

## Analysis of bifurcation phenomena in the Large Helical Device

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### Abstract

The electron internal transport barrier (eITB) formation in the Large Helical Device (LHD) is studied with the transport code TOTAL and a GyroBohm-like model. The reduction of anomalous transport by the  $E \times B$  shear has been also included. With the aim of studying the eITB formation as a phase transition phenomenon, the electron average density is taken as the control parameter and the  $E \times B$  shearing rate as the order parameter. Results show how the eITB formation in LHD is compatible with a continuum phase transition with critical exponent  $\beta = 0.40$ .

### 1. Introduction

Electron internal transport barrier (eITB) scenarios are one of the most important regimes in both tokamaks and stellarators. Main characteristic of eITB scenarios in stellarators are the high electron temperature plasmas obtained with peaked profiles like those that have been found in the Large Helical Device (LHD) [1] as well as in others stellarator devices, as Compact Helical System (CHS) [2]. These profiles share the common characteristic of having a high positive electric field in the plasma core with a large shear.

The transition from the ion root to the electron root in CHS [2] and LHD [1] has the typical behaviour of bifurcation phenomena. Below a critical density the eITB is formed and thermal electron transport is clearly reduced, on the contrary, above that value no eITB is detected. Therefore, the electron density seems to be a clear control parameter of the eITB formation. In addition, the  $E \times B$  shearing rate may be understood as a measure of the turbulence levels (an order parameter): low turbulence transport in the eITB scenarios with high shearing rate and high transport in non-eITB scenarios with low shearing rate [3].

### 2. Analysis of the eITB formation in the LHD

As a first step in this study, the shot #26943 is analyzed with the TOTAL code [4]. It corresponds to the fifth campaign of the LHD experiment. The high peaked electron temperature profile has been obtained by using 1 MW of Electron Cyclotron Heating (ECH) power. Figure 1 shows the experimental electron temperature and density profiles. The GyroBohm-like model used in this study is the following one:

$$\chi_e = \alpha_e^{gB} \chi_{gB}, \quad \chi_{gB} = (cT_e / eB)(\rho_i / L_{Te}), \quad L_{Te} = \left| \frac{\nabla T_e}{T_e} \right|^{-1} \quad (1)$$

where  $\rho_i$  is the ion larmor radius and  $\alpha_e^{gB} = 1.1 \times 10^{-3}$  is a constant that is adjusted to fit the central electron temperature of shot #26943 and it is kept fix throughout the paper. The factor which takes into account of the anomalous transport reduction due to the  $E \times B$  flow is the following one:

$$\chi_{e, shear} = \frac{\chi_e}{1 + (\tau \omega_{E \times B})^\gamma} \quad (2)$$

where  $\omega_{E \times B} = \partial_r (E_r / B_\theta)$ , with  $E_r$  the plasma radial electric field and  $B_\theta$  the poloidal magnetic

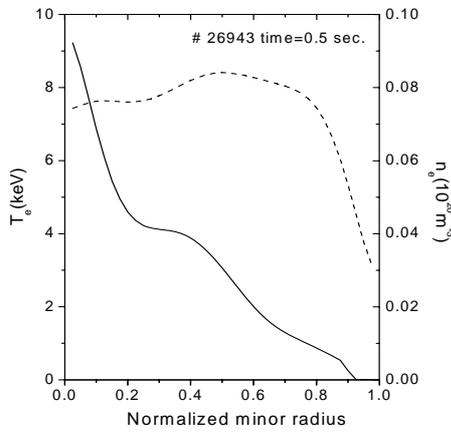


Figure 1. Experimental profiles of electron temperature (solid) and density (dashed) obtained in LHD for the shot #26943.

field. The expression  $v_\phi = E_r / B_\theta$  for the drift velocity, although deduced for quasi-axisymmetric fusion devices, seems to be also valid, as a first approximation, for non-axisymmetric ones [2]. The following values  $\tau = 5.5 \times 10^{-4}$  s,  $\gamma = 1.5$  have been used throughout this study. These values were chosen after a sensitivity study. The neoclassical transport model used as well as the main equations solved can be found in [5].

