JET progress towards an Advanced Mode of ITER operation with current profile control

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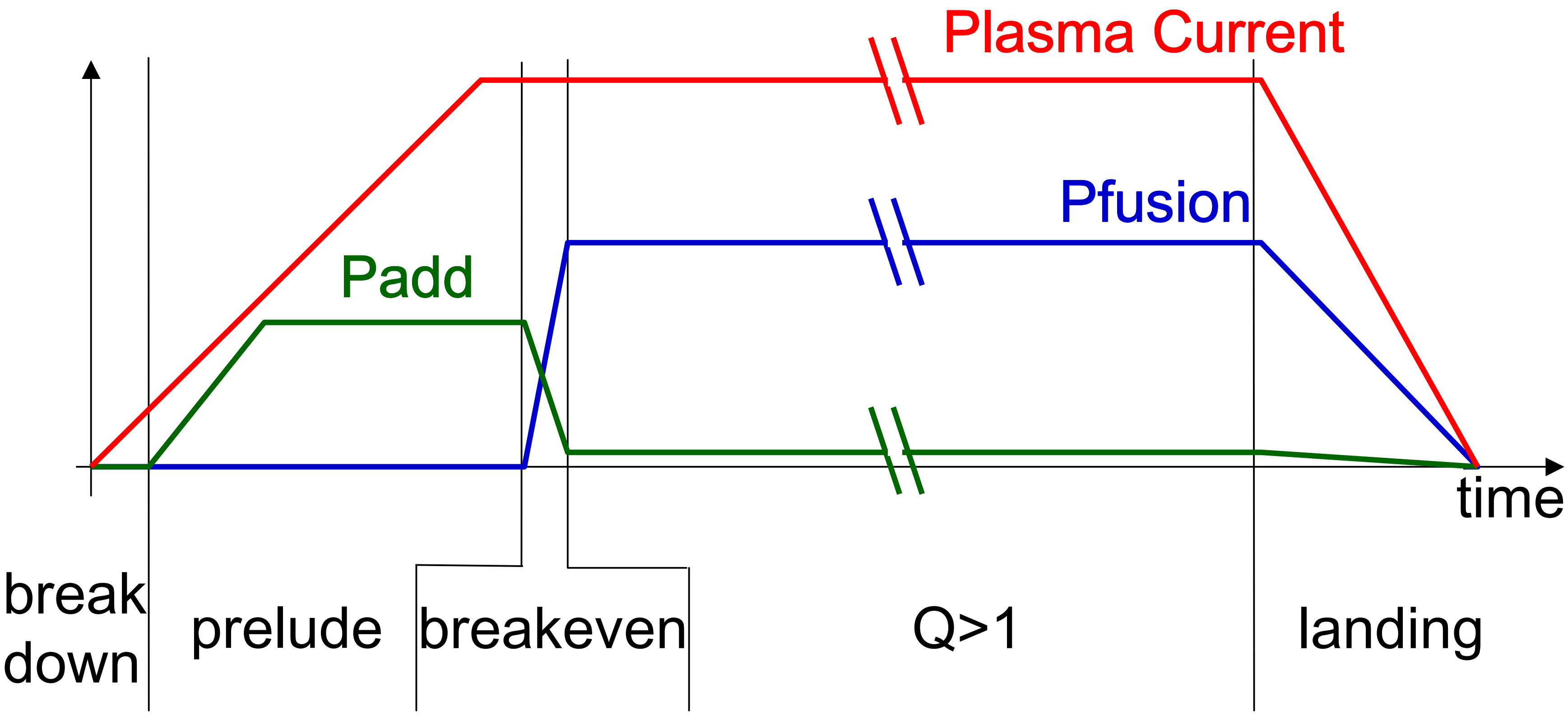
on behalf of

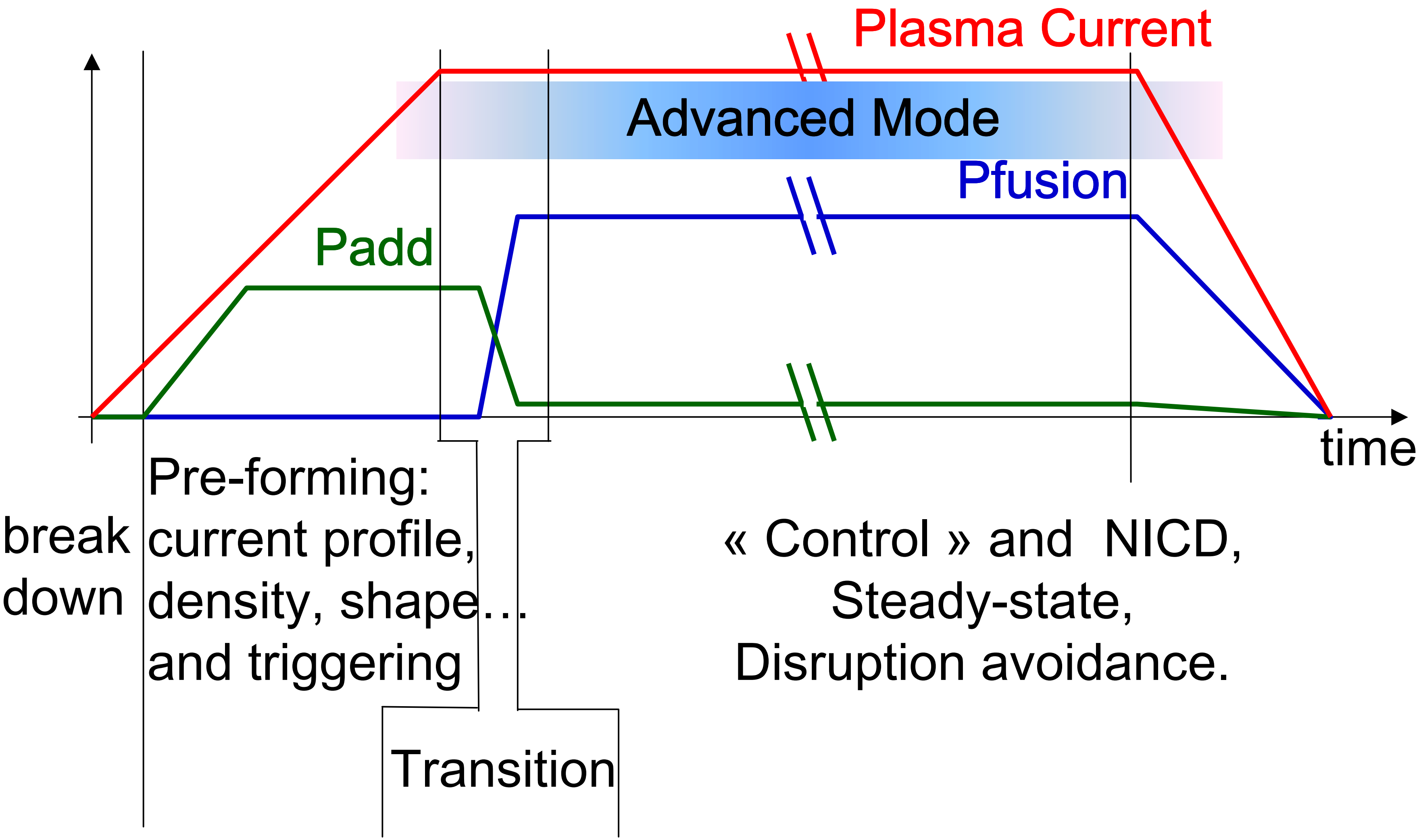
the EFDA-JET task force S2

and the contributors to the EFDA-JET Workprogramme

A Burning Tokamak Plasma...

