SPIDER in the roadmap of the ITER Neutral Beams

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To reach fusion conditions and control plasma configuration in ITER, a suitable combination of additional heating and current drive systems is necessary. Among them, two Neutral Beam Injectors (NBI) will provide 33MW hydrogen/deuterium particles electrostatically accelerated to 1MeV; efficient gas-cell neutralisation at such beam energy requires negative ions, obtained by caesium-catalysed surface conversion of atoms inside the ion source. As ITER NBI requirements have never been simultaneously attained, a Neutral Beam Test Facility (NBTF) was set up at Consorzio RFX (Italy), including two experiments. MITICA is the full-scale NBI prototype with 1MeV particle energy. SPIDER, with 100keV particle energy, aims at testing and optimising the full-scale ion source: extracted beam uniformity, negative ion current density (for one hour) and beam optics (beam divergence <7mrad; beam aiming direction within 2mrad). This paper outlines the worldwide effort towards the ITER NBI realisation: the main results of the ELISE facility (IPP-Garching, Germany), equipped with a half-size source, are described along with the status of MITICA; specific issues are investigated by small specific facilities and by joint experiments at QST and NIFS (Japan). The SPIDER experiment, just come into operation, will profit from strong modelling activities, to simulate and interpret experimental scenarios, and from advanced diagnostic instruments, providing thorough plasma and beam characterisation. Finally, the results of the first experiments in SPIDER are presented, aimed at a preliminary source plasma characterisation by plasma light detectors and plasma spectroscopy.

Keywords: neutral beam injectors, negative ion beam, negative ion source.

1. Introduction

The ITER experiment represents the next step in realising nuclear fusion as a viable energy source. To reach the fusion conditions and to control the plasma configuration in ITER, additional heating and current drive are provided by a combination of Neutral Beam Injectors (NBIs), Electron Cyclotron Resonance Heating and Ion Cyclotron Resonance Heating [1]. Two Heating NBIs will be installed to supply ITER with 16.5MW power each, with the possibility of a third injector, for a total of 50MW. The beam particles (hydrogen or deuterium) will be electrostatically accelerated up to 1MeV; efficient (≤60%) gas-cell neutralisation at such beam energy can only be achieved with negative ions, which are obtained by caesium-catalysed surface conversion of hydrogen/deuterium atoms in an ion source. ITER NBI requirements (1MeV, 40A negative deuterium ions) have never been simultaneously attained; therefore, a dedicated Neutral Beam Test Facility (NBTF) was set up at Consorzio RFX (Italy) [2]. Experiments will verify the continuous operation of the NBI for one hour, with stringent requirements on beam optics (divergence <7mrad, aiming within 2mrad). To study and optimise the performance of the ITER NBI, the NBTF includes two experiments: MITICA, the full-scale ITER NBI prototype with 1MeV particle energy, and SPIDER, the full-scale prototype of the ITER NBI source, with a 100keV

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accelerator. SPIDER will profit from the experience gained at the ELISE test facility, at IPP-Garching (Germany), which aims at achieving the ITER requirements in a half size source. SPIDER will focus on the objectives, relevant for ITER, that cannot be addressed by ELISE, like beam source operation for 3600s as well as validation of the electrostatic and magnetic configurations and of caesium distribution in an ITER-size source.

This paper gives an outline of the worldwide effort towards the realisation of ITER NBIs; the specific role of SPIDER is evidenced. Then the start of SPIDER experimentation is described along with the first characterisation of SPIDER source plasma.

2. Main facilities in view of ITER NBIs

2.1 ELISE

The ELISE test facility was set up within the R&D activities towards the ITER NBI, as an intermediate step between the small prototype RF source at IPP and the ITER source. The ELISE source has the same width, but half the height of the ITER source ($0.9\times1m^2$) and a three grid extraction system with a similar aperture pattern and geometry as ITER with an extraction area of $0.1m^2$ (Fig. 1). The plasma is generated in 4 drivers and can be operated for 1 hour. H^- and D^- beams can be extracted (up to 12kV) and accelerated (up to a total voltage of 60kV) presently only in pulsed mode (9.5s every 150s) due to limitations of the HV power supply; a steady state power supply is going to be procured.

