

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

J Jacquinet on behalf of the Tore-Supra Team



- 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:

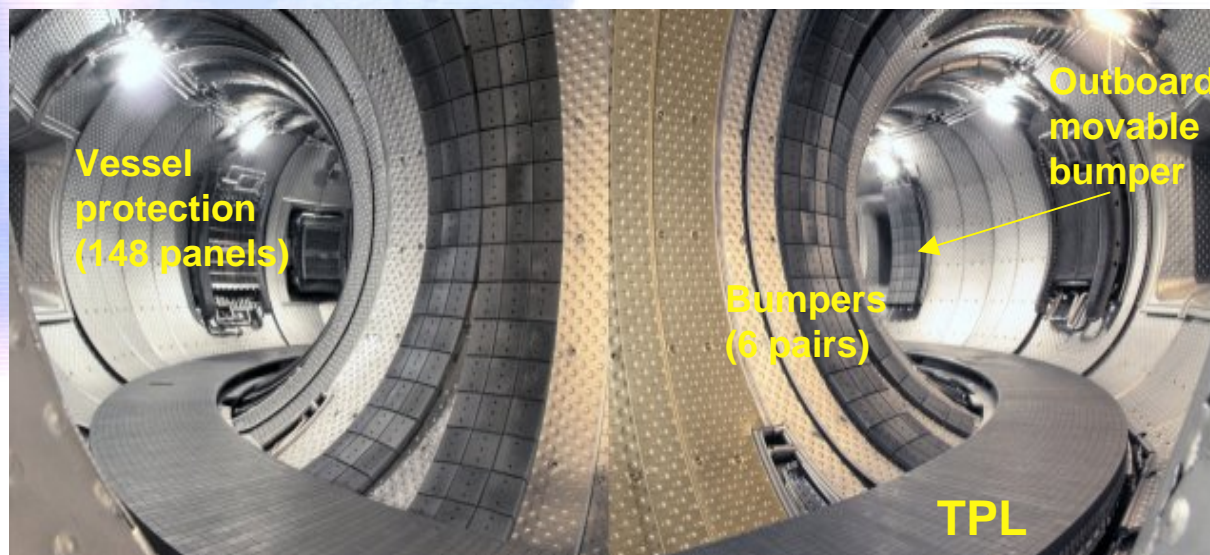
- $V_{loop} \sim 0$, no Ware pinch
- Slow interplay between particle/energy transports and current profile
 - **Irreversible bifurcations** → stable conditions require feedback

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

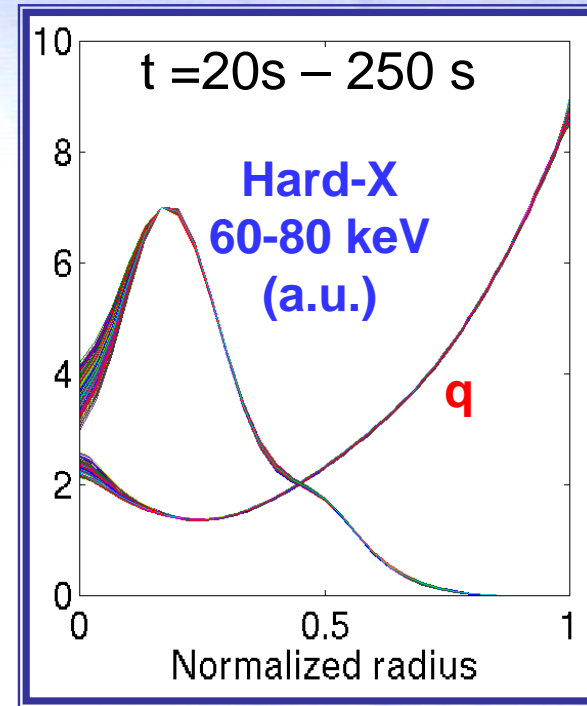
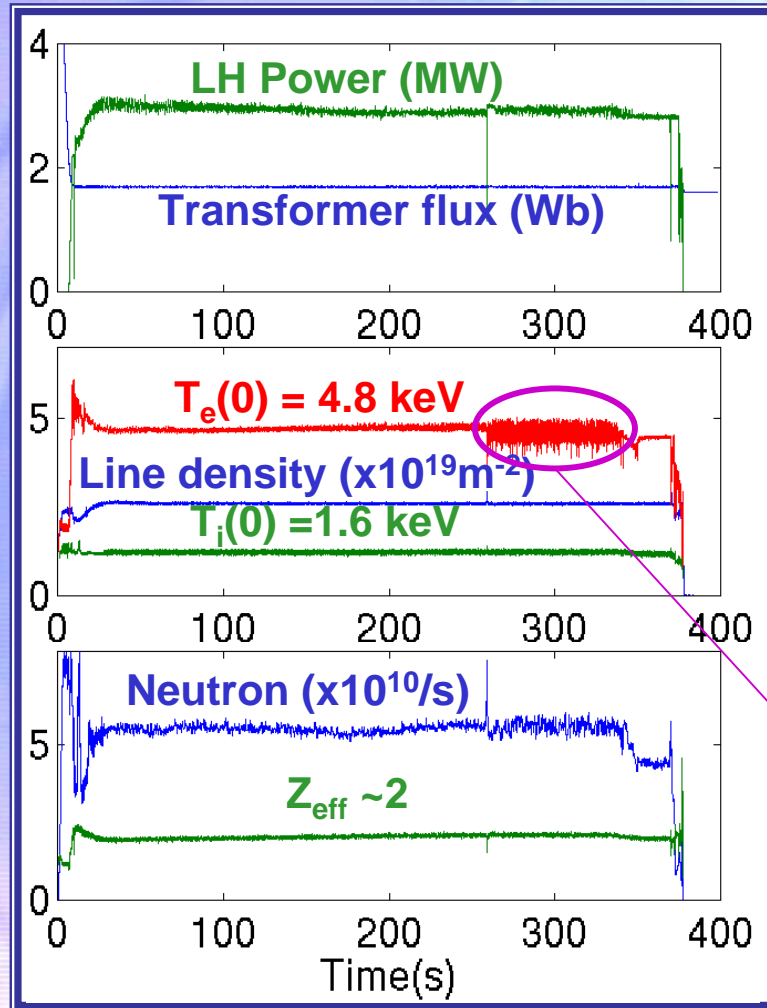
- Toroidal Pumped Limiter; heat exhaust capability 15 MW (10 MWm^{-2})
- Vessel protection against thermal radiation and plasma contact
- 10 actively cooled neutralizers below the TPL; max. flux 15 MW/m^2 ; total pumping speed $20 \text{ m}^3/\text{s}$
- 30 Diagnostics (actively cooled also)