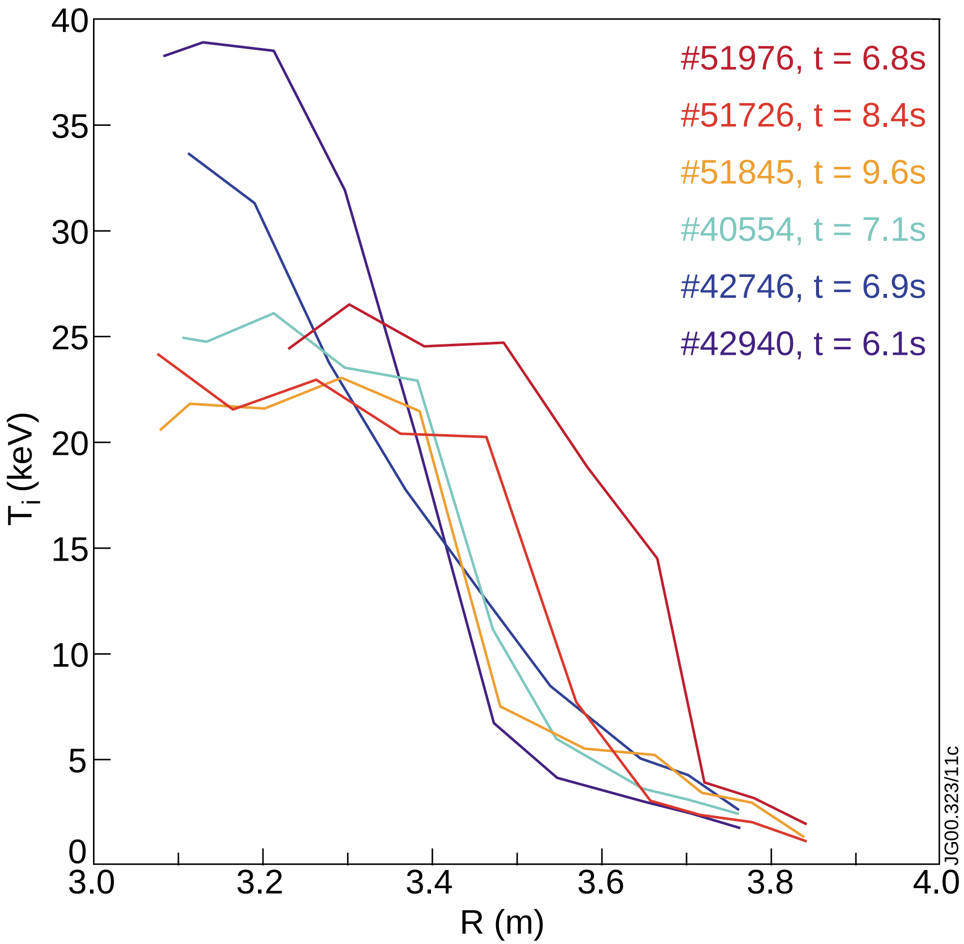


… using a Steady-State Advanced Mode



Internal Transport Barriers as an Advanced Mode

JET ion temperature ITB profiles



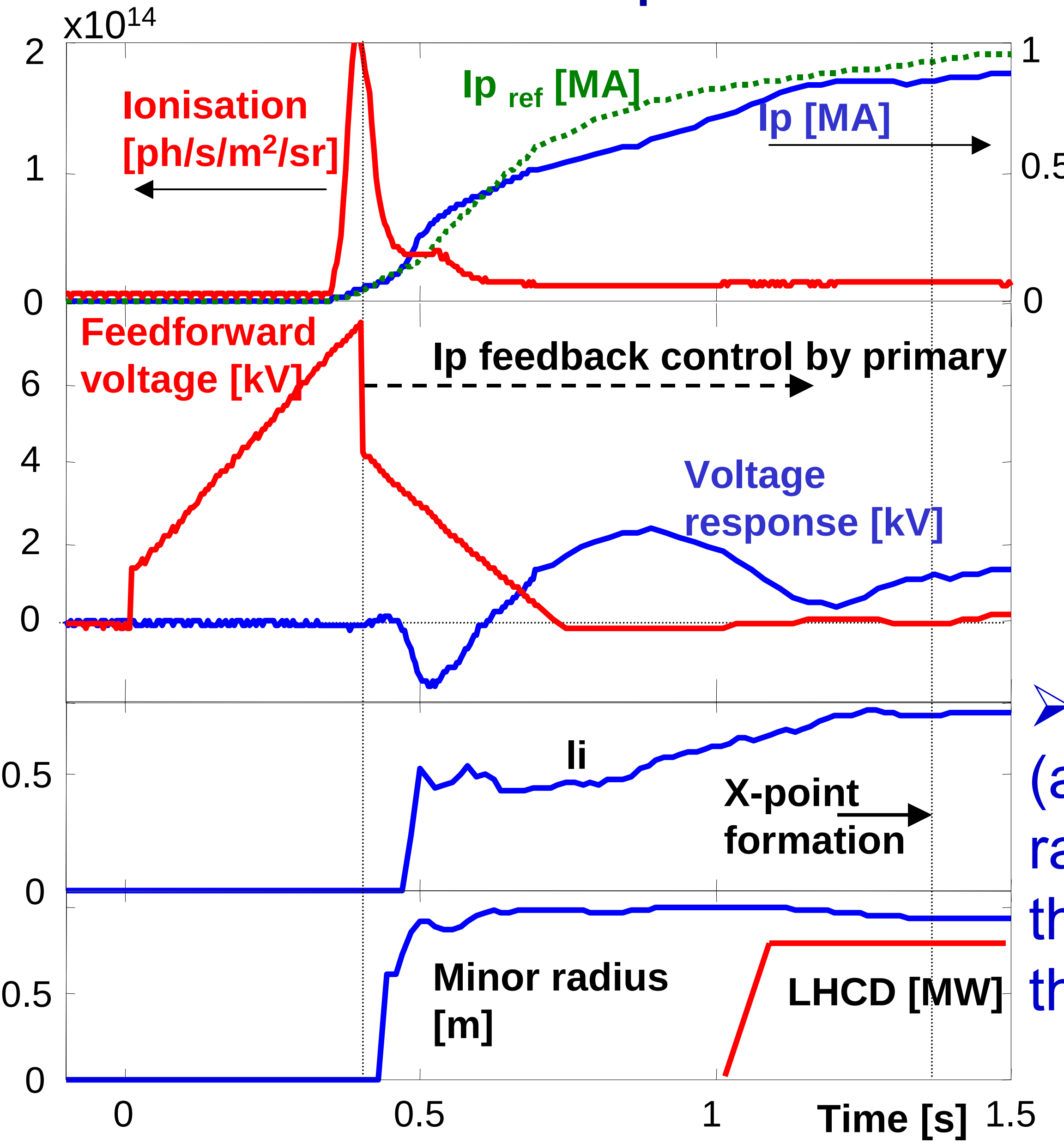
- hot/dense core discharges
- $H_{IPB98(y,2)} > 1$

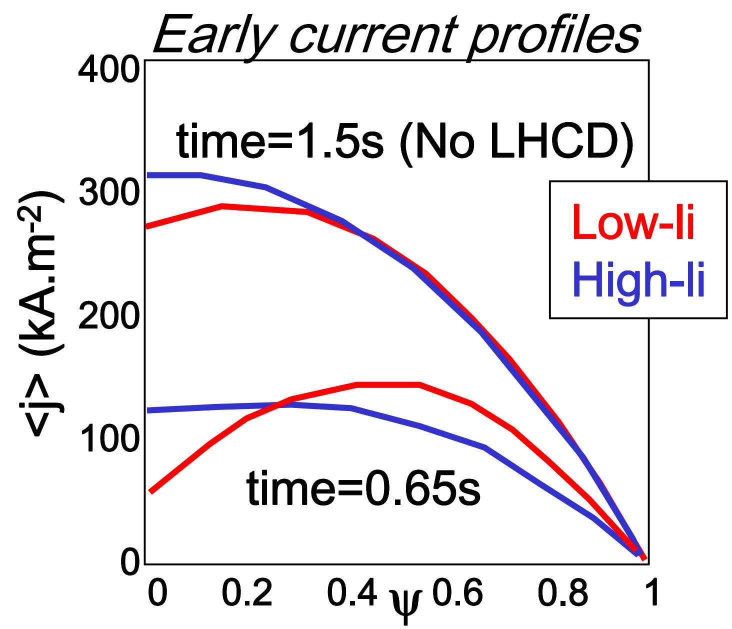
=>

- operation at reduced current
- possible steady-state at high bootstrap current fraction

Target: q_{95}~4-5, β_N>2.5, $H_{IPB98(y,2)}$~2 maximising $Q_{DT}^{(eq)}$, $P_{fusion}^{(eq)}$ and the time duration.

Optimised breakdown conditions





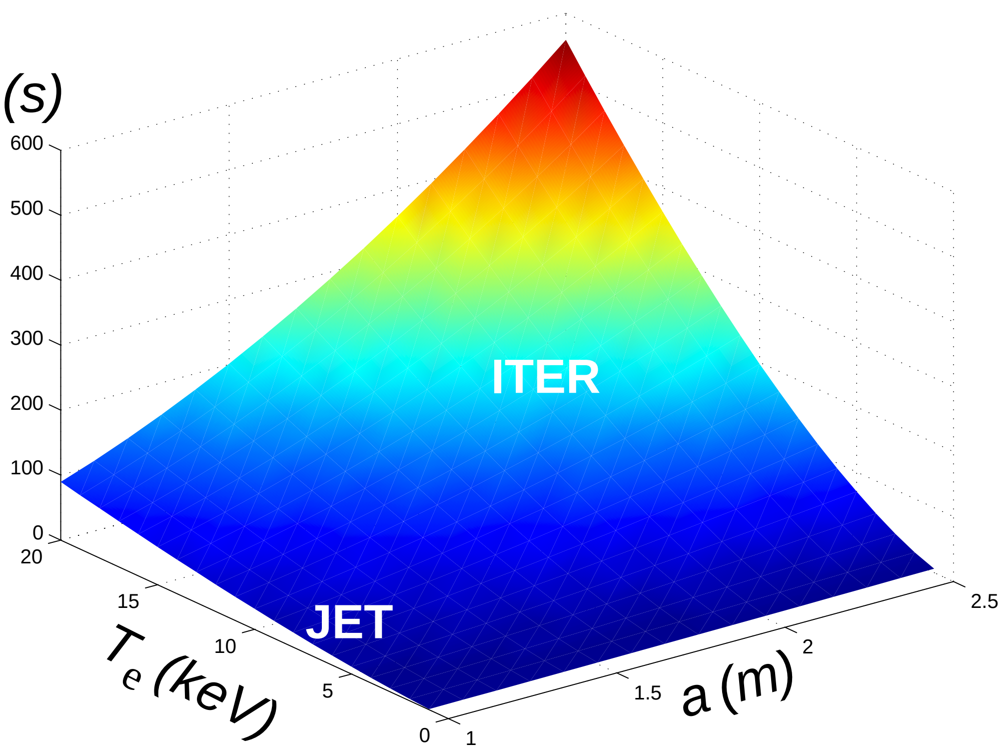
➤influence of breakdown (avalanche phase, current ramp, plasma radius, …) on the early current profile, and thus on the reproducibility.

