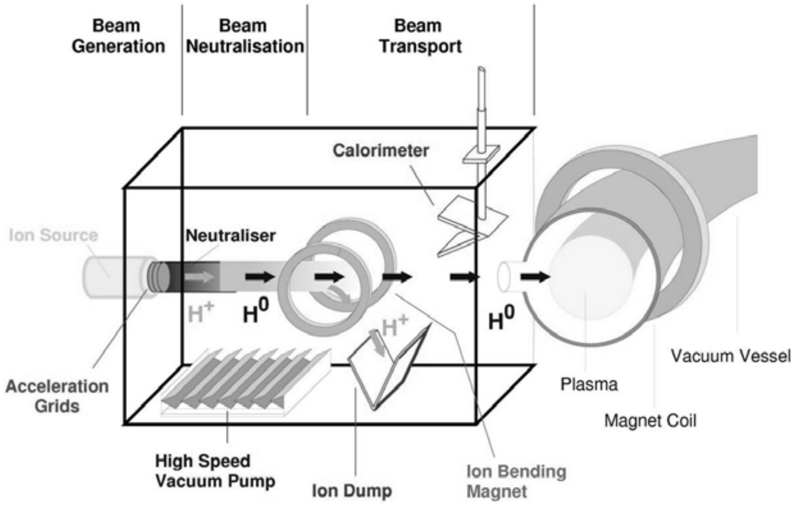
Current drive efficiency

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

R major radius
P_{dep} deposition power

At present about 0.2 – 0.3

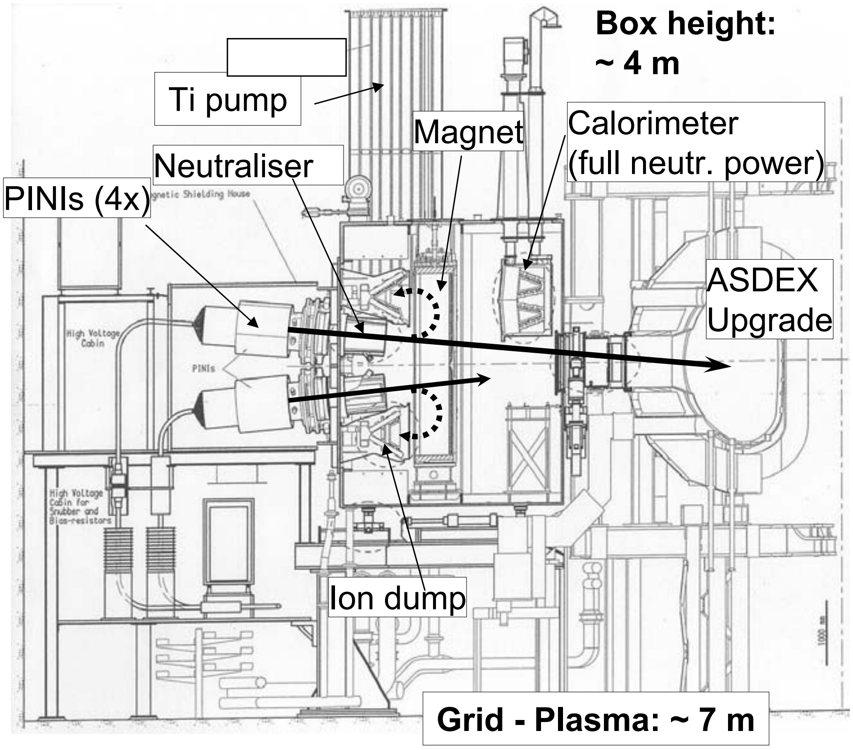
Neutral Beam Systems



Neutral beams are produced by:

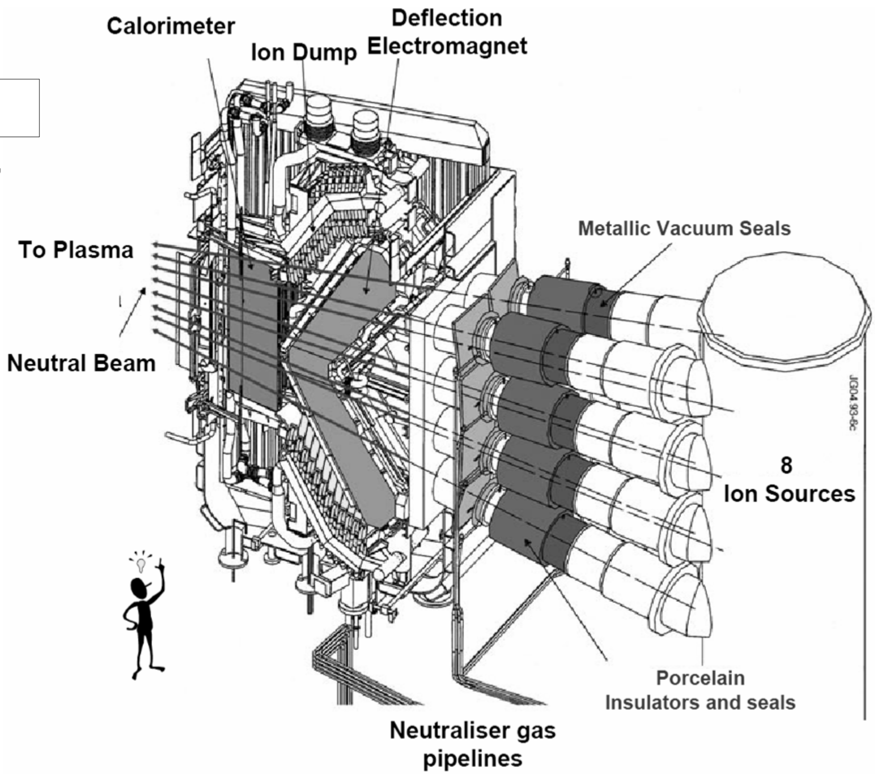
- Powerful ion beam by the ion source and the extraction system
- Neutralisation by charge exchange collisions of the fast ions with the cold gas in the neutralizer
- Not neutralised part of the beam is deflected to the ion dump
- The beam power is measured by a calorimeter

The ASDEX Upgrade NBI System (Garching, Germany)

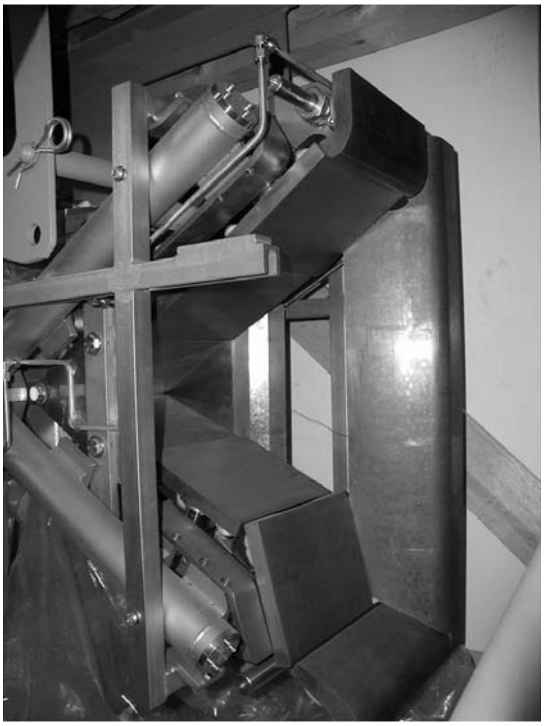


NBI system of JET (Joint European Torus, Culham, UK)

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

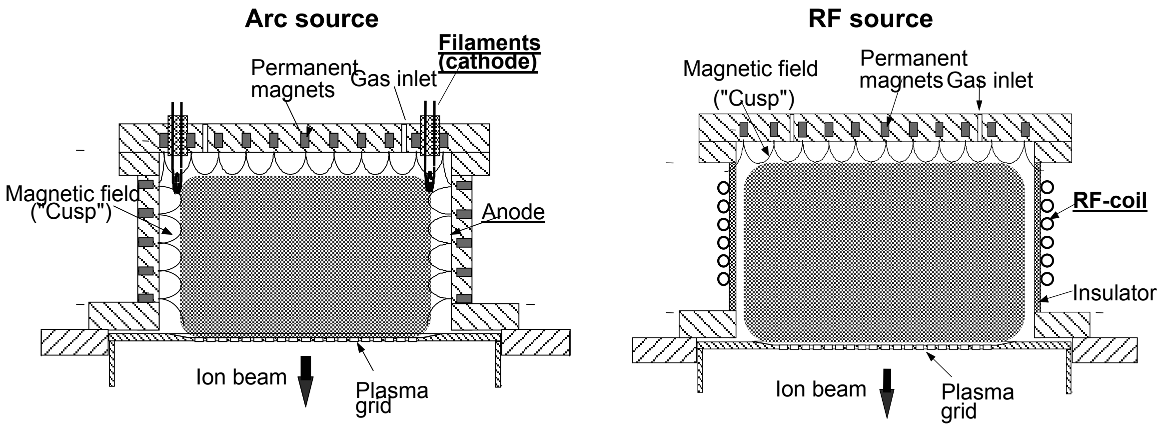
Requirements:

Beam species	H_n^+, D_n^+
Beam current	30 – 90 A
Current density	**230 – 300 mA/cm²**
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



Advantages of the RF source

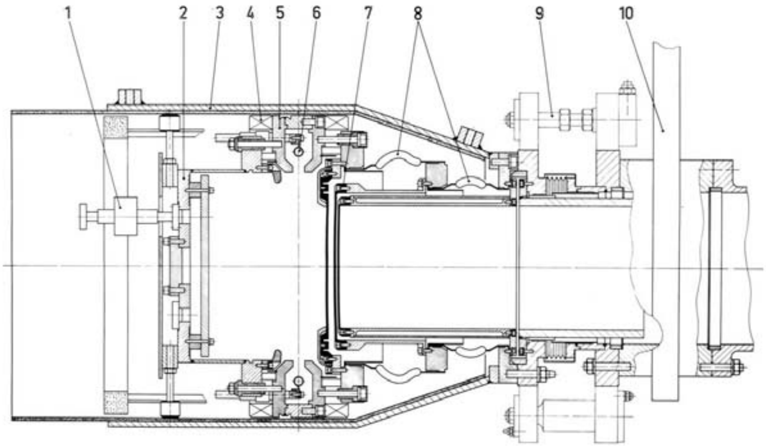
- No filaments => no lifetime limitations
- Cost saving due to the cheaper power supply
- Power supply on ground potential (separation by a transformer)

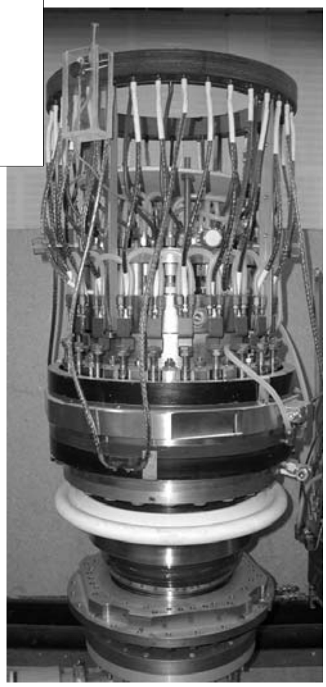
=> RF sources used in the second injector of ASDEX-Upgrade since 1997

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

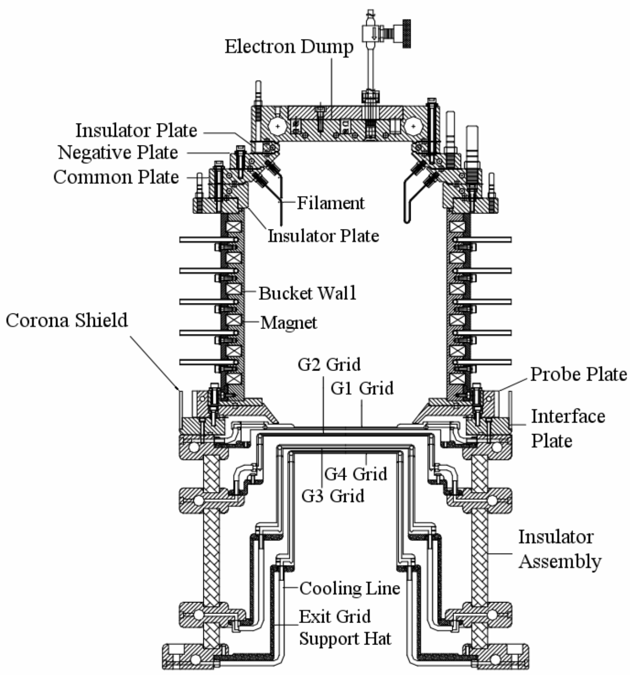
Used at **ASDEX**

- 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





Arc sources: TFTR source



Upgraded version used at KSTAR (Korea)

