Ion Sources for Fusion

W. Kraus

Max-Planck-Institut für Plasmaphysik
EURATOM Association
Boltzmannstr. 2, D-85748 Garching
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.

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<tr>
<th>Device</th>
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<th>$a$ (m)</th>
<th>$I_p$ (MA)</th>
<th>$B_t$ (T)</th>
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<th>N-NBI</th>
<th>ECRH</th>
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<td>ASDEX Upgrade</td>
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<td>20</td>
<td>-</td>
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</table>

*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

\[ I = I_0 e^{-\frac{n_e \lambda}{18 \cdot n \cdot A}} \]

Approximation for the absorption length for ionisation

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

Penetration depth depends on the energy

Example AUG: 100 keV D beam, \( n_e = 5 \times 10^{19} \text{ m}^{-3} \) => \( \lambda = 0.5 \text{ m} \)

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

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

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

\( E_c \) depends on the electron temperature
Lower energy of \( E_0/2 \) and \( E_0/3 \)
\[\Rightarrow \text{ion heating dominates for } E_0 < 100\text{kV}\]
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**

\[ I_{\text{NBCD}} \]

**Current drive efficiency**

\[ \eta_{\text{CD}} = \frac{I_{\text{NBCD}} n_e R}{P_{\text{dep}}} \]

- \( R \) major radius
- \( P_{\text{dep}} \) deposition power

At present about 0.2 – 0.3
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)

- Ti pump
- Neutraliser
- PINIs (4x)
- Magnet
- Calorimeter (full neutr. power)
- Ion dump
- Box height: ~ 4 m
- 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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  - Negative ion based neutral beam injection
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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

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
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 cm²
- Transparency: 49 %
- Beam Divergence: 1 deg

Plasma Chamber: Cusp Bucket
- Current Density: > 210 mA/cm²
- Plasma Volume: 26 x 64 x 32 cm³
- 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 cm²
- **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
- $B \times L \times H = 30 \times 60 \times 19$ cm$^2$
- Arc power 120 kW

**“Tent” filter** to reduce the electron temperature

$\Rightarrow H^+/D^+$ 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 cm³
   (=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

- RF coil: 6 windings, 10 - 12 µH
- Plasma
- HV area
- Matching capacity
- C2
- HV
- C1
- 50 Ohm-
- 125 m transmission line
- HF Generator (self excited)
  - 120 kW
  - 1 MHz

Power supply on ground potential
Beam extraction

- Three electrodes
- AUG: 774 apertures, 8 mm diameter
- Extraction area 390 cm² in 50.66 × 22.8 cm²
- Negative decel voltage reflects electrons from the neutralizer

Child-Langmuir law

\[ I = CxV^{3/2} \sqrt[4]{\frac{Z}{M}} \left( \frac{a}{d + x} \right)^2 \]
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

\[
\begin{align*}
R_{\text{major}} & = 6.2 \text{ m} \\
R_{\text{minor}} & = 2.0 \text{ m} \\
V_{\text{plasma}} & = 840 \text{ m}^3 \\
I_{\text{plasma}} & = 15 \text{ MA} \\
B_{\text{Tor}} & = 5.3 \text{ T} \\
P_{\text{fusion}} & = 500 \text{ MW} \\
\text{NBI:} & = 33 \text{ MW} \\
\text{ICRF} & = 20 \text{ MW} \\
\text{ECRH} & = 20 \text{ MW}
\end{align*}
\]

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

MaMuG accelerator
RF ion source

~25 m
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ITER acceleration system

Breakdown voltage $\sim (\text{gap length})^{1/2}$
$\Rightarrow$ Multistage acceleration is shorter
$\Rightarrow$ 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
JAERA for 2 s
Secondary particle generation during the acceleration

**Stripping**
Negative ions destroyed by collisions with the background 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 background gas
⇒ High power load on the source back plate

⇒ Limitation of the source pressure
\[ p = 0.3 \text{ Pa} \rightarrow f_s = 25\% \]
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

\[ \frac{j_e}{j_D} \leq 1 \]
Giant ion sources for the NNBI

Achieved negative ion current densities:

\[ j = 200 \text{ A/m}^2 \text{ D}^- \]

(\sim 1/10 \text{ of positive ion systems})

ITER: Required for 16.7 MW at 1 MeV

\[ 40 \text{ A D}^- \]

\[ \Rightarrow \text{ extraction area } 2000 \text{ cm}^2 \]

\[ \Rightarrow \text{ Giant sources} \]

ITER source

\[ 1.9 \times 0.9 \text{ m}^2 \]

1280 apertures

1.5m

0.6m
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Volume production of negative ions

Problems

- Low ion currents < 5 mA/cm²
- 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

\[ H^0, H_n^+ + \text{surface-e} \rightarrow H^- \]

(Swanson 1968)

