Progress in the ITER Neutral Beam Test Facility

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The ITER Heating Neutral Beam (HNB) injectors, one of the tools necessary both to achieve burning conditions and to control plasma instabilities, are characterized by such demanding parameters as to require the construction of a test facility dedicated to their development and optimization. This facility, called NBTF, is in an advanced state of realization in Padua, Italy, with the direct contribution of the Italian government, through the Consorzio RFX as the host entity, IO, the in kind contributions of three DA’s (F4E, JADA, INDA) and the technical and scientific support of various European laboratories and universities.

The NBTF hosts two experiments: SPIDER and MITICA. The former is devoted to the optimization of the HNB and DNB ion sources and to the achievement of the required source performances. It is based on the RF negative ion source concept developed at IPP, Garching. MITICA is the full size prototype of the ITER HNB, with an ion source identical to the one used in SPIDER.

The construction and installation of SPIDER plant systems was successfully completed with their integration into the facility, followed by integrated commissioning with control (CODAS), protection and safety systems. The mechanical components of the ion source have been installed inside the vessel and connected to the plants. Finally, the integrated commissioning of the whole system ended positively and the first experimental phase began. The realization of the MITICA project is well advanced, although the completion of the system and its entry into operation is expected in 2022 due to the long procurement times of the in-vessel mechanical components. In particular, the power supply designed to operate at 1 MV are in an advanced phase of realization, all the high voltage components have been installed and the complex insulation test phase has begun in 2018. Furthermore, all the other auxiliary plant systems are being installed and/or are undergoing testing. This paper gives an overview of the progress of the NBTF realization with particular emphasis on issues discovered during this phase of activities and to the adopted solutions in order to minimize the impact on the schedule while maintaining the goals of the facilities. Finally, the first results obtained with SPIDER experimentation and with the 1 MV insulation tests on the MITICA HV components will be presented.

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PROGRESS IN THE ITER NEUTRAL BEAM TEST FACILITY

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Abstract

The ITER Heating Neutral Beam (HNB) injectors, one of the tools necessary both to achieve burning conditions and to control plasma instabilities, are characterized by such demanding parameters as to require the construction of a Neutral Beam Test Facility (NBTF) dedicated to their development and optimization. The NBTF was realized in Padua (Italy), with the direct contribution of the Italian government, through the Consorzio RFX as the host entity, IO, the in kind contributions of three Domestic Agencies (F4E, JADA, INDA) and the technical and scientific support of various European laboratories and universities. The NBTF hosts two experiments: SPIDER and MITICA. The former is devoted to the optimization of the HNB and DNB ion sources and to the achievement of the required source performances. MITICA is the full size prototype of the ITER HNB, with an ion source identical to the one used in SPIDER.
This paper gives an overview of the progress of the NBTF realization with particular emphasis on issues discovered during this phase of activities and to the adopted solutions in order to minimize the impact on the schedule while maintaining the goals of the facilities. The realization of MITICA is well advanced; it is expected to enter into operation in 2023 due to the long procurement times of the in-vessel mechanical components. The power supply designed to operate at 1MV are in an advanced phase of realization; all the high voltage components have been installed and the complex insulation test phase has begun in 2018. The construction and installation of SPIDER plant systems was successfully completed with their integration into the facility. The mechanical components of the ion source were installed inside the vessel and connected to the plants. The integrated commissioning with control (CODAS), protection and safety systems ended positively and the first experimental phase began. Finally, the first results of the SPIDER experimentation and of the 1MV insulation tests on the MITICA high voltage components are presented.

