Design of ITER-FEAT RF Heating and Current Drive Systems

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Abstract. Three radio frequency (RF) heating and current drive (H & CD) systems are being designed for ITER-FEAT: an electron cyclotron (EC), an ion cyclotron (IC) and a lower hybrid (LH) System. The launchers of the RF systems use four ITER equatorial ports and are fully interchangeable. They feature equal power outputs (20 MW/port), similar neutron shielding performance, and identical interfaces with the other machine components. An outline of the design is given in the paper.

1. Introduction

The achievement of the main ITER-FEAT operation regimes has set new challenges to the design of heating and current drive (H&CD) systems. ITER-FEAT is a driven machine, whose performance rests, for a large part, on auxiliary heating system availability and performance. Three RF auxiliary heating systems operating at the electron cyclotron (EC), ion cyclotron (IC), and lower hybrid (LH) resonant frequencies, and a (negative ion) neutral beam injection (NBI) system, have been developed during the EDA, and their design has been revised in the last year to fulfil the latest ITER requirements.

The key issues of the reference scenario are to deliver sufficient central heating power to access the H-mode regime, to rise the plasma temperature as the density is increased to a plasma pressure adequate for the requisite fusion power, and to maintain burn by controlling excursions about the operating point and pressure driven instabilities. Steady-state operation requires an active current profile control, necessary to access enhanced confinement regimes, in which a large fraction of the plasma current is generated via the bootstrap effect. The onset of neoclassical tearing modes (NTM) potentially poses serious challenges to ITER high-β operation, and provisions for active control by EC CD appear at present to be unavoidable.

Compared to the 1998 ITER design, the reduced contribution of α-particles to bulk plasma heating in ITER-FEAT requires further optimization of the heating systems and a more flexible approach in their use. A graded implementation of the H&CD power is now foreseen in ITER, with different options, depending on the evolution of the experimental program.

H&CD systems are also required to heat non-fusion plasmas in early operating phases, for example, to commission the divertor target plates. They are used for plasma initiation, assisted start-up, and soft-landing. They have the capability to control sawteeth, to induce plasma rotation, and can provide ancillary services such as wall conditioning.

The reduction of ITER size has decreased the number and dimensions of the ports available, and increased the competition for access to the plasma. For the heating systems, this is reflected in a general increase of the design power density. Four equatorial ports are now assigned to RF systems and four additional upper ports are used for EC CD NTM stabilization.

2. General design features

A modular approach is adopted in the design of the RF launchers located in the equatorial ports. They are designed as interchangeable plugs with the same nominal installed power (20 MW/port), similar neutron shielding/activation performance, identical vacuum/tritium confinement boundaries and interfaces with the VV port, and the same remote maintenance requirements, interface and procedures.

The launcher assemblies are supported by the same mechanical structure (cantilevered at the port closure plate and otherwise disconnected from the other port components), providing a standardized interface with vacuum vessel and blanket. At the plasma end, the RF plugs are flush with the blanket first wall and therefore shielded from conduction heat loads. A gap of 20 mm is allowed all around the plug perimeter from the port walls and an overlap of 30 mm with the adjacent blanket modules (dogleg) avoids direct neutron streaming in the gap. The nominal separation between plasma separatrix and the first wall in the outer midplane is 12 cm.

For all systems, the primary confinement boundary is located at the vacuum vessel closure plate and a secondary vacuum extends up to the cryostat closure plate. Single-disk, water-cooled ceramic windows are used in each wave-guide or coaxial line. The dielectric window materials are different in different systems: BeO is used for IC and LH and polycrystalline diamond for EC.

