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The effect of transient density profile shaping on transport in large stellarators and heliotrons

A. Dinklage[1], R. Sakamoto[2], M. Yokoyama[2], K. Ida[2], J. Baldzuhn[1], C.D. Beidler[1], S. Cats[3], K. Mc Carthy[4], J. Geiger[1], M. Kobayashi[2], H. Maaßberg[1], S. Morita[2], G. Motojima[2], M. Nakata[2], M. Numami[2], N. Pablant[5], K.Ogawa[2], J.H.E. Proll[1], S. Satake[2], K. Tanaka[2], F. Warmer[1], R. Wolf[1], P. Xanthopoulos[1], H. Yamada[2], R. Yasuhara[2], M. Yoshinuma[2] and the LHD Experiment Team[2]

[1]Max-Planck-Institut für Plasmaphysik, Greifswald, *Germany*
[2]National Insitute for Fusion Science, Toki, *Japan*
[3]Technical University Eindhoven, Eindhoven, *The Netherlands*
[4]CIEMAT, Madrid, *Spain*
[5]Princeton Plasma Physics Laboratory, Princeton, NJ, *USA*

Summary:

Transport studies of pellet fuelling experiments on LHD are reported. Spatio-temporal evolutions after pellet injection into LHD discharges show cases with central density increase on the time scale of particle transport processes. Both the temperature gradient and the density gradient change during the density relaxation, the latter even in sign. The resulting thermodynamic forces influence radial electric fields - both as a driving term but also by, e.g., affecting the E_r dependence of ion transport.

Central fuelling has been observed in response to diffusive particle transport after pellet deposition in the periphery of the confinement volume. The initially (after pellet injection) very hollow density profile also results in marginally unstable pressure profiles and correlated fluctuations were observed. A response in the radial electric field was observed but not the change in sign as predicted from local neoclassical theory. The attained conditions represent an experimental case to further assess the role of non-local radial coupling in neoclassical transport and – at the same time – to study the impact of the ratio of temperature and density gradients on turbulent mechanisms.

Motivation:

- scenario development for reactor grade helical plasmas: fuelling
- compensation of large neoclassical thermodiffusion: mitigation of problems with density control in ECRH heated plasmas (e.g. W7-X)
- contribution to the understanding of pellet fueling in helical systems
- case for oppositely pointing thermodynamic forces: effect on neoclassical and turbulent transport mechanisms

Experiments on LHD (see also [1])

- Inward shifted magnetic configuration, NI heating
- single pellet injected
- measurements of transport relevant quantities

