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The RF Heating Systems of Italian DTT

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Abstract. The Divertor Tokamak Test (DTT) facility will be built to study a solution to the issue of power exhaust in conditions relevant for DEMO. The Italian DTT tokamak, by coupling to plasma up to 45 MW of additional power, will reach the needed condition of power flow to the divertor of 15 MW/m. The selected Heating Systems to achieve this goal are Electron Cyclotron Heating (ECH), Ion Cyclotron Heating (ICH) and Negative Neutron Beam Injector (NNBI). The power will be installed in two stages: a day-1 configuration with a coupled power of 25 MW and a second step where the completion of the 45 MW will be realized in 4 years from the day-1. At first stage 16 MW of ECH power and 4 MW of ICH will be installed, making the DTT plasma dominated by RF heating. The EC system is based on 170 GHz, 1 MW gyrotron, while for the transmission line a Quasi Optical approach has been chosen, with the feature to install the multi-beam mirrors (8 beams on each one) under vacuum. The goal is to reduce the overall losses at ~10% avoiding atmospheric absorption and selecting the proper polarization for the longest section. The power will be injected into the tokamak using front steering individual antennas and capable to real time steer all the beams for the tasks assigned to EC waves. The first module of the ICH systems will be based on transmitters, capable of a wide frequency range (60-90 MHz), connected, though standard coaxial cables and RF components, to two movable antennas inserted in the equatorial ports of DTT. The selected range is done to exploit different heating schemes. The choice of the antenna type will be based on reliability (i.e. power density) rather than on its performance in term of peak coupled power. This led to choose a two-strap antenna with a power density of 3.5 MW/m2, shaped to fit the DTT scrape-off plasma and with an adjustable radial position. An external matching system is envisaged to cope with fast variation of antenna loading, e.g. due to edge localized modes.

INTRODUCTION

DTT [1] has been conceived to tackle the exhaust issue in a DEMO relevant context. To fulfil this requirement a $P_{Sep}/R \approx 15$ MW/m is required, that can be obtained with an additional power of 45 MW, coupled to the plasma by a mix of heating systems: ECH, ICH and NNBI. The power exhaust issue will be address in an integrated way: this means that it is necessary, for the given divertor under study, to guarantee the plasma quality (in term of confinement and cleanliness) regardless of the divertor material/configuration performances (erosion, integrity, power handling). The selection of additional heating will be based therefore not only on the capability to inject a gross power in the plasma, but also on the functionality of a particular system to obtain high plasma performances. Moreover the coupling of sufficient additional power to the plasma must be guaranteed in the several different magnetic configurations expected to be used in DTT.

The full power installation in DTT will be organized in two steps, to better finalise the final power distribution (power mix) after the design and procurement of the first part. At the *day-1* (the day-0 being the first check of ohmic machine) the foreseen power is 25 MW defined as that required to reach the H-mode in a 4 MA plasma. The first experimental plasma (magnetic field 3T, plasma current up to 2 MA) is compatible with 8 MW of second harmonic ECH, while for the injection of the rest of the power the magnetic field will be increased up to the nominal one (magnetic field of 6T) with a current of 4 MA. The day-1 additional power configuration will be therefore composed

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by 1 NNBI injector (7.5 MW at plasma), 2 ICH antennas (1.5 MW coupled power each) and 2 EC clusters (8 gyrotrons at 170 GHz each for 8 MW installed). During the procurement phase of the first step of the systems, the design of the final stage (45 MW) will be finalized and completed. This strategy will reduce the risk in the procurement of the DTT power systems, leaving enough time to verify, evaluate and modify the initial design.

ICH SYSTEM

DTT ICH system is designed to work in the frequency range 60-90 MHz, defined by the cyclotron resonances of ^{3}He and H minorities, respectively, at the DTT magnetic axis in the reference 6 T scenarios. The system can also support electron heating via mode conversion and wall conditioning through 2nd harmonic cyclotron heating of majority D ions. Other physical tasks, like generation of fast particles, density peaking, impurity accumulation and q-profile controls are possible, mostly after the upgrade to full power (9 MW), while current drive is not foreseen.

