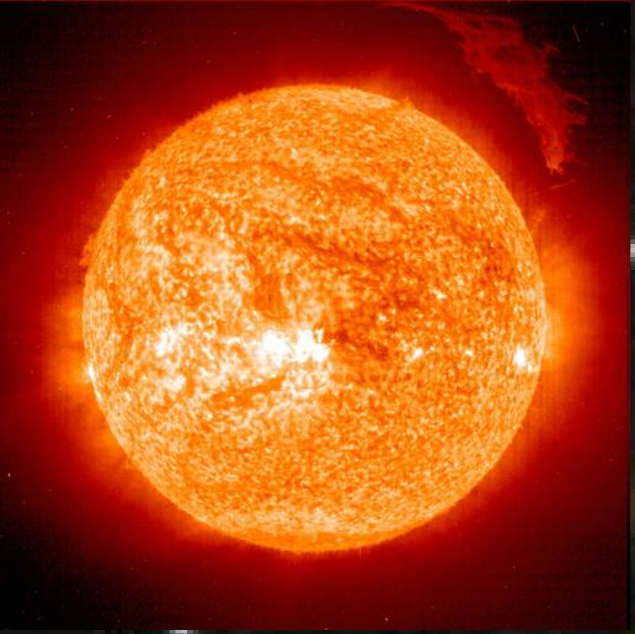
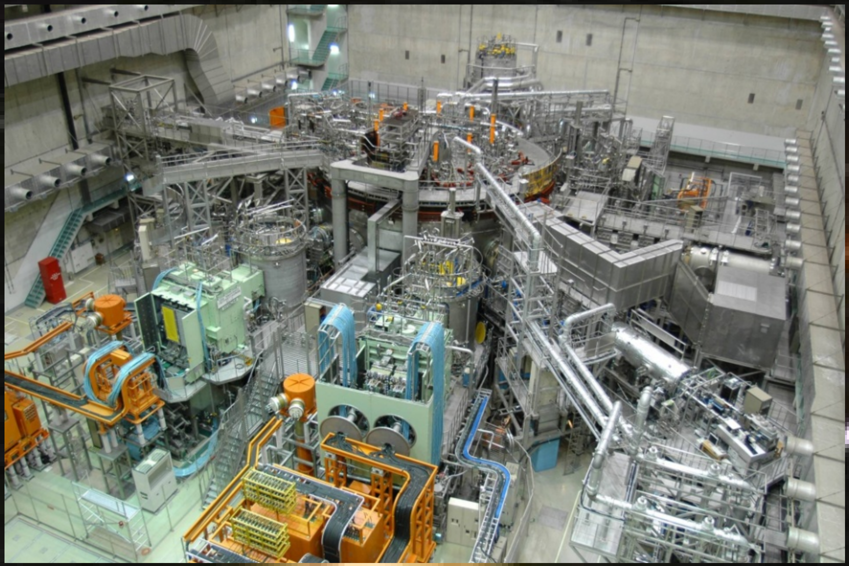
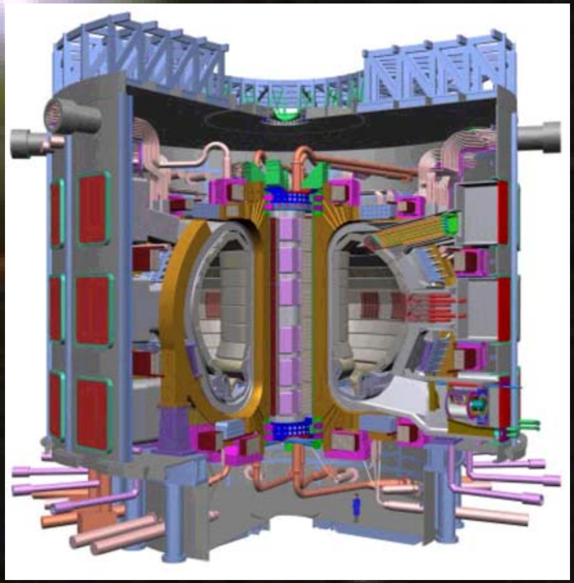


Progress & Challenges of CW operation



LHD



ITER

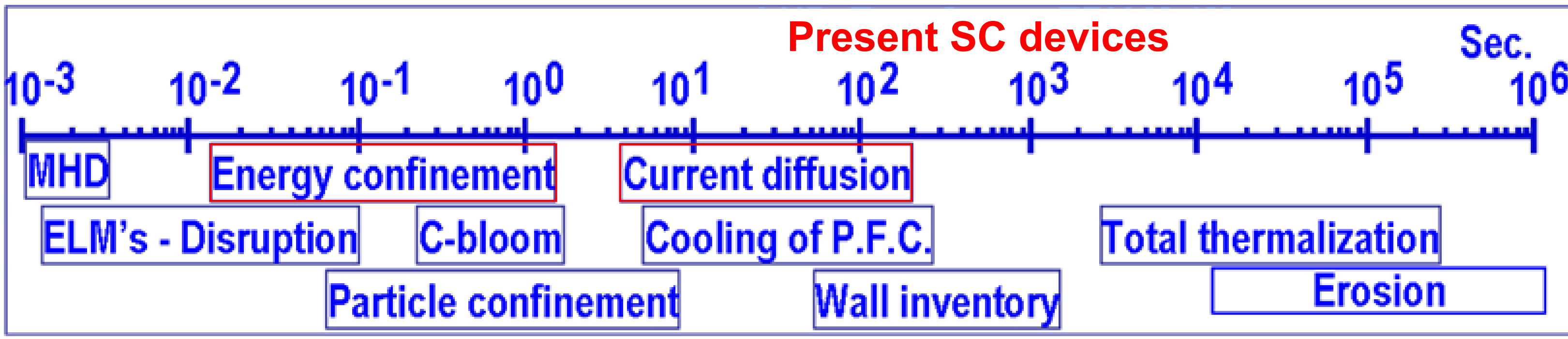
The challenge:

At reactor parameters (beta, n, H factor), demonstrate and optimize:

- Burning plasmas
  - ITER after >2020
- Operation in CW or QCW (quasi CW, pulsed with high duty cycle)
  - LHD, TS, East, KSTAR, ST1, W7x + …but no QCW Tokamaks foreseen; When ? rapid progress is essential!

Steady State versus CW/QCW

- **"Steady-state" refers to a particular physics timescales**
  - **On present devices, it often refers to the Energy confinement time, sometimes to the current diffusion time**



CW demonstration requires: t > largest time scales

They are set by erosion, deposition, flake formation

~ several hours

How?

- What counts is the engineering Q_{eng}
  - $Q_{eng} = P_{fus}/(P_{aux}+P_{inj}/\eta)$

$$= \eta Q/(1+\eta P_{aux}/P_{inj}) \quad \text{with } Q=P_{fus}/P_{inj}$$

ITER:

$\eta < 0.5$; $P_{aux} \sim 200$ MW (cryoplant, pumps etc.)