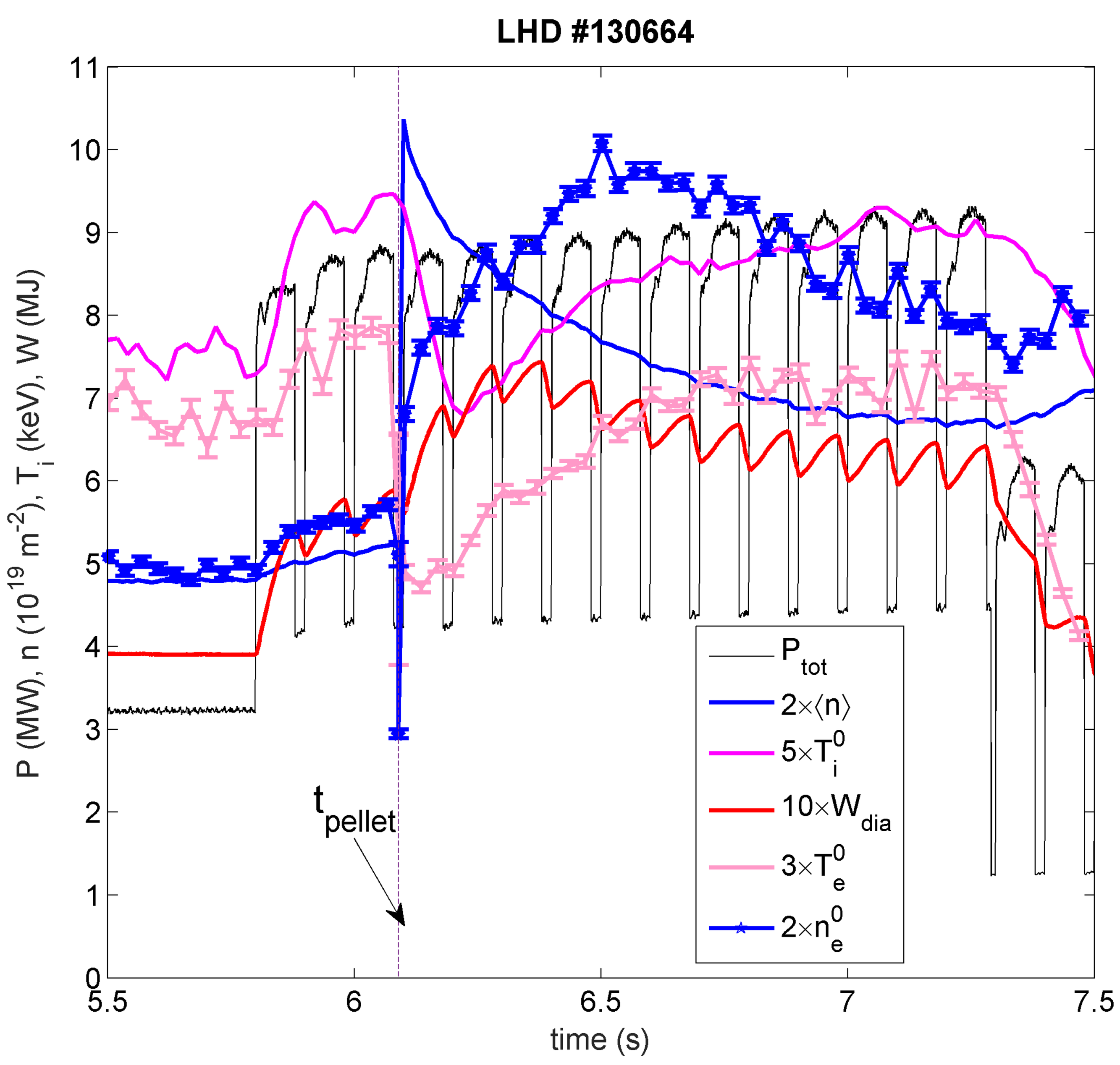

Fig. 1: Waveforms of heating power, mean density, central density, central ion- and electron temperature and diamagnetic energy in a pellet injection discharge. The pellet injection time is indicated at t = 6.079 s). The data are scaled.

Plasma response – two phases

1) Adiabatic release of particles ↗
2) Profile relaxation with central fueling (τ_P) ↗