1. INTRODUCTION

The ITER Heating Neutral Beam (HNB) injectors [1], one of the tools necessary both for the achievement of the burning conditions and for the control of plasma instabilities, are characterized by demanding parameters, such as 1MeV particle energy, 40A beam current over an extraction area of 0.2 m², and long pulse operation up to 3600s. So the development and optimization of the HNB called for the construction of a dedicated test facility [2]. This Neutral Beam Test Facility (NBTF) [3], is in an advanced state of realization in Padua (Italy), with the direct contribution of the Italian government, through Consorzio RFX as the host entity, ITER Organization (IO), the in-kind contributions of European, Japanese and Indian Domestic Agencies (DA) and the technical and scientific support of various European laboratories and universities. The NBTF hosts two experiments: SPIDER [4] and MITICA [5]. The former is devoted to the optimization of the HNB and Diagnostic Neutral Beam (DNB) ion sources and to the achievement of the required source performances. Both are based on the RF negative ion source concept developed at IPP (Garching) [6]. MITICA is the full size prototype of the ITER HNB, with an ion source design close to the one used in SPIDER, but with modifications in view of its integration into the 1MV design. The development of SPIDER and MITICA are progressing in parallel. Realization and commissioning of SPIDER have been successfully completed and the first experimental phase has begun. During the installation of the components some issues were identified and are being thoroughly analyzed. Since the first experimentation is at low power and for short duration, the problems which are not critical for the experiments in the near term are deferred to subsequent shut-downs. This way a robust and scientifically meaningful experimental program can be carried out for the first months along a stepladder approach towards the full performance capability, while meeting the required operational parameters in each experimental phase. The MITICA project is also in a well advanced stage, although the completion of the system and its entry into operation is expected in 2023 due to the long procurement time of the in-vessel mechanical components. The power supply systems of MITICA, designed to operate at 1MV, are in an advanced phase of realization, all the high voltage components have been installed and the complex insulation test phase has begun in 2018.

Within this framework, the present paper gives an overview of the progress of the NBTF development with particular emphasis on issues that emerged during this phase of activities and to the adopted solutions in order to minimize the impact on the schedule while maintaining the goals of the facilities. Finally, the first results of the SPIDER experimentation and of the 1MV insulation tests on the MITICA High Voltage (HV) components will be presented.

2. SPIDER

SPIDER is the prototype of the negative ion source for the HNB. The source design, of the RF type, was based on the R&D developed at IPP in the past years [6], with specific improvements to achieve long duration pulses on a full ITER-size ion source, in a vacuum environment and with optimized beamlet optics. Main SPIDER requirements are reported in Table 1. Moreover, the beam optics will be investigated and compared with numerical models both in terms of beamlet divergence and beam aiming, including the different methods for negative ion steering. The SPIDER experiment is also necessary to assess the design of the 800kW inductive plasma source and of the cooling efficiency of the ion source and the extractor, which are the same as for MITICA. For this reason it was important that SPIDER operation started in 2018, in time to provide confirmation of the design of ion source and extractor during the manufacturing of the MITICA beam source.

<table>
<thead>
<tr>
<th>TABLE 1. SPIDER REQUIREMENTS</th>
<th>Unit</th>
<th>H</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>keV</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Max beam source pressure</td>
<td>Pa</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Maximum deviation from uniformity</td>
<td>%</td>
<td>±10</td>
<td>±10</td>
</tr>
<tr>
<td>Extracted current density</td>
<td>A/m²</td>
<td>&gt;355</td>
<td>&gt;285</td>
</tr>
<tr>
<td>Beam on time</td>
<td>s</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>Co-extracted electron fraction (e-/H-), (e-/D-)</td>
<td>&lt;0.5</td>
<td>&lt;1</td>
<td></td>
</tr>
</tbody>
</table>
2.1. Power Supply and auxiliary systems

The period from 2015 to 2017 was particularly abundant of activities related to system realization processes i.e. acceptance tests and integration of the components into the whole system. Interface management was challenging in this phase. The objective was to complete Power Supplies (PSs) and auxiliaries before commencing commissioning and the experimental activities scheduled for the beginning of 2018.

The ion source and extractor power supplies (ISEPS) include the RF generators feeding the RF drivers, the extraction grid HV generator plus other secondary power supplies for pre-ionization filaments, magnetic filter, etc.; they are installed inside a Faraday cage (HVD) and powered via an insulation transformer. ISEPS, HVD and the transmission line connecting HVD to vacuum vessel, were completed, tested and accepted in 2016. Subsequently, they were commissioned and integrated with CODAS and Interlock on dummy loads and made ready to be used for the experiment [7].

Similarly, gas and vacuum plant and cooling plant were installed and commissioned by 2017. Unfortunately, due to an accident that occurred at the end of 2017, part of the cooling system was flooded and partially damaged. A temporary solution was soon identified and implemented that allowed the experimentation to start albeit with reduced performances. Indeed preliminary studies have shown that this solution allows carrying out the first experimental campaigns, including the beam extraction for tens of seconds, without limitations, and to carry out in parallel the recovery activities of the damaged parts.

