# Fusion Reactor Technology I
## (459.760, 3 Credits)

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# Contents

# Contents

# Tokamak Operation Scenario

| Plasma Initiation | Current Ramp-up | High Power Phase | Plasma Quench |
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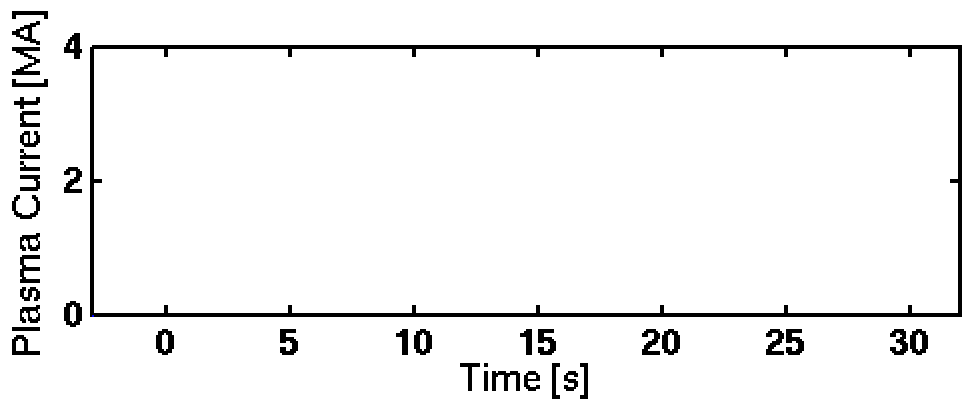
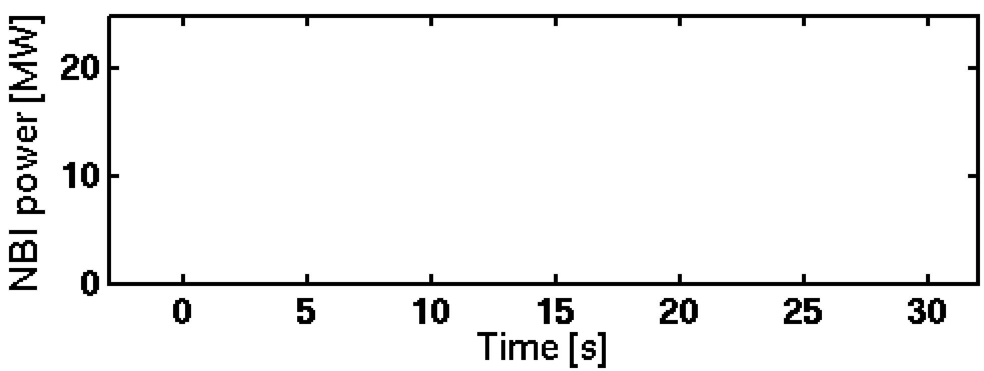
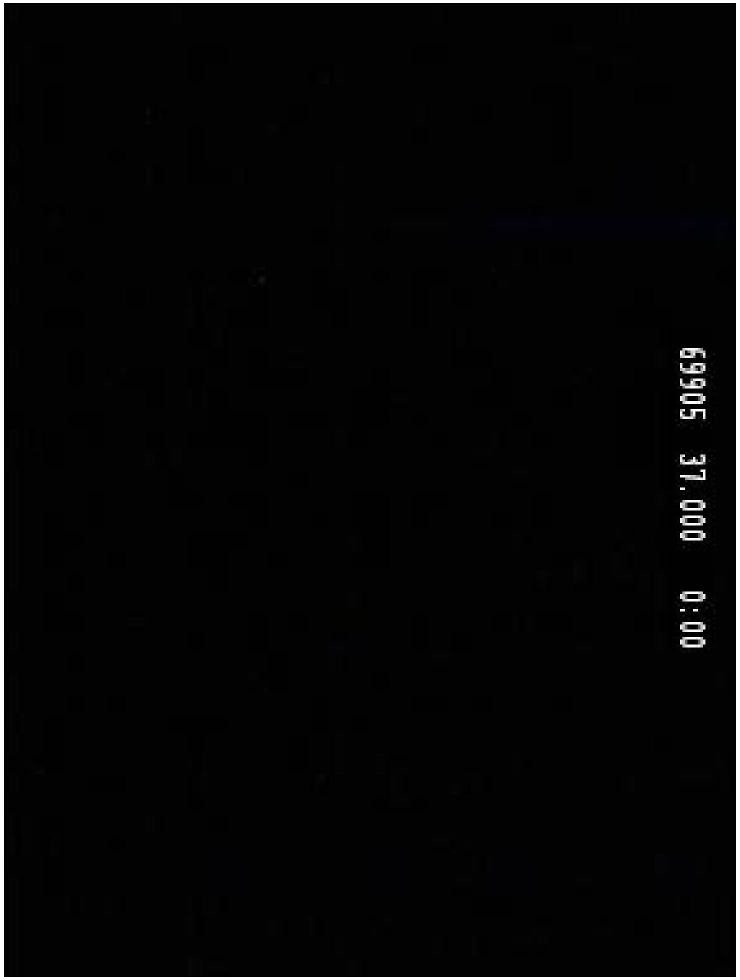


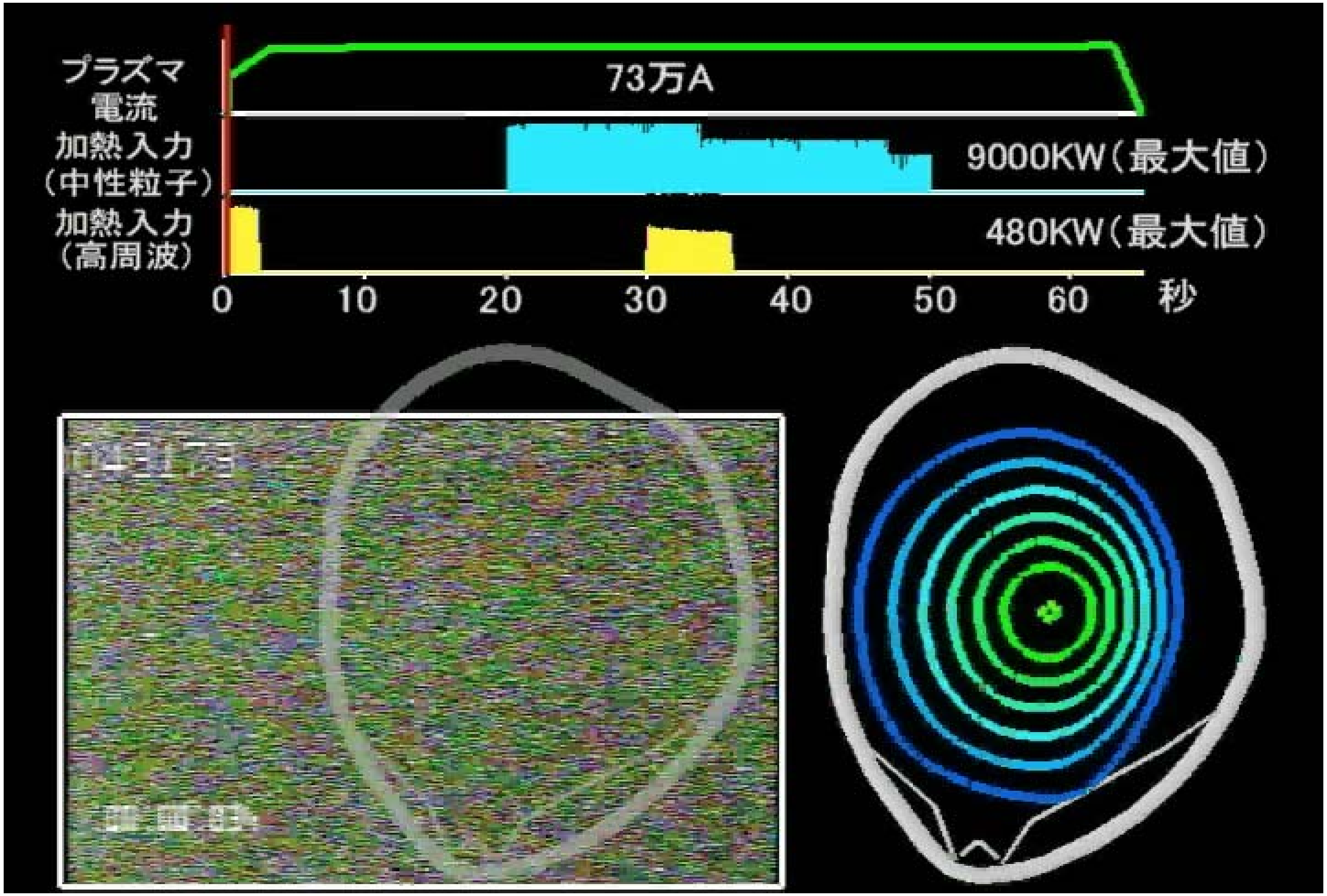




**JET pulse 69905 ($B_T$ = 3.1 T)**



# Tokamak Operation Scenario

JT-60U



# H-mode

- 1982 IAEA F. Wagner et al. (ASDEX, Germany)

- Transition to H-mode: state with reduced turbulence at the plasma edge
- Formation of an edge transport barrier: steep pressure gradient at the edge

**Regime of Improved Confinement and High Beta in Neutral-Beam–Heated Divertor Discharges of the ASDEX Tokamak**

F. Wagner, G. Becker, K. Behringer, D. Campbell, A. Eberhagen, W. Engelhardt, G. Fussmann, O. Gehre, J. Gernhardt, G. v. Gierke, G. Haas, M. Huang,[a] F. Karger, M. Keilhacker, O. Klüber, M. Kornherr, K. Lackner, G. Lisitano, G. G. Lister, H. M. Mayer, D. Meisel, E. R. Müller, H. Murmann, H. Niedermeyer, W. Poschenrieder, H. Rapp, H. Röhr, F. Schneider, G. Siller, E. Speth, A. Stäbler, K. H. Steuer, G. Venus, O. Vollmer, and Z. Yü[a]

*Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-8046 Garching, München, Germany*

(Received 6 August 1982; revised manuscript received 1 October 1982)

A new operational regime has been observed in neutral-injection–heated ASDEX divertor discharges. This regime is characterized by high $\beta_p$ values comparable to the aspect ratio $A$ ($\beta_p \leqslant 0.65A$) and by confinement times close to those of Ohmic discharges. The high-$\beta_p$ regime develops at an injection power $\geqslant 1.9$ MW, a mean density $\bar{n}_e \geqslant 3\times10^{13}$ cm$^{-3}$, and a $q(a)$ value $\geqslant 2.6$. Beyond these limits or in discharges with material limiter, low $\beta_p$ values and reduced particle and energy confinement times are obtained compared to the Ohmic heating phase.

