# Steady-State operation of Tokamaks: Key Physics and Technology Results on Tore-Supra

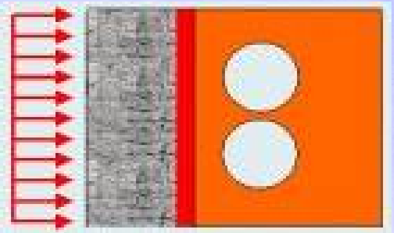
J Jacquinot on behalf of the Tore-Supra Team

Cadarache, EU

Euratom cea

- Motivations
- Tore Supra and operating conditions
- Key results in technology and physics
  - Consequences for ITER
- The way forward

# Steady state issues



## Systems:

- Cooling channels must be close to plasma: (e < 10 mm)
  - **Joining methods, erosion**
- Surveillance of large area with fast response (< 1 s), hot spots..
  - ➔ IR cameras
- New requirements on diagnostics, fuelling and heating and CD systems (LHCD, ICRH, ECRH, NNBI)

## New physics:

- $V_{loop}$ ~ 0, no Ware pinch
- Slow interplay between particle/energy transports and current profile
  - **Irreversible bifurcations** ➔ stable conditions require feedback

## Active new area of research

- **Presently:** Tore Supra, TRIAM-1M, LHD, HT7…
- **New devices:** W7X, KSTAR, EAST, SST1 and ITER (all superconducting)

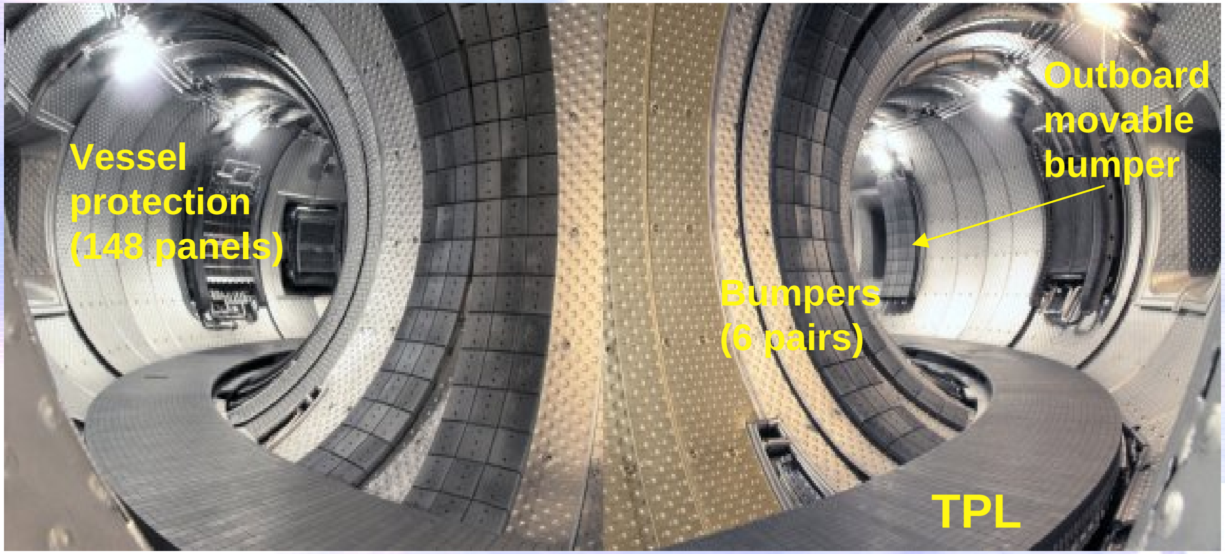
# TORE SUPRA 2004

- Toroidal Pumped Limiter; heat exhaust capability 15 MW (10 $MWm^{-2}$)

- Vessel protection against thermal radiation and plasma contact

- 10 actively cooled neutralizers below the TPL; max. flux 15 $MW/m^2$; total pumping speed 20 $m^3/s$

- 30 Diagnostics (actively cooled also)



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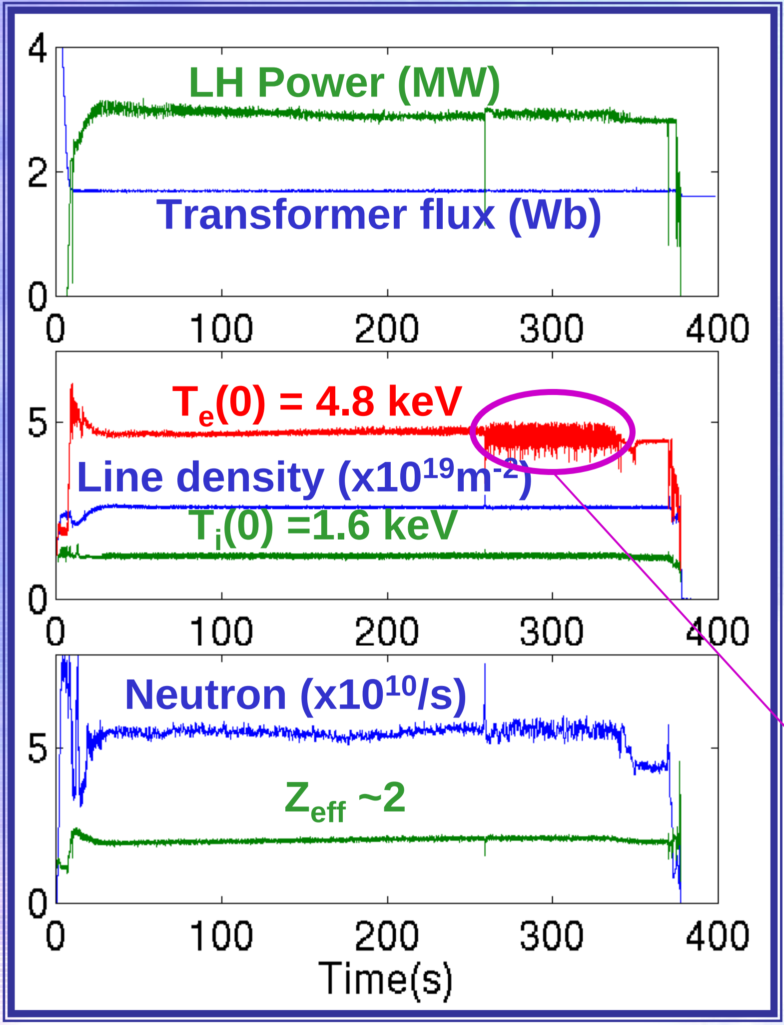
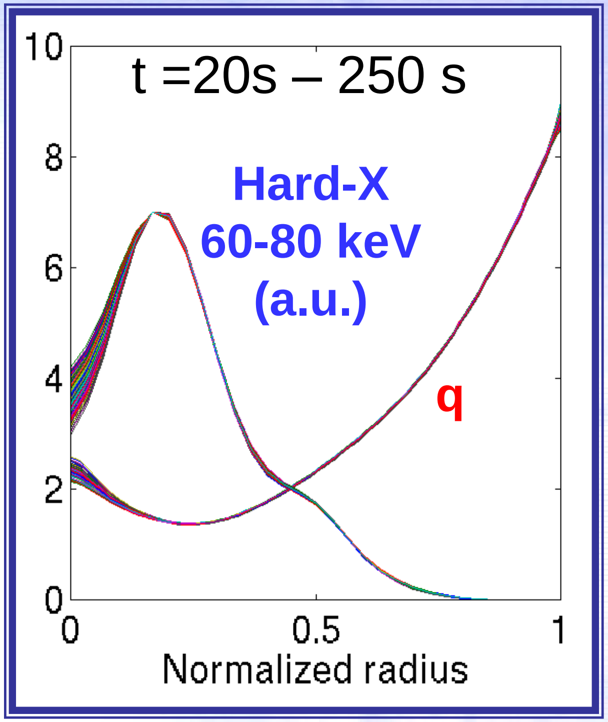
# Vloop = 0 for > 6 minutes injected energy of 1.1 GJ

