ITER NEUTRAL BEAM SYSTEM*

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Abstract

The Neutral Beam (NB) system for the International Thermonuclear Experimental Reactor (ITER) has reached a high degree of integration with the tokamak and with the rest of the plant. Operational requirements and maintainability have been considered in the design. The paper considers the integration with the tokamak, discusses design improvements which appear necessary and finally notes R&D progress in key areas.

1. INTRODUCTION

In the final design of ITER [1, 2], 100 MW of power for Heating and Current Drive (H&CD) is required and is to be provided by at least two of the four possible H&CD systems under study: ion cyclotron, electron cyclotron, lower hybrid and neutral beams.

The ITER NB system is designed to deliver 50 MW of power to the ITER plasma. The beam energy, 1 MeV, has been chosen as a reasonable compromise between the heating, the current drive and the plasma rotation requirements. Three adjacent ports are allocated to NB and three injectors are foreseen, each with a power capability of 16.7 MW. The beam tangency radius (to the toroidal plasma) is about 6.5 m. Deuterium negative ions are produced in a caesiated arc discharge source. Filaments are used as a cathode. This technology is already used in JT-60U [3] where recently 18.5 A, H^-, at 360 kV and 14.3 A, D^-, at 380 kV have been achieved. In both cases the quoted current corresponds to the accelerated ions from one source.

The design of the ITER NB system has been described in [4]. The main concepts and the basic design of the main components have not changed. This paper will concentrate on the progress made in the design and its most relevant modifications and the integration with the tokamak. Finally, a short report is given on recent R&D results on the most critical components; the beam source, the accelerator, the large insulators and the plasma neutraliser.

2. INTEGRATION WITH THE TOKAMAK

The integration of the NB system with the tokamak has progressed, in particular in the critical area of the NB duct (shown in Fig. 1) which is the main interface with the vacuum vessel and the blanket. The beam passes through an equatorial port, the structure of which has been modified in order to provide a shielding thickness not less than 450 mm (stainless steel 75 %, water 25 %: shells are included) that reduces the neutron fluence to the cryostat wall and keeps the dose rate below 300 μSv/h. This value allows the development of local shielding solutions for a few specific maintenance areas close to the NB duct, which comply with ALARA personnel exposure criteria. Based on this analysis, the port structure was improved slightly to make the closure plate thicker. This was analysed by the JA Home Team, which showed a reduction in dose rate to about 150 μSv/h. The neutronic calculations have also confirmed that the nuclear heating of the toroidal field coils are well below the design limits.

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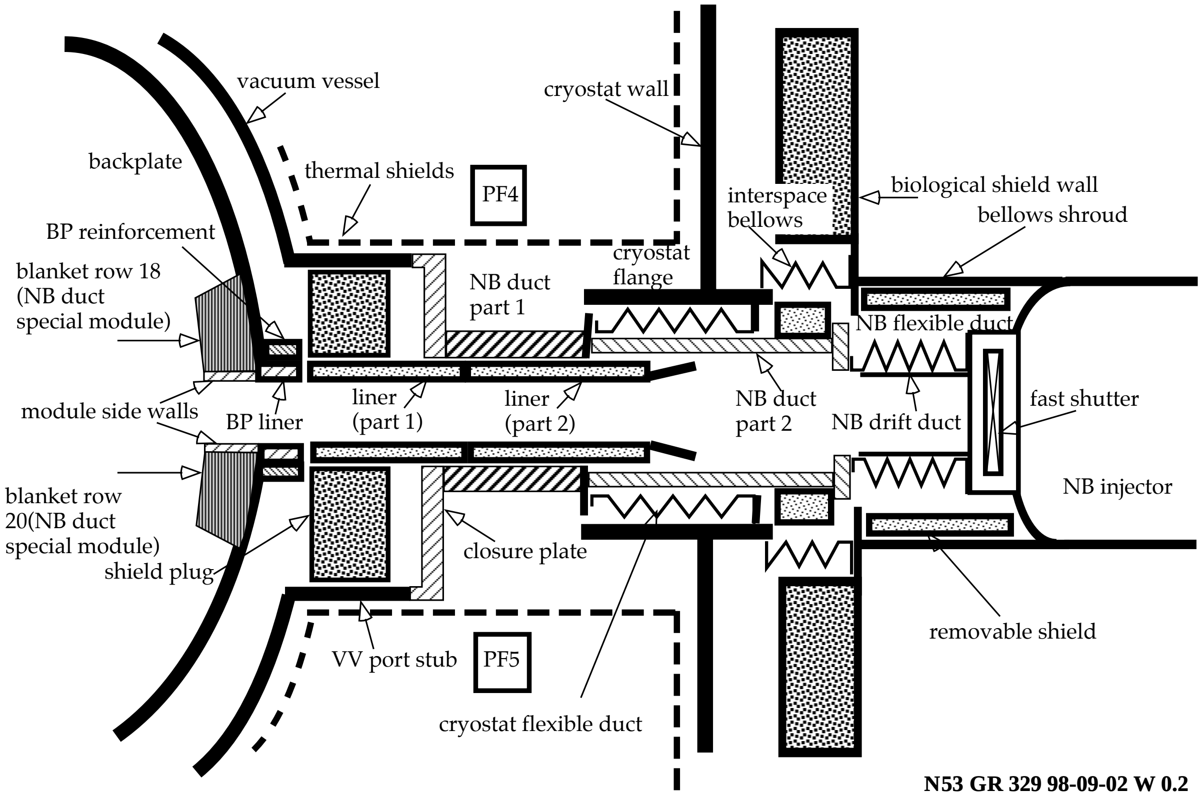

