Overview of the FTU results OV/3-4

V. Pericoli Ridolfini, on behalf of FTU team and [1]ECH team

A. Alekseyev[2], B. Angelini, S.V. Annibaldi, M.L. Apicella, G. Apruzzese, E. Barbato, J. Berrino[1], A. Bertocchi, W. Bin[1], F. Bombarda, G. Bracco, A. Bruschi[1], P. Buratti, G. Calabrò, A. Cardinali, L. Carraro[3], C. Castaldo, C. Centioli, R. Cesario, S. Cirant[1], V. Cocilovo, F. Crisanti, G. D'Antona[4], R. De Angelis, M. De Benedetti, F. De Marco, B. Esposito, D. Frigione, L. Gabellieri, F. Gandini[1], E. Giovannozzi, G. Granucci, F. Gravanti, G. Grossetti[1], G. Grosso[1], F. Iannone, H. Kroegler, V. Lazarev[2], E. Lazzaro[1], M. Leigheb, L. Lubyako[5], G. Maddaluno, M. Marinucci, D. Marocco, J.R. Martin-Solis[6], G. Mazzitelli, C. Mazzotta, V. Mellera[1], F. Mirizzi, G. Monari, A. Moro[1], V. Muzzini[1], S. Nowak[1], F. Orsitto, L. Panaccione, M. Panella, L. Pieroni, S. Podda, M. E. Puiatti[3], G. Ravera, G. Regnoli, F. Romanelli, M. Romanelli, A. Shalashov[5], A. Simonetto[1], P. Smeulders, C. Sozzi[1], E. Sternini, U. Tartari[1], B. Tilia, A.A. Tuccillo, O. Tudisco, M. Valisa[3], A. Vertkov[7], V. Vitale, G. Vlad, R. Zagórski[8], F. Zonca

[1] *Associazione EURATOM-ENEA, IFP-CNR, Via R. Cozzi, 53 - 20125 Milano, Italy*

[2] *TRINITI, Troitsk, Moscow reg., Russia*

[3] *Consozio RFX, Corso Stati Uniti 4, I-35100, Padova, Italy*

[4] *Politecnico di Milano, Piazza Leonardo Da Vinci 32, 20133 Milano, Italy*

[5] *Institute of Applied Physics, Russian Academy of Science, Nizhny Novgorod, Russia*

[6] *Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911 Madrid, Spain*

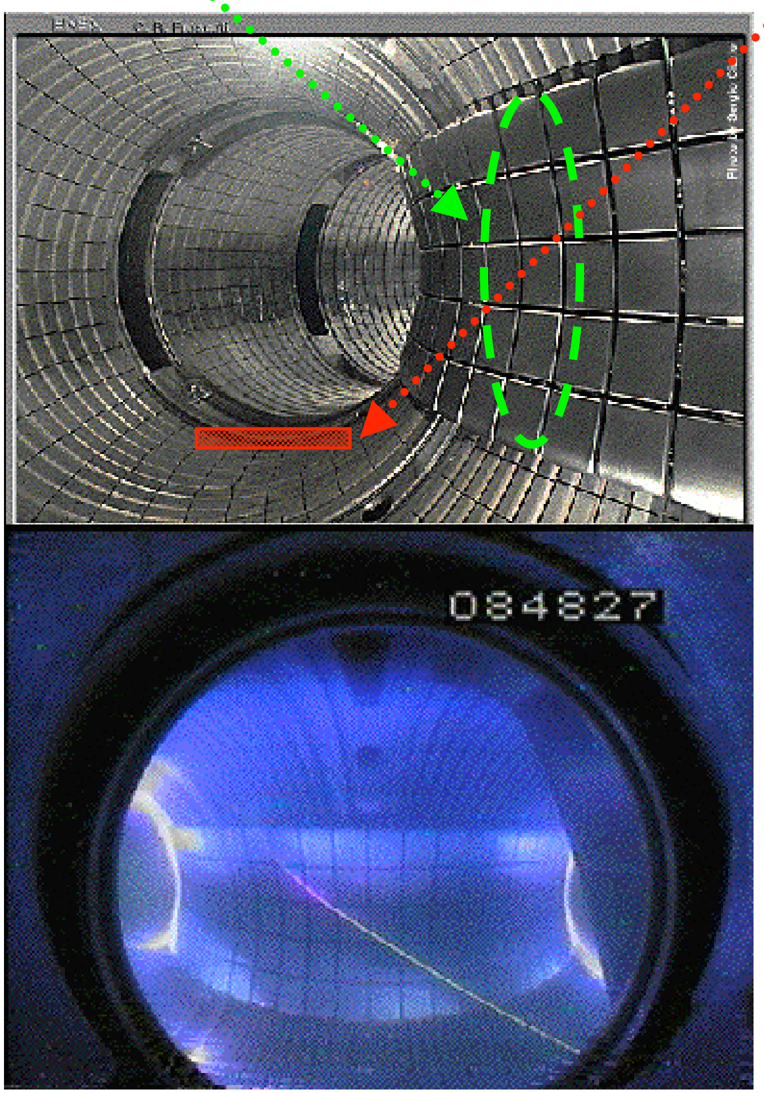
[7] *FSUE, RED STAR, Moscow, Russia*

[8] *Institute of Plasma Physics and Laser Microfusion, EURATOM Association, 01-497, Warsaw, Poland*

THE FTU DEVICE

TZM (Mo alloy) Toroidal limiter

Liquid Lithium Limiter (if inserted)



Compact all metallic device (circular)
R=0.93 m, a=0.3 m
$B_T \leq 8$ T, $I_p \leq 1.6$ MA

ONLY RF HEATING

LHCD	**P≤2 MW**	**f=8 GHz**
ECH	**P≤1.5 MW**	**f=140 GHz**
IBW	**P≤0.5 MW**	**f=433 MHz**

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

- Advanced Tokamak scenarios
- Techniques
- Physics issues

OUTLINE

- Progress in the physics of advanced scenarios
- Results with the Liquid Lithium Limiter (LLL)
- Active control of the MHD instabilities with the EC power
- Progress in disruption mitigation with ECH
- Flash on the theoretical activity (e^--fishbones dynamics)
- Test of the Collective Thomson Scattering (CTS) diagnostics in ITER-like configuration
- Flash on the physics study on LHCD
- Conclusions

FTU Internal Transport Barriers - review

ITER relevant for:

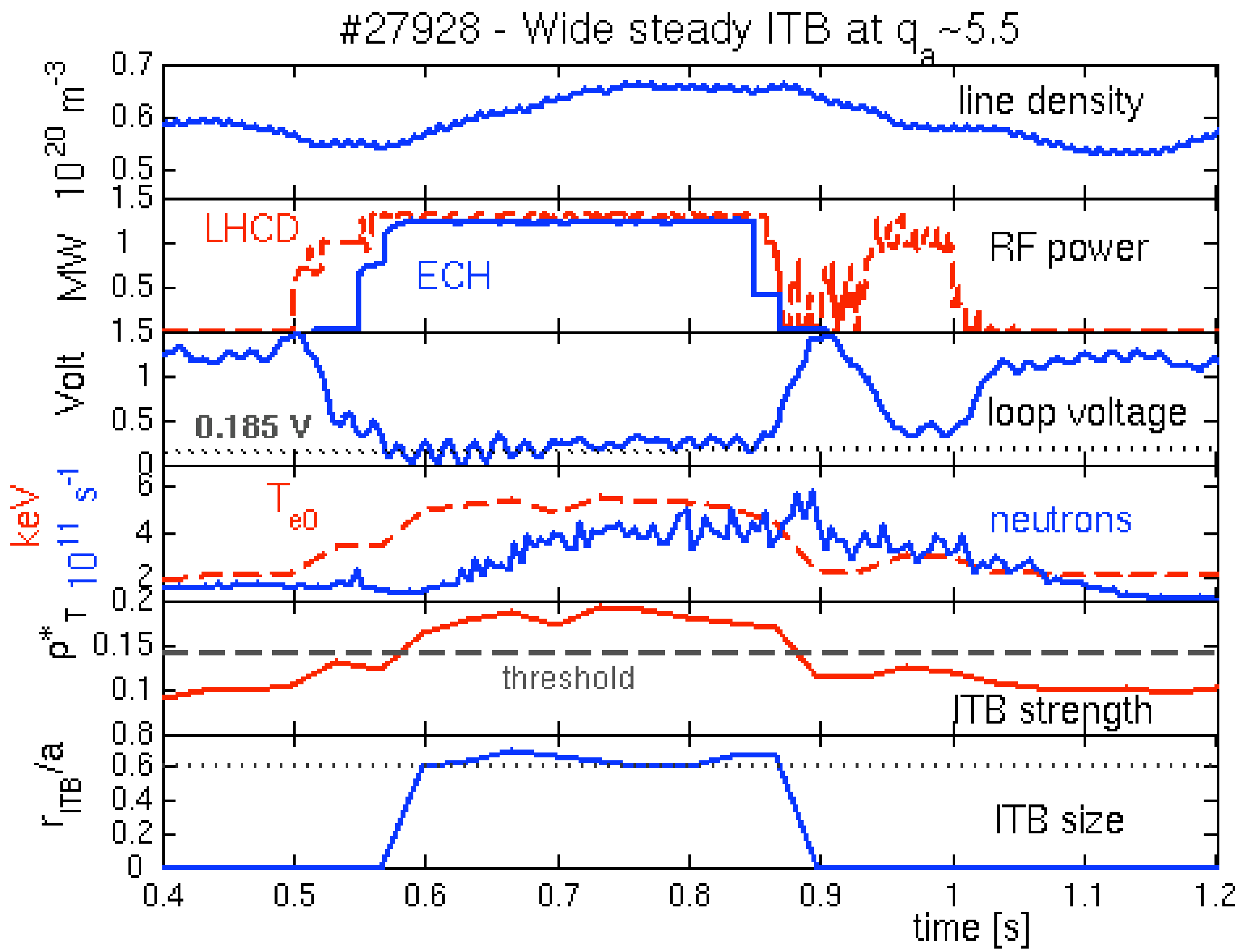
- High density (n_{e0}>1.3·10^{20} m^{-3}), magnetic field (B_{T0}≥5.3 T)
- Electron heating + CD only - no momentum input
- Collisional ion heating

Main achievements

- Steadiness (full CD) as long as the LHCD+ECH pulse (I_{bs}/I_p >30%)
- High confinement (1.6·$\tau_{ITER97-L}$ at the highest n_{e0})
- Control of size (0.2 ≤ r_{ITB}/a ≤0.65 through control of r_{LHCD})
- Improved ion transport
- Good density peaking without Ware pinch ($n_{e0}/\langle n_e \rangle \geq 1.7$)

q(r) profiles close to hybrid regimes (q_0~1.5, q_{min}~1.2-1.3)
Initial full relaxed j_{OH}(r) (ITB recovery possible)

ITB physics - steady control of the radius



$0.2 \leq r_{ITB}/a \leq 0.65$

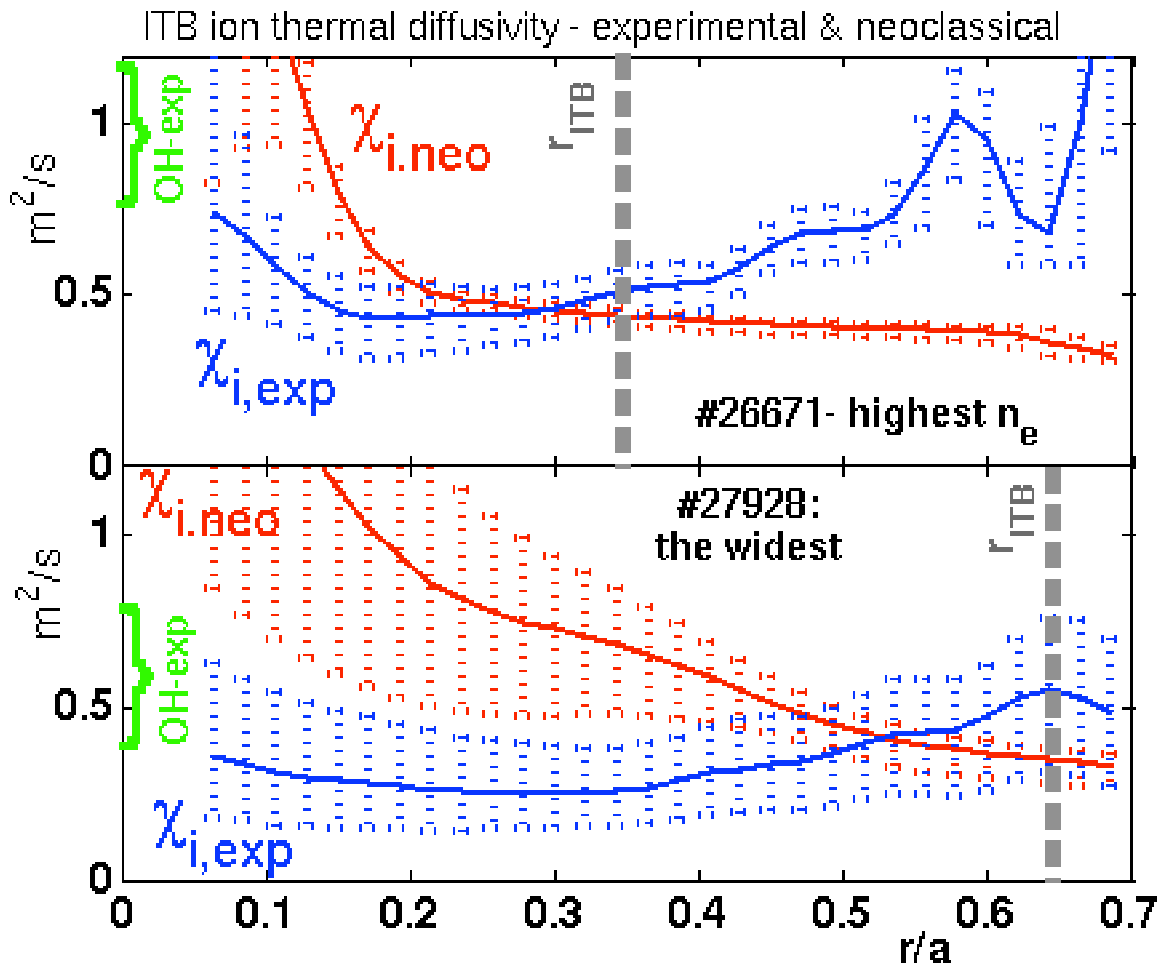
- **Main control parameter = q_a (acts on $r_{dep,LH}$)**

