EFDA–JET–PR(07)40

J.P.S. Bizarro, X.L. Litaudon, T.J.J. Tala and JET EFDA contributors

Computational Images of Internal-Transport-Barrier Oscillations in Tokamak Plasmas

Computational Images of Internal-Transport-Barrier Oscillations in Tokamak Plasmas

J.P.S. Bizarro[1], X.L. Litaudon[2], T.J.J. Tala[3] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*Centro de Fusão Nuclear, Associação EURATOM–IST, Instituto Superior Técnico, 1049-001 Lisboa, Portugal*
[2]*Département de Recherches sur la Fusion Contrôlée, Association EURATOM–CEA,*
Centre d'Etudes de Cadarache, 13108 St. Paul lez Durance, France
[3]*Association EURATOM–Tekes, VTT, P. O. Box 1000, FIN-02044 VTT, Finland*
** See annex of M.L. Watkins et al, "Overview of JET Results ",*
(Proc. 21 st IAEA Fusion Energy Conference, Chengdu, China (2006)).

Preprint of Paper to be submitted for publication in
IEEE Transactions on Plasma Science

ABSTRACT

A well-known, benchmarked code, where a Bohm–gyro-Bohm transport model is complemented with an empiricalscaling for the dynamics of Internal Transport Barriers (ITBs), is used to model the ITB oscillations often seen in advanced tokamak scenarios with a dominant fraction of bootstrap current.

INTRODUCTION

Internal Transport Barriers (ITBs) are an important field in magnetic-fusion research, attracting a considerable theoretical and experimental effort, particularly in the pursuit of socalled Advanced-Tokamak (AT) scenarios for the Steady-State (SS) operation of nuclear-fusion reactors [1]–[11]. ITBs lead to a strong increase in central plasma confinement and also provide, via the steepening of the plasma-pressure gradient ∇P, a significant fraction of the self-generated BootStrap (BS) current that very much helps to minimize the amount of power recirculated to the external Current-Drive (CD) sources. Present theories and experimental evidence point to the interplay between the $E\times B$ flow and the magnetic shears, $\omega_{E\times B}$ and s, respectively, as a basic ingredient governing ITB dynamics [2], [4], [6]–[8]. With a fair amount of success, the physics underlying ITB formation and sustainement has been captured by scaling criteria for transport reduction of the form $C_1+C_2s-C_3\omega_{E\times B}/\gamma_{ITG} < 0$, with $C_1 \approx 0$ and $C_2 \approx C_3 \approx 1$ empirically fitted constants, and γ_{ITG} a linear growth rate that properly normalizes $\omega_{E\times B}$ [2], [4], [7], [8], [11].

AT BS-dominated plasmas sometimes exhibit a cyclic behavior linked to ITB buildup and collapse, a phenomenon deleterious for SS plasma performance that has been identified numerically [1], [3], [10], [11] and observed experimentally [5], [8], [9]. Computationally, ITB oscillations can be seen when $\omega_{E\times B}$ is either neglected [1], [3] or negligible [11], so the ITB criterion becomes essentially $s \lesssim C_1/C_2 \approx 0$. In such cases, an ITB is formed when there is locally a MagneticShear Reversal (MSR), which demands an off-axis peaking of the plasma current density, as can be provided by LowerHybrid (LH) CD. Basically, on the one hand, the foot of the ITB coincides roughly with the MSR layer, the latter initially defined by the LH current density j_{LH}, and, on the other hand, the peak in the BS current density j_{BS}, which sits where ∇P is the strongest, is located slightly inwards from the ITB foot [1], [3], [10], [11]. So, and introducing a normalized fluxsurface coordinate ρ, one has $\rho_{ITB} \approx \rho_{MSR}$ and $\rho_{BS} \lesssim \rho_{ITB}$, with $\rho_{MSR} \approx \rho_{LH}$ in the early stages of ITB formation. As the ITB builds up, further steepening ∇P, at one point there is an inversion in the relative strengths of the j_{BS} and j_{LH} peaks, the former controlling now the location where MSR occurs. So, $\rho_{MSR} \approx \rho_{BS}$ in the ITB fully developped phase, whence $\rho_{ITB} \approx \rho_{BS}$ which, togehter with the mismatch between the BS peak and the ITB foot, yields $\rho_{BS} \lesssim \rho_{BS}$. Hopelessly trying to comply to such a condition, the BS peak "runs after itself" and drifts towards the plasma center until it no longer defines an MSR layer, which causes the ITB collapse and gives the lead back to j_{LH} to start a new cycle. Understanding this mechanism is crucial to devise ways of circumventing, or controlling, these ITB oscillations [11], and much can be learned from a suitable visualization of the time evolution of the profiles for quantities such as j_{LH}, j_{BS}, and P.

