Non-inductive tokamak: advanced scenario
with radio frequency heating and current drive

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1. Introduction

A possibility of advanced operation with full non-inductive current maintained by lower hybrid (LH) waves and by a large bootstrap (BS) current is studied using 1D transport modelling for long pulse tokamaks. Strong electron heating with ion cyclotron waves is applied in this scenario. Different operational techniques including (1) the conventional operation at fixed plasma current, (2) the operation with controlled plasma flux and non-inductive current [1] and (3) the operation with the current profile control scheme [2] are compared. An optimization of BS current in plasmas with an internal transport barrier (ITB) formed due to a reversed magnetic shear (RS) configuration is discussed. As an example, the simulations are performed for a tokamak with the parameters of Tore Supra where flat or reversed q-profiles have been routinely obtained.

2. Scenarios with global plasma current control

We simulate the plasma evolution using the standard balance equations for the plasma density, electron and ion temperature and current diffusion equation taking into account the non-linear coupling of empirical shear-dependent transport coefficients [3, 4] and additional heating sources with the plasma parameters. LH power deposition profile is estimated using the wave diffusion model [5]. Gas puffing into the discharge governed by a feedback on the volume-averaged density, $<n_e>$, $\Gamma_{gas} \sim (n_{ref} - <n_e>)$, provides a fast density evolution towards the programmed value, n_{ref}. The modelling has been performed using the 1.5D transport code ASTRA [6] coupled with the neoclassical code NCLASS [7].

We start the modelling with the LH power launch at the beginning of the ohmic (OH) current ramp up in a low density plasma following previous experiments on Tore Supra [8]. The RS configuration has been produced at a low density and maintained during the density rise by increasing the LH current drive (LHCD) power. The ion cyclotron radio frequency heating (ICRH) power is applied at the end of the current ramp up when the density is large enough to provide a good antenna coupling. Then the plasma relaxes to the steady state equilibrium while staying in an improved core confinement state in the configuration with a flat or reversed q-profile.

This initial phase has been applied in the scenarios described below. In the first scenario we impose the total plasma current, I_{pl}, and make some assumption about the amount of H&CD power required to drive this current non-inductively, $I_{pl} \approx I_{BS} + I_{LHCD}$ (here I_{BS} is the BS current and I_{LHCD} is the LH current). The OH current is not strictly zero in this scenario and a small residual OH current is still maintained by the OH power supply. The second scenario is performed under the condition of zero loop voltage, $U_{loop} = 0$, while the plasma current is maintained at a fixed value through a simple feedback loop involving the LHCD power, $\Delta P_{LHCD} \sim I_{ref} - I_{pl}$ (here I_{ref} is the programmed value for the plasma current and ΔP_{LHCD} is the variation of the LHCD power) (Fig.1). A similar feedback scheme has been used in the experiments on Tore Supra [1].

Steady state equilibria obtained in these scenarios are characterized by a reversed q-profile and improved core confinement when the LHCD power deposition profile is well off-axis (r/a~0.4-0.5) and the BS current is less than 40% of the total plasma current. The self-consistent simulations of the LH power deposition profile with the ray-tracing/Fokker-Planck code DELPHINE and plasma transport show that the off-axis LHCD profile can be obtained for typical CIEL equilibria with presently available LH antenna [9]. As a next step, a possibility to increase the BS current fraction above 40% by increasing the ICRH power or by producing a far off-axis LH power deposition profile has been examined. We found that a strongly localized and well off-axis (r/a>0.5) LH current density profile results in a deeply reversed shear and larger BS current fraction, but a central current may be required in this case to maintain the equilibrium in the plasma core. If the central and LH current density profiles are well separated a non-regular q-profile with a local maximum located inside the plasma radius with shear reversal is produced (Fig. 2). Further analysis of the MHD stability of such configurations is required to conclude about their viability for future experiments.

