Fusion Reactor Technology I
(459.760, 3 Credits)

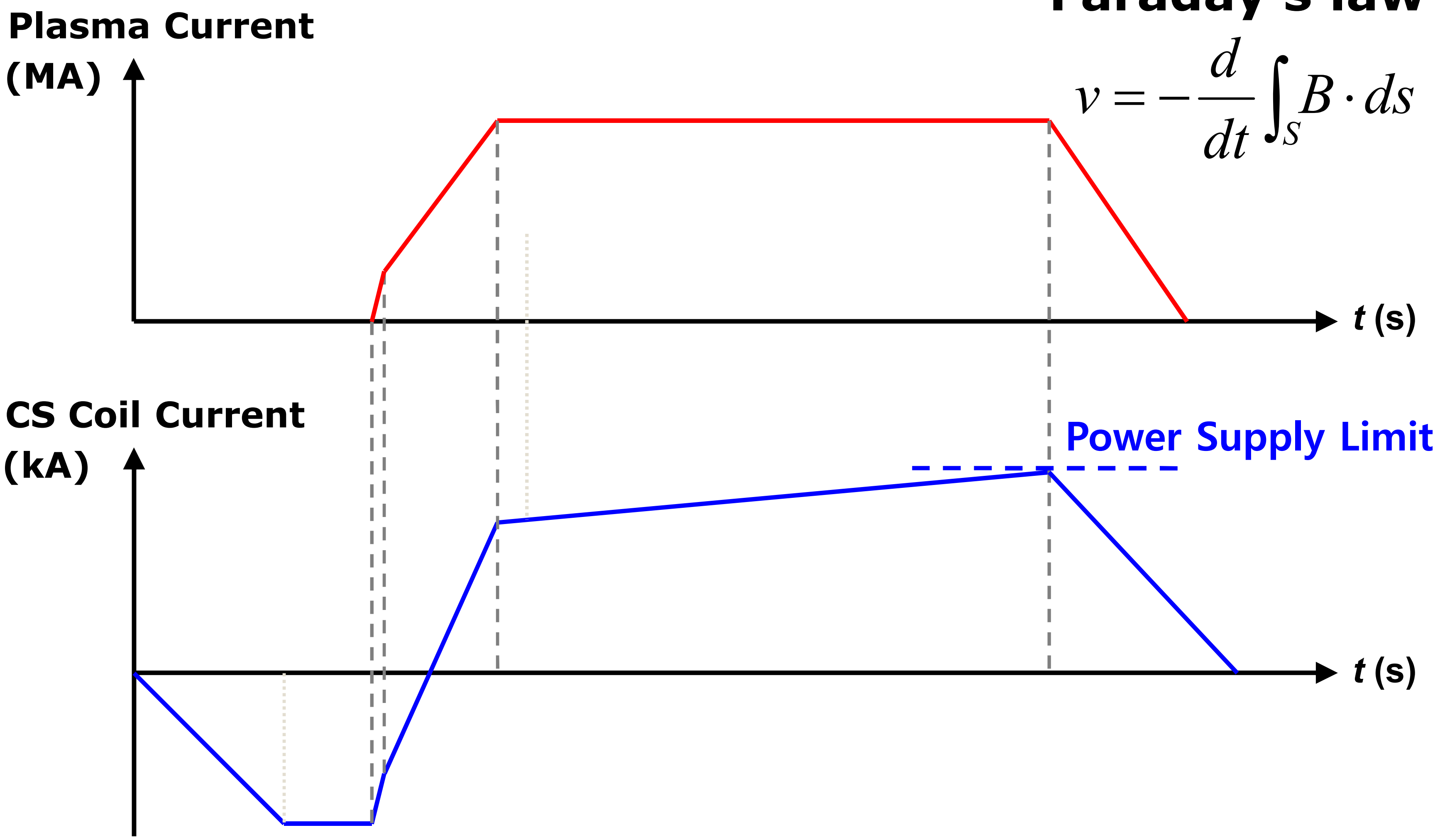
Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

Pulsed Operation

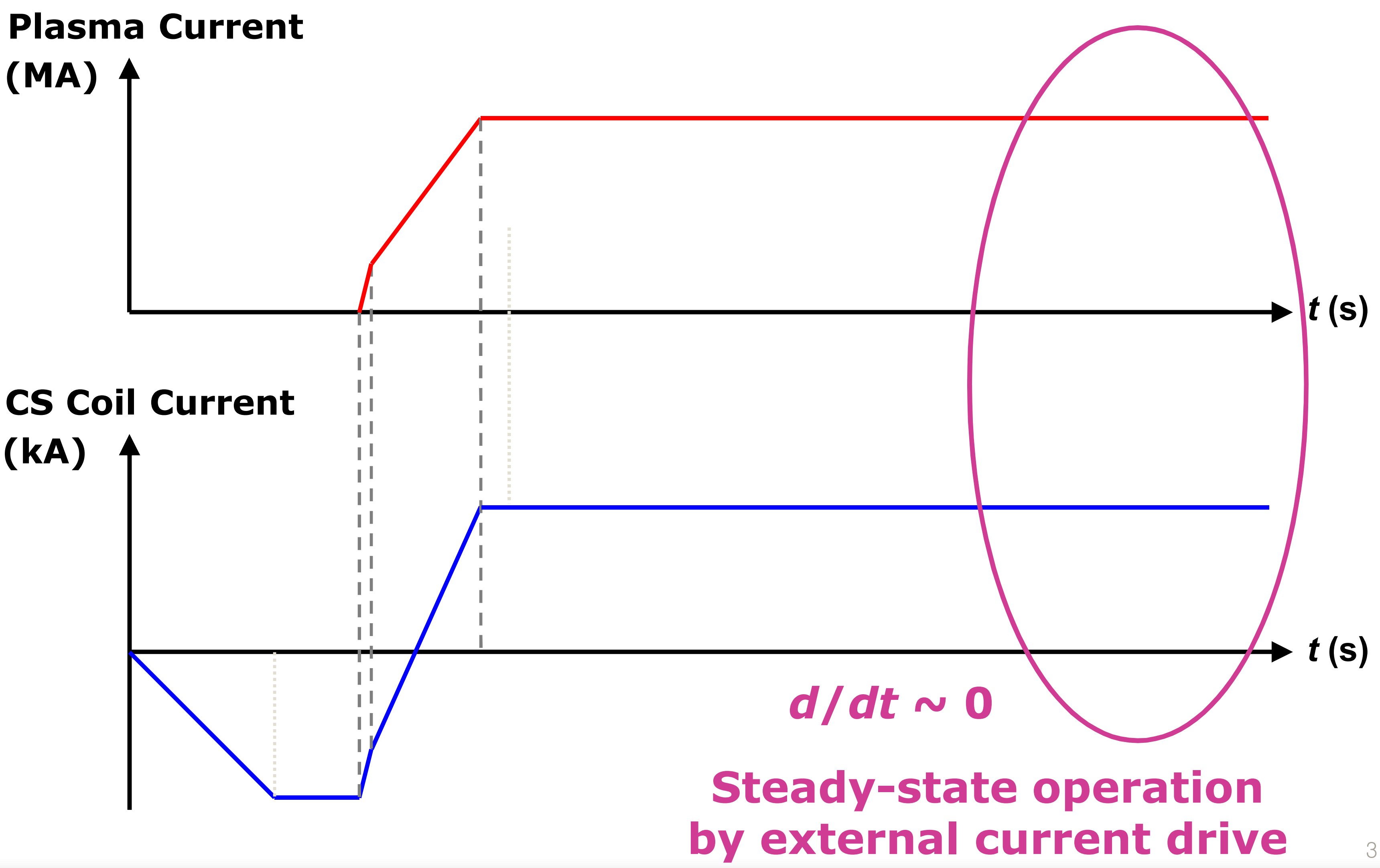
Faraday's law

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

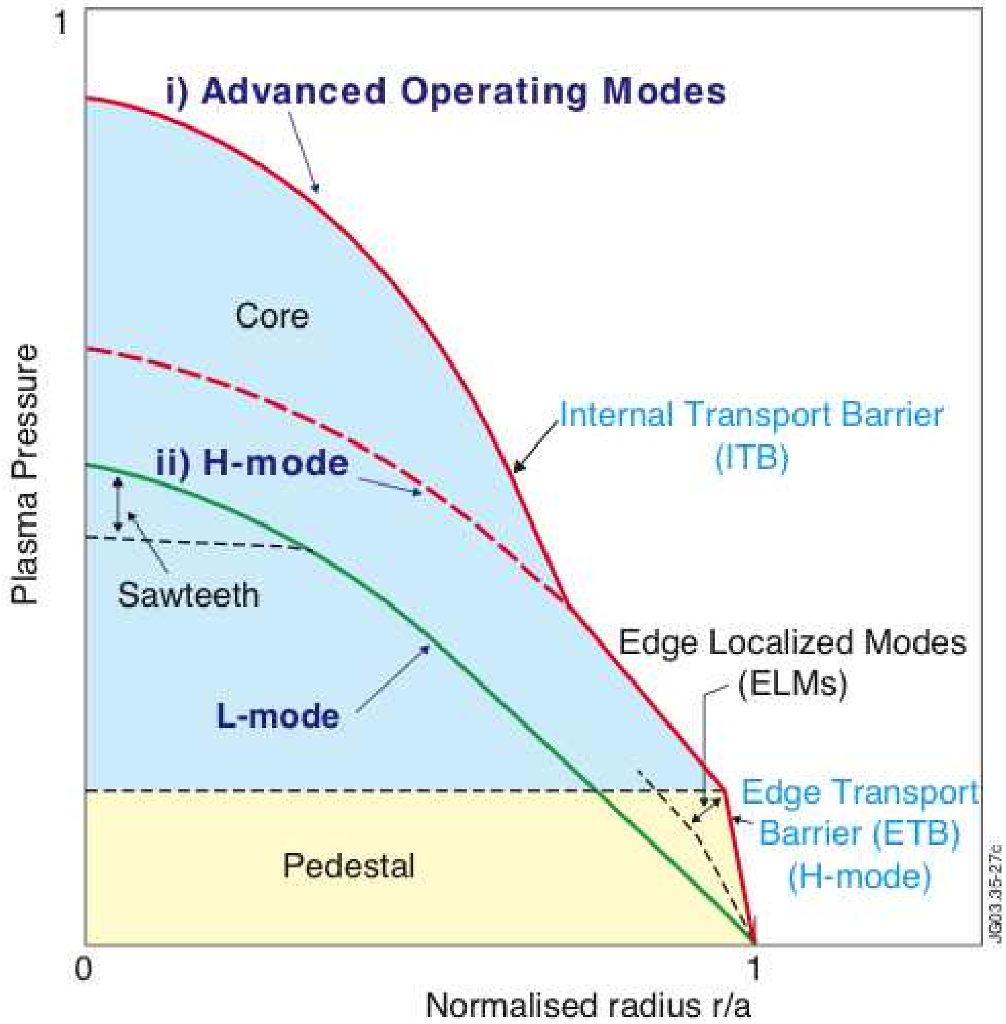


Inherent drawback of Tokamak!

