Special Topic Article

4. ITER NB System: Compact Beamline and Design against Radiation

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The present ITER NB system includes two design features: short beamline design and vacuum insulated beam source (ion source and accelerator) which sustain 1 MV high voltage under radiation environment. The short beamline design is achieved by subdividing interior of the neutraliser into narrow channels to reduce gas conductance, and hence, the gas flow rate to ensure target thickness required for neutralisation. Optimizing the beam transmission and reionisation loss of neutral beams, the axial length of the ITER NB injector was shortened to be 23.4 m with a reasonably high injection efficiency. Three-dimensional neutron transport analyses clarified possible excess power dissipation due to radiation-induced conductivity, if the high voltage is insulated by conventional gas such as SF_6. Thus, design of vacuum insulated beam source has been established for the present ITER NB system.

Keywords:

fusion, ITER, neutral beam, accelerator, negative ion, H^-, beamline, neutraliser

4.1 Introduction

The physics functions of the ITER neutral beam (NB) system are: 1) to assist transition of plasma confinement from L- to H-modes, 2) to heat the plasma to the temperature of several tens of keV to initiate plasma burn, and 3) to drive plasma current so as to sustain the plasma for long pulses. To satisfy the functions above, the ITER NB system consists of two injectors, each delivering 16.5 MW (total of 33 MW) at the beam energy of 1 MeV. Negative ion (D^-) beams are generated as the primary beam species to achieve reasonable neutralisation efficiency (≈ 60%). Each NB injector equips only one single large beam source (ion source and accelerator), which makes the design simpler than existing systems such as JT-60U and LHD NB injectors [1,2]. The design assumes the current of D^- ions to be 40 A from each beam source at the current density of 200 A/m^2.

The engineering design of the ITER NB system, including the beam source and also the beamline components, has been developed [3,4] during the ITER Engineering Design Activity (EDA) utilizing the existing technologies and their reasonable extrapolations. The outline of the design has been reported in [5-7]. Physics requirement, on-/off-axis current drive capability, and layout design of the NB injector were described in [8].

In this article, some specific design features of the NB system are highlighted as follows.

The present ITER (ITER-FEAT) was designed so as to achieve its technical mission within a reduced initial construction cost. This implies compact design of the ITER machine including the tokamak building. The NB system was also designed within the constrains to fit within available floor area of the NB cell, a common enclosure of the injectors. Thus the NB injector was designed to be compact, in particular, to shorten the beamline axial length to mitigate impact on the cost of the tokamak building. However, the short beamline concept raised various design issues: beam transmission and heat loading in the beamline component.

Another notable feature of the ITER NB system is its design against radiation environment. The NB ports for the beam injection are the largest openings among those on the vacuum vessel of ITER. As the plasma burn starts, neutrons and gamma rays stream into the NB duct, and then through the beamline to the beam source. Hence, the NB injector is operated in the radiation environment. The design provides proper shielding around the NB duct, to attenuate the nuclear heating in the superconducting magnets and shutdown dose in the cryostat. Dose rates were estimated to be low enough in the NB injector for responses of NB cryopump, permanent magnet and alumina ceramic insulator [9]. However, it was estimated from three dimensional Monte Carlo analyses that radiation induced conductivity (RIC) was unacceptably high in insulation gas, such as SF_6, if it is used for high voltage insulation of the beam source. Thus the present design utilizes vacuum insulation, instead of original gas insulation, for the high voltage applied to the beam source.

