Fusion Reactor Technology I

(459.760, 3 Credits)

Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

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Contents

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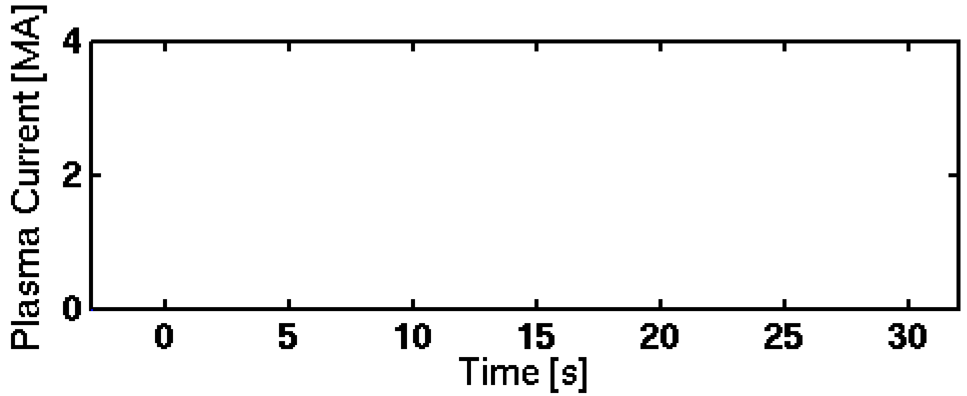
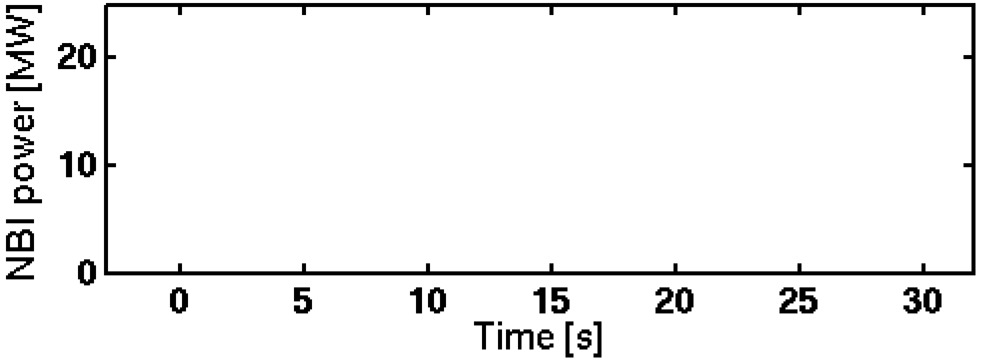
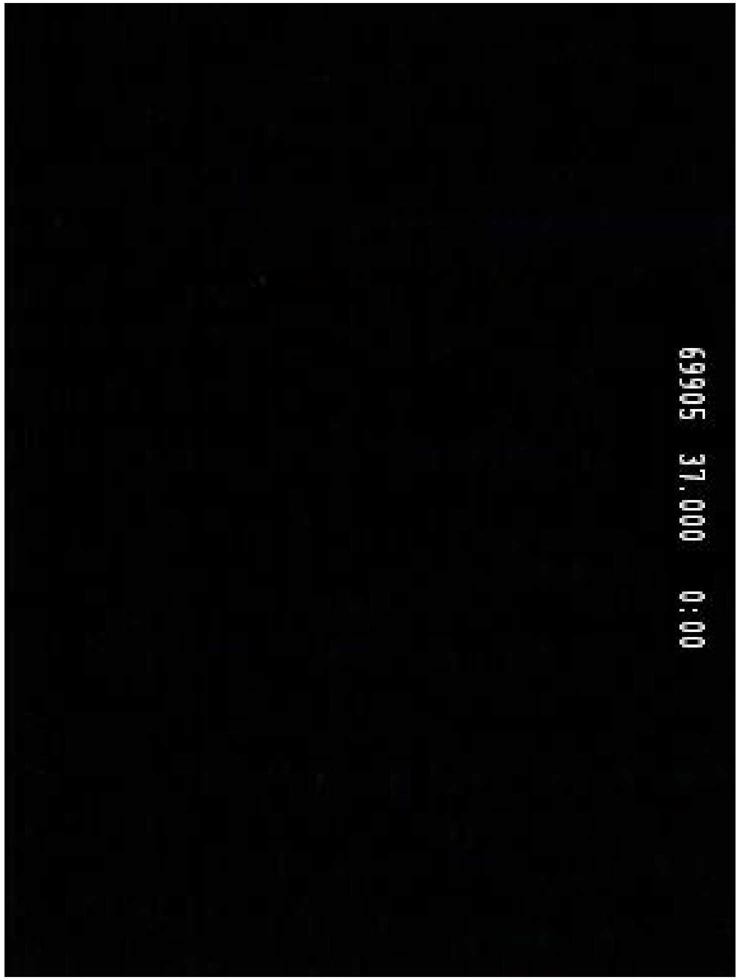
Tokamak Operation Scenario

JET pulse 69905 (B_T = 3.1 T)