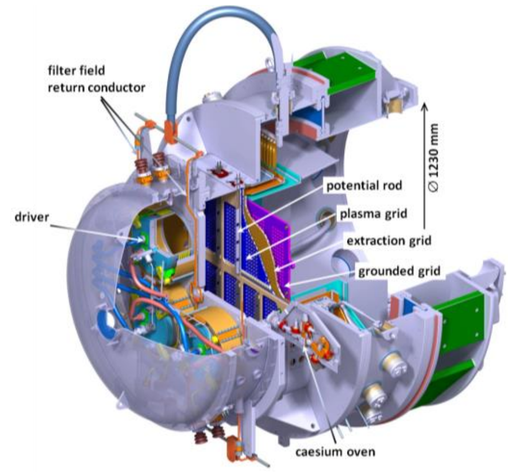

Fig. 1: ELISE ion source and extraction system.

The aim of ELISE is to demonstrate the ITER NBI requirements of $330A/m^2$ extracted H^- current density for 1000s and $285A/m^2$ (D^-) for 1h, both at 0.3Pa filling pressure. The ratio of co-extracted electrons to extracted ions has to stay below one and the beam uniformity above 90%. Furthermore ELISE should identify any physical or technical issues which could prevent reaching those targets and provide input for the NBTF operation.

Since the start of experiments in 2013, continuous progress was achieved: from the technical viewpoint several obstacles (mainly related to RF matching and RF breakdowns in the driver region) in applying full RF power of 75kW/driver were overcome. Details of source improvements are described in [3][4]. From the physical viewpoint long pulses at high RF power could be achieved for both isotopes (fig. 2) by a further refined caesium conditioning procedure [5]. In hydrogen $290A/m^2$ were extracted in 1000s plasma pulses (~90% of the ITER target), with accelerated current density of $237A/m^2$ (stripping of negative ions by collision with background gas in the accelerator is 10% at ELISE). In deuterium, current densities of $194A/m^2$ (extracted) and $152A/m^2$ (accelerated) were achieved in 3600s plasma pulses.

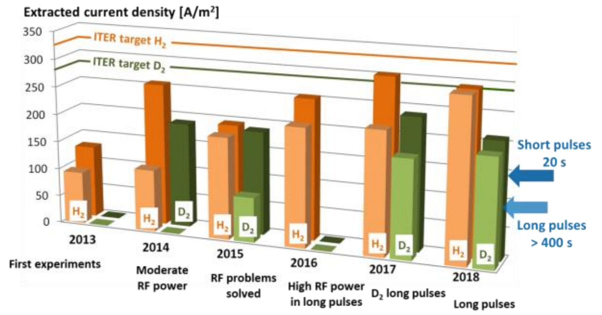

Fig. 2: Current densities achieved at 0.3Pa in hydrogen (orange) and deuterium (green) for short pulses (back) and long pulses > 400s (front).

The amount of the co-extracted electrons and their temporal increase during long pulses appear the most critical issue, in particular for D_2 operation: the heat load of the deflected electrons onto the second grid (extraction grid - EG) limits the applicable source power. Additionally a strong top-bottom-asymmetry of the electron current was detected, caused by plasma drifts in the presence of the magnetic filter field, necessary to increase the survival of negative ions near the plasma grid (PG), which closes the plasma chamber. A possible way to reduce and symmetrise the electron currents was found by shaping the magnetic filter field (e.g. by adding permanent magnets or current conductors along the side walls) and by modifying the electric potentials in front of the PG (vertical potential rods) [3]. These studies will continue in order to achieve the ITER targets.

