Fusion Reactor Technology II
(459.761, 3 Credits)

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Fusion Plasma Technology

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Blanket and Material Technology

Safety Technology

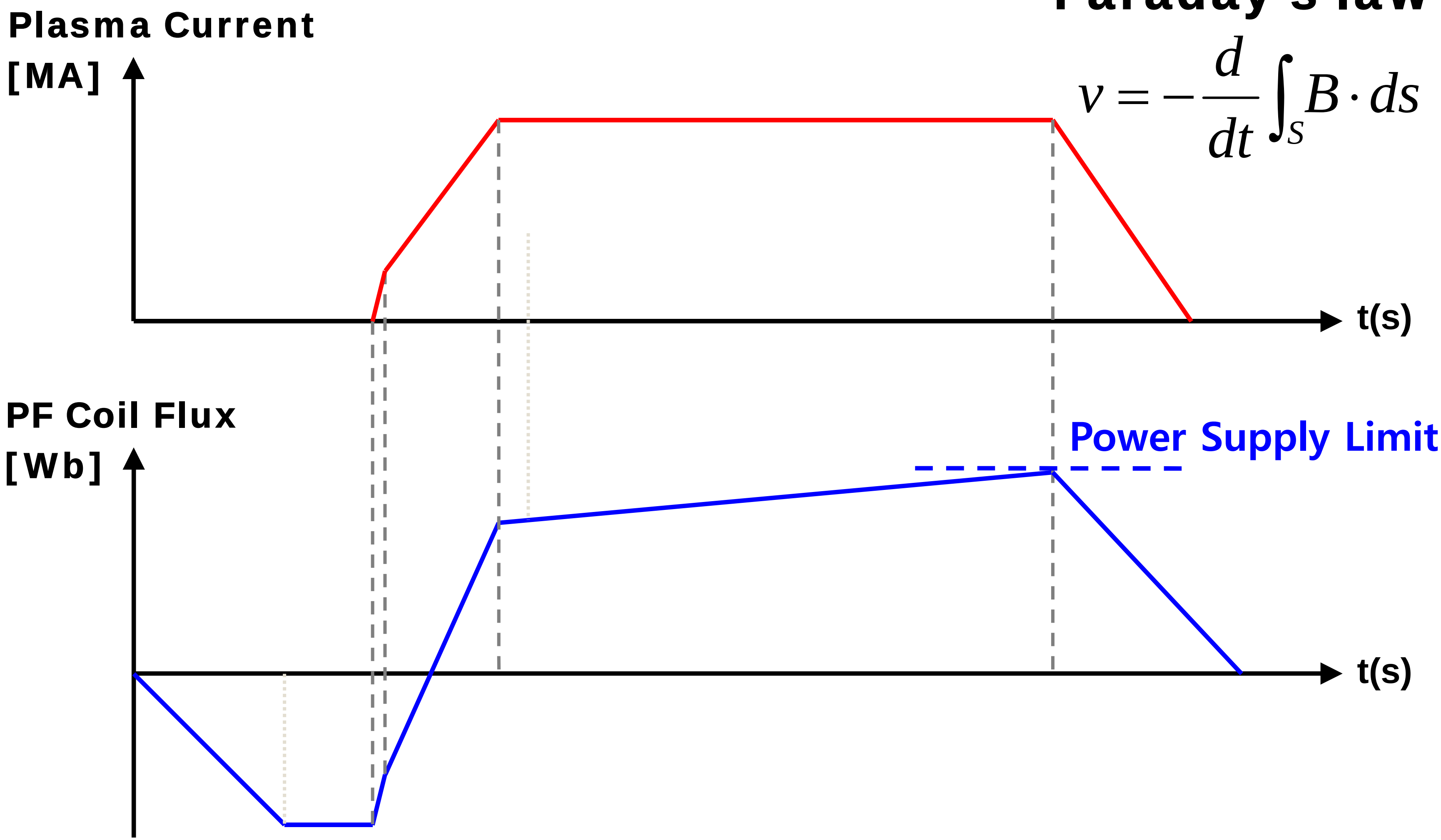
Operation and Maintenance Technology

Issues and prospects for confinement performance

H-mode: Limitation

Faraday's law

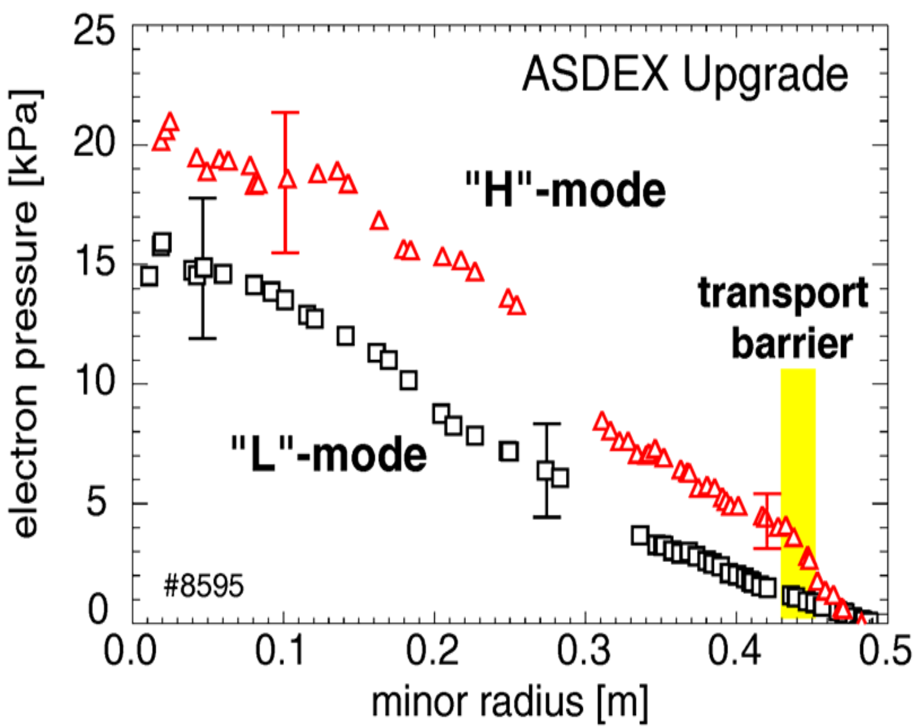
$$v = -\frac{d}{dt}\int_S B \cdot ds$$



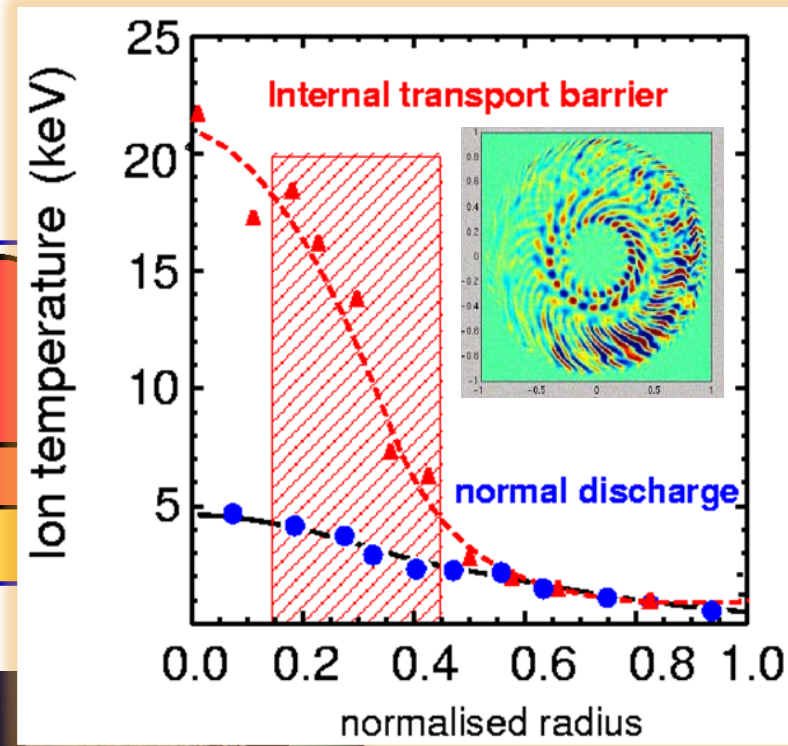
Inherent drawback of Tokamak!

