Status of NBI for ITER and the related test facility

The NBTF team – presented by G. Serianni

Consorzio RFX, Padova, Italy
LNL, Legnaro (PD), Italy
Neutral Beam Injectors (NBI) for ITER H-CD

- 2 N-HNBs (+1)
- $P_{\text{beam}} = 16.5$ MW
- $I = 40$ A
- $V = 1$ MV
- $T_{\text{pulse}} = 3600$ s

Large scientific/technological step from existing NBIs ➔ a full scale Neutral Beam Test Facility (PRIMA)

Agreements between IO and F4E (with endorsement of Japan and India) and between F4E and Consorzio RFX

L. Grisham et al., Fusion Eng. Des. 87 (2012) 1805
Summary

- Physics of ITER Neutral Beam Injectors (NBI)
  - SPIDER

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>H</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>keV</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Maximum Beam Source pressure</td>
<td>Pa</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>Uniformity</td>
<td>%</td>
<td>±10</td>
<td>±10</td>
</tr>
<tr>
<td>Extracted current density</td>
<td>A/m²</td>
<td>&gt;355</td>
<td>&gt;285</td>
</tr>
<tr>
<td>Beam on time</td>
<td>s</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>Co-extracted electron fraction (e⁻/H) and (e⁻/D⁻)</td>
<td>&lt;0.5</td>
<td>&lt;1</td>
<td></td>
</tr>
</tbody>
</table>

- MITICA

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>H</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>keV</td>
<td>870</td>
<td>1000</td>
</tr>
<tr>
<td>Acceleration current</td>
<td>A</td>
<td>49</td>
<td>40</td>
</tr>
<tr>
<td>Maximum Beam Source pressure</td>
<td>Pa</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Beamlet divergence</td>
<td>mrad</td>
<td>≤7</td>
<td>≤7</td>
</tr>
<tr>
<td>Beam on time</td>
<td>s</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>Co-extracted electron fraction (e⁻/H) and (e⁻/D⁻)</td>
<td>&lt;0.5</td>
<td>&lt;1</td>
<td></td>
</tr>
</tbody>
</table>

- Status of PRIMA, the ITER NBI test facility

The accelerators of ITER Neutral Beam Injectors
Physics design: particle trajectories & heat loads

- Based on designs by IPP (RF source) and JAEA (5-stages accelerator)

P. Agostinetti et al., Nucl. Fusion 56 (2016) 016015
MITICA: Magnetic configuration

G. Chitarin et al., patent WO2014191890), MAGNET GRID
Background gas density

- single impact on nanoscale
- \( \text{H}_2, \text{D}_2 \) on \( \text{Cu} \)
- different gas temperatures
- sampling gas velocity distrib. (1000 simulations per point)
- C++, parallel implementation

Heat loads and optics: feedback

P. Agostinetti et al., Nucl. Fusion 56 (2016) 016015
SPIDER: magnetic system

1. Mechanical offset of the GG apertures

   - Electron suppression magnets
   - Horizontal mechanical offset

2. Deflection magnets and ferromagnetic material added to the GG

   - Electron suppression magnets
   - Compensation magnets
   - Ferromagnetic plate

---

P. Agostinetti et al., Nucl. Fusion 51 (2011) 063004
SPIDER grid system

P. Agostinetti et al., Nucl. Fusion 51 (2011) 063004
Simulations of SPIDER magnetic deflection compensation systems

\[ J_{\text{extr}} = 100\% \]
\[ \frac{V_{GG}}{V_{EG}} = 100\text{kV}/9.4\text{kV} \]

\[ J_{\text{extr}} = 10\% \]
\[ \frac{V_{GG}}{V_{EG}} = 22.4\text{kV}/2.14\text{kV} \]

C. Baltador et al., Rev. Sci. Instrum. 87 (2016) 02B141
G. Serianni et al., Rev. Sci. Instrum. 87 (2016) 02B927
Drift region: space charge compensation

At $t=0$ the beamlets expand under the influence of their own space charge.

By interactions with background gas the secondary particles are created: main reactions: ionization of $H_2$ by $H$- and stripped electrons.

A balance between trapped and ejected particles establishes.

System reaches the equilibrium in a time: $t = 1/(n_{gas} \sigma_{ion}^* v_b) \approx 3$ $\mu$s. ($n_{gas}$, $\sigma_{ion}$, $v_b$ are gas density, ioniz. Cross section and beam speed respectively.)