FIG. 1. NB Duct illustrative scheme

The components associated with vacuum and pressure confinement are distinct from those receiving power deposited from beam re-ionisation and interception, plasma radiation and the largest part of nuclear heating. Power removal is entrusted to the liner (two parts) and to the NB drift duct, with the advantages of a thermohydraulic design adapted to the beam power deposition profile and of an installation procedure simplified by manageable sizes and weights. The port structure and the liner are cooled with forced circulation using water derived from the vacuum vessel Primary Heat Transfer System (PHTS), while the NB drift duct is cooled by the NB PHTS.

The exit of the beam through the tokamak first wall (580 mm width, 915 mm height) fits the geometry of the blanket segmentation in the equatorial port area. The blanket modules (NB duct special modules) surrounding the beam exit include module side walls suitable for the power deposition due to nuclear heating, plasma radiation and beam interception. The dimensions and weight of the modules are chosen so that the maintenance removal procedure used for all other blanket modules (in-vessel vehicle and manipulator) applies also to them. The backplate is locally reinforced to sustain the electromagnetic loads and provides the mechanical and hydraulic connections for the blanket modules.

A bellows (the NB flexible duct) connects the NB duct to the injector vessel. The design of this bellows takes into account the beam size, the thermal expansion, the assembly tolerances and the relative displacements occurring during normal operation and off-normal events.

3. DESIGN MODIFICATIONS

3.1. Radiation Induced Conductivity (RIC)

Radiation analyses in and around the NB injectors have been carried out, and the results are reported in [5] where, in addition, the consequences for the NB injector system materials have been assessed. In particular RIC in the compressed gas used for insulation is expected to cause leakage currents and therefore power losses both around the beam source and in the section of the transmission line between the ion source and the HV deck. The estimated losses due to RIC, with nitrogen at about 6 bar, are > 100 kW around the beam source and ~ 70 kW in the transmission line. Removal of such powers is considered too complicated from the gas around the source but is thought feasible from the gas in the transmission line. To overcome the problem of RIC, a Vacuum Insulated Beam Source (VIBS) has been considered: the design criteria for vacuum insulation and the VIBS design are described in [6]. The concept is shown in Fig. 2: the boundary between the vacuum insulation and the compressed gas (nitrogen ~ 6 bar) insulation is provided by the High Voltage (HV) bushing that becomes also the first confinement boundary of the tokamak. Fig. 2 shows the Multi Aperture Multi Grid (MAMuG) beam source (the reference design) supported from the front flange of the beam source vacuum vessel, but the large cylindrical insulators (diameter 2.7 m) are replaced with post insulators. Cylindrical insulators are still required in the HV bushing but their diameter is reduced to 1.8 m. Several insulating materials are being considered for this purpose [6], among others, an industrial type of porcelain with which cylinders of 1.2 m diameter are already feasible. The electrostatic analyses performed so far indicate that the VIBS satisfies the design criteria for vacuum insulation mentioned above. The VIBS design can be easily modified to accept the single aperture, single gap (SINGAP) accelerator (considered a possible design improvement).

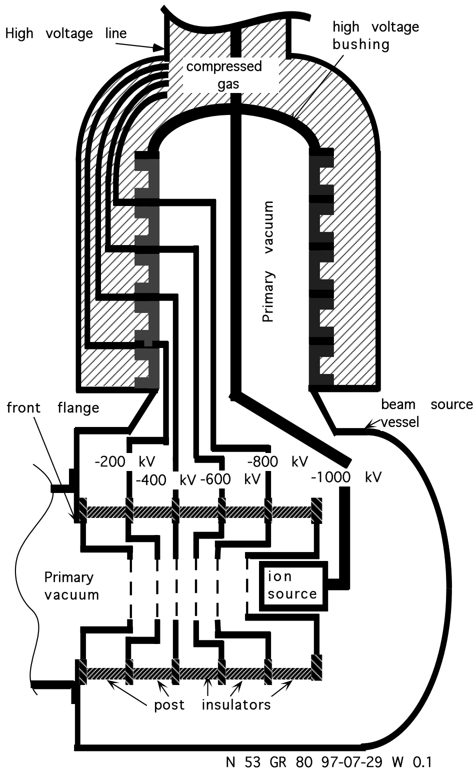

FIG. 2. VIBS illustrative scheme

3.2. Magnetic Field Reduction

The Magnetic Field Reduction System has also been modified. The previous design aimed to compensate the vertical component of the field produced by the tokamak in the injector volume, but the large radial component still present was able to saturate the iron and partly penetrate the injector. The three compensation coils [4] have been replaced with six which are able to remove the flux from the injector volume, in particular the innermost coil, above the injector, is inclined so that its axis is about parallel to the tokamak field lines. The iron shield is less saturated than with the previous design and the field requirements in the injector volume are met without the inner layer of mu-metal previously foreseen.