Important also

- OH and ECCD central counter CD
- off-axis ECH but much power required

More details in poster EX/P1-15
(V. Pericoli Ridolfini)

ITB physics - confinement and ion transport



Global confinement
$\tau_E > 1.6 \cdot \tau_{ITER97-L}$
($n_{e0} \geq 1.3 \cdot 10^{20}$ m^{-3})

Ion transport improves just for $r < r_{ITB}$

$\chi_{i,ITB} \leq \chi_{i,OH}$

NO MOMENTUM INJECTION!

but $T_{i0} \leq 1.6$ keV

The LLL (Liquid Lithium Limiter) - motivations

Longer term: **assessments for a liquid as plasma facing component (Solution of the divertor target erosion?)**

Shorter term: **studying in a medium size high field tokamak**

(collaboration with TRINITI and RED STAR - Russia)

wall conditioning (lithization)

effects on plasma discharges (Z_{eff}, recycling, density limit, P_{rad}, etc)

heat loads and damage of LLL

the modified physics in the edge plasma

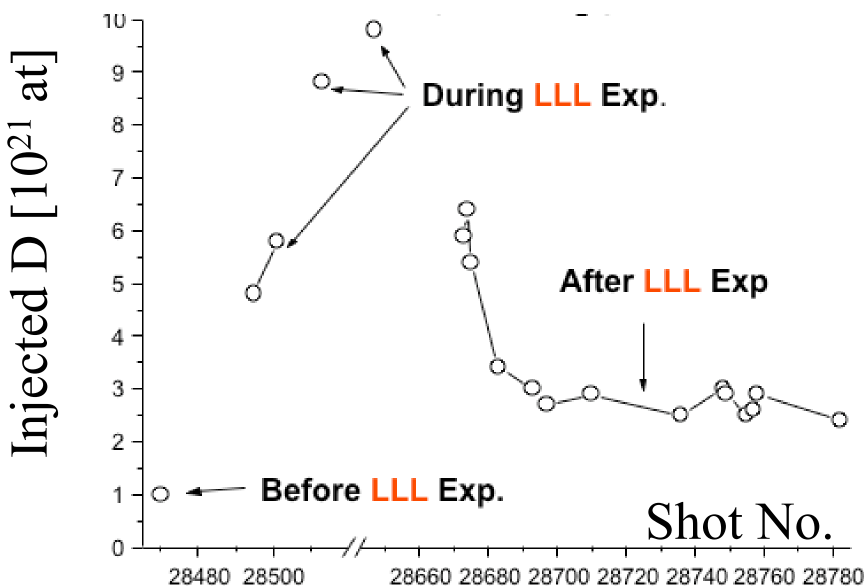
Lay-out and more details on the poster EX/P4-16 by ***G. Mazzitelli***
and poster EX/P4-17 by ***S.V. Mirnov*** - Thursday19 Oct. morning

LLL - Technical aspects

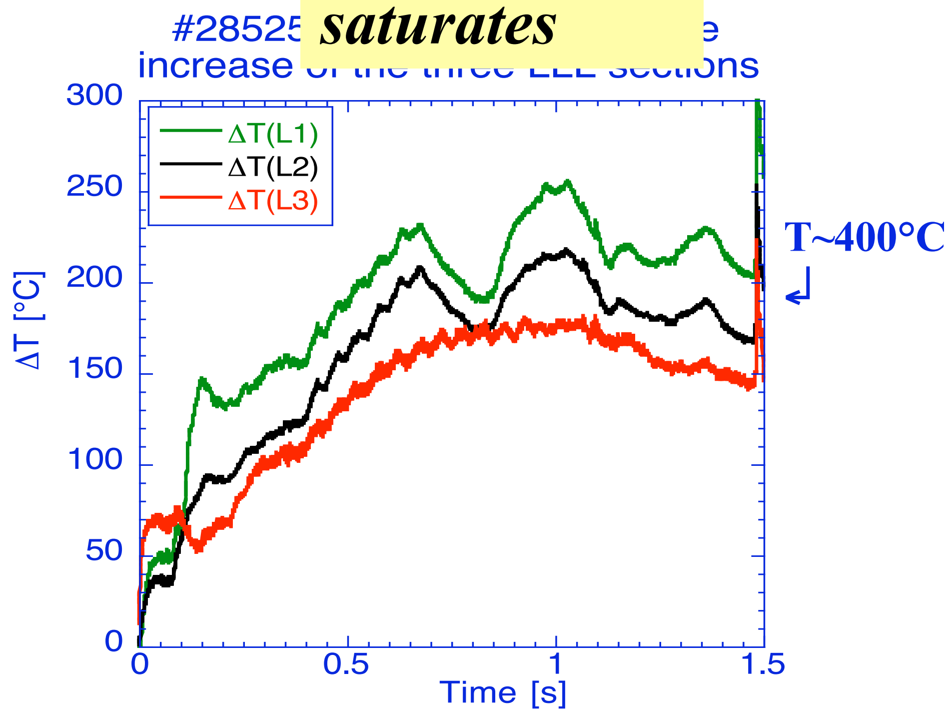
So far $Q_{LLLsurf} \geq 5\ MW/m^2$ (only OH discharges)