Plasma Initiation	Current Ramp-up	High Power Phase	Plasma Quench

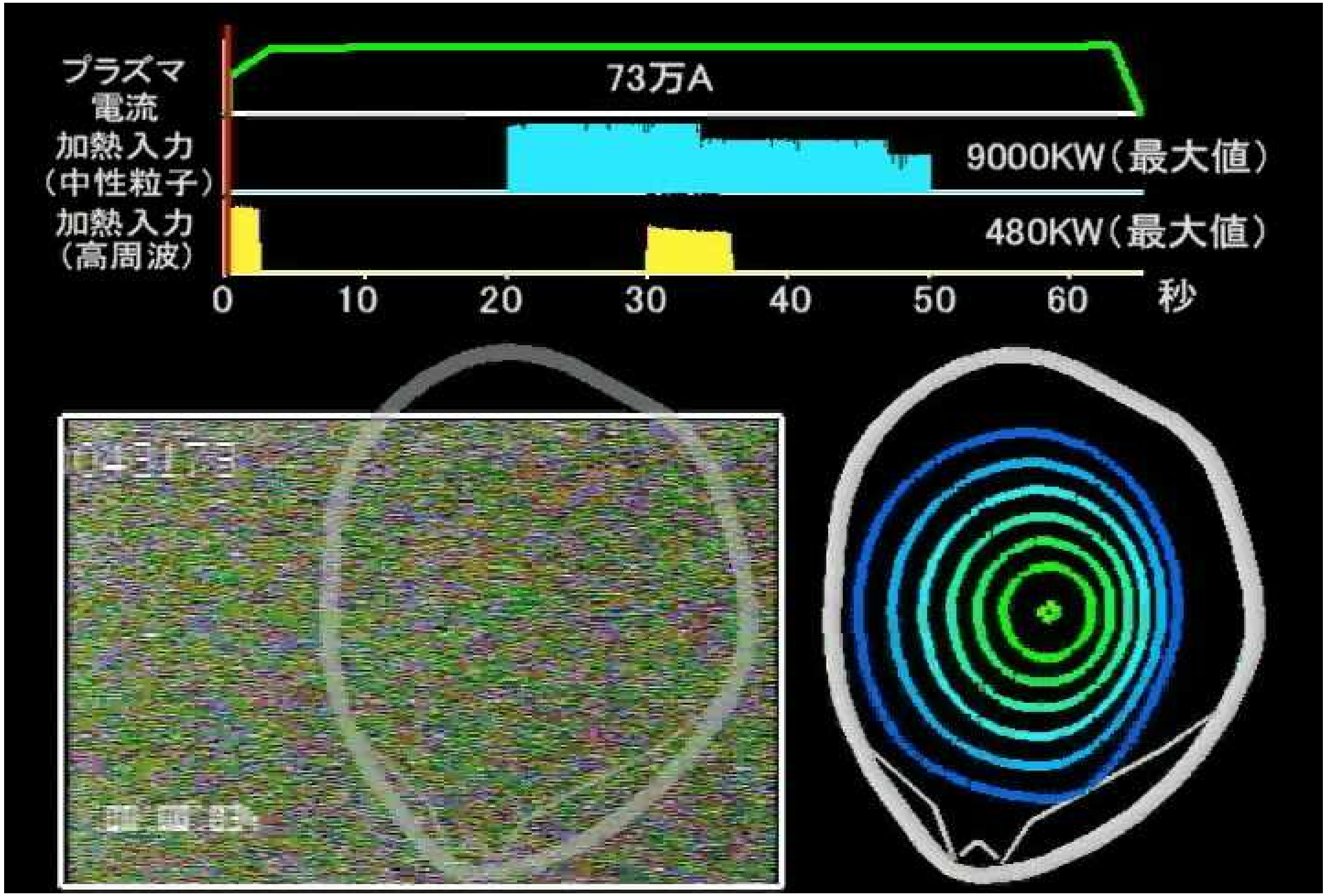






Tokamak Operation Scenario

JT-60U

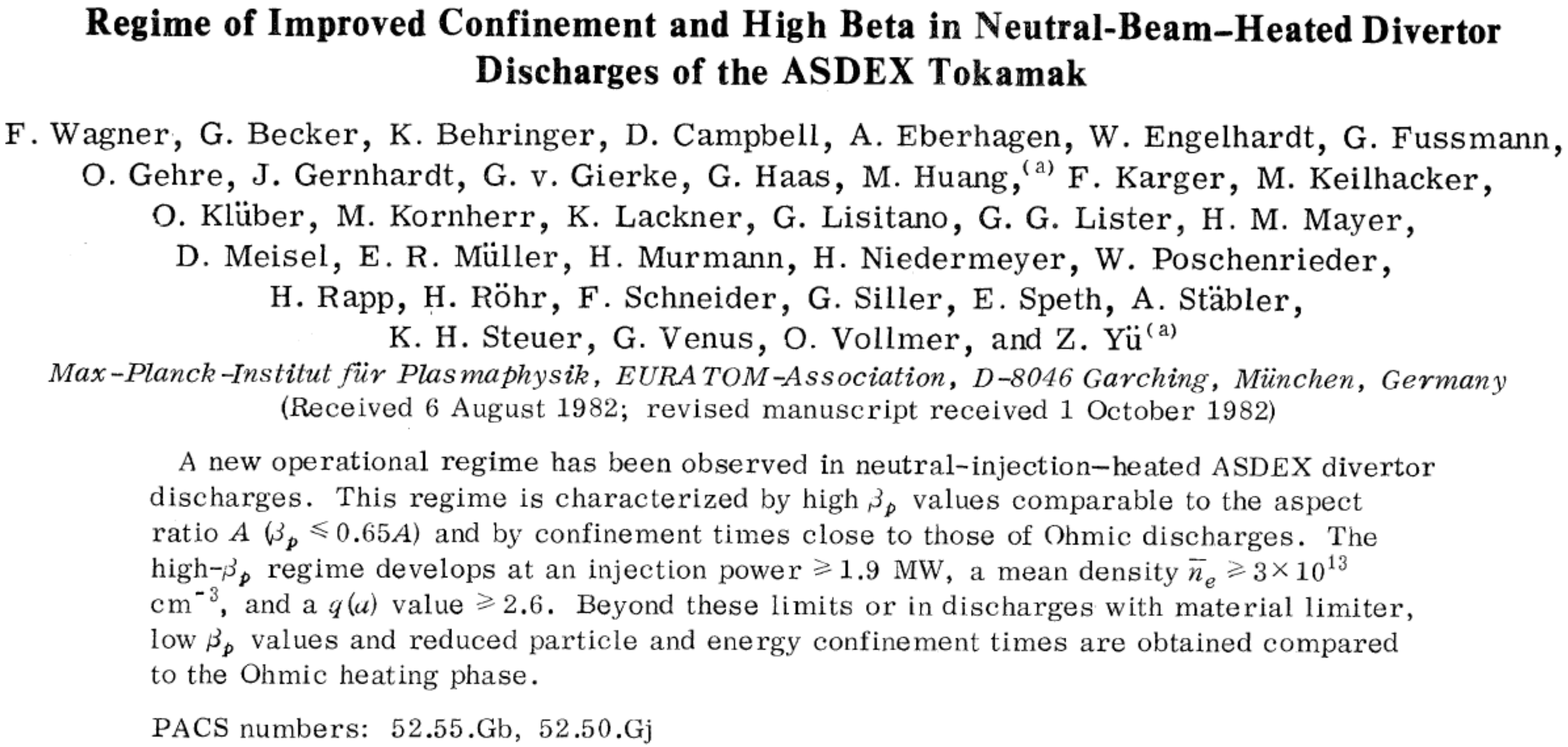


H-mode

- 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 β_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-β_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 β_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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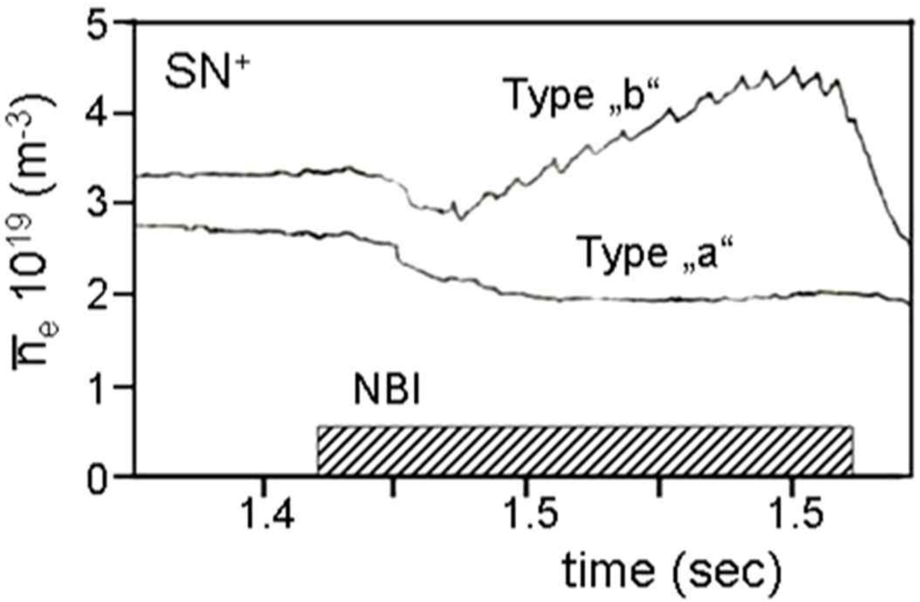
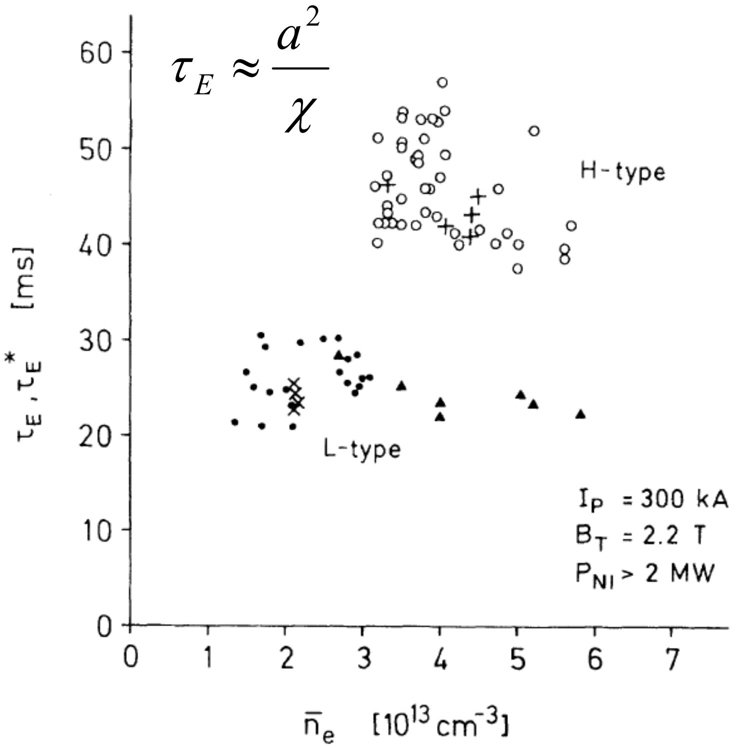


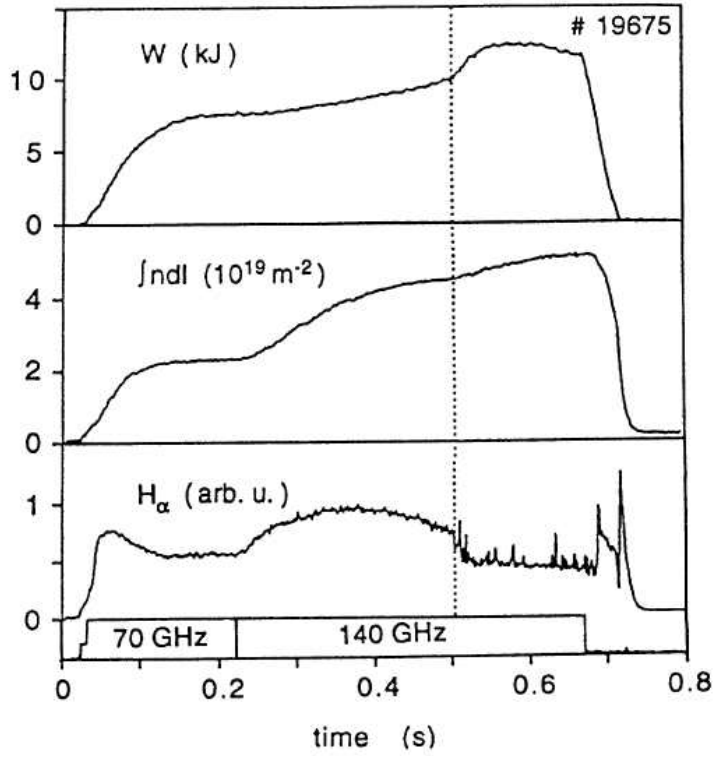


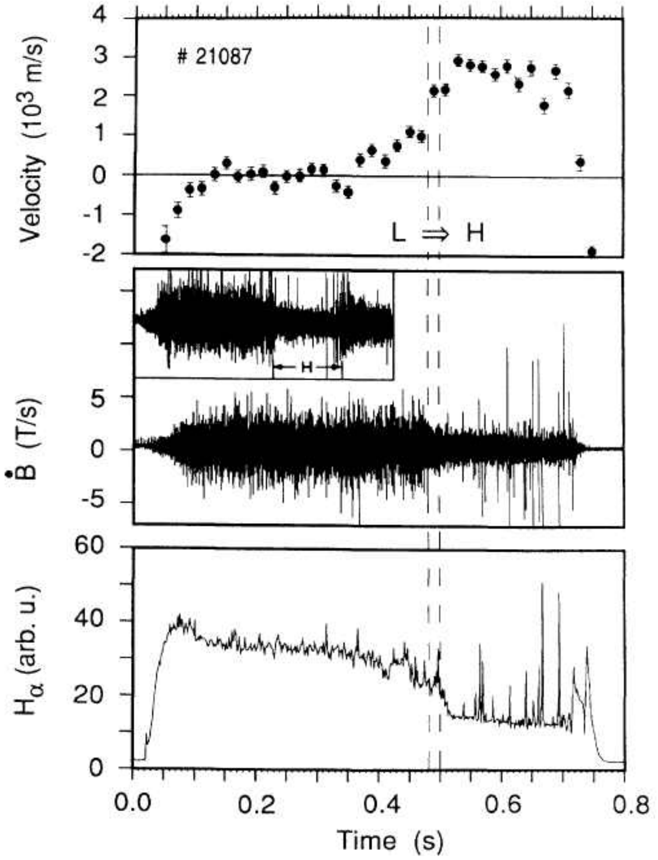
$$\tau_E \approx \frac{a^2}{\chi}$$

H-mode

- Established in stellarators as well

Wendelstein 7-AS





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

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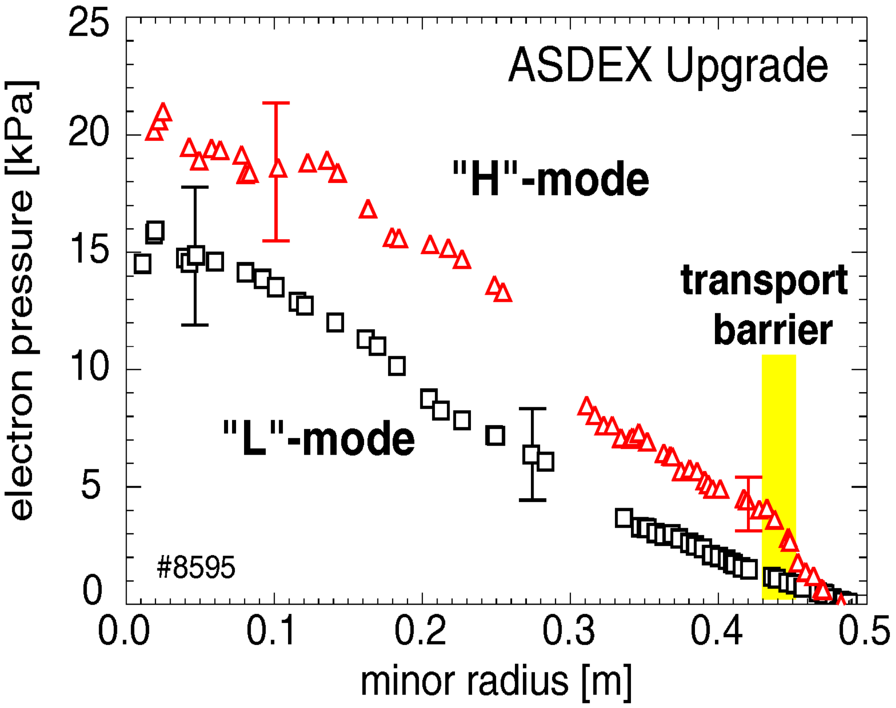

