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Start of SPIDER Operation Towards ITER Neutral Beams

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Abstract. In June 2018 the SPIDER device, which is the full-size prototype of the negative ion source and extractor for the ITER Heating Neutral Beam has entered the first operation phase at the Neutral Beam Test Facility (NBTF) in Padova, Italy. This paper describes the present status of the device, the experimental plans and the results obtained during the first experimental campaign of the radio-frequency driven plasma source.

INTRODUCTION AND NEUTRAL BEAM TEST FACILITY

Heating Neutral Beam (HNB) Injectors will constitute the main plasma heating and current drive tool both in ITER and JT60-SA, which are the next major experimental steps for demonstrating nuclear fusion as viable energy source. In ITER, in order to achieve the required thermonuclear fusion power gain Q=10 for short pulse operation and Q=5 for long pulse operation (up to 3600s), two HNB injectors will be needed [1], each delivering a total power of about 16.5 MW into the magnetically-confined plasma, by means of neutral hydrogen or deuterium particles having a specific energy of about 1 MeV. Since only negatively charged particles can be efficiently neutralized at such energy, the ITER HNB injectors [2] will be based on negative ions, generated by caesium-catalysed surface conversion of atoms in a radio-frequency driven plasma source. A negative deuterium ion current of more than 40 A

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will be extracted, accelerated and focused in a multi-aperture, multi-stage electrostatic accelerator, having 1280 apertures (~ 14 mm diam.) and 5 acceleration stages (~200 kV each) [3]. After passing through a narrow gas-cell neutralizer, the residual ions will be deflected and discarded, whereas the neutralized particles will continue their trajectory through a duct into the tokamak vessels to deliver the required heating power to the ITER plasma for a pulse duration of about 3600 s. Although the operating principles and the implementation of the most critical parts of the injector have been tested in different experiments, the ITER NBI requirements have never been simultaneously attained. In order to reduce the risks and to optimize the design and operating procedures of the HNB for ITER, a dedicated Neutral Beam Test Facility (NBTF) [4] has been promoted by the ITER Organization with the contribution of the European Union's Joint Undertaking for ITER and of the Italian Government, with the participation of the Japanese and Indian Domestic Agencies (JADA and INDA) and of several European laboratories, such as IPP-Garching, KIT-Karlsruhe, CCFE-Culham, CEA-Cadarache.

The NBTF, nicknamed PRIMA, has been set up at Consorzio RFX in Padova, Italy [5]. The planned experiments will verify continuous HNB operation for one hour, under stringent requirements for beam divergence (< 7 mrad) and aiming (within 2 mrad). To study and optimise HNB performances, the NBTF includes two experiments: MITICA, full-scale NBI prototype with 1 MeV particle energy and SPIDER, with 100 keV particle energy and 40 A current, aiming at testing and optimizing the full-scale ion source. SPIDER will focus on source uniformity, negative ion current density and beam optics. In June 2018 the experimental operation of SPIDER has started.