PACS numbers: 52.55.Gb, 52.50.Gj

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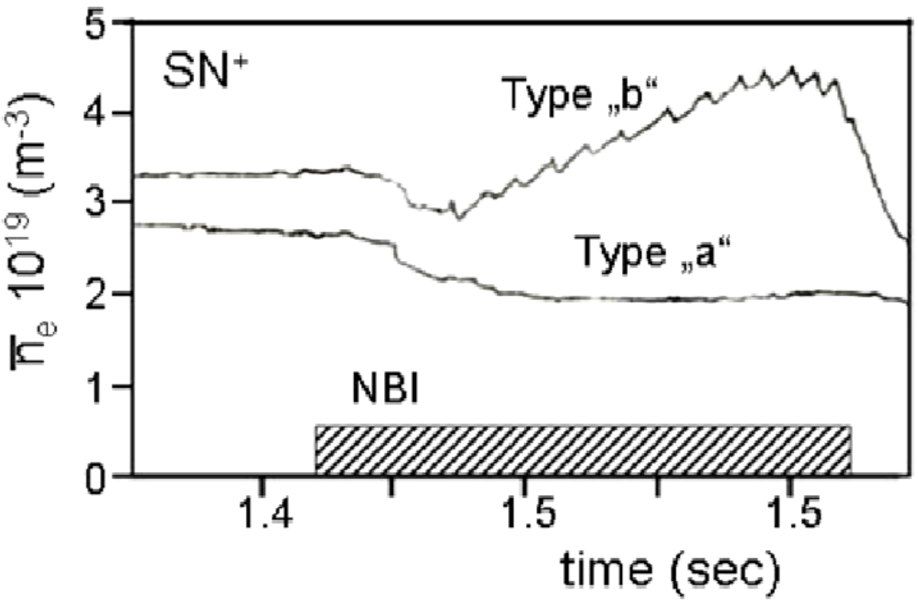
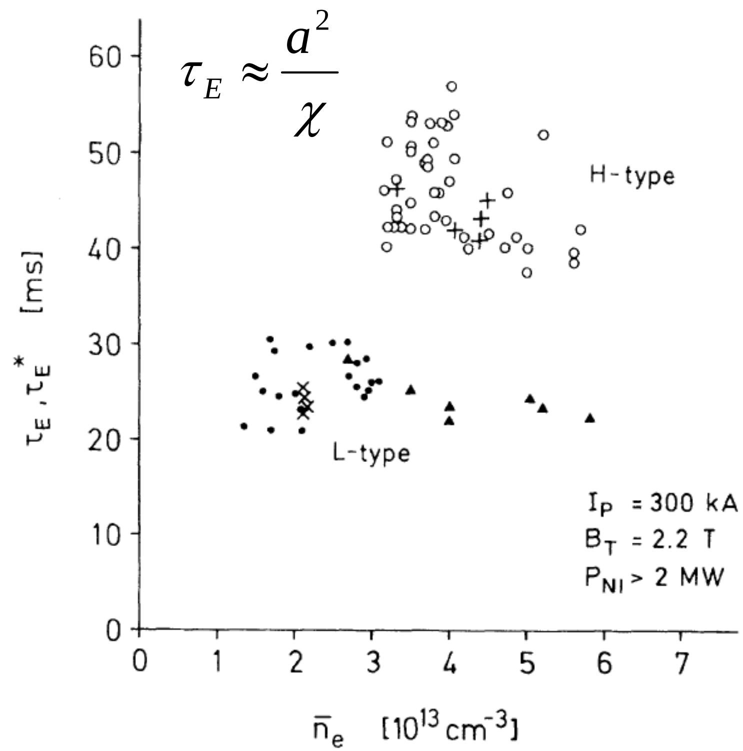
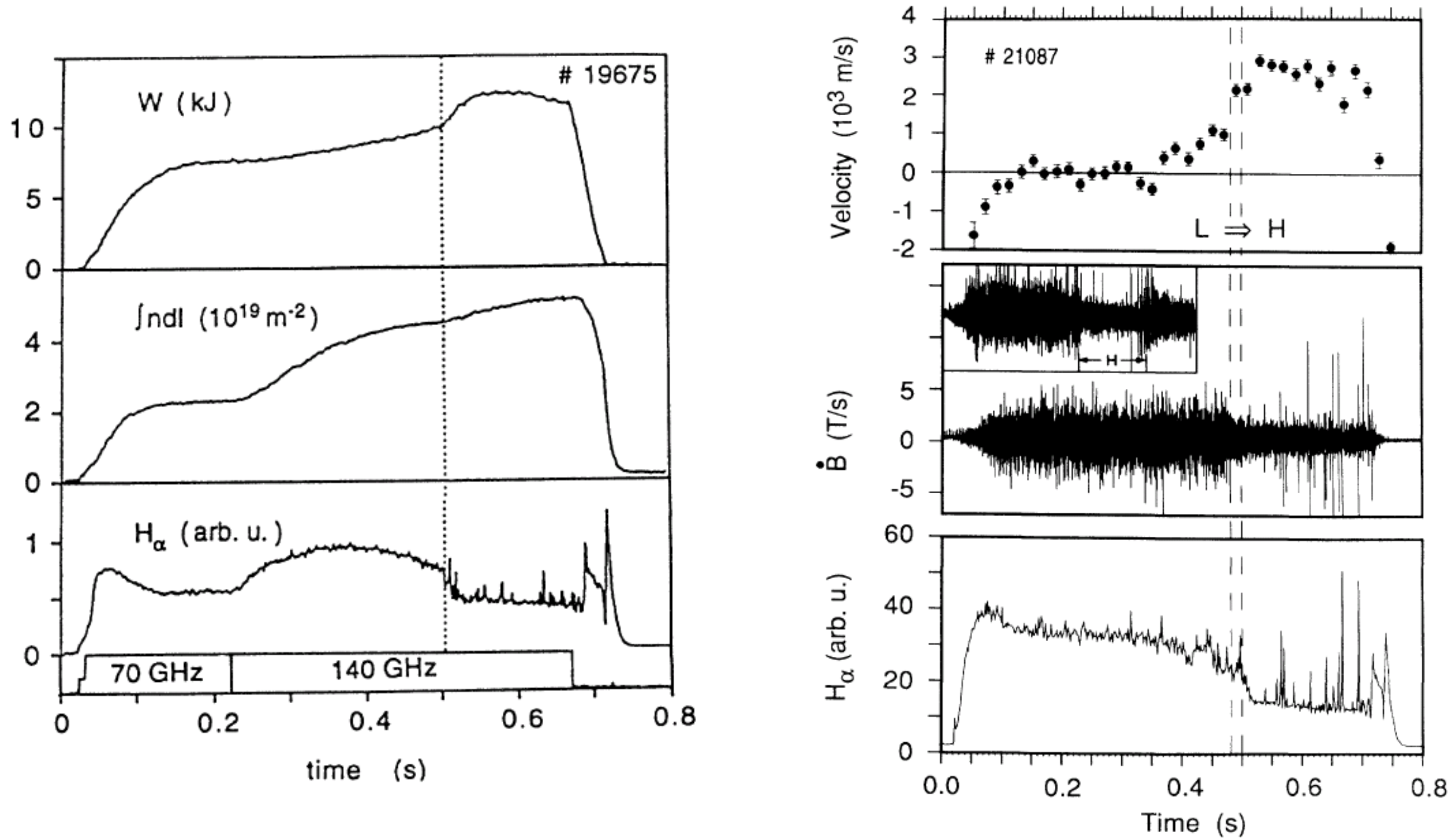


# H-mode

- Established in stellarators as well

Wendelstein 7-AS




*V. Erckmann et al, Physical Review Letters **70** 2086 (1993)*

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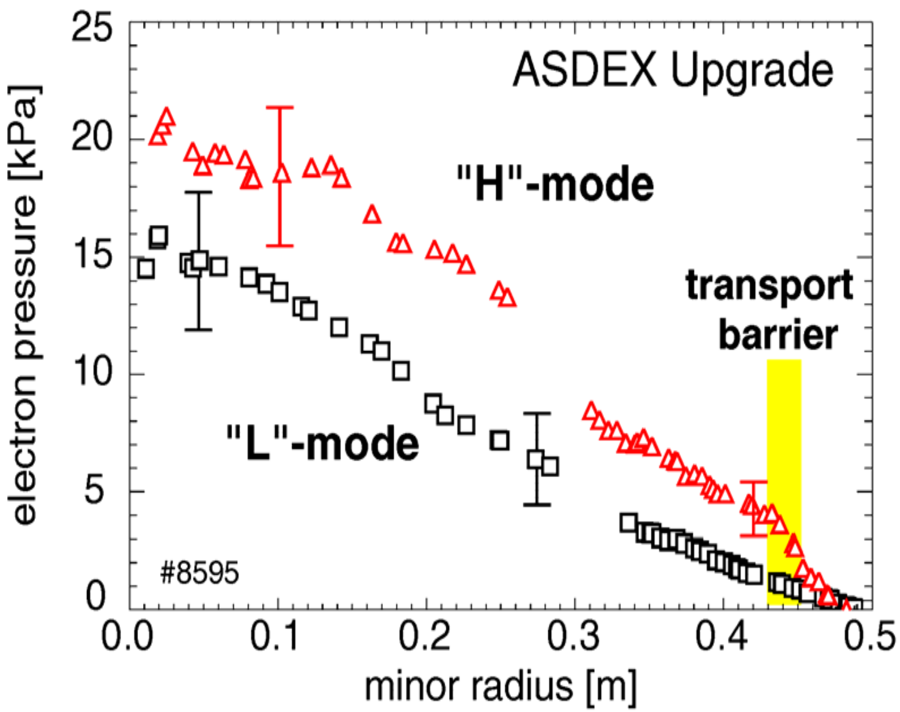
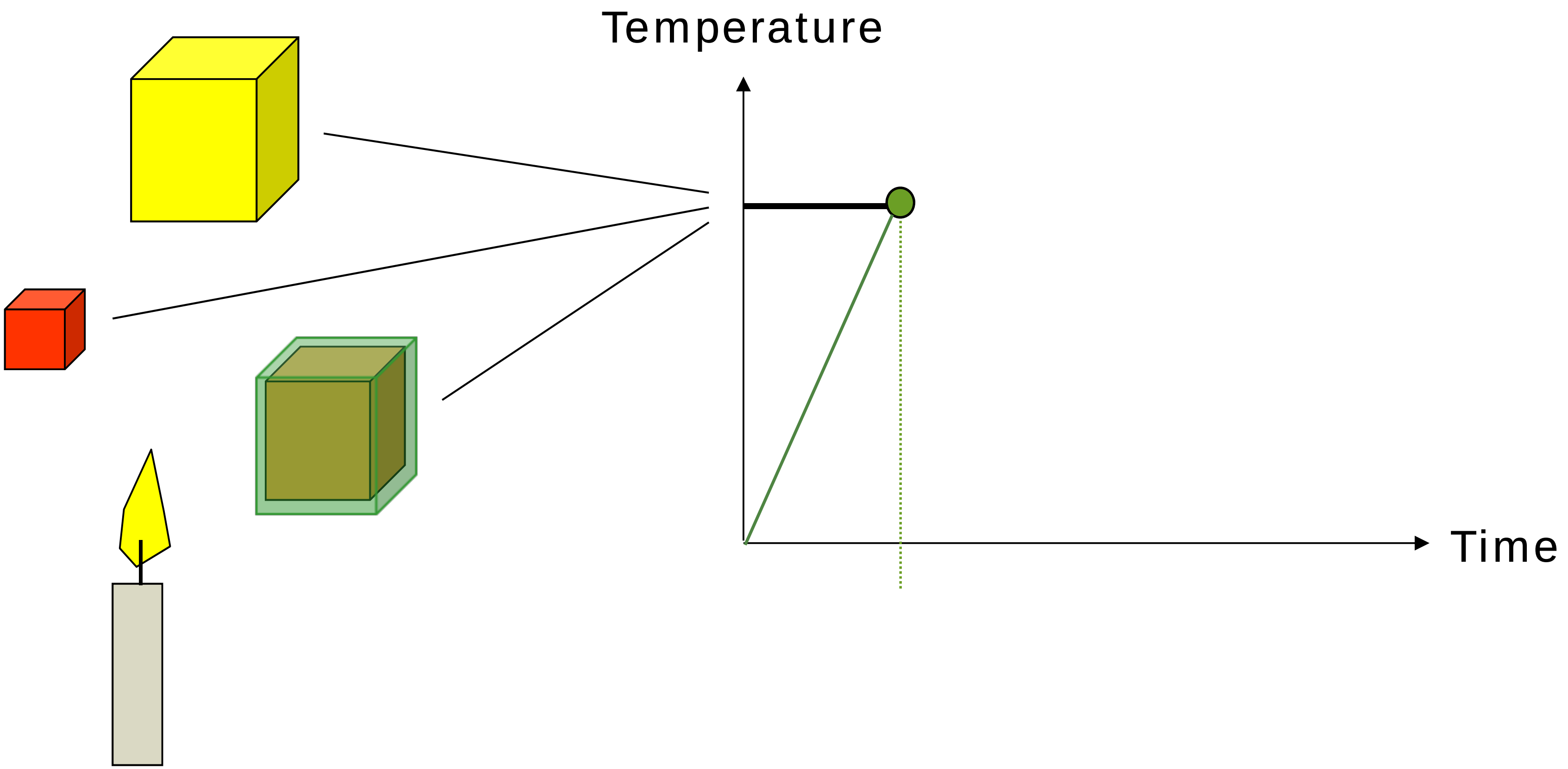