After a brief introduction of the beamline structure, the

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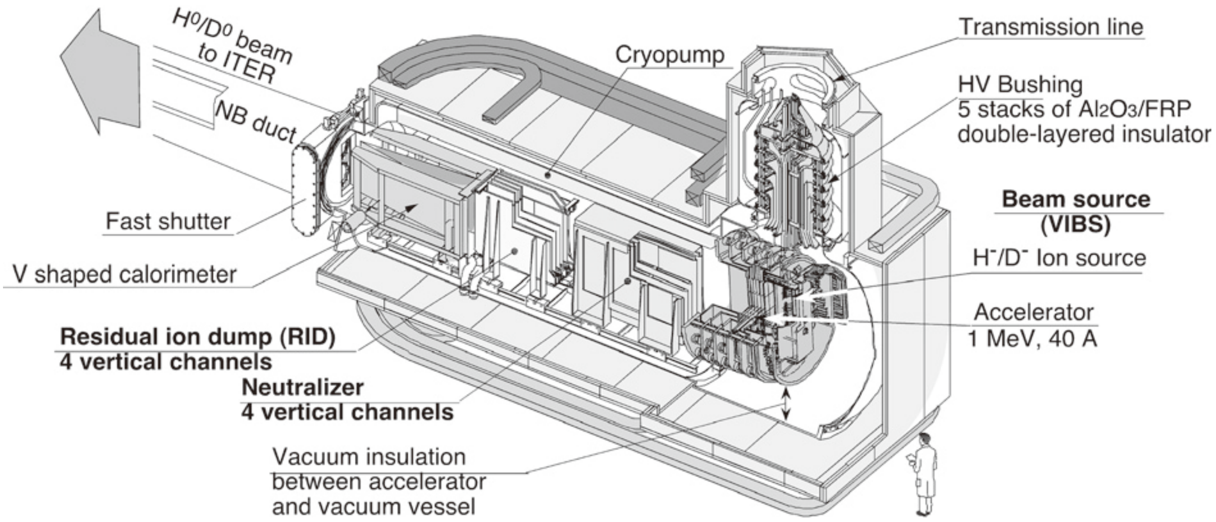

Fig. 1 An isometric illustration of the ITER NB injector.

short beamline design is discussed together with the evaluation of beam transmission efficiency. Then the article describes the radiation environment of the ITER NB system followed by the design of vacuum insulated beam source.

4.2 Beamline Structure

An isometric view of the ITER NB injector is illustrated in Fig. 1. Each injector has a large single ion source, mounted directly on an electrostatic accelerator. The negative ions are produced in an arc discharge struck in the ion source, and then extracted through 1,280 apertures drilled in the grids of extractor. The electrostatic accelerator has five-grids with multi-apertures, each arranged according to those in the upstream extractor grids. The D^- ion beams are fired with the current density of 200 A/m^2 at the grounded grid, i.e. at the exit of the accelerators.

The negative ion beams are converted (neutralised) into energetic atoms in a simple gas cell, so called neutraliser, by electron stripping reaction between the ions and thermal gas molecules ($D^- + D_2 \rightarrow D^0 + D_2 + e$). High neutralisation efficiency of ≈ 60% is achieved owing to relatively small reaction rate of reionisation of neutrals ($D^0 + D_2 \rightarrow D^+ + D_2 + e$) as a dominant competing reaction. The neutralisation efficiency, i.e. fraction of neutrals converted from the ions, depends on the gas thickness in the neutraliser. At the optimum gas thickness the output of fast neutrals reaches its maximum, while the rest of the beam consists of negative and positive ions of approximately equal fractions. To maintain the optimum gas thickness in the neutraliser (1.4×10^{20} m^{-2} for D^- ions at 1 MeV) D_2 gas is fed in the neutraliser. The gas emerging from the neutraliser is pumped down by cyropumps installed around the inner surface of the beamline vacuum vessel. The gas from the neutraliser is the main gas source in the system and it defines together with the dedicated cryopumps reionisation losses downstream of the neutraliser and the voltage holding capability of the beam source.

The ions are removed from path of the neutral beam by electrostatic field onto the residual ion dump (RID). The neutral beams are either injected into the ITER plasma or intercepted inside the injector by a movable calorimeter that can accept the full neutral beam power.