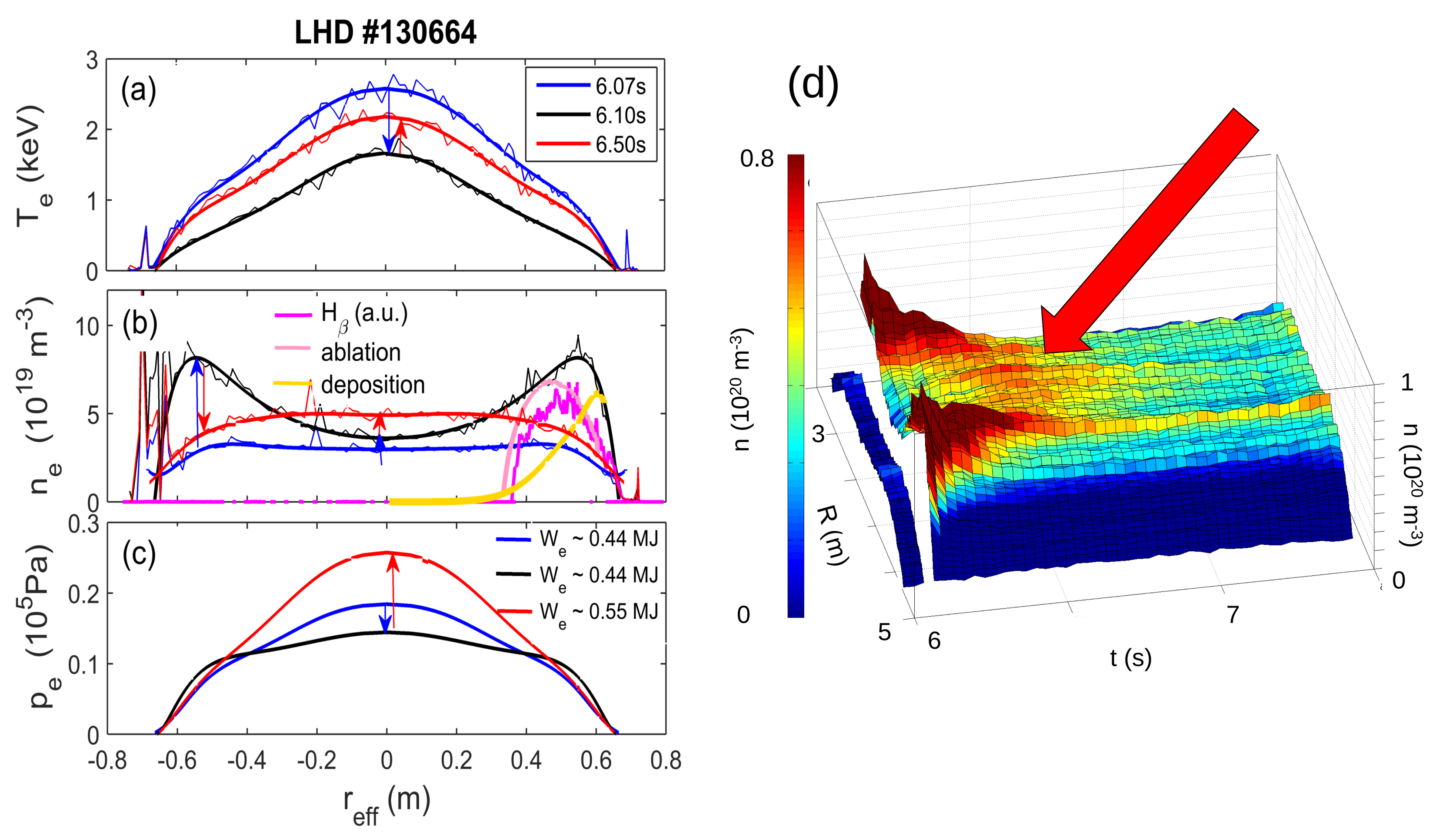

Fig. 2: Electron temperature (a), electron density and pellet ablation signals and deposition calculations (b) and electron pressure before pellet ablation and about 23 ms after pellet injection (6.079 s). Right plot (d): Density profile evolution showing central core fuelling.

Observation of fluctuations in magnetic signals

E.g. destabilization of resistive interchange modes

$$p'V''-\left\langle j_\perp^2\right\rangle-\left\langle j_\parallel^2\right\rangle<0$$

But configuration has global magnetic hill.

