

## Reproducing JET electron ITBs with the RTP $q$ -comb model

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### I. INTRODUCTION

Historically the larger tokamaks concentrate on ion physics, and the smaller machines on the electrons. At the larger machines conditions have been achieved [1,2] such that the transport in the ion channel reduces to its neoclassical level, which is the lowest possible. The electron transport however is always anomalous, making it most urgent to start taking into account the electrons. The first thing to do is to incorporate the existing knowledge of the electron physics from the small machines into the large tokamaks.

The conceptual model [3] from the small RTP tokamak (also ‘ $q$ -comb’ model) was very successful in describing the transport phenomena in RTP and could in fact reproduce the  $T_e$  profiles of the entire barrier campaigns of 1997 and 1998 [4].

In this paper we take this model to the JET tokamak to try to capture the electron temperature ( $T_e$ ) evolution of shots with strong electron internal transport barriers (ITBs).

### II. NUMERICAL CODES

The 1.5 D predictive transport code JETTO can make use of different transport modules. When equipped with a mixed Bohm/gyroBohm model [5] it could reproduce ion ITBs in JET optimized magnetic shear (OMS) discharges. Prominent electron ITBs could however not be reproduced. For our experiment we used the JETTO code with the  $q$ -comb model as the electron thermal transport module. We will concentrate on the electron ITBs, simulating  $T_e$  and current profiles only.

The RTP model features an electron thermal diffusivity  $\chi_e$  as a function of  $q$  rather than radius. The  $\chi_e(q)$  profile consists of a fixed anomalous  $\chi_e$  level ( $\chi_e^{\text{high}}$ ) with narrow regions of fixed width  $w_q$  with low  $\chi_e$  (barriers) close to simple rational values of  $q$ .

The simulations turn out to be not very sensitive to the exact value of  $\chi_e^{\text{high}}$  and we picked a value to match  $\nabla T_e$  towards the edge of the plasma.

A fixed  $w_q$  introduces a trade off in the solution: A slightly smaller  $w_q$  and all barriers  $\chi_e$  values lower by the same amount leads to an equally good solution in the simulations. For numerical purposes we used  $w_q=0.15$ .

The actual barrier levels of  $\chi_e$  are determined by running simulations of discharges with not too different plasma parameters, and demanding that there is a solution of the  $q$ -comb that is able to reproduce the time evolutions of the  $T_e$  profiles of the selected discharges with the same set of parameters i.e. the same  $q$ -comb.

Initial profiles for JETTO will be obtained as follows:  $T_e$  from KK3 (electron cyclotron emission radiometry); Electron density from LIDAR (Thomson scattering); Ion data from charge exchange spectroscopy;  $q$  profile from EFIT [6] (magnetics reconstruction).

### III. EXPERIMENT AND RESULTS

JET's most prominent ITBs surface in the OMS discharges. The 'standard JET optimized magnetic shear scenario' consists of a current ramp up, a pre-heating phase with ion cyclotron heating (ICRF), followed by a main heating phase with neutral beam heating (NBI) added. The simulations use initial profiles from well before the main heating phase, and try to reproduce the ITB phase of the discharge.

The  $T_e$  profile from JETTO is to be compared with the observed KK3 data, noting in particular: *i)* Time and position of the formation of the ITB. *ii)* Growth rate of the barrier. *iii)* Maximum temperature obtained. If we find agreement on these three points, the simulation is judged successful. Table I contains the list of discharges treated so far.

Our simulations have indicated that discharges can be categorized by the ratio  $B_\phi/I_p \equiv \tilde{q}_a$ . All discharges in a category can be reproduced with the same  $q$ -comb. For  $\tilde{q}_a=1$  and  $\tilde{q}_a=3.4/2.5$  the corresponding  $q$ -combs are depicted in Figs. 1 and 2. Examples for both categories of the level of agreement between observation and simulation are shown in Figs. 3 and 4.

Shot	NBI [MW]	ICRF [MW]	$B_\phi$ [T]	$I_p$ [MA]
40847	19	6	3.4	3.3
45623	16	6	3.4	3.3
46664	16.5	6	3.4	3.4
46669	16.5	6	3.4	3.4
46716	18	6	3.5	3.5
46050	16.2	6.2(2)	3.4	2.5
46133*	17.5	5.0(3)	3.4	2.5
49015	12.2	5.1	2.5	2.5
49017	12.1	5.2	2.5	2.5

TABLE I. JET OMS discharges modelled with the  $q$ -comb model so far. The marked shot has Argon puffing and 2.2 MW lower hybrid current drive (LHCD) added to the OMS scenario. Halfway in the main heating phase the ICRF power for shots #46050 and #46133 was switched to the value in brackets.

