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Overview of diagnostics on ITER neutral beam test facility

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ITER operation relies on heating neutral beam injectors (HNB) based on negative ion deuterium beams accelerated at 1 MeV, with up to one hour 17 MW power, uniform intensity and low divergence. A neutral beam test facility is being built at Consorzio RFX to demonstrate the feasibility of a prototype injector with such demanding specifications and to optimize its performances. It comprises SPIDER, a 100 kV negative hydrogen/deuterium RF source, full size prototype of the HNB source, and MITICA, a prototype of the full HNB. The diagnostics for SPIDER and MITICA are essential to qualify and optimize the HNB for ITER and to assess the information on source and beam obtainable with the reduced set of the HNB diagnostics. Main parameters are measured with different complementary techniques to exploit the combination of their specific features. In the source the still open issues of cesium dynamics, negative ion generation and uniformity are investigated with a set of electrostatic probes, with optical emission spectroscopy, laser absorption for neutral cesium density and cavity ring down spectroscopy for negative ion density. The beam profile uniformity and its divergence will be studied with beam emission spectroscopy, visible tomography, neutron imaging and a special calorimeter made of carbon tiles which can achieve a spatial resolution of few millimetres. All components heated by beam power load will be monitored with a large set of thermocouples behind the heated surfaces and on the cooling water circuits. The test facility will also be the natural choice for hosting experiments on innovative concepts for DEMO HNBs, e.g. more efficient neutralization techniques and cesium free source operation.

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1. ITER heating neutral beam injectors and test facility

ITER nuclear fusion experiment requires delivering to the plasma a total power of 50 MW, out of which 33 MW up to one hour in a stationary condition are provided by two heating neutral beam injectors (HNB). Negative deuterium ion beams are generated by an RF source and accelerated at 1 MeV by a multi-grid multi-aperture accelerator, made of 1280 apertures distributed over an area 1.5 m high and 0.6 m wide in 4x4 groups of 5x16 apertures each. The negative beam is neutralized by a gas neutralizer, positive and residual negative ions are then removed from the beam by an electrostatic dump (ERID) and finally a water cooled calorimeter dumps the beam when closed [1]. Negative ions are chosen because of their neutralization efficiency, but they are more difficult to produce and with lower current density: 20 mA/cm^2 instead of 200 mA/cm^2 typical of positive beams.

ITER injectors will use a radio frequency (RF) source at 1 MHz, developed and optimized at IPP-Garching, first on the BATMAN small source and then through intermediate steps up to ELISE, the half size ITER source, with up to 60 keV, 10 s, beam pulses [2]. To guarantee reliable and efficient operation of HNB on ITER at the nominal parameters and optimize its performance, a neutral beam test facility is being built at Consorzio RFX, comprising SPIDER, a 100 kV negative hydrogen/deuterium RF source, full size prototype of the HNB source, and MITICA, a 1 MeV full performance prototype of the complete HNB [3]. SPIDER specifications are: 285 A/m^2 extracted deuterium current density at 0.3 Pa in the source, co-extracted electron fraction $e^- / D^- < 1$ and beam uniformity within 10%, for up to one hour beam pulse, while MITICA is specified for an extracted current of 40 A and a beam divergence < 7 mrad. The facility will then assist ITER HNB operation and will be the most suitable existing facility to develop new technologies for beam injectors, e.g. for DEMO. Overall, ITER injectors are considered viable, but with still open issues like: 1MV voltage holding; high power load on the beam line components and on beam source, especially on extraction grid because of co-extracted electrons and on rear wall due to back-streaming ions; difficulty in controlling the dynamics of the cesium evaporated in the source to enhance the D^- production.

