

19 Neutral Beam Heating and Current Drive System and Diagnostic Neutral Beam

19.1 Functions, Basic Configuration, and System Boundaries

19.1.1 Function

The general functions of the NB H&CD system are listed in the DRG1, section 2.15.

The function of the diagnostic neutral beam (DNB) injector is to provide the probe beam part of the diagnostic systems to measure:

- local density of thermal alpha particles (helium ash);
- local density of light impurities (Be, C, O, Ne);
- plasma rotation velocity;
- ion temperature.

Specific requirements for each of these measurements are listed in the DRG1, Table 1.12-2 (measurements # 10, 11, 12 and 28).

19.1.2 Basic Configuration

The NB H&CD system consists of two injectors (hereinafter these two injectors are referred to as the heating neutral beams, HNB). The possibility of adding a third injector, with a design identical to the other two HNBS, is retained.

The main components, forming the NB H&CD system and the DNB, are introduced here to allow comprehension of the associated requirements in section 19.2. Each injector consists of the following sub-components:

- the beam source where D^- (or H^-) ions are produced and accelerated;
- the beam-line components including:
 - the neutraliser, where the D^- (or H^-) ions produced by the beam source are converted to neutrals by collisions with D_2 gas;
 - the residual ion dump (RID), where the ions emerging from the neutraliser are deflected onto a set of water-cooled plates;
 - the calorimeter, a moveable beam dump, that can be introduced into the beam path downstream of the RID and allows the injectors to be commissioned and tested independently of plasma operation;
 - the cryogenic pumps, needed to maintain the appropriate vacuum level inside the vacuum confinement;
- the primary vacuum confinement consisting of:
 - the high voltage (HV) bushing, that allows the passage of all the coolant, gas and electrical lines from the gas-insulated transmission line to the beam source, immersed in the primary vacuum;
 - the beam source vessel (BSV) and the beam-line vessel (BLV), that contain respectively the beam source and the beam-line components;
 - the fast shutter that can close the beam-line vessel, avoiding the back-streaming of tritium from the vacuum vessel (VV) to the injector's cryogenic pumps in tokamak operation without beams, and allowing the regeneration of the injector cryogenic pumps with minimum release of gas to the VV;

- the drift duct (DD), that consists of a set of bellows (de-coupling the beam-line vessel from the displacements of the vacuum vessel) and an internal liner intercepting fractionally ionised parts of the beam, deflected by the magnetic field;
- the passive magnetic shield (PMS) that shields the injector volume from the tokamak magnetic field and also acts as a radiation shield for the NB cell;
- the active compensation coils, that together with the passive magnetic shield limit the magnetic field in the injector volume;
- the active correction coil, that reduces the perturbation of the magnetic field in ITER, mainly the error field on the $q = 2$ surface, due to the presence of the NB H&CD system and of the DNB;
- the duct box enclosing the fast shutter and the drift duct.

19.1.3 System Boundaries

The main boundaries of the NB H&CD system are the following:

- on the vacuum vessel side:
 - the flanges connecting the drift ducts of the injectors and the NB ducts on ports # 4 and # 5;
 - the flanges connecting the duct boxes to the cryostat flanges on ports # 4 and # 5;
 - the flanges connecting the duct boxes to the biological shield wall flanges corresponding to ports # 4 and # 5;
- on the power supplies side:
 - the flanges connecting the HV bushing and the transmission line.

The boundaries of the DNB are:

- on the vacuum vessel side:
 - the flange connecting the drift duct of the DNB injector and the NB duct on port # 4;
 - the flange connecting the duct box to the cryostat flange on port # 4;
 - the flange connecting the duct box to the biological shield wall flange corresponding to port # 4;
- on the power supplies side:
 - the flange connecting the DNB HV bushing and the DNB transmission line.

19.2 Specific System-Internal Requirements

The system internal requirements are, in general, the same for the HNBS as for the DNB. In the following, requirements for the DNB are stated only when they differ from the HNB requirements.

