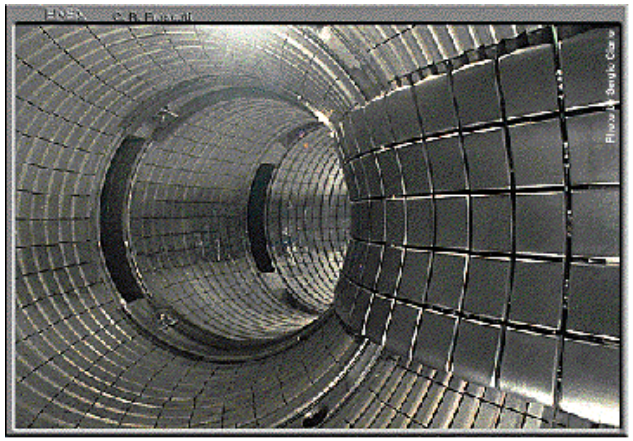
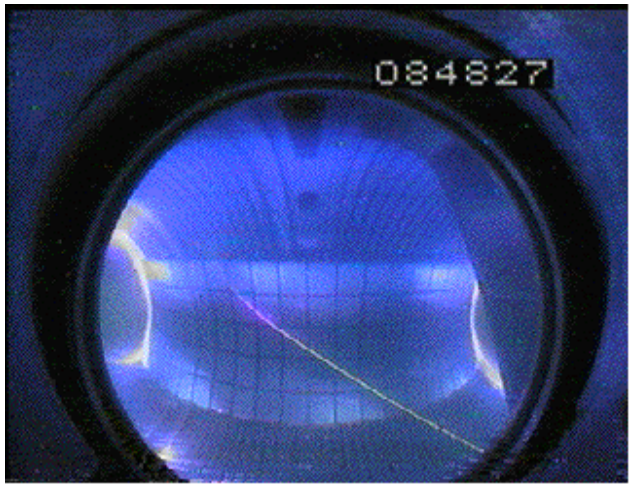
OVERVIEW OF THE FTU RESULTS by C. Gormezano

on behalf of the FTU and the ECRH teams

EURATOM/ENEA Frascati, Italy





Compact all metallic device (circular)

R=0.93m, a=0.3m, $B_t \leq 8T$, $I_p \leq 1.6MA$

LHCD P≤2 MW f=8 GHz

ECRH P≤1.5MW f=140 GHz

IBW P≤0.5MW f=433 MHz

Aims: develop ITER-relevant (in particular ITER-like magnetic field and density)

- Techniques
- Advanced Tokamak scenarios
- Physics issues

New hardware since last IAEA

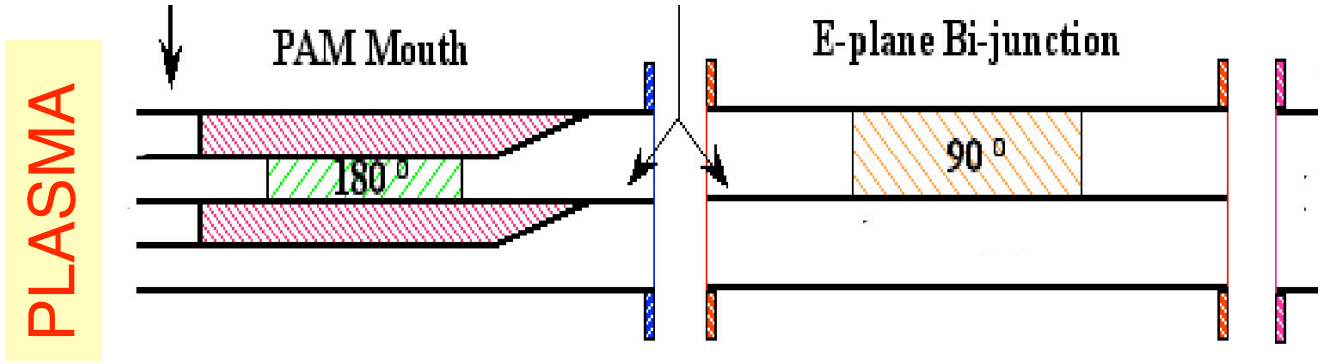
- Prototype LHCD launcher for ITER
- ECRH system up to nominal performance (1.5MW coupled to plasma)
- High Field Side vertical pellet injector
- Diagnostics
  - Fast Electrons Bremsstrahlung cameras (20-200 keV X-rays)
    - Spatial localisation of energetic electrons induced by LHCD
  - Fast scanning interferometer (<0.01ms) for density profiles (40 radial points)

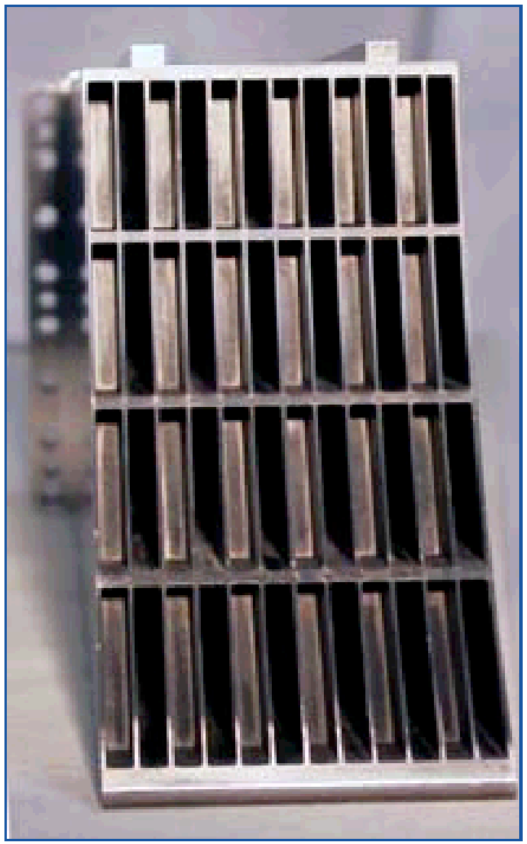
Test of an ITER-relevant LHCD launcher

LHCD launcher compatible with ITER demands:

- operation in the full shadow of the vessel port
- withstanding high level of radiation and neutron fluxes
  - Passive Active Multijunction (PAM)

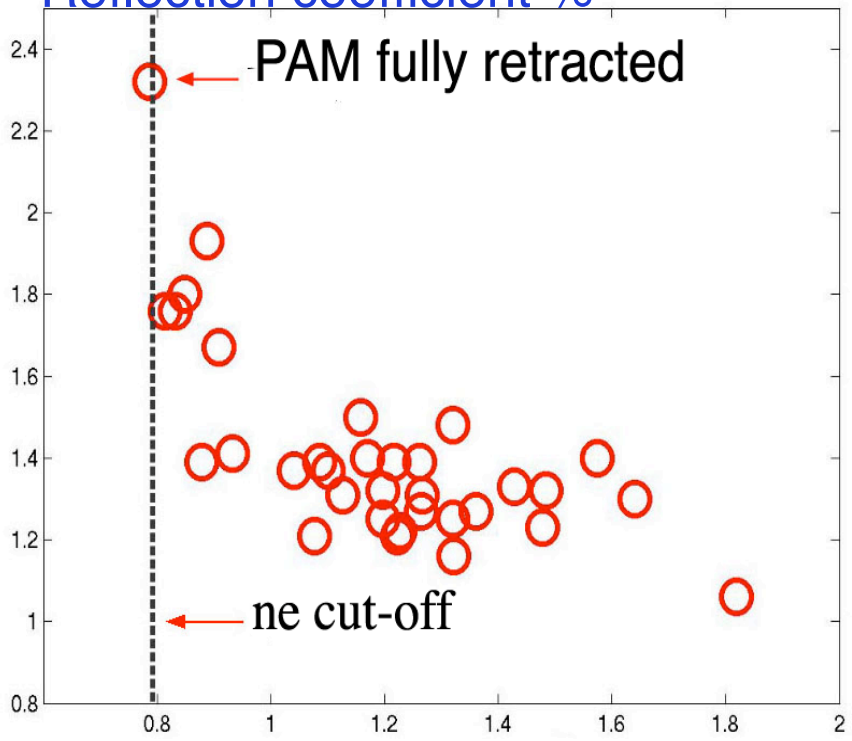
one passive waveguide between each active waveguide allowing cooling to be installed