➔ $Q_{eng} \sim 2$!

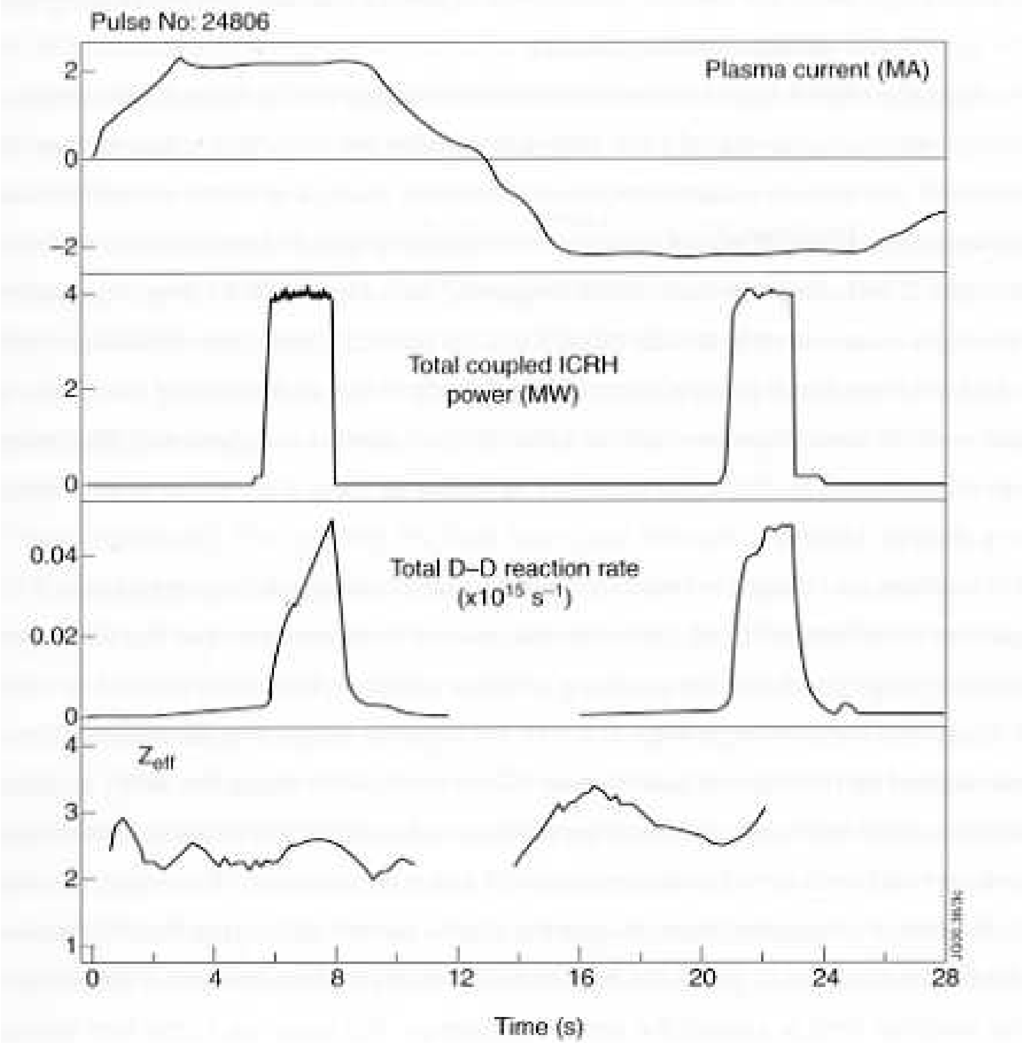
DEMO:

➔ Must reduce P_{aux} and P_{inj}

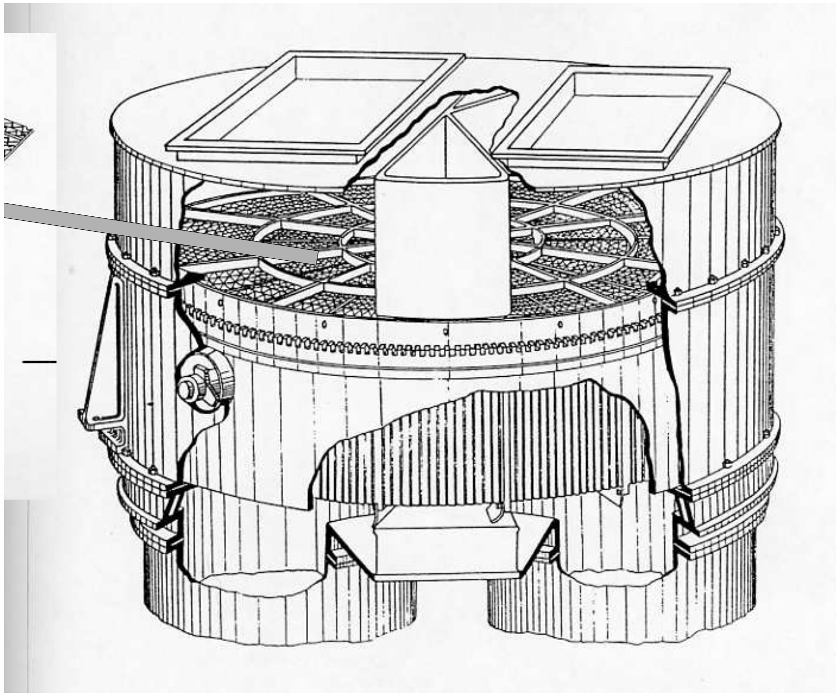
NB: Off axis power (e.g. CD) has lower η

➔ advantage to Stellarators and Pulsed Tokamaks

A QCW Tokamak



JET AC discharges 1991



Heat storage module
20m long, 850 tons cast iron
Belgatom study, W. D'haeseleer et al 1994