Hoover dam

H-mode

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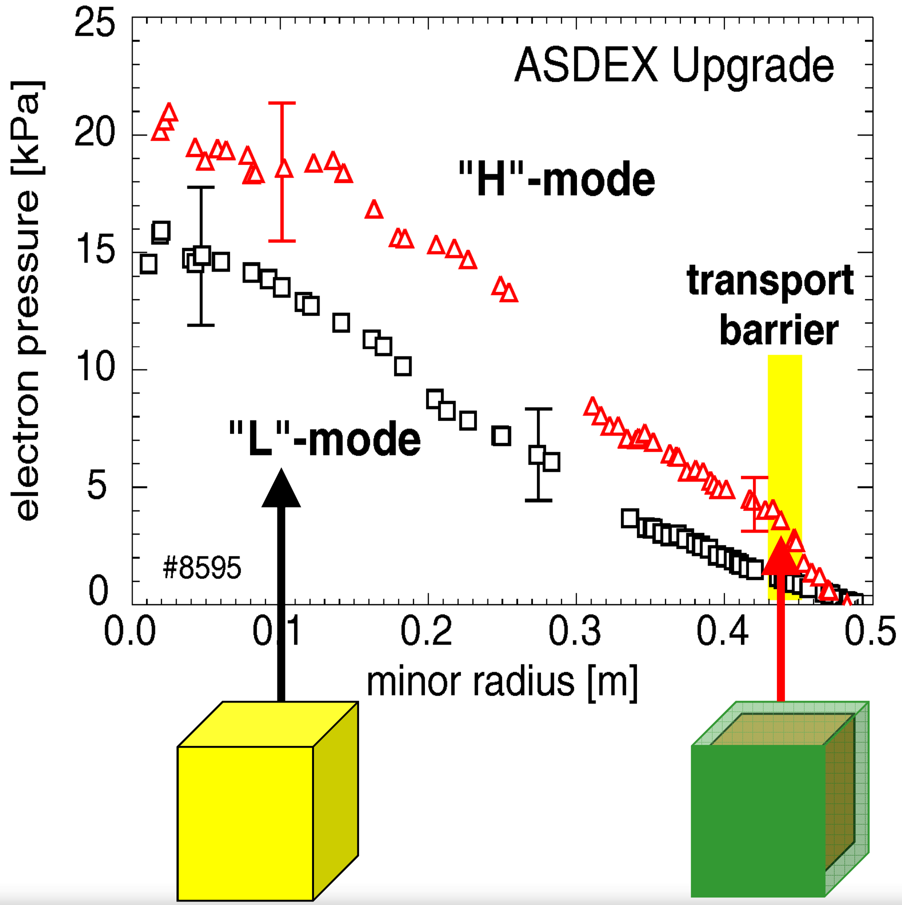
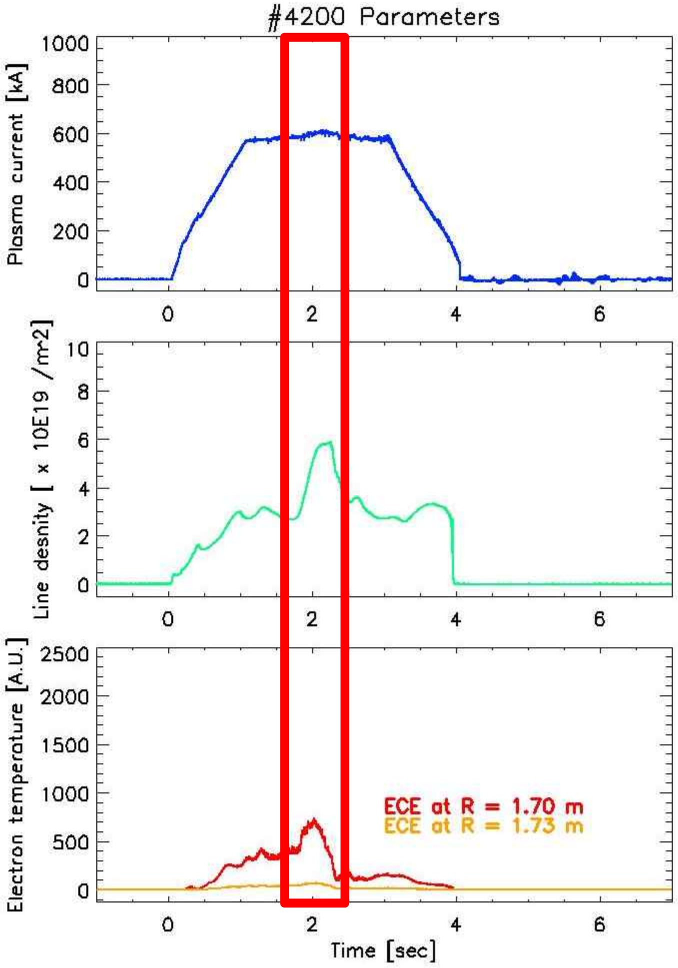
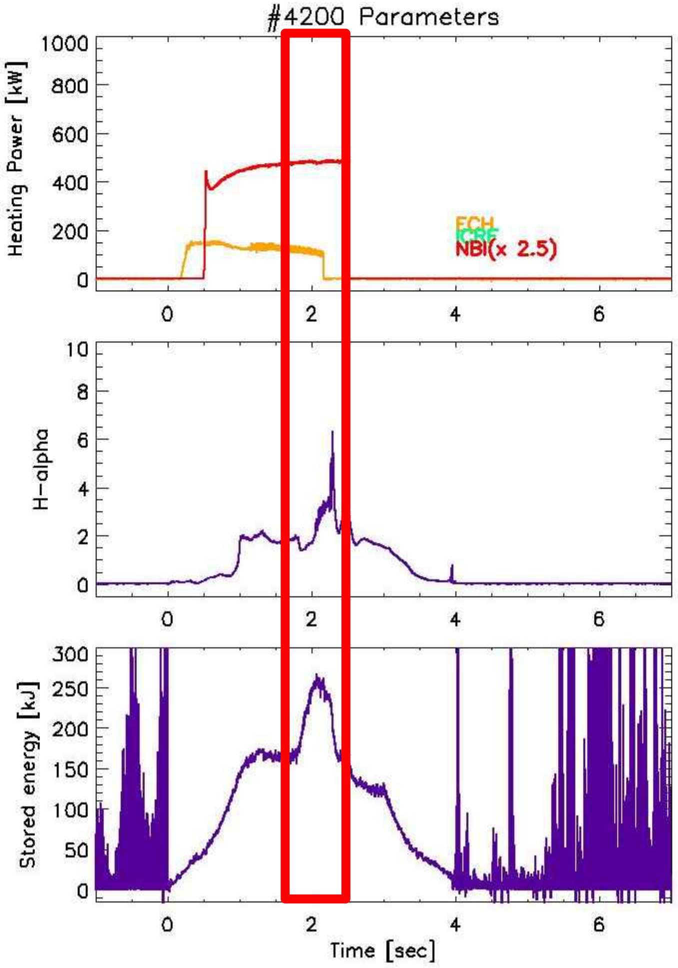


Hoover dam

H-mode

- **First H-mode Transition in KSTAR (November 8, 2010)**

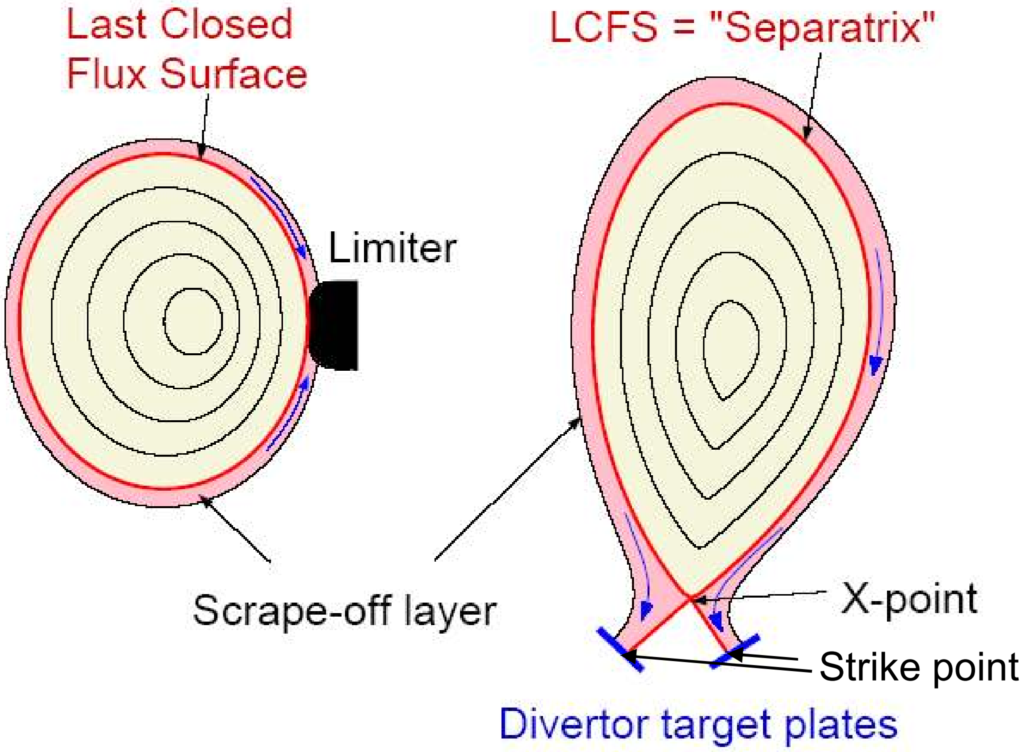




- B_0 = 2.0 T, Heating = 1.5 MW (NBI: 1.3 MW, ECH: 0.2 MW)
After Boronization on November 7, 2010

H-mode: How to?

