Transient Transport Experiments in Rijnhuizen Tokamak Project: Transport Barriers, Heat Convection, and ‘Non-Local’ Effects

P.Mantica[1)], G.Gorini[1),2)], G.M.D.Hogeweij[3)], J. de Kloe[3)], N. J. Lopes Cardozo[3)],
A.M.R.Schilham[3)] and RTP team

1) Istituto di Fisica del Plasma ‘P.Caldirola’, Associazione Euratom-ENEA-CNR, Milano, Italy
2) INFM and Dipartimento di Fisica 'G.Occhialini', Università degli Studi di Milano-Bicocca, Milano, Italy
3) FOM Instituut voor Plasmafysica 'Rijnhuizen', Associatie Euratom-FOM, Trilateral Euregio Cluster, 3430 BE Nieuwegein, The Netherlands

e-mail contact of main author: mantica@ifp.mi.cnr.it

Abstract. An overview of experimental transport studies performed on the Rijnhuizen Tokamak Project (RTP) using transient transport techniques in both Ohmic and ECH dominated plasmas is presented. Modulated Electron Cyclotron Heating (ECH) and oblique pellet injection (OPI) have been used to induce electron temperature (T_e) perturbations at different radial locations. These were used to probe the electron transport barriers observed near low order rational magnetic surfaces in ECH dominated steady-state RTP plasmas. Layers of inward electron heat convection in off-axis ECH plasmas were detected with modulated ECH. This suggests that RTP electron transport barriers consist of heat pinch layers rather than layers of low thermal diffusivity. In a different set of experiments, OPI triggered a transient rise of the core T_e due to an increase of the T_e gradient in the $1<q<2$ region. These transient transport barriers were probed with modulated ECH and found to be due to a transient drop of the electron heat diffusivity, except for off-axis ECH plasmas, where a transient inward pinch is also observed. Transient transport studies in RTP could not solve this puzzling interplay between heat diffusion and convection in determining an electron transport barrier. They nevertheless provided challenging experimental evidence both for theoretical modelling and for future experiments.

1. Introduction

A significant fraction of the research programme of the Rijnhuizen Tokamak Project (RTP) was dedicated to transient transport studies, with the aim of investigating electron heat transport by combining steady state and dynamic evidence. Dynamic experiments, though more difficult to perform and interpret, provide unique transport information that can be used as a benchmark of existing transport theories.

Transient transport experiments in RTP ($R=0.72$ m, $a=0.16$ m, $B_T<2.5$ T, $I_p<150$ kA, pulse length ~ 0.5 s, boronised vessel) started in 1991 with sawtooth heat pulse propagation and Modulated Electron Cyclotron Heating (MECH) using a 60 GHz , 200 kW gyrotron launching 1st harmonic O-mode waves from the low field side. These studies confirmed previous observations that heat perturbations in a tokamak plasma propagate with a heat diffusivity (χ_e^{pert}) larger than the power balance one (χ_e^{PB}). This result was found to be independent of the perturbation technique used and of the amplitude of the perturbation [1]. The radially increasing χ_e^{pert} profile appeared to be rather insensitive to variations in plasma parameters such as plasma current or safety factor, density, total power [2]. After these initial studies, transient transport experiments in RTP continued until the shut down in 1998. They focussed on two topics: 1) the use of MECH to probe the electron transport barriers observed in steady-state plasmas with dominant ECH power; 2) the use of oblique pellet injection (OPI) to study the “non-local” positive central T_e reaction to peripheral cooling. MECH was performed using a 110 GHz gyrotron launching 400 kW of 2nd harmonic X-mode waves from the low field side. The power could be localised within 10% of the minor radius. The deposition radius (ρ_{dep}) was varied by changing the toroidal field or the poloidal launching angle. Modulation frequencies up to 2 kHz and duty-cycles from 0.1 to 0.9, with different modulation depths, were used to produce different waveforms of the T_e perturbation. Cold pulse experiments were performed with OPI – i.e., launching hydrogen pellets obliquely in the poloidal plane - with impact parameters in the range $0<r/a<0.7$. The ensuing negative T_e perturbation (cold pulse) propagated inwards, sometimes inverting its sign as it approached the plasma core. RTP was equipped with a comprehensive set of diagnostics capable of measuring T_e and n_e with good space and time resolution: a 20 channel ECE heterodyne radiometer, a 16 channel ECE-imaging diagnostic, a 19 channel interferometer, an 80 channel, 5 camera soft x-ray tomographic system, and a double pulse Thomson scattering system covering the full plasma with a spatial resolution <3 mm.

