Achievements and challenges for ITER heating & current drive systems

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Abstract—**The ITER project is a major step in the development of fusion energy aiming to demonstrate the feasibility of exploiting magnetic confinement fusion for the production of energy in an experiment close to the dimensions of a future commercial fusion reactor. To achieve high fusion gain and control several aspects of the plasma behavior, three heating systems capable of injecting a total power up to 73 MW will be installed. This paper will summarize the requirements of the three systems and will highlight the main achievements in their design and construction.**

I. INTRODUCTION

The level of plasma quality required to satisfy the fusion performance goals of the ITER project is deeply linked to the performance of auxiliary heating systems. They are comprised of the Neutral Beam system (NB), the Ion Cyclotron system (IC) and the Electron Cyclotron system (EC). They will not only provide plasma heating, but will be required for plasma initiation, plasma current profile control, current drive and plasma instabilities control.

II. THE ITER TOKAMAK AND OPERATION PHASES

ITER is an international project established by an agreement among seven Members (China, the European Union, India, Japan, Korea, the Russian Federation and the United States of America); its goal is to construct and operate a tokamak experiment which can confine a DT (Deuterium-Tritium) plasma in which the alpha-particle heating resulting from the fusion reactions dominates the plasma heating (i.e. a "burning plasma") (see Fig. 1). Formally, its principal scientific mission is to demonstrate a ratio of fusion output power to input heating power (fusion gain), Q, of at least 10 with ~500 MW of fusion power in DT plasmas for durations of 300 – 500 s and to explore physics basis for long-pulse, non-inductive scenarios aiming at maintaining Q ~ 5 for periods of up to 3600 s.

Fig. 1. Aerial view of the ITER project from February 2020.

A phased approach has been developed for the operation of the tokamak, with a first technical plasma followed by two periods of experiments in H and He plasmas, PFPO1 (Pre-Fusion Power Operation) and PFPO2 with progressive upgrade of the capabilities of the machine, to bring the tokamak and its auxiliary systems up to their full performance level and capabilities for the Fusion Power.

To produce the initial plasma conditions for achieving high fusion gain, ITER will be provided with three heating systems (NB, IC and EC) capable of injecting 73 MW into the plasma.
The development of the heating systems is done according to the needs of the various campaigns, starting with a part of the EC system ready for the First Plasma (FP), whereas the whole EC system will be operational for PFPO1. Both The NB and IC are required for PFPO2.

III. HEATING SYSTEMS

In order to fulfil all functional requirements for the ITER project, a combination of three heating systems is planned: the NB injection will provide 33 MW of power, while both the EC and IC will each provide 20 MW of injected power. The three systems near the ITER tokamak are shown in Fig. 2, which includes the transmission lines to the two IC antennas, 5 EC launchers and the 2 HNBs (Heating Neutral Beam Injectors), (with a third as an optional upgrade). There exists also a Diagnostic Neutral Beam Injector which is not covered in this paper.

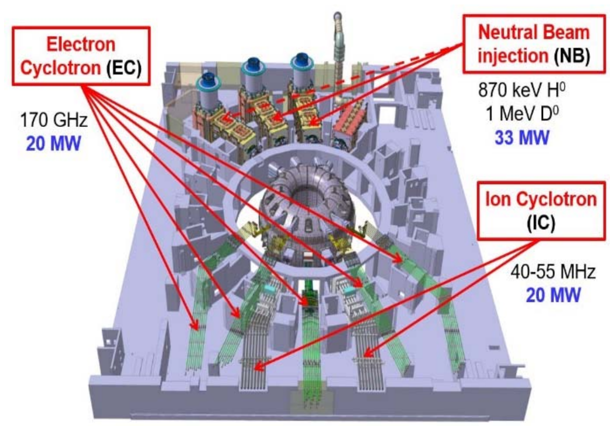

Fig. 2. The ITER heating systems in the tokamak building.

High energy neutral beams transfer their energy to plasma particles whereas high energy radio frequency and microwaves are coupled to the plasma through specific absorption mechanisms. The power balance between the three heating systems is chosen to take advantage of the different functional capabilities of each of them; The NB system is used for centralized plasma heating and has high current drive efficiency, the IC system allows direct ion heating and offers stabilization of instabilities, completed by the EC system which is used too for localized heating, current profile tailoring and some current drive.
The performance of the ITER heating systems requires extensive R&D and multiple prototypes to validate the development of new state of the art technologies and to meet the stringent requirements from a nuclear environment.

The final HNB system is mainly procured by EUDA and JADA, but to ensure an optimized performance of the NBI on ITER, a Neutral Beam Test Facility (NBTF) has been constructed in Italy with a specific agreement between IO and Consorzio RFX. The NBTF features two major experiments (see Fig. 3) to complete the development and demonstrate nominal parameters of NBI components prior to their installation on ITER, aiming at demonstrating the full 16.7 MW capabilities for 3600s; the first one, SPIDER, which has started in 2018, is a full ITER scale negative ion source, rated for 56A Deuterium beams at 0100kv (the same as the ITER Diagnostic NB)The objective of this testbed is to demonstrate the performance of the ITER sources. The ion source characterization in Hydrogen and Deuterium plasmas has been completed this year and the first H-beam were successfully extracted and accelerated in 2019. The plasma operation is reliable and has been operated up to 50% of the maximum power with 4 RF generators. Nevertheless, several upgrades are planned, in order to avoid RF breakdowns, plasma quench and to optimize the electromagnetic configuration.

