First operation of SPIDER and integrated power tests in MITICA

D. Marcuzzi on behalf of NBTF team and contributing staff of IO, F4E, QST, IPR, IPP and other European institutions

Consorzio RFX, Padova, Italy
Outline

- Introduction: from Heating systems at ITER to NBTF

- SPIDER experiment
  - Early results
  - More recent results

- MITICA experiment
Critical components which have direct impact on functionality:
  - Negative ion beam source to produce 40A of D-,
  - Caesiated source
  - 1280 beamlets
  - Vacuum insulated source
  - 1MV beam acceleration
  - 1MV voltage holding
  - 1MV Transmission line and feedthrough - HVB
  - Electrostatic RID

The criticality and step from current technologies used in NBI justified the need for a Neutral Beam Facility (NBTF), aimed mainly at:

- achieving nominal parameters of source and beam
- optimizing HNB operation

and consisting of:

- **SPIDER**: optimisation of ion source: current density, uniformity, stability
- **MITICA**: full-size prototype of ITER NBI: high voltage holding, beam optics
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 radiation and neutrons produced by the injectors. Thanks to these shielding the assembly/maintenance area will be fully accessible also during experiments.
### SPIDER: the full scale prototype of the ITER HNB/DNB ion sources

<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></td>
<td>&lt;0.5</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
First SPIDER operations

- SPIDER operation started on 4 June 2018
- After some tuning, first plasma ignition on 6 June 2018 with 1/4 source…
Introduction: from Heating systems at ITER to NBTF

SPIDER experiment
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MITICA experiment - status

June 2018 first plasma...

..... 24 May 2019 first beam
First SPIDER results

- Large flexibility of SPIDER control system

- But also…

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D.Marcuzzi  
NIBS 2020  
3 September 2020
RF breakdown outside plasma chamber

- Beam source in vacuum
- Breakdown on source rear side due to RF:
  - analysis by fast cameras
  - investigation of pressure effect
- Hypothesis: RF breakdowns induced by large background gas pressure

STRATEGY

- Long term solution: enhancement of vacuum speed
- Temporary solution: Installation of mask on downstream side of PG (only 80 beamlet open)
Installation of plasma grid mask

In the meantime:

- installation of plasma grid mask between PG and EG
- number of 80 beamlet determined by numerical simulations

View from top

Molybdenum plate, installed downstream of PG

Pyrex pushers press mask against PG, fixed onto GG and passing through EG apertures

Molybdenum plate 0.6 mm thick
The SPIDER RF system

- **4 RF generators** (ISRF-TRF), coaxial line (TL), ion source RF load

- Each RF generator: pair of **power tetrodes** in push-pull connection; **variable capacitor** $C_v$ to tune operating frequency
The SPIDER RF system

RF power limit identified:

- power transfer depending on equivalent load impedance
- sudden frequency flips near impedance matching
  - RF power constrained, as observed in other facilities

Strategy:

- implementation of feedforward control of capacitances inside RF generators
- development of model reproducing different behaviours of ISRF system to:
  - support SPIDER operation
  - analyse its performances
  - help in achieving nominal performances
- experimental campaign to analyse different matching network parameters

Simultaneous operation of 4 RF generators:
  - max RF power 100kW so far
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MITICA experiment - status
Original filter field configuration:

- PG busbar layout designed for: max B field strength and uniformity in plasma source (upstream of PG), B field parallel to PG, low B field in drivers
- Non-uniformity of return currents implies high axial component of B field in drivers

Effect of filter field on driver plasma - Observation:

- During plasma experiments a strong dependence of the plasma parameters from the magnetic field generated by the filter field circuit has been demonstrated
- Filter field can quench the plasma in low RF power conditions
- Electrons might be driven towards the walls of the drivers by the filter field
New configuration of magnetic filter field

Original

33% - 66%

$P_{RF} = 4 \times 90kW; P_{source} = 0.32Pa; \text{no bias}; V_{BEO} = 2kV$
Electrostatic probes & plasma characterization

- Pattern of axially movable probes with respect to drivers
- Probe design improved to withstand thermal gradients
Electron density quite linear with filling pressure

- UNSTABLE DISCHARGE AT 4mT
Measurements inside driver and in extraction region

Filter field scan in D\textsubscript{2} and H\textsubscript{2}

- Electron density increases with filter field in driver and decreases in extraction region
- Electron temperature decreases with filter field in extraction region
- Electron density higher in D\textsubscript{2} inside drivers
Rightmost driver has different behaviour:
High $T_e$ in wider region of expansion region
(consequently lower $n_e$ in driver)

No qualitative change with pressure, bias, etc.
- Currents of co-extracted electrons and negative ions increase with extraction voltage and decrease with magnetic field.