Hoover dam

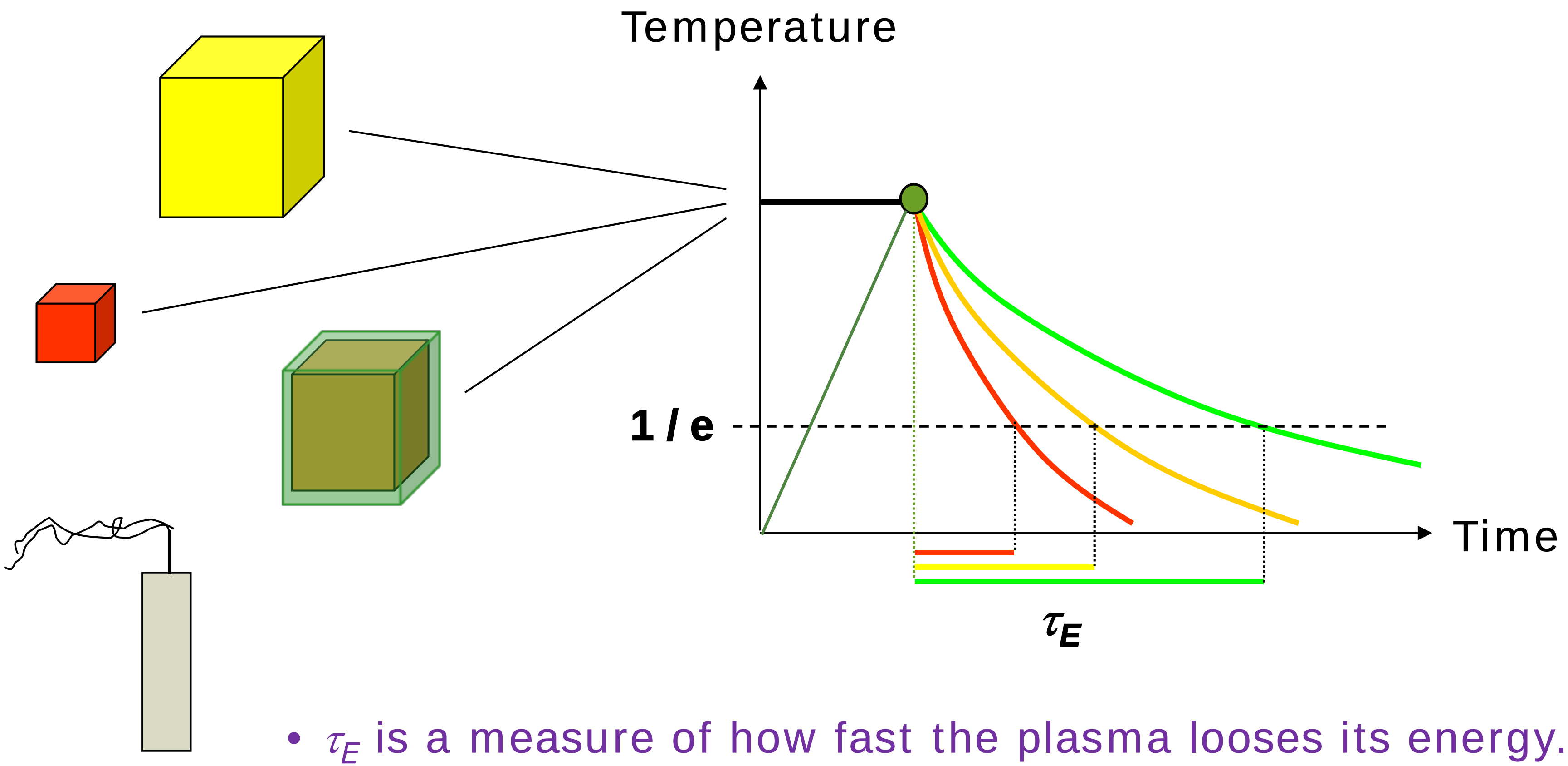
# Basic Tokamak Variables

- **Energy confinement time**



# Basic Tokamak Variables

- **Energy confinement time**




- $\tau_E$ is a measure of how fast the plasma looses its energy.
- The loss rate is smallest, $\tau_E$ largest
  if the fusion plasma is big and well insulated.

# H-mode

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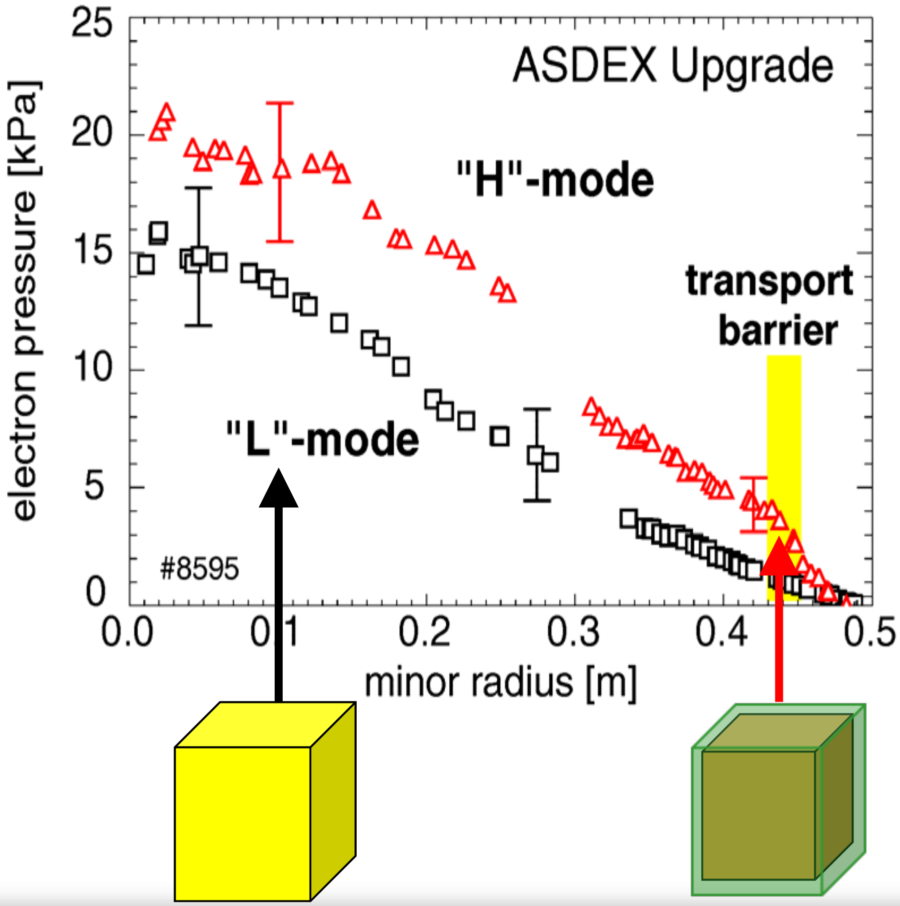
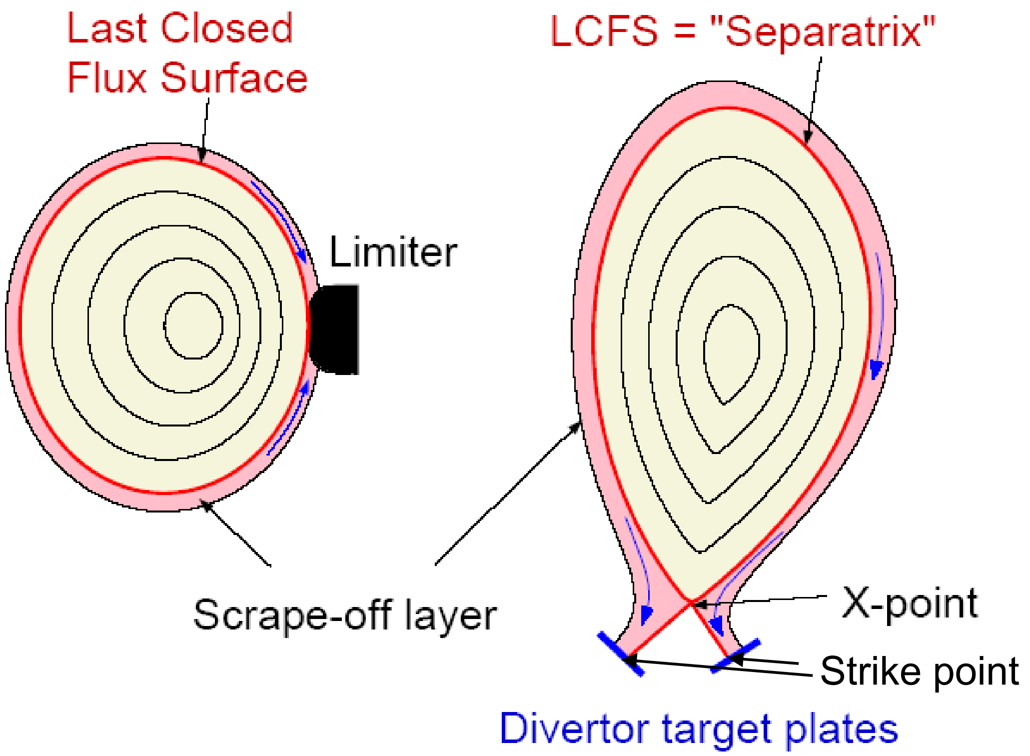



Hoover dam

# H-mode: How to?

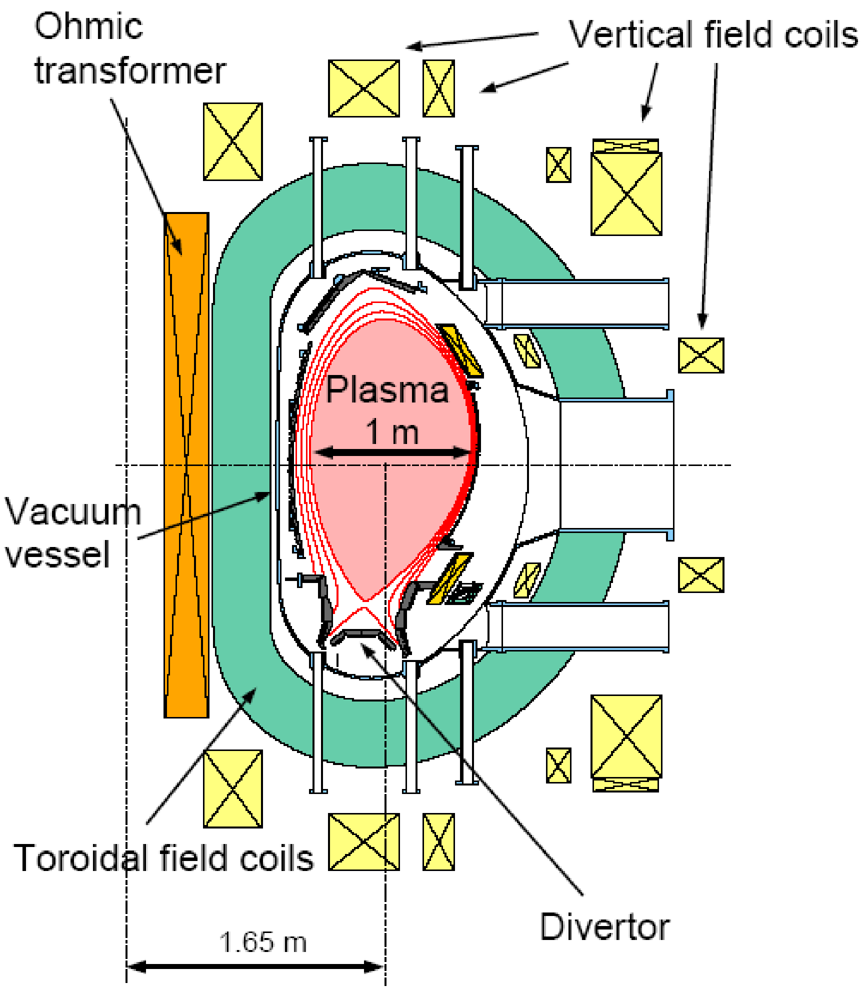
- **Separation of plasma from wall by a limiter and a divertor**



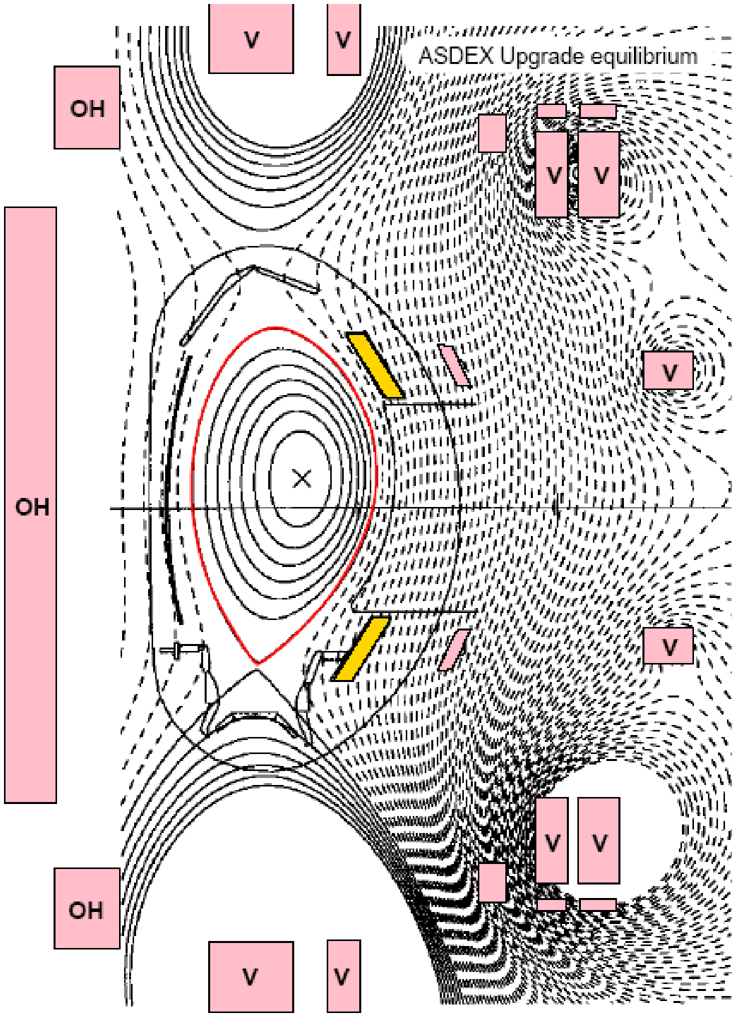

- Advantage of the divertor configuration

- First contact with material surface at a distance from plasma boundary
- Reducing the influx of ionized impurities into the interior of the plasma by diverting them into an outer „SOL“