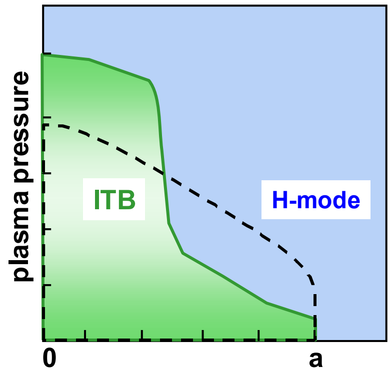
Steady-State Operation



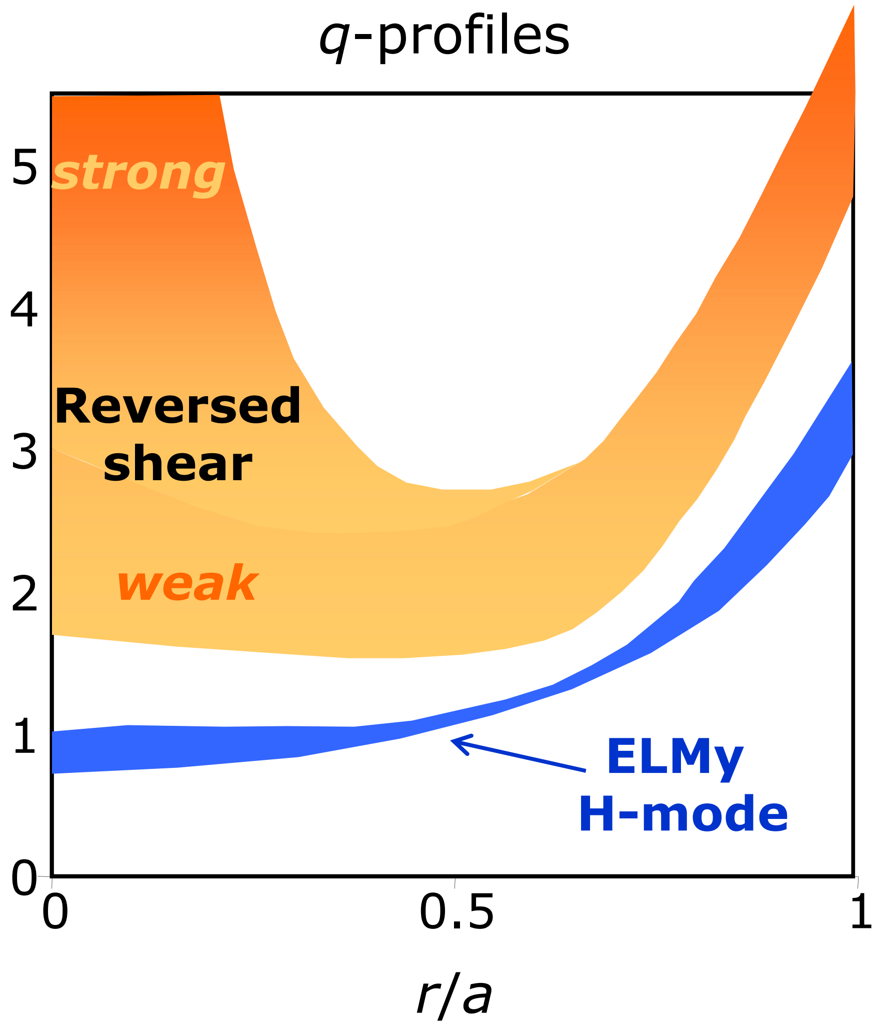
Tokamak Operation Modes



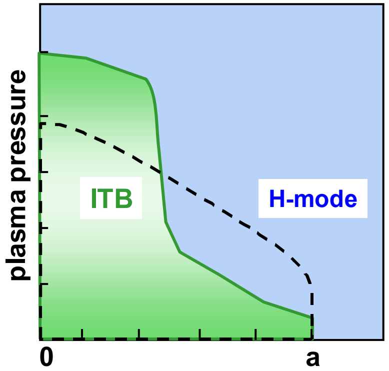
Tokamak Operation Modes



- Good confinement
- Poor stability



Tokamak Operation Modes



- Good confinement
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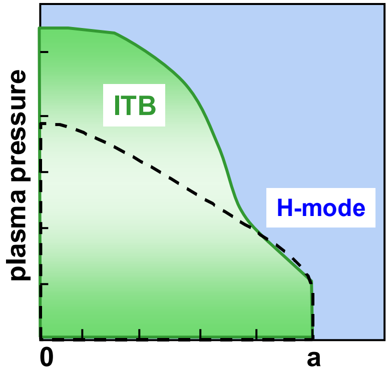
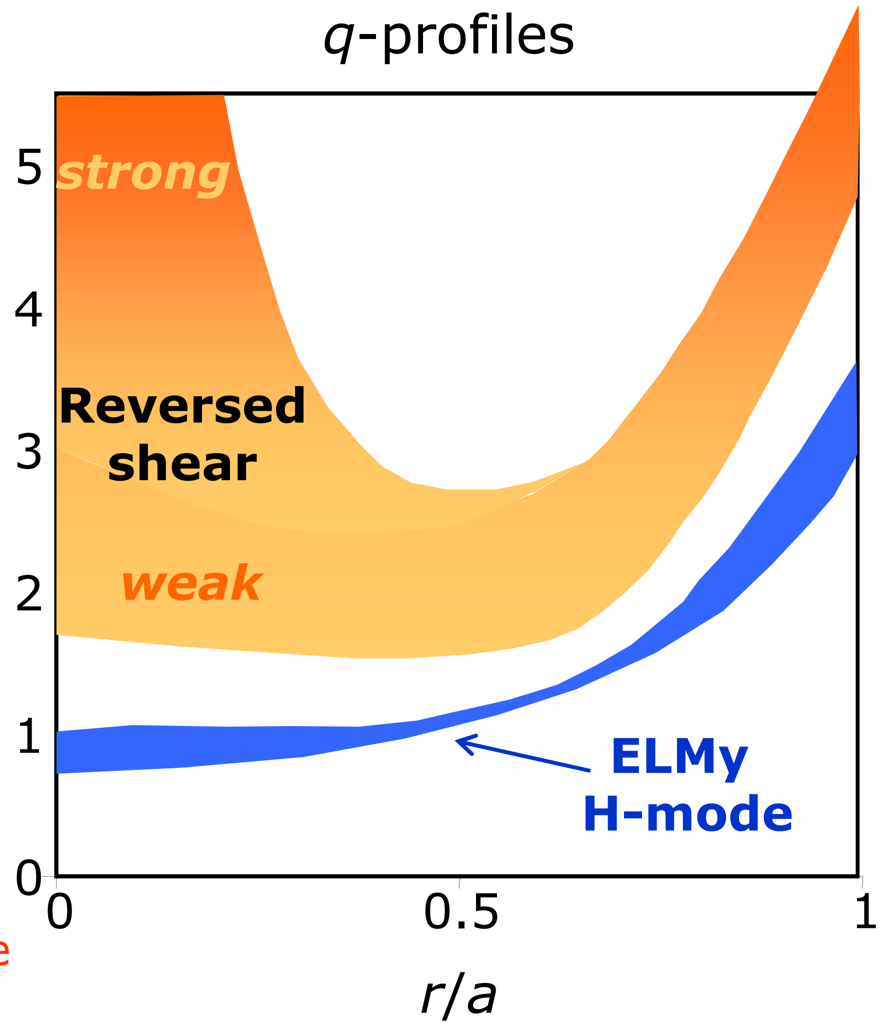
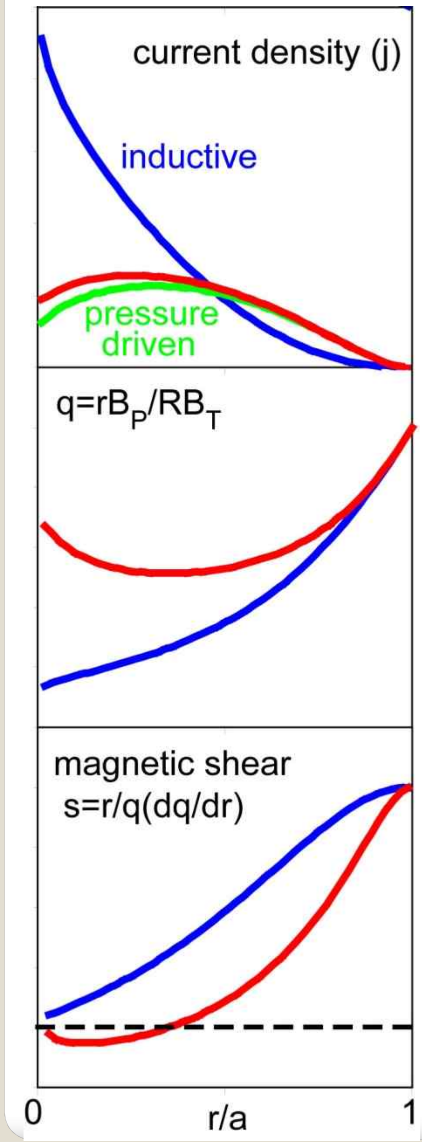
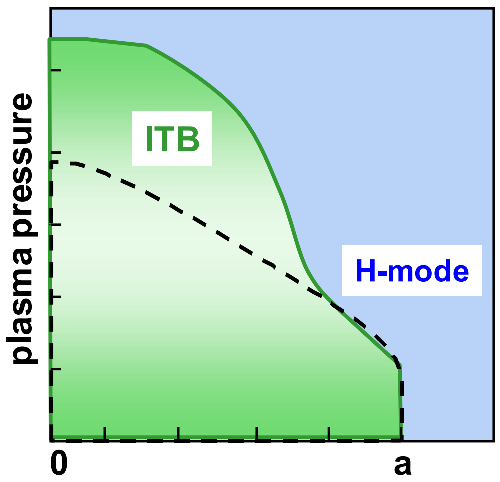


- Only “weak” RS plasmas are stable but they require a delicate active control



Reversed Shear Mode



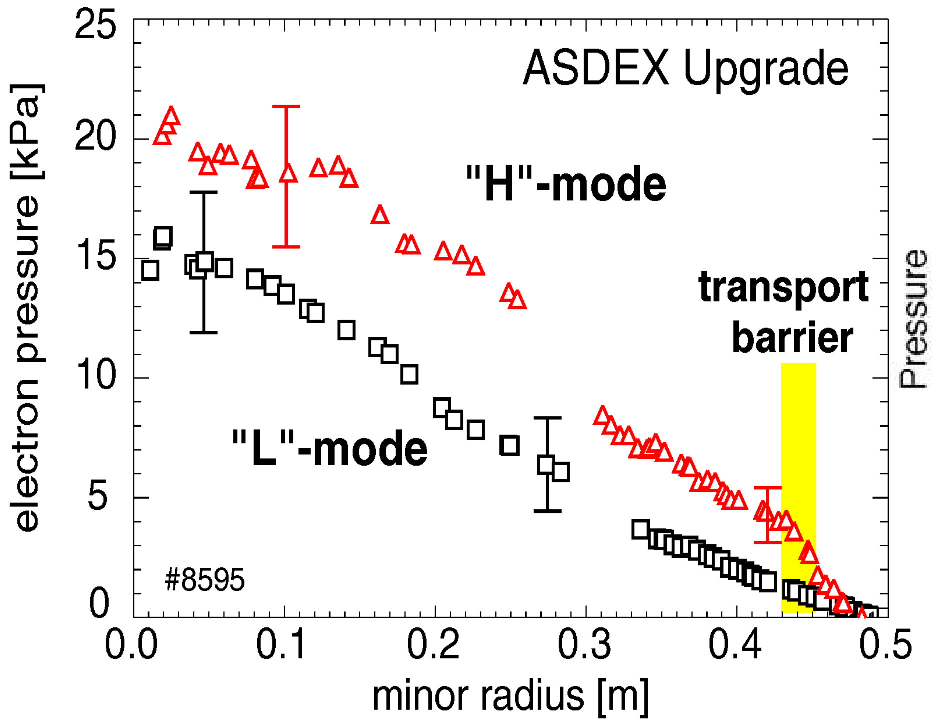


High bootstrap current!

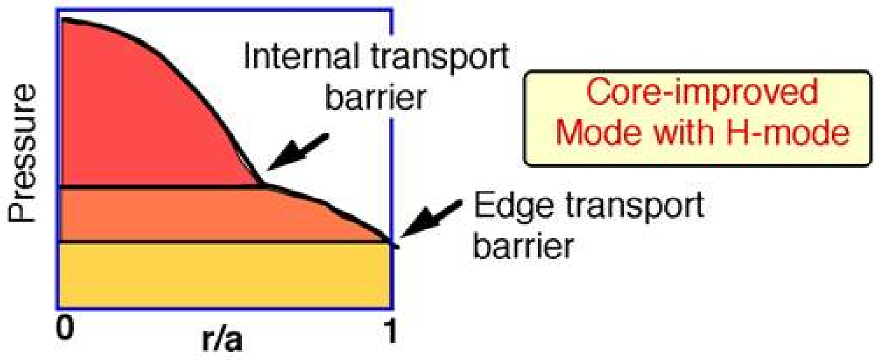
- Higher pressure gradient region in the core with steep edge pedestal
- Hollow current profile
- Reversed *q*-profile
- With negative magnetic shear

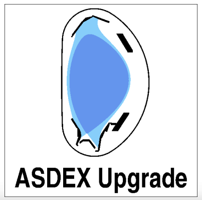
Reversed Shear Mode

H-mode



Reversed shear mode

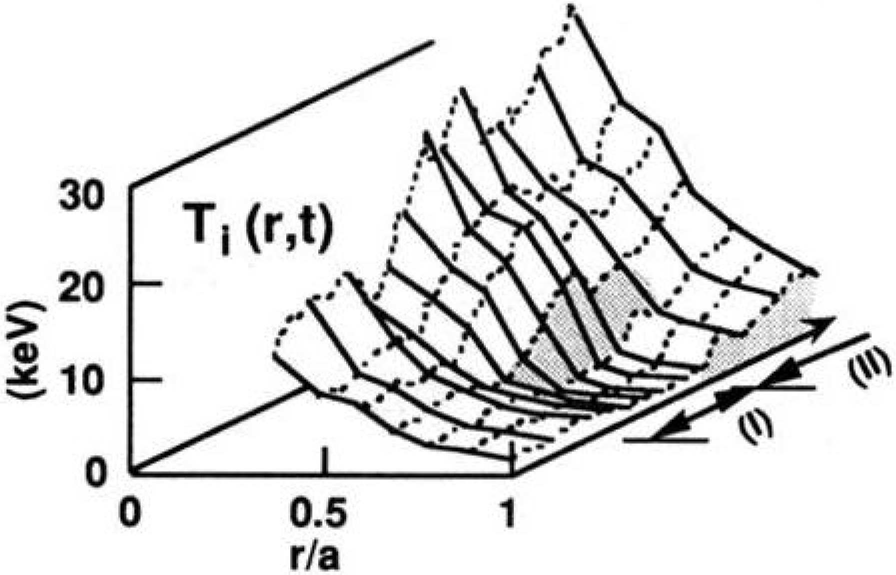




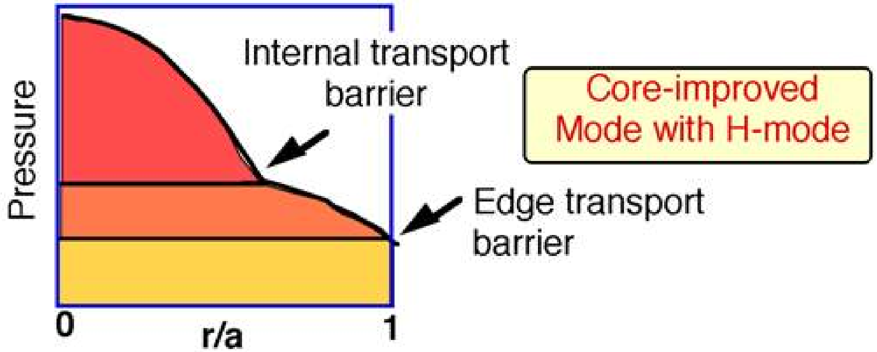
Internal Transport Barrier

Tokamak operation in the high-β_p regime is a promising concept for a steady-state tokamak reactor [1,2]. Here the poloidal beta is defined as $\beta_p = 2\mu_0\langle p\rangle / B_p^2$, where $\langle p\rangle$ is the volume-averaged plasma pressure and B_p is the averaged poloidal magnetic field on the face. An energy confinement time, τ_E, more that for L mode (for example, ITER89-P [3] in the high-β_p regime to reduce the plasma cu nition and hence to achieve efficient steady-st operation [4]. Improved confinement time w in the high-β_p regime ($\beta_p = 1-2$) in JT- the confinement improvement factor, τ_E/τ creased with $\varepsilon\beta_p$ [5]. In this regime, the "hig a bootstrap-current fraction of up to 58% a ion temperature, $T_i(0)$, of 38 keV were ach taneously. Recently the high-β_p mode regime ed to a lower q regime ($q_{\text{eff}} \sim 4.3$; q_{eff} is the e face safety factor defined in Ref. [6]) by using current profile control to avoid sawteeth. And high fusion performance was attained in this regime [7,8]. This Letter describes two distinctive features of this high-β_p mode: (1) the formation of an "internal" transport barrier near the $q = 3$ rational surface and (2) the appearance of high poloidal plasma rotation velocity of $\sim$50 km/s in the plasma interior.

