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

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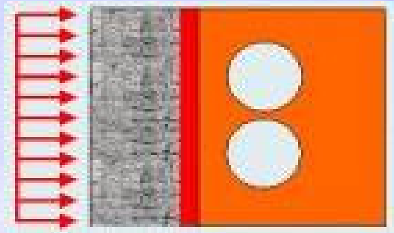
Steady state issues

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:

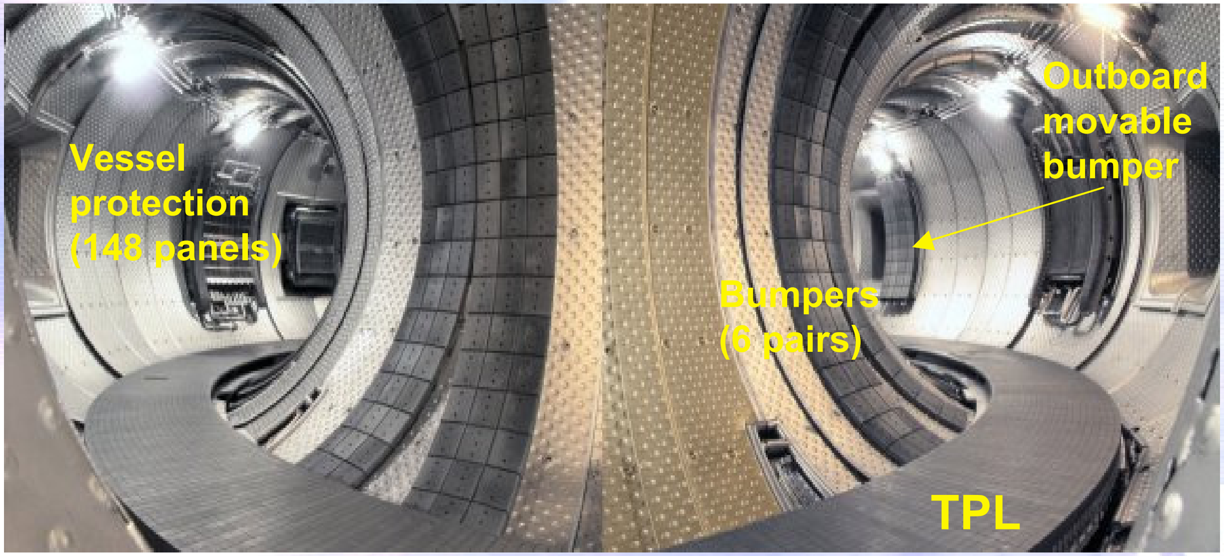
- V_{loop} ~ 0, no Ware pinch
- Slow interplay between particle/energy transports and current profile
  - **Irreversible bifurcations** ➔ stable conditions require feedback

Active new area of research

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

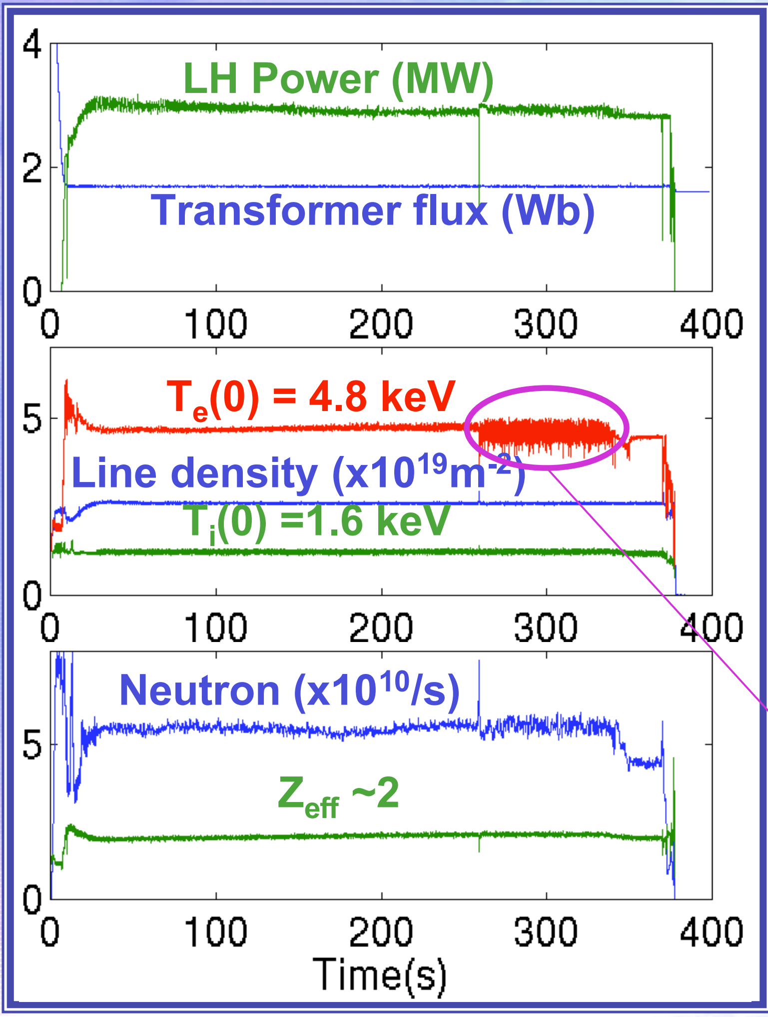
TORE SUPRA 2004

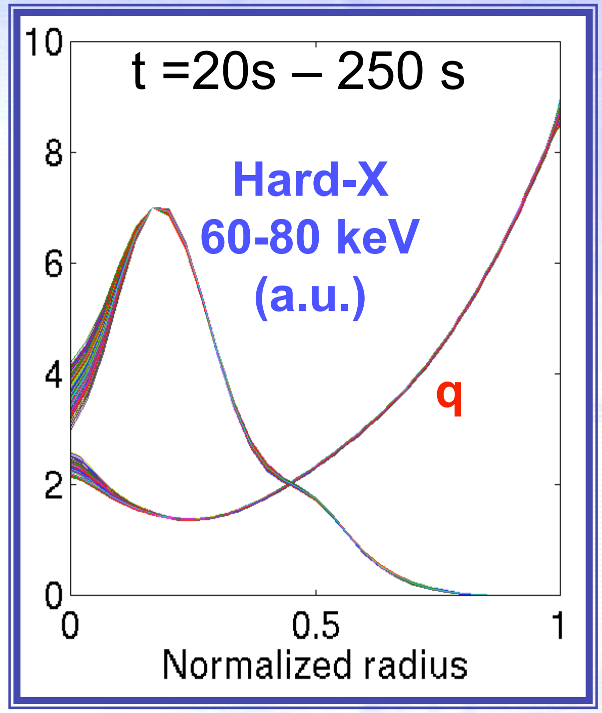
- Toroidal Pumped Limiter; heat exhaust capability 15 MW (10 MWm^{-2})
- Vessel protection against thermal radiation and plasma contact
- 10 actively cooled neutralizers below the TPL; max. flux 15 MW/m^2; total pumping speed 20 m^3/s
- 30 Diagnostics (actively cooled also)



