ELECTRON CYCLOTRON HEATING AT 140 GHZ ON FTU TOKAMAK IN STEADY-STATE CONDITIONS AND DURING CURRENT RAMP-UP

S.Cirant, FTU Group[1)] and ECRH/IFP Group[2)]
[1)]P.Buratti, G.Bracco, O.Tudisco, M.Zerbini, F.Alladio, B.Angelini, M.L.Apicella, G.Apruzzese, E.Barbato, M.R.Belforte[4)], L.Bertalot, A.Bertocchi, M.Borra, G.Buceti, A.Cardinali, C.Centioli, R.Cesario, P.Chuilon, C.Cianfarani[4)], S.Ciattaglia, V.Cocilovo, F.Crisanti, R.De Angelis, F.De Marco, B.Esposito, D.Frigione, L.Gabellieri, G.Gatti, E.Giovannozzi, M.Grolli, F.Iannone, H.Kroegler, M.Leigheb, G.Maddaluno, M.Marinucci, G.Mazzitelli, P.Micozzi, P.Orsitto, D.Pacella, L.Panaccione, M.Panella, V.Pericoli, L.Pieroni, S.Podda, G.B.Righetti, F.Romanelli, F.Santini, S.E.Segre[3)], S.Sternini, N.Tartoni, A.A.Tuccillo, V.Vitale, G.Vlad, V.Zanza, F.Zonca
[2)]A.Bruschi, G.Granucci, A.Simonetto, C.Sozzi, A.Airoldi, G.Cenacchi[5)], E.Lazzaro, S.Nowak, G.Ramponi
[1)]Associazione Euratom-ENEA sulla Fusione, Centro Ricerche Energia Frascati, Frascati, , Italy
[2)]Associazione Euratom-ENEA-CNR sulla Fusione, Istituto di Fisica del Plasma, Milano, Italy
[3)]I.N.F.M. and Dipartimento di Fisica, II Università degli Studi di Roma, Tor Vergata, Rome , Italy
[4)]ENEA guest
[5)]Associazione Euratom-ENEA sulla Fusione, Centro Ricerche Energia, Bologna, Italy

Abstract
Localized absorption of EC waves at 140 Ghz, 0.7 MW, in FTU is used to shape the current density profile ($q_a \approx 6$) in a way to affect sawteeth. If absorption is localized near the inversion radius, temporary stabilization occurs. Sawteeth with a small inversion radius (r/a<0.2) do not affect electron energy confinement. Energy transport appears diffusive, and global confinement is found to be in good agreement with ITER89P L-mode scaling law.

1. Introduction

The paper reports of ECRH/ECCD experiments performed on FTU tokamak with the aim of testing electron thermal transport when varying, by localized absorption of EC waves, the current density profile and the MHD mode content. In particular, off-axis absorption was pursued in steady-state conditions, in a way to attempt sawtooth stabilization [1], aiming at the achievement of the condition $q_0 > 1$ at full power (1.6 MW). Central and off-axis ECRH was performed during current ramp-up also, the additional heating pulse extending up to nearly steady-state conditions. The time evolution of the central temperature and of the global electron energy content are considered, in the phase when the MHD mode content is progressively enriched until the onset of the sawtooth activity.

ECCD could be used to contribute to the shaping of the current density profile. Switching from co to counter-current drive adds the capability of switching from s.t. stabilization to destabilization with the same ECR heating term. The scheme has been tested, although significant effects are expected at full power only.

Up to two 140 Ghz gyrotrons were used, with a power to the launching antenna of 350 kW each, and a typical pulse length in the experiments of 0.1-0.3 s [2]. The launched beams can be steered toroidally for ECCD [3]. Plasma current was 350 kA, feedback controlled, with $q_a \approx 6$ (B_{tor} at plasma centre ≈ 5.3 T), and the line electron density in most of the experiments was $5\ 10^{19}\ m^{-3}$. The ohmic power in these experiments is ≈350 kW, which falls to ≈200 kW during ECRH.