Acknowledgements:
JET session leaders team

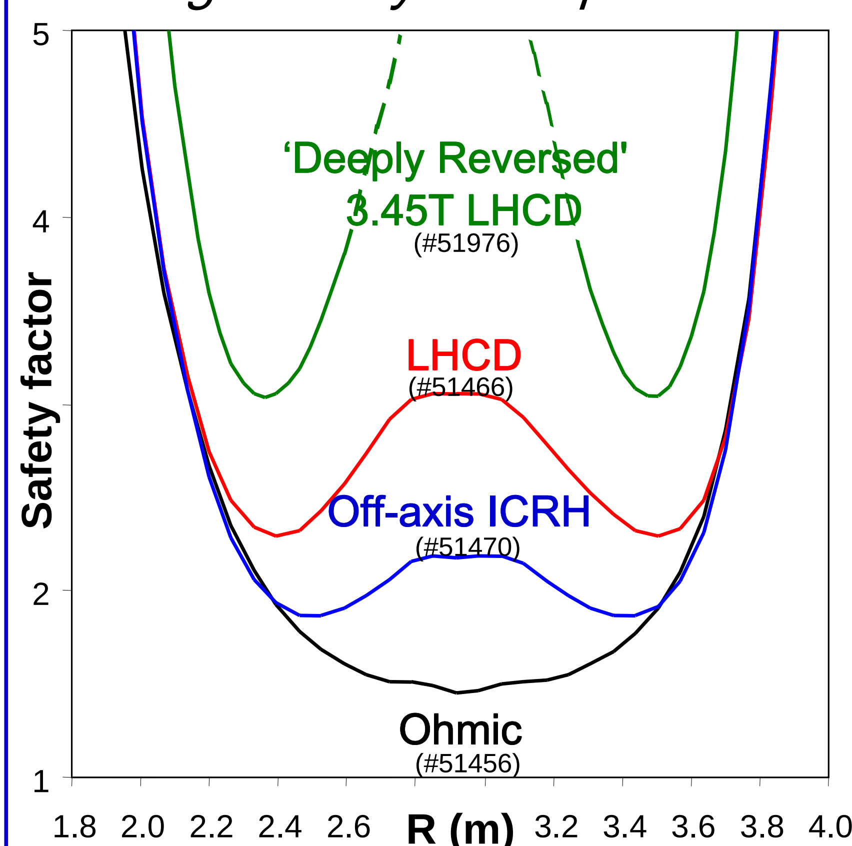
A. Bécoulet, *on behalf of* the contributors to the EFDA-JET workprogramme

The prelude phase: shaping the target current profile

τ_R *versus* T_e *and size*



target safety factor profiles

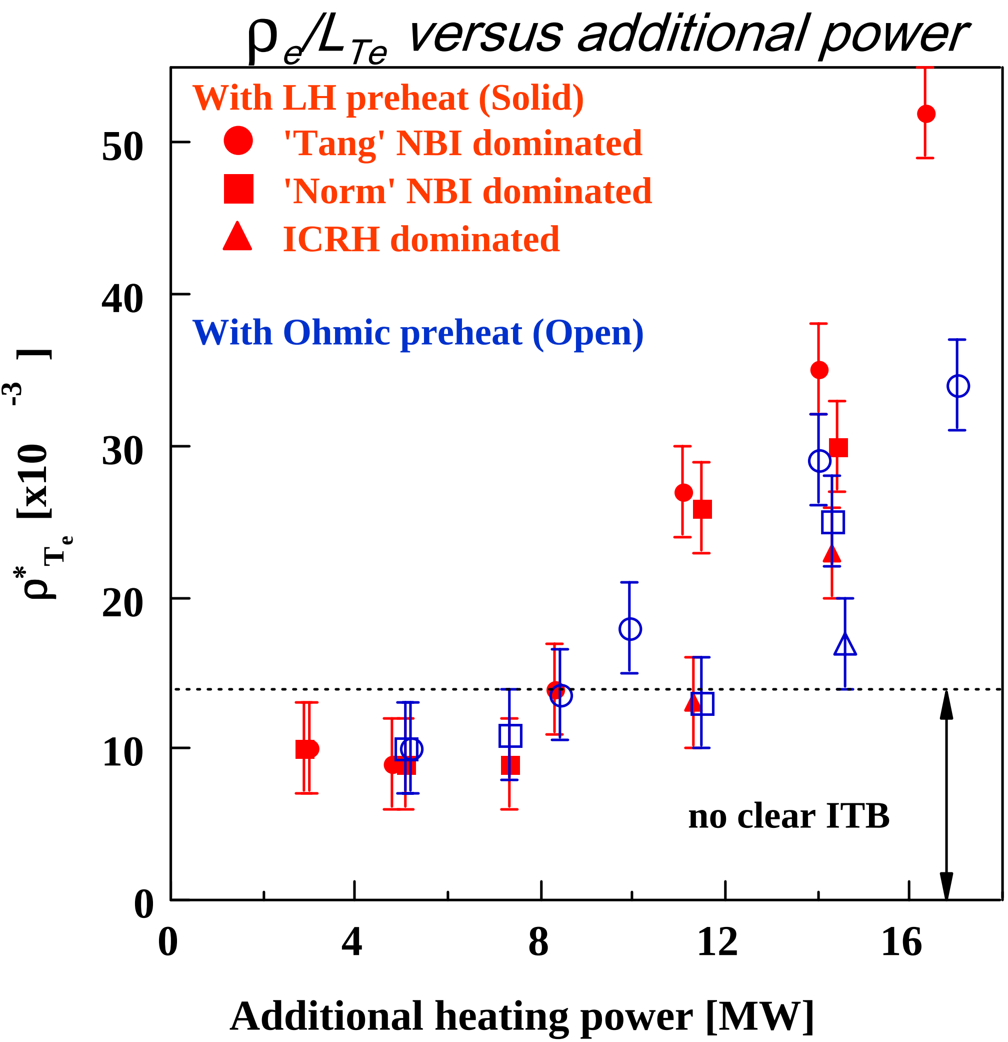


➢ Necessity for a low performance prelude in present machines.

➢ Additional H/CD for Reversed Shear targets

Related contributions: *N. Hawkes et al., Or.02; T. Tala et al., P2.016*

Accessing the ITB regime

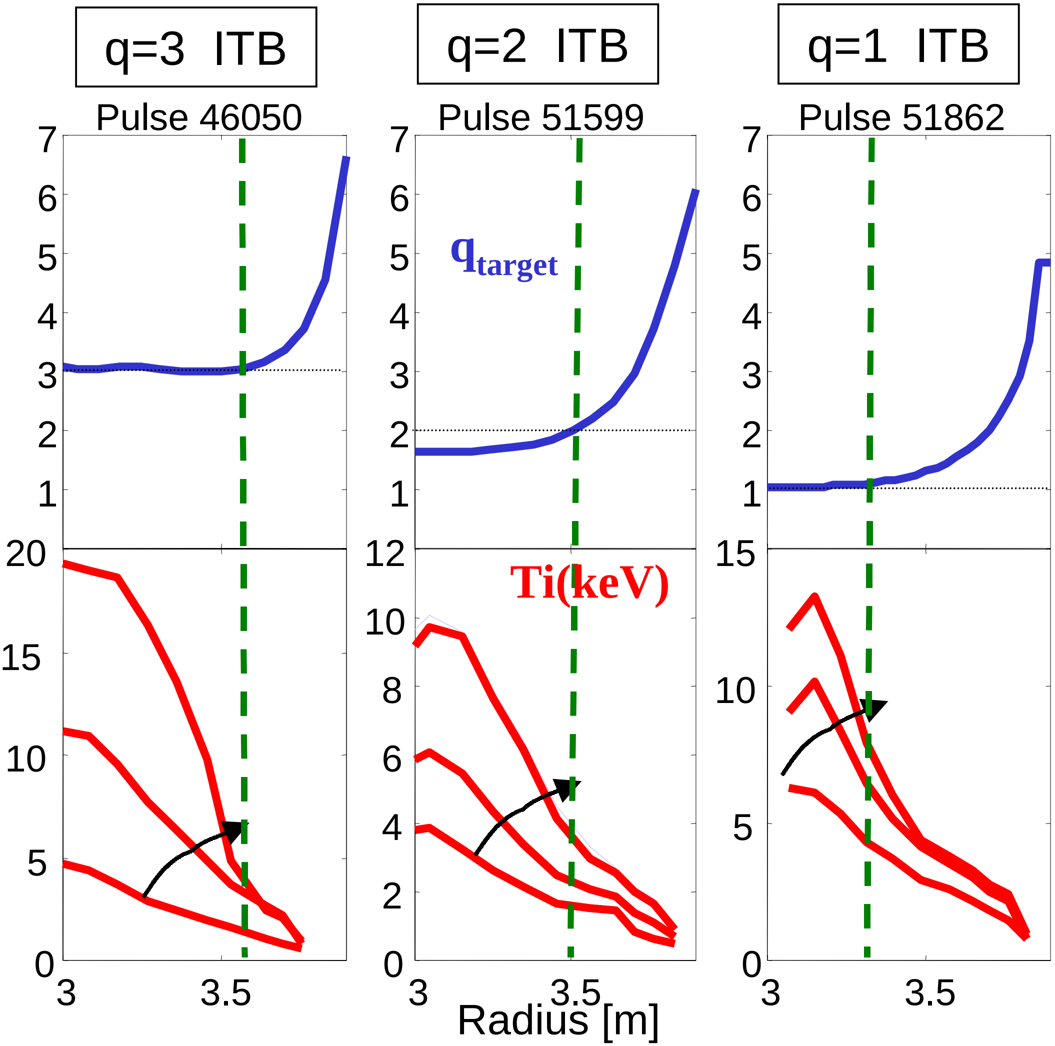


- I_P = 2.2MA
- B = 2.6T
- $n_{e0} = 1.5x10^{19}m^{-3}$ (target)
- comparing 2 target plasmas (Low vs Reversed Shear) and 3 heating schemes (NBI norm and tang, ICRH)