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

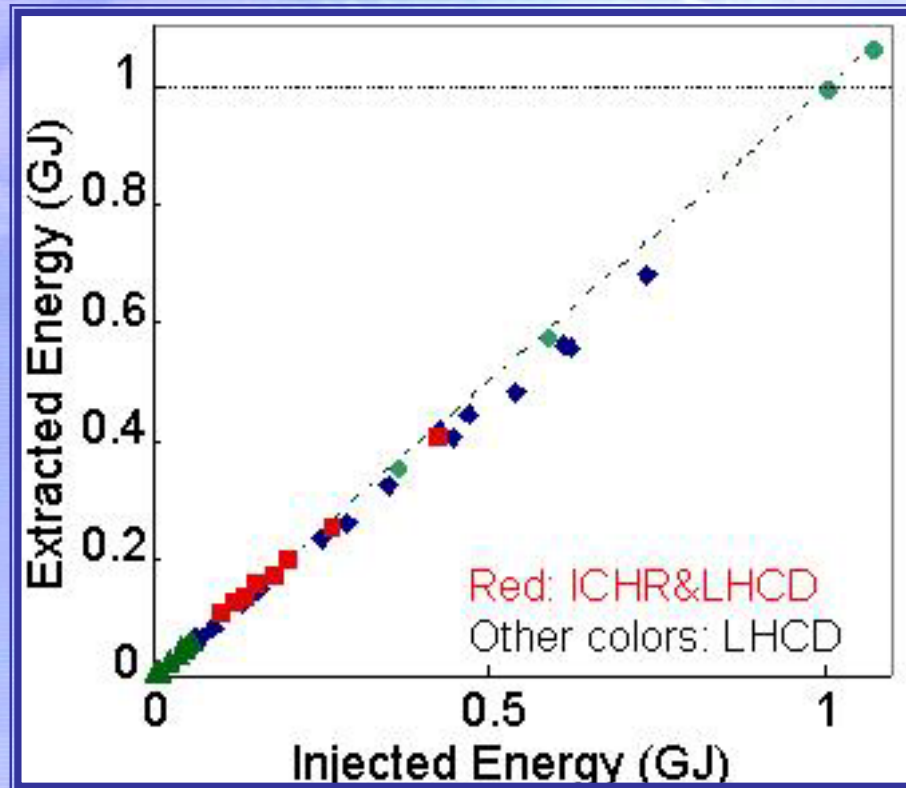
(Van Houtte, poster EX/P4-14)



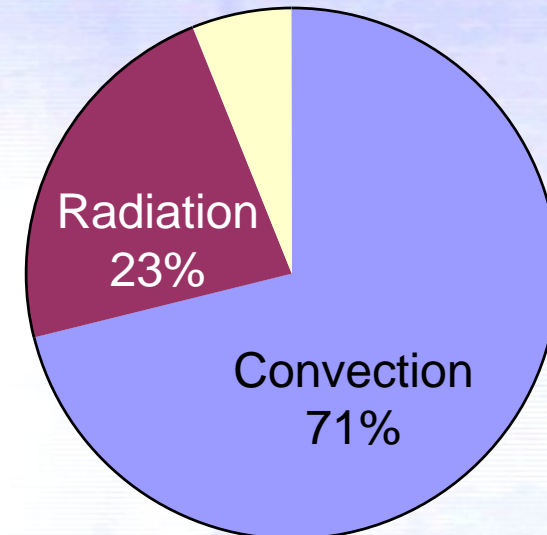
Stable plasma until 258s
then MHD activities
switched on (no effect on
global confinement)



Heat Exhaust



Fast particle losses



~ 50% on the TPL (7 m²)

25% on the first wall panels (75 m² with the bumpers)

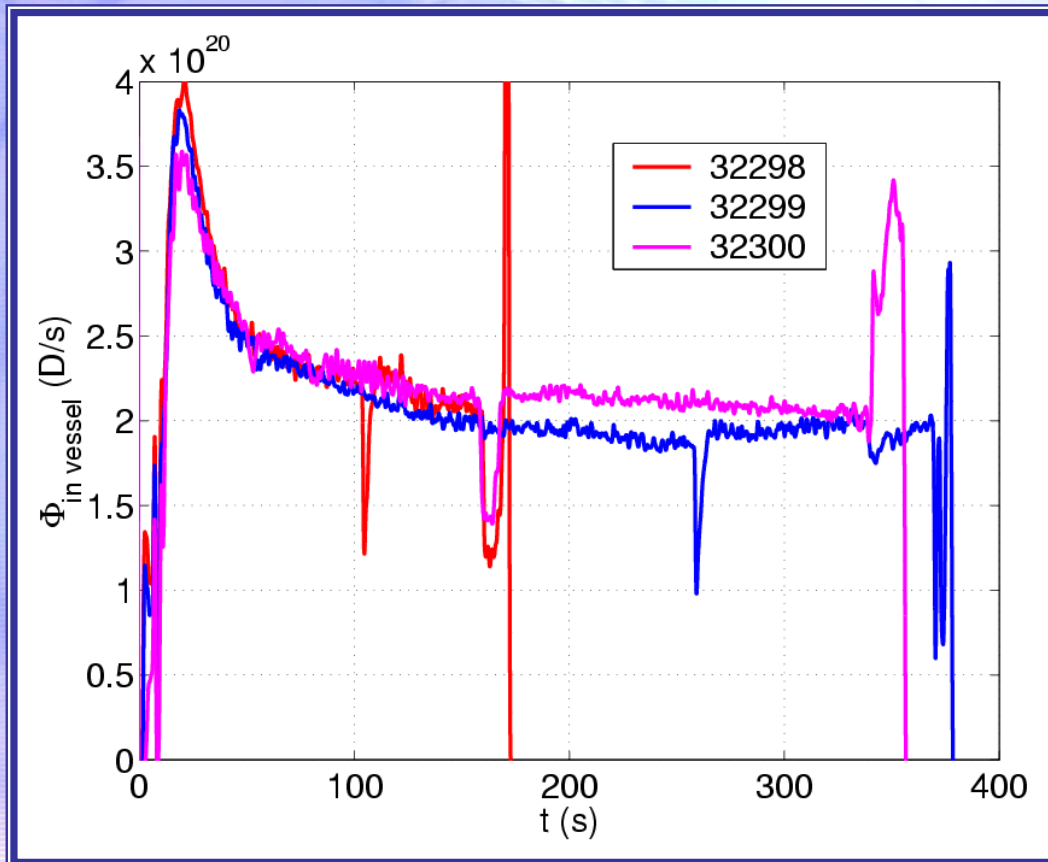
25% shared between the outboard limiter and antennas

Beware of fast particles: ripple and later alphas!



