ACHIEVEMENT AT THE ITER NEUTRAL BEAM TEST FACILITY AND PROSPECTS FOR THE R&D ACTIVITIES WITHIN THE ITER RESEARCH PLAN

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Abstract

The ITER Neutral Beam Injection Heating and Current Drive system is essential to reach burning plasma condition and control the fusion performance, providing heating power at a level of 33 MW by firing high energy beams of neutral particles, i.e. hydrogen at 0.87 MeV or deuterium at 1 MeV, into the ITER plasmas. In order to ensure the reach of the expected target parameters, a Neutral Beam Test Facility (NBTF) has been set up in Padova, Italy. The contribution describes the R&D

strategy for the establishment of HNB at ITER that meet the target performances and the related long-term schedule, in particular highlighting the recent contributions of activities at NBTF on the two devices foreseen. SPIDER is targeted at optimizing in advance the ITER-size ion source and, after the first major shutdown, has completed a significant experimental campaign with important new results, prior to completing the configuration in a next shorter shutdown and proceed with the quest to the target parameters. Meanwhile, MITICA, the full-scale prototype of the ITER HNB, has completed an operation addressing the critical aspect of high voltage insulation in vacuum towards the first milestone of the long-term plan, waiting to complete the restoration and improvement process for the power supply damaged during the first integrated tests, and then the full system will be used.

1. INTRODUCTION

The ITER Neutral Beam Injection Heating and Current Drive system consists of 2 (upgradable to 3) Heating Neutral Beams (HNB) and 1 Diagnostic Neutral Beam (DNB). As the demanding target parameters have never been reached simultaneously [1] (40A/1MeV D- for ≥1 hour; 46A/870keV H- for ≥1000s; divergence <7mrad; aiming <2mrad), the ITER Neutral Beam Test Facility (NBTF) was set up at Consorzio RFX premises (Italy) aimed at developing the injector prototype and attaining the challenging requirements. The facility includes two test beds [2]: the full-scale HNB prototype, named MITICA, that will enter into full operation in 2026, and SPIDER, with 100keV particle energy, aimed at testing and optimizing in advance the ITER-size ion source, in operation since 2018. The paper describes the recent activities and results obtained on both devices at NBTF, highlighting the integrated approach in the NB community in the quest of the target parameters within the facility long-term schedule integrated in the ITER research plan. First a summary of the scientific results in SPIDER will be provided, which shows the progress in the performance attained during the recent experiments, with respect to the previous campaign, confirming the estimated projected values at full operation capabilities. Some details are also given regarding the ongoing shutdown, targeted at integrating the last two improvements foreseen to complete the configuration that will quest the target performances in the next 2026 campaign. Regarding MITICA, the restoration of the high voltage power supply entered the final phase of installation of new components arrived from Japan towards the repetition of the overall integrated tests, while the completion of the campaign on voltage holding tests in vacuum provided results in line with the requirements for operation in hydrogen.

2. OVERVIEW OF EXPERIMENTS AND DEVELOPMENTS IN SPIDER

The SPIDER beam source is a vacuum-insulated source, with a functional design identical to the ITER source (FIG. 1) from the driver to the extraction electrodes. After the first experimental campaign (SPIDER Operation-1, SO-1) occurred in 2018-2021, SPIDER underwent a major shutdown [3] and operation restarted in 2024 (SO-2). The refurbishment and improvements demonstrated effective and remarkable results, right on the expected path towards target performances. SPIDER recent operation was primarily aimed at the characterization of the bottom segment of the source, by operating most of the 320 beamlets simultaneously for the first time (¼ of the total extraction area).