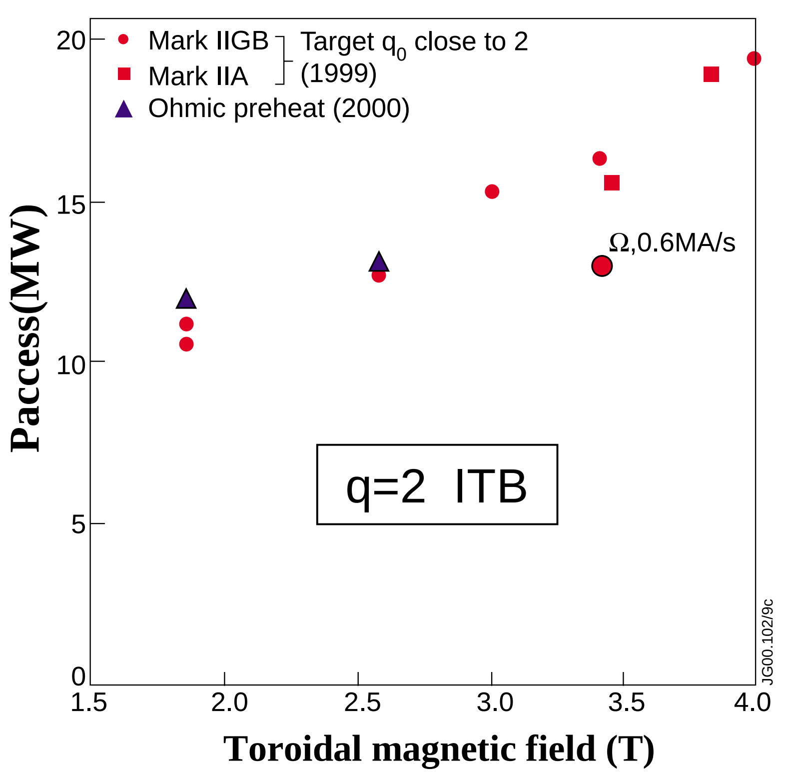
- ➢ lower ITB access power for reversed shear target plasmas
- ➢ strong beneficial effect from NBI (bulk ion heating, fuelling)
- ➢ slight beneficial effect from torque

Related contributions: *C. Challis et al., P2.008*

The ITB access conditions : Low Shear



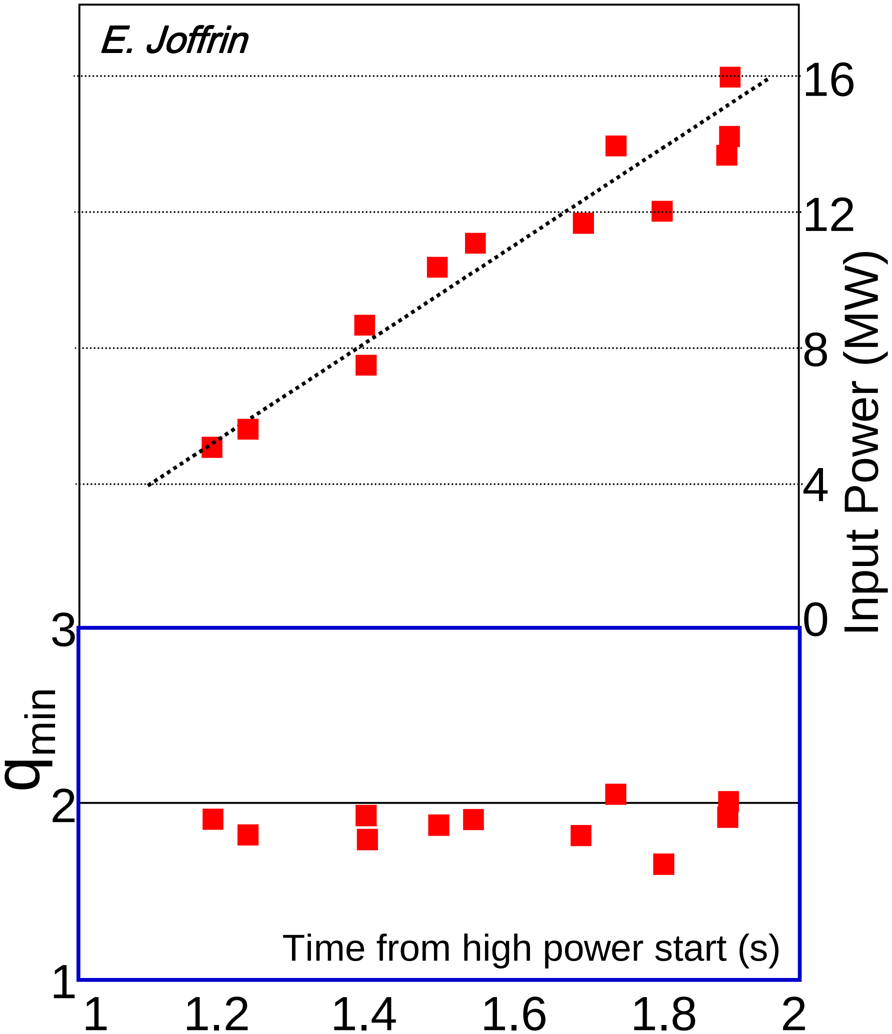
➢ An ITB is triggered in the vicinity of a rational q-surface



Related contributions: *E. Joffrin et al., P2.015 ; G. Gorini et al., P2.005*

The ITB access conditions: Reversed Shear

ITB growth-event linked to rational q-surfaces

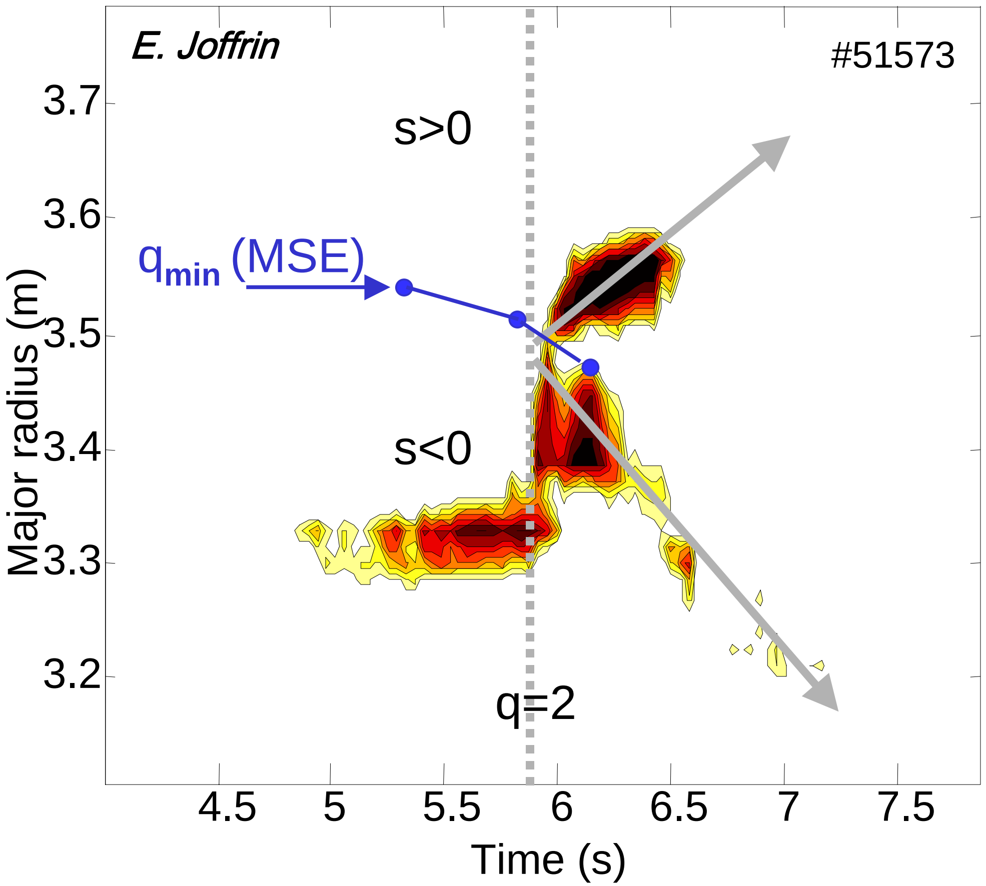


- An ITB is triggered when q_{min} reaches a rational q-surface (q_{min}=2 or 3 observed on JET)
- The access to the ITB regime is not clearly linked to an input power, but more to an optimum q-profile.
- Possibilities for « external » triggering (pellet, LA, saddle coils, …)
- The access to the regime is to be disconnected from the high performance.