This paper is organised as follows. Section 2 presents an overview of the results obtained with MECH in ECH dominated plasmas, while Section 3 presents the main results from cold pulse experiments in Ohmic and ECH plasmas. Section 4 presents the conclusions and some relevant issues for future transient transport investigations of electron transport barriers in tokamaks.

2. Modulated ECH experiments

In RTP ECH dominated plasmas a shot-by-shot scan of ρ_{dep} showed a discontinuous behaviour of the core T_e (Fig.1) with sudden drops occurring when low order rational magnetic surfaces are lost [3]. In between transitions, five plateaux are observed (labelled with letters from A to E), in which T_e is rather insensitive to changes in ρ_{dep}. This behaviour was attributed to narrow layers of low diffusivity (transport barriers) located in the proximity of low order rational magnetic surfaces [4] and embedded in a background plasma with higher transport. In order to probe these transport barriers, MECH experiments were carried out at a modulation frequency $\omega/2\pi$=310 Hz and with two duty-cycles: d_c=0.15 and d_c=0.85. These d_c values provide an identical spectrum of the power waveform, respectively in a quasi-Ohmic (d_c =0.15) and in a ECH dominated plasma (d_c=0.85). About 50 modulation cycles were used to provide adequate signal/noise ratio for standard Fourier analysis; reliable radial profiles of amplitude (A) and (φ) were obtained for 3 harmonics of the MECH frequency.

Shown in Fig.2 is a comparison between low (left) and high (right) d_c values for two discharges with ρ_{dep}=0.25. The ECH dominated case (d_c=0.85) belongs to the A' plateau (a narrow sub-plateau between A and B, see Fig.1 [5]). As expected, there is a clear difference in the time averaged T_e and q profiles for the two discharges. More striking is the difference in the MECH data. In the low d_c case, the behaviour of the A and φ profile has the usual 'diffusive' features: the amplitude decays and the modulation phase lag increases moving away from the heat source (ρ_{dep}) so that the locations of the peak amplitudes and minimum phases coincide. In the high d_c case, in contrast, the data show an inward shift of the amplitude peak at 1st harmonic. This feature gradually disappears at higher harmonics, the 3rd one presenting a standard 'diffusive' pattern. Even the 1st harmonic phase profile is not immune from non-diffusive features: diffusive transport requires φ to increase with frequency at ρ_{dep} and elsewhere; instead, a larger 1st harmonic φ value relative to the other harmonics is found in the region just outside ρ_{dep}.

A similar behaviour is found as ρ_{dep} is moved outward. Fig.3 shows four cases of MECH in discharges belonging to different plateaux (A, A', B, C). An inward shift of the 1st harmonic amplitude peak relative to ρ_{dep} is clearly observed in all four cases. Again, the shift disappears at higher harmonics.