PAM: good coupling, power handling and CD efficiency

Reflection coefficient %

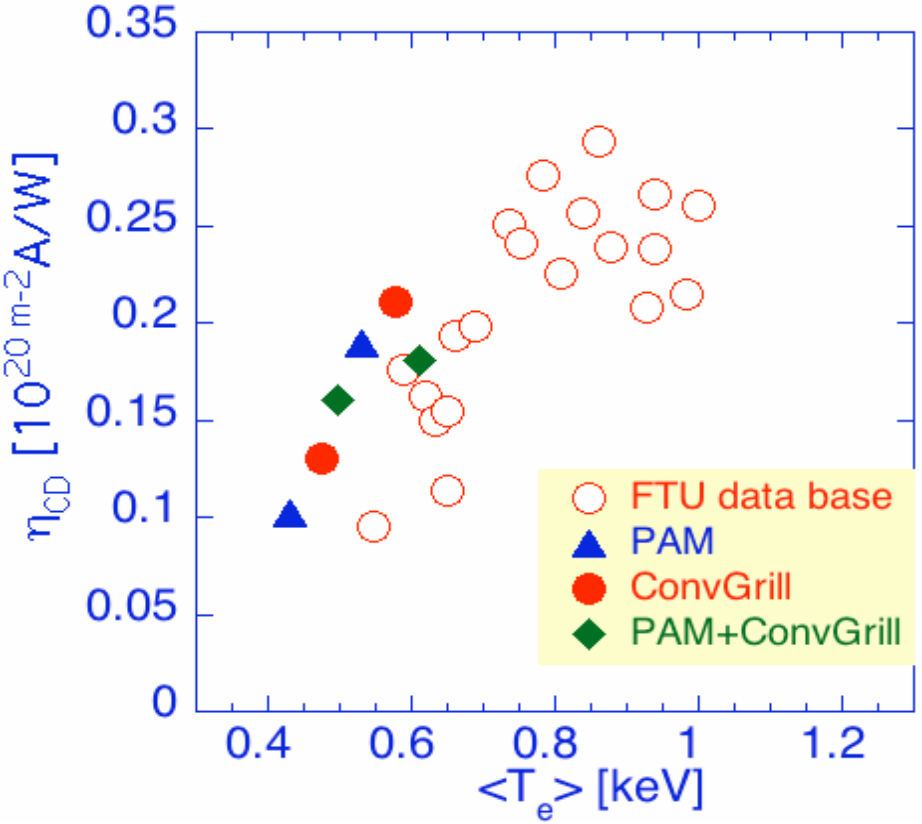


density at grill mouth $10^{18} m^{-3}$

- Power density equivalent to 1.5 ITER power density ($33 MW/m^2$)

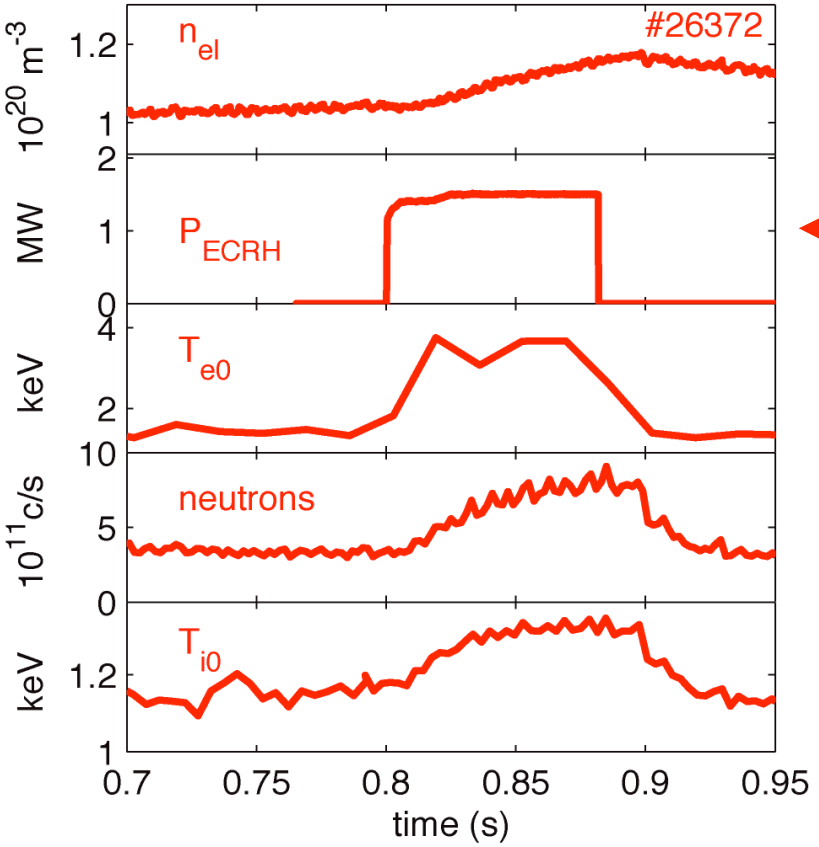
Current drive efficiency of PAM and conventional grill assessed at low power (1 module out of 6)

→ lower $<T_e>$

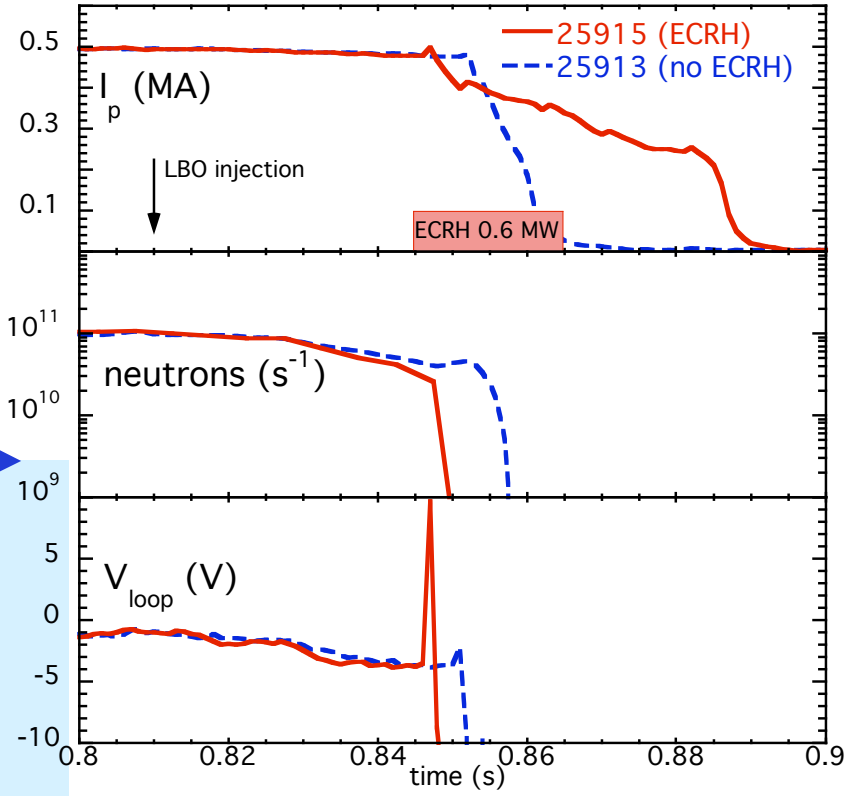


Pericoli EX/5-5

ECRH used for H&CD, MHD control, transport studies…



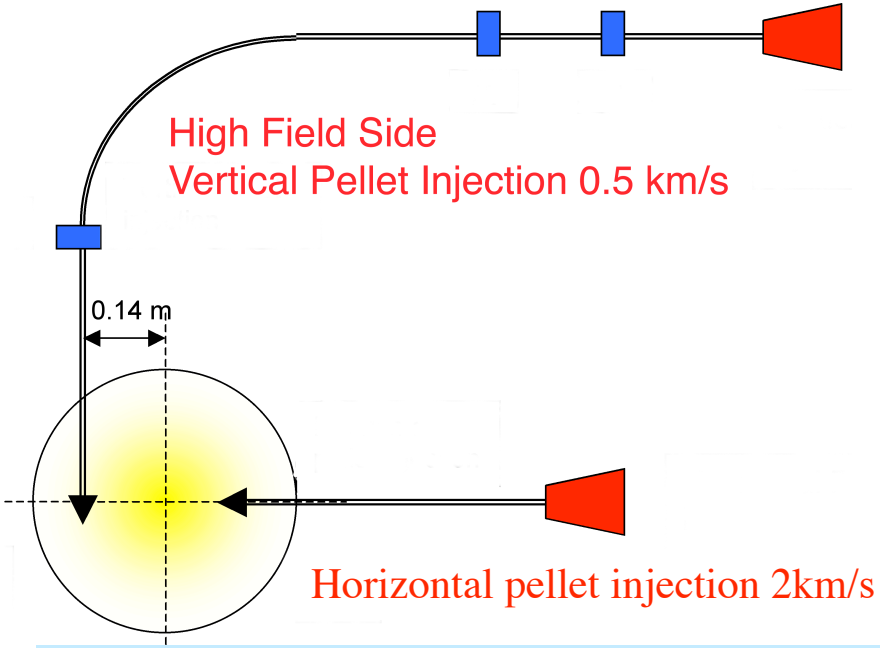
With 1.5 MW at $n_{e0}=1.6 10^{20} m^{-3}$
Te goes from 1.8 to 4keV
Neutron rate multiplied by ~3
$\Delta T_i/T_i=25\%$



