Indian Test Facility (INTF) and its updates

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Abstract. To characterize ITER Diagnostic Neutral Beam (DNB) system with full specification and to support IPR’s negative ion beam based neutral beam injector (NBI) system development program, a R&D facility, named INTF is under commissioning phase. Implementation of a successful DNB at ITER requires several challenges need to be overcome. These issues are related to the negative ion production, its neutralization and corresponding neutral beam transport over the path lengths of ~ 20.67 m to reach ITER plasma. DNB is a procurement package for INDIA, as an in-kind contribution to ITER. Since ITER is considered as a nuclear facility, minimum diagnostic systems, linked with safe operation of the machine are planned to be incorporated in it and so there is difficulty to characterize DNB after onsite commissioning. Therefore, the delivery of DNB to ITER will be benefited if DNB is operated and characterized prior to onsite commissioning. INTF has been envisaged to be operational with the large size ion source activities in the similar timeline, as with the SPIDER (RFX, Padova) facility. This paper describes some of the development updates of the facility.

1. Introduction
The function of Diagnostic Neutral Beam (DNB) [1] is to diagnose the Helium (He) ash content in the Deuterium – Tritium (D–T) phase of ITER plasma, using the charge exchange recombination spectroscopy (CXRS) [2] technique. DNB, for ITER, is a negative ion source based neutral beam injector (NBI) system. The beam is designed to deliver 18–20 A of 100 keV beam of hydrogen neutrals [3] to the ITER plasma [4], through a narrow beam transmission duct with small blanket aperture opening (H × W = 45 mm × 40 mm). The beam will be operated with a 3 s ON/20 s OFF duty cycle and modulated at 5 Hz to ensure improved signal-to-noise ratio in CXRS diagnostic. There are several challenges involved in DNB development project to achieve its specifications, which are related to transmission of high current (18 – 20 A), low divergence beam (7 mrad or less) over a long distance ~ 20.67 m. In this regard, an accelerated ion beam current of value ~ 60 A, having ~ 35 mA/cm² extracted negative ion current density from the ion source of total extraction area (H × W = 1.6 m × 0.6 m) is needed. To transmit the beam through a narrow blanket aperture, placed at distance 20.67 m away from the grounded grid of the ion source, highly focussed beam is required. Such focussing has been achieved by combination of grid segment geometrical shaping, bending and with grid aperture offset setting. The effect on the beam optics due to the bending of the grid segments under heat loads from the incident co-extracted electrons, stripped electrons and back streaming.
positive ions during the beam operation also needs extensive testing. The DNB beam source, which is under manufacturing, consists of an ion source based on European design [5], and the 100 keV accelerator is designed by India [6]. Functionality of the beam line components (BLCs) like neutralizer, residual ion dump (RID) under different operational scenarios are also matter of concern. INTF is established in IPR, India in order to address these challenges and support ITER in realising a working DNB. The uniqueness of this facility is that, INTF has housed a vacuum vessel of ~23m long to accommodate 20.67 m beam transport experimental setup to characterize the full DNB beamline and establishes itself as the largest NBI beamline testbed. The following sections of this paper describe the facility and some of its R&D activities in detail.

To operate INTF successfully, learning experience to operate negative ion beam source with multi-driver setup operation with a CODAC based data acquisition and control system (DACS) including Cs injection is useful. In this regard, a set of experiments; ROBIN experiment [7], TWIN source experiment [8], High Voltage Bushing experiment [9], Cs oven long delivery tube experiment [10] etc. are being carried out in IPR, to learn different aspects of design, integration and remote operation of large size negative ion source having multiple RF drivers fitted with multiple high power RF generators, HV power supplies, sophisticated diagnostic systems under CODAC based DACS platform. All these experiments are part of IPR’s negative ion beam based neutral beam injector (NBI) system R&D program and generate experimental database, useful for ITER NBI activities.

