NBI Systems for DEMO: Status and Prospects

Ursel Fantz, Christian Hopf
P. Sonato, A. Simonin, R. McAdams, M. Tran, ....
Towards the ITER NBI systems

Heating beams: 16.7 MW at 1 MeV
- Based on neg. ions

Heating beams
- 50% EU, 50% JA

Diagnostic beam
- 100% IN

- Bellows
- Gate valve
- Calorimeter
- Residual ion dump
- Neutralizer
- Accelerator
- RF ion source

~ 25 m

NBTF in Padua, Italy

ELISE, 2012+
- Validate or alter source concept

SPIDER, 2017+
- Gain experience with operation of large sources

MITICA, 2021+
- Validate or alter accelerator and beam line components

ITER NBI

Based on neg. ions

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NBI activities for DEMO on an international level

Japan, Naka: JT60-SA

- N-NBI system (H and D beams)
  1 beam line, 500 keV, 10 MW, 100 s
  Arc sources → maintenance
- 1 MeV test facility
  1 MeV, 60 s
  0.97 MeV, 190 A/m², 60 s ✓
- 1 MeV accelerator for NBTF
- Priority: ITER
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- 1 MeV accelerator for NBTF
- Priority: ITER

Japan, NIFS: LHD
- N-NBI system (H beams)
  - 3 beam lines, 180 keV, 16 MW, up to 120 s
  - Arc sources -> maintenance
- Source test facility for optimization
- Priority: ITER

Activities started to replace arc sources by RF sources, also in view of DEMO.
NBI activities for DEMO on an international level

Korea, Daejeon: KSTAR in view of K-DEMO
- NBI systems (pos. ions)
  100 keV, 5.5 MW, 70 s
  Upgrade to 12 MW (also off-axis), in 2018
  Current drive studies for 2021+
  Arc sources -> maintenance
- R&D on RF sources

NBI-1 (100 keV)
6MW, 100 keV, on-axis

NBI-2 (100 keV)
6MW, (on- & off-axis) ('18)

China, ASIPP: EAST in view of CFETR
- NBI systems (pos. ions)
  80 keV, 4+4 MW, ? s
  Arc sources -> maintenance
- N-NBI for CFETR: 300 keV, 50 MW
- Low level R&D on RF sources

India, IPR
- DNB (H⁻) for ITER
- R&D on RF sources

Concept similar to EU concept, e.g. 800 keV envisaged, RF sources.
NBI activities for DEMO within Eurofusion

The concept developed under the System Engineering Task within WPHCD
N-NBI systems: 0.8 – 1 MeV, 50 MW with 2 – 3 beam lines for 7200 s
EU DEMO: Beam line concept

The concept developed under the System Engineering Task within WPHCD
N-NBI systems: 0.8 – 1 MeV, 50 MW with 2 – 3 beam lines for 7200 s

Diagram showing various components like Laser sources, Electron dump, Modular RF ion sources, Accelerator, NEG pumps, Neutron dump, Absolute gate valve, Duct heat dump #1, Duct heat dump #2, Residual ion dump, and NEG pump.
A modular extraction / acceleration system for 0.8 – 1 MeV by using a 4 or 5 stage accelerator with 200 keV each
Current drive efficiency of NBI

 Dependence on beam energy for a given temperature (ITER parameters)

At 25 keV:
7% less for 800 keV
10% more for 2 MeV
The concept is focused on “DEMO advanced” but is compatible with “ITER baseline”.

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>DEMO ITER baseline</th>
<th>DEMO advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted current density [A/m²]</td>
<td>286</td>
<td>260</td>
<td>200</td>
</tr>
<tr>
<td>No. of apertures</td>
<td>1280</td>
<td>1280</td>
<td>60</td>
</tr>
<tr>
<td>No. of sub-sources</td>
<td>1</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Extracted current [A]</td>
<td>56.33</td>
<td>51.20</td>
<td>36.93</td>
</tr>
<tr>
<td>Acceleration voltage [kV]</td>
<td>1000</td>
<td>1000</td>
<td>800</td>
</tr>
<tr>
<td>Stripping losses</td>
<td>30%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Accelerated current [A]</td>
<td>39.43</td>
<td>46.08</td>
<td>33.23</td>
</tr>
<tr>
<td>Neutraliser efficiency</td>
<td>0.55 (Gas)</td>
<td>0.6 (with energy rec.)</td>
<td>0.7 (Laser)</td>
</tr>
<tr>
<td>Power per injector [MW]</td>
<td>16.5</td>
<td>25</td>
<td>16.8</td>
</tr>
<tr>
<td>Beam line transmission efficiency</td>
<td>0.8</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Injector efficiency</td>
<td>0.26</td>
<td>0.44</td>
<td>0.51</td>
</tr>
<tr>
<td>No. of injectors</td>
<td>2 (3)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total power [MW]</td>
<td>33 (50)</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
The modular RF-driven ion source concept as for ITER