(Van Houtte, poster EX/P4-14)




Stable plasma until 258s then MHD activities switched on (no effect on global confinement)

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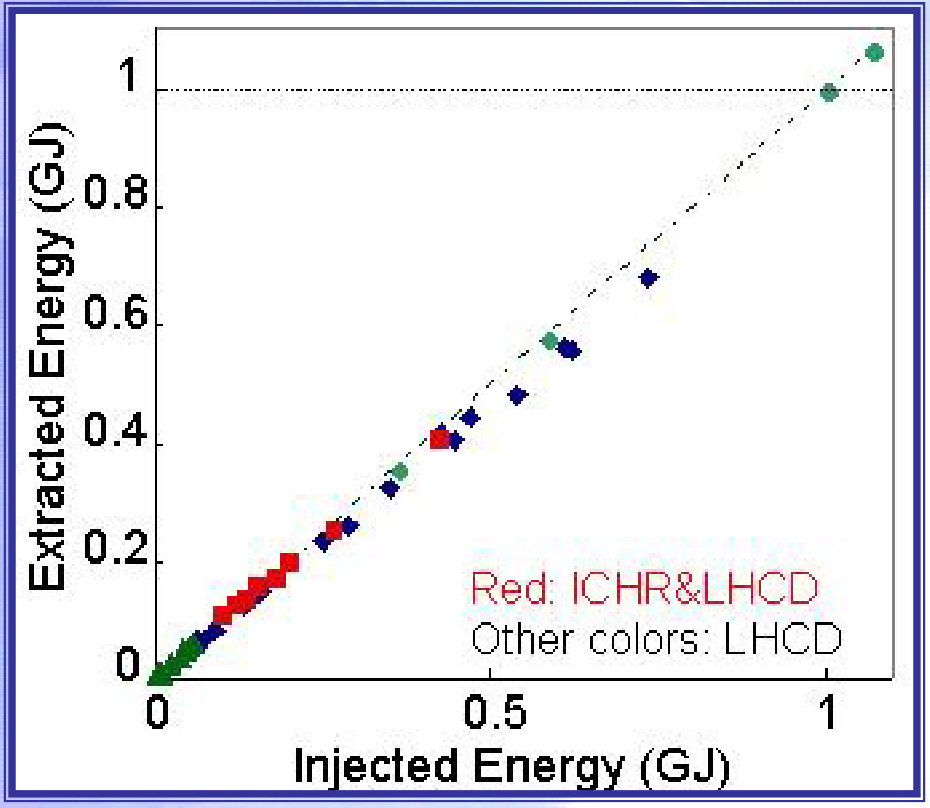
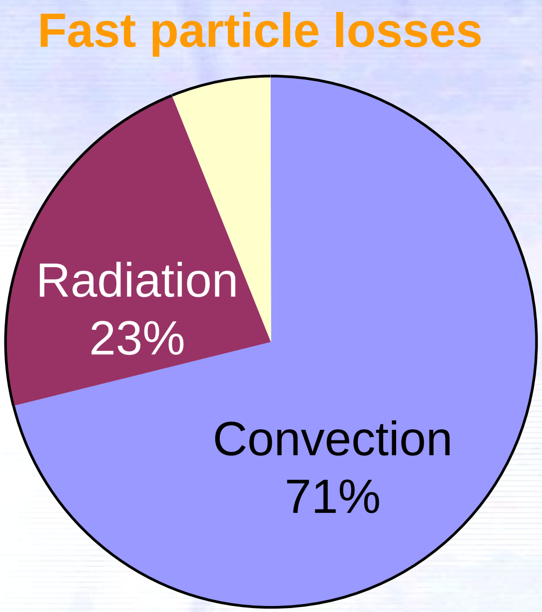
# Heat Exhaust




~ 50% on the TPL (7 m$^2$)

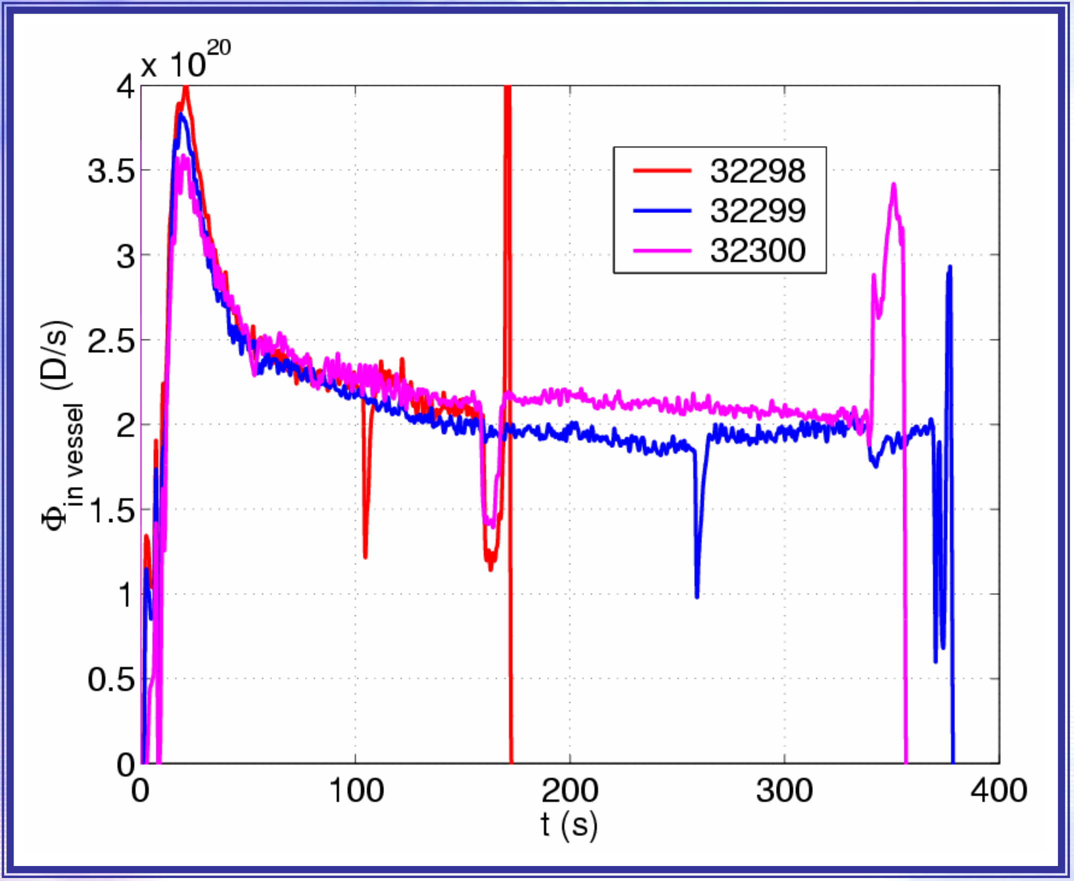
25% on the first wall panels (75 m$^2$ with the bumpers)

25% shared between the outboard limiter and antennas

Beware of fast particles: ripple and later alphas!