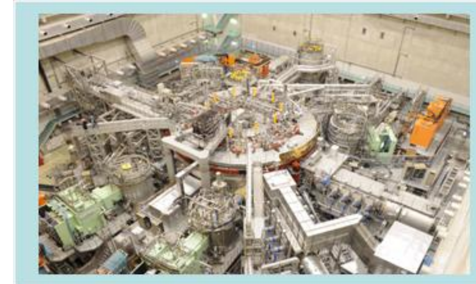
Physics/Integration Issues

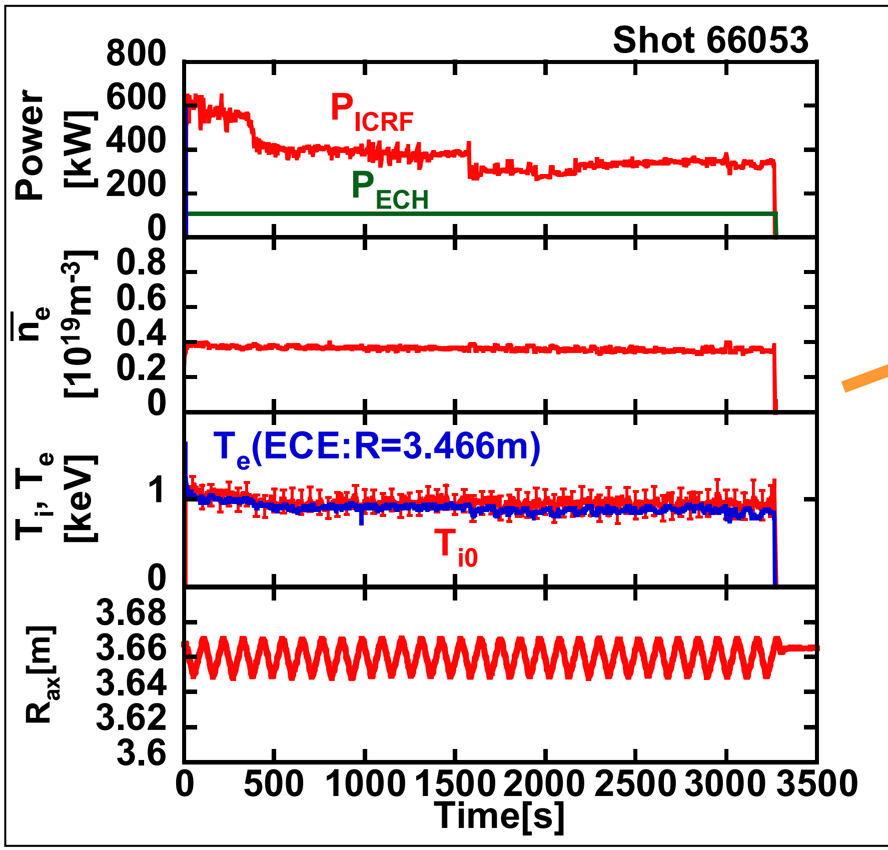
- Generic issues
  - Undesired bifurcations; Plasma control under α heating
    - UFO; TAE
  - Fuel inventory
    - Choice of 1st wall material
  - Overall engineering Q (impact of control auxiliaries)
- Specific to advanced tokamak issues
  - 90% bootstrap, MHD, NTM
    - Stabilisation requires auxiliary power

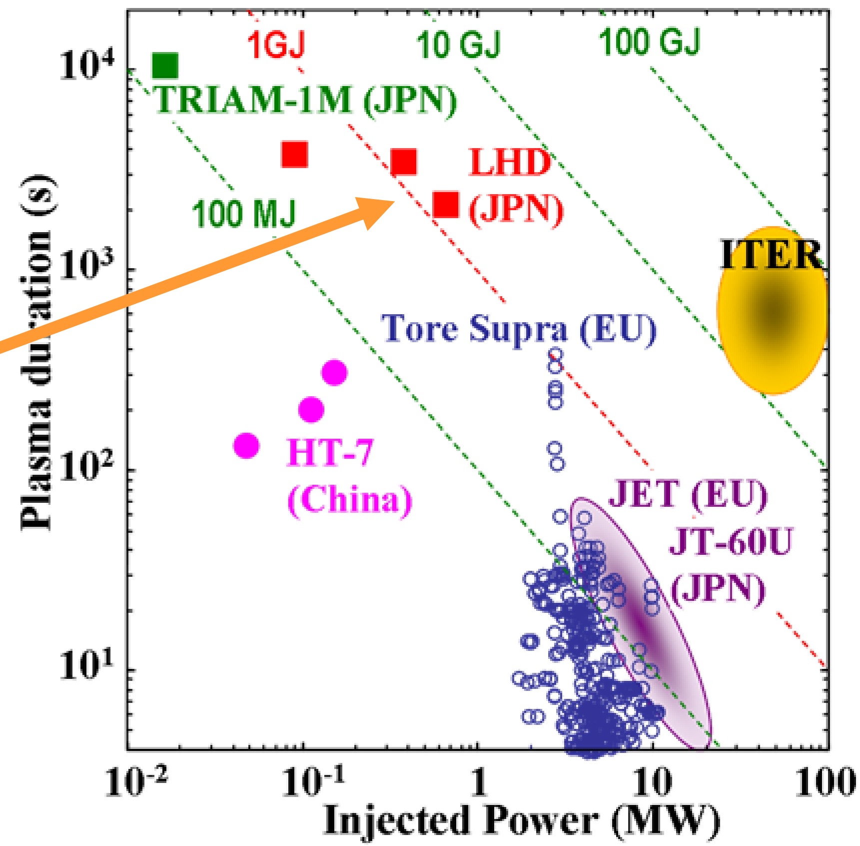
➔ too much of it?

Where are we? LPO experience

- **LHD:** t ~ 54', P_{inj} ~ 490 kW, 1.6 MJ or 13', P_{inj} ~ 1.1 MW
- **TRIAM-1M:** t = 5h 16', 0.28 GJ (Nov 03)







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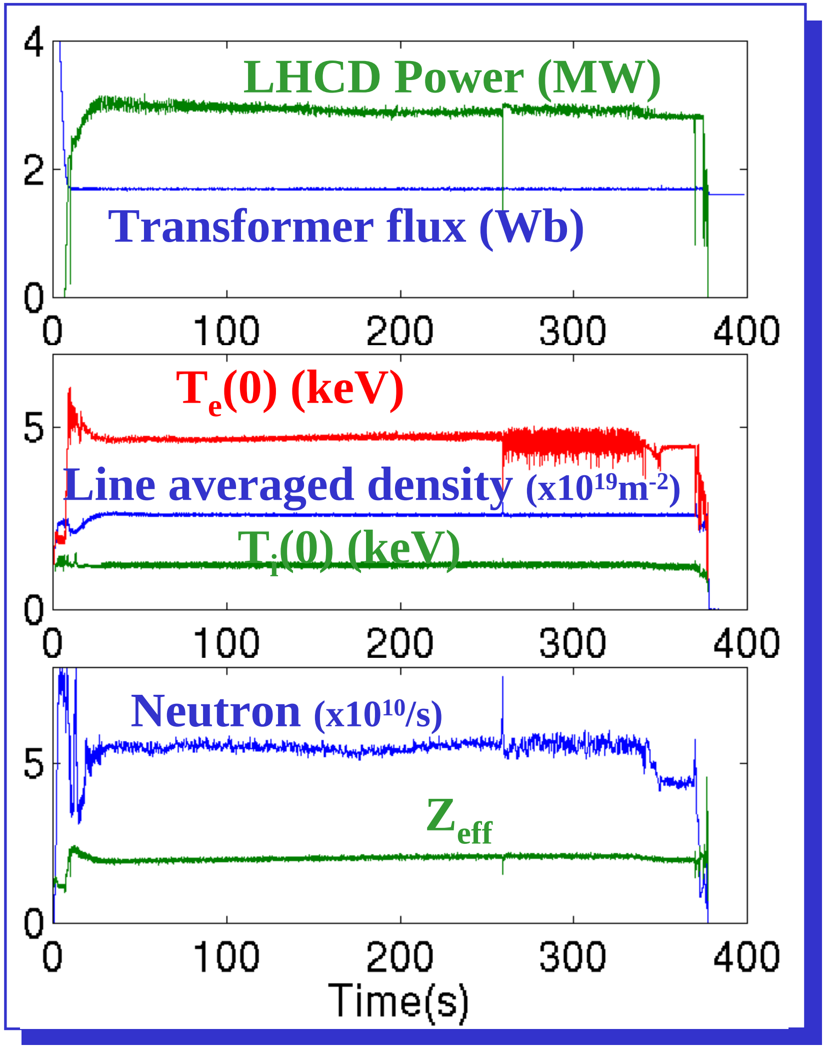
Very good progress but not at reactor n and β!