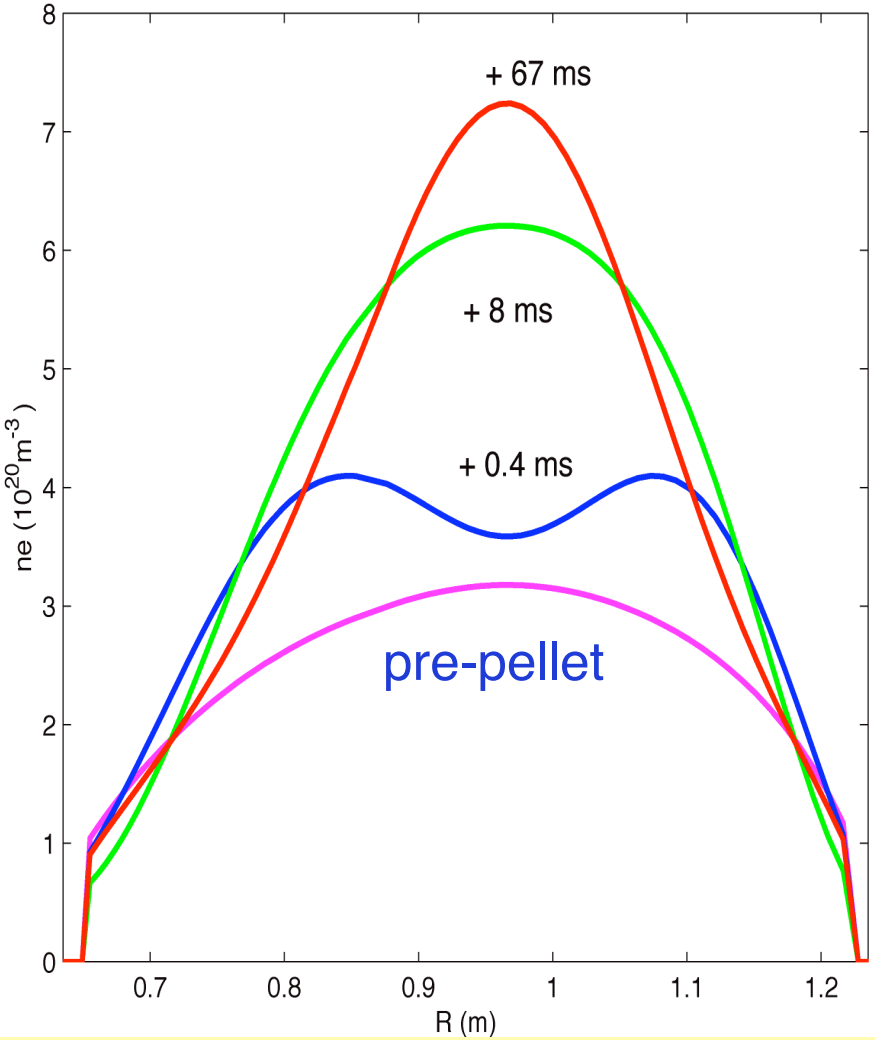
Mitigation of disruptions by changing resistivity with on-axis EC heating

- Disruptions generated by LBO
- $P_{EC}=35\%P_{OH}$ sufficient to soften current decay
- Feedback using $d(V_{loop})/dt$ is being prepared

Peaked density profiles achieved with HFS vert. injection



magnetic reconnection mixes plasma center with q=1 pellet fuelled region for t > 0.4s



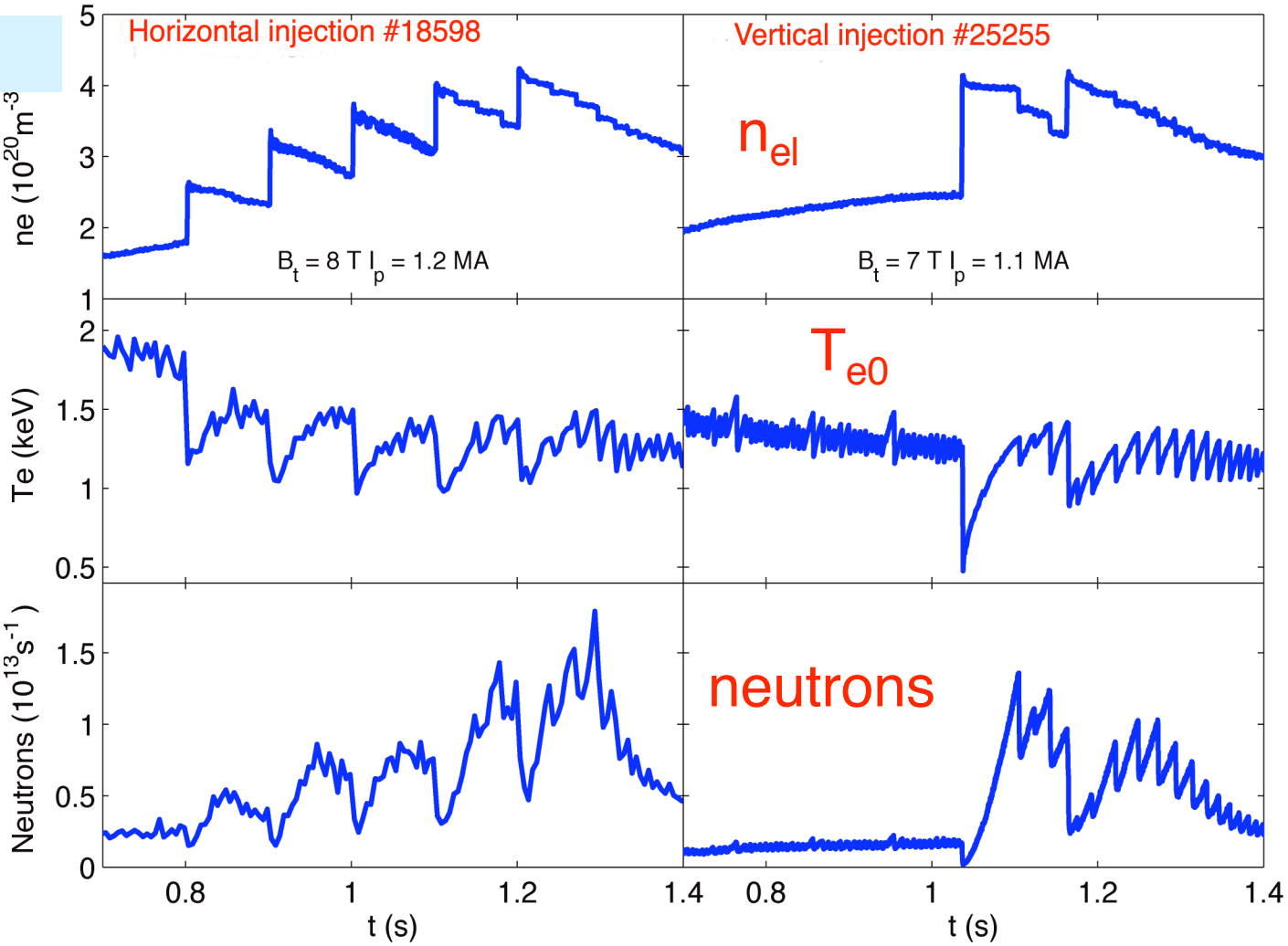
profiles remain peaked for 60ms, stopped by mild sawtooth activity

