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Numerical Simulations of Turbulence in RTP Discharges with Dominant Off-Axis ECH

DE BAAR Marco R., THYAGARAJA Anantanarayanan[1], KNIGHT Peter J.[1], HOGEWEIJ Pick G.M. and LOPES CARDOZO Niek J.

FOM instituut voor plasmafysica Rijnhuizen, Trilateral Euregio Cluster, Nieuwegein, The Netherlands, Association Euratom-FOM

[1] *EURATOM/UKAEA Fusion Assoc., Culham Science Centre, Abingdon, OX14 3DB, UK*

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Abstract

A two-fluid computer model, CUTIE, of saturated global tokamak turbulence is used to study the transition from an Ohmic to an Rijnhuizen Tokamak Project (RTP) type-D discharge (a discharge with dominant, off-axis ECH featuring steady state hollow temperature profiles). The simulations were done for a few current diffusion times. In particular the role of the evolving q-profile in the self-organization of the plasma has been studied. The dynamics of the bootstrap current, the turbulence drive terms, the E×B flow and the dynamo terms in the induction equation will be discussed. The effect of MHD activity on turbulent transport has been investigated. It will be explained why CUTIE 1) produces barriers near simple rational q values as in RTP, and 2) naturally generates the required advective transport to support off-axis maxima in T_e.

Keywords:

anomalous plasma transport, numerical simulation, turbulence, ITB, 2 fluid code, global simulation

1. Introduction

Internal Transport Barriers (ITBs) are being considered for reactor relevant advanced tokamak scenarios. In recent years, considerable progress has been made both on the development of diagnostics for ITB relevant parameters and on the modeling of ITB dynamics. However, much of the physics of tokamak turbulence and its suppression is currently not well-understood. Notably the role of the q-profile in the ITB dynamics remains obscure.

Barriers have been observed in the profiles for the electron temperature $T_e(r)$, the ion temperature $T_i(r)$ and the density $n_e(r)$ [1-8]. In TFTR, so-called Enhanced reversed shear type I discharges show barriers in $n_e(r)$ [1]. These are excited when the ratio between the linear growth rate of the dominant turbulent mode and the $\boldsymbol{E}\times\boldsymbol{B}$ sheared velocity $\gamma_{\rm lin}/\gamma_{E\times B} < 1$, and the turbulent vortices can be decorrelated. Type II discharges show barriers in T_e and T_i when $P_{\rm NBI} < 5$ MW and $q_{\rm min}$ approximately 2 [2]. In JET, ITBs form in the vicinity of $q = 1$, $q = 2$ and $q = 3$, and maybe near $q = 3/2$ [3]. Joffrin [4] suggests that in JET, due to toroidal coupling, magnetic braking can increase the local sheared velocity and yield co-evolution between the rotation profile and the simple rationals in the q-profile. Power threshold experiments suggest a synergy between details in the q-profile and the rotational shear. The JT-60 team reports [5] that in negative central shear discharges barriers may form at the $q = 3$ surface. In RTP, a series of barriers was disclosed near m/n = 1, 4/3, 3/2, 2/1, 5/2 and 3/1 [6].

Corresponding author's e-mail: mdebaar@jet.uk

These cases illustrate the key profiles associated with barrier dynamics: the ***E***×***B*** zonal flow and q. The theory of ***E***×***B*** sheared decorrelation and suppression of turbulence is well developed. Zonal flows can be taken into account numerically and the subtle interaction between the driving and stabilizing terms of the turbulence can be investigated [7]. The role of the q-profile in turbulence suppression and ITB formation is not well understood. Beklemishev [8] and Garbet [9] mention that low magnetic shear widens the gap between two adjacent rationals in real space. This effect is most easily observed where the density of rationals is lowest in the q-profile, *viz.* in the vicinity of simple rationals.