19.2.1 General Requirements

19.2.1.1 NB H&CD System

The main parameters of the NB H&CD system are summarised in the DRG1, section 1.10, Table 1.10-1. The general requirements for the NB H&CD system are the following:

- the NB H&CD shall be designed to provide 33 MW, steady-state, auxiliary heating power to the plasma by injection of deuterium neutrals; the NB H&CD shall use two equatorial ports of the vacuum vessel and therefore two heating injectors (based on negative ions), each providing 16.7 MW of power at the energy of 1 MeV;
- the NB H&CD shall be designed to inject also hydrogen, up to 27 MW at the energy of 800 keV, without design modifications of the beam source and beam-line components;
- the beam axis of injection shall allow on-axis and off-axis current drive by tangential injection; consequently, the system shall allow two different angles of injection in the vertical plane;
- space will be allocated to retain the possibility for the installation of a third H&CD injector to increase the total NB H&CD power to 50 MW.

19.2.1.2 DNB Injector

The DNB shall provide a hydrogen beam with the following parameters:

- 24 A equivalent H^0 current at 100 kV energy within a footprint 30 cm x 30 cm, at a radial position in the plasma corresponding to $r/a = 0.3$;
- pulsed operation (1 to 3 s) with trains of pulses at 5 Hz (100 ms beam on/100 ms beam off) and 20 s dwell time, between two subsequent train of pulses.

19.2.2 **Layout**

The NB H&CD system and DNB layout shall be developed according to the following requirements:

- the two injectors of the NB H&CD system shall be connected by (tangential) ducts to the vacuum vessel at ports # 4 and # 5. The optional third injector shall be connected by a (tangential) duct on port # 6. The DNB injector will share the use of port # 4 with one of the injectors of the NB H&CD system and shall be connected by a (radial) duct to the vacuum vessel;
- the NB H&CD system beam aiming shall be such to provide co-injection (beam direction same as the plasma current direction) for the reference current directionality defined in the DRG1, section 1.6;
- the beam aiming and the beam dimensions shall be consistent with the openings of the NB duct and the blanket segmentation, including the clearances for beam misalignment, duct movements during operation, assembly and manufacturing tolerances;
- the plasma-facing components of the RF H&CD system port plugs and test blanket modules shall not be in the line of sight of a neutral beam (see the DRG1, section 1.10);
- the NB H&CD system and the DNB, outside the bioshield surrounding the cryostat, shall be fully contained inside one single volume, referred to as the NB cell;
- the layout of the NB H&CD system and the DNB shall be compatible with the use of the upper ports # 4, 5, 6 and 7, which have to be accessed for maintenance through the NB cell.

19.2.3 **Structural**

The structural requirements can be classified as follows:

- normal operation;
- over-pressure protection;
- investment protection.

19.2.3.1 Normal Operation Requirements

These requirements derive from the structural loads foreseen in the normal operation of the system. All the components forming the primary vacuum confinement shall be designed for the combination of:

- the external pressure of 0.1 MPa (absolute), with the exception of the HV bushings, that shall be designed for the external pressure of the insulation gas;
- the weight of the components supported by the primary vacuum boundary;
- the operation displacements (only for the bellows connecting the injectors to the NB duct).

The design shall include the fatigue verification for:

- the number of evacuation/pressurisation cycles consistent with tokamak operation and the maintenance schedule;
- the number of operation displacements at the NB duct / drift duct interface flange (VV displacements due to thermal expansion, VV supports displacement, electromagnetic forces, etc).

The alignment of the beam source and of the beam-line components shall be done at atmospheric pressure and at room temperature. For normal operation loads, the deformation of the primary vacuum confinement, with respect to alignment conditions, shall be calculated and verified to remain within the prescribed limits.

The neutraliser, the RID and the calorimeter (high heat flux components) shall be designed for:

- normal operation coolant parameters;
- maximum power and power density.