2.2 SPIDER

The SPIDER testbed will allow 4 years of ion source experience prior to beam experiments with MITICA [8] and, in parallel to MITICA, will increase the experimental time devoted to the ITER NBI ion source. SPIDER aims at testing and optimising the ion source performance in terms of source uniformity (over a beam area of ~$1.5m^2$), negative ion current density and beam optics. Specifically, SPIDER will focus on objectives, relevant for ITER NBIs, that cannot be addressed by ELISE, like beam source operation for 3600s, validation of magnetic configurations of ITER NBI, optimisation of caesium distribution, validation of ITER NBI extraction and acceleration systems in the ITER-size source [9]. Moreover SPIDER is the only beam source immersed in a low-pressure gas like MITICA and ITER NBIs. SPIDER parameters are given in Table 1. Also in the SPIDER source, negative ions are created by caesium-catalysed surface conversion of atoms impinging on the PG: caesium is evaporated by 3 ovens installed on the rear plate of the plasma chamber, which houses also the 8 RF drivers. The beam is made of 1280 beamlets in a 4×4 horizontal and vertical arrangement of 5×16 apertures drilled in the grids. Negative particles are electrostatically extracted and accelerated and the inevitably co-extracted electrons are dumped onto the EG by permanent magnets embedded in the EG. The magnetic and electrostatic configurations of SPIDER accelerator are described in [10]. The beam source was delivered to Consorzio RFX in autumn 2017 and installed into the cylindrical vacuum vessel (4m diameter, 6m length, Fig. 3) in March 2018, after some ex-vessel preparatory activities [11]. Two Power Supply (PS) systems provide the electric power to the SPIDER experiment: the Ion Source and Extraction Power Supply system (ISEPS) and the Acceleration Grid Power Supply system (AGPS). ISEPS is a collection of power supplies for generation and extraction of negative ions [12], comprising: EG power supply (-12kV, 140A); 4 tetrode-based push-pull oscillators as RF generators (0.9÷1.1MHz 200kW on 50Ω load each), each feeding two drivers; PG filter power supply (5kA, 15V). AGPS (procured in-kind by ITER India) provides the high voltage for ion acceleration (-96kV, 75A) [13]. The gas and vacuum system provides the high vacuum required in the vessel ($10^{-6}/10^{-7}$Pa) and feeds the gas for the SPIDER operation [14]. SPIDER goal includes the validation of the design of ITER NBI support plants: cooling plant, removing thermal power (10MW) from power supplies, ion source, and beam dump [15]; central Instrumentation and Control systems (I&C) [16], providing conventional control (CODAS, Control and Data Acquisition System) [17], personnel protection (Central safety System) [18], investment protection (Central Interlock System, CIS) [19], managing also breakdowns in between the acceleration grids).

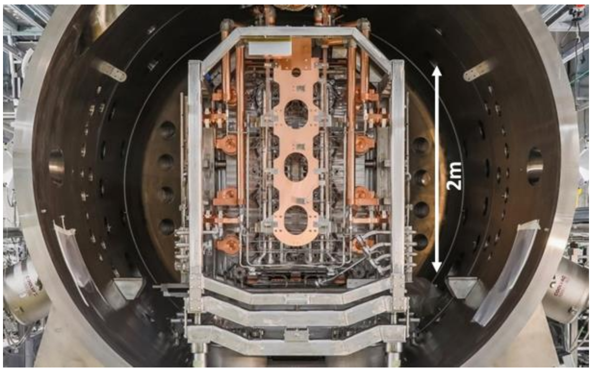

Fig. 3: Rear view of SPIDER beam source in vacuum vessel.

Table 1: Main SPIDER parameters.

Parameter	Value
Beam energy [keV]	100
Max source filling pressure [Pa]	0.3
Max deviat. from beam uniformity	±10%
Extr. ion current density [A/m^2]	>355 H_2; >285 D_2
Beam on time	1 hour
Co-extracted electron fraction	<0.5 (H_2); <1 (D_2)

SPIDER is equipped with a large set of diagnostic systems performing the measurements of the significant physics quantities [20]: thermocouples mounted on ion source, vacuum vessel and beam dump, flow and pressure sensors, electrostatic probes, emission and absorption spectroscopy, plasma light, visible and infrared cameras, beam tomography, neutron monitoring, cavity ring-down spectroscopy, STRIKE (Short-Time Retractable Instrumented Kalorimeter Experiment). Lines-of-sight (LoSs) observing the inside of the source through each of the drivers are used both for source emission spectroscopy and for total light emission [21].

