

Performance predictions for the COMPASS upgrade tokamak

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COMPASS Upgrade [1] (COMPASS-U) is a flexible tokamak designed to capable of addressing many of the key challenges related to the plasma exhaust physics as well as to explore innovative divertor regimes and advanced confinement modes. It is a compact, medium-size (0.89 m major radius, 0.28 m minor radius), high-magnetic-field (5 T) and high-density ($1.5 - 2.5 \times 10^{20} \text{ m}^{-3}$) device. A cross section of the devie is shown in Fig.1. COMPASS-U will explore and compare different divertor configurations (single null, double null). It will be equipped with relevant heating systems: 4-5 MW of neutral beam injection (NBI) and 4 MW of electron cyclotron resonant heating (ECRH). The scrape off layer (SOL) power decay length is predicted to be extremely short ($\lambda_q \sim 1 \text{ mm}$), similar to the ITER case.

High power fluxes on the divertor targets are predicted and the metal first wall will be capable of operation at high temperatures ($300^\circ - 500^\circ \text{ C}$). COMPASS-U will also offer a possibility to study enhanced confinement modes, variable and low torque operation, edge and SOL physics and many other issues relevant to next-step devices. In this document, we assess the core plasma performance in the foreseen operation scenario parametric range. Equilibria with various plasma shapes, created using the planned ITER-like PF coils, are calculated, including the PF coil currents, using the free-boundary equilibrium code FREEBIE [2]. The effect of placing the poloidal field PF coils inside or outside the toroidal field (TF) coils is compared. MHD stability of the equilibria with respect to most unstable ideal and resistive modes is assessed by means of analytical estimates and equilibrium evolution simulations. Confinement, heating and SOL properties are studied using the rapid integrated tool METIS [3].

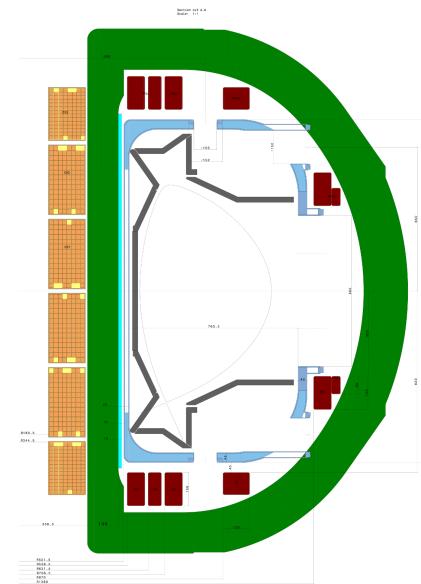


Figure 1: Design of COMPASS-U vacuum vessel, poloidal and toroidal field coils

Equilibrium calculation and stability evaluation

COMPASS-U will be able to explore different magnetic configurations thanks to a set of PF coils designed for this purpose. The possible plasma shapes include single-null plasma with triangularity up to 0.6 and double-null geometry. Equilibrium calculations have been performed with FREEBIE, an evolutive, free-boundary equilibrium (FBE) solver. FREEBIE calculates the dynamic evolution of the plasma equilibrium self-consistently with the evolution of currents in the conducting structures and PF coils. Calculations performed with FREEBIE with the parameters expected for COMPASS-U operation, elongation $\kappa = 1.8$ and triangularity $\delta = 0.6$, have shown that the desired equilibrium configurations can be obtained by appropriately changing the currents in the PF coils. The configuration with the PF coils placed inside the TF coils provides a better control over plasma and a more homogeneous toroidal magnetic field (Fig.2).