The RF systems are designed to make maintenance operations simple, in situ and in the hot cell. All RF launcher assemblies are delivered to the torus fully commissioned, thoroughly tested to full performance in a test stand, and leak tested, and the integration in the port requires installation and sealing of the closure plate only. The plasma-facing components are all easily detachable, to be replaced in the hot cell in case of damage. The first wall is built in copper alloy, plated by a 10 mm Be layer, with cooling holes lined with 0.5 mm 316 SS LN, and welded to a base plate supported from the top and bottom of the launcher frame

In all systems, a water-cooled 316 SS LN nuclear shield limits the average activation level outside the primary closure plate to a level below 100 μSv/hour, 2 weeks after shutdown, sufficient to allow hands-on maintenance at that port closure plate location. A vacuum wave-guide/transmission line assembly is located outside the primary vacuum boundary, in the inter-space between VV and cryostat closure plates.

High voltage regulated DC power supply units, similar in design and specifications, are required for the main supply of the RF power sources (gyrotron oscillators for EC, multi-stage amplifiers for IC, and klystron amplifiers for LH). Complex networks of plant parameter monitoring, control and data acquisition interface the RF systems with the ITER control and data acquisition system (CODAC). Standardization in this area is also sought, to minimize costs and to simplify operation.

3. Electron Cyclotron System

The electron cyclotron system uses an equatorial port to initially deliver a power of 20 MW at 170 GHz for H&CD and 2 MW at 120 GHz for plasma start-up assist. A second equatorial port is reserved for further power extension. Four upper ports are available to accommodate up to 30 MW of RF power at 170 GHz for neo-classical tearing mode (NTM) stabilisation. Complementary beam steering capabilities are available in equatorial and upper port launchers: the beams can be toroidally steered ± 12.5° in the former and poloidally steered ± 5° in the latter.

The equatorial launcher (Figure 3a) consists of a front shield, and 3 sets of steerable mirrors,

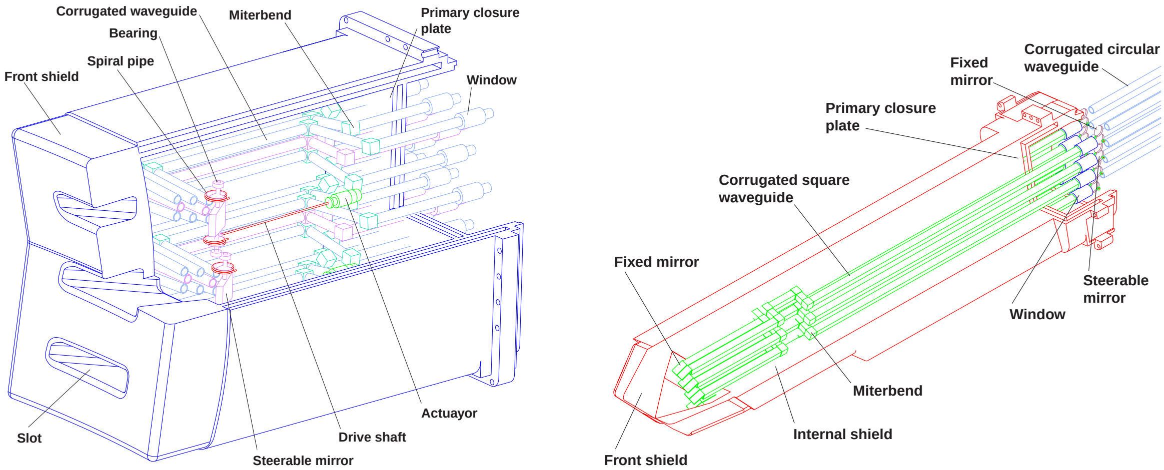

FIG. 3a) Equatorial Launcher, b) Upper launcher(remote steering type)

collecting 8 RF beams each, 24 circular corrugated wave-guides, mitre-bends, and diamond windows located at the port primary closure plate of the launcher. The front shield reduces the high-energy neutron flux and plasma radiation on the internal elements, has 3 horizontal injection slots and is segmented into several modules. The steerable mirrors are supported by bearings at the pivot end and water-cooled to accommodate RF power losses (about 50 kW/mirror), plasma radiation and nuclear heat.