# Tokamak

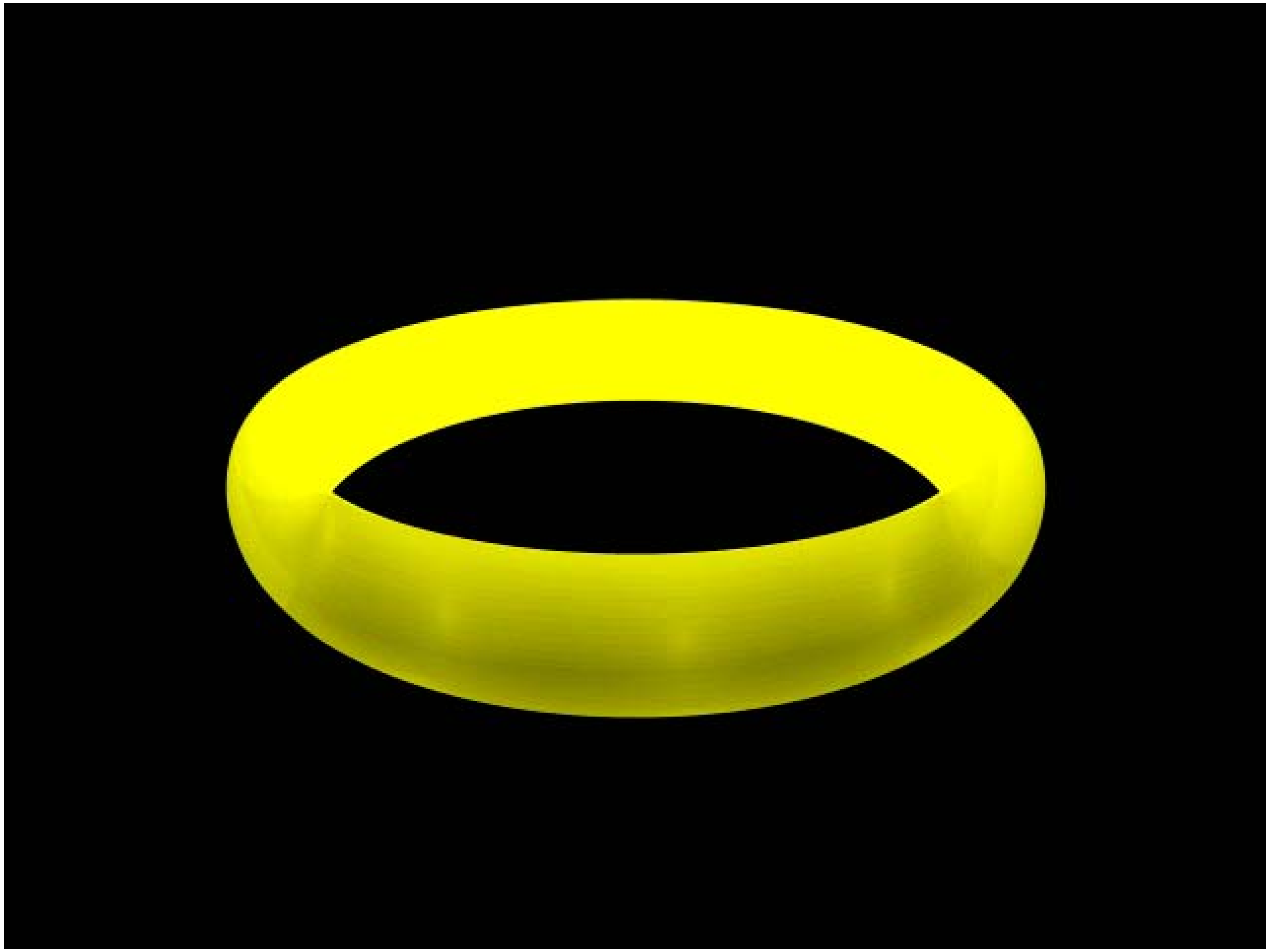


Ohmic transformer
Vertical field coils
Plasma
1 m
Vacuum vessel
Toroidal field coils
Divertor
1.65 m

ASDEX Upgrade equilibrium
OH
V

# H-mode: How to?

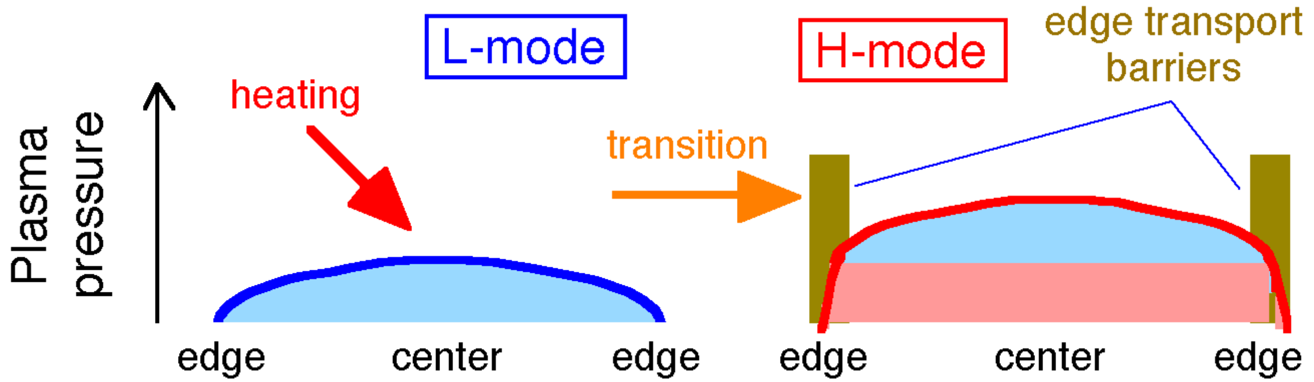


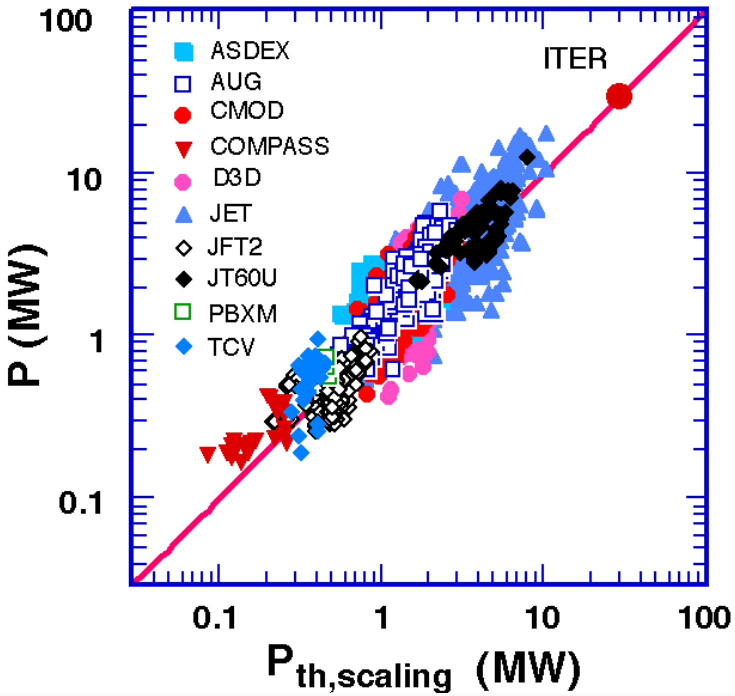
# H-mode: How to?

KSTAR

- Role of wall condition

# H-mode: How to?




$$P_{th} = 2.84 M^{-1} B_t^{0.82} n_{20}^{0.58} R^{1.0} a^{0.81}$$

# H-mode: Why?

- 1982 IAEA F. Wagner et al. (ASDEX, Germany)

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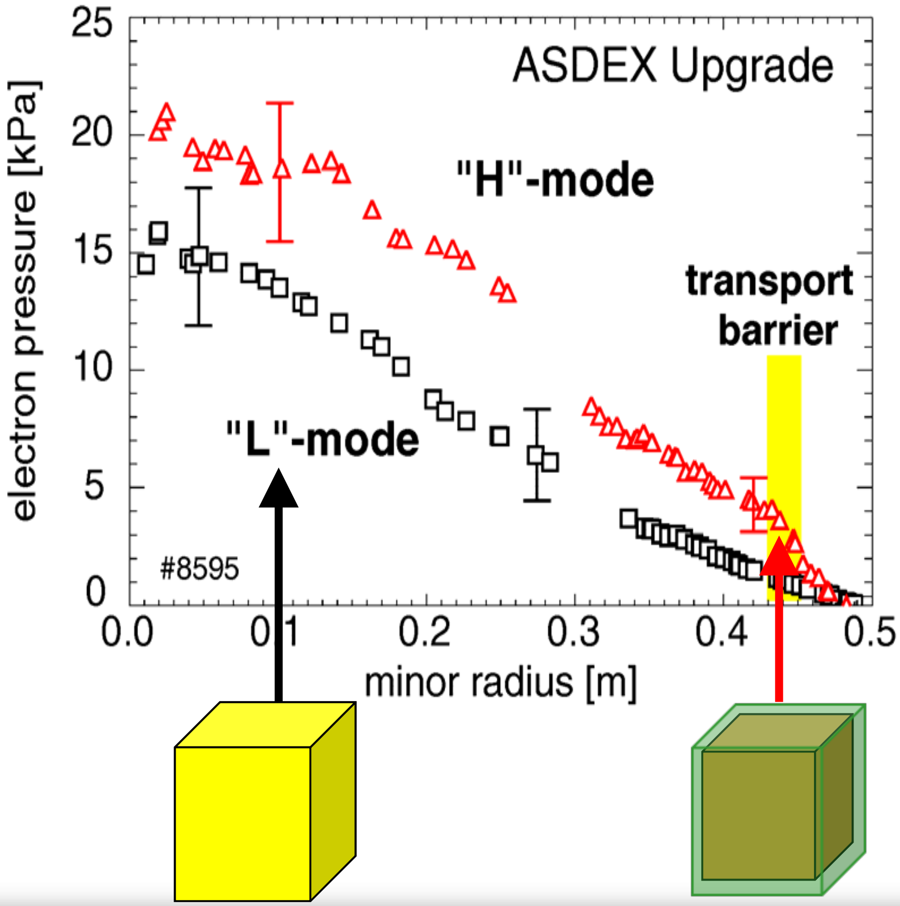
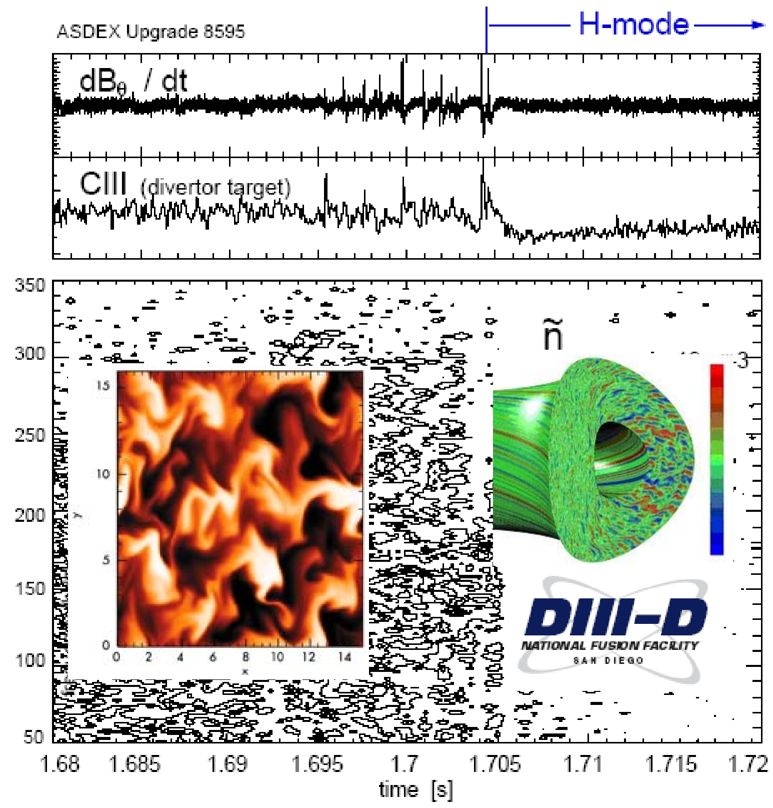


