

Lessons learned after three years of SPIDER operation and the first MITICA integrated tests

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ITER envisages the use of 2+1 heating neutral beam injectors as part of the auxiliary heating and current drive system, to help demonstrate the desired goals during its various phases of operation. The 16.5 MW expected neutral beam power per injector is several notches higher than worldwide existing facilities.

In order to enable such development, a Neutral Beam Test Facility (NBTF) was established at Consorzio RFX, exploiting the synergy of two test beds. SPIDER is dedicated to developing and characterizing large sources at relevant parameters in ITER-like conditions: source and accelerator located in the same vacuum where the beam propagates, electromagnetic interference of multiple radio-frequency (RF) antennas, RF-induced discharges on the outside of the source. Three years of

experiments on SPIDER have indicated the necessary design modifications to enable full performances. The source is presently under a long shut down to incorporate such learnings.

Parallely, developments on MITICA, the full-scale prototype of the ITER NBI featuring a 1 MV accelerator, are underway including manufacturing of the beam source and the beam line components. Power supplies and auxiliary plants have been installed.

Integration, commissioning and tests of the 1MV power supplies are essential for this first-of-kind system, unparalleled both in research and industry field. 1.2MV dc insulating tests of high voltage components were successfully completed. The integrated test to confirm 1MV output by combining inverter systems, DC generators and transmission lines extracted errors/accidents in some components, started. To realize a concrete system for ITER, phenomena have been addressed and solutions for the repair and the improvement of the system were developed.

Hence, NBTF is emerging as a necessary facility effectively dedicated to identify issues and find solutions to enable successful ITER NBI operations in a time bound fashion. The lessons learned during the implementation on NBTF and future perspectives are here discussed.

Keywords: ITER; NBTF; SPIDER; MITICA; Neutral Beam Injector

1. Introduction

The ITER Neutral Beam Test Facility (NBTF) is targeted at the development and testing up to nominal performances of the prototype for the ITER Heating Neutral Beam Injector (HNB) [1,2,3].

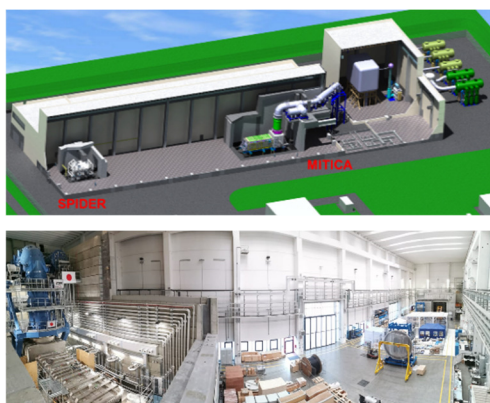


Fig. 1 – The Neutral Beam Test Facility, with SPIDER and MITICA experiments: (a) overview, (b) inside experiment building

The NBTF is established in Padova, integrated in an international framework of responsibility and collaboration with ITER Organization (IO), Fusion for Energy, JADA/QST and the involved European research institutes, and liaising with the Indian Test Facility (INTF) in charge of the ITER Diagnostic Neutral Beam (DNB).

Two experiments are foreseen on NBTF site: SPIDER features the first prototype of ITER ion source, with strong similarities with DNB configuration, while MITICA is the 1:1 prototype for ITER HNB.

In 2021, after three years of operation, SPIDER entered the long shut down phase with the aim of solving problems present from the beginning of the operation and found during the first operational phase, while MITICA is under the final integrated tests for the overall power supply system.

2. SPIDER

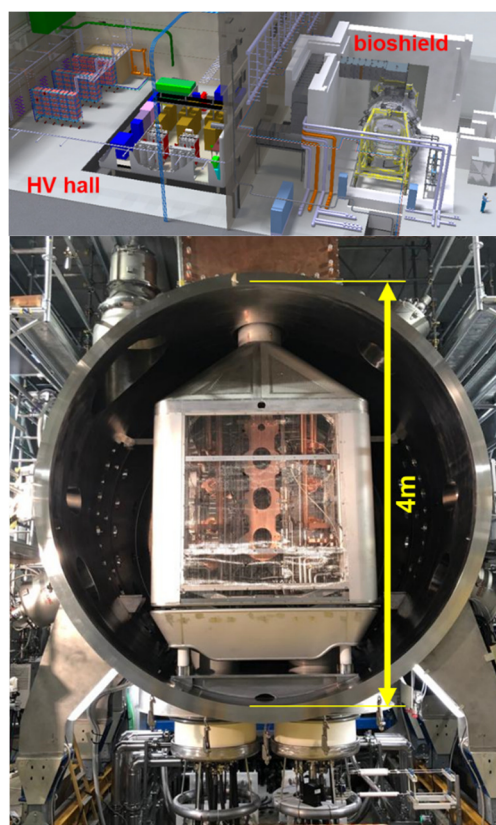


Fig. 2 – SPIDER experiment

Even before MITICA operation, already SPIDER experiment represents a novelty for many aspects, and not only dimensions.