Related contributions: *G. Gorini et al., P2.005*

The ITB access conditions: Deep Reversed Shear

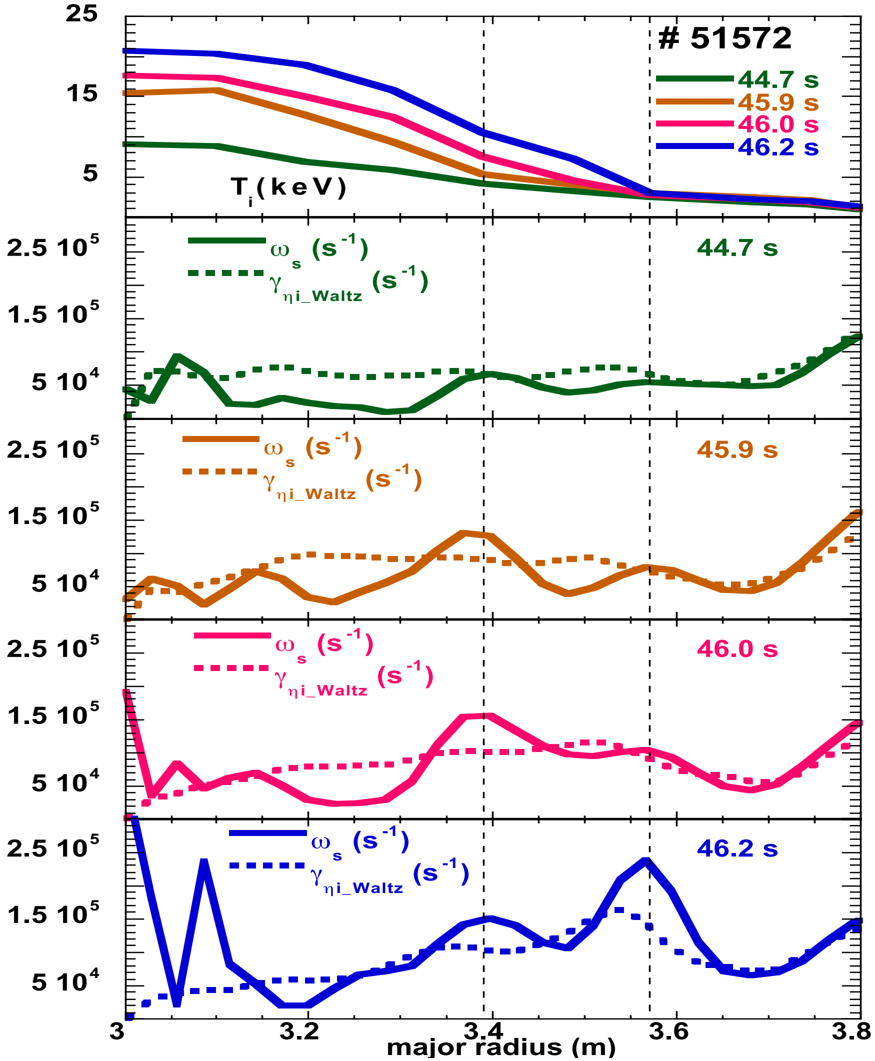
« Inner-ITBs » during deep Reversed Shear preludes



- An e-ITB is triggered during the prelude (LHCD) phase.
- Simultaneously, a « zero-current » core region is observed on MSE.
- This « inner » ITB is located in the negative magnetic shear region (|s| maximum?), and experiences sawtooth-like MHD.
- The low frequency turbulence is reduced below noise level inside the e-ITB.
- Later, a bifurcation towards previous situation if q_{min} reaches an integer, or the inner ITB can be sustained by LHCD and/or ICRH.

Related contributions: *D. Hogeweij et al., P2.002; N. Hawkes et al., Or.02 G. Conway et al., P2.017; T. Hellsten et al., P2.024; P. Hennequin et al., P2.022*

Shearing rate versus linear growth rate



- The access to ITB regime also require the right pressure, rotation, density, … profiles.
- The ExB shear flow suppression of ITG-driven electrostatic turbulence seems confirmed in JET, provided that a magnetic shear dependence is included in the linear growth rate.
- Consistent with cold pulse propagation studies.

- some e-ITBs do not seem to follow this picture.
- causality ?

Related contributions: *B. Esposito et al. P2.019; V. Parail et al., P2.027; P. Mantica et al., Or.19, X. Garbet, Thursday 08:45*

Transition to a high performance plasma in a burning experiment

Entering an Advanced Tokamak regime at Q>1

☺ ➢ The fusion product power helps triggering the ITB (power and bootstrap current)

☹ ➢ The tokamak must have a conventional ELMy H-mode operational point @ Q>1.

➢ More MHD

➢ Very long transients (AT regime set up @ high performance)

➢ requires superconducting high-performance machines for demonstration.

Entering Q>1 thanks to an Advanced Tokamak regime

☺ ➢ The confinement enhancement provided by the AT regime drives the break-even

➢ No need for a conventional ELMy H-mode operational point @ Q>1.

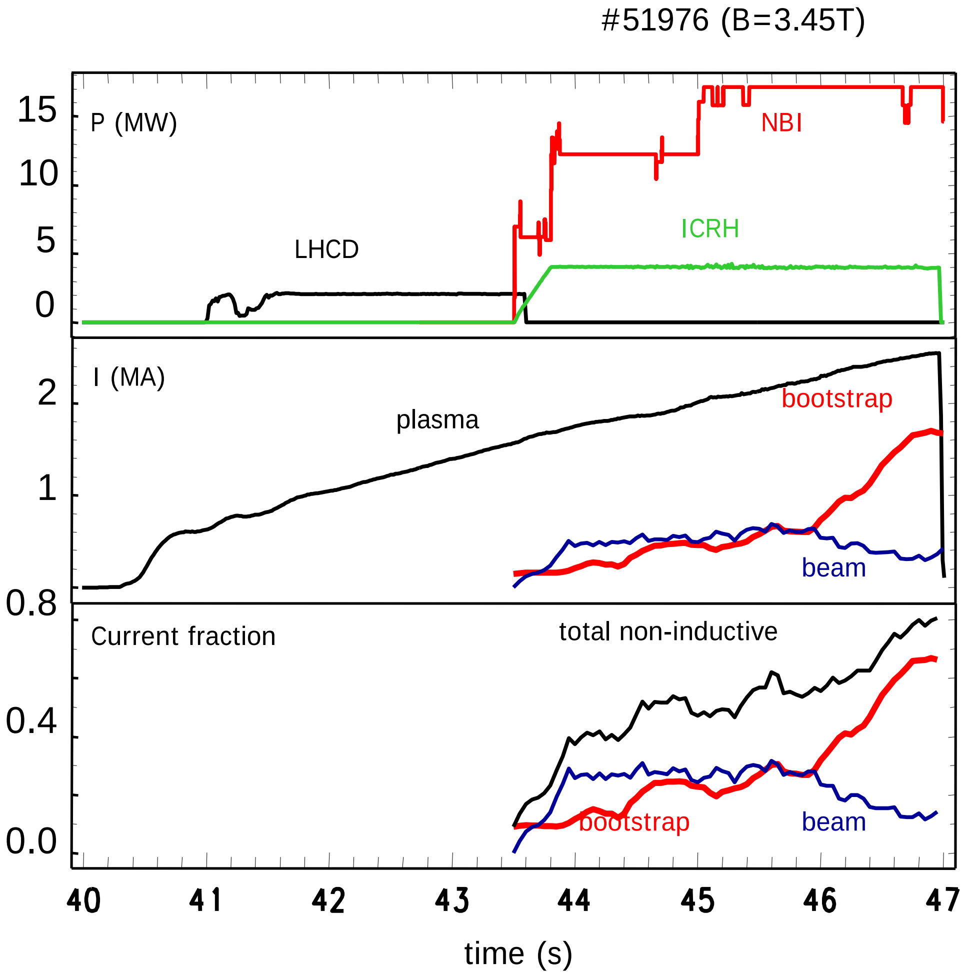
➢ possible demonstrations in machines like JET

➢ low performance prelude

☹ ➢ Requires specific H/CD capabilities during the prelude phase

➢ The AT regime has to survive major changes in heating/torque/fuelling due to the break-even.