Giovannozzi EX/P4-4

Repetitive PEPs similar for vertical and horizontal pellets

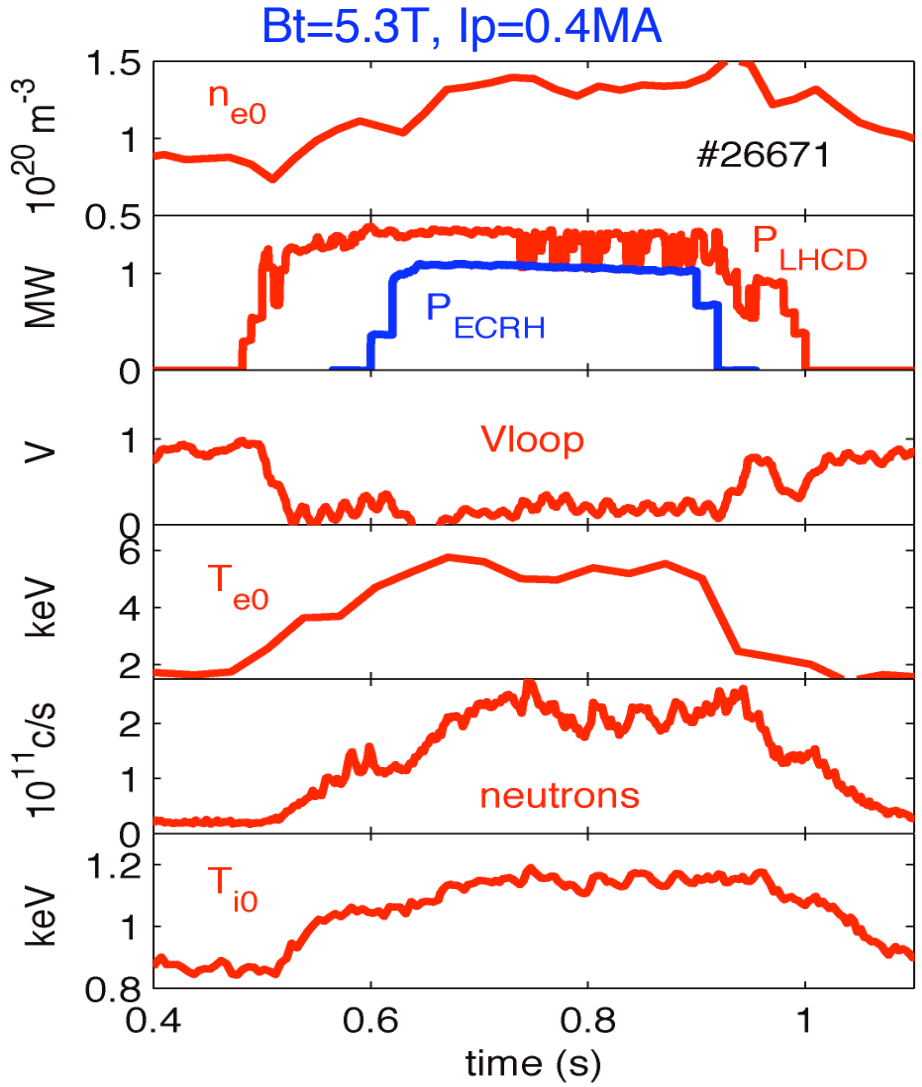
Ip=1.1MA Bt=7.2T

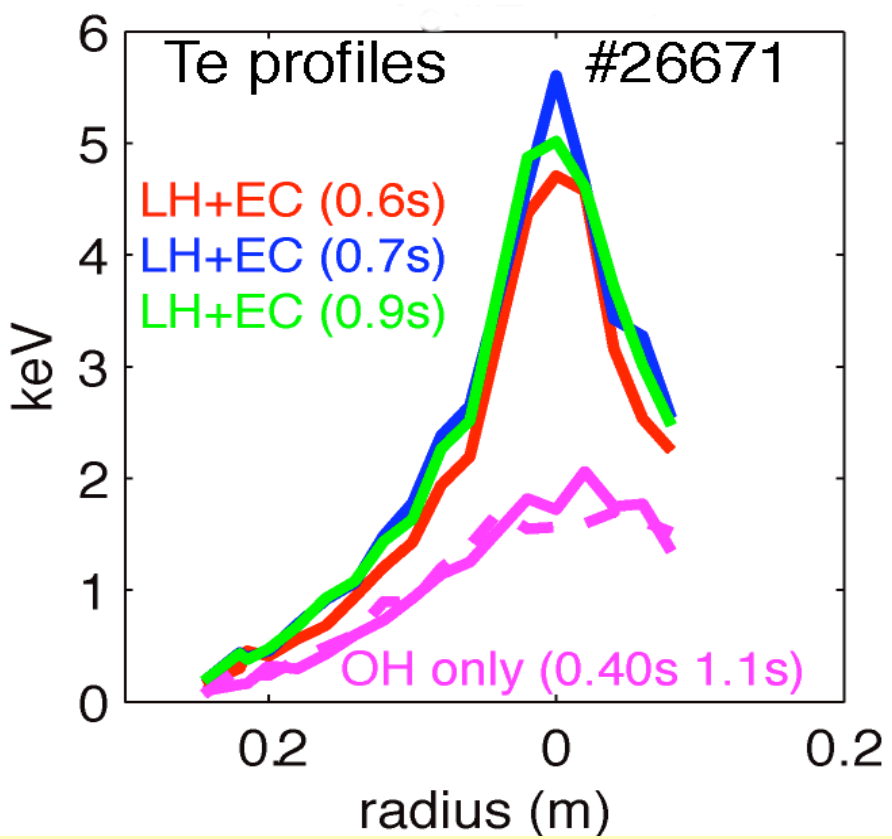
in FTU record neutron yield (and $n\tau_E T_i$: $0.8\times10^{20}m^{-3}$ keV/s)



"magnetic" reconnection could ease the demand on pellets in burning plasmas: reaching q=1 sufficient to fuel plasma center ?