Where are we? Long pulses in TS

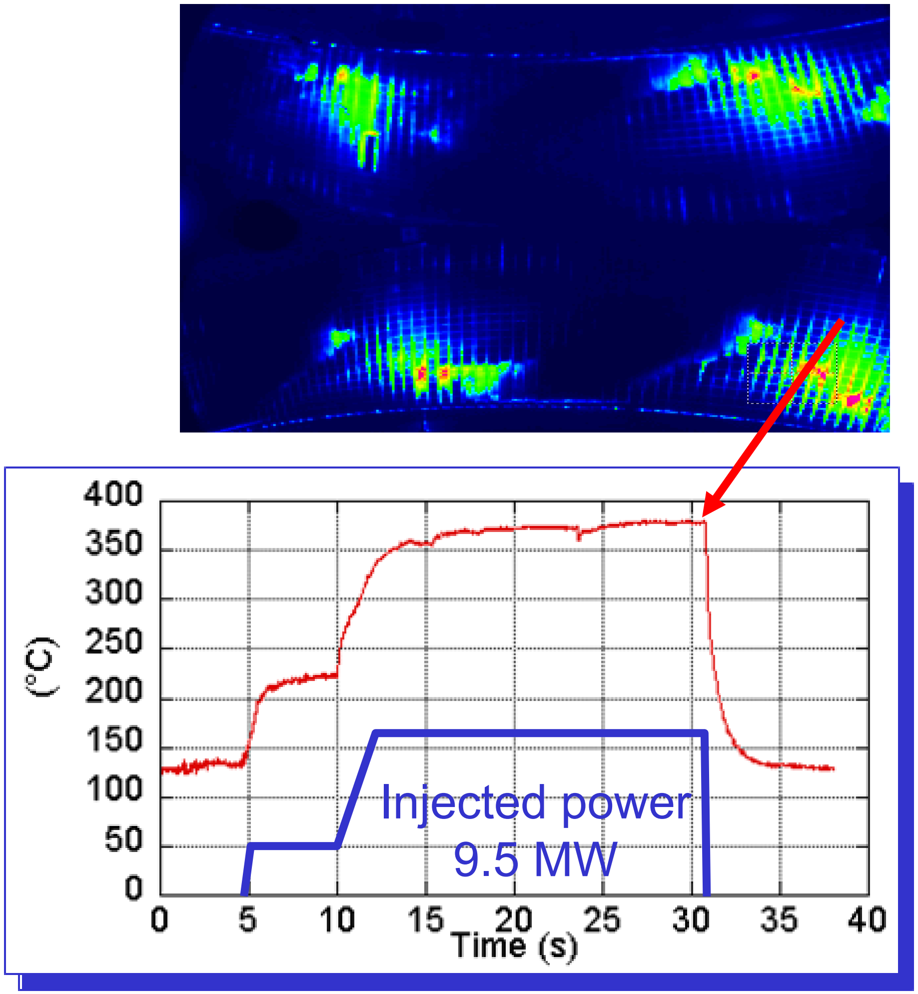
- Large superconducting tokamak in operation
  - Cryo-magnetic system with trouble free operation for 20 years
  - All PFCs actively cooled
  - Powerful H/CD systems
- 6 min discharges (2003) with 1 GJ injected/exhausted energy
  - $P_{LHCD} = 3$ MW
  - $I_p = 0.5$ MA
  - $n_{e0} = 2.5\ 10^{19} m^{-3}$

➔ Missing n, β, bootstrap ➔ more H&CD power required



IAEA 2003

Towards long discharges at higher power



- Convective losses routinely handled by the TPL (3-5 MWm^{-2})
- Routine high power long duration discharges
- Studies of discharges in which
  - loop voltage is evanescent for duration much longer than current diffusion time
  - Stationary PFC surface temperature
- Testing key technologies in real Tokamak environment

Need longer CD power or bootstrap
➔ New klystrons being procured

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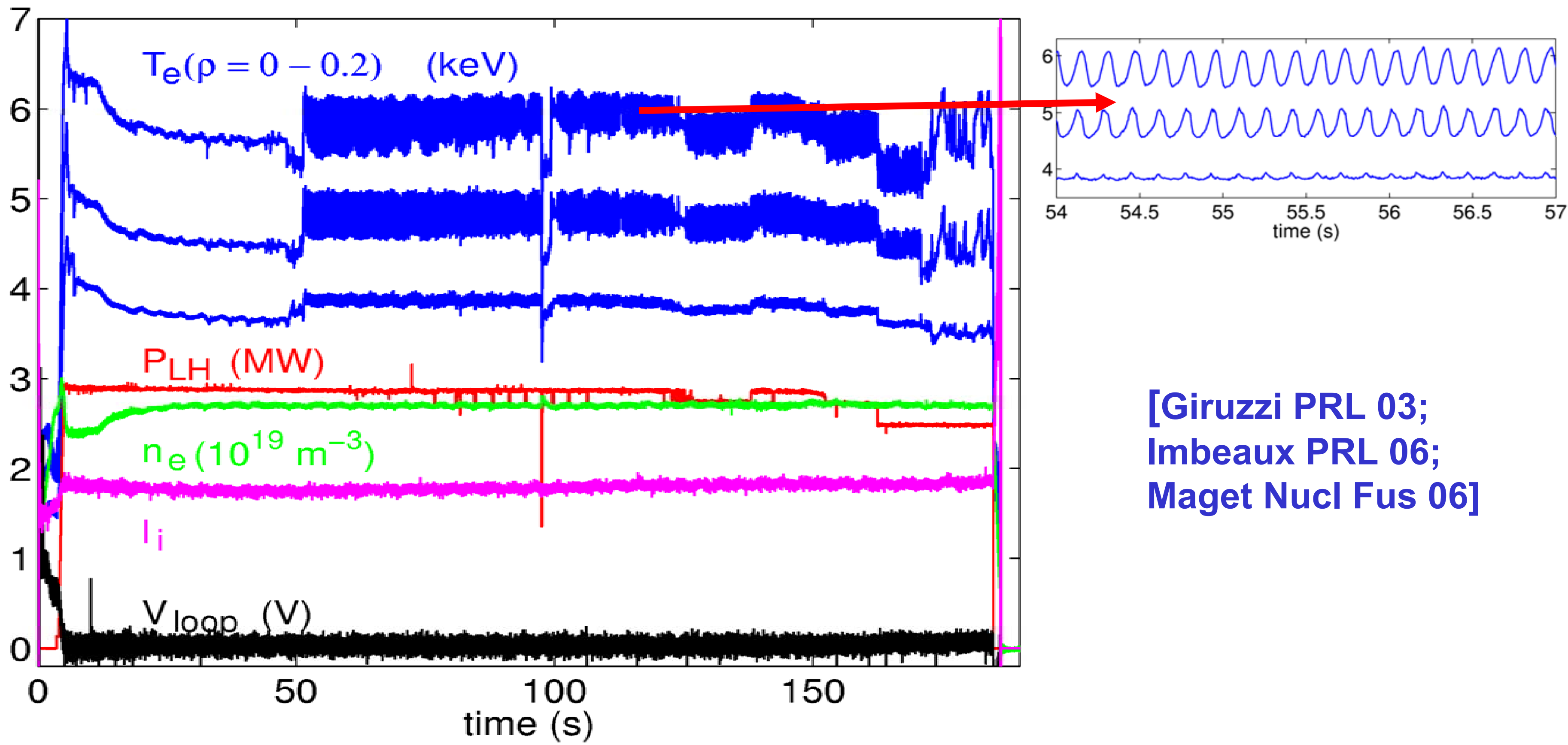
Non-linear behaviour @ Vloop=0

