Negative Ion Based Heating and Diagnostic Neutral Beams for ITER

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Abstract. To meet the requirements of the four operating and one start-up scenarios foreseen in the International Tokamak Experimental Reactor (ITER) a flexible heating mix will be required, which has to include a reliable contribution from neutral beams. The current baseline of ITER foresees 2 Heating Neutral Beam (HNB) systems based on negative ion technology, each operating at 1 MeV 40 A D^- ions, and each capable of delivering up to 16.7 MW of D^0 to the ITER plasma. A 3rd HNB injector is foreseen as an upgrade option. In addition a dedicated Diagnostic Neutral Beam (DNB) injecting 100 keV 60 A of negative hydrogen ions will be available for charge exchange resonant spectroscopy (CXRS). The significant R&D effort necessary to meet the design requirements will be provided in the Neutral Beam Test Facility (NBTF), which is to be constructed in Padua, Italy. This paper gives an overview of the current status of the neutral beam (NB) systems and the chosen configuration. The ongoing integration effort into the ITER plant is highlighted and open interface issues are identified. It is shown how installation and maintenance logistics has influenced the design. ITER operating scenarios are briefly discussed, including start-up and commissioning. For example it is now envisaged to have a low current hydrogen phase of ITER operations, essentially for commissioning of the many auxiliary systems used on ITER. The low current limits the achievable plasma density, and hence the NB energy due to shine through limitations. Therefore a possible reconfiguration of the auxiliary heating systems is now being discussed. Other NB related issues identified by the ongoing design review process are emphasized and possible impact on the implementations of the HNB and DNB systems is indicated.

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Introduction

In the current ITER baseline, four operating scenarios are foreseen with up to 73MW of auxiliary heating power using a variable heating mix (TABLE 1). In all scenarios a substantial contribution (up to 45%) will come from neutral beam injection. The scenarios are currently being re-assessed, and corrections might be necessary to take account of recent results in scaling and modelling. Flexibility

TABLE 1. DESIGN SCENARIOS FOR ITER OPERATION [1]

	Start up	**Scenario 1:** Elmy Hmode I	**Scenario 2:** Elmy HMode II	**Scenario 3:** Hybrid	**Scenario 4:** Steady state
	Power [MW]	Power [MW]	Power [MW]	Power [MW]	Power [MW]
NB	33	33	50	50	50
IC	20	40	20	40	20
EC	20	40	40	40	20
LH	0	20	20	0	40
Total	73	133	130	130	130

and upgradeability is therefore an important factor in the design of the heating systems. In the past modelling effort has understandably focussed on the burn phases of ITER, but with the start of construction on the horizon, start-up and commissioning scenarios will have to be studied and prepared in more detail. Currently it is foreseen to end the ITER construction phase with the demonstration of the first plasma at 2MA. This will be followed by several years of hydrogen operation, which should allow plasma commissioning and testing of all major components. Access to the H-Mode should be assured to allow in particular full power testing of the divertor components.

The Heating Neutral Beams for ITER

The current baseline of ITER includes 2 Heating Neutral Beam (HNB) systems based on negative ion technology, each operating at 1 MeV 40 A D^- ions and delivering up to16.7 MW to the ITER plasma. The current timeline foresees the first neutral beam injector to be operational in 2016, the second in 2018. A 3rd HNB injector is foreseen as an upgrade option to meet the requirements of scenarios 2 to 4. Each HNB injector (Fig. 1) consists of an RF ion source and a 5 stage accelerator, a neutraliser, a residual ion dump (RID) and a calorimeter. The latter doubles up as a moveable beam dump, that can be introduced into the beam path downstream of the RID and