The linear absorption of RF power by electrons, majority and minority ions has been investigated with TORIC [2] for several fractions of the minority species in the full-power scenario. TORIC provides a linear two-dimensional solution of the integro-differential full-wave equation relevant to ICH wave propagation and linear damping. Its result, showing that maximum absorption occurs at a fraction of the minority species of 6%, have been used to analyse the effect of relaxation and thermalisation processes by means of SSQLFP [3]. The latter solves the 2D quasi-linear Fokker-Planck equation in the velocity space. At the minority fraction of 3%, the final power distribution is more balanced with a main electron heating in the order of 60%. It allows the generation of a fast ion population with peak perpendicular energy up to 500 and 700 keV, respectively.

The ICH system is conceived in modular units. Each module relies on a pair of antennas that are fed in parallel, through external conjugate T or 3-dB hybrid couplers, to better cope with abrupt variations of the coupling due to edge-localized modes (ELM) or during the L-H transition. The system has to rely on standard technology and well-assessed solutions to meet the tight schedule of DTT construction. The state-of-the-art for power density handling capability of ICH antennas in ELMy H-mode plasmas suggest a power density of 3.5 MW/m^2 for DTT. This choice leads to a coupled power of around 1.5 MW per antenna (i.e. 3 MW per module) for an equatorial port of 0.7 x 0.8 m^2. One module is scheduled for the initial phase of DTT and an upgrade with two more modules may be decided at a later stage.

Typical efficiencies for antenna coupling and transmission lines are 90% and 80%, respectively, entailing that the installed RF power per module has to be at least 4 MW. The transmitters have to provide this output power from 60 to 90 MHz in presence of a voltage standing wave ratio of 1.3, preferably 1.5, with periodic peaks up to 2.0 for 10 ms. Transmitters at ICH frequencies consist in multi-stage amplifiers, whose end stage is a high-power grid tube placed in a suitable RF cavity equipped with tuning motors to vary the working frequency on a pulse-to-pulse basis. Two types of grid tubes are under consideration: tetrode and diacrode, while cavities need a specific development. In the diacrode case, the output level is almost constant vs. frequency, while the tetrode power derates after 80 MHz. The ICH system needs either 2 diacrode-based or 4 tetrode-based transmitters per module. High voltage and auxiliary power supplies for the transmitters, as well as the hardware for commands, controls and data acquisition, and low-power RF units, rely on standard technology.

The transmission line is made of rigid coaxial cables, the external conjugate-T (ECT) scheme is preferred as ELM-resilient matching network since it has been successfully tested at JET [4]. Schemes based on 3-dB hybrid couplers would be simpler than ECT but more expensive, so they are only considered as backup solution if circuit simulations will dissuade from using ECT. The characteristic impedance of the transmission line is 50 Ω from the transmitters, whose output impedance is 50 Ω too, to the Tee junction, while lower impedance is used from the junction to the antenna feeders to improve coupling. Water cooling of coaxial cables seems unnecessary from a preliminary analysis and decouplers are not foreseen.

Many antenna concepts have been considered to identify the candidate for DTT. The performances of optimized models have been simulated with TOPICA [5] in the full-power single-null scenario, assuming a decay length of 4 mm in the scrape-off layer. Simulations showed that only a movable antenna can couple 1.5 MW to the plasma. Assuming a distance of 3 cm from the last close magnetic surface (LCMS) and a conservative value of 35 kV for the stand-off voltage the power coupled has been reported in Fig. 1 for two different 2–strap antennas.

