Technological considerations for the steady state operation of an NBI beamline for heating and current drive

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The ITER prototype beamline MITICA, under construction at RFX, Padova
What makes NBI attractive for steady state on tokamaks?

Today

NBI serves as the workhorse among the heating systems on tokamaks
- due to robust power coupling (if only the density is high enough)
- relatively matured technology for positive-ion-based NBI and short pulses

Many DEMO scenarios assume the availability of NBI because
- of high current drive efficiency ($\sim 0.3–0.4 \times 10^{20} \text{A}/(\text{W m}^2)$) compared with competing systems ($\sim 0.2 \times 10^{20} \text{A}/(\text{W m}^2)$).
- robust power coupling in ramp-up.

Keep in mind:

Mean free path of injected neutrals approx. $\propto E_{\text{neutral}}/n_e$
→ high energy is required for large machines ($\sim 1 \text{MeV}$ for ITER/DEMO/FPP)
→ Makes the use of negative ion sources necessary as the neutralization efficiency of positive ions becomes vanishingly small at these large energies
Outline

Introduction

Required specifications of an NBI for a steady state DEMO or FPP

Implications of continuous vs. pulsed operation

Summary
### NBI Specifications ITER/DEMO/FPP

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>pulsed DEMO [1]</th>
<th>steady-state DEMO/FPP [1,2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>1 MeV</td>
<td>0.8–1 MeV</td>
<td>≥ 0.8 MeV</td>
</tr>
<tr>
<td>Total injected power</td>
<td>50 MW</td>
<td>50 MW flat top</td>
<td>135–210 MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 MW start up</td>
<td></td>
</tr>
<tr>
<td>Number of beamlines</td>
<td>3</td>
<td>2–3</td>
<td>2–3 (?)</td>
</tr>
<tr>
<td>Wall plug efficiency*</td>
<td>0.27</td>
<td>0.4</td>
<td>0.5–0.6</td>
</tr>
</tbody>
</table>

**For a steady-state DEMO/FPP: Energy efficiency becomes essential!**

Low recirculating power fraction → Minimum wall-plug efficiency* of 0.5–0.6

* (injected power)/(gross power for injector operation)

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Wall plug efficiency > 0.5

**Auxiliary power**
- RF cooling
- cryo supply
- magnet PS cooling
- cooling

**Losses/efficiencies**
- stripping losses/halo/backstreaming ions
- neutralization (energy) efficiency
- duct transmission reionization losses

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>ITER NBI [1]</th>
<th>SS-DEMO/FPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction (accelerated power/gross power incl. aux.)</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Accelerator (stripping/halo/backstreaming ion losses)</td>
<td>0.70</td>
<td>0.85 (target)</td>
</tr>
<tr>
<td>Neutralization</td>
<td>0.55</td>
<td>0.80 (target)</td>
</tr>
<tr>
<td>Duct transmission</td>
<td>0.80</td>
<td>0.90 (target)</td>
</tr>
<tr>
<td><strong>Wall plug efficiency</strong></td>
<td>0.27</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Neutralizer concepts: gas neutralizer

**Gas neutralizer** (as used on ITER):

- **Maximum efficiency** $\sim 0.6$, independent of energy
- Has an optimal target thickness
- Residual ions approx. $1/2 \ D^-$ and $1/2 \ D^+$
Neutralizer concepts: laser neutralizer

**Principle:**
- Laser photo detachment of the 2\textsuperscript{nd} electron of D\textsuperscript{-} (binding energy 0.75 eV $\cong$ 1650 nm).
- **No theoretical limit to neutralization efficiency.**
- Convenient choice: Nd:YAG laser @ 1064 nm ($\sigma = 3.6 \times 10^{-21} \text{ m}^2$).

**Practical aspects:**
- Approx. 3 MW circulating laser power required.
- Resonant coupling into high-finesse optical cavity with amplification $\sim$ 6000.
- Requires $\sim$ 500 W single Gaussian mode laser.

**State of the art:**
- Several small-scale proof-of-principle experiments under way.
- Recently 50 % neutralization reported with 1 keV, $\sim$ mW ion beam and 10 W laser. (Christophe Blondel, Laboratoire Aimé-Cotton)
Energy recovery

If sufficient neutralization efficiency cannot be obtained, the energy efficiency could still be increased by recovery of the residual ion energy.

**Natural energy recovery** (negative ions only)
- Residual ion dump at same potential as ion source (except for a slight positive bias).
- Residual ions decelerated to ~ zero energy.
- Reverse acceleration of secondary electrons must be prevented.

**Recovery of negative and positive ion energy**
- Positive ion collector biased to $+E_{D+}/e$ (e.g. + 1 MV) by energy conversion module (ECM).
- ECM feeds back the recovered energy into the grid at any voltage as designed.

**State of the art:** ECMs being proof-of-principle tested.
Stripping, reionization, and transmission losses

Losses in the accelerator due to interaction with background gas

- Approx. 30% in the ITER NBI
- Reduction requires lowering the background gas density by
  - further reduction of the source pressure (0.3 Pa on ITER)
  - higher conductance, i.e. better pumping, of the acceleration grid assembly.