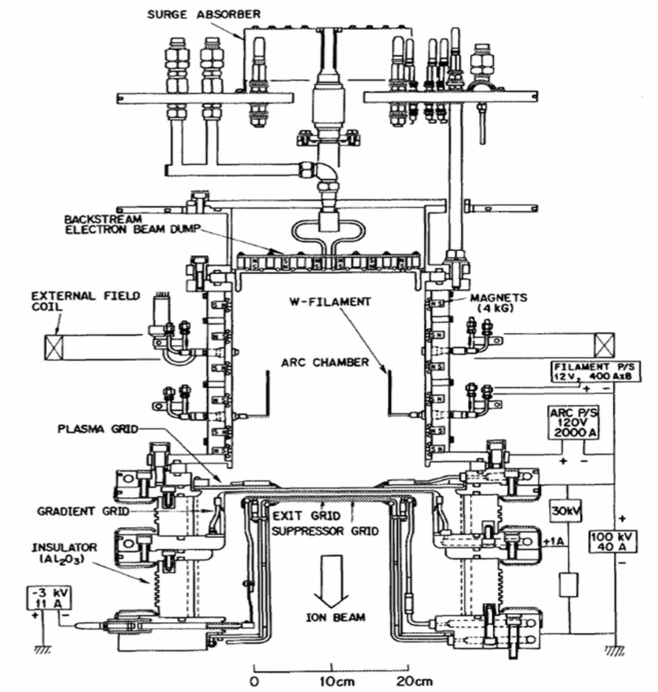
Accelerator Part : Circular Aperture Grids

- 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

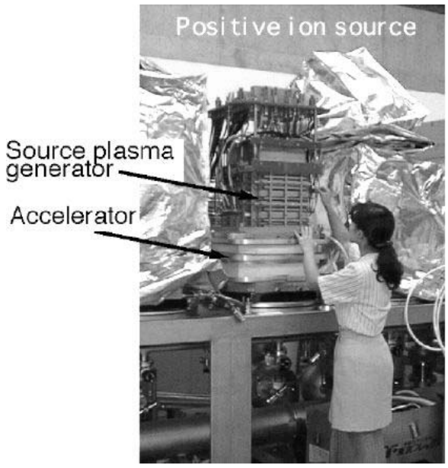
Beam current : 40A

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

Extraction area : 12 × 27 cm^2

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

No of ion sources : 28



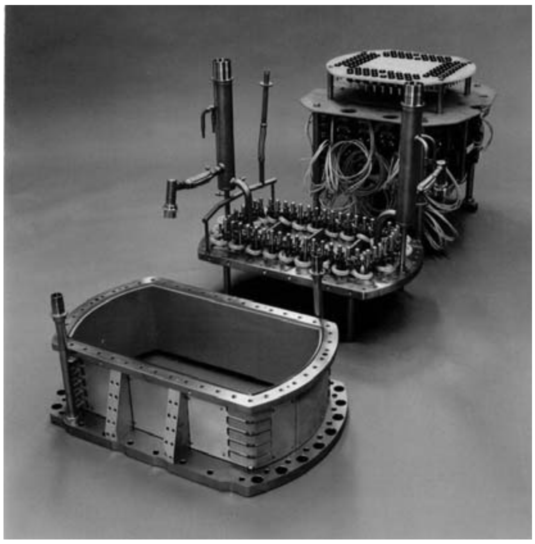
Arc sources: “Bucket” source

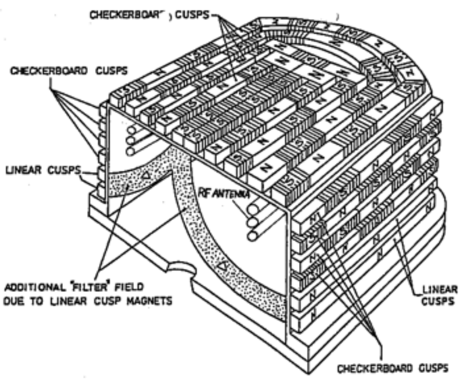
Used at

ASDEX-Upgrade, Textor, JET

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

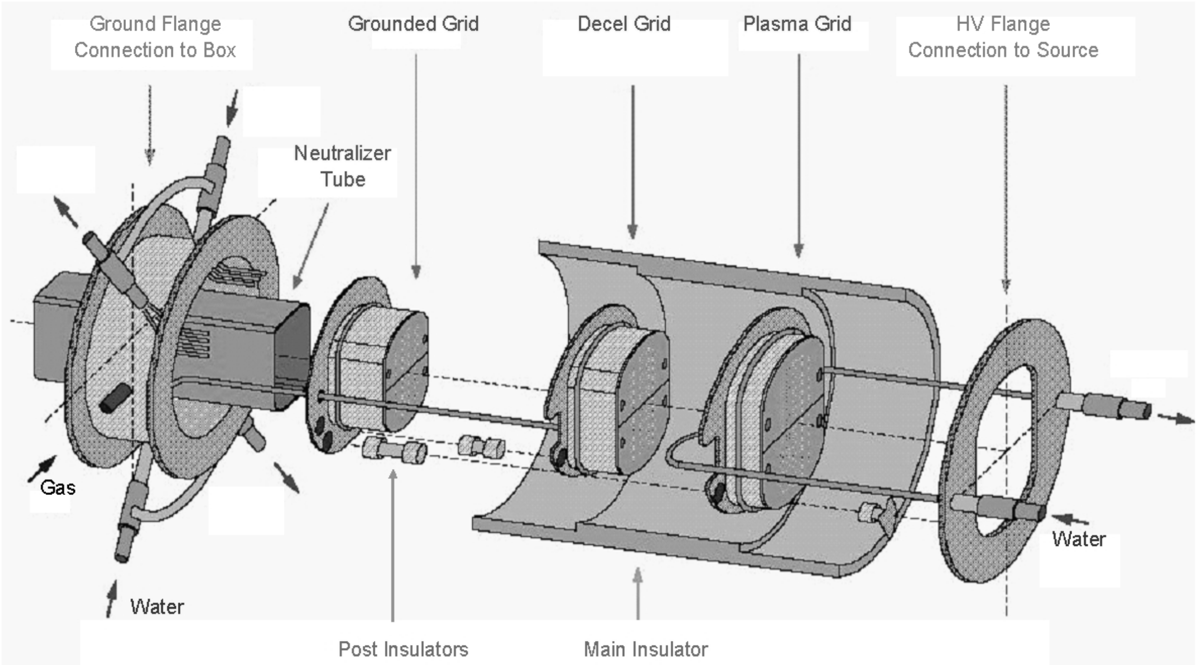
- 24 filaments
- Water-cooled Copper chamber with confinement magnets
- B x L x H = 30 x 60 x 19 cm^2
- Arc power 120 kW



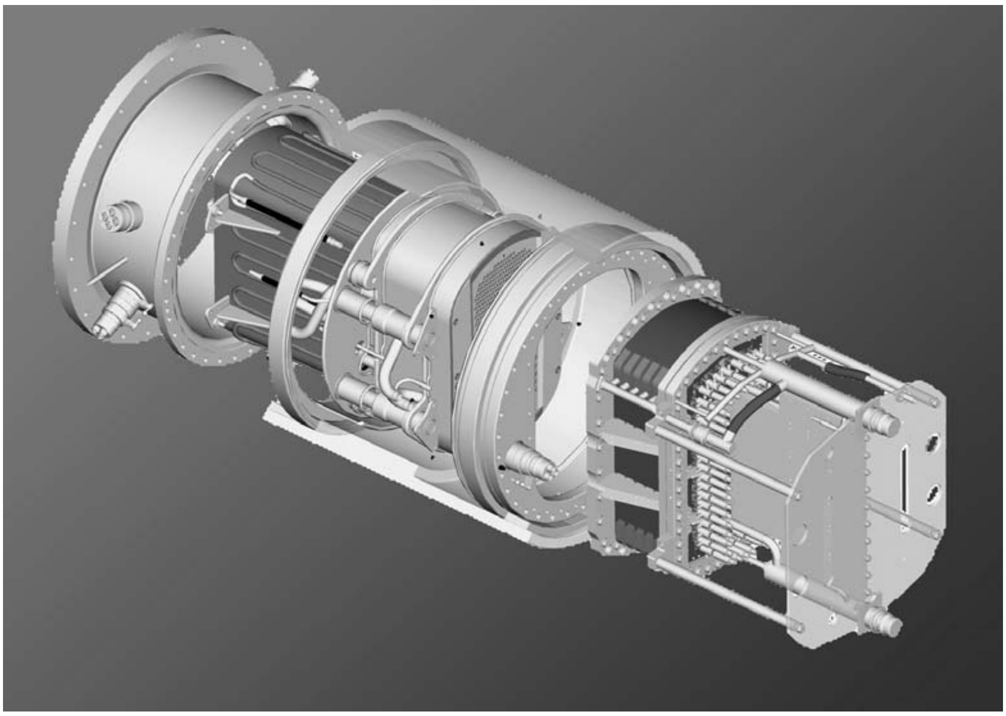


PINI extraction system (Plug In Neutral Injector)

Used with the bucket source



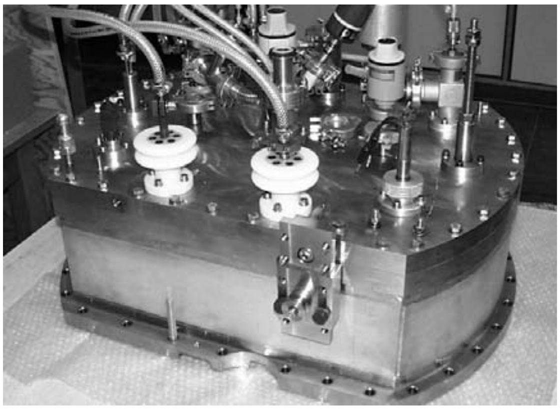
Bucket source on the PINI extraction system



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

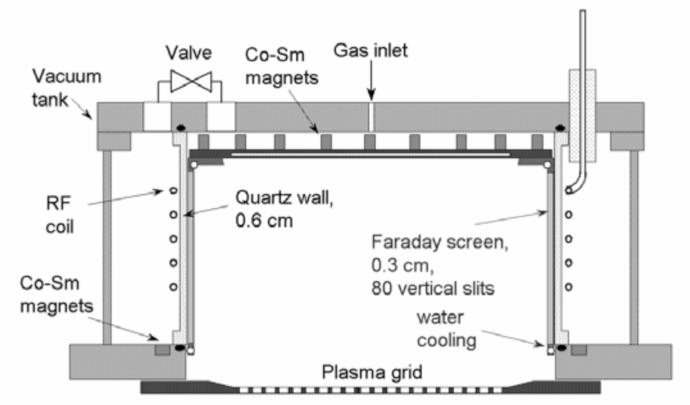
Dimensions
B x H x L = 32 x 19 x 59 cm^3

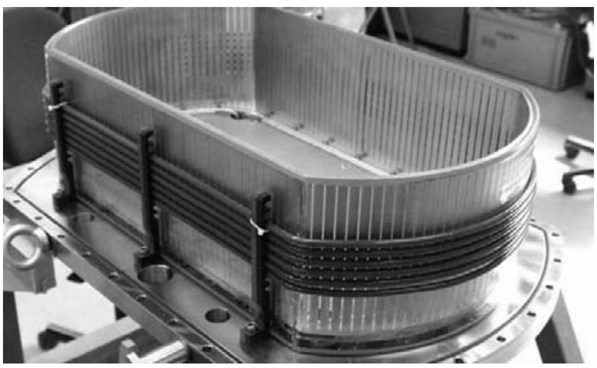
Beams
Hydrogen: 90 A / 100 kW / 55 kV
Deuterium: 65 A / 80 kW / 93 kV
Pulse duration < 10 s