# Particle retention (Tsitrone, EX10-2)

$$dN_p/dt = \Phi_{inj} - \Phi_{pump} - \Phi_{\text{in vessel}}$$




Phase 1: Decreasing retention rate ➔ filling carbon porosities

Phase 2: Constant retention rate : 2 $10^{20}$D $s^{-1}$ (= 50% of injected flux) ➔ co-deposition observed but not enough (deep penetration in carbon?)

In vessel inventory : up to 8 $10^{22}$ D for 6 mn (>> saturation of 15 $m^2$ of carbon)

**Identical shot to shot behaviour. No saturation of in-vessel retention after 15 minutes of cumulated plasma time**

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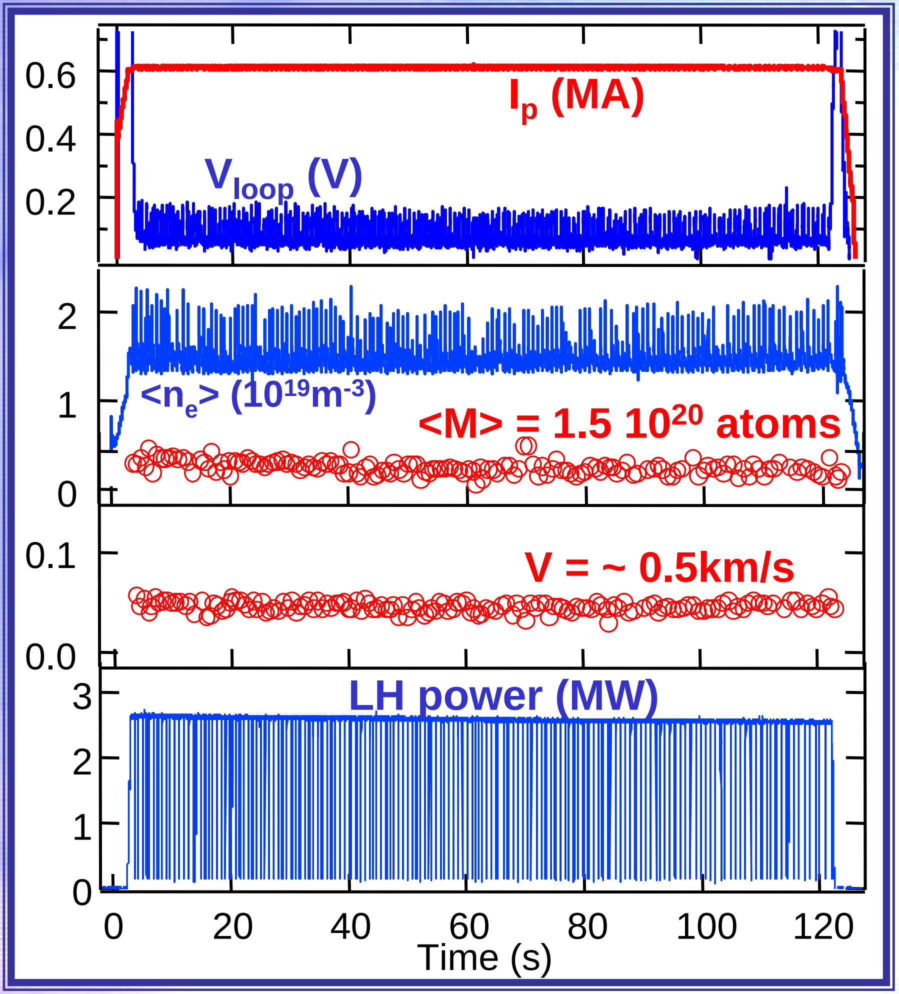
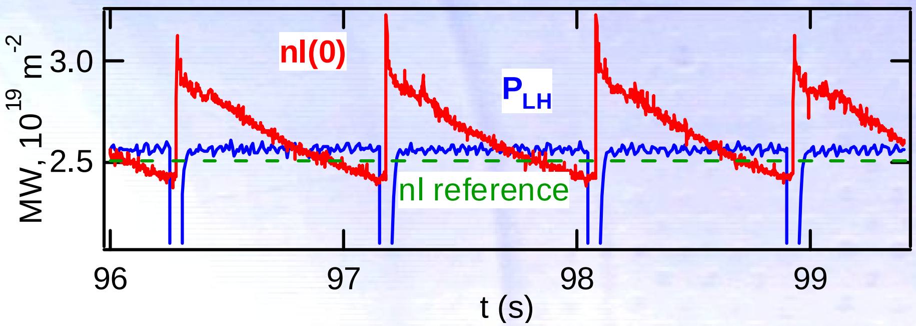
# Pellet injection during 2 minutes in presence of LH




