FIP/1-3Ra

TECHNOLOGIES FOR REALIZATION OF LARGE SIZE RF SOURCES FOR –VE NEUTRAL BEAM SYSTEMS FOR ITER -Challenges, experience and path ahead

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FIP/1-3Rb

PROGRESS IN ITER NEUTRAL BEAM FACILITY

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FIP/1-3Rc

DEMONSTRATION OF 1 MV VACUUM INSULATION FOR THE VACUUM INSULATED BEAM SOURCE IN THE ITER NB SYSTEM

Kojima et al
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Presented by: Jaydeep Joshi on behalf of FIP/1-3Ra, FIP/1-3Rb and FIP/1-3Rc

27th IAEA-FEC, Gandhinagar, October 2018
1. Negative ion systems in ITER
2. ITER Neutral Beam Test Facility (NBTF)
3. Indian test facility (INTF)

4. Technologies for realization of large size RF source for –ve Neutral Beam system for ITER- Challenges, experience and path ahead
   a. Development of ‘angled’ grid segment, Welding technologies, Post insulators
   b. Overview of components produced till now
   c. Deviation and non-conformities
   d. Learnings

5. Progress in ITER Neutral Beam Facility
   a. SPIDER- components, installation and first operation
   b. MITICA- mechanical components, power supplies and tests
   c. NBTF Status

6. Demonstration of 1 MW Vacuum insulation for the vacuum insulated Beam source in the ITER NB System
   a. Schematics
   b. Electric Field Analysis for BS and HVB
   c. Design of shields for the BS and HVB in the vessel
   d. Demonstration of Improvement by Shields

7. Summary
### Negative ion systems in ITER

- **2 (+1) HNB**: Heating Neutral Beam
- **1 DNB**: Diagnostic Neutral Beam
- **NBTF**: Neutral Beam Test Facility
- **INTF**: Indian Test Facility

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#### Equipment Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
</table>
| **2 HNBs (+1): deuterium** |                             | • I = 40 A  
• V = 1 MV  
• \( t_{\text{pulse}} \) = 3600 s  
• \( P_{\text{beam}} \) = 16.5 MW |
| **1 DNB**: hydrogen  |                             | • I = 60 A  
• V = 0.1 MV  
• \( t_{\text{pulse}} \) = 3s every 20s  
• Modulation = 5Hz |

**EUDA & JADA procurement**  
**INDA procurement**
Progress in the ITER Neutral Beam Test Facility

NBTF 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.
Indian Test Facility (INTF)

- Second Calorimeter
- Transport Duct
- Cryopumps
- HV transmission line
- Cooling water system
- Calorimeter
- Residual Ion Dump
- Neutraliser
- Ion source and accelerator
- 100kV hushing

FULL SCALE NEUTRAL BEAM TEST BED
Largest Beam line till date

Refer contribution number FIP P1-40 for R&D STATUS OF INDIAN TEST FACILITY FOR ITER DNB CHARACTERIZATION
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RF Ion Source for –ve Neutral Beam system

- Designed to produce a 100keV, 60A, 60MW Hydrogen beam
- To measure the Helium ash content in the Deuterium–Tritium (D-T) phase of the ITER machine using the Charge Exchange Recombination Spectroscopy (CXRS)
## Requirements and related challenges

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Realization of accelerator with focusing requirement of beam at a distance of 20.665m</td>
<td>Overall assembly tolerance of +/- 0.2mm Aperture positioning of 50 microns Flatness of 40 microns Aangles within the tol. Of +/-0.002</td>
</tr>
<tr>
<td>[Diagram of grounded grid segments and beam groups]</td>
<td></td>
</tr>
<tr>
<td>ITER Vacuum Handbook for water to vacuum boundary application</td>
<td>Design of full penetration weld joint with 100% volumetrically inspectable configuration</td>
</tr>
<tr>
<td>Functional and configurational requirements</td>
<td>Customized design of alumina insulators to provide the mechanical connection between grid mounting flanges and electrical isolation upto 90kV</td>
</tr>
<tr>
<td>Radioactive environment</td>
<td>Material selection and procurement with the restricted chemical composition of Cobalt (Co), Niobium (Nb) and Tantalum (Ta) for adaptability to ITER’s radiative environment</td>
</tr>
<tr>
<td>QA</td>
<td>Extensive quality interventions Handling of Deviation and Non-conformities</td>
</tr>
</tbody>
</table>