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

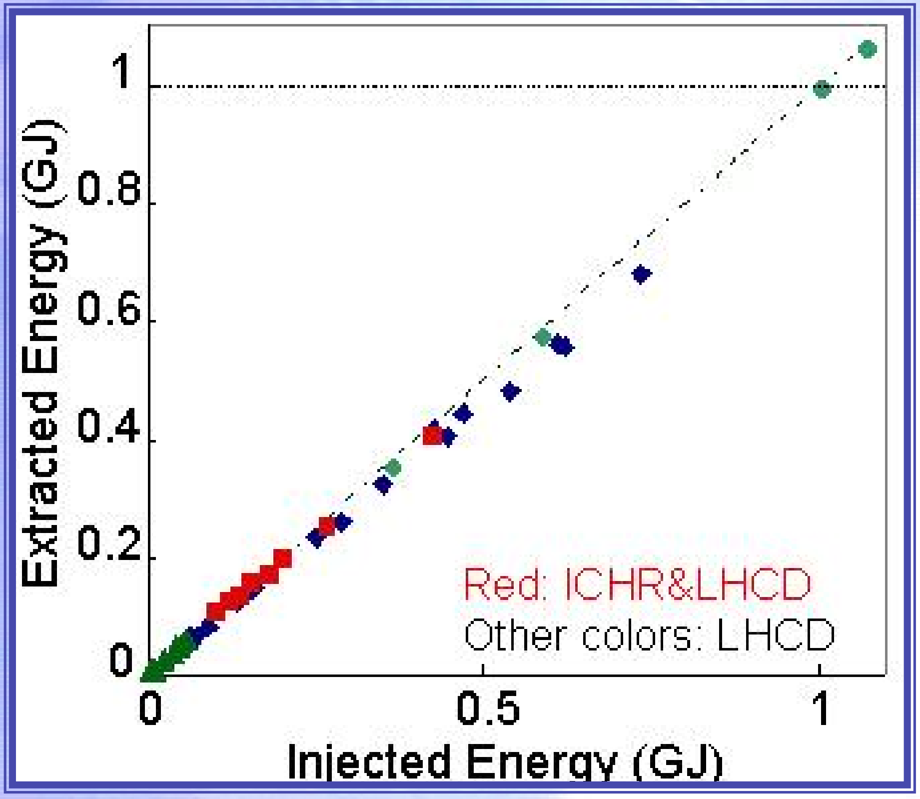
(Van Houtte, poster EX/P4-14)



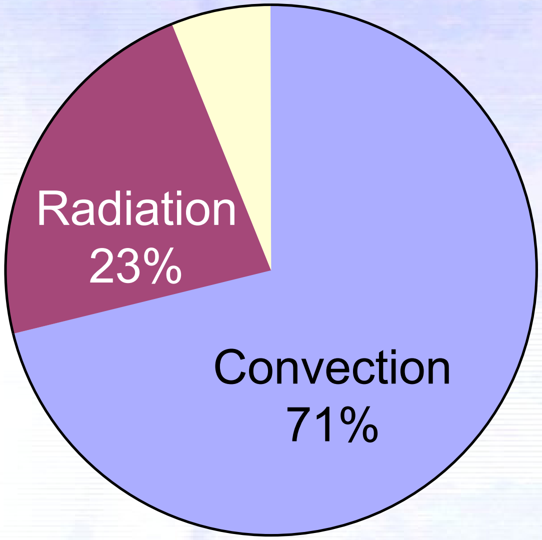


Stable plasma until 258s then MHD activities switched on (no effect on global confinement)

Heat Exhaust



Fast particle losses



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

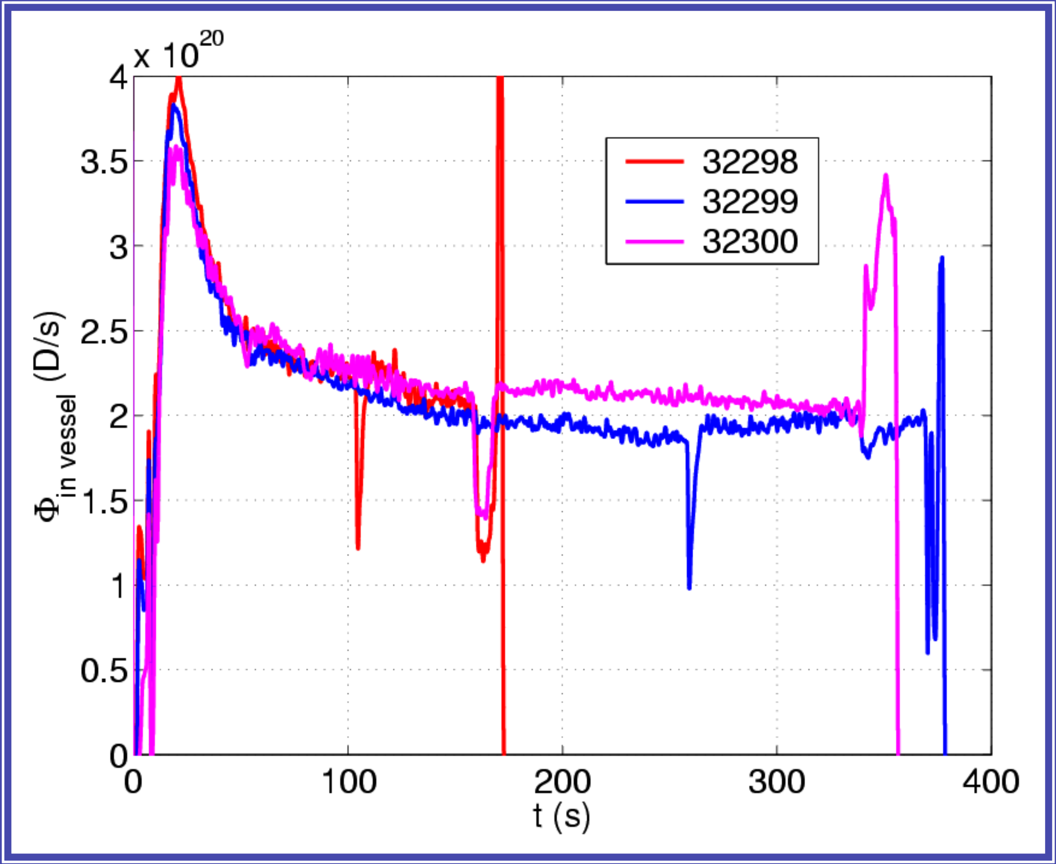
25% on the first wall panels (75 m^2 with the bumpers)

25% shared between the outboard limiter and antennas

Beware of fast particles: ripple and later alphas!