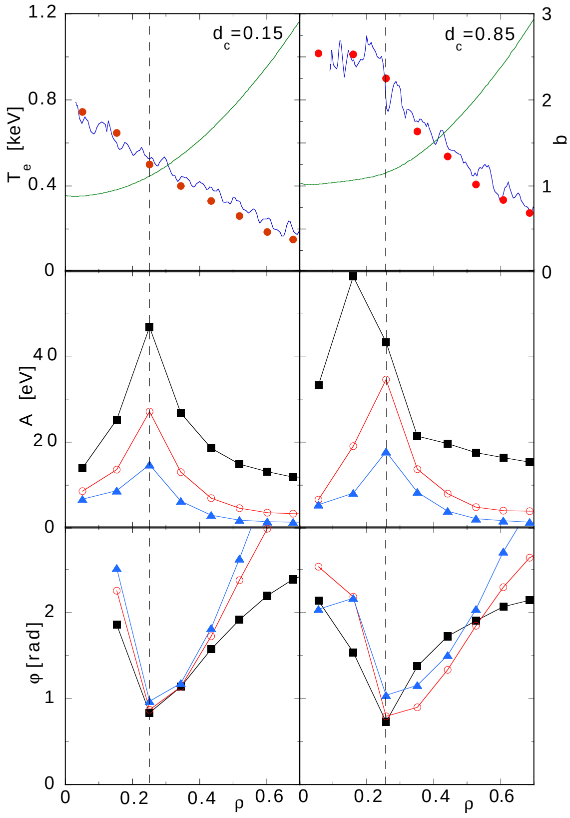


FIG.2. T_e and q profiles and MECH A and φ profiles at 3 harmonics for two similar discharges with d_c=0.85 (right column) and d_c=0.15 (left column). Plasma parameters: I_p=80 kA, q_a~5, $n_e(0)$=5 10^{19} m^{-3}, ρ_{dep} =0.25.

FIG.3. MECH amplitude profiles at 1^{st} (■) and 3^{rd} (○) harmonics (measured with ECE) for 4 MECH discharges in plateaux A, A', B, C. The ρ_{dep} locations are marked with a vertical line.

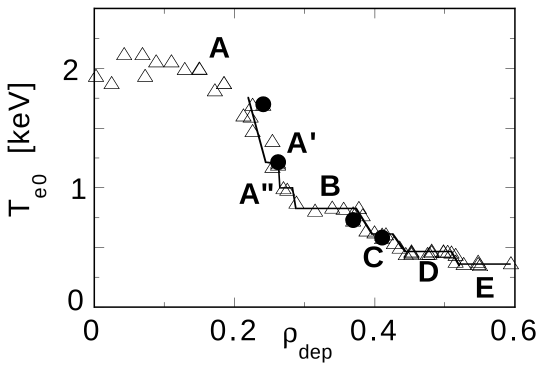
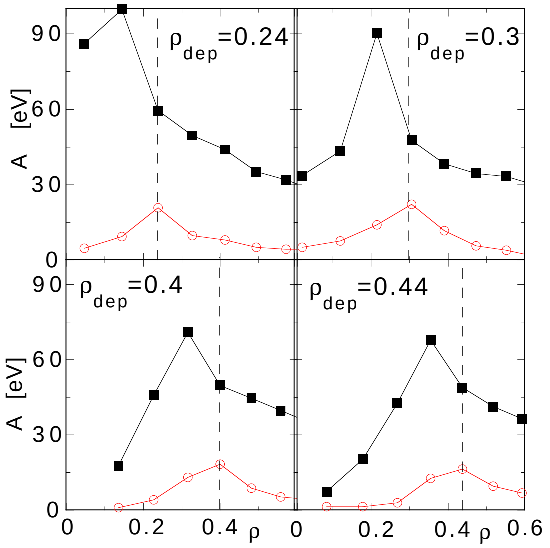


FIG.1. Central T_e vs. ρ_{dep} for a set of similar discharges (I_p=80 kA, q_a~5, $n_e(0)$ =4 10^{19} m^{-3}) in which ρ_{dep} was increased in small steps from shot to shot. The full dots mark the discharges where the ECH power was modulated. The line is a guide to the eye.



The above observations can be accounted for, at least qualitatively, by assuming a model for the electron heat flux (q_e) including a 'heat pinch' component in addition to the usual diffusive component: $-q_e = n_e \chi \nabla T_e + n_e U T_e$ where U(r) is the heat pinch velocity profile. Simulations using the transport code ASTRA [6] indicate that a heat pinch velocity with peak value in the range U=50-80 m/s, localized in a narrow (Δρ≈10%) region of the plasma just inside ρ_{dep}, can match the main features of the data [7]. This is the same location where the strongest steady-state barriers are found. The time scale for the onset of the heat pinch, comparable to the current diffusion time (10 ms), suggests that the magnetic shear may play a role in the process.