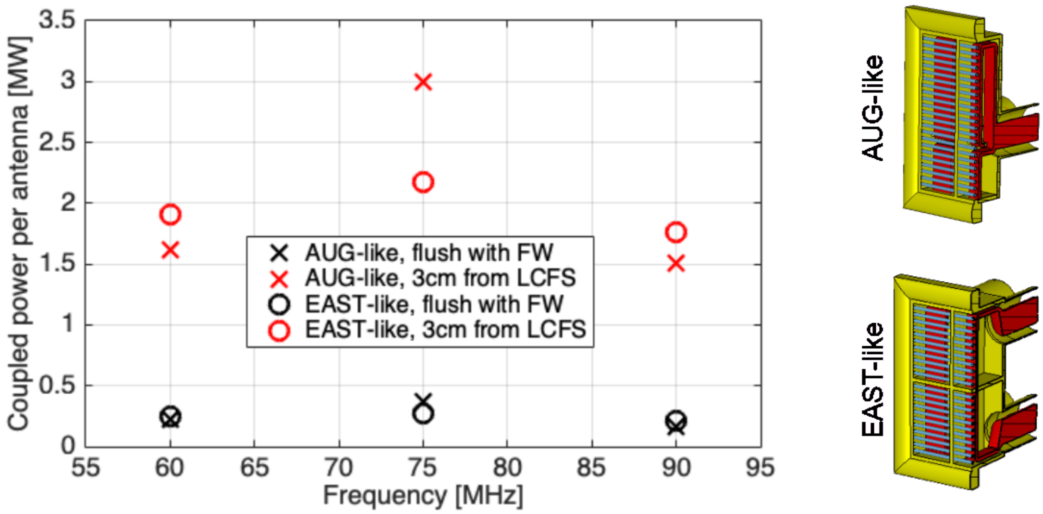

Figure 1. Power coupling capability of two antenna designs sketched aside, when they are flush with the first wall (FW) or moved closer to the DTT full-power single-null plasma, assuming perfect matching and dipole phasing.

The AUG-like antenna [6] is the preferred choice because its two feeders simplify the connection to diacrode-based transmitters and imply a lower number of transmission lines than the EAST-like antenna [7]. The latter is taken as backup solution in case of technical difficulties due to the inclusion of cooling of the straps.

ECH SYSTEM

The main guideline driving the EC project is to provide a compact and simplified design of the system, exploiting as far as possible the experience gained on the EC systems of ITER [8] and W7-X [9, 10]. The reference gyrotron (1MW/170GHz/100s) has requirements similar to those of the ITER tube, in order to minimize the risk and the cost of R&D.

The basic architecture consists of clusters of 8 gyrotrons fed by 4 main high voltage power supplies for the cathode and 8 body power supplies plus the possible use of anode power supplies in case of triode gyrotron. The power supplies are based on Solid State technology with a power modulation capability up to 5kHz. The 8 microwave beams are transmitted by an evacuated [11] Quasi-Optical (QO) Multi-Beam Transmission Line (MBTL) and delivered to one DTT sector where independent launching mirrors systems are located: 6 in the equatorial port and 2 in the upper port. All the single launching lines are in principle identical with max toroidal and poloidal steering angle capability of ±30° and ±40° respectively.

The level of the Stray Magnetic Field (SMF) that can affect the performance of the gyrotron establishes the minimum distance among adjacent gyrotrons and their distance from the tokamak. The SMF, calculated by considering the contributions of plasma current and of the poloidal field coils, brings to a safe distance of about 50 m from the centre of tokamak and a mutual distance of 4.5 m for gyrotrons, this leads to a TL length of about 60 m requiring up to 19 mirrors. The target efficiency for the Transmission Line (TL) is 90%. Considering the large number of single beams (32÷40) the MBTL concept is chosen, for its compact arrangement and simplicity, reduced required volumes and number of components. The design exploits QO propagation and is based on large confocal mirrors layout with 8 beams (corresponding to one EC cluster) on the same optical surface. The single TL module is composed by a straight path and a dogleg with one plane and one shaping mirror for beams refocusing. The beams of each MBTL propagate alternatively crossing or parallel to each other between two focusing mirrors. The present reference TL for each EC cluster consists of a shaping mirror after the gyrotron, a polarizer mirror (to match the low-losses polarization at the entrance of the MBTL) and a plane mirror to reach the collector composed by 8 mirrors (one for each beam), that directs the beams towards the first large mirror of the MBTL. Large mirrors (MBTL units) transmit the beams into the tokamak hall where a splitter (i.e. a collection of 8 mirrors) separates the bundle into 8 single beams. Then, after reflection from a shaping mirror, two real-time controlled polarizers mirrors set the final polarization of the wave. The crossing of the back plate of the port is a short section of corrugated waveguides (WG) (63.5mm diameter) where a gate valve is placed to separate the vacuum of the machine from those of MBTL (Fig. 2). The WG realizes the input waist of the beam in the launcher. Both launchers are based on the front steering concept with two mirrors for each line, the first shaping (fixed) and the second one, faced to the plasma, plane and movable. The mirror dimensions are respectively 200x210 mm and 270x140 mm, compatible with a beam radius of 46 mm on the shaping mirror. The mirrors are cooled with water and linear/rotary piezoelectric actuators are presently considered. The same plug-in structure is foreseen for all equatorial launchers and one similar for all the upper launchers to simplify design and construction and increase the maintainability.

