Preliminary concept of electron cyclotron resonance heating for the COMPASS-U tokamak

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Plasma heating in the COMPASS-U tokamak will be provided by neutral beam injection and electron cyclotron resonance heating system. Injected power of 1-2 MW in the initial phase of operation with possible future upgrades up to 10 MW is planned for the electron cyclotron heating system. The injection of 140 GHz waves is considered for the fundamental harmonic heating of O-mode and the second and the third harmonic X-mode from the low-field side equatorial port. Preliminary evaluations of EC wave propagation and absorption, obtained from simulations with the beam-tracing code TORBEAM, are shown. Simulations from the beam-tracing proves the feasibility of the ECRH heating in lower magnetic field scenarios. Basic parameters of considered technical solution of gyrotrons, transmission line and launcher is described.

1) Introduction

COMPASS-Upgrade[1] (COMPASS-U) is a compact-sized (R = 0.89 m, a = 0.27 m), high magnetic field (up to 5 T) and high density ($\approx$ units of 10^{20}) tokamak under development at IPP Prague. It will be capable to operate with plasma current up to 2 MA. COMPASS-U will address the key challenges related to the plasma exhaust physics and it will contribute to provide scalings towards ITER and DEMO. The device is designed to generate and test various DEMO relevant magnetic configurations, such as single null, double null and exotic plasma shapes like snow-flake. Additional heating will be provided by the neutral beam injection (NBI) with planned 4-5 MW delivered power. The electron cyclotron heating system (ECRH) should deliver the power of 2-10 MW. Apart from the heating, the main features of the ECRH heating are to prevent the heavy impurity accumulation [2] (tungsten, nickel, etc.), to assist the plasma breakdown and to suppress instabilities e.g. neoclassical tearing modes (NTMs) [3].

2) TORBEAM Simulations

There are several scenarios for the COMPASS-U in developement. These include wide range of magnetic field (1.25 - 5.00 T). Finding the optimal heating frequency for all given scenarios (see Table 1) is a challenging task. With respect to the existing gyrotrons and their operation, the 140/105 GHz solution was preliminarly chosen. Tunability of a gyrotron between the frequencies 105 GHz and 140 GHz is favourable for the low magnetic field discharge scenario utilisation.

Table 1: Four main scenarios of the COMPASS-U discharges.

B_T [T]	I_p [MA]	$t_{flattop}$ [s]	ECRH	f_{ECRH} [GHz]	$n_{e,cut}$ [10^{20} m^{-3}]
1.25	0.4	4.3	3rd harm. X-mode	105	0.9
2.50	0.8	3.2	2nd harm. X-mode	140	1.2
4.30	1.4	1.5	1st harm. O-mode	140	2.5
5.00	2.0	1.0	1st harm. O-mode	140	2.5

First baseline scenario is the single-null divertor shape with $B_T = 1.25$ T and $I_p = 0.4$ MA. It is possible to heat the core of the plasma by the 3rd harmonic X-mode waves with the frequency of 105 GHz. Cutoff density for these waves is above estimated core electron density ($0.5 \cdot n_{GW}$) during these discharges.

Second harmonic heating X-mode waves with the 140GHz frequency can be used for the $B_T = 2.5$ T discharge core heating. Its estimated core density could reach the limit of the cutoff density ($n_e = 1.2 \cdot 10^{20}$ m^{-3}). ECRH operation must be avoided, in the case of the high density, to prevent damage to the machine and diagnostics. The TORBEAM[4] beam-tracing simulations for the core density $n_e = 10^{20}$ m^{-3} show feasibility of this solution. The suggested 2 MW of power are fully absorbed everytime the resonance is reached, see Figure 1 and Figure 2.

