The stiffness of electron temperature profile in ECRH current ramp-up scenario on FTU


Associazione Euratom-ENEA sulla Fusione, Frascati
*Associazione Euratom-ENEA-CNR, Istituto di Fisica del Plasma, Milano
Introduction (1)

The highly localized ECRH in the current ramp-up phase has produced high electron temperature plasma (15 keV) in the on-axis heating experiments on FTU.

Off–axis ECRH has been used to study the electron energy transport in the ramp-up scenario, characterized by a variety of current density radial profiles \( j(r) \), due to the details the plasma startup, gas feed and impurity content.

Previous analysis have already shown that the electron temperature radial profile \( T_e(r) \) is consistent with standard diffusive transport models in the region where \( j(r) \) is flat or hollow.
Introduction (2)

The focus has now shifted to the experiments with very peaked profiles \( j(r) \) and early onset of sawtooth activity in the pre-ECRH phase.

Off-axis heating of these discharges results in peaked \( T_e(r) \) inside the deposition layer due to a decrease of the electron thermal diffusivity in the plasma core, as shown by the local energy balance.

This experiment can be interpreted as the result of a modification of the electron thermal transport that depends on the proximity to a “critical” gradient, as shown by other recent ECRH experiments both on ASDEX-Upgrade and FTU tokamaks.
Outline

• FTU, diagnostics and analysis tools

• ECRH in the current ramp-up scenario; analysis of two cases for fast and slow ramp-up rate:
  – Global energy balance
  – Local energy balance, temperature and pressure radial scale length
  – Comparison between the two scenarios for similar q profile in the central plasma region.
  – Comparison with temperature and pressure scale lengths characterizing FTU OH plasma

• Conclusions
FTU, diagnostics and Analysis tools (1)

- FTU: R=0.935 m, a=0.3, B_{Tmax}=8T, ECRH experiments B_T~5T.
- Diagnostics:
  - Density profile: inversion of the line averaged densities measured by a 5 chords DCN interferometer.
  - Z effective: visible bremsstrahlung signals.
  - Radiation losses: 12 chords bolometer array.
  - Ion temperature: the computed neutron yield is compared to the experimental value (Deuterium is the working gas)
  - The current density profile is obtained by the solution of the diffusion equation for the magnetic poloidal field, checking that the obtained profiles are consistent with the observed MHD behavior.
  - The ECRH power deposition profile has been computed by means of a ray-tracing code.
FTU, diagnostics and Analysis tools (2)

- **EVITA code**: the plasma energy transport has been evaluated using the EVITA code (Esperimento Virtuale con Toro Assimmetrico) that allows both the interpretative and the predictive time-dependent analysis of a plasma configuration.

- The code solves the diffusion equations for the poloidal magnetic field, the electron and the ion temperatures using the plasma geometry obtained from the equilibrium reconstruction code, based on the magnetic measurements.

- All the code results are stored in form suitable for direct comparison with the experimental results.

- EVITA runs on Alpha workstation with True64 UNIX.

- Information on the code can be found in:
  
  http://efrw01.frascati.enea.it/Software/Unix/FTUcodici/evita/index.html
Fast $I_p$ ramp-up with ECRH: scenario

- Current ramp to 0.7 MA, $\frac{di}{dt} \sim 5$ MA/s
- 140 GHz ECRH, 0.8 MW
- Off-axis heating by tilting ECRH launchers; deposition layer $r_{ecrh} \sim a/4$.
- Weak e-i coupling $T_i \sim 1$ keV.
- $Z_{eff} \sim 7$, High Z impurities.
Fast $I_p$ ramp-up with ECRH: global confinement

- The global energy confinement is close to ITER97L scaling value
- Radiation losses are relevant in the outer part of the discharge
- Total ohmic power is comparable with $P_{ECRH}$

G. Bracco, 43th APS Plasma Physics, Long Beach, California, Oct.28-Nov.2, 2001
Fast $I_p$ ramp-up with ECRH: $T_e$ evolution

- Peaked pre-ECRH $T_e$ and current profiles: sawtooth activity starts in the early phase of the discharge
- A sawtooth activity with a narrow reconnection radius is present during the high $T_e$ phase

At $t=0.163$ s a sawtooth with a large reconnection radius terminates the high $T_e$ phase

G. Bracco, 43rd APS Plasma Physics, Long Beach, California, Oct.28-Nov.2, 2001
Fast $I_p$ ramp-up with ECRH: local transport analysis (1)

The time slices correspond to the colored arrows in the previous slide.

$\chi_e$ decreases inside the power deposition radius. The low $\chi_e$ region becomes wider with the widening of the $1<q<2$ region.