2. Sawtooth activity during on-axis & off-axis ECRH

The typical response of sawteeth to ECRH is shown in Fig.1.During on-axis heating, T_e rise is faster and sawtooth period decreases. On the contrary, stabilization can be achieved if the absorption layer r_{abs} is set near to the sawteeth inversion radius r_{inv}. At this ECRH power level, however, stabilization is only temporary. After ≈25 ms, corresponding to ≈2% of the resistive skin time over the m=1 island ($\tau_{res} = \mu_0 r_1^2 / 4\eta_0$), slowly growing m=1 oscillations at ≈ 10 kHz start again and grow to collapse in another ≈ 30 ms (Fig.2). The reconnection is very fast ($\tau_{rec} \approx 40\ \mu s$), in the order of the collisionless inertial time scale $\tau_{rec} \approx r_1/v \approx r_1(\omega_{pe}/c)\tau_A$. As usually occurs at these internal disruptions, the profiles are flattened inside the inversion radius (Fig.3).

Due to the increased central pressure, the plasma axis shifts outwards by ≈15 mm, during the heating pulse. The flattening of the current density profile causes the observed increase in the saw-tooth inversion radius of ≈12 mm.

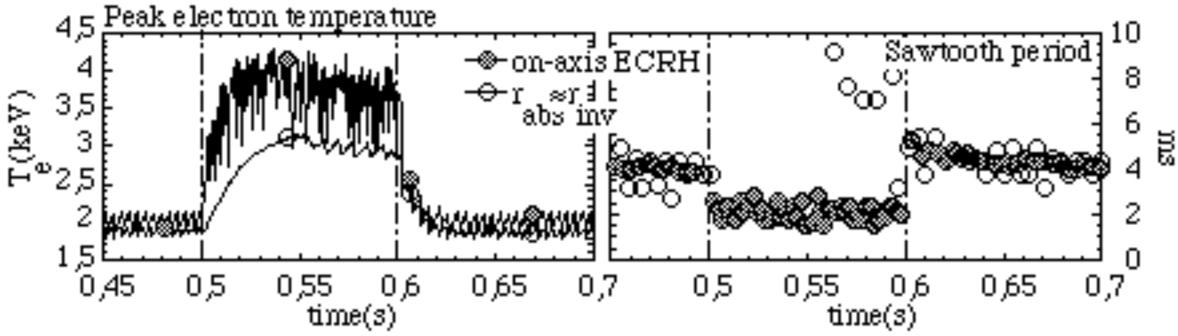

FIG. 1. In case of central absorption, the sawteeth period is immediately reduced and the rate of temperature rise increases accordingly to the local heating power density. On the contrary, sawteeth stabilization can be achieved if $r_{abs} \approx r_{inv}$ and reconnections are immediately suppressed.

Both these effects contribute to dilute the stabilizing effect of off-axis ECRH, which is most sensitive to localization of the absorption layer. The ideal condition $r_{abs} \approx r_{inv}$, met at the start of the ECRH pulse, is lost later in the pulse, when $r_{abs} < r_{inv}$.

As a guideline to a possible explanation to the observed MHD behaviour, we consisder that after a short transient an m=1 mode enters in a nonlinear phase where the growth of a finite size island under the effect of modifications of the pressure gradient and of the resistivity due to localized EC heating [4,5]:

$$\frac{\partial W}{\partial t} = 0.2\frac{r_1}{\tau_{res}}\left[\frac{r_1}{W}\left(1 - g^*\frac{\alpha^2}{S^2}\right) - 0.8\frac{\eta_1'}{\eta_1}\frac{q}{q'}\right]; \quad S = \frac{q' r_1}{q}; \quad \alpha = \frac{8\pi p' R}{B^2}; \quad g^* \approx 2 \text{ (form factor).}$$

After switching ON of ECRH, on the timescale $t << \tau_{res} \approx 1.5\,s$ there can be no significant change of the current density profile on the r_{inv} scale length. Prompt stabilization must be due to the electrodynamic electric field induced by the fast drop in resistivity, which opposes to the local flux swing associated to reconnection A slowly growing m=1 mode develops under the control of the parameters $0.8\frac{\eta'}{\eta}\frac{q}{q'}$ and α^2/S^2 when the current density starts to change and to short-circuit the freezing field. As the plasma axis moves towards the resonance and r_1 increases, the shear at q=1 increases and m=1 mode grows until reconnection can take place again [6,7].

3. Heating and transport during off-axis ECRH

The evolution of the electron energy density profile following off-axis ECRH is qualitatively consistent with a local diffusive transport model. Heating concentrates first at the absorption layer, and diffuses in the plasma column along the temperature gradients. After the transient phase, the ΔT_e profiles are flat inside the absorption radius. The global energy confinement time, which is $\tau_E \approx 42$ ms with 330 kW of ohmic heating, drops to ≈26 ms at P_{tot}=900 kW during ECRH.

