COMPASS–D magnetic equilibria with LH and NBI current drive

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Plasma equilibria are investigated numerically, using the ACCOME and ASTRA codes, on the COMPASS–D tokamak ($R_0 = 0.56$ m, $a = 0.17$ m, $B_T = 1.2$ T, $I_p = 200$ kA, $k = 1.7$, $\delta_x = 0.4$) for the planned Neutral Beam Injection (NBI) and Low Hybrid Current Drive (LHCD) systems. The LH system provides $P_{LH} = 0.4$ MW at $n_\parallel = 2.1$ and $f_{LH} = 1.3$ GHz. The NBI system has two 40 keV deuterium beams in co– or counter–directions with a total power of 0.6 MW. The COMPASS–D tokamak can typically operate in two configurations – single null divertor (SND) and single null divertor with a higher triangularity (SNT). Higher triangularity provides access to higher confinement and improved stability, and leads to larger $n_\parallel$ up–shifts for better slow LH wave absorption.We investigate the range of densities $n = 2 \div 6 \times 10^{19}$ m^{-3}. Both the LH and NB driven currents decrease with density. The magnetic shear reverses with off-axis beam incidence. In the given plasma parameter range, typically up to 60 kA of bootstrap current is driven and with NB co–injection up to 80 kA of NB current is driven. LHCD is weak at $f = 1.3$ GHz and $B_T = 1.2$ T, but at $n = 3 \times 10^{19}$ m^{-3} the LH driven current is about 40 kA, so that the required plasma current of 200 kA is supported almost non–inductively.

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Key words: tokamak, COMPASS–D, magnetic equilibrium, ACCOME code, ASTRA code, Neutral Beam Injection, Low Hybrid Current Drive

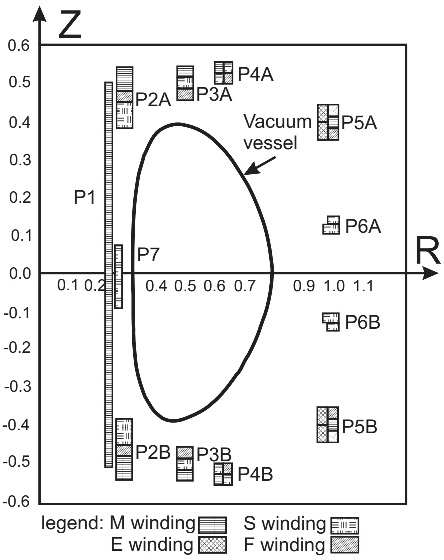
1 Introduction

The COMPASS–D (COMPact ASSembly) tokamak ($R_0 = 0.56$ m, $a = 0.17$ m, $B_T = 1.2$ T, $I_p = 200$ kA, $k = 1.7$, $\delta_x = 0.4$) will be installed at The Institute of Plasma Physics (IPP) Prague (IPP.CR). This device, designed as a flexible tokamak in the 1980s, has an ITER–like plasma shape and a clear H–mode. With the Lower Hybrid (LH) heating and current drive (CD) system and the foreseen Neutral Beam Injection (NBI) system a plasma parameter range relevant in many respects to

ITER will be accessible. Because the COMPASS–D and JET tokamaks are the only devices with X–point divertor and LH system, the study of the LH waves interaction with the edge plasma in COMPASS–D tokamak is of high importance for the possible incorporation of LH systems in ITER.

2 Device and simulation codes

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 foreseen NBI system consists of two injectors at 40 keV and 300 kW per injector. Two basic tangential configurations are considered here: co–injection and balanced injection (counter–injection) with on– and off–center injection. Normal injection will also be possible. The COMPASS–D 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 poloidal field coils (P) shown in Fig. 1 provide the different requirements of magnetic flux linkage:



- "M" windings, controlled by the Magnetising Field Power Supply (MFPS), provides the necessary plasma loop voltage control,
- "E" windings, controlled by the Equilibrium Field Power Supply (EFPS), adjusts the plasma position and shape,
- "S" windings, controlled by the Shaping Field Power Supply (SFPS), provide the different plasma shapes,
- "F" windings provides feedback control of plasma position.

Fig. 1. Poloidal coil system

In order to assess the performance of COMPASS–D with the planned NBI and LH systems a number of combined simulations of codes ACCOME (**A**nalyzer for **C**urrent drive **CO**nsistent with **M**HD **E**quilibrium) [1] and ASTRA (**A**utomated **S**ystem for **TR**ansport **A**nalysis) [2] 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 codes FAFNER [3],[4], NBEAMS [5] and ACCOME [1].

The ACCOME code computes a free boundary magnetic equilibrium from the Shafranov equation with input from the plasma current density, pressure and the COMPASS–D poloidal field coil system geometry shown in Fig. 1. The coil currents and the separatrix also can be prescribed. A consistent state between the equilibrium and the ohmic, bootstrap, NB and LH current densities is achieved in a number of iterations between the equilibrium and current drive modules.