Particle retention (Tsitrone, EX10-2)

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



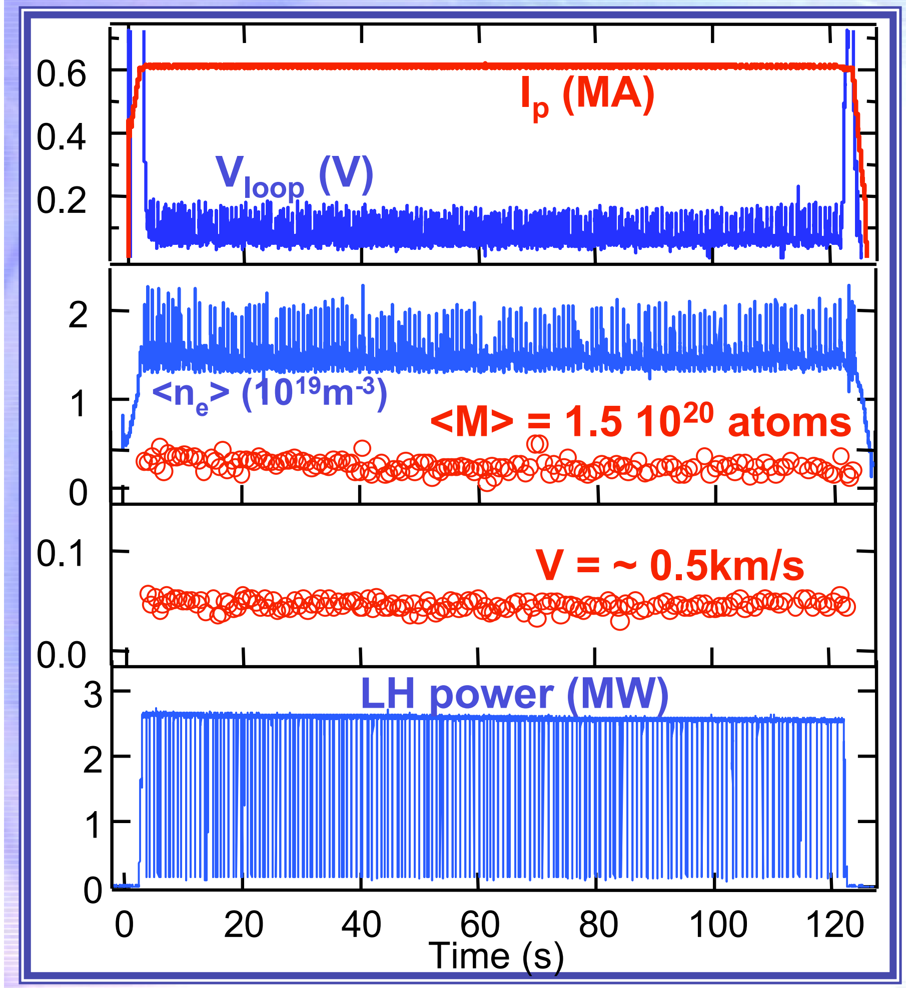
Phase 1: Decreasing retention rate ➔ filling carbon porosities

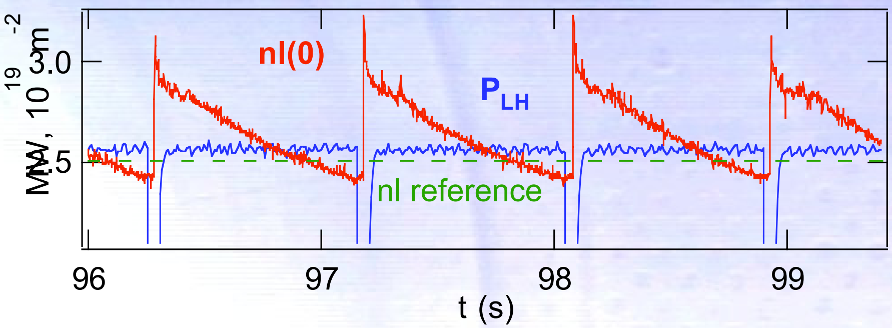
Phase 2: Constant retention rate : 2 10^{20}D s^{-1} (= 50% of injected flux) ➔ co-deposition observed but not enough (deep penetration in carbon?)