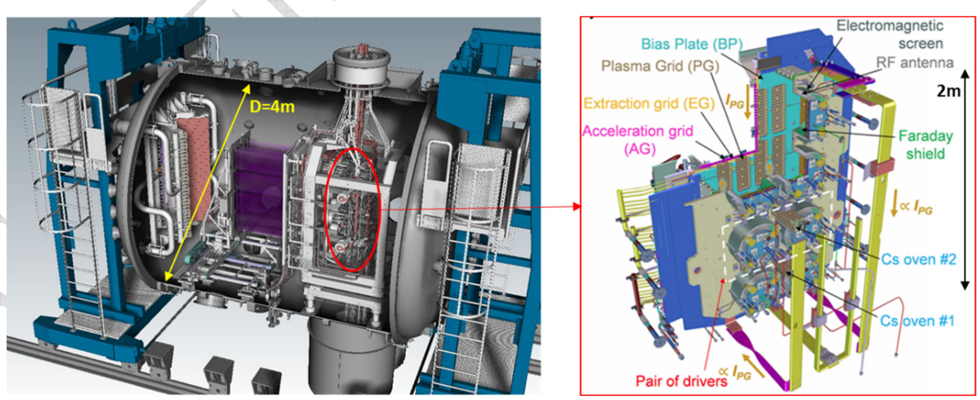

FIG. 1. SPIDER test bed (left), and its beam source (right).

SPIDER source was operated for the first time at ~700 kW beam power in a multi-beamlet configuration, operating in hydrogen at extracted current density of 220 A/m^2 at 0.3 Pa filling pressure. The main goal was to investigate the relationship between current density and RF power at the required ITER pressure of 0.3 Pa at the bottom segment, with regard to the attainment of the ITER NBI requirement (330A/m^2) at 100kW/driver (FIG. 2). Results are in line with expectations from the half-size source test facility ELISE [4], also discussed in sect.4. The results indicate that the target current density shall be achieved by increasing to 100 kW the RF power per driver, confirming the specifications of the RF generators upgrade. FIG. 2 also compares the present results to SO-1, obtained operating very few isolated beamlets: in the latter case, the few active apertures take advantage from the wider surface production of the closed apertures around. With a single segment operation, the beamlet group uniformity was significantly impacted by the filter field, nevertheless the uniformity of both plasma and beam improved in multi-driver operation.

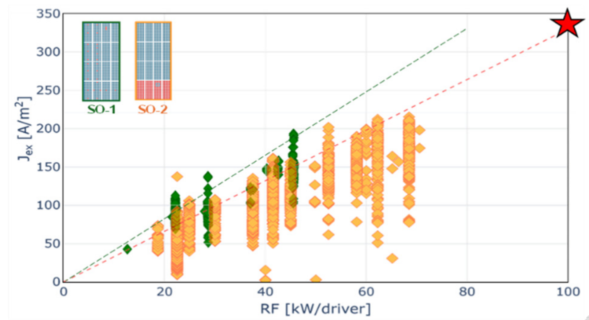

FIG. 2. Negative ion current density as a function of the RF power at 0.3Pa filling pressure: green points refer to SO-1 campaign, yellow ones to SO-2, the red star is ITER target

FIG. 3 (b-c) presents the processed IR image of two cases with different filling pressure with standard filter field at high RF power, demonstrating a rather good beam uniformity. The uniformity on the scale of the beamlet group can be discussed in terms of average current density per beamlet row: at 0.3 Pa, the majority of the beamlet rows exhibit a variation of the current within ±10%. Clearly the possibility to operate mostly on a single segment out of four impacted the performances, e.g. vertical plasma drift has a larger detrimental effect, and also the procedures to manage caesium conditioning were affected, including filter field and bias voltages; these shall be investigated further once the complete configuration is available at the next campaign SO-3. Moreover, an assessment of beamlet vertical divergence was derived from the measurements by the Allison emittance scanner. The graph in FIG. 3 (d) indicates that the influence of filling pressure and extraction/acceleration voltage is confirmed, with values above 10 mrad so far. A positive effect of plasma grid biasing on the optics was found (within a certain interval, after which the extracted current decreases); the optimal bias was not applied in the comparison presented in FIG. 3 (d); additionally, operating the voltage ratio U_{acc}/U_{ext} to a larger value i.e. 10.5 was found to decrease the minimum of divergence by additional 1/1.2 mrad. As an additional remark, the f_{core} fraction indicated that at higher pressure, the lower divergence represents a slightly lower fraction of the beamlet current, mitigating the beneficial effects of operating at higher pressure (the transmitted power to ITER is linearly dependent on f_{core}). This effect will be further investigated in the next campaign.