The evidence described above suggests that the steady-state electron transport barriers observed in RTP ECH dominated plasmas are in fact heat pinch layers rather than regions of reduced χ_e, as assumed in a previous modelling based on steady-state experiments only. It has been found that a new model featuring heat pinch layers at simple rational q-values does reproduce the stair-step behaviour of $T_e(0)$ vs ρ_{dep}, but has too many free parameters for the present data set to uniquely determine the pinch layers [7]. Further experimental evidence is required on this point and will have to be provided by other tokamaks with strong ECH power.

3. Cold pulse experiments

Oblique pellet injection in low density (line average densities $n_e < 2.710^{19} m^{-3}$) Ohmic plasmas triggered a core T_e rise and an increased T_e gradient within the q=2 surface (Fig.4) [8]. The transient T_e rise lasts for about 5 ms, i.e. about one energy confinement time. A similar core T_e rise had previously been observed in other tokamaks and found to be "non-local" in the sense that the transport change in core does not appear related to changes in the local thermodynamic quantities. In RTP there appears to be a short (~0.6 ms) delay in the T_e rise, suggesting in fact a propagating mechanism involving small changes in some non measured quantity. A tentative explanation of the T_e rise could be the formation of transient transport barriers near low order rational magnetic surfaces [9,10] following a small, localised change in the q profile.

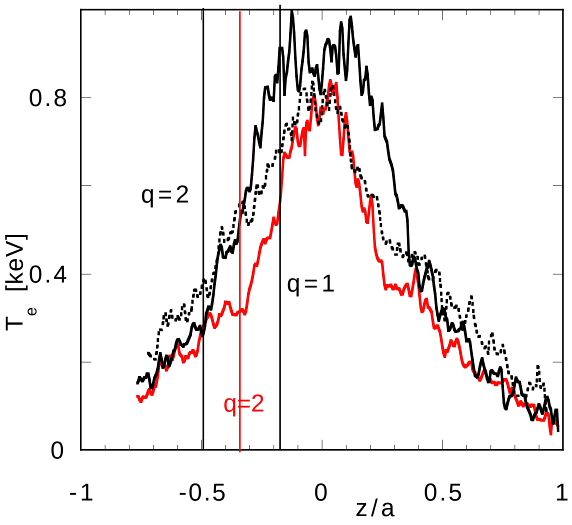


FIG.4. T_e profiles measured with Thomson scattering at the top of the rise (full lines) for two discharges at $\bar{n}_e = 1.4\ 10^{19}\ m^{-3}$ with different q_a : q_a=4.7 (black) and q_a=6.55 (red). For the lower q discharge the reference T_e profile measured just before the cold pulse is also shown (dashed line).

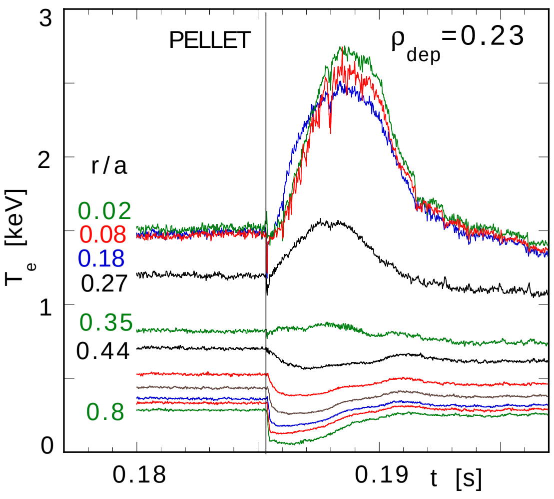


FIG.5: ECE T_e time traces for a discharge with cold pulse in a ECH plasma with ρ_{dep}=0.23 (P=280 kW, q_a= 5.3, $\bar{n}_e = 1.8\ 10^{19}\ m^{-3}$)

MECH has been used to probe the transient enhancement in the T_e gradient. The observation of a strong attenuation of the heat wave where the gradient increases supports the claim that a transient reduction of χ_e (transient transport barrier) in the region 1<q<2 is taking place [9]. The spatial resolution is insufficient to resolve between one broad barrier or more localised barriers associated with rational surfaces. In any case, unlike the steady-state barriers described in Sect.2, these transient barriers are mainly diffusive.

