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Status of the ITER Neutral Beam Test Facility and the first beam operations with the full-size prototype ion source

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The present contribution is devoted to the neutral beam injectors (NBIs) for ITER heating and current-drive. First, updated information is provided about the development status of the entire NBI prototype (MITICA); starting in 2021, the first experiments will be dedicated to high-voltage holding tests in vacuum. Then the contribution describes the full-scale prototype of the NBI ion source (SPIDER) and the activities performed in the first two years of operation, devoted to investigating the operational regimes of the ion source and verifying the performances of the various plants in view of extensive beam operation. Some improvements have already been implemented; others are being prepared for the next shutdown. The characterisation of the SPIDER plasma is presented and the results of the first beam operations are reported.

The ITER experiment represents the next step in realising nuclear fusion as an environment friendly energy source for the future. To reach fusion conditions and to control plasma configurations, two heating and current-drive neutral beam injectors (NBIs) will provide the ITER plasma with 17MW each, by accelerating negative hydrogen/deuterium ions. The requirements of ITER neutral beam sources (40A D- ions at 1MeV for up to 1 hour, 46A H- ions at 870keV for up to 1000s) are so challenging that current-voltage-duration have never been simultaneously attained yet. So, in the dedicated Neutral Beam Test Facility (NBTF) at Consorzio RFX (Italy), an extended R&D activity is aimed at reaching full performances and optimizing reliable operation, in time for ITER experiments. To speed up the beam development, imposed by the tight ITER schedule, the NBTF includes two experiments: MITICA, full-scale ITER NBI prototype, and SPIDER, full-scale prototype of the ITER NBI source with 100keV particle energy, whose simpler construction allows anticipating several R&D activities with respect to MITICA. SPIDER operation started in spring 2018 aiming at investigating source and beam uniformity (over a 1m×2m area), negative ion current density, beam optics in conditions relevant to ITER requirements. MITICA will focus on beam acceleration, in terms of optics (divergence <7mrad, aiming <2mrad) and high-voltage holding in vacuum, and on beam propagation, governed by neutralisation and by electrostatic removal of residual ions.
Concerning MITICA, all power supplies and auxiliary systems were tested and installed; the vacuum vessel was completed, whereas the in-vacuum mechanical components are under procurement by F4E (see fig. 1).

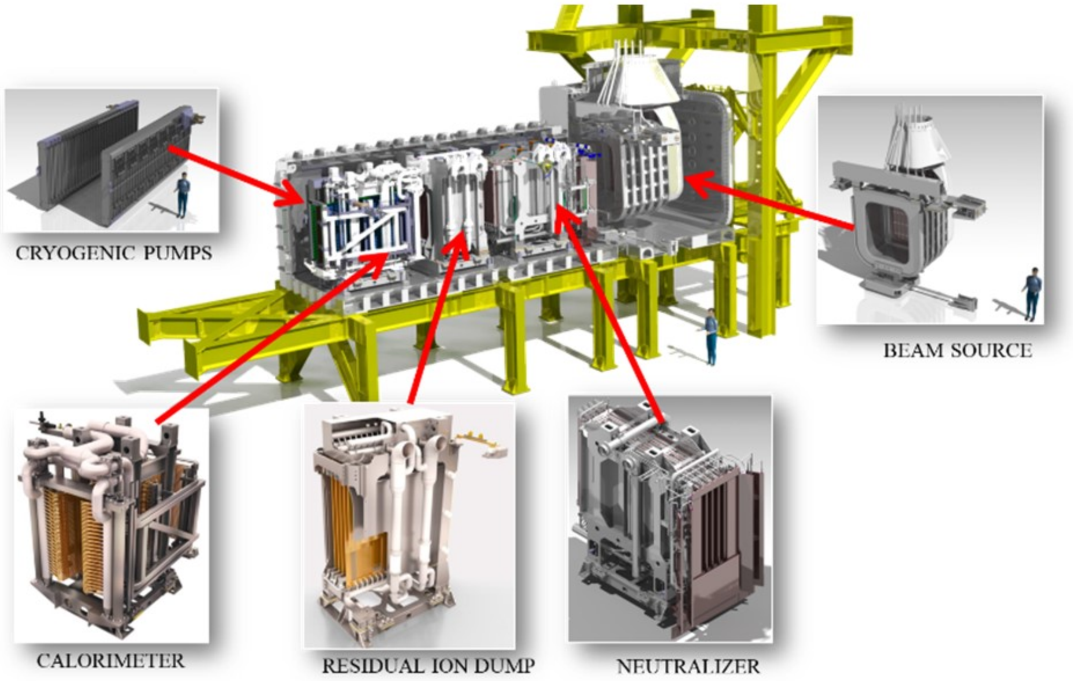

Figure 1: Main in-vacuum components of MITICA.