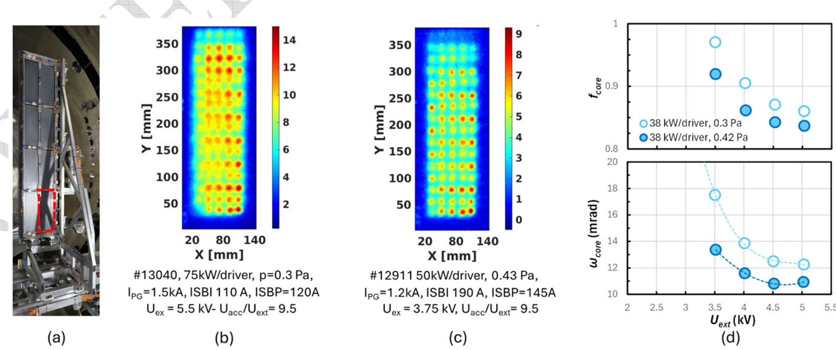

FIG. 3. Examples for results of preliminary investigations on beam uniformity and divergence: (a) CFC tile considered in the analysis, (b) and (c) processed IR image at 0.3 and 0.43 Pa filling pressure, (d) core fraction and divergence measured with the Allison emittance scanner

FIG. 4 summarizes the performances achieved in the SO-1 and SO-2 phases. The power delivered to the RF driver and the beam energy were increased by a factor 1.5 FIG. 4a/b, while the most striking improvement concerned the total extracted current (FIG. 4d), due to the total number of active apertures. With a pragmatic approach consisting in closing the beamlet apertures at the plasma electrode, SO-1 could anticipate the operation at relatively high current densities J_{ex}, to allow characterizing the beamlet optics in a ITER-relevant regime (FIG. 4c), and in SO-2 a comparable J_{ex} was reached. In addition, in SO-2 a tenfold increase of the achieved beam duration was achieved (FIG. 4e), still far from the target (for hydrogen beam, 400s to be extended to 1000s). FIG. 4f reports a first evaluation of the beam uniformity over a 5x16 beamlet group, reporting the fraction of beamlet rows within ±10% from a reference power; even though this figure of merit appears to be rather good, SO-3 targets a similar homogeneity on the scale of the whole beam, a much more ambitious result.

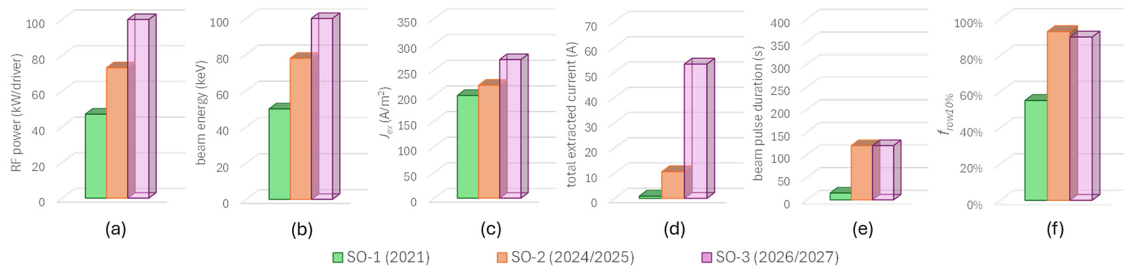

FIG. 4. Comparison between parameters and results related to the SPIDER campaigns in 2021 (SO-1), in 2024/2025 (SO-2), and the target performances for the next 2025/2026 campaign (SO-3).

Together with the installation of new solid-state RF generators and of the improved pumping system, the overall results obtained open the way to the operation of the full source in the next experimental campaign.

The early occurrence of RF-driven discharges during the first SPIDER campaign led to the identification of a vacuum pumping plant enhancement, for which an additional system was designed and procured, based on Non-Evaporable Getter (NEG) pumps. In SO-2, additional issues related to back-streming positive ions from the beam plasma confirmed the necessity of the enhancement. The full set of components has been manufactured and the final assembly on-site is ongoing, as shown in FIG. 5.