Particle retention (Tsitrone, EX10-2)

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



Phase 1: Decreasing retention rate → filling carbon porosities

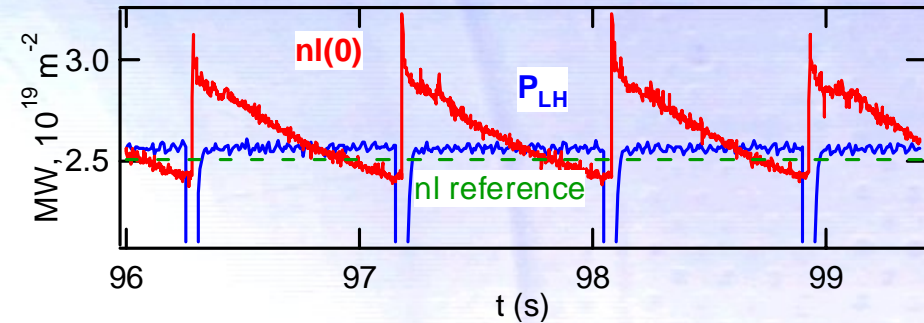
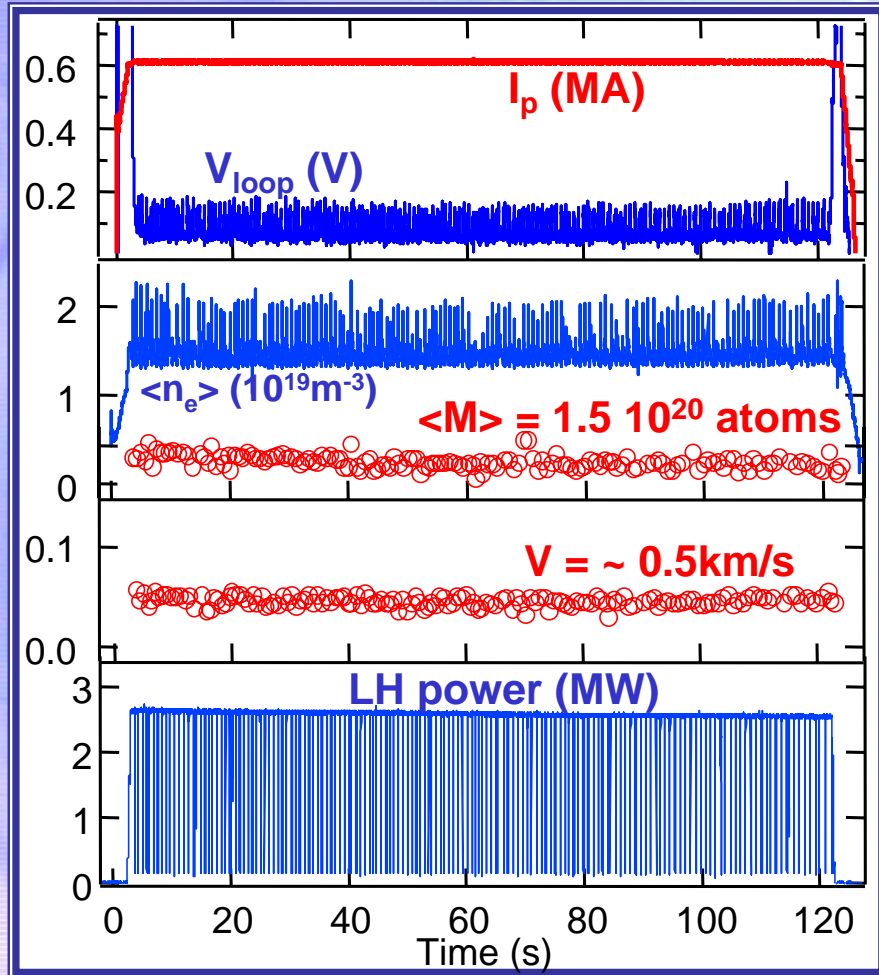
Phase 2: Constant retention rate : $2 \cdot 10^{20} D s^{-1}$ (= 50% of injected flux) → co-deposition observed but not enough (deep penetration in carbon?)

In vessel inventory : up to $8 \cdot 10^{22} D$ 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