First of its kind manufacturing
Technology development for ‘angled’ accelerator grid segment

Identification of important geometries
Define the tolerances
Incorporate the manufacturer’s feedback on the feasibility
Re-define the achievable tolerances
Prove the achievability of targeted tolerances by Prototype route
Implement the recommendations for improvement
Production of grid

Material selection
Fixture development
Measuring Technique development

Manufacturing process development
Copper electrodeposition over angled surface
Precision milling of channels and apertures
Full penetration electron beam welding of water connectors*

* This design along with the configuration and its realization has been protected and patent is filed for the same.

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Technology development for ‘angled’ accelerator grid segment

Production of grid

- **Typical values of the achieved dimensions**

<table>
<thead>
<tr>
<th>Beam group angles (Deg)</th>
<th>Beam group plane flatness (microns)</th>
<th>Aperture position (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG 1</td>
<td>BG 2</td>
<td>BG 3</td>
</tr>
<tr>
<td>Nominal Value</td>
<td>0.665</td>
<td>0.222</td>
</tr>
<tr>
<td>Targeted Tolerance</td>
<td>+/-0.002</td>
<td>+/-0.002</td>
</tr>
<tr>
<td>Deviation-Segment 3</td>
<td>-0.003</td>
<td>0.010</td>
</tr>
<tr>
<td>Prototype Grid</td>
<td>-0.072</td>
<td>0.031</td>
</tr>
</tbody>
</table>

- Production with incorporating the recommendations -> led to the best possible methodology of manufacturing
- Three segments of Plasma Grid segments have been produced till now.
- Effect of minor deviation on functionality is assessed to move ahead for production
Welding Technology development

Compatibility * with respect to IVH

Weldability*

Repairability

- An important aspect of production of grid
- Requires customized solution for repair, depending on the type of defect and location of defect
- Re-fuse the weld seam, within the parameter range £ Separate qualification has been performed to ensure the strength as equivalent to the original weld seam

(a) front side

(b) root side
As welded seam

Full penetration CuOF to CuOF EBW joint with 100% volumetric examinable configuration

Macro-picture of the weld seam

Full penetration EBW of CuOF to Inconel joint with strength in the range of 234 to 261 MPa

* This design along with the configuration and its realization has been protected and patent is filed for the same.

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Post Insulator Manufacturing

- Multi Aperture Grid System
  - Plasma Grid (PG)...-100kV
  - Extractor Grid (EG)...-90kV
  - Grounded Grid (GG)...Grounded

Each grid is **Mechanically connected and Electrically isolated** by set of Post Insulators

**Configurational Aspects**

- **Bolts to connect Ceramic and SS flange**
- **Bolts to connect SS flange and Grid holder flanges**

**Electrostatic shield**
- Size
- Shape
- Distance between anode and cathode

**Alumina; Al₂O₃**
- Grade C795 as per IEC 60672-3
- Dia 50mm
- Mechanical Connection by vacuum bolts
- Helical element as compliant element in ceramic threads

**Stainless Steel (SS) Flanges**
- Link Between the Grid Holder Flanges and Alumina

Stringent requirements on assembly dimensions to reach the final alignment of accelerator
Prototyping: To establish (1) manufacturing route (2) to qualify them for mechanical and electrical specification (3) to assess the feasibility of stringent tolerances on the assembly

- **Spec requirement:** 10kN
- **Broken at 16kN**
- **Broken at 13kN**

**Mechanical test**

Total 40 Nos. of Post insulators have been manufactured with end flange flatness of 60 microns in assembled condition

**Electrical test**

Ceramic #1 Typ "EG-GG 05-05-00-00" - 140 kV; 3h

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Major components produced till now

Plasma Grid
Segments- 3 Nos.