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

Pellet injection during 2 minutes in presence of LH





LH power notching allows penetration of 155 pellets

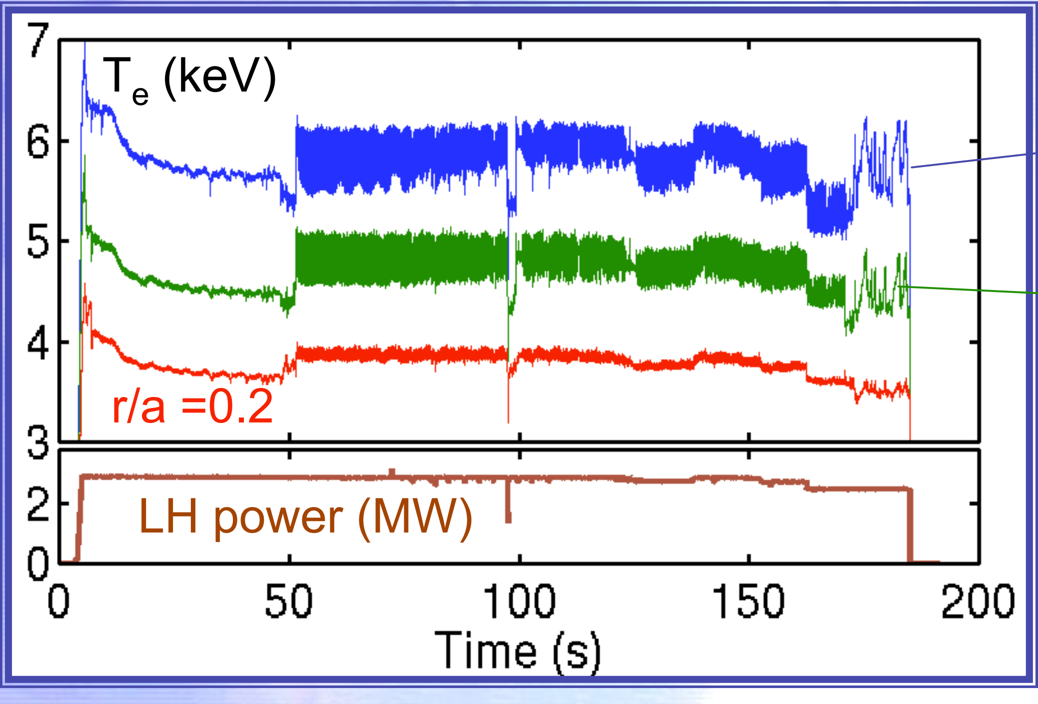
Very stable speed of 0.5 km/s

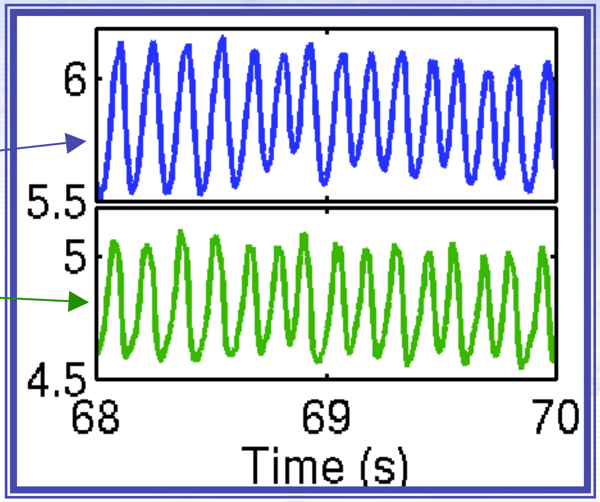
Relevant for ITER:

- 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.



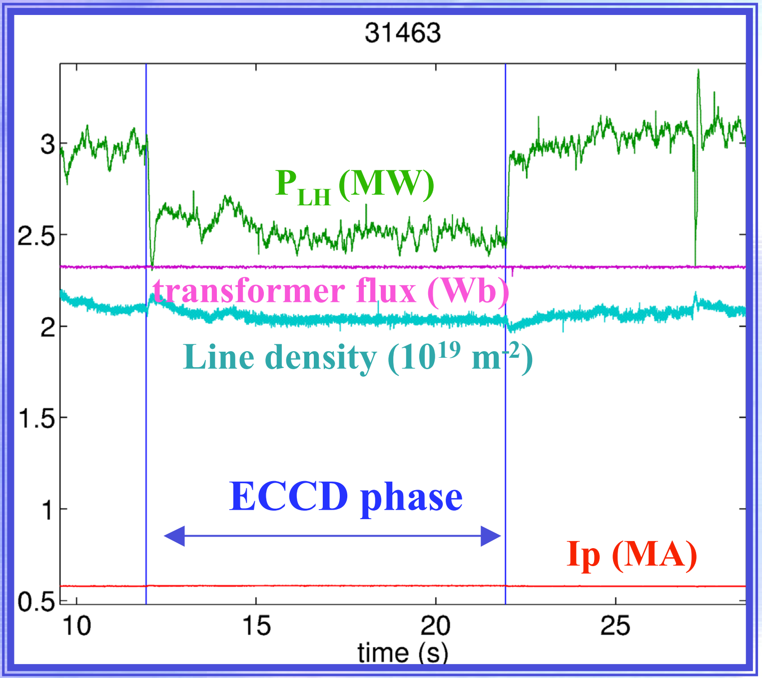


Radial structure, low frequency (a few Hz)

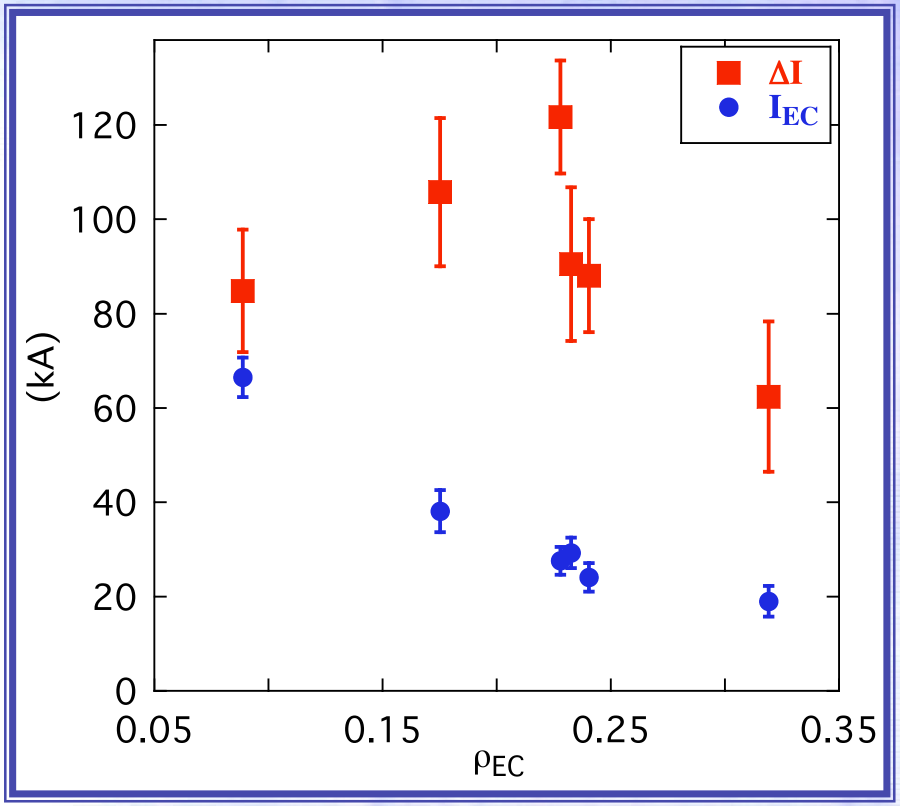
Non linear interplay between transport and current profile at the onset of the core ITB

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

Evident synergy ECCD &LHCD at Vloop = 0 (Giruzzi et al EX/P4-22)