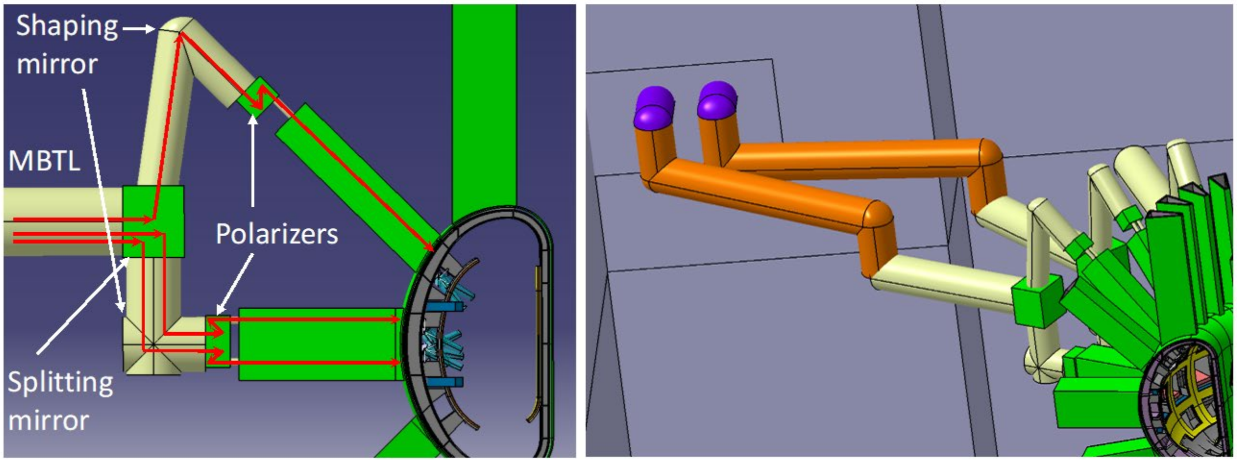

Figure 2. Preliminary schematic CAD design of the connection between the TL and the launchers.

The upper launcher is real-time controlled (fast movable in poloidal and toroidal directions: 300 ms for full angular range ± 30°), dedicated to the MHD activity and the equatorial launcher is also movable for main heating and other tasks. The design and the manufacturing of the launchers are under evaluation as well as the choice of the materials for the bulk (CuCrZr, Al and Mg alloys) and the coating (electroplating on all surfaces in contact with water for non-Cu materials).

A first assessment of the EC wave absorption and current drive (CD) capabilities has been performed with the beam-tracing code GRAY [12] to properly select the poloidal (α) and toroidal (β) launching angles. Complete absorption can be achieved for both launchers in the $0.2<\rho<0.8$ range. Maximum current drive, of the order of 15-20 kA/MW, is achieved in the central region for $15º\leq|\beta|\leq 20º$. At mid radius, maximum CD is obtained at larger toroidal angles, with small variations in the $20º\leq|\beta|\leq 30º$ range. CD at the q=3/2 and q=2 rational surfaces for NTM control is better performed from the UL where CD is maximized at $|\beta| \approx 10\div15º$ (5 kA/MW at q=3/2).

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