EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(06)03-01

P. Mantica, A. Casati, F. Imbeaux, N.A. Kirneva, A. Marinoni, T. Tala,
D. Van Eester and JET-EFDA Contributors

Heat Wave Propagation in JET ITB Plasmas

Heat Wave Propagation in JET ITB Plasmas

P. Mantica[1], A. Casati[2], F. Imbeaux[3], N.A. Kirneva[4], A. Marinoni[5],
T. Tala[6], D. Van Eester[7] and JET-EFDA Contributors*

[1]*Istituto di Fisica del Plasma, EURATOM-ENEA-CNR Association, Milan, Italy*
[2]*Politecnico di Milano, Dipartimento di Ingegneria Nucleare, Milano , Italy*
[3]*Association Euratom-CEA, CEA Cadarache, St Paul-lez-Durance Cedex, France*
[4]*RRC 'Kurchatov Institute', 123182 Moscow, Russia*
[5]*EPFL CRPP, Association Euratom-Confédération Suisse, CH 1015, Lausanne, Switzerland*
[6]*Association EURATOM-Tekes, VTT, P.O. Box 1000, FIN-02044 VTT, Finland*
[7]*LPP-ERM/KMS, Association Euratom-Belgian State, TEC, B-1000 Brussels, Belgium*
** See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
33rd EPS Conference,
(Rome, Italy 19-23 June 2006)

First results of heat wave propagation experiments in plasmas with Internal Transport Barriers (ITBs) were obtained in JET and reported in [1]. These showed that ITBs are narrow layers and induce strong damping and slowing down of the heat wave. This implies a very low perturbed heat diffusivity, indicating a transport regime which is sub-critical with respect to turbulence thresholds.

In this paper more analysis is presented of an extended database of JET ITB discharges with ICH power modulation in Mode Conversion (in D_2 plasmas with 18% concentration of 3He), which provides direct and localized electron heating. The plasma scenario is characterized by a reverse magnetic shear configuration, leading to the formation of an electron and ion ITB in the negative shear region. New experimental evidence is gained from the heat wave propagation, which provides new insight into ITB transport physics.

First, the heat wave "sees" an ITB (through clear changes in propagation) even in conditions where the temperature gradient is not high enough that the ρ_T* parameter ($\rho_T^* = \rho_s/L_T$ where ρ_s is the ion Larmor radius at the sound speed and $L_T = |\nabla T|/T$) exceeds the threshold value commonly assumed for ITB detection ($\rho_T^* = 0.014$) [2]. An example is shown in Fig.1. Although the electron ITB is undetectable from examination of the Te profile only, still the modulation amplitude shows a strong damping in the region $3.2m < R < 3.3m$. This is due to the presence of a layer of reduced transport, although not appearing as a strong T_e gradient due the lack of electron power density inside the ITB. Heat waves are therefore confirmed as a powerful tool to detect ITBs and their radial extension, since ITB formation is linked to being below or above turbulence thresholds which vary with plasma parameters, whilst the actual ITB strength is not very significant from a physics point of view, as it depends not only on transport reduction but also on application of power inside the ITB radius.

Second, an interesting convective-like effect leading to amplitude growing instead of decaying when moving away from source may be seen near the foot of the ITB, which is the region where the plasma is very close to threshold. This is illustrated in Fig.2(b). The phase minimum indicates the power deposition location and the amplitude maximum is clearly shifted inward. Although this feature is located outside the ITB (the heat wave being strongly damped by the ITB layer as already observed in [1]), it appears only when the ITB is present. Fig.2(c) shows that in a later phase when the ITB is lost, phase minimum and amplitude maximum coincide as expected from a diffusive behaviour. This observation is reminiscent of similar convective-like effect seen on ECH modulation in ASDEX-Upgrade in discharges with strong off-axis ECH power [3]. Although the AUG discharges did not have ITBs, one common ingredient was that this effect shows up in a region where the Te profile is very close to the threshold, which is the one for Trapped Electron Mode onset, as discussed in [6].