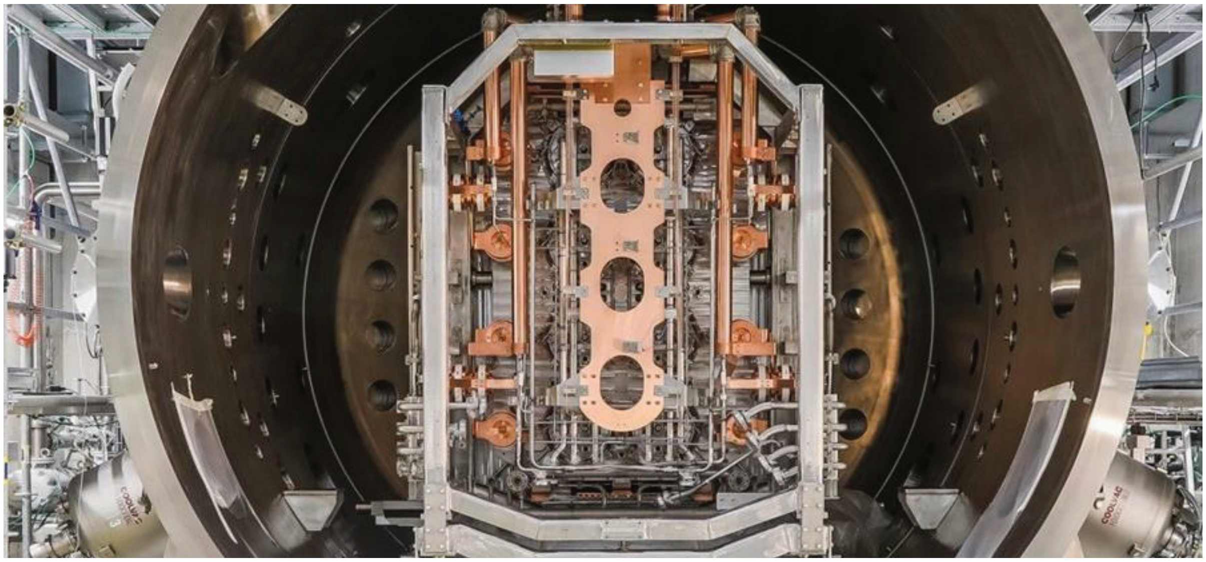


FIGURE 1. View of SPIDER beam source and vacuum vessel from rear side, after installation in the NBTF in Padova.

TABLE 1. Main SPIDER target parameters.

Parameter	H^-	D^-
Surface for ion production	about 1 x 2 m^2 and 1280 apertures	
Plasma source filling pressure	0.3 Pa	
Plasma source power (8 driver coils at 1 MHz)	8 x 100 kW	
Ion current density extracted from the plasma	>355 A/m^2	>285 A/m^2
Co-extracted electron fraction (e–/H–) and (e–/D–)	< 0.5	< 1.0
Max deviation of ion current density from uniformity	± 10%	
Accelerated ion beam current	46 A	40 A
Beam acceleration energy	100 keV	
Magnetic filter field upstream of the PG	up to 4 mT	
Max heat load on accelerator grid and pulse duration	660 kW for 3600 s	

THE SPIDER DEVICE

The scope of the SPIDER device (Fig. 1) is the assessment and optimization of H^- or D^- ion beam extraction from a source having the same features and physical dimensions as those foreseen in the ITER HNB. This is an essential step for the mitigation of the risk involved in the operation of the ion source of the ITER HNB, whose design is based on concepts developed in different laboratories (QST Naka, Japan, IPP Garching, Germany, NIFS Gifu, Japan, CEA Cadarache, France) [6, 7, 8], but never tested at full performance at once in a single experiment. The crucial features of the ITER HNB design, which shall be achieved in SPIDER for the first time are the following:

- value and uniformity of H^- or D^- ion current density, extracted from a large plasma chamber driven by 8 RF coils through a Cs-catalyzed grid (1280 beamlet apertures, about 1×2 m^2), with low extracted electron/ion ratio
- voltage holding between components at different electric potentials (acceleration grids, plasma source, RF driver coils and conductors, vacuum vessel) in vacuum and low pressure gas, in the presence of pressure gradients produced by the gas flow escaping from the plasma source, which is not vacuum-tight
- the tolerance to substantial heat loads caused by co-extracted and stripped electrons in a large multi-aperture high voltage accelerator (46 A, 100 kV, up to about 660 kW/grid), acceptable grid deformation and effects in terms of beamlet optics quality (divergence and deflection)
- the stability of beam operation for pulse duration up to 3600 s.

The main target parameters of SPIDER are summarized in Table 1.

The SPIDER Beam Source

The beam source is designed to produce, extract and accelerate more than 40 A of negative ion beam up to 100 keV [9] and to reproduce the layout and operating conditions of the ITER HNB source. Views of the actual SPIDER assembly are shown in Fig. 2. The ion source, consisting of plasma source and extractor, is two times larger than ELISE [8]. The beam source is contained in a stainless steel cylindrical vessel having diameter of 4 m and an overall length of about 6 m (Fig. 1). The vessel is provided with three 100 kV ceramic bushings for service line feedthroughs: one for electrical connections (DC and RF power and diagnostic signals) and two for hydraulic and gas injection pipes. The vessel bushings have been successfully tested at 130 kV for one hour at a vacuum level of 3×10^{-7} mbar, after about four hours of conditioning at increasing voltage levels.