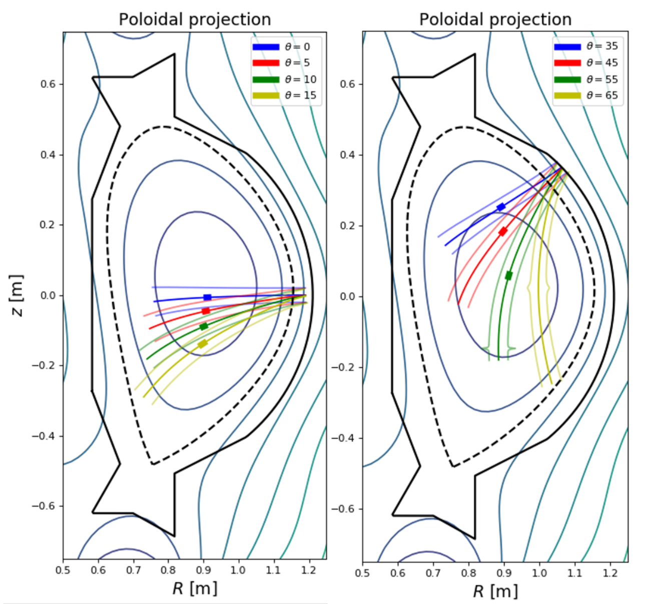

Figure 1: Trajectories of 140 GHz X-mode waves for poloidal angle (θ) scan in 2.5 T scenario.

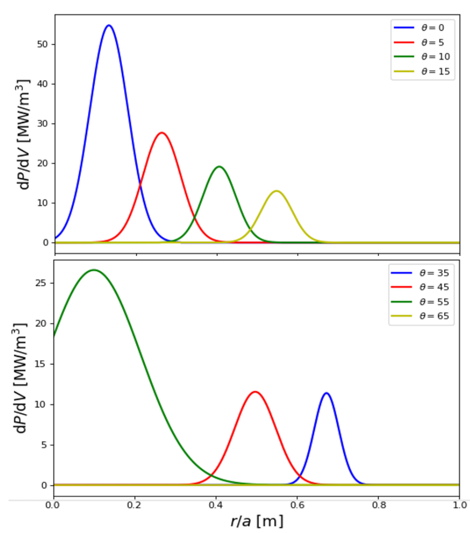

Figure 2: Power density deposition of 140 GHz waves in 2.5 T scenario.

Two launcher positions are considered in the preliminary design. One of them is the LFS upper port, the other is low field side midplane port i. e. equatorial. The second location is more favourable as it has uniform resonance region width.

Another scenario with B_T = 4.3 T and I_p = 1.4 MA will be heated via 140 GHz O-mode waves. In this case, the resonant layer for fundamental harmonic is off-axis, shifted to the high-field side. Perpendicular radiofrequency beam is absorbed around $r/a = 0.65$. Absorption region can be shifted by injecting the wave with some toroidal angle ϕ (oblique injection). This shift is shown in the Figure 3 and Figure 4. Core electron density in these simulations is $n_\mathrm{e} = 2 \cdot 10^{20}$ m^{-3}. Introducing the angle $\phi = 20°$, the absorbtion shifts towards the core of the plasma to $r/a = 0.2$.

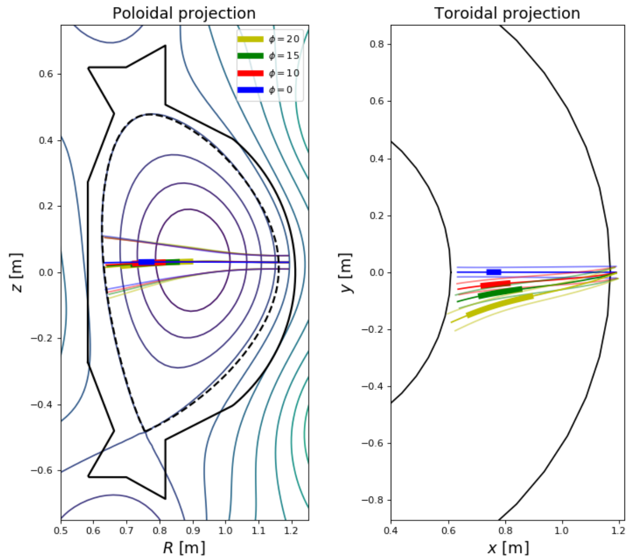

Figure 3: Trajectories of 140 GHz X-mode waves for poloidal angle (θ) scan in 4.3 T scenario.