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**

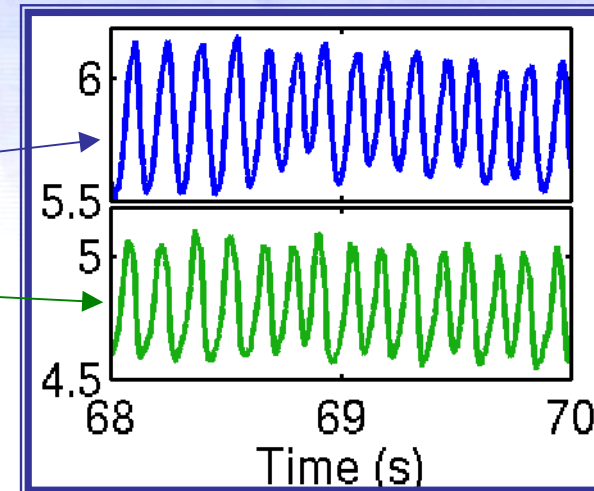
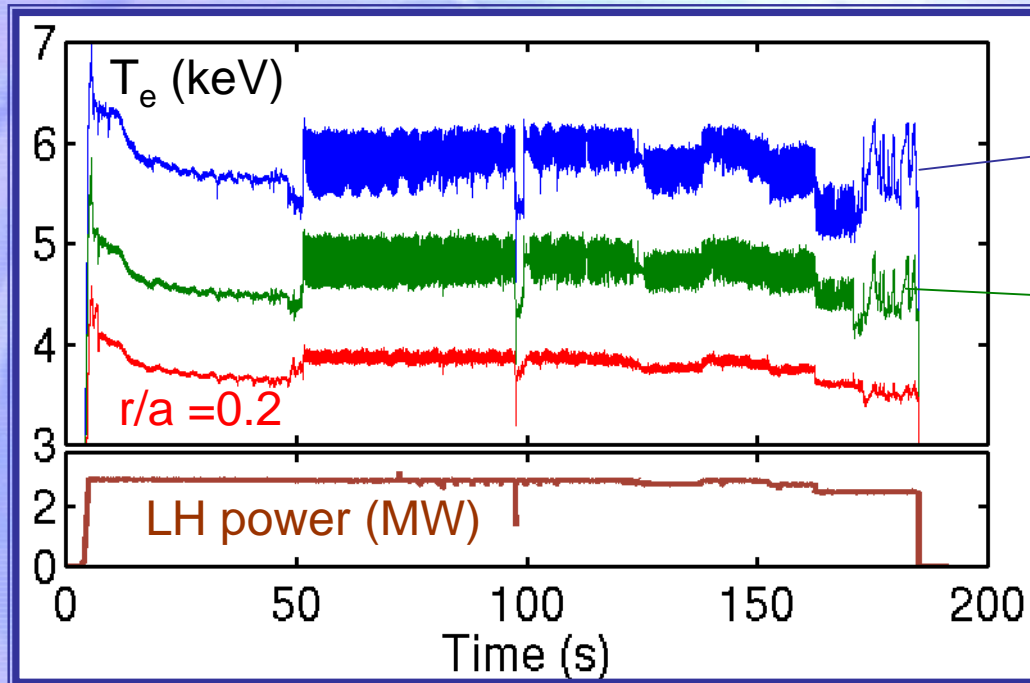
Relevant for ITER:

- 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

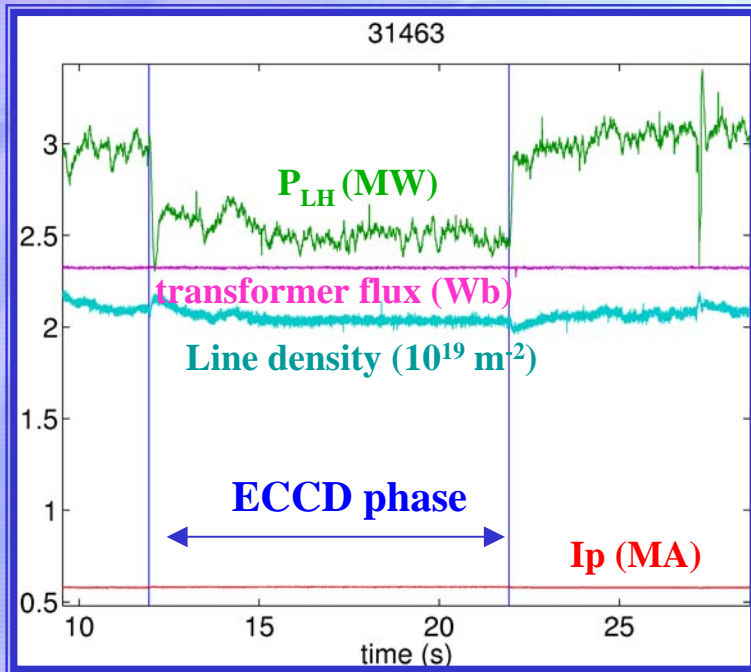
→ RT control of current profile required (for ex, ECCD)



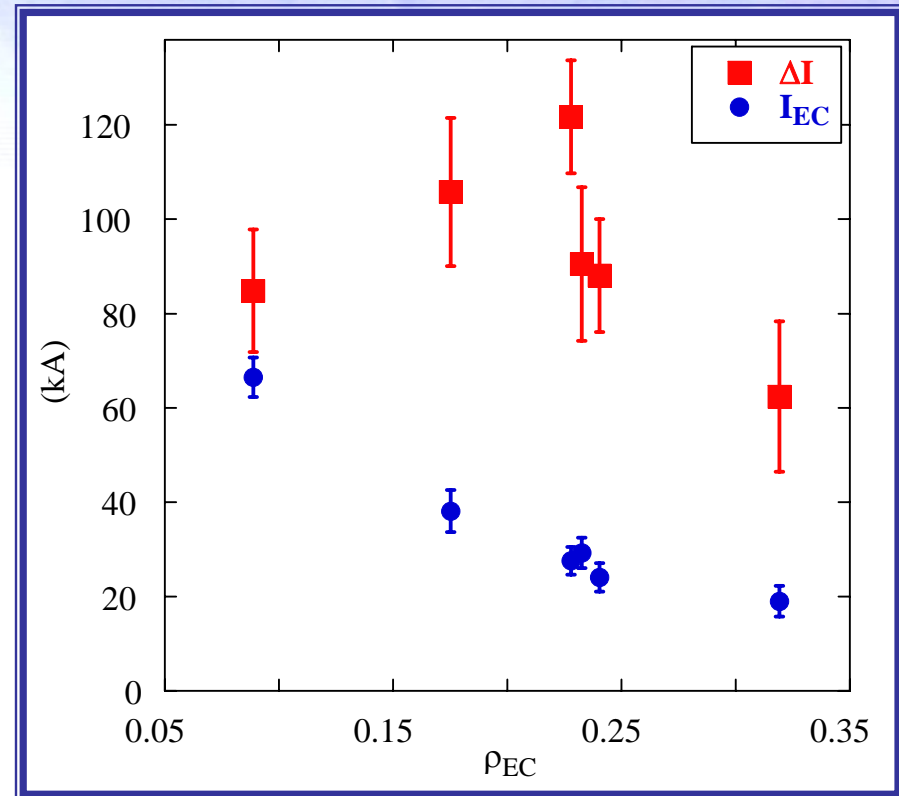
Evident synergy ECCD & LHCD

at $V_{loop} = 0$

(Giruzzi et al EX/P4-22)