2. Role of diagnostics in neutral beam test facility and HNB

As ITER HNB qualification is required before installation on ITER, where a much reduced set of diagnostics will be available, mainly thermocouples (TCs), the diagnostics to be installed on SPIDER and MITICA [4] (Figure 1) are essential. In particular their objectives are: a) characterize the source extraction region, next to the plasma grid, where negative ions are mainly produced and extracted, measuring the D^- density and the cesium dynamics over the wide grid surface and during long pulses; b) correlate the physics of the source with the beam characteristics in the actual HNB geometry and operational parameters; c) verify the design and investigate the operational space of beam source and injector. Another key objective is to assess capabilities and limitations of the subset of diagnostics that will be installed also on the ITER HNB, by comparing the information obtainable from their dataset with that from the larger set of diagnostics available in SPIDER and MITICA. MITICA diagnostics will suffer a neutron flux at the viewports of about 10^8 n/cm^{2}s, originating from the d-d reaction between deuterons implanted on the beam dump and ERID and the incoming beam deuterons [5], marginally critical for electronic components like CCD cameras. On ITER HNB the neutron flux is 100 times higher, due to the facing burning plasma, which will make impossible to install electronic components while refractive optics like windows, lenses and fibres are at risk. In SPIDER, with about 10^6 n/cm^{2}s, no serious radiation compatibility issue is expected.

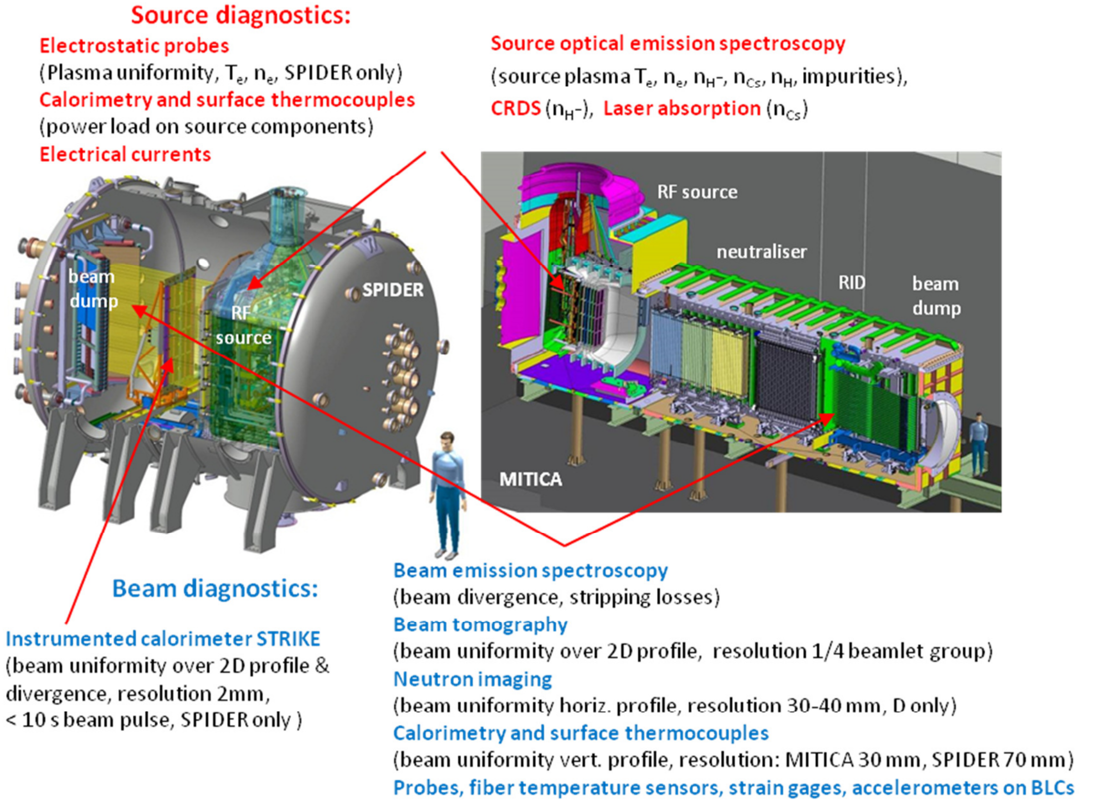

Figure 1. CAD models of SPIDER (left) and MITICA (right) with RF source and beam line components. Their diagnostics are listed, with the measured source or beam parameters.