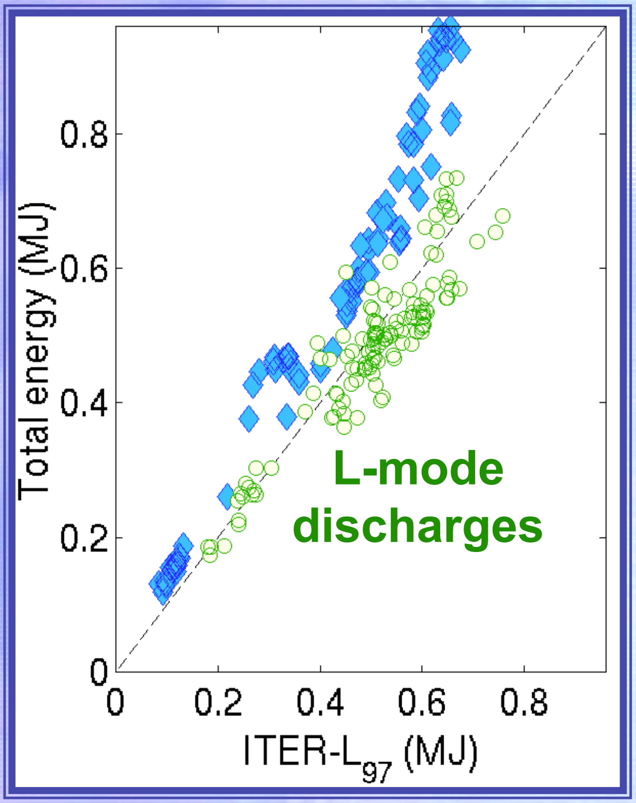
0.5 MW of LH power replaced by
0.7 MW of EC power to drive 80 kA



Synergy when LH and EC waves absorbed at same location

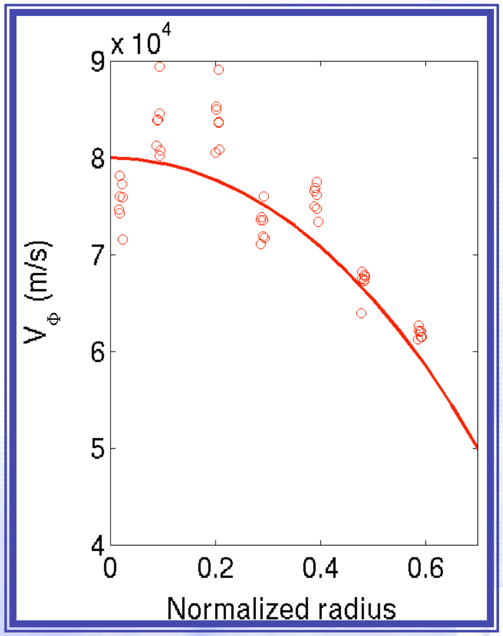
Promissing for NTM control using ECCD in ITER

Combined LHCD & ICRH



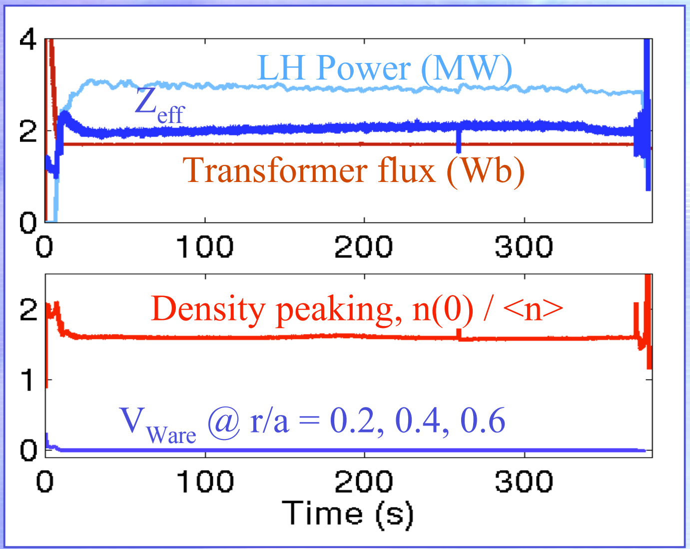
- Achieving 10 MW / 10s pulses
- Exhibit good L-mode, H_L up to 1.7, when optimzing H minority concentration (n_D/n_e ~6%):

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

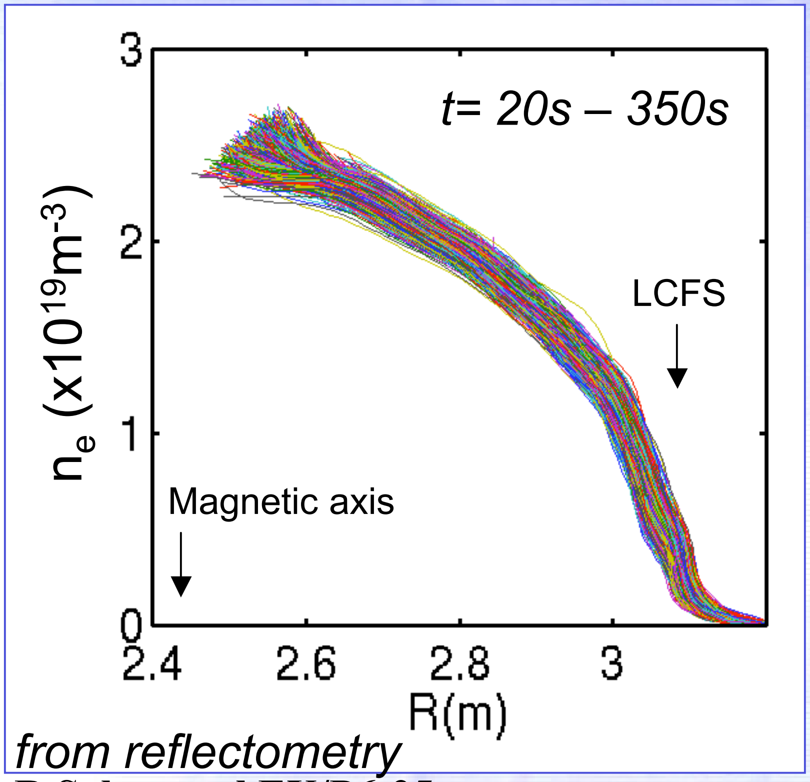


(C. Fenzi-Bonizec et al, 31st EPS Conf)