In fact, a model for the χ_e profile based on the existence of a critical gradient (CGM model, described in [4]) does feature the existence of convective-like effects arising from the Te dependence of χ_e:

$$\chi_e = \lambda T_e^{3/2}\left(\frac{R}{L_{T_e}} - \kappa_c\right) H\left(\frac{R}{L_{T_e}} - \kappa_c\right) + \chi_0 \tag{1}$$

where χ_0 gives the level of residual transport, λ the strength of the turbulent transport term, and κ_c is the threshold. H is the Heaviside function. The apparent convection yielded by such model is given by

$$U_e = -\frac{\delta\chi_e}{\delta T_e}\ \nabla T_e = -\frac{1}{2}\lambda T_e^{3/2}\frac{\nabla T_e}{T_e}\left(\frac{R}{L_{T_e}} - 3\kappa_c\right) H\left(\frac{R}{L_{T_e}} - \kappa_c\right) \tag{2}$$

which close to threshold (R/L_{Te}~k_c) yields

$$U_e \sim -\frac{\lambda}{R}\ T^{3/2} k_c^{\ 2} \tag{3}$$

This implies the existence close to threshold of an apparent convective term directed inward and proportional in magnitude to the square of the threshold value.

Indeed numerical simulations with the ASTRA code of the discharge in Fig.2 using the critical gradient model and a threshold featuring an increase of kc at the ITB location (where the plasma is sub-critical and the heat wave is damped) and a region where the plasma is very close to threshold just outside the ITB reproduces fairly well the experimental data as shown in Fig.3. The difference between this case and the case shown in Ref.[1] which did not exhibit any convective like effect is that the value of threshold outside the ITB was lower in that case than in the present one, therefore not giving origin to strong convective-like effects according to Eq.(3). In the simulation of Fig.3 no real convection was required to reproduce the data, whilst in the AUG experiments a small real convection was also required [3]. In fact, attempting to reproduce the data of Fig.2(b) with only real convection would require large values of heat convection, inconsistent with the steady-state T_e profile and difficult to justify theoretically, whilst the effect of apparent convection is fully consistent with theoretical expectations.

The possibility of reproducing the data shown above, rather odd at first sight, with a model of the type of Eq.(1) is in fact supplementary evidence that such dynamics of plasma transport is indeed at play. This adds a further element on top of the various observations in favour of a critical gradient behaviour, as summarized in [5, 6]. In fact, even more unexpected behaviour is sometime observed, as shown in Fig.4, with two peaks appearing in the amplitude profile and only one phase minimum corresponding to power location. Such second more internal amplitude peak is a pure transport effect, originated by an oscillation of the T_e profile below and above threshold during the modulation cycle. This double humped A profile is in fact reproduced in simulations where the T_e profile in the region around power deposition is very close to threshold and oscillating across it, as shown in Fig.5. In this case the ITB was unclear in the electron channel, with a situation intermediate between a fully developed ITB with a plasma fully below threshold and a standard H-mode discharge with a plasma fully above threshold.

In summary, we have presented new experimental results of heat wave propagation in plasmas with Internal Transport Barriers. Rather unexpected features with respect to standard diffusive behaviour are observed, such as convective-like effects or double humps on the radial profile of heat wave amplitudes, whilst phases are basically unaffected. These features can be explained on the basis of a transport model featuring a threshold in inverse Te gradient length, in situations respectively where just outside a properly established ITB the plasma is close to threshold or where the ITB is marginal and the plasma oscillates below and above threshold. These results are complementary evidence to the existence of a threshold-regulated electron transport, as found in several experiments and summarized in [6].