Steady e-ITBs maintained for n_{e0} up to $1.4\times10^{20}m^{-3}$



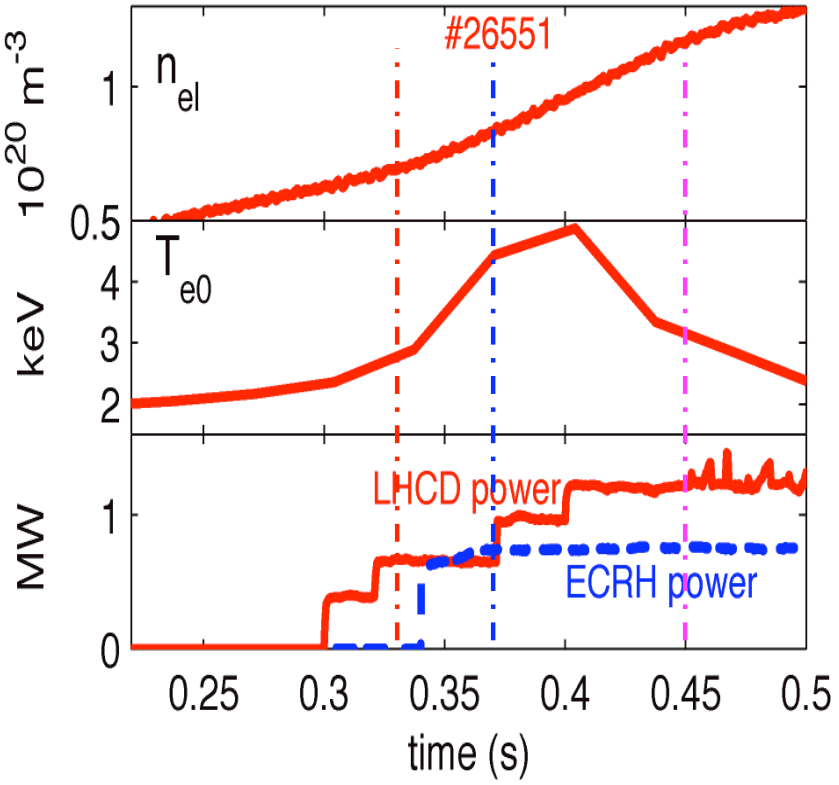


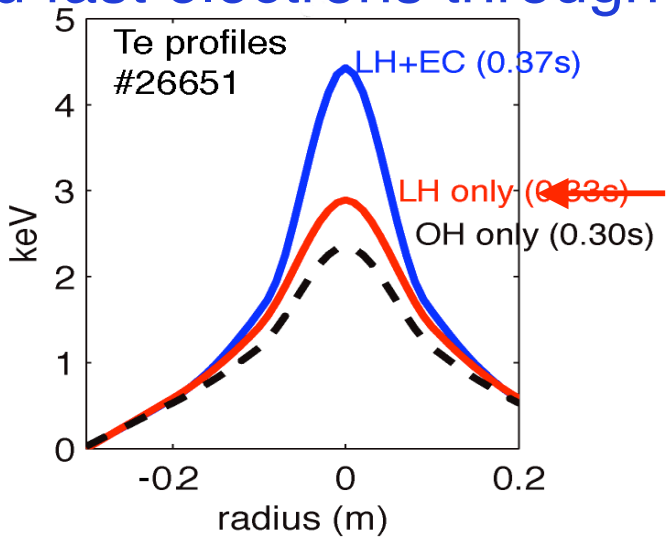
ITBs (from $\nabla T_e/T_e$) produced within r/a=0.3, Turbulence (reflectometry) strongly reduced

- Significant ion heating from electron-ion collisions: $\Delta T_i/T_i$= 35% without degrading electron ITBs

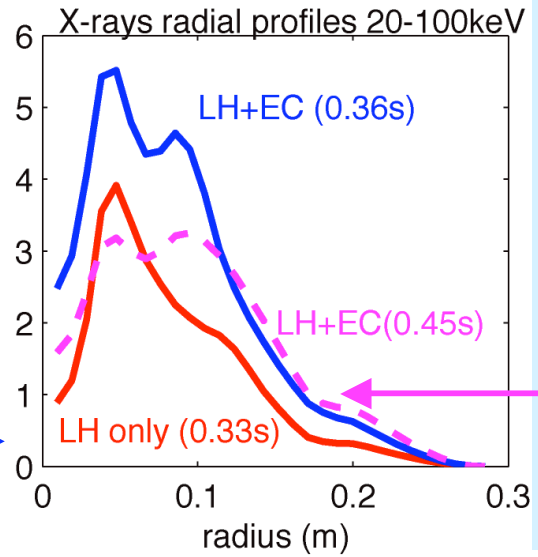
Synergy between LHCD+ECRH:ITB triggered at Bt=7.2T

- at 7.2T, 5.3T "cold" resonance outside plasma: EC waves absorbed by LHCD induced fast electrons through Doppler shift





ITB triggered by LH +down-shifted EC

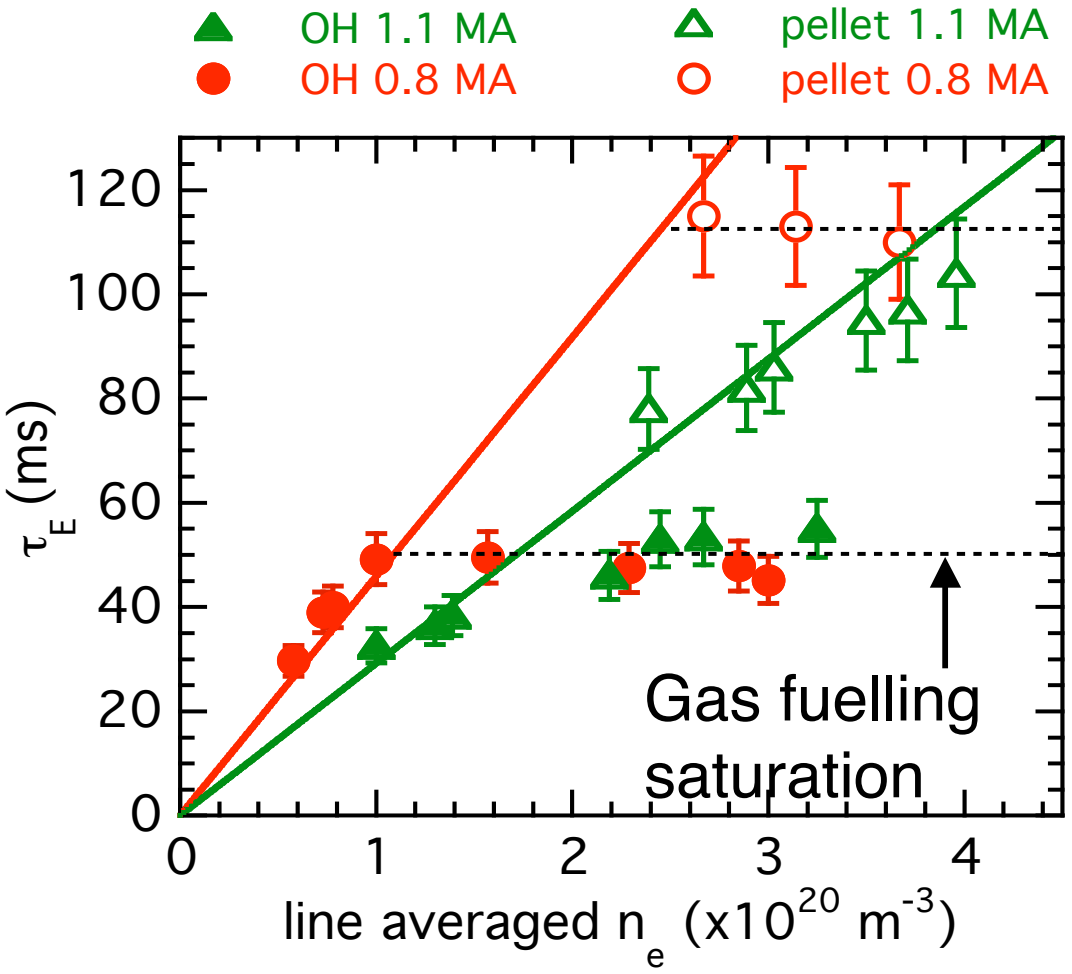


Radial inverted X-ray profiles (20-100keV)

At t >0.4s, P_{LHCD} not high enough to provide large electron tails: synergy with EC waves disappears

Transport: τ_E increases with peaked density profiles

- FTU transport data base: H_{97} up to 1.6 for e-ITBs (steady) and 1.3 for PEPs (transient)