In this paper, we use the two fluid code CUTIE to study the transition from an Ohmic to an RTP type-D discharge [6]. In particular the role of the evolving q-profile in the self-organization of the plasma has been studied. The dynamics of the bootstrap current, the turbulence drive terms, the E×B flow and the dynamo terms in the induction equation will be discussed. The effect of MHD activity on turbulent transport has been investigated. Implicitly, this means that we need to simulate ITB dynamics for several resistive timescales. The dynamics of the bootstrap current, the turbulence drive terms (∇p and ∇j), the E×B flow and the dynamo terms will be followed. The effect of MHD activity on turbulent transport will be investigated. We are interested in the formation of mesoscale structures such as islands, barriers and other corrugations in the profiles of density and temperature and the way these structures influence the turbulence.

2. CUTIE and RTP Overview

CUTIE [10] is a quasi-neutral, electromagnetic, two-fluid computer model to simulate saturated global tokamak turbulence. The partial differential equations (resulting from conservation laws and Maxwell's equations, suitably reduced in tokamak ordering) for n_e, T_e, T_i, the potential vorticity θ, the electrostatic potential ϕ, parallel vector potential ψ and the ion parallel velocity v_i are solved numerically using a pseudo-spectral scheme. CUTIE uses a periodic cylinder equilibrium model, but field-line bending and curvature effects on the turbulence are included. Electron inertia and trapped particle turbulent dynamics are neglected, apart from the use of the neo-classical transport coefficients. In particular, the bootstrap-current j_{bs}, has been included, and will be shown to play a crucial role in the barrier dynamics. We use CUTIE to model the transport on so-called mesoscales. Mesoscale times, τ are between the Alfvén time and the resistive timescale ($t_{Alfvén} < \tau < t_{res}$) and mesoscale length-scales L are between the ion Larmor radius and the minor radius of the tokamak ($\rho_i < L < a$). When subject to external sources (in our case a localised ECH power source), the system of equations gives rise to turbulence, which yields "corrugations" (ie., regions of relatively high radial gradients; ITB's are a special case of these) in the profiles. An essential feature of CUTIE is that these corrugations are allowed to feed-back on the turbulence itself. Thus, in CUTIE, the *non-linear co-evolution of instabilities and corrugated profiles* is studied.

RTP [2] was a small tokamak (R = 0.72 m, a = 0.164 m) with dominant Electron Cyclotron heating. RTP's diagnostics were suited to follow small scale structures in $T_e(r)$ such as barriers and islands. Moving the ECH power deposition radius in steps of approx. 1 mm from the plasma centre to half radius revealed 7 distinct plateaux of constant central T_e. The plateaux are separated by sharp transitions. The transitions are associated with the loss of transport barriers in the electron transport channel. The plateaux (and the associated self similar T_e profiles) have been labeled as A, A', A'', B, C, D, and E.

Interestingly, the profiles of type D and E (ECH deposition approximately at half radius) show strong steady-state off-axis maxima in T_e. Neither the electron-ion exchange nor the total radiated power can explain this phenomenon, which therefore implies that an outward heat pinch must exist for these discharges [11]. Off-axis saw-tooth like events implied that the barriers are close to, but not at, the simple rationals [12] in the q-profile. The sharp transitions between the consecutive plateaux are thought to be associated with the loss of the q = 1, 4/3, 3/2, 2/1, 5/2, 3/1 surfaces respectively. A phenomenological "q-comb" model of the $\chi(q)$ profile and an outward heat pinch up to the ECH power deposition radius reproduced the experimental observations [13].

RTP is, in many ways, the ideal candidate for our CUTIE simulations. RTP has small a/R = 0.23, justifying a periodic cylinder approximation. Its small minor radius results in not too small a value for $\rho^* = \rho_s/a$. Medium density RTP plasmas were relatively cold (upto 2 keV), which limits the resistive time and hence the 'macro' time scale of our simulations. Most importantly, RTP's phenomenology is non-trivial and rather well diagnosed [6, 11-13].

3. CUTIE Ssimulations and Comparisons with RTP Observations

We now report on a CUTIE study of the transition from an Ohmic to an RTP type-D discharge [6]. This is a discharge with dominant, off-axis ECH. The plasma parameters for this case are I_p = 80 kA, B_ϕ = 2.24 T, neav ~ 2.7×10^{19} m^{-3}. We start our calculations from arbitrary (Gaussian) profiles and switch-on the ECH at t = 0 s. The ratio P_{ECH}/P_Ω is typically 350 kW/100 kW. The power is deposited at $\rho = 0.55$ with a localization of approximately 1 cm, as indicated by the experiment. The time step in the simulations is Δt = 50 ns. The grid consists of 100 radial gridpoints, 32 poloidal and 16 toroidal harmonics.

