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Modelling of plasma performance on COMPASS-D tokamak in the presence of NBI and LHCD

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Abstract

The potential scenario with Neutral Beam Injection (NBI) and Lower Hybrid Current Drive (LHCD) on the COMPASS-D tokamak ($R_0 = 0.56$ m, $a = 0.17$ m, $\kappa = 1.7$, $\delta = 0.4$) is investigated numerically using the ASTRA and ACCOME codes. With ASTRA, the thermal electron transport in ELMy H-mode plasmas achieved previously with ohmic (OH) and electron cyclotron (EC) heating on COMPASS-D tokamak [1] is analysed with a goal of testing transport models. It is found that both the Multi-Mode Model (MMM) and mixed Bohm-gyroBohm (BgB) models [2] have to be re-normalised to achieve a satisfactory agreement with measured central electron temperature and diamagnetic energy. The re-normalisation multiplier in the MMM model has to vary from 2 (OH H-mode) to 5.8 (EC heated H-mode) while a fixed re-normalisation multiplier (equal to 7.2) has to be used in the Bohm-like term of the BgB model in order to provide a better agreement with the data.
NBI heating and current drive (two 40 keV deuterium beams in co- or counter-directions with the total power of about 0.6 MW) is simulated using ACCOME and NBEAM. The possibility of obtaining a reversed shear configuration with co-injection and off-axis incidence is demonstrated. The LHCD scenario (P_{LH}=0.4 MW, $N_{//}$ = 2.1, f_{LH} = 1.3 GHz) for Phase I operation (B_t=1.2 T, I_{pl}=0.2 MA) is examined using the re-normalised BgB model with fixed re-normalisation coefficient.

Device and simulation codes

The COMPASS-D tokamak (R_0=0.56 m, a=0.17 m, B_T =1.2 T, I_p=200 kA, κ=1.7, δ=0.4) will be installed at The Institute of Plasma Physics Prague (IPP.CR). This device, designed at the Culham laboratory, UKAEA, as a flexible tokamak in the 1980s, has an ITER-like plasma shape and a clear H-mode [1]. The plasma in the COMPASS-D tokamak is started up by the ohmic heating (OH) system and ultimately sustained by additional heating and current drive systems. The NBI system consists of two injectors at 40 keV and 300 kW per injector. We consider here two basic tangential configurations: co-injection and balanced injection (one of the beams counter- injected). The COMPASS LH grill consists of 8 wave-guides at 1.3 GHz. The RF generator has maximum output power 400 kW at a maximum pulse length 1.5 s. The COMPASS poloidal field coils shown in Fig. 1 provide the various requirements for magnetic flux linkage:

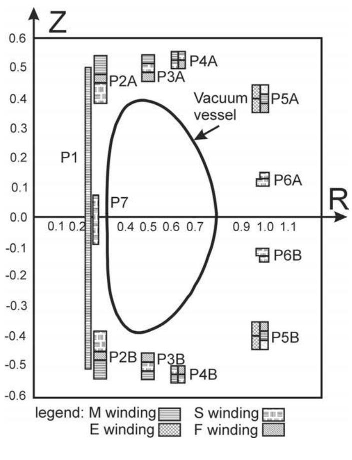

Fig. 1 Poloidal coil system. The "M" windings provide the necessary plasma loop voltage control, the "E" windings adjust the plasma position and shape, the "S" windings provide the different plasma shapes, and the "F" windings provide feedback control of plasma position.

The ACCOME code computes a free boundary magnetic equilibrium from the Shafranov equation with input from the plasma current density, pressure and the poloidal field coil system shown in Fig. 1. The COMPASS-D single-null equilibria SND and SNT calculated by ACCOME are shown in Fig. 2. We note that double-null equilibria can also be set up in the poloidal field configuration of Fig. 1. The equilibrium module also provides the coil currents needed to support the equilibria.