Improved confinement suitable for the steady-state operation

H-mode



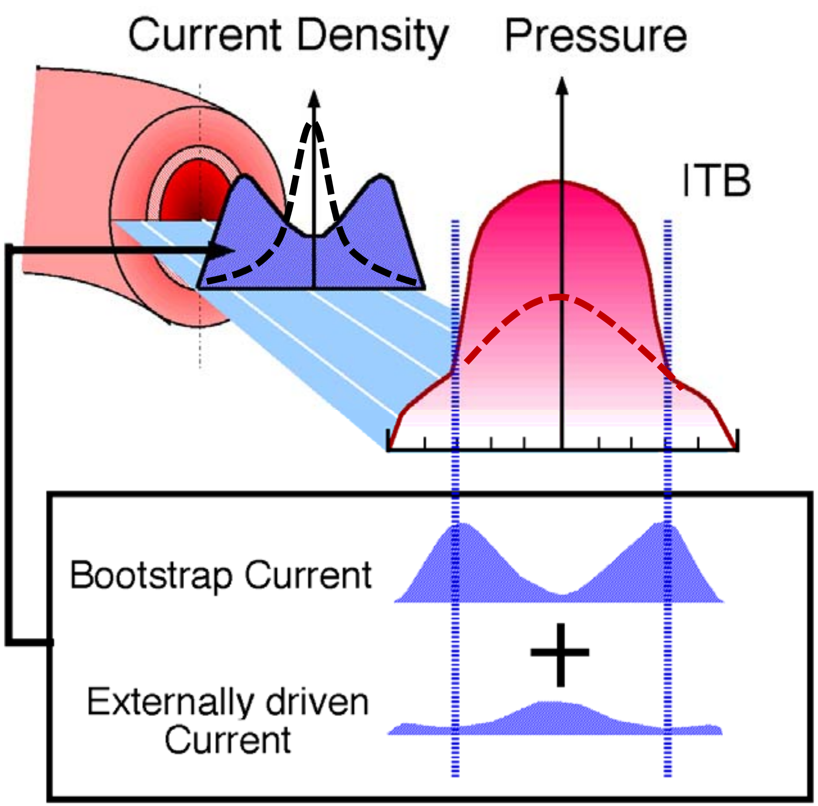
Reversed shear mode



ved
mode

ASDEX Upgrade

Improved confinement suitable for the steady-state operation



Non-monotonic current profile

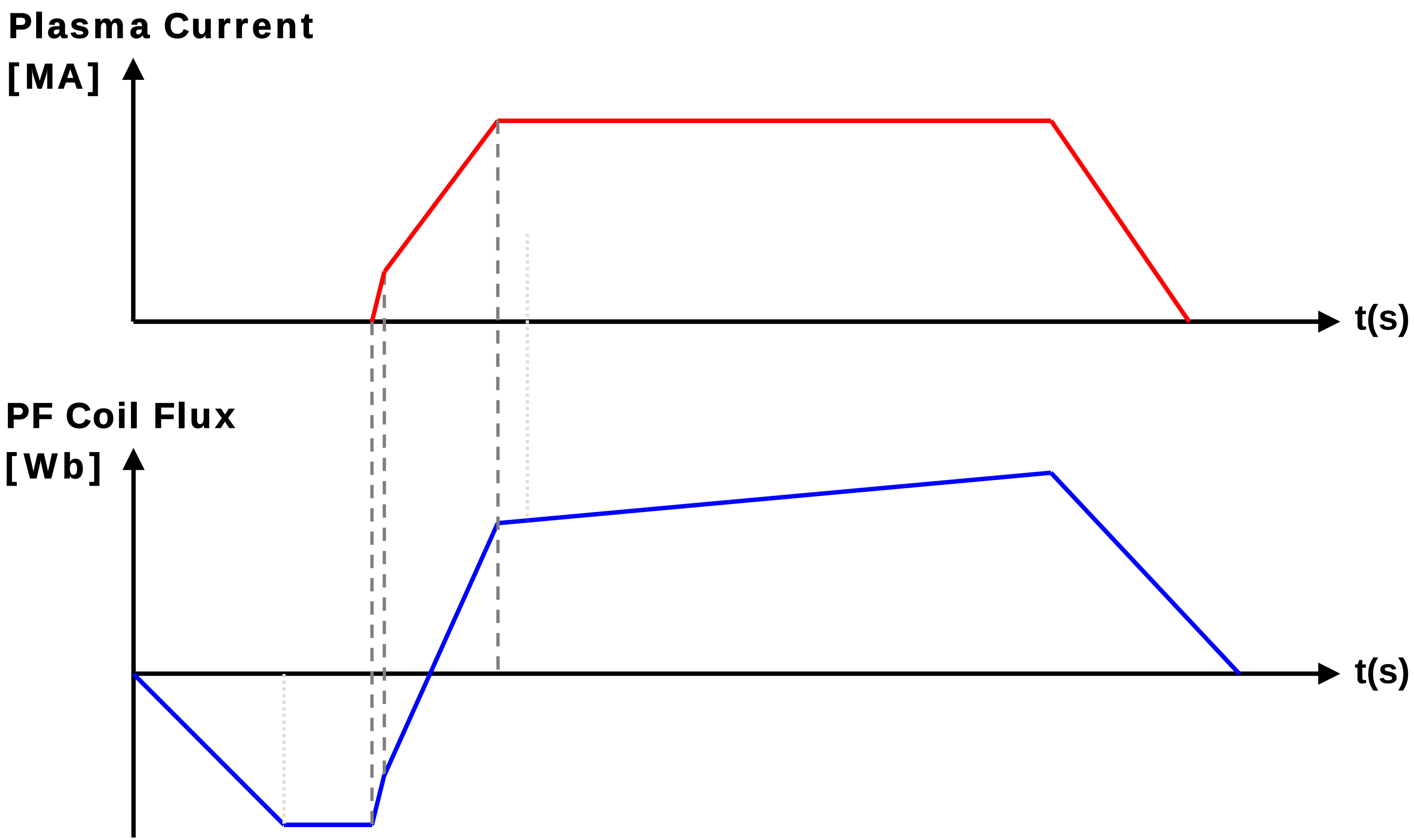
Turbulence suppression

High pressure gradients

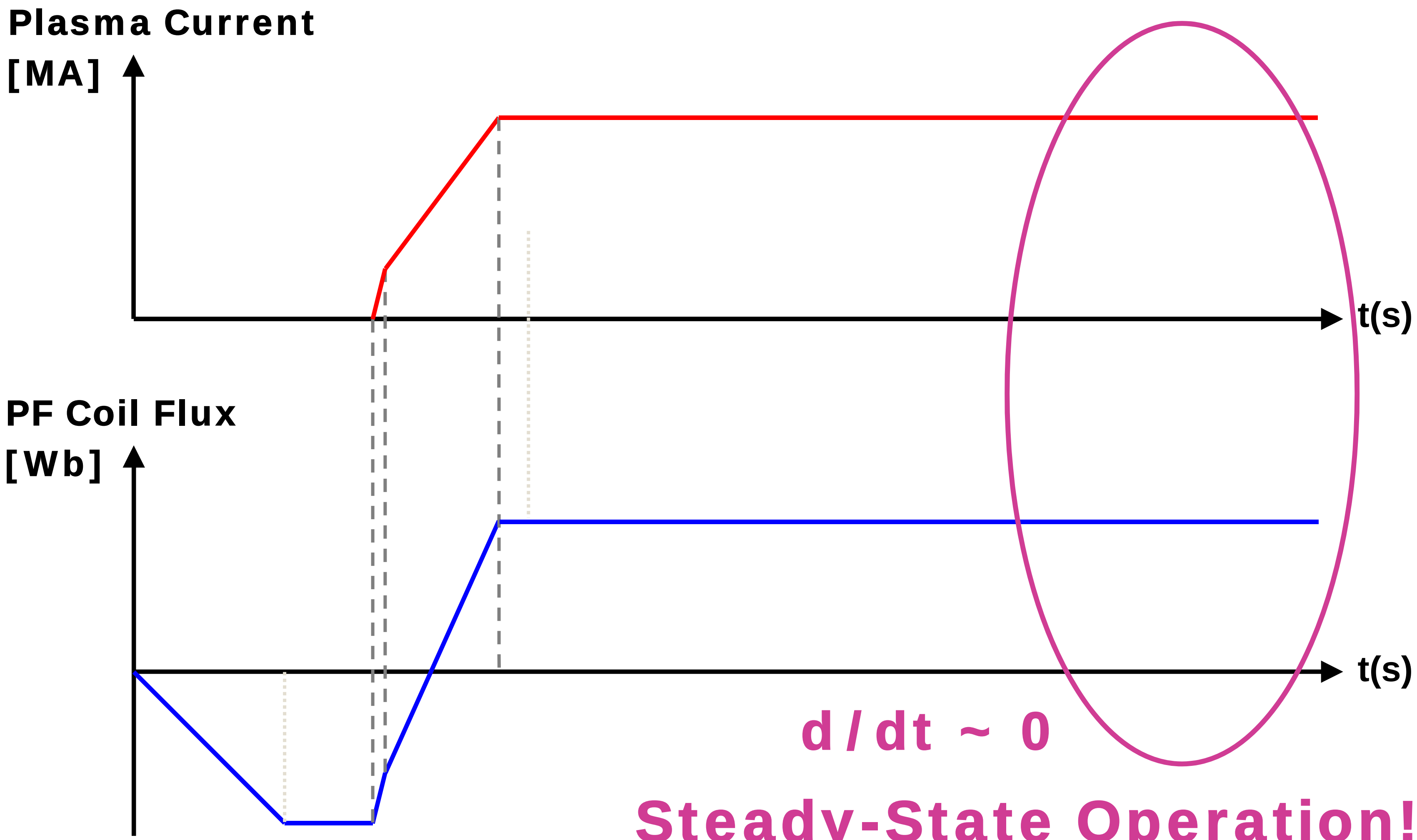
Large bootstrap current

Non-inductive current drive

Improved confinement suitable for the steady-state operation

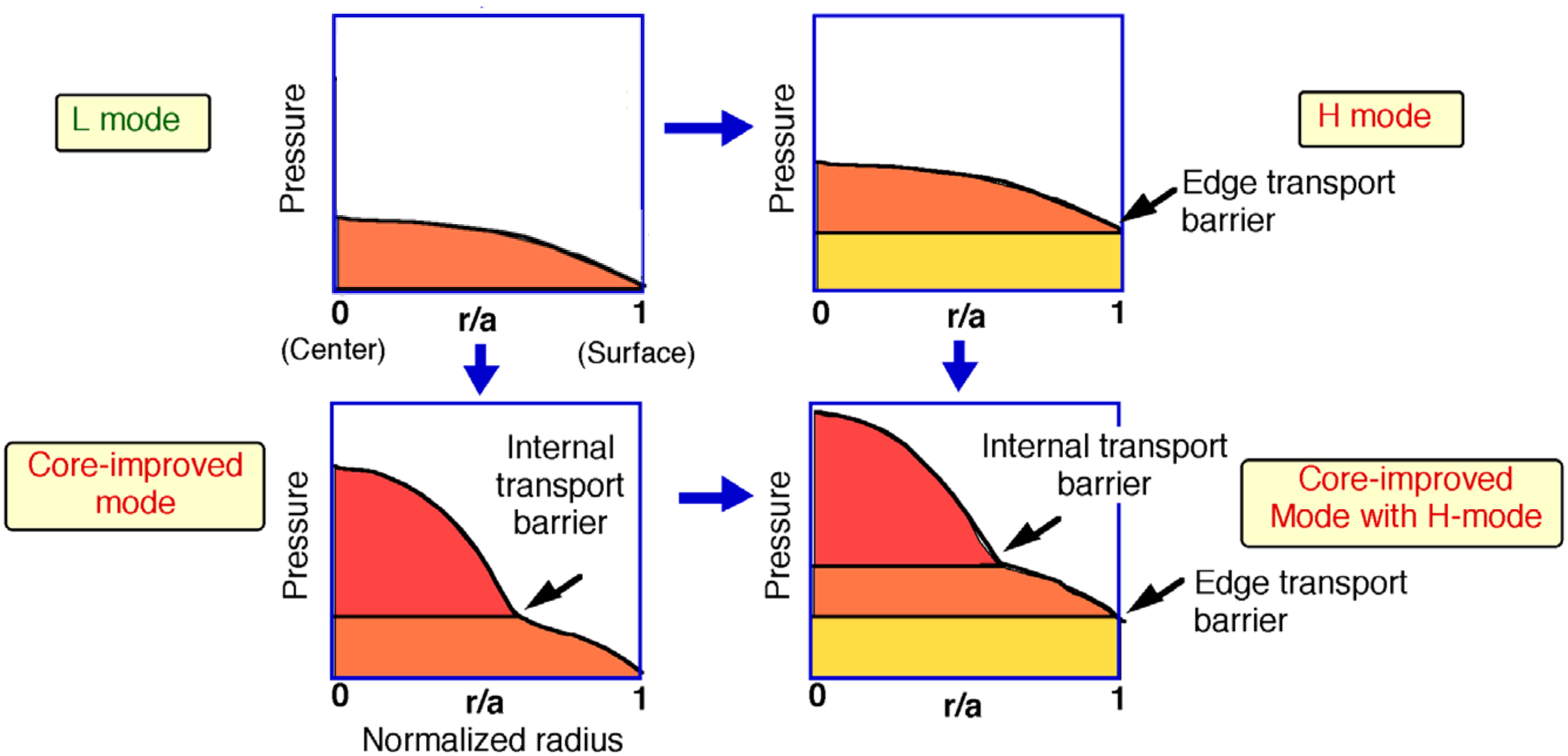


Improved confinement suitable for the steady-state operation

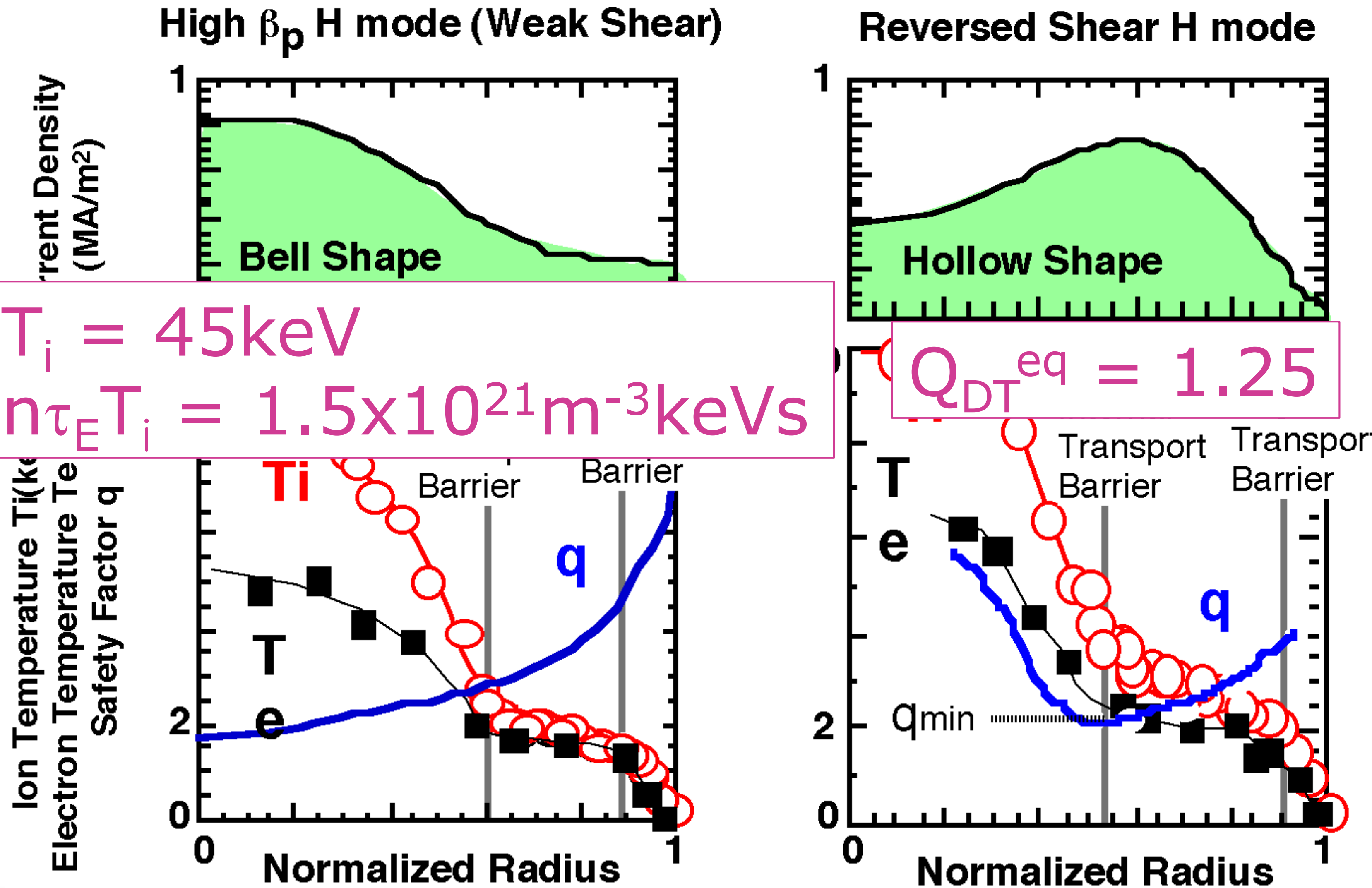


Steady-State Operation!