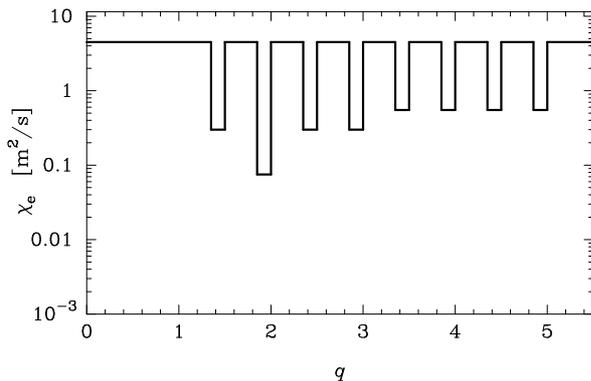


FIG. 1. The  $q$ -comb used for OMS shots with  $\tilde{q}_a = 1$  (#40847, #45623, #46664, #46669, #46716, #49015, and #49017 from Table I).

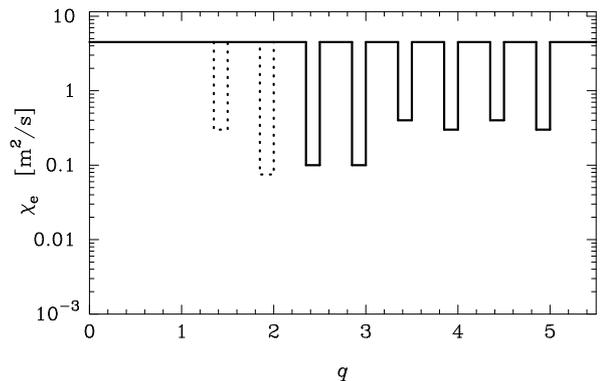


FIG. 2. The  $q$ -comb used for OMS shots with  $\tilde{q}_a = 3.4/2.5$ . The  $q = 3/2$  and  $q = 2$  surfaces were not present in these discharges. The dashed barriers indicate their values for  $\tilde{q}_a = 1$  discharges.