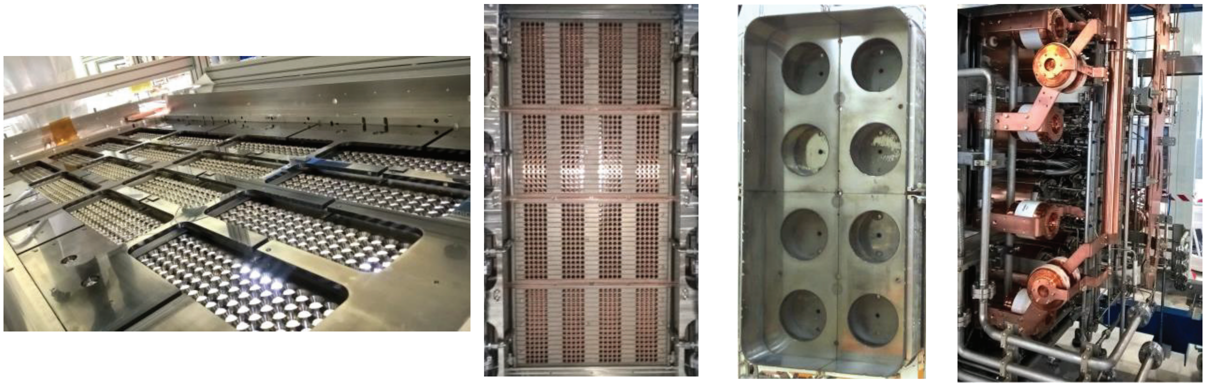

(a) (b) (c) (d)

FIGURE 2. (a) Plasma Grid (PG) and Bias Plate (BP) during assembly; (b) Grounded Grid (GG) from downstream side of beam source; (c) view of Plasma Source chamber with 8 RF drivers; (d) lateral view of the beam source with auxiliaries

Plasma is generated inside eight cylindrical chambers called drivers (see Fig. 2c), when RF power is applied to 8 coils wound around each driver and gas (H_2 or D_2) is injected at a pressure of 0.3 Pa. The coils are connected to 1 MHz power supplies via a matching network (fixed and variable capacitors) installed on the rear side of the ion source. Plasma diffuses into an expansion chamber towards the plasma grid (PG); this grid is also molybdenum-coated and covered with a thin layer of caesium, which lowers the work function so that the impinging hydrogen/deuterium atoms are more easily turned into negative ions. A bias plate (BP) electrode is mounted 10 mm upstream of the PG and can be used to adjust the electric field in the region of negative ion production for maximizing the extracted ion current. In the plasma source a magnetic filter field is produced by a current flowing in the PG and in a busbar system. Only a low residual magnetic field penetrates into the RF drivers [10].

The grid geometry is also similar to that of MITICA and ITER HNB, with 1280 apertures and an overall surface of about 0.9×1.8 m^2 (Fig. 2a and 2b). When negative voltage (~ 10 kV) is applied between the PG and the EG, H^- or D^- ions are extracted through the PG apertures, constituting 1280 negative ion beamlets. The negative ions are then accelerated to about 100 keV energy thanks to the -90 kV voltage between the EG and the grounded grid (GG). Both the extraction voltage and the acceleration voltage can be adjusted on the basis of the extracted ion current, so as to keep perveance matching and minimize divergence. Since electrons are unavoidably co-extracted along with the negative ions, Sm_2Co_{17} magnets located in the EG are used to deflect the electrons and to dump them onto the EG. These magnets are arranged in horizontal arrays located between the aperture rows. As the arrays are magnetized along the beam direction with alternate orientation, two opposite swings of vertical field By are produced along the axis of each beamlet. This arrangement also produces an undesired deflection of the ions, smaller magnet arrays and a ferromagnetic plate are embedded in the GG, with the purpose of correcting the undesired ion deflection. The design of the accelerator for SPIDER was aimed at obtaining the best beamlet optics by an integrated approach, considering at the same time physics and engineering aspects [10]. Aperture shape and distance between grids were optimized, and suitable protrusions of the grids (called kerbs) were adopted; moreover, apertures were arranged to steer the beamlets and to counteract electrostatic repulsion among neighboring beamlets.

In accordance with ITER HNB design, in SPIDER there is no vacuum-tight separation between the low pressure gas in the plasma source and accelerator and the upstream side of the source, where many auxiliaries such as RF coils, electric power and diagnostic lines, cooling water, gas feeding pipes and caesium ovens are located. This is a substantially different approach from that of previous experimental devices at QST and IPP, where all the ion source auxiliaries were kept in a separate vacuum or insulating gas environment, completely segregated from the vacuum/low pressure gas environment of the ion source and accelerator.

SPIDER Diagnostics

The use of diagnostics in MITICA and in ITER HNB will be limited due to the neutron flux generated respectively by collisions of accelerated deuterium atoms and by fusion reactions in the tokamak. Diagnostics are a key feature of SPIDER, whose expected neutron flux of ~10^{12} n/s will not affect the operation of CCD cameras, which are the most delicate diagnostic sensors.