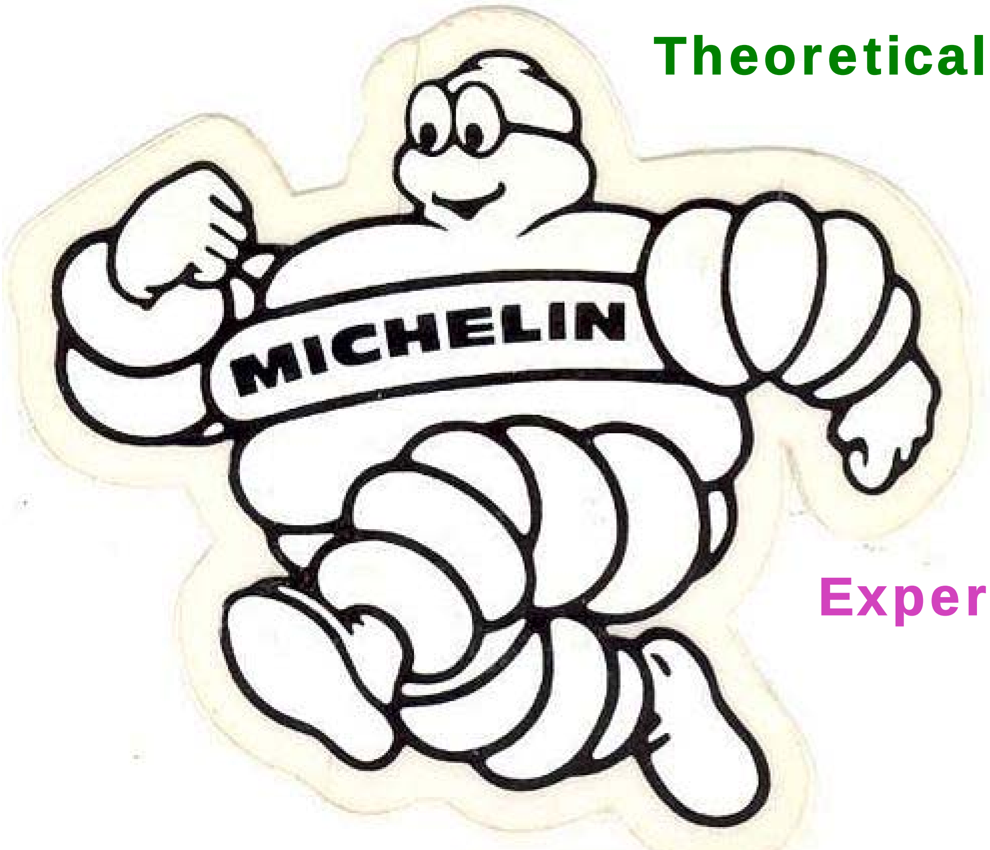



# H-mode: Why?

**Theoretical physics**

# H-mode: Why?

Theoretical physics

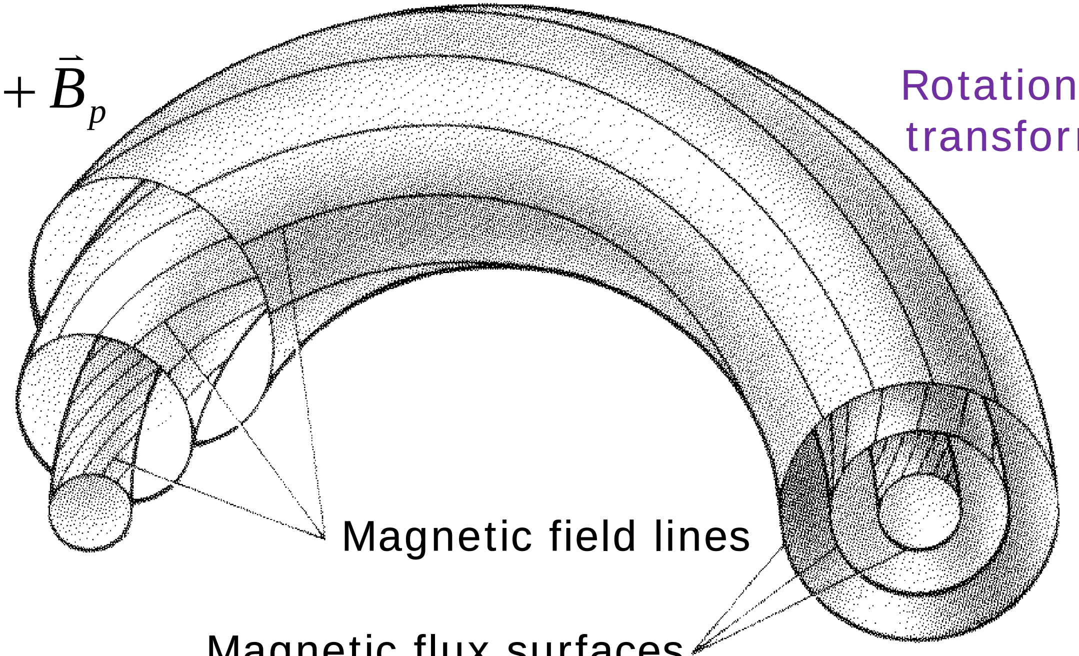



Experimental physics

# Basic Tokamak Variables

- **Safety factor *q* = number of toroidal orbits per poloidal orbit**

$$\vec{B} = \vec{B}_\phi + \vec{B}_p$$




Rotational transform

$$\iota = \frac{\Delta\theta}{\frac{\Delta\phi}{2\pi}} = \frac{\frac{B_\theta}{r}}{\frac{B_\phi}{2\pi R}}$$

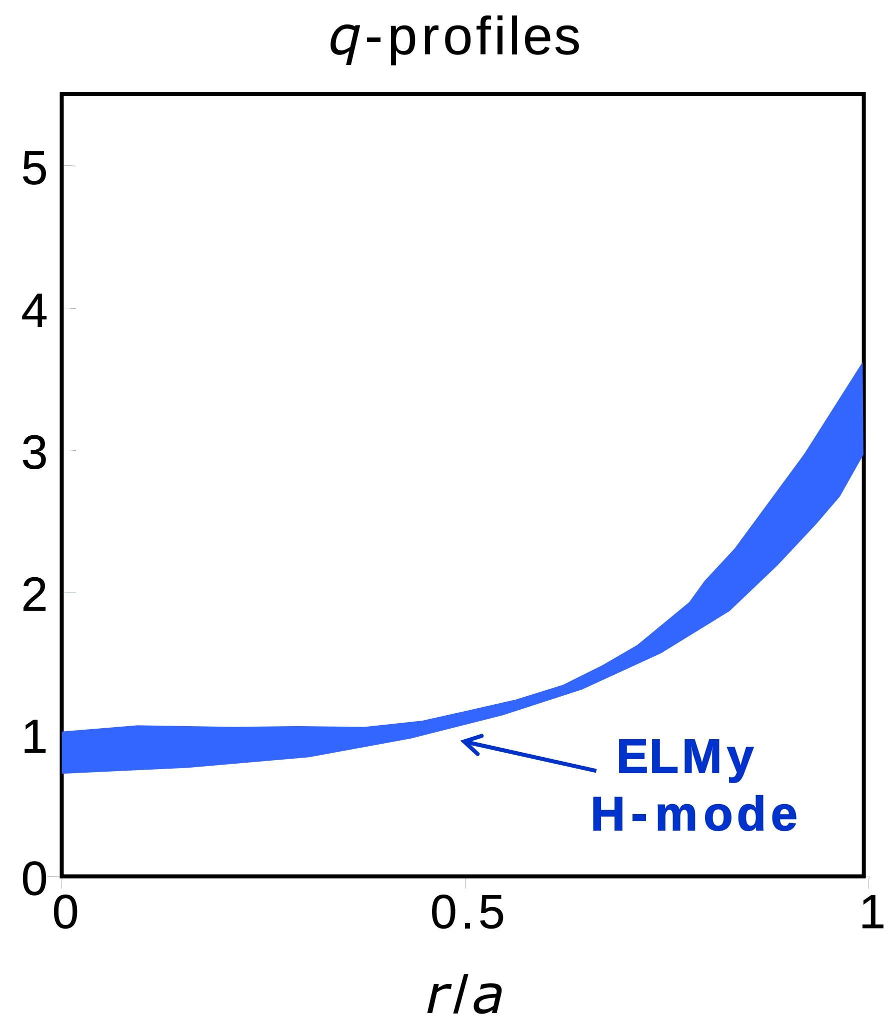
$\Delta\theta$ ?
when $\Delta\Phi = 2\pi$

$$\frac{Rd\phi}{B_\phi} = \frac{rd\theta}{B_\theta}$$

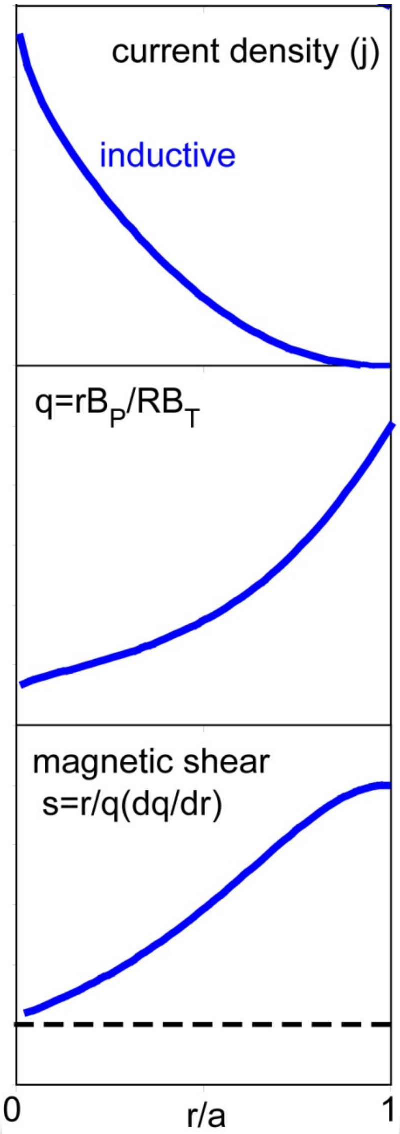
- The effect of the twisted magnetic field lines–each of which completely traces out a magnetic flux surface by its revolutions around the toroidal and poloidal axes–is to create a system of nested toroidal flux surfaces which guide ion motion.

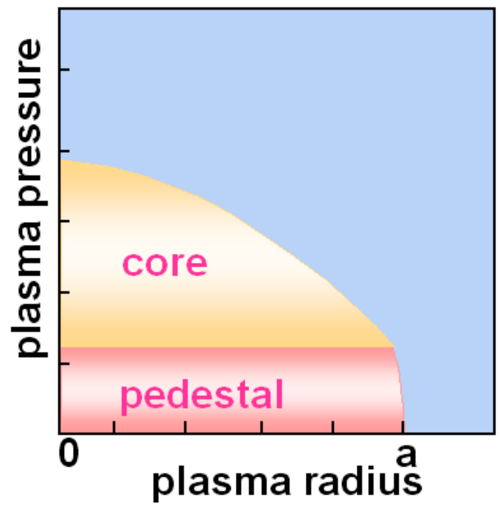
$$q = \frac{\text{number of toroidal windings}}{\text{number of poloidal windings}} = \frac{2\pi}{\iota} = \frac{r}{R}\frac{B_\phi}{B_\theta}$$

# Tokamak Operation Modes



# Conventional Operation Mode – H-mode

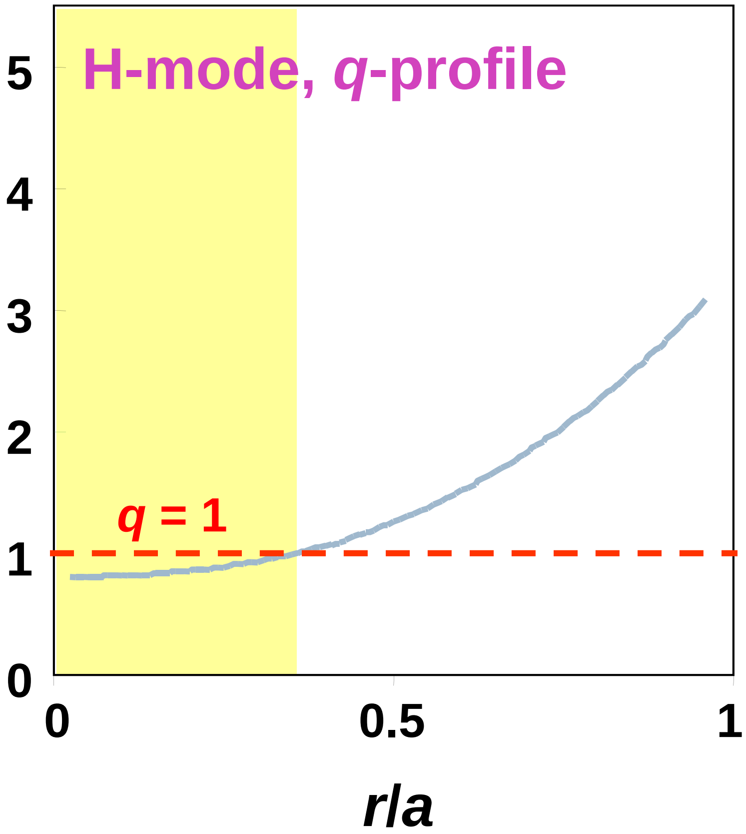



- Mild pressure gradient with steep edge pedestal
- Naturally peaked current profile
- Monotonic *q*-profile
- Positive magnetic shear

