The ITER Neutral Beam Test Facility toward SPIDER Operation

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In order to achieve thermonuclear-relevant plasma parameters in ITER, the auxiliary heating systems have to provide 50 MW, out of which 33 MW by two neutral beam injectors (NBI), each designed to operate at 1 MV, 40 A for one hour. The unprecedented parameters and the complexity of the NBI systems have led to recognize the need of a dedicated test facility to carry out an international R&D programme aimed at realizing, testing and optimizing the prototype of the NBI and to assist ITER during its operation. This facility is under construction in Padova Italy at Consorzio RFX premises and hosts two experiments: MITICA, a 1 MeV full-size prototype of the ITER NBI, and SPIDER, a full-size prototype of the ion source for ITER NBI.

The realization of the two experiments is carried out with the main contribution of the European Union, channelled through the Joint Undertaking for ITER (F4E), the ITER Organization and Consorzio RFX, with the Japanese and the Indian ITER Domestic Agencies (JADA and INDA) and European laboratories, such as IPP-Garching among others. The realization of MITICA and SPIDER progresses in parallel; presently, the installation phase of SPIDER is proceeding in good agreement with the general plan.

This paper mainly focusses on the integration issues and complementary research toward the SPIDER first operation, expected for next year. This is a very crucial phase, evolving along three main parallel paths: integration and testing of SPIDER components, completion and implementation of diagnostics and preparation of operation and research plan. The most interesting aspects of the wide set of activities, studies and further developments, all concurrent to determine the success of the SPIDER start of operation and exploitation will be described and discussed.

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Abstract. SPIDER is one of the two projects of the ITER Neutral Beam Test Facility (NBTF) under construction in Padova, Italy, at Consorzio RFX premises; it is the full-size prototype of the radiofrequency (RF) ion source for ITER Neutral Beam Injector (NBI), with beam energy of 100keV, designed to operate with pulse length up to 3600 s, featuring ITER-like filter field configuration, caesium oven layout and a wide set of diagnostics. These features will allow reproducing the ion source operation like in ITER as cannot be done in any other existing test facility. SPIDER realization is well advanced and the first operation is expected at the beginning of 2018, with the mission to prove the possibility of achieving the ITER NBI ion source target requirements and of improving its performance in terms of reliability and availability. This paper mainly focuses on the preparation of the first SPIDER operations: integration and testing of SPIDER components, completion and implementation of diagnostics and control and workout of operation and research plan, based on a staged strategy.

1. Introduction

In order to achieve thermonuclear-relevant plasma parameters in ITER, the auxiliary heating systems should provide 50 MW, out of which 33 MW by two Neutral Beam Injectors (NBI), each designed to operate at 1MV, 40 A for one hour [1]. The unprecedented parameters and the complexity of the NBI systems have led to recognize the need of a dedicated Neutral Beam Test Facility (NBTF) to carry out an international R&D programme aimed at realizing, testing and optimizing the prototype of the NBI and at assisting ITER during its operation. This ITER NBTF is under construction [2] in Padova, Italy, at Consorzio RFX premises and hosts two experiments: MITICA, the 1 MeV full-size prototype of the ITER NBI, and SPIDER, the full-size prototype of the ion source for ITER NBI.

The realization of MITICA and SPIDER is proceeding in parallel; the substantial progress of the overall activities is reported in [3]. The ITER Test Facility is realized with the main contribution of the Consorzio RFX, of the European, Japanese and Indian Domestic Agencies (F4E, JADA and INDA), with the support of the ITER Organization and the collaboration of several European laboratories, such as IPP-Garching, KIT-Karlsruhe, CCFE-Culham, CEA-Cadarache.

This paper mainly focuses on the preparation of the SPIDER first operation, expected at the beginning of 2018. SPIDER is a radiofrequency (RF) ion source, based on the configuration developed by IPP [4]; Table I summarizes the requirements to be fulfilled. Achieving them is very challenging and it will be a common effort, in close collaboration mainly with IPP-Garching, where ELISE is in operation [5], a device half the size of ITER negative ion source also aimed at assessing issues relevant to ITER. However some operating conditions can only be reproduced in SPIDER. In fact, SPIDER is characterized by the same size of the ITER NB ion sources, pulse length up to 3600 s, ITER-like filter field configuration and caesium oven layout. Moreover, a wide set of diagnostics can provide design validation and help in operation optimization. Several years of operation are expected for SPIDER before the use of HNBs in ITER; that period will be used to exploit the SPIDER mission to prove the possibility of achieving the ITER target requirements in an ion source of the same characteristics and size. SPIDER is also aimed to improving the performance in terms of reliability and availability, thus contributing to a significant risk mitigation for the successful operation in ITER

TABLE I: SPIDER REQUIREMENTS.