For these reasons, the SPIDER set of diagnostics [11] is crucial to demonstrate the achievement of the target performance in terms of beam intensity, ratio between co-extracted electrons and negative ions, uniformity and divergence over the beam profile for up to one hour pulses. Some of the diagnostics are dedicated to the characterization of the plasma in the RF ion source and of the extraction region (measuring D- density and Cs dynamics). Others will measure the beam intensity profile, uniformity and divergence. The main SPIDER diagnostics are described in Table 2. The position of the current measurement sensor is also shown in Fig. 3.

TABLE 2: List of SPIDER Diagnostics.

Source Diagnostic	Measured Quantities and Output from Basic Analysis
Electrical currents	Current at power supplies and grounded grid, extracted and accelerated current
Calorimetry & surface thermocouples	Power load on source components and heat deposited over source surfaces
Electrostatic probes	Plasma uniformity, T_e, n_e
Source Optical Emission Spectroscopy	Source plasma T_e, n_e, n_{H-}, n_{Cs}, n_H, impurities, emission spectra, homogeneity
Cavity Ring Down Spectroscopy	Negative ion density $n_{H,}$, amount of H-/D- near plasma grid vs time
Laser absorption Spectroscopy	Atomic Cesium density $n_{Cs,}$, amount of caesium in source vs time
Beam Diagnostics	**Measured Quantities**
Beam dump calorimetry & thermocouples	Beam uniformity, divergence, aiming, vert. resolution 7 cm
STRIKE calorimeter with CFC tiles	Beamlet deflection, divergence & uniformity, res. 2mm,< 10 s beam pulses,
Beam Emission Spectroscopy (BES)	Beam divergence, stripping losses, beam uniformity, emission spectra,
Optical tomography	Beam uniformity over 2D profile, resolution 1/4 beamlet group
Neutron Imaging	Beam uniformity horizontal profile, resolution 3-4 cm, D only

Information from the two sets of measurements will allow to correlate the physical phenomena to the beam characteristics and to optimize the operational space. Some parameters can be measured by multiple diagnostics, allowing a mutual validation and a better physics insight. It is also expected that the results of the SPIDER experiment will be relevant for the ITER Diagnostic NBI, which will operate at 100 kV, 60 A. All the Source diagnostics are installed and operate, and most of beam diagnostics are also installed.

SPIDER Power Supply System and other Auxiliaries

The scheme of the SPIDER Power Supply system (Fig. 3) is consistent with that of ITER HNB. It is constituted by the Acceleration Grid Power Supply (AGPS) and by the Ion Source and Extraction Power Supply (ISEPS), which includes all the auxiliary power supplies necessary for RF source operation. As the ion source operates at -90 kV to ground, ISEPS is hosted in a large Faraday cage (13 × 11 × 5 m^3), called High Voltage Deck, mounted on supporting insulators and clad with a conductive metal sheet to reduce the electromagnetic interference. Figure 3 reports the scheme and the main rating of all the power supplies, together with the layout and their connections. The AGPS has been procured by INDA (the on-site tests are still in progress), whereas ISEPS have been procured and commissioned by F4E. All the other plant systems necessary to operate SPIDER, such as the Gas injection and Vacuum Systems (GVS), which includes high flow rate turbopumps and cryopumps (up to 50 mbar l/s for 3600 s), the water Cooling Plant (CP), capable of removing up 10 MW thermal power from the source and the power supplies, the Control and Data Acquisition system (CODAS) and Central Interlock System (CIS) have been procured and installed by F4E.