The design shall prove a thermal fatigue life consistent with the total number of pulses/pulse duration foreseen by ITER operation and by the commissioning and testing of the system.

The thermal fatigue life cycles shall include the effect of power supply switch-off/switch-on at the occurrence of an electrical breakdown. For the DNB, the additional thermal fatigue due to the pulse operation mode shall be taken into account.

The supports of the passive magnetic shielding and of the active compensation coils are to be designed for the forces deriving from magnetic field variations during normal operation and disruptions.

19.2.3.2 Over-pressure Protection Requirements

All the components forming part of the primary confinement barrier with respect to radioactive material coming from the torus must be designed for:

- an over-pressurisation accident due to large coolant leak in the vacuum vessel with maximum absolute pressure 0.20 MPa;
- seismic load case SL-2¹.

¹ DRG1 – section 5.1

19.2.3.3 Investment Protection Requirements

These requirements are those to retain the integrity of the NB H&CD system and of the DNB under off-normal events:

- the beam source and the beam-line components shall be designed to withstand, without damage, an SL-1 seismic load case;
- the high heat flux components of the beam-line shall be designed to withstand, without damage, the increased power due to the loss of neutralisation or loss of deflection voltage, for the time required for fault detection and beam switch-off.

19.2.4 **Mechanical**

The mechanical requirements deriving from structural functions are dealt with in section 19.2.3.

Additional mechanical requirements are:

- the design shall allow the tilting of the beam source in the vertical plane, within two extreme positions corresponding to the on-axis and off-axis injection positions (see section 19.2.1.1.) The supports, the tilting mechanism and the electrical, hydraulic and gas connections to the beam source shall be designed for a maximum number of 100 changes of the beam source alignment in the vertical plane;
- the beam-line components shall be mounted on rails via devices that allow the misalignment due to assembly tolerances and support deformations to be recovered;
- the system shall be subdivided in components to be assembled on-site, whose maximum dimensions and weights are consistent with the available access route;
- the design of the DNB shall use, to the maximum possible extent, the same components and the same maintenance approach used for the HNBs.

19.2.5 **Vacuum**

19.2.5.1 Allowable Leak Rates

A global leak rate is specified for the NB H&CD system and the DNB primary vacuum confinement¹. Individual leak rates limits for each component shall be specified consistent with the global allowance.

As a rule, welded seals are foreseen for the primary vacuum confinement. For all U-lip vacuum seals to be welded with RH equipment, design provisions shall be included allowing the in-situ leak tests. For full-penetration structural welds, no in-situ leak test is required. On detection of a leak, an independent leak test of the beam source and of each of the beam-line components shall be possible.

19.2.5.2 Vacuum Pumping

The vacuum pumping is provided by a set of cryogenic pumps similar in design concept to the torus cryogenic pumps. The requirements of pumping speed and regeneration time for the cryogenic pumps are given in the DRG1, Table 1.24-1.

¹ ITER vacuum design handbook (VDH), section 3.1

The evacuation of the injectors prior to cool-down and the regeneration of the cryogenic pumps to a schedule (provided by the vacuum pumping and fuelling system) shall be compatible with the operation of the NB H&CD system and of the DNB.

19.2.5.3 Gas Fuelling

The gas fuelling rate, gas inlet pressure and gas purity, for the NB H&CD system and for the DNB injector are specified in the DRG1, Table 1.25-8.

19.2.6 **Thermohydraulic**

The electrical power entering the NB H&CD system and the DNB is only partially converted in neutral beam power delivered to the ITER plasma. The remaining part is lost and exhausted by the NB injector primary heat transfer system (PHTS) (primary loop) and eventually by the NB heat rejection system (secondary loop).

The NB PHTS is divided in three circuits:

- the low voltage circuit that serves the beam line components;
- the high voltage circuit that serves the accelerator and extractor;
- the high voltage circuit that serves the arc chamber of the ion source.