Some difficulties were found during the installation of the accelerator PSs (AGPS), see Fig.1, which led to a delay in the availability of the system, also due to the strong integration of the system with the buildings and to the need for adaptations necessary to meet the safety requirements prescribed by Italian laws. Subsequently, the Site Acceptance Tests (SATs) of the AGPS were carried out successfully, and in very limited time, demonstrating the full performance of the system, thanks to the debugging previously carried out on an identical prototype available at the supplier premises in India. Also in this case, even in the presence of a delay in the availability of this power supply system, the initial phases of the SPIDER experimental activity were not affected, as acceleration of the beam was not required. Integration of the AGPS is scheduled for Q4 2018.

2.2. The Beam Source and the overall commissioning

Given the complexity of the system, the realization of the ion source, the core of the SPIDER experiment, required a great effort and continuous monitoring by the involved companies and by the expert supervisors. Many technical issues were encountered during manufacturing and assembly of components [8]: e.g. the surface conditions of the cooling circuit elements, which would degrade the cooling water quality in terms of electrical conductivity, and the polluted/oxidized internal surfaces of the source, on which a molybdenum layer was deposited, to reduce the sputtering yield of surface material in view of caesium operation. Each of these problems were analyzed in detail by applying multidisciplinary competencies; despite the efforts to implement all individual corrective actions, they eventually resulted in a delay of the conclusion of the procurement, while still leaving a few points open, like a leak on a grounded grid segment, which would have required a significant time to recover. Pre-assembly activities were completed in the first half of 2017, immediately followed by factory acceptance tests. During the realization, some modifications were also implemented, taking into account recent results obtained in other accompanying experiments, like the electromagnetic shields decoupling the 8 RF drivers, derived from the experience in the ELISE facility. Some novel concepts, introduced in the design phase, were validated in parallel in existing experiments, like the magnetic compensation of electron and ion trajectories, tested at QST in Japan [9].
The Beam Source (BS) was delivered to the NBTF premises by the end of October 2017. Visual inspections and on-site tests were carried out before installation into the vessel. To this end, a series of tools were set up, such as a Class 8 cleanroom; a dedicated scaffolding was realized and installed inside the vessel to allow easy access to all parts of the BS during installation and the first commissioning phase. The precise mechanical alignment of accelerator grid apertures was finally achieved; deviations of maximum ±0.2 mm for the relative position off-axis of corresponding apertures on different grids were measured again on site [8], [10], in line with design requirements. The source was installed in the vessel in the first quarter of 2018 (Fig. 2), thus complying with the ITER milestone and allowing the start of experiments. The problems identified during these phases (like a leaky GG segment, already under procurement, the reconfiguration of a group of permanent magnets incorrectly assembled, and the enhancement of the electrical connections of the drivers as a consequence of results obtained in ELISE [11] and HVRFTF [12]) together with simulations carried out at Consorzio RFX [13], will be addressed in the major shutdown scheduled for mid-2019. Quartz driver cases are under consideration for the replacement of current alumina ones, together with optimized vespel® combs holding the RF coils detached from the insulating cases, in order to minimize the electrical field in this critical area.

2.3. Diagnostics ready for the first operation

All SPIDER diagnostic systems have been developed within a common procurement program well integrated with the overall experimental schedule [14]. Procurement of key diagnostics for the beam source was completed in due time allowing a logical integration of their assembly and integration with those of the other SPIDER systems, in particular with installation of the beam source and with integrated commissioning of the CODAS system dedicated to diagnostics. Installation and integration of beam diagnostics has been postponed to the beam extraction experimental phase, so as not to overload the tight schedule in preparation of the initial source experiments. First plasma experiments could then benefit from operation of an initial set of diagnostics with two purposes: on the one hand to complete their integration within the automated pulse procedure, to tune the setting up optimizing the measured signal, to characterize the RF induced noise and to investigate mitigation actions; on the other hand to simultaneously provide information essential to steer the source operation, allowing to understand the effects of the available parameters. Photodiodes with low noise amplifiers measure at 100 kS/s the light intensity through the 8 RF drivers [15]. CMOS visible cameras with high dynamic range look at the source sides through viewports on the vacuum vessel. Cameras can follow and identify the spatial distribution of undesired plasma discharges occurring outside the source case, between source and vacuum vessel (see section 2.4). Imaging grating spectrometers measure along about 30 lines of sight distributed over the source perpendicularly and parallel to the grids, either the full 300-900 nm spectrum with low resolution (for Balmer hydrogen lines and identification of undesired pollutants like metals or water related compounds), or narrower bands with high resolution (Fulcher molecular hydrogen lines). Line intensities are being analyzed to derive the dissociation degree and electron temperature and density. Thermocouples are so far measuring small temperature increase after each plasma shot because of short duration and low RF power; a significant RF induced noise still prevents their use during the pulse, but mitigation actions are under investigation. Electrostatic probes have been fully integrated and will be the next diagnostic to start operation, while the other source diagnostics, cavity ring down spectroscopy and laser absorption, will be installed and integrated at a later stage.