Transition to high performance plasmas in JET



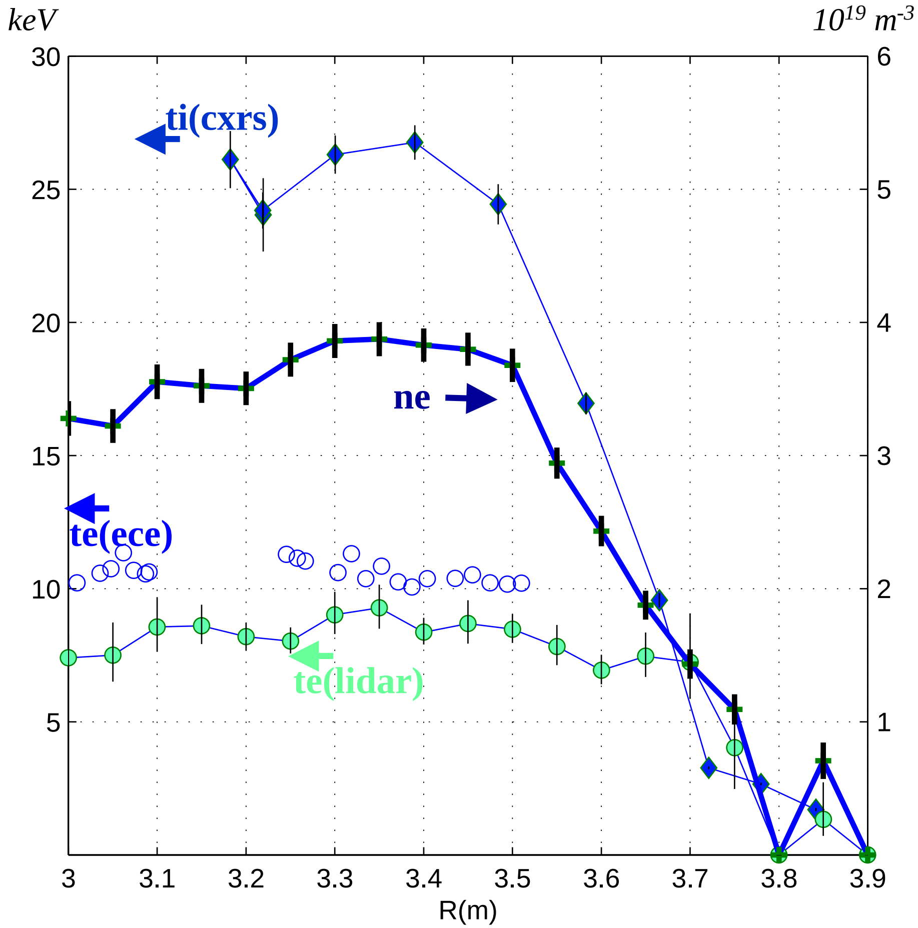
- A reversed shear ITB with $q_{min}=3$
- Ip ~ 2.5MA, B=3.45T; q_{95} ~ 5
- Neutron rate ↗ $4.1 \times 10^{16} s^{-1}$
- P_{DT}^{eq} ↗ 10MW
- Q_{DT}^{eq} ↗ 0.5 (P_{fusion}/P_{input})
- $H_{IPB98(y,2)}$ ↗ 2, $H_{ITER89L-P}$ ↗ 3.3
- β_N ↗ 2.4
- $H_{ITER89L-P} \cdot \beta_N$ ↗ 7.8

- Reversed Shear vs Low Shear: high performance ITBs at same location (stronger gradients in RS cases?).
- High performance phase ends with disruption at giant ELM.

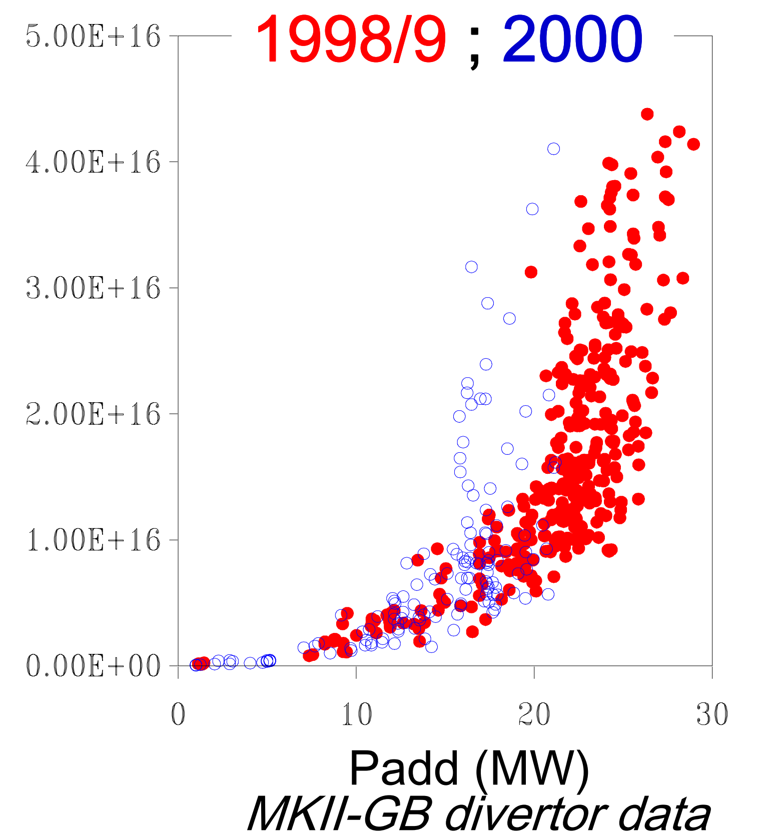
Related contributions: *C. Challis et al., P2.008; P. Hennequin et al., P2.022*

Transition to high performance plasmas in JET

Profiles, pulse 51976

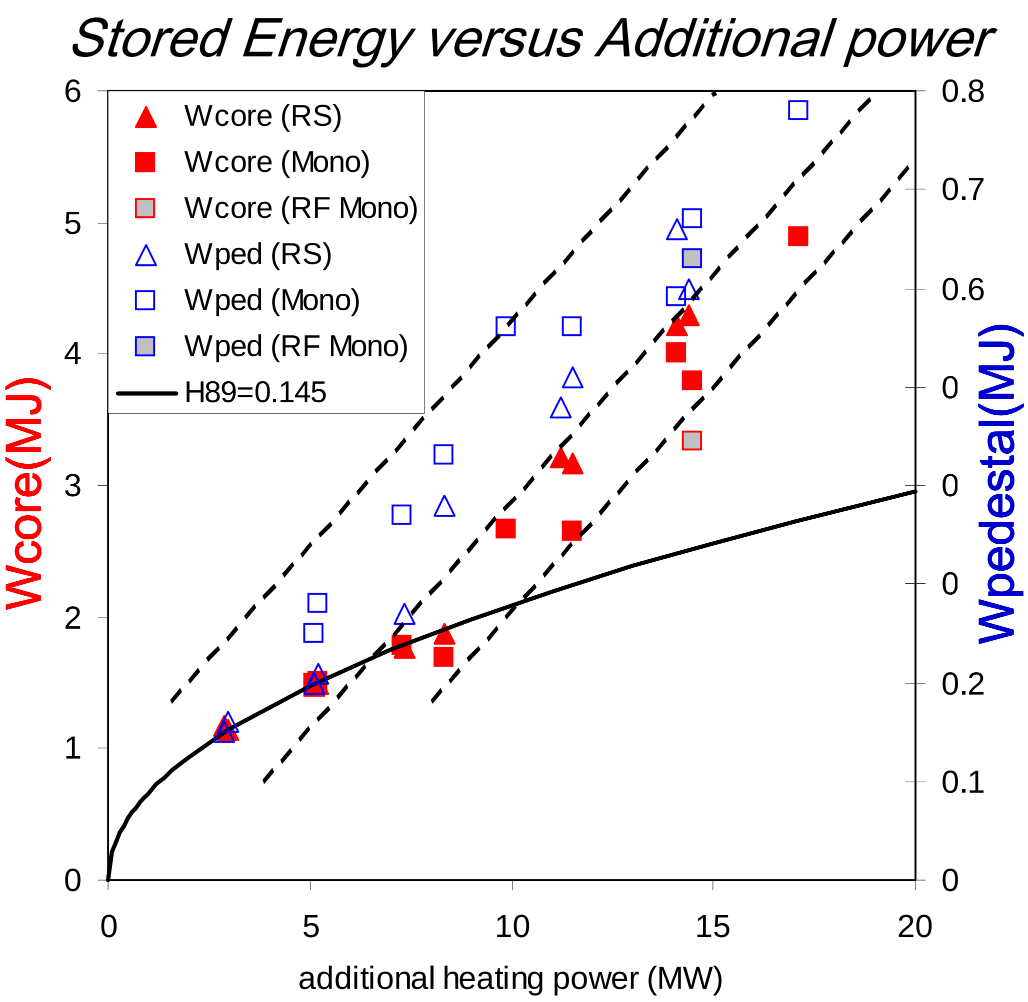


Neutron rate versus Additional power



Related contributions: *C. Challis et al., P2.008*

Transition to high performance plasmas in JET



- $W_{pedestal}=3 x vol x n_{pedestal} x T_{pedestal}$
- $W_{core}=W_{dia} - W_{pedestal}$