- **Oscillations of core electron temperature**
- **Complex coupling between q-profile, MHD (double tearing, e-fishbones), transport and heat sources**

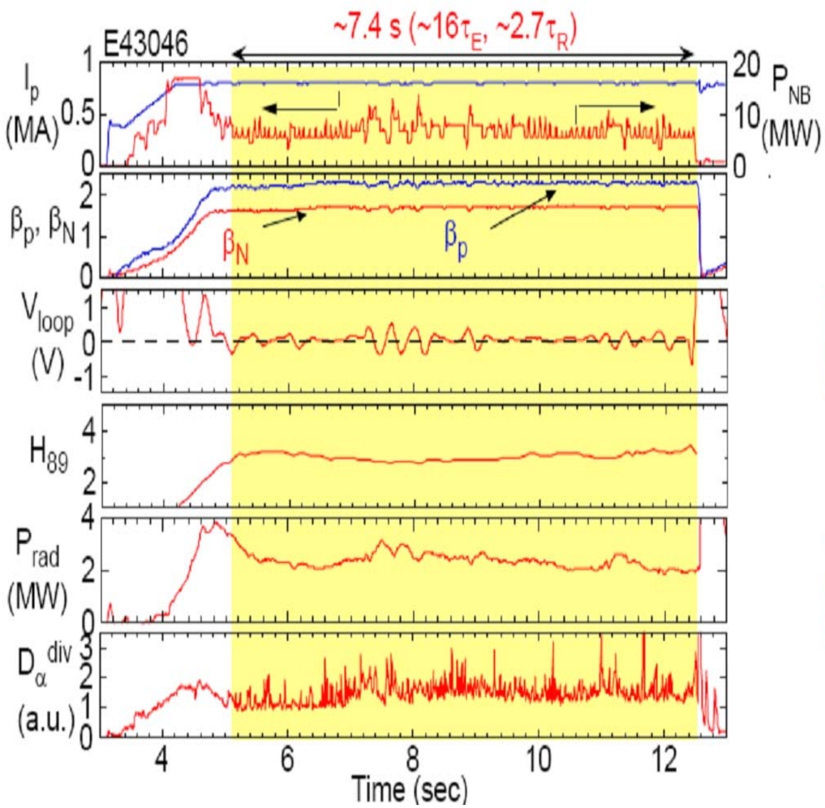


[Giruzzi PRL 03; Imbeaux PRL 06; Maget Nucl Fus 06]

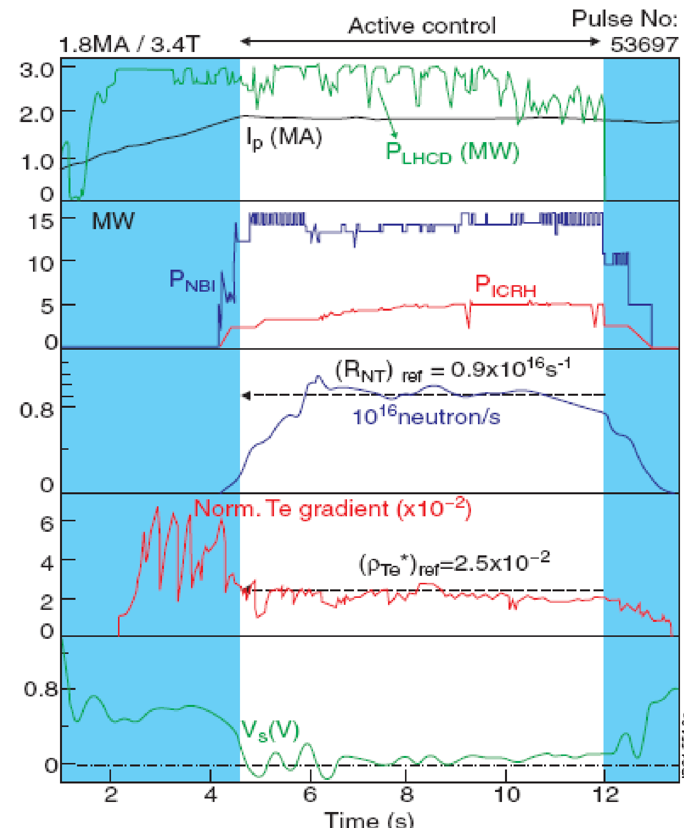
Where are we? Non-inductive operation with RT control

Fully non-inductive regimes with large bootstrap over several resistive times achieved in many tokamaks

JT60-U (75%)



JET (30%- 40%)



[Sakamoto, Nucl Fus 05]

[Litaudon, PPCF 03]