- Conversion rate high at low work function $\Phi$
- $\Phi$ can be reduced by coating with alkali metals
  - $\Phi$ [eV]
    - Cs 1.9
    - Rb 2.08
    - K 2.24
    - Na 2.28
    - Li 2.42
- $\Phi$ 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

\[ \text{H}^- + \text{e} \rightarrow \text{H} + 2\text{e} \]
\[ \text{H}^- + \text{H}_i^+ \rightarrow \text{neutrals} \]
\[ \text{H}^- + \text{H} \rightarrow \text{H} + \text{H} + \text{e} \]

or \( \text{H}_2^+ + \text{e} \)

**electron detachment**
for **hot electrons** with \( T_e > 2 \text{ eV} \)

**mutual neutralisation**

**associative detachment**

Survival length of \( \text{H}^- \) 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
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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

**Semicylindrical 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

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/cm², 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

Three injectors with two sources each
Operating since 1998
**Design:** 30 A, 180 keV, 1 s (one source)
**Achieved:** 37 A or 340 mA/cm², 190 keV, 1.6 s

*(Takeiri, 2010)*
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

- Gas feed
- Cs evaporator
- Water cooled Faraday screen
- Al₂O₃ ceramic
- Filter field
- Plasma grid (~ -20 kV)
  - Pos. bias (10 – 20 V) for electron reduction
  - At 150 ºC – 250 ºC for optimum Cs coverage
- Extraction grid (~ -15 kV)
- Grounded grid
- Magnets turned by 90º

Diagram highlights:
- Driver
- Expansion Region
- Extraction Region

W. Kraus  2. June 2012  CERN Accelerator School – Ion Sources
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 cm³
RF coil, 1 MHz, 100 kW SF₆ insulated
Gas feed
Quartz or Al₂O₃ and internal Faraday shield
Cs oven
Filter magnets
Plasma grid
Cover plate

U_{extr} < 9 kV
U_{acc} = 20 kV
Driver design

Used in all NNBI RF sources
High power density $P_{RF}/V \sim 10 - 15 \text{ kW/l}$
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
Drifting plasma in presence of a perpendicular magnetic field

Plasma drifting downwards (or upwards)

Combination of several cross B drifts

⇒ Inhomogeneous plasma density close to the plasma grid

(Schiesko, 2012)
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

Surface production of negative Hydrogen ions

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

Reproducibility very good

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

=> **Detioriation by impurities** in the background gas (Cu, O$_2$, H$_2$O, …)

=> Constant Cs evaporation required
Conditioning procedure:
Optimize $t_{\text{Pulse}}$, $t_{\text{Pause}}$, Cs evaporation rate

=> reduction of electron current, increasing ion current

• Faster conditioning at low background pressure
• Plasma grid temperature $>140^\circ$C
• Source body temperature $35^\circ$ to avoid trapping of Cs on the walls
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° (°C),
   • 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/cm²
Pulse length ITER 400s

**Deuterium:**
10 - 20 mA/cm²
Pulse length ITER 3600s
Higher electron current (?)
One hour pulse in Deuterium

Deuterium

Jel

Jion

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

Stable long pulses at reduced power
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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
\[ I(D^-) = 40 \text{ A (one beamline)} \]

Diagnostic beam DNB by IPR, India
3 MW, 100 keV, negative ions!
\[ I(H^-) = 60 \text{ A, same source type} \]

Requirements for the HNB ion sources
Accelerated current density
20 mA/cm² (D⁻)
24 mA/cm² (H⁻)
\[ \frac{j_e}{j_{ion}} < 1, \text{ at 0.3 Pa} \]
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)
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 m²

4 Drivers
1.0 x 0.9 m²

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
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)
- Driver dome for operation in vacuum
- Extraction system
- Grid holder boxes
- Gain insulator
- Ground support tube
- 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

Bias plate

Electron deflection magnets
ELISE: Shape of plasma grid apertures

Chamfered apertures

- Less collisions with particles
- Less losses on the electrode

$\Rightarrow$ **Higher extraction probability**
Assembly of the ELISE source

Commissioning in June 2012

RADI and MANITU shut down in August 2011
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## NNBI test facilities

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<th></th>
<th>ITER (rf)</th>
<th>LHD (arc)</th>
<th>JAEA JT60U (arc)</th>
<th>JAEA MV TF (arc)</th>
<th>IPP (rf source)</th>
</tr>
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<tbody>
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<td><strong>Species</strong></td>
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<td>H⁻</td>
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### Footnotes:

- ITER (rf): International Thermonuclear Experimental Reactor (injection by radiofrequency)
- LHD (arc): Large Helical Device (arc discharge)
- JAEA JT60U (arc): Japan Atomic Energy Agency, Tokamak Fusion Test Reactor (arc discharge)
- JAEA MV TF (arc): Japan Atomic Energy Agency, Magnetic Fusion Test Reactor (arc discharge)
- IPP (rf source): Institute Plasma Physics (source driven by radiofrequency)
ELISE testbed

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<td>Extraction area</td>
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<td>Acceleration voltage</td>
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<td>Plasma on time</td>
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<td>Beam extraction</td>
<td>10 s every 180 s</td>
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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.