This subdivision allows the use of a low inlet temperature for the ion source ($\sim 20^{\circ}\text{C}$) that is needed to keep the average temperature of the arc chamber wall below 40°C . In this way the consumption of caesium, by evaporation, is kept within reasonable limits.

In addition, for each injector, component cooling water is supplied to the active compensation/correction coils (ACCC), which are located outside the primary boundary.

The overall thermohydraulic requirements for the NB PHTS are given in Table 14-1 and Table 14-3 respectively and in section 14.2.2.1. The water chemistry requirements for the NB PHTS are specified in section 14.2.2.2 and in Table 14-9.

The draining and drying of each injector shall be possible independently. The segregation of the hydraulic circuit of each of the beam line components shall be possible, to allow independent leak tests.

19.2.7 **Electromagnetic**

The stray magnetic field from ITER is above the values required for good beam source performance, and to avoid beam deflection and beam divergence increase. Therefore the stray field has to be reduced by a dedicated magnetic field reduction system. The magnetic field reduction system must not result in a disturbance of the ITER plasma confining fields above the prescribed limits (see the DRG1, sections 1.7 and 1.9).

19.2.8 **Electrical**

A set of reference design criteria for the electrostatic design of the beam source and the HV bushing shall be developed based on the review of experimental data on vacuum and pressurised gas insulation. Reduction of the insulating properties of material and insulation

media as result of irradiation will be taken into account using appropriate safety factors.

The selection of the insulating materials and pressurised insulating gases must take into account their levels of RIC (radiation induced conductivity) and RIED (radiation induced electric degradation) under the relevant neutron and ionising radiation fluxes. Provisions shall be included, as necessary, for the removal of the power lost in the insulated gas as a consequence of the RIC and associated leakage currents.

19.2.9 Nuclear and Radiation

The NB H&CD system and the DNB shall have a nuclear shielding to limit, within prescribed values (see below):

- the nuclear heating, damage to the insulation and to the copper stabiliser of the superconducting magnets, see the DRG1, Table 1.16-1;
- the activation of materials in the cryostat structures surrounding the NB duct. This to reduce doses, at the relevant positions for hands-on in-cryostat maintenance, below 100 $\mu\text{Sv/h}$ after 10^6 s from the shutdown of DT plasma operation;
- the activation of the NB cell, so as to have, within the NB cell, dose levels < 100 $\mu\text{Sv/h}$ after 10^6 s from the shutdown of DT plasma operation; this allows personnel access for limited hands-on maintenance;
- the dose levels in the area and volumes surrounding the NB cell, to be < 10 $\mu\text{Sv/h}$ (to allow access after 10^6 s from the shutdown of DT operation);
- the neutron and gamma-ray flux and fluence to the beam source, and the HV bushing and to the HV transmission line within prescribed limits.

19.2.10 Fabrication

The fabrication shall be based, to the largest possible extent, on conventional processes for which the applicable standards shall be specified. Quality assurance (QA) shall follow the "ITER QA Manual" and the QA prescriptions contained in the applicable standard and codes. For all non-conventional processes, a detailed process specification shall be developed by the supplier, on the basis of the fabrication and test of relevant samples and mock-ups.

19.2.11 Materials

Commercial materials shall be utilised to the maximum possible extent. Commercial materials will conform to the applicable standards (ASTM, JIS, DIN) for the definition of their grade, physical, chemical, mechanical and electrical properties and for related testing. All materials, for which a suitable certification from the material supplier is not available, shall be tested to determine the relevant properties, as part of the procurement.

19.2.12 Assembly

The assembly procedure must fulfil the following requirements:

- to ensure the required alignment tolerance of beam-line components among themselves and with respect to reference datum points of the ITER system;
- to be possible within the space allotted in the NB cell (when the NB cell civil structure is fully completed);
- to be subdivided in a number of sub-components and of steps compatible with the maximum sizes and loads of components that can be transported or lifted by the

- equipment available at the ITER site and limited ad-hoc equipment installed for assembly purposes;
- to allow for intermediate vacuum and pressure test of primary vacuum confinement.