LH power notching allows penetration of 155 pellets

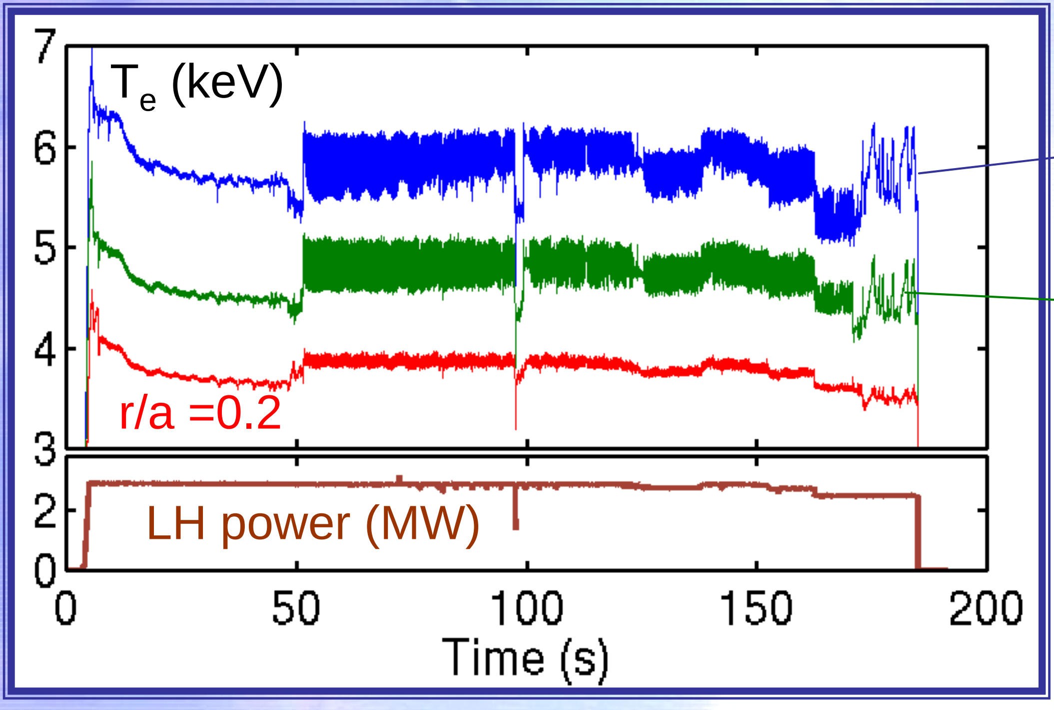
Very stable speed of 0.5 km/s

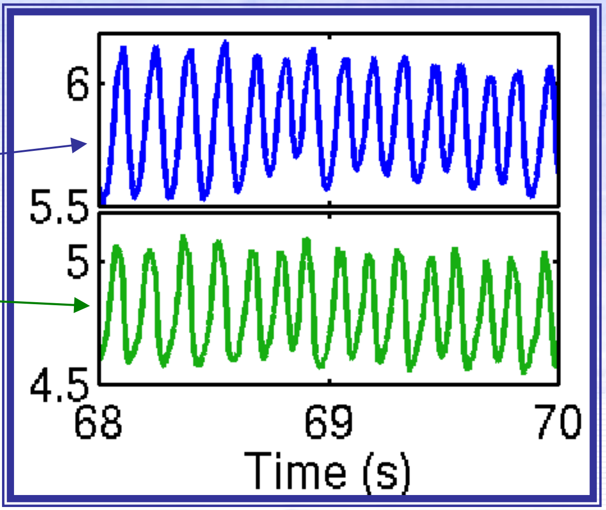
Relevant for ITER:

- Reliable screw extruder
- Pneumatic acceleration does not require large pumping system (<15 mbar.l for 2mm pellets up to 800 m/s)

# Slow temperature oscillations

Poster EX/P6-16 Imbeaux et al.



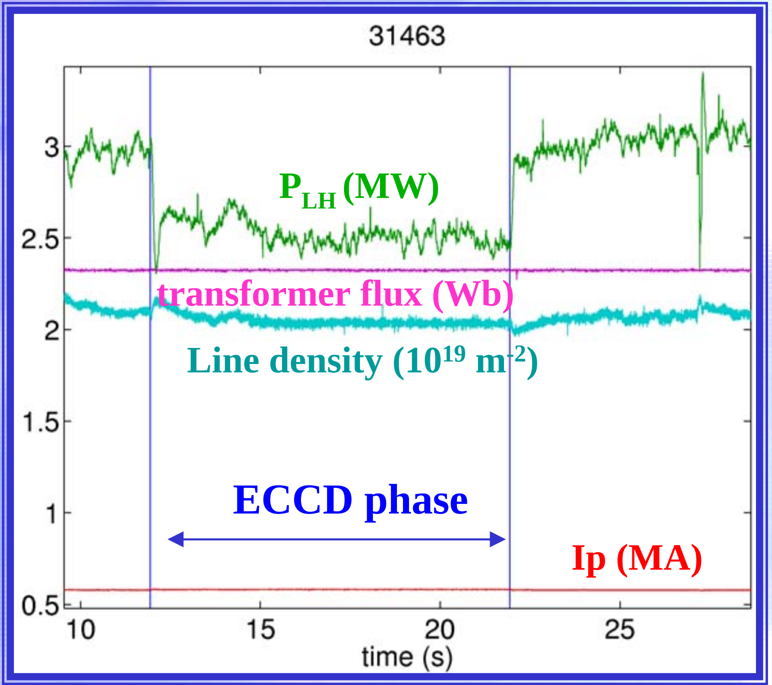

Radial structure, low frequency (a few Hz)

Non linear interplay between transport and current profile at the onset of the core ITB

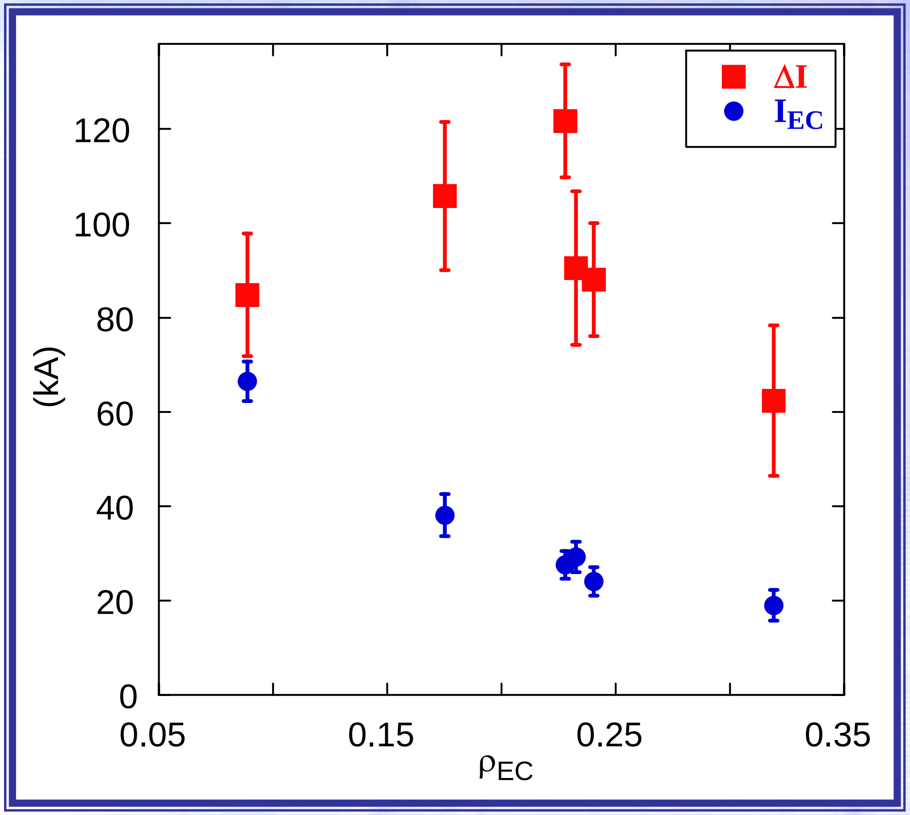
➔ RT control of current profile required (for ex, ECCD)

# Evident synergy ECCD &LHCD at Vloop = 0

(Giruzzi et al EX/P4-22)