2.4. The SPIDER experiments: first results and issues

After the integrated commissioning of plants and control systems [7], SPIDER operation started in mid-May 2018 by a preliminary characterisation of gas pressure, pre-ionisation filament circuits and plasma ignition [16]. A numerical model was set up to interpret the transient behaviour of the gas considering long inlet pipes and grid conductance; in steady state a calibration of the source pressure relative to the vessel pressure was performed; a factor of 4 was found as expected from numerical simulations [17]. The current emitted by the pre-ionisation filaments was measured in different conditions as a function of the heating current, also with the aim of inserting suitable protection resistors in the heating circuit to extend the filament lifetime, while producing an electron current sufficient for plasma ignition of a few mA per filament.

**FIG. 3.** Scan of RF power (top); plasma light through operating drivers (bottom).

**FIG. 4.** Scan of filter field current (top); Hβ line intensity through the operating drivers (bottom).
The ignition procedure used by IPP for the ELISE device [18] was adopted also with single SPIDER generators (corresponding to first, second and fourth rows of drivers from the top), with some adaptations to the specific experimental constraints encountered in SPIDER. After reaching the desired pressure for ignition, the RF power was ramped up from the minimum value allowed by the generators to the desired value; during the increase of the RF power, the plasma generally ignites with a source pressure >0.2Pa and a ramping rate of the RF power 1-2.5kW/s. The magnetic filter field is required during the plasma ignition phase for single generator operation, but not when two generators are employed, even though the corresponding pairs of drivers are not neighbouring. SPIDER control system allows programming the waveforms of the various power supplies. Thus parameter scans can be performed within single pulses. As an example, Fig. 3 shows a scan in the RF power. During the first SPIDER experiments, scans have been performed of the RF power, the magnetic filter field and the source pressure [16], [19]. Plasma light (Fig. 3) and spectroscopy (Fig. 4) show a dependence on these parameters. The plasma light and the intensity of the Hβ hydrogen line of the Balmer series exhibit a left-right asymmetry, which decreases with increasing pressure and RF power and increases with the magnetic filter field. The reasons of such possible plasma drift are under investigation.

First operation of SPIDER evidenced some issues. A short circuit was identified between plasma grid and source body and was solved. Plasma discharges occurred on the rear side of the source. Correspondingly, the filament bias power supply is subjected to over-voltages so that protections had to be strengthened. Direct inspection showed signs of electrical discharges inside the vacuum vessel, like on the busbars of the RF circuits, on the filament supports and on the internal surface of the vacuum vessel. These discharges are peculiar of SPIDER, where the entire beam source, including the high voltage grids, is inside a vacuum vessel, namely at low gas pressure. A thorough investigation of the occurrence conditions of the rear discharges is in progress using fast cameras (to follow the path of individual arcs across the source) and aimed at identifying the vessel pressure range in which these discharges can be avoided.

Fig. 5 shows SPIDER operations and planning for 2018 and 2019. After the characterization of the ion source, the extractor and accelerator will enter into operation by the end of 2018. At the beginning of 2019 the caesium ovens will be tested in the Caesium Test Stand (CATS) [20], a small facility dedicated to the characterization of the caesium emitted from the oven nozzles, and they will be installed in SPIDER allowing the increase of the negative ion current. In spring-summer 2019 a major shutdown will be devoted to the substitution of the insulator inside RF coil [13], based on the most recent indications originated from the ELISE experimentation during the assembly phase of the SPIDER source. Further motivations of the shutdown are the resolution of some non-conformities in SPIDER source manufacturing (i.e. the leak in one of the sectors of the grounded grid) and the improvement of the device with interventions suggested by the experimentation. After the shutdown, the SPIDER plant is expected to meet the design requirements. The beam operations will resume, devoted to increase the beam performances.