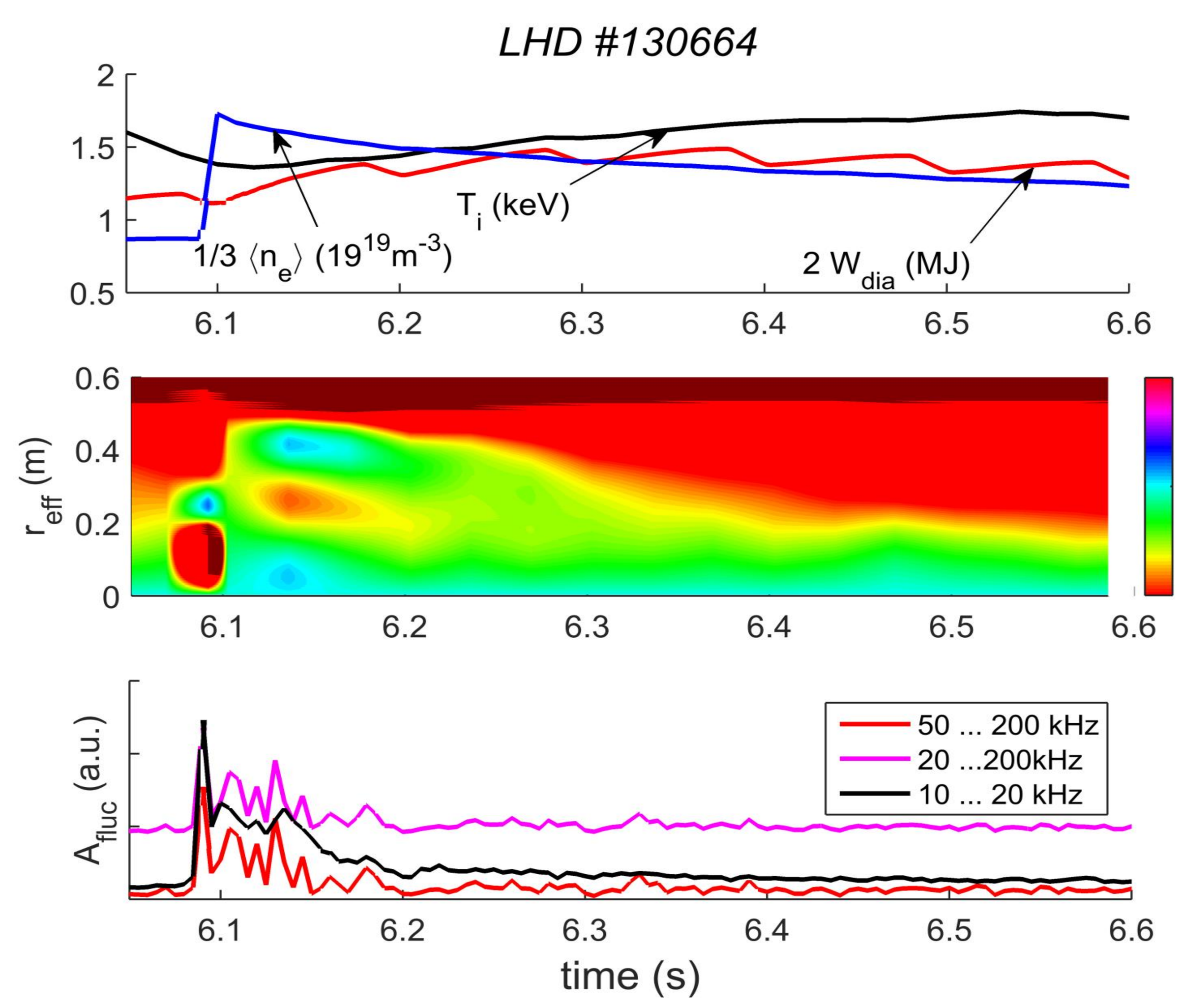

Fig. 3: Density, ion temperature and diamagnetic energy evolution (top plot) along with spatio-temporal evolution of inverse electron pressure gradient length (second plot from top). The third plot shows fluctuation levels in frequency ranges as indicated (from Mirnov data).