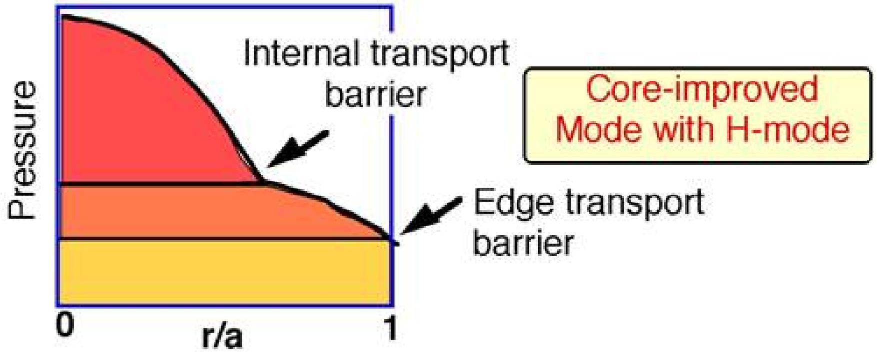
and Poloidal Plasma Spin Up



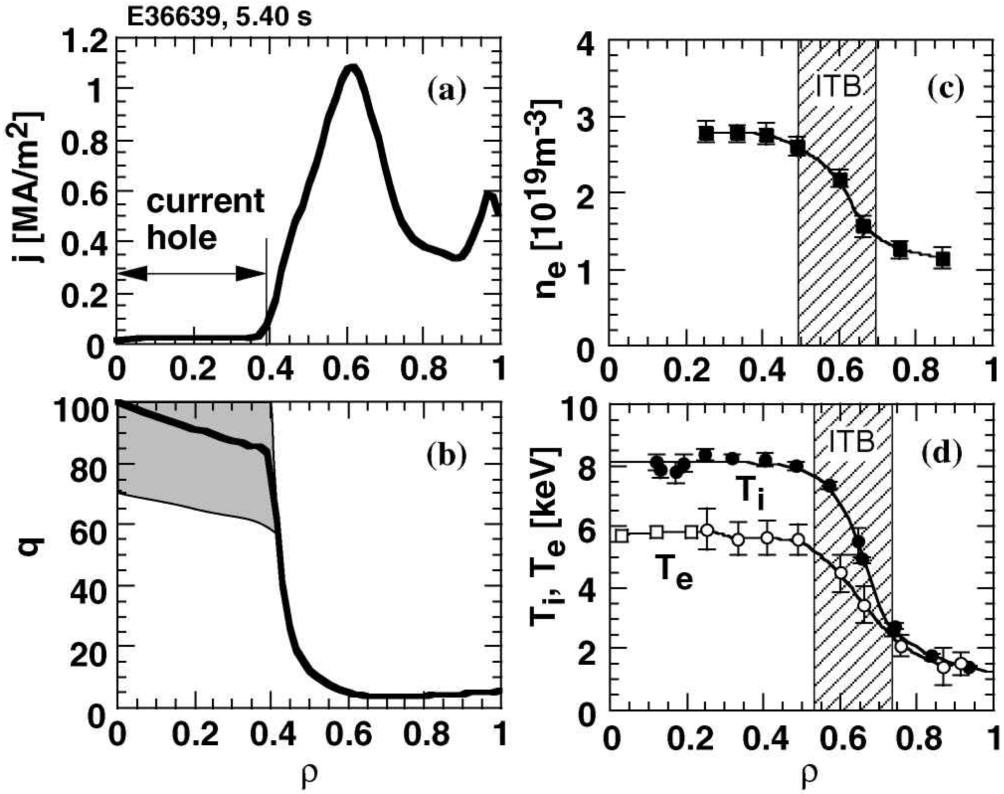
Reversed Shear Mode

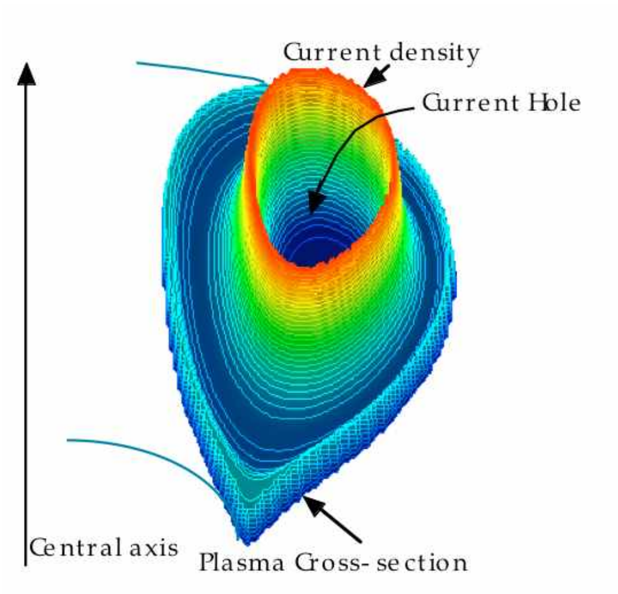


Reversed Shear Mode



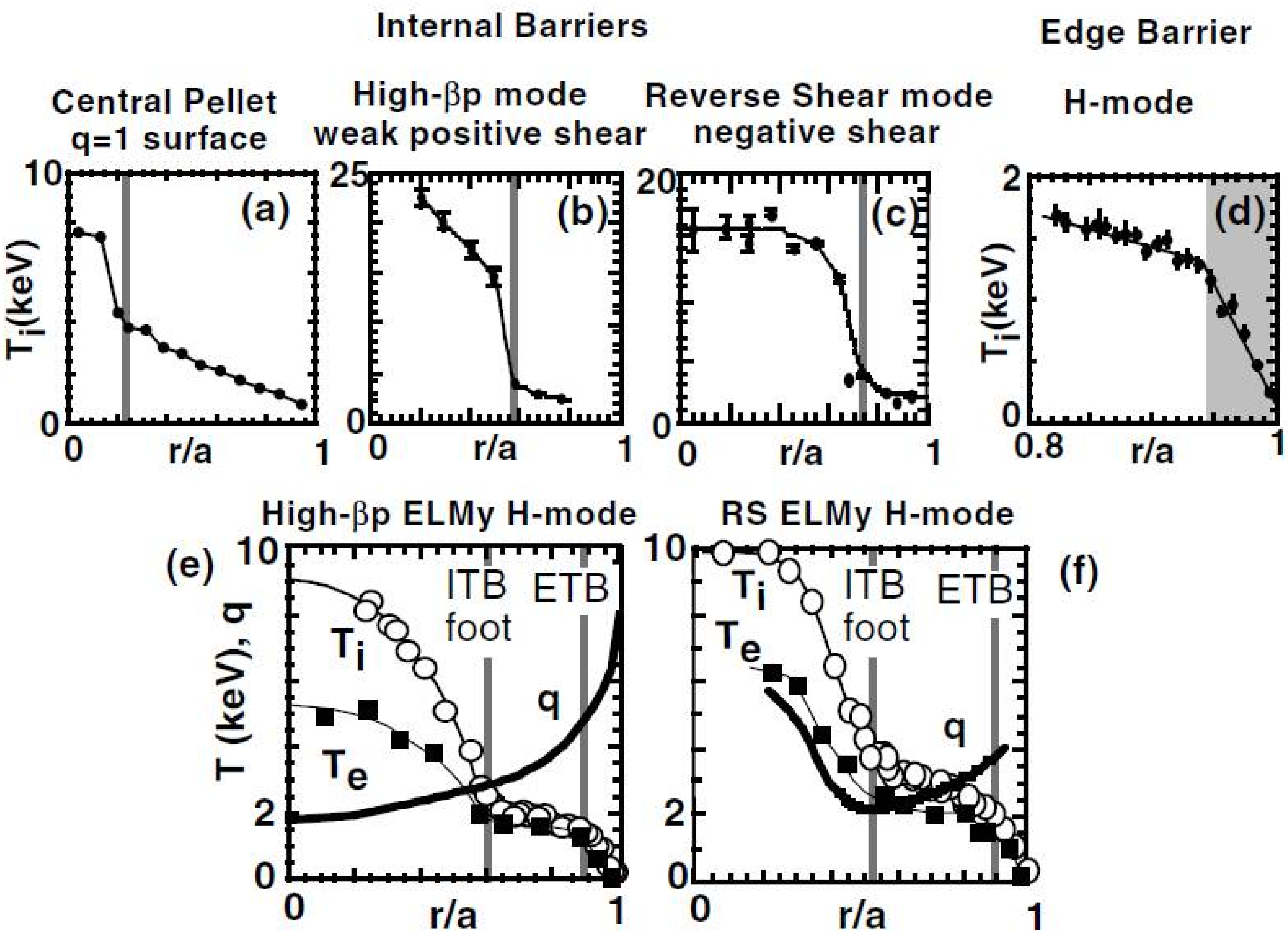
Current Hole Regime





*T. Fujita et al, PRL **87** 245001 (2001)*

Internal+Edge Transport Barrier

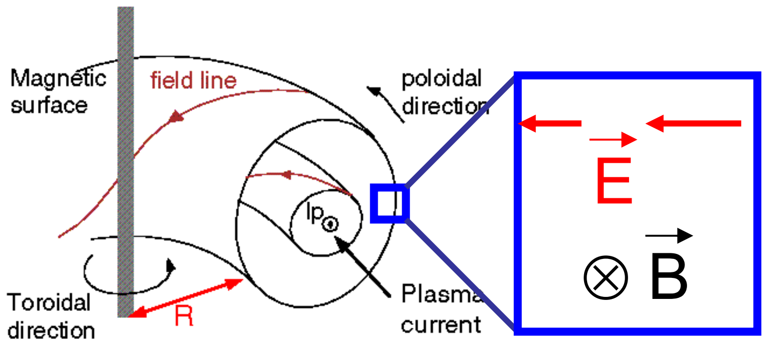


Y. Kamada, PPCF **42** A65 (2000)

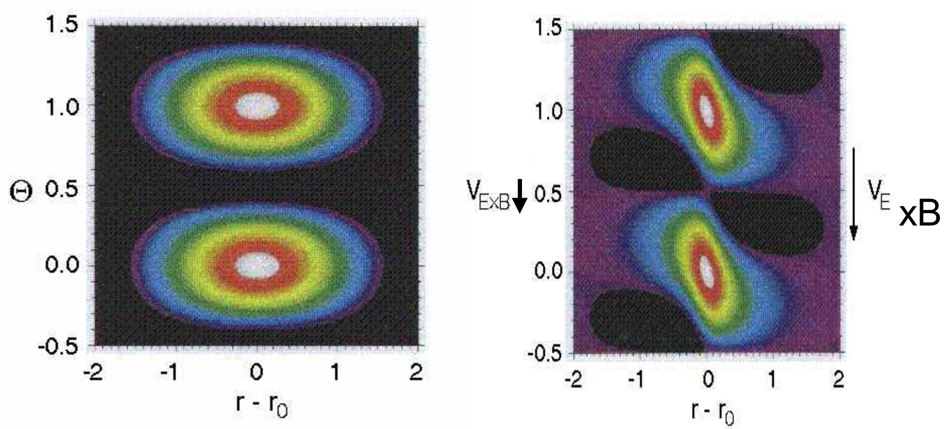
Turbulence Stabilisation

- **Formation of internal transport barriers to improve confinement**

- Reversed magnetic shear
- Differential rotation (input power)
} **Stabilises turbulence**



- **One reason:**
Losses of fast ions at the plasma edge
➔ sheared radial electric field
➔ sheared ExB rotation
➔ eddies get tilted and ripped apart
cause turbulence suppression!



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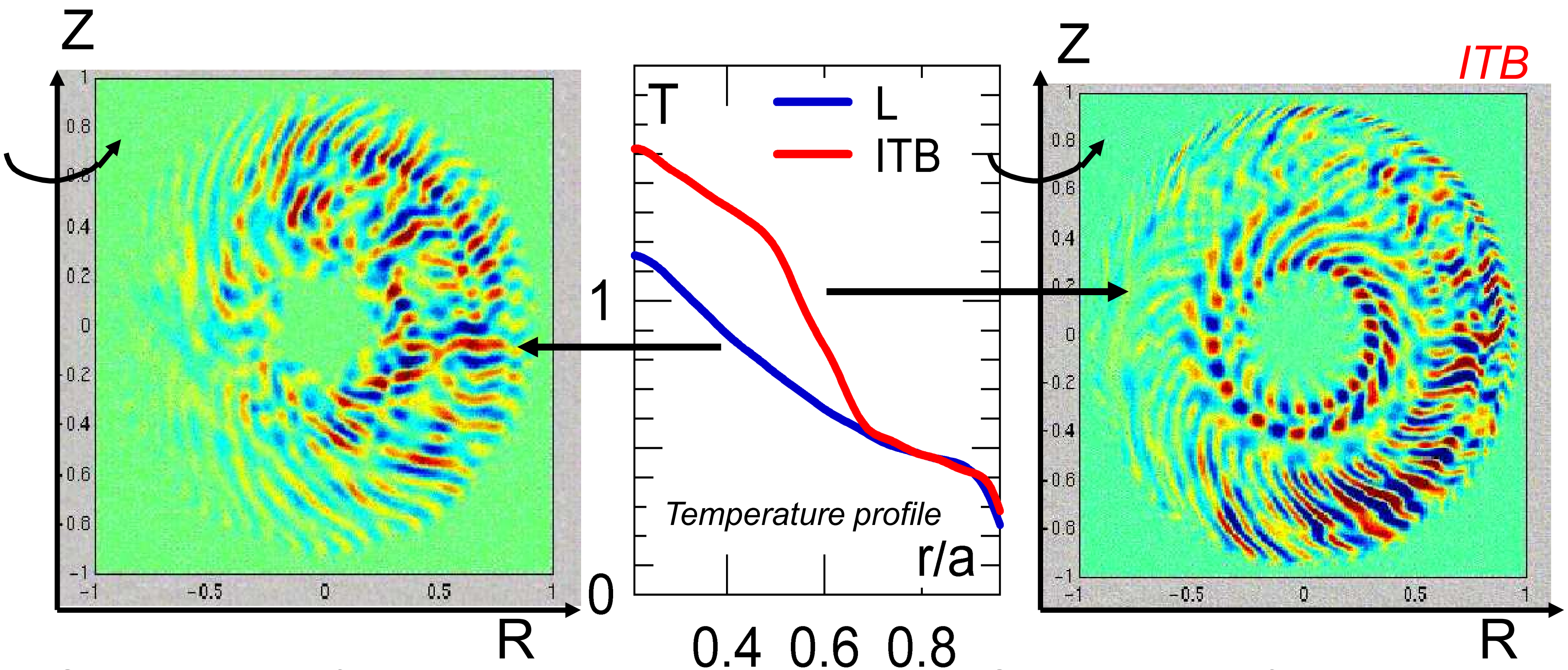


Contour lines of electric potential. *Contour lines of electric potential.*

Turbulence Stabilisation

Gyrokinetic Simulations of Plasma Microinstabilities

simulation by

Zhihong Lin et al.

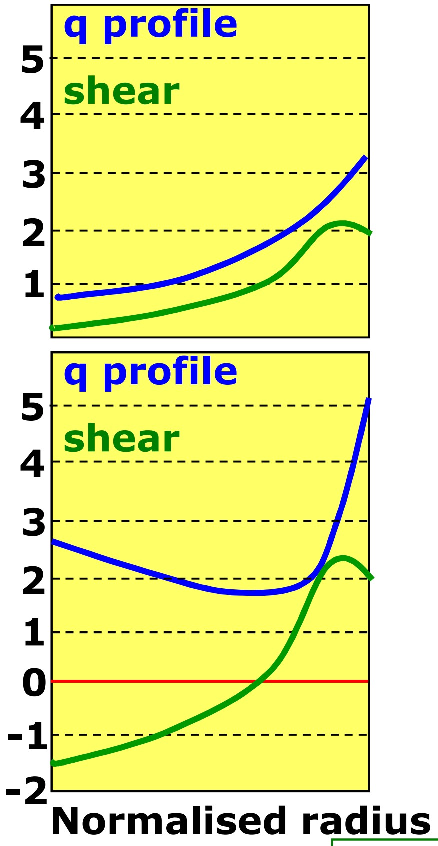
Science 281, 1835 (1998)