19.2.13 Testing

19.2.13.1 Factory Tests

The fabrication shall be subdivided in a number of sub-components allowing independent factory test to the largest possible extent. Special fixtures and test auxiliary equipment shall be used as necessary. In general, the following types of factory tests shall be performed on sub-components or parts of sub-components:

- dimensional checks;
- pressure tests;
- vacuum leak tests;
- vacuum compatibility tests; mechanical tests (fatigue and reliability);
- electrical tests (voltage holding under vacuum / pressurised gas).

19.2.13.2 Weld Tests (onsite)

All on-site welds shall undergo leak test, and non-destructive examination on site as required by the applicable codes and standards. As an intermediate step of the assembly procedure, the vessels forming the primary vacuum confinement of the NB H&CD injectors and of the DNB injector, after the on-site seal welds will be pressure and leak tested.

19.2.13.3 Commissioning

Commissioning of the NB H& CD system and of the DNB will be independent of torus operation. The injectors will be blanked off with a temporary flange on the NB duct side allowing an independent vacuum in the injector and providing the necessary shielding for neutrons and X-rays.

Each of the two NB H&CD injectors and the DNB injector shall be tested to full performance on the calorimeter prior to the final connection to the NB duct.

During testing and commissioning the injectors shall be operated by the ITER command control and data acquisition system (CODAC). The test will include the check of all control software and the efficiency of all interlocks.

19.2.14 Instrumentation

The instrumentation of the NB H&CD system and of the DNB shall include the measurements of:

- temperatures on;
 - neutraliser;
 - RID;
 - calorimeter;
- magnetic field at relevant locations inside the injector's volume;
- residual gas pressure in the injector's volume;

- gas flow for the neutraliser and ion source;
- beam-line components coolant temperature and flow rate;
- insulation gas pressure and temperature (in the transmission line);
- calorimeter position (open/close);
- fast shutter position (open/close);

All measurements of the voltage and current (beam source, RID and active compensation coils) shall be derived from the instrumentation foreseen as part of the NB power supplies.

19.2.15 Control System

The ITER control and data acquisition system (CODAC) is structured in a hierarchy composed of the supervisory control system and individual dedicated plant control subsystems to ensure the integrated control of the whole ITER plant.

Local control cubicles (LCCs) must be provided for the integrated operation of the neutral beam injection power supplies and of the neutral beam injectors. The main functions are:

- real time operation control and monitoring;
- emergency operation requests;
- personnel safety interlocks.

Each major component/subsystem will be provided with its own LCC. If more than one LCC is necessary, one will act as the LCC supervisor. All signals from and to the component in the field will be made available at the terminal boxes in the local control cubicle(s). The LCCs will have the necessary functional ability to operate the subsystems. PLCs are to be used for this purpose and to perform the interface to CODAC cubicles. The operation of the component “in local” will be organised according to “state machine” logic. Enough information, among that available to the LCC, will be transferred to CODAC to allow the correct operation of the subsystems in “remote”. A local to remote change-over switch will allow control of the subsystems to be transferred from its LCC to CODAC. In addition, the LCC must be able to receive, from CODAC, the appropriate signals for the integrated remote control and set points for all the main parameters required for the injector operation. The LCC shall perform a pre-pulse check to ensure that all systems and sub-systems are in the required states and that the requested parameters are within all prescribed limits. It will also monitor the system performance during the injection pulse, giving real time information on parameters such as the beam current, power to the residual ion dump, gas flow, gas pressures, etc.

I&C functions (such as interlocks and access control) which are related to personnel safety shall be grouped in different categories and designed accordingly.

19.2.16 Operation

The operation of the NB H&CD system and of the DNB is possible, whenever the plasma parameters guarantee the power deposited by the beam on the first wall (shine-through) to stay within prescribed limits.

The NB H&CD system shall be able to operate in deuterium in a range of acceleration voltages between 400 kV and 1,000 kV. Operation in hydrogen shall be also possible in the

energy range 400 kV – 800 kV.