Results of the simulation are given in figure 2. As can be seen from the figure an electron temperature profile with a steeped gradient is obtained when the  $E \times B$  shear suppression is applied, otherwise, a rather parabolic profile is obtained. In addition, these values of the temperature are compatible with the experimental data, as deduced form figure 2(c). A high temperature gradient is obtained in the region  $0.1 \leq \rho < 0.2$ , where  $E_r$  and its shear is maximum, as shown in figure 2(b), whereas for  $\rho > 0.2$  a rather flat profile is obtained. This a typical behaviour of an eITB shot in LHD [1]. As has been pointed previously, the eITB formation in stellarator plasmas is strongly linked with the average density. In the LHD plasmas, it has been experimentally shown that exists a critical density below which the eITB is formed. In order to study the validity of the previous transport model to predict this behaviour, some simulations have been carried out with the same electron density profile than in the previous section but with different average densities.

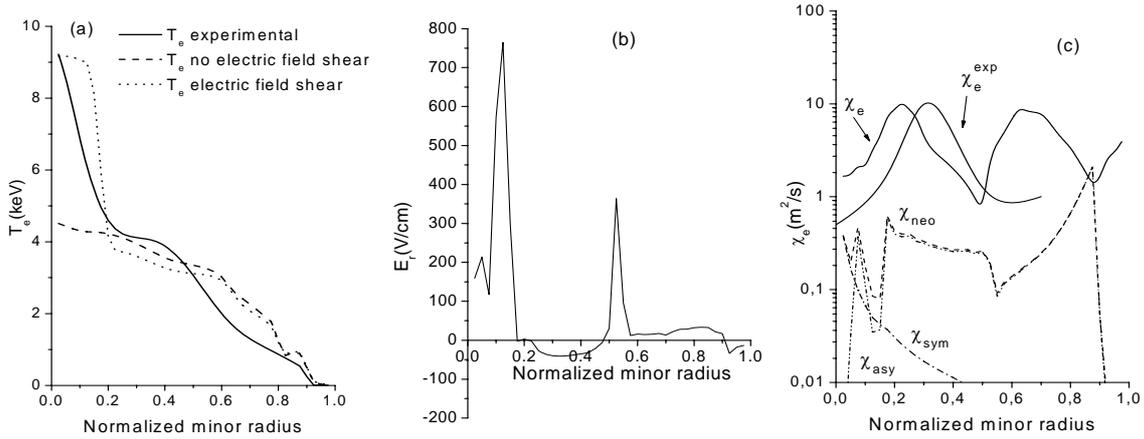


Figure 2. Comparison between the electron temperature profiles obtained by means of the GyroBohm-like model with the inclusion of the electric field shear (dotted), with no electric field shear effect (dashed) and the experimental temperature profile (solid) (a). Electric field obtained in the simulation (b). Comparison between the heat diffusivities obtained and the experimental one (c).

The electron density profiles used are shown in figure 3(a) and the central temperature dependence on average density is shown in figure 3(b). Clearly two confinement regimes arise, one with  $T_e(0) \propto \langle n_e \rangle^{-0.70}$  for the eITB case, and  $T_e(0) \propto \langle n_e \rangle^{-0.42}$  in the non-eITB one. Comparing these results with experimental data [1], we can conclude that the exponents of the temperature dependence on density are close to experimental LHD data. In order to analyze in a deeper way the critical transition region previously obtained and to characterize the eITB formation as a phase transition, the average density has been chosen as the control parameter and the maximum  $E \times B$  shearing rate ( $\max(\omega_{E \times B})$ ) for each density as the order parameter. It is deduced from figure 3(c) that a typical bifurcation point is obtained at  $\langle n_e \rangle \approx 0.12 \times 10^{20} m^{-3}$ . This point divides a region with  $\max(\omega_{E \times B}) \approx 0$  and another one with  $\max(\omega_{E \times B}) > 0$ , corresponding to the eITB formation. The dependence of the order parameter  $\max(\omega_{E \times B})$  on the average density can be described as,