REFERENCES

[1]. P. Mantica et al., Phys. Rev.Letters **96** (2006) 095002

[2]. G. Tresset, Nucl. Fusion **42**, 520 (2002)

[3]. P. Mantica et al., Plasma Phys. Control. Fusion **48** (2006) 385

[4]. F. Imbeaux et al., Plasma Phys. Control. Fusion **43** (2001) 1503

[5]. P. Mantica and F. Ryter, “Perturbative studies of turbulent transport”, to be published in Comptes Rendus – Physique, Elsevier

[6]. F. Ryter et al., “Electron transport studies”, invited talk in this conference

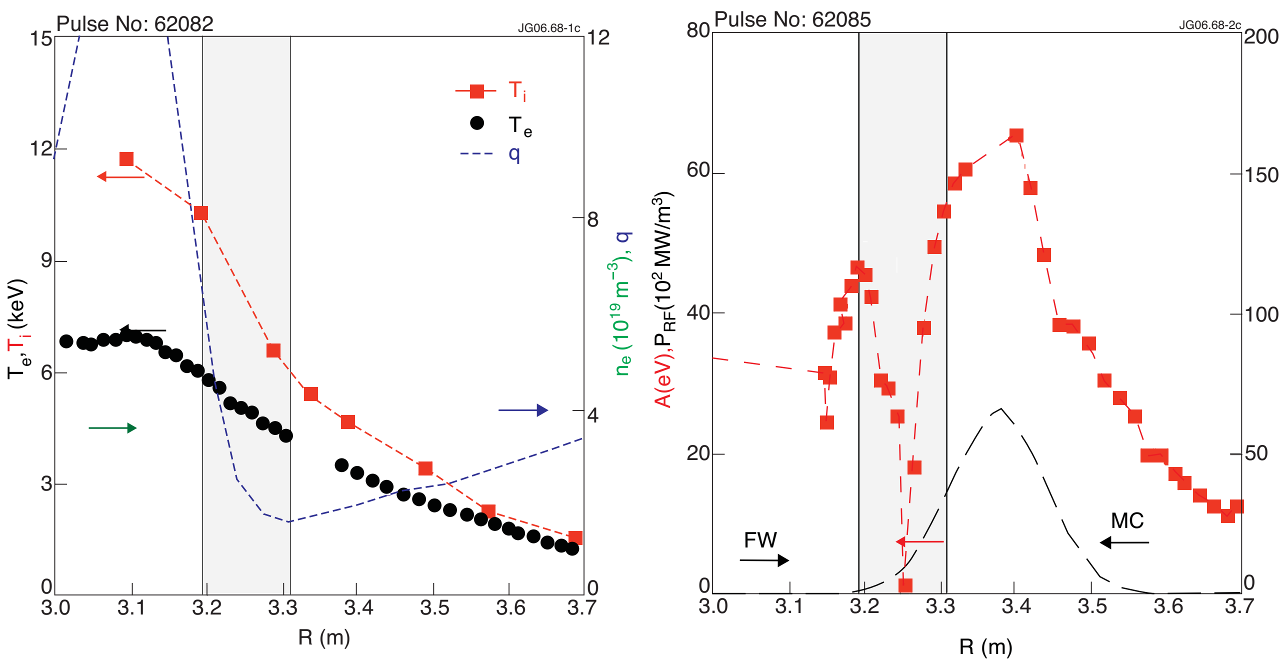

Figure 1: (a) Profiles of T_i, T_e, and q for Pulse No: 62082; (b) Profiles of modulation amplitude and estimated RF power deposition. The ITB layer is clearly evidenced by the strong damping of the amplitude.