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

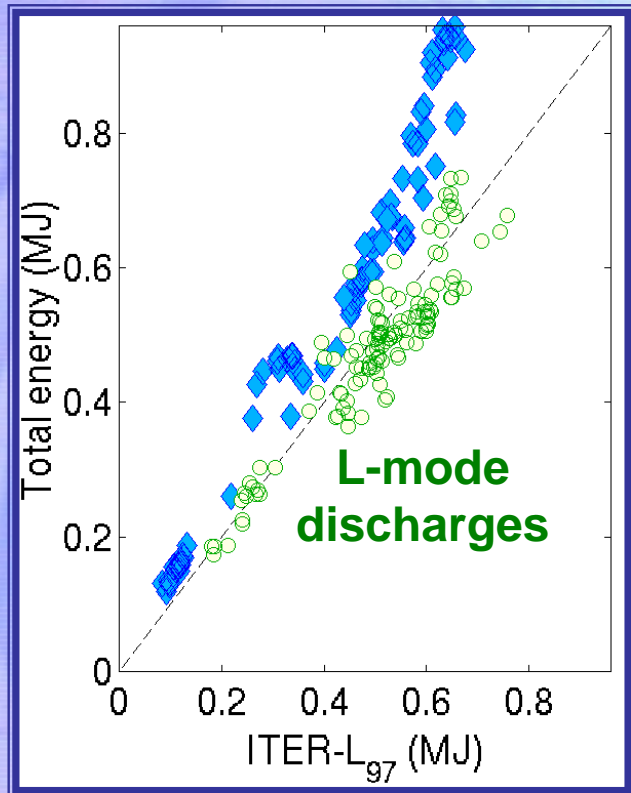


Synergy when LH and EC waves
absorbed at same location

Promising for NTM control using ECCD in ITER

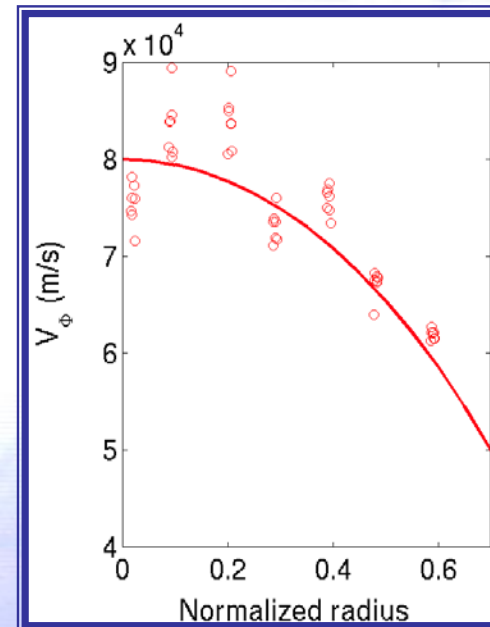


Combined LHCD & ICRH



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

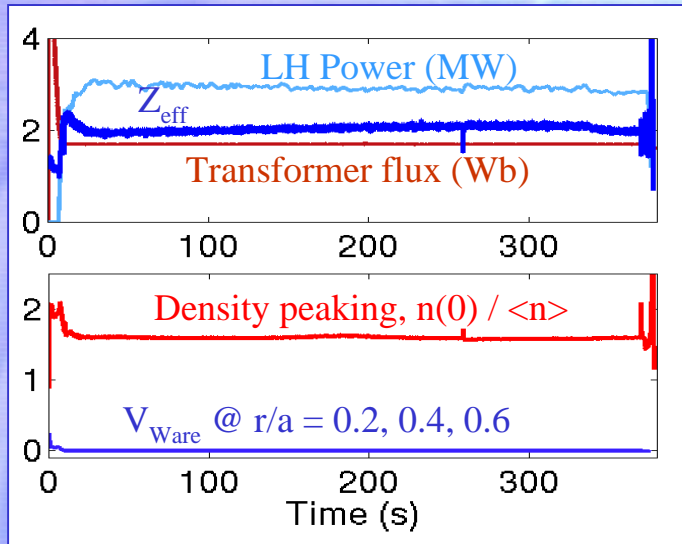
Spontaneous toroidal co-rotation
ITG & TEM stabilized by $E \times B$ shear ($r/a < 0.6$)



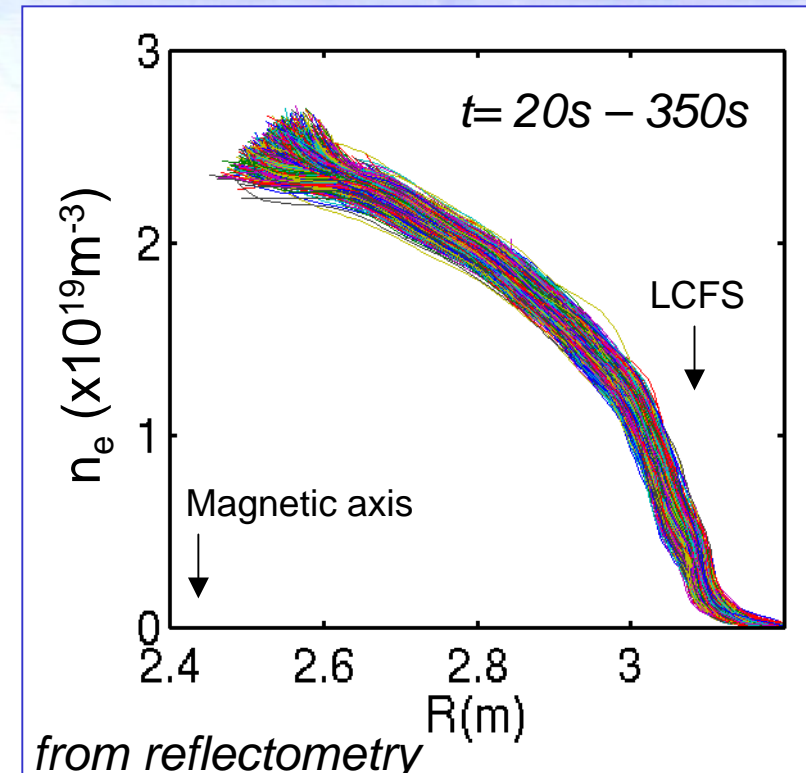
(C. Fenzi-Bonizec et al, 31st EPS Conf)