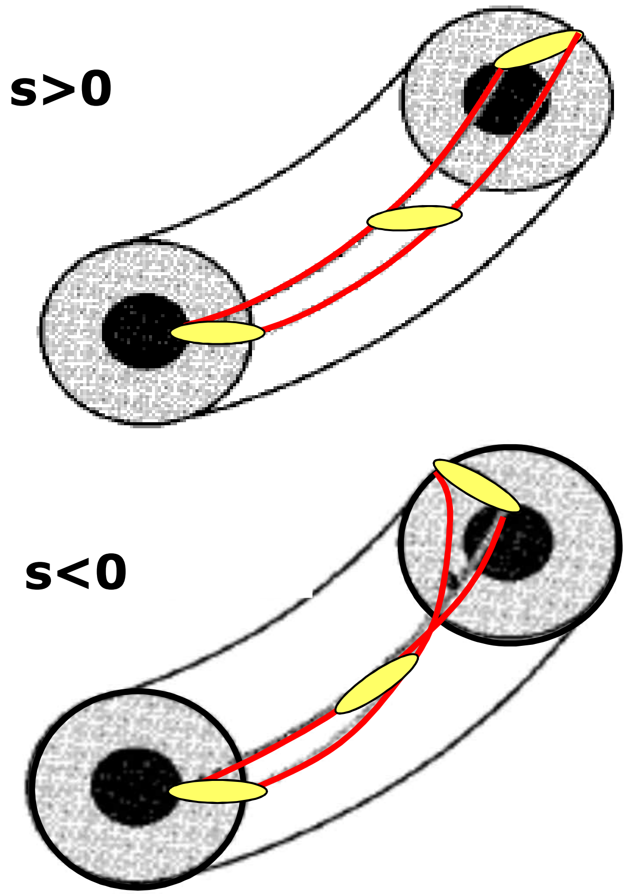
Turbulence Stabilisation

q & magnetic shear: $s = r/q \, dq/dr$

Standard scenario

Advanced tokamak scenario

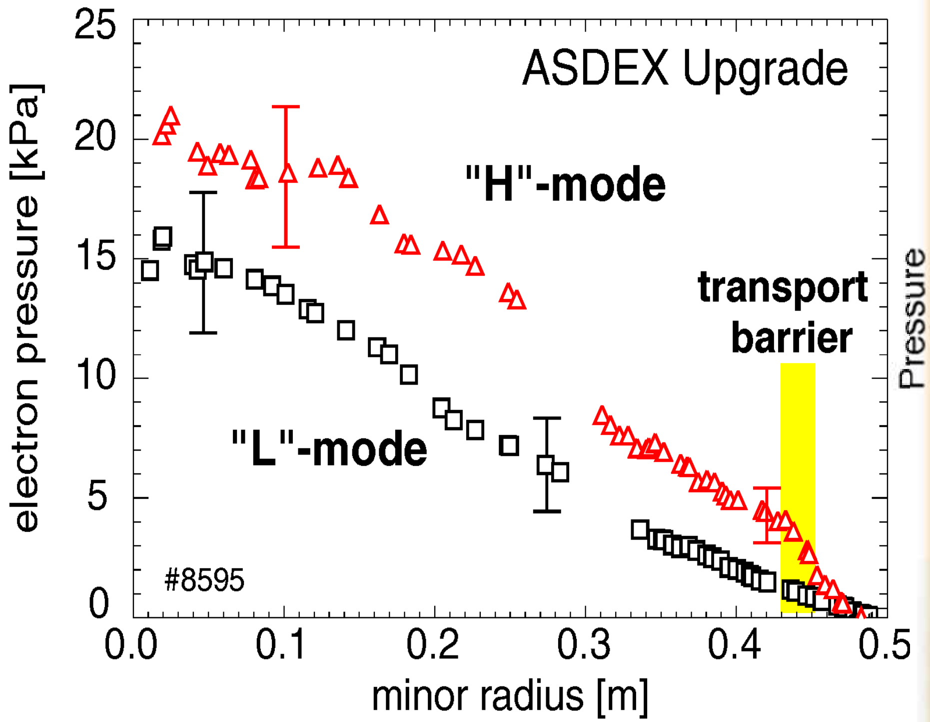


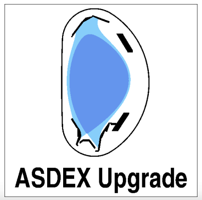


Magnetic shear can twist plasma disturbances

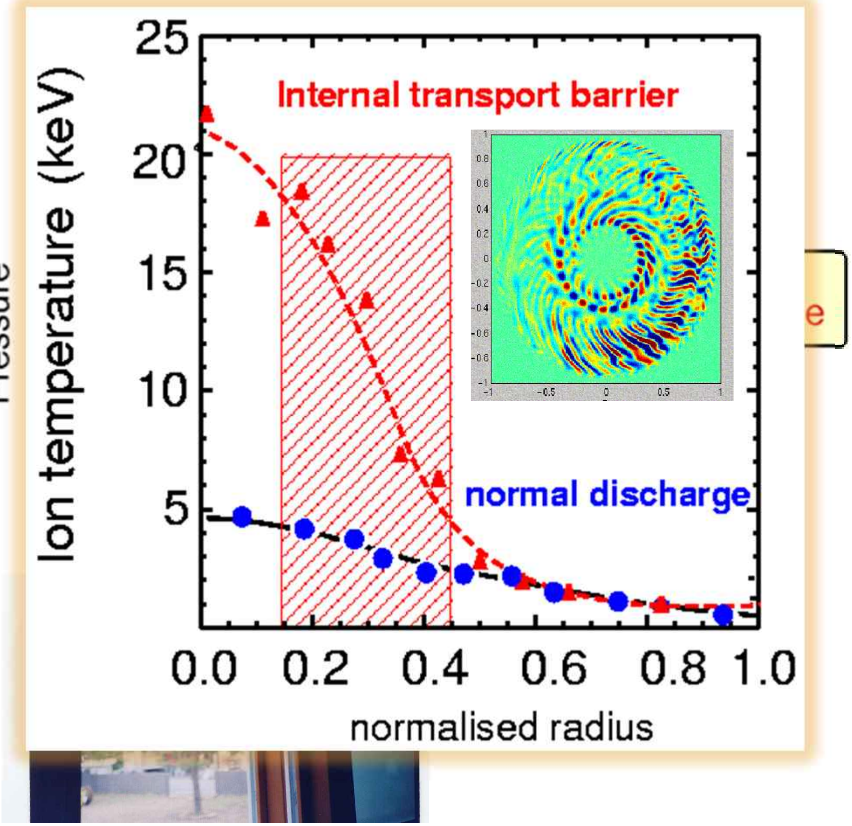
Reversed Shear Mode

H-mode



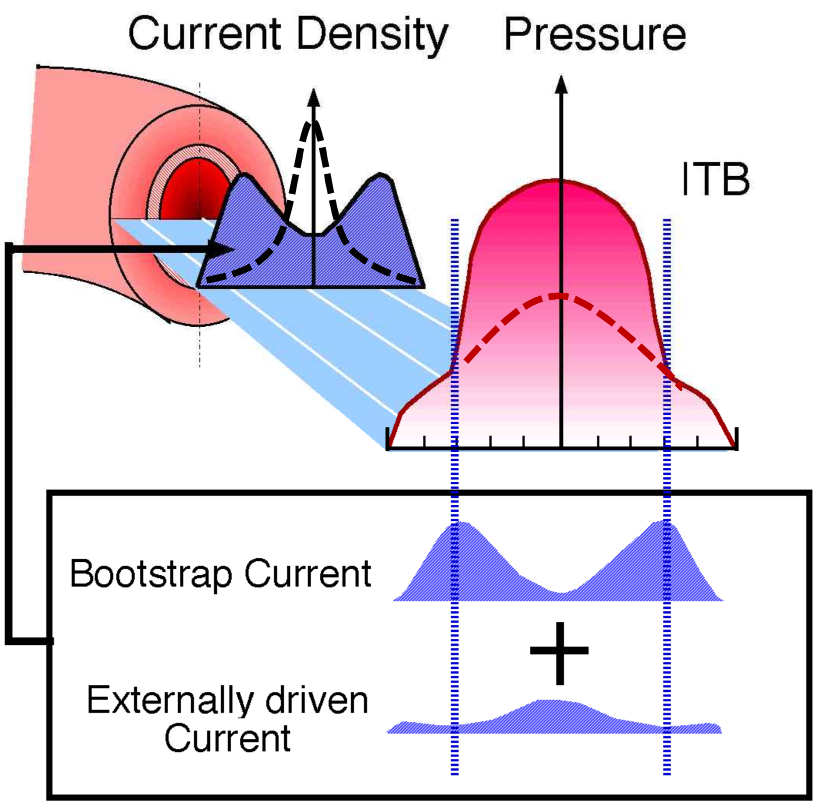


Reversed shear mode



Reversed Shear Mode

- **Operation at lower plasma current: $f_{BS} \sim \beta_p \sim I_p^{-2}$**
  - → **Confinement degradation: $\tau_E \sim H_{98}(y,2)\ I_p^{0.93}$**
  - → **To get enough fusion power: $H_{98}(y,2) > 1$ (advanced)**



Non-monotonic current profile

↓

Turbulence suppression

↓

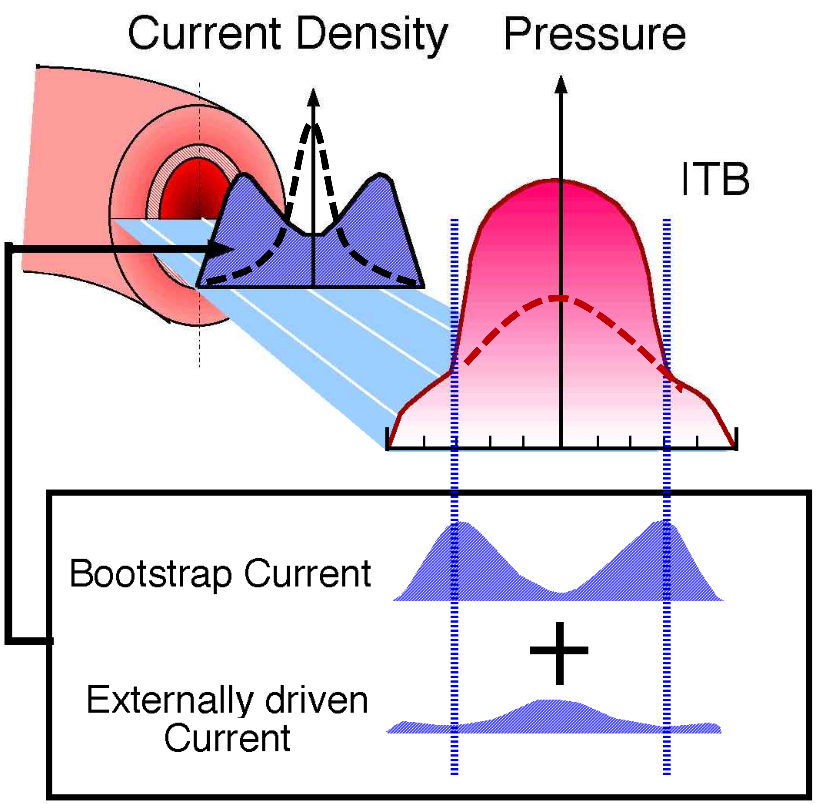
High pressure gradients

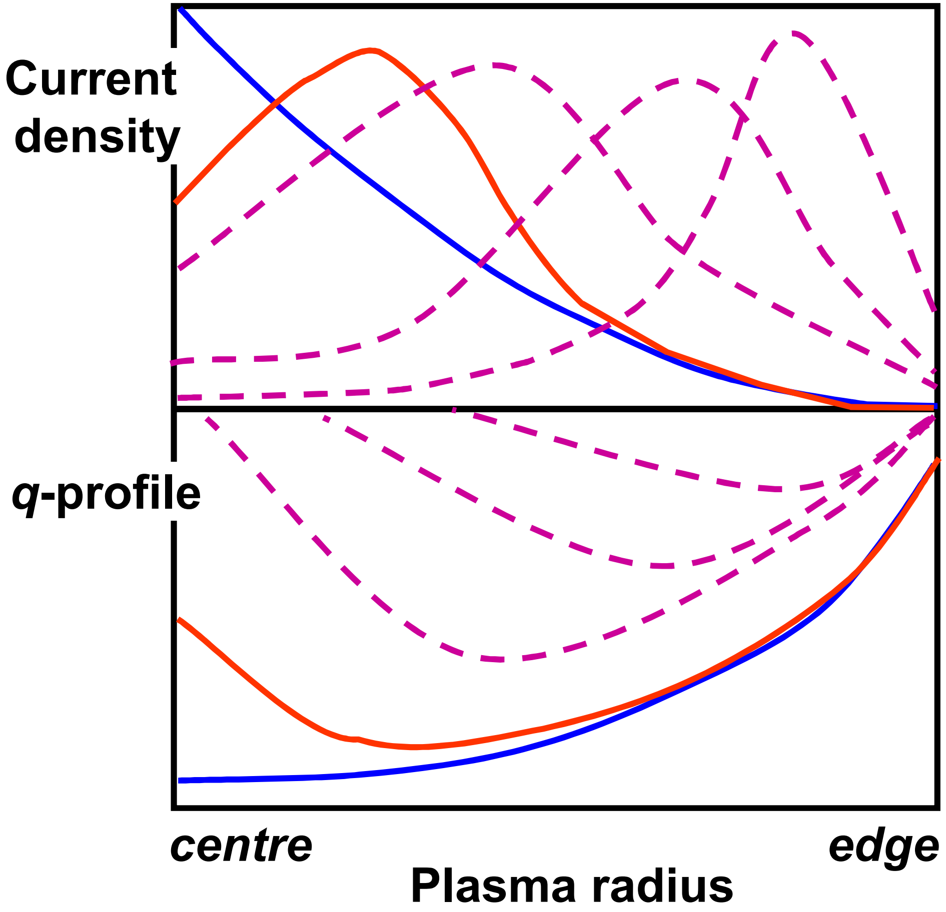
↓

Large bootstrap current

Sustainment of Non-monotonic Current Profile

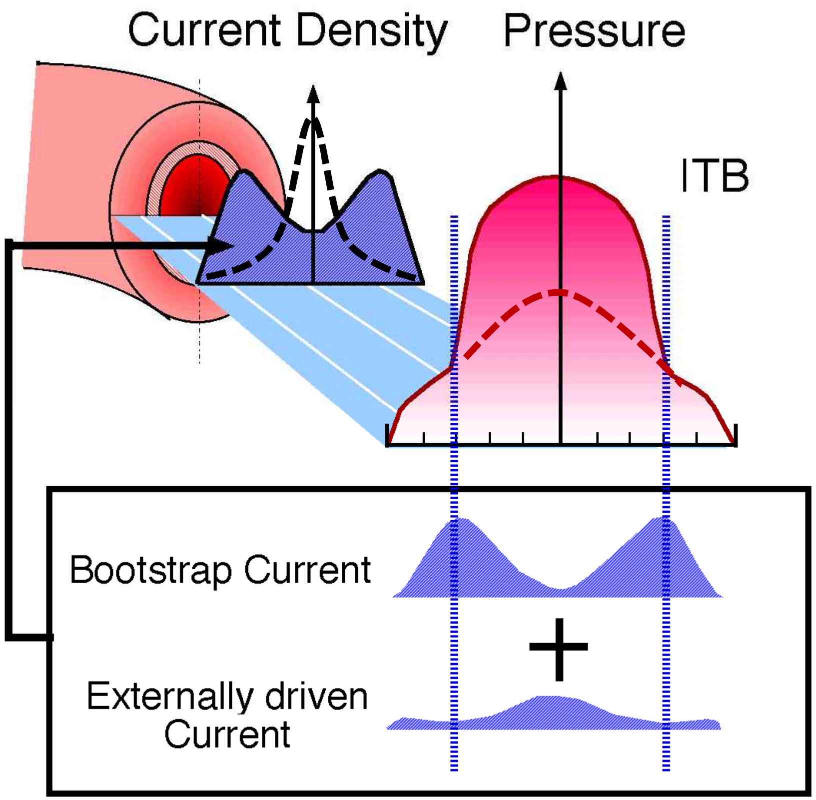
- Plasma current diffusion into the core from the edge





Current and pressure profile control !