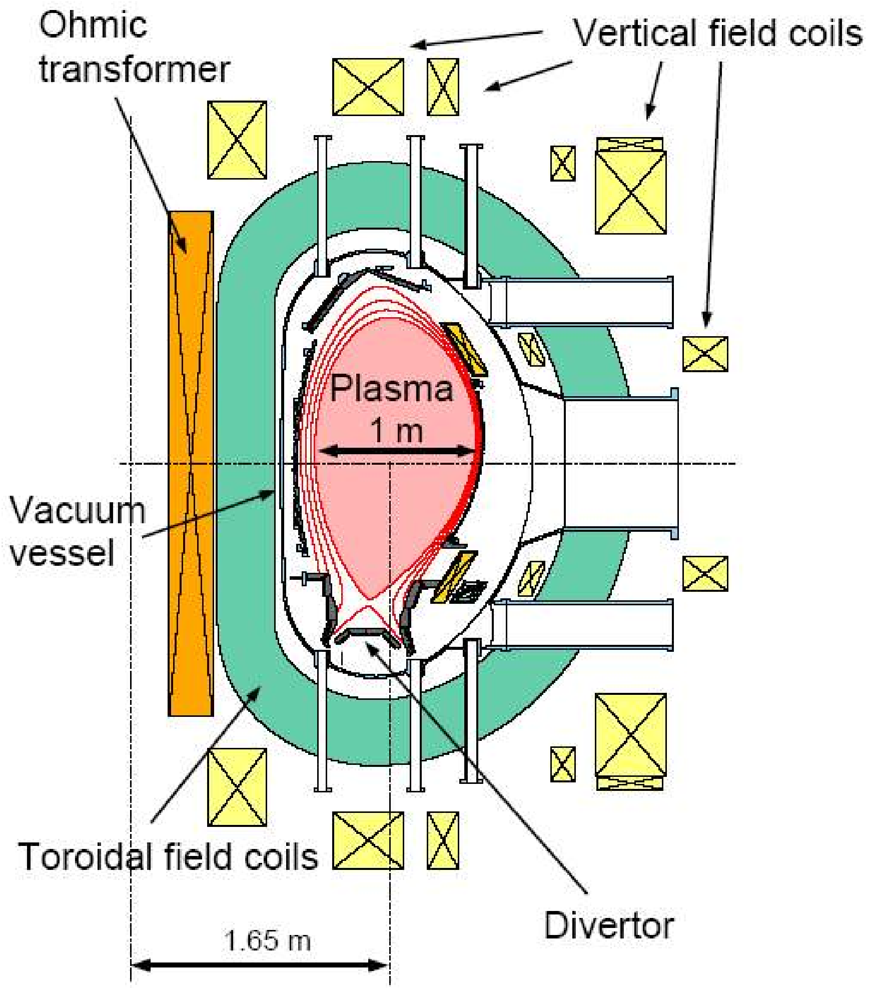
- **Separation of plasma from wall by a limiter and a divertor**

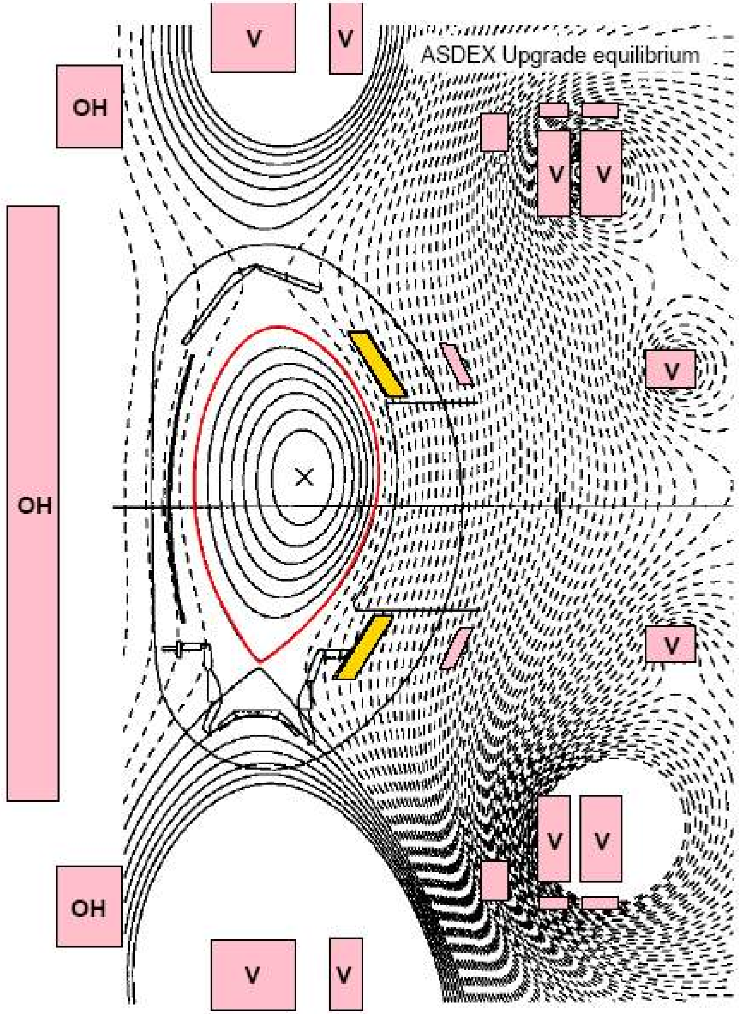


- Advantage of the divertor configuration

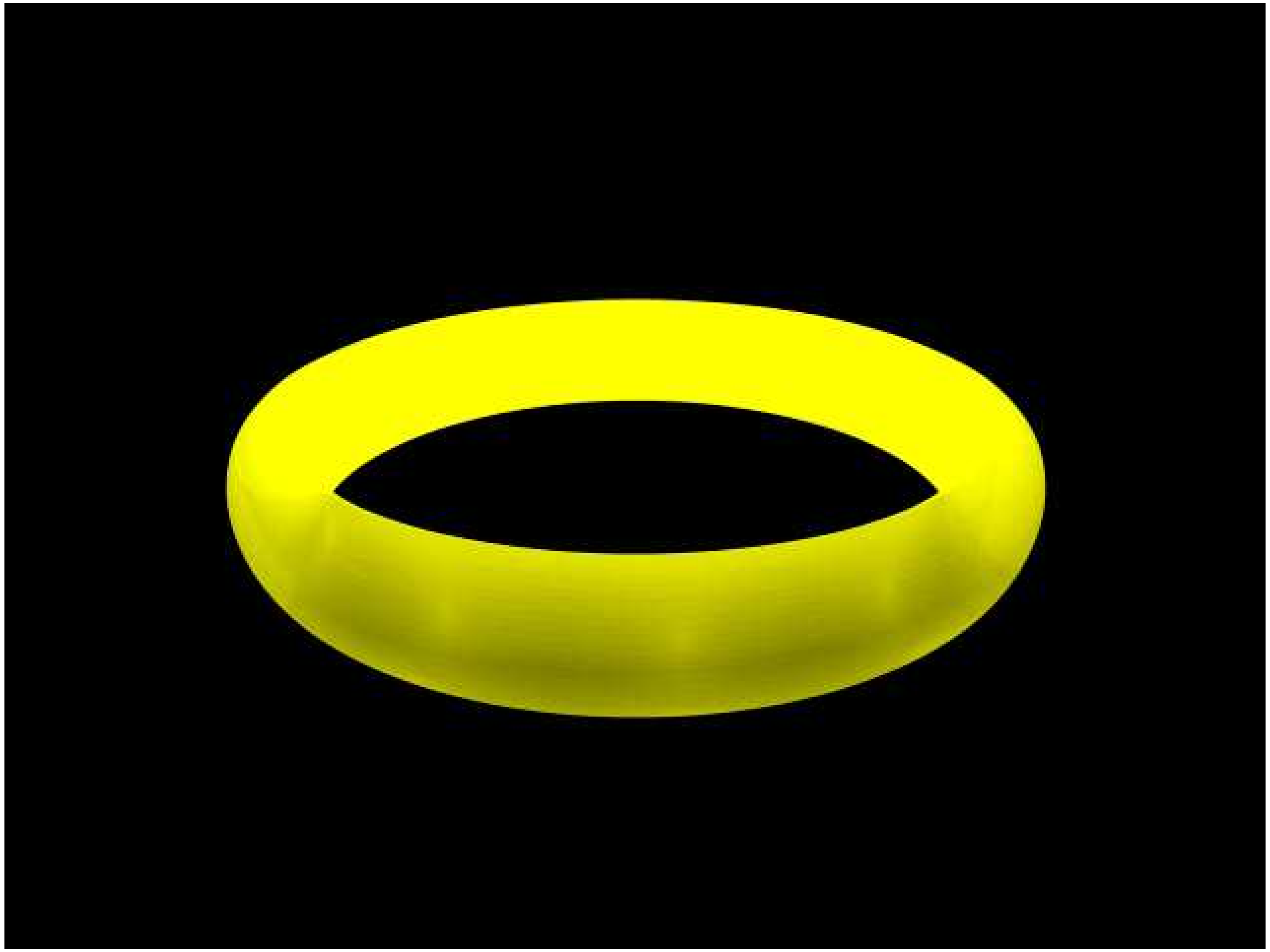
- First contact with material surface at a distance from plasma boundary
- Reducing the influx of ionized impurities into the interior of the plasma by diverting them into an outer „SOL“

Tokamak


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


ASDEX Upgrade equilibrium
OH
OH
OH
V
V
V
V
V
V
V
V
V
V
V
V

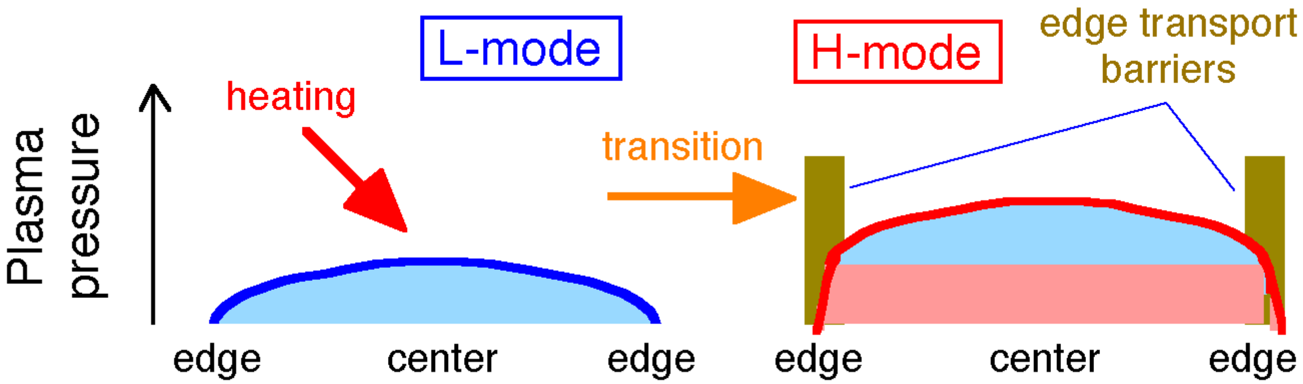
H-mode: How to?