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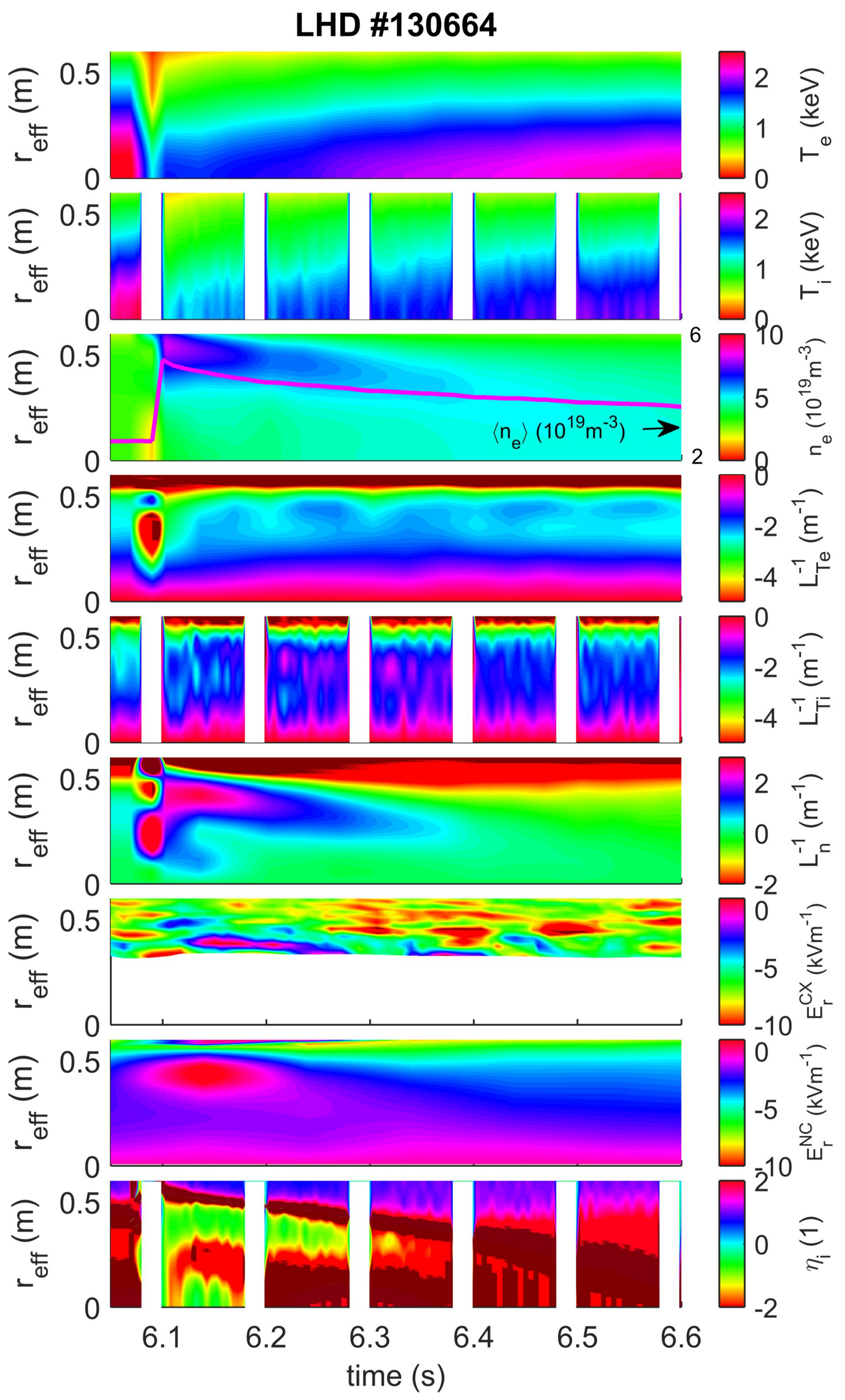

Fig. 4: Spatio-temporal evolution electron temperature (T_e), ion temperature T_i, electron density n_e, respective gradient lengths (L^{-1}), measured radial electric field ($E^{CX}r$), the radial electric field from GSRAKE calculations (E^{NC}_r).

Radial electric fields:

$$E_r > 0: \quad L^{-1}_{n_\alpha} > -\frac{D^i_{12}}{D^i_{11}} L^{-1}_{T_\alpha} \qquad \left(\text{ion root}\,(\sqrt{\nu}): \frac{D^i_{12}}{D^i_{11}} = \frac{5}{4}\right)$$ [2]