2.3 MITICA

MITICA, the full-scale prototype of the ITER NBIs, represents a large step forward in terms of power and energy output with respect to the existing NBIs. MITICA is expected to demonstrate the operation of the whole ITER injector; it will provide several years of experience with the whole injector before the start of ITER NBI and will accompany the ITER NBI operation to solve possible injector issues. MITICA parameters are given in Table 2; except the duration of H_2 pulses, they correspond to ITER NBI parameters, as indicated. MITICA 5-stages accelerator provides the particles with 1MeV total energy; its physics design is described in [6].

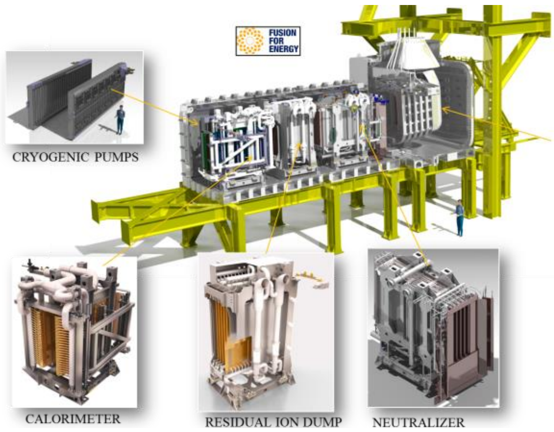

Fig. 4: View of the MITICA injector.

Table 2: Main MITICA parameters; the difference with ITER NBI is indicated.

Parameter	Value
Beam energy [keV]	1000 (D_2); 870 (H_2)
Max source filling pressure [Pa]	0.3
Beamlet divergence [mrad]	≤ 7
Accelerated current [A]	46 H_2; 40 D_2
Beam on time	1 hour (H_2 in ITER: 1000s)
Co-extracted electron fraction	<0.5 in H_2; <1 in D_2

The specific features of the magnetic fields share the basic principles with SPIDER, in terms of plasma confinement and compensation of the deflection of the accelerated ions, although the compensation is performed inside the EG itself [7]; the source of negative ions is essentially identical to SPIDER (see section 2.2). Hence MITICA will profit from the design solutions of SPIDER and from SPIDER experimentation, in terms of operation of RF source and generation of negative ions. MITICA will mainly address 1MeV issues in vacuum, attainment of the target neutral beam power (16.5MW, after neutralisation) and beam aiming, minimisation of heat loads and thermo-mechanical stresses on all components (for fatigue lifetime). MITICA is a complete injector; so it will also verify the operation of the beam line components: neutraliser, residual ion dump, calorimeter and cryogenic pumps; all components are located inside a vacuum vessel (Fig. 4). The mechanical components of MITICA are being procured. The 1MV power supplies (procured in-kind by JA-DA) are already installed; insulation tests and commissioning have started; first tests of transformers and rectifiers are in progress.

2.4 Accompanying programme

Outstanding issues (optimal coupling of RF to the plasma, 1MV voltage holding in the presence of magnetic fields, optimal distribution of caesium) are also investigated by small test facilities at the NBTF. The High Voltage RadioFrequency Test Facility (HVRFTF) [24] is devoted to the characterisation of the dielectric strength in vacuum of the RF drivers to address potential issues of voltage holding of beam source components under RF electric fields at low gas pressure. In the CAesium Test Stand (CATS) [25] the characterisation of the caesium ovens before installation into SPIDER and MITICA is performed, in terms of diagnostics, oven maintenance and caesium management [26]. The High Voltage Padova Test Facility (HVPTF) [27] aims at performing optimised experiments of voltage holding up to 1MV in vacuum and with gas, with tight control of voltage, current, pressure and vacuum quality.