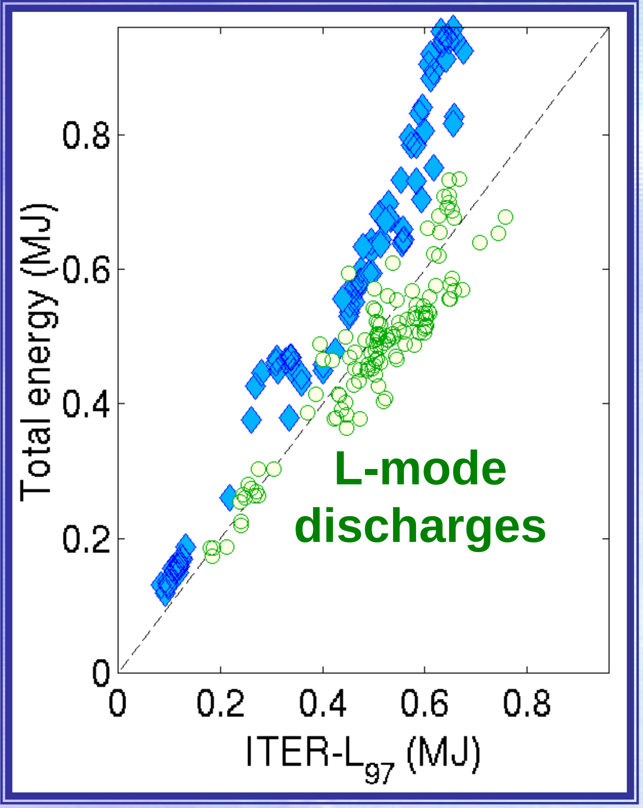

0.5 MW of LH power replaced by
0.7 MW of EC power to drive 80 kA




**Synergy when LH and EC waves absorbed at same location**

Promissing for NTM control using ECCD in ITER

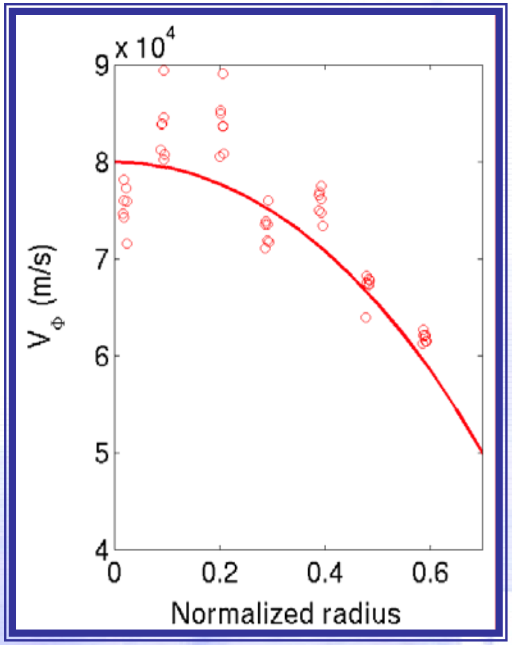
# Combined LHCD & ICRH




- Achieving 10 MW / 10s pulses
- Exhibit good L-mode, $H_L$ up to 1.7, when optimzing H minority concentration ($n_D/n_e$ ~6%):

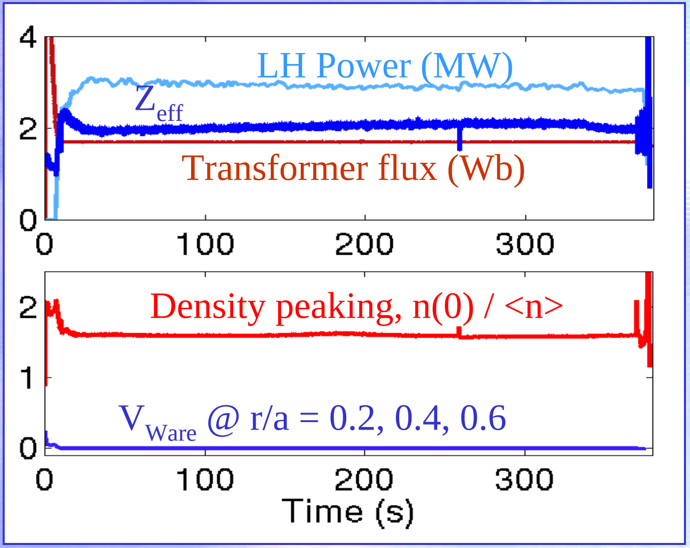
  Spontaneous toroidal co-rotation

  ITG & TEM stabilized by E×B shear (r/a <0.6)

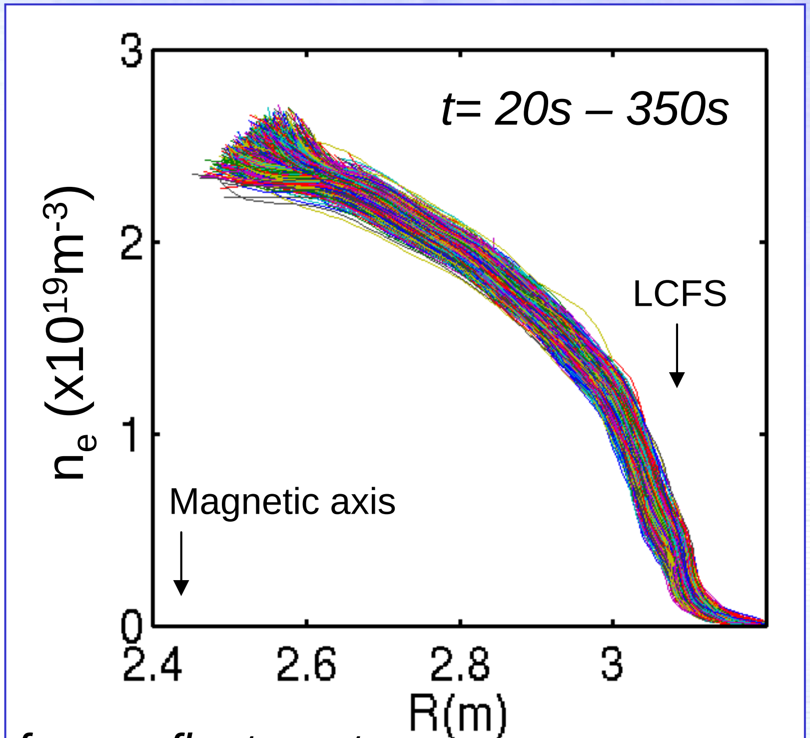



(C. Fenzi-Bonizec et al, 31st EPS Conf)