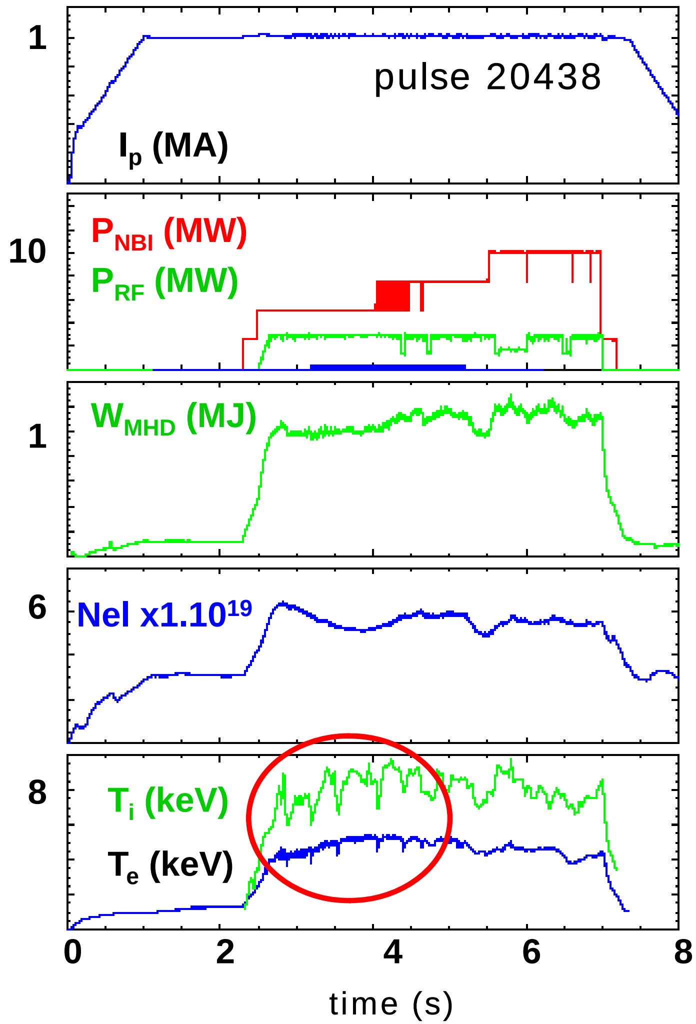
# H–mode: Limitations

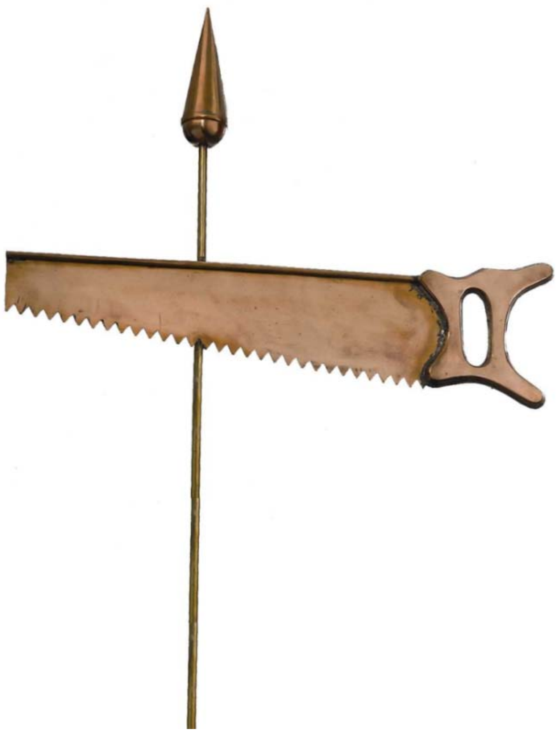
Stability of H-mode plasmas related safety factor profile: $q(r)$




$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

# Sawtooth



- nonlinear low-*n* internal mode
- internal (minor) disruption
- enhanced energy transport in the plasma centre

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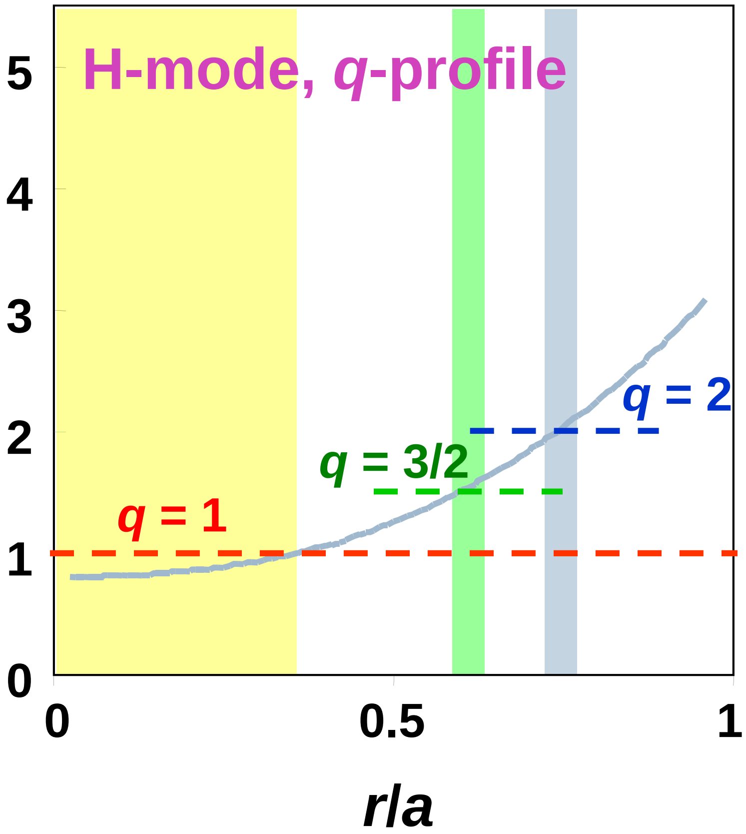



$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

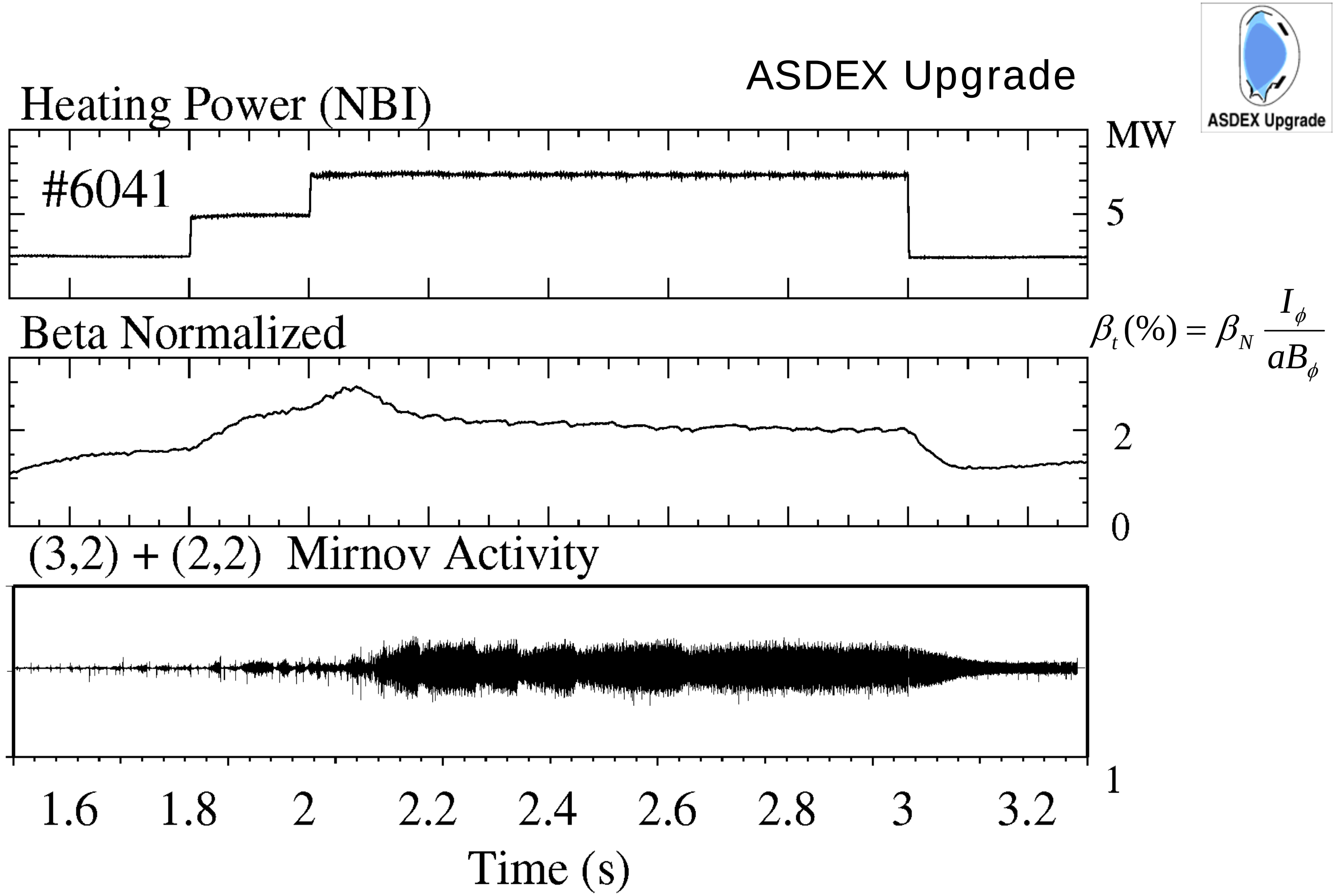
$q = 3/2$ and $q = 2$:

Neoclassical Tearing Modes (NTMs):

- limit the achievable $\beta \equiv 2\mu_0 p/B^2$
- degrade confinement (+ disruptions)
- often triggered by sawteeth.

- ITER work point is chosen conservatively: $\beta_N \leq 1.8$ !

# Neoclassical Tearing Mode (NTM)



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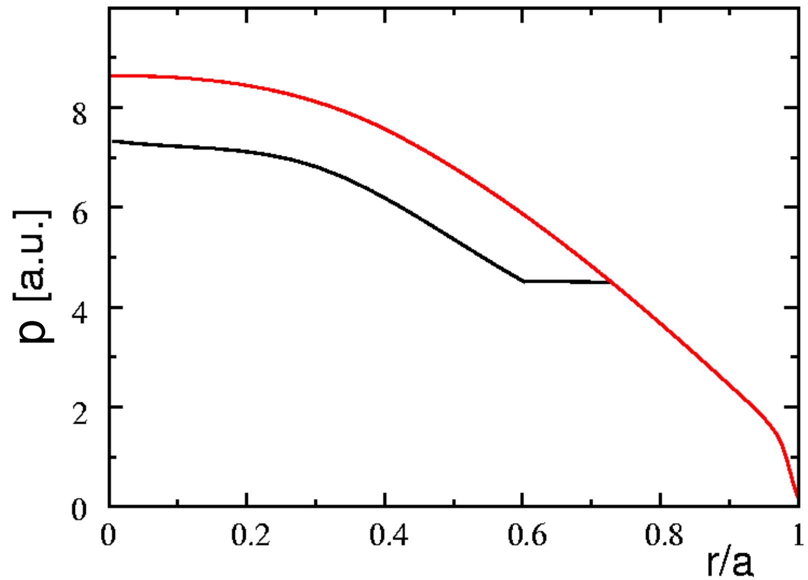


- Pressure flattening across magnetic islands due to large transport coefficients along magnetic field lines

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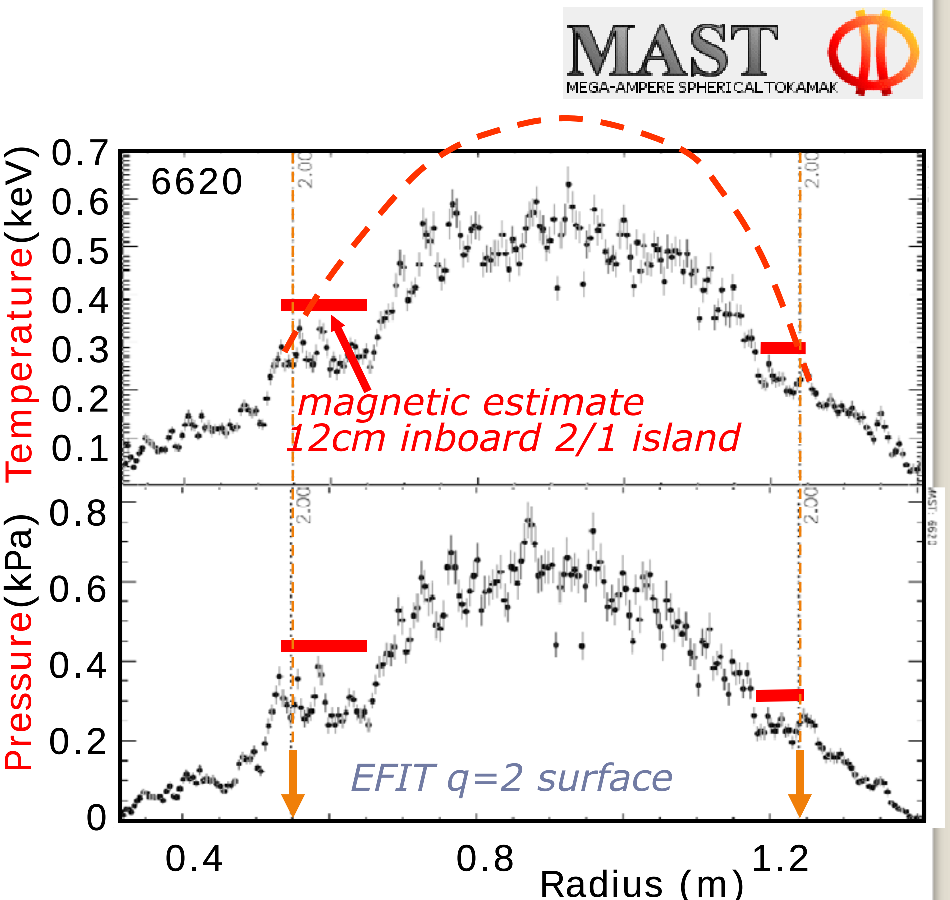