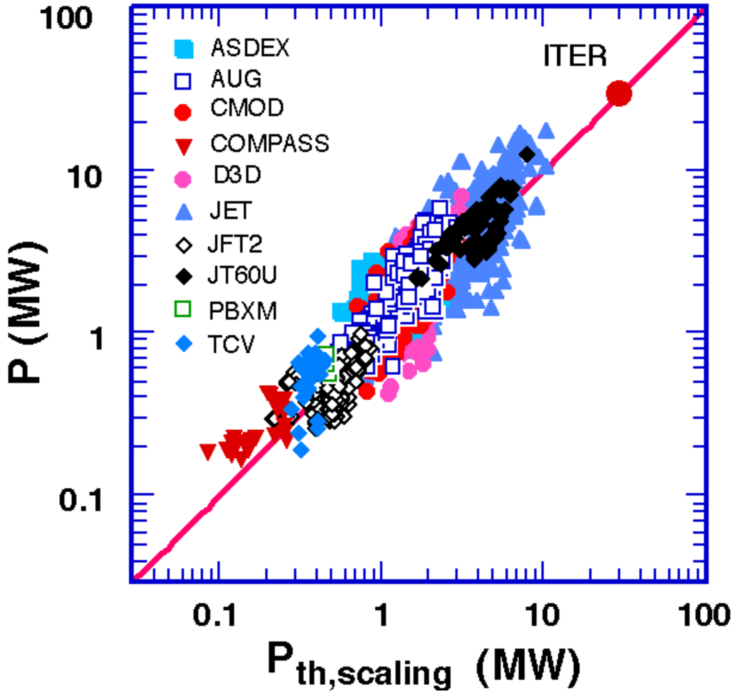


H-mode: How to?

- **Role of wall condition**

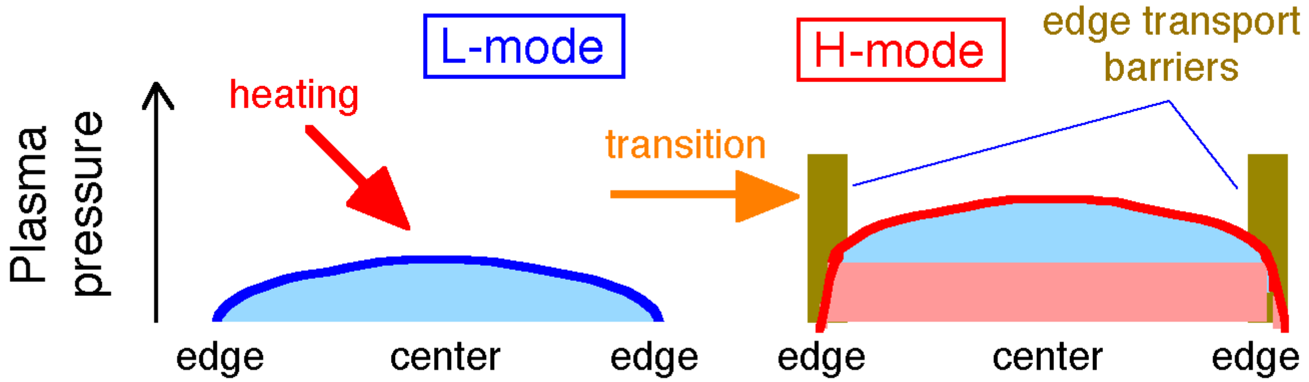
H-mode: How to?

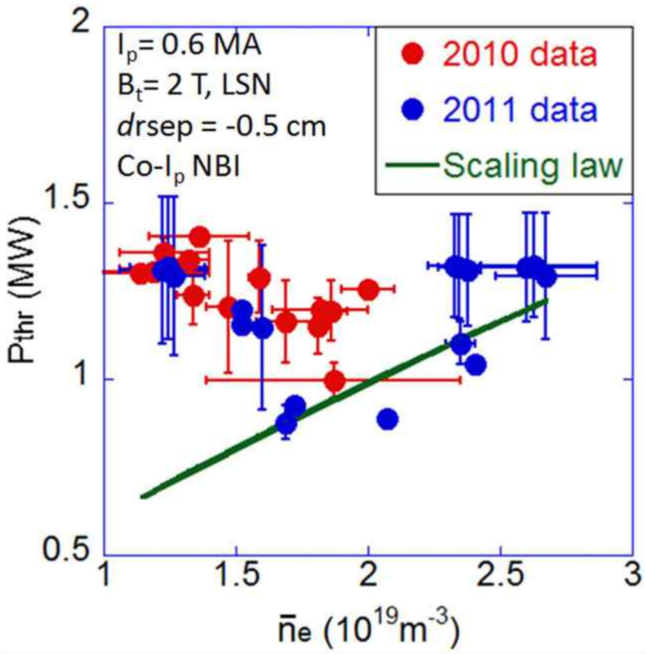




$$P_{th} = 2.84 M^{-1} B_t^{0.82} n_{20}^{0.58} R^{1.0} a^{0.81}$$

H-mode: How to?





$$P_{thr,scaling} = 0.0488 \pm 0.0028 n_{e20}^{0.717\pm0.035} B_T^{0.803\pm0.032} S^{0.941\pm0.019}$$

Y. R. Martin et al., "Power requirement for accessing the H-mode in ITER", J. Phys.: Conf. Ser. 123 012033 (2008)

J-W. Ahn, H.-S. Kim et al., "Confinement and ELM characteristics of H-mode plasmas in KSTAR", Nucl. Fusion 52 114001 (2012)

H-mode: Why?

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

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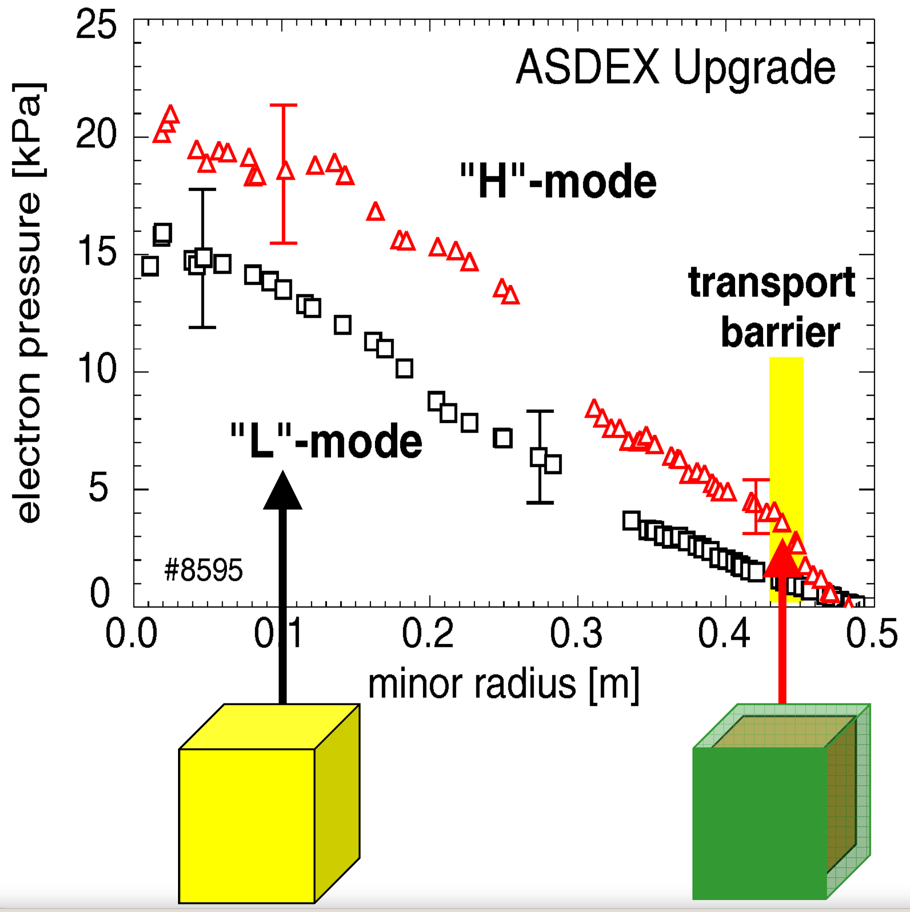
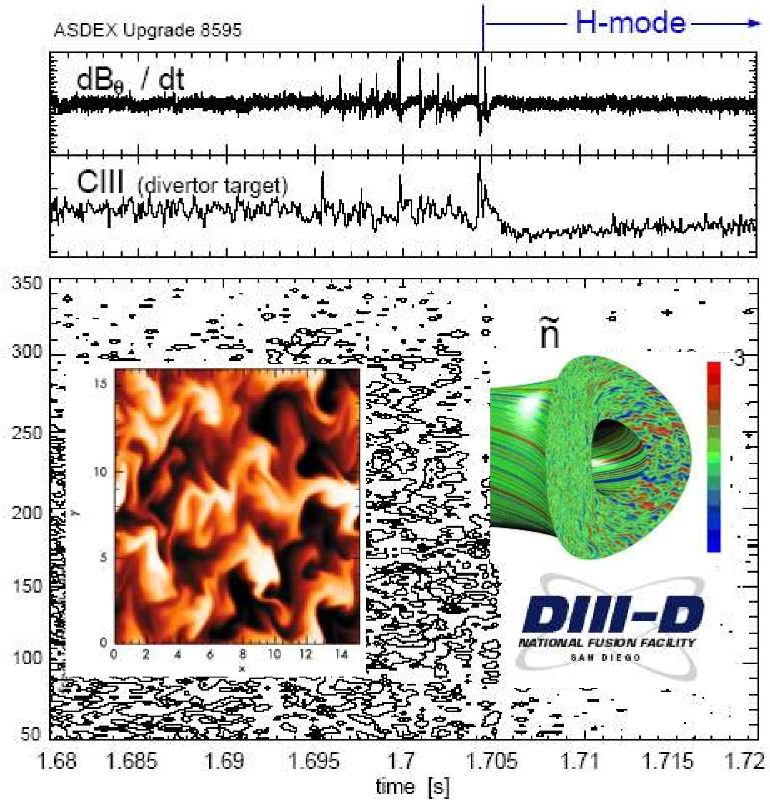
- Formation of an edge transport barrier: steep pressure gradient at the edge