	Unit	**H**	**D**
Beam energy	keV	100	100
Max beam source pressure	Pa	0.3	0.3
Maximum deviation from uniformity	%	±10	±10
Extracted current density	A/m^2	>355	>285
Beam on time	s	3600	3600
Co-extracted electron fraction (e^-/H^-) and (e^-/D^-)		<0.5	<1

The preparation of the SPIDER operation is presently on-going; it is a very crucial phase, evolving along three main parallel paths: integration and testing of SPIDER components, completion and implementation of diagnostics and of the Control and Data Acquisition System (CODAS), and preparation of the operation and research plan, based on a staged strategy.

2. Integration of SPIDER components and complementary research

The SPIDER realization is well advanced, the next phase on site being the integrated commissioning of the Power Supply (PS) and auxiliary systems. A wide-range testing is planned first on the individual PS components, in remote mode, under the supervision of CODAS. The subsequent phase will consist of a step by step integration of all the PS subsystems to achieve their contemporaneous operation on dummy loads before moving toward the integrated commissioning of SPIDER. In this phase, the attention will not be particularly addressed to the verification of the target parameters of each subsystem in terms of voltage, current, dynamics, already verified during the contractual tests, but mainly on their coordinated operation. At this purpose, special tests requiring specific procedures are planned to verify the correct operation of the subsystems when working together, the coherence of the required sequences, the coordination and reliability of the protection actions, in particular in case of grid breakdowns.

On the SPIDER side, a demanding task is the achievement of the target voltage holding of the High Voltage (HV) bushing that must guarantee the insulation of the Beam Source (BS) and PS feeding lines to ground. The capability to sustain 120 kVdc for more than 3h without breakdowns has already been verified [6] after the development and optimisation of a conditioning procedure. Nevertheless, keeping the voltage holding capability over time under the final operational conditions with the BS installed inside the vessel remains a challenging task. Another important target to be achieved was an adequate outgassing rate and vacuum level of the SPIDER vessel, necessary to guarantee the correct performance of the ion source. Repeated and accurate cleaning of internal surfaces was carried out and eventually the target outgassing rate was achieved by means of a special baking process carried out for some days, up to 120 °C, using IR lamps in vacuum. As regards gas injection, given the pumping speed installed, tests will be performed to characterize the pressure profile inside the ion source as a function of the injected gas flow. The nominal operating pressure in the source is 0.3 Pa (with a reference flow of 5 Pa m^3 s^{-1} for H_2). The gas injection will allow to adjust the pressure from 0.1 to 0.6 Pa. The successful completion of the Beam Source (BS), Fig. 1, the most complex component of SPIDER, is the most challenging task. All the parts of the BS have been manufactured and tested in factory. Major efforts were required for qualification of manufacturing processes especially for Cu electrodeposited parts (grids, bias plate and ion source chamber) and heterogeneous Cu/SS joints. Difficulties have been encountered in reaching the required quality level especially in terms of extremely tight machining/assembly tolerances, compatibility with vacuum environment and ultrapure water inside the cooling circuits. Assembly of BS in factory has already started, but some corrective actions were finally necessary to recover the proper quality for hydraulic circuit pipes and molybdenum coated surfaces. Actions are on-going to limit within some months the consequent delay in the delivery.