Typical ITB oscillations in P and j_{BS} when $\omega_{E\times B}$ is negligible are shown, together with j_{LH}, in Fig. 1, which has been obtained using the JETTO code, in which a Bohm–gyro- Bohm (B–gB) transport model is combined with the empirical ITB criterion given above [2], [7]. JETTO has been used to simulate AT discharges relevant for future operation of the Joint European Torus (JET) [10], [11], the set–C_1 = 0.1 and $C_2 = C_3 = 1$ having been fixed by analyzing shots from different tokamaks [7], and having been kept after benchmarking to an actual JET discharge [10], [11]. [1]The data are for a JET-like deuterium plasma with ion effective charge Z_{eff} = 3, magnetic field on axis B_0 = 3.45T, total plasma current I_P = 2.3MA, pedestal values of electron density and electron and ion temperatures $n_{eped} = 2.5\times10^{19}$ m^{-3}, T_{eped} = 1.5keV, and T_{iped} = 1.8keV, and power levels for Ion Cyclotron Resonance Heating (ICRH), Neutral-Beam Injection (NBI), and LHCD of P_{ICRH} = 10MW, P_{NBI} = 32MW, and P_{LH} = 4MW. In addition, the volume-averaged electron density and electron and ion temperatures, as well as the NBI-, LH-, and BS-driven currents oscillate around $\langle n_e \rangle \approx .\,4.4\times10^{19}$ m^{-3}, $\langle T_e \rangle \approx 5.2$keV, $\langle T_i \rangle \approx 6.5$keV, $I_{NBI} \approx 0.2$ MA, $I_{LH} \approx 0.5$MA, and $I_{BS} \approx 1.6$MA, respectively. Looking at Fig. 1, one sees that ρ_{LH} remains fairly at the same location, whereas ρ_{BS} follows the cycles of ITB growth and collapse, successively rising slightly inwards from ρ_{ITB} and moving towards the plasma center. Moreover, ρ_{BS} evolves well correlated with ρ_{ITB} except for a small delay at the start of each cycle, indicating the first does define the location of the second for most of the time but for the very beginning of ITB formation, when the externally driven j_{LH} is there to locally promote MSR and thus trigger an ITB.

CONCLUSIONS

In conclusion, using the well-known and benchmarked JETTO transport code, which features a B–gB model with an empirical ITB threshold condition, AT scenarios in JETlike plasmas have been simulated to yield images of ITB oscillations that very much help in grasping the mechanism behind such cyclic behavior.

ACKNOWLEDGEMENTS

This work has been conducted under the European Fusion Development Agreement (EFDA), as well as within the framework of the Contract of Association between the European Atomic Energy Community and the Instituto Superior Técnico (IST), and it has also received financial support from the Fundação para a Ciência e a Tecnologia (FCT, Lisboa). The content of this paper is the sole responsibility of the authors and does not necessarily represent the views of the European Commission, of FCT, of IST, or of their services.

REFERENCES

[1]. A. Fukuyama *et al.*, "Self-organized dynamics and thermal instability in steady state tokamaks," *Nucl. Fusion*, vol. **35**, pp. 1669–1677, 1995.

[2]. T.J.J. Tala *et al.*, "ITB formation in terms of $\omega_{E\times B}$ flow shear and magnetic shear s on JET," *Plasma Phys. Control. Fusion*, vol. **43**, pp. 507–523, 2001.