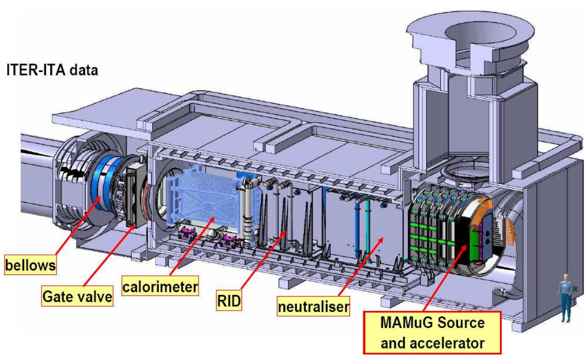

Figure 1 Schematic of the HNB injector

allows the injectors to be commissioned and tested independently of plasma operation. Cryo-pumps are maintaining the appropriate vacuum level inside the vacuum confinement. The primary vacuum confinement consists of the beam source vessel (BSV) and the beam-line vessel (BLV), which contain the beam source and the beam-line components respectively (see also Fig. 3). The high voltage (HV) bushing allows also the passage of coolant and gas lines from the SF6 insulated transmission line to the beam source. To shield the beam line from the resident magnetic field in ITER, a ferromagnetic shielding vessel and active compensating coils are foreseen.

The ITER baseline has been modified only recently to accept the RF ion source, based on the Garching design (Fig. 2) [2], as the reference ion source for ITER. The main advantages demonstrated are significantly reduced caesium consumption and a longer filament lifetime. This translates into a much improved maintainability of the beam source as the number of maintenance interventions will be significantly reduced. The first 1hour long stable pulse has also recently been demonstrated in Garching [3] with 120A/m^2 extracted current.

Table 2 shows the baseline operating parameters of the ITER NB systems. The required parameters (e.g. 1MeV 200A/m2 for the HNB) have not been met simultaneously in today's NB testbeds. At the moment two accelerator concepts are being developed in parallel, the Single Gap, Single Aperture (SINGAP) in the EU

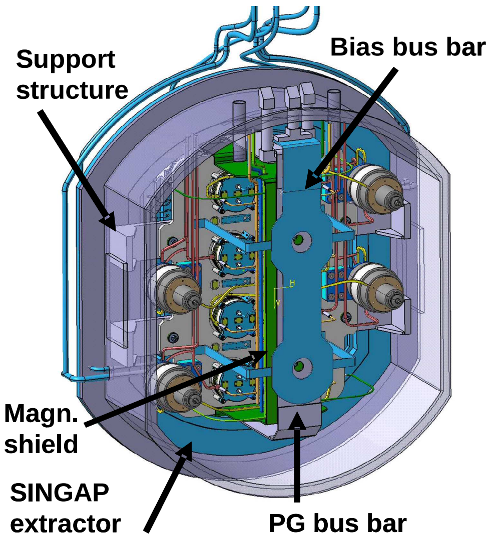

Figure 2 The RF Source for ITER

TABLE 2. NEUTRAL BEAM SPECIFICATIONS

	HNB	DNB
Beam Power	16.7 MW	3.6MW excl. duct losses
Beam Energy	1 MeV (D^-) / 870 keV (H^-)	100 keV (H^-)
Extracted Current	40 A (D) / 46 A (H^-)	60 A (H^-)
Current density	200 A/m^2 (D^-) / 300 A/m^2 (H^-)	300 A/m^2
Current density uniformity	± 10%	± 10%
Divergence	10mrad	7 mrad
Pulse Length	≤ 3600s	5Hz. 1/6 of ITER pulse

and the Multi Aperture Multi Grid accelerator (MAMuG) in Japan [4, 5]. It is expected that a decision on the design option for the ITER accelerator can be taken beginning of 2008. The HNB power supplies have been designed to be compatible with both accelerator options should the decision have to be corrected in the future.