Improved confinement suitable for the steady-state operation



Improved confinement suitable for the steady-state operation

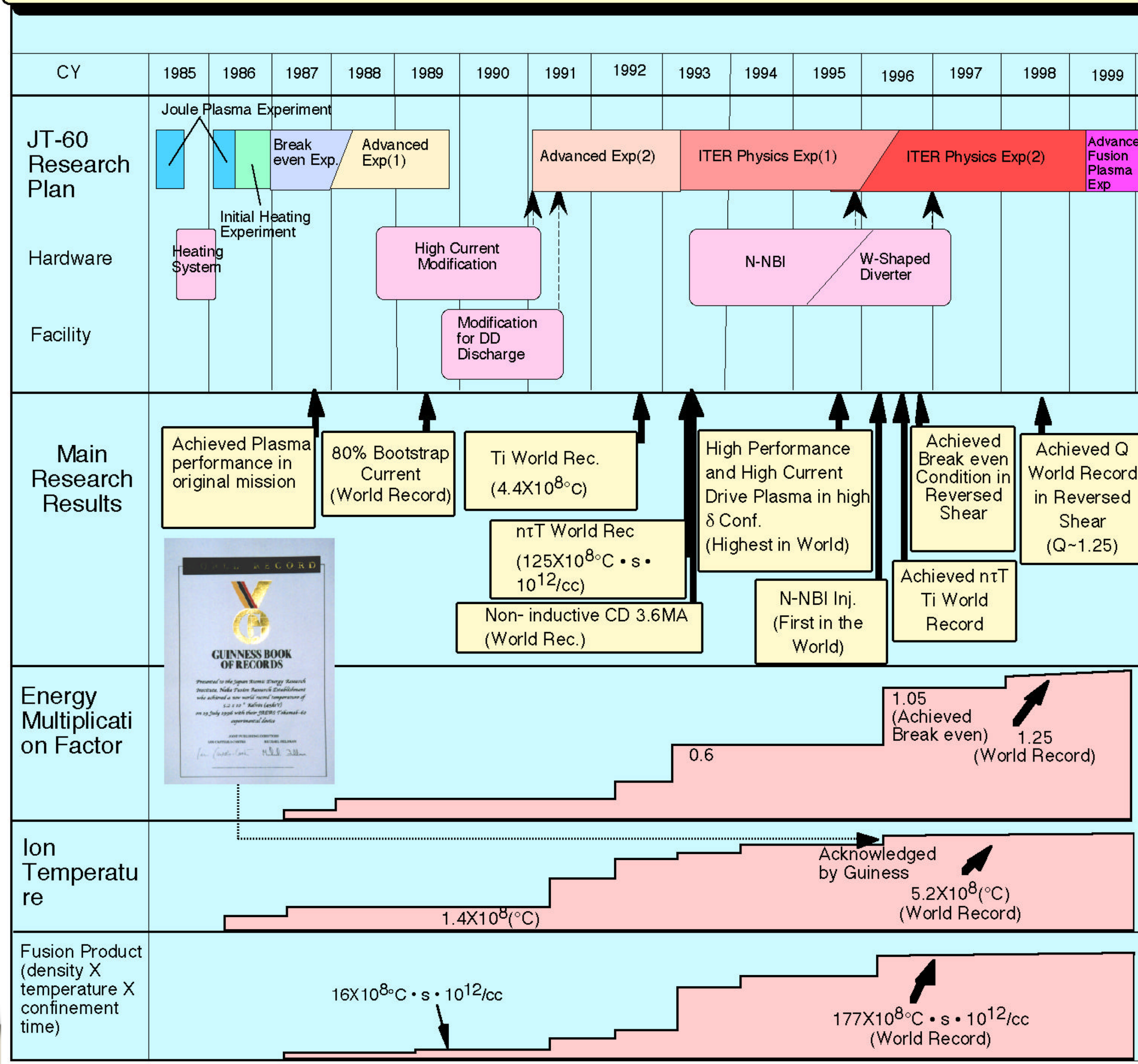


$T_i = 45\text{keV}$

$n\tau_E T_i = 1.5\text{x}10^{21}\text{m}^{-3}\text{keVs}$

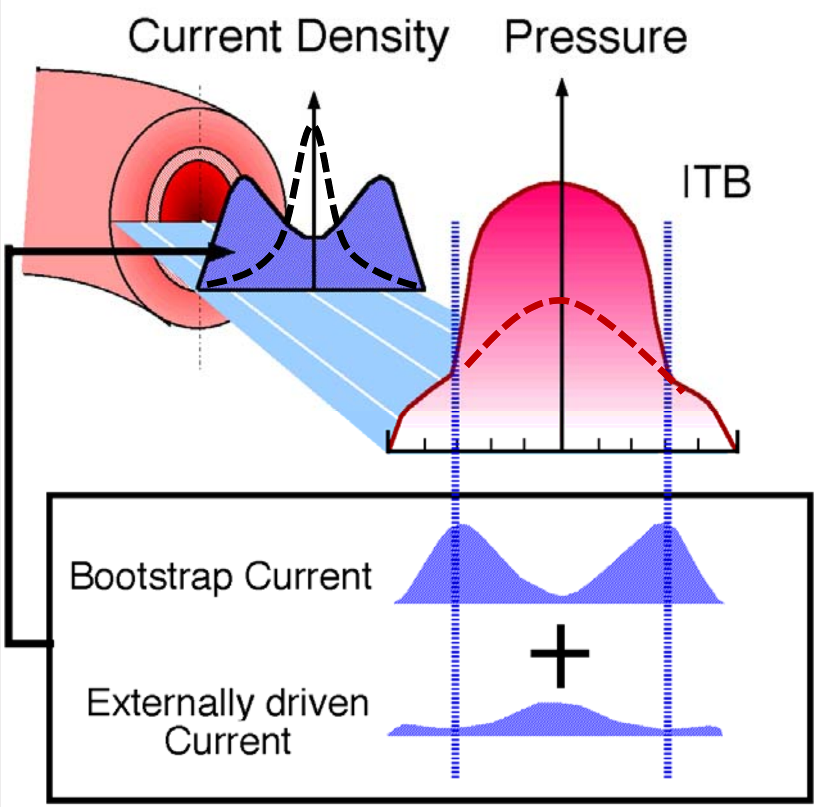
$Q_{DT}^{eq} = 1.25$

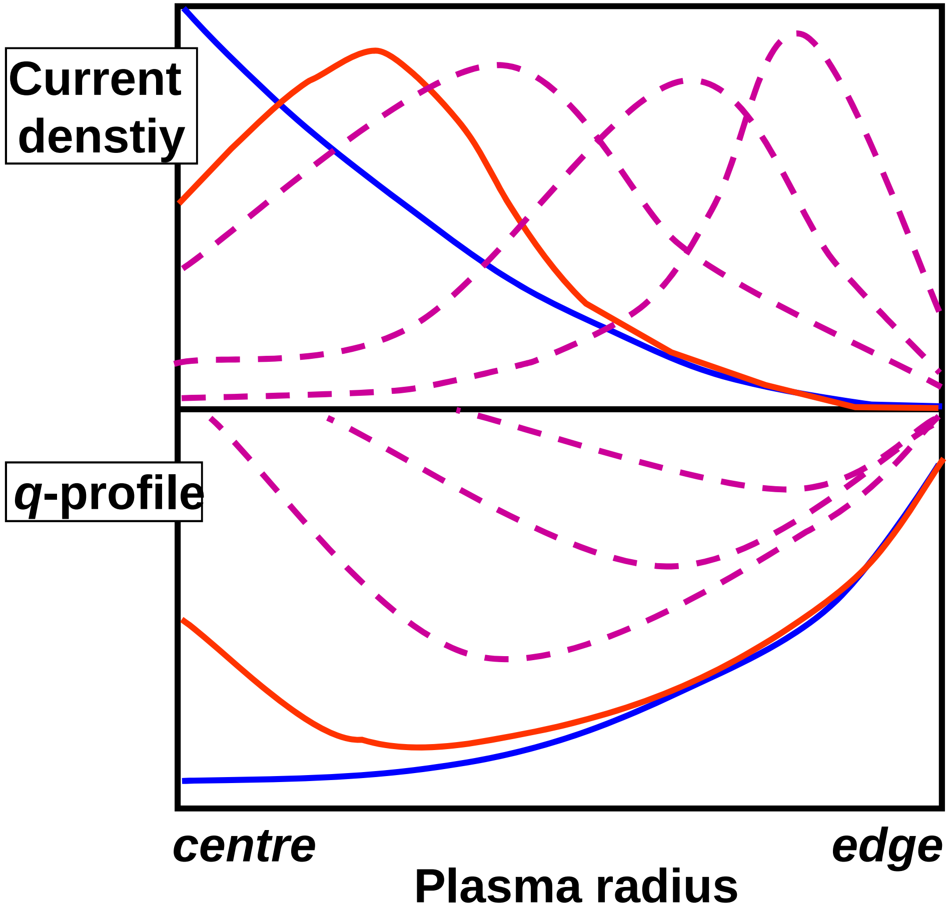
Transition of JT-60 Program and Progress in Plasma Performances



Current profile control

- Plasma current diffusion into the core from the edge

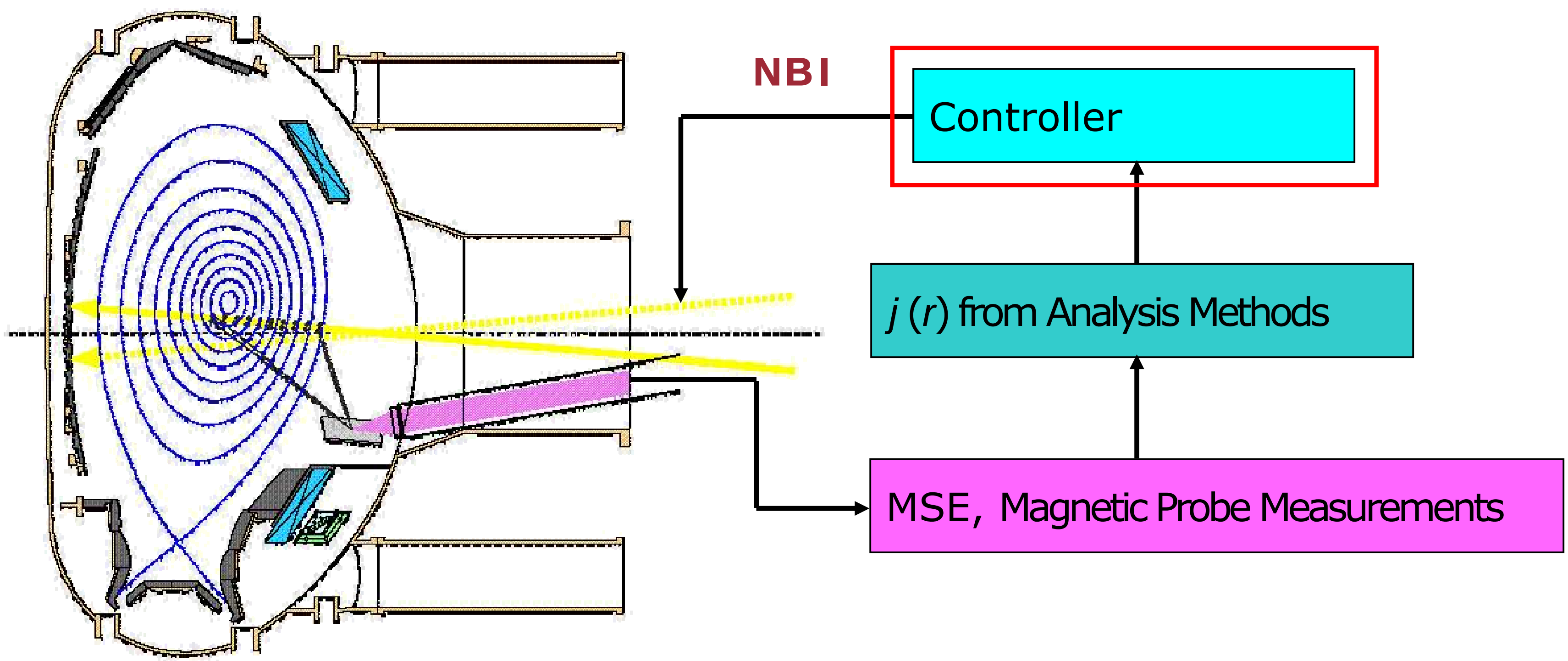




Current and pressure profile control !