4. PROGRESS IN THE R&D

The R&D performed by the three Home Teams (EU, JA, RF) working on this field has made good progress. The development programme has been highly integrated and the close cooperation among the three Home Teams has allowed duplications to be avoided, the only exception being the accelerator for which the development of two alternatives (MAMuG and SINGAP) mentioned above is considered prudent.

The JA Home Team has continued the development of the large, low pressure (about 0.3 Pa), “Kamaboko” source and of the MAMuG accelerator [7]. As regards the accelerator, after several modifications to the test bed and to the experimental set-up, and improvements to the conditioning procedures, the nominal voltage 1 MV has been achieved with a drain current of 25 mA for 1 s, with H^-. In addition 180 mA, H^-, have been accelerated at 900 kV.

The EU Home Team has continued the development of the SINGAP accelerator [8]: 43 mA of H^- ions at 860 kV, and 106 mA of D^- ions at 630 kV have been achieved for 1 s. Higher voltages could not be reached because of failures in 2 of the 9 insulators making up the 1 MV bushing. New insulators have been built and the tests should soon restart. Porcelain insulators have been built by EU Industry to be used in the SINGAP experiment and studies are in progress on large diameter, ITER-relevant, insulators.

These results are very encouraging, as it should now be possible to increase the accelerated current, at full energy (1 MV), for 2-3 s, towards the target 0.5 A (with current density > 280 A/m^2, H^-) for the JA Home Team, and towards the target 0.1 A (with current density > 200 A/m^2, D^-) for the EU Home Team. Reliability should be demonstrated by repeating the same pulse with these parameters many times (100-1000).

The SINGAP accelerator is expected to be simpler and cheaper than the MAMuG accelerator which, instead, is more conservative: development should continue on both since none has reached the target values mentioned above. The deadline of October 2000 has been agreed with both Home Teams as a reasonable date by which these target values should be met, then the design will be finalized on the agreed accelerator.

Two Home Teams (JA & EU) are also working together on the development of a steady-state, low pressure source for ITER, in the framework of the ITER R&D. Recently, using an actively-cooled plasma grid, 240 A/m^2 of H^- ions and 200 A/m^2 of D^- ions have been achieved with a pressure of about 0.3 Pa and a pulse duration of 100 s. The EU Home Team has demonstrated 1000 s operation using the "ITER model source" (KAMABOKO III) at ITER-relevant parameters (pressure and power density, H_2 and D_2) with the plasma grid temperature being held constant at between 200 °C and 350 °C, as required for efficient negative ion production.

Radio frequency driven ion sources are used for positive ion production. The EU Home Team has started R&D to produce negative ions with this method. Preliminary experiments have shown promising results even if high pressure is used (above 1 Pa). This development could simplify the source, reduce its cost and its routine maintenance by avoiding the use of filaments.

The RF Home Team has continued R&D on a plasma neutraliser [9] that would allow an increase of the neutralisation efficiency up to 80 %, as compared to 60 % achievable with the reference gas neutraliser [4]. If the same power is assumed at the output of the injector, the plasma neutraliser could allow a reduction in the required negative beam current extracted from the source (smaller beam source and reduced power supply requirements), and therefore a reduction in the power deposited in the residual ion dump and the total gas input to the injector. The RF Home Team has built an experimental plasma neutraliser, PNX-U, described in [9]. Recently a hydrogen plasma has been produced using radio frequency sources (50 kW at 7 GHz): the plasma density in the central region is 3-5 x 10^{17} m^{-3} and the target thickness is 8-12 x 10^{17} m^{-2} (the design value for an ITER plasma neutraliser is > 2 x 10^{19} m^{-2}). Experiments with a negative ion beam will start soon. The design of the next experiment is in progress, however, its construction will start only when the agreed target results for the PNX-U experiment are met.

5. CONCLUSIONS

A fully integrated design of the three NB injectors with the tokamak has been completed. All required auxiliary systems, not described in this paper, are fully defined and consistent with the overall project. To achieve this result a lot of care has been dedicated to detailed development as reported in [1]. Substantial progress has been made on the R&D but more effort is required to complete the programme defined jointly by the Home Teams and the JCT in the Spring 1994. Two more years of work are required on both the 1 MV test beds but the experience acquired so far gives confidence that the required results will be achieved within the allocated time.

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