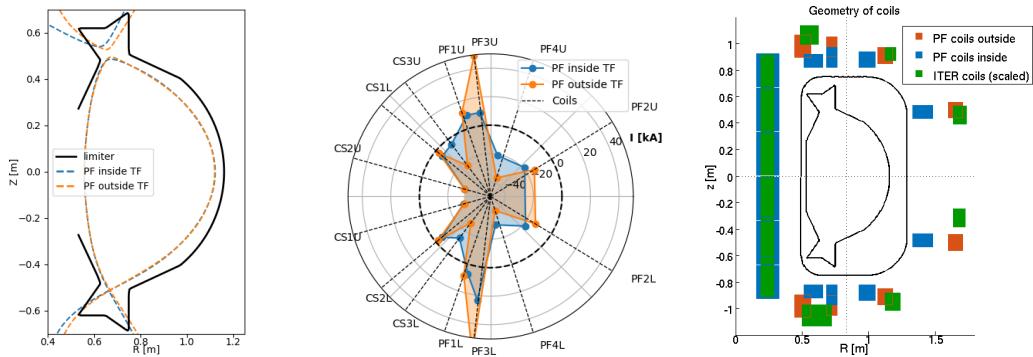


Figure 2: Separatrix shape (left) and PF coils currents (center) calculated with the different configurations of PF coils, either outside or inside the TF coils (right)

MHD stability with respect to the ideal modes for the planned operation of COMPASS-U has been assessed. Vertical instability and external kink modes, which can grow on time scales of a few μs , cannot be completely wall-stabilized because of the finite resistivity of the wall, and their growth takes place on the resistive time ($\sim ms$). The slowly-growing branch of the external kink mode is named "resistive wall mode" (RWM). If the residual growth time is short enough, these modes can be stabilized by active control with a feedback system or by plasma rotation. According to equilibrium evolution simulations with FREEBIE, the residual growth time of vertical instability is $\sim 1.5 - 2.5 ms$. Preliminary simulations with CarMa code [4], which couples the single-fluid MHD code MARS-F/K with the code CARIDDI are ongoing. Because of the short growth time, additional conductive elements will be inserted inside the vacuum vessel to provide further stabilization. For the vertical instability, wall distances r_W as large as ~ 1.6 times the plasma surface a are sufficient for ideal stabilization. Marginal wall

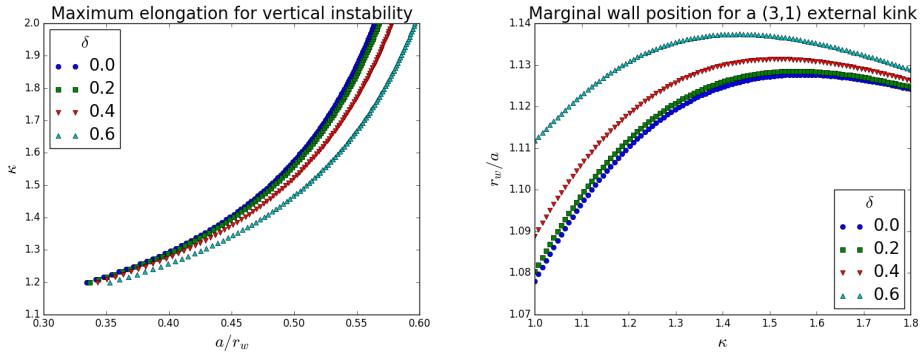


Figure 3: Maximum elongation for the vertical instability (left) and marginal wall position for a (3,1) external kink mode for $q(a) = 2.64$ (right)

position for external kink modes is even closer to the plasma (Fig.3), therefore more accurate stability caculations with respect to external kink and RWMs must be performed.

Confinement, heating and performance predictions

COMPASS-U is designed to operate at high density, high magnetic field and with additional heating power, which is necessary to improve the Type-I ELM My High-confinement mode (H-mode) as well as to reach divertor and edge plasma conditions relevant to future fusion devices.