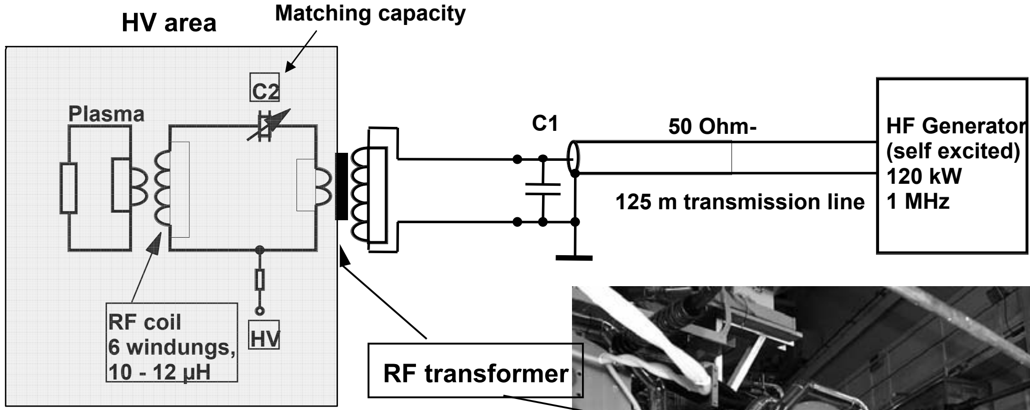
Design of the AUG RF source

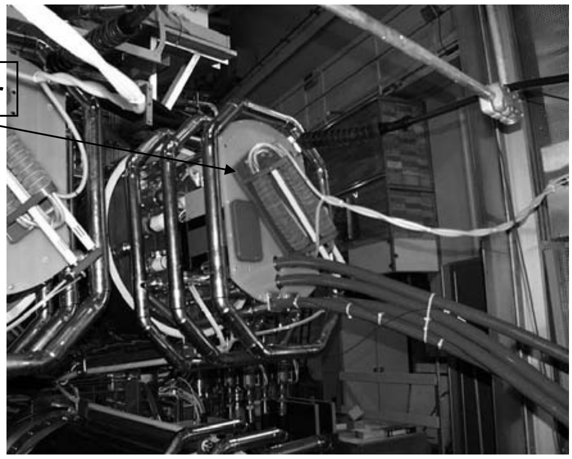
- Water cooled **Faraday shield** to protect the insulator from physical and chemical sputtering
- Power supply 1 MHz/120 kW
- Quartz insulator in a vacuum tank
- Confinement magnets on the source back plate
- Compatible with the PINI extraction system





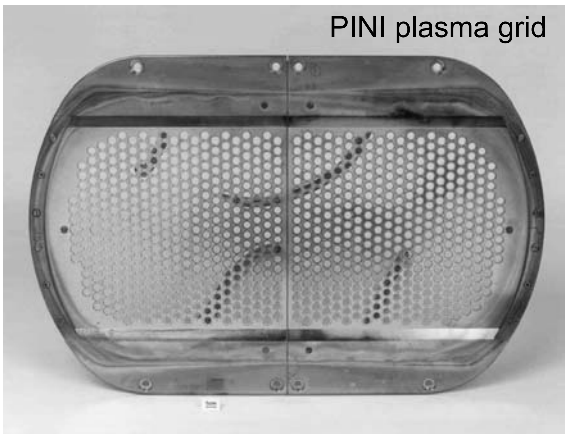
RF matching

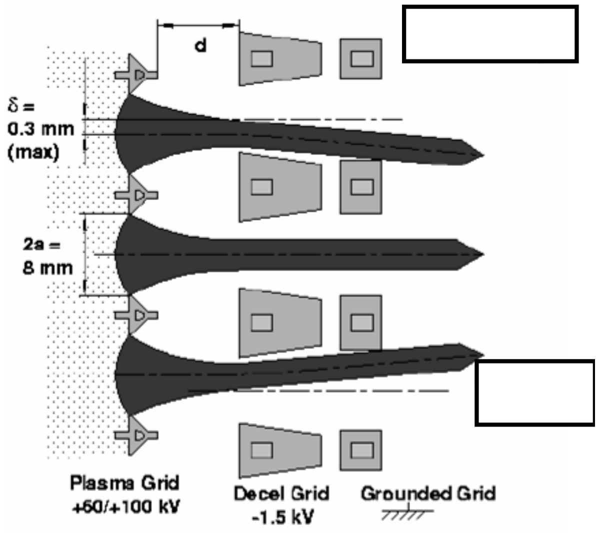




Power supply on ground potential

Beam extraction





- 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

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

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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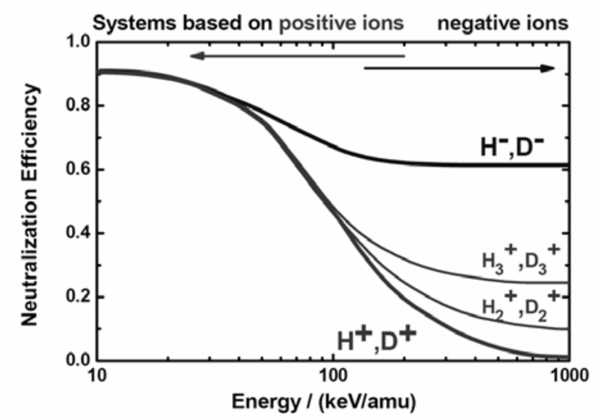
Beam neutralization

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

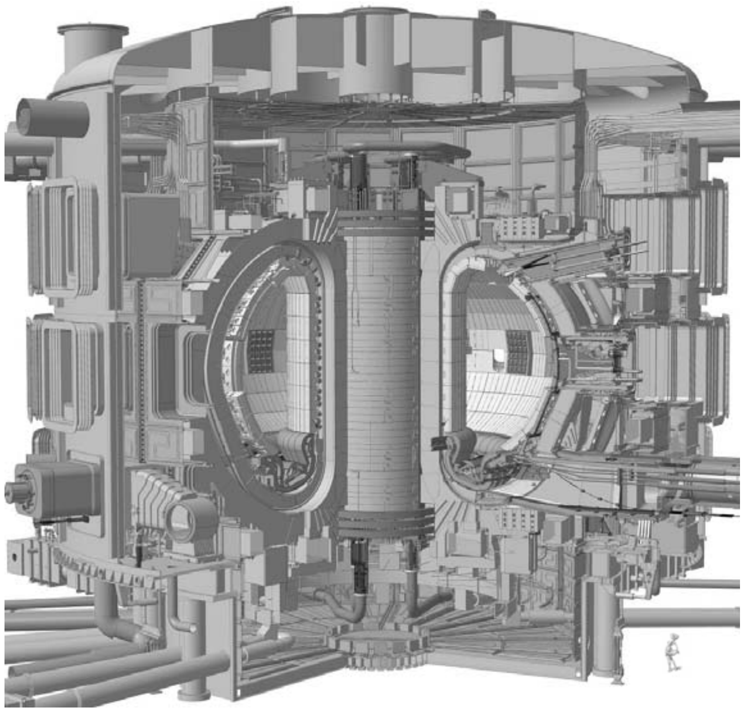
=> **NBI based on negative ions NNBI**

The ITER Tokamak

International **T**hermonuclear **E**xperimental **R**eactor

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

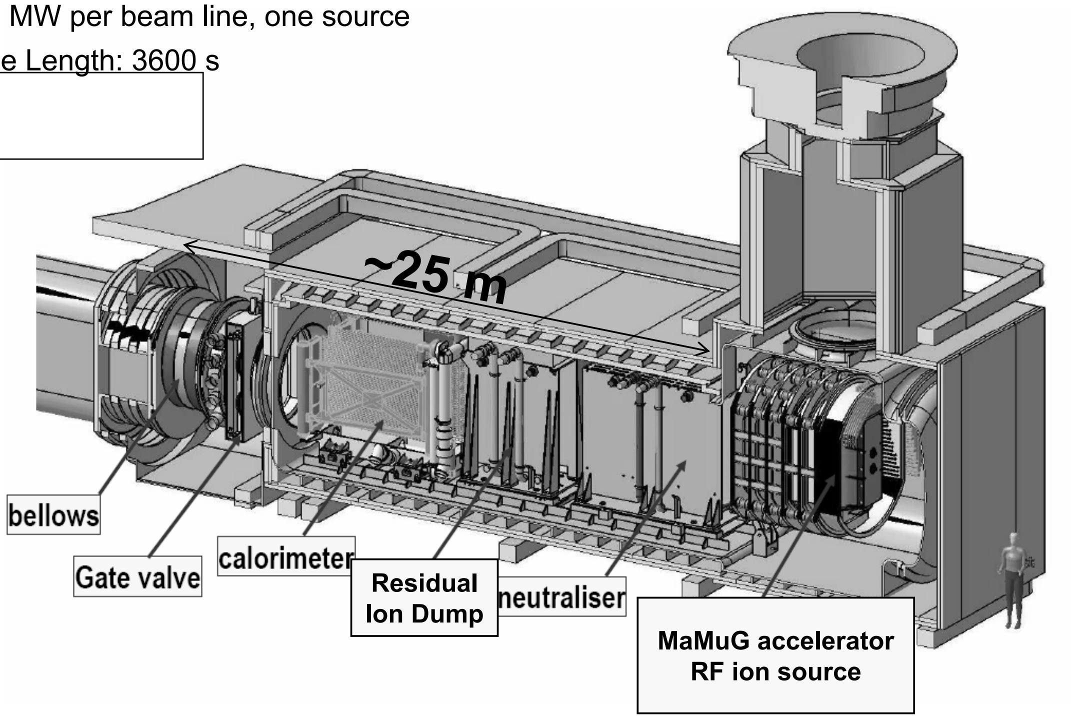


ITER Negative Neutral Beam Heating Injector

Two beam lines

16.7 MW per beam line, one source

Pulse Length: 3600 s



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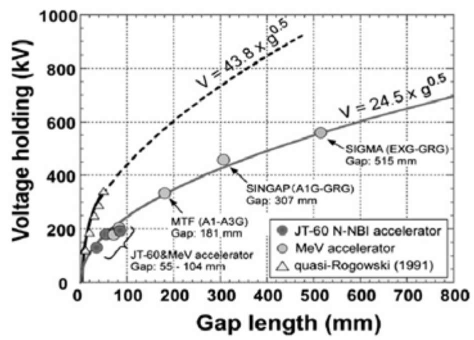
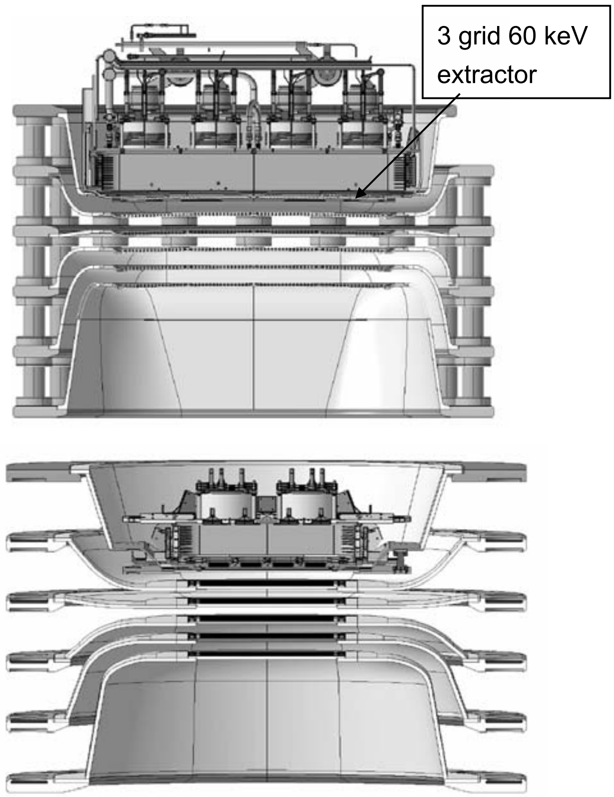
ITER acceleration system