The ACCOME schematic flowchart indicates the iteration process of obtaining self-consistent equilibria:

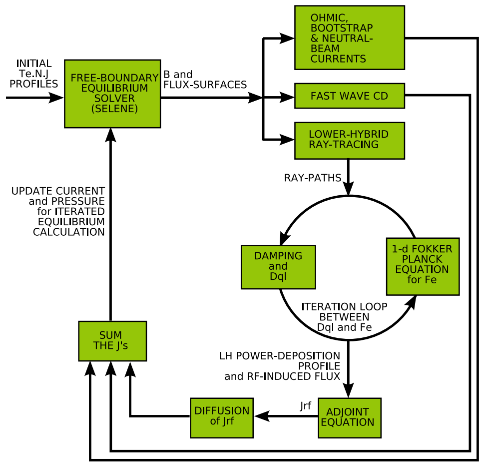


Fig. 2. ACCOME equilibrium and current drive simulation code.

The ACCOME calculation is started with a guess for $T_{\rm e}$ and $T_{\rm i}$ profiles. ASTRA then uses the calculated LH and NB current density and power deposition profiles to determine the new ion and electron temperature profiles. Astra uses transport coefficients compatible with earlier COMPASS–D experimental results [7]. The plasma density profile in both codes is fixed in form:

$$n(r) = n_0[(1 - n_{\rm b})(1 - r^2)^{1.5} + n_{\rm b}] \tag{1}$$

where $n_{\rm b}$ 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.

The calculated $T_{\rm e,i}(r)$ are then re–applied in ACCOME and the cycle is repeated until a consistent state between $T_{\rm i}$, $T_{\rm e}$, and the current and power deposition profiles is reached.

The NB module in ACCOME does not calculate ion orbit losses, which we therefore determined from the Monte–Carlo NB code FAFNER [3].

3 Results and discussion

We concentrate here on the Phase I operating regime $I_{\rm p} = 0.2$ MA and $B_{\rm T} = 1.2$ 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 $\Delta \approx 0.3 \div 0.4$) and SNT (high triangularity $\Delta \approx 0.5 \div 0.7$). 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.

The COMPASS–D magnetic field equilibria calculated by ACCOME are shown in Fig. 3. The single–null equilibria SND and SNT are illustrated in Figs. 3a and 3b, respectively. For completeness, Figs. 3c,d show that double–null equilibria DND and DNT can also be set up in the given configuration of magnetic coils shown in Fig. 1. The equilibrium module also provides the coil currents needed to support the equilibria.

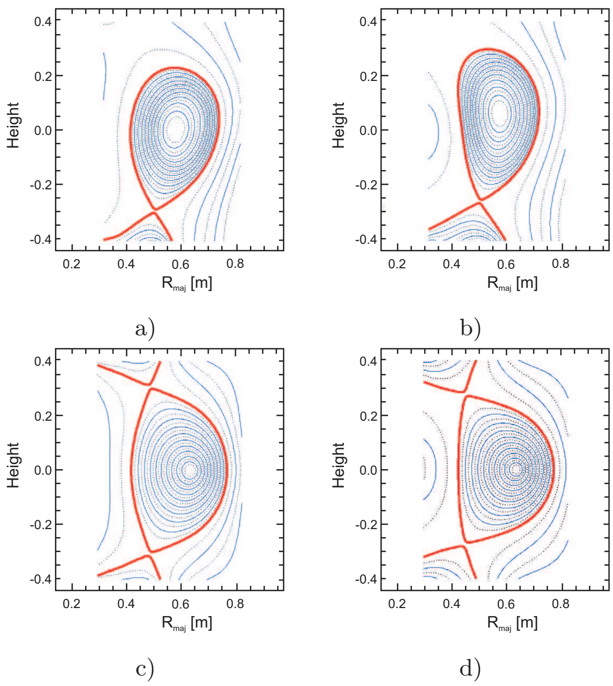


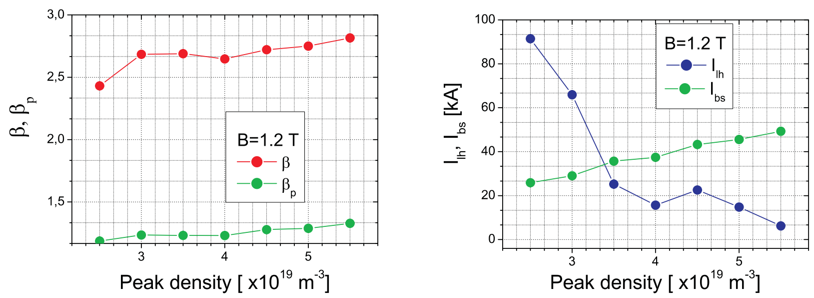
Fig. 3. Phase I, COMPASS-D magnetic equilibria in terms of poloidal flux contours computed for a) SND, b) SNT, c) DND, d) DNT configurations by ACCOME code.