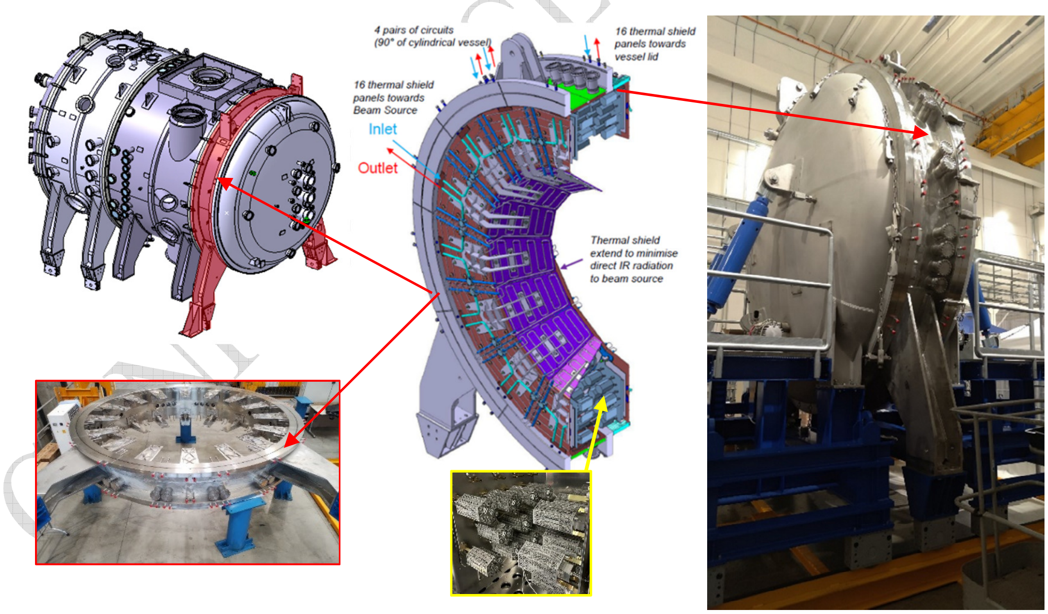

FIG. 5. Status of activities on vacuum enhancement system, NEG cartridges being installed onto the new vessel module

Similarly, replacement of RF generators, from tetrode oscillators to solid state amplifiers, had already been established: the more modern concept is much more efficient in many aspects, as already demonstrated on an existing similar device [4]. Manufacturing of SPIDER units has been completed and installation is already well advanced, as shown in FIG. 6.

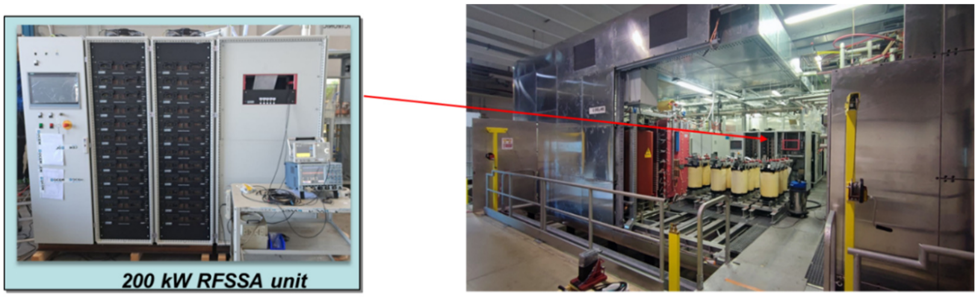

FIG. 6. SPIDER solid state amplifier (left), installation ongoing (right)

3. STATUS OF MITICA ACTIVITIES

3.1. High voltage power supply restoration

In 2021, during the first MITICA power supply integrated tests, a pair of events occurred involving unexpected breakdowns and overvoltage, which led to the damage of a few components [5]. Activities for the power supply restoration and improvements are in the mid of onsite final activities: the new additional protections, designed to prevent overvoltage on the refurbished components [6], with the help of interpretative discharge models [7], have been procured and installed, as shown in FIG. 7 and FIG. 8.