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

⇒ Multistage acceleration is shorter

⇒ for ITER

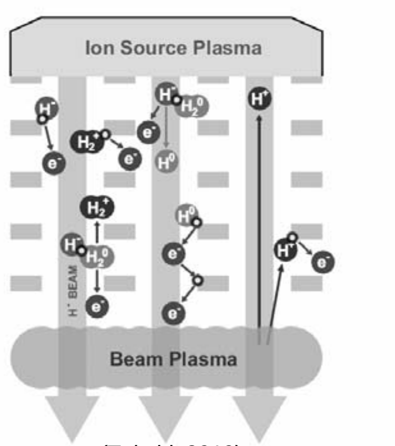
1 MeV in five 200 keV stages

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

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

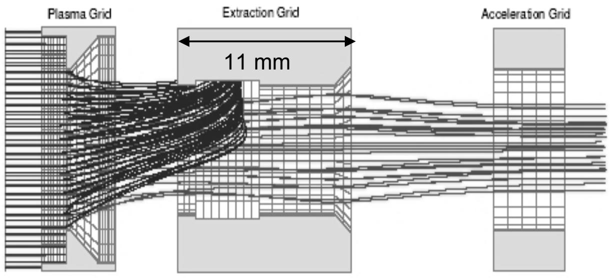
=> Limitation of the source pressure

$p = 0.3$ Pa → $f_s = 25\%$

Negative Ion Extraction

Co-extraction of electrons

Electrons are deflected by small permanent magnets to the extraction grid



0 kV 9 kV 40 kV

To limit the power load on the grid

=> Limitation of the current of co-extracted electrons

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

Giant ion sources for the NNBI

Achieved negative ion current densities:

j = 200 A/m² D⁻

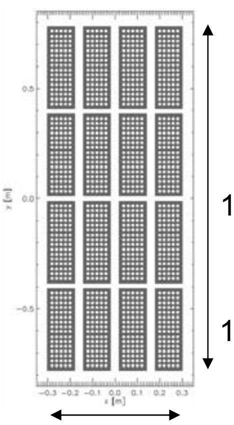
(~1/10 of positive ion systems)

ITER: Required for 16.7 MW at 1 MeV

40 A D⁻

$\Rightarrow$ **extraction area 2000 cm²**

$\Rightarrow$ **Giant sources**



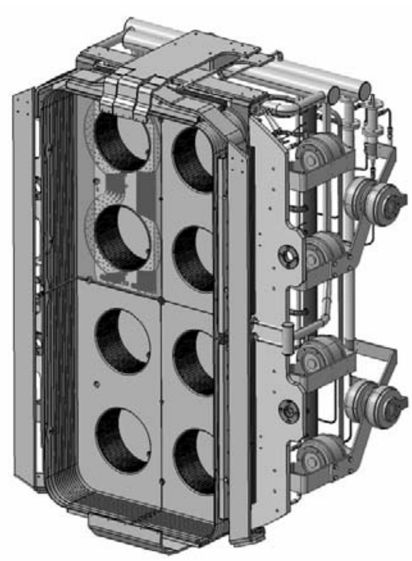
1.5m

1280 apertures

0.6 m

ITER source

1.9 x 0.9 m²



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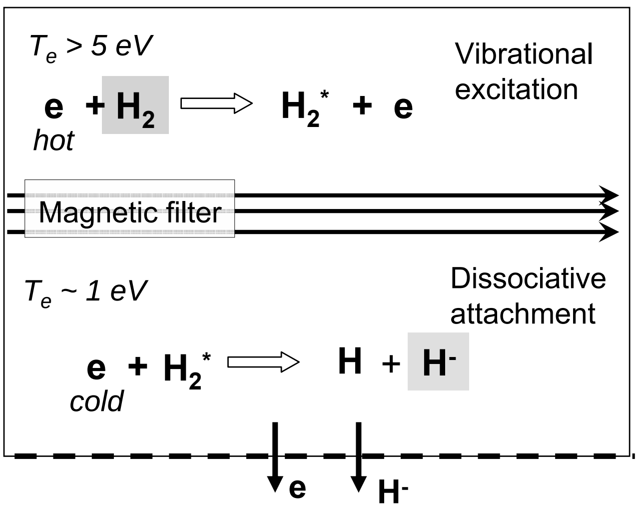
Volume production of negative ions



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

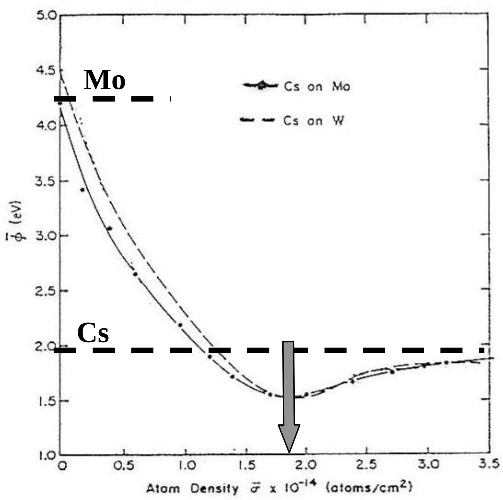
H^0, H_n^+ + surface-e ⟹ H^-

(Swanson 1968)

- 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

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*
$H^- + H \rightarrow H + H + e$ or $H_2 + e$	*associative detachment*

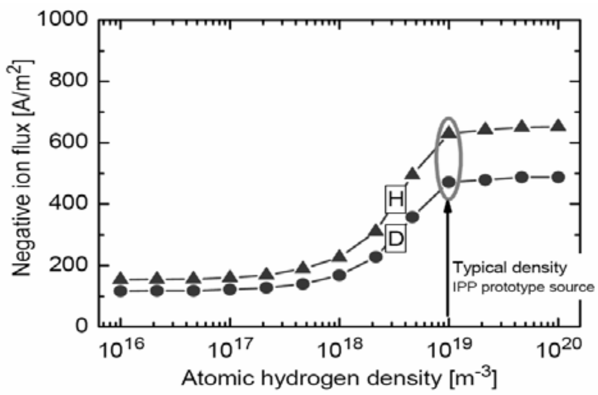
Survival length of H^- only a few cm

⇒ **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

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



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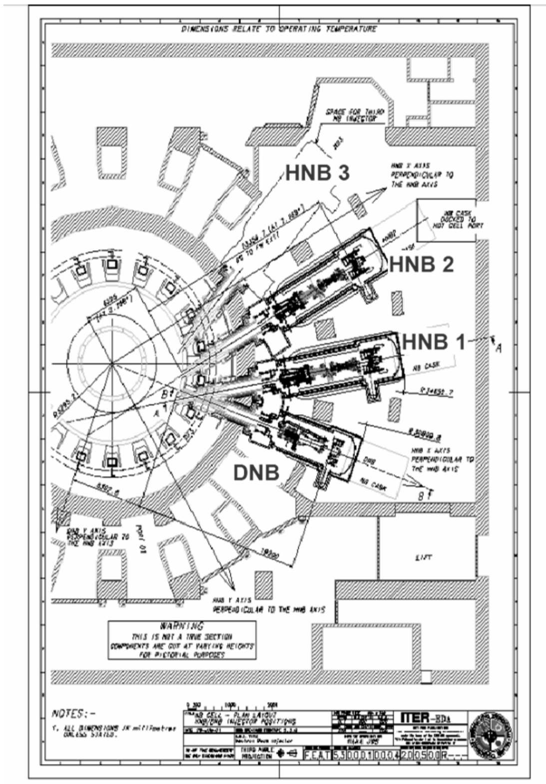
Requirements for the ITER NBI

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^-)



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)

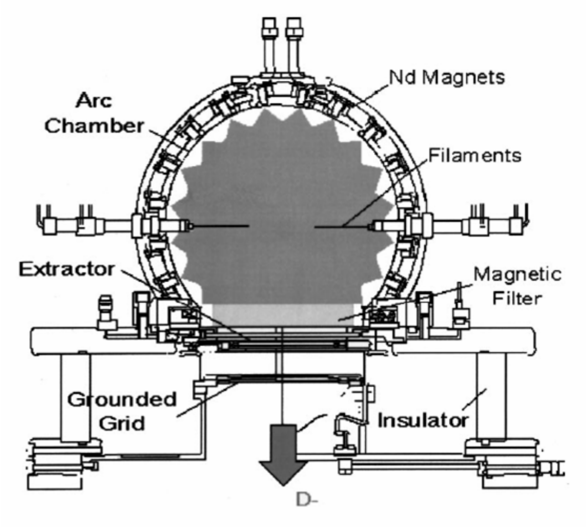
Initially part of the reference design of ITER

Concept of the semicylindical chamber shape

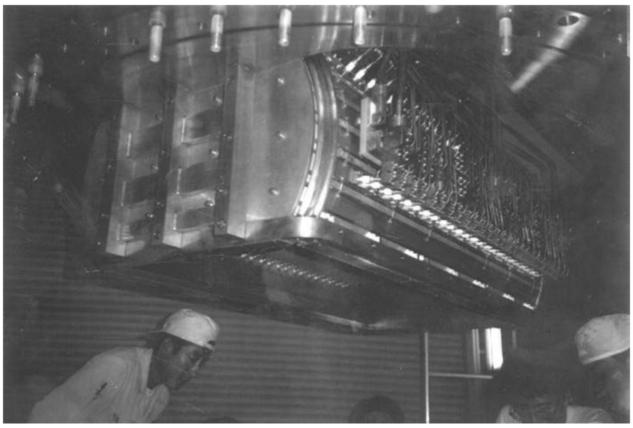
- Maximize plasma volume
- Minimize plasma loss area

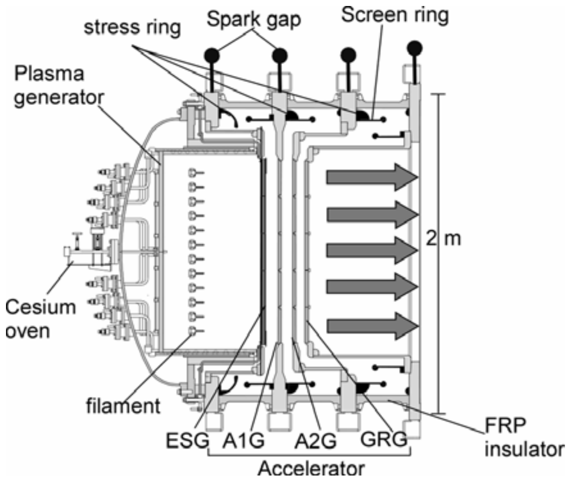
⇒ High negative ion production efficiency at low pressure was expected

Tested 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

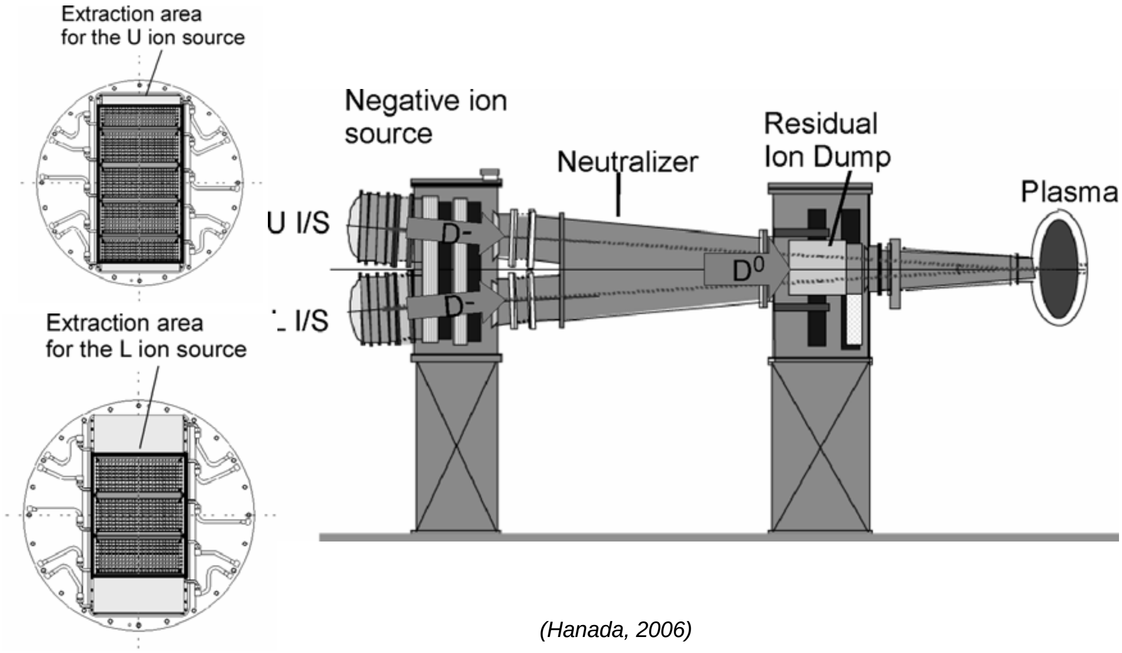
Achieved (2010):