E. Sartori et al., Rev. Sci. Instrum. 87 (2016) 02B917
Mitica Extractor and Accelerator

- **Aiming:**
  - Horizontal & vertical beamlet aiming
  - Vertical beamlet group aiming

- **Compensation of repulsion:**
  - Aperture displacement
  - Kerbs

Asymmetric deflection compensation magnets

Co-extracted electrons suppression magnets

Kerb
Test of diagnostic systems: collaboration IPP-Consorzio RFX

- Test of SPIDER diagnostic calorimeter (STRIKE)
- Test of diagnostic tools (CCD)
- Collaboration on diagnostic exploitation (spectroscopy)
- Direct experience on RF sources and beams

R. Maurizio et al., under review for publication in Nucl. Fusion
Benchmark of numerical codes: collaboration NIFS-Consorzio RFX

- Measurements with mini-STRIKE in NIFS-RNIS
- Comparison with numerical simulations
- Test of current measurement

Recently, analogous comparison activity started with NIO1 (see Veltri)

P. Veltri et al., Rev. Sci. Instrum. 87 (2016) 02B908
Test of Asymmetric Deflection Compensation: collaboration JAEA-Consorzio RFX

- Magnetic Grid for Asymmetric Deflection Compensation under validation in Negative Ion Test Stand at JAEA

Half-grid featuring uncompensated magnetic deflection

Half-grid provided with Asymmetric Deflection Compensation Magnets

Vacc: 10.5

ΔT [K]

0
0.5
1
1.5
2
Status of ITER NBI test facility, PRIMA
Prima hosts the two experiments: the negative ion source **SPIDER** and the 1:1 prototype of the ITER injector **MITICA**

Each experiment is inside a concrete biological shield against X-rays and neutrons produced by the injectors.

Thanks to this shielding the assembly/maintenance area will be fully accessible also during experiments.
PRIMA - Buildings and Auxiliaries

PRIMA buildings and auxiliaries available for plant installations since October 2014

Main building hosting experiments

SPIDER PS hall

Control rooms

HV Hall & Control Rooms
SPIDER shall test the full scale ITER HNB ion source to full ITER specification:

- Full extracted current
- Full pulse length for the HNB and DNB
- With a source uniformity within ±10%
- In hydrogen and deuterium operation

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>H</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>keV</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Maximum Beam Source</td>
<td>Pa</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniformity</td>
<td>%</td>
<td>±10</td>
<td>±10</td>
</tr>
<tr>
<td>Extracted current density</td>
<td>A/m²</td>
<td>&gt;355</td>
<td>&gt;285</td>
</tr>
<tr>
<td>Beam on time</td>
<td>s</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>Co-extracted electron fraction (e-/H) and (e-/D+)</td>
<td></td>
<td>&lt;0.5</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
SPIDER Source Components

- Beam Dump
  - PVA Tepla (D)

- Vacuum Vessel
  - Zanon (I)

- Beam Source
  - Thales (F)
  - Cecom (I)
  - Galvano-T (D)
  - Zanon (I)
The procurement contract includes Vacuum Vessel, Beam Source and Handling Tool.

Contract signature in Oct 2012 with a Consortium (Thales, Zanon, Galvano-T, Cecom)

Vessel, realized by Zanon, delivered on Site in March 2015, Site Acceptance Tests passed, now electric and hydraulic flanges under installation.

SPIDER VV during vacuum tests on-site

SPIDER VV during baking on-site

SPIDER VV inside the bio-shield
SPIDER - Beam Source

Plasma Grid segments machined

In vacuum He pressure and leak tests of the cooling circuit of a Plasma Grid segment

SPIDER Faraday Shields Lateral Walls manufactured and tested by Galvano-T

Views of: 112kV BS ceramic supports (a), 12kV PG-EG post insulators (b), 100kV EG-GG post insulators

Section view of the updated Cs Oven for SPIDER with main components

View of the updated CAD model of SPIDER Cs Oven
SPIDER - Beam Dump

- SPIDER Beam Dump (BD) procured by INDIA Domestic Agency
- BD delivered to Site on December 2014; Site Acceptance Tests performed in July 2015
- In 2016 Beam Dump to be completed with TC’s and then installed on a SPIDER Vessel Lid