The SPIDER testbed is operational since 2018. A number of occurrences characterized SPIDER operation, leading to the identification of early issues that in part were solved or worked around on the run, and other triggered requirements for repair or modification and opportunities for improvements. Among the most impacting factors, it is necessary to highlight that, unlike any other existing NBIs, the entire beam source of SPIDER (and MITICA) lies inside the vacuum vessel, so that it is surrounded by the same background gas at low pressure, in which the beam propagates.

2.1. Main recent experimental results

In these first three years, SPIDER operations generated a wealth of experimental information, which provided insight into the source performance and evidenced operational issues that must be resolved in view of extensive beam operation and particularly of MITICA.

The following figure summarizes SPIDER experimental campaign so far, highlighting main events, outputs and implications for the shutdown.

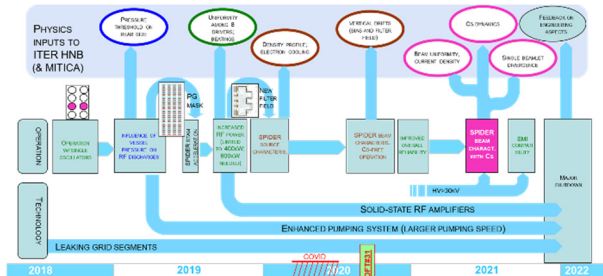


Fig. 3 – Summary of SPIDER experimental campaign

During the last campaign without Cs injection, the improved maturity of the system allowed to increase the performances, in particular the acceleration voltage, still with the mask on PG, allowing only few beamlets to be extracted, in order to prevent RF discharges occurred earlier [4].

It was possible to perform several scans to characterize the beam optics in volume up to 50kV, both in hydrogen and deuterium, with different settings of filter field and the other ion source power supply generators, exploiting in full the capabilities of the large set of diagnostics put in place.

Then, the first campaign featuring Cs injection was carried out: the production of negative ions in the proximity of the plasma grid clearly benefitted from the evaporation of caesium into the source, and the beamlet divergence decreased with respect to the operation without caesium.

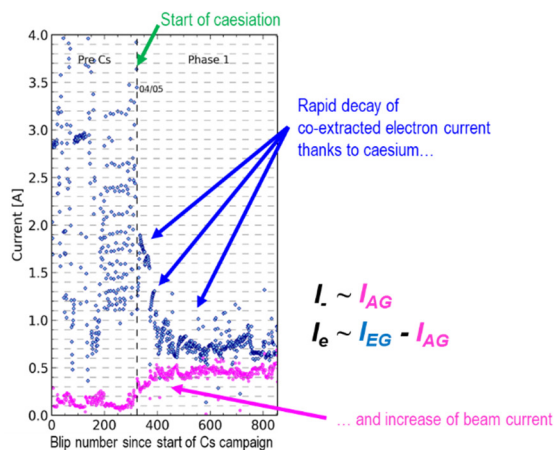


Fig. 4 – Immediate effect of first cesiation on electron and ion current

It was recognized that the negative ion current density and the current of co-extracted electrons, in the same conditions of RF power, gas pressure and bias voltages,

depend on the ratio between the caesium evaporation rate and the plasma on-off duty cycle, and the time evolution of H- density revealed the importance of the magnetic filter field in preserving the caesium layer on the plasma grid from the action of plasma.

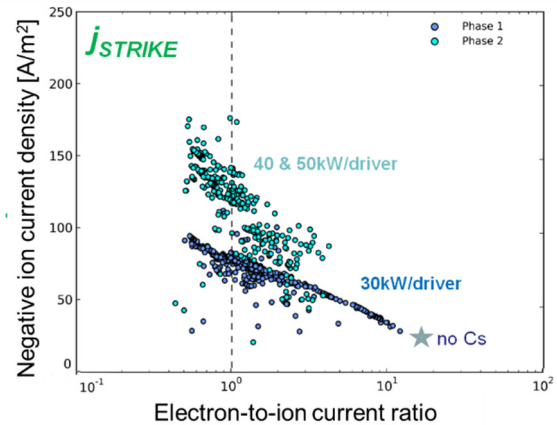


Fig. 5 – Electron-ion ratio and negative ion current density in the first cesium campaign, compared with no-Cs result

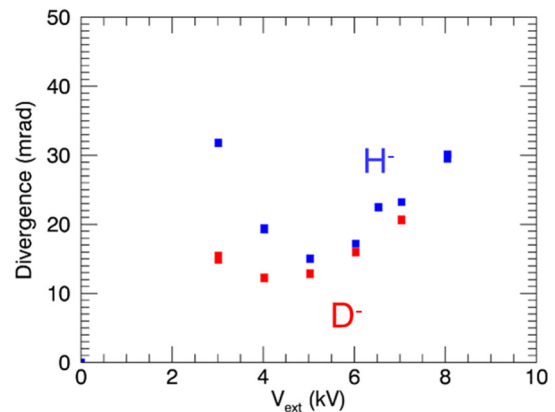


Fig. 6 – Beamlet divergence in the first cesium campaign

While for the ratio of co-extracted electrons to ions obtained results already match the target range, it has been recognized that ion current density, beam uniformity and divergence require further efforts in the future campaign to reach the objectives, in part due to the impossibility up to now to exploit in full the RF generators [5].