# Peaked density profile in absence of Ware pinch




Supression of Ware pinch over 6 minutes




*from reflectometry*

**R Sabot et al EX/P6-25**

No central source; $V_{neo}$ ~$10^{-3}$ m/s cannot explain peaked $n_e$ profile

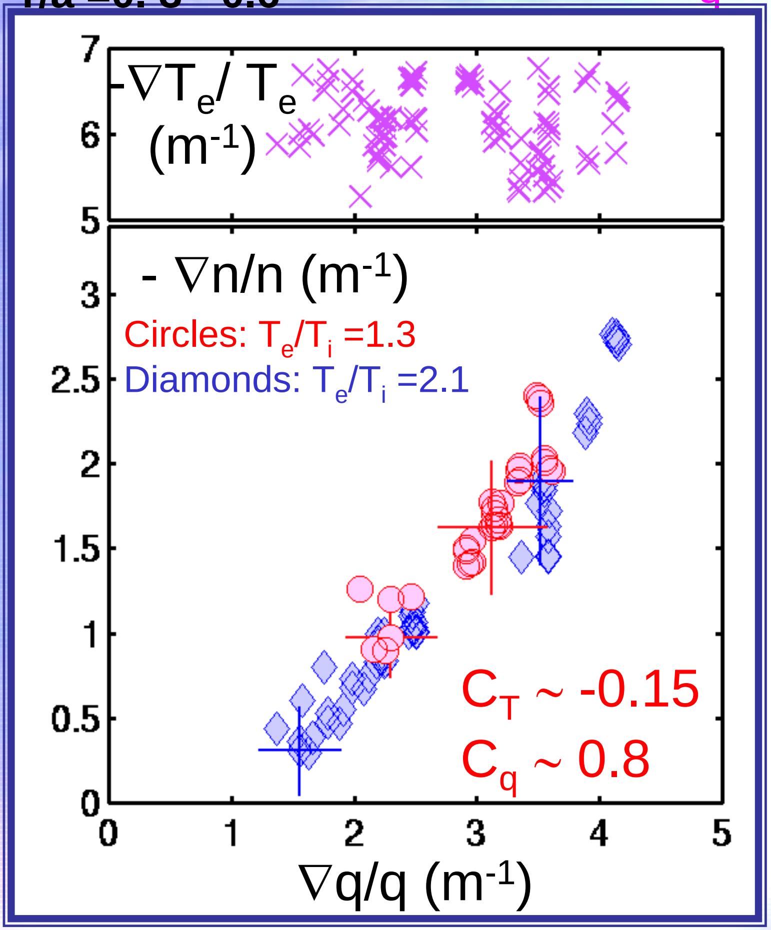
G.T. Hoang, Phys. Rev. Lett. 90 (2003)

# Turbulent pinch coefficients

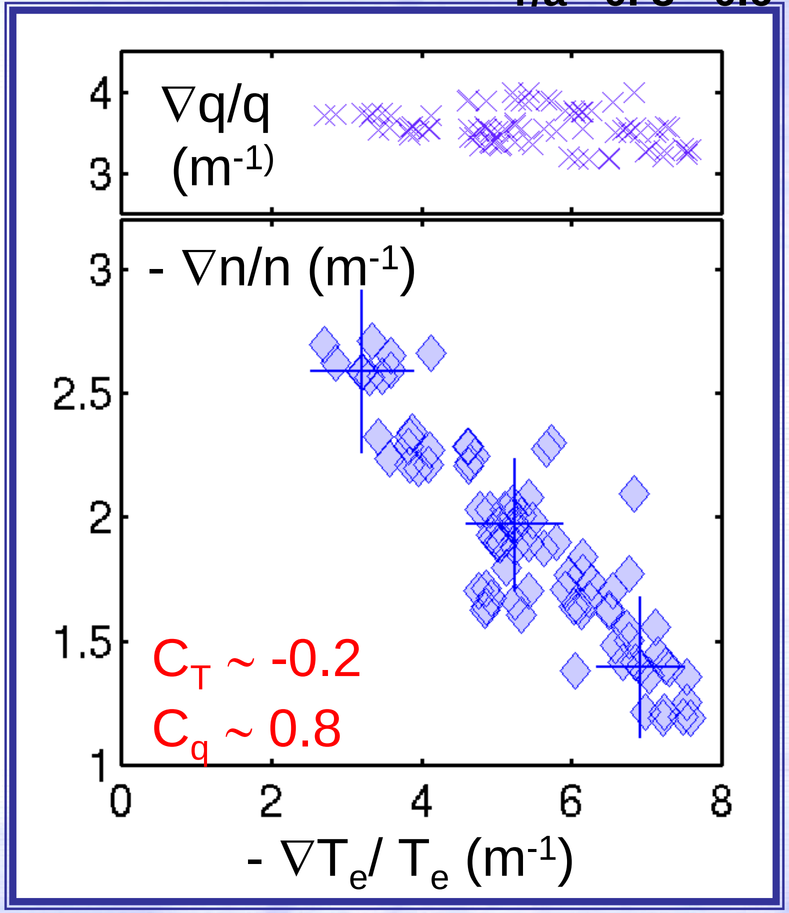
(G.T Hoang, EX8-2)