[3]. I. Voitsekhovitch and D. Moreau, “Modelling of “advanced tokamak” scenarios with radiofrequency heating and current drive for Tore Supra,” *Nucl. Fusion*, vol. **41**, pp. 845–864, 2001.

[4]. J.W. Connor *et al.*, “A review of internal transport barrier physics for steady-sate operation of tokamaks,” *Nucl. Fusion*, vol. **44**, pp. R1–R49, 2004.

[5]. P.A. Politzer *et al.*, “Stationary high bootstrap fraction plasmas in DIII-D without inductive current control,” *Nucl. Fusion*, vol. **45**, pp. 417–424, 2005.

[6]. K.H. Burrell, “Role of $E\times B$ shear and magnetic shear in the formation of transport barriers in DIII-D,” *Fusion Sci. Tchnol.*, vol. **48**, pp. 1021– 1041, 2005.

[7]. T. Tala–*et al.*, “Fully predictive time-dependent transport simulations of ITB plasmas in JET, JT-60U and DIII-D,” *Nucl. Fusion*, vol. **46**, pp. 548–561, 2006.

[8]. X. Litaudon, “Internal transport barriers: critical physics issues?,” *Plasma Phys. Control. Fusion*, vol. **48**, pp. A1–A34, 2006.

[9]. S. Coda *et al.*, “The physics of internal transport barriers in the TCV tokamak,” *Nucl. Fusion*, vol. **47**, pp. 714–720, 2007.

[10]. X. Litaudon *et al.*, “Prospects for steady-state scenarios on JET,””*Nucl. Fusion*, vol. **47**, pp. 1285–1292, 2007.

[11]. J. P. S. Bizarro *et al.*, “Controlling the internal transport barrier oscillation in high-performance tokamak plasmas with a dominant fraction of bootstrap current,” *Nucl. Fusion*, vol. **47**, pp L41–L45, 2007.

[1]*Experimental and computed profiles coming from a benchmarking exercize conducted for JET Pulse No:66498 are compared in [10, Fig. 6]*

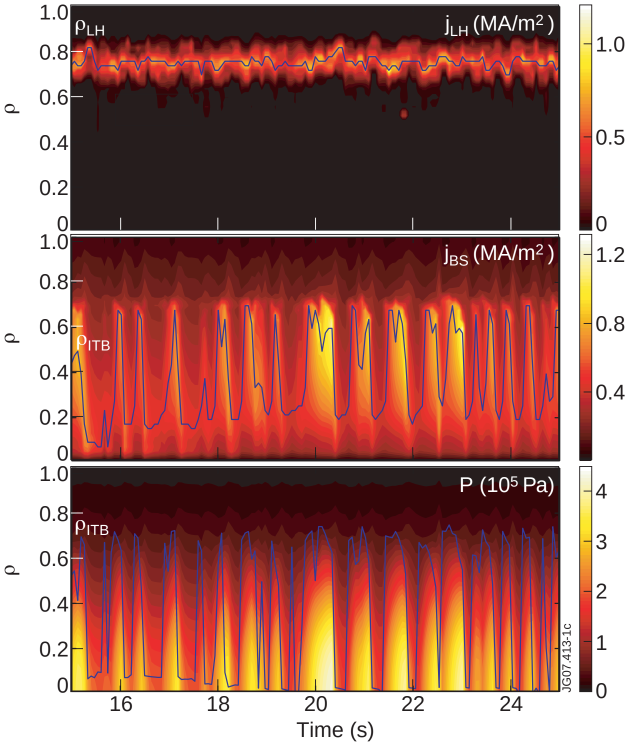

Figure 1. Time evolution of the profiles for the LH- and BS-driven current densities j_{LH} and j_{BS}, and for the plasma pressure P. Also shown is the time evolution of the locations for the LH and BS current-density peaks and for the ITB foot, respectively, ρ_{LH}, ρ_{BS}, and ρ_{ITB}. The latter is retrieved as the outermost ρ value that verifies the condition $C_1 + C_2 s - C_3\omega_{E\times B}/\gamma_{ITG} = 0$.