- Pedestal energy increases linearly with power

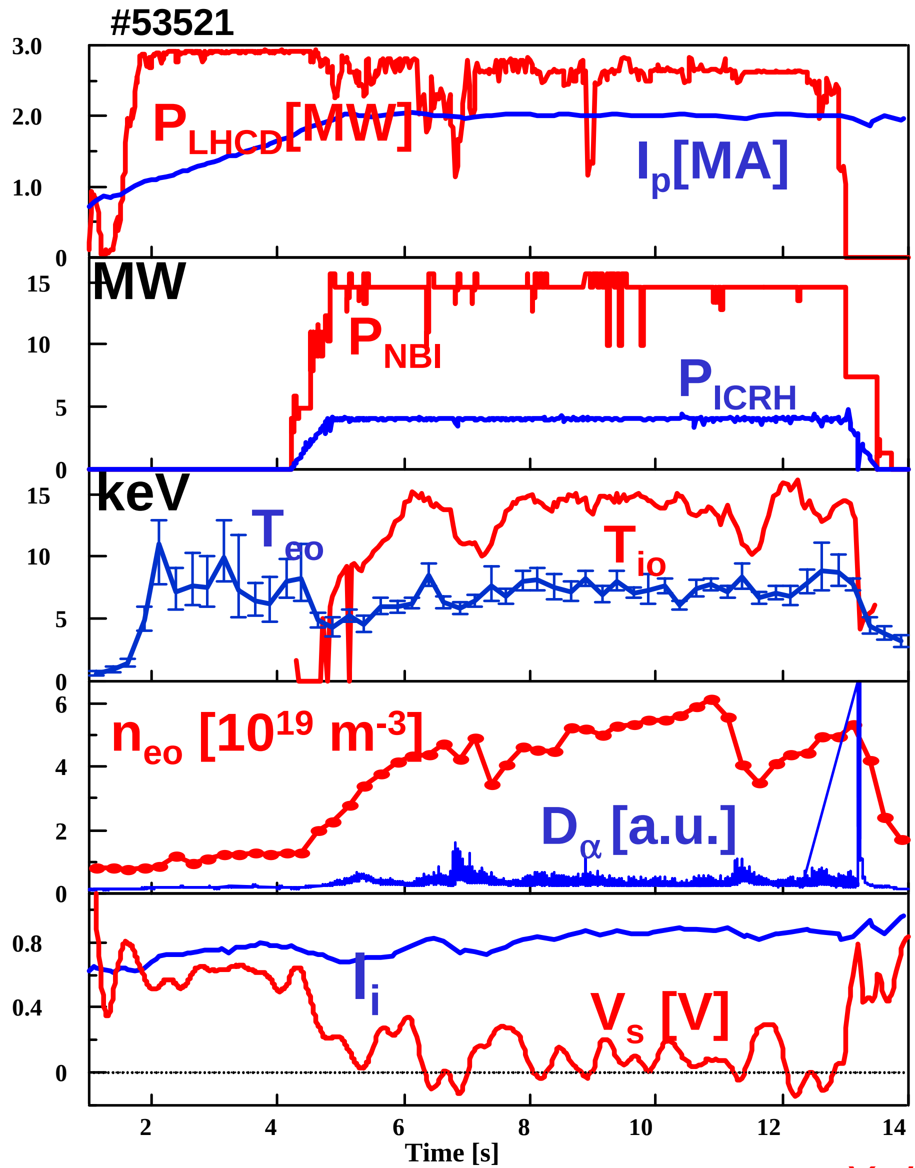
- Core energy degrades with $\sim P^{0.5}$ until the ITB is formed, then follows the pedestal energy

- ICRH cases under-perform

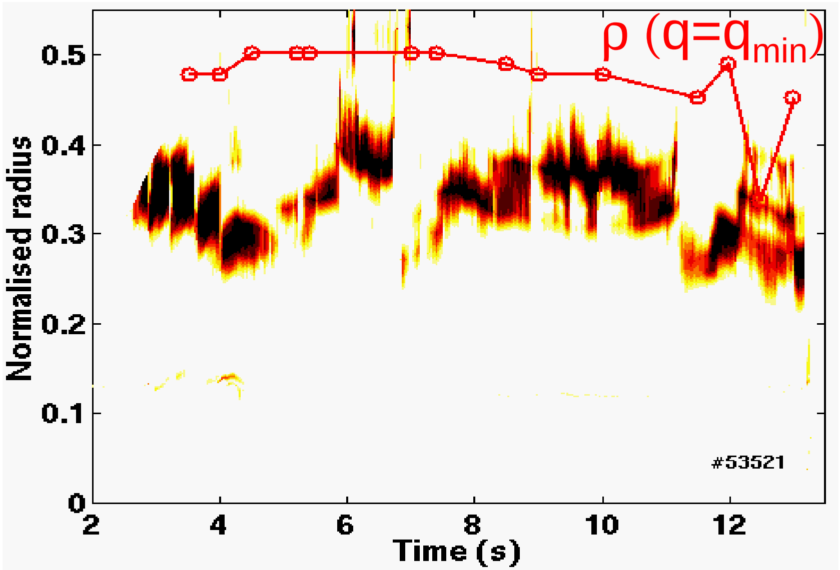
- Core energy dominates performance ($W_{pedestal} / W_{dia} \sim 15\%$)

Related contributions: *C. Challis et al., P2.008*

Steady-state ITB on JET



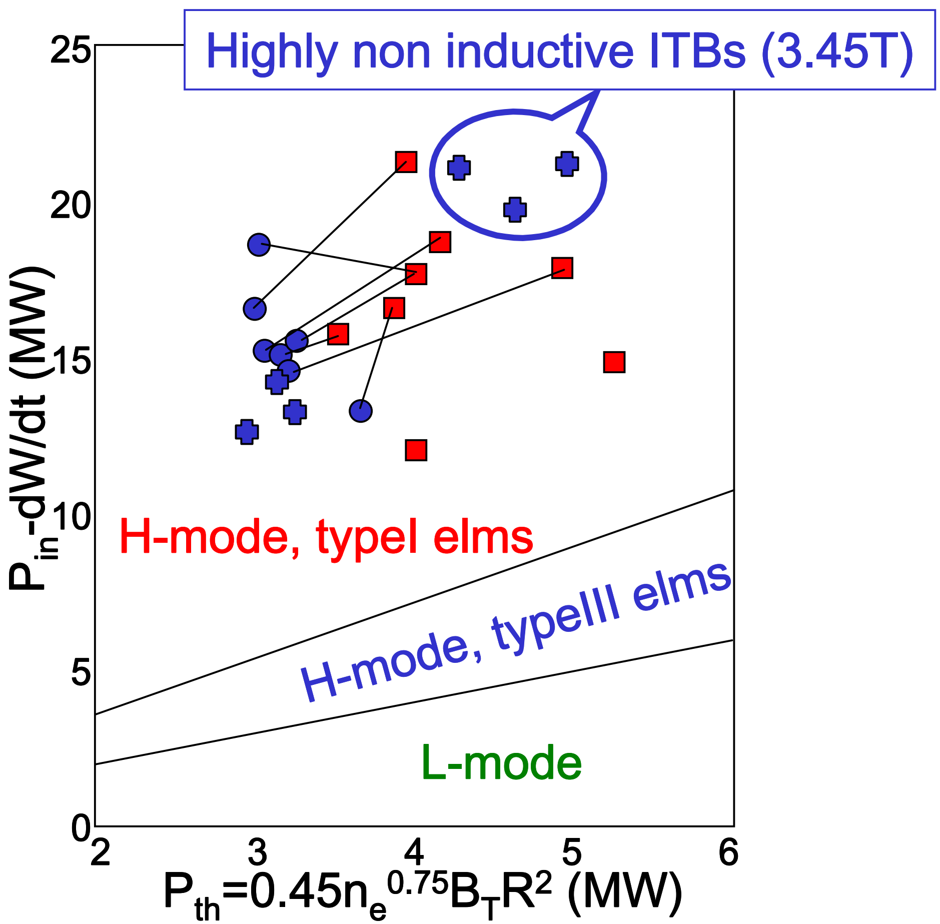
- LHCD power sustained all along the high power phase (CD_4 puff)
- e-ITB sustained for 11s ($36\tau_E$)
- Ti/Ne/Vtor-ITB sustained for 8s ($27\tau_E$)
- I_{lhcd}=0.4-0.8MA; $I_{bootstrap}$=0.8MA; I_{nbcd}=0.2-0.4MA (~80% non inductive)



- The ITB time history is strongly linked to the current profile.