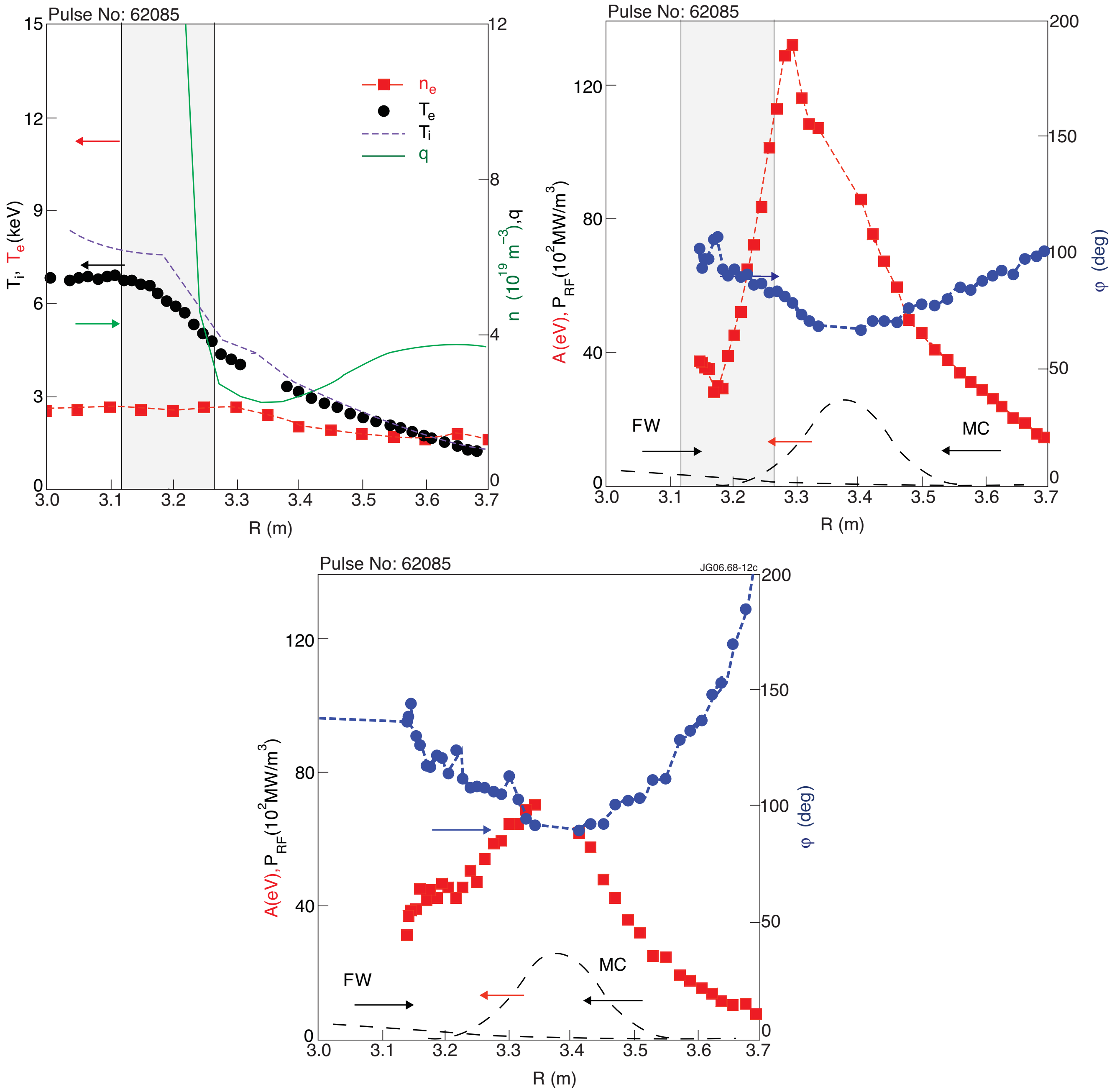

Figure 2: (a) Profiles of T_i, T_e, n_e and q for Pulse No: 62085; (b) Profiles of modulation amplitude and phase and estimated RF power deposition. (c) Same as (b) in a time range where the ITB is no longer present.