2. Description of INTF and some of its major activities

The INTF facility is in the ITER-India experimental building in IPR [11]. The facility comprises of a large Vacuum vessel (VV), Beamline components (BLCs), Beam source (BS), Cryosorption pumps (CP), HV Bushing, Beam diagnostics, Data acquisition and control system (DACS) and different power supplies with transmission line.

![INTF Vacuum Vessel Schematic](image)

**Figure 1.** INTF vacuum vessel schematic and its snap inside INTF area.

2.1. Vacuum vessel.

INTF vacuum vessel provides the vacuum confinement to characterize DNB injector system. It serves as the structural support for all in-vessel components like; Beam line components (BLCs) [3], cryopumps and the Beam Source (BS). The Vessel has two tori-spherical dish-ends at two sides with large openings for High-Voltage Bushing on one side & 13 m long beam transmission Duct on another side. INTF main Vacuum Vessel which houses all the above components is of cylindrical shape with dimensions of 9 m in length and 4.5 m in diameter and with a detachable top lid configuration for mounting as well as removal of internal components during installation and maintenance phases. Top lid has ~ 30 m long vacuum sealing boundary with double O-ring sealing associated with inter-space pumping provision. The achieved flatness of the top lid after manufacturing is below 2mm over the complete sealing area. At the end of duct, a small vessel is provided which housed the actively cooled beam dump, named “2nd Calorimeter”. Total volume of the vessel is ~ 150 m³ and the vessel is installed and commissioned in INTF lab. The achieved ultimate vacuum is $10^{-6}$ mbar with maximum deflection on the wall is below 5mm. The global leak tightness is ~ $10^{-6}$ mbar l/s and corresponding local leak rate is ~ $10^{-7}$ mbar l/s. The vessel picture inside INTF lab is shown in fig.1. The beamline components (BLCs) and the beam source (BS) are housed inside the vacuum vessel and will be operated under vacuum. Detailed design of the INTF vacuum vessel can be found in ref. [12].
2.2. Beamline components

The neutralizer, residual ion dump (RID) and the calorimeter are the beam line components [1]. The layout of the components is identical to DNB with a 1 m, 0.75 m and 0.2 m gaps between the grounded grid & neutralizer, neutralizer & RID and RID & calorimeter respectively [3]. In correspondence with the DNB, the 3 m long neutralizer and 1m long RID are 4 channelled structures. Out of five Cu walls in RID for four channels, 2nd and 4th walls are connected to ~8 kV potential to generate electric field sufficient to filter out un-neutralized negative ions as well as re-ionized positive ions. Negative hydrogen ions are deflected towards the electrically grounded 1st, 3rd and 5th plates, whereas positive ions are deflected on 2nd and 4th plates respectively. The calorimeter is a movable V – shaped structure made up of two panels with CuCrZr alloy based hyper-vapotron type heat transfer element (HTE) [13] to handle large heat flux when it intercepts the complete beam. The detailed technical specification of each BLC has been prepared by ITER-India and subsequently reviewed and approved by ITER. After successful completion of tendering process, contract has been awarded for procurement of the BLCs. The components are now under initial stage of manufacturing. A parallel prototype manufacturing activity of these BLCs has been also initiated indigenously including material development, high precision machining and electron beam welding for dissimilar metal joining.

![Figure 2. Schematic of beamline components (a, b, c) and its manufactured parts (d, e, f) respectively.](image)