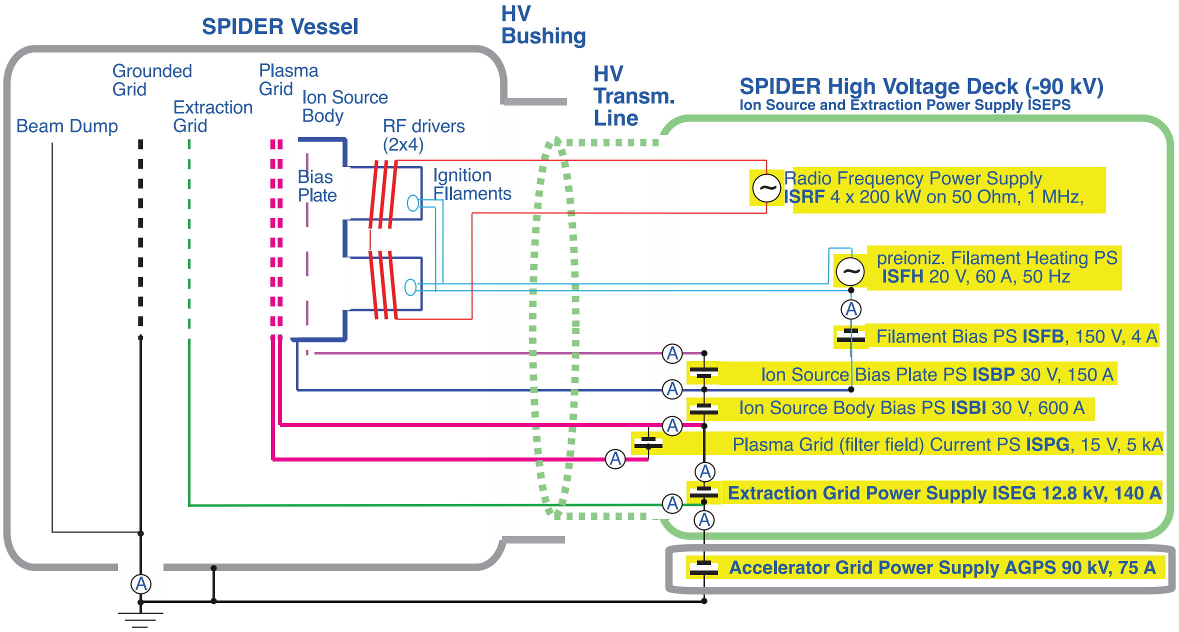


FIGURE 3. Scheme of the SPIDER power supplies, the current meters directly connected to the ISEG and to the AGPS will be used for evaluating the extracted current and the accelerated ion current.

SPIDER OPERATIONAL PLAN

The objective of SPIDER is the validation and optimization of all aspects concerning the generation of negative ions (quantity and uniformity) and the operation of the extractor (extracted current, co-extracted electrons suppression, voltage holding). In order to take maximum advantage of the results, the SPIDER operational plan was started in May 2018 to address most of these aspects in a period of about 2 years, i.e. before the MITICA beam source construction will be completed. Numerical simulations [12] and investigation in specific test beds, such as [13, 14, 15] will be instrumental in the interpretation of the results. On this basis, the operational plan consists of a sequence of integrated commissioning sessions immediately followed by experimental phases. The early phases of the plan are shown in Fig. 4. During each commissioning session, the test parameters of the plants are chosen on the basis of the parameters foreseen for the following experimental phase. This staged strategy is preferred with respect to the full-performance commissioning of each plant before the start of operation, as it represents a faster track towards the experimentation, which would anyway start at reduced performance. This staged approach also reduces the risk of delays in starting experiments; on the other hand, every time it is necessary to increase a plant parameter above the commissioned value, a dedicated commissioning session is required.

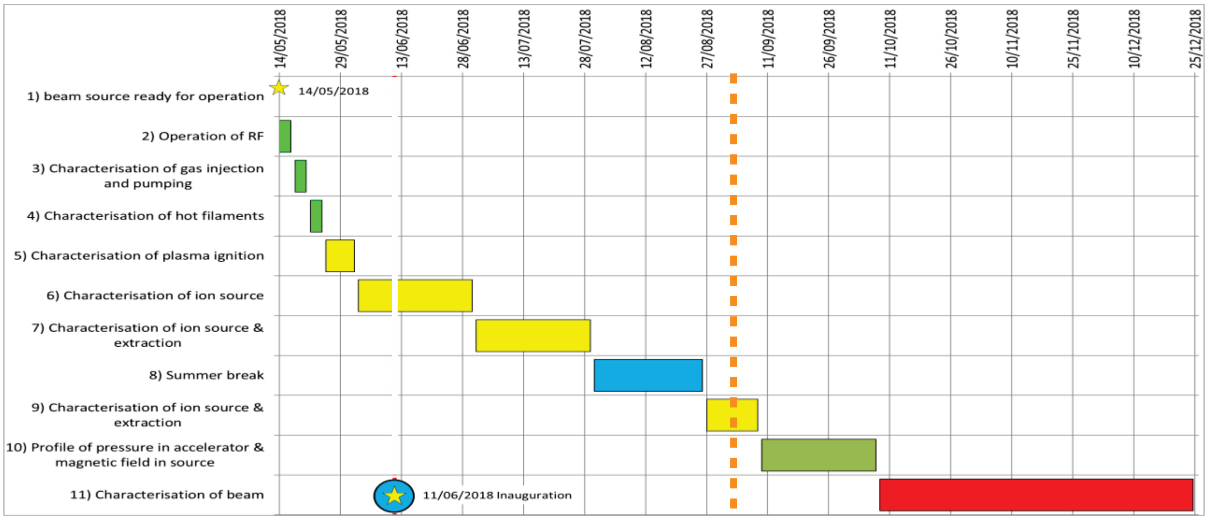


FIGURE 4. First phases and present progress of the SPIDER operational plan.