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

10 A, 360 keV, 25 s

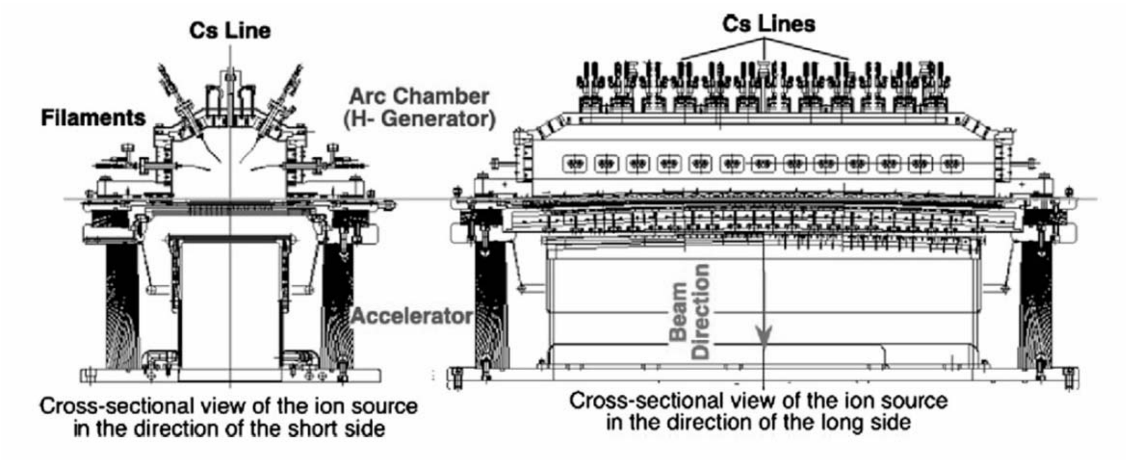
Problem: voltage holding

JT-60 negative ion beam line



(Hanada, 2006)

LHD negative ion source



(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

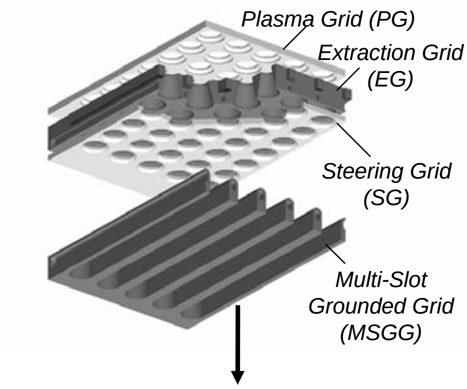
LHD negative ion source

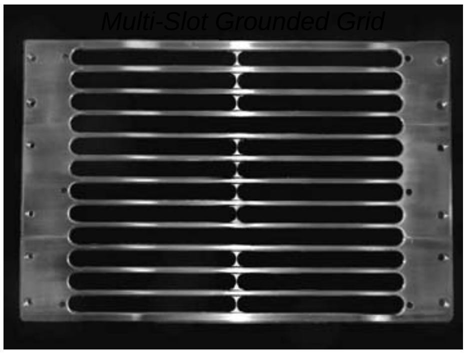
Problem:

High power load on the grounded grid

Solution

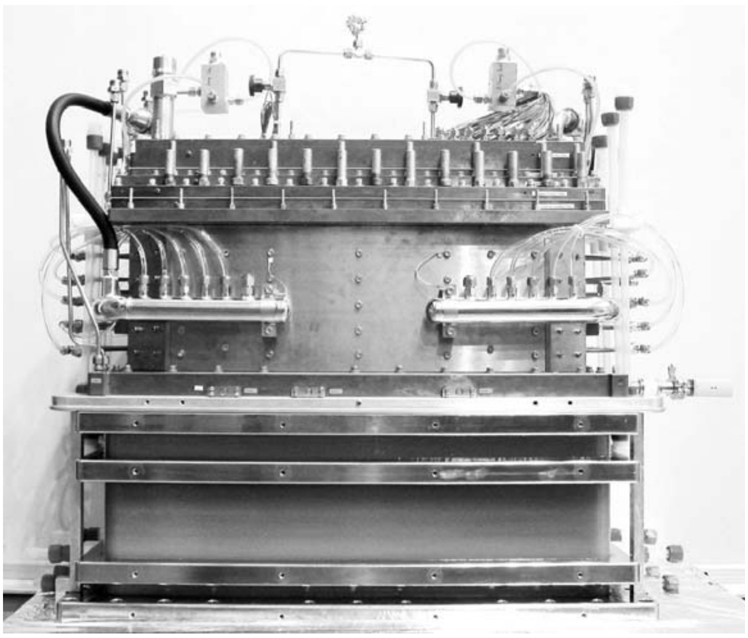
Slots instead of apertures in the grounded grid

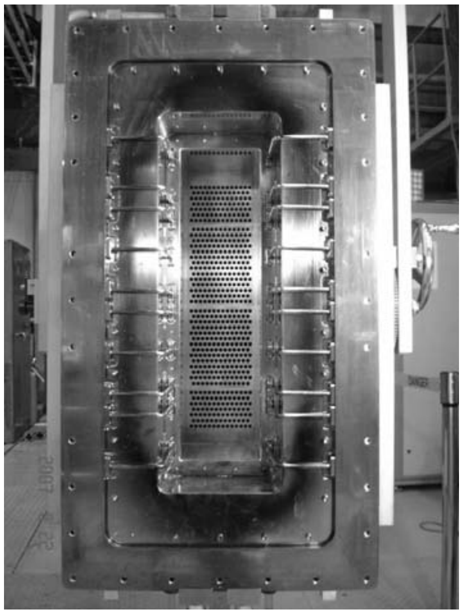




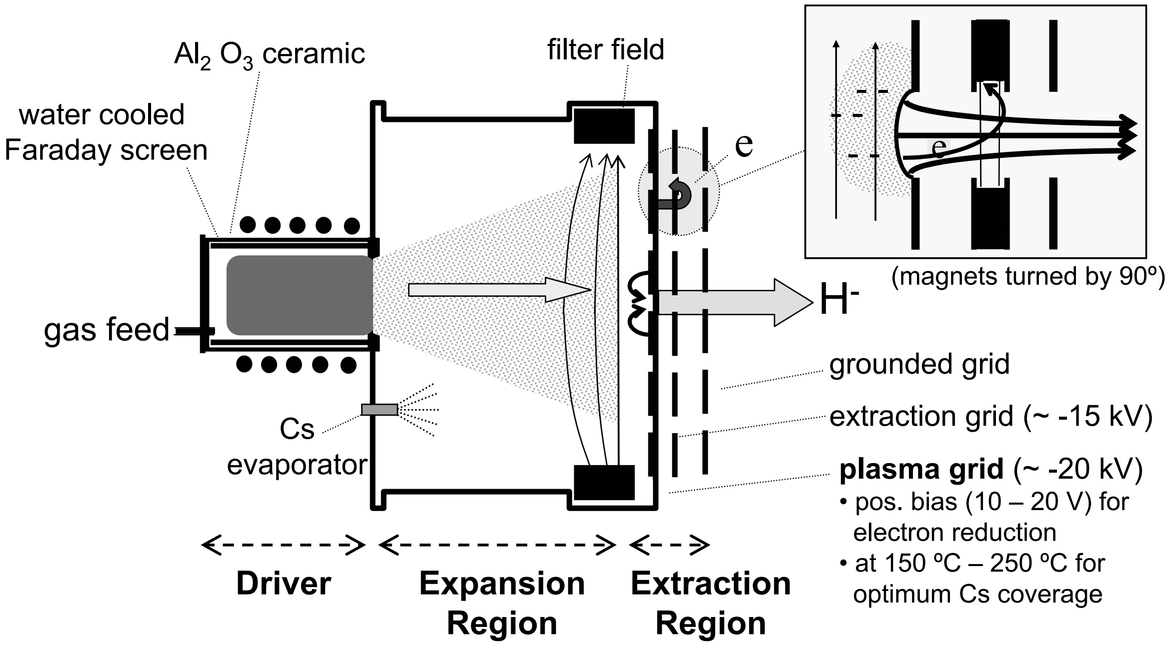
(Tsumori, 2009)