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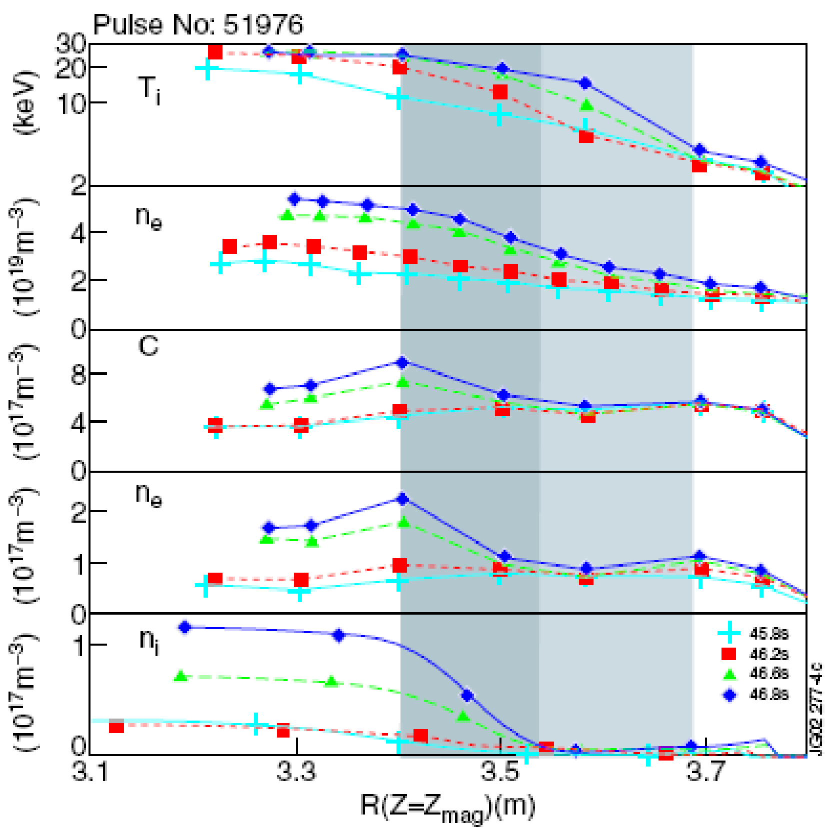
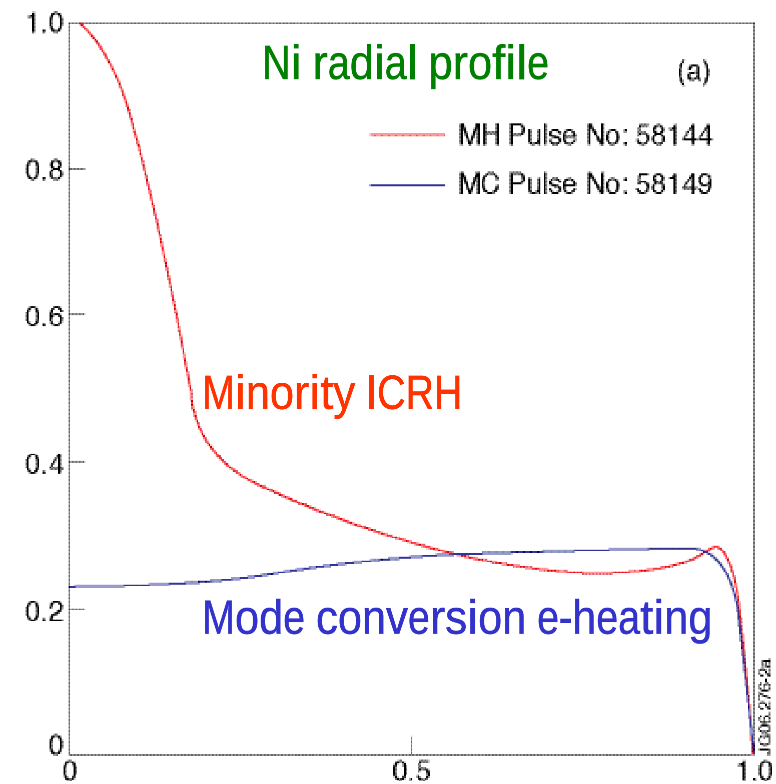
Impurity Issue

- **Core impurity accumulation in negative magnetic shear configuration (Internal Transport Barrier)**
- **e-heating shows control capability (JET, AUG)**



[Dux, Nucl Fus 04]



[Puiatti PoP05; Giroud, IAEA 06]

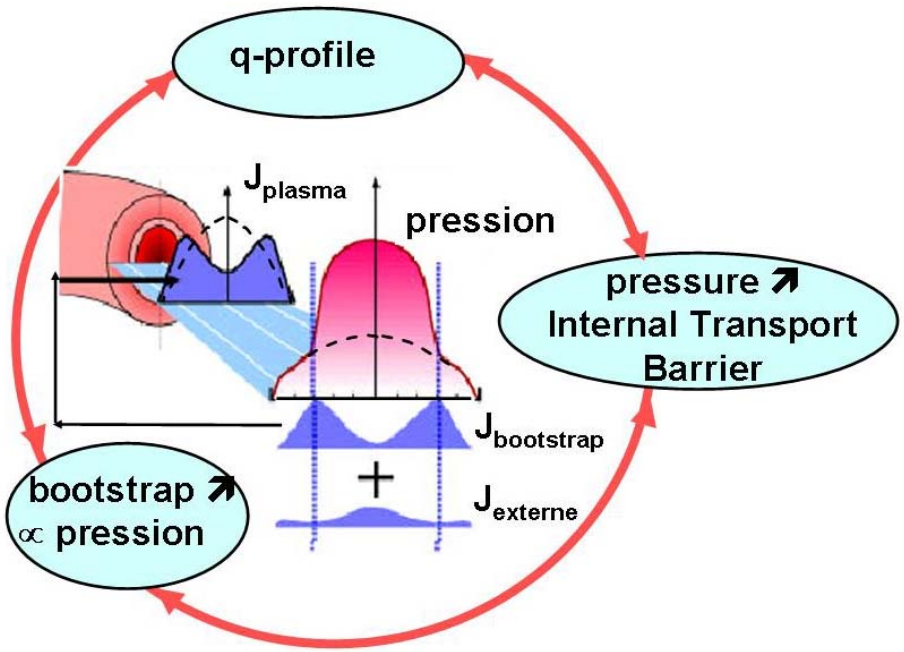
The "Holy Grail" of CW Tokamak

- **A virtuous circle seems to exist, related to the intimate link between current density profile and heat transport**
- **Only a partial solution so far: particle transport, rotation, edge, ..?**

More modelling, theory, R&D and longer pulses needed

CRONOS

Will α heating preserve the loop?