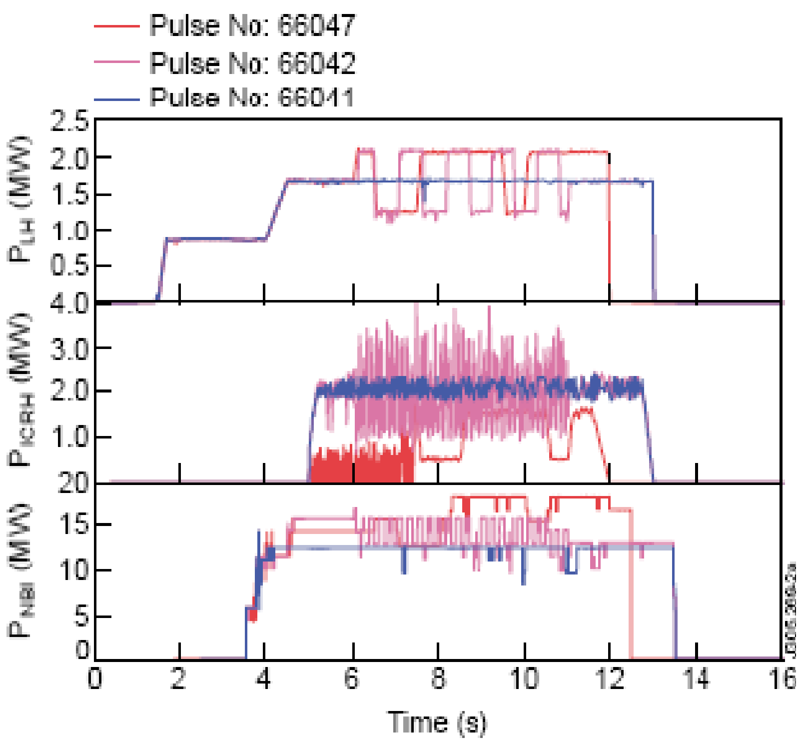
Current profile control

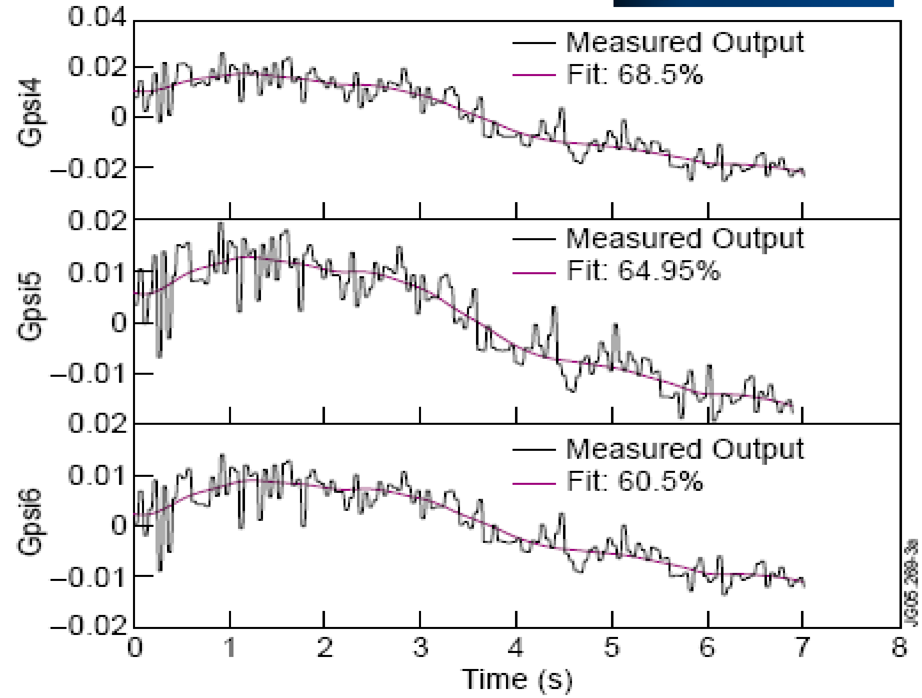
- Current density profile control at ASDEX Upgrade



Current profile control

- Real-time current and pressure profile control at JET

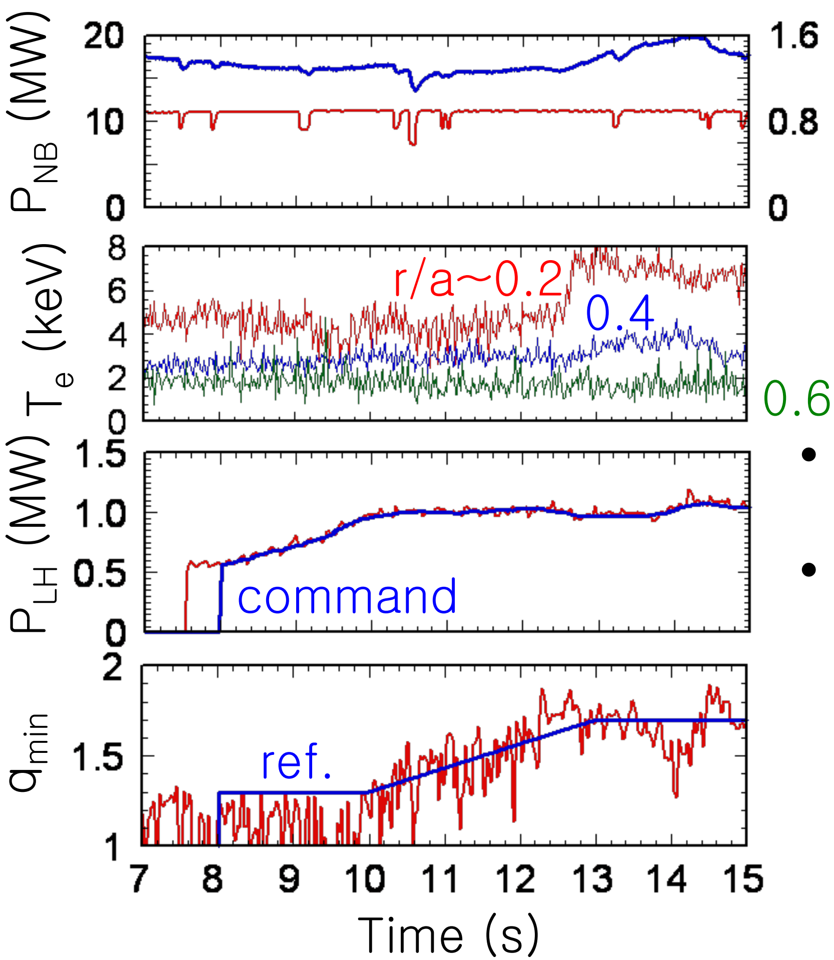


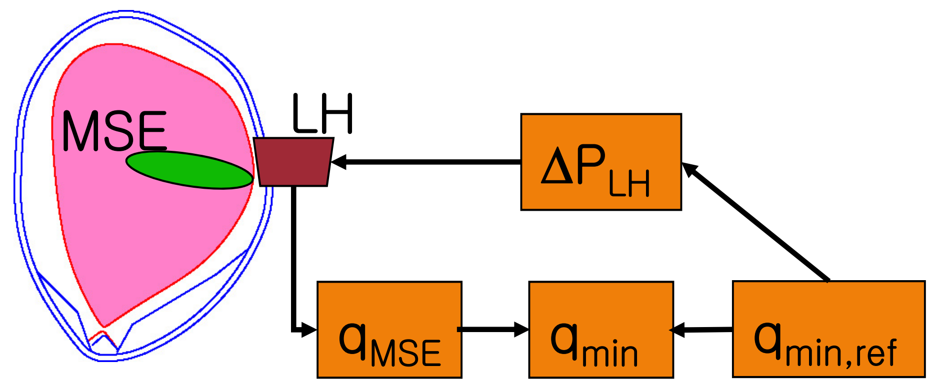


- **Modulation combinations of actuators (NBI, LH, ICRH) to infer the coefficients of the state space model of the slow loop.**
- **Two control loops, 4 actuators (NBI, LH, ICRH, PF)**

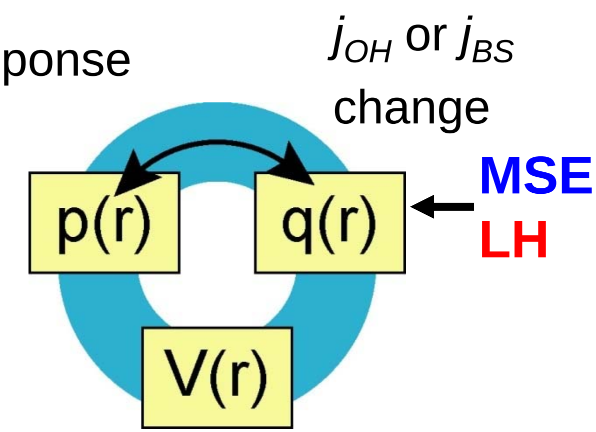
Current profile control

- JT60-U: Real time q_{min} control with MSE diagnostics and LHCD

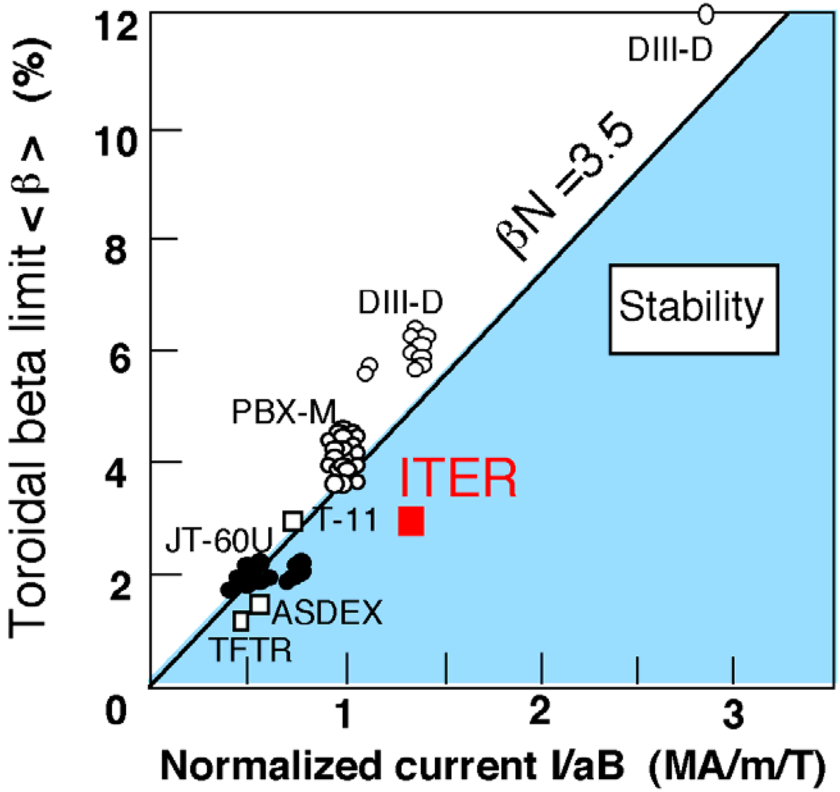




- Transport reduction at t = 12.4 s
- Time delay in response of q_{min}



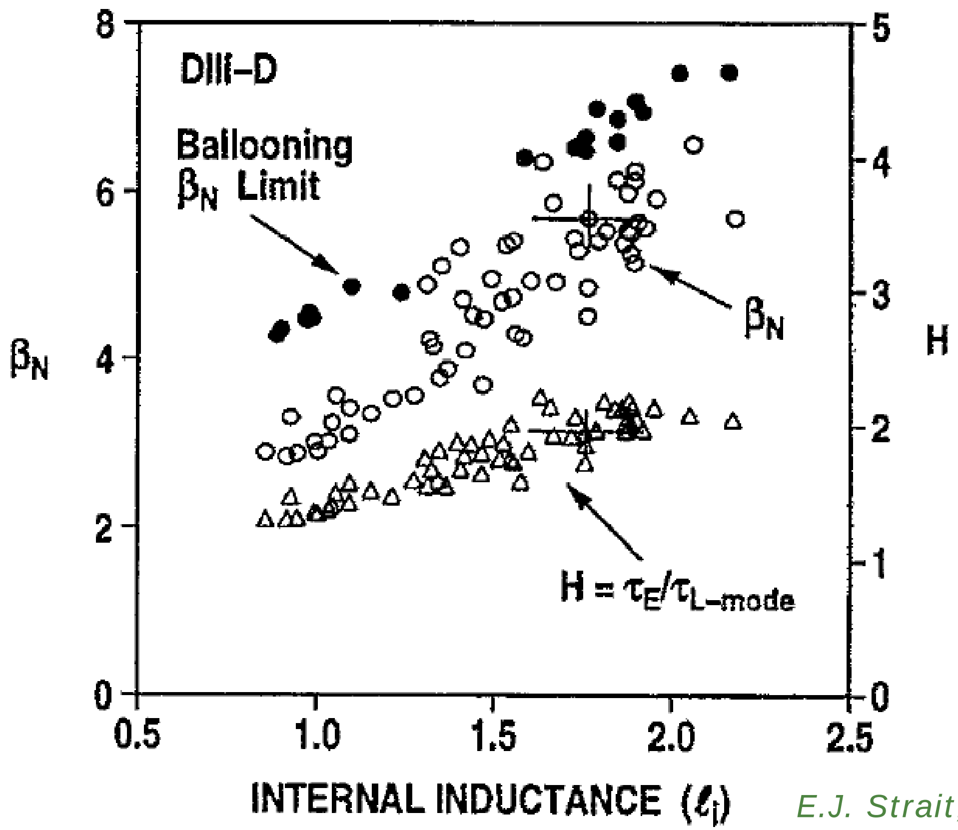
β-limit and optimisation of the MHD stability