No damage on the exposed surface - No Li-bloom phenomenon

Strong D-pumping



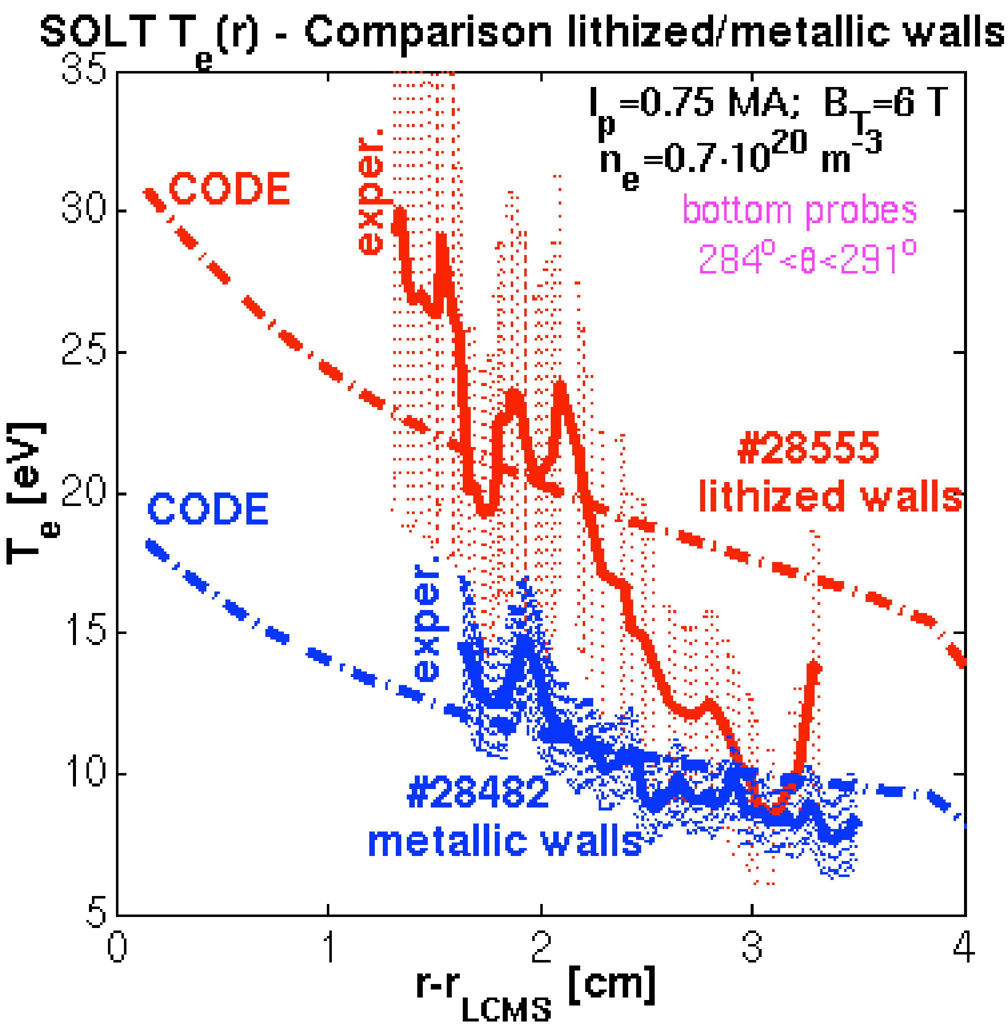
T_{surf} saturates



Recycling drops, wider density range: $0.15 \leq n_e \leq 2.7 \cdot 10^{20}\ m^{-3}$

Self-protecting mechanisms? (radiation mantle? Local clouds?)