In February 2018 the SPIDER source was installed in the vacuum vessel, after separate commissioning the individual plants (power supplies, gas and vacuum and cooling), in March - May 2018 an integrated commissioning session was carried out first in air and then in vacuum. This allowed easy access for measuring voltages and currents without the need of repeatedly venting and vacuum pumping; the voltage holding test of the extractor and accelerator insulators were carried out within the permissible limits in this testing condition. The following steps were carried out:

- electrical characterization tests of each RF power supply (connected to two RF drivers and the relevant matching network capacitors) up to 40 kW, assessment of RF-induced noise on other components.
- tests of Ion Source Body Bias circuit, Ion Source Bias Plate circuit and ignition filament circuit .
- high voltage tests of Extraction and Acceleration stages using a test power supply, preliminary check of the high voltage insulation and assessment of leakage currents of insulators and of insulating breaks of the cooling water circuits (AGPS was unavailable due to site acceptance tests still in progress)
- test of Plasma Grid current circuit up to 3 kA, so as to produce a magnetic filter field.

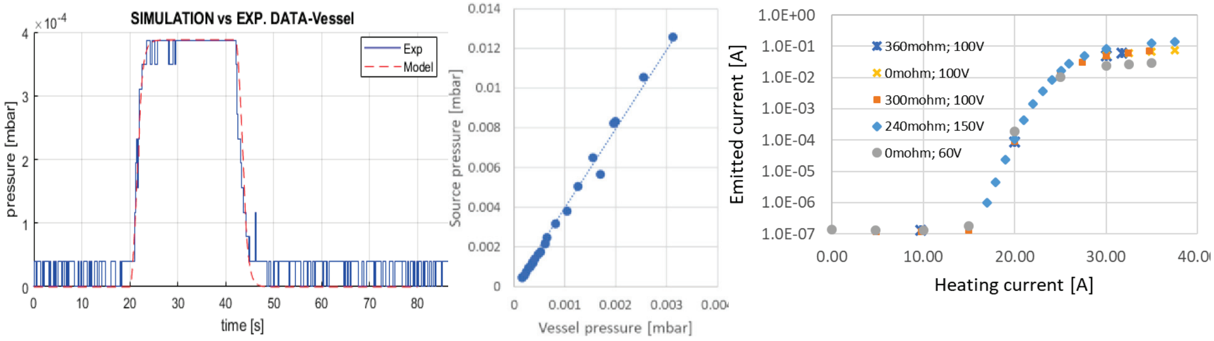
After the tests in air, similar tests were successfully carried out in vacuum, verifying the insulation of the various gaps, including those in the RF coils of the drivers. As a result of these tests, the correct operation of the whole system and the voltage holding capabilities of the cooling water circuits and of the insulators was verified. This concluded the first integrated commissioning phase.

START OF SPIDER OPERATION AND FIRST EXPERIMENTAL RESULTS

After the integrated commissioning phase in vacuum, SPIDER operation with hydrogen gas injection started at the end of May 2018. The first objectives were characterization of the gas pressure, operation of pre-ionization filaments and plasma ignition. The subsequent objective was the characterization of ion source operation, without caesium, initially with one or two RF power supplies (2 or 4 drivers). A first assessment of the influence of the filter field on plasma ignition and the ion source uniformity was also planned. The dependence of plasma parameters on filter field, bias plate bias and PG bias were investigated in the vicinity of the Plasma Grid (PG) at different gas pressures; the plasma drifts and non-uniformities in the same region have been identified. The pulse duration was limited to a few tens of seconds, taking into account in particular the heat load measured at all surfaces.

Gas Pressure Characterization and Pre-ionization Filament Characterization

Hydrogen gas was injected in the plasma source through the source backplate by means of two electromagnetic valves; the gas pressure was measured both inside the plasma source and near the front lid of the vessel, using capacitive pressure sensors. As shown in Fig. 5, the dynamic response of the vessel pressure to the gas injection was in agreement with the numerical models and the hydrogen pressure inside the plasma source was about a factor of 4 larger than in the vessel. The current emitted by the tungsten ignition filaments was measured in different conditions as function of the heating current. Fig. 5c shows the electron current emitted by the filaments in different operation conditions.