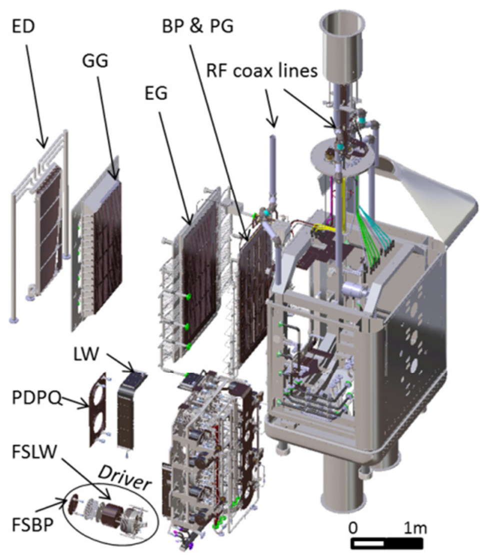

Fig. 1. Beam Source 3D exploded view.

A complementary research toward the SPIDER first operation, in collaboration with IPP, is the development of a caesium oven (Fig.2) capable of assuring vacuum and high temperature (300°C) compatibility and remote operation.

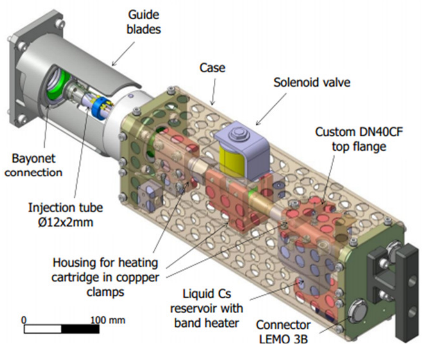

Fig. 2. Caesium oven 3D view.

This is an important program, since the production of negative hydrogen (or deuterium) ions inside the sources mainly relies on the generation of ions on caesiated surfaces with a low work function, which enhances the negative ion yield and reduces the co-extracted electrons, as verified at ELISE test bed [5]. In the SPIDER beam source fresh caesium will be injected in a controlled way by means of three caesium ovens. The design is complicated by the high reactivity of caesium, the difficulty in setting a stable (but adjustable) temperature distribution among the parts in vacuum, and the need for a special customized solenoid valve in vacuum. Before the procurement of the three ovens a caesium oven test bed has been set up, where a prototype of oven [7] is being tested and characterised inside a vacuum chamber.

The design of suitable Electromagnetic (EM) Shields (Fig. 3) for RF drivers required specific studies: copper EM shields are expected to help in reducing the coupling among the BS drivers, thus allowing improvements of the uniformity of the magnetic field inside each driver, as emerged from ELISE operation [5]. The work was mainly addressed to study how the implementation of the EM shields can be performed on the existing BS layout of SPIDER from all the viewpoints: mechanical, electrical and thermo-hydraulic.

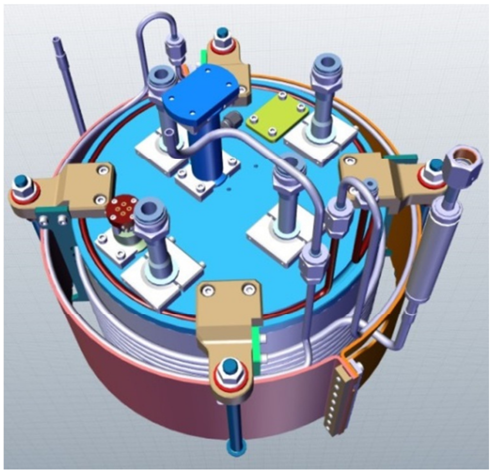

Fig. 3. EM shield with RF driver.

3. SPIDER Diagnostics

Since diagnostics in ITER NBIs are essentially limited to thermocouples, due to neutron and gamma radiation and to a limited number of access ports, it is crucial to get as much as possible information from more accessible experiments like MITICA and SPIDER, where diagnostics should demonstrate achievement of the challenging target performance in terms of beam intensity, ratio between coextracted electrons and negative ions, uniformity and divergence over the beam profile for up to one hour pulses. MITICA and SPIDER diagnostics have been designed with this scope [8]. Some of the diagnostics are dedicated to the RF source, to characterize the source extraction region, where negative ions are mainly produced and extracted. Others will measure the beam characteristics: the intensity profile, its uniformity and divergence. Information from the two sets of measurements will allow to correlate the physics of the source to the beam characteristics in the actual HNB geometry, and to optimize the operational space of the RF source and of the accelerator. SPIDER is the ideal test stand to perform this investigation, because MITICA will allow much less access and a neutron rate intermediate between SPIDER and ITER NBIs. Different methods are used to measure the same parameters, so that they complement and validate each other, thus mitigating the intrinsic limitations of each technique. The measurements will then be more confidently used to validate the physics models of source and beam and to understand what information can be obtained by the limited set of measurements available on ITER NBIs. The suite of diagnostics, shown in Fig. 4, includes both techniques well established in other facilities and new methods never used before in this application [8], [9].