3. Diagnostics common to neutral beam test facility and HNB

HNB will have an instrumentation set of the electrical power supply, water cooling calorimetry and vacuum and gas inlet systems, together with a large distributed array of TCs installed in vacuum on the surface of the source and beam line components, very similar to MITICA. These diagnostics [6] will be used for beam monitoring and system protection: accelerator currents will estimate the extracted beam current and the co-extracted electron fraction e^- /D^- and they are fast enough to serve as an interlock protection, differently from the slow thermal measurements. Water cooling calorimetry measures power losses on source, neutralizer, ERID and beam dump calorimeter. This is made of two panels arranged in a “V” shape, each built with horizontal swirl tubes on which TCs are installed, arranged midway and at the end of each swirl tube (Figure 2), that measure four vertical profiles of the beam, one for each column of beamlet groups, with few cm resolution. On neutralizer and ERID, calorimetry and surface TC measurements of power loads from beam edges show the combined effect of beam divergence, focusing and aiming. Electric current and thermal load on the ERID are also used to estimate the neutralizer efficiency through the flux of deflected residual charged particles; in particular, this current signal can be employed as interlock signal.

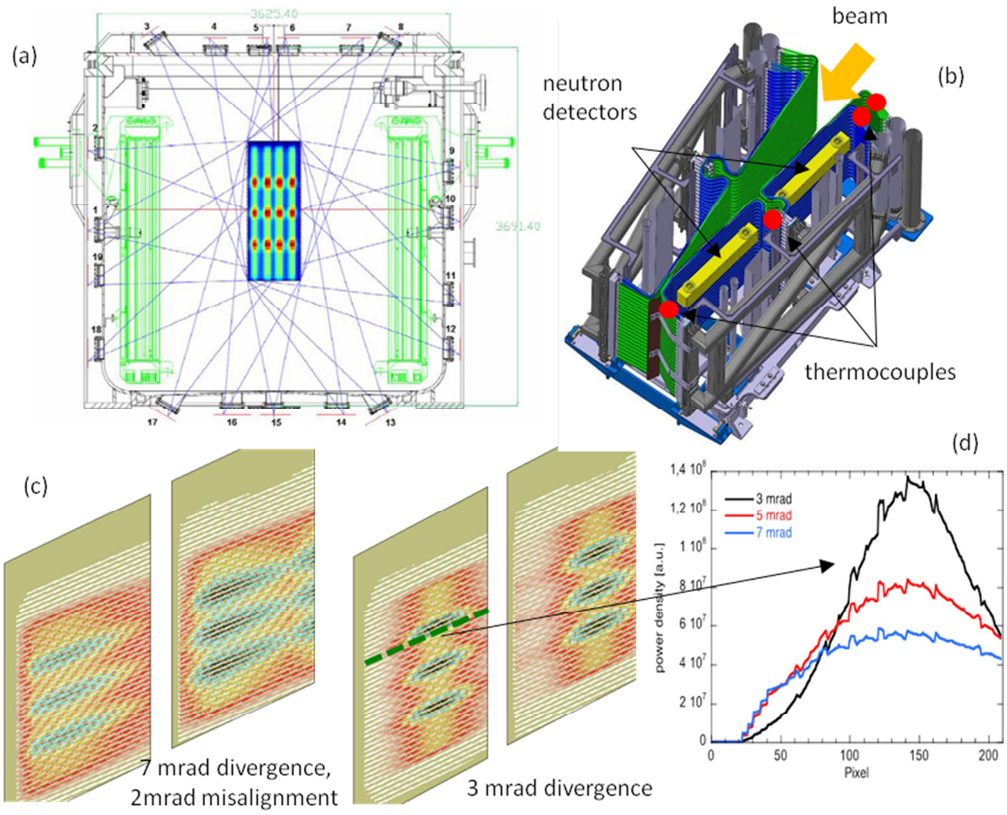

Figure 2. a) tomography layout and simulation of 2D beam profile reconstruction; b) beam dump calorimeter with position of TCs and neutron detectors; c) modeled beam power deposition on a calorimeter panel and d) horizontal power profile