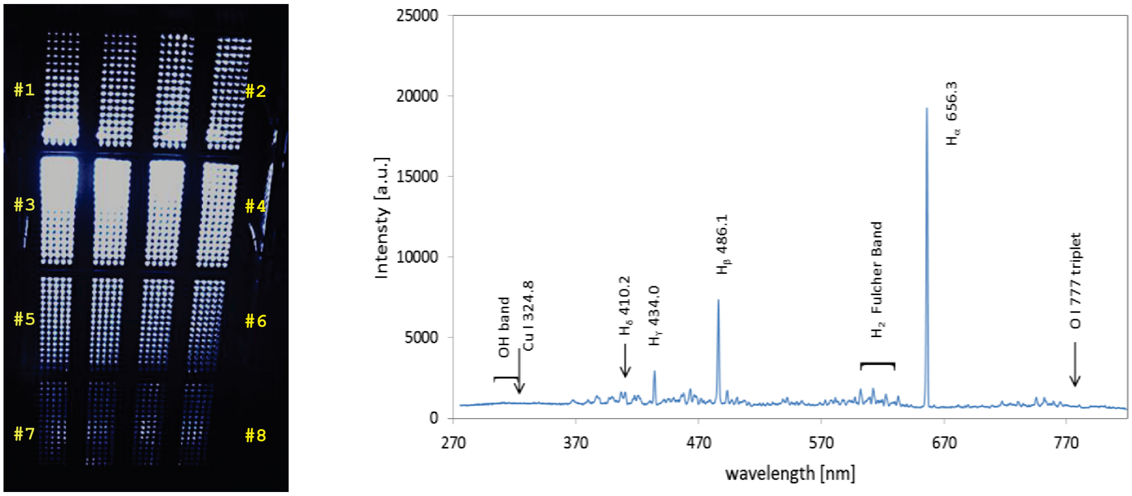


(a) (b) (c)

FIGURE 5: (a) Simulated and measured vessel pressure; (b) measured source and vessel pressures; (c) current emitted by pre-ionization filaments as a function of the heating current, a series resistor was used for adjusting the heating current.

Plasma Ignition and Plasma Light Characterization

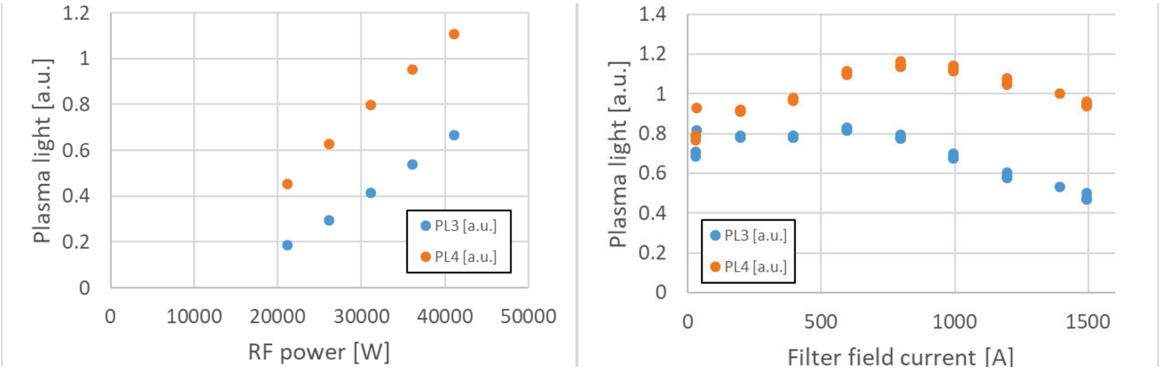
Different procedures were tested for igniting a hydrogen plasma in the ion source, but the most effective option consisted of applying a pre-defined hydrogen gas pressure by opening the electromagnetic valves and then ramping up the RF power. This procedure is different from the one used so far in ELISE and appears to be the only one which could avoid the occurrence of electrical breakdowns in the rear side of the plasma source,



(a) (b)

FIGURE 6. (a) Plasma light seen through accelerator grids from downstream side, only drivers #3 and #4 are powered; (b) plasma light spectra measured through the RF drivers;

In the first experimental phase, only one RF generator was powered so that plasma was ignited in the second row of drivers from the top (drivers #3 and #4). In a subsequent phase, also another generator was powered, and drivers of the fourth row (drivers #7 and #8) were also ignited. The light emission signal was intense as soon as the plasma was ignited. Figure 6a shows the plasma light produced by the drivers seen through the accelerator grids and Fig. 6b shows the typical spectrum of the light measured through each driver, after several weeks of operation (pulse #5210). No traces of OH, Cu or O emission were visible. (At the beginning of SPIDER operations some OH emission was visible, sometimes also Cu lines are also visible when discharges occur on the rear side of the source.)