- Fundamental elements for the β_N-limit

1. Current profile
2. Pressure profile
3. Plasma shape
4. Stabilising wall
5. Resistive instability

1. Current profile



Circular cross-section

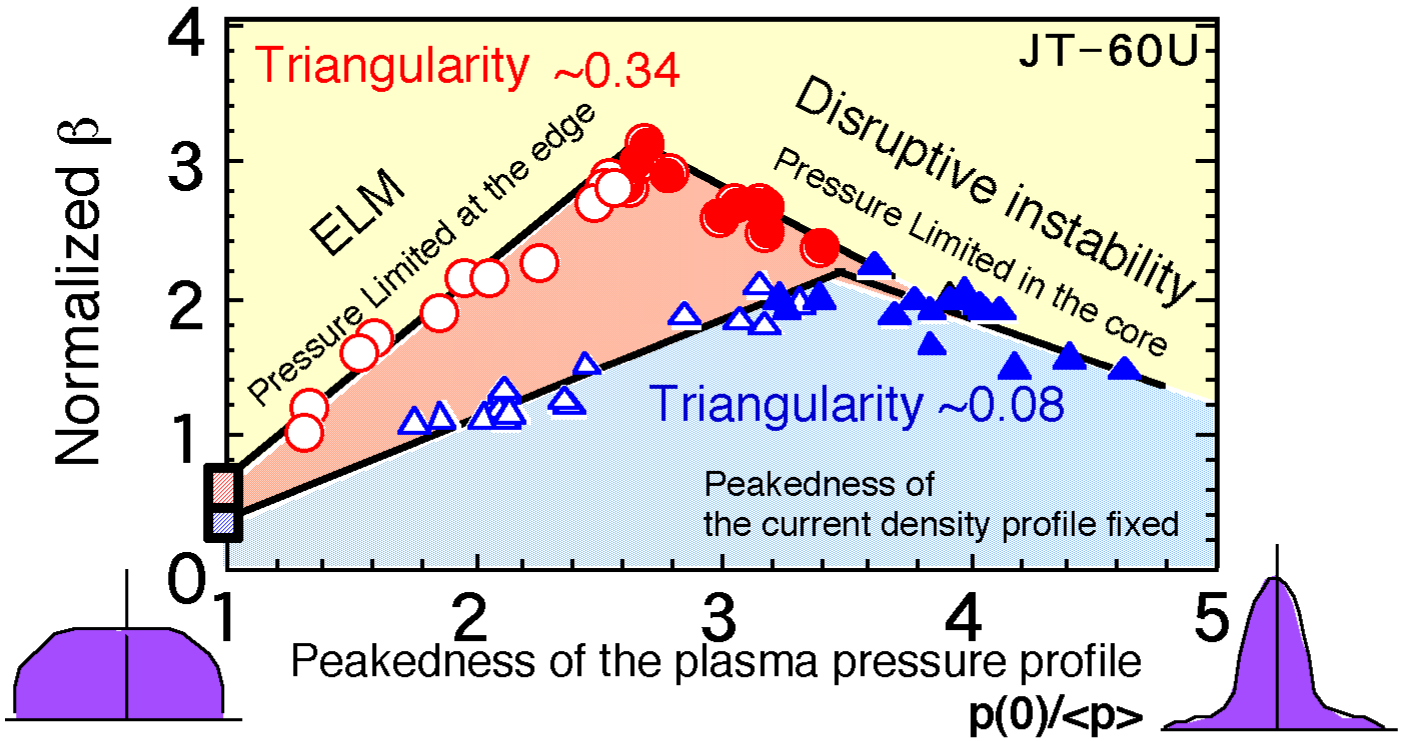
*E.J. Strait, Phy. Plasmas **1** 1415 (1994)*

- Dependence of the achieved β_N on l_i in DIII-D L-mode discharge (open circles) compared to the calculated ballooning mode limit (solid circles)

HW: Why?

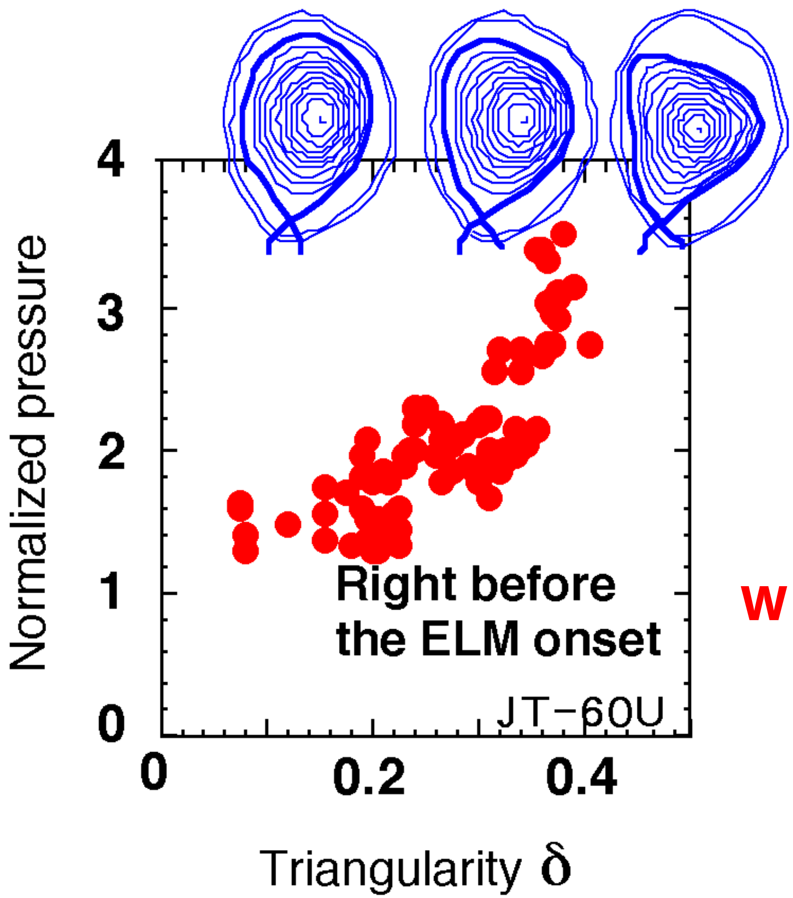
- High l_i is unfavourable for axisymmetric stability: high β_N operation not compatible with extreme shaping of the discharge

2. Pressure profile



- Pressure profile determined by the α-particle heating with higher peakedness in ITER and DEMO

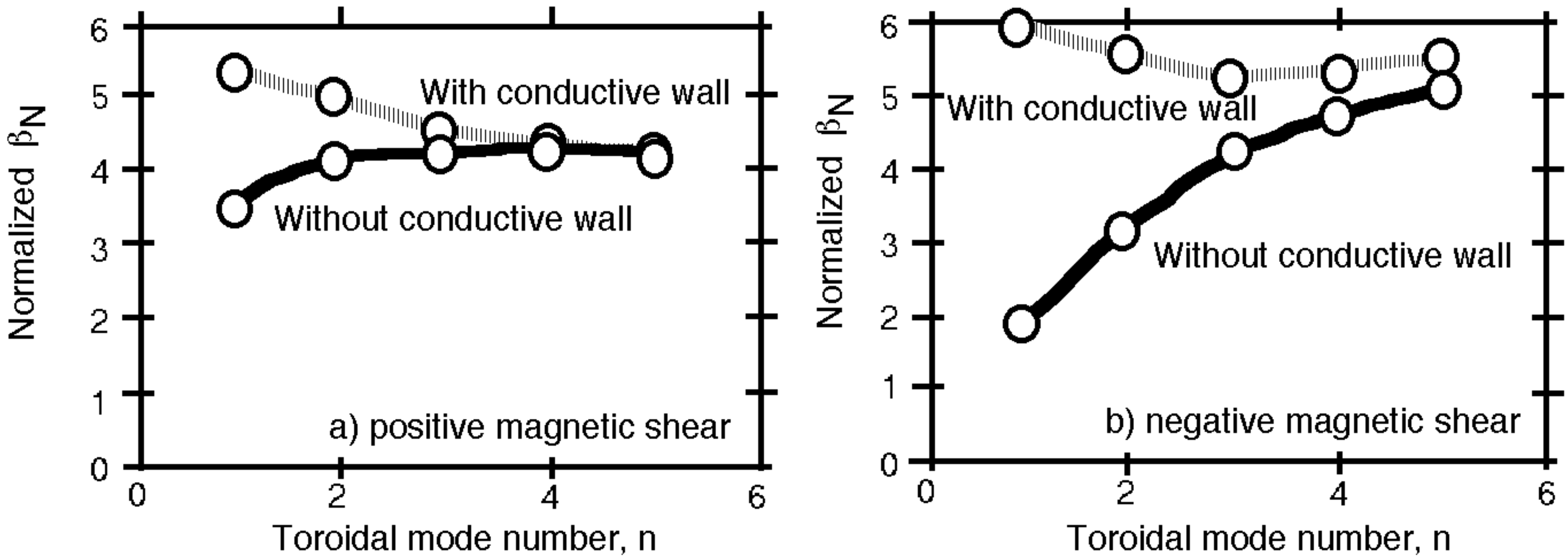
3. Plasma shape



Why?

- ITER designed to enable a high δ, 0.35-0.4

4. Stabilising wall

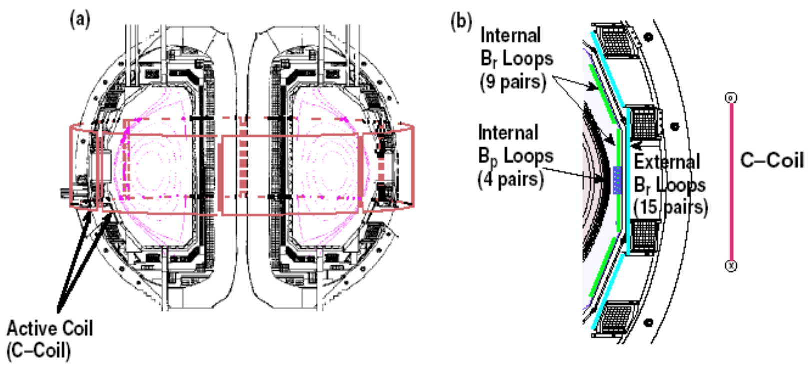


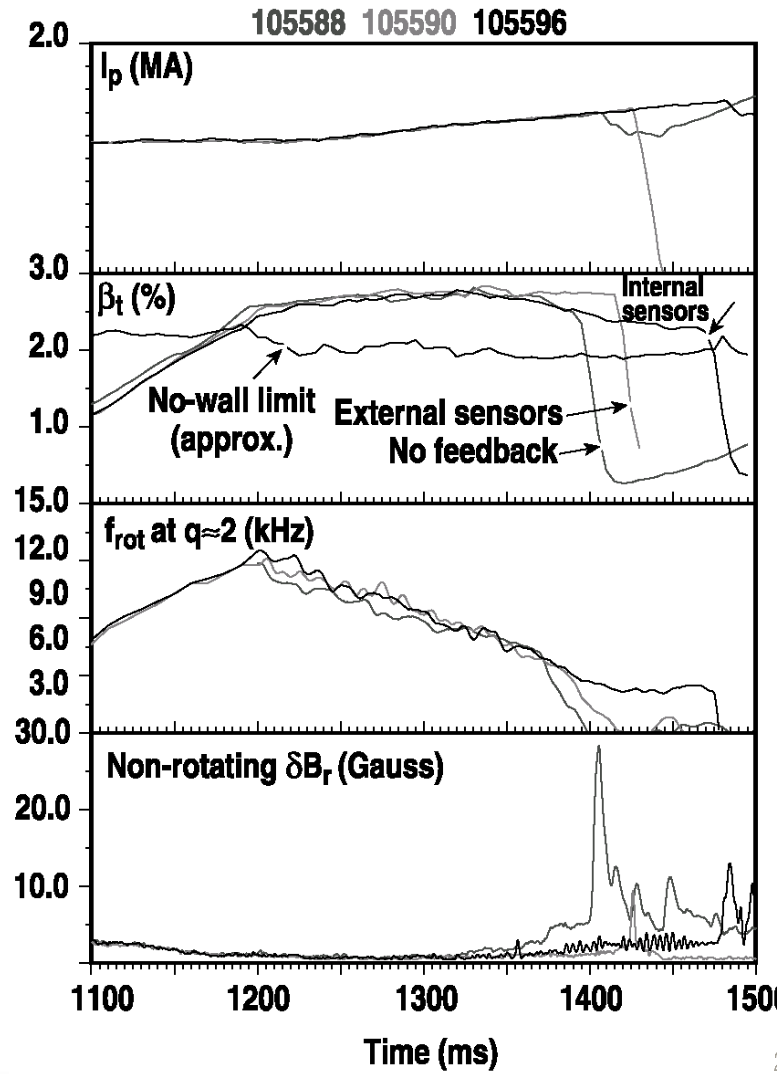
- Wall stabilising effect remarkable for RS plasmas
- Stabilisation of RWM

- plasma rotation
- corrective magnetic field canceling the perturbed magnetic field by the instability