Prototype source

≈ 1.5 A

0.6 m

0.3 m

0.9 m

RF power
100 kW

1 m

x 4

ELISE source

20 A

ITER sources: NBTF, HNB & DNB

40 A

2 m

x 2

RF power
400 kW

RF power
800 kW

0.9 m

RF power
20 A

40 A
Critical issues with the RF generators → source availability and reliability

RF generator development: replace free-oscillators by solid state generators (amplifiers)

- Efficiency → about 90% (instead of 50-60%)
- No water cooling system
- Stable frequency → matching easier
- High reliability → series produced radio transmitters

Automatic power control and frequency matching developed with industry
EU DEMO: Ion source and RF issues

Critical issues with mutual RF coupling → source availability and reliability

1 RF generator per source: change or adapt RF drivers to source geometry

Larger driver (AUG source concept) already successfully tested at prototype source.
EU DEMO: Alternative ion source concepts

Reduce required RF power → source reliability
Increase source efficiency: ion current / kW power

Helicon-type sources

Bird-cage antenna

Helmholtz coils ($B_{\text{max}} = 14 \text{ mT}$)

RF circuit
13.56 MHz
600 W

Both concepts under investigation in lab scale → promising results

13.56 MHz,
5 kW, 15 mT
Stability of source performance and caesium consumption
→ source reliability and maintenance

Present systems need Cs to
- generate sufficient neg. ions
- suppress co-extracted electrons

Cs consumption is estimated to be
- 40 g / year at ITER \[^1\] for one beam line
- 350 – 700 g / year for DEMO \[^2\] for one beam line


- Reduce Cs consumption
  - source operation, Cs ovens
  - Cs doped materials
- Find Cs alternatives

Consumption recently reduced by a factor of 4
EU DEMO: Ion source

Investigation of Cs alternatives → Cs-free ion source
→ source reliability and maintenance

Measurement of negative ion yields of various promising materials (lab experiment)

Focus on low work function materials: cathode materials and doped materials as MoLa or ...
**EU DEMO: Ion source**

**Investigation of Cs alternatives → Cs-free ion source**

→ source reliability and maintenance

Measurement of negative ion yields of various promising materials (lab experiment)

LaB$_6$: feasibility tests on grid manufacturing

Focus on low work function materials: cathode materials and doped materials as MoLa or ...
**EU DEMO: Ion source and accelerator**

**Backstreaming ions** → might limit the lifetime of source
- formation of positive ions in the accelerator by collisions with background gas
- accelerated to back plate of ion source
- small spots due to focusing effects

**Very high power densities (80 MW/m²)**

**Might set upper limit for beam energy due to power handling limits**

- Reduction of neutral gas density
- New accelerator concepts, ...

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*Footprint of one beamlet*

*Calculations of the back streaming positive ions at the back plate of the ITER source*

[P. Agostinetti, RFX-MITICA-TN-33 (2011)]
Neutralizer – a key component to boost the plug-in efficiency from \( \approx 25\% \) to about 60\%

**Different neutralizer concepts**

- Gas neutralizer with **energy recovery** \( \rightarrow \approx 35\% \)
- Plasma or Li neutralizer \( \rightarrow \approx 35\% \) with **energy recovery** \( \rightarrow \approx 45\% \)

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**Energy recovery of neg. ions**

Recirculation of the un-neutralized ions to reduce the drain current in the main HV power supply
- slow down the un-neutralized ions
- collection at low energy and low power density

**make use of positive ions as well**

McAdams, AIP Conf. Proc 1515 (2013) 559

**Positive ions recovery will be tested soon**
EU DEMO: Neutralizer concepts

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Neutralizer – a key component to boost the plug-in efficiency from $\approx 25\%$ to about $60\%$

A radically new concept: the photon (laser) neutralizer $\rightarrow \approx 60\%$

$$D^- + h\nu \rightarrow D^0 + e^-$$

Neutralization efficiency almost $100\%$

**Challenging project at limits of laser systems (800 kW), ... ⇒ Feasibility?**

**Additional benefits:**
- Reduced gas throughput & pumping requirements
- Shorter beam line
- No ion dumps, no bending magnets, ...
- May reduce stripping losses and source size

**Direct drive cavities**

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\[
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\( \Rightarrow \) Feasibility?