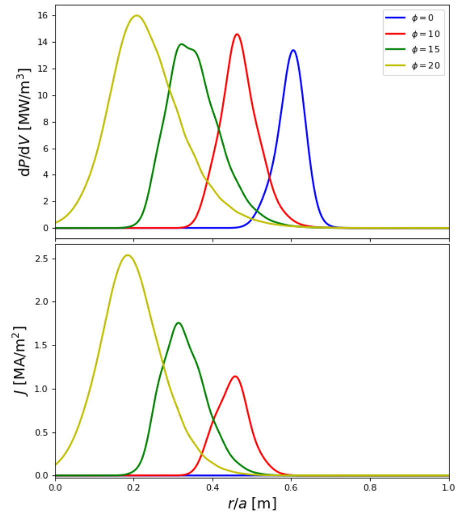

Figure 4: Power and current density deposition of 140 GHz in 4.3 T scenario.

The most advanced scenario of B_T = 5 T and I_p = 2 MA will probably reach and overcome the cutoff density. Natural H-mode density, lowest achievable density during type I ELMy H-mode, is predicted to be around $0.5 \cdot n_\mathrm{GW} \approx 4 \cdot 10^{20}$ m^{-3}. It is worth mentioning that type I ELMy H-mode is not considered for DEMO anymore and other ELM-free regimes are likely to be prominent, however development of high-density scenarios is still relevant for DEMO and future reactors. Heating via 140 GHz O-mode at the fundamental harmonic could be still problematic, especially when the plasma enters the H-mode. Thus, for the 5 T discharges, the I_p would have to be lowered to < 1.15 MA in order to lower density below cutoff condition. The ECRH system at COMPASS-U has to be designed for the future upgrade to the higher frequency. For the 2^{nd} harmonic heating, the DEMO relevant gyrotrons in developement (250+ GHz) could be utilised.

3) Suggested Components

As it was mentioned above, in the first stage we plan to install two 140/105 GHz gyrotrons with output power 1 MW. Similar gyrotrons are used in ASDEX-U tokamak[5]. Required pulse length is up to 10 s. In later stages we expect to add the high frequency DEMO relevant gyrotrons with frequency 250+ GHz and output power 1 MW. Pulse length can be shorter, around 2 s, due to decreased flattop duration in top performance scenario.

Transmission line from the gyrotrons to the tokamak will be approximately 30 m long. The corrugated oversized waveguides seem to be the best solution for this purpose. These waveguides are comparable with the quasi-optical lines with parabolic mirrors, in terms of transmission efficiency, but they are more compact and easy to build.

Launchers can be placed in the upper and the equatorial port. The equatorial port is preferable in the first stage of operation. In the both locations, the toroidal and poloidal steering mirror should be utilised. It is necessary for active suppression of NTMs and adjustment of power deposition.

Conclusion

Preliminary design specifications together with the TORBEAM simulations were described. Feasibility of the 105 GHz X3 heating of the 1.25 T scenario together with 140 GHz X2 heating of 2.5 T scenario and O1 heating of 4.3 T scenario was shown. Future upgrade to DEMO relevant 250-280 GHz heating will be needed if the COMPASS-U physics programme requires operation with densities higher than $2.5 \cdot 10^{20}$ m^{-3}.

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References

[1] R. Panek, *et al.*, Fus. Eng. and Design **123** 11-16 (2017)
[2] R. Dux, *et al.*, Journal of Nuclear Materials **313** 1150-1155 (2003)
[3] M. Maraschek, *et al.*, Nucl. Fus. **52** 074007 (2012)
[4] E. Poli, *et al.*, Comp. Phys. Comm. **225** 36-46 (2018)
[5] D. Wagner, *et al.*, Nucl. Fus. **48**(5) 054006 (2008)
[6] M. Bornatici, *et al.*, Nucl. Fus. **23**(9) 1153-1257 (1983)