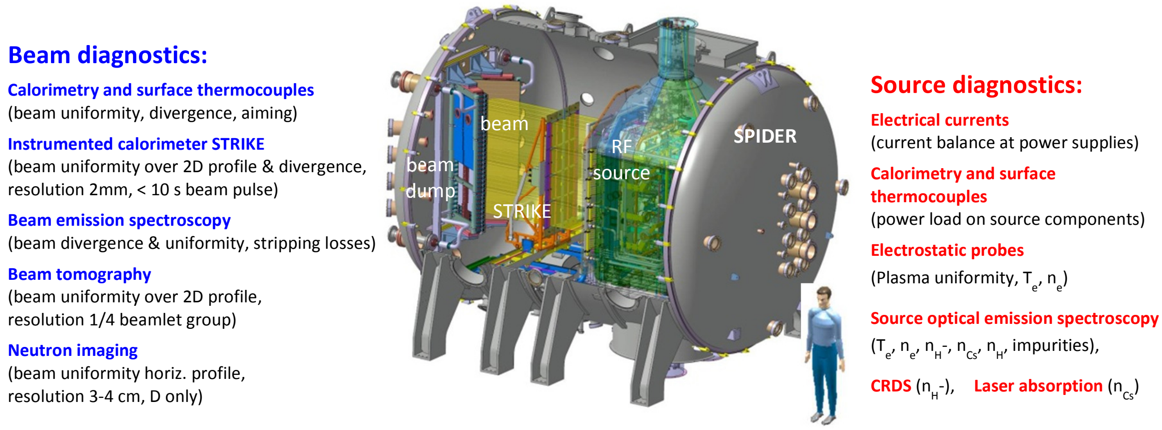

Fig. 2. SPIDER in-vessel view and list of source and beam diagnostics with measured parameters

Given the wide variety of implemented techniques and the level of customization needed, requiring a wide range of specialized expertise, the overall development path, from design to procurement, installation and commissioning, is managed directly by the hosting laboratory rather than through a contract with industry as for other plants. The design of SPIDER diagnostics is now finalized for most systems and components are being procured, while installation and integration are also starting. In the ion source and on the water cooled beam dump, thermocouples (TCs) are used both for calorimetry, fastened to the inlet and outlet pipes of the cooling circuit, and for local heat load estimates, located just at few mm from the heated surfaces. Source plasma parameters are measured by the combination of optical emission spectroscopy, assisted by a collisional radiative model, and electrostatic probes (Te, ne), together with cavity ring-down spectroscopy for H^- density, and laser absorption spectroscopy for atomic caesium density. Spectroscopy measurements distributed over multiple lines-of-sight (LOS) and Langmuir probes over the Plasma Grid (PG) and Bias Plate shall give information on the spatial distribution of the plasma parameters over the extraction region, investigating drift and non-uniformity of the plasma profile induced by the filter magnetic field and caesium evaporation. Probes have a custom design and can be configured as either single sensors, to measure the ion saturation current, or coupled to a reference electrode to get the whole characteristic curve. An in-vacuum RF compensation circuit with passive components has been developed and tested, to minimize the noise and distortion induced by the RF environment. Emission spectroscopy measures both time evolution of single spectral lines and of the entire spectrum, and is used to verify the correct ignition of RF drivers and the plasma pollution by impurities, particularly important in the first commissioning phase, and detects the spectrally resolved Balmer series and molecular spectra of hydrogen or deuterium, to extimate density and temperature of all plasma species.