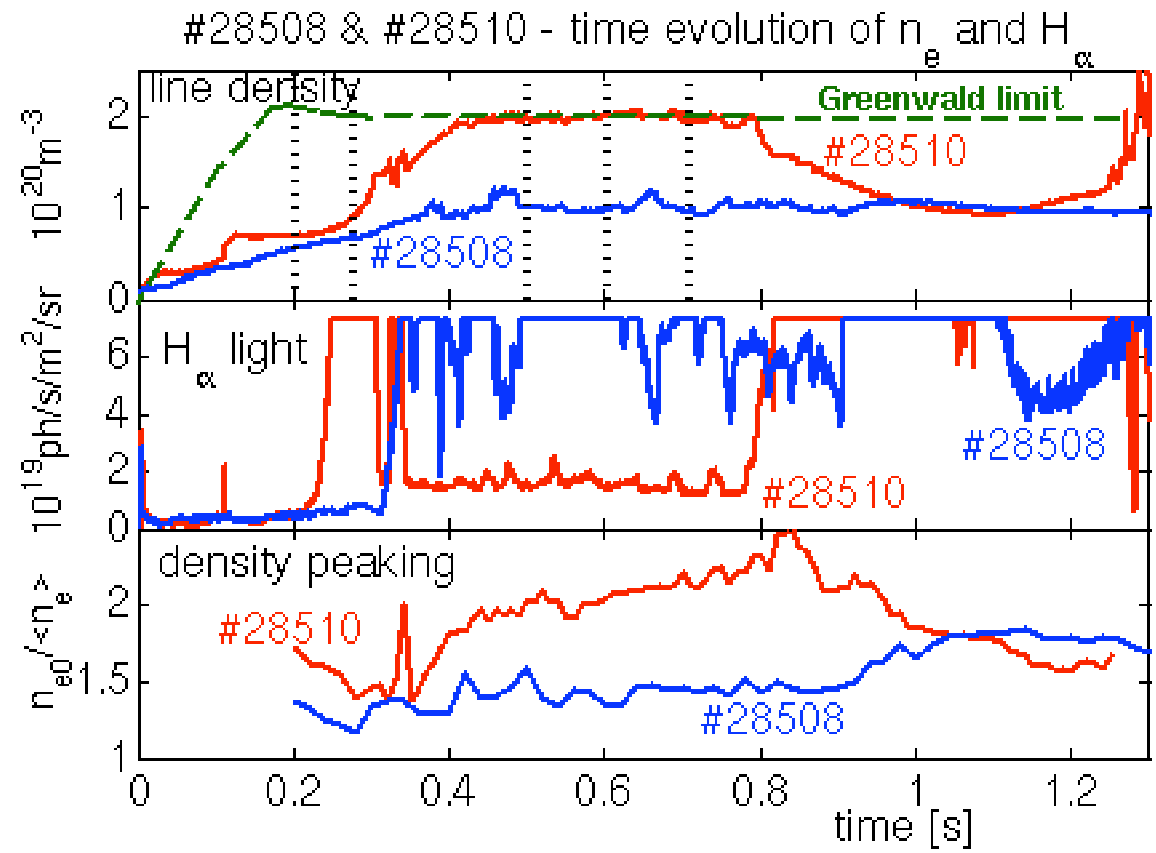
LLL - effects of the lithized walls

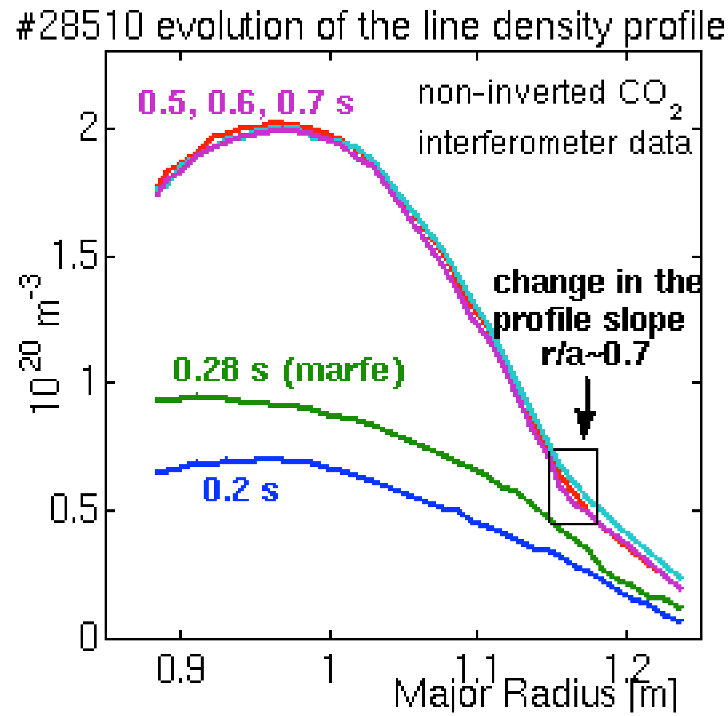


SOL temperature lithized/metallic
Code (TECXY)/ experiment

Same $Q_{inp,SOL}$ yet quite high ΔT_e
reproduced by TECXY only if:
i) Recycling→0 (R=0.02)
ii) a small Mo content is retained

LLL - new high-density regimes





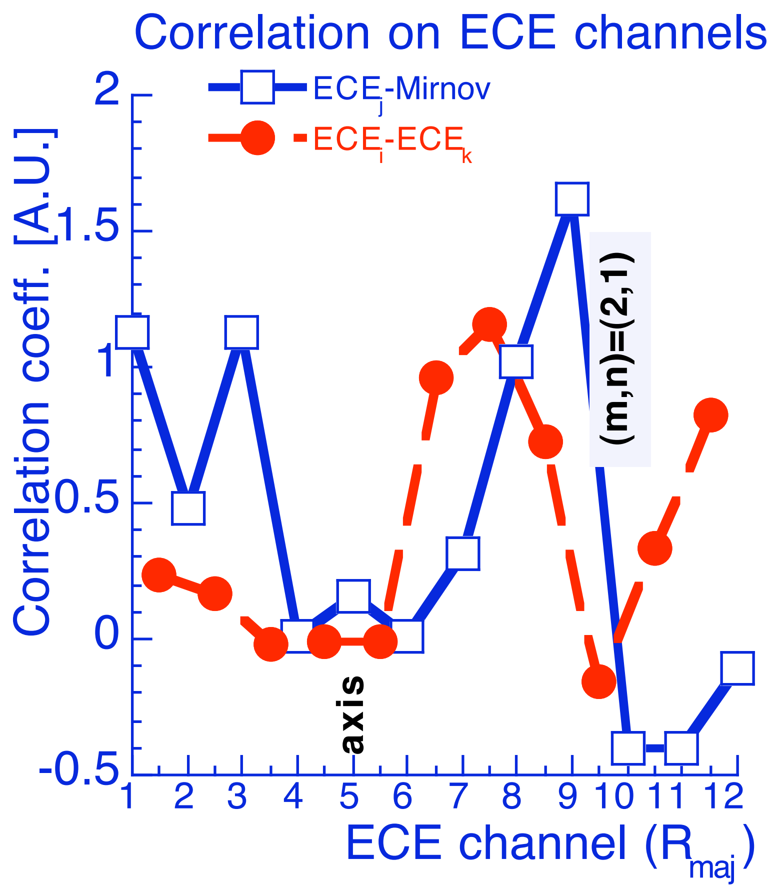
DENSITY BARRIER ??
τ_E~52 ms (top of the data-base)

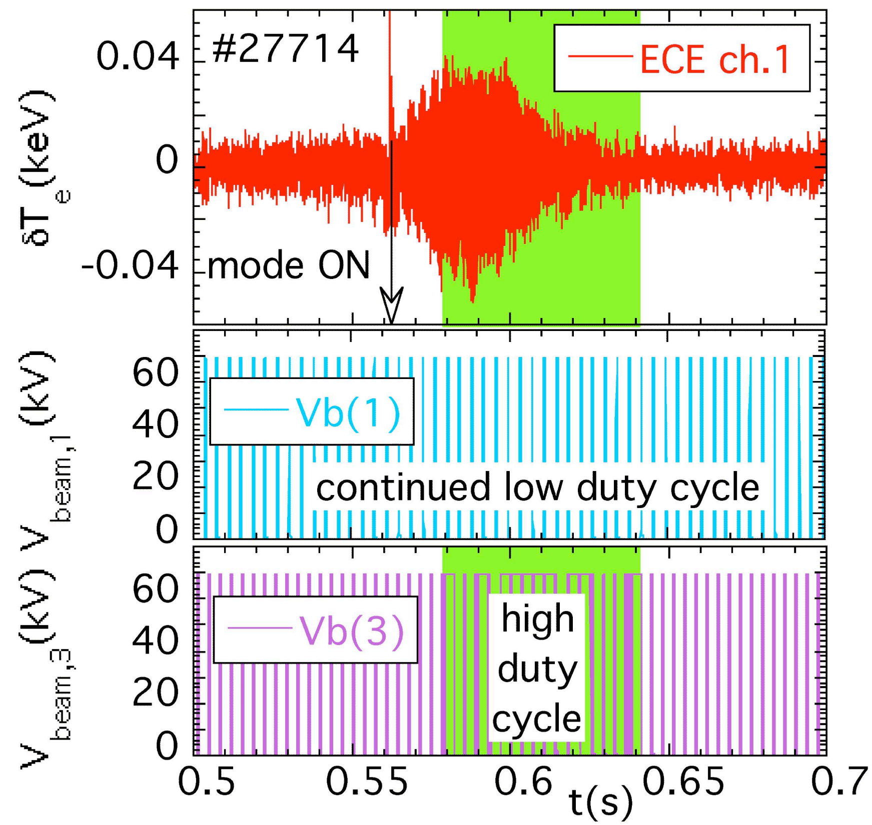
#28510: LLL inserted ~1.4 cm in the SOL:
MARFE disappears in 0.31-0.78 s

#28508: LLL outside.