The Negative Ion Optimisation facility, phase 1 (NIO1) [28], is a versatile multi-aperture H_2 source, with compact and modular design, capable of continuous operation. It aims at reproducing the physics conditions of the much larger ion sources, to readily verify the effects of individual source components/parameters and to compare results with simulations. Numerical modelling at the NBTF will accompany the experiments of RF-plasma coupling, caesium injection, beam-gas interaction; simulation of the expected features of SPIDER beam in the early phases will provide the operational parameters [29] and will confirm the electrostatic and magnetic configuration [30], in synergy with the diagnostic systems. Joint experiments are performed with colleagues of QST (Naka, Japan) and NIFS (Toki, Japan); the innovative magnetic configuration, cancelling the "criss-cross" deflection of ion trajectories in multi-beamlet negative ion accelerators, is experimentally verified [31]; the SPIDER beam diagnostics are tested [32] and the interaction of the beam and the background gas is studied.

3. First operations of SPIDER

After the integrated commissioning phase [16], to test the plants and the related control systems, SPIDER operation started in mid-May 2018 by characterising gas pressure, pre-ionisation filaments and plasma initiation.

3.1 Gas pressure characterisation

SPIDER gas injection system includes a reservoir and two pneumatic valves; the gas is injected on the back plate of the 8 drivers by 4m long pipes. Pre-programming valve opening and reservoir pressure controls the gas injection. Capacitive pressure measurements are installed at the front and rear lids of the vessel. Source pressure affects plasma initiation, integrity of the beam (stripping; see sect. 2.1 and [33]), probability of discharges. So the gas injection system was characterised by an additional source pressure measurement by a 4m long pipe towards the connecting flange on the vessel. A numerical model is being set up to assess the transient (few seconds) behaviour of the gas in the presence of such long pipes and the conductance of the grids; an example is shown in Fig. 5. Steady state measurements of source and vessel pressures provide a calibration factor of 4, roughly as expected numerically [34]. The vessel pressure reaches steady state in about 2s, but in the source the pressure is stationary after 1.5s.

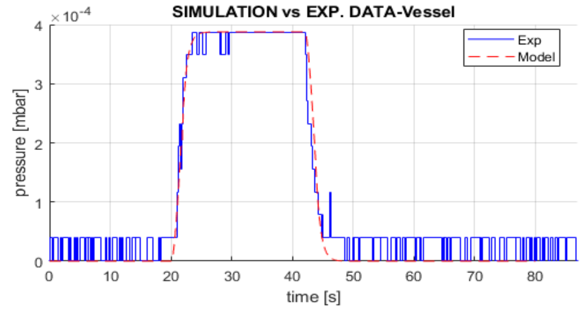

Fig. 5: Calculated and measured vessel pressure.

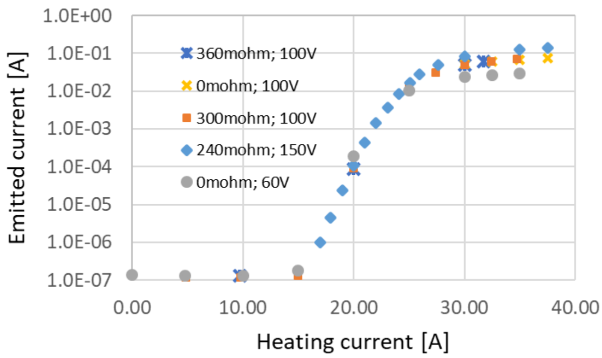

Fig. 6: Current emitted by pre-ionisation filaments as a function of heating current in different conditions.

3.2 Pre-ionisation filament characterisation

Inductively-coupled plasmas featuring a Faraday shield, like SPIDER [35], require external means for plasma initiation; specifically SPIDER drivers are provided with tungsten filaments, heated by a $30V_{rms}$ power supply. The filaments emit thermoionic electrons and a current is drawn towards the source walls by applying a suitable voltage. The emitted current was measured in different conditions as a function of the heating current to identify the ohmic value of a suitable series resistor in the heating circuit to extend the filament lifetime, while producing an electron current of few mA; an estimate of the filament work function was also obtained. Fig. 6 shows the electron current emitted by 7 filaments (one was not operating) with different values of series resistance and with different filament bias voltage. The final choice was 0.36Ω. A 60V bias was experimentally found to suffice.