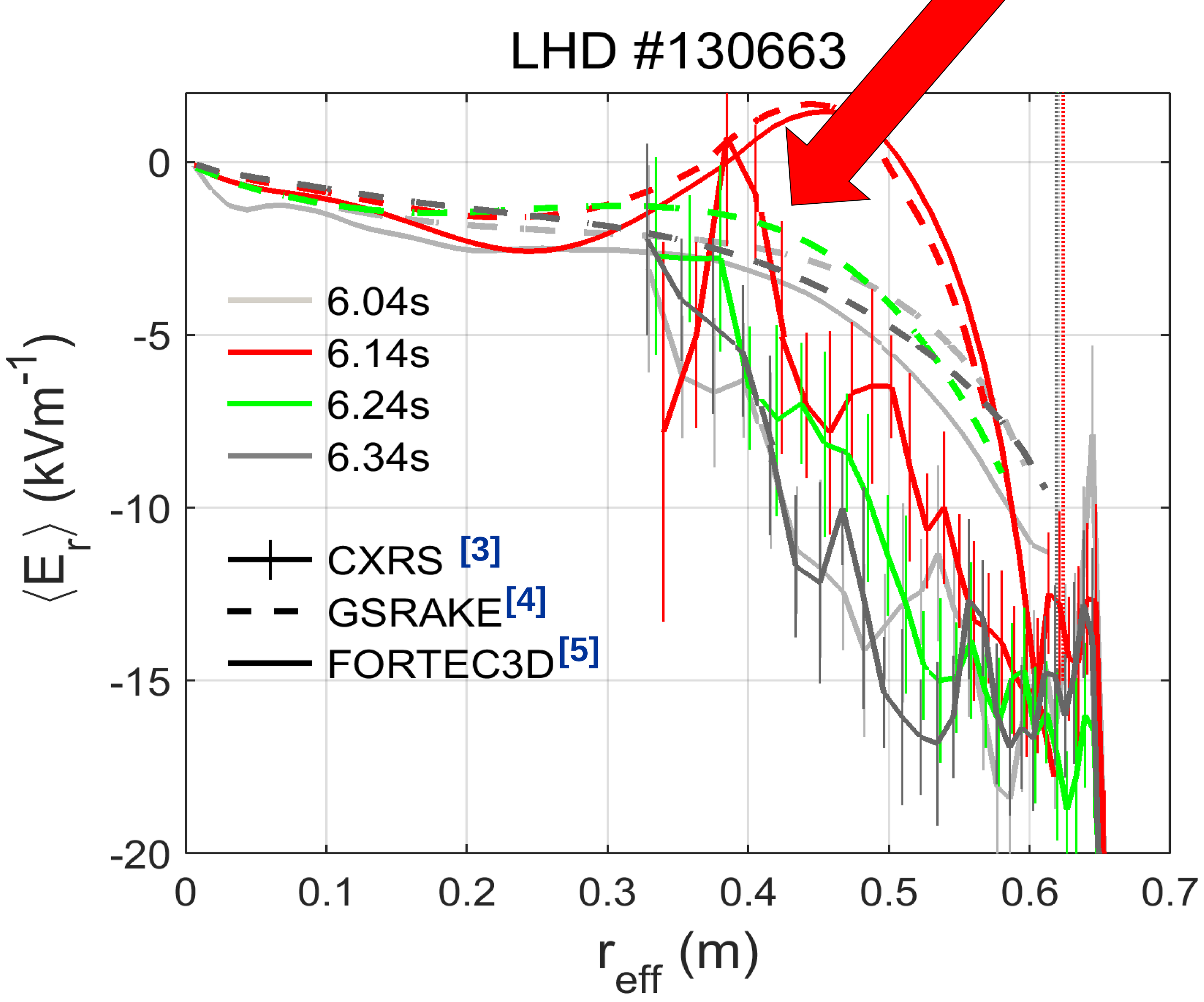

Fig.5: Measurements of the radial electric field with charge exchange recombination spectroscopy (lines with error bars ±25ms averaging) and calculations of the radial electric field from temperature and density profiles. The pellets were injected at t = 6.079 s, respectively. Parameters as for #130664.

Transport Analysis: The spatio-temporal measurements relevant to determine thermodynamic forces allow a comparison to local neoclassical theory. Neoclassical particle fluxes are not intrinsically ambipolar in helical devices and radial electric fields must arise to meet with the ambipolarity condition

$$\Gamma_e = Z\,\Gamma_i$$

In local neoclassical theory (e.g. [2]), the particle fluxes and energy fluxes of species are related to the inverse gradient lengths of densities and temperatures and the radial electric field:

$$\Gamma_\alpha = -n_\alpha \left[D^\alpha_{11}\left(L^{-1}_{n_\alpha} - \frac{q_\alpha}{T_\alpha} E_r \right) + D^\alpha_{12} L^{-1}_{T_\alpha} \right]$$

$$Q_\alpha = -n_\alpha T_\alpha \left[D^\alpha_{21}\left(L^{-1}_{n_\alpha} - \frac{q_\alpha}{T_\alpha} E_r \right) + D^\alpha_{22} L^{-1}_{T_\alpha} \right]$$