Soft Iron Plate segment

Rear Driver Plate

Electron Dump Panels- 10 Nos.

EG Mounting Flange

GG Flange

Post Insulators- 40 Nos.

Plasma Box components and Faraday shield

Technologies involved:
- High precision milling of copper
- Vacuum Brazing
- Electron beam welding of copper and dissimilar material
- Copper Electro deposition
- Ceramic to metal joining
- Heavy fabrication of stainless steel
- Deep hole drilling
Non-conformities and deviation

Extensive Quality interventions:

Tool to ensure and establish the close adherence of manufacturing activities with respect to laid procedures

Each NC and DR to be supported by technical assessments (like FEA, experimentations, prototyping, imposing additional inspection / test etc.) and check that they do not impact the overall functionality of the system
• ‘angled’ grid segment manufacturing remains a challenge, even after establishing the complete manufacturing procedure through 1:1 prototype. Each segment has to be handled with careful monitoring at all the stages of production.

• Welding for vacuum boundary connection according to ITER requirements, is one of the most critical activity in terms of process selection, configuration and its qualification for timely execution of the project.

• Inspite of sufficiently detailed and thoroughly detailed specification, there are possibilities of deviations to suit the manufacturing needs, which have to be accommodated without impact on the function of components.

• Prototyping is essential for the components where no past experience is available to establish the feasibility and to unfold the uncertain areas of manufacturing.

• It is essential to be a ‘Technical Partner’ to ‘Contractor’ for every challenge they come across to fulfil the specification requirement, for the success of such a challenging project.

• Significant learnings generated from this manufacturing is expected to provide the guideline on manufacturing design for upcoming ITER ion sources with similar challenges for seamless manufacturing with reduced time and efforts.
FIP/1-3Ra

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Optimisation of production of negative ions in terms of:

- Density
- Uniformity
- Stability
- Co-extracted electrons

<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>
Vacuum-insulated beam source

Beam Dump

Vacuum Vessel

Beam Source

STRIKE
High resolution calorimeter
SPIDER power supplies

Multi-winding transformers

Ion Source Power Supply

Transmission Line

High Voltage Deck (HVD)

Acceleration Grid Power Supply

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In March 2018

- all connections and vacuum vessel lid closed
- leak test of hydraulic circuits from external flanges started
First SPIDER operations

- SPIDER operation started on 4 June 2018
- After some tuning, first plasma ignition on 6 June 2018 with 1/4 source
Characterisation of source plasma

$I_{PGF}$ scan with different RF powers ($p_{source}=0.24\,\text{Pa}; \, I_{ISBI}=0\,\text{A}$)

$I_{PGF}$ scan with different $p_{source}$ (RF power=25kW; $I_{ISBI}=0\,\text{A}$)

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Source emission spectroscopy in first SPIDER experiments

- $H_\beta$ radiation through drivers: RF power scan

![Graphs showing $H_\beta$ radiation intensity vs. RF power for different LPGF values.](image)
MITICA full scale prototype of ITER HNB

Optimisation of neutral beam in terms of:
- Performances
- Reliability
- Availability

<table>
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<th></th>
<th>Unit</th>
<th>H</th>
<th>D</th>
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<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>46</td>
<td>40</td>
</tr>
<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>
<td>s</td>
<td>3600</td>
<td>3600</td>
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<td>&lt;0.5</td>
<td>&lt;1</td>
<td></td>
</tr>
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Procurement contracts of mechanical components are all in progress

Beam Source procurement is in the critical line. Procurement contract signed in 2018; delivery expected in 2022
MITICA power supply system

- AGPS-DC Generator
- 1MV Faraday Cage (hosting Ion Source PSs)
- HV Bushing
- Vacuum Vessel
- HV Transmission Line
- AGPS Conversion system
- 60MW CW
AGPS-DCG insulating tests: 1.2MV (1h), 1.06MV (5h)