Peaked density profile in absence of Ware pinch



Suppression of Ware pinch
over 6 minutes



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

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

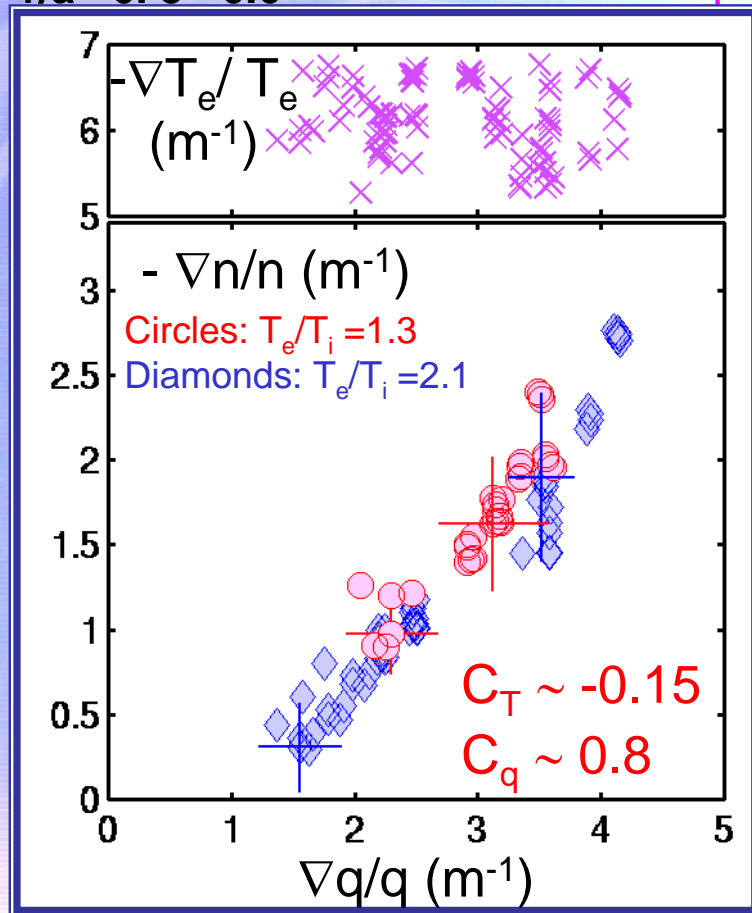


Turbulent pinch coefficients

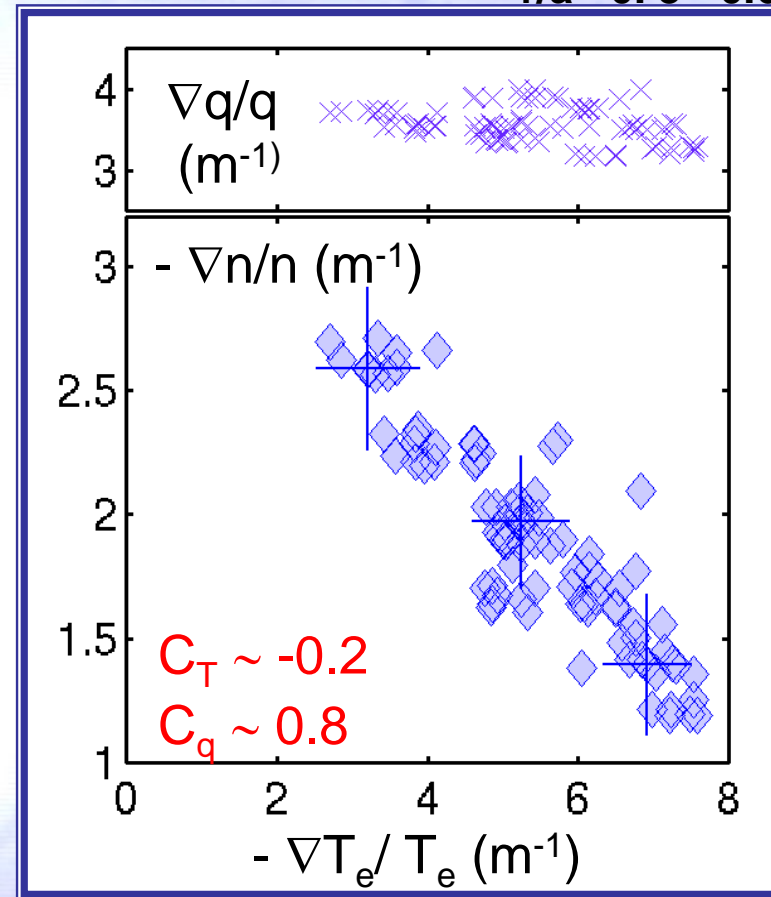
(G.T Hoang, EX8-2)

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

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)