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**Fabry-Pérot-cavities**

- High R mirrors
- Ion beam
- Laser source (Nd:YAG at 1064nm)
- (Additional enhancement of stored power via constructive interference possible)

*Kovari et al., Fus. Eng. Design 85 (2010)*
EU DEMO: Activities on the laser neutralizer concept

Proof-of-principle experiments in lab-scale
Experimental realization of a substantial (measurable, i.e. 10% - 25%) neutralization of a small negative ion beam:
8 W cw-laser coupled to external cavity (ampl. $10^4$)
Realization envisaged with the Siphore concept

A photoneutralizer-based NBI system aiming for a high power photon flux (~3 MW) generated within a Fabry–Perot cavity

Simonin, Nucl. Fusion 55 (2015) 123020
Realization envisaged with the Siphore concept

A photoneutralizer-based NBI system aiming for a high power photon flux (~3 MW) generated within a Fabry–Perot cavity.
EU DEMO: Activities on the laser neutralizer concept

**Design activities** although laser neutralizer still in the very early development concept

- Two structures for improved **dimensional control**
  - Upper flange supporting the two structures
  - Stainless steel support structure (temperature controlled)
  - Laser mirrors

1. **Internal structure**: only for laser optical systems, temperature very carefully controlled
   - 2 lasers (35 kW each)

2. **External structure**: for other components (ED, ND, NEG)
   - Stainless steel support structure
   - Electron dump
   - Non Evaporable Getter pump
   - Neutron dump
EU DEMO: Interface of NBI with breeding blanket

Study of different options

Option 2:
Injection angle: 30°
Port size: 0.7 m x 0.7 m
EU DEMO: Reduction of breeding blanket by NBI ports

Opening size determined by
- beamline length
- beamlet divergence
- the way to cut and hole in neutron shielding

Impact on TBR determined by (Giovanni Grossetti, KIT)
- opening size
- poloidal position

Of the same order as for the other systems \( \approx 1\% \)

ITER size: \( 0.55 \times 0.97 \text{ m}^2 \)

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<thead>
<tr>
<th></th>
<th>DEMO 1</th>
<th>TBR reduction [%]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>narrow opening</td>
<td>HCBP</td>
</tr>
<tr>
<td>ITER-like source</td>
<td>cut (a)</td>
<td>2 ports 1.2 ( \times ) 1.0</td>
</tr>
<tr>
<td></td>
<td>cut (b)</td>
<td>2 ports 0.7 ( \times ) 1.0</td>
</tr>
<tr>
<td>Advanced source</td>
<td>cut (a)</td>
<td>1 port 1.2 ( \times ) 1.0</td>
</tr>
<tr>
<td></td>
<td>cut (b)</td>
<td>1 port 0.7 ( \times ) 1.0</td>
</tr>
</tbody>
</table>
EU DEMO: Maintenance strategy

Accessibility

Beam source and beam line components:
- Neutralizer and RID blocks can be independently removed from above.
- Beam source block and NEG pumps can be independently removed from the right side.

Duct components:
- Duct heat dump #2 can be rotated and extracted from the radial port.
- After this, duct heat dump #1 can be removed by sliding along its rail.
Needs for NBI activities towards DEMO

**More ion source test facilities to**
- study Cs consumption
- find Cs alternatives
- improve source performance (electrons!)
- ...

**More facilities for neutralizer concepts**
- energy recovery
- laser neutralizer
- ...

... taking RAMI issues into account

... neutron-irradiation issues (grids, ...)

**Accelerator studies to**
- address (reduce) back streaming ions
- optimize grid system (stripping, transm.)
- address voltage holding

**Engineering tasks:** power loads of
- co-extracted electrons
- backstreaming ions
- residual ion dump