Photos of the Constructed LHD Ion Source



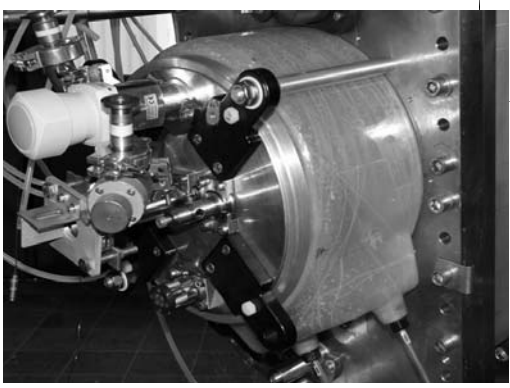


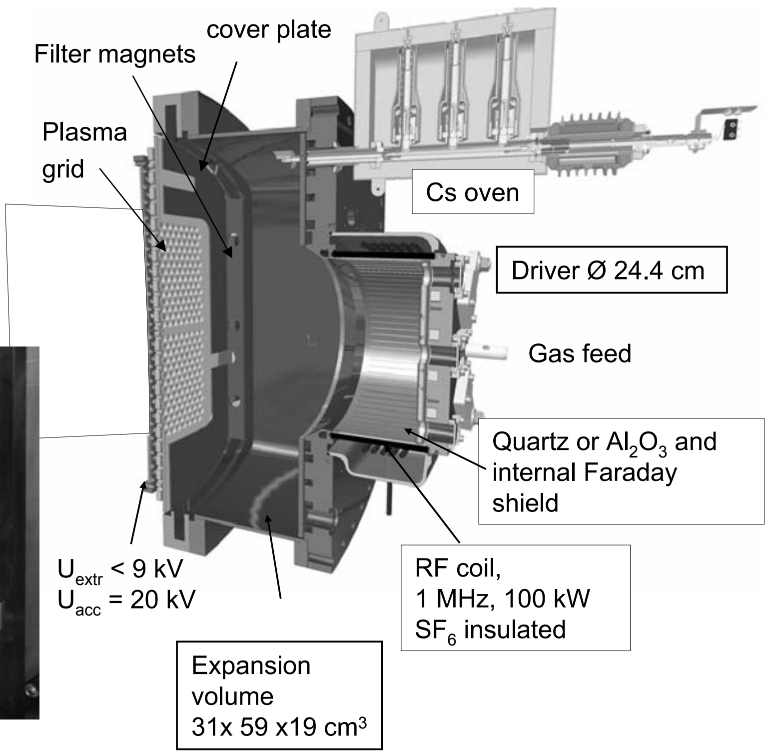
IPP RF Source: Working principle



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

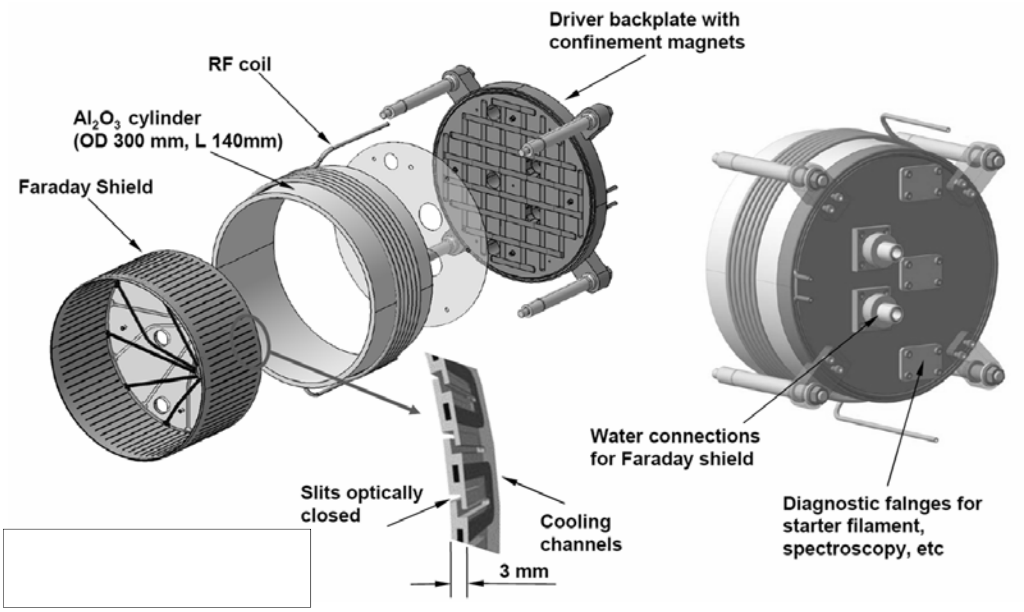




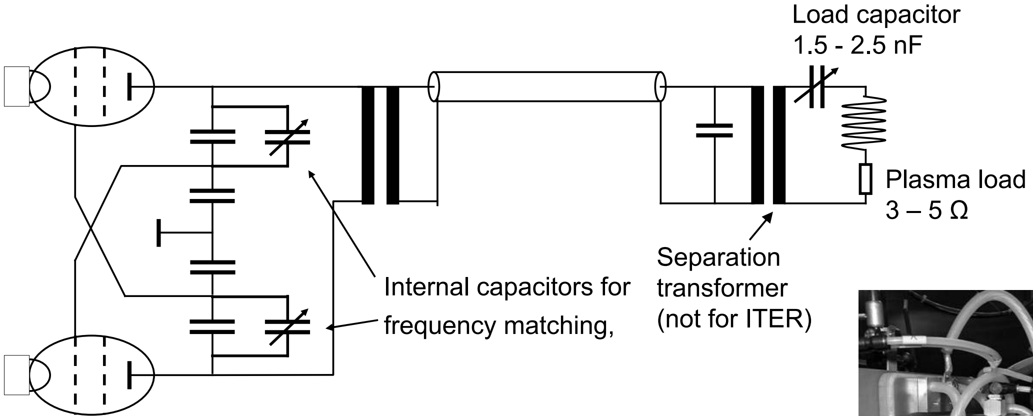
Driver design

Used in all NNBI RF sources

High power density P_{RF}/V~*10 – 15 kW/l*



RF matching

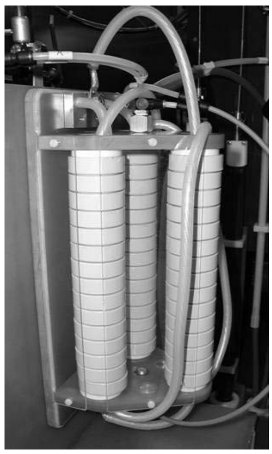


Self-excited 1 MHz oscillator

+ Frequency matching possible

  => no remote controlled capacitors at the source

- Limited frequency stability

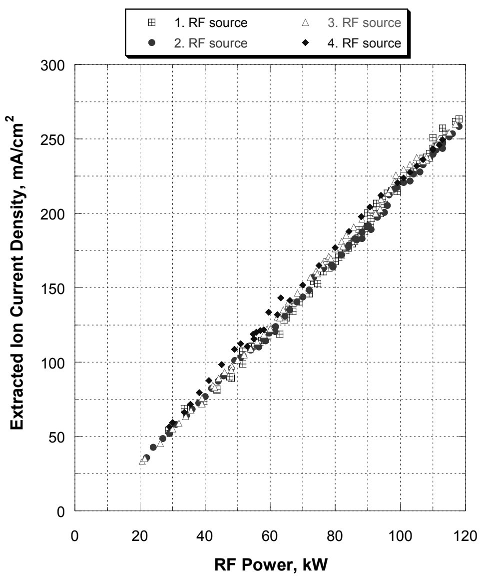


Outline

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

Cs dynamics: Reproducibility of beam currents

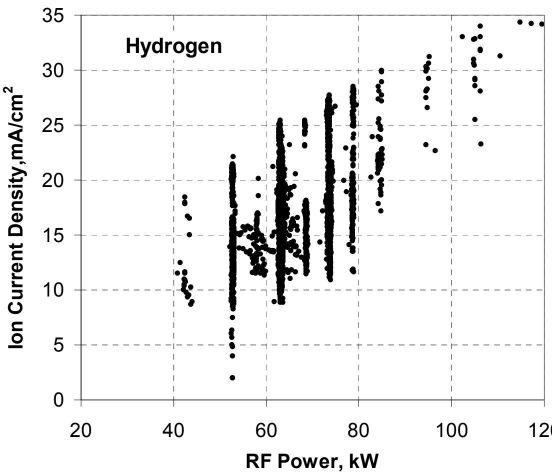
Volume production of **positive** Hydrogen ions



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

Reproducibility very good

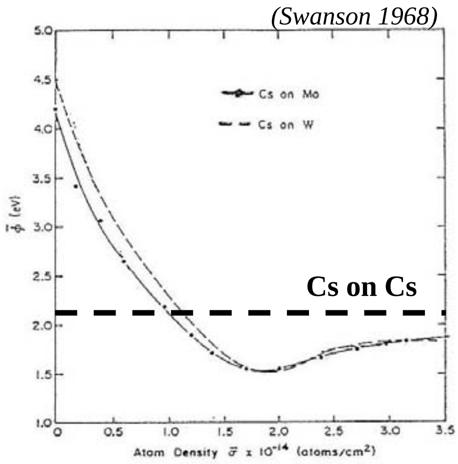
Surface production of **negative** Hydrogen ions

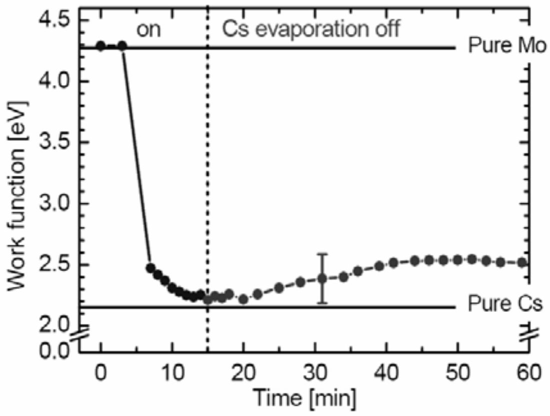


Two months experimental campaign with the negative ion prototype source, max. current 4 A

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

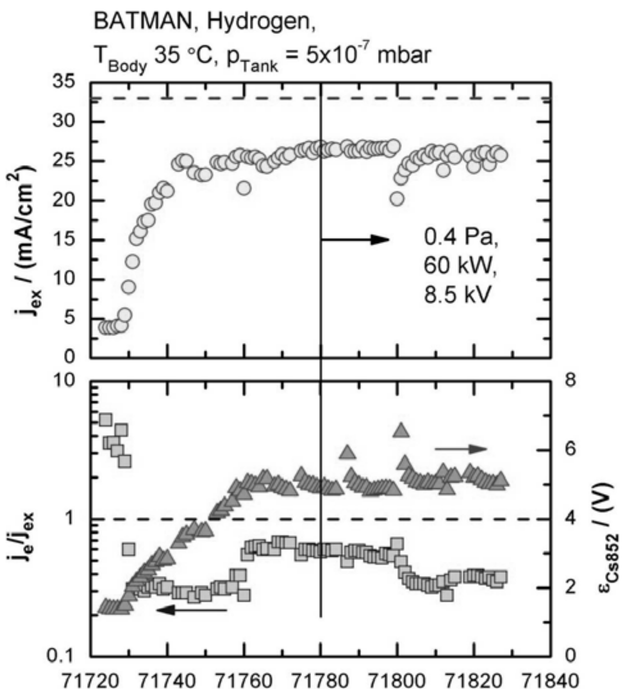
CS handling: Source conditioning at BATMAN (short pulses)

Conditioning procedure:

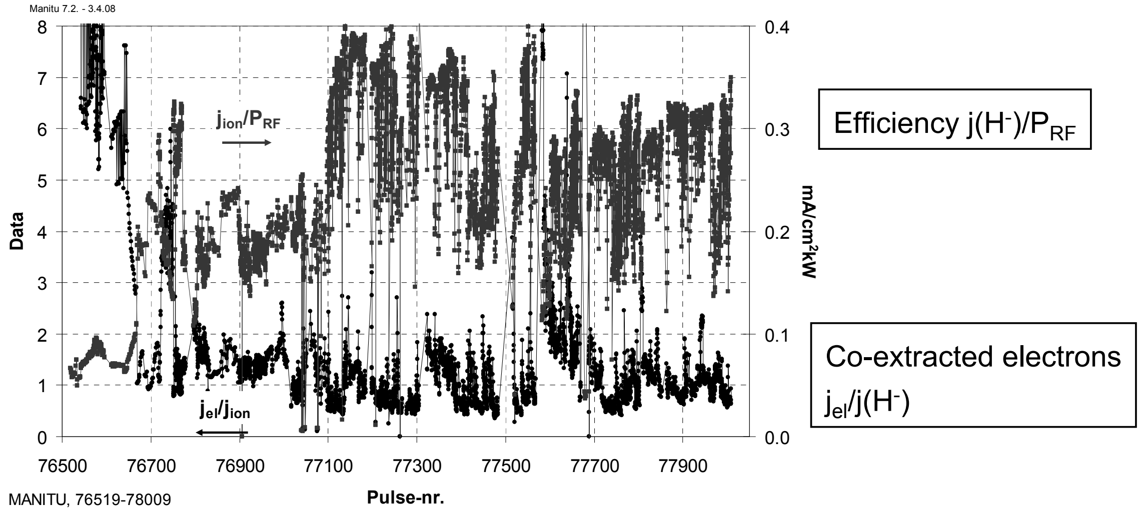
Optimize t_{Pulse}, t_{Pause}, Cs evaporation rate

=> reduction of electron current, increasing ion current

- Faster conditioning at low background pressure
- Source body temperature 35°
- Plasma grid temperature >140°



Long pulse conditioning at MANITU



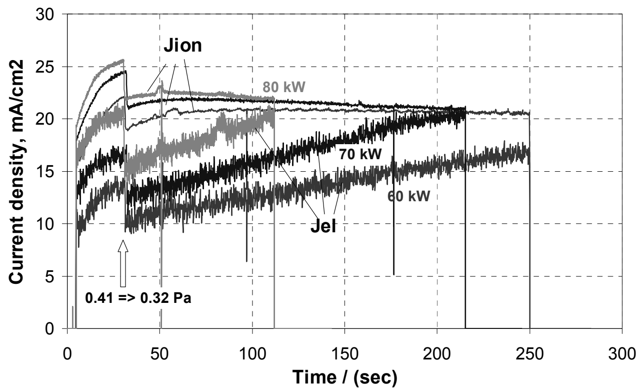
- Large variation of the currents at the same parameters
- Long-term degradation by impurities

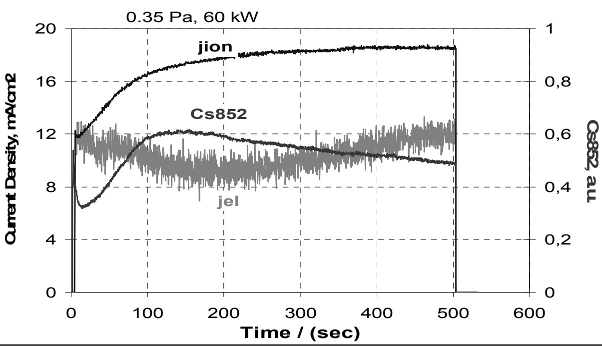
Electron currents in long pulses

- **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)

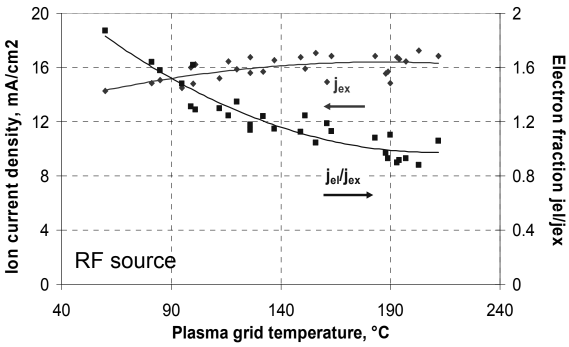




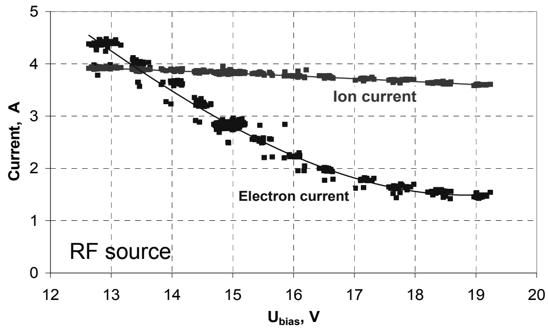
Minimizing the current of co-extracted electrons

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 ?