3.3 Initiation of plasma discharge

The sequence of the various actions to initiate the plasma was preliminarily assessed on the basis of ELISE procedure. In ELISE, first the pre-ionisation filaments are heated and biased, then the RF generators are started (at low power) and the plasma is initiated with a gas puff [22]. After plasma initiation, the filaments are switched off and pressure and RF power reach their final values.

This procedure was revised for application to the experimental constraints of SPIDER (see section 5): the final pressure was set and the RF power was ramped up from the minimum value allowed by the generators to the final value. In the case of SPIDER also the magnetic filter field [10] was on since the beginning.

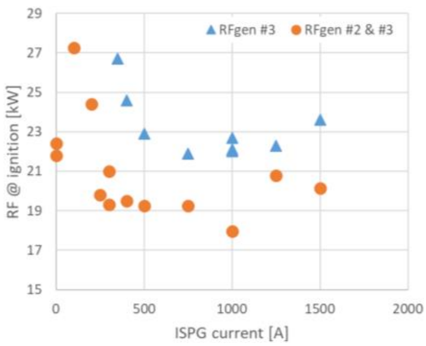

Fig. 7: RF power per generator at plasma initiation (single and pair of generators) vs filter field current (source pressure 0.3Pa; RF power ramping rate 2kW/s).

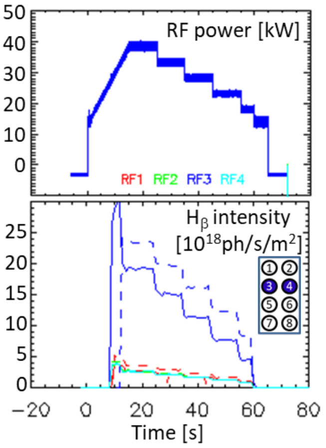

Fig. 8: RF power (a), H_β line intensities (b), measured through drivers #3 (continuous line) and 4 (dashed line).

The plasma was initiated with one row of drivers and then with two rows. Within a cautious limit of the RF power per generator at 40kW, successful plasma initiation was obtained with a pressure in the ion source >0.2Pa and a suitable ramping rate of the RF power in the range 1-2.5kW/s. Fig. 7 shows the RF power required to initiate the plasma as a function of the filter field current: with one generator the plasma is not initiated with filter field current <350A; this limit is not present with two generators even when the corresponding pairs of drivers are not neighbouring.

4. First characterisation of SPIDER plasma

In the first operational phase of SPIDER only one RF generator was used, corresponding to the second row of drivers from the top (#3 and #4). Subsequently also bottom drivers (#7 and #8 together with the second row) were used as well as top drivers alone (#1 and #2). Experiments are presently devoted to the identification of the plasma initiation conditions and to the characterisation of the plasma with one or more RF generators. SPIDER control system allows programming the waveforms of the various power supplies. Thus complete scans of different parameters can be performed in single pulses (see Fig. 8a). In the data presented herein PG and bias plate were not polarised.

4.1 RF power scan

During pulse #5214 a RF power scan was performed from 40kW to 20kW (Fig. 8a). Correspondingly, the total light emitted by the plasma of the powered drivers (#3 and #4) exhibits a dependency on RF power (Fig. 9). A similar trend is generally found also in the single spectral lines (e.g. see the H_β line intensity in Fig. 8b). Fig. 9 shows a large (around a factor of 2) asymmetry between the plasma light in the two drivers at low RF power. Analogously, the asymmetry is detected also on the spectrum lines (see the intensity of the H_β line in Fig. 8b). This topic is discussed in the next section.

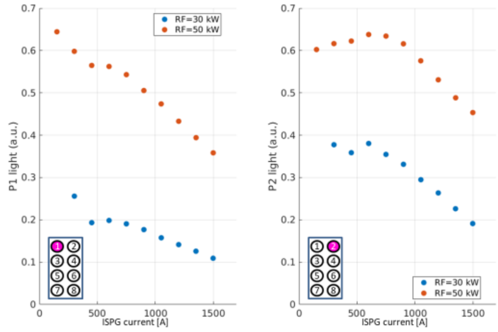

Fig. 9: Plasma light measured through drivers #1 (left) and #2 (right) vs filter field current and RF power.