SPIDER Beam Dump: Rear side

SPIDER Beam Dump: Front side
SPIDER PS - HV Deck & Transmission Line

HVD during installation

HVD completed, tested and accepted, during Installation of ISEPS inside

HV Deck is a Faraday cage, air insulated to ground at -100kV and hosting Ion Source Power Supply
External size: 13m x 11m x 5m
Insulating distance from ground and walls: 1m

Transmission Line connects HVD to SPIDER Vessel. Outer conductor grounded. Internal conductor, at -100kV, contains all ISEPS conductors. Insulation between inner and outer conductors by natural air

Supplier: Coelme srl (I)
Insulating Cooling pipes
Cross-section

Factory tests of SPIDER Transmission Line

Serianni, IPAB, 14 March 2016
SPIDER – Summary of status

- procurement of SPIDER components shared between F4E and INDA
- design of all components concluded; all procurement contracts launched between 2010 and 2013
- Factory activities, including manufacturing of components and factory acceptance tests, well advanced for almost all components; many components and plant systems delivered on site and now under installation
  - AGPS: shipping started 8/3/2016; start of work on site expected end April 2016
- All components to be installed by middle 2016 apart SPIDER Beam Source, to be delivered to site in Q4 2016 and installed right afterwards
- During 2016 integrated commissioning including power supply integrated tests to be performed
- Experimental phase to start at beginning of 2017
MITICA: 1:1 scale prototype of the ITER HNB injector.

- 40 A extracted and accelerated current
- 1 MV beam energy
- 1 hour pulse length
- Same beam optics as needed for ITER
- Both hydrogen and deuterium operation

MITICA bio-shield and injector. Transmission line (Japan Domestic Agency procurement) connected to vacuum vessel via High Voltage Bushing (in green), also procured by JADA.
MITICA: Neutral Beam Injector Components

Cryogenic pumps
Tender 2016

Vacuum Vessel
De Pretto [I]

Calorimeter
CfT 2016

Residual Ion Dump
CfT 2016

Neutralizer
CfT 2016

Beam Source
CfT 2015

Serianni, IPAB, 14 March 2016
**MITICA Power Supply**

**Aim:** to feed Acceleration Grids (AGPS), Ion Source (ISEPS), and Residual Ion Dump (RID-PS) of MITICA injector

**Main Systems:**
- AGPS composed of conversion system (AGPS-CS) feeding step-up transformers and diode rectifiers (AGPS-DCG)
- HV Transmission Line (TL) connecting power supplies to injector
- HV Deck (HVD1) Faraday cage air insulated, hosting ISEPS and connected to TL through air-gas High Voltage Bushing
- Residual Ion Dump Power Supply (RID-PS) applying electric field between plates of Residual Ion Dump

**HVD1 1MV Faraday Cage hosting ISEPS**
Main characteristics
- Insulation: 1 MV dc
- Size: 8.4 m × 12.5 m × 9.6 m
- Insulating supports: 8 fiberglass insulators > 6 m
- Total weight (including PS): about 100 ton
- Total height: 15 m

**AGPS-CS**
Main characteristics
- Input section: ac/dc rectifiers 6.5 kV, 9 kA
- Output section: 5 dc/ac three phase inverters
  - Configuration: neutral point clamped (NPC)
  - Modulation: square waveforms 150 Hz
  - Current: 1700 A rms

**Hitachi Ltd**

RID-PS
Dc generator
Ratings: 30 kV, 60 A

Serrianni, IPAB, 14 March 2016
Almost all of components realized

First batch of them tested in factory and delivered to Site

Ship arrived at Marghera port, closest port to Padova, in December 2015; first components delivered to Site

Installation of JADA components started in December 2015 and due to be completed at beginning of 2017

Afterwards insulating tests and power integrated tests to be performed
Firsts JADA components stored in RFX
Installation of 200kV step-up transformer

Installation of transmission line
Procurement of MITICA components shared between F4E and JADA

Design of all components concluded (tech spec documentation of Beam Line Components under finalization)

Procurement contracts signed since 2012 (JADA power supply components), in 2014 (F4E components Vessel, HVD1 and Bushing), and in 2015 (AGPS-CS, GRPS). Further procurement contracts to be signed in 2016–2017

JADA components at well advanced manufacturing phase

Installation of first JADA components started in December 2015

By end 2016 also installation of F4E components to begin starting from Vacuum Vessel
International collaborations

[Diagram showing logos of various international organizations and institutions involved in plasma research, including ITER, JAEA, and INFN.]