$$\nabla n/n = - C_q \nabla q/q + C_T \nabla T_e/T_e$$

r/a =0. 3 - 0.6




r/a =0. 3 - 0.6

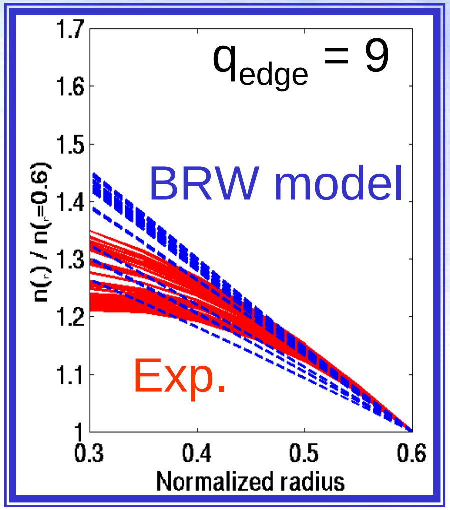


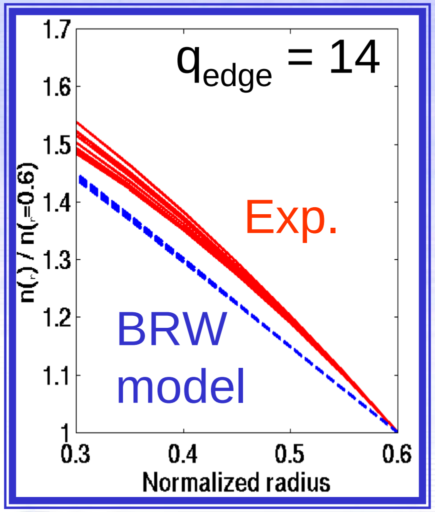

**$\nabla q/q$ term dominates**, consistent with TEM driven transport simulations

*G.T. Hoang, Phys. Rev. Lett. 93 (2004) X. Garbet, Phys. Rev. Lett. 91 (2003)*

# Extrapolation to ITER

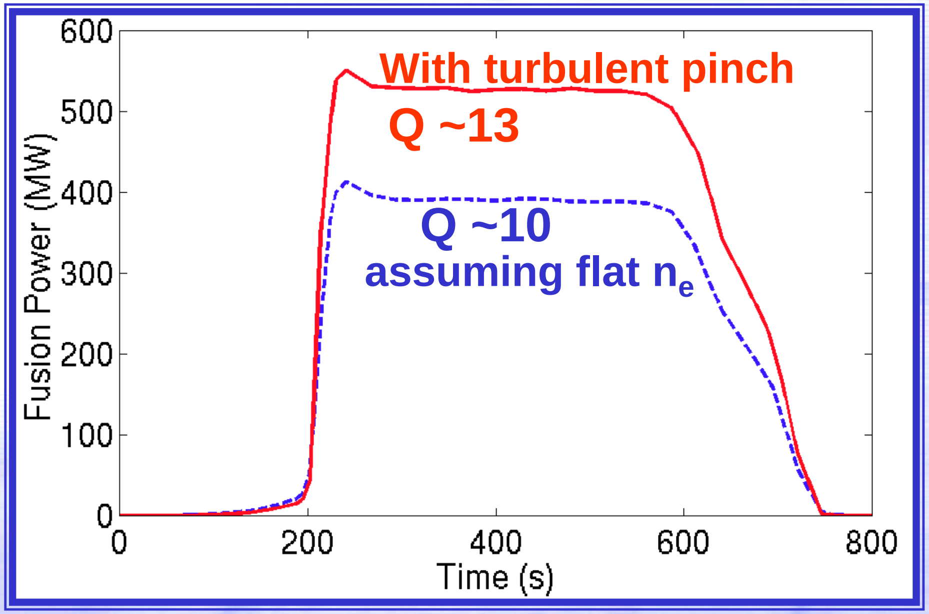
Tore Supra: $n \sim 1/q^{0.5}$
As found by Boucher, Rebut, Watkins for JET



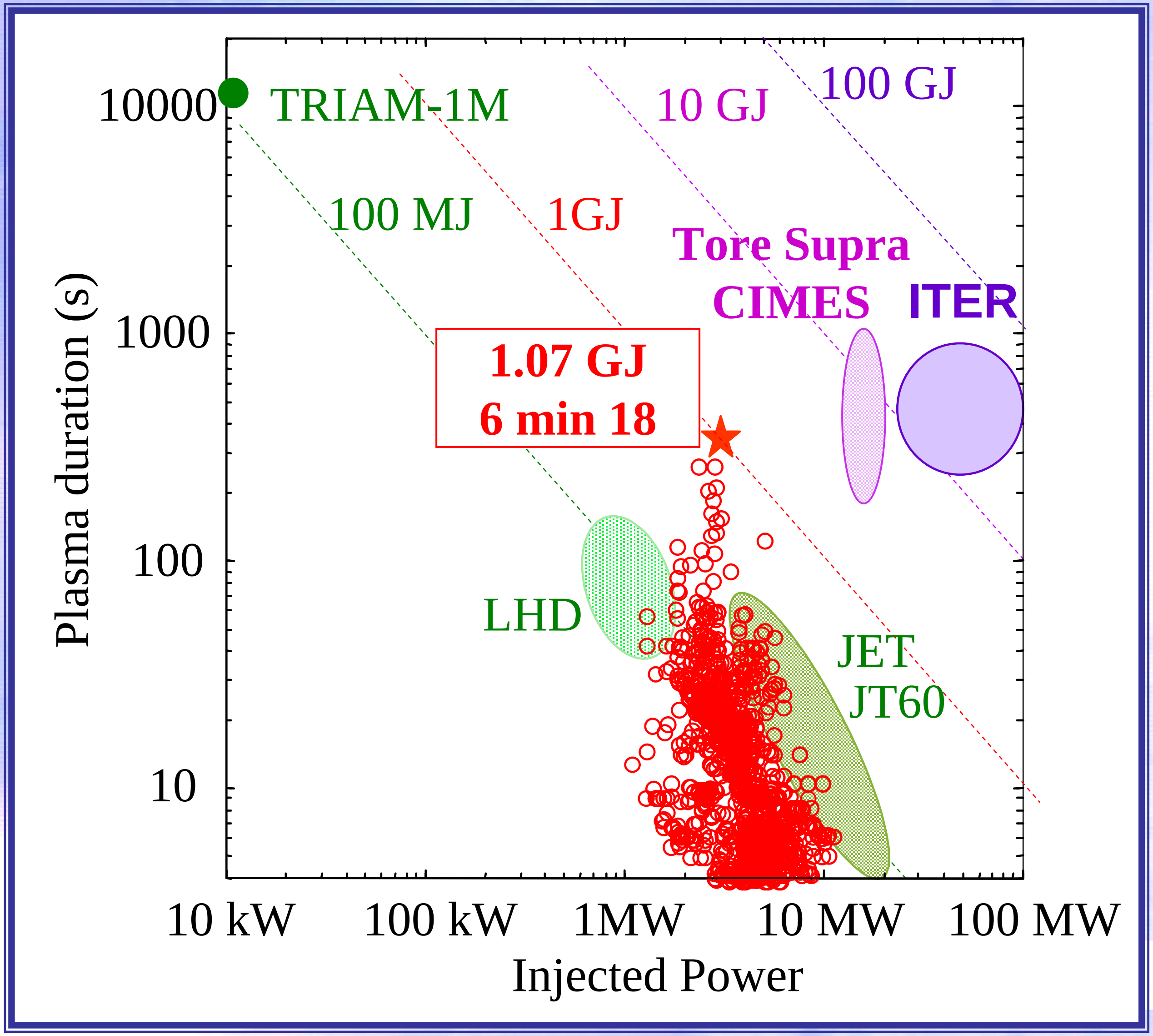




TEMs expected in ITER as in Tore Supra (similar effective collisionality related to detrapping of electrons)

→ Peaked $n_e$ → Fusion Power increased to 530 MW instead of 400 MW with a flat $n_e$ profile(ref. scenario)

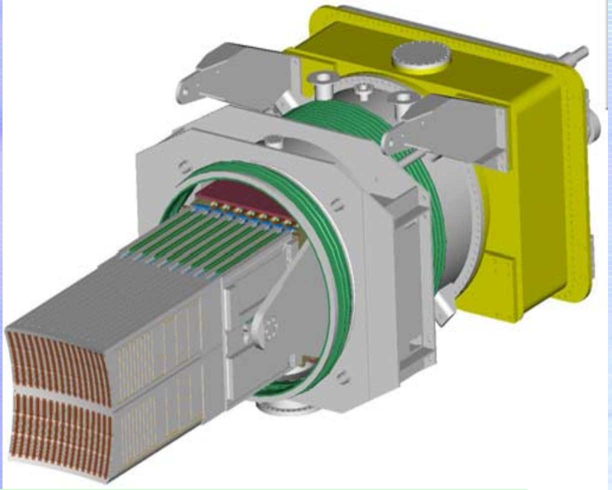


# Progress in Long Pulse Operation



# Tore Supra ongoing upgrades

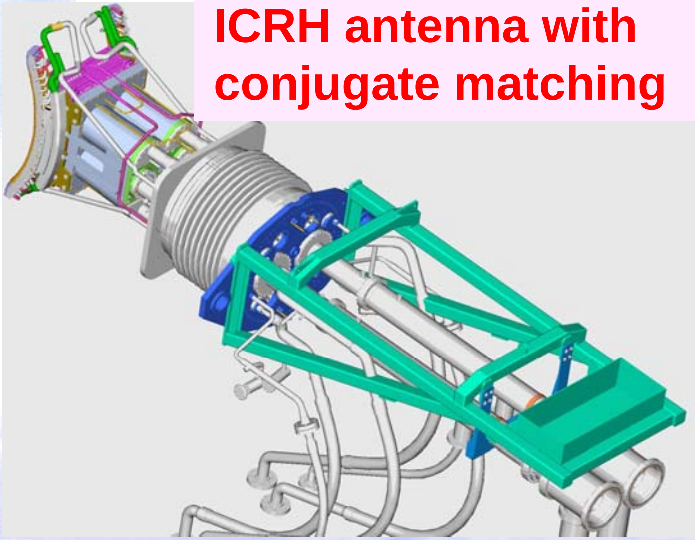
LHCD system



Passive Active Module (PAM)