The Beam line Components are subjected to several acceptance tests. (i) **Visual inspections**: All the Beam Line Components shall be visually checked according to ASTM Sec. V/ Equivalent EN ISO std. and they shall be free from visual defects like weld spatter, surface cracks, surface porosity etc. (ii) **Dimensional Inspection**: Dimensional control shall be established & verified at different level of manufacturing i.e. after receiving the raw material, during manufacturing of sub-components/sub- assemblies & after assembling of all the sub-components/sub-assemblies to form Main Beam Line Component assembly. The Non-conformance (if any) w.r.t approved drawings observed the same shall be disposed through approved non-conformance report (NCR) procedure. (iii) **Pressure Test**: Cooling circuit of all the BLCs shall be tested for high pressure test at 25 bar. Test pressure is specified according to the recommendation available in the applicable ASME/ EN ISO code. (iv) **Leak Test**: Cooling circuit of all the BLCs shall be subjected to the leak test. Leak test shall be performed at both ambient temperature and at the maximum and minimum design temperature. During testing, the direction of pressure differential shall be kept in the same direction as during operation. The observed leak shall be less than $1 \times 10^{-10}$ Pa m$^3$/s. In addition, some functional tests are also specified for each BLCs. For example, (a) **High voltage Test**: Residual Ion Dump assembly shall be tested for High voltage test at 12 KV for 3 hours. (b) **Flow Test**: One element of each BLCs shall be tested for flow test. (c) **Demonstration of functionality of Movement Mechanism for calorimeter**: The functionality of the Calorimeter Movement Mechanism (CMM) shall be demonstrated in vacuum after installing the Calorimeter assembly along with CMM in the INTF Vessel.

2.3. Beam source

The accelerator system of DNB BS is based on three grid system, consisting of a plasma grid (PG), an extractor grid (EG) with embedded magnets and the grounded grid (GG) [6]. Each grid is made of four segments. A total number of 1280 apertures are arranged on these segments in 16 beam groups in
5×16 matrix, which overall provides a beam extraction area of 0.197 m². All the beamlets to be focused at a distance of 20.665 m from the GG to ensure minimum size of the beam near ITER blanket. Stringent focusing requirement is a special design feature of DNB and it is achieved by using a combination of geometrical aiming by placing each segment in a specified angle with respect to the beam axis, aperture offset and geometrical shaping. Apart from that each PG segment is manufactured in a curved profile in horizontal direction to achieve desired horizontal focusing. Prototype of a segment of plasma grid is manufactured and achieved tolerances are ~ 50 micron on flatness over the complete grid segment surface area (1 m × 0.4 m) and ± 0.002 degree in angle tolerance. It is the first time in the world that manufacturing of a six stage angled grid segment is realized, as shown in fig.3a. To hold all the grids and its segments in desired position with respect to the beam axis, maintaining HV isolation requirements, specially designed alumina based ceramic isolators (post insulator) are also manufactured (see fig.3b) as prototypes. These have achieved 140 kV DC voltage isolation for 3hrs with 13 kN cantilever load bearing capability.

Figure 3. Manufactured angled plasma grid segment and ceramic post insulator on test zig.

Figure 4. Deployment of characterization diagnostics in INTF

2.4. Diagnostics
Since INTF is envisaged to characterize ITER DNB system and to establish the functionality of its eight inductively coupled RF plasma driver based negative hydrogen ion source with its beam performance including its beam line components, diagnostics plays an important role for its safe and optimized operation. A number of diagnostics are planned in INTF to characterize the ion source and its beam performance. Negative ions and its Cesium contents in the source, will be monitored by optical emission spectroscopy (OES) and cavity ring down spectroscopy (CRDS). Plasma near the extraction region will be studied using standard electrostatic probes. The beam divergence and negative ion stripping losses are planned to be measured using Doppler Shift Spectroscopy (DSS). During initial phase of ion beam characterization, Carbon Fiber Composite (CFC) based infrared (IR) imaging diagnostics will be used. Safe operation of the beam will be ensured by using standard thermocouples and electrical voltage-current measurement sensors. Detailed description of different diagnostic systems corresponding to different beam operation scenarios are depicted and discussed in ref. [14]. The dispersion of all these diagnostics, envisaged in the test facility for characterization, is shown in fig.4. To gain experience, (i) a table top experiment for CRDS is being carried out; (ii) one IR camera is already being procured for CFC based IR diagnostics and will be incorporated in ROBIN [7] beamline for beam characterisation; (iii) Probes, OES, DSS, Calorimetric diagnostics are regularly being utilized in ROBIN test facility to characterize the plasma and the beam respectively.
2.5. **Control and Data acquisition system**