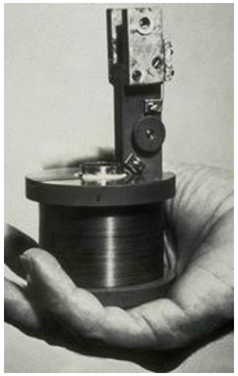
Bécoulet EPS 2008

Technology Issues

- Supra conductors
  - High T_c ? ➔ Higher engineering Q
- Erosion/redeposition/T inventory
  - Choice of material
    - Carbon, Tungsten etc..
- Structural longevity
  - Radiation resistant material
  - Disruption (Tokamaks)

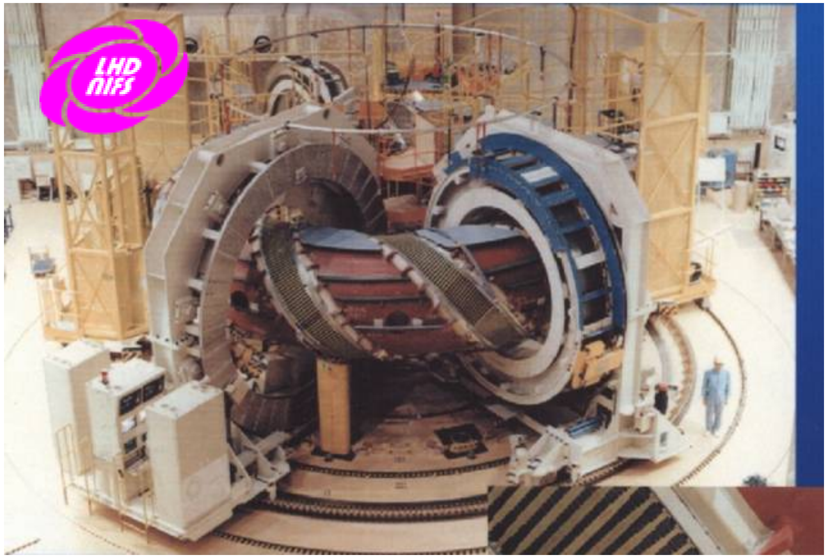
Progress in superconducting coil R&D

One of 1st SC magnets (courtesy Oxford Instruments) **(1962)**



Non-planar winding for W7-X (EU)

Winding machine of helical coils for LHD (JPN, 1998)



And now EAST and KSTAR

The Nb_3Sn conductors of the ITER coils

CSMC
51 mm x 51 mmm40 kA 13 T

TFMC
Φ 40,7mm, 80 kA, 9.7 T

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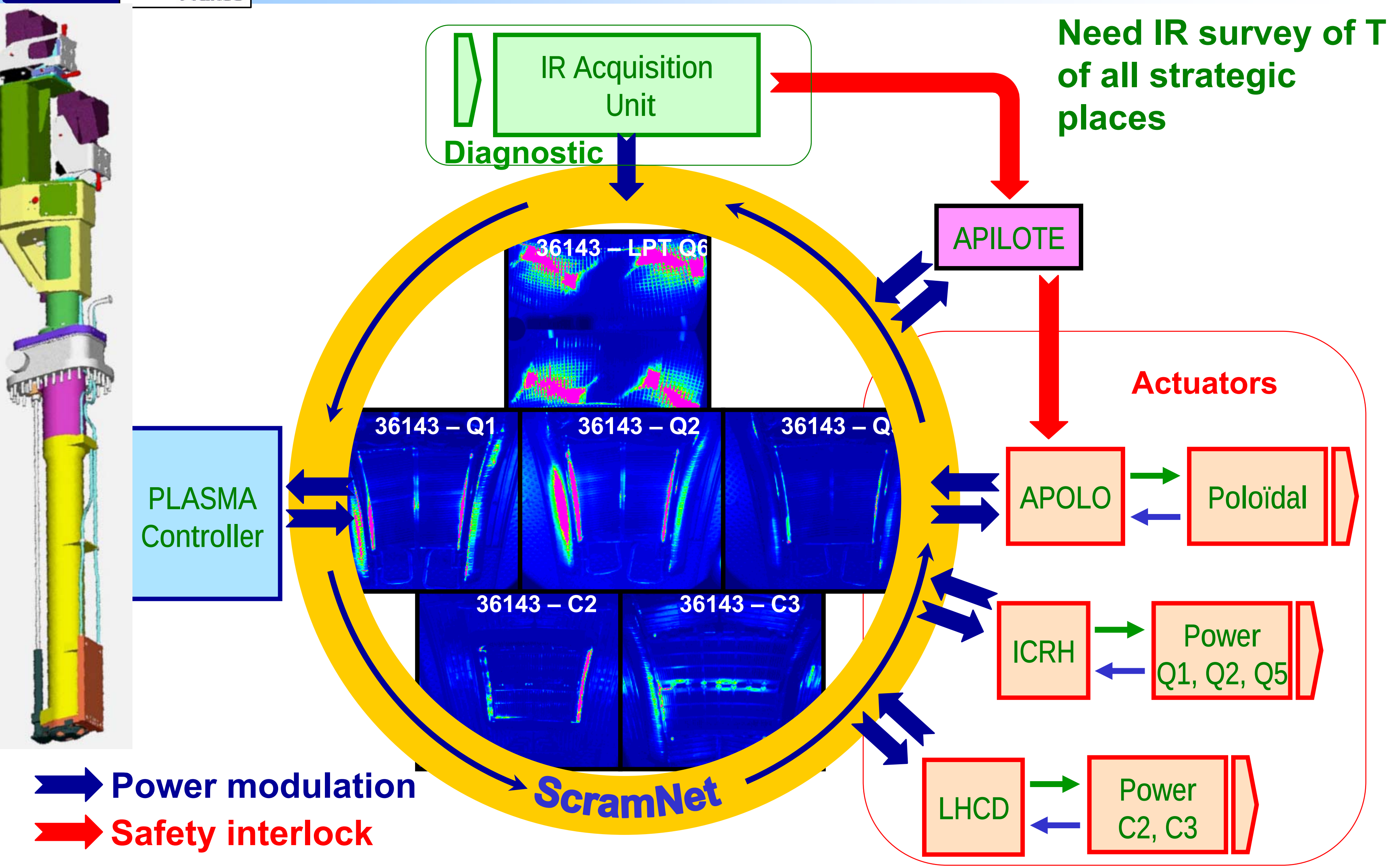
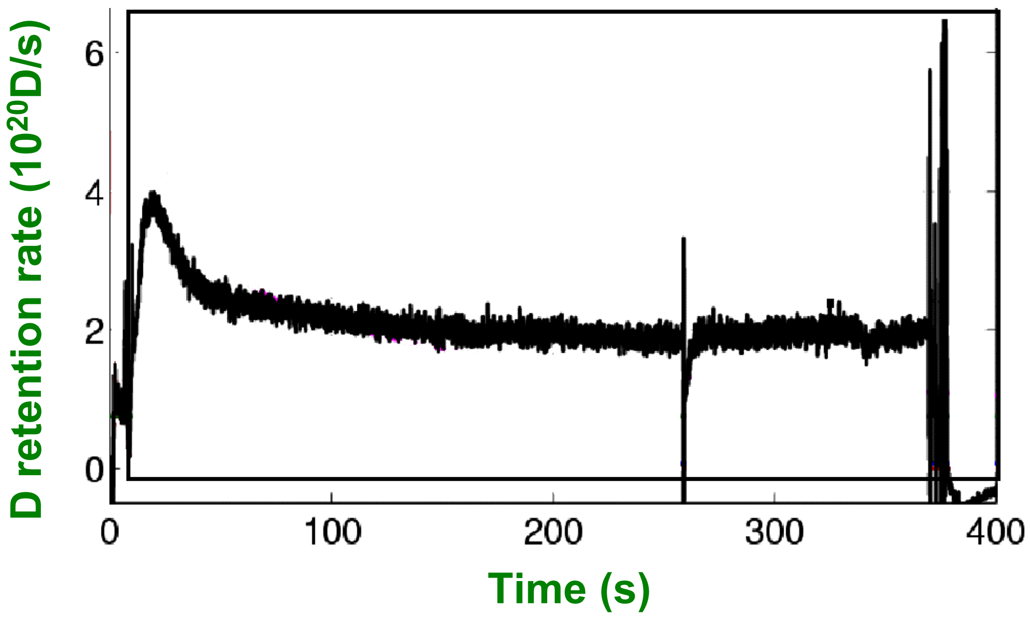
Real time control of CW discharges