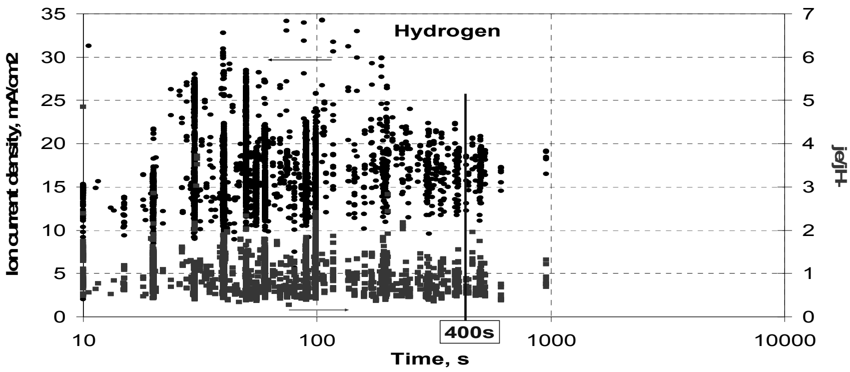


3. **Positive biasing** the plasma grid with respect to the source
• Electron current more sensitive
• Dependence on the bias voltage is different according to the Cs conditions

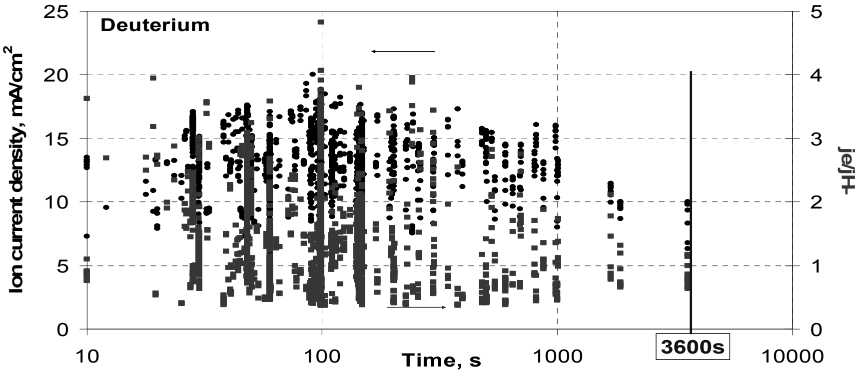


Long pulse performance of one experimental campaign

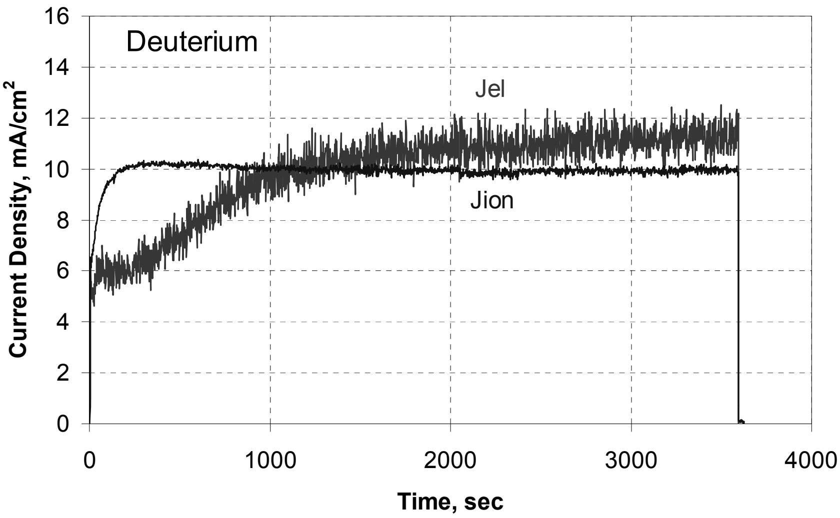
Hydrogen:
20 - 30 mA/cm^2
Pulse length ITER
400s



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/cm²

Stable long pulses at reduced power

Outline

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

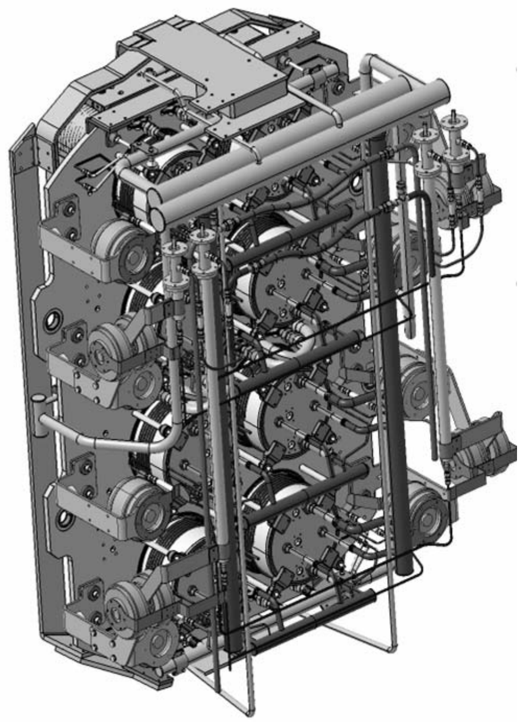
In 2007 RF Source was chosen for the reference design of ITER

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

Further development with large RF sources

Test of

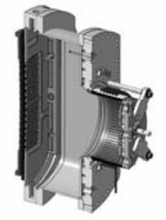
- the modular concept: multi driver – large expansion volume,
- RF power supply with two drivers in series,
- new filter field concepts,
- optimized extraction system

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

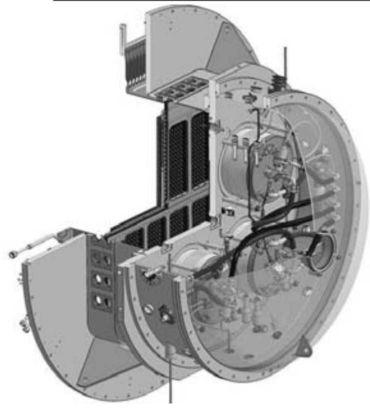
Extrapolation to the ITER Source

Intermediate step at IPP



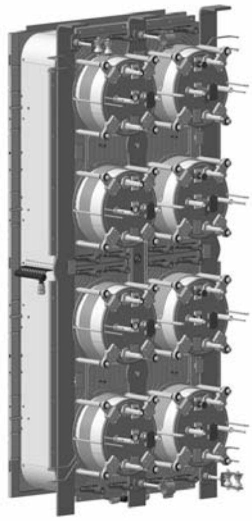
1 Driver
0.59 x 0.31 m²

4 x →



4 Drivers
1.0 x 0.9 m²

2 x →



8 Drivers
1.9 x 0.9 m²

Batman 5s
Manitu cw
Robin 5s, IPR

Radi without extraction
ELISE

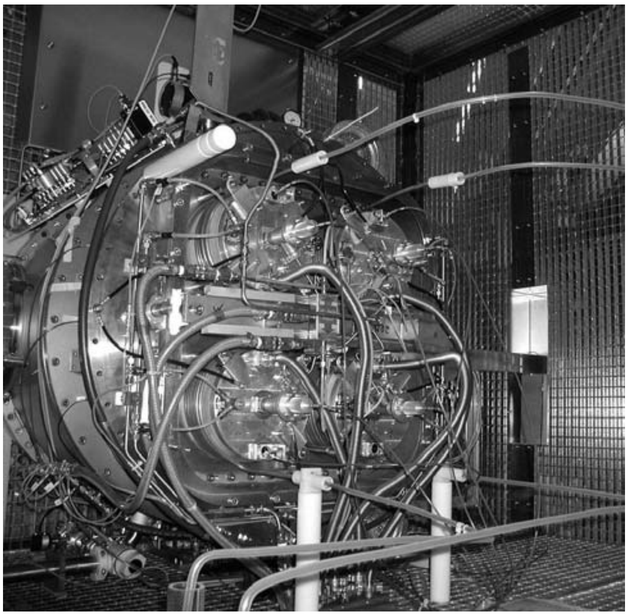
HNB (RFX, Italy), 58 A D^-
DNB (IPR, India), 70 A H^-

RADI source

- About full width and half the height of ITER source (0.76 x 0.8 m²)
- 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



New filter field concepts for the ITER Source

Prototype source

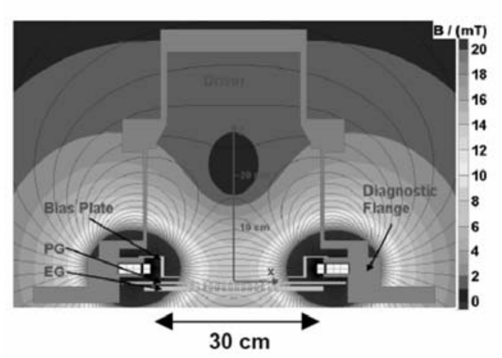
Filter field generated by permanent magnets close to the PG

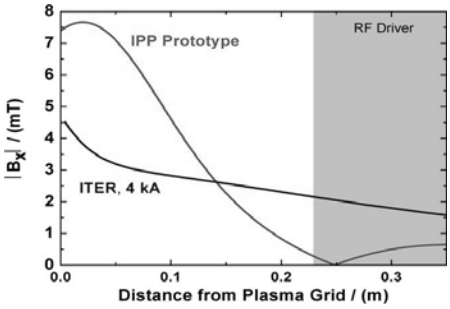
Large source

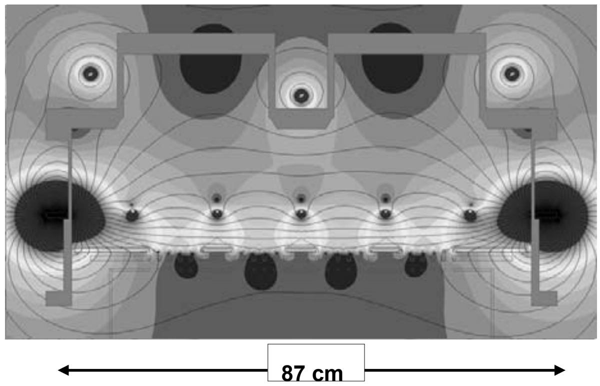
ITER: Current through the plasma grid (4kA)