The scenarios with a large BS current fraction and/or weak overlapping of the external current source profiles may exhibit thermal relaxation oscillations (Fig. 3). The cause of these oscillations is a misalignment between the BS current density profile and LH current density profile obtained in RS configurations. The BS current density profile is peaked in the ITB region, i. e. it is shifted towards the center with respect to the LH current density profile providing the shear reversal. When the maximum of the BS current density becomes larger than the maximum of the LH current density the location of the minimum q-value moves towards the center (Fig. 3b). This leads to the continuous peaking of the BS current density profile and to the appearance of two minima in the q-profile produced by the LH current and BS current. Negative electric field generated by the locally overdriven BS current penetrates towards the center and produces a large increase of the q_0-value (Fig. 3a). The electron temperature evolves during these oscillations passing from the profile with a strong ITB to the profile with a weak ITB and a double barrier shape when the BS current and LH current produce two local minima on the q-profile. Thus our analysis shows that a broad off-axis BS current density profile cannot be self-sustained due to the RS configuration if this configuration is maintained by the BS current alone. However the capability of the BS current to drive a large fraction of the off-axis current can be used in advanced scenarios if the mechanism for an ITB formation is decoupled with the BS current evolution. Such scenarios can be realized by applying the seeding off-axis currents, strong off-axis heating or the control of the ITB evolution by using the ExB rotation shear.

3. Scenario with current profile control

The capability of the current profile control scheme proposed in Ref. 2 to provide a steady state operation without thermal relaxation oscillations at a large BS current fraction and with a regular shape of the q-profile has been examined in numerical modelling. Central current in this scenario is driven by fast magnetosonic waves but ECCD could be used as well. The feedback control starts at 15 seconds in the cold and dense plasma and a programmed q-profile with $q_0 = 5$ and $q(r/a=0.5) = 1.7$ has been produced (Fig. 4). Then the ICRH power was increased slowly to maintain the magnetic configuration. We stop the ICRH ramp at 8 MW when the BS current density has a nearly flat profile in the plasma core and its maximum is comparable to the maximum of the LH current density profile (Fig. 5). In this case 46% of the non-inductive current is due to the BS current. The

steady state *q*-profile controlled through the feedback loops has a regular shape in the plasma core and ITBs on the density and temperature profiles have been produced (Fig. 5). This numerical example shows that the programmed current profile can be obtained within a time scale of one hundred seconds. Discharges with comparable durations have been already produced on Tore Supra [1].

4. Summary

Numerical "advanced tokamak" study performed here for Tore Supra showed that the long pulse operation with an improved core confinement in the RS configuration may be obtained at high plasma density by using a dominant electron heating and off-axis LHCD. The absorbed RF power required for this performance is estimated as 7 - 10 MW for the ICRH and 5 - 8 MW for the LHCD within assumed plasma current and density range. These estimations for the LHCD power have been obtained with the efficiency range (0.8-1) $\times 10^{19}$ A/W/m^2. The improvement factor 2 in the thermal energy confinement with respect to the L-mode confinement has been obtained for these scenarios and this factor can be increased by strong ion heating. It has been shown that the application of the current profile control scheme [2] allows an operation with a regular shape of the *q*-profile at a large BS current fraction.
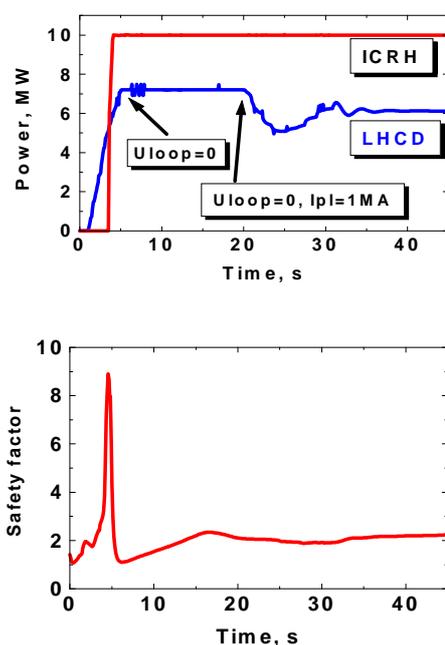
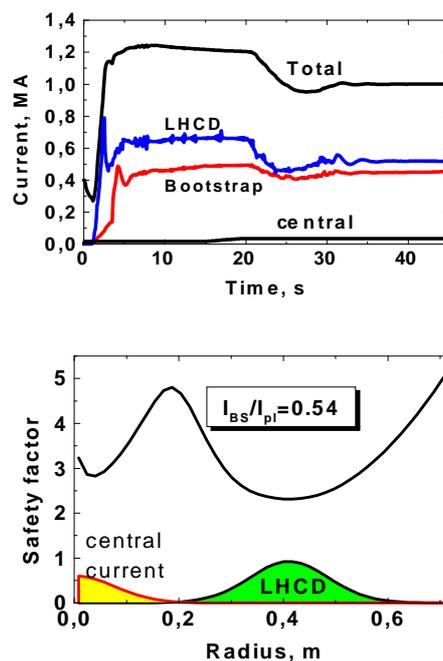*Fig. 1. Scenario with global control of plasma current (top and left bottom).*

Fig.2. Equilibrium with narrow LH current density profile and central current.