4. MITICA diagnostics

MITICA will have the same set of diagnostics of HNB plus additional ones, used to better measure the individual effects of divergence, focusing and aiming, generated by the accelerator grids, on the beam profile along the beam line and to assess by comparison the diagnostic capability of calorimetry and surface TCs. The adopted strategy has been to implement a complementary set of diagnostic techniques to measure the most critical beam and plasma parameters (Figure 1), thus mitigating individual system limitations. Beam dump TCs give information on vertical uniformity of beam intensity and on vertical aiming of each beamlet group (the three intensity peaks on the vertical profile in Figure 2 are due to the overlapping of merging beamlet groups). The combined effect of divergence and horizontal alignment and focusing of each column at the ERID exit are investigated by TCs on its walls, which are alternatively grounded and 20 kV biased. On biased panels TCs are impractical and are replaced by temperature sensors on optical fiber, e.g. FBG fibers. [7]

Beam emission spectroscopy will measure the beam divergence along a number of horizontal and vertical lines of sight and investigate the beam particles lost by neutralization mainly in the accelerator (stripping losses). The beam focusing in MITICA, with four different beam – line of sight angles in the vertical direction and twenty in the horizontal one, complicates the spectra analysis and divergence estimate, but can possibly provide the vertical divergence of each beamlet group [8]. Optical tomography, made of an array of 18 linear CCD cameras looking perpendicularly at the beam through viewports all around the vacuum vessel at three positions in between the beamline components, allows to reconstruct the 2D beam profile from a tomographic inversion of line-integrated measurements of H_α radiation originating from the interaction of the beam with the background gas (figure 2a) [9]. When operated in deuterium, a neutron imaging diagnostic based on nGEM detectors measures the horizontal beam intensity profile, providing an estimate of the beam horizontal alignment and divergence, as shown in figure 2b-d [10]. A diagnostic with potentially similar capabilities is under investigation: an array of biased plates just behind the beam dump panels collects the secondary electrons generated at the swirl tubes; being radiation hard, it would be suitable also for HNB. A reduced set of optical emission spectroscopy lines of sight than on SPIDER, will be installed also on MITICA beam source, mainly to monitor cesium and impurities, possibly produced by back-streaming ions sputtering the source walls.

5. SPIDER diagnostics

The RF source of SPIDER will be diagnosed with a larger set of thermal measurements and spectroscopy lines of sight than in MITICA. An array of electrostatic probes is installed on the bias plate and plasma grid to monitor plasma uniformity and measure its density and temperature [11]. Prototype probes have been already tested in BATMAN demonstrating their operability in an RF environment, with magnetic field, cesium evaporation and HV breakdown during beam extraction [12]. Optical emission spectroscopy, through the line ratio of atomic and molecular transitions and helped by collisional radiative model, has the capability to measure plasma parameters in the different source regions. Direct measurements of negative hydrogen density by cavity ring-down spectroscopy (CRDS) and of neutral cesium density by laser absorption are particularly useful to characterize the complex dynamics of the plasma in the extraction region, to be correlated with the spatial uniformity of beam properties [13].

These are measured in SPIDER by the same diagnostics as in MITICA [14][15], plus an instrumented calorimeter, STRIKE, composed of an array of unidirectional carbon fiber composite (CFC-1D) tiles, with perpendicular thermal conductivity twenty times higher than that parallel to the tile, which completely intercept the beam, whose footprint is detected from the back by an infrared thermal camera [16]. The capabilities of this diagnostic have been exploited with a small size version on BATMAN and at NIFS test facility, developing first analysis algorithms [17]. The capability to manufacture the tiles for SPIDER is however not demonstrated yet. Alternative approaches are being investigated, like tiles made of isotropic material with a suitable geometry (e.g. castellated graphite tiles), or moving to a completely different concept, a tungsten wire calorimeter, i.e. an array of parallel tungsten wires exposed to the beam, emitting blackbody radiation with a spatial profile sufficiently resolved to distinguish the single beamlet and to provide information on the beam parameters [18].

Simulation and analysis codes have been developed for most diagnostics, like BES spectra modeling and analysis [8], tomographic inversion with regularization [9], CRDS and laser absorption simulations, thermal analyses of STRIKE tiles and of wire calorimeter [17][18].

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