3. MITICA

3.1. General progress

The design phase of MITICA was completed in 2016 and all calls for tender have been launched. SPIDER and MITICA common plant systems as MV power grid, Cooling plant and Gas injection and Vacuum System are in a very advanced stage of realization, installation or commissioning. The power supply systems are all in an advanced phase of realization or already completed and installed, the same for the cryogenic plant. Procurement contracts for beam source and cryopumps have been assigned, while the first phase of the process for the procurement of the Beam Line components (revision of the design including some prototype realization by potential suppliers) is nearing completion and will be followed by a mini-competition between the three competitors to select the one that will be awarded the supply.
Though delay was introduced in the delivery of MITICA Vacuum Vessels (VV) by some major technical issues encountered during contract execution, a robust corrective action plan was developed to ensure the realization of a technical solution, which is being implemented and monitored closely. Moreover, the support structure of the Vacuum Vessel and the vertical mechanical support structure of the HV Bushing (HVB), see Fig. 6, have been installed, in order to reduce the duration of the activity for installation of the HVB and connection of the Transmission Line (TL), once the VV has been installed. Accurate metrology and careful installation procedure allowed the successful execution of the static test using the HVB itself.

The most critical procurement is that of the Beam Source [21] both from the point of view of technological complexity and delivery time. In fact, the BS includes the accelerator, consisting of a system of 7 parallel grids each featuring 1280 holes that must be aligned within tolerances of 0.3-0.4mm. Grid deformations must be compatible with such tolerances even in the presence of thermal loads produced by the ion beam as high as 1.5MW per grid. The manufacturing process of the grids, very complex and long, dictates the supply time of the entire BS. The supply contract has just been assigned; the BS is expected to be completed and delivered by the end of 2022, allowing the start of the MITICA experimentation by middle of 2023.

### 3.2. The MITICA cryogenic system

Two large cryopumps will be installed inside the MITICA Beam Line Vessel (BLV) to guarantee proper vacuum conditions inside the vessel during MITICA operation (Fig. 7). The cryopumps are based on adsorption pumping by charcoal coated cryopanels (CP), 8m long, 2.8m high, 0.45m deep, and operated between 4.5K and 400K. These cryopanels are surrounded by a Thermal Radiation Shield (TRS) operated between 80K and 400K. The CPs will be at the lower temperatures during normal operations, and at 100K or 400K during the periodic pump regenerations necessary to remove from the CPs the adsorbed gas (H\textsubscript{2} or D\textsubscript{2}). The pumping speed estimated for the two pumps operating in parallel are 5000m\textsuperscript{3}/s for H\textsubscript{2} and 3800m\textsuperscript{3}/s for D\textsubscript{2}.

The MITICA Cryogenic Plant is designed to manage the expected heat loads in pulse-on scenario: 800W on CP assembly (by producing supercritical helium at 4.6K) and 17.4kW on TRS assembly (by gaseous helium at 81K). The same plant shall also manage the regeneration of cryopumps at different temperatures. The procurement contract for MITICA Cryogenic Plant was launched in September 2016; presently the on-site installation activities are well advanced (Fig. 8) and the completion of acceptance tests on-site is foreseen within Q2 2019. The procurement contract for MITICA Cryopumps started in May 2018 and the delivery at NBTF site is foreseen by the end of 2020.

### 3.3. The power supplies

The MITICA power supply system is very complex, even if based on the same conceptual scheme applied to SPIDER [22]; the operating voltage, 1MV, to feed the accelerator required remarkable technological developments, to the cutting edge of present day technologies. The system is provided with contributions from both European and Japanese industries. Fig. 9 shows a 3D model of this system which includes a HV transmission line (over 100m long) and also requires a high voltage hall to host a 1MV Faraday cage (HVD1) containing the MITICA ISEPS. The realization is well advanced; some power supply systems provided by F4E, such as AGPS conversion system and HVD1, have already been installed and tested; others power supplies are being tested at the factory and will be installed by the end of 2018. As for the Japanese HV components, shown in blue in Fig. 9,
the installation began at the end of 2015 and continued in the following 2 years. Unfortunately, the delay in the delivery of the VV prevents the installation of the HV Bushing (HVB) and the connection of the TL to the HVB. To limit the impact of the unavailability of MITICA VV on completion and power tests of the power supplies, an alternative plan was adopted. In particular, a special cap was procured and installed at the end of the TL in correspondence to the not yet installed HVB, thus allowing to fill the TL with the SF6 insulating gas and carry out the HV insulation tests. An additional insulation test will be done after completing the installation of the VV, to check also the HV electrical insulation of the last part of the line and the HVB.