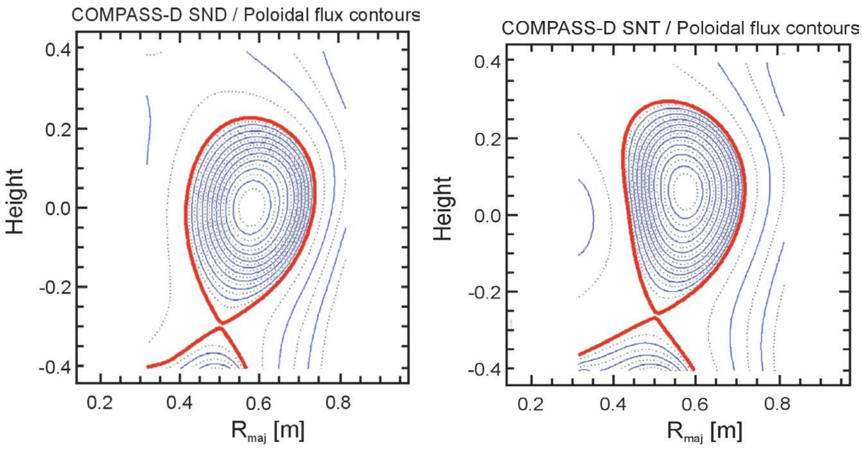

Fig. 2

B_T=1.2 T, I_p=0.2 MA

a) SND-low triangularity,
b) SNT-high triangularity

In order to assess the performance of COMPASS with the planned NBI and LH systems a number of combined simulations of codes ACCOME (Analyzer for Current drive COnsistent with MHD Equilibrium) [3] and ASTRA (Automated System for TRansport Analysis) [4] were carried out. The simulations proceed in a sequence of iterations between the two codes in order to reach a consistent state between power deposition profiles from ACCOME needed by ASTRA, and temperature profiles from ASTRA needed by ACCOME. NBI simulations have been performed using the ACCOME [3], FAFNER [5, 6] and NBEAMS [7] codes. A consistent state between the equilibrium and the ohmic, bootstrap, NB and LH current densities is achieved in a number of iterations between the ACCOME equilibrium and current drive modules.

Results and discussion

We concentrate here on the Phase I operating regime I_p = 0.2 MA and B_T = 1.2 T, foreseen for COMPASS-D initial operation after its installation. We examine auxiliary heating and current drive operation in the two basic COMPASS-D single-null magnetic equilibrium configurations: SND (low triangularity $\delta \cong$ 0.3 - 0.4) and SNT (high triangularity $\delta \cong$0.5 - 0.7). In all simulations we applied the full available NB power of 300 kW per NB injector, but only 50 %, i.e. 200 kW, of the nominal LH power was used, taking into account a limited antenna-plasma coupling capability.

In Table 1 we show the deposited NB and LH powers, the driven NB and LH currents and the peak temperatures T_{e0}, T_{i0}, as functions of NB injection geometry, i.e. on-axis or off-axis, and as functions of the SND or SNT equilibrium.

Table 1. Phase I absorbed powers, currents and peak temperatures at n_0=3×10^{19}m^{-3}

equilibrium	P_{NB} [kW]	P_{LH} [kW]	I_{NB} [kA]	I_{LH} [kA]	T_{e0} [keV]	T_{i0} [keV]
Ohmic base case	0	0	0	0	0.81	0.25
SND	0	94	0	59.4	1.00	0.25
SND on-axis	508	0	48.0	0	1.71	3.73
SND on-axis	505	122	79.8	45.6	1.80	4.29
SND off-axis	430	87	53.6	39.1	1.04	0.62
SNT on-axis	506	0	72.6	0	1.24	2.42
SNT on-axis	507	181	83.0	53.0	1.10	2.05
SNT off-axis	416	71	50.0	33.0	1.10	0.47

All these results are obtained at peak density n_0 = 3x 10^{19} m^{-3} with the profile $n(r) = n_0[(1-n_b)(1-r^2)^{1.5} + n_b]$, where n_b is the plasma edge density, r is the plasma mid-plane normalized radial coordinate, and the exponents 2 and 1.5 were selected to approximate the density profile of previous COMPASS-D auxiliary heating experiments [1].

Since the COMPASS-D operating regime can extend up to a peak density of about 10^{20} m^{-3}, we also show here in Figs. 3a,b global results for peak densities n_0 between 2 – 6 x10^{19} m^{-3}, obtained from ACCOME simulations with fixed temperature profiles, i.e. without transport evolution from ASTRA.

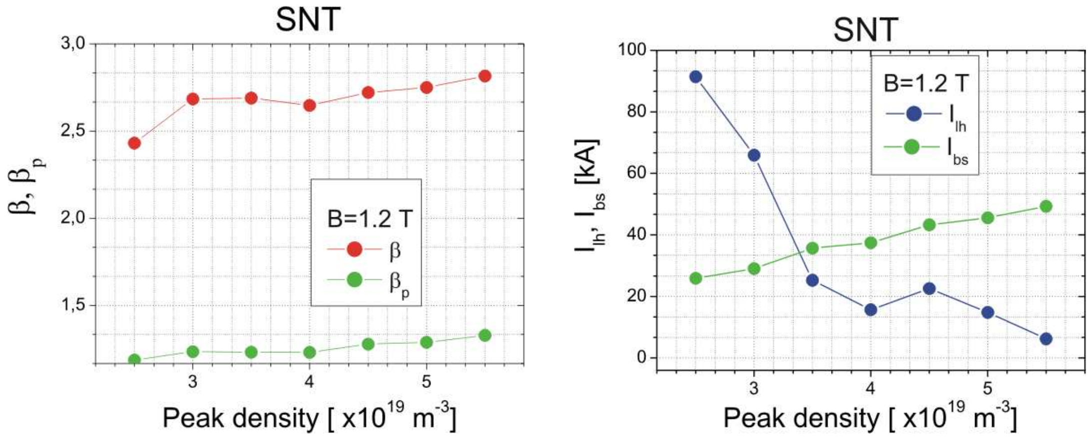

Fig. 3 SNT equilibrium, $B_T = 1.2$ T, $I_p = 200$ kA, a) β [%] and $\beta_{poloidal}$ versus peak density, b) LH current I_{LH} and bootstrap current I_{BS} versus peak density.