The global plasma behavior during H-mode operation can be studied by performing simulations with METIS, an integrated tool which uses scaling laws (such as the ITERH-98 for energy confinement time), 1-D current diffusion, 2-D equilibrium and simplified heat and current drive source models to calculate several relevant plasma quantities during the discharge, such as confinement times, current drive efficiencies, radial profiles etc. Simulations of a full discharge with METIS (Fig.4) show that the H-mode can be accessed and the desired performances for COMPASS-U operaton, $\beta_N \sim 1.1\%$, $P_{ped} \sim 30kPa$ and $\langle T_e \rangle \sim 2keV$ can be reached when both the additional heating systems (NBI

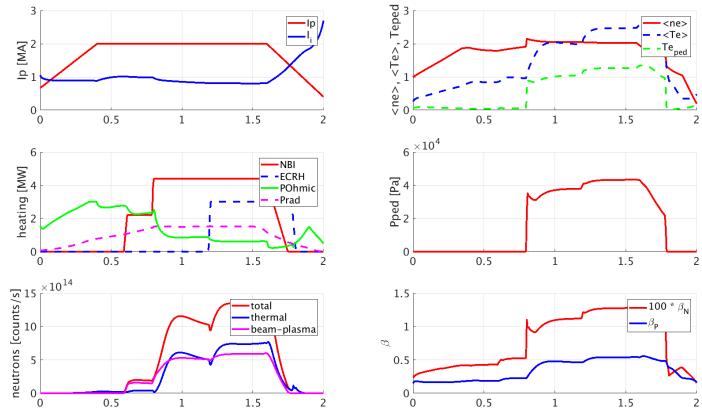


Figure 4: Time traces of different relevant plasma quantities during a discharge for COMPASS-U operation as predicted by METIS

and ECRH) are turned on.

Electron temperature on the divertor $T_e(DIV)$ is an important indicator of SOL cooling performances. This quantity has been calculated by using the two-point model prediction for the SOL collisionality ($v^* = 10^{-16}n_e L_C/T_e^2$, where $L_C = 2\pi R_0 q$ is the connection length) and its value has been normalized to the temperature on the LCFS $T_e(LCFS)$ (Fig.5). The ratio between these two temperatures provides a measure of the SOL cooling efficiency, which is essential for reducing the heat load on the divertor target. METIS simulations show that very small values of $T_e(DIV)/T_e(LCFS)$ can be reached for high densities ($\sim 2.7 \times 10^{20} m^{-3}$); to achieve complete divertor-plasma detachment, the use of liquid metal divertor to improve heat radiation is being considered.

Conclusions

We have shown that COMPASS-U will be able to operate at 5 T, 2 MA plasma current with high elongation and triangularity. Equilibrium calculations with FREEBIE show that the configuration with the PF coils inside the TF coils provides a better control over plasma and a more homogeneous toroidal magnetic field. Equilibrium evolution simulations with FREEBIE give a growth time of vertical instability $\sim 1.5 - 2.5 ms$. Simulations with CarMa code are ongoing to obtain more accurate results in the presence of conducting elements in the vessel and to correctly address the RWM calculations. METIS simulations show that COMPASS-U can access the H-mode when the additional heating systems (NBI and ECRH) are turned on, reaching $\beta_N > 1\%$, $\langle T_e \rangle, \langle T_i \rangle \sim 2 keV$ and $P_{ped} \sim 30 kPa$. Electron temperature on the divertor as calculated with the two-point model suggest that a good SOL cooling efficiency can be obtained for high plasma densities. The use of liquid metal divertor to improve heat radiation is being considered.

References

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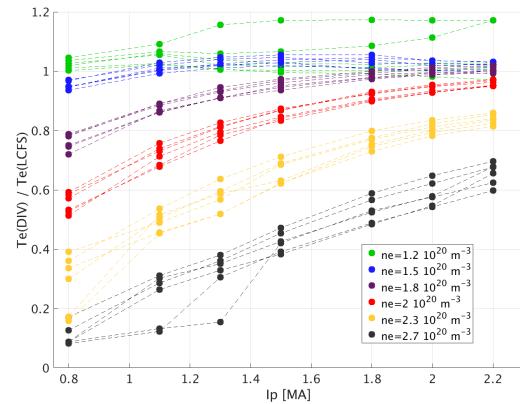


Figure 5: Electron temperature on the divertor normalized to its value on the LCFS for different values of density and current