- Current ratio increases at low extraction voltages (beam interception of accelerator grids?)
Values and trends are similar despite different principles of operation
First tests of short pulses with high duty cycle: 8 consecutive plasma pulses: 30s plasma; 5s acceleration, every 100s
- 120s with 4×60kW; 70s extraction; 50s acceleration

Extension of plasma and beam duration
Outline: strategy for SPIDER improvement

Improvements to address RF driven discharges:

- Driver configuration
- “On-source” RF circuit upgrade
- Vacuum pumping enhancement

Other BS modifications during the shutdown:

- GG4 segment replacement
- GG permanent magnets reversal

Further modifications during the shutdown or earlier:

- AGPS from 30 kV to 100 kV
- RF generators output power and voltage measurement
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Optimisation of neutral beam in terms of:

- Performances
- Reliability
- Availability

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<td>Beam energy</td>
<td>keV</td>
<td>870</td>
<td>1000</td>
</tr>
<tr>
<td>Acceleration current</td>
<td>A</td>
<td>46</td>
<td>40</td>
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<tr>
<td>Max 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>
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</table>
The insulation tests performed in successive steps, adding each part of the system. The process lasted 1.5 years. The overall insulating tests were completed up to 1.2MV for one hour in Nov 2019.
MITICA construction schedule

- The reference schedule of MITICA, before the Covid-19 event, provided for carrying out power integrated tests in Q2-Q3 2020
- Covid-19 affects MITICA schedule: slowdown and interruption of activities in Q1-Q2; non-availability of experts of laboratories and industries from other countries

### MITICA integration schedule

<table>
<thead>
<tr>
<th>On site activities</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
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<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
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<td><strong>Auxiliaries</strong></td>
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<td>Cooling Plant</td>
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<tr>
<td>Gas and Vacuum System</td>
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<tr>
<td>Cryoplant</td>
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<td><strong>Power Supply</strong></td>
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<td>ISEPS</td>
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<tr>
<td><strong>Mechanical Components</strong></td>
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<tr>
<td>Vacuum Vessel</td>
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<td>Beam Source: Delivery on site</td>
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<td>Beam Line Components: Delivery on Site</td>
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<td>Cryopumps: Delivery on Site</td>
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<td><strong>Power tests</strong></td>
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<td>MITICA 1MV integrated power test</td>
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<td><strong>HV tests in vacuum</strong></td>
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<td>Test set up</td>
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<td>HV holding test in vacuum</td>
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<td><strong>Integration on mechanical components</strong></td>
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<tr>
<td>Installation of cryopumps</td>
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<td>Integration and functional tests of cryosystem (cryoplant + cryopumps)</td>
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<td><strong>Experiments</strong></td>
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<td>Negative ion production</td>
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<tr>
<td>Accelerated beam production</td>
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MITICA integration schedule

- Integration of cryopumps
- Integration and functional tests of cryosystem (cryoplant + cryopumps)
- Installation of Beam Source & functional tests
- Installation of Beam Line Components & functional tests
- Negative ion production
- Accelerated beam production

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The reference schedule of MITICA, before the Covid-19 event, provided for carrying out power integrated tests in Q2-Q3 2020.

Covid-19 affects MITICA schedule: slowdown and interruption of activities in Q1-Q2; non-availability of experts of laboratories and industries from other countries.
Now power integrated tests on dummy loads (1MV, 50MW, 2s) are under preparation.
After completion of power supply integrated tests and waiting for arrival of in-vessel components... (BS in particular!)

**HV test in vacuum - objectives:**

1. verify and improve the insulation of MITICA up to 1 MV in vacuum and low pressure gas, before the installation of the Beam Source
2. establish Voltage Holding scaling laws for large gaps and multiple electrodes

**HV Test guidelines:**

1. in high vacuum (5 $10^{-5}$ Pa)
2. up to 1 MV, with minimum number of Intermediate electrostatic shields (ref config vs QST exp)
3. intermediate electrostatic shields with apertures for gas conductance
4. a realistic geometry for all the electrodes
MITICA HV tests in vacuum

**features:**

- **staged approach**: start from simple configuration
- **surface/size and all details of the electrostatic configuration** are as representative of real BS as possible
- lightweight structures, also for reduced manufacturing cost/time
- intermediate electrostatic shield at -600, shape “identical” to reference one
- **Staged approach also for design/procurement**
- Design of stage 1-2 ongoing
Thanks for your attention