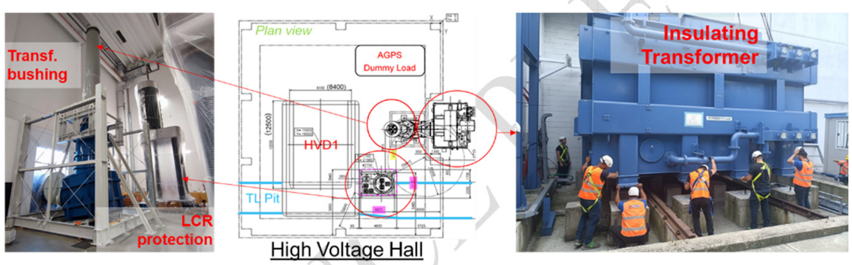

FIG. 7. New layout of the High Voltage Hall, the new insulating transformer (right), bushing and the additional LCR protection (left)

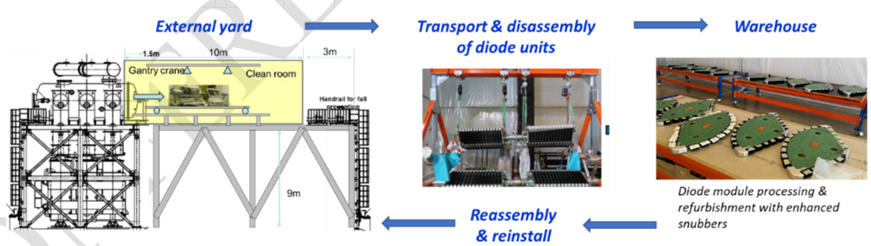

FIG. 8. Refurbishment activities on step-up transformer diodes

Overall integrated tests are under preparation, while insulation capabilities had already been recovered and demonstrated in dedicated tests, in which enhanced diagnostic capabilities had been implemented [8].

3.2. High voltage tests in vacuum

Voltage holding in vacuum at 1 MV level, with electrodes of the MITICA beam source dimensions and complexity is a challenge in a fully unchartered territory, characterised by strong non-linearities in the possible extrapolations from smaller devices. Addressing this issue in advance is a strong and strategic risk mitigation in the plan that leads to the start of the full MITICA operation. The campaign of HV insulation tests in vacuum was completed (FIG. 9), reaching very promising results and gathering lots of precious information [9] regarding the behaviour of such a huge device under these conditions, using the power supply sub-systems not affected by the cited events, in advance of the completion of the repair.

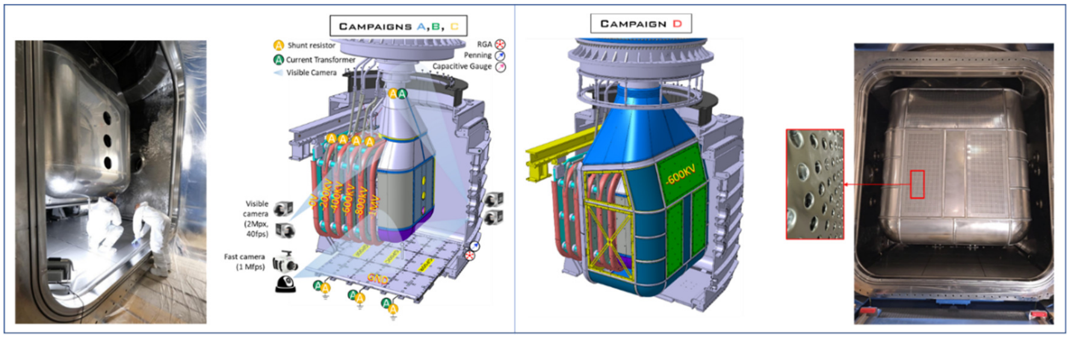

FIG. 9. Testing configurations for HV tests in vacuum: without (left) and with (right) intermediate electrostatic shield

After completing the experiments with the base source configuration, and reaching up to the mid of the target value, the first intermediate shield was installed, in line with indications obtained in QST experiments (sect.4). The intermediate shield, expected to reach -600 kV, divides the vessel volume in two basically independent parts and voltage holding is expected to improve. In order to speed up the conditioning procedure and the test execution, as new components for high voltage power supply restoration had the priority to be installed once arrived onsite, it was decided to focus the efforts on the volume between the intermediate shield and the grounded vacuum vessel, hence on three out of the five 200 kV stages that constitute MITICA accelerator. Two operation conditions were investigated, high vacuum and gas injection at a filling pressure relevant for future beam operation in hydrogen. Results in FIG. 10 show that the maximum values obtained are relevant with respect to the corresponding target for ITER campaigns. Moreover, additional positive aspects are that voltage insulation at the maximum value was held for more than an hour, and the overall conditioning time to reach such value was in the order of few days.