A chemical vapour deposition (CVD) diamond disc is used as a primary vacuum window in each line, owing to its low dielectric losses ($\tan\delta = 2 \times 10^{-5}$) and high thermal conduction (~2000 W/mK), which allows a simple edge cooling of the disc. The RF power is transmitted from the window to the steerable mirror by standard corrugated circular wave-guides with an inner diameter of 63.5 mm and mitre-bends installed in the frame with an internal shield structure.

In the upper launcher, a similar beam-mirror concept is used. Here particular emphasis is devoted to an accurate focussing of the RF power on m=2 and m=3/2 plasma flux rational surfaces by injecting 6.7 MW of RF power from 8 corrugated wave-guides. An assessment of the remote steering (RS) concept, allowing to locate all movable components outside the primary vacuum, is being developed in parallel with the use of corrugated square-cross-section wave-guides, a fixed exit mirror and (ex-vessel) steerable mirror installed at the input of the wave-guide (Figure 3b).

4. Ion Cyclotron System

The IC H &CD system has been re-designed in order to substantially upgrade its power handling at constant RF voltage. A power of 20 MW is launched from an equatorial port (with a second port reserved for power upgrade) in the frequency range f = 35-55 MHz, which encompasses all important IC heating scenarios as shown in Table 1:

TAB. 1. ION CYCLOTRON RESONANCE FOR ITER-FEAT

Resonance	Frequency (MHz)	Comments
$2\Omega_T=\Omega_{He3}$	53	Second harmonic and minority heating
Ω_D	40	Minority heating
FWCD	55	On axis current drive

The IC array (Figure 4a) consists of an array of 4x2 elements fed by 8 coaxial transmission lines each carrying a nominal RF power of 2.5 MW.

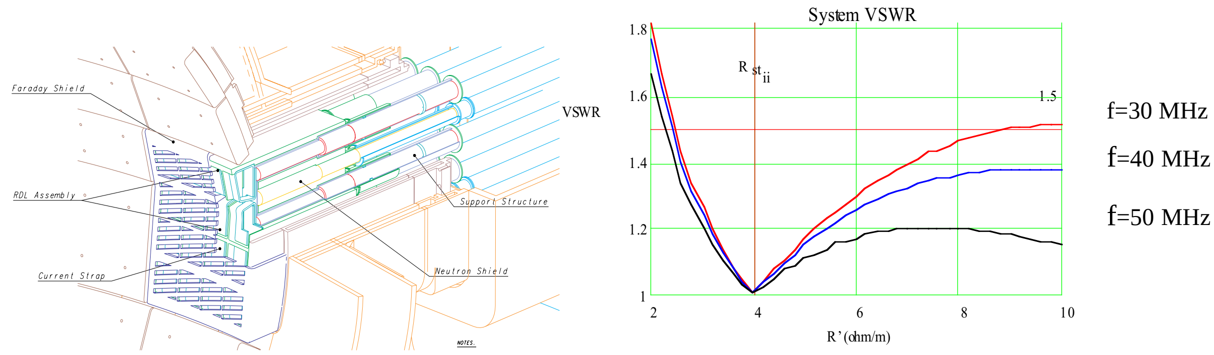

FIG. 4a) Layout of IC array, b) VSRW as function of load (R) and frequency (f)

Space limitations in the reduced size ports have imposed changes in the mechanical design. A variation of the resonant double loop [1] concept used earlier has been adopted, with the series tuning reactance located at the input of the double loop, allowing a more convenient mechanical arrangement for the current straps, which are now self supporting. Short straps are used in order to decrease the operating voltage at the plasma interface and to improve its structural resistance.The tuning elements are short-circuited coaxial sections of variable length, supported by stub-like dielectric spacers and running in the port. The variable short circuits are tubular sections protruding from the neutron shield and can be individually maintained without disassembling the plug from the port.