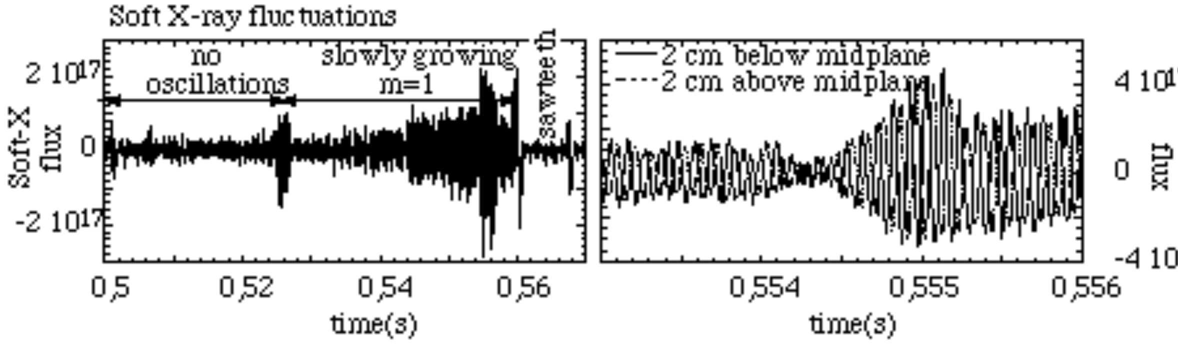

FIG.2. Prompt stabilization lasts for ≈25 ms, correspoding to ≈2% of the resistive time over the q<1 region. Coherent and slowly growing m=1 MHD oscillations develop to collapse at the first reconnection ≈60 ms from the start of ECRH pulse. The traces shown in figure are the fluctuating signal from soft-X ray multicollimator.

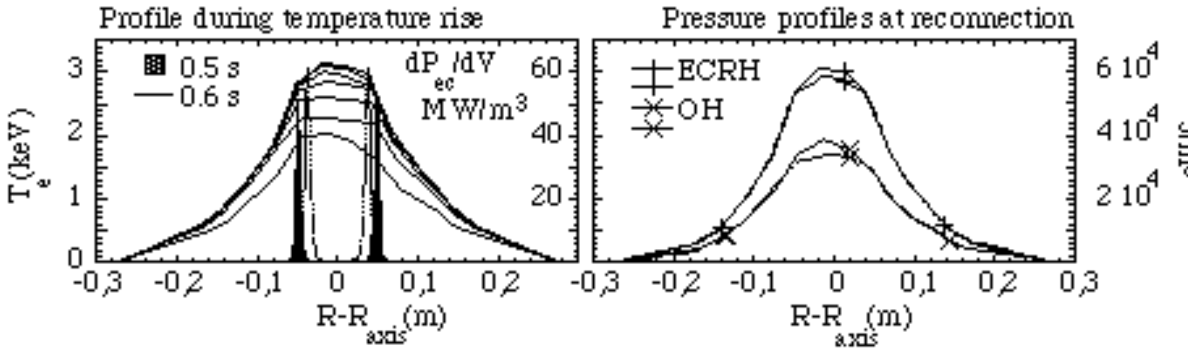

FIG. 3. The figure shows temperature profiles at different instants during the transient heating phase, together with the power deposition profile given by ray-tracing calculations (left). At each reconnection, occurring on the very fast inertial time scale (≈40 μs), the profiles are flattened inside the inversion radius (right),