2.2. Shutdown activities

The SPIDER shutdown started at the end of 2021, extracting the source from the vessel, then carrying out a full disassembly and inspection of the status of individual parts.



Fig. 7 – Removal of SPIDER source

During inspection after disassembly many interesting details have been noted, bringing further inputs for the shutdown activities.



Fig. 8 – Disassembly and inspection of source parts (to be noted, copper peeking out from under molybdenum coating on PG)

Throughout the disassembly process, initial analyses of the machine and components were continuously performed and are still being done: chemical analyses of surface depositions; magnetic measurements of the permanent magnets embedded in the drivers, source walls and grid segments; He leak tests at hydraulic connections; grid relative positions by optical metrology; plasma facing surface state scanning and analysis.

Notable degradation of some parts was recorded and is under careful assessment: general surface condition of the source main chamber, effects from electrical discharges on the rear side of the source, damages to some alumina parts (bushings, washers, insulators) on driver back cover fixation and grid segments interfaces, damages on the bottom four drivers [6].

Nevertheless, the main goal of the shutdown focusses on the already identified substantial changes:

- modification of the beam source, consisting of already identified items plus findings during disassembly activities;
- replacement of RF oscillators with solid state amplifiers;
- upgrading of the pumping system to be able to operate the source up to 0.45 Pa of pressure with a $P_{\text{vessel}} \leq 40 \text{ mPa}$ in order to avoid the risk of discharges induced by the RF electric field, with no grid masking, hence all beamlets active;

- the replacement of damaged parts.

During the shutdown other activities will also be carried out, including maintenance and implementation of improvements to power supply and other auxiliary systems, updating of diagnostic systems [7,8,9,10].

At the end of the shutdown SPIDER is expected to be ready to proceed towards full performances.

2.3. Source modifications

The activities for the refurbishments and the modifications to the SPIDER Beam Source have been organized in projects, in order to better control the progress status and to follow-up the procurements:

- RF Driver enhancement: in addition to the improvement to the RF circuit layout and connections onboard the beam source, other modifications were designed, like electrostatic screens for shielding triple-points on capacitors and ceramic breaks, shown in Fig.90, and a new less cumbersome bias busbar on the back of RF source [11].

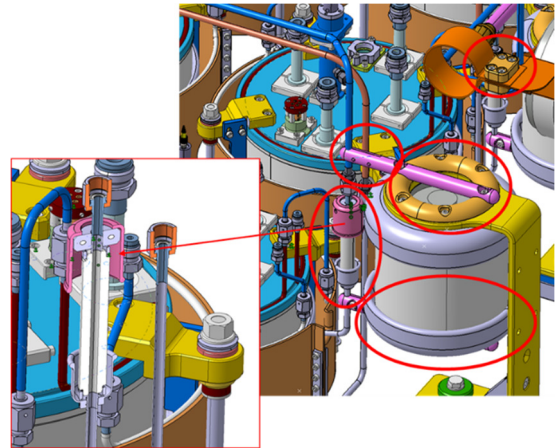
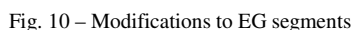


Fig. 9 – Modifications to electrostatic shield

- RF circuit layout improvement to reduce the mutual coupling between different driver pairs, which were found responsible for the modulation of the plasma light when two or more driver pairs were supplied [12]

- EG modifications: EG segments will be modified to be electrically insulated among themselves, in order to measure the electrical current collected by each segment from extracted beam, hence to identify excessive non-uniformities potentially dangerous for the segment integrity, plus the EG apertures will be tapered in order to increase the margin preventing the beamlets from colliding with the aperture' rims.