$q$ profile evolution is compatible with the detail of the sawtooth activity behavior.
Fast $I_p$ ramp-up with ECRH: local energy balance (2)
Fast $I_p$ ramp-up with ECRH: local energy balance (3)

- At the ECRH switch-on $T_e(r)$ becomes steeper outside the deposition layer $r_{ECRH}$ and flatter inside, as shown by $T_e / T_e(0)$ and $1/L_T$ plots.
- $\chi_e$ value decreases inside and increases outside $r_{ECRH}$.
- As the current profile becomes wider with the current ramp-up the region with low $\chi_e$ values becomes wider and the decrease of $\chi_e$ involves also a region outside $r_{ECRH}$. $1/L_T$ is in the range 15-20 m$^{-1}$ in these conditions.
- Qualitatively this corresponds also to a decrease of the s/q parameter; magnetic shear is lower than 1 in the region of low $\chi_e$ values.
- The analysis of the region inside $r_{ECRH}$ shows that no heat pinch term is required to explain the power balance ($\chi_e$ is small but >0) so that the peaking of $T_e(r)$ is due to the combined effect of the low $\chi_e$ value and the residual OH heating.
Slow $I_p$ ramp-up with ECRH: scenario

- Slow current ramp at $dI/dt \sim 1$ MA/s (fast ramp-up case $\sim 5$ MA/s)

- 140 GHz ECRH, 0.7 MW off-axis heating ($r_{ecrh} \sim a/3$) by tilting ECRH launchers: the deposition layer is more external than in the fast ramp case ($r_{ecrh} \sim a/4$) to avoid DTM reconnection at $q=2$

- $T_i$ and $Z_{\text{eff}}$ are similar to the fast $I_p$ ramp scenario
Slow $I_p$ ramp-up with ECRH: global confinement

- The global energy confinement is near to ITER97L scaling value as in the fast ramp-up scenario. The experimental values are closer in this case to RLW scaling which has a lower current dependence.
Slow $I_p$ ramp-up with ECRH: $T_e$ evolution

- Peaked pre-ECRH $T_e$ and current profiles
- The sawtooth activity starts at $t=0.145$ s
The time slices are marked by colored arrows in the previous slide.

\( \chi_e \) decreases only inside the power deposition radius.

q profile evolution is compatible with the detail of the MHD behavior: the value of \( q(0) \) attains 1 at \( t=0.140 \) s about at the onset of the sawtooth activity.
Slow $I_p$ ramp-up with ECRH: local transport analysis (2)

$T_e$, $\chi_e$, $1/L_T$, $s$, $s/q$ vs. $r$ with different time markers.

$T_e$, $r_{ECRH}$, and $T_e/T_e(0)$ at 0.140 s, 0.055 s, and 0.047 s.

$\chi_e$ and $1/L_T$ with OH markers.

$s$ and $s/q$ with OH markers.

G. Bracco, 43th APS Plasma Physics, Long Beach, California, Oct.28-Nov.2, 2001
In the slow current ramp-up scenario the value of $\chi_e$ inside the deposition region decreases at the switch-on of the ECRH as in the fast ramp-up experiment. Also in this case no inward punch term is required too explain the local power balance.

The main difference between the two scenarios is that in the case of the slow ramp-up the region of reduced $\chi_e$ is limited by the ECRH deposition region.

$1/L_T$ is in the range 10-12 m$^{-1}$, lower than in the fast ramp-up case.
Fast/slow $I_p$ ramp-up: comparison at equal central $q(r)$ (1)

The fast (15027) and slow (15124) $I_p$ ramp-up discharges have a similar $q$ profile in the plasma core ($r<a/2$) at different times:

- 15027 $t=0.090$ s
- 15124 $t=0.150$ s

Density values are similar but the density profile is more peaked in the slow ramp-up case. Temperature is substantially higher in the fast ramp-up case.
Fast/slow $I_p$ ramp-up: comparison at equal central $q(r)$ (2)

Local energy balance results are compared for pulses 15027 $t=0.090$ s and 15124 $t=0.150$ s at similar values of $q(r)$ in the core region:

- for $r<a/3$, $\chi_e$ seems to scale as $T_e^{3/2}$.
- $1/L_T$ is higher for the fast ramp-up case (15027).
- the pressure scale length, $1/L_p$, is more similar ($n_e(r)$ is more peaked for the slow ramp-up case, 15124).
In OH discharges the temperature and pressure scale lengths have a density dependence similar to $Z_{\text{eff}}$ and $T_e(0)/T_i(0)$.

For ECRH heated plasma in the fast $I_p$ ramp-up scenario $1/L_T$ values are in the range $20\div30$ m$^{-1}$ at $\langle n_l \rangle \sim 4\div6 \times 10^{19}$ m$^{-3}$. The highest values are obtained with on-axis ECRH.
Conclusions (1)

- In some cases off-axis ECRH in current-ramp-up scenario produces quasi stationary plasma conditions with very reduced MHD activity providing a good set of experimental data for the understanding of plasma energy transport.

- In the reported experiments the main sign of the stiffness of the electron temperature profile is the abrupt change in the $\chi_e$ value at radial position of the deposition layer: it decreases inside towards the plasma core and increases outside, indicating the proximity to a critical gradient.

- The residual OH heating in the low $\chi_e$ region of the plasma core can sustain peaked $T_e$ profile during the off-axis ECRH heating and in the reported experiments the local analysis does not require the introduction of an inward heat pinch term to match the power balance.
Conclusions (2)

- Qualitatively the critical gradient appears to be higher in the region of low magnetic shear but the understanding of its parametric dependencies is usually made more difficult by the very transient conditions of the current-ramp up scenario where several parameters changes at the same time.

- An attempt has been made to look for situations with similar q profile and density in the plasma core but with different temperature profile: $\chi_e$ seems to scale simply as $T^{3/2}$ and the temperature scale length $L_T$ is different, suggesting that the critical temperature gradient is different between the two cases. Due to differences in the density profile, the pressure scale length $L_P$ is more similar than $L_T$ between the two cases, suggesting that the marginality could be related to the pressure profile. A similar argument can also be used in comparison with OH database.