The second one, MITICA, is a full scale NBI, rated for 40A Deuterium beam at full energy of 1MeV and scheduled to start the operation in 2023.

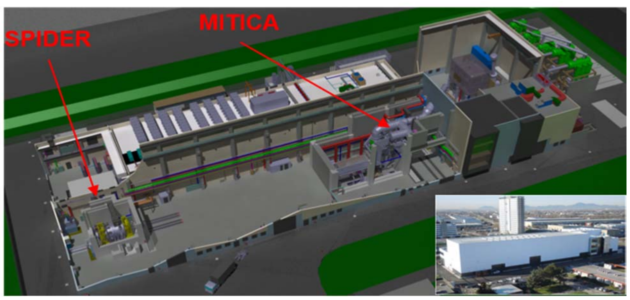

Fig. 3. SPIDER and MITICA experiments in the NTBF.

The design of the 9 IC RF sources based on 2 amplifier chains combined to produce 3 MW on unmatched load, have already been demonstrated: a viable technical solution has been tested and 1.7 MW CW achieved for one chain. The antenna design has undergone substantial modifications, with the introduction of four RF modules inserted from the front side into the plug body. Each module features two columns of three straps behind a single Faraday screen, two inner and outer conductors, and vacuum windows. A solid resonant stub (T-stub) provides a strong support to the front-end components, a path for cooling water and, at the same time, delivers the broadband radio-frequency characteristics of the antenna. The main advantage of this new design is that the windows are relocated at the back of the antenna, on the ex-vessel side of the bulkhead (see Fig. 4),

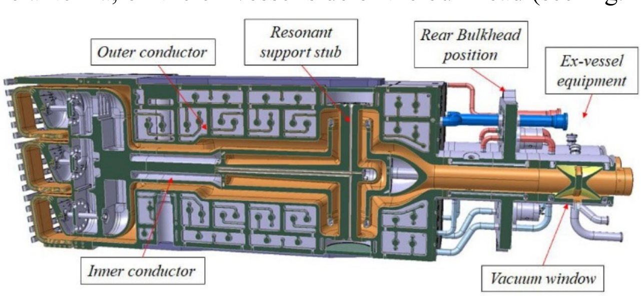

Fig. 4. Antenna section through RF module.

reducing the load and easing manufacture of this component. A few remaining issues will be solved prior to the Preliminary Design Review scheduled at end of this year, without impacting the power coupling performance.

The final EC system procurement is shared between five parties, EU-DA, IN-DA, JA-DA, RF-DA and US-DA but only a part of the EC system (about 1/3 of the total power, meaning 8MW) is installed to provide plasma breakdown in the First Plasma campaign planned end of 2025. These components are advancing according to the schedule and some components have already passed the FAT (Factory Acceptance Tests): 2 sets of HVPS from EU-DA are in storage and ready to be installed in 2021. All gyrotrons needed for the first plasma (from RFDA and JADA) have been manufactured and 7 FATs are completed already (see Fig. 5), demonstrating long pulse capability at 1MW with 50% efficiency.

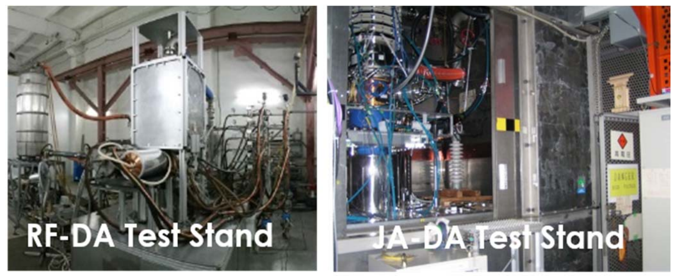

Fig. 5. Gyrotrons on their respected test-bed for their FAT.

All Transmission Line (TL) components have been prototyped for the first plasma (for 8 lines) and will be delivered between 2023 and 2024. Only one launcher is required for FP, which is located in an upper port and procured by EU-DA. The launcher and the ex-vessel waveguides, characterized by a challenging nuclear environment and stringent remote handling requirements, are at the Final Design stage with a delivery planned for 2024 (see Fig. 6).

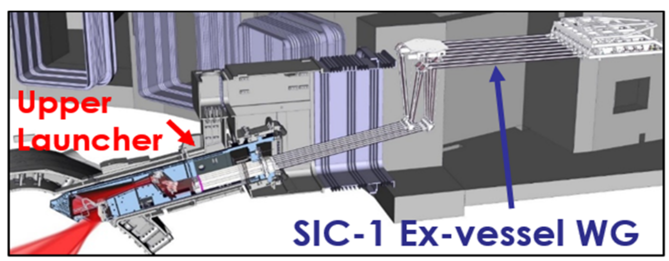

Fig. 6. The Upper Launcher and ex-vessel waveguides.

Despite the achievement of critical components, extensive R&D is ongoing: a 1MW CW test facility has been built in SPC in Switzerland, to test TL and UL components, as well as gyrotrons developed by EU-DA, Other works, all aiming in optimizing the gyrotron reliability and performances are under study in various laboratories.

IV. Summary

This paper will give an overview of the ITER, focused on the research and development of the heating systems and the various challenges they face especially through the nuclear environment, pushing existing technologies to their limits.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.