Current drive and current profile control



Non-monotonic current profile

⬇

Turbulence suppression

⬇

High pressure gradients

⬇

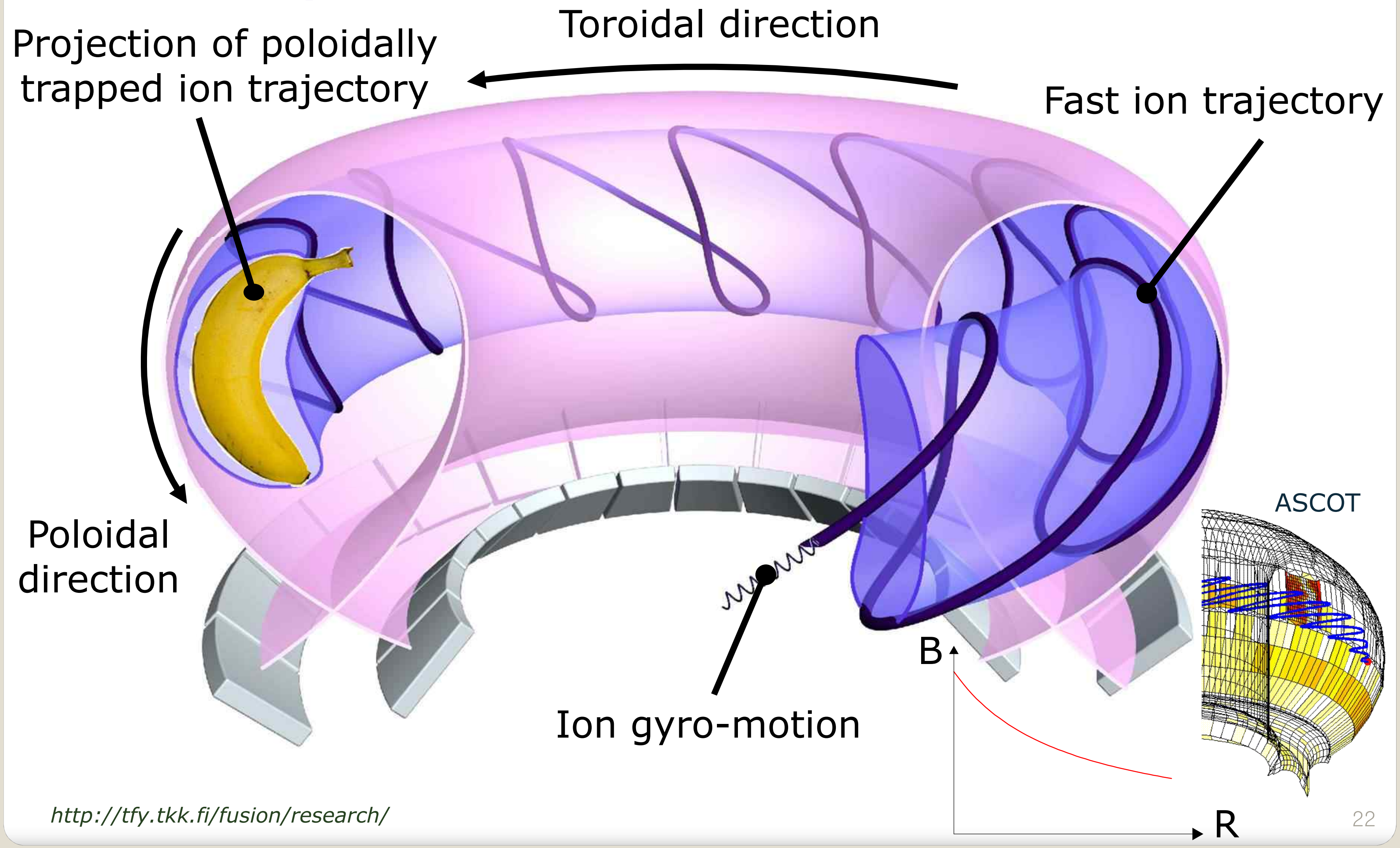
Large bootstrap current

⬇

Non-inductive current drive

Current drive and current profile control

- **Bootstrap current**

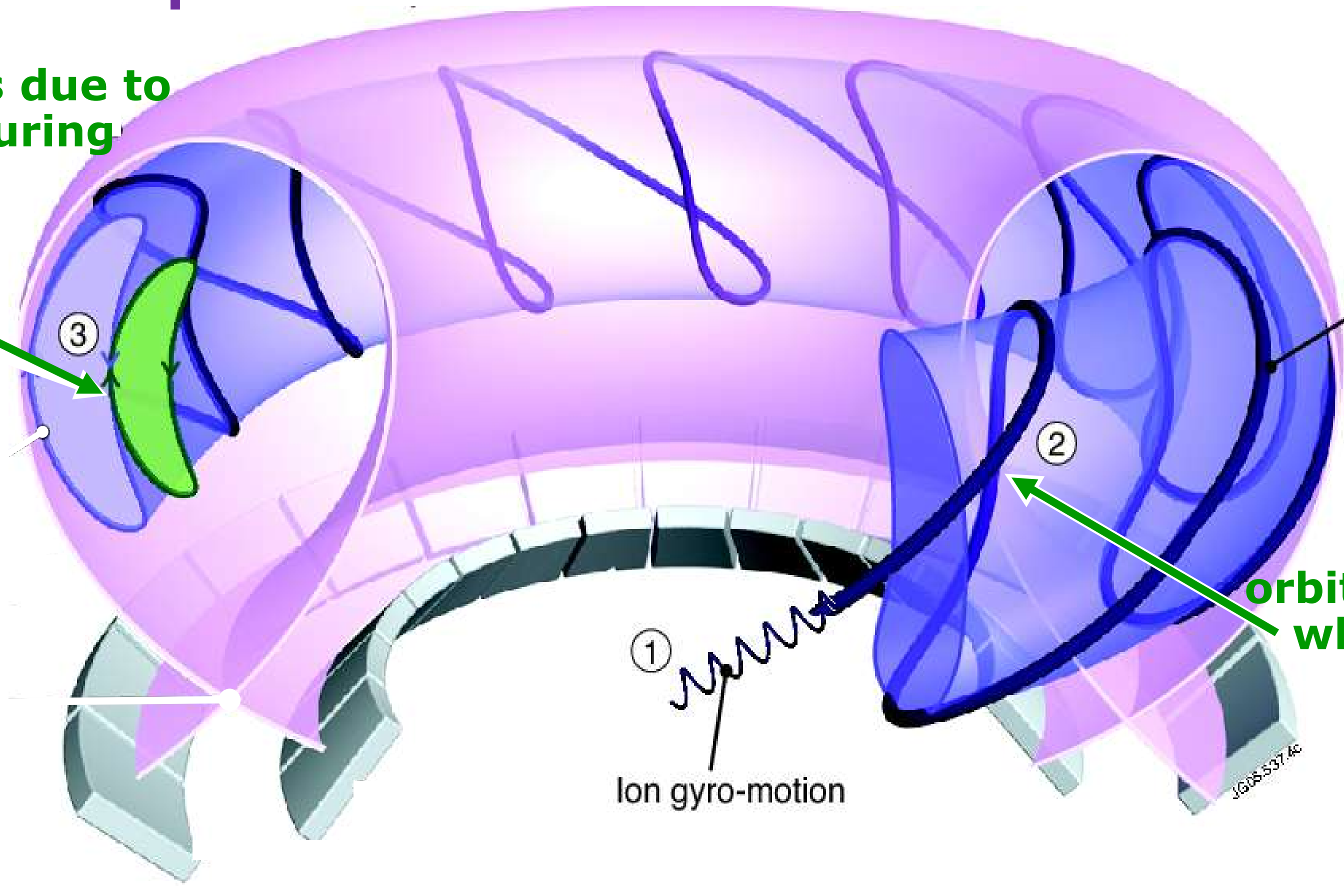


http://tfy.tkk.fi/fusion/research/

Current drive and current profile control

- **Bootstrap current**

Currents due to neighbouring bananas largely cancel



orbits tighter where field stronger

- But more & faster particles on orbits nearer the core (green cf blue) lead to a net "banana current"
- this is transferred to a helical bootstrap current via collisions

$$J_{boot} \sim \frac{dP}{dr}$$

Current drive and current profile control

- **Bootstrap current**

110 NATURE PHYSICAL SCIENCE VOL. 229 JANUARY 25 1971

Diffusion Driven Plasma Currents and Bootstrap Tokamak

by

R. J. BICKERTON, J. W. CONNOR & J. B. TAYLOR

UKAEA Research Group, Culham Laboratory, Abingdon, Berkshire

In toroidal systems of plasma confinement the intrinsic diffusion driven toroidal current modifies estimates of the maximum ratio of plasma pressure to magnetic field pressure. This intrinsic current may also make possible a type of Tokamak machine which operates in a steady state, unlike present pulsed designs.

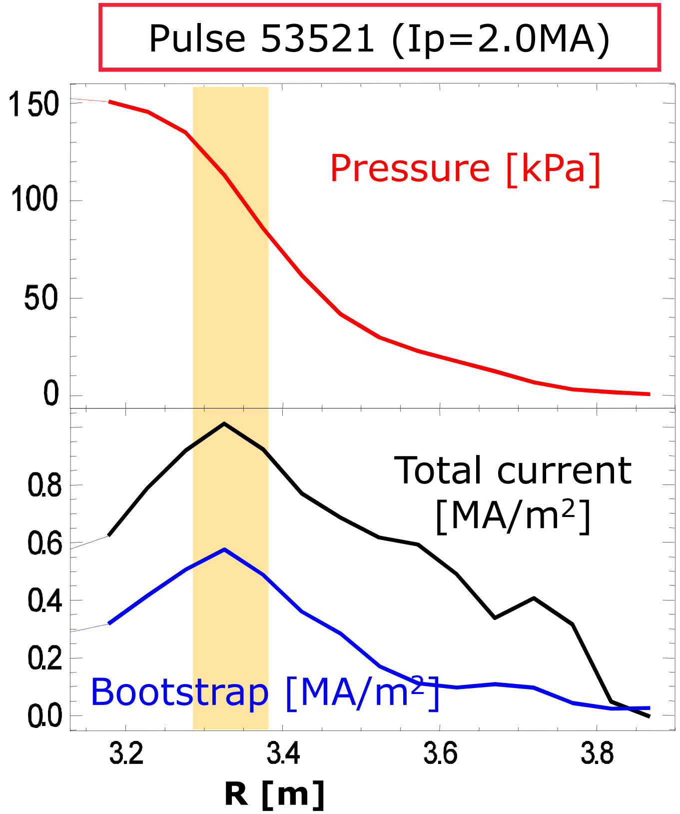
in what we call a "bootstrap" Tokamak. Such a machine could operate in a steady state, unlike present pulsed designs, because refuelling and thermonuclear reactions provide a continuous source of plasma to diffuse across the lines of force.

The existence of the intrinsic toroidal current is implicit in all calculations of toroidal diffusion and its value may be obtained easily from such calculations, so that only the result need be quoted here. For simplicity we consider the usual axisymmetric system with concentric magnetic surfaces $B\varphi = B_0/h$, $B_\theta = \Theta B\varphi$ with

$$\Theta = \varepsilon \frac{\iota}{2\pi} \ll 1, \; h = 1 + (r/R) \cos \theta, \text{ and } r, \theta, \varphi$$

Current drive and current profile control

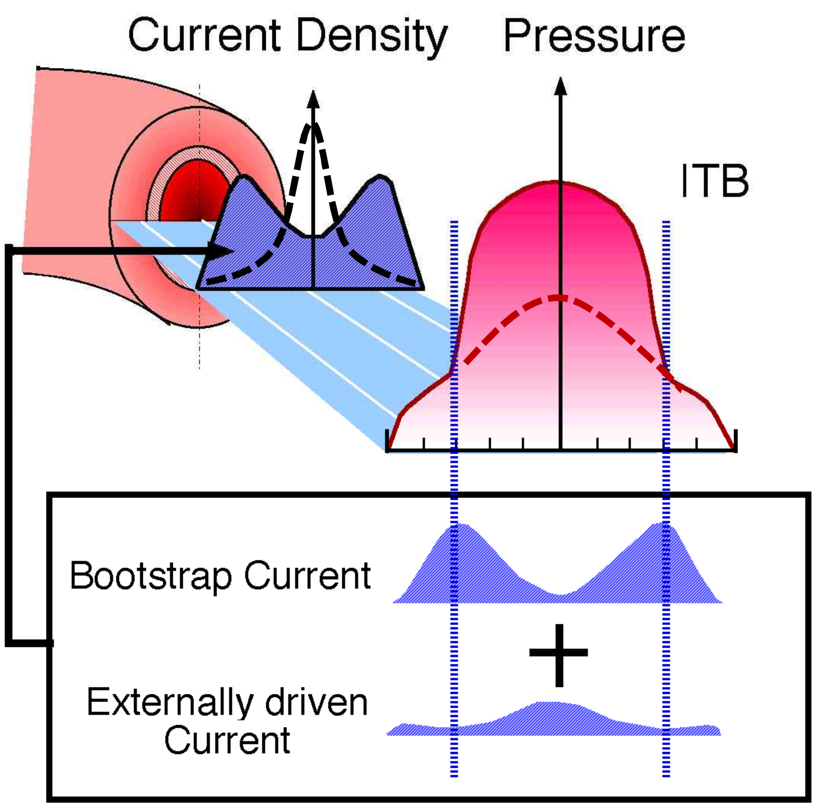
- **Bootstrap current**



Bootstrap current is an off-axis current drive

Bickerton 1971 & Galeev 1970

Current drive and current profile control



Non-monotonic current profile

↓

Turbulence suppression

↓

High pressure gradients

↓

Large bootstrap current

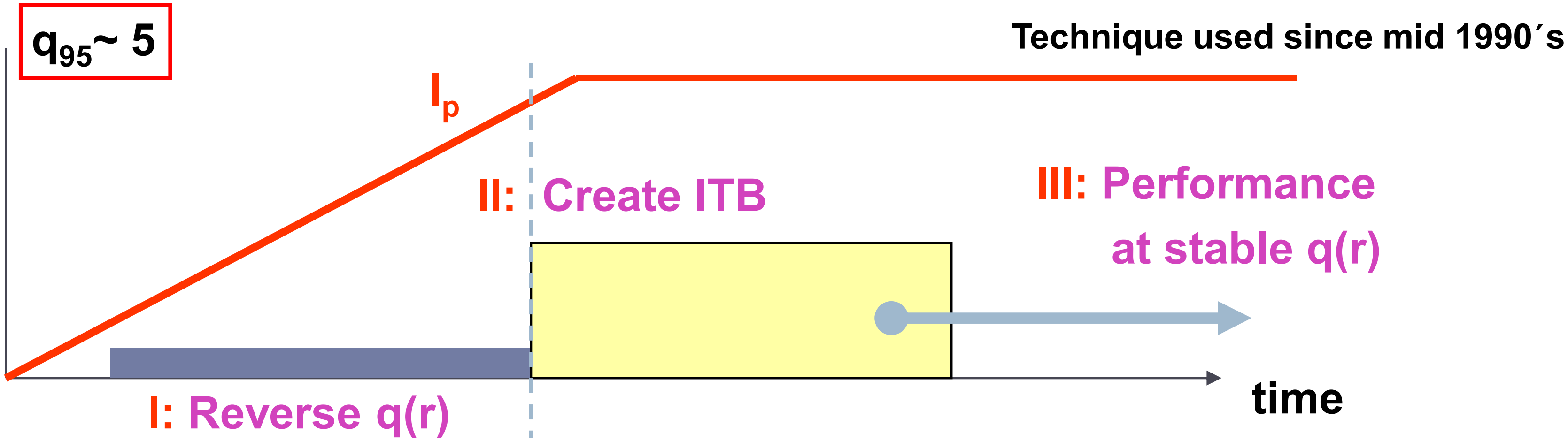
↓

Non-inductive current drive

Cf. NTM control

HW: Which heating & CD sources for fusion reactors?

Reversed Shear Scenario



I: Heat during current rise, external current drive (reverse q).