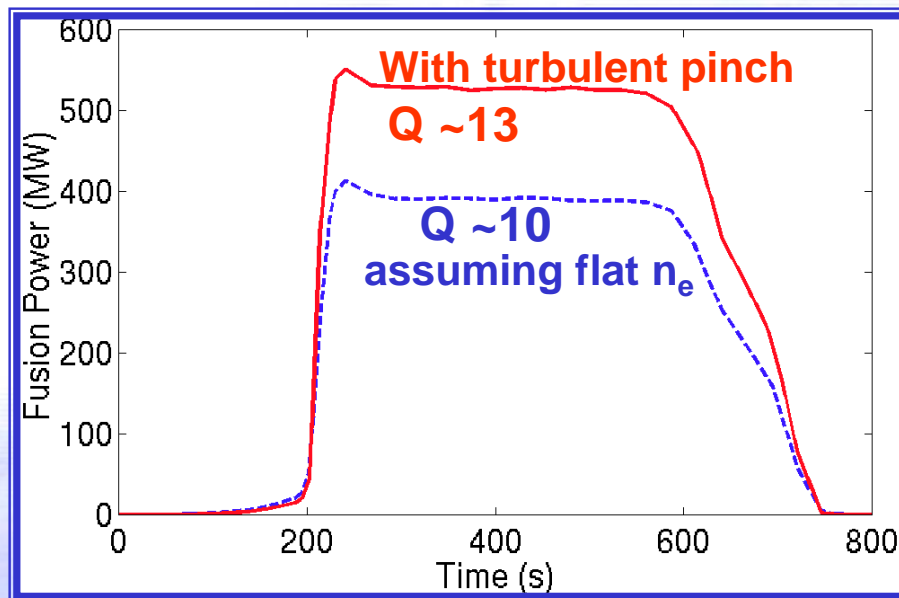
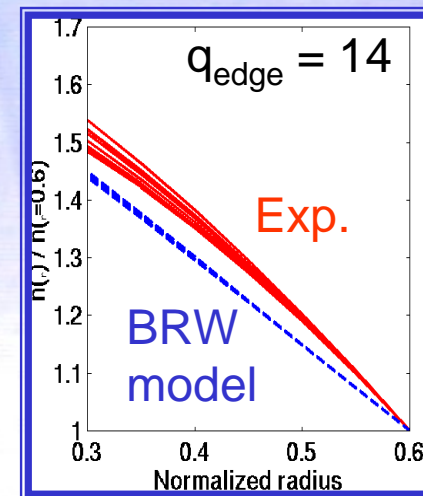
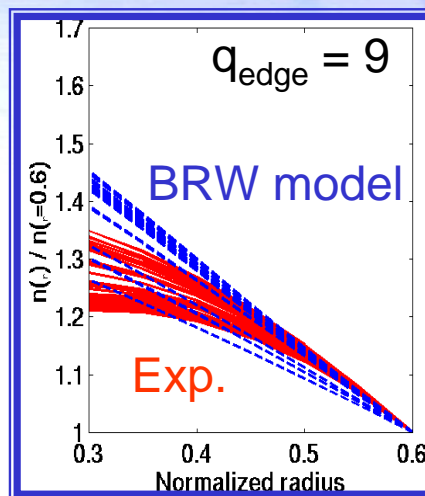


Extrapolation to ITER

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

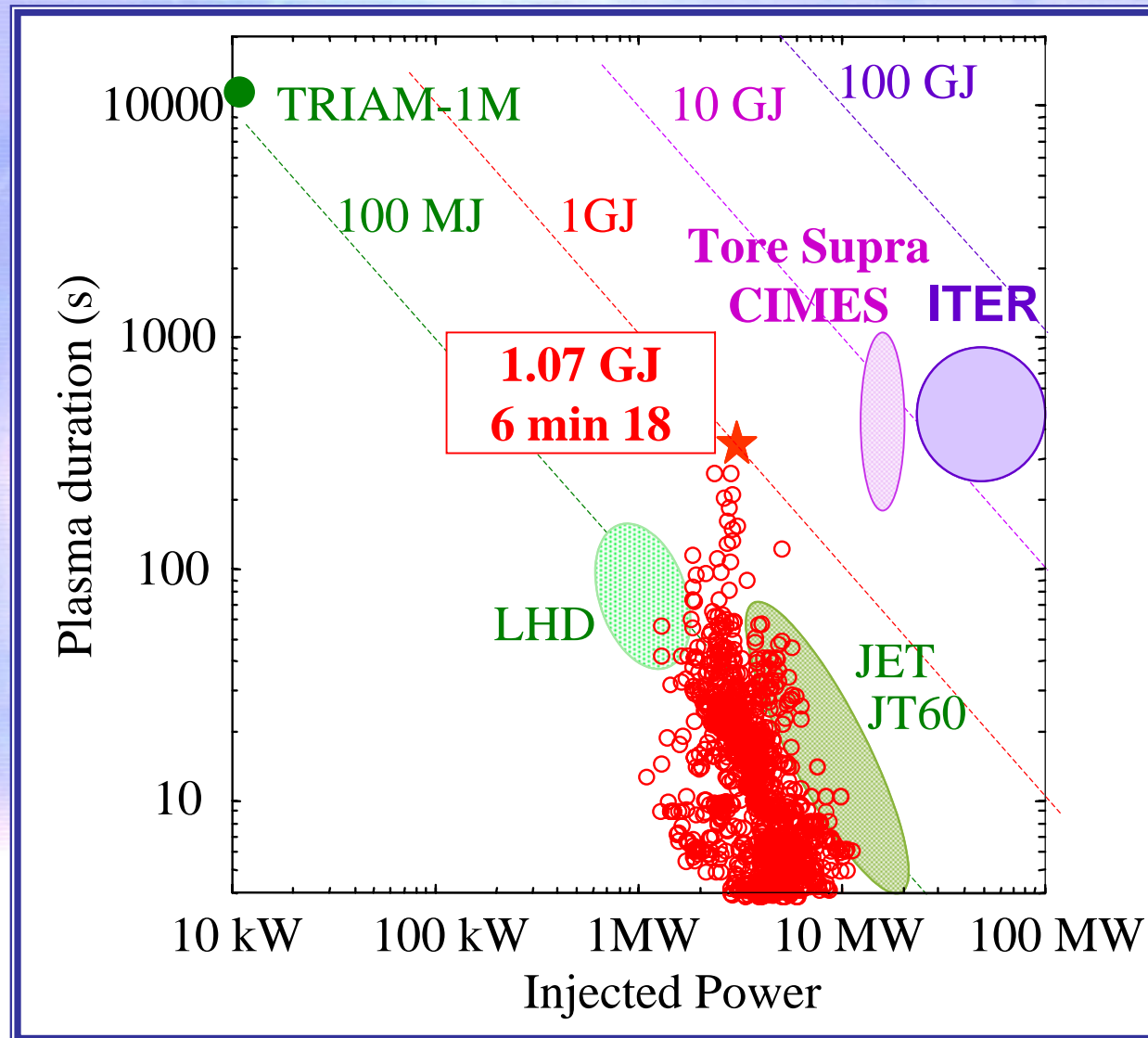
TEMs expected in ITER as in
Tore Supra (similar effective
collisionality related to detrapping
of electrons)