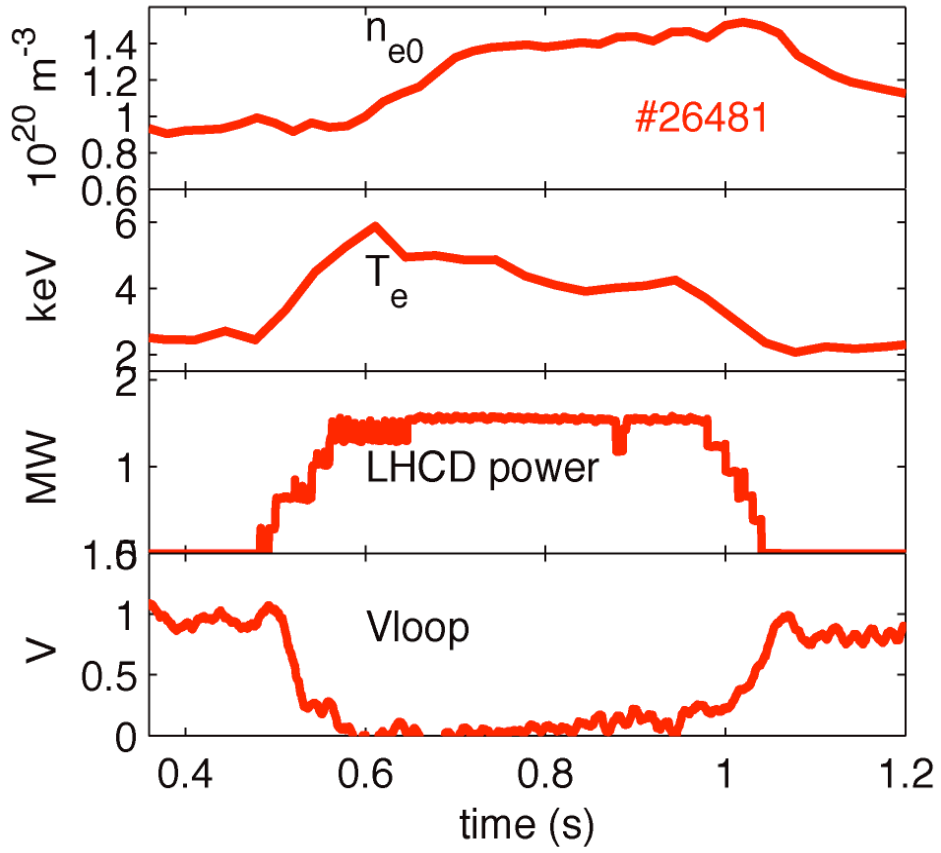


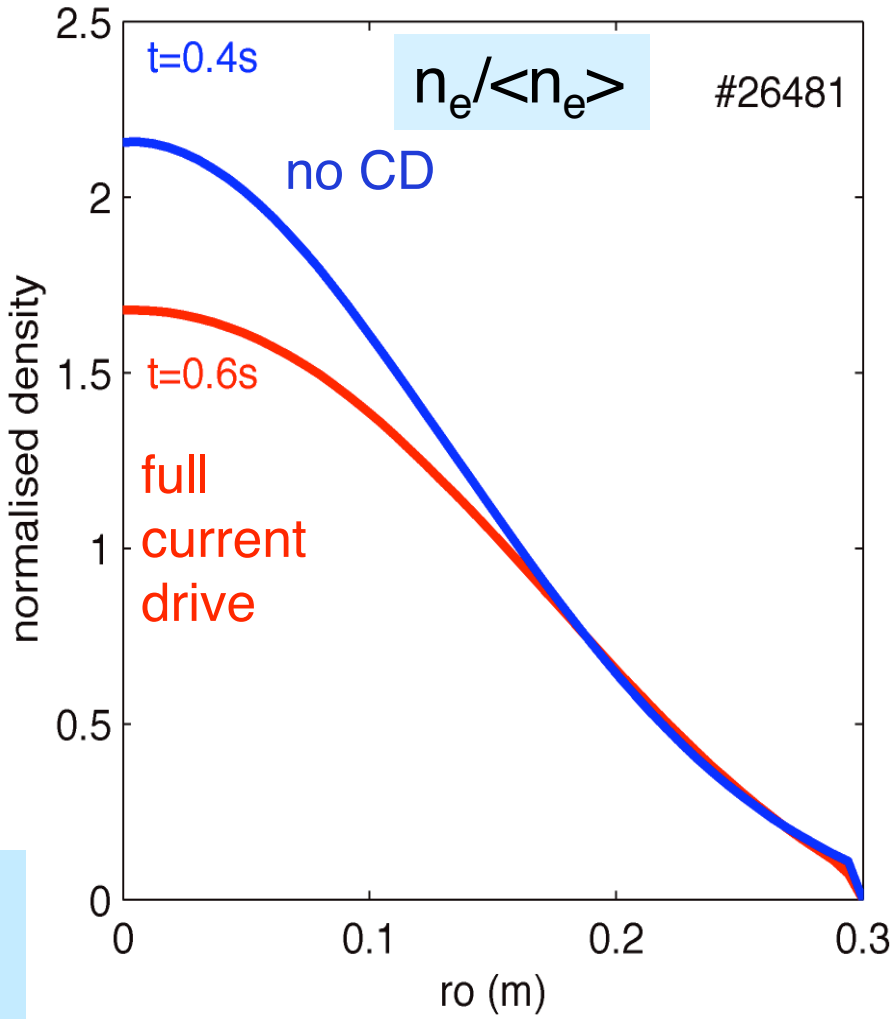
- Saturation of τ_E in gas-fuelled plasmas removed in pellet-fuelled plasmas with peaked density profiles (Te=Ti)
- τ_E seems to saturate when electron losses are dominant once ion losses are neo-classical

Particle pinch at high density *in collaboration with Tore Supra*

$$\Gamma = -D\,[\nabla n + C_q\,\nabla q/q\; n - C_T\,\nabla T_e/T_e\; n] + V_{Ware} n$$

Ware pinch negligible when $E_{//}=0$ ➔ full current drive



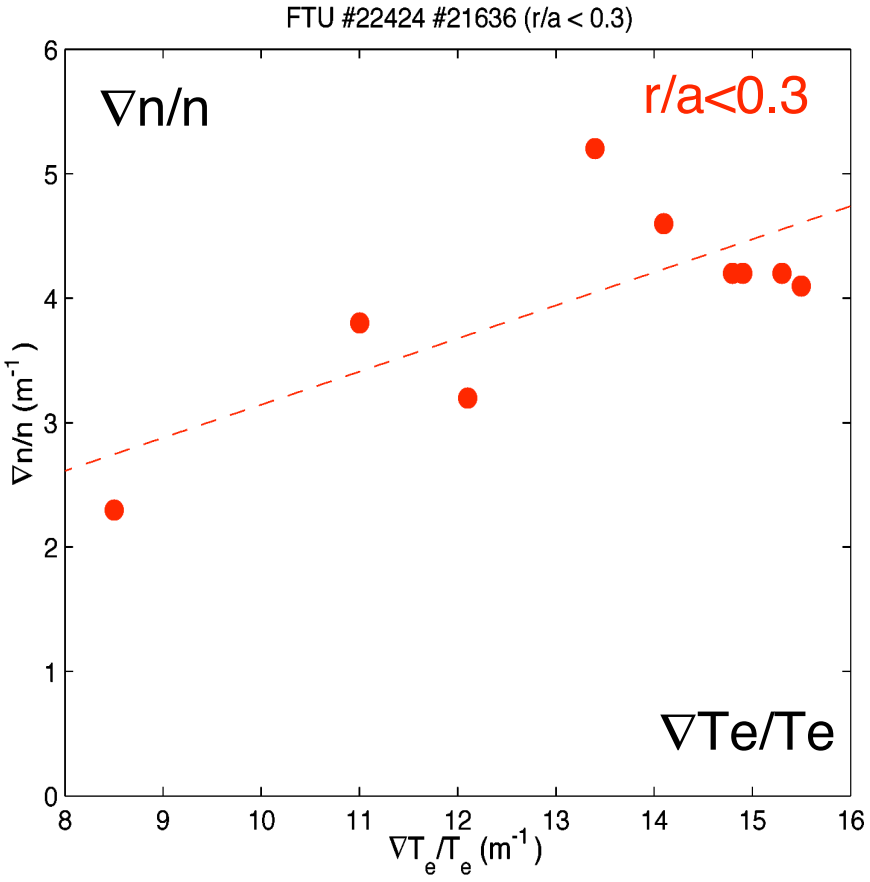


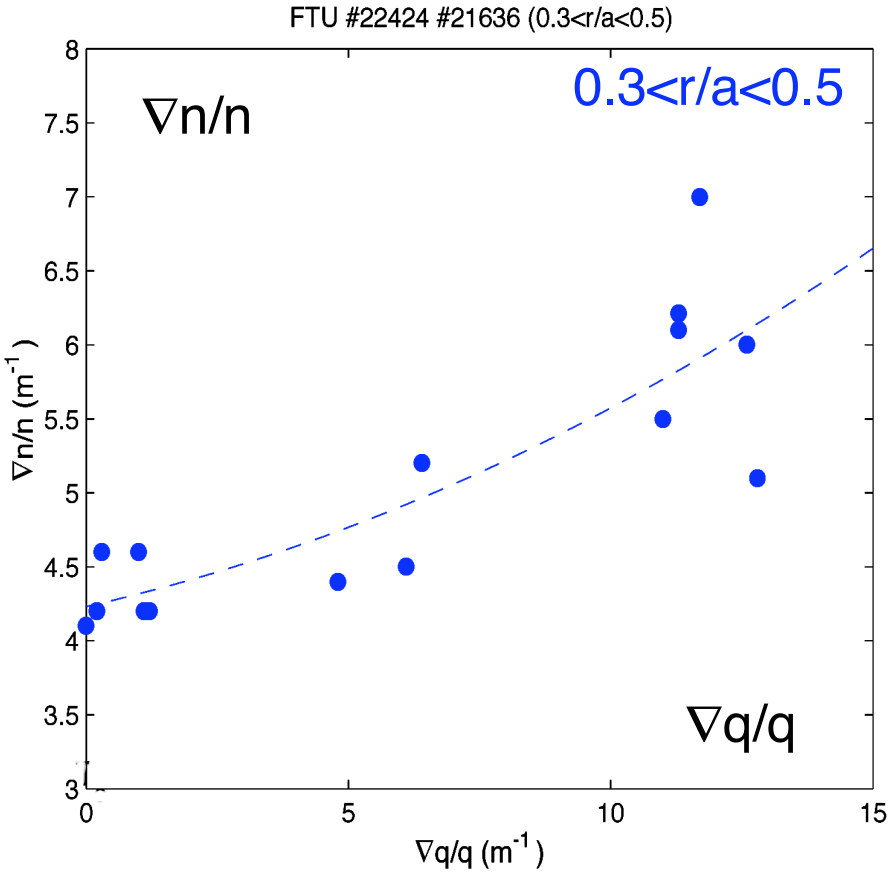
n_e profile flattens but remains peaked even for $V_{loop} \approx 0$