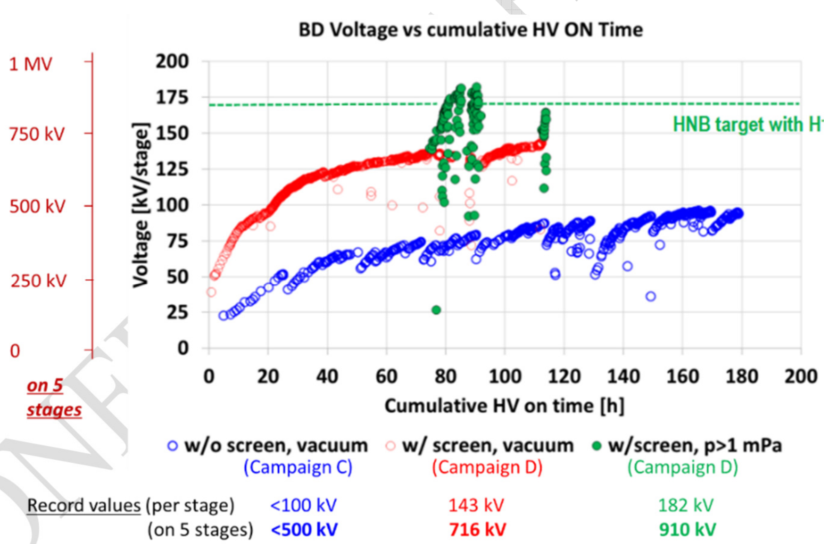

FIG. 10. Overview of main results from the HV tests in vacuum campaign

4. LONG TERM STRATEGY AND INTEGRATION WITHIN THE ITER RESEARCH PLAN

The plan of the R&D related to ITER Neutral Beam Injectors has been revised to meet the needs of the new ITER Research Plan (IRP), following the overall ITER Re-baseline in 2024 [10]. Hence, the overall NBTF plan of activities with the relevant time schedule is now fully integrated with the ITER research plan, emphasizing milestones, links with the inputs expected by the HNB development, aiming in 2032 at the first main milestone demonstrating the soundness of the configuration for HNB operation (870 kV, 330 A/m2, 10 s), and in particular to start the procurements for HNB components [11]. With this goal, SPIDER and MITICA will alternate between operational phases and maintenance phases, during which the lessons learned from previous experimental campaigns will be integrated into the design, as shown in FIG. 11.

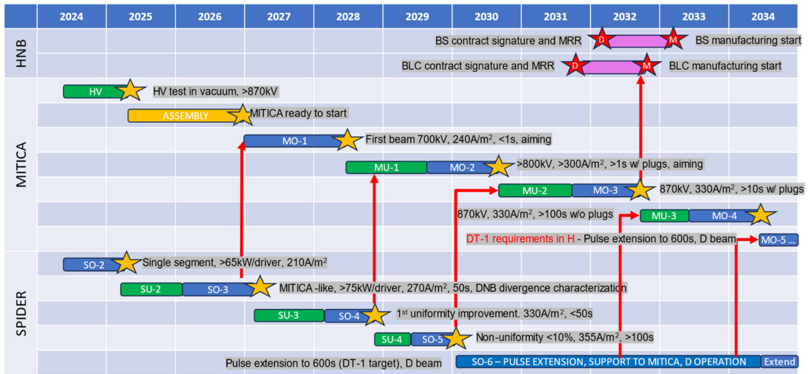

FIG. 11. NBTF long term schedule and main links with ITER research plan

Fully integrated and essential part of this approach, the NB community is significantly involved in this challenging project, supporting directly the NBTF with dedicated experiments and inputs for SPIDER and MITICA on most critical aspects. For example, the half-size source test facility ELISE, at IPP [4][12], has already demonstrated the ITER target in hydrogen for 10 s and more than 90% for 600 s with only 75% of the RF power, representing a record in the performance of negative ion sources (FIG. 12).