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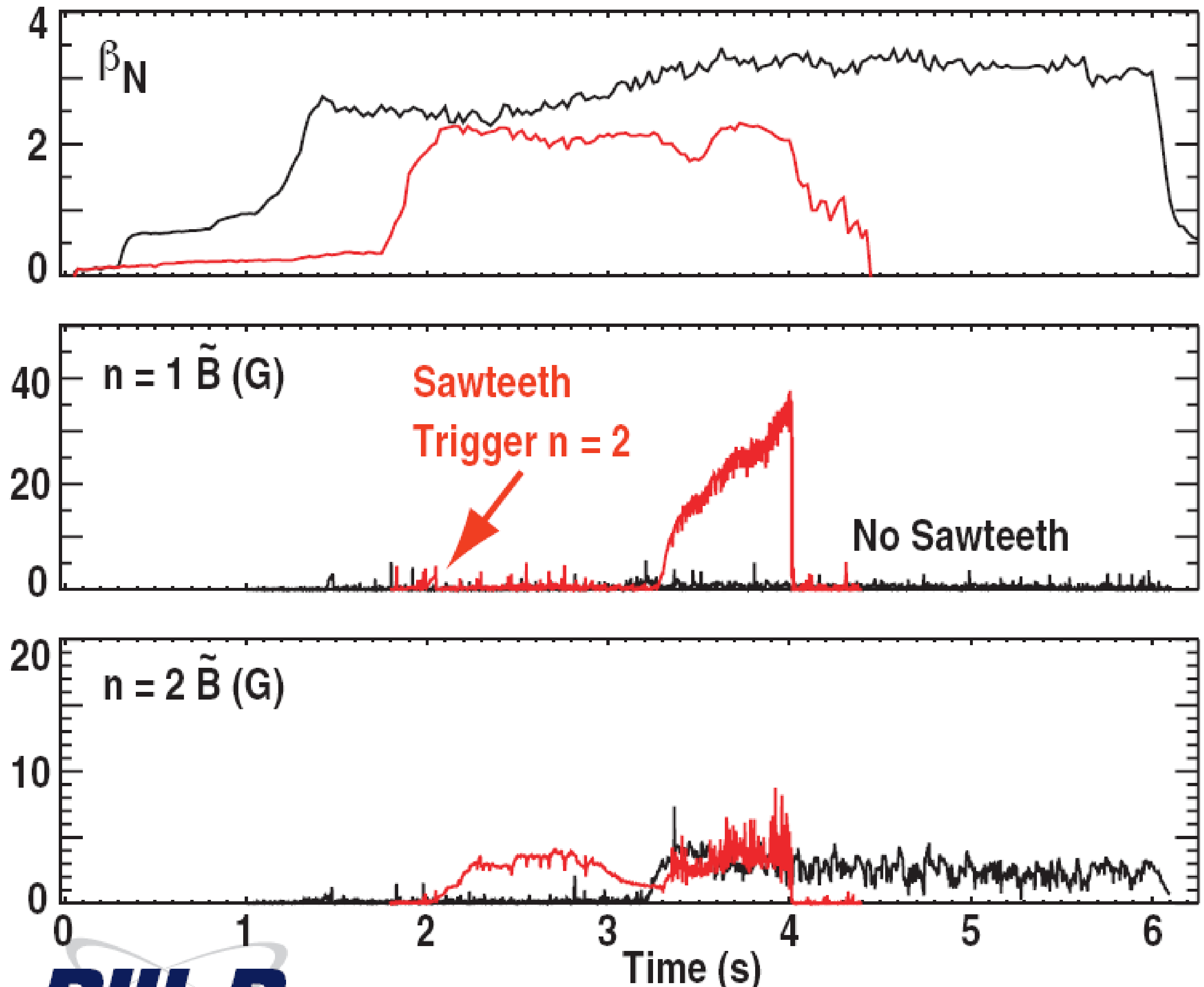


DIII-D
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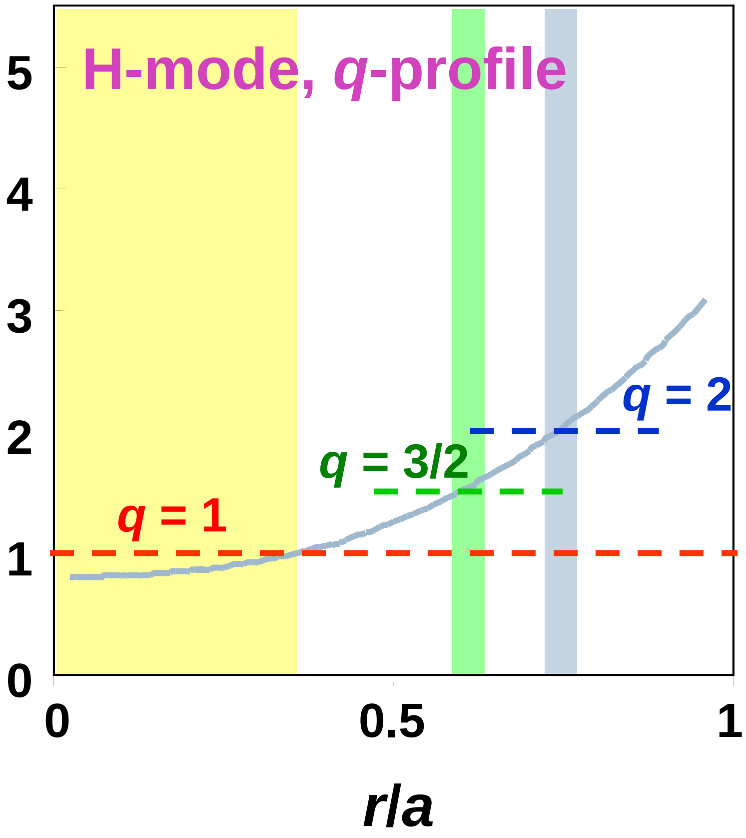
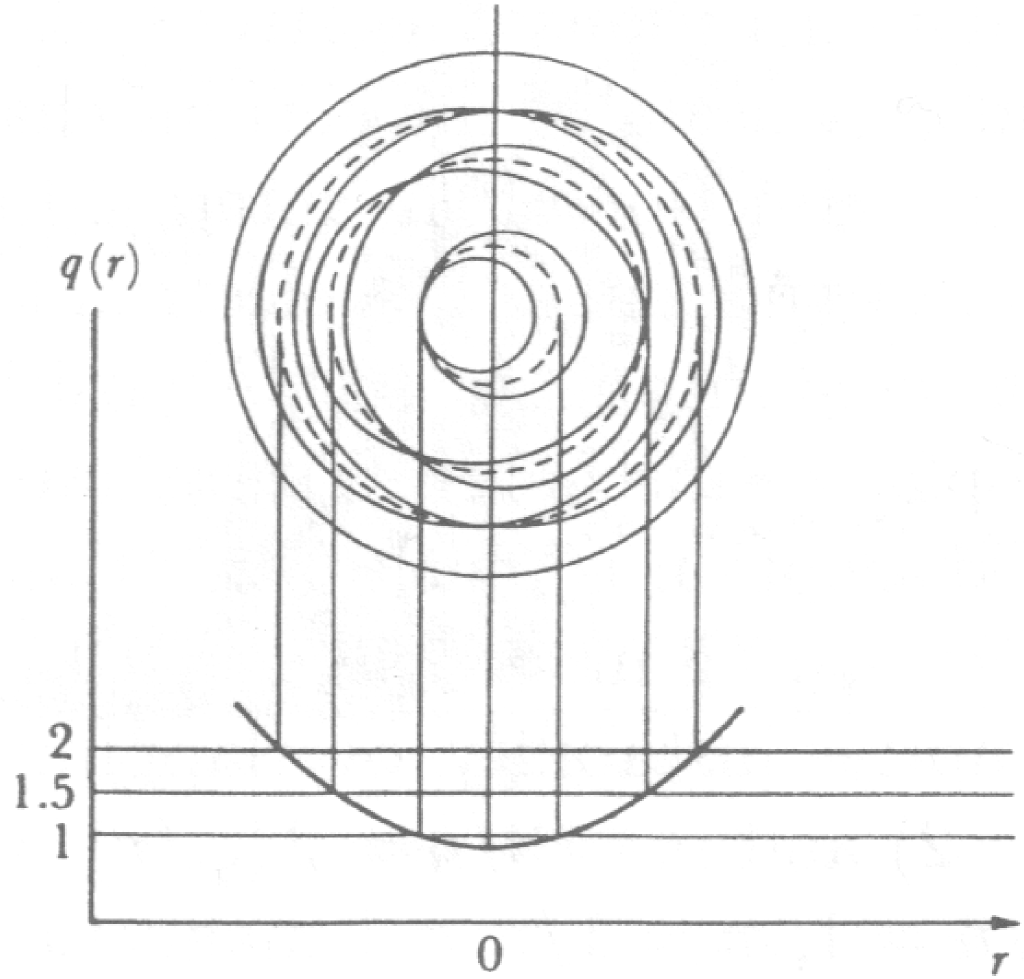
SAN DIEGO

# H-mode: Limitations

Stability of H-mode plasmas related safety factor profile: $q(r)$

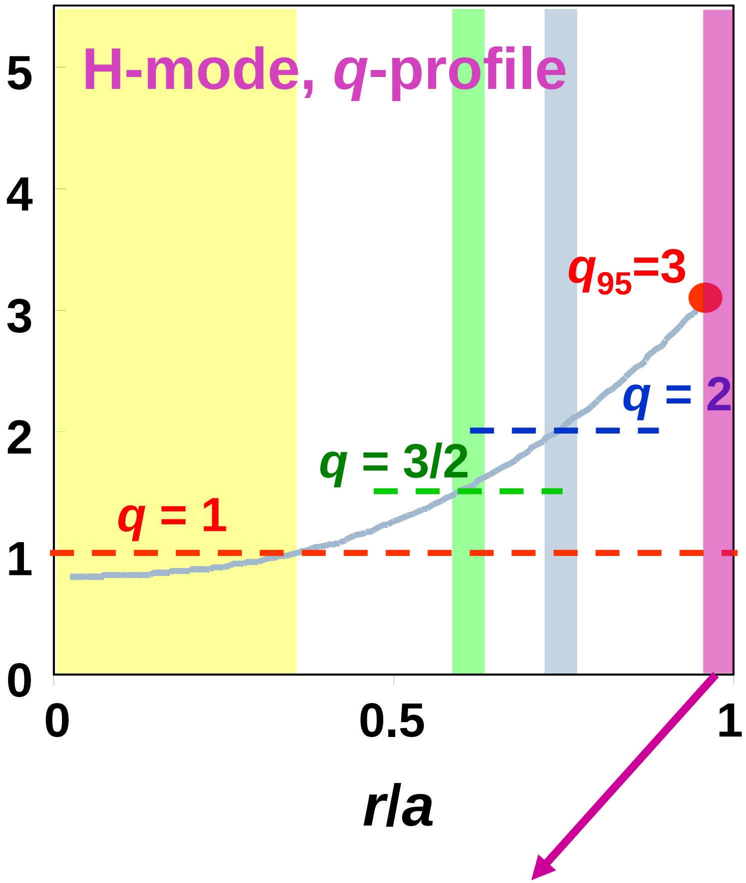



*K. Miyamoto, "Controlled Fusion and Plasma Physics" Taylor & Francis (2007)*

# H–mode: Limitations

Stability of H-mode plasmas related safety factor profile: $q(r)$




Periodic collapses of the ETB (ELMs)

$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

$q = 3/2$ and $q = 2$:

Neoclassical Tearing Modes (NTMs):

- limit the achievable $\beta \equiv 2\mu_0 p/B^2$
- degrade confinement (+ disruptions)
- often triggered by sawteeth.