Anomalous particle diffusion at high density and collisionality

Particle pinch observed for n_{e0} up to $1.5\times10^{20}m^{-3}$ ($\nu_e^*\sim0.1$ at plasma center)

M Romanelli EX/P6-24

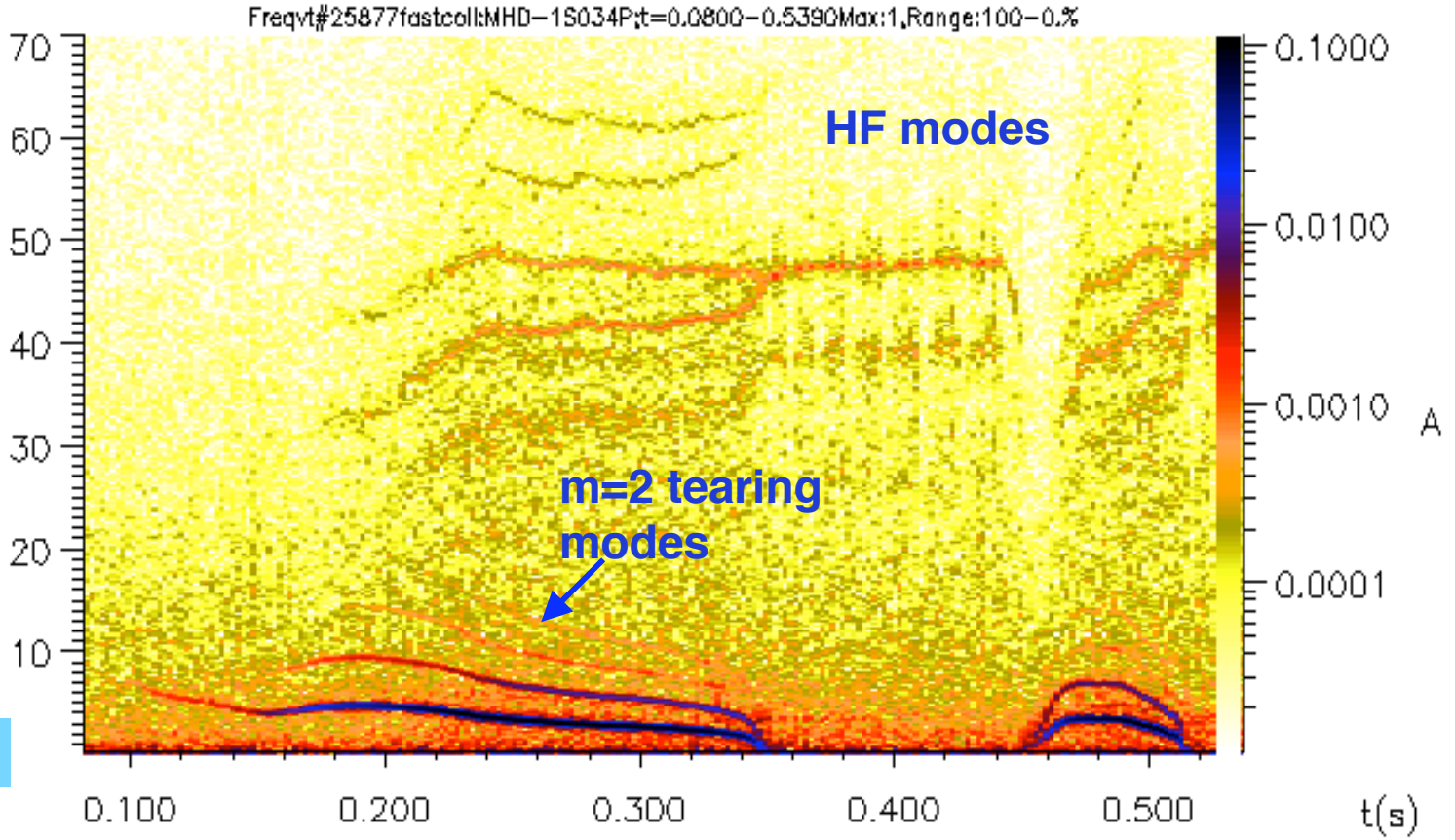




Consequences for density peaking in ITER being evaluated

MHD Spectroscopy: High frequency modes without EP

- 70kHz modes associated with development of m=2/n=1 islands, inside low frequency gap of Alfvenic modes
- Non-linear excitation of shear Alfven waves by magnetic island
- New loss mechanism in burning plasmas?