700kW, 1000s, 3.7GHz Klystrons

400kW, 600s, gyrotrons

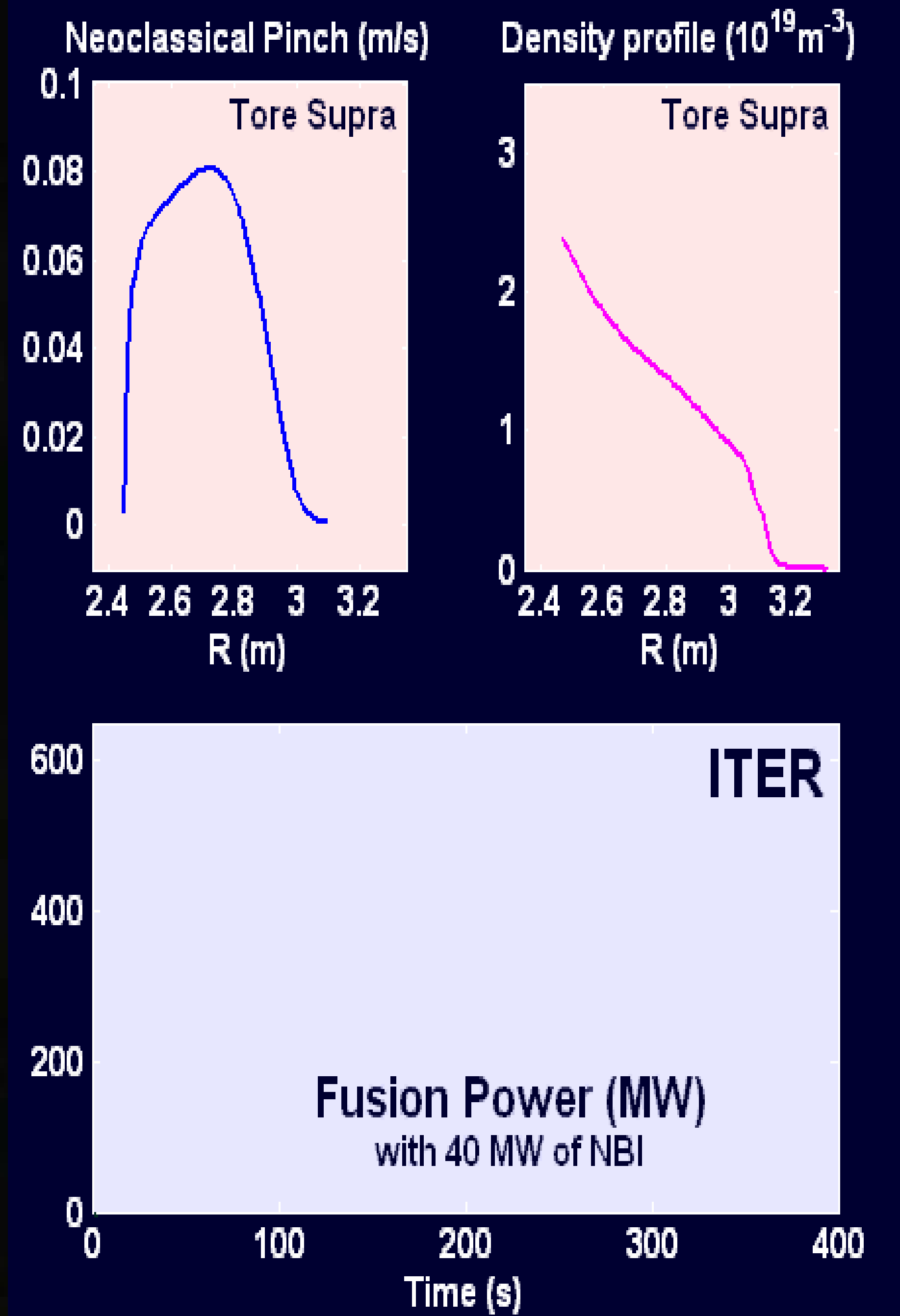


ICRH antenna with conjugate matching

# Conclusions

- Routine SS operation with superconducting coils, RF heating and thin walled PFC's
  - Coping with detailed in-vessel power deposition is tough!
  - Slow non-linear oscillations/bifurcations
  - Unexplained long lasting in-vessel retention of D (low density regime)
  - Turbulent particle pinch documented

    A gift from mother nature to ITER ?
- Exciting scientific developments in Cadarache in preparation of ITER


*CRONOS, Association Euratom-CEA*

- G.T. Hoang, **EX8-2** ***Turbulent Particle Transport in Tore Supra*** **Fri.**
- E. Tsitrone, **EX10-1** ***Deuterium retention in Tore Supra long discharges*** **Sat.**
- D. van Houtte, **EX/P4-14** ***Real Time Control of Fully Non-Inductive 6 minute, 1 Gigajoule Plasma Discharges in Tore Supra*** **Thurs.**
- G. Giruzzi, **EX/P4-22** ***Synergy between EC and LH Current Drive on Tore Supra*** **Thurs.**
- F. Imbeaux, **EX/P6-16** ***Non-linear electron temperature oscillations on Tore Supra: experimental observations and modelling by the CRONOS code*** **Fri.**
- R. Sabot **EX/P6-25** ***Measurements of density profiles and density fluctuations in Tore Supra with refclectometry*** **Fri.**
- T. Loarer **EX/P5-22** ***Overview of gas balance in Plasma Fusion devices*** **Fri.**
- G. Martin, **EX/10-6Rc** ***Disruption&Mitigration in Tore Supra*** **Sat.**
- Ph. Ghendrih, **TH 1-3** ***Relaxation & Transport in Fusion Plasmas*** **Thurs.**
- Y. Sarazin, **TH/P6-7** ***Interplay between density profile and zonal flows in drift kinetic simulations of slab ITG turbulent*** **Fri. & Sat**
- Ph. Ghendrih, **TH/1-3Ra** ***Scaling Intermittent Cross-Field Particle Flux to ITER*** **Thurs.**
- S. Benkadda, **TH/1-3Rb** ***Nonlinear Dynamics of Transport Barrier Relaxations in Fusion Plasmas*** **Thurs.**
- M. Bécoulet, **TH/1- 3Rc** ***Non-linear Heat Transport Modelling with Edge Localized Modes and Plasma Edge Control in Tokamaks*** **Thurs.**
- G. Falchetto, **TH/1-3Rd** ***Impact of Zonal Flows on Turbulent Transport in Tokamaks*** **Thurs.**