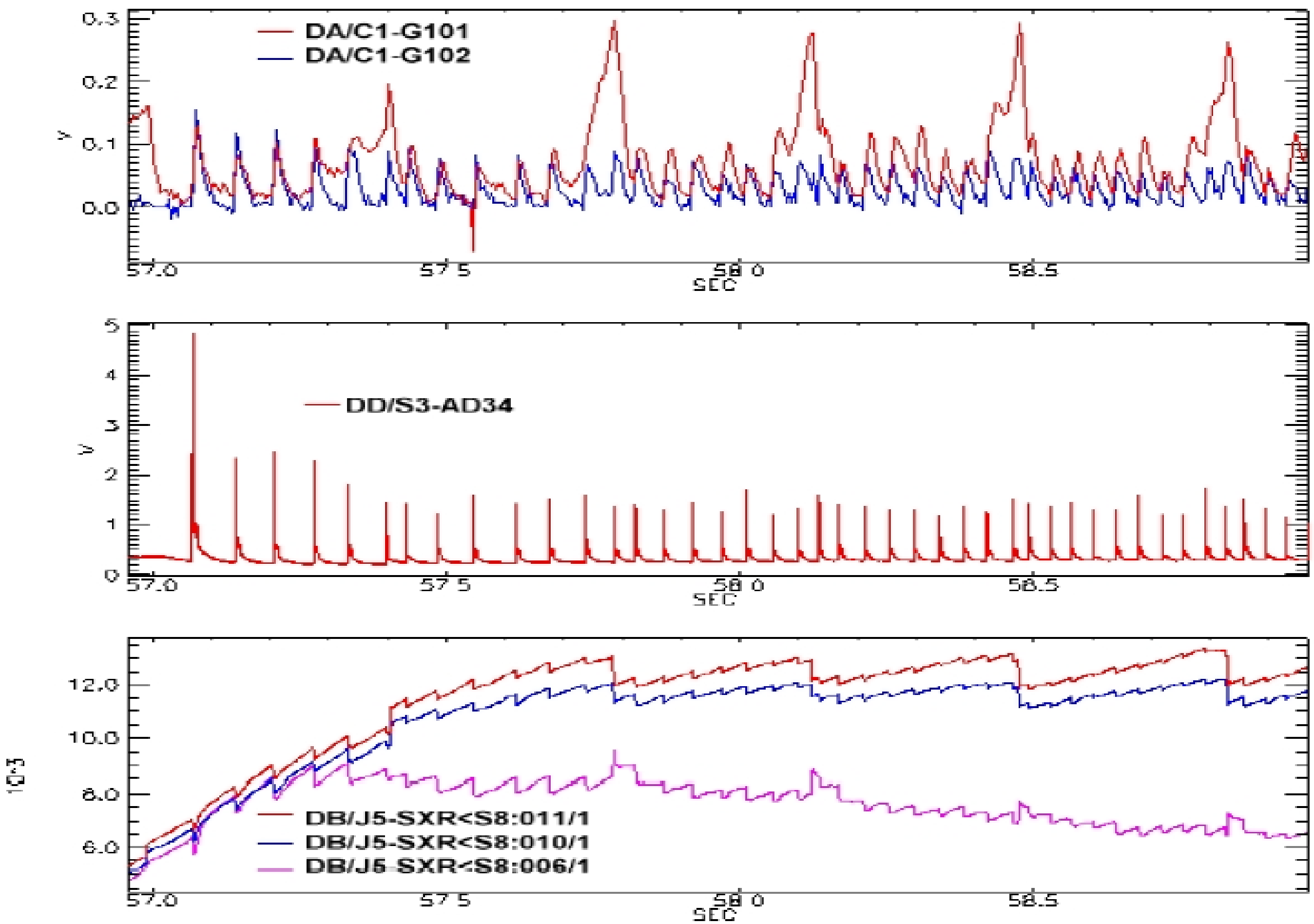
> • ITER work point is chosen conservatively: $\beta_N \leq 1.8$ !

$q_{95}$ ($\propto 1/I_p$) = 3: Safe operation at max. $I_P$

# Edge Localised Mode (ELM)

- Example of sawteeth and ELMs

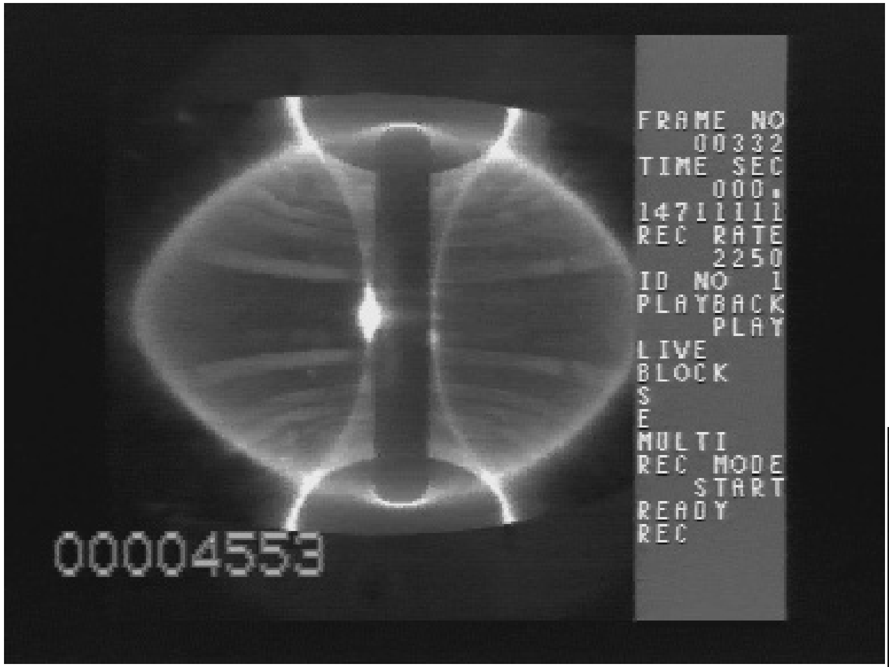
JET, Pulse 52022




EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

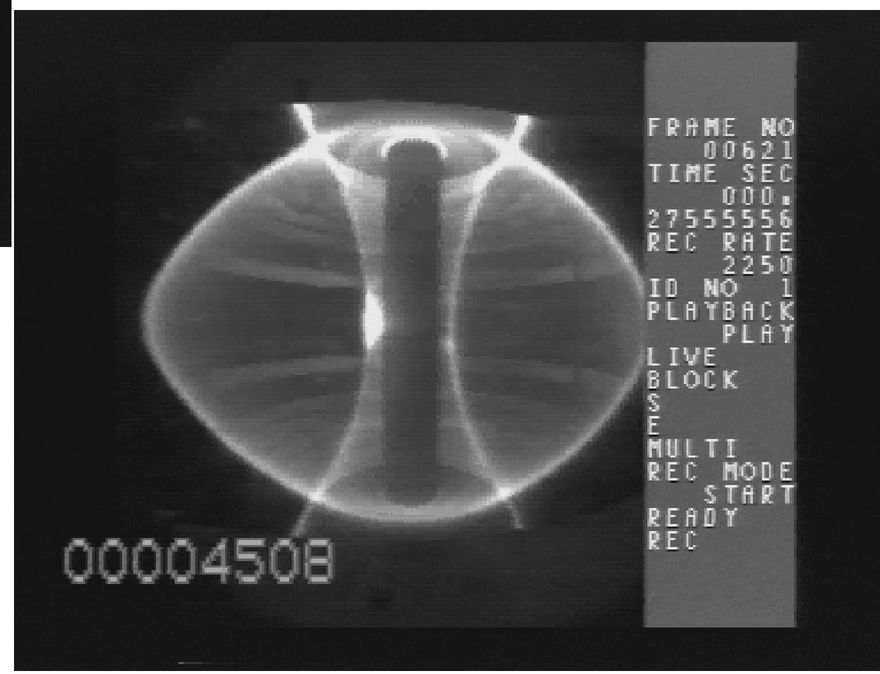
# Edge Localised Mode (ELM)

MAST
MEGA-AMPERE SPHERICAL TOKAMAK

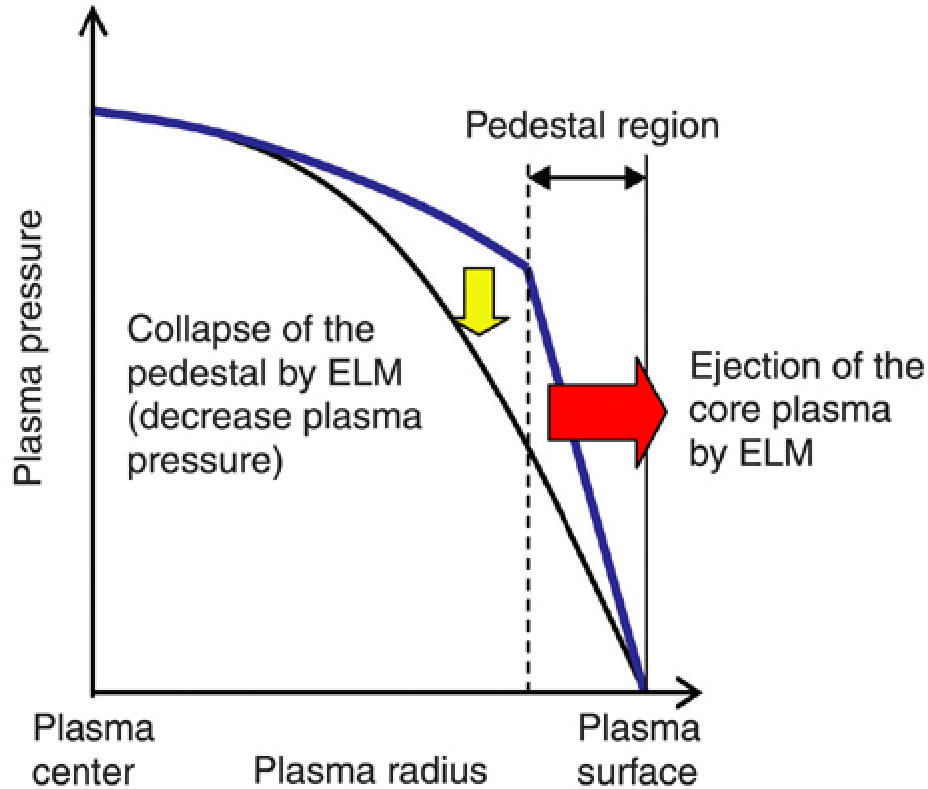



Edge Localised Mode

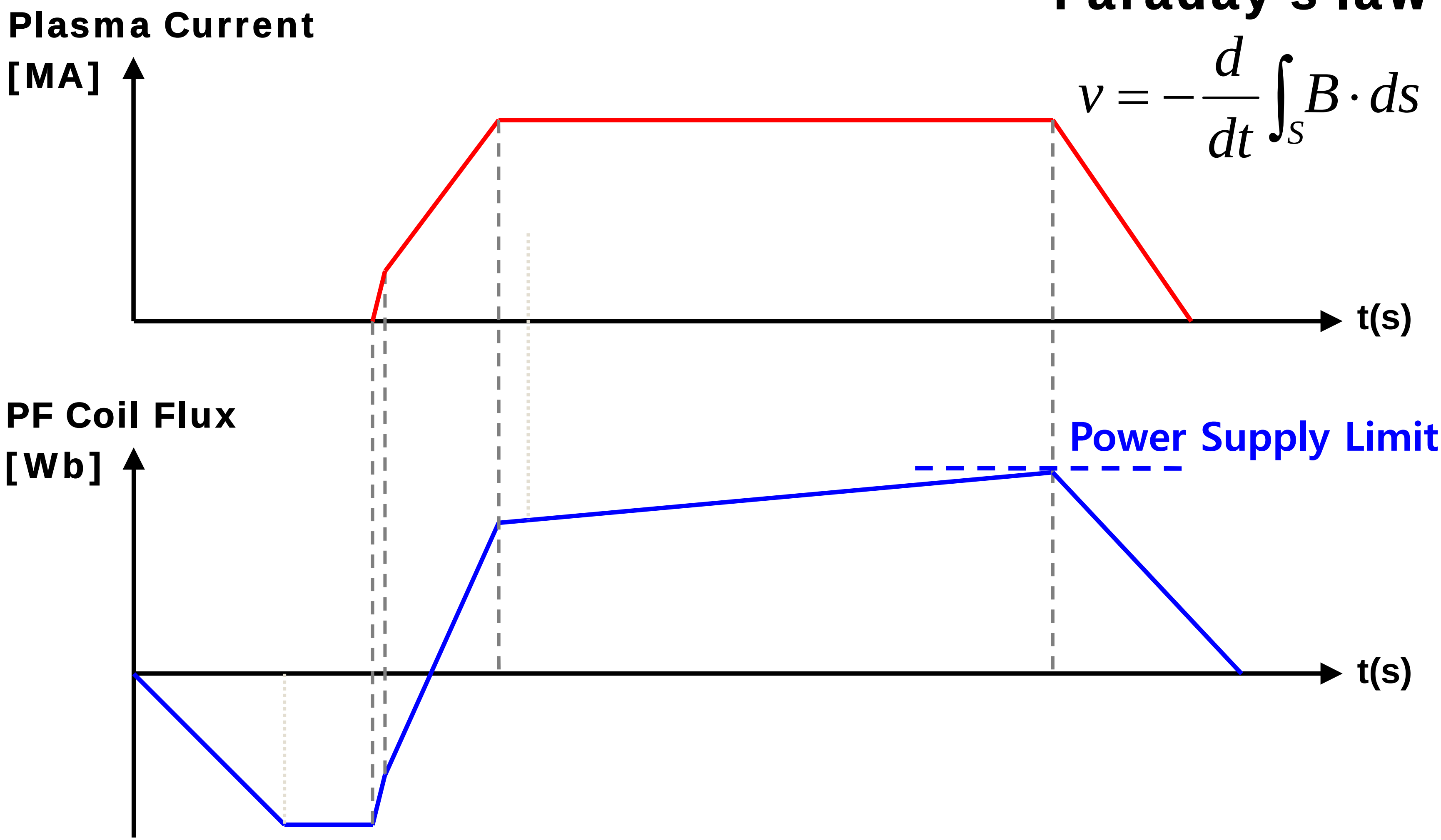
Disruption



# Edge Localised Mode (ELM)



# H-mode: Limitation




**Faraday's law**

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

**Inherent drawback of Tokamak!**