Installation, commissioning and test of the 1MV power supplies started in autumn 2018 and are nearing their end. In particular, insulating tests for high-voltage components were successfully completed, after solving various technical issues and by adopting a step-by-step procedure during the integration of the sub-systems procured by different Domestic Agencies (European and Japanese). Power supply integrated tests with a dummy load (1MV, 50MW, 2s) are ongoing in 2020 and include the simulation of accelerator grid breakdowns using a short circuit device installed inside the vacuum vessel in the place of the beam source. These tests will allow verifying the full performances of the power supply systems and their reliability during grid breakdowns in normal operation. In the present contribution, the activities for completing and commissioning the power supply system, together with the results obtained during the integrated tests, are presented.

In the first two years, SPIDER operations generated a wealth of experimental information, which provided insight into the source performance and raised operational issues that must be resolved in view of extensive beam operation and particularly of MITICA. It is worth mentioning that, unlike any other existing NBIs, the entire beam source assembly of MITICA (and SPIDER) lies inside the vacuum vessel, so that it is surrounded by the background gas at low pressure in which the beam propagates. RF-induced overvoltages around RF drivers are found to result in electrical discharges when the gas pressure inside the vessel exceeds a threshold. In order to carry out experiments with all 8 RF drivers, the gas conductance between source and vessel was reduced by installing a mask limiting the number of beamlets to 80 out of 1280, thus lowering the gas pressure near the RF drivers. The mask will be removed when improved pumping system will be available (ongoing design). As for the SPIDER RF system, mismatch between self-oscillating frequency of the generators and resonance frequency of drivers and plasma can result in frequency jumps with consequent plasma stop; this condition was demonstratedly avoided by implementing feedforward control of the generator frequency and tailoring the RF frequency to plasma conditions. Several circuits and diagnostics are plagued with RF noise; the cause was shown to be due to currents flowing in the capacitive voltage dividers measuring the RF power; an alternative solution will soon be tested. Experiments allowed also clarifying the cause (layout of RF circuits) of interference between neighbouring drivers along with identifying some limitations to maximum RF power; solving these issues however requires major modifications of the RF circuits. Experiments showed that the magnetic filter field currents (aimed at extending the negative ion lifetime) affect the plasma performances; the cause lies in the SPIDER magnetic filter topology, which exhibits a null point and a large intensity inside the RF drivers; thus distorting electron trajectories. This issue was addressed by modifying the magnetic field topology installing additional busbars. Other issues regard: extension of plasma grid and bias plate voltages to comply with the higher plasma potential found in operations without caesium; characterisation of caesium evaporators; limitation to 30kV instead of 100kV of the acceleration power supply voltage.

In the meantime, the plasma was characterised by means of spectroscopy (including optical diodes). Additionally, at the beginning of 2020 an experimental campaign was devoted to performing spatially resolved measurements of plasma parameters by means of an array of electrostatic sensors installed on a temporary, remotely controlled structure entering the plasma through accelerator grid apertures. Electron temperature and density are shown in fig. 2: as expected with low magnetic filter field, plasma expands out of the drivers, whereas temperature decays gently towards the plasma grid (PG).

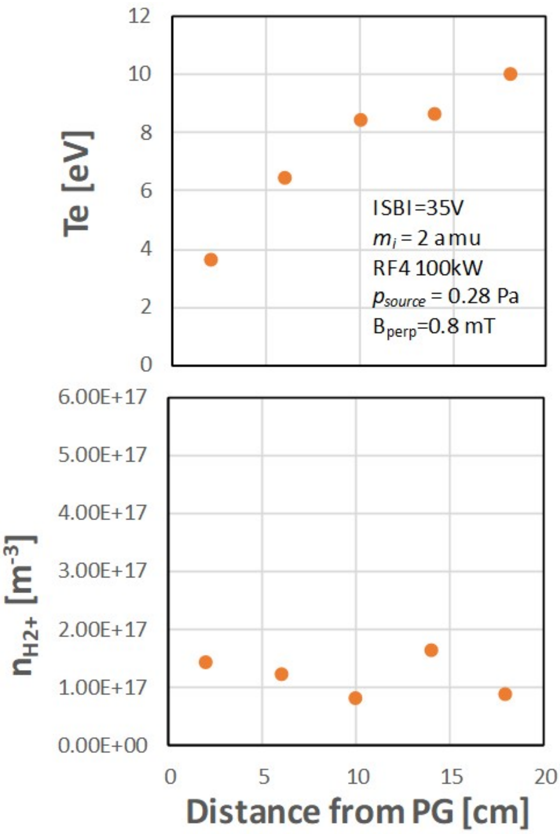

Figure 2: Temperature (top) and density (bottom) profiles with small magnetic filter field.