Paper submitted to PPCF: ***V. Pericoli Ridolfini***
Previous related work : PoP 2002, ***C. Castaldo***

Automatic ECH real-time MHD stabilization





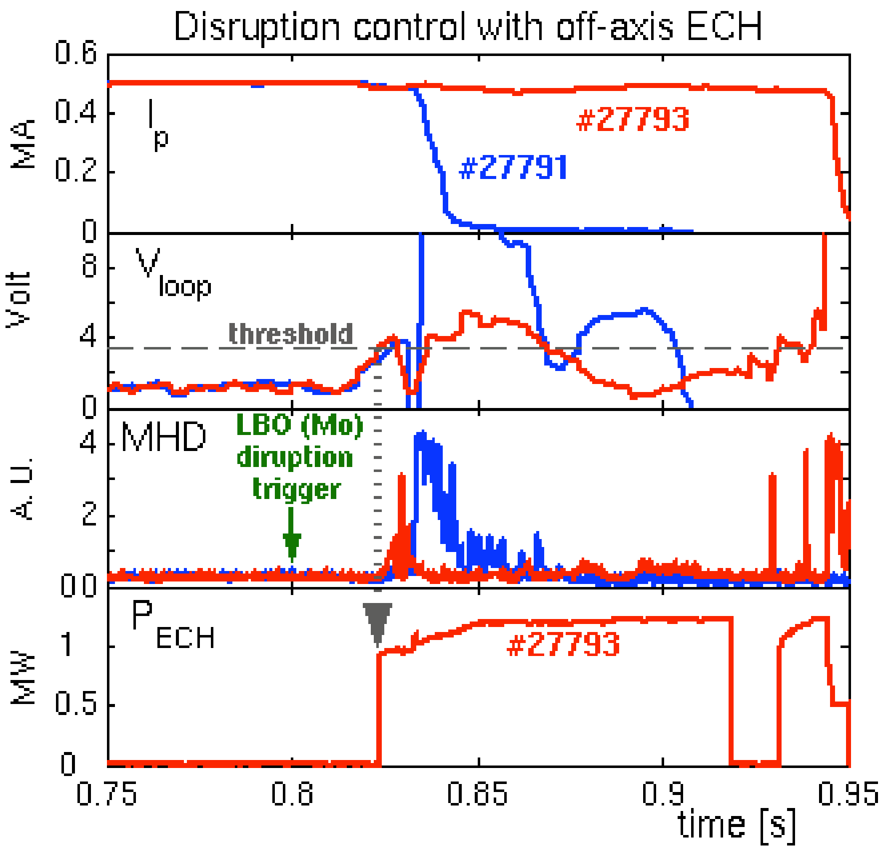
1) the island and the ECH deposition radii are localized

2) a real time algorithm switches on the gyrotron with the minimum $|r_{dep,ECH} - r_{island}|$