First HV insulating tests successfully passed
NBTF status

**SPIDER**
- Experimentation started in 2018
- Plants and diagnostics entering into operation one by one
- Characterisation of source and beam in progress
- Increase of parameters planned from 2019

**MITICA**
- High voltage power supplies almost completed and under test on-site
- Other auxiliary plant systems under installation and/or commissioning phase
- All procurement contracts for mechanical components in progress
- Expected delivery on site of Beam Source in 2022
Collaborations of NBTF

Max-Planck-Institut für Plasmaphysik
EURATOM Association

Karlsruhe Institute of Technology

Istituto di Fisica del Plasma “Piero Caldirola”
Consiglio Nazionale delle Ricerche

Laboratori Nazionali di Legnaro

ITER India

Institute for Plasma Research
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Demonstration of 1 MV vacuum insulation for the vacuum insulated beam source in the ITER NB system

- JADA delivers 3 sets of 1 MV power supply and an 1 MV accelerator of beam source for ITER NB.
- So far, insulation technology for DC 1 MV in gas, oil, water and air has been developed.

**Vacuum insulation of ultra-high voltage of 1MV is the most critical issue.**

**< Issue of 1 MV insulation for Beam Source >**

- Beam Source(BS) installed in vacuum (1 MV) directly faces to the vessel (0 V), therefore 1 MV vacuum insulation with 0.9 m gap is required, which was originally designed by extrapolation from small-scale experiments.
- Recent experiment indicated voltage holding with such long gap was much lower than expected.
Design basis of voltage holding capability on corner region has been developed for the first time.

<Recent experiment for 1 MV vacuum insulation>
- Voltage holding capability of HVB was based on the empirical scaling for plane and coaxial electrodes.
- **Available voltage was limited to 0.7 MV due to breakdowns at 1.3 m single gap** where >1 MV was expected.
  - Effect of locally concentrated electric field (E_L) on corner was not fully understood

<Scaling for design of corner region>
- EV value (Breakdown indicator) has been investigated by using several cylindrical configurations.
- Allowable E_LV is found to be limited according to surface area (~R)
  - **Empirical scaling to design the electric field on corner.**

These empirical scaling for plane, coaxial and corner are easily applicable to the design of the ITER BS and HVB.
Voltage holding capability of vacuum insulated beam source has been analyzed by the empirical scaling.

**<Electric Field Analysis for BS and HVB >**
- Based on the empirical scaling, EV is analyzed for the BS and HVB in the vessel.
  
- Although the electric field $E$ is not so high (< 3kV/mm), high voltages caused higher EV than allowable level.
- Estimated total voltage holding capability ~ 0.6 MV
  
$\rightarrow$ $E$ is almost saturated even in large $R$.

**Possible measure is inserting shields having intermediate potentials to reduce applied $V$.**
Intermediate shields for the beam source has been developed as measure for the 1 MV vacuum insulation.

<Design of shields for the BS and HVB in the vessel>

- An intermediate shield can be simplified as plane, coaxial and corner regions.
- Gap and electric field on corner is optimized to maximize the total voltage holding capability.
- Number of the shields has been analyzed.

• Required gap length between shields and electric field at the corner has been designed.

• Estimated voltage has been improved from 0.6 MV to >1 MV.
1 MV vacuum insulation has been achieved by applying the developed intermediate shields for the HVB.

<Demonstration of Improvement by Shields>

- Intermediate shield for the HVB has been developed by taking into account the all scaling.
- Voltage holding tests in vacuum were carried out by using the HVB with the shields.

- **Voltage holding capability has been much improved from 0.7 to 1 MV.**
- **The design basis of the 1 MV vacuum insulation with intermediate shields has been demonstrated.**
- **This design technique is directly applicable to the BS for ITER too.**
Successful demonstration of collaborative efforts in the area of technology developments, installation, operation and physics experiments towards the realization of ITER NB system.
THANK YOU