4.2 Filter field scan

Stepwise variation of the filter field current was employed to obtain scans in the range 0-1500A. The plasma light is found to exhibit a clear dependence on the filter field current (Fig. 9). Specifically, both LoSs exhibit a decrease above 600-700A; their dependencies at low filter field current is different, so that at zero current the spread of the points of both drivers is only 15%. It can be deduced that some sort of plasma drift exists near the drivers, deserving further investigations. The H_β line intensities (Fig. 10) exhibit similar dependence, but not identical in that both LoSs decrease at low filter field current. The LoSs parallel to the PG display an analogous behaviour (not shown herein).

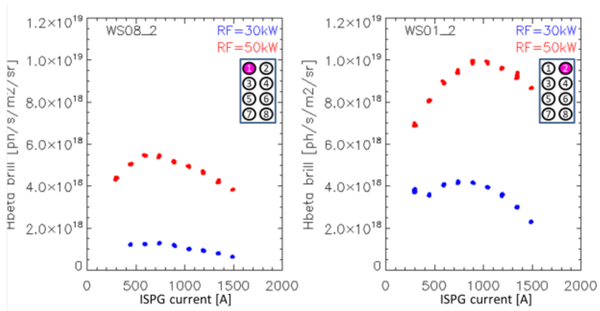

Fig. 10: H_β line intensity through drivers 1 (left) and 2 (right) as a function of the filter field current.

5. Main issues in first SPIDER operations

First operation of SPIDER evidenced some issues: plasma discharges occurred on the rear side of the source; a short circuit was identified between PG and source body. Because of the inherent risks for the facility, a thorough investigation of the occurrence conditions of the rear discharges was not performed. A specific feature of SPIDER is that the beam source is completely surrounded by low-pressure gas. Thus the rear discharges resulted in the operational limits for plasma initiation mentioned in section 3.3: when the gas pressure outside the source was <60mPa, the plasma was not initiated, even with 40kW RF power. The effect of the magnetic field on plasma initiation was discussed in section 3.3; in the cases in which plasma initiation was not achieved, rear discharges mostly occurred; they seem to be facilitated by a fast ramping rate of the RF power. In correspondence to the rear discharges, the filament bias power supply was frequently subjected to excessive overvoltages. Direct inspection inside the vacuum vessel showed signs of electrical discharges on the busbars of the RF circuits, on the filament supports and on the surface of the vacuum vessel. The distribution of the discharge signs and their occurrence conditions are under investigation with the aim of identifying their causes and long-term solutions. The discharges might have also played a role in the short circuit between PG and source body, specifically between one of the return busbars of the magnetic filter field circuit and the rear plate of the source; this problem has been fixed by carefully positioning the busbar.

6. SPIDER short-term planning and summary

As already mentioned, in May 2018 the first stage of SPIDER operations, as described in [9], started. The final integration of the acceleration power supply is planned for autumn 2018. Experiments are presently devoted to the characterisation of the plasma with one or more RF generators; in parallel, the noise immunity of the various diagnostic systems is verified while they enter operation.

In the next future, the characterisation of the ion source will continue as a function of the various parameters (including polarisation of the PG and of the bias plate) until all RF generators will be powered simultaneously and while the RF power will be raised up to 100kW per generator. Voltage holding of the beam source will be verified, so that extraction of negative particles can start (allowing the characterisation of the co-extracted electron current) and the negative ion beam can be accelerated.

In the first half of 2019, the caesium ovens will be installed and the study of the effectiveness of caesium evaporation on the SPIDER negative ion beam will start. These phases are expected to provide an assessment of SPIDER design and operational capabilities. Some issues were identified [11] during factory and on-site tests before the installation of SPIDER beam source into the vacuum vessel (vacuum leak in one segment of the grounded grid; wrong orientation of the magnets in the grounded grid). In the second half of 2019 a shut-down period will be devoted to solve these issues. Afterwards SPIDER experiments will resume, aiming at the characterisation of the beam with increasing performances in view of the start of the operations of ITER beam prototype, MITICA.

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