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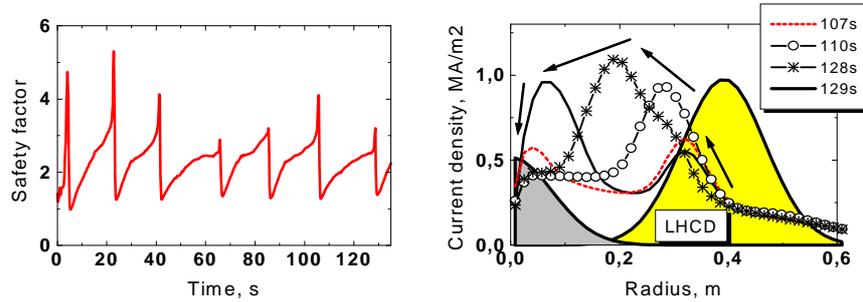

Fig. 3. Oscillations of the central safety factor (left) and evolution of BS current density profile during these oscillations (right).
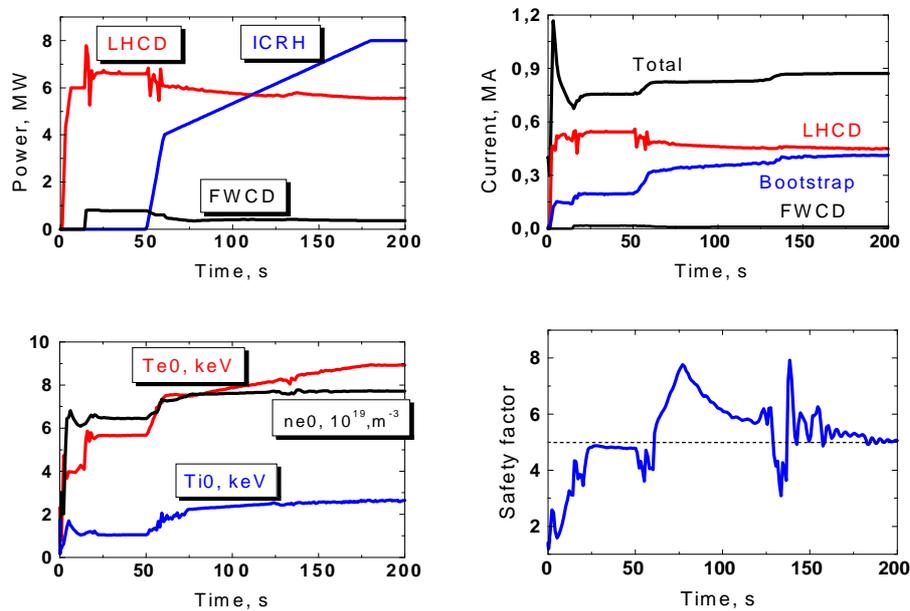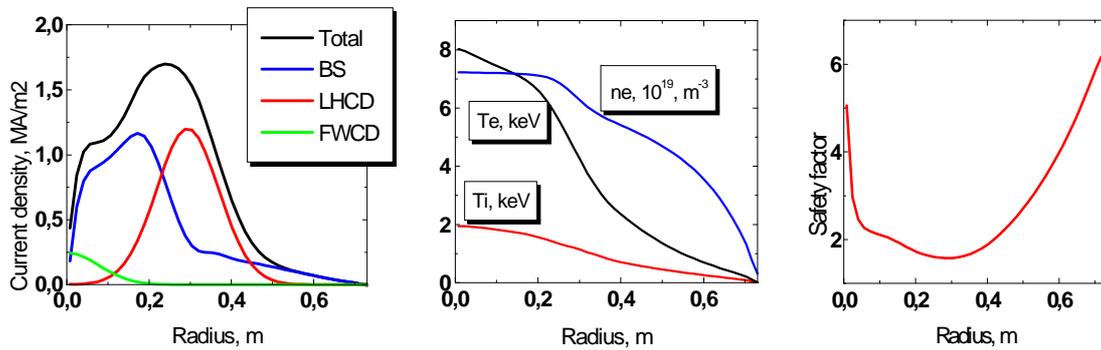

Fig. 4. Scenario with current profile control.

Fig. 5. Steady state equilibrium for the scenario shown in Fig. 4.