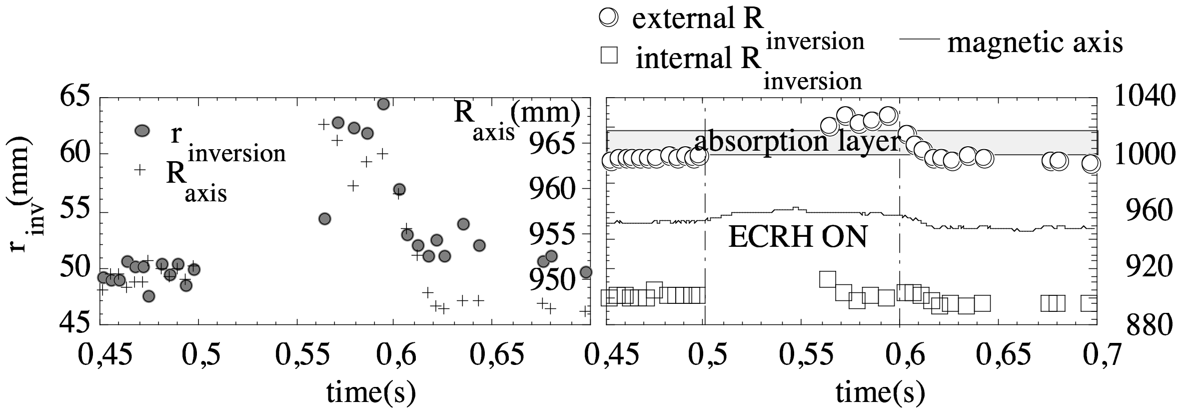

Fig. 4. Both R_{axis} and r_{inv} increase by ≈15 mm during the stabilizing phase, and $r_{abs}< r_{inv}$ when s.t. set in again. Stabilization is very sensitive to the localization of the absorbing layer.

The dependence of τ_E with P_{tot}, is therefore well in agreement with ITER89P L-mode scaling, which would give 40 ms and 25 ms respectively in the two cases.

In the sawtoothing plasma during ECRH, the peak electron temperature decreases because the profile flattens, but without any significant loss of the energy content. Peak electron temperature and global kinetic energy content in discharges with ECRH set off-axis in slightly different positions can be almost identical, in spite of a different sawtooth activity.

4. Sawteeth & MHD with ECRH during current ramp-up

ECRH during current ramp-up at 5 MA/s is shown in Fig.7. P_{ecrh}=220 kW at the antennae, 0.3 s pulse length. When q=2, and q=1 surfaces enter the discharge, a transient increase in the central temperature is observed [8]. The increase is more significant for q=1, and it is terminated by sawteeth. As observed during ECRH on current flat-top, at the onset of sawteeth there is no appreciable change in the total electron nergy content.

5. Concluding remarks

By applying ≈700 kW of ECRH power to a saw-toothing discharge at 350 kA, q_a≈6, P_{ohmic}≈400 kW, reconnections of the m=1 mode are frozen on a time scale much less than the resistive time., and freezing is very sensitive to the localization near the inversion radius of the absorption layer. Plasma shift due to increased pressure and the limited ECRH power available for these experiments prevent the formation of a steady current density profile with q>1 everywhere.

Sawteeth control the peak temperature, but without a significant impact on the global energy content. More relevant to energy losses are MHD oscillations, and similar behaviour is found with ECRH during the current ramp-up. In these conditions, thermal transport in FTU appears diffusive, with a L-mode ITER89P global confinement time scaling.

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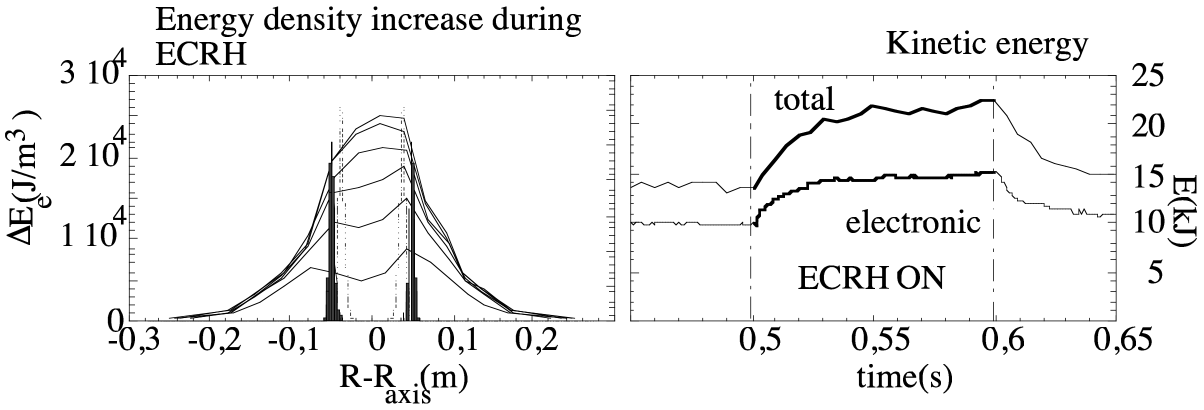

FIG. 5. Thermal transport appears diffusive, with a global energy confinement time scaling with $1/\sqrt{P_{tot}}$: τ_{ohmic}=42 ms; τ_{ecrh}=26 ms. Confinement is in very good agreement with L-mode scaling $\tau_{ITER89P}$ (40 ms and 25 ms respectively).