The bootstrap and LH current drive density scaling are evident from Fig. 3b. The theory for LHCD predicts efficiency inversely proportional to density [8].

A substantial effect of on-axis and off-axis NB incidence was found. While strong ion heating is noted for on-axis incidence, very little heating occurs for off-axis incidence. On the other hand, off-axis co-NBI incidence can lead to reversed shear, as seen in Fig. 4b.

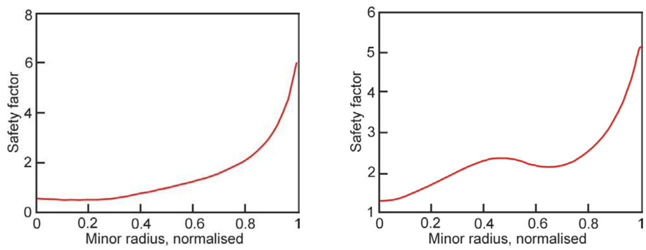

Fig. 4 Phase I, SNT, safety factor as function of radial position:
a) LH + on-axis NB,
b) LH + off-axis NB.

We point out that about 20-30 % of the absorbed NB power is deposited on the electrons. From Table 1 it is then clear that NBI is an important electron heating mechanism, in fact more important than LH electron heating at Phase I conditions. All simulations of Table 1 are done for co-injected beams since at Phase I conditions the orbit losses for counter-injected beams are close to 50 % [6].

We emphasize the important effect of NB geometry with respect to plasma position. A slight shift in the plasma column, such that beams aimed at the plasma center will absorb even slightly off-axis, can substantially change the temperature profiles and their peak values. For example, the relatively high T_{e0}, T_{i0} for SND on-axis NB of Table 1 results from exact on-axis incidence in this case.

The magnetic equilibrium makes little difference to NB operation, but has an effect on LHCD and heating. LH wave absorption is sensitive to the magnetic equilibrium because of the higher degree of poloidal asymmetry and larger $n_{||}$ upshifts associated with SNT. The toroidal evolution of $n_{||}$ influences LH wave absorption through the electron Landau damping condition $n_{||}T^{1/2}_{[keV]} \geq 7$. In the low-temperature COMPASS-D situation it is therefore essential that the launched value $n_{||}= 2.1$ upshift sufficiently for absorption to occur. We note, however, that the Phase I operating regime I_p = 0.2 MA and B_T = 1.2 T is unfavourable to LHCD because of poor LH slow wave accessibility at these conditions. This is clear from the accessibility diagram, Fig. 5

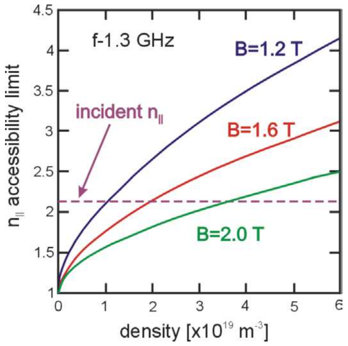

Fig. 5 LH slow wave accessibility (i.e. the condition for avoiding mode conversion from LH slow to fast wave) as a function of peak density and toroidal magnetic field.

$$n_{||} \geq n_{||acc} = \frac{\omega_{pe}}{\omega_{ce}} + \sqrt{K_\perp}, \quad K_\perp = 1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2 - \frac{\overline{\omega}_{pi}^2}{\omega^2}$$

Conclusion

Results from ACCOME-ASTRA simulations of COMPASS-D indicate that ion and electron heating from NBI depends sensitively on the NB power deposition profile because of very high NB power density. Further, T_e and T_i depend on NB co- or counter-injection; strong ion heating is observed for on-axis co-NBI ($T_{i0} \cong 2$ keV); diffusivity $\chi_i / \chi_{neo} \cong 2 - 2.5$ in regimes with strong central ion heating; weak ion heating but reversed shear is observed for off-axis NBI. LH absorption is weak because of poor slow LH wave accessibility. LH electron heating and current drive depends sensitively on $T_e(r)$ and the equilibrium. The SNT equilibrium is more favourable than SND to LHCD and heating because of the larger $n_{||}$ upshifts associated with the poloidally more asymmetric SNT equilibrium.

Acknowledgment

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