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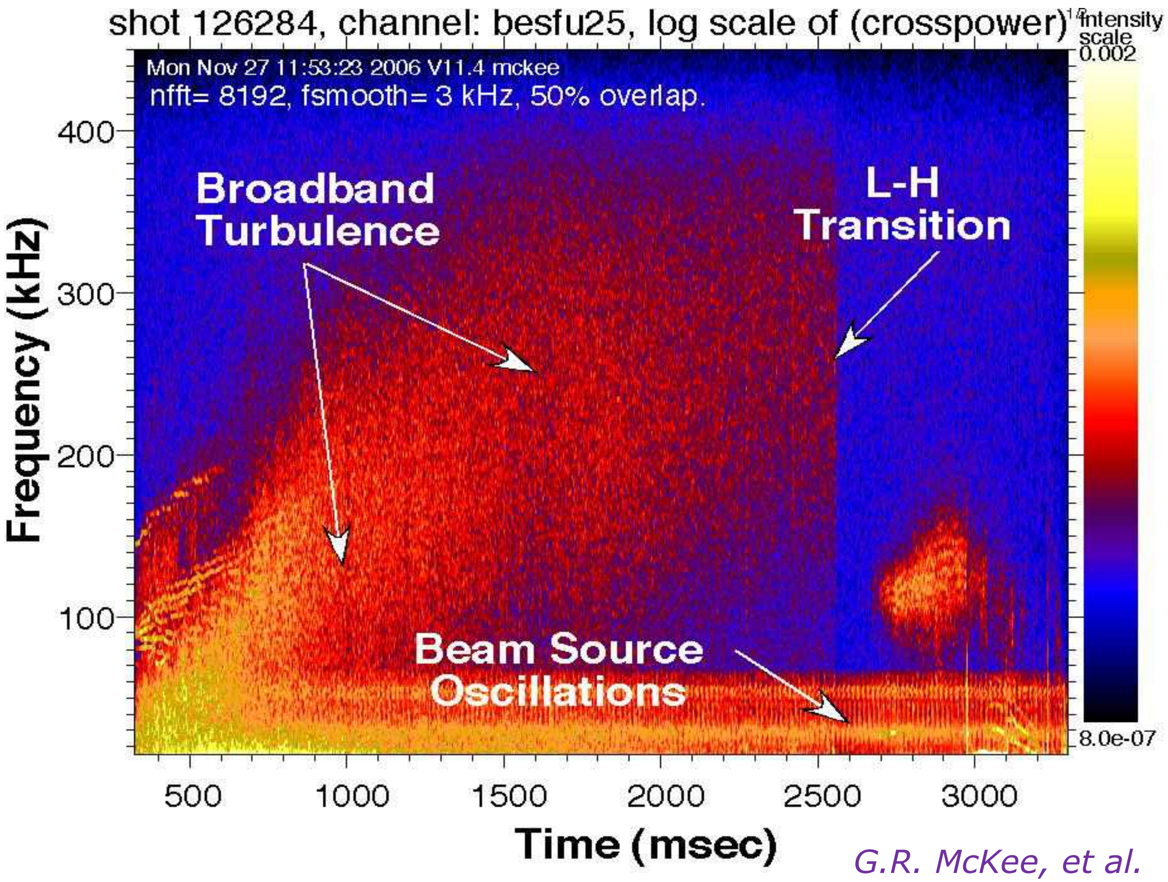

Density fluctuations at $r/a = 0.65$

G.R. McKee, et al. Plasma Fusion Res. (2007)

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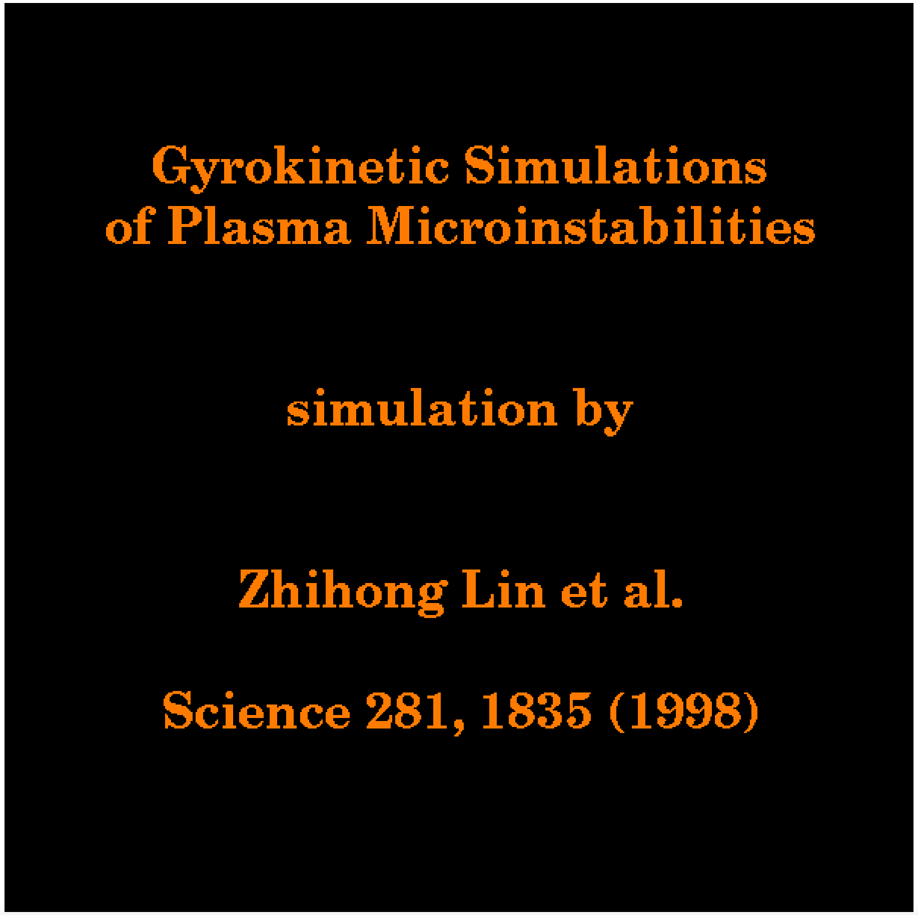


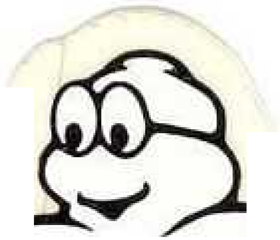
Gyrokinetic Simulations
of Plasma Microinstabilities

simulation by

Zhihong Lin et al.

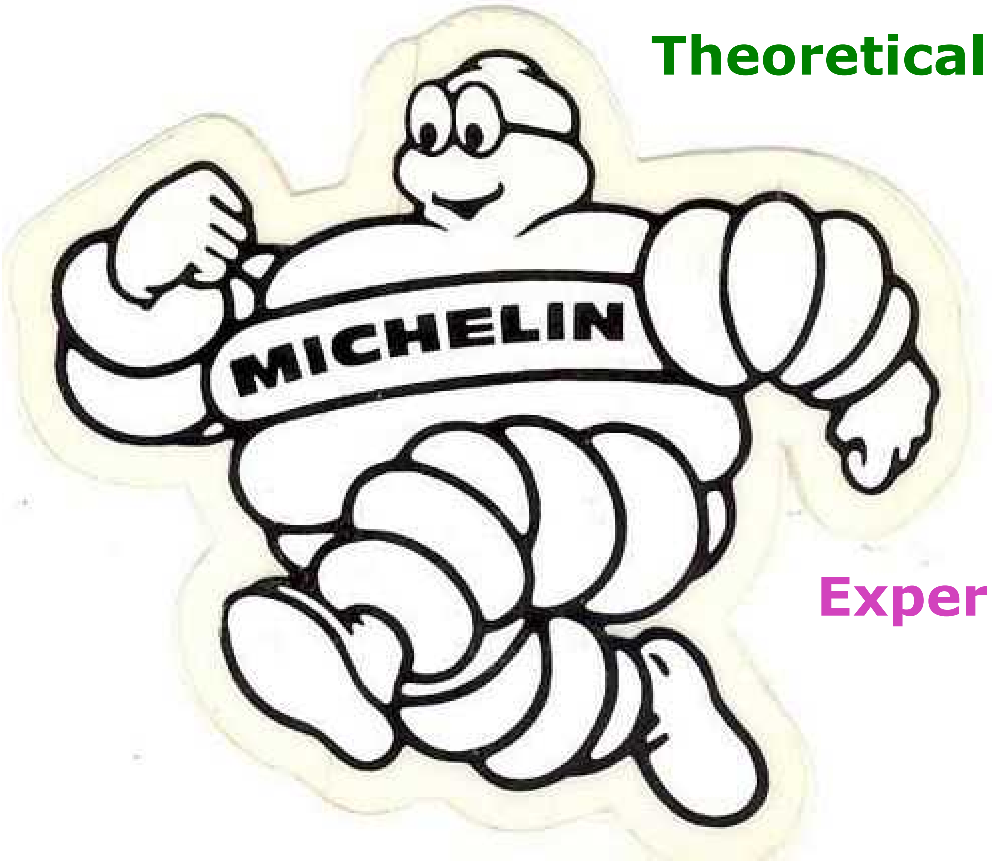
Science 281, 1835 (1998)

H-mode: Why?



Theoretical physics

H-mode: Why?