Peaked density profile in absence of Ware pinch



Supression of Ware pinch over 6 minutes



R Sabot et al EX/P6-25

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

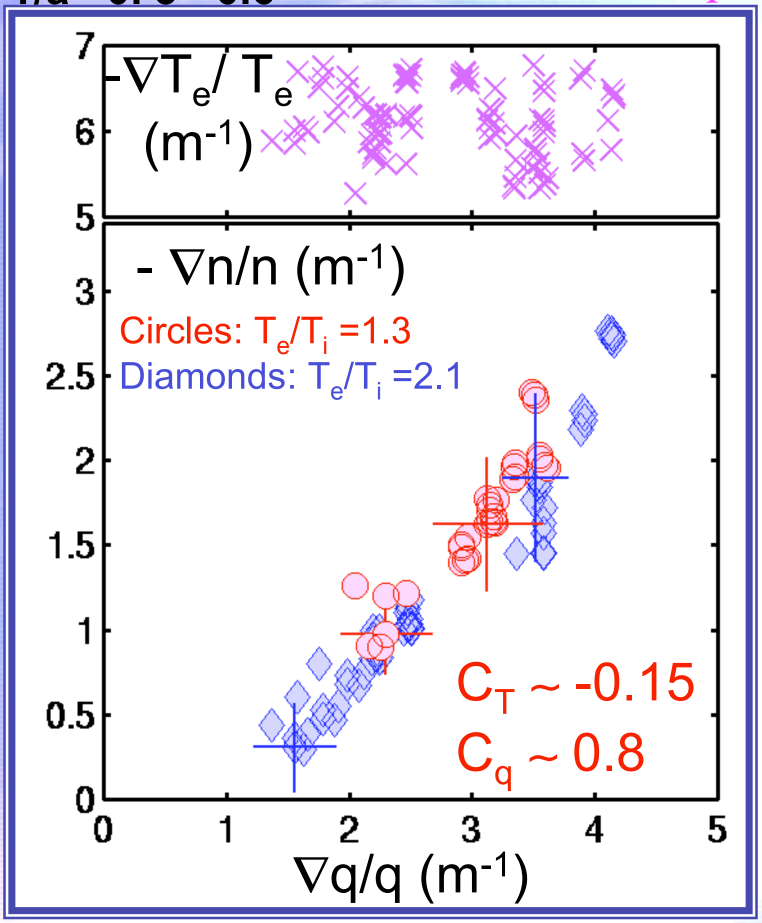
G.T. Hoang, Phys. Rev. Lett. 90 (2003)

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



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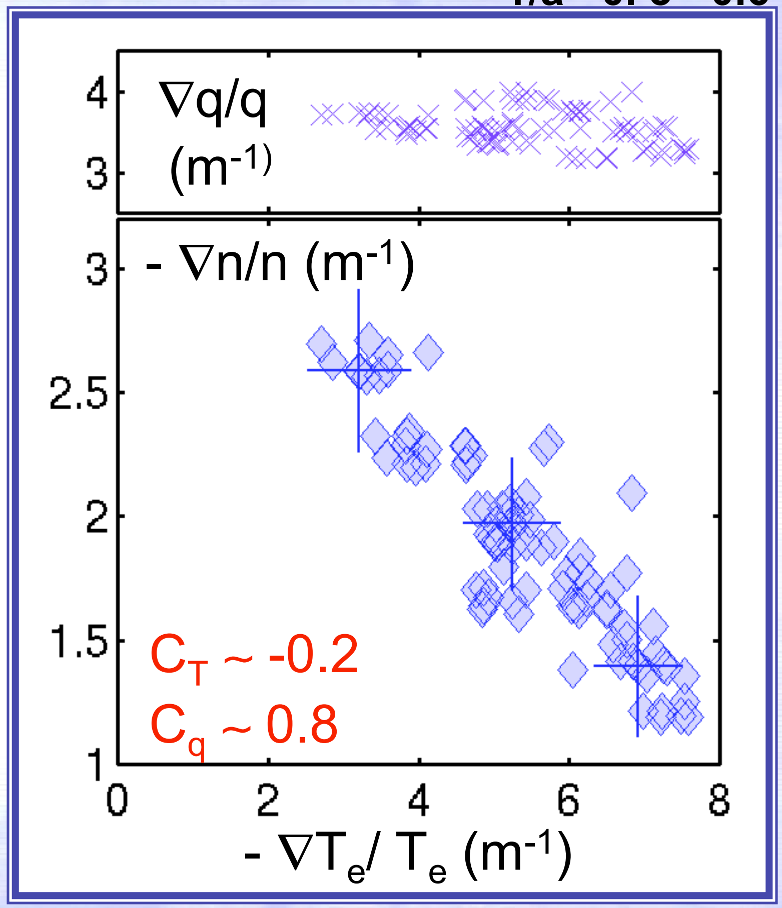


$\nabla q/q$ term dominates, consistent with TEM driven transport simulations

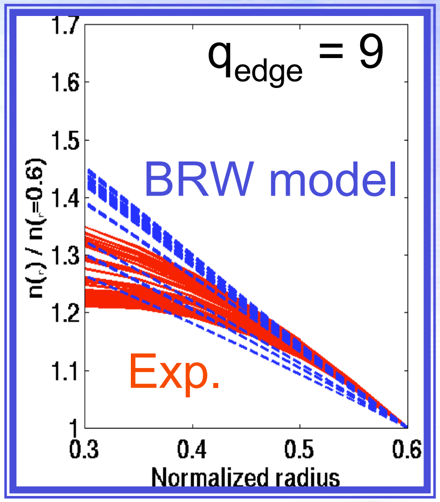
G.T. Hoang, Phys. Rev. Lett. 93 (2004) X. Garbet, Phys. Rev. Lett. 91 (2003)