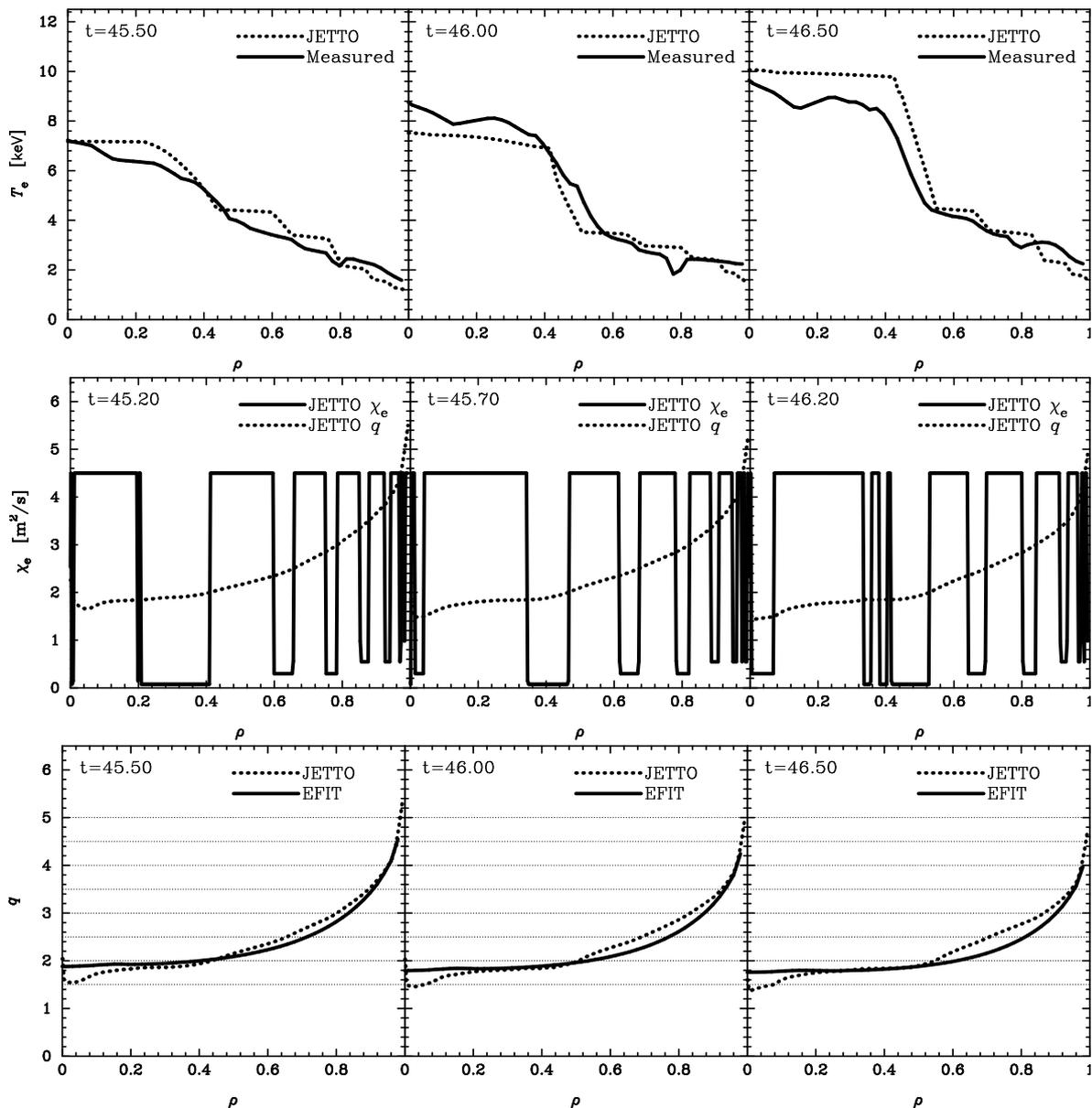


FIG. 3. The upper panels show the time evolution of the  $T_e$  profile of a characteristic JET OMS discharge (#46669), in the  $B_\phi=3.4$  T,  $I_p=3.4$  MA scenario. The solid lines are interpolated KK3 radiometer measurements. The dashed lines are JETTO simulation results, using the  $q$ -comb model. The intermediate panels show the corresponding  $q$  profiles (dashed lines) and  $\chi_e$  profiles (solid lines). The lower panels compare JETTO's  $q$  profiles (dashed lines) with EFIT reconstructions (solid lines). The simulation runs from well before the main heating phase until the end of the main heating. The three times shown are all during the main heating phase.

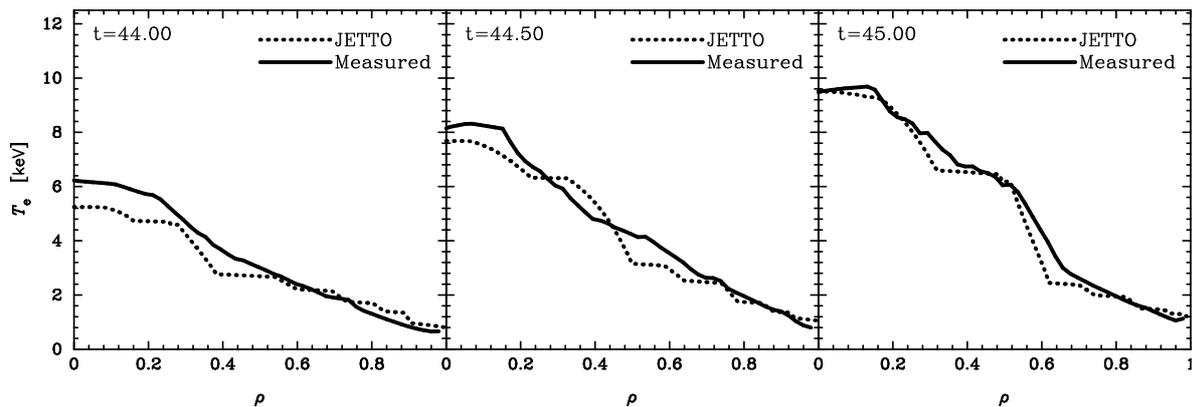


FIG. 4. Comparison of simulation and experiment for a JET OMS discharge (#46133), in the  $B_\phi=3.4$  T,  $I_p=2.5$  MA scenario.

#### IV. DISCUSSION

It is fascinating that the conceptual  $q$ -comb model for thermal electron barriers that works well for the electron physics dominated plasma of RTP works equally well for the ion physics governed plasma of JET. The differences in size and plasma shape between the two devices, put them in totally different regimes of characteristic time scales. Added to that the additional heating at RTP was only electron cyclotron heating, whereas there is neutral beam injection, and ion cyclotron heating, and lower hybrid current drive at JET. Still the model is valid for both machines. From this we can conclude that it is indeed possible to separate the physics governing the formation of ion ITBs and that for electron ITBs.

Further credence to the validity of the  $q$ -comb model for JET stems from the observation in [7]. There it was reported that JET ITBs are strongest if the main heating phase starts when the central  $q$  drops below an integer value. Since these are OMS discharges, this translates to a low magnetic shear region close to an integer value of  $q$ . That is exactly the condition for which the barriers are most prominent in the RTP model.

The success of the  $\chi_e(q)$  concept hints at a mayor role to be played by the magnetics for the electron transport. This will be an area for further research in the near future.

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