In the early (between t = 0 and 48 ms) "switch-on phase" of the ECH power (not shown here), we observe a direct increase of $T_e(\rho = 0.55, t)$. The T_e profile broadens on an electron energy confinement time-scale (approx. 4 ms). On the longer resistive time scale (approx. 15 ms), the current profile evolves such that the central Ohmic input power is reduced. Consequently $T_e(\rho = 0, t)$ decreases at a rate associated with the current diffusion time of the system. The central q rises steadily from q = 1 at the start of the simulation to q = 2.5 at 48 ms through a series of `resonances' associated with rational values at which the profile acquires very small local shear ($q' \sim 0$), while remaining monotonic throughout.

We consider in some detail the processes during t = 48 ms to t = 70 ms when the q-profile changes from being monotonic to a type-D 'reversed shear' profile. In the described time window, the central q value rises from 2.5 to 3.3 and the q-profile becomes non-monotonic before finally settling into a steady state.

Figure 1(a) shows the simulated traces of central temperature $T_e(\rho = 0, t)$ (full) and the temperature at the ECH deposition radius $T_e(\rho = 0.55, t)$ (dashed) from 48 ms to 70 ms. As explained above, due to a redistribution of the Ohmic input power, $T_e(r = 0, t)$ decreases. At 48 ms, the T_e profile is almost flat out to the ECH deposition radius. We observe that pronounced off-axis maxima develop subsequently.

Unlike the power source, the particle source S is not strongly localised. We use a simple source profile S, featuring a maximum at half radius [11]. In addition, a density feedback system injects particles into the plasma when $n_e^{av} < 2.7\times10^{19}$ m^{-3}. Given the experimental uncertainties in the particle source profile, the simulated n_e-profiles are not expected to be quantitatively accurate. The evolution of the n_e-profile shape however is of interest and can be compared qualitatively with the experiment. Figure 1(b) shows the evolution of the central density $n_e(0, t)$ (full) and the density at the ECH deposition radius $n_e(r = 0.55, t)$ (dashed) over the same period as in Fig. 1(a). Around t = 55 ms, a change of slope is observed for the two n_e traces, indicating a sudden improvement in the central particle transport.

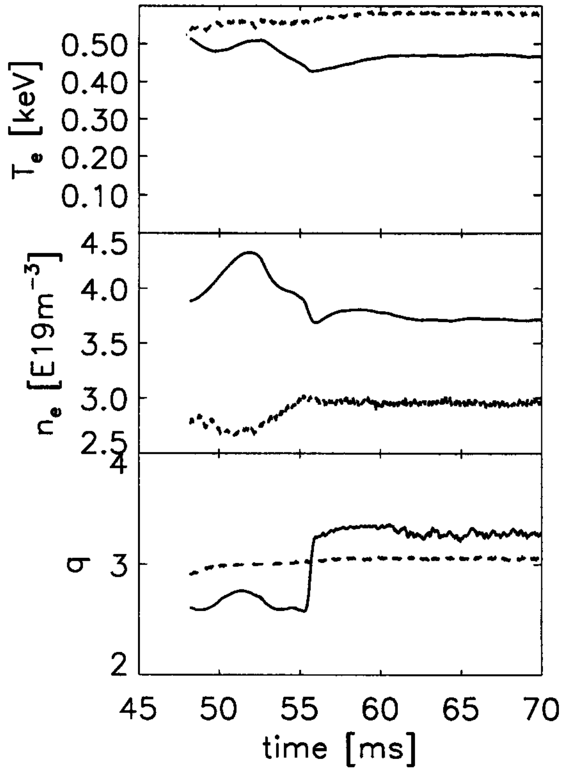

Fig. 1 Time traces for T_e, n_e and q. The full lines indicate the central values, the dashed line indicate the values evaluated at r/a = 0.55. Note the in version in T_e, the strong correlation with q and the episodic behavior.