Table 1 gives a basic idea of the differences entailed by operating in SND and SNT, respectively. All of the results in these Table are obtained at peak density $n_0 = 3 \times 10^{19}$ m^{-3} with the profile (1).

Table 1. Phase I absorbed powers, auxiliary driven plasma currents and peak temperatures at $n_0 = 3 \times 10^{19}$ m^{-3}.

equilibrium	$P_{\rm NB}$ [kW]	$P_{\rm LH}$ [kW]	$I_{\rm NB}$ [kA]	$I_{\rm LH}$ [kA]	$T_{\rm e0}$ [keV]	$T_{\rm i0}$ [keV]
Ohmic base	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

The COMPASS–D operating regime can extend up to a peak density of about 10^{20} m^{-3}. In Figs. 4a, b global results for peak densities n_0 between $2 \div 6 \times 10^{19}$ m^{-3}, obtained from ACCOME simulations with fixed temperature profiles (i. e. without transport evolution from ASTRA), are shown.



a) b)

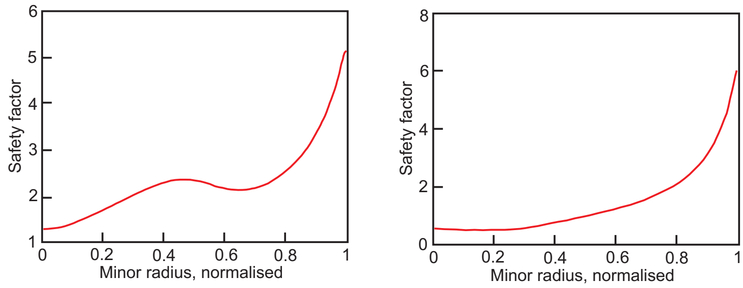
Fig. 4. Phase I, SNT configuration; a) dependence of β [%] and $\beta_{\rm poloidal}$ on peak density, b) dependence of LH current $I_{\rm LH}$ and Bootstrap current $I_{\rm BS}$ on peak density.

The current drive density scaling is evident from Fig. 4b. The theory for LHCD predicts an efficiency inversely proportional to density [6].

In Table 1 we note other global tendencies – the deposited NB and LH powers, the driven NB and LH currents, and the peak temperatures $T_{\rm e0}$, $T_{\rm i0}$, as function of NB injection geometry, i. e. on–axis or off–axis, and as function of SND or SNT.

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. 5a.

We note that about $20 \div 30$ % of the absorbed NB power is deposited on the electrons [4]. From Table 1 it is then clear that NBI is an important electron heating



a) b)

Fig. 5. Phase I, SNT configuration; safety factor profiles calculated by ASTRA code for the cases a) with LH and off–axis NB, b) with LH and on–axis NB.

mechanism, in fact more important than LH electron heating at Phase I conditions.

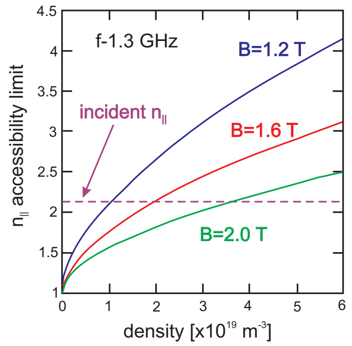
We next emphasize the important effect of NB geometry with respect to plasma position. A slight shift in the plasma column, such that beams originally aimed at the plasma center will absorb even slightly off–center, can substantially change the temperature profiles and their peak values. For example, the relatively high T_{e0}, T_{i0} for SND on–axis NB of Table 1 comes 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 $n_\parallel$ upshifts associated with SNT. The toroidal evolution of $n_\parallel$ has an impact on LH wave absorption via the electron Landau damping condition $n_\parallel T^{1/2}_{[\mathrm{keV}]} \geq 7$.

Hence, in the low–temperature COMPASS–D situation it is essential that the launched value $n_\parallel = 2.1$ upshift sufficiently for absorption to occur. We note that the Phase I operating regime $I_{\mathrm{p}} = 0.2$ MA and $B_{\mathrm{T}} = 1.2$ T is unfavorable to LHCD because of poor LH slow wave accessibility at these conditions. This is clear from the accessibility diagram, Fig. 6.

4 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 ($T_{\mathrm{i0}} \gg 2$ keV); $\chi_{\mathrm{i}}/\chi_{\mathrm{neo}} \sim 2 \div 2.5$ 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 depends sensitively on $T_{\mathrm{e}}(r)$ and the equilibrium; the SNT equilibrium is more favorable to LHCD and heating than is SND because SNT has more poloidal asymmetry leading to larger $n_\parallel$ upshifts.



$$n_{\|} \geq n_{\|acc} = \frac{\omega_{\rm pe}}{\omega_{ce}} + \sqrt{K_{\perp}}$$

$$K_{\perp} = 1 + \left(\frac{\omega_{\rm pe}}{\omega_{\rm ce}}\right)^2 - \frac{\overline{\omega}_{\rm pi}^2}{\omega^2}$$

Fig. 6. 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.

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