The Diagnostic Neutral Beam for ITER

The only diagnostic capable of providing absolute measurements of He density profiles in the centre of the ITER plasma and thereby monitoring the He ash, is the charge exchange recombination spectroscopy (CXRS). CXRS necessitates a dedicated diagnostic neutral beam. To concentrate R&D effort it was decided that the DNB should follow the HNB concept wherever possible (Figure 3). The specifications of the DNB are also listed in Table 2, demonstrating that some DNB performance parameters are even more stringent than those for the HNB. Source uniformity and beam divergence in particular have an important impact on the signal to noise ratio of the diagnostics. The DNB will operate in hydrogen for all ITER plasmas, the target parameter for the divergence is <7mrad. A low divergence is necessary to minimise both the aperture size in the vessel wall and the heat loads in the beam duct. The DNB will be modulated at 5Hz with a duty cycle of ~1/6 mainly limited by technical constraints, namely the fatigue life of the components. The DNB will use the same RF ion source as the HNB, but a simplified accelerator with one acceleration stage as the required voltage is lower (100kV, but note that the extracted current is 60A H^-). The magnetic shielding system will have to be optimised to minimise the divergence. Originally injected radially, the injection angle of the DNB has been reviewed recently to avoid damaging the inner wall below the injection point due to ripple trapped ions. Minor adjustments to the NB cell and repositioning of the DNB allowed a ~6 degree injection angle. Detailed design of the DNB duct upstream is underway, aimed at minimising the heat loads. In parallel the beam optics has been optimised to maximise the throughput. The low beam energy makes operation of the DNB possible even at the low plasma densities achievable with 2MA current. The diagnostic tool can therefore be available for all ITER operating scenarios from the start-up phase onwards.

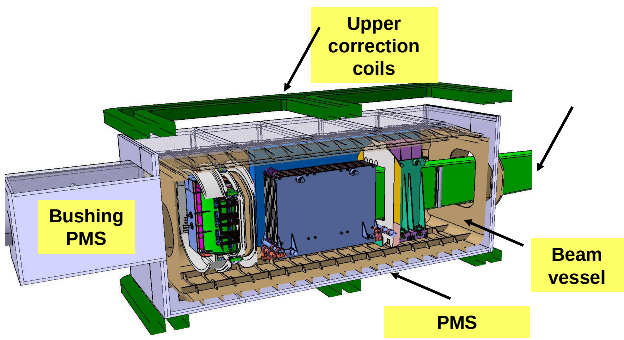

Figure 3 View of the DNB, PMS passive magnetic shield

NB R&D Issues

The ITER NB systems, like all heating systems, will be provided by in kind procurement: the HNBs provided by the EU and Japan, the DNB by India. The ITER International Organization will provide the integration. The requirements for the NB injectors for ITER represent a large step forward from present day injectors. The intensive R&D and integrated testing necessary to meet the ITER design requirements will be provided by the EU (with participation of Japan and India) in the Neutral Beam test facility (NBTF) in Padua, Italy. This testbed will have real 1MeV handling capability and demonstrate the full scale ITER neutral beam. The design of the NBTF facility is under way, low voltage testing expected to start in 2010. Some of the specific topics to be addressed in the NBTF are the homogeneity of the RF ion source; avoidance of uncontrolled breakdowns in the accelerator and control of back-streaming ions. Material fatigue of high heat flux components has to be studied and reliability analysis undertaken. A viable 1MV technology has to be developed including adequate isolation transformers and transmission lines with 1MV holding capability. On ITER beamline diagnostics will be reduced to the necessary minimum for control and feedback purposes, whereas the NBTF will incorporate extensive diagnostic tools, most of which still have to be designed. In parallel to the NBTF, research should be encouraged on a variety of NB topics: exploring alternative ion sources, that can either reduce the caesium consumption even further or use an alternative to caesium; the study of alternative neutraliser concepts; development of diagnostic systems for beam testbeds; basic study of beam plasma interaction and studies aimed at resolving uncertainties in beam optics calculations. This work can be supported by ITER tasks that can be given to industry or laboratories in support of the ITER R&D program.

Plant Integration and Integration Issues

The NB systems are installed in the neutral beam cell, which occupies most of the northern part of the equatorial level of the tokamak hall. The injectors are shown in Fig. 3, including the space reservation for the optional 3rd injector on the right hand side. Also shown is the current proposal for the remote handling (RH) monorails. HNB1, sharing the port with the DNB, and HNB2 will be installed on equatorial ports 4 and 5. The third HNB will be installed in port 6. The injectors are connected directly to the torus vacuum via the neutral beam ducts, which will be equipped with a suitable liner to withstand the power load due to the beam particles striking the wall either due to the beam divergence or deflection from the residual magnetic field. Passive magnetic shields are foreseen to protect the injector vessels from the tokamak magnetic field. They will also act as radiation shields for the NB cell. In addition active correction coils are necessary to reduce the perturbation of the magnetic field in ITER.