$$\max(\omega_{E \times B}) \begin{cases} \approx 0 & n_e \geq n_{ec} \\ \propto (n_{ec} - n_e)^\beta & n_e < n_{ec} \end{cases} \quad (3)$$

with  $n_{ec} = 1.18 \times 10^{19} m^{-3}$  and  $\beta = 0.40 \pm 0.05$  is the critical exponent. The value of  $\beta$  is comparable with other typical bifurcation phenomena in completely different physical systems, e.g. critical magnetic exponents or fluid theory (where  $\beta$  is in the range  $0.30 < \beta < 0.36$ ). These values for the  $\beta$  critical exponent have been also obtained using the 3d Ising model. Therefore, the eITB formation can belong to the same ‘‘universality class’’ of

the ferromagnetic-paramagnetic systems or the liquid-gas mixtures, which have similar critical exponents.

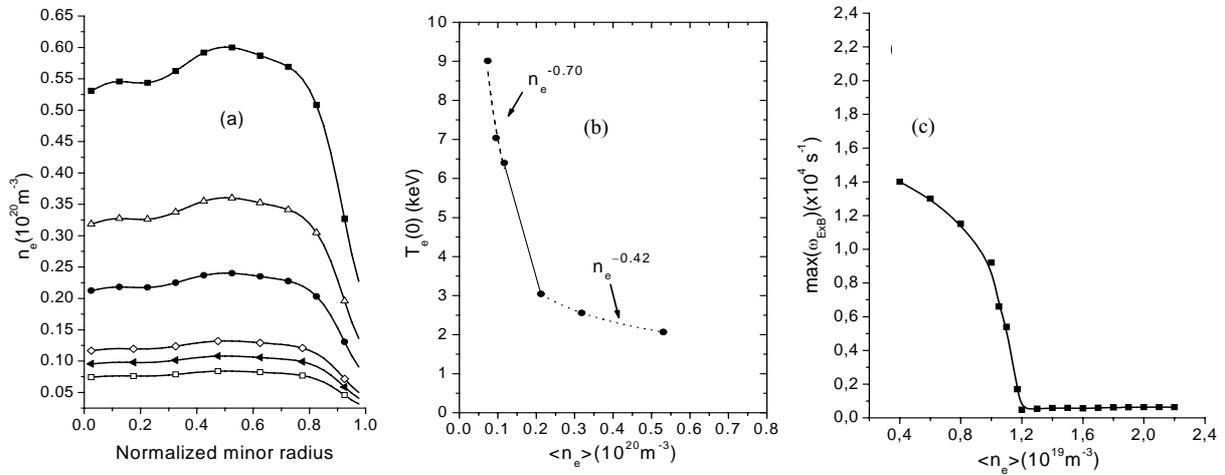


Figure 3. Density profiles used along the simulations (a). Central electron temperature dependence on average density obtained with the GyroBohm-like model (b). Order parameter,  $\max(\omega_{E \times B})$ , dependence on average electron density. A typical bifurcation point is obtained at  $\langle n_e \rangle \approx 0.12 \times 10^{20} \text{ m}^{-3}$  (c).

## Conclusions

With the GyroBohm-like model that has been added to TOTAL code and the factor which takes into account of the anomalous transport suppression by the  $E \times B$  shear flow, a critical plasma behaviour, which leads to the LHD eITB formation, is obtained. From the analysis, it is deduced that the eITB formation can be described as a second order phase transition with critical exponent  $\beta = 0.40 \pm 0.05$ . This critical exponent is comparable to other critical exponents of different phase transition, e.g. ferromagnetic and liquid phase transitions. Thus, the eITB formation in LHD may belong to the same “universality class” of other physical bifurcation phenomena. Anyway, according to [5], the inclusion of electromagnetic drift wave transport in equation 1 seems to be necessary to completely understand and simulate the eITB formation. With this inclusion, the  $\beta$  parameter may be even closer to the more usual levels  $0.30 < \beta < 0.36$  for similar phase transitions. This point will be clarified in the future.

## References

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