- Procurement of a grounded grid segment to replace the leaky one

2.4. RF power supply generators

Since the beginning of the experiments in SPIDER, however, the operation of the RF oscillators has been hindered by some important limitations. First of all, the appearance of the so called “frequency flips” [15], which are frequency instabilities intrinsic in the operation of the oscillator on a resonant load preventing the achievement of the matching conditions [16]. Even though the mechanism of their onset has been understood and modelled in SPIDER, frequency flips are unavoidable and

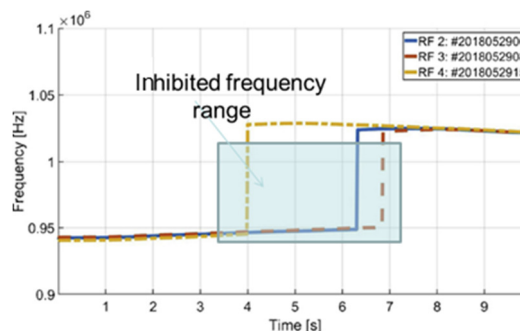


Fig. 11 – Frequency flips with RF oscillators, impeding to reach the best matching conditions with plasma impedance

The above-mentioned evidences led to the decision to replace the RF generators in SPIDER and MITICA and change the current ITER baseline from self-excited free running tetrode oscillator technology to solid-state amplifier technology [12,18,19]. The solid-state amplifier technology is believed to be strongly attractive for ion source operation, since no frequency flip phenomena are expected and there are no tetrodes requiring high voltage. In fact, at IPP solid-state generators have already been tested with positive feedback.

2.5. Vacuum system enhancement

All these aspects, which are linked, require the installation of an additional pumping system to be operated in parallel to the existing one.

The agreed solution consists of the NEG pump system, based on the Non-Evaporable Getter cartridges of ZAO® alloy, developed by SAES Getters company [20,21]. The cartridge is composed by NEG disks organized in stacks. The cartridges are arranged on panels with a regular pattern, to be installed inside the SPIDER vessel.

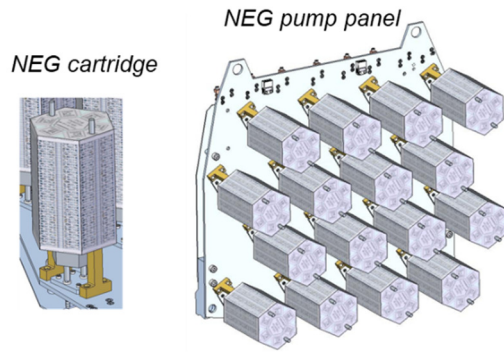


Fig. 12 – NEG pump basic elements, cartridge and panel

The system is completed with the power supply necessary to heat the NEG elements for activation and regeneration and the local control unit needed to operate the pump.

An additional cylindrical sector is needed to extend the existing SPIDER vessel and to host the NEG system; moreover, thermal electrostatic shields shall be included with the double scope to protect the NEG pump from electrical discharges occurring on the beam source, and to protect all the components surrounding the NEG pump from thermal radiation during regeneration, requiring high temperature for the cartridges. All these new elements will be actively cooled by a dedicated water circuit [22].

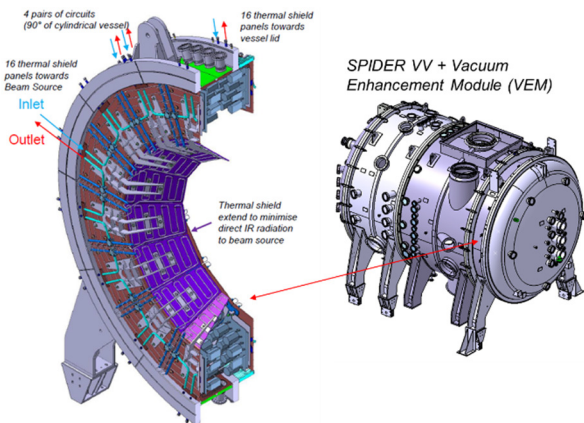


Fig. 13 – Additional vessel module with NEG panels and actively cooled thermal shields