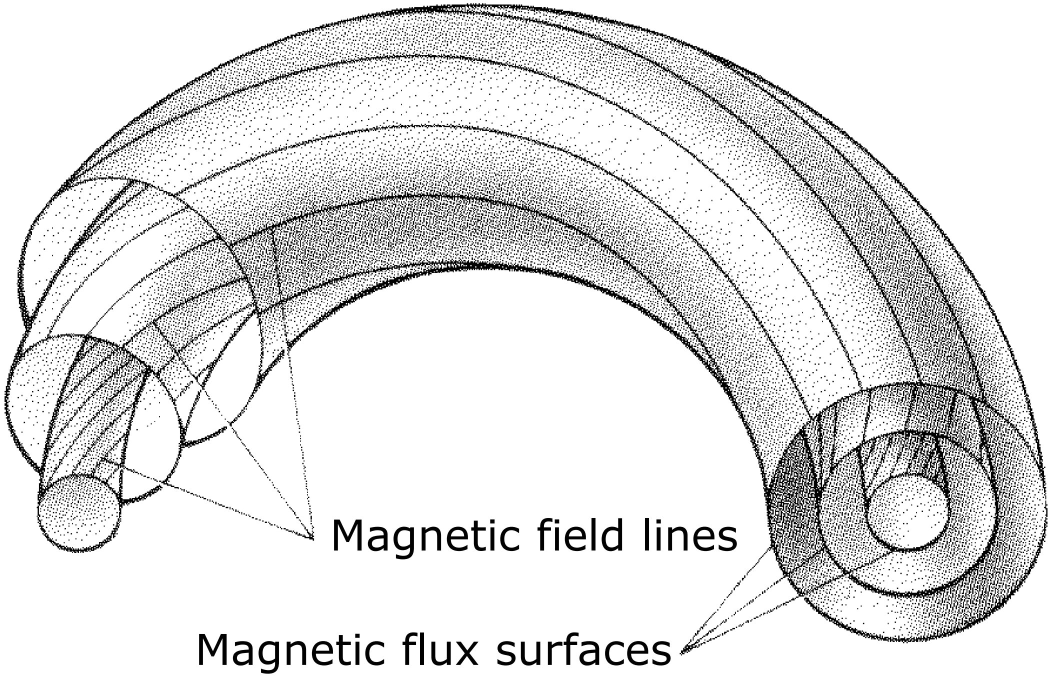


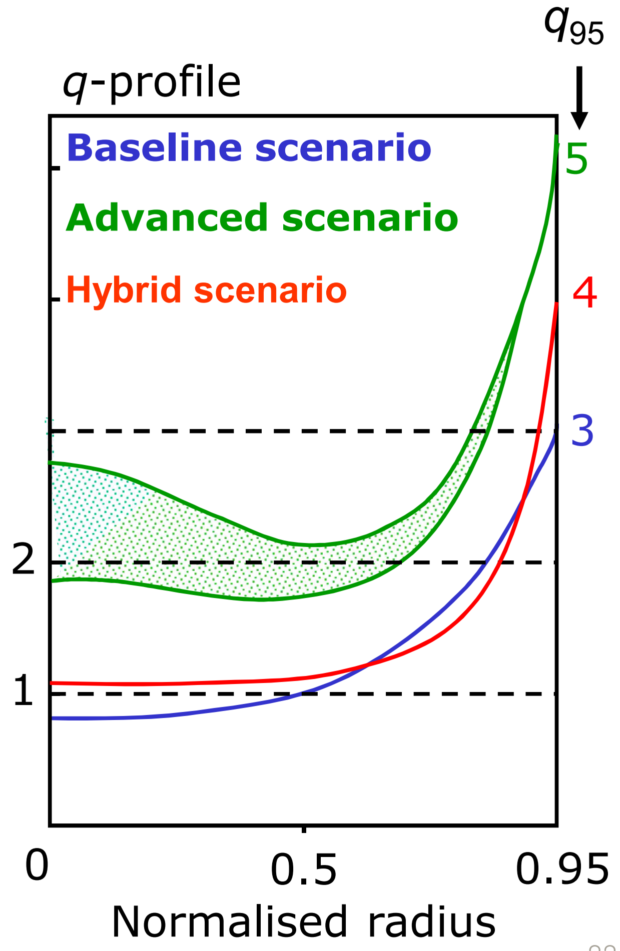
Theoretical physics

Experimental physics

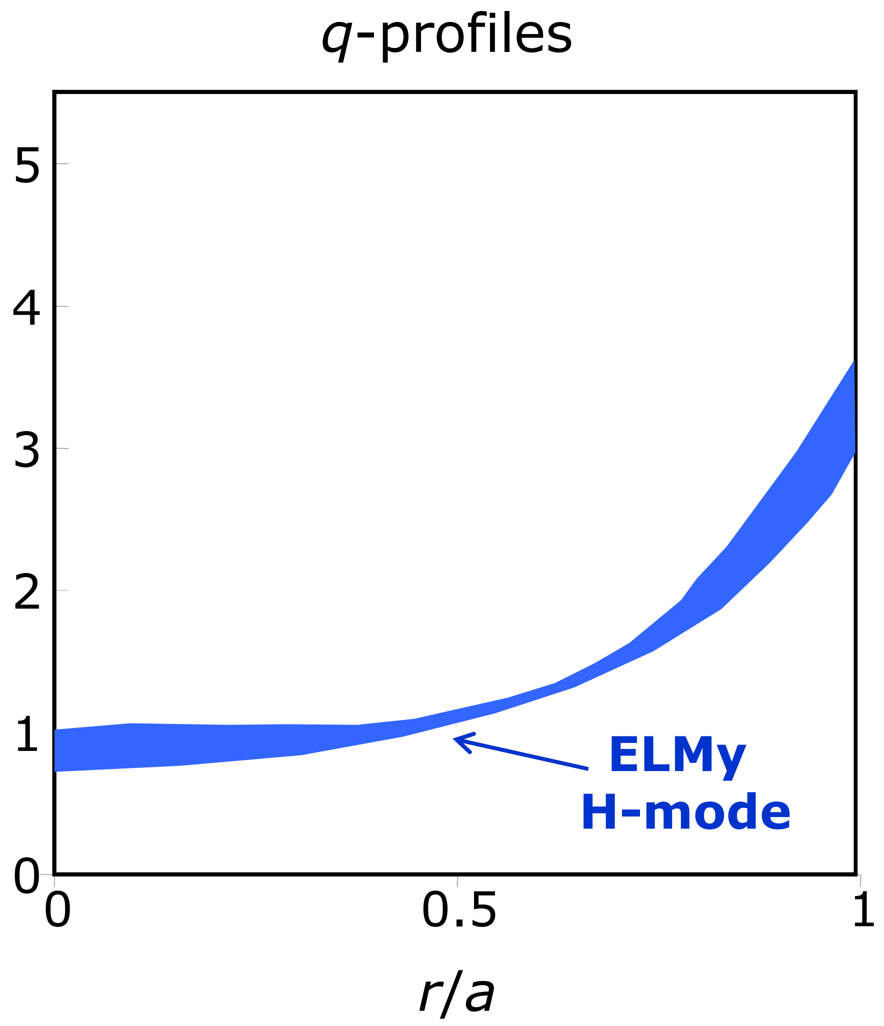
Basic Tokamak Variables

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

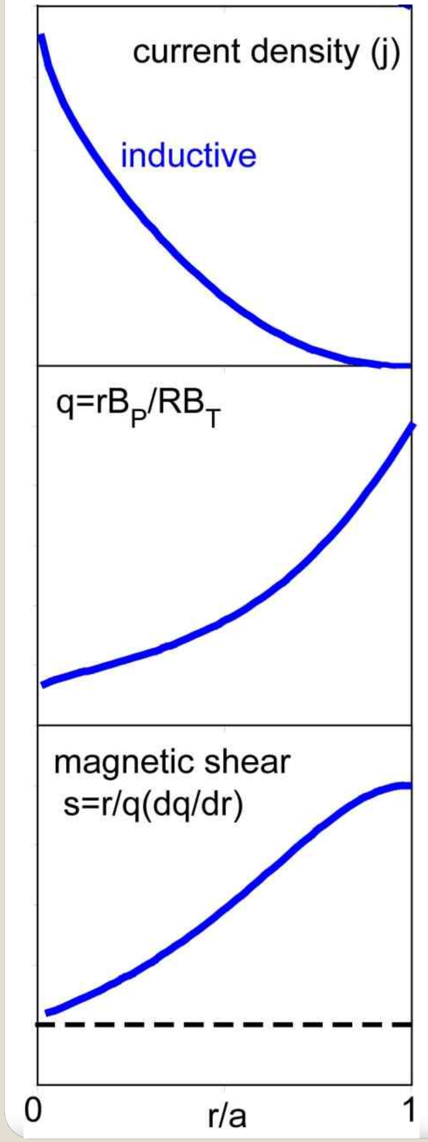


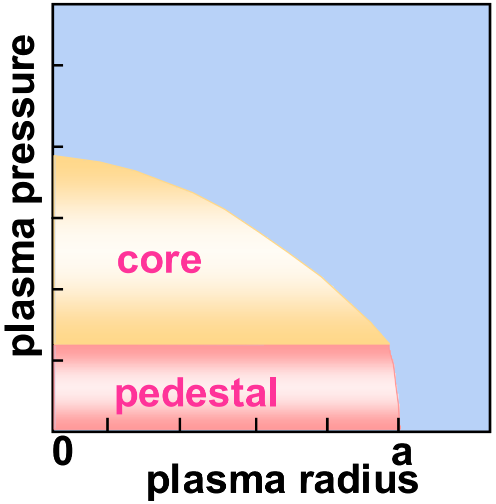


Tokamak Operation Modes



Conventional Operation Mode – H-mode

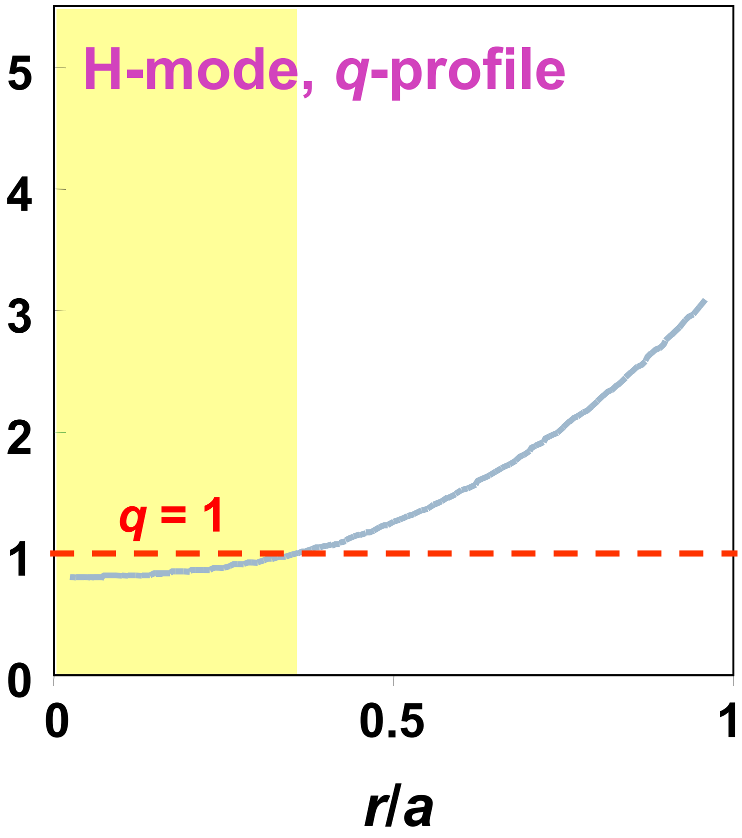




- Mild pressure gradient with steep edge pedestal
- Naturally peaked current profile
- Monotonic *q*-profile
- Positive magnetic shear