The highest voltage regions are located about 1 m away from the plasma interface. The electric field on the plasma end is reduced to ~ 3.5 kV/mm at a power density of 9.2 MW/m^2. Calculations show that, with a judicious choice of the tuning network impedance, a large tolerance to load variations (such as ELMs, etc), is to be expected. Based on the voltage standing wave rectification (VSWR) plot shown in Figure 4.b, a power transfer efficiency <°95% can be obtained, over the whole range of loads and frequencies.

6. Lower Hybrid System

The LH system is designed to deliver a power of 20 MW at 5 GHz using a single equatorial port. The launcher is powered by 8 main transmission lines (MTL), connected to 24, 1 MW klystrons by means of combining units, to accommodate transmission losses of the order of 0.7 dB.

The launching structure (Figure 5) is composed of 4 passive/active multijunction (PAM) stacks, with a radiated spectrum operating at a $N_{//0} = 2$. Each PAM stack is made of 24 active and 25 passive quarter wavelength wave-guides. For an injected power of 20 MW, the power density in the wave-guide is 33 MW/m^2.

The splitting/phasing network of each PAM stack is composed of 4 rows of 3 TE_{10} to TE_{30} mode converters, each feeding 8 PAM wave-guides. A limited flexibility in $N_{//}$ ($1.9 < N_{//} < 2.1$) is obtained with this layout, by a toroidal phase variation of ± 90° around the nominal phase offset. Sections of standard oversize wave-guides connect the output of the four groups

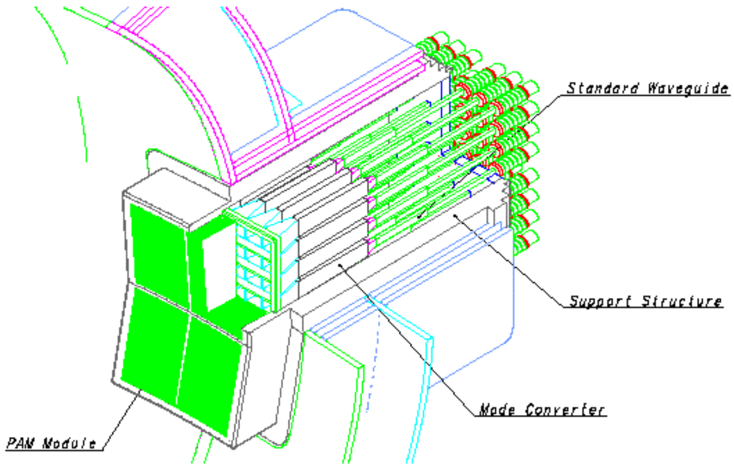

FIG 5. Lower Hybrid Launcher

of mode converters to 48 double-disk, RF windows, isolating the primary vacuum from the secondary one. The 48 inputs are connected, by means of a set of 24 matched hybrid junctions, and six rectangular-to-four-sector transformers, to the output of six main transmission lines (MTL) made from oversized circular wave guide, operated in the TE_{10} mode at reduced RF losses. Each MTL is fed by 4 klystrons via a combining network (CN) composed of 4 symmetric rectangular-to-sector transformers. Mode filters are used to suppress axisymmetrical TE_{0n} modes and to damp high order TE_{nm} and TM_{nm} modes. Mitre bends are used in the wave-guide. The LH transmitter layout consists of three stages: a low power solid state RF source (20 dBm) connected to a solid state driver (10 W), followed by the klystron amplifier (1 MW).

7. Conclusions

The design of ITER RF auxiliary heating and current is currently being completed. The design has mainly addressed issues related to the in-vessel components, including manufacturing, installation, testing, survival in the reactor environment, plant control and operation, remote handling, and hot cell maintenance. The overall group of RF H&CD systems offers prospects for an efficient, reliable, and flexible service.

8. References

[1] D.J.Hoffman et al, Proc VII Topical AIP Conf., 159, 302 (1987)