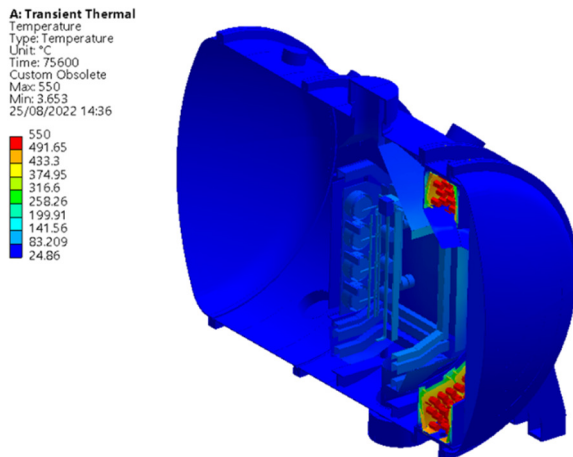


Fig. 14 – Temperature distribution during regeneration

2.6. Other sub-systems

The Cs oven plant is composed of an insulated cubicle inside the HVD containing the power supplies, the diagnostic racks and the PLC periphery (I/O modules) that are connected to the ovens by means of the transmission line, at the beam source potential. This cubicle is connected to that one in the I&C room which hosts the local control panel, the PLC CPU and the connections to CODAS and Interlock by means of fiber-optics to allow electrical insulation as shown in Fig. 15. Before the operation on SPIDER a Cs oven prototype and the 3 definitive ovens have been tested and characterized on the CATS (Caesium Test Stand) facility at NBTF [23,24]. After the tests, the 3 Cs ovens have been installed with no Cs on the rear side of the BS and the system integrated commissioning was carried out, with special attention to check whether the RF system of the source could affect the reliability of Cs plant and the feedback control of the Cs evaporation temperature. After having successfully completed the commissioning, demonstrating compatibility and resilience to EMI and noise, each oven was filled with 10g of metallic Cs and re-installed on the beam source. Cs evaporation has been successfully performed at different flow rates (6 – 20 mg/h per oven) throughout the whole campaign and its effect on the co-extracted electrons and negative ion generation has been shown in [4,6]. Cs flow is controlled by adjusting the evaporation temperature in the reservoir and it is constantly measured by means of a Surface Ionization Detector (SID) placed directly on the injection nozzle. Finally, during the oven inspection at the end of the campaign, contaminated Cs was found in the reservoirs. This probably was due to the massive water leak occurred at last causing water vapor to react with the remaining Cs and impurities, so compromising the leak tightness of the valve of the oven. Therefore, the total quantity of evaporated Cs during the experimental campaign could not be inferred by direct weighting of residual Cs in the reservoir, but it can only be estimated by the SID data. SID measurements are sufficiently accurate as shown in [6] and, specifically, they show that a total of 2.4g of Cs has been evaporated by the 3 ovens.

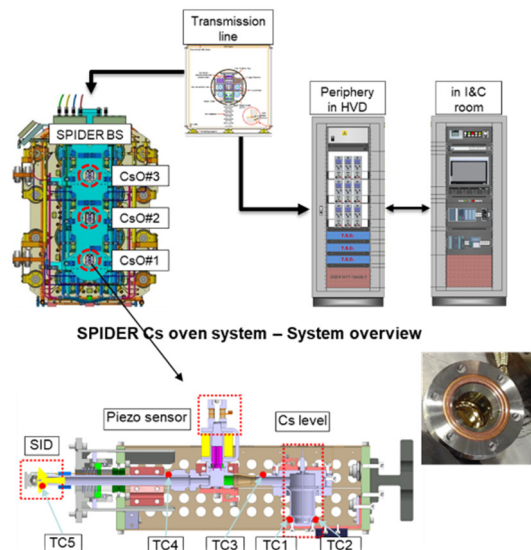


Fig. 15 – SPIDER Cs oven

The suite of diagnostics with complementary capabilities dedicated to the SPIDER source and beam proved essential to characterize the performance and identify the still open issues. The beam diagnostics used so far are illustrated in Fig.16 [25,26,27,28,29,30,31]: STRIKE uncooled calorimeter, with high spatial resolution, measures the single beamlet intensity profile, visible tomography and beam emission spectroscopy derive the beamlets intensity and divergence respectively without intercepting the beam; current monitors of individual beamlets measure also the high frequency components of the beam intensity and the Allison scanner provide the full emittance of specific beamlets. The last two systems were not part of the initial set and have been developed and installed during the experimentation phase, to validate and extend the capabilities of the other systems. Along the same logic, other diagnostics will be introduced in the current shutdown, mainly to better investigate the non-uniformity in the plasma source both locally inside a beamlet group and globally over the source extension [32,33,34,35]. Among them, insertable probes are foreseen to measure the plasma parameters along a driver axis up to the grids and parallel to the plasma grid; a retarded field energy analyzer will measure the positive ions energy distribution at the plasma grid; Fiber Bragg Grating sensors will replace thermocouples where they were strongly affected by electromagnetic noise.

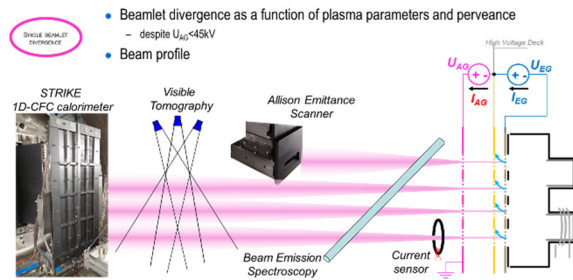


Fig. 16 – Single beamlet characterization

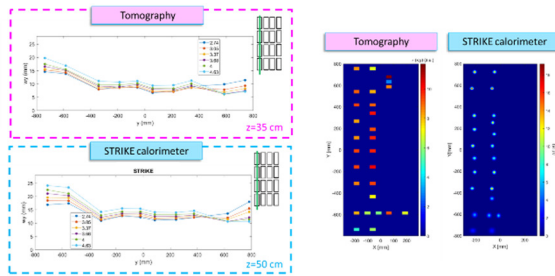


Fig. 17 – Multi-beamlets characterization & (plasma)/beam uniformity

3. MITICA

MITICA, the one-to-one prototype for ITER HNB, is gradually approaching the start of operation.