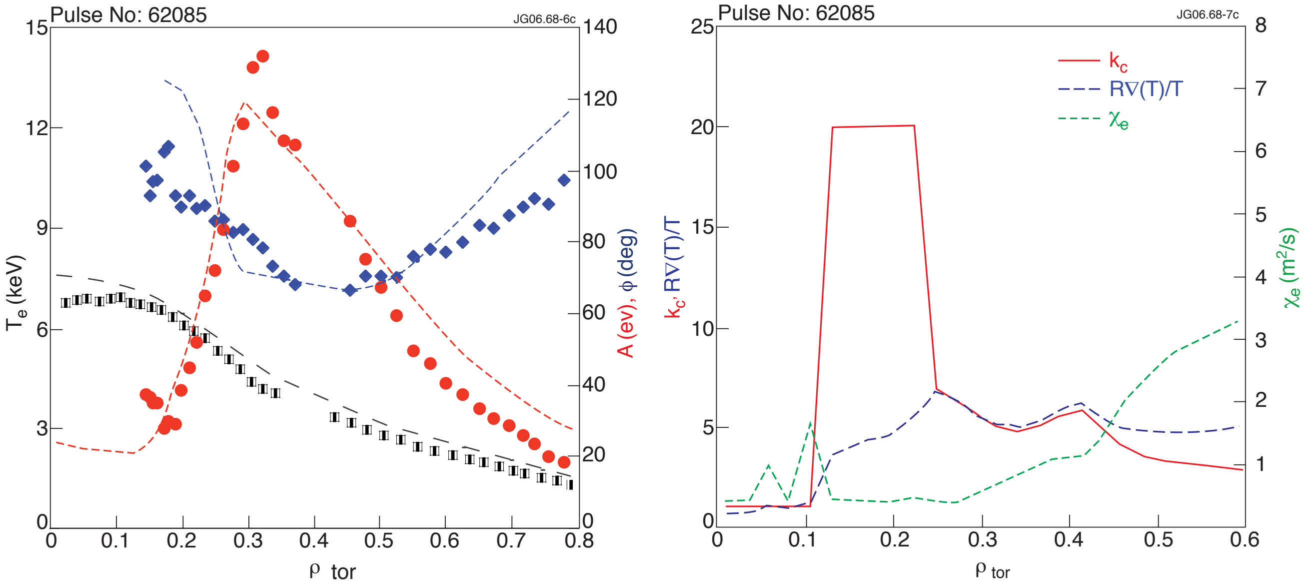

Figure 3: Simulation using the ASTRA code of the discharge in Fig.2. (a) Profiles of T_e, A and . (dots: experiment, lines:simulation); (b) Profiles of threshold k_c, value of R/L_{Te} and χ_c profile assumed in the simulation for the CGM model of Eq.(1).