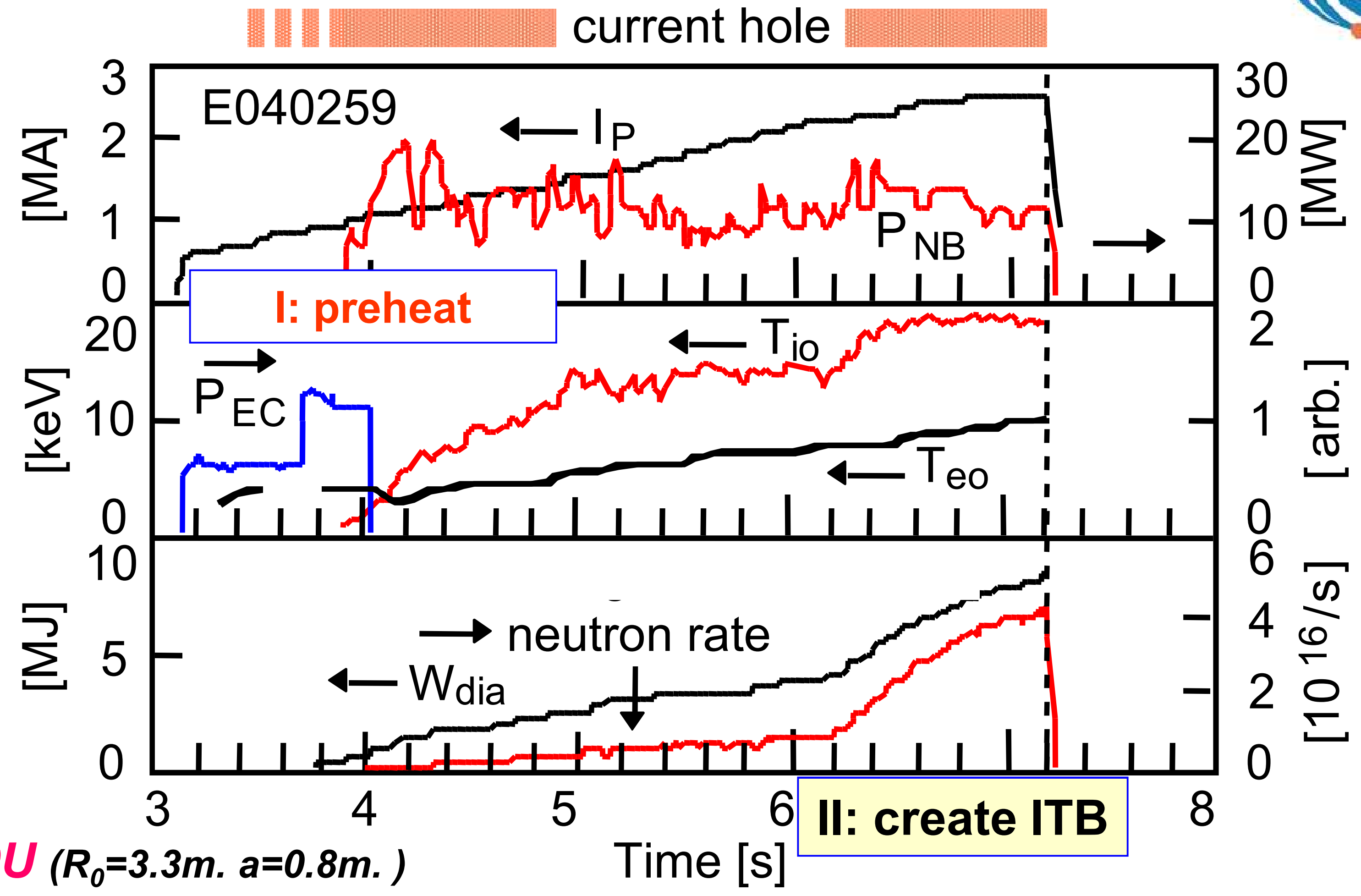
II: Increase heating power to stabilise turbulence (ITB).

Improve plasma confinement, try to increase pressure (β_N)

III: Keep going: ITER non-inductive regime: $H_H \approx 1.6$; $\beta_N \approx 3.0$

(ITER: 9MA, 50% external current drive (73MW), 50% bootstrap fraction)

Reversed Shear Scenario

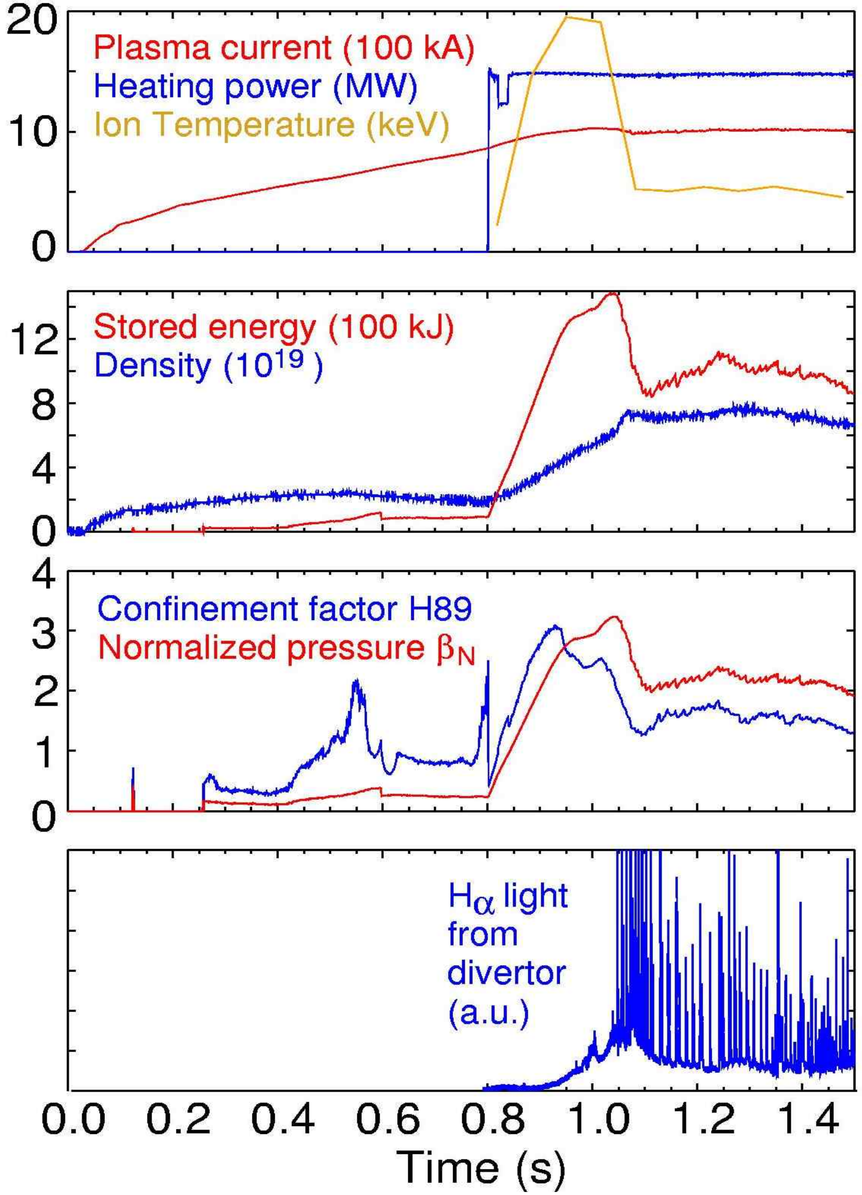


JT-60U *(R_0=3.3m. a=0.8m.)*

I: Form q(r), II: create ITB, III: But discharge terminates (unstable)

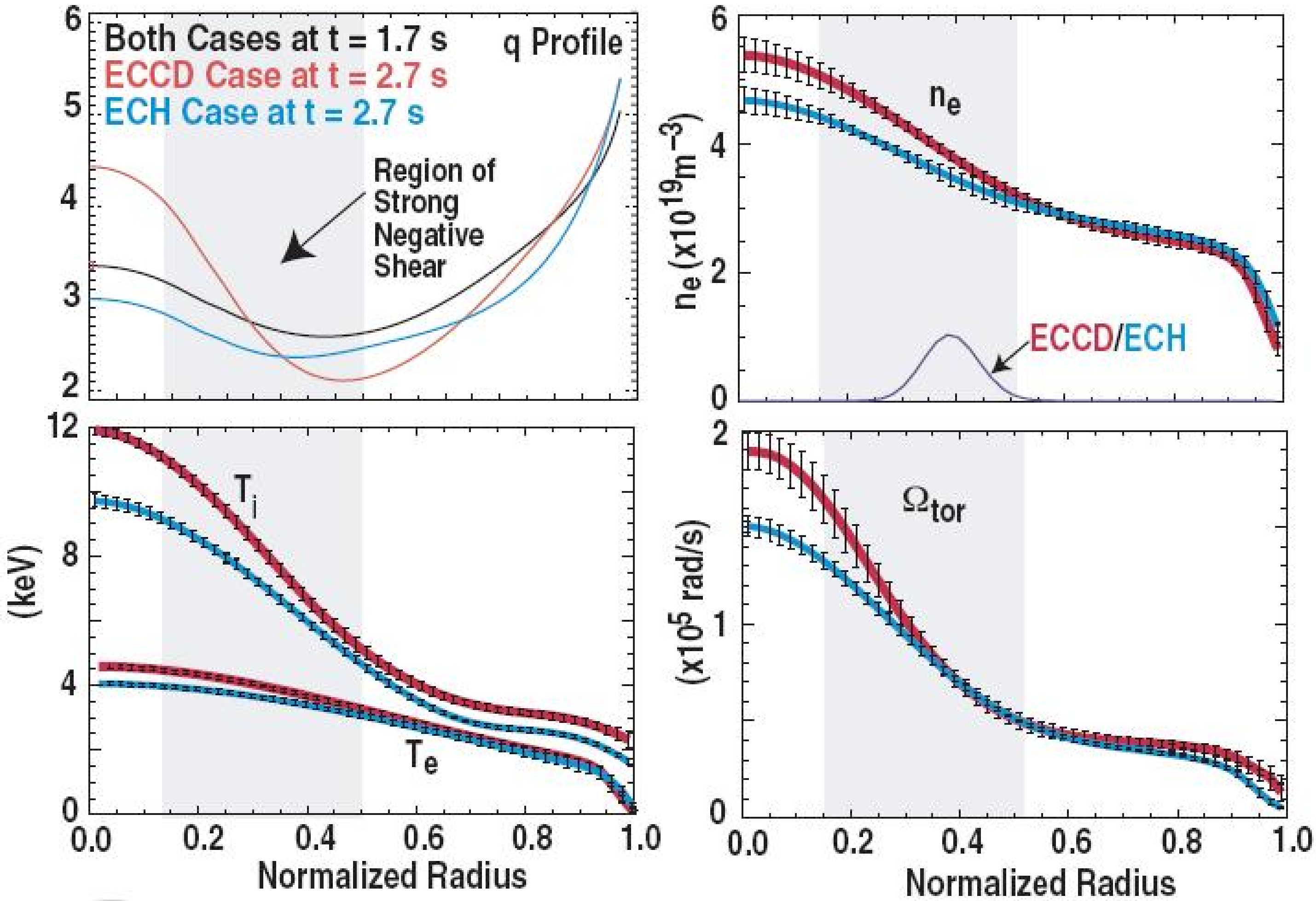
Fukuda T and the JT-60U team 2002 *Plasma Phys. Control. Fusion* 44 B39–B52

Reversed Shear Scenario



- Formation of an ITB at low n_e, with 15 MW NBI power $T_i > T_e$, high rotation shear
- ITBs are relatively short lived, only few τ_E
- Good, transient performance: H_{89}~3, β_N ~ 3
- ITB not compatible with H-mode edge barrier and large ELMs

Reversed Shear Scenario



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

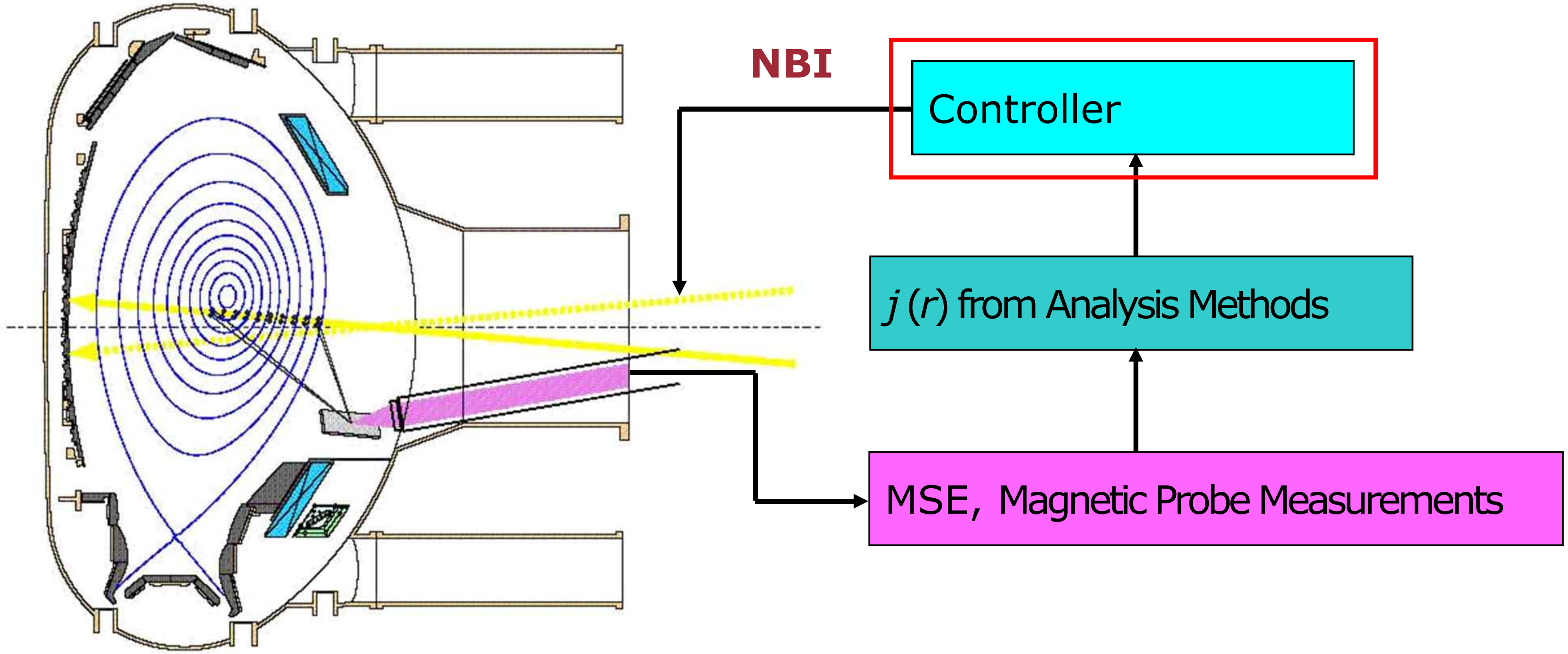
(R_0=1.7m. ,a=0.6m.)