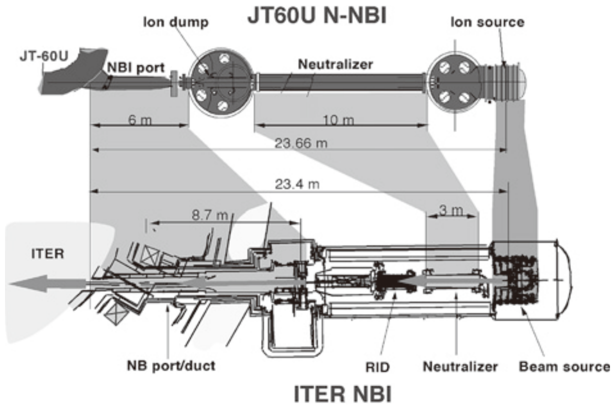

Fig. 2 A comparison of the beamlines for the JT-60U N-NBI and the ITER NB injector.

4.3 Short Beamline Design and Beam Transmission

Figure 2 shows a comparison of the beamline horizontal cross section for the JT-60U negative ion based NB injector (N-NBI, rated injection power: 10 MW at 500 keV) [1] and the ITER NB injector. Note that the JT-60U N-NBI was designed and constructed based on a long neutraliser concept [10], of which neutraliser length was 10 m long. On the other hand, the neutraliser of the ITER NB injector is only 3 m long to minimize the beamline footprint. Consequently, as shown in the figure, the axial length (from the beam source grounded grid to the NB port mouth) of the ITER NB beamline is reduced to 23.4 m, which is in the same range in the JT-60U N-NBI (23.66 m).

Basically gas flow rate escaping from the neutraliser

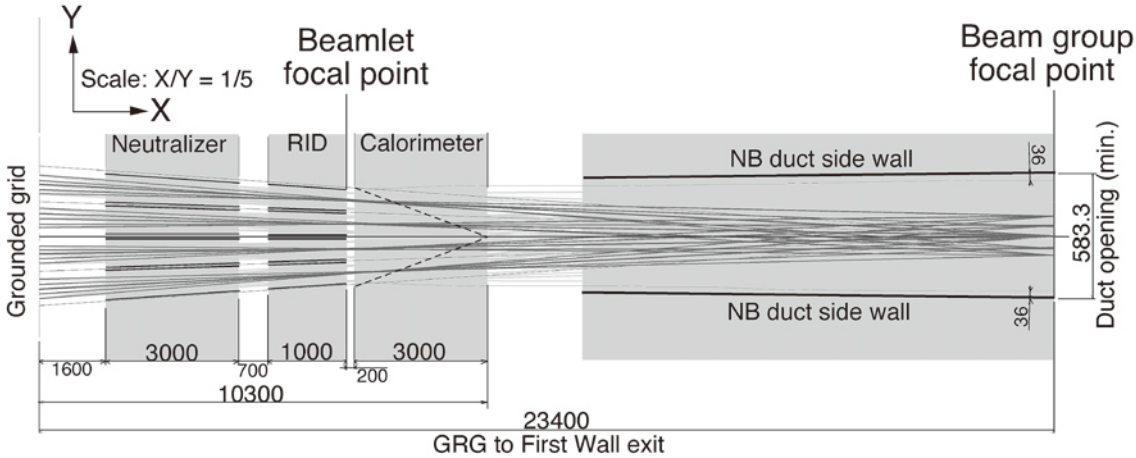

Fig. 3 An example of the ray trancing diagram for the 4 vertical beam channel design.

becomes high, due to large gas conductance in the short neutraliser. And hence higher rate of gas feed is required in the short neutraliser to maintain the optimum gas thickness. However, this would lead to pressure increase in the downstream followed by higher reionisation loss of neutral beams. In the ITER NB injector design, the short neutraliser is realized by subdividing its interior to form several vertical channels of each 3 m long, 1.7 m high and narrow width (to be optimized below), which reduces gas conductance and subsequently required gas flow rate, even in the short neutraliser. The RID is also subdivided in channels to reduce its axial length and the power density on its panels. The grid apertures in the extractor and the accelerator are arranged to form several vertical beam columns, so as to match the channels of the neutraliser and RID.