4. Stabilising wall

• **Resistive Wall Mode**

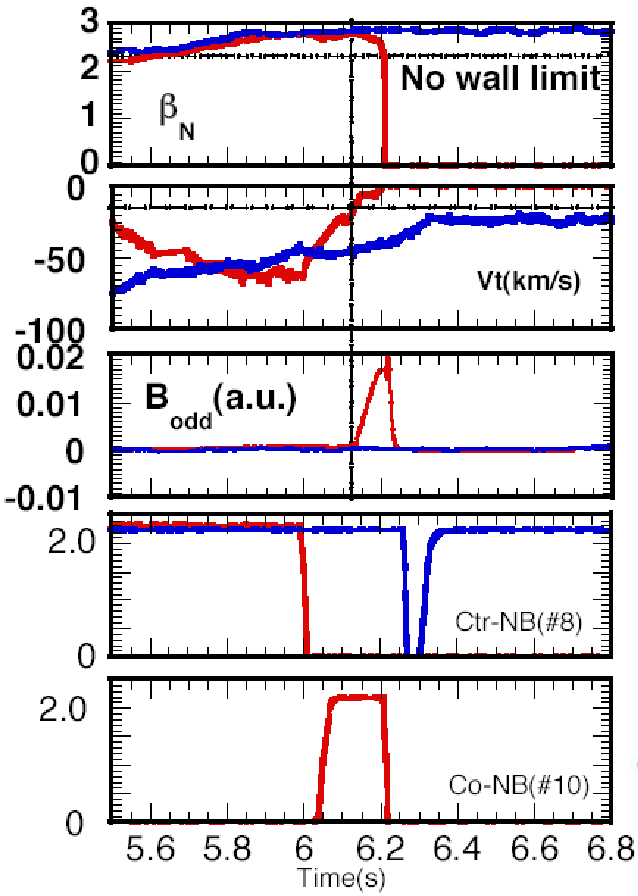


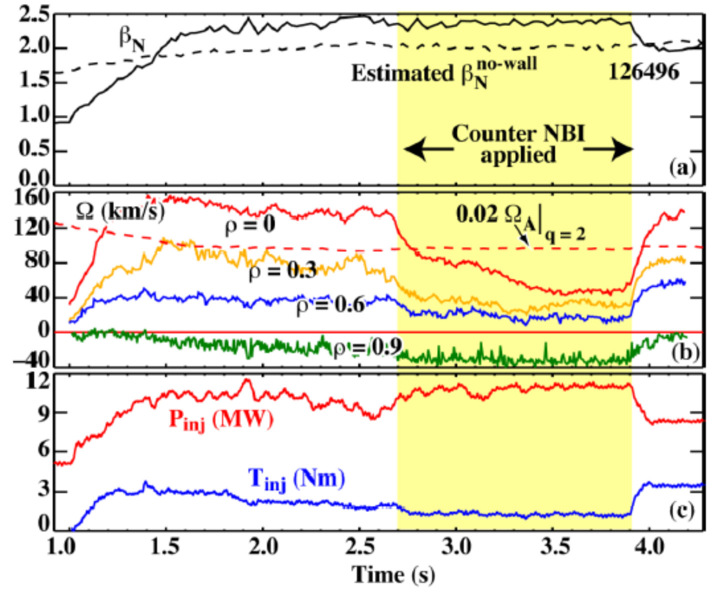


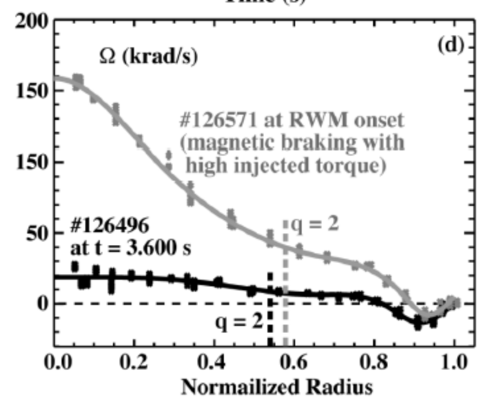
• Saddle coils for direct stabilisation
- Different feedback schemes exist
- First results look promising
- New experiments with in-vessel coils under way on DIII-D

4. Stabilising wall

- **Resistive Wall Mode**

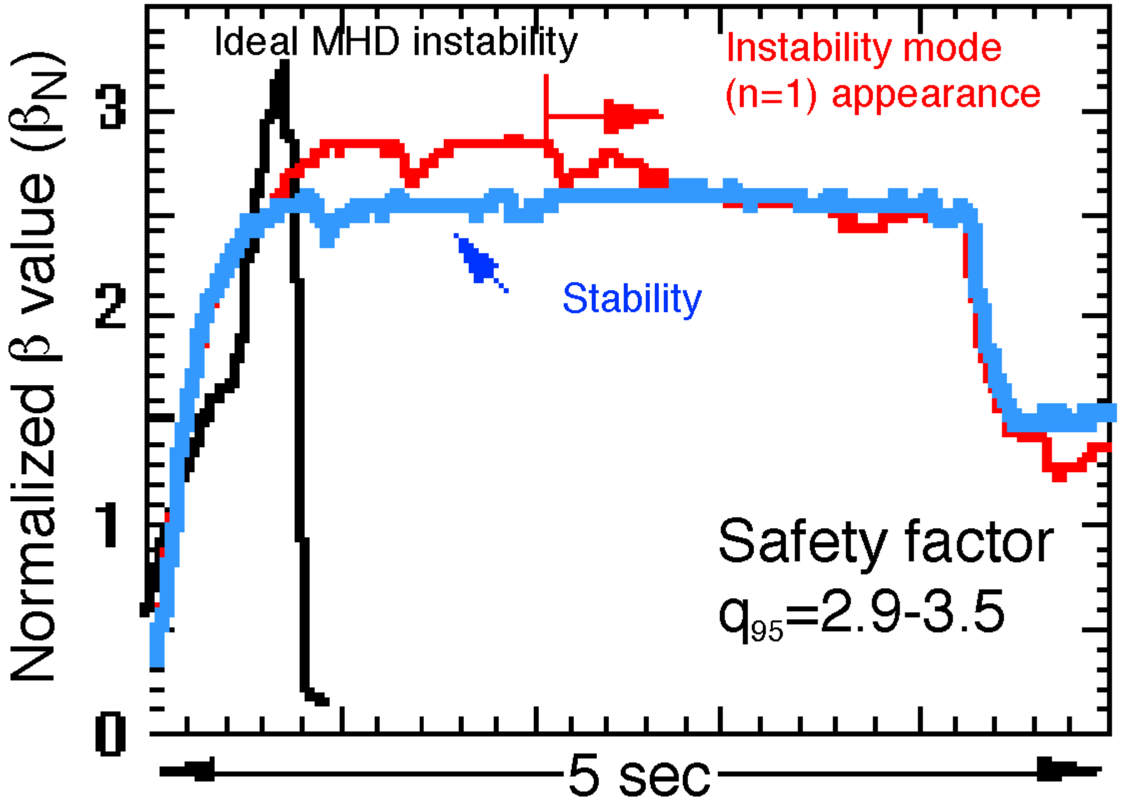






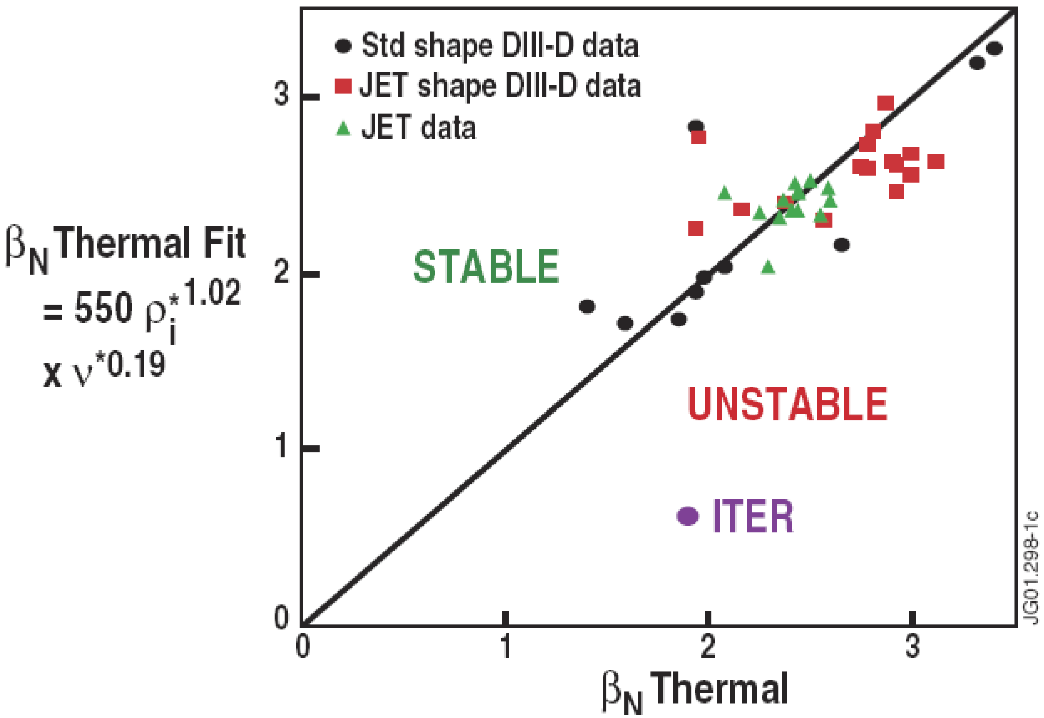
- (Positive) surprises as we go to lower net momentum input…
- The rotation threshold may be very sensitive to ambient error field!
- But physics not yet clear (e.g. role of n_i as highlighted by NSTX)

5. Resistive instabilities



- In quasi-SS discharges, β_N is lower than the ideal MHD limit due to appearance of resistive MHD instabilities (JT-60U)