=> lower field close to the PG, larger range

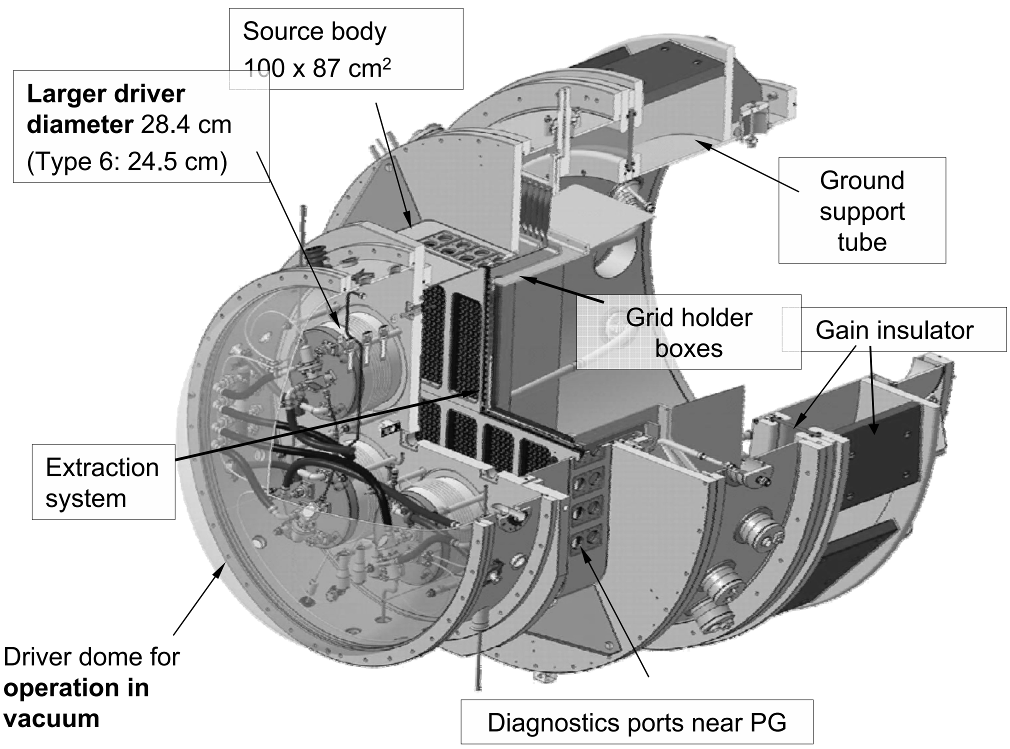
=> new concepts to be tested





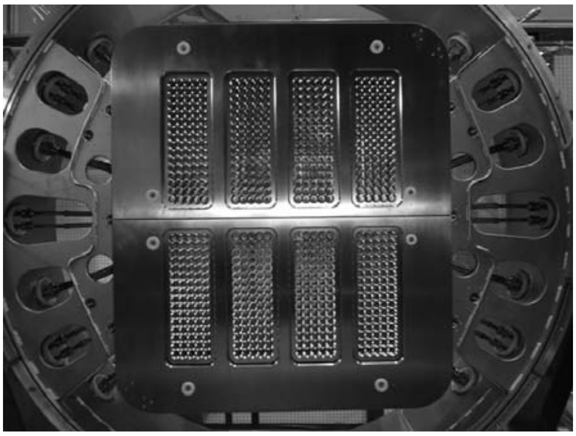


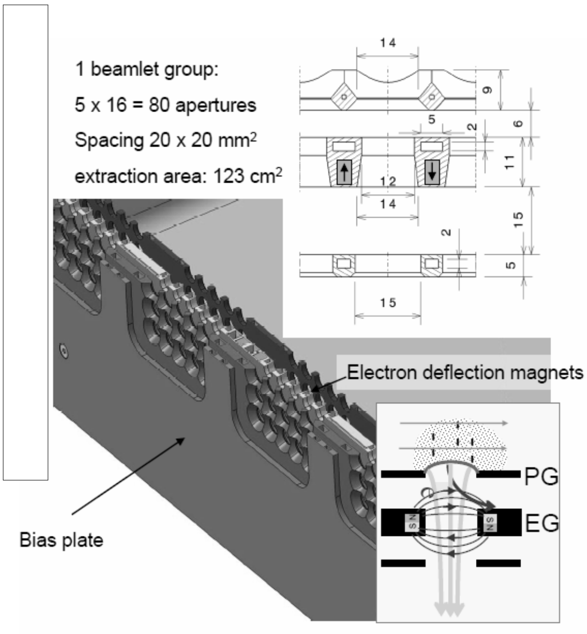
ELISE ion source
(Extraction from a Large Ion Source Experiment)



ELISE extraction system

4 beamlet groups



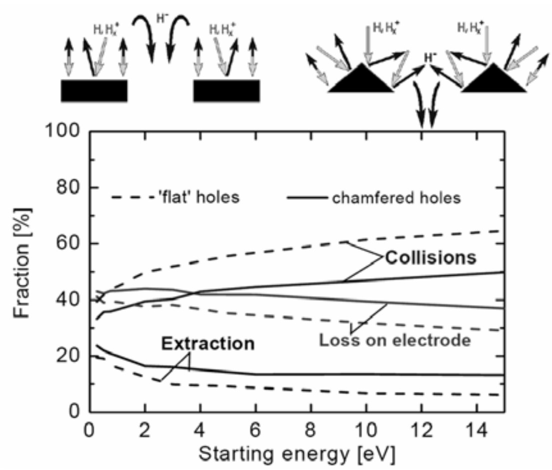


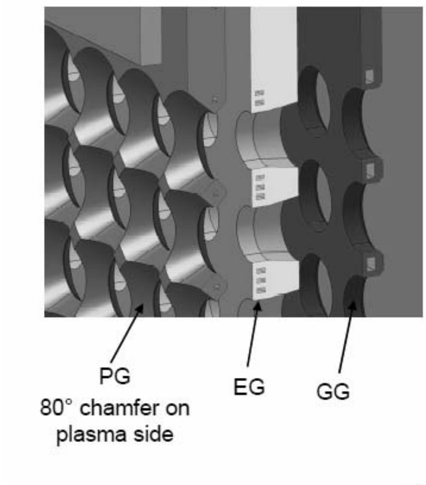
ELISE: Shape of plasma grid apertures

Chamfered apertures

- Less collisions with particles
- Less losses on the electrode

=> **Higher extraction probability**

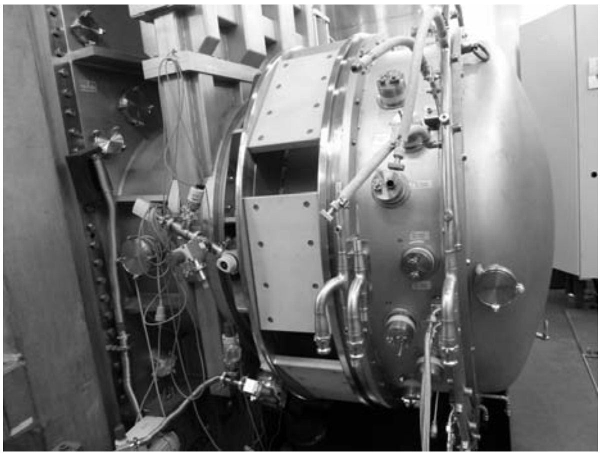


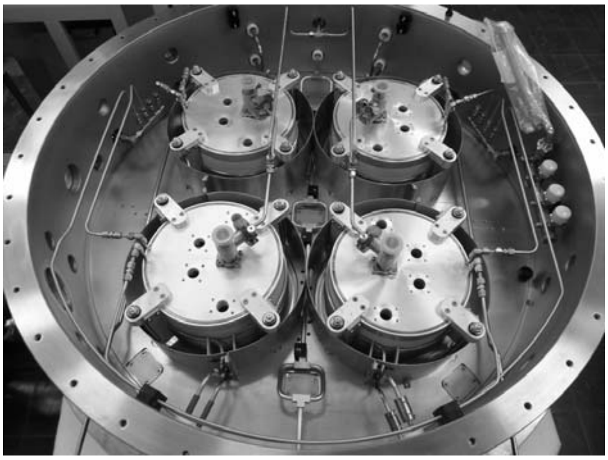


Assembly of the ELISE source

Commissioning in June 2012

RADI and MANITU shut down in August 2011





Outline

- Plasma heating by neutral beam injection
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- Experimental results with the RF prototype
- Giant source for ITER
- **Test facilities**

NNBI test facilities

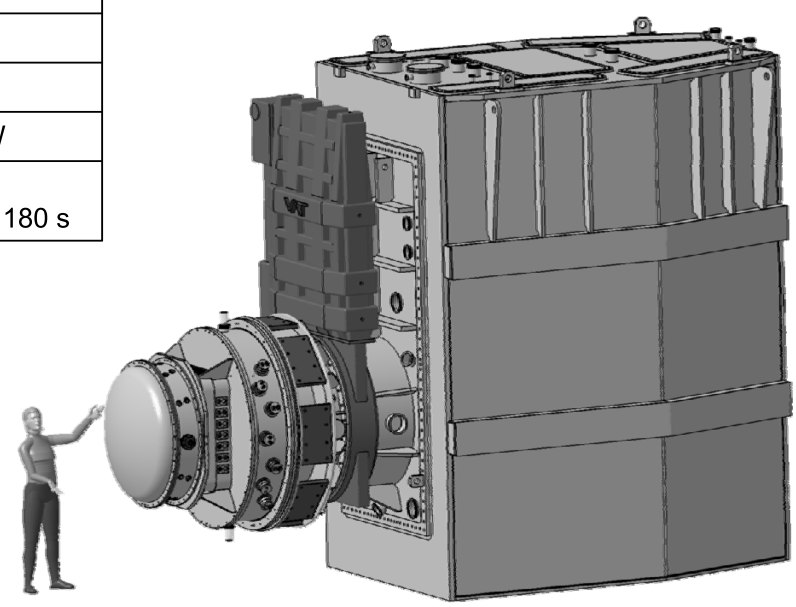
		ITER (rf)	LHD (arc)	JAEA JT60U (arc)		JAEA MV TF (arc)	IPP (rf source)	
Species		D^-	H^-	D^-	H^-	H^-	H^-	D^-
Energy	**MeV**	1000	**180**	**400**		**937**		
Voltage holding	**MV**	1000	**190**	**500**		1000		
Source height	**m**	1.95	**1.45**	**1.22**			**0.59**	
Source width	**m**	1.55	**0.35**	**0.64**			**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/m²**	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

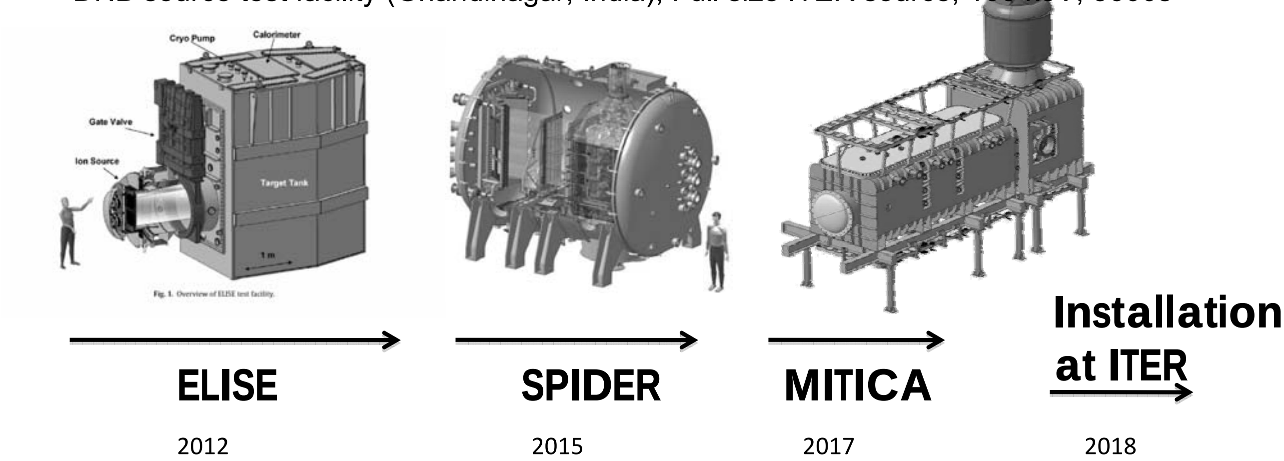
Gate valve

=> 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



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.