Figure 1(c) shows $q(r = 0, t)$ and $q(r = 0.55, t)$ (full and dashed respectively) over the same period as in Fig. 1(a). Up to t = 55ms the q-profile is monotonic featuring a large region of low shear ($q \cong 3$) which is extended out to the power deposition radius (see also Fig. 3). At t = 56 ms, the shear is reversed. The two q-traces show the tendency to be clamped by the simple rationals in the q-profile, *viz.* 5/2, 3/1 and even 13/4 = 3.25.

Interestingly the evolution of the q-profile is episodic: periods of sudden changes are alternated by periods of slow evolution. Apparently, there is not a single time-scale associated with the evolution of the system. The sudden changes in q are also reflected in the other traces. Note the strong correlation between

$q(r, t)$ and the other two parameters. $T_e(0, t)$ shows an almost stepwise decrease, fully correlated with changes in $q(0, T_e)$. Also, the sudden improvement in the local particle confinement is correlated with the sharp transition in q_C. This resembles the experiment [6].

The simulated T_e-profiles (t = 48 (full), 50 (dotted) and 70 ms (dashed)) are presented in Fig. 2(b). As in the experiment, steady state hollow T_e profiles are obtained in these simulations. The transition from flat T_e to hollow T_e profiles occurs between 48 and 50 ms, after which the hollow T_e profiles are maintained up to 70 ms, for approximately 5 electron energy confinement times τ_{Ee}. The experimental $T_e(r)$ profile for the D-plateau is presented in Fig. 2(a). The match between the experimental and the simulated profiles is reasonable considering many assumptions in the theoretical model and experimental uncertainties. Radiation losses have not been included in the code and the ion-electron exchange (calculated to be somewhat smaller than local Ohmic power) is not sufficient by itself to explain these profiles. If the heat conduction in this system were purely diffusive, this would have resulted in flat $T_e(r, t)$ profiles out to the power deposition radius. Clearly, in the code an outward advective heat flow is active, supporting the off-axis maxima in $T_e(r)$.

In Fig. 3 the q-profiles at 50 and 70 ms are presented. (full and dashed respectively). At 50 ms the q-profile is marginally below 2.5 with large low shear region out to the deposition radius This flattening is due to the dynamo term. In addition, pronounced elbows form in the q-profile. Following the broadening of the T_e profile, current is being expelled from the center. This induces a slow inward movement of the elbows. As soon as the elbow reaches the center of the system, it can no longer be supported. Consequently, a fast transition occurs to a new q-profile with flat inner q-region and an elbow at the next simple rational. The transition from a monotonic q-profile to reversed shear occurs at $q_{\min}$ approx. 3 with $q_0 > 3$.

The total current density (70 ms) is presented in Fig. 4(a). The local minimum of central current density is clearly born out in this graph. The region of shear reversal is restricted to the very center of the plasma. The regions of constant current density are associated with the regions of low shear in the q-profiles. The elbows are not reflected in the j-profile at 70 ms. Elbows are transients, showing up in the dynamic phase from 48–55 s. They correspond to regions of high j. The profiles for the bootstrap current j_{bs} (70 ms) are shown in Fig. 4(b). The bootstrap current is localized, and