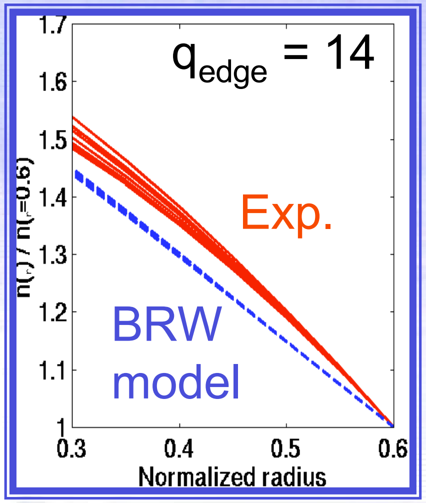
Extrapolation to ITER

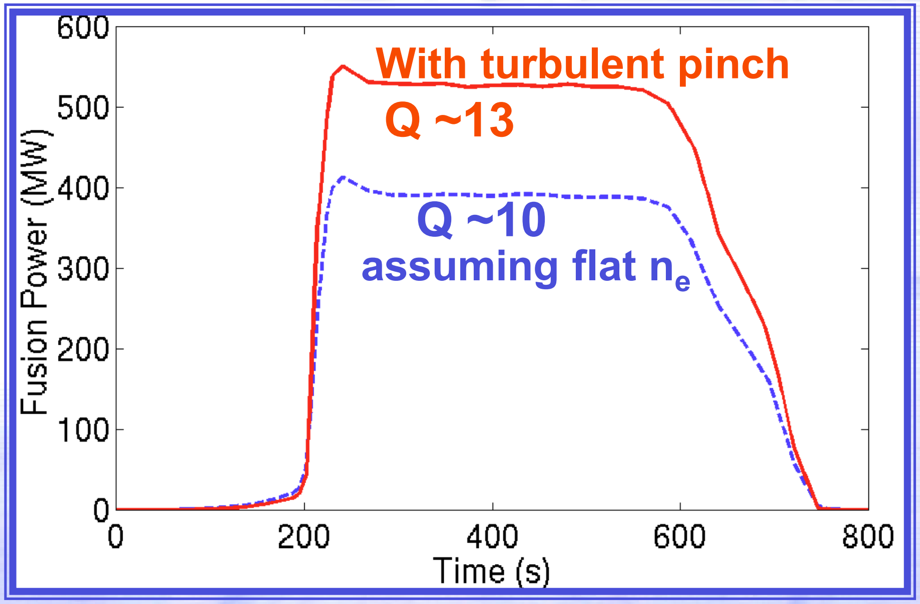
Tore Supra: $n \sim 1/q^{0.5}$
As found by Boucher, Rebut, Watkins for JET

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

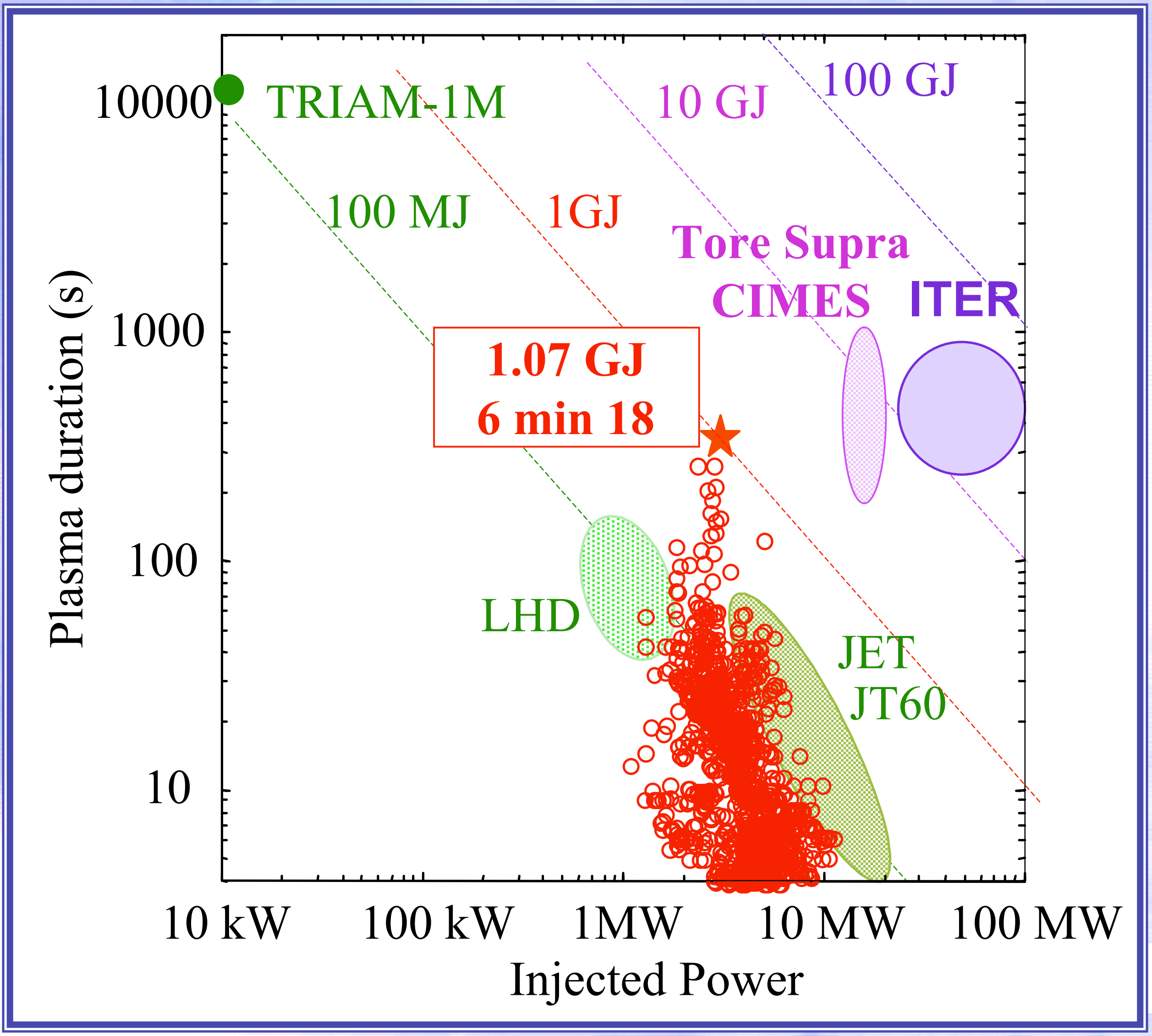
→ Peaked n_e → Fusion Power increased to 530 MW instead of 400 MW with a flat n_e profile(ref. scenario)