Even more exciting observations were made by OPI in ECH dominated plasmas [10,11]. A strong dependence of the amount of central T_e increase on the location of ρ_{dep} relative to the q=1 surface is observed. For ρ_{dep} just inside q=1 (i.e. for discharges just before the first transition in Fig.1) a record T_e rise is observed, with T_e transiently increasing from 1.5 keV to 2.8 keV (Fig.5) [11]. Transport simulations of the discharge of Fig.5 [11] show that the detailed behaviour of the T_e profile in the plasma core cannot be accounted for unless a transient heat pinch enhancement in the $1<q<2$ region is assumed (in addition to the aforementioned reduction of χ_e). In other words, the transient transport barriers induced by OPI, while being mainly diffusive in Ohmic plasmas, have an additional heat pinch component in ECH dominated plasmas. These are the same plasmas where steady-state transport barriers are also due to heat pinch layers according to MECH studies.

4. Conclusions

Transient transport techniques have proven to be valuable tools for detailed investigations of transport in RTP.

MECH experiments revealed the existence of heat pinch layers in ECH dominated plasmas. This led to a re-interpretation of steady-state electron transport barriers, which are now believed to be predominantly due to some convection process giving rise to heat pinch layers.

OPI experiments turned out to be related to the transport barrier issue in that the “non-local” T_e rise appears to be due to the onset of transient transport barriers with a similar correlation as the steady-state ones with rational magnetic surfaces. However, the main component of such transient barriers appears to be diffusive, with an additional convective component for cold pulses in ECH dominated plasmas.

It is tempting to relate the transient changes in transport in OPI experiments to the steady-state transport observations. Accordingly, transient transport barriers and steady-state barriers could be manifestations of the same underlying transport mechanism, giving rise to both diffusive and convective heat fluxes. The interplay between diffusion and convection, however, is yet to be fully understood. Transient transport experiments are suitable for this and other kinds of investigations. It would therefore be desirable that this type of studies be pursued by other tokamak experiments equipped with powerful electron heating.

This work was performed under the Euratom-FOM and the Euratom-ENEA-CNR association agreements, with financial support from NWO, CNR and Euratom.

References

[1] GORINI, G., et al., Phys. Rev. Lett. **71** (1993) 2038.
[2] MANTICA, P., et al., Nucl. Fusion. **36** (1996) 1317.
[3] LOPES CARDOZO, N.J., et al., Plasma Phys. Controlled Fusion **39** (1997) B303.
[4] HOGEWEIJ, G.M.D., et al., Nucl. Fusion **38** (1998) 1881.
[5] DE BAAR, M., et al., Phys. Plasmas **6** (1999) 4645.
[6] PEREVERZEV, G.V., et al., "ASTRA: an Automatic System for Transport Analysis in a Tokamak", Max-Planck- IPP Report, IPP 5/42 (1991).
[7] MANTICA, P., et al , in Proceedings of the 27th Conference on Controlled Fusion and Plasma Physics, Budapest, 2000 (European Physical Society, 2000), P3.023.
[8] GALLI, P., et al., Nucl. Fusion **39** (1999) 1355.
[9] MANTICA, P., et al, Phys. Rev. Lett. **82** (1999) 5048.
[10] GORINI, G., et al., Plasma Phys. Controlled Fusion 42 (2000) A161.
[11] HOGEWEIJ, G.M.D., et al.,accepted for publication in Plasma Phys. Controlled Fusion.