Fuel retention: a major issue for C based PFC

- Long term constant retention rate observed (~ 50% injected flux) from particle balance of long discharges



Where does it go?

D inventory: the 5hour marathon TS project

- Three steps:
  - Dedicated long discharge campaign in D
  - Dismantling one sector of TPL (20°) for samples extraction
  - Analysis of samples
- The campaign
  - **160 long discharges** (1 min < duration < 2 min)
  - Total of **5 hours of plasma**
  - no wall conditioning during the entire period
  - **10 g** (3 10^{24} D) retained of **19.3 g** (5.8 10^{24} D) injected
  - ~ 25 g of C redeposited on TPL

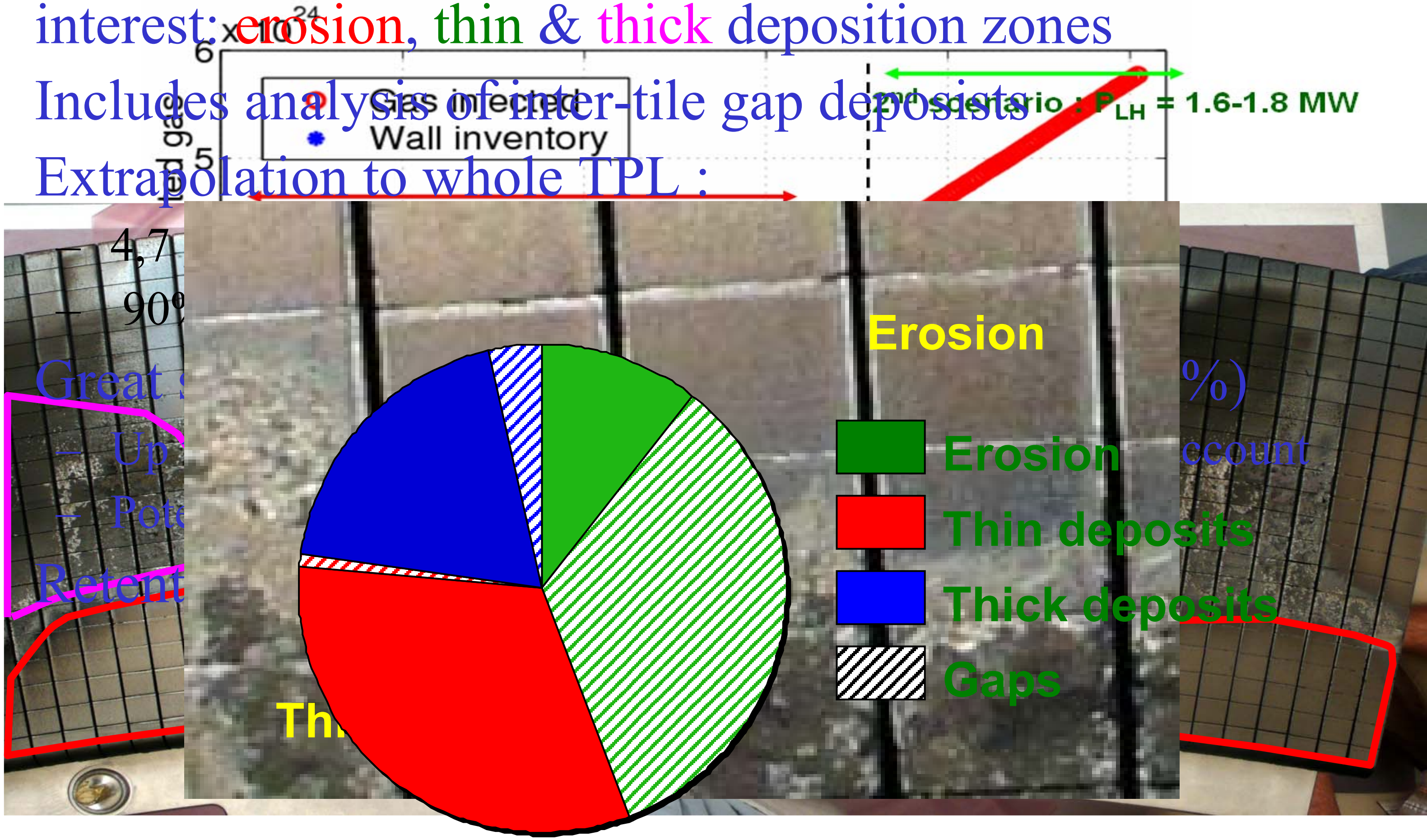
Objective:

Explore the erosion /re-deposition issue

B. Saoutic et al. SOFT 2008

Results of the 5hour marathon

- No sign of saturation
- First analysis conducted on 10 samples situated in 3 zones of interest: erosion, thin & thick deposition zones
- Includes analysis of inter-tile gap deposits
- Extrapolation to whole TPL :
  – 4,7
  – 90
- Great s %)
  – Up ccount
  – Pote
- Retent



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Need for worldwide cooperation

- **Preparing Long Pulse Operation of fusion devices is of strategic importance for the future of Magnetic Fusion**
  - **We are far from a demonstration of CW/QCW operation at reactor normalised parameters**
    - **Slow equilibrium drifts, first wall material, Elm's, α confinement (wall loading by α losses)**

- **Long Pulse Steady-State developments deserve a worldwide coordinated effort:**
  - **Joint Experiments** ***(short & long pulse, Tokamaks & Stellarators)***
  - **Theory / Simulation** ***(First principle; Integrated & Real Time)***
  - **Technology R&D programme**

In summary

CW/QCW operation : A major challenge for fusion

Broad topics: Technology and physics

A world wide coordinated effort seems indispensable