Prior to that, three main areas of work are being dealt with in order to complete the experiment assembly, testing and commissioning:

- Last components/plants still under completion [36,37]

- Power supply integrated final tests and commissioning
- Preparation for a dedicated campaign of HV holding tests in vacuum



Fig. 18 – Current status of MITICA injector

3.1. Ongoing procurements

While power supply system installation on site has been completed some years ago to allow the necessary long testing phase, other components and auxiliaries are still under procurement or installation activities:

- procurement is still ongoing for in-vessel mechanical components (F4E procurement), such as beam source, beam line components and cryopumps;

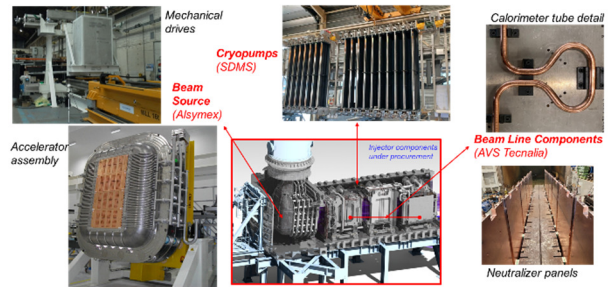


Fig. 19 – Ongoing procurements for MITICA in-vessel components

- Auxiliary plants procurement under completion (F4E procurement), like cryogenic plant
- Last one to one “single-plant”/CODAS integrated commissioning ongoing or expected soon

3.2. Integrated power supply tests

MITICA power supply is a very complex system, beyond the limit of modern technologies [38]. It is the first prototype developed in the world at 1MVdc with such power rating. One major purpose for MITICA is to test and fine-tune these power supplies.

Designed by the European and Japanese teams under IO coordination, and based on international Codes and Standards and previous experience at JT60 plus additional

specific R&D, the high voltage components for power supplies were procured by JADA and F4E. Each team supplied its share, including installation onsite and standalone Site Acceptance Tests.

Nevertheless, systems at the end are strongly integrated and this required a deep coordination for the interfaces and an integrated commissioning process, very complex in technical terms and also responsibility-wise.

After successful completion of insulation tests and functional tests at low power, in 2021 failures occurred during the 1MV power integrated tests due to Breakdowns (BD) that damaged two components of the power supply system [39,40,41,42]:

- one branch of the diode bridge of stage DCG1 (800kV-1MV)
- HV bushing of the 1 MV insulating transformer

Before the faults, the integration tests showed the capability of the MITICA power supply to successfully achieve 700kV for 1000s.

Inspections and analyses using high frequency models were carried out to determine the root cause: the dynamics of failures due to a breakdown was explained, and solutions to increase the reliability and availability of the system have been identified. They will be implemented in MITICA during the repair phase. Very useful inputs for improving the design of the power supplies of ITER has been derived also, triggering a review of the existing project to include additional protections.

However clear evidence of where the BDs occurred was not found.

Hence, currently the overall activity, undertaken by QST, NBTF team and IO, is proceeding on parallel lines:

- execution of insulation test campaigns to find the position of the BDs and increase the tightness of the system's insulation, also exploiting additional BD diagnostics and monitoring system developed with the support of experts from a high voltage laboratory;
- development of repair and improvement plans for the diode bridges and the 1MV insulating transformer with introduction of additional protection systems.

3.3. Preparations for HV tests in vacuum

HV test campaigns on MITICA experiment foreseen starting before the installation of in-vessel components aim at gaining insights to one of the main topics to be investigated by the MITICA testbed.

The test strategy has been discussed among all the international stakeholders, and the main objectives of these tests have been identified:

- verify and improve the insulation of MITICA up to -1 MV in vacuum and low-pressure gas, before the installation of the Beam Source;

- establish and validate Voltage Holding scaling laws for large gaps and multiple electrodes (required for effective design optimization).

A project was launched to cope with the design, procurement and installation of the BS mockup to exploit the time window before the delivery of the actual source [43,44].