3.3.1. HV insulating tests

The commissioning and integrated power tests activities will require a period of about 2 years due to the complexity of the PS system themselves and to the different systems being under different responsibilities (IO, F4E, JADA, and NBTF Team). The HV components must be individually subjected to insulation tests before being connected to the power supplies. HV components are provided by JADA and F4E and are connected to each other; therefore the tests will have to be repeated up to 5 times as the parts of the system are added one by one. Furthermore, it is necessary to completely evacuate the gas insulated components and ventilate them with air to guarantee the technicians’ access, to then perform the reverse operations and inject the gas back. Such procedure will require several months and can only take place in series, therefore any delays in one of these activities would result in a progressive delay of the availability of the PSs; moreover the delay of the activities under responsibility of one DA can impact the activities under other DAs or parties. In July 2018, all the activities of installation and preliminary verifications of JADA HV components were completed. During the same period, the SF6 Gas Handling and Storage Plant was made available by F4E, including the storage of approximately 35 tons of SF6 gas. The first filling operation of the components with SF6 was made, after a preliminary test in which the components were filled with nitrogen, in order to avoid risks of release of SF6 in the environment in case of faults of some components. At the beginning of September, the first insulation test was performed to verify the voltage holding of the AGPS-DCG (direct current generator) components: step-up transformers, diode rectifiers, DC Filters. Two different tests, agreed among parties, simulate the operating conditions of the system: 1.2MVdc for 1h; 1.06MV for 5h followed by 5 quick sawteeth up to 1.2MV [23]. The tests were positively passed by the system, allowing to reach another important milestone on the road of the NBTF project. Fig. 10 shows the voltage profiles measured by the HV transducers on the stages of AGPS-DCG system.

3.4. Tests of high voltage holding in vacuum

One of the most critical issues of the injector is the high voltage holding in vacuum. Recent experiments carried out at QST [24] showed a voltage limit around 700kV in the case of a single gap and in the vacuum conditions at which the injector will operate. These findings, the development of theoretical models, the study of solutions and the investigations in a dedicated HV test facility [25], resulted in the introduction of additional intermediate screens, to be implemented on MITICA to guarantee the expected performance. Before installation of the mechanical components inside the vessel, the MITICA PS system can be connected to the evacuated vacuum vessel and can be used as a privileged test facility for carrying out experimental tests on this specific issue. Mockup of electrostatic screens can be realized and tested to validate the theoretical models of HV holding in vacuum and to envisage solutions to be adopted in the MITICA injector.
4. SUMMARY

The realization of the NBTF is well progressing also thanks to the commitment of all the actors involved in the project. Although some components of the PS and of the cooling system are still unavailable, SPIDER has entered into operation and is providing the first data on the source plasma. This corresponded to the attainment of an important ITER milestone. As the NBTF is part of the ITER project, this event corresponds also to the start of the experimentation of the first part of ITER. During a shutdown in 2019 a leaking grid segment will be substituted, the RF drivers will be modified, according to recent ELISE results and other interventions will be performed as indicated by the experimentation. All MITICA auxiliaries are being installed or commissioned; most of the PS have been installed or will be installed by the end of 2018. As the MITICA VV is not yet available, the insulation tests of the HV components is in progress according to an alternative plan, which allowed to partially recover the delay. In particular the test up to 1.2MV of the AGPS-DCG has been successfully passed, reaching another goal along the NBTF roadmap. According to present planning, MITICA PS will be integrated in 2020, while the mechanical components will be installed inside the VV in 2022. Nevertheless, in the meantime the MITICA plant can be used for HV holding tests in vacuum, one of the most important issues in view of MITICA operation.

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BIBLIOGRAPHY

[23] H. Tobari et al., FIP/P1-10, Proc. of IAEA FEC 2018