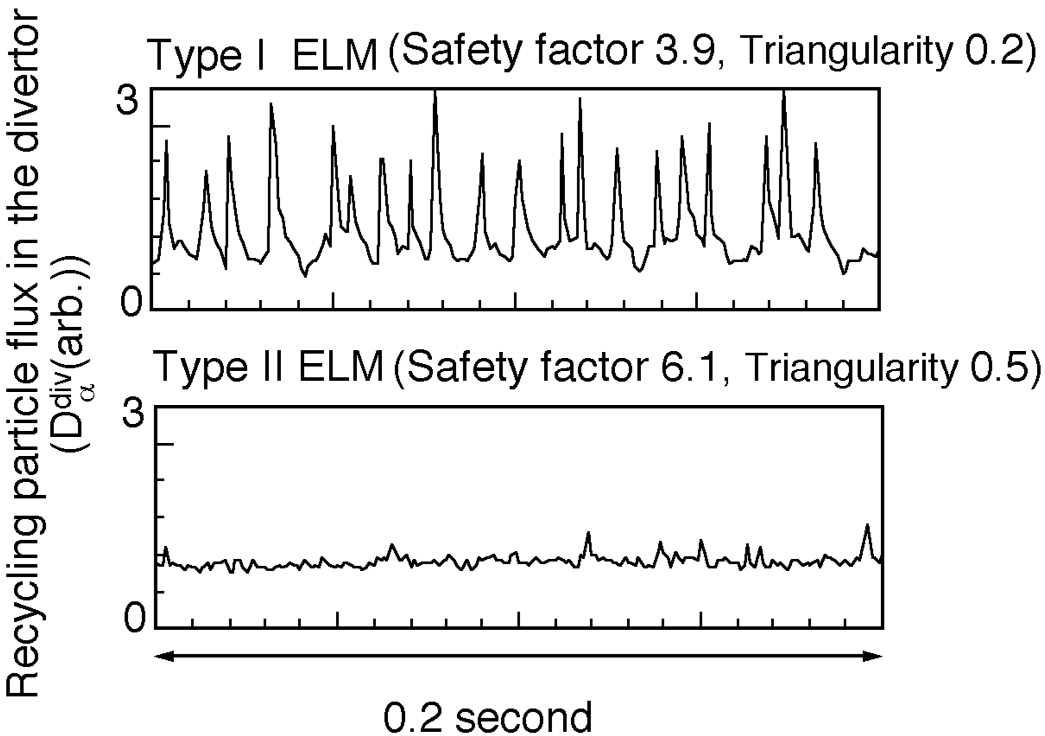
5. Resistive instabilities

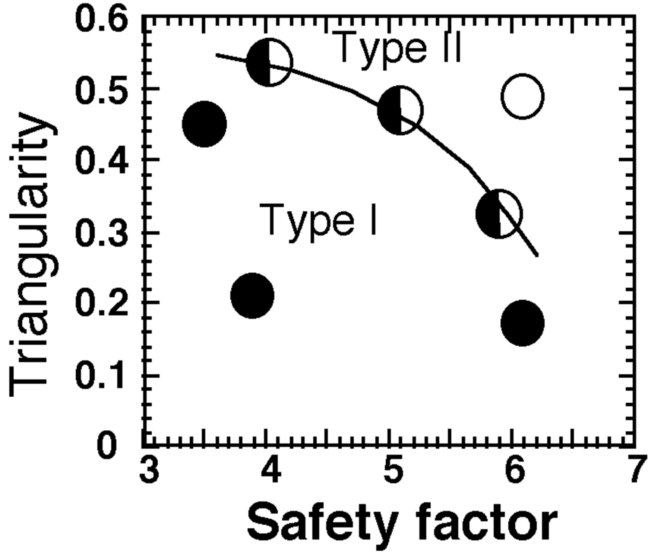


- Critical beta for m/n=2/1 NTM
  - scales with ρ_i^*, ν^*

*T.C. Hender et al. Nucl. Fusion **44** 788 (2004)*

6. Heat and Particle control using the ELMs



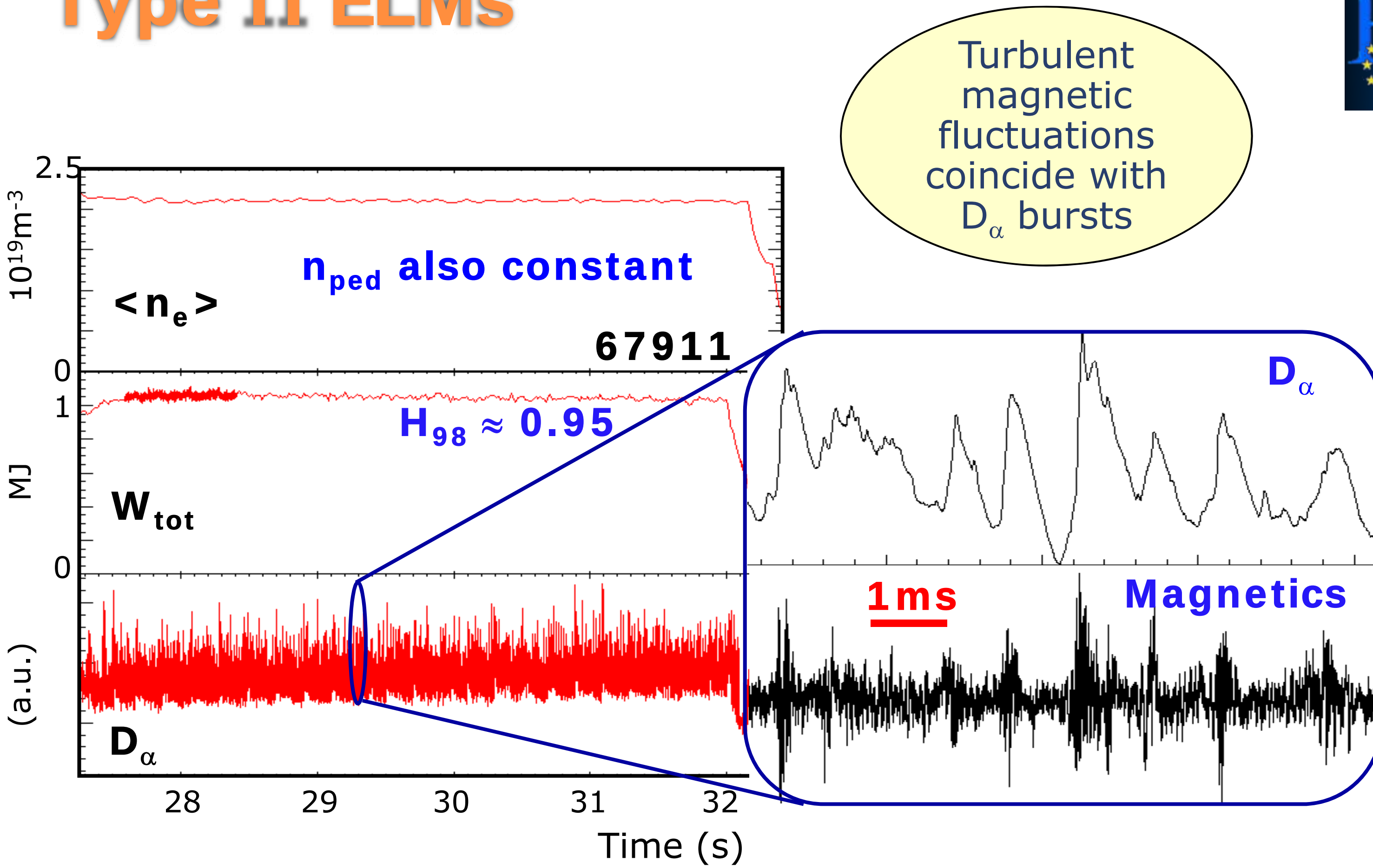


HW: Other types of ELMs

- Type II ELMs

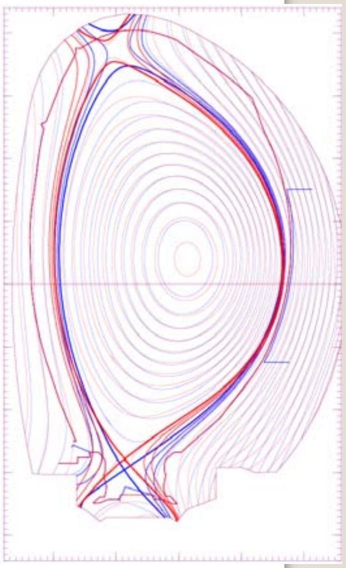
- confinement not degraded, relatively small impurity accumulation, lower heat load on divertor
- at high triangularity and in a high safety factor regime

Type II ELMs



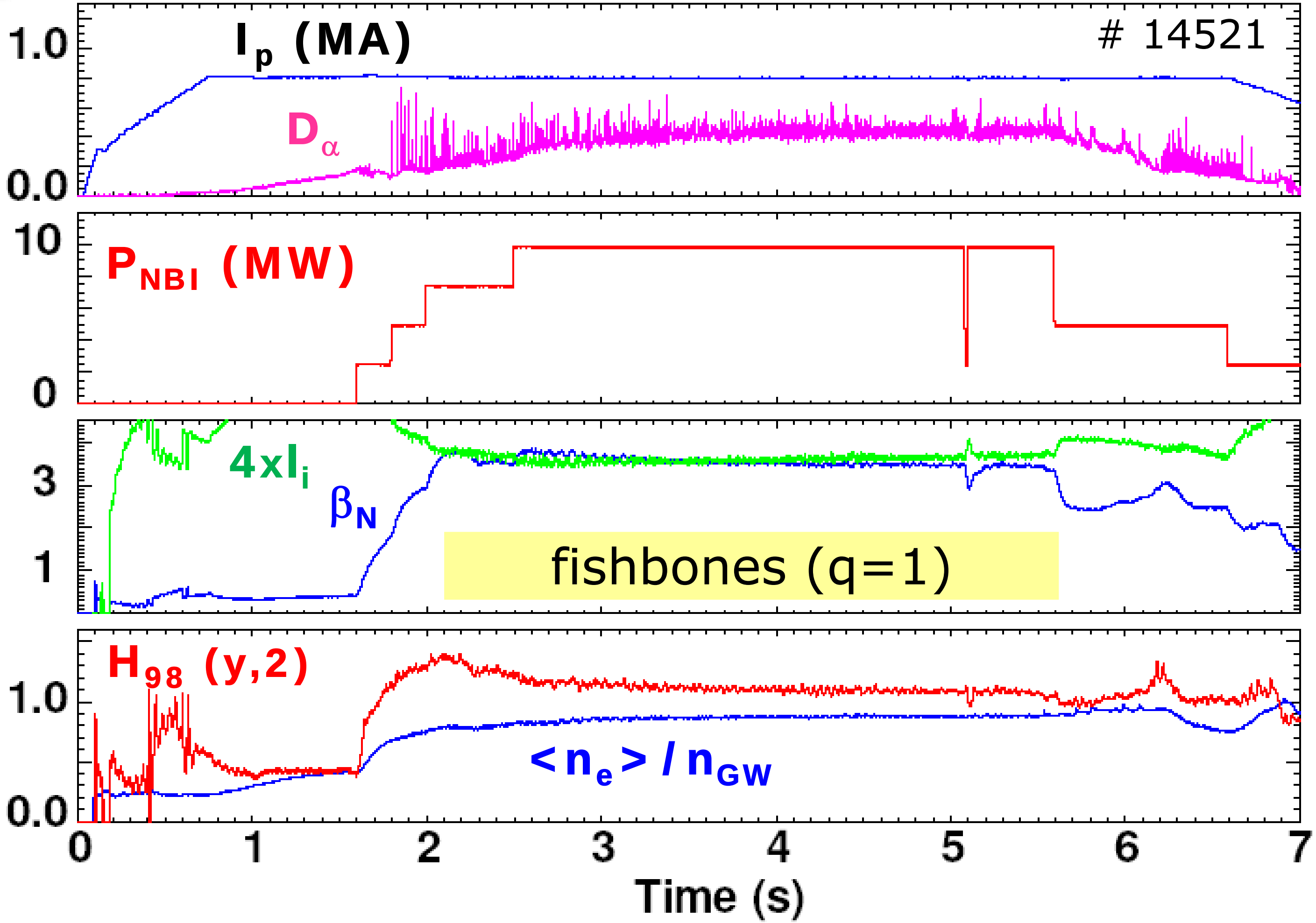
Blue: New #66476

Red:Previous experiment #62430



- ELM behaviour constant over pulse
- Very fine scale activity - distinct ELMs almost indistinguishable