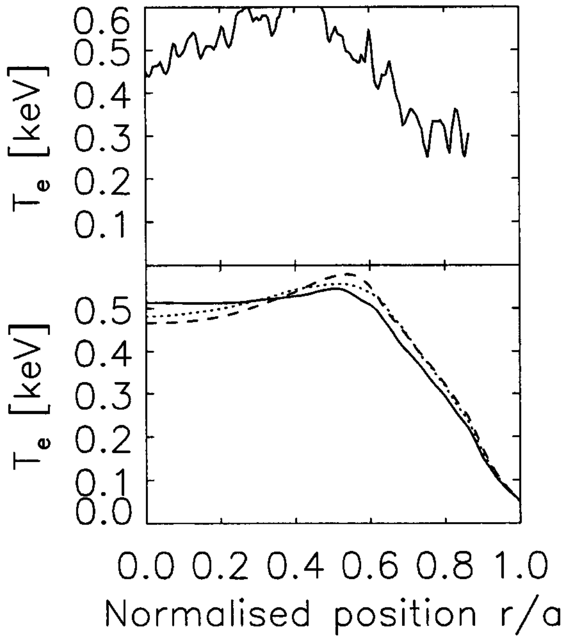

Fig. 2 Experimental (a) and simulated T_e profiles. The evolution from flat to inverted is shown for the simulations.The full line shows the T_e profile for t = 48 ms, dotted for t = 50 ms and dashed for t = 70 ms.

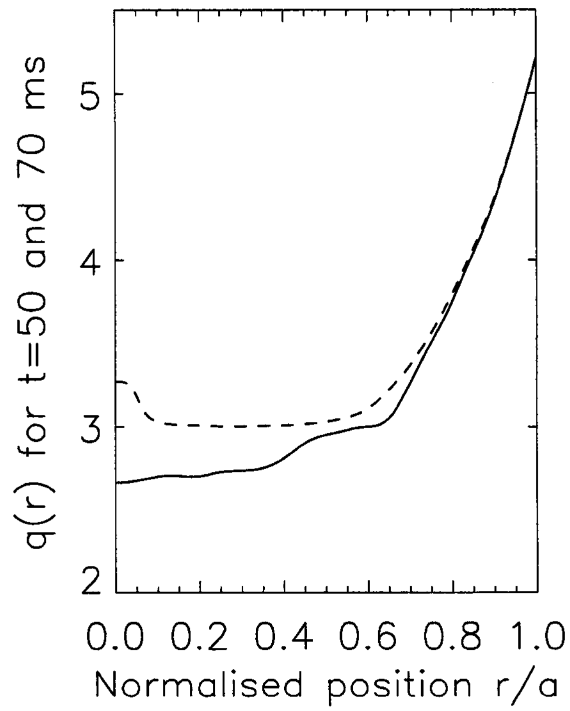

Fig. 3 q-profiles at 50 (full) and 70 ms (dashed). Note the q-profile is clamped at simple rationals.

peaks just outside the power deposition radius, where ∇p has a maximum value.

Figure 5 shows the poloidal zonal flow ($-cE_r/B$) in km/s at t = 70 ms. The zonal flow is self-consistently calculated and shows pronounced spatial variations outside the deposition radius. These are indicative of strong shearing of the radial electric field.

4. Discussion

What is the role of the bootstrap current and the dynamo term in the evolution of the q profile? Both components lower the local magnetic shear, but the difference between these quantities is their degree of localization. The dynamo term $<\delta v \times \delta \boldsymbol{B}>$ is extended over the whole central region and leads to a flattening of the current density profile within the power deposition radius. As the dynamo term extends over the central low shear region in the plasma, it allows for radially extended magnetic modes. The dynamo is responsible for the clamping of the q-profile at the simple rationals. The modes drive the dynamo term and the dynamo term extends the mode. Sometimes even two low (m, n) modes form within the power deposition radius. In such cases, the two modes start a competition for maximum size. The two extended modes form a current sheet within the thin layer separating the modes.

The bootstrap current leads to a local flattening of the q-profile at the barrier. In CUTIE, the bootstrap current plays an essential role in the barrier dynamics. Due to the intense heating, a mode forms in the vicinity of the power deposition radius. Asymmetric fluxes over the mode give rise to the formation of a high ∇p region. j_{bs} flattens q and changes the driving terms of turbulence. The mode is extended, and simultaneously the density of modes is decreased. The barrier and the q-profile are thus coupled via the bootstrap current and the mode.

Another dynamical process going in parallel is the zonal flow which is rather corrugated and therefore decorrelates the turbulence (see Fig. 5). In CUTIE two feed-back loops (associated with E_r' and q' respectively) operate. It is essential that these loops can interact synergistically. In fact, as both profiles are correlated with ∇p, the zonal flow and j_{bs} are well aligned and can co-evolve. We note that the zonal flows are driven by the ion pressure gradients as well as by turbulent Reynolds stresses [10] and therefore are also closely related to the dynamo term in the induction equation.