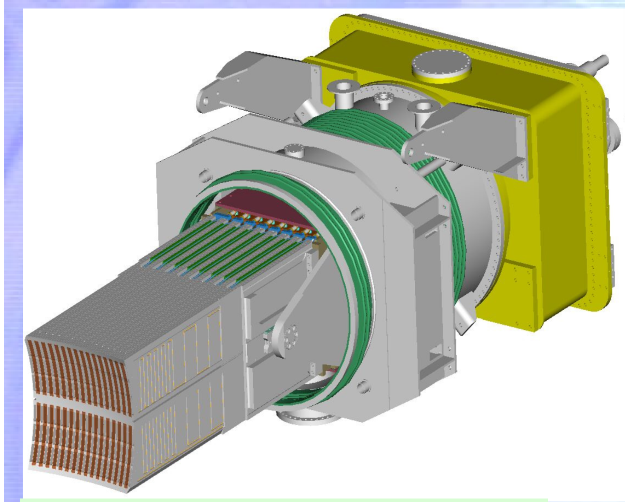


Progress in Long Pulse Operation

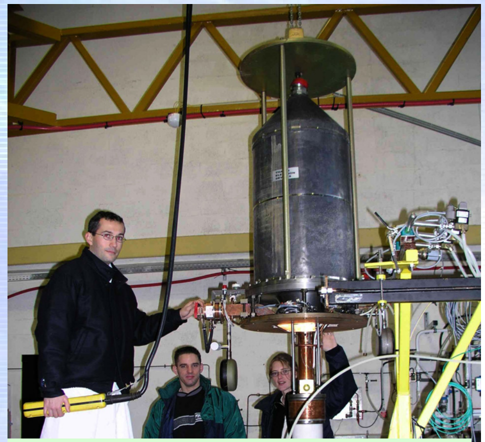


Tore Supra ongoing upgrades

LHCD system



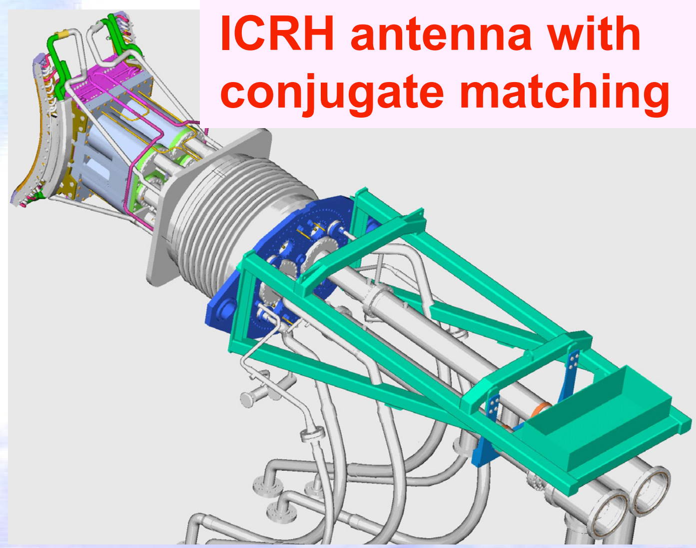
Passive Active Module (PAM)



700kW, 1000s, 3.7GHz Klystrons

400kW, 600s, gyrotrons

ICRH antenna with conjugate matching



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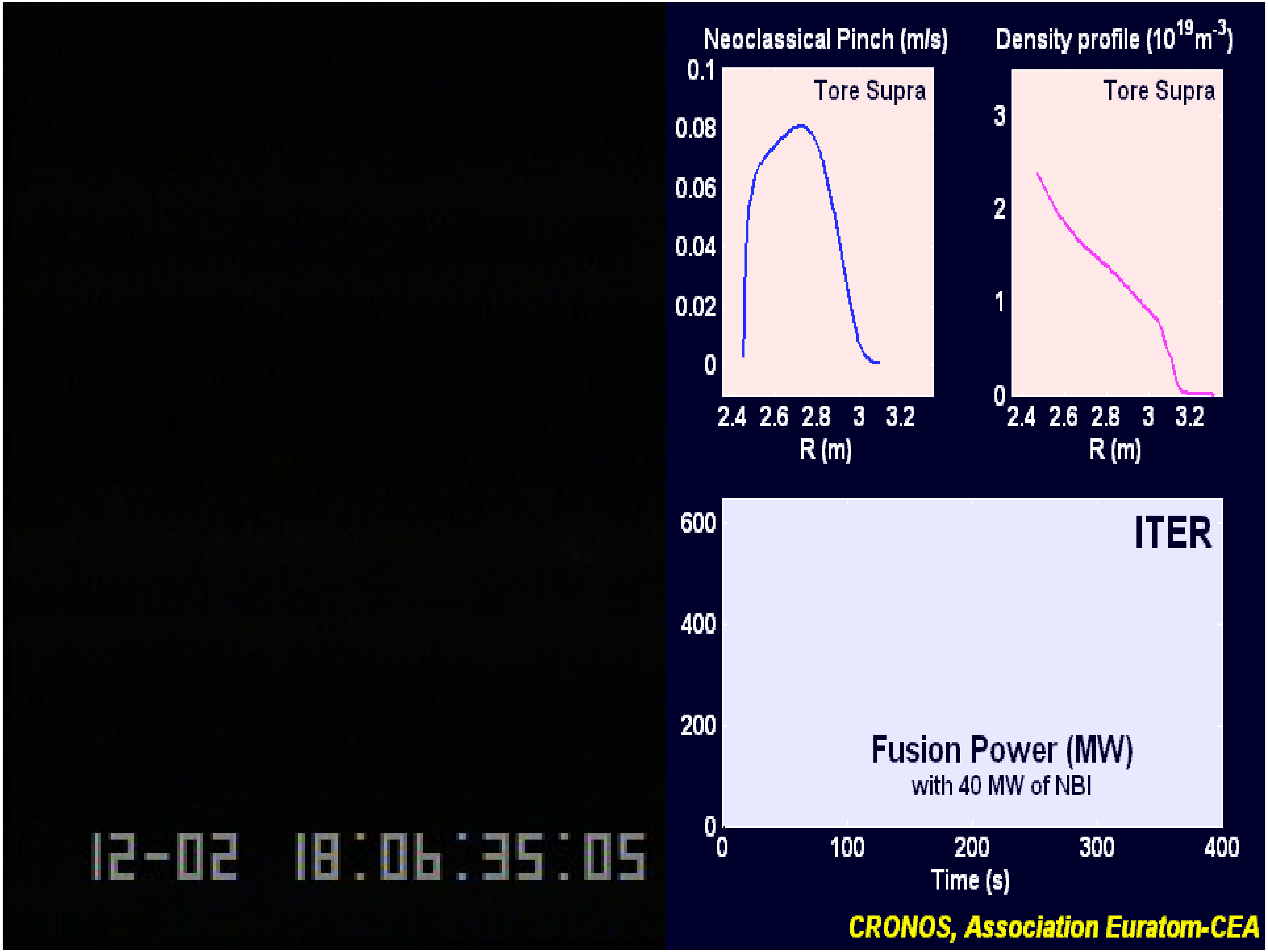
Conclusions

- 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


12-02 18:06:35:05
Neoclassical Pinch (m/s)
Tore Supra
0.1
0.08
0.06
0.04
0.02
0
2.4 2.6 2.8 3 3.2
R (m)
Density profile ($10^{19}m^{-3}$)
Tore Supra
3
2
1
0
2.4 2.6 2.8 3 3.2
R (m)
ITER
600
400
200
0
Fusion Power (MW)
with 40 MW of NBI
0 100 200 300 400
Time (s)
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.**