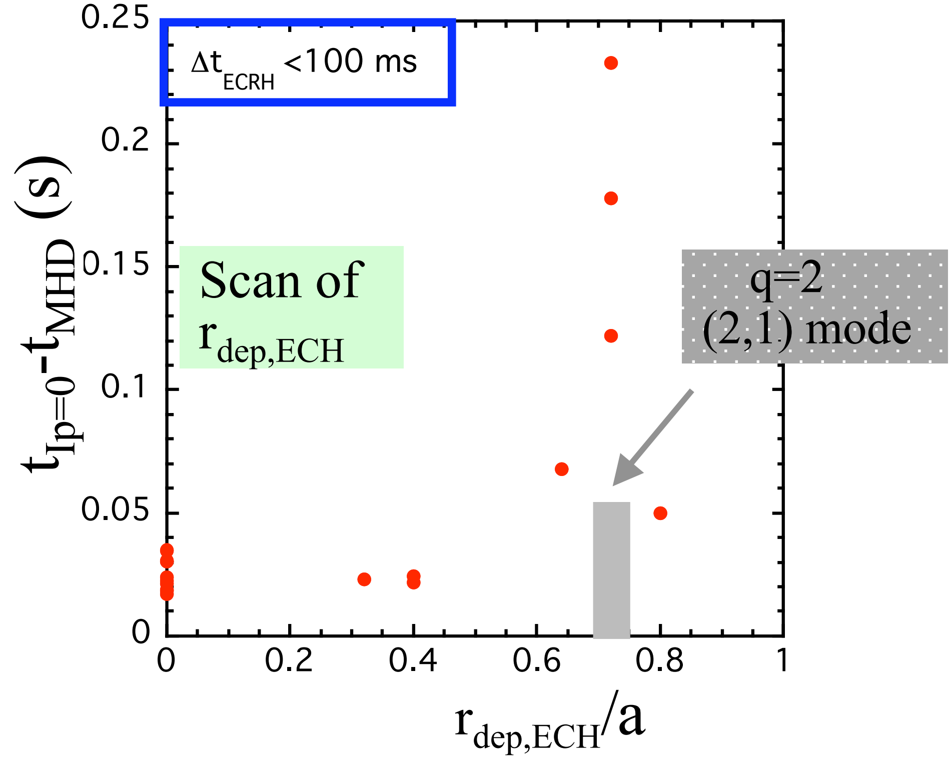
Disruption mitigation by ECH

P_{ECH} acts on the MHD mode growth rate

Disruption triggered by laser blow-off of Mo



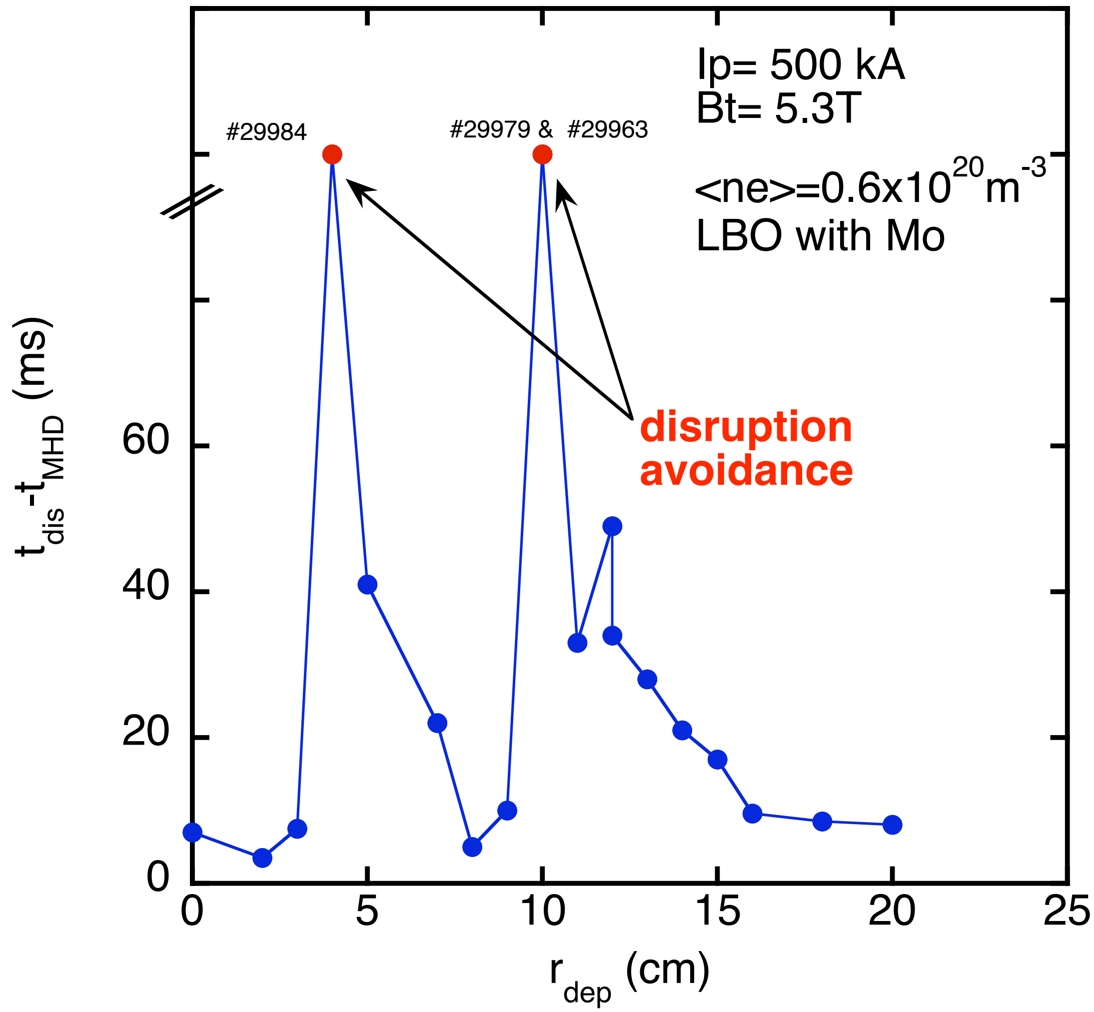
$r_{dep,ECH}$ must be set correctly



Density limit driven disruptions mitigated by central ECH (sawteeth restored)

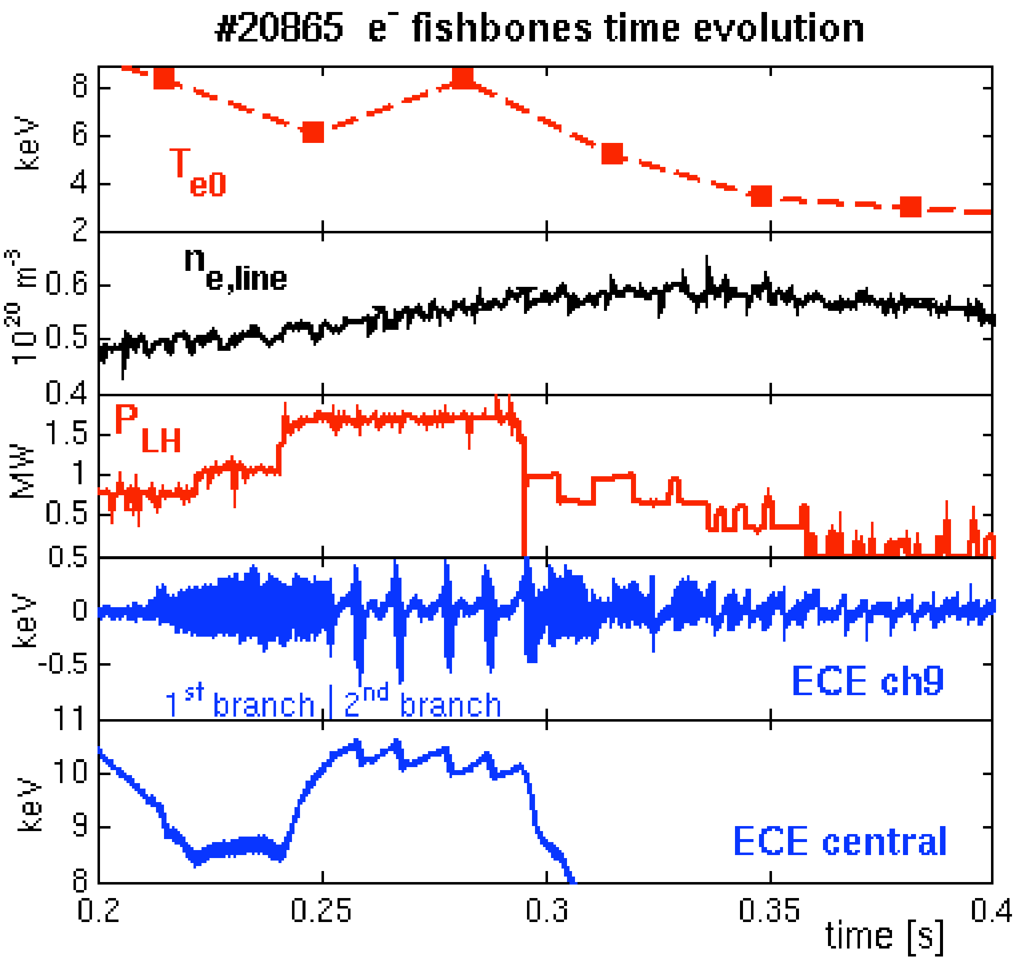
33rd EPS - Roma 2006 P5.071 - ***B. Esposito***

Disruption Mitigation by ECH on FTU with Lithized Wall (October 2006)



- **ECRH Deposition scan by poloidal steering**
- **Power from 2 gyrotrons ≈0.75 MW sufficient to stabilise disruptive modes**
- **Disruption avoidance occurs at 2 locations:**
  r_{dep}=4 cm → q=3/2
  r_{dep}=10 cm → q=1
- **Detailed analysis on-going**

Theory ⇔ FTU experiment (e^- fishbones)