What is the mechanism leading to the formation of the pronounced off-axis maxima in the T_e profiles? In

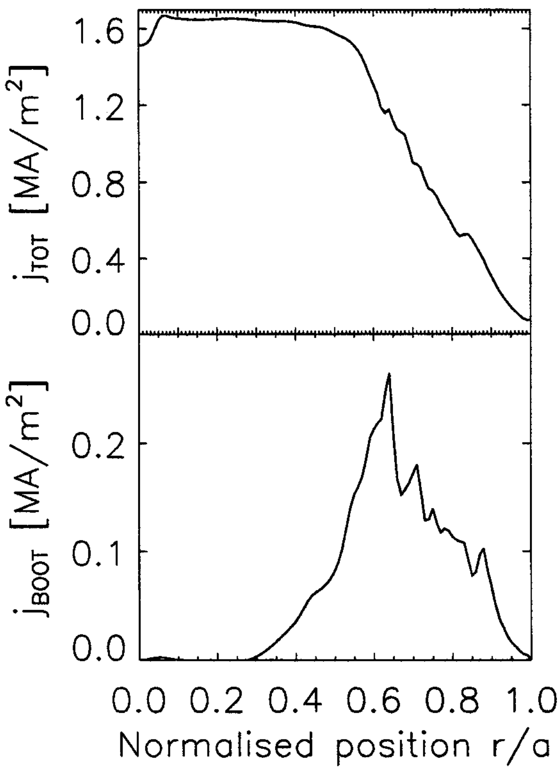

Fig. 4 Total (a) and bootstrap current (b). The total current is inverted in the very center of the discharge. The bootstrap current peaks just outside the power deposition radius.

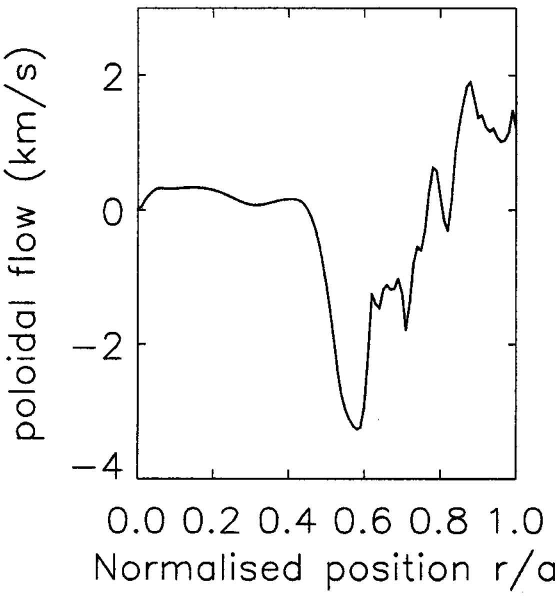

Fig. 5 Zonal flow at 70 ms. Note the corrugations in the profile outside the ECH deposition radius.

the RTP model, these are sustained by an outward heat flow up to the ECH-power deposition radius. In CUTIE the outward heat flow naturally correlates with the switch-on of the off-axis ECH: Directly after switch-on, the the fluctuation level within the deposition radius is enhanced. The interplay of the EM-and ES-component of the fluctuations gives rise to the outward heat-flow. No extra loss term such as radiation was modelled. Clearly, this outbound flow is sufficient for supporting pronounced off-axis maxima in CUTIE. The 'ears' are comparable to the experimental observations.

5. Conclusions

CUTIE simulations of RTP discharges with dominant off-axis ECH have been carried out. The electromagnetic, quasi neutral two-fluid model with the dynamo-term, self-consistent zonal flows and neo-classical effects reproduced many of the non-trivial features observed in the experiments. We mention the episodic co-evolution of n_e, T_e and q. The code positions barriers at rationals in q and naturally generates an outward heat advection for off-axis ECH discharges. The outward heat flow is sufficient for supporting off-axis maxima in the T_e, which are quite comparable to the experimental observations.

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