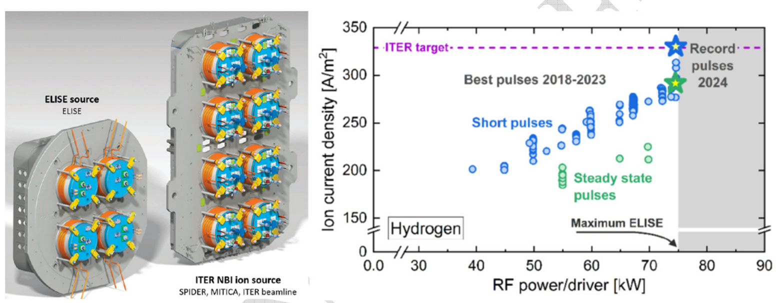

FIG. 12. Results from ELISE experiment with respect to ITER target, record obtained with optimized configuration regarding magnetic filter field, bias voltage, etc.

In addition, QST are contributing with expertise on voltage holding with large-area electrodes simulating a nested structure of electrostatic screen in the high-voltage bushing [13][14]. Considering the technical input from QST on voltage holding with area-effect and experimental results in the MITICA BS mock up, the final configuration (number) of intermediate electrostatic shields necessary for withstanding 1 MV is being discussed and finalised. Moreover, a joint experiment was agreed and set up in collaboration between QST and the NBTF team in order to validate in advance the concept adopted on MITICA EG for magnetic compensation of ion deflection as a consequence of the filter field to dispose of the co-extracted electrons. FIG. 13 shows the preparation of the setup, and a summary of the results obtained so far.

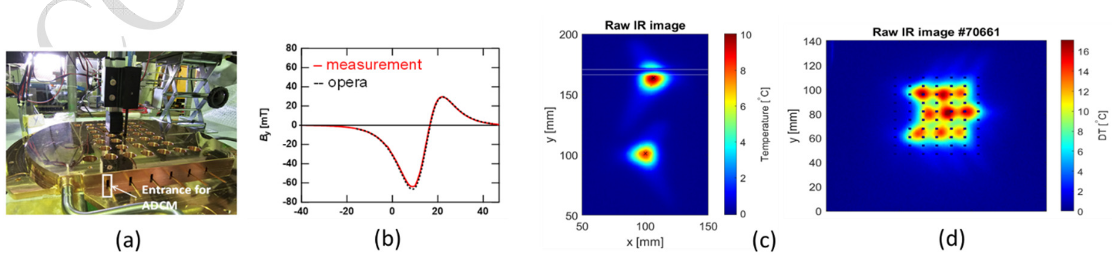

FIG. 13. Joint QST-NBTF experiment on Megavolt Test Facility (MTF) in Naka, to test MITICA EG arrangement for permanent magnets: (a) setup, (b) measurement of magnetic field, (c) first experiment with two beamlets available, (d) second experiment with nine beamlets

5. CONCLUSIONS AND OUTLOOK

The paper presents an overview of the activities carried out at the ITER Neutral Beam Test Facility, targeted at the operation of SPIDER and MITICA according to the final requirements set for the ITER beam. The program is defined as integrated in the ITER research plan, with links to the main milestones set in view of the procurement of HNB components and then the injector operation. A community effort is ongoing, with other labs supporting the NBTF, by tackling specific critical issues in dedicated devices. The first operation of SPIDER in multi-beamlet configuration was a key step in the development of the facility and in the progresses towards the ITER neutral beam injectors. The source performance in terms of extracted negative ion current demonstrated the scaling to the ITER target, also confirming the specifications of the new RF generators being procured. Important results concerning the beam uniformity and the role of the filter field were also successfully obtained. The residual limitations related to the vacuum system and the RF generators are being solved, and the next campaign will allow a full configuration, aiming at target parameters. In MITICA, components targeted at replacing the failed ones, together with additional protections, were manufactured and delivered on-site. Installation is well advanced, and preparations ongoing for the final commissioning and integrated tests of the power supplies. Meanwhile the campaign on HV tests in vacuum was completed, demonstrating the need to integrate the intermediate shield to reach values of voltage insulation relevant to the future MITICA operation in hydrogen.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the ITER-RFX Neutral Beam Testing Facility (NBTF) Agreement and has received funding from the ITER Organization. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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