Too many channels in the neutraliser and RID enhance, of course, D^- and D^o beam loss due to the direct interception on the channel walls. And contrary, in the case of fewer numbers of channels the higher gas input to the neutraliser is required and hence the loss of the neutral beam increases due to reionisation downstream from the neutraliser on the way to the tokamak. Number of channels was optimized taking into account both type of these beam losses. Beam transmission was calculated first by a simple ray tracing, an example is shown in Fig. 3 for a horizontal cross section. The diagram shows trace of each beamlet ejected from the grounded grid (left), passing through the neutraliser and RID. Considering various constraints, such as maximum width of the ion source, thickness of panels subdividing interior of the neutraliser and RID, the beam transmission was analyzed for various number of channels. In each channel beamlets were focused on the vertical center line of each channel at the RID exit, while beam columns (beam groups) themselves were focused on the vertical center line of the NB duct opening to the ITER plasma. For each case the gas density along the injector was then calculated with three dimensional Monte Carlo gas flow code and reionisation loss was evaluated. The results of calculations for different number of channels are shown in Fig. 4. As number of the beam channels increases,

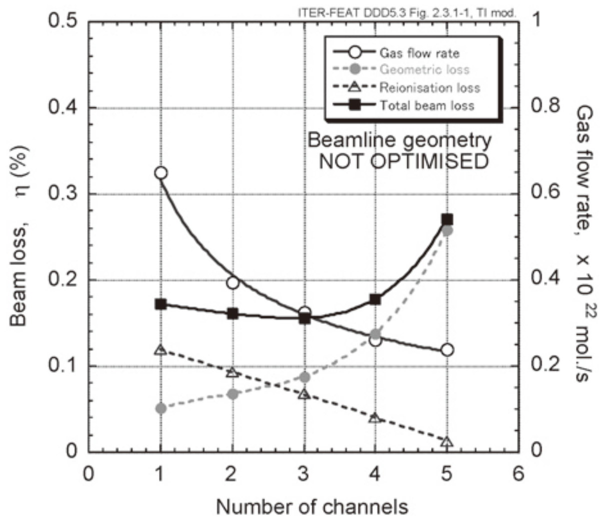

Fig. 4 Beam losses due to direct beam interception (geometric loss) and due to reionisation of neutrals as functions of number of channels in the neutraliser and RID. Gas flow rate from neutraliser is also shown.

- Reionisation loss of the neutral beam decreased, as a result of lower pressure downstream by reduced gas flow rate, however,
- The beam loss due to direct interception at the subdividing plates increases.

In the ITER NB beamline 4-channels design has been adopted [11] in favor of 2- or 3- channel solutions accounting additional considerations like lower power density onto the RID plates, lower deflection voltage between its plates and voltage symmetry in the RID (outer and central panels are at ground potential, while other two are at –23 kV).

The apertures were arranged to form four beam columns, each corresponding to the four beam channels in the neutraliser and RID, and each beam column consisted of four beam groups of a 5×16 aperture array. This design is referred to as the $(4 \times 4) \times (5 \times 16)$ arrangement as shown in Fig. 5.