It shall be possible to change the beam aiming within the limits indicated in DRG1. This operation shall be performed as a remote handling intervention and may require the venting of the primary vacuum. It is therefore considered an operation to be co-ordinated with planned maintenance interventions on the torus.

19.2.17 Maintenance

All the components internal to the neutron shielding, that may require replacement, shall be designed to be compatible with remote handling maintenance. All maintenance operations shall be done minimising the release and spread of radioactive contamination. In particular, all the remote handling equipment and all the contaminated/activated components of the NB H&CD system and of the DNB shall be transported inside sealed casks.

The NB H&CD system and the DNB are connected to the primary vacuum (the fast shutter is not an absolute valve); in general all maintenance interventions, inside the primary vacuum confinement, shall require the venting of the primary vacuum and its filling with inert atmosphere. As a consequence a routine maintenance intervention should be coincidental with planned maintenance operations on the torus.

The beam source shall require routine maintenance for the replacement of the filaments and of the caesium oven and may require periodic maintenance, at a lesser frequency for caesium deposits removal. Therefore, the maintenance of the beam source shall be based on a "multi-layer" approach (first priority repair in-situ, then removal of the component) to minimise the down-time and the production of radioactive waste.

The beam-line components shall be designed to avoid maintenance during the operation lifetime of ITER. Procedures shall developed at the feasibility level for the remote maintenance and replacement of these components.

All components are classified as to their RH maintenance frequency in the DRG1, Table 1.25-1.

As foreseen in section 19.2.9, outside the neutron shield, the dose rate inside the volume of the NB cell, shall be lower than 100 $\mu\text{Sv/h}$, at any location, within 10^6 seconds from the end of DT operation. Limited operations of hands-on maintenance on components, as well hands-on assistance and preparation for remote-handling tasks, shall be possible. The number, duration and procedure of the maintenance interventions shall be defined according to the ALARA principle, reducing the number of components and taking into account the simplicity of maintenance in their design.

19.2.18 Decommissioning

Where possible, the design of the NB H&CD system and of the DNB is based on the following criteria relevant to decommissioning:

- use of modular components for ease of dismantling;
- segregation of radioactive systems or components;
- avoidance of contamination;

- decontamination to be as easy as possible;
- selection of construction materials to reduce activation products in materials subject to irradiation.

19.3 Code and Standards

The code and standards, proposed for the vacuum confinement of NB H&CD system and of the DNB, are listed in Table A-1 of the DRG1, annex “Summary of Structural Design Criteria”.

An exception is the HV bushing, that includes non-metallic materials (ceramic and fibre reinforced plastic) as part of its vacuum/pressure retaining boundary. This prevents the direct application of the ASME section VIII div. 2 to this part of the confinement. Specific design, fabrication and test criteria shall be proposed for this component, as part of the site-specific design activities.

For all conventional pressure/vacuum-retaining components, not part of the primary vacuum confinement, the following standards shall apply:

Pressure vessels:	ASME Section VIII div. 2
Piping:	ANSI/ASME B31.3
Valves:	ANSI/ASME B16.34

For all other metallic components, having structural functions, the rules contained in the AISC “Specification for Structural Steel Buildings - Allowable stress design and plastic design” shall apply.

For material having structural functions, the source of material property information for design analysis shall be either the applicable structural code or the ITER structural design criteria¹ based on the materials assessment report² and ITER material properties handbook³. In case of conflict, the ITER structural design criteria shall take precedence.

All the components having vacuum confinement functions will comply also with the recommendations of the “ITER Vacuum Design Handbook”.

The fabrication shall follow the general prescriptions of the ITER QA manual and the specific prescriptions given in the applicable standards.

¹ S 74 MA 1 97-12-12 R0.2, ITER structural design criteria

² G A1 DDD 1 98-05-28 W0.3, materials assessment report

³ G 74 MA 4 98-06-28 R0.1, material properties handbook