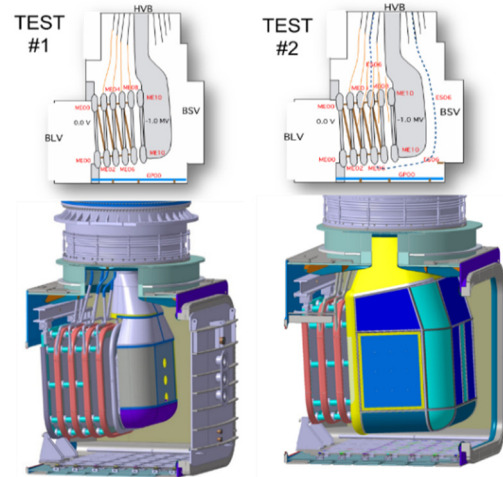


Fig. 20 – Configurations for HV tests in vacuum

Experiments carried out at QST showed the likely need of at least one intermediate shield at intermediate voltage in order to enhance the voltage holding between ion source at -1 MV and the grounded vessel. An intermediate electrostatic shield that will be installed on the -600 kV stage has been designed, in order to be tested on the mockup and also reused on the actual beam source, if confirmed necessary. The design takes into account electrostatic purposes and conflicting need to allow evacuation of the volume around the outer rear side of the source, resulting in a double-skin configuration with staggered patterns of holes.

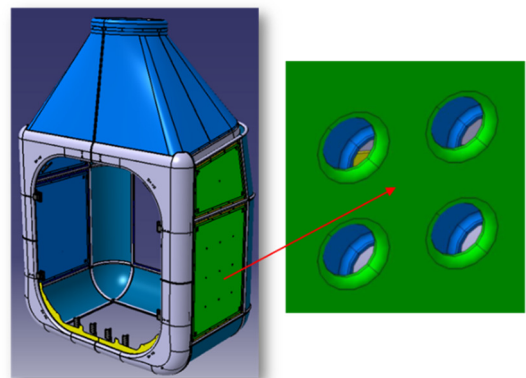


Fig. 21 – Design of the intermediate electrostatic shield

In addition, ancillary elements have been identified and added to the project: vacuum pumping system monitoring cameras and integration of electrical measurements and dedicated control system.

The Testing Power Supply (TPS) is the identified system to be used to carry out the HV holding tests, but it requires upgrade in view of them, as it was designed for insulation tests and not to withstand breakdown events.

Moreover, it shall be integrated in the control system targeted to manage these tests.

4. Conclusions

SPIDER is entering the first long shutdown after the first three years of experiments. Interesting results have been obtained, which have also identified necessary modifications, mainly focused on source upgrade, RF generators replacement and enhancement for the vacuum pumping system, in order to quest the target performances during the next operational phase.

MITICA is proceeding towards the end of preparatory activities prior to the start of the first experimental campaign. Some breakdowns occurred during final integrated tests for the power supply system, which anyway demonstrated the capability of the system to generate 700kV for as long as 1000s. Such BDs showed that MITICA is very useful also in this phase to identify weak point of the design in advance of the ITER installation and derive, thanks to new models developed ad-hoc, remedial actions and additional protections which can be applied both in MITICA and in ITER-HNBs identified.

In parallel to the completion of the procurements for in-vessel components, preparations for the execution of HV tests in vacuum are ongoing to investigate this critical aspect prior to the first experimental campaign.

Overall, the most positive aspect of these experiences on both SPIDER and MITICA is that the facility is fully fulfilling its role, highlighting the critical issues of the project and allowing to intervene before the system is implemented on ITER.

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Bibliography

- [1] L.R. Grisham et al., *Fus Eng. Des.* 87 (2012) 1805-1815
- [2] V. Toigo et al., *New J. Phys.* 19 (2017) 085004
- [3] V. Toigo et al., *Fus. Eng. Des* 168 (2021) 112622
- [4] E. Sartori et al., Influence of plasma grid-masking on the results of early spider operation, proceedings for this SOFT congress
- [5] N. Marconato et al., Integration of new sets of magnets for improved plasma confinement in the SPIDER experiment, proceedings for this SOFT congress
- [6] C. Gasparini et al., Status of the SPIDER source after 3.5 years operation, proceedings for this SOFT congress A. Luchetta et al., As built design of the control system of the ITER full-size beam source SPIDER in the Neutral Beam Tests Facility - A critical review,