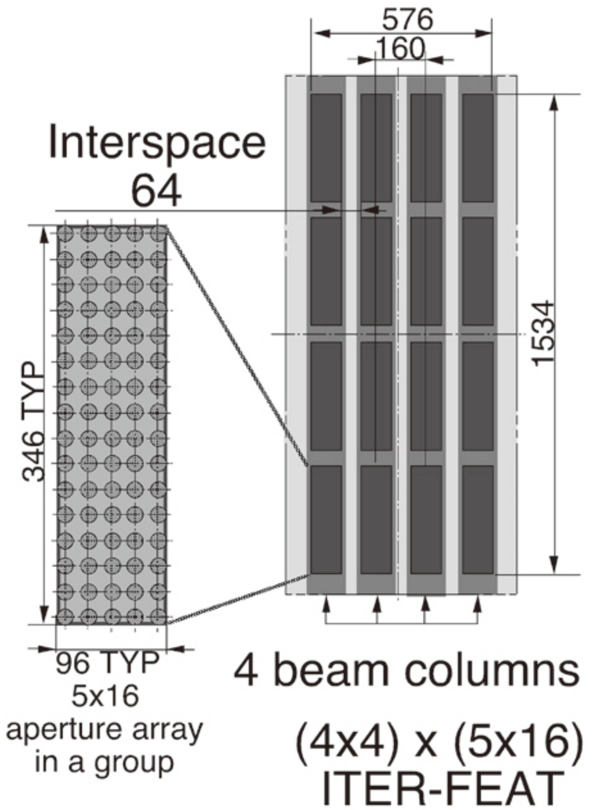

Fig. 5 A (4 × 4) × (5 × 16) arrangement of grid aperture in the ITER NB beam source.

Table 1 Summary of the heat loading on each component and NB injection efficiency of the ITER NB system.

Components	Beamlet core divergence	
	5 mrad (reference design)	7 mrad (maximum acceptable divergence)
Neutraliser	2.9 MW	4.6 MW
RID	17.9 MW	18.5 MW
NB duct	0.6 MW	0.6 MW
NB power to be injected	18.6 MW	16.3 MW
NB injection efficiency*)	0.4	0.35

*) NB injection efficiency was defined as (Injected NB power) / (Input power to the NB injector). Note that input power includes electric power for ion production etc. whilst heat load in the ion source and accelerator is not show in the table.

The interspace between beam columns (distance between aperture edges of neighboring groups) was defined to be 64 mm to achieve good beam transmission inside the neutraliser and RID within reasonable width of the beam source.

The result of the beam trajectory analyses is summarized in Table 1 for various beam divergence conditions. Note that the beam divergence was defined with bi-Gaussian profile for beamlets generated from each aperture in the ITER NB design. In the R&D [12,13], typical beamlet consisted of a core delivering 85% of power with 5 mrad divergence, and a halo part with 15% power at 15 mrad. The injection power of 16.5 MW is ensured if the core divergence angle of the primary D^- ion beam is ≤ 7 mrad. The transmission efficiency and the overall NB injection efficiency are estimated to be 91% and 41%, respectively, in the present ITER NB design.

4.4 Radiation Analyses and Vacuum Insulated Beam Source

The neutron transport calculation was carried out using a three dimensional, continuous energy Monte Carlo code MCNP-4B [14] together with the nuclear cross section library FSXLIB-J3 [15]. A new computerized 3D model of the NB injector was built for the reference design of the ITER NB injector in 1998, in which SF_6 gas was filled around the beam source at 6 bar for high voltage insulation. Figure 6 shows the result obtained by the MCNP analysis, total neutron flux along the NB injector axis, from the NB port opening to the beam source. The flux (ϕ) distribution can be correlated to $\phi \sim 1/z^2$ as a function of the distance (z) along the beamline axis. From the analysis, the absorption dose rate in the volume filled with SF_6 insulation gas was estimated. The result showed that 1 Gy/s around the beam source, and 0.1 Gy/s at the interface of the beam source vessel and the transmission line. A similar analysis was extended from the beam source vessel to HV deck along the transmission line, showing the neutron flux attenuated to $\phi \sim 1/z^2$ also in the transmission line (z from the beam source vessel, along the transmission line axis). Then the dose rate was estimated to be 0.01 Gy/s at the HV deck.