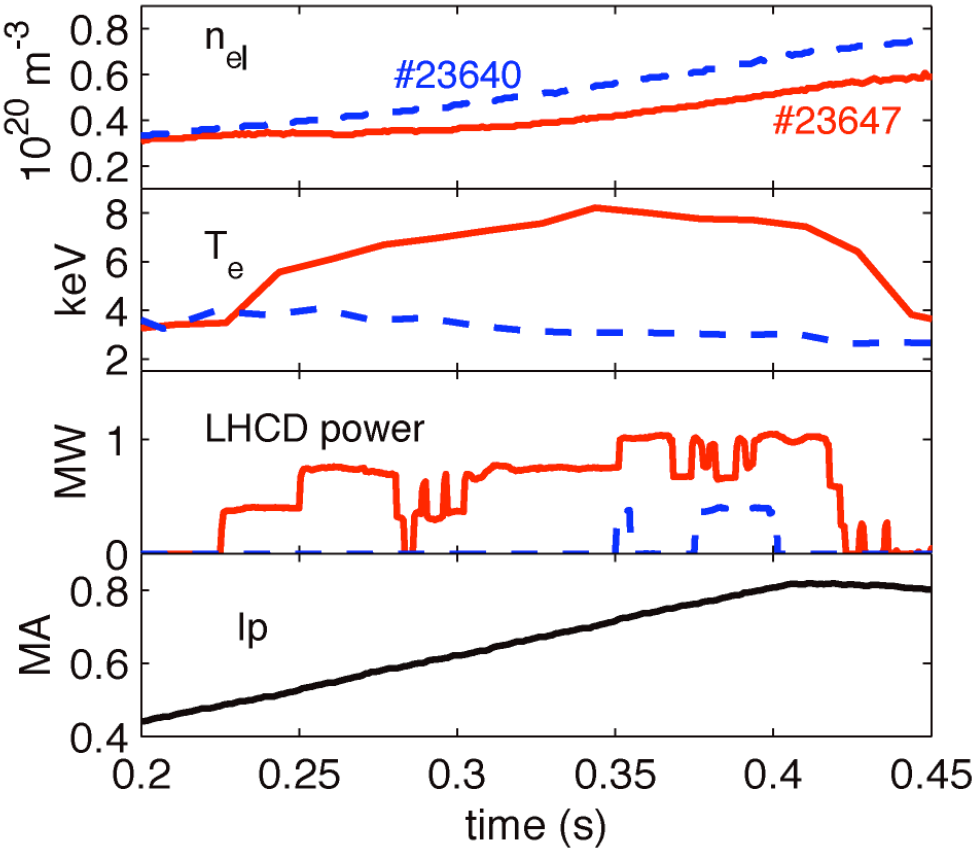
Buratti EX P5-1

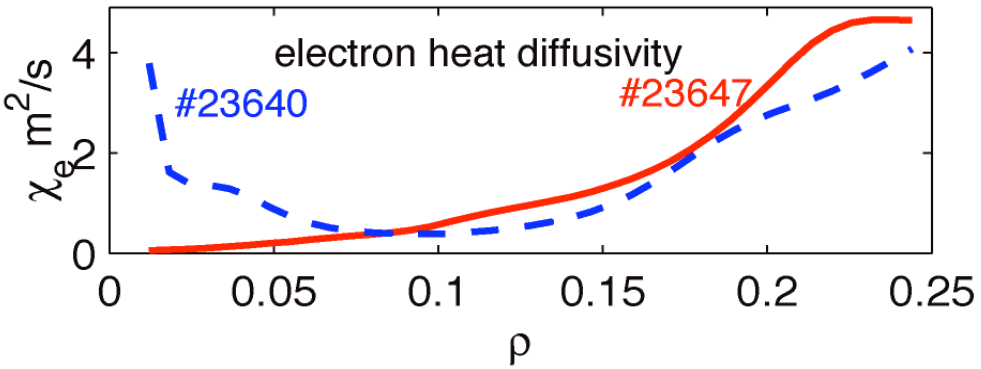
Summary

- Prototype ITER LHCD launcher successfully tested
- ECRH achieved nominal performances (1.5MW coupled)
- Effective down-shifted damping of EC waves on LH-induced energetic electrons
- High Field Side vertical pellet injection (r/a ≈0.5) produces very peaked plasmas (PEP modes)
- Steady electron ITBs achieved at high density: T_{e0} up to 5keV at $n_{e0}=1.4\times10^{20}m^{-3}$
  - Significant ion heating from e-i collisions without degradation of e-ITBs
- Density profiles remains peaked in steady full current drive conditions at high density($T_{e0}=4keV$, $n_{e0}=1.5\times10^{20}m^{-3}$)
  - Anomalous inward pinch confirmed
- High frequency Alfvenic type modes observed without energetic particles

- V Pericoli Ridolfini EX/5-5
  - LHCD and coupling experiments with an ITER-like PAM launcher on the FTU Tokamak
- P Buratti EX/P5-1
  - Observation of High frequency secondary modes during strong tearing mode activity In FTU plasmas without fast ions
- E Giovannozzi EX/P4-4
  - Pellet ablation in FTU discharges
- M Romanelli EX/P6-24
  - Studies of confinement and turbulence in FTU high field high density plasmas

Electron ITBs at high density with LHCD only



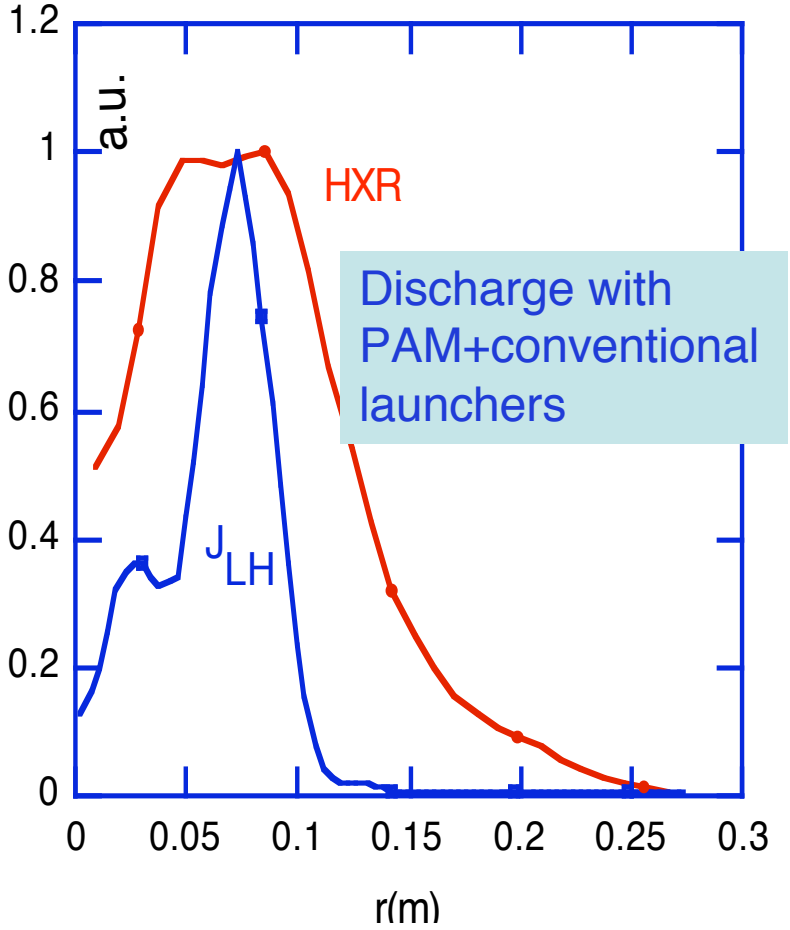


- ITBs produced with LHCD only at 7.2T and densities up to $n_{e0}=8\times10^{19}m^{-3}$
- T_{e0} reaches 8keV

- χ_e reduced by an order of magnitude at plasma center

PAM results well simulated by LHCD code

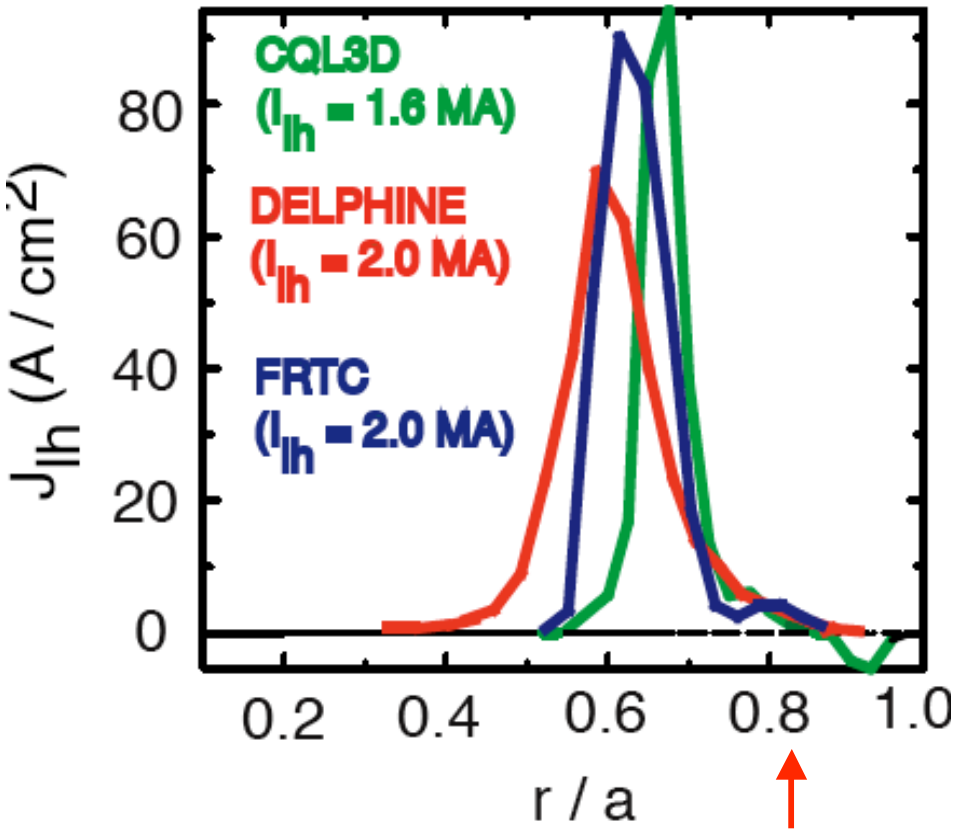
Comparison between Hard X-Rays emitted by LHCD induced fast electrons and 1D FRCT code



Discharge with PAM+conventional launchers

C Gormezano OV FTU 2004

E.Barbato, A Saviliev, EPS 2004 P2.104



Simulation of ITER steady state scenarios: comparison between FRTC and 2D DELPHINE and CQL3D

Houlberg IT/P3-33

REFLECTOMETRY: Comparison of turbulence with and without ITB

With ITB:Reduction of spectra both at low frequencies and broad band, Reduction of coherency to zero between the 2 poloidal channels,Reduction of cross correlation to zero,Width of auto correlation shrinks.