- proceedings for this SOFT congress
- [7] G. Manduchi et al., CODAS for long lasting experiments. The SPIDER experience, proceedings for this SOFT congress
- [8] G. Serianni et al., SPIDER real-time data visualization tool, proceedings for this SOFT congress
- [9] L. Grando et al., As built design, commissioning and integration of the SPIDER and NBTF central safety systems, proceedings for this SOFT congress
- [10] M. Bigi et al., An update of the design of SPIDER Ion Source and Extraction Power Supplies after four years of operation, proceedings for this SOFT congress
- [11] M. Recchia et al., Improvement in the electrical design of the SPIDER beam source, proceedings for this SOFT congress
- [12] A. Maistrello et al., Overview on electrical issues faced during the SPIDER experimental campaigns, proceedings for this SOFT congress
- [13] R. Zagorski et al., 2D simulations of inductive RF heating in the drivers of the SPIDER device, proceedings for this SOFT congress
- [14] A. Zamengo et al., Electrical and thermal analyses for the radio-frequency circuit, *Fusion Engineering and Design*, vol. 84, p. 2025–2030, 2009
- [15] M. J. Singh et al, RF-Plasma Source Commissioning in Indian Negative Ion Facility, *AIP Conference Proceedings*, vol. 1390, no. 1, pp. 604-613, 2011
- [16] F. Gasparini et al, Investigation on stable operational regions for SPIDER RF oscillators, *Fusion Engineering and Design*, vol. 146, pp. 2172-2175, 2019
- [17] A. Zamengo et al, Power supply system for large negative ion sources: Early operation experience on the SPIDER experiment, *Fusion Engineering and Design*, vol. 173, p. 112790, 2021
- [18] R. Casagrande et al., Design of RF solid-state generators for the high-power ion sources of NBTF experiments and ITER HNB, proceedings for this SOFT congress
- [19] M. De Nardi et al., Special tests of the solid-state RF amplifiers prototype for the ITER HNB and the NBTF experiments, proceedings for this SOFT congress
- [20] F. Siviero et al., Characterization of ZAO® sintered getter material for use in fusion applications, *Fusion Engineering and Design*, vol. 146, pp. 1729-1732, 2019
- [21] F. Siviero et al., Robustness of ZAO based NEG pump solutions for fusion applications, *Fusion Engineering and Design*, vol. 166, 112306, 2021
- [22] C. Cavallini et al., Study, design and thermal-hydraulic simulations of Vacuum Enhancement Module cooling circuit, proceedings for this SOFT congress
- [23] M. De Muri et al., SPIDER Cs Ovens functional tests, , *Fusion Engineering and Design* (2021)
- [24] A. Rizzolo et al., Characterization of the SPIDER Cs oven prototype in the CAesium Test Stand for the ITER HNB negative ion sources, *Fusion Engineering and Design* (2019)
- [25] M. Barbisan et al., Characterization of cesium and H-/D- density in the negative ion source SPIDER, proceedings for this SOFT congress
- [26] B. Duteil et al., First characterization of the SPIDER beam AC component with the Beamlet Current Monitor, proceedings for this SOFT congress
- [27] R. Delogu et al., STRIKE beam characterization by means of machine learning techniques: application on experimental data, proceedings for this SOFT congress
- [28] I. Mario et al., Beam uniformity studies based on neutrons measured with a scintillator array at SPIDER with Cs injection, proceedings for this SOFT congress
- [29] R. Agnello et al., Measurement of stripping losses in the negative ion source SPIDER, proceedings for this SOFT congress
- [30] A. Shepherd et al., Characterization of SPIDER beam homogeneity in caesium using a direct measure of the beamlet current, proceedings for this SOFT congress
- [31] O. McCormack et al., Flux symmetry and operational comparison of EJ276 and EJ309 scintillators for fusion neutron spectroscopy at SPIDER, proceedings for this SOFT congress
- [32] R. Pasqualotto et al., Improvement of SPIDER diagnostic systems, proceedings for this SOFT congress
- [33] M. Ugoletti et al., Development of the tomographic reconstruction technique of SPIDER negative ion beam, proceedings for this SOFT congress
- [34] V. Candeloro et al., Design of a movable electrostatic diagnostic for the investigation of plasma properties in a large negative ion source, proceedings for this SOFT congress
- [35] M. Brombin et al., Custom thermocouple input module for sensors

on the Grounded Grid of SPIDER, proceedings for this SOFT congress

- [36] M. Battistella et al., Functional safety assessment process for MITICA safety system in the ITER neutral beam test facility, proceedings for this SOFT congress
- [37] R. Moron et al., The beam source of the MITICA experiment: strategy adopted, manufacturing design, engineering and fabrication of the main components, proceedings for this SOFT congress
- [38] L. Zanutto, A. Ferro and V. Toigo, Fus. Eng. Des 84 (2009) 2037-2041
- [39] M. Boldrin et al., Partial discharge detection in 1 MV power supplies in MITICA experiment, the ITER heating neutral beam injector prototype, proceedings for this SOFT congress
- [40] L. Zanutto et al., A strategy to identify breakdown location in MITICA test facility: results of high voltage test campaign, proceedings for this SOFT congress
- [41] M. Dan et al., Modelling activity in support of MITICA High Voltage System protection, proceedings for this SOFT congress
- [42] M. Kashiwagi et al., Progress of R&D for 1MV High Voltage Power Supply for ITER NBI, proceedings for this SOFT congress
- [43] D. Aprile et al., Design of electrodes for high voltage tests in MITICA, proceedings for this SOFT congress
- [44] T. Patton et al., Electrical diagnostics for high voltage tests in MITICA, Electrical diagnostics for high voltage tests in MITICA, proceedings for this SOFT congress