Under the irradiation, the SF_6 gas molecules are to be ionized. Note that there is a high electric field in the gas, between the beam source at –1 MV and the vessel wall at

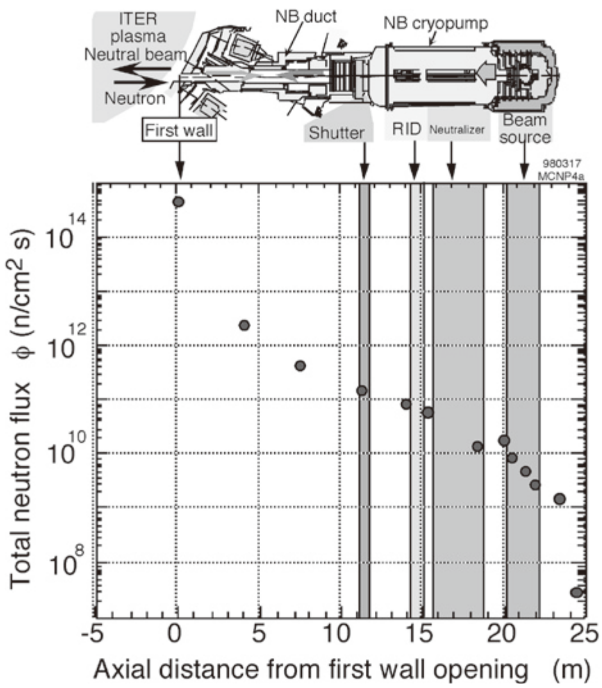

Fig. 6 The total neutron flux along the NB injector axis, from the NB port opening to the beam source, obtained by the MCNP analysis.

ground potential. And hence, generated ions and electrons are attracted to negative (beam source) and positive (vessel wall) electrode, respectively. This is the radiation-induced conductivity (RIC), and electric current is to be flowed in the gas, just like in an ionisation chamber.

RIC in the ITER relevant condition has been well characterized by the EU [16] and the JA [17] Home Teams. The analyses revealed that the RIC current in SF_6 gas around the beam source was ~1 ampere. And having 1 MV potential difference between the beam source and the vessel, the power dissipation in the gas was anticipated to reach 1 MW. Dissipation of such high power in the gas is not acceptable, primarily for efficiency of the NB system. And secondly from engineering design point of view, heat removal system for such high power in gas would require huge heat exchanger. Therefore a vacuum insulated beam source (VIBS [9]) was proposed instead of the original gas insulated design.

Figure 7 shows an illustration of the vacuum insulated beam source and the HV bushing. The ITER primary vacuum, from the torus vacuum vessel, extends through the beamline and then to the beam source. The HV bushing forms a part of primary vacuum boundary above the beam source. Since the dose rate, and hence the RIC current were estimated to be one order of magnitude less in the transmission line, SF_6 gas was utilized for the high voltage insulation in the transmission line and power supplies upstream to achieve a compact design.

The HV bushing is a double layered, stack of five insulator rings, the inner rings made of alumina (Al_2O_3) ceramic and the outer with fiber-reinforced epoxy. The interspace between two layers of rings are filled with dry air at 10 bar, which act as a "guard gas" to prevent leakage of SF_6 outside to the ITER primary vacuum inside. The HV bushing allows penetration of services, such as electric power at various potential, cooling water etc., from the transmission line to the beam source.

The beam source is installed in the beam source vessel under vacuum. For the high voltage (–1 MV) applied to the beam source, a conventional "clump" theory [18] was applied to the vacuum insulation design, in which the sustainable voltage is proportional to square root of vacuum insulation distance. For example, the design of the accelerator allows direct line of sight all around the beam source at –1 MV potential to the vessel wall at ground. The insulation distance in vacuum was designed to be more than 0.4 m around the beam source to the vessel. By inserting five grids at intermediate potential (every 200 kV), the gap length between each grid is reduced for compact design of the accelerator. This multi-grid concept is expected to be effective to prevent discharge (breakdown) occurred in one vacuum gap to propagate to the others.