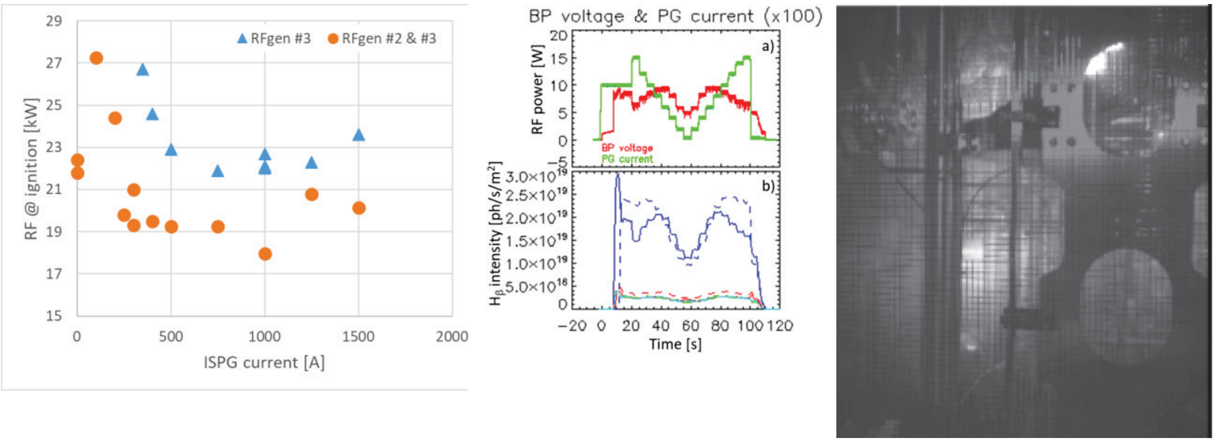


(a) (b)

FIGURE 7. (a) Plasma light measured through the RF drivers #3 and #4 as a function of RF power; (b) asymmetry of plasma light as a function of PG current

Figure 7 shows the plasma light from drivers #3 and #4 as a function of RF power and of Filter Field current; the plasma cannot be sustained when RF power is below 15 kW. The large asymmetry between plasma light in the two drivers (up to 2x) is very reproducible, and clearly depends on filter field current; similar results are found for the H_β intensity (Fig. 8b). The emitted light reaches a maximum for 600-700A and the asymmetry increases with current. Such left-right asymmetry has never been observed at ELISE (or RADI). This behavior could be attributed to a plasma drift near the drivers and needs further investigations.

Within the precautionary limit of 40 kW RF power per generator allowed during this first experimental phase, plasma ignition was obtained with a pressure in the ion source > 0.2 Pa. The magnetic filter field produced by the PG current also had important effects on ignition. Fig. 8a shows the RF power required to ignite the plasma as a function of the filter field current.



(a) (b) (c)

FIGURE 8: (a) RF power per generator at plasma ignition (single and pair of generators) as a function of filter field current (source pressure 0.3Pa; ramping rate of RF power 2kW/s. Source pressure: 0.3Pa, Vessel pressure: 0.075Pa) ; (b) time history of PG current, RF power and plasma light during a pulse; (c) visible light image of electric discharge on the rear side of the source.

The experiments also evidenced the occurrence of electric discharges between different components on the rear side of the source. These discharges can dissipate part of the RF power and sometimes hamper the RF load matching and thus the operation of the RF power supplies, particularly when the pressure in the vessel is larger than 80 mPa. Direct inspection of the beam source showed signs of electrical discharges on busbars of the RF circuits, on the filament supports and on the vacuum vessel. The conditions of the discharge occurrence are under investigation both theoretically and experimentally (high-speed camera images) with the aim of identifying a long-term solution and assuring a complete risk mitigation for the successful operation of MITICA and ITER HNB as well.

CONCLUSIONS

After assembly and commissioning, the first two months of operation of SPIDER have successfully demonstrated the ignition of hydrogen plasma in the ion source with up to 4 RF drivers. The experiments also evidenced the occurrence of electric discharges between different components on the rear side of the source. During SPIDER operation, by ion source spectroscopy and optical diagnostics the investigation of the effect of RF power and filter magnetic field on the plasma is already in progress.

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