<u>FTU e- fishbones</u>: LH power alone in low n_e and ~full CD

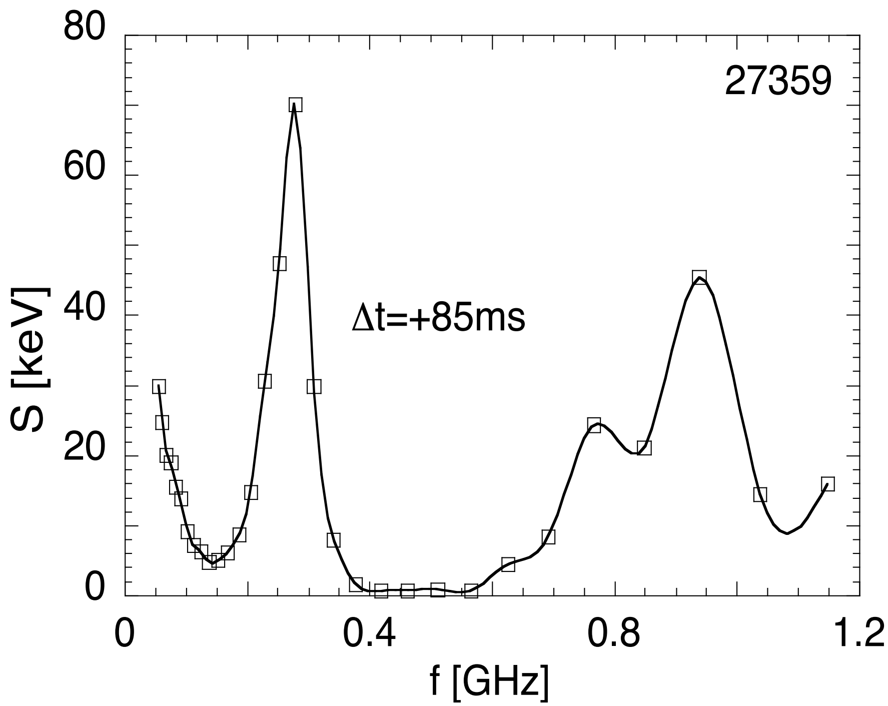
<u>similar MHD by fusion α's</u>

- α's have small dimensionless orbits like fast e^-
- dynamics: no dependence on mass (only on energy)

simple yet relevant nonlinear dynamic model: talk **TH/3-2** by ***F. Zonca***
(Thursday 19 Oct. Afternoon)

Collective Thomson Scattering (CTS) tests

f_{gyr}=140 GHz < f_{EC}=198 GHz - Same ITER configuration



Typical anomalous spectrum - (Ion feature ~ 1-2 keV)

Any back reflection to the source to be avoided

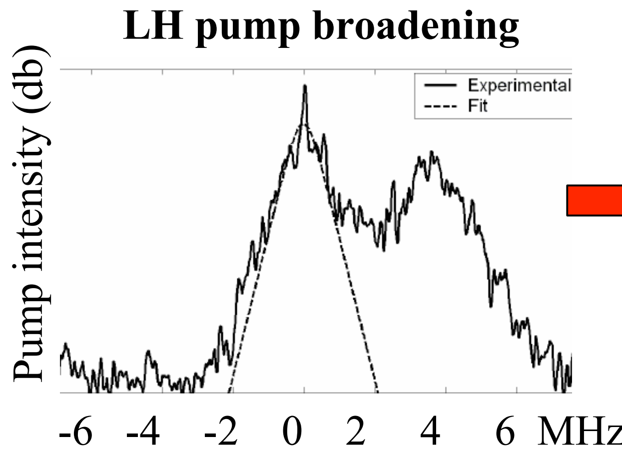
New design antennas - good perspectives

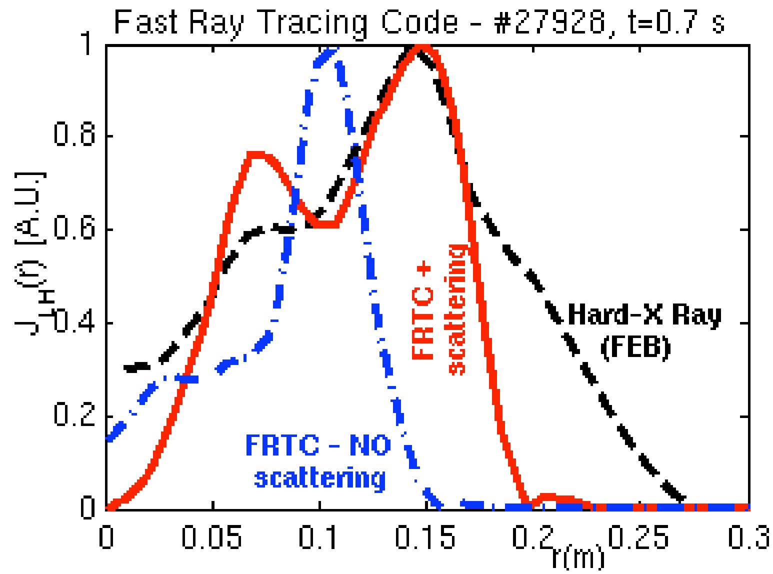
Nucl. Fusion **V. 45,** p. 928 (2006) ***U. Tartari***

LH physics: LH waves - edge interaction

FTU - 8 GHz linear model

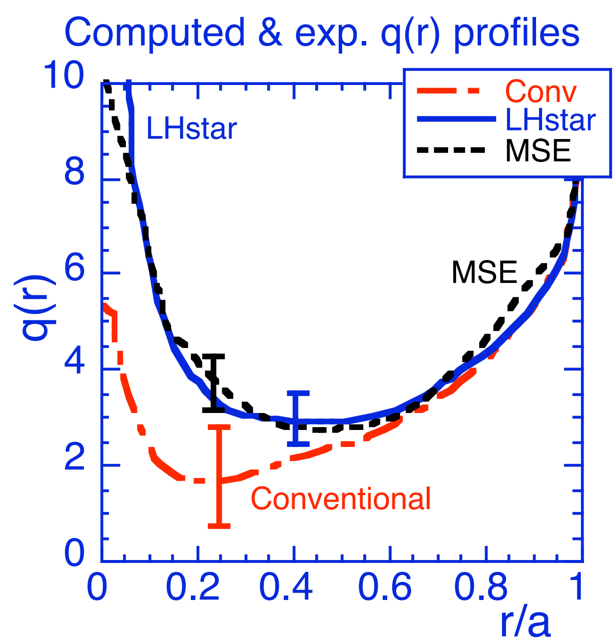
33rd EPS-Roma
Paper P5-077
G. Calabrò





JET - 3.7 GHz non linear model (PDI)

LHstar code
PRL **92**,175002
R. Cesario



Small amount of power shifted to high $N_{||}$ (~4) : deposition profiles better reproduced

Conclusions - I

Steady ITBs

- **Steady, high n_e ITBs ($t>35\tau_E$, $1.5\approx\tau_{R/L}$) with e^- heating and CD only**
- **ITB radii within $0.2\leq r_{ITB}/a<0.65$ by acting on the $r_{dep,LH}$**
- **$\tau_E \geq 1.6\cdot\tau_{ITER97-L}$; ion transport inside ITBs improves**
- **Density peaking in the absence of Ware pinch at high n_e**

Liquid Lithium limiter (LLL)

- **first successful test on a medium size tokamak**
- **drop of the recycling, large D-pumping action**
- **SOL physics accounted for**
- **New high density($=n_{GW}$) strongly peaked regimes accessed**

MHD control

island suppressed by local ECH with a prompt (on line) digital signal processing for r_{island} and $r_{dep,ECH}$

Conclusions - II

Disruptions

Avoidance attained with the right choice of a precursor + localized ECH to act on the MHD island growth rate

Theory

Understood the non-linear dynamics of the e^- fishbones

ITER-like Collective Thomson Scattering

Careful tests have singled out the most significant obstacles to be removed - good perspectives

LHCD physics

Progress in modeling the interaction LH waves - turbulent edge + LH absorption