Reionization losses along the beamline

- Approx. 1% per $10^{-5}$ mbar beamline pressure.
- Reduction requires better pumping or less gas flow.
- Laser neutralizer beneficial, as it requires no gas.

Transmission losses

- Reduction by decreased beamlet divergence, i.e. improved ion optics.
Implications for material selection

- Need to replace the permanent magnets that deflect the co-extracted electrons in contemporary designs by other means. The permanent magnets are unlikely to survive the neutron fluence in an FPP.
- Material selection has to be compatible with neutron irradiation.

Impact on TBR

- For every NBI beamline at least one breeding blanket module has to be taken out.
- One midplane module corresponds to approx. 1 % TBR reduction.
- → Install all NBI on as few beamlines as possible.

NBI impact on tritium processing

- Usual requirement of high isotope purity for NBI feed gas together with high gas throughput (> 100 mbar L/s) puts high demand on the isotope separation facility.
- → Operation of NBI with D/T mix would be very beneficial.
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Here we assume:

Power plant
- runs continuously for 46 weeks/year and has
- one scheduled maintenance of 6 weeks/year.
Most contemporary NBI systems have huge numbers of very short beam pulses.
- Cyclic heat loads up to 25 \( \text{MW/m}^2 \) and motion of movable parts.
- Main problem: fatigue
- Examples: Ion dump panels, frequently moved bellows ...

Continuous operation replaces fatigue issues by wear issues.
- Example: Source backplate sputtering by backstreaming ions (\( \sim 1 \text{ MW} \) at up to 1 MeV).
- **NBI should be designed with plug-in components**, such that the entire source (and other components that suffer wear alike) can be exchanged during scheduled maintenance and refurbished during FPP operation.

How far is the ion source from 46 weeks continuous operation?
Accumulated RF-on time at IPP’s ion source installations:
- **AUG**: 20 years, > 30 000 beam pulses < 40 h (2 days)
- **ELISE**: mostly RF only \( \sim 150 \text{ h} \) (6 days)
- **MANITU**: long pulses with beam extraction \( \sim 600 \text{ h} \) (25 days)
  (that is only a factor of 13 below FPP requirements!)
Continuous pumping

<table>
<thead>
<tr>
<th></th>
<th>NBI beamline</th>
<th>Divertor [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow [mbar L/s]</td>
<td>~ 100</td>
<td>~ 5000</td>
</tr>
<tr>
<td>Pressure [mbar]</td>
<td>$10^{-5}$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Required pumping speed [L/s]</td>
<td>$10^7$</td>
<td>$5 \times 10^4$</td>
</tr>
</tbody>
</table>

Such high pumping speed requires huge pump cross sections, i.e. pumping surfaces.

**Possible choices:**
- Cryo(sorption) pumps
- Non-evaporable getter (NEG) pumps (KIT & RFX)
- With much reduced gas flow (e.g. with laser neutralizer) maybe mercury diffusion pumps (KIT development for DEMO divertor pumping)

**Cryo and NEG pumps require cyclic regeneration**
- Regeneration during NBI operation requires vacuum separation of pump.
- Currently no satisfactory solution exists.

Ion source temporal stability

The function of Cs in current NNBI ion sources

- Cs evaporated onto the plasma grid provides low work function.
- $D^+/D^0$ converted efficiently into $D^-$ on these surfaces.
- Co-extracted electrons deflected onto extraction grid by magnets $\rightarrow$ allowable limit $j_e/j_{ion} \sim 1$.
- Low co-extracted $e^-$ current requires almost a pure $D^+/D^-$ plasma in front of the grid.
Degradation of Cs conditioned surfaces affects the minority species (e) more than the majority species (negative ions).

Example from ELISE:
- Ion current practically constant during 400 s plasma puls with three beam extractions
- Electron current not stable

**H₂ operation**

\[ I_{\text{ion}} = 18.3 \, \text{A}, \, j_e/j_{\text{ion}} < 0.73 \] (45 kW/driver)
Better understanding and control of Cs dynamics

- Modelling going on in parallel with experiments.

Improved ways of applying Cs to the surface

- Implantation instead of evaporation.
- Tests ongoing, first encouraging results.

Alternatives to Cs

- Various materials tested, selection based on the literature.
- La-doped Mo and LaB$_6$ performed best so far (but far from caesiated surfaces)
- Grid manufacturing tests from LaB$_6$ begun.
## Summary of development needs for continuous (not just long pulse) operation

<table>
<thead>
<tr>
<th>Stable continuous ion source operation</th>
<th>Work/Success (thickness/length)</th>
</tr>
</thead>
</table>
| RF driver                              | ![Work/Success](image)
| Stable Cs conditioning in long-pulse or continuous operation | ![Work/Success](image) |
| Operation with non-evaporable Cs alternatives | ![Work/Success](image) |

### Increased neutralization efficiency

| Laser neutralizer with efficiency > 80 % | ![Work/Success](image) |
| Energy recovery                        | ![Work/Success](image) |

### Continuous pumping

| Continuously operating cryo/NEG pumps | ![Work/Success](image) |
| Concepts for injector operation with non-getter pumps | ![Work/Success](image) |

### Nuclear issues

| NBI-specific material selection issues | ![Work/Success](image) |
| Keeping impact on TBR small | ![Work/Success](image) |