- Less RS
- $H_{H98(y,2)}$ = 1.37
- β_N = 2.62
- q_{95} = 5
- „Weak“ ITBs

Wade, Nucl. Fusion 43 (2003) 634–646

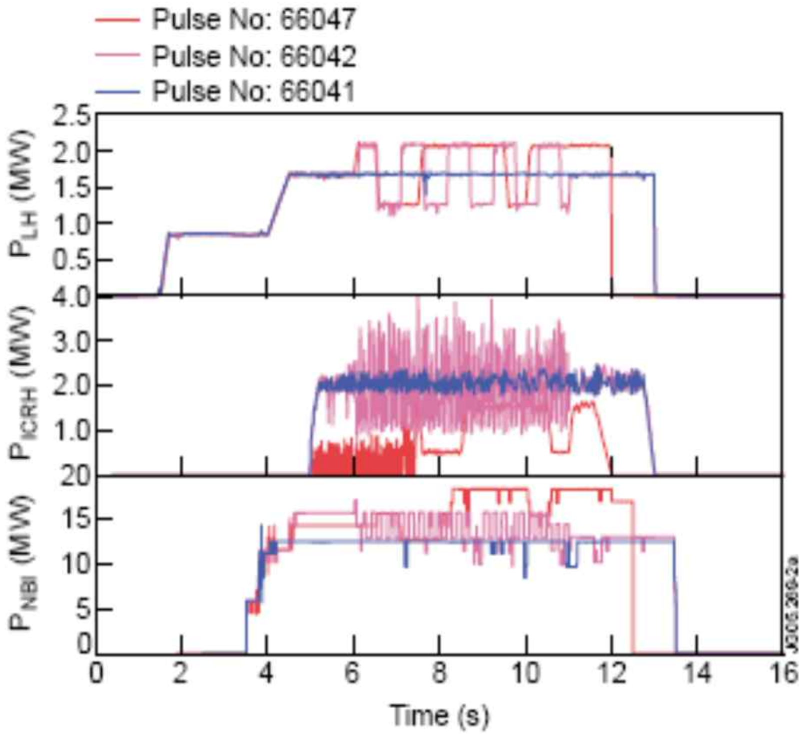
Reversed Shear Scenario

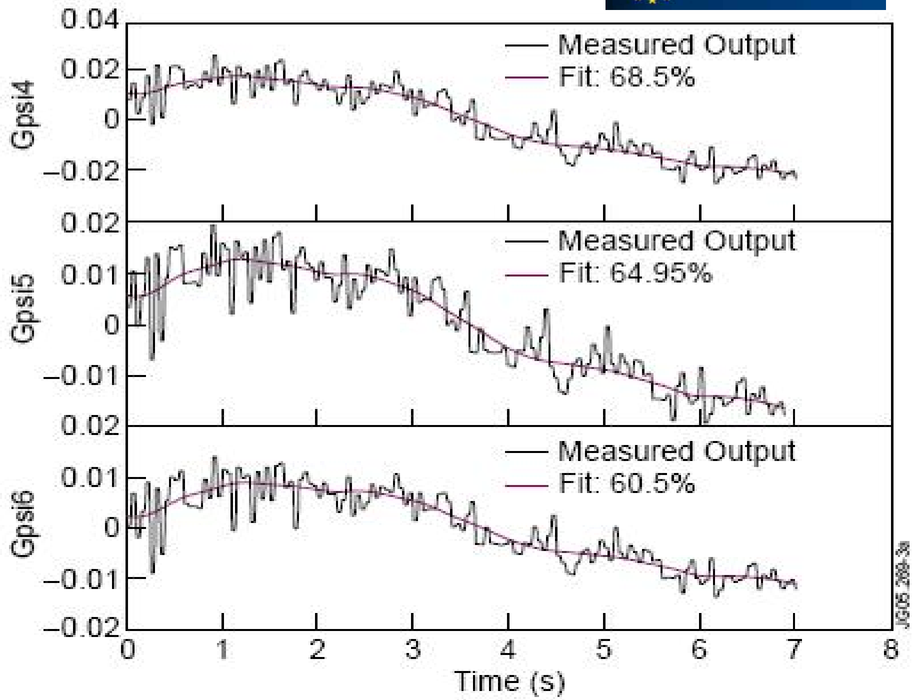
- Current density profile control at ASDEX Upgrade



RT Current and Pressure Profile Control

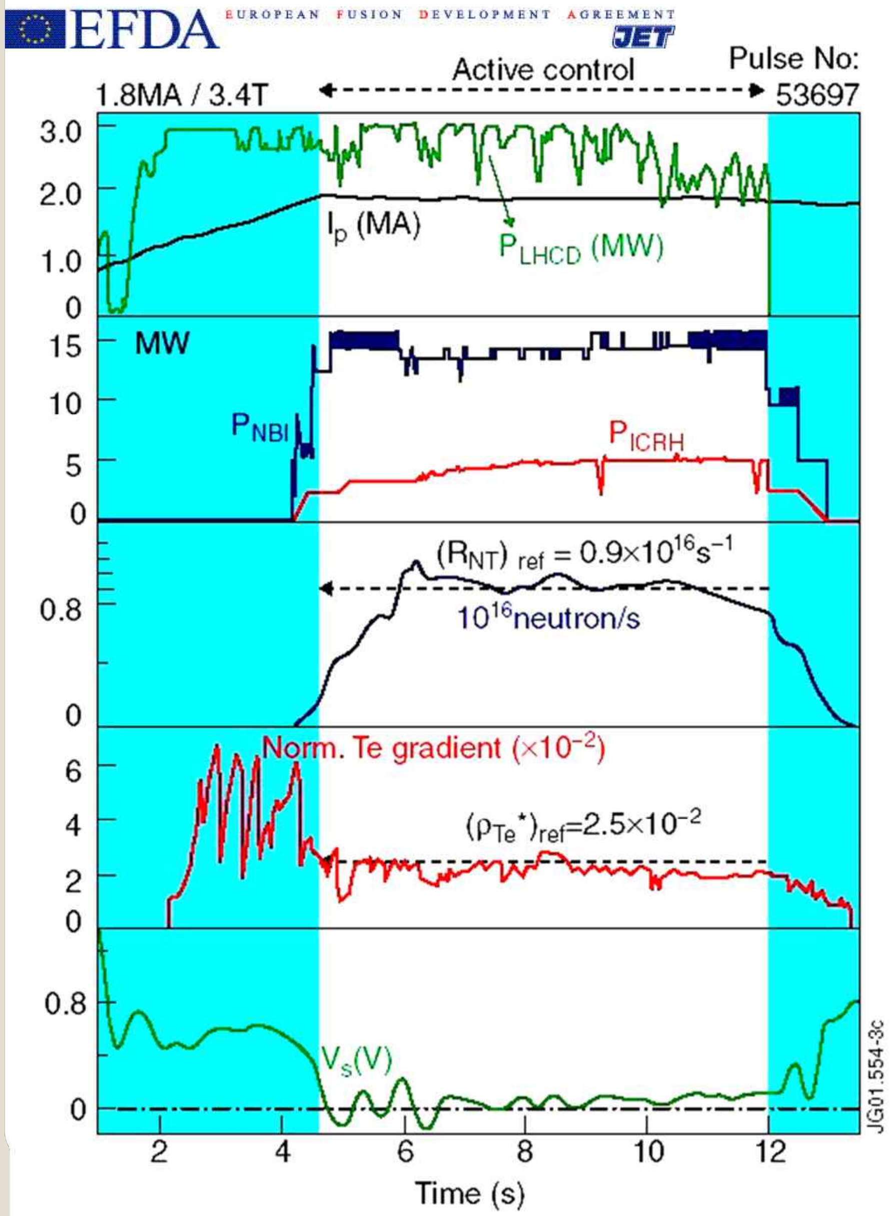
- Simultaneous control of distributed magnetic and kinetic paramters
- Dedicated experiments to identify controller coefficients

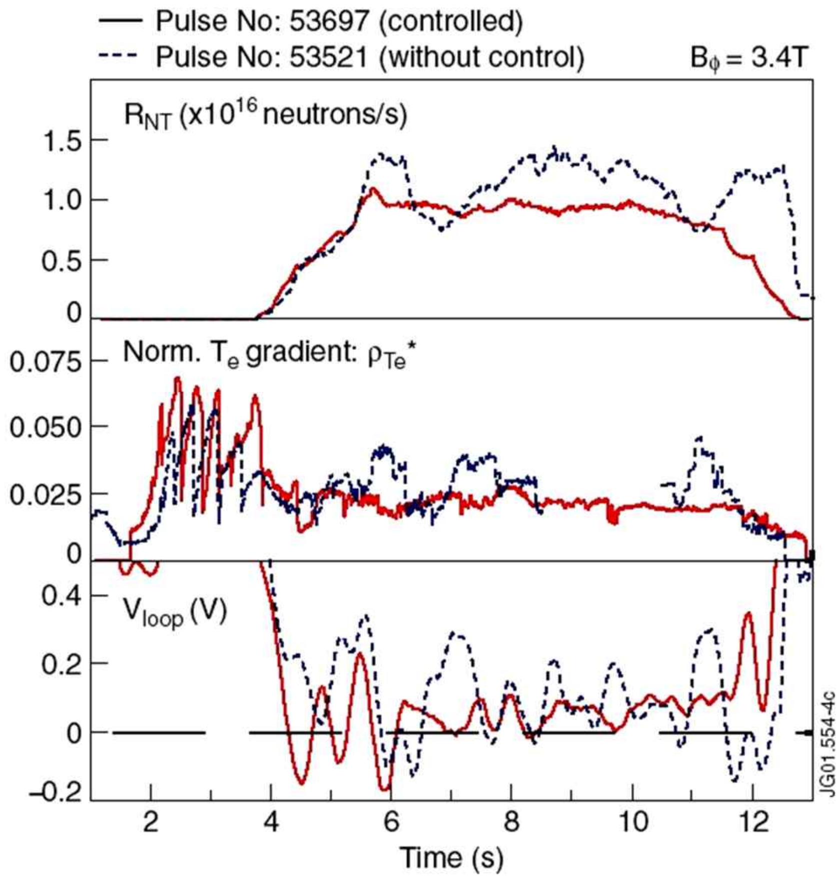




- Modulation combinations of actuators (NBI, LH, ICRH) to infer the coefficients of the state space model of the slow loop.
- Two control loops, 4 actuators (NBI, LH, ICRH, PF)

RT Current and Pressure Profile Control



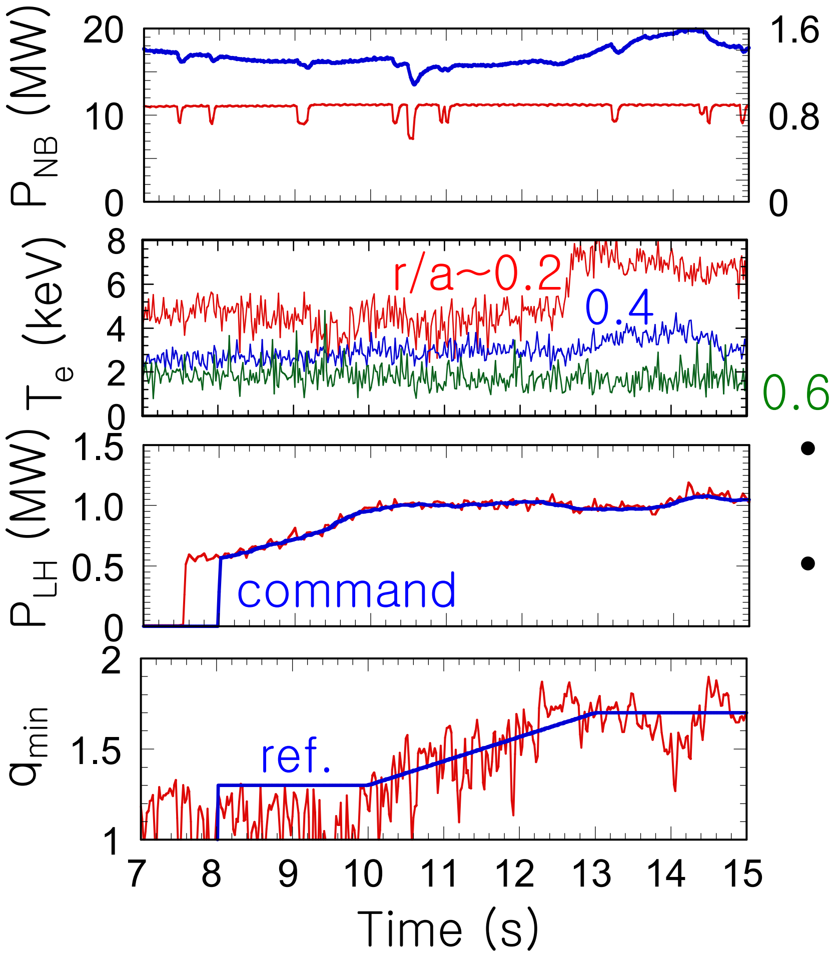


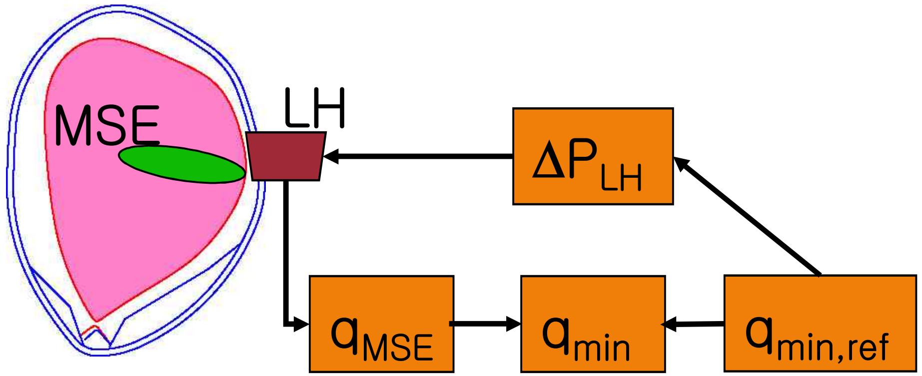
- Real time pressure profile and *q*-profile control to keep ITB steady