The beam profile uniformity and its divergence are studied with well-assessed techniques like TCs and beam emission spectroscopy (BES), and by innovative methods like visible tomography, neutron imaging and an instrumented calorimeter (STRIKE). STRIKE is the main beam diagnostic in SPIDER as it is expected to achieve the spatial resolution of 2 mm over the entire beam profile, thus validating all other systems, especially those based on LOS integrated measurements like BES and tomography. STRIKE is made of 16 CFC-1D tiles that intercept the entire beam and, thanks to the preferential heat conduction through the tile rather than along it, well reproduce the front heated surface on the back side, whose temperature map can then be recorded by two infrared cameras. Beside beam uniformity, STRIKE can measure its divergence, by positioning the tiles at different distances from the source exit, and the collected beam current, as tiles are insulated from their support. The main limitation is due to the fact that the tiles are inertially cooled and then they can only survive up to 10 s beam pulses at full power; on the other hand, STRIKE will be particularly important in the initial

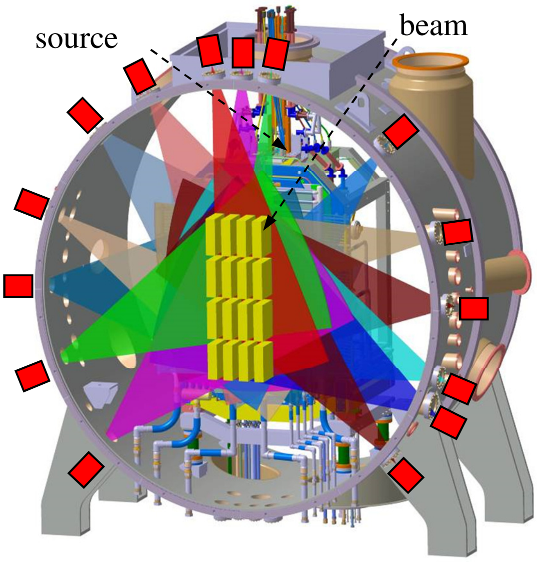

Fig. 3. Vertical cross-section of the SPIDER vessel with view of the 4x4 beamlet groups and 15 linear cameras of the tomographic diagnostic with corresponding fans of lines of sight

operational phase at lower power to tune the source and accelerator parameters. For longer pulses the highest spatial resolution is achieved by visible beam tomography, which measures the light emitted by the interaction of the beam with the background gas along about 3000 LOSs, arranged in 15 fans associated to linear cameras (Fig. 5). Tomography can measure beam uniformity with a resolution down to a pair of beamlets if suitable regularization is applied in the inversion. Beam intensity profile will be also derived from the map of neutron emission on the beam dump surface, due to fusion reactions between beam deuterons and deuterons previously adsorbed in the dump, for a global yield of $\approx 10^{12}$ n/s. It is based on GEM detectors with a cathode that serves also as neutron-proton converter, installed just behind a beam dump panel. It achieves a resolution of about 3 cm, but it can operate only in deuterium. Finally, information on beam intensity map, its uniformity and divergence can be derived by TCs on the water cooled beam dump. Comparing these measurements with the other beam diagnostics will help understanding what information on the beam can be achieved in ITER NBIs, through TC measurements distributed over the beam line components. SPIDER diagnostic prototypes are being operated in other experiments to verify their capabilities and to validate models. As an example, a small scale prototype of STRIKE has proven capable of resolving small-scale structures in the beam profile at other sources in operation.

4. Operation and research Plan

The preparation of the SPIDER operation and research plan is proceeding in parallel to the integration and testing of SPIDER components and diagnostics. The present scenario involves an integrated commissioning followed by the SPIDER operation. The integrated commissioning will be performed after a first commissioning of the individual plants, associating the test parameters of the plants in each commissioning phase to the values required for the following operational phase. This staged strategy is preferred with respect to the alternative full commissioning of each plant before the start of SPIDER operation, as it represents a faster track towards the experimentation, which would anyway start at reduced performance. The staged commissioning will also reduce the risk of delays in starting experiments; on the other hand, subsequent SPIDER operation with higher parameters of the various plants will require dedicated commissioning phases at a later time.