Related contributions: *X. Litaudon et al., Or.22; J. Mailloux et al., P2.084*

Steady-state ITB on JET: edge behaviour

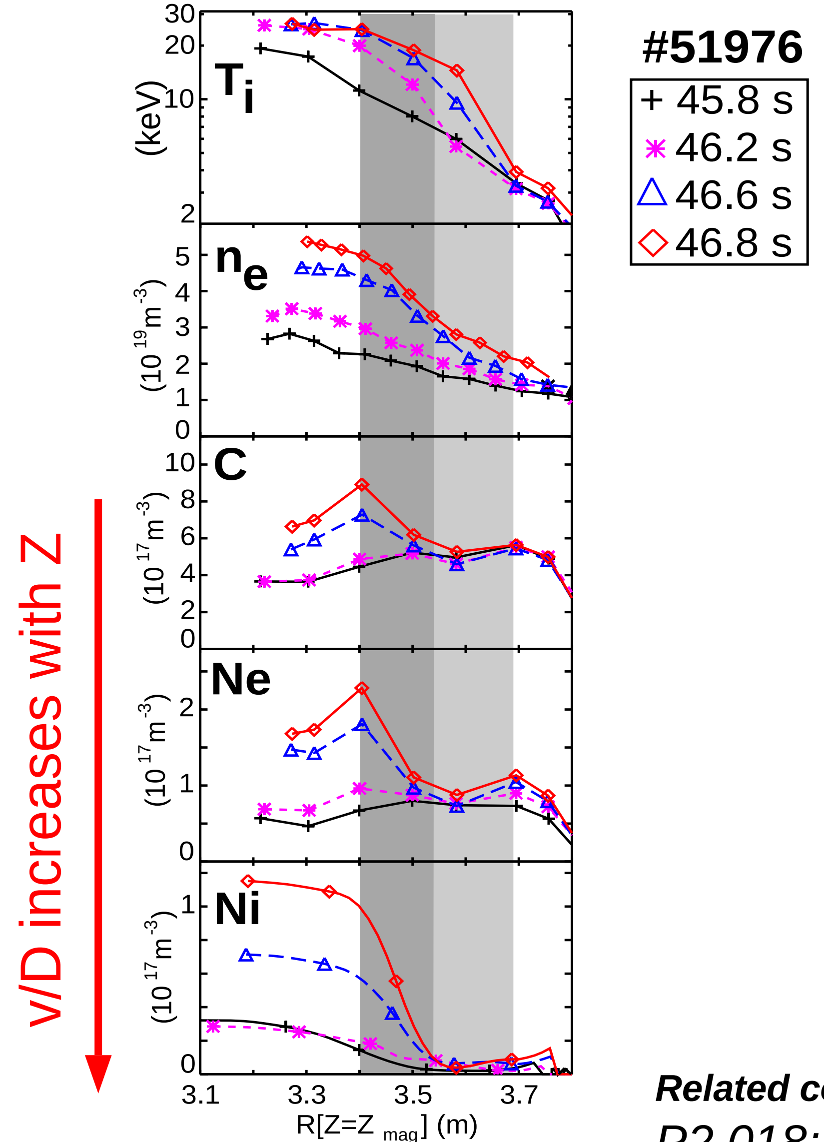


- ➢Strong deviation of the typeIII->typeI ELM transition in ITB discharges.
- ➢ some effect from divertor pumping, but not sufficient.
- ➢Steady-state ITBs stay in typeIII ELMs well above the expected threshold (no transitory effect)

- ➢ Influence of the edge current density on ELM behaviour.

***Related contributions:** M. Bécoulet et al., P4.076*

Steady-state ITB on JET : particle transport



- impurity concentrations determined using SXR, CXRS and spectroscopy.
- Z dependence of peaking in ITBs
- location of strong impurity gradient inside T_i-barrier, where n_e is peaked.
- good agreement with neoclassical theory.

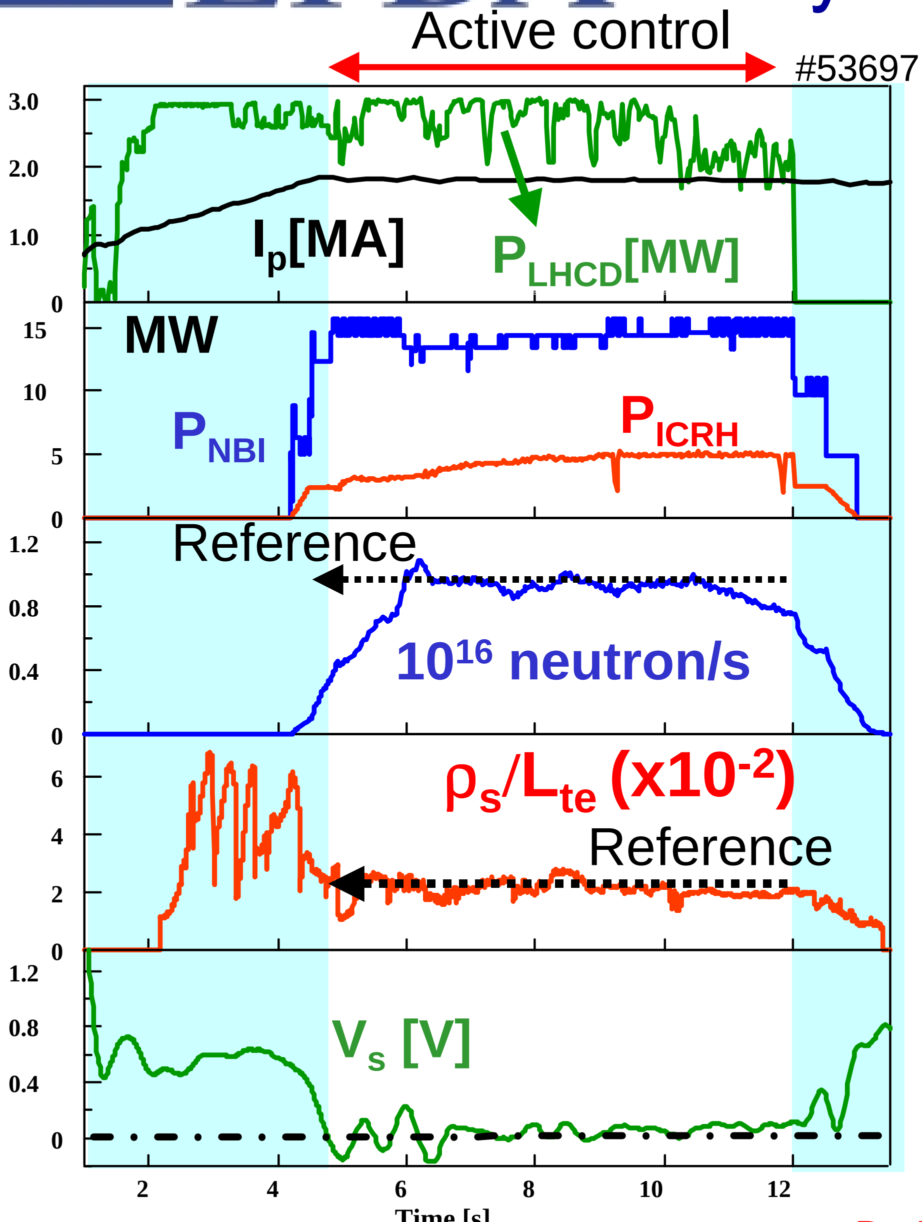
- Accumulation of Nickel -> radiative collapse in very long pulses.

- Necessity for broader T_i-barriers and flatter density profiles (density profile control) and/or soft MHD

***Related contributions:** R. Dux et al., P2.007; C. Giroud et al., P2.018; P. Lomas et al., P2.023; E. Joffrin et al, P2.015*

EUROPEAN FUSION DEVELOPMENT AGREEMENT

Steady-state ITB on JET: control



- ➢ Real time feedback loop on <u>Te-profile</u> (normalized gradient length control), plus on neutron rate.
- ➢ Highly non inductive current profile preventing ITB evolution, and strong ELMs

=> long pulse steady-state ITB far from MHD limits and with mild impurity accumulation.

- ➢ feasibility demonstration of a controlled AT regime.
- ➢ requires <u>margins on actuators</u>, and thus somewhat reduced performance.

Related contributions: *D. Mazon et al., P2.011; G. Tresset et al.; P2.014*

Conclusions

- Important new results from JET concerning the link between the current profile and the ITBs:
  - importance of the breakdown on the whole regime history
  - influence of the current profile on the route towards ITB & access power: magnetic shear and rational-q surfaces
  - strong link between current profile evolution and ITB evolution all along the discharge.
- High performance regimes obtained in all cases (LS, RS)
- ITB core energy increasing linearly with power
- The ExB shear flow suppression of ITG-driven electrostatic turbulence seems confirmed, when magnetic shear dependence included in the linear growth rate.
- Stationary ITB regimes obtained in highly non inductive cases:
  - LHCD+NBCD+bootstrap
  - modification of ELM behaviour by edge current
  - neo-classical impurity transport behaviour constraining the profiles for a steady-state solution.
- First demonstration of stationary ITB regimes with profile feedback loop control.

Related Contributions

- N. Hawkes et al., Or.02: **Extreme shear reversal in JET discharges**
- P. Mantica et al., Or.19: **Cold pulse propagation experiments in ITB plasmas of JET**
- X. Litaudon et al., Or.22: **Towards full current drive operation in JET**
- D. Hogeweij et al., P2.002: **Electron heated ITBs in JET**
- G. Gorini et al., P2.005: **Peripheral plasma perturbations & transient improved confinement in JET OS discharges**
- R. Dux et al., P2.007: **Impurity behaviour in ITB discharges with reversed shear in JET**
- C. Challis et al., P2.008: **High fusion performance in JET plasmas with highly negative central magnetic shear**
- R. Wolf et al., P2.009: **Influence of electron heating on confinement in JET & AUG ITB plasmas**
- D. Mazon et al., P2.011: **Real-time plasma control of ITBs in JET**
- O. Tudisco et al., P2.013: **Effect on internal flux shaping in JET transport barriers**
- G. Tresset et al.; P2.014: **Characterisation of ITBs in JET & simulation of control algorithms.**
- E. Joffrin et al., P2.015: **Similar advanced tokamak experiments in JET and AUG.**
- T. Tala et al., P2.016: **Impact of different preheating methods on q-profile evolution in JET**
- G. Conway et al., P2.017: **Turbulence behaviour during electron heated RS discharges in JET**
- C. Giroud et al., P2.018: **Neon transport in JET close to ITB formation in monotonic and reversed q-profiles**
- B. Esposito et al. P2.019: **Correlation between magnetic shear and ExB flow shearing rate in JET ITB discharges**
- P. Hennequin et al., P2.022: **MHD performance limits in JET optimised shear discharges**
- P. Lomas et al., P2.023: **Effects of target density, plasma shaping & divertor configuration on H-mode pedestal in ITB experiments on JET**
- T. Hellsten et al., P2.024: **Sawtoothing in RS plasmas**
- V. Parail et al., P2.027: **Predictive modelling of JET plasmas with edge and core transport barriers**
- J. Mailloux et al., P2.084: **use of LHCD/H in OS plasmas in JET**
- M. Bécoulet et al., P4.076: **Influence of edge current profile on typeIII-typeI elm transition in OS dicharges on JET.**