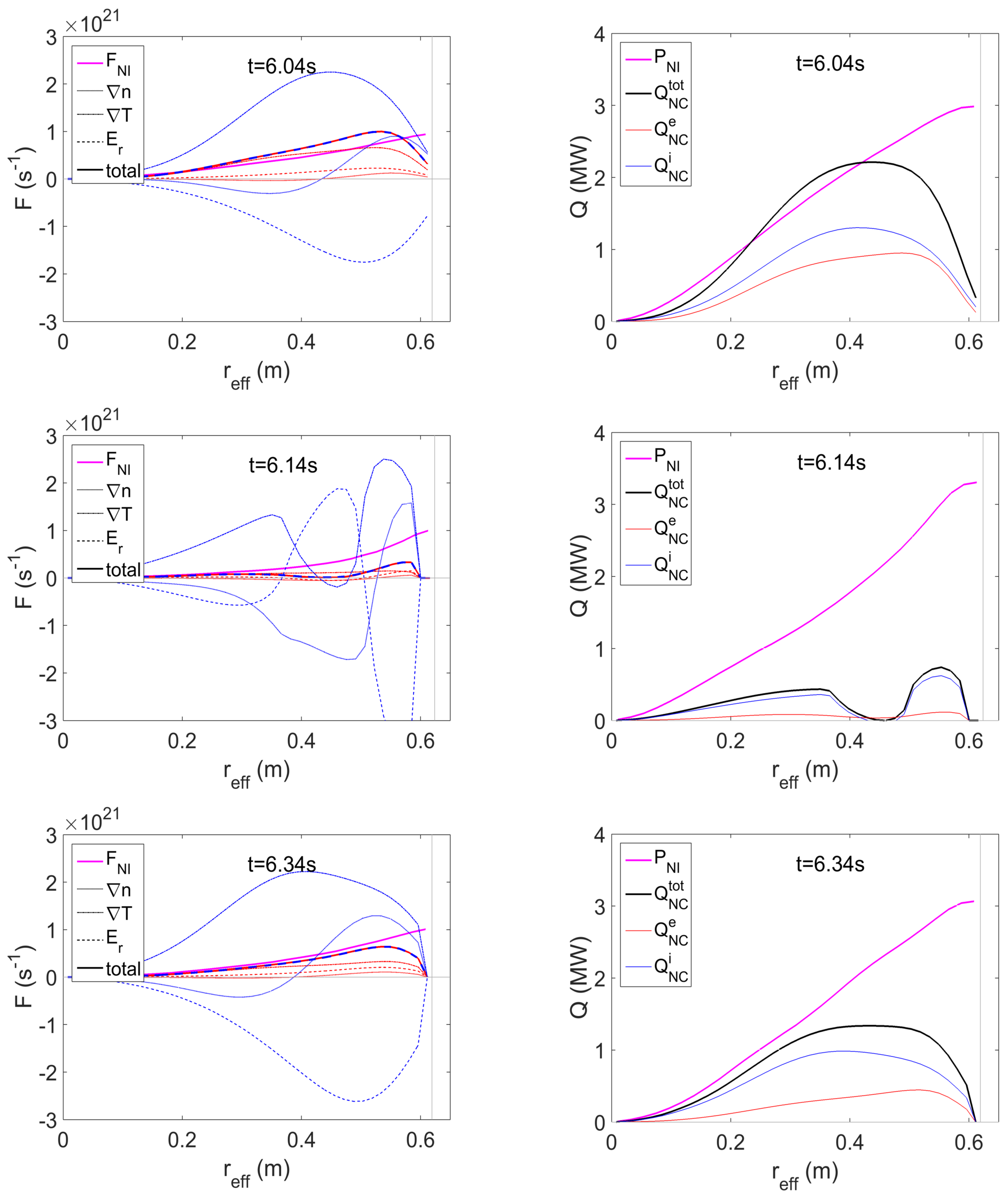

Fig. 6: Neoclassical particle (first column) and energy fluxes (second column) in comparison to power deposition calculations for t=6.04, 6.14 and 6.34 s in discharge LHD #130664. Red lines refer to electrons, blue lines to ions. Calculations with TASK3D [6]

Main findings:

- Fluxes are not described by NC calculations for times directly after pellet injection.
- Stationary cases or slowly changing evolution show particle fluxes to match with NC calculations to about ¾ of the minor radius, energy fluxes (Q+FT) to about ½ of the minor radius.
- Radial electric field measurements show similar profile shapes but are significantly more negative than the NC ambipolar field. A positive ion-root was not found but a response of E_r at times of highest density gradients.

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