Installation and maintenance logistics have necessitated several changes from the original design. Man access to the neutral beam cell will be severely restricted because of the high activation. Maintenance and interventions on the beamline components have to be carried out by remote handling (RH). A vertical maintenance scheme has been developed where the beamline components are handled via an overhead crane. The beamline and shielding vessels, as well as the cryo-pumps, had to be re-designed to rectangular shape with RH-able removable lids. Another major change to the NB design concerned the modification of the NB power supplies. Using air-insulation and re-locating the high voltage deck outside the tokamak building allows easier access to electronic control equipment [6].

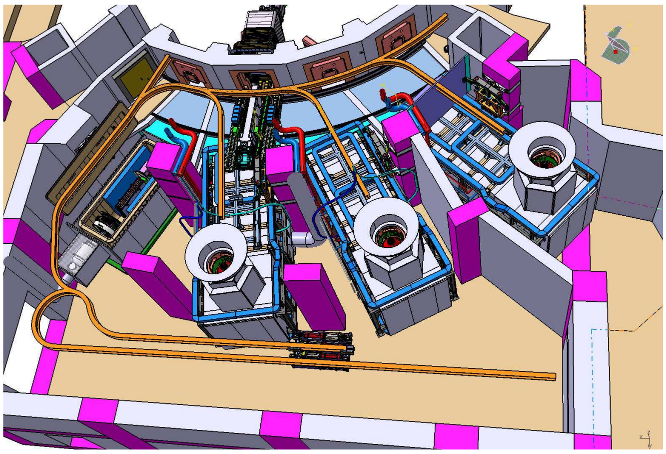

Figure 3 Lay-out of the neutral beam cell showing (left to right) the DNB and 2 (+1 optional 3rd) HNB injectors.

As the NB injectors are directly coupled to the tokamak and represent the extension of the first confinement barrier for radioactive materials, an extra absolute valve was added to the existing fast shutter. Detailed design of the beam ducts is ongoing, with the HNB-DNB cross-over representing a technically challenging engineering task.

The NB systems will be installed through a hatch on the north wall of the ITER building, to be closed once plasma operation starts. Detailed studies of the installation logistics have been undertaken, which have influenced the installation sequence. The large components for HNB 1 and 2 like the beam line vessel and the correction coils will have to be installed in the NB cell for day1 independently of the availability of the beamline components. As the NB cell will become activated during NB and tokamak operation, a wall will be erected separating the area for the 3rd injector from the beam cell to allow installation in a non-activated area. The temporary wall will be torn down after installation.

Start-up issues

It is now expected that ITER will have an extensive hydrogen phase, during which the achievable plasma densities will prevent the neutral beam injection from efficiently deliver power to the plasma at full beam energy. This will lead to an important shine through exceeding the power density limit on the inner wall of the tokamak (P<0.5MW/m2). As installation of additional wall protection seems difficult, it is being assessed if the NB system can be modified to operate at 500keV in the hydrogen phase, upgrading to 1MeV for in the deuterium phase. Operating the NBs at a lower beam energy implies also a lower beam power delivered to the plasma. As concern had already been raised that the originally foreseen 73MW of total heating power would be insufficient to allow access to the H-Mode in hydrogen, it is being assessed if an alternative heating mix can make up for the reduced NB power. As it is not clear to what extend the different heating systems can be interchangeable, an accompanying physics program will help clarify the influence of on- and off-axis power deposition and fast electron tails on the ITER scenarios

Summary and Outlook

ITER is an international collaboration with major contribution coming from fusion laboratories worldwide. The design activities aimed at providing NBs for ITER are progressing and several changes have been accepted into the ITER baseline recently. Both the RF ion source and the air insulated power supply will guarantee better maintainability of the NB system. The R&D necessary for the design of the 1MeV NBs for ITER will be provided by the EU in the NBTF in Padua, with participation of Japan and India. It is planned to have a design freeze on the lay-out of the NB cell and the main components at the beginning of 2008; this will allow to start the detailed design phase. A strong accompanying program in parallel to the dedicated R&D can contribute to shed light on outstanding physics and technology issues. Scaling and benchmarking studies can be performed independent of a full power test bed, and can provide valuable input to the R&D program.

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