The integrated commissioning of SPIDER is divided into three phases depending on the atmosphere inside the SPIDER vacuum vessel, which can be air, vacuum, and hydrogen. The first activities will be performed in air to have easy access for measuring voltages and currents without the need of high voltage electrical feedthroughs and of repeatedly opening the vacuum; the voltage holding test of the extractor and accelerator insulators can be carried out within the permissible limits in this testing condition. Specifically, the following steps are planned in air:

- the RF circuits are first tested separately, for their electrical characterisation and verification of the frequency response

- the RF circuits are tested in pairs and finally all of them are switched on together; RF-induced noise will be assessed
- the magnetic filter field will be powered, while monitoring the voltage drops along the circuit branches; correspondingly, the magnetic field will be measured in the relevant positions for an experimental mapping to be compared with numerical computations; the influence of the filter field on the RF circuits will be assessed
- bias plate, bias circuit and PG bias circuit will be powered and a low current will be applied to the ignition filaments
- the high voltages will be applied to the extraction stage and to the acceleration stage, to check the voltage holding of the insulators and to assess the leakage currents

At the end of these tests, it is expected that the correct operation of the whole system and the voltage holding capabilities of the coolant circuits and of the insulators are verified.

In vacuum, the tests aim to verify the voltage holding capabilities of the various gaps, including the drivers. High voltage conditioning of the accelerator grids will be performed by gradually raising the voltage. Some of the tests of other power supplies, already performed in air, will be repeated; the current in the ignition filaments will be raised so that they start emitting a thermoionic current.

Finally, while injecting hydrogen into the beam source and verifying the pumping capabilities, the voltage holding of extractor and accelerator gaps will be verified in the range of expected pressure conditions; the RF circuits will be powered without filament current; then the plasma ignition will be tested and its influence on other plants can be assessed.

The early experimental phase of SPIDER is planned to follow a staged approach [10][11], as summarized in Table II.

TABLE II: FIRST SPIDER OPERATION PLAN.

Stage	H/D	RF Power	Extraction	Caesium
1	H	<200kW	NO	NO
2	H	<200kW	YES	NO
3	H	<400kW	YES	NO
4	H	<400kW	YES	YES

The main results of the first phase should be a characterization of the plasma ignition and ion source operation, without caesium and at low RF power (around 200 kW), an assessment of the influence of the filter field on plasma ignition and the ion source uniformity. The dependence of plasma parameters on filter field, bias plate bias and PG bias will be investigated in the vicinity of the PG at different gas pressures; the plasma drifts and non-uniformities in the same region will be verified.

After checking that the plasma leaking out of the ion source has not spoilt the voltage holding capabilities of the accelerator, a first beam at low current density will be extracted and accelerated, allowing the assessment of the effect of charged particles on voltage holding. In this phase the design of SPIDER extractor and accelerator [12], including the specificities similar to the design of MITICA accelerator [13], will be validated: extraction and acceleration optics, which combined together determine the final optimal perveance [10], will be studied, including the assessment of beam aiming and beam clearance inside the apertures of the EG. This phase will involve several investigations of the accelerator performance, like the amount of co-extracted electrons, the influence of PG bias, bias plate, bias and filter field, and the compensation of the zigzag pattern due to the permanent magnets located in the EG. After this phase, the RF power will be progressively raised and the characterisation of the source and of the beam will continue, extending the range of parameters. The operational phase will continue with caesium injection and with the corresponding characterisation of the ion source plasma and of the beam; a first attempt to optimize the beam properties will be performed in view of the ITER requirements, see Table I: beam uniformity, compensation of zigzag deflection, electron-to-ion ratio; a first assessment of caesium consumption will also ensue. In all stages of Table II, hydrogen will be generally used, but there will be some tests with deuterium in analogous conditions for comparison.

After the exploitation of the early experimental phase, the RF power will be increased and operation with deuterium will be also performed and continued toward the full achievement of the whole set of requirements.

5. Conclusions

The realization of SPIDER, the full-size prototype of the radiofrequency ion source for ITER NBIs is well advanced, the integration and testing of SPIDER components and the completion and implementation of diagnostics and control are in progress and the operation and research plan, based on a staged strategy, outlined. The SPIDER first experimental phase will start in early 2018, after the delivery and installation of the beam source; therefore several years of operation are expected before the use of the heating NBIs in ITER. That experimental period will be dedicated to exploit the SPIDER mission: to achieve the ITER target requirements in an ion source of the same characteristics and size and to improve its performance in terms of reliability and availability, thus contributing to a significant risk mitigation for the successful operation in ITER.

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