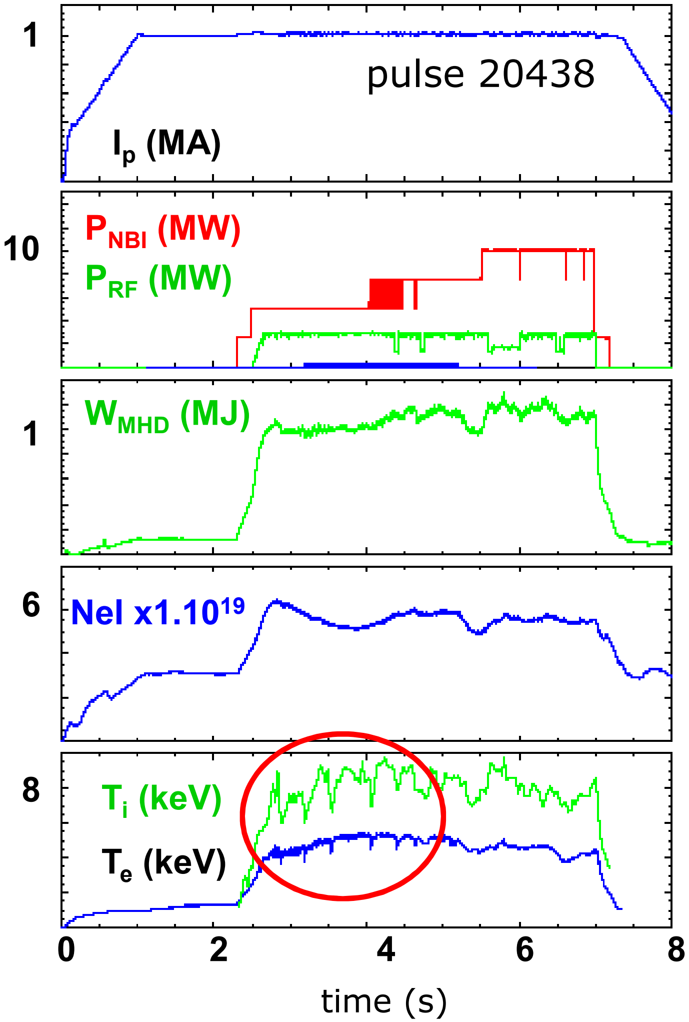
H–mode: Limitations

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



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

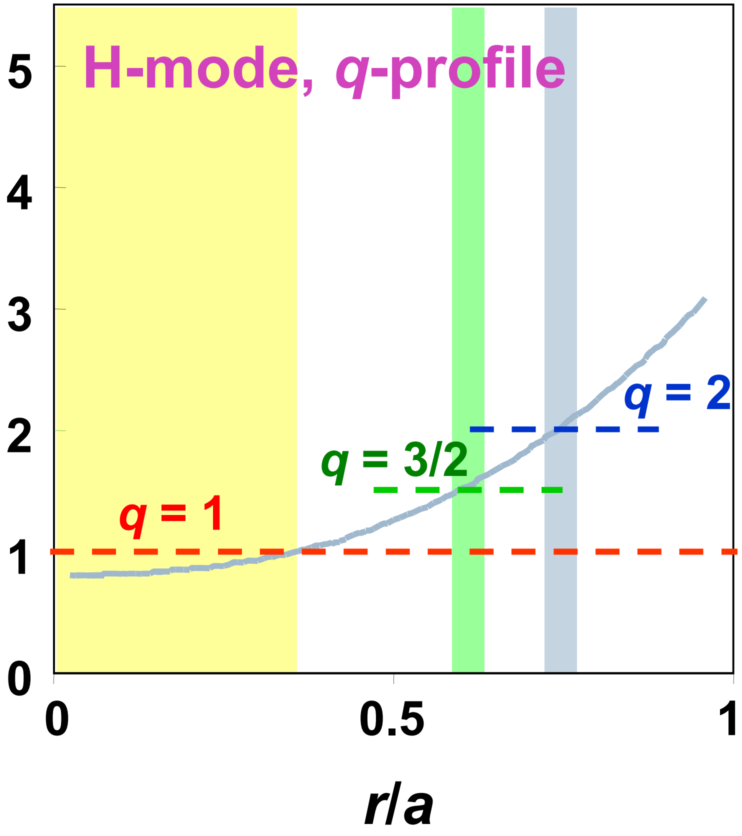
Sawtooth



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

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

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

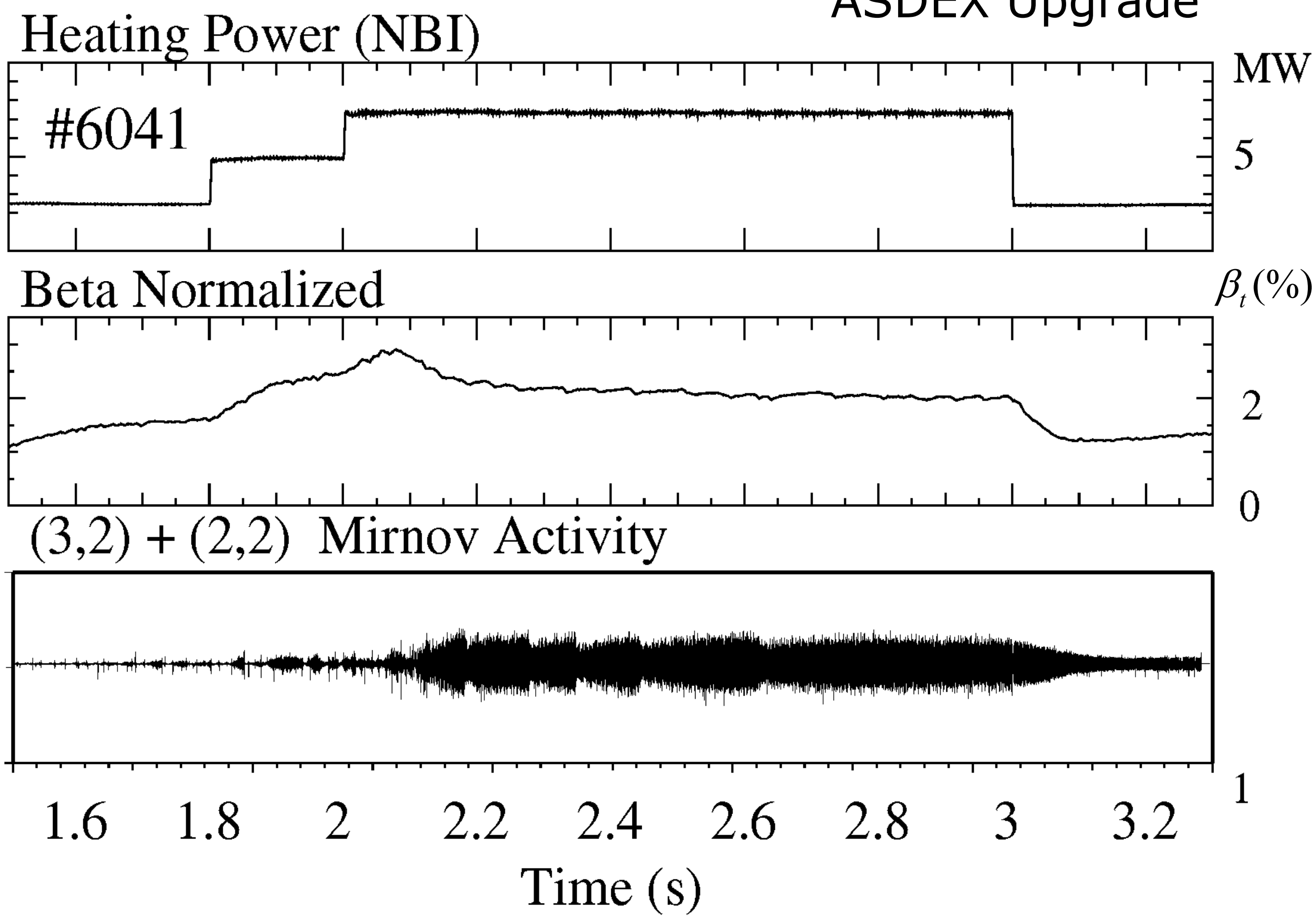
Neoclassical Tearing Modes (NTMs):

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

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

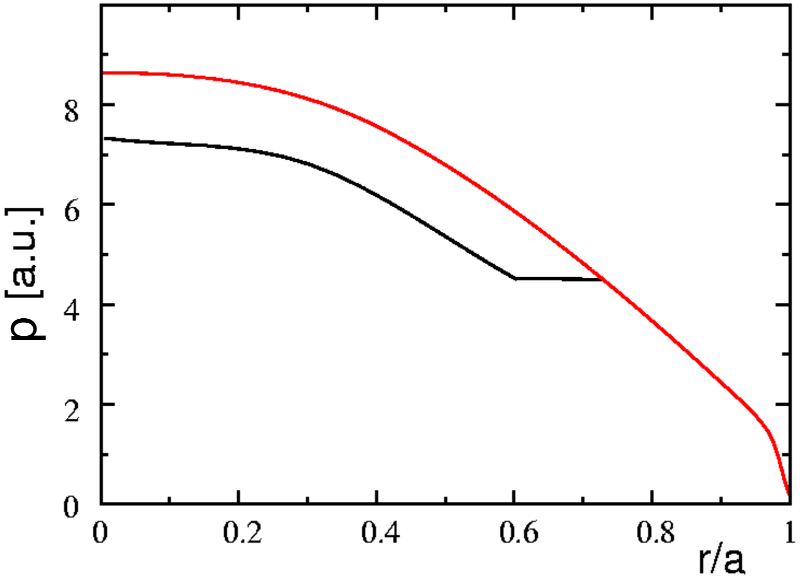
Neoclassical Tearing Mode (NTM)

ASDEX Upgrade