During the first extraction of negative particles from the source, features of negative ion beam and of co-extracted electrons were studied and correlated with plasma parameters. Particularly, the magnetic filter field effectiveness in reducing the co-extracted electron current was verified (down to ~30 times the H- current), along with its influence on negative ion current. The first characterisation of the SPIDER beam, in terms of beamlet divergence and deflection, was compared with numerical models while varying source parameters. The calorimetrical estimate of the current, which is not affected by secondary particles, is lower than the corresponding electrical measurements (see fig. 3).

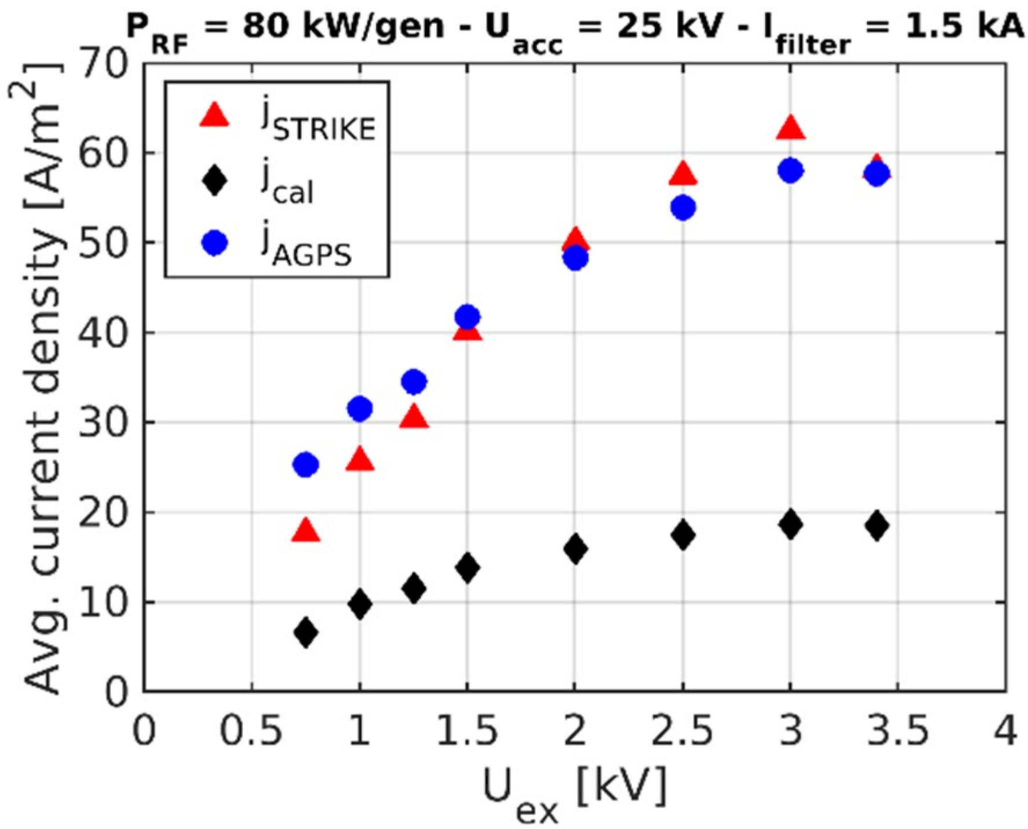

Figure 3: Dependence of electrical beam current densities (measured at the power supply and on STRIKE tiles) and of equivalent calorimetrical current on extraction voltage.

The negative ion beam is confirmed to exhibit values of current density (up to ~25A/m2) and optics parameters (down to ~25mrad) similar to those usually obtained in volume operation. Finally, in 2020 for the first time, caesium will be injected into the SPIDER source to increase the negative ion density; the results of the first campaign will be described.
After these experimental activities, SPIDER will enter a long shutdown, to carry out a set of modifications identified either during the procurement phase or during the first year of operation, like the aforementioned rearrangement of the RF circuit configuration and the enhancement of the vacuum system to keep the vessel pressure low with no plasma grid mask.

Country or International Organization

Italy

Affiliation

Consorzio RFX

Author: SERIANNI, GIANLUIGI (ItRFX)

Co-authors: TOIGO, Vanni (Consorzio RFX); Dr BOILSON, Deirdre (ITER Organization); Dr ROTTI, Chandramouli (ITER Organization); Dr BONICELLI, Tullio (Fusion for Energy); KASHIWAGI, Mieko; SINGH, Mahendrajit (ITER - India Institute for Plasma Research Bhat Gandhinagar Gujarat 382428 India)

Presenter: SERIANNI, GIANLUIGI (ItRFX)

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