Since the ion source is mounted directly on the accelerator, the gas fed in the source is pumped through the accelerator. And thus the pressure in and around the beam source is kept high during operation. The pressure estimated by a Monte Carlo analysis [19] ranges 0.02 to 0.1 Pa, which is high enough to cause glow (gas) discharge in the accelerator. In the ITER NB design, the Paschen law for the glow discharge has been considered in addition to the clump theory.

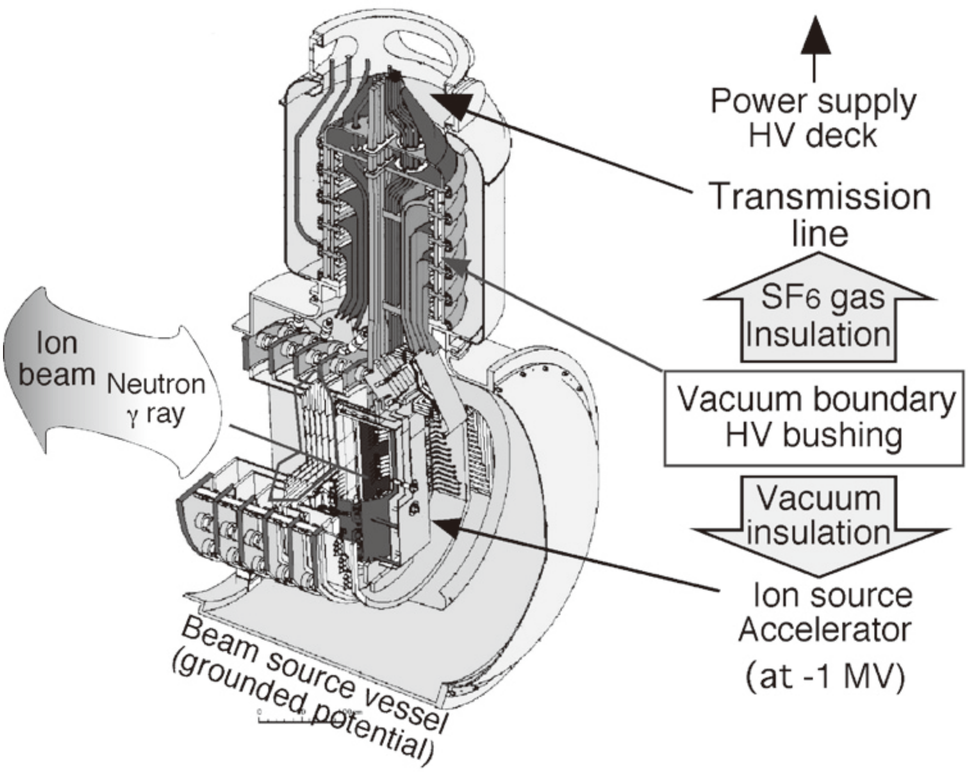

Fig. 7 An isometric illustration of the vacuum insulated beam source (VIBS) and the HV bushing for the ITER NB system.

4.5 Summary

The following features of the present ITER NB injector was described:

- The neutraliser interior is divided to form four vertical elongated channels, each width of typically 100 mm. The number of channels, and hence the channel width, was optimized as a compromise of two competing requirements, reduction of both gas flow rate to achieve less reionisation loss and direct interception of the beams in the narrow channels. As the result, the axial length of beamline (accelerator exit to the NB port opening) was shorten to be 23.4 m, so as to mitigate cost impact to the building.
- Three-dimensional analyses of neutron transport clarified the radiation environment inside the NB beamline. The result verified feasibility of functional materials, such as permanent magnets and ceramic insulators. However, it was revealed that SF_6 gas is not applicable to the high voltage insulation. Hence the present ITER NB design utilizes vacuum for the high voltage insulation.

In particular the latter required considerable design change and new R&D on the vacuum insulation of the accelerator. Fortunately the R&D is successful as described in chapter 5 of this article. Thus the design of the ITER NB system was completed and ready for its construction.

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