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



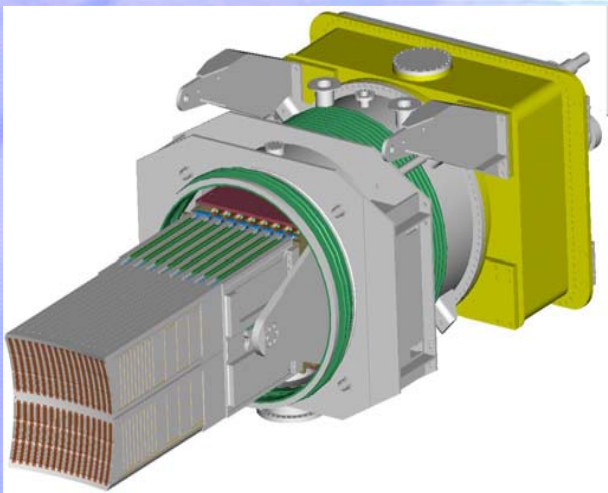


Progress in Long Pulse Operation



Tore Supra ongoing upgrades

LHCD system



Passive Active Module (PAM)

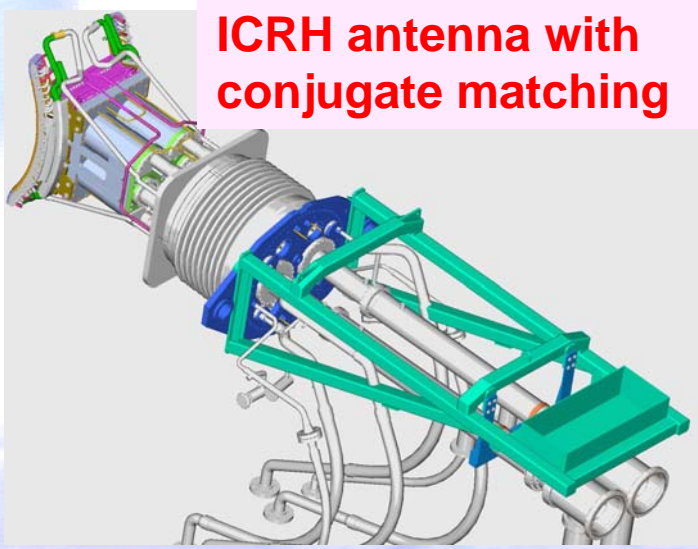


700kW, 1000s,
3.7GHz Klystrons



400kW, 600s,
gyrotrons

ICRH antenna with conjugate matching



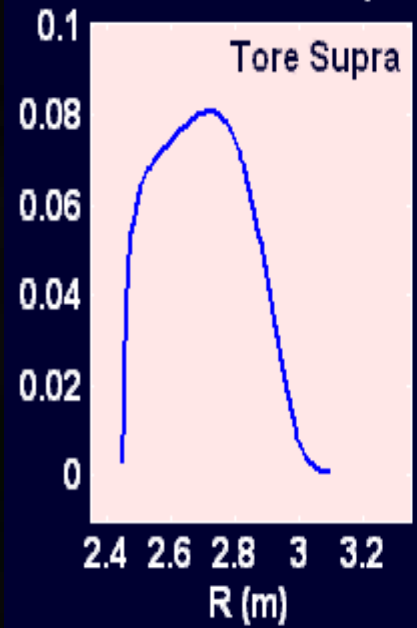


Conclusions

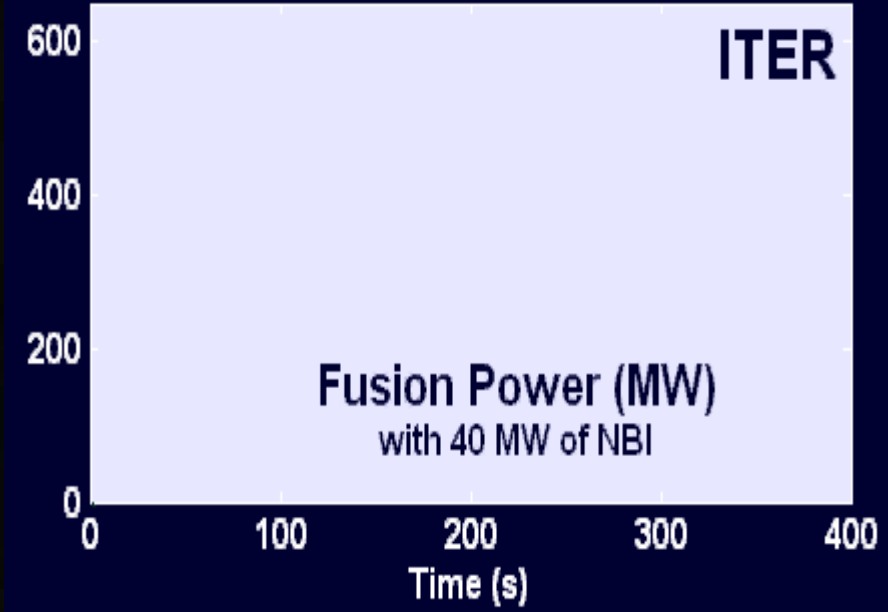
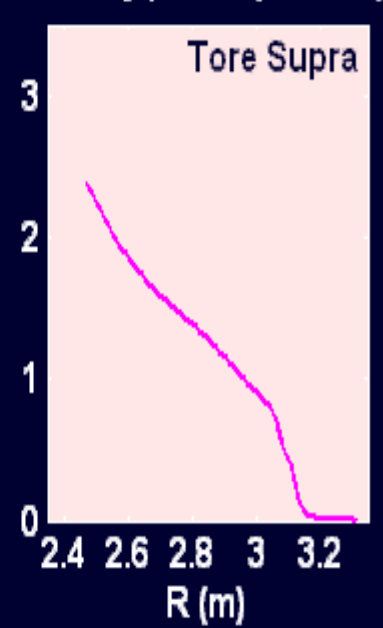
- Routine SS operation with superconducting coils, RF heating and thin walled PFC's
 - Coping with detailed **in-vessel power deposition** is tough!
 - Slow **non-linear oscillations/bifurcations**
 - Unexplained long lasting in-vessel retention of D (low density regime)
 - Turbulent particle pinch documented

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

Neoclassical Pinch (m/s)



Density profile (10^{19} m^{-3})



12-02 18:06:35:05

- 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 reflectometry* Fri.
- T. Loarer **EX/P5-22** *Overview of gas balance in Plasma Fusion devices* Fri.
- G. Martin, **EX/10-6Rc** *Disruption&Mitigation 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.