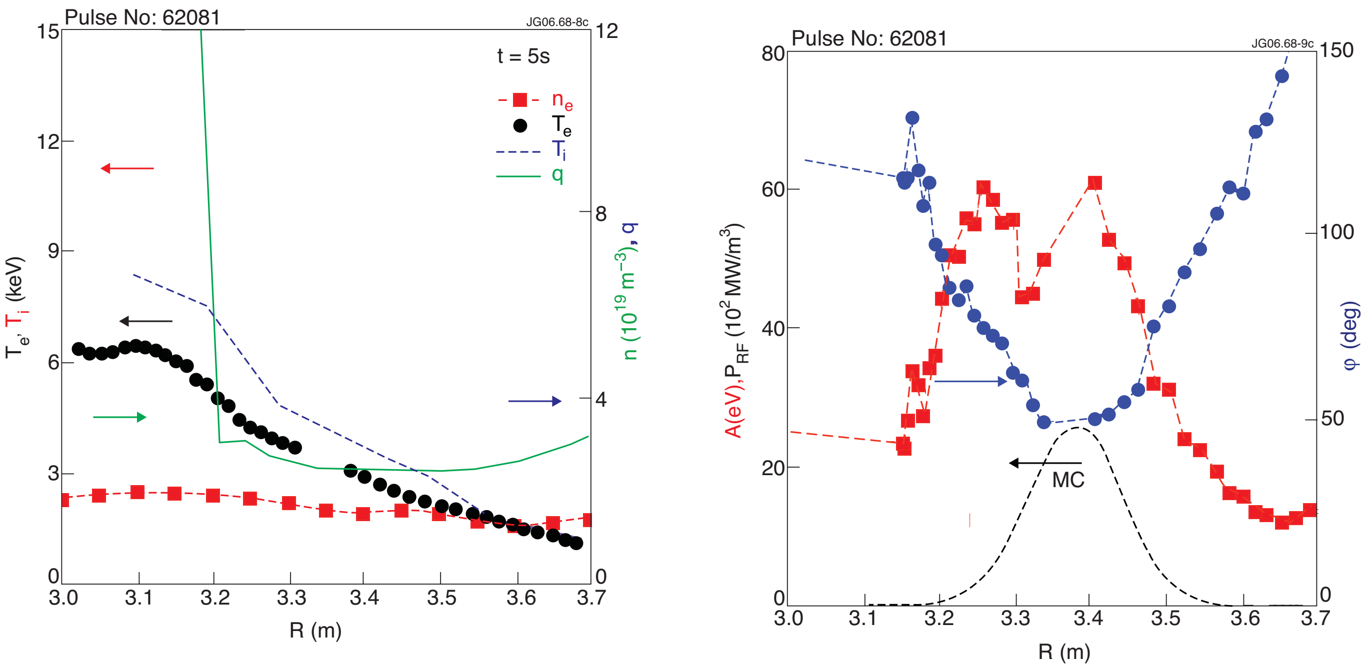

Figure 4: (a) Profiles of T_i, T_e, n_e and q for Pulse No: 62081; (b) Profiles of modulation amplitude and phase and estimated RF power deposition.

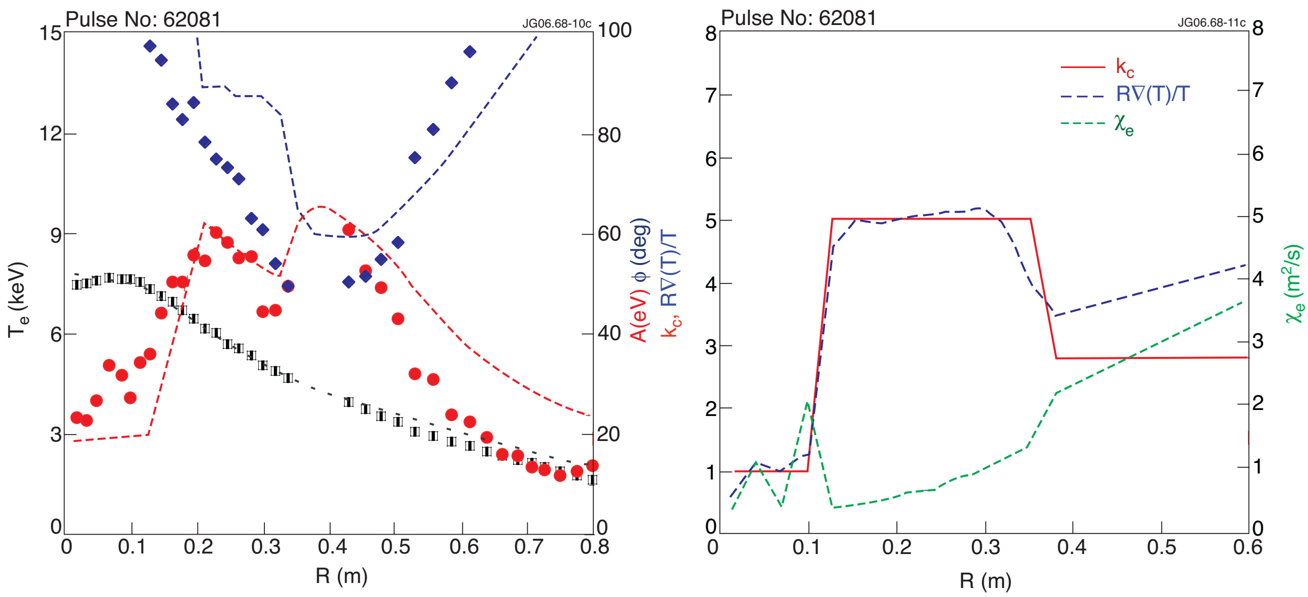

Figure 5: Simulation using the ASTRA code of the discharge in Fig.4. (a) Profiles of T_e, A and φ (dots: experiment, lines:simulation); (b) Profiles of threshold k_c, value of R/L_{Te} and χ_c profile assumed in the simulation for the CGM model of Eq.(1).