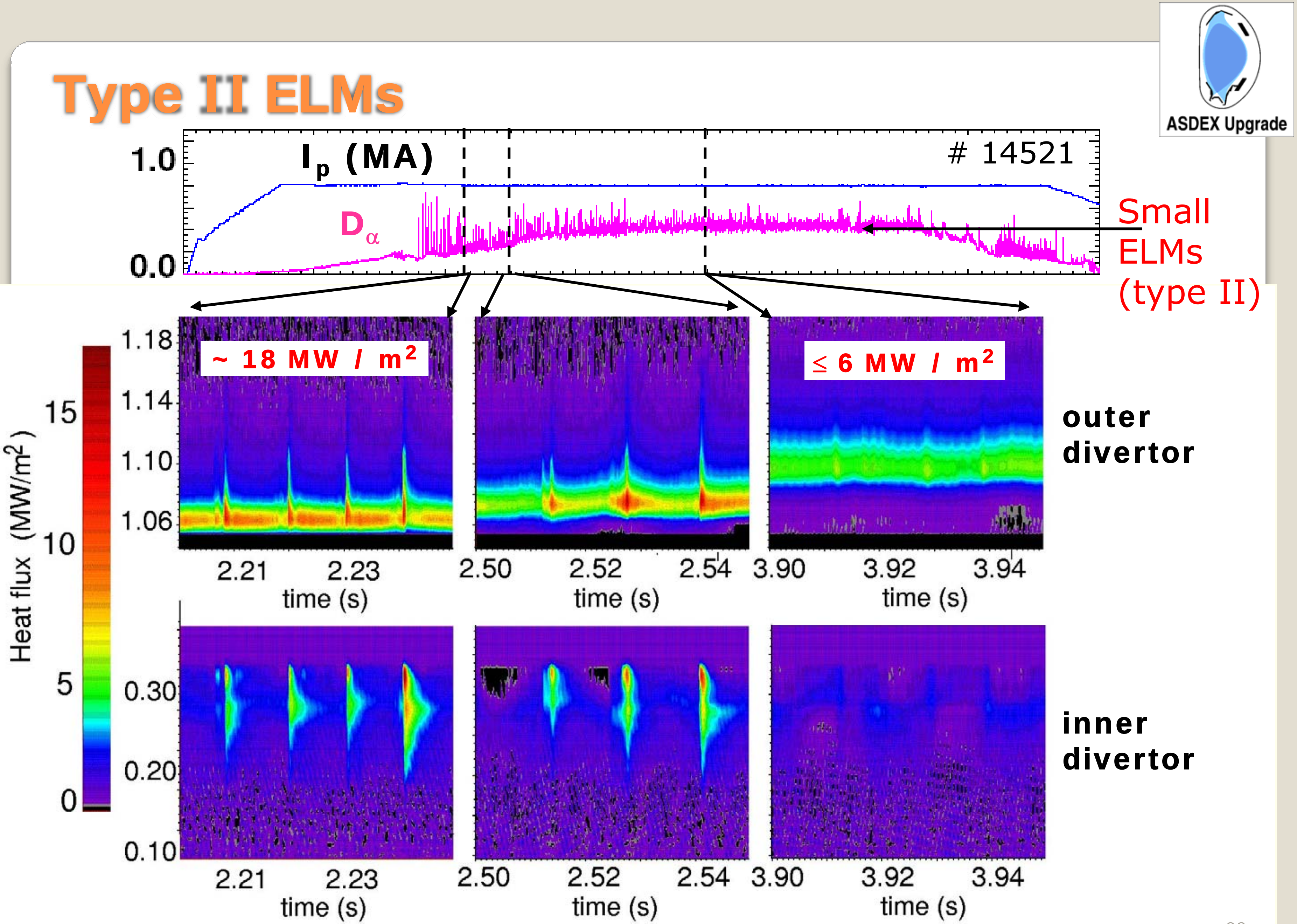
Type II ELMs



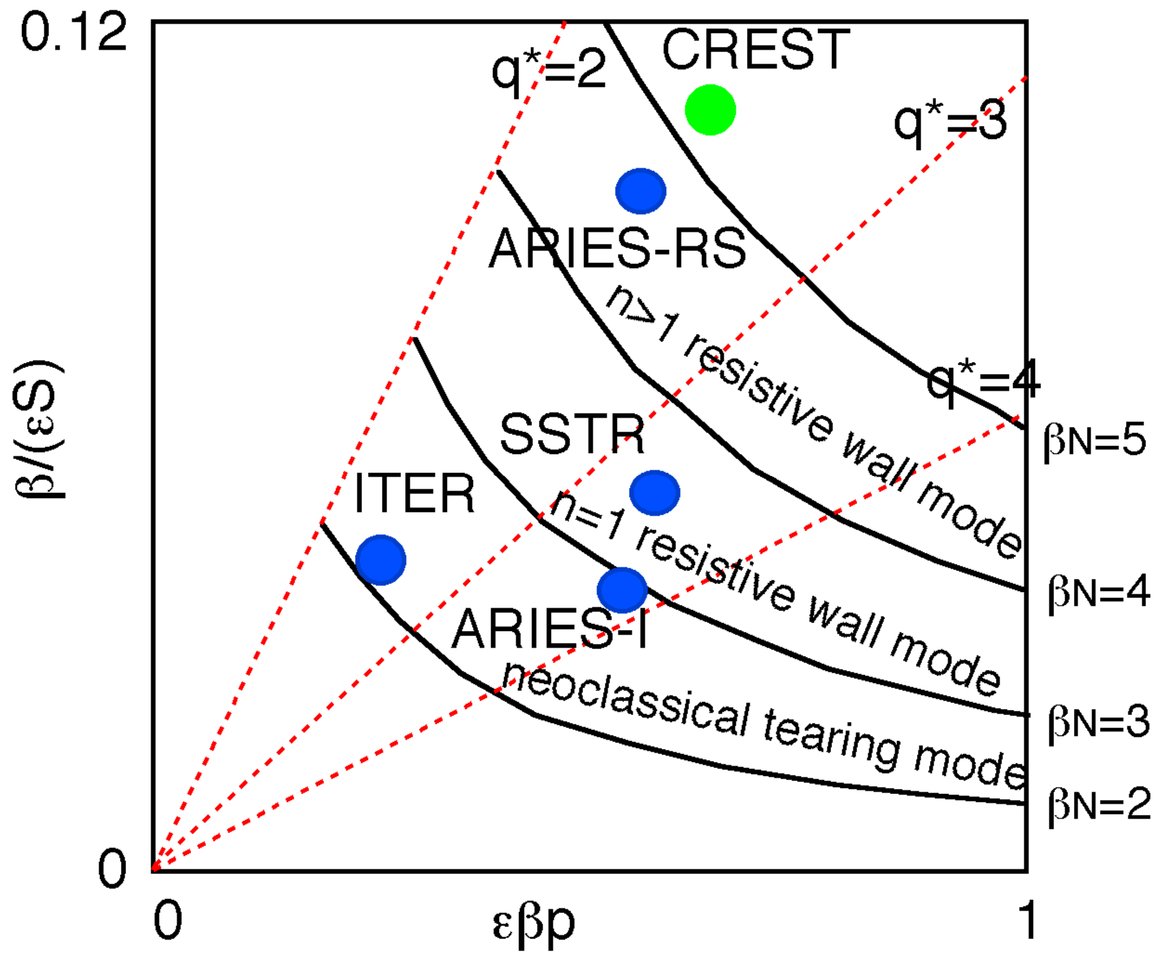
ASDEX Upgrade

- No sawteeth, good confinement, and $\beta_N \sim 3.5$, $T_i \sim T_e$, $<n_e>/n_{GW} \sim 0.88$, $\beta_N H_{89}/q_{95}^2 = 0.5$, averaged over 3.6 s ($\sim 50\tau_E$)

Type II ELMs


ASDEX Upgrade
I_p (MA)
14521
1.0
0.0
D_α
Small ELMs (type II)
~ 18 MW / m^2
≤ 6 MW / m^2
Heat flux (MW/m^2)
15
10
5
0
1.18
1.14
1.10
1.06
0.30
0.20
0.10
2.21
2.23
2.50
2.52
2.54
3.90
3.92
3.94
time (s)
outer divertor
inner divertor

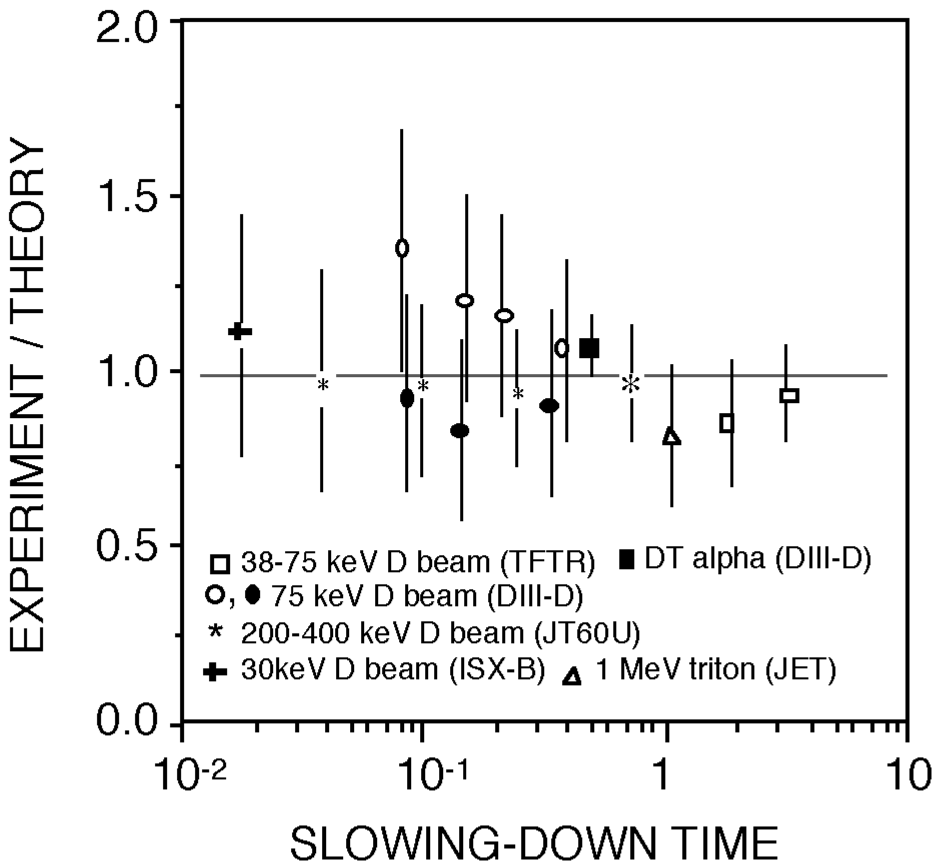
Tokamak MHD operation region



Confinement of energetic particles

- Heating by energetic particles (alpha particles)
- Ripple loss
- Alfven eigenmodes (AE)

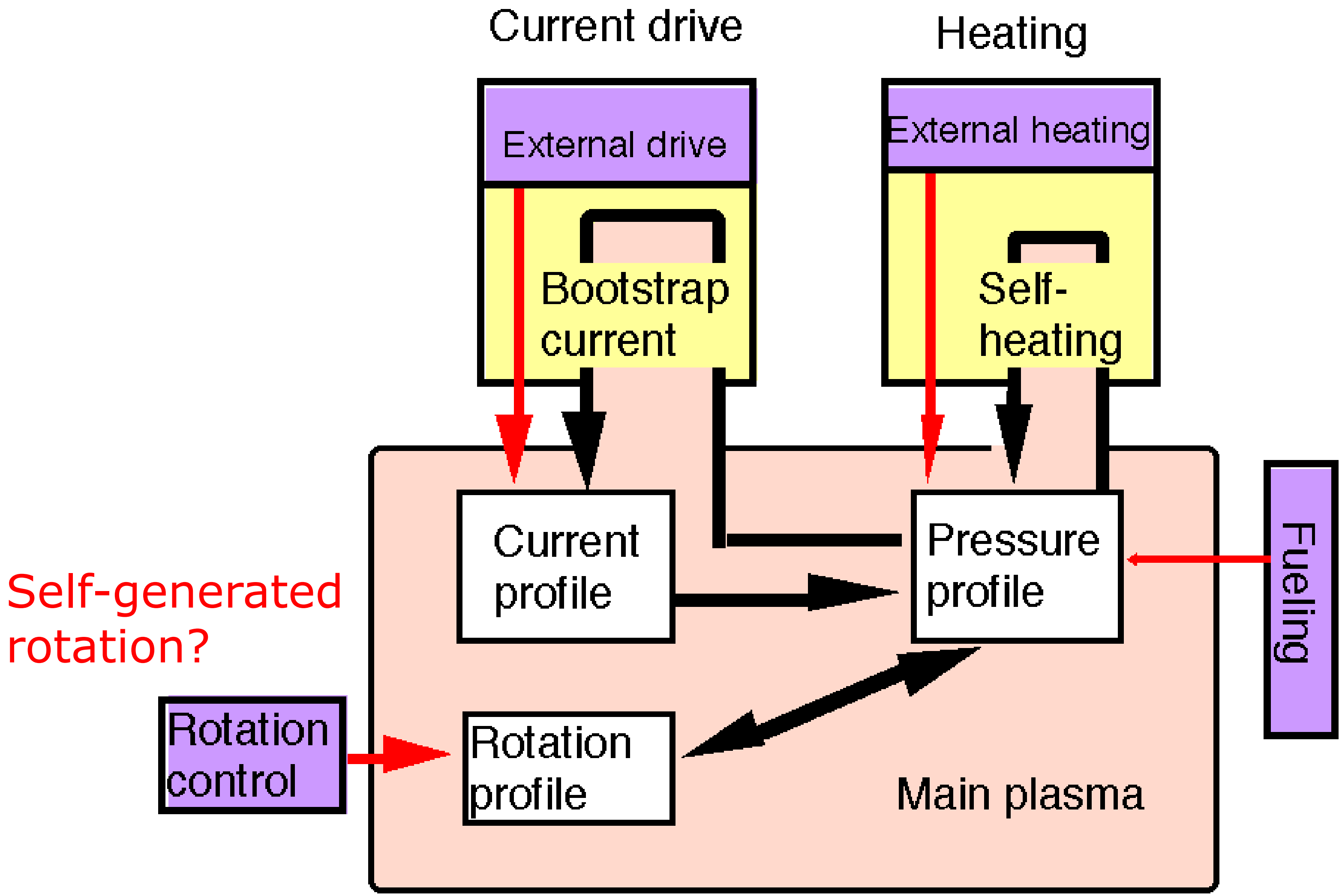
HW: Issues on Ripple



- The slowing-down time of energetic ions agrees well with classical estimate.
- The diffusion coefficient of energetic particles is consistent with the NC model.

- orbit averaging
- Small TAE due to small β_α

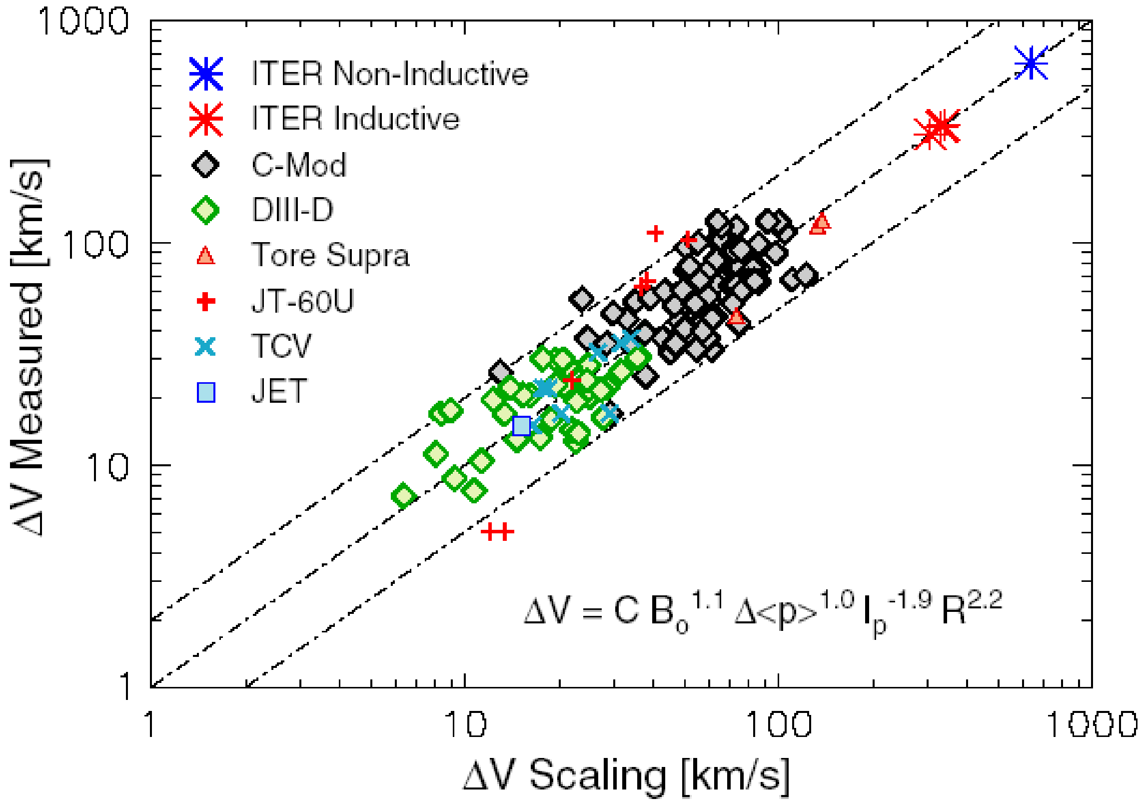
DT burning and burn control



Load following operation

DT burning and burn control

- **Intrinsic rotation**



J. E. Rice *et al*, *Nucl. Fusion* **47** 1618 (2007)