Mazon et al, PPCF 2002

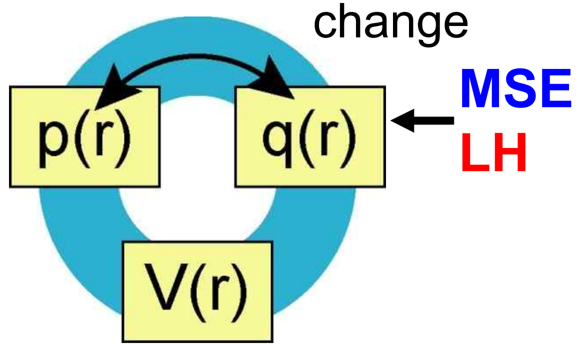
RT Current and Pressure Profile Control

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

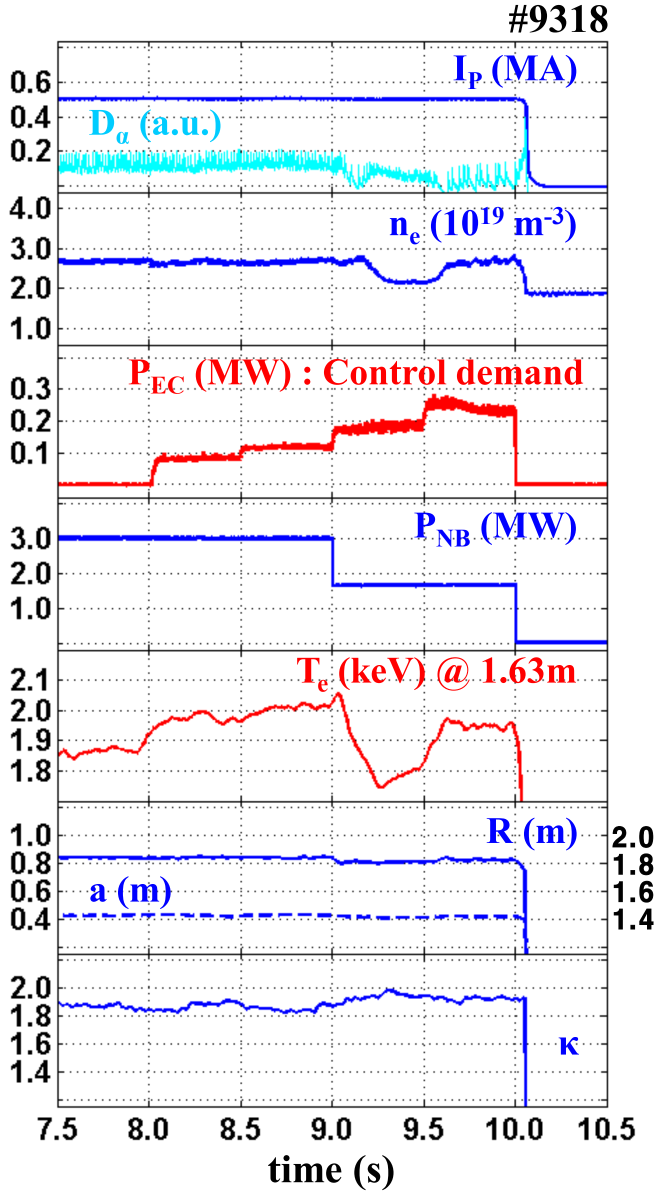


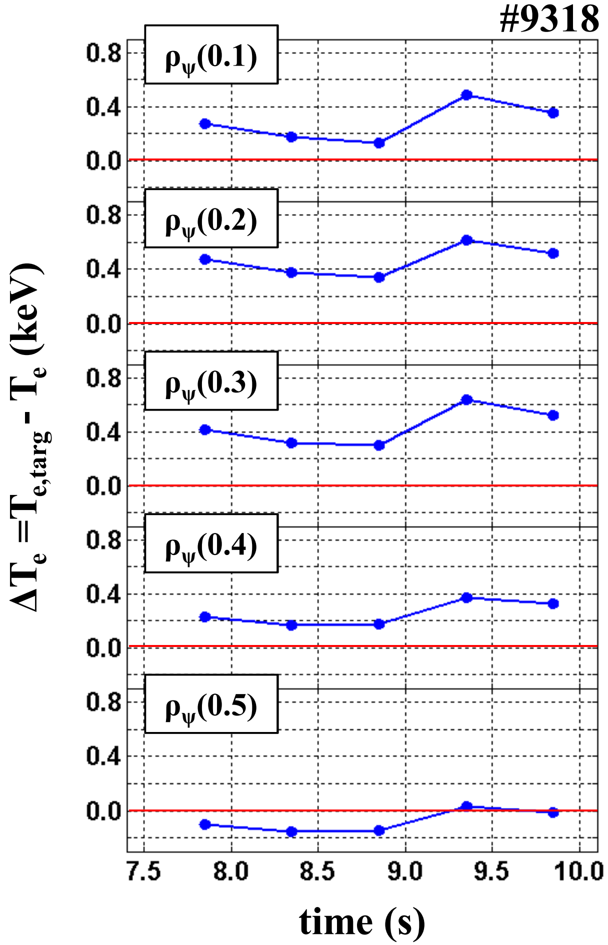


- Transport reduction at t = 12.4 s
- Time delay in response of q_{min}

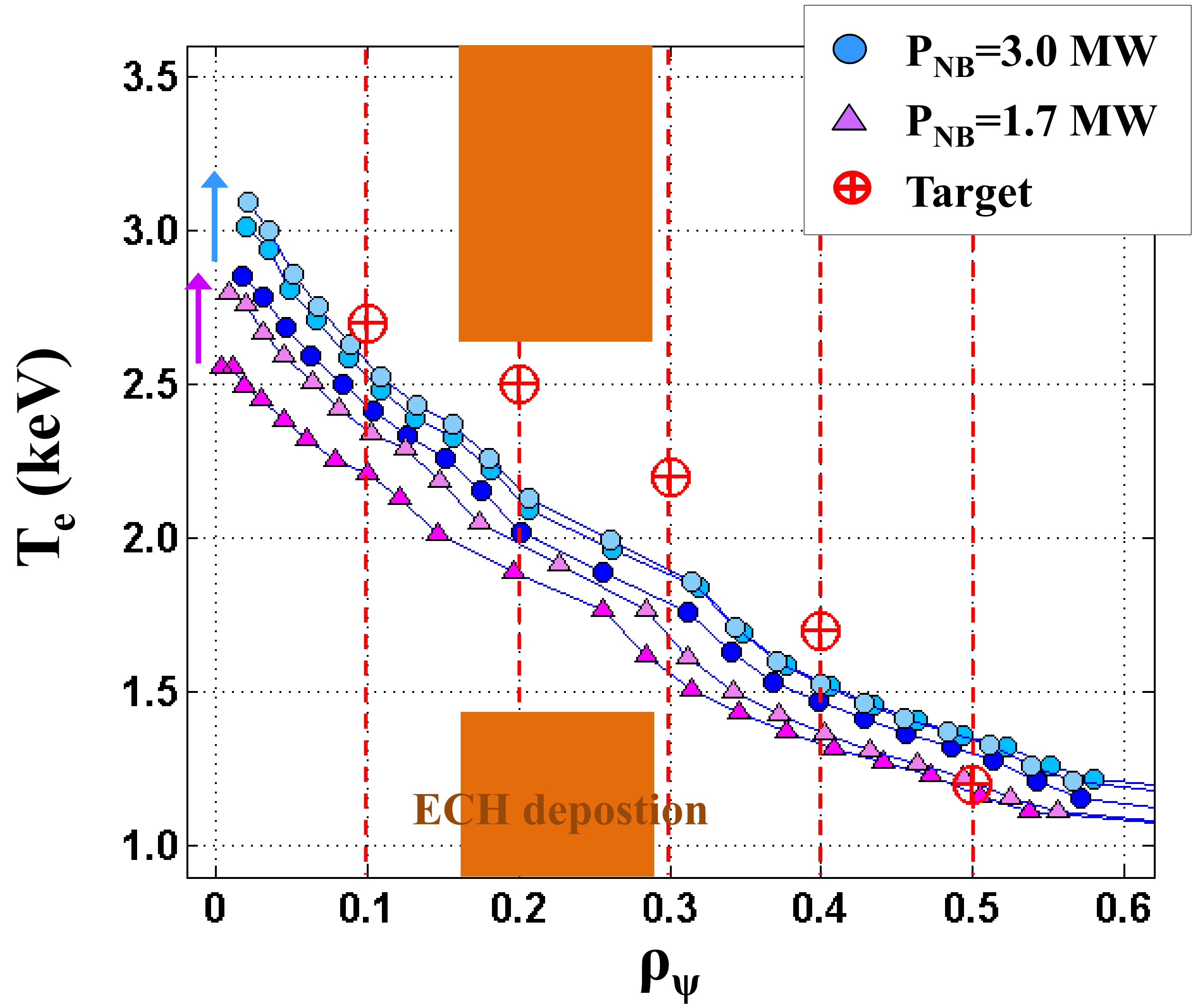


RT-T_e profile control in H-mode discharge (#9318)

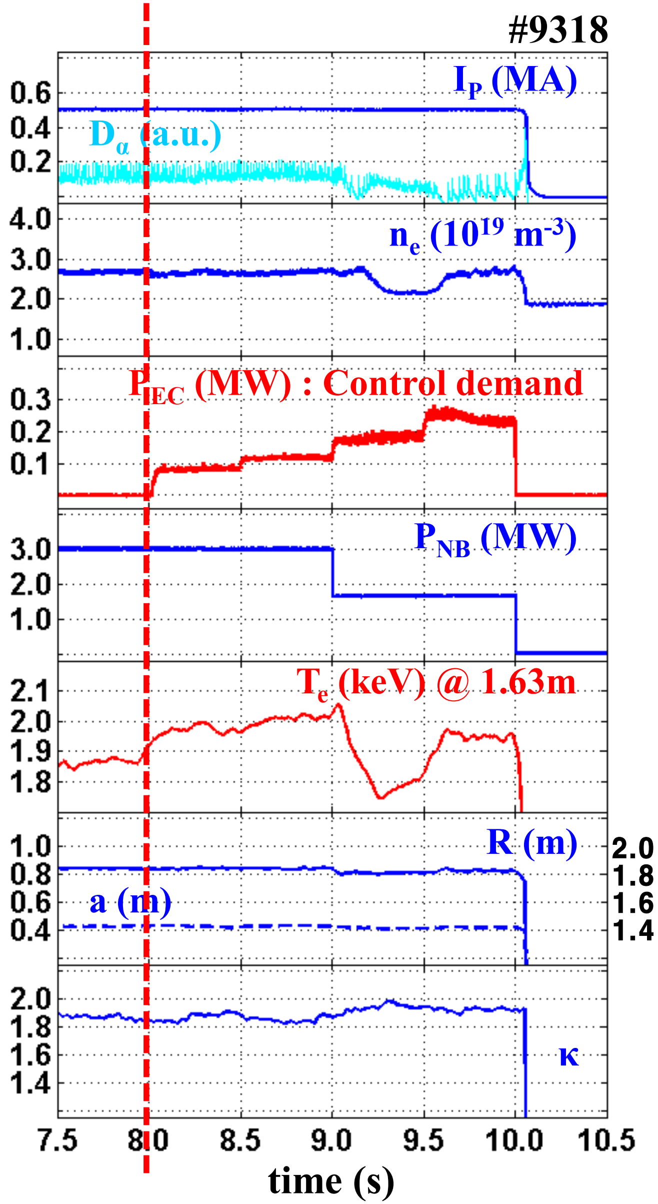


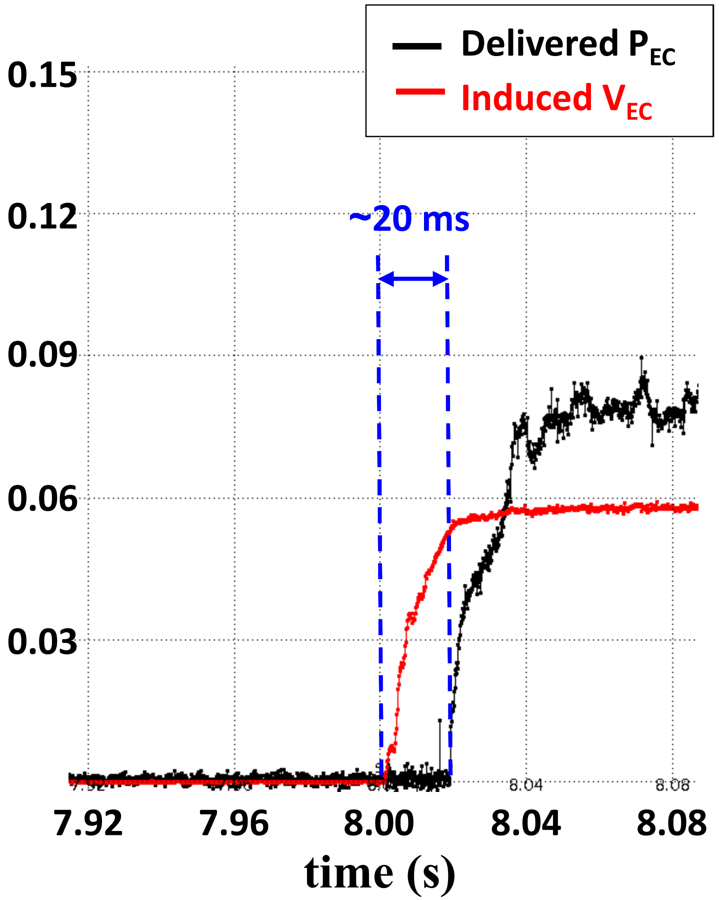


RT-T_e profile control in H-mode discharge (#9318)

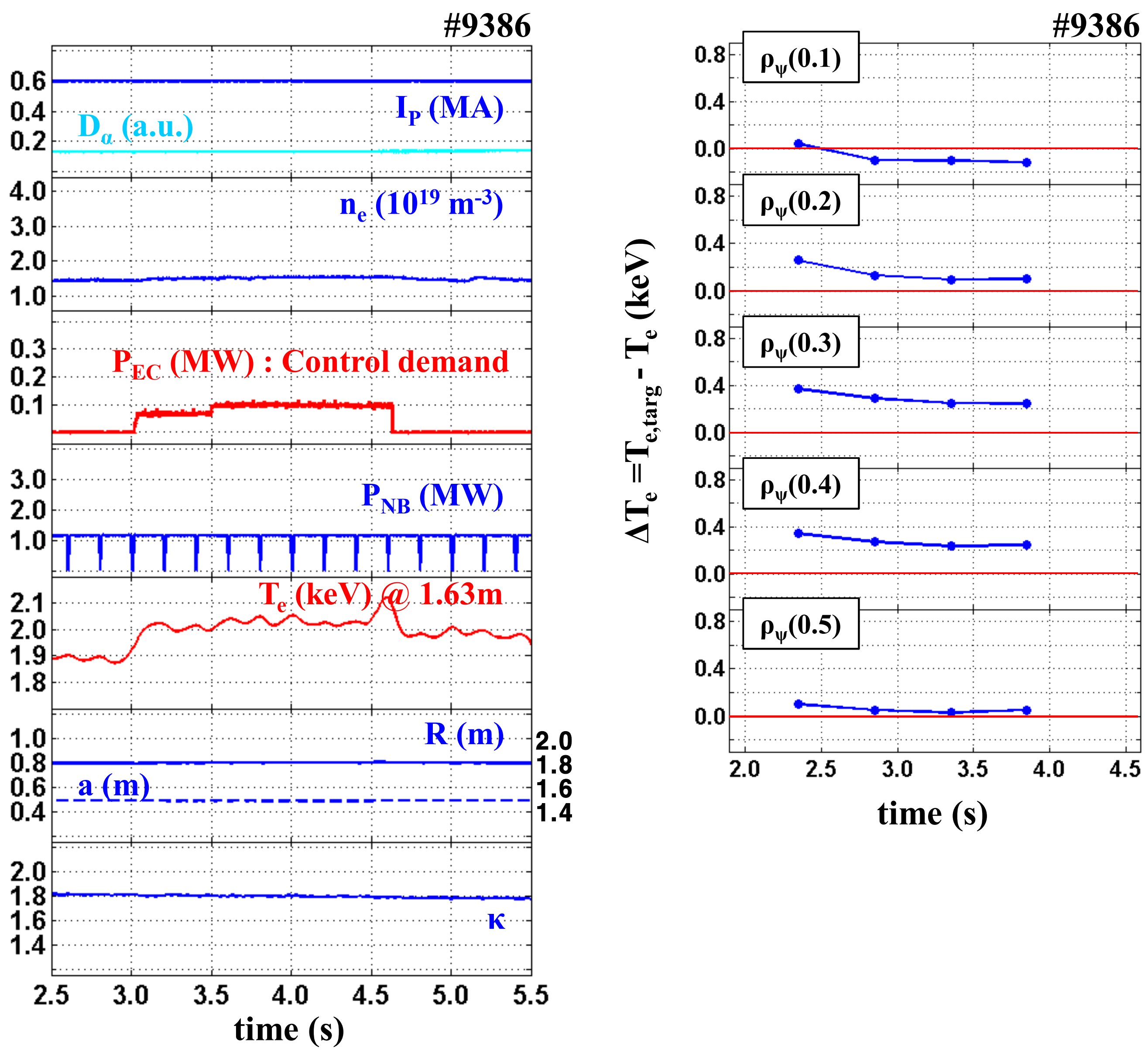


Time delay of first P_{EC} injection





RT-T_e profile control in L-mode discharge (#9386)



References

- *A. C. C. Sips*, Seminars