To ensure successful operation of INTF involving integrated operation of all the constituent plant systems a matured Data Acquisition and Control System (DACS) is required. The INTF DACS is based on Control, Data Access and Communication (CODAC) platform following on Plant Control Design Handbook (PCDH) guidelines. However, the roadmap to learn operation with CODAC platform is through ROBIN experiment [7] and TWIN source experiment [8]. Operation of INTF requires several plant systems like, beam source, gas feed, vacuum, cryogenics, high voltage power supplies, high power RF generators, mechanical systems and diagnostics systems. The experimental phases involve application of HV power supplies (100 KV) and High RF power (~ 800 KW) which will produce energetic beam of maximum power 6MW within the facility for longer durations. Hence the entire facility will be exposed to high heat fluxes and RF radiations. Therefore, to ensure investment protection and to provide occupational safety for working personnel a matured Interlock and Safety system is required for INTF. The Interlock and Safety systems are high-reliability systems devoted completely to the specific functions. These systems will be separate from the conventional DACS of INTF which will handle the conventional control and acquisition functions. Both, the Interlock and Safety systems are based on IEC 61508 and IEC 61226 standards as prescribed by the ITER PCDH guidelines. For complete operation of INTF, approximately 900 numbers of signals are required to be super-intending by the DACS. In INTF, conventional control loop time requirement is within the range of 5–100 ms. It requires sampling rates in the range of 5 sample per second (Sps) to 10 kSps. For high-end diagnostics, the required sampling rates are normally up to 100 MSps. All the corresponding hardware components have been selected from the ITER slow and fast controller catalogues, procured and tested. Combined use of CODAC core software (CCS) and NI-LabVIEW have been finalized due to the fact that full required DAQ support is not available in present version of CCS. Several prototype set-ups have been tested on CODAC-LabView integration. Some details are available in [15]. DACS for ROBIN is already in operation and for TWIN source, it is ready for integration. Different hardware components for INTF DACS are under procurement and testing using developed software.

2.6. **High voltage bushing**

High voltage bushing (HVB) or feedthrough for INTF is placed on the BS side dish-end of the VV in horizontal configuration and carries all the required feedlines (25 nos.) from transmission line to the beam source, which includes all the cooling lines like, RF transmission lines, HV lines, Instrumentation lines, Gas feed lines, Cesium oven delivery tube along with its heater connections etc. It also forms a primary vacuum boundary. INTF HVB has been designed considering the basic configuration of porcelain based large diameter (~ 1 m) insulator to provide 100 kV isolation. The design is validated using some analytical calculation and finite element method [16] and prototype experiments. Maximum stress obtained on porcelain ring and epoxy is 2.02 kV/mm and 2.23 respectively. Maximum localize stress obtained on the triple point of EG is 0.7 kV/mm. Maximum stress and the deflection due to vacuum and cantilever load by all the feedlines is determined to be 207 MPa and 3.3 mm respectively. All the stresses and deflections are under acceptable limit. Large diameter (~ 1 m) porcelain ring for HVB is being fabricated at BHEL, India. Several tests on individual components of HVB have been started before going for full-scale manufacturing.

3. Conclusion

The paper describes an overview of INTF facility which will characterize ITER DNB BS and its PSs along with BLCs with full specification before delivery of these components to ITER. Once established and functional, the facility shall provide rich database for the operation of a large size, multi-driver negative hydrogen ion based neutral beam system. The ROBIN and TWIN source experiments are important steps in the development roadmap, to acquire adequate experience on the understanding of operation of negative ion sources and ensuring preparedness for operation of INTF. INTF BS is expected by the end of 2017 and experimentation will initiate following integration of the
BS and experiments on characterisation and operational optimisation shall continue for next 2-3 years before the delivery of the system to ITER site.

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