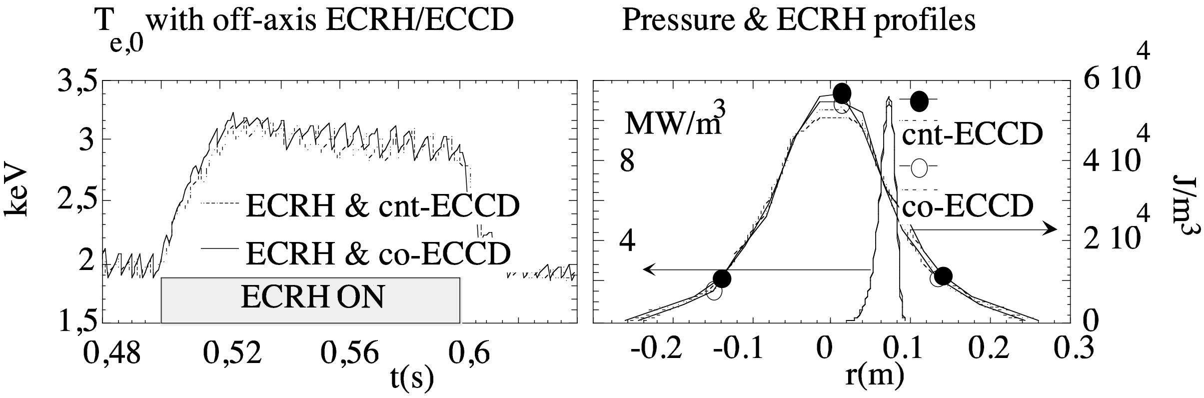

FIG. 6. ECCD is used, by launching at 10° from perpendicular, to enhance the effect of ECRH on J(r) in 350 kA discharges. As expected for off-axis localization of the driven current, the inversion radius is larger (by≈2 cm) and the temperature profiles are broader with co-ECCD than with cnt-ECCD, although the effect is marginal because of the small amount of the current driven (≈8 kA). The power deposition profile for oblique injection is broader than for perpendicular launch; the heating power density, in this case, is not high enough to achieve stabilization.

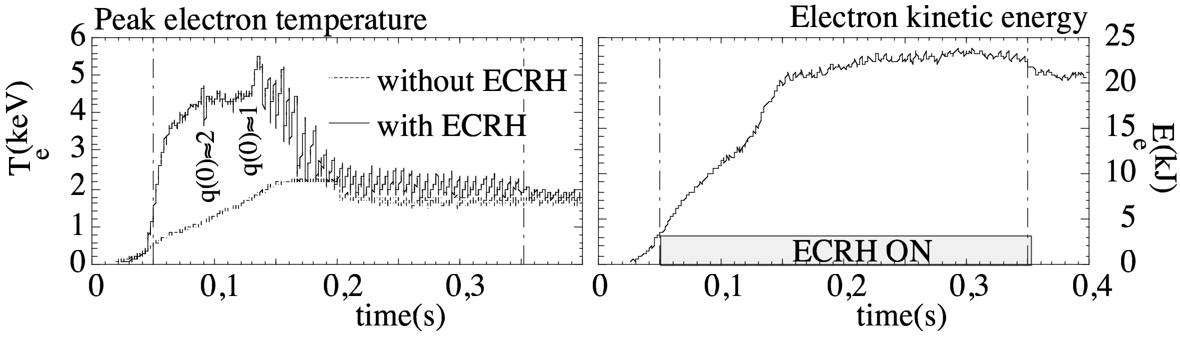

FIG. 7. ECRH&MHD during current ramp-up at 5 MA/s. P_{ecrh}=220 kW, 0.3 s pulse. A transient $T_{e,0}$ rise develops at the appearance of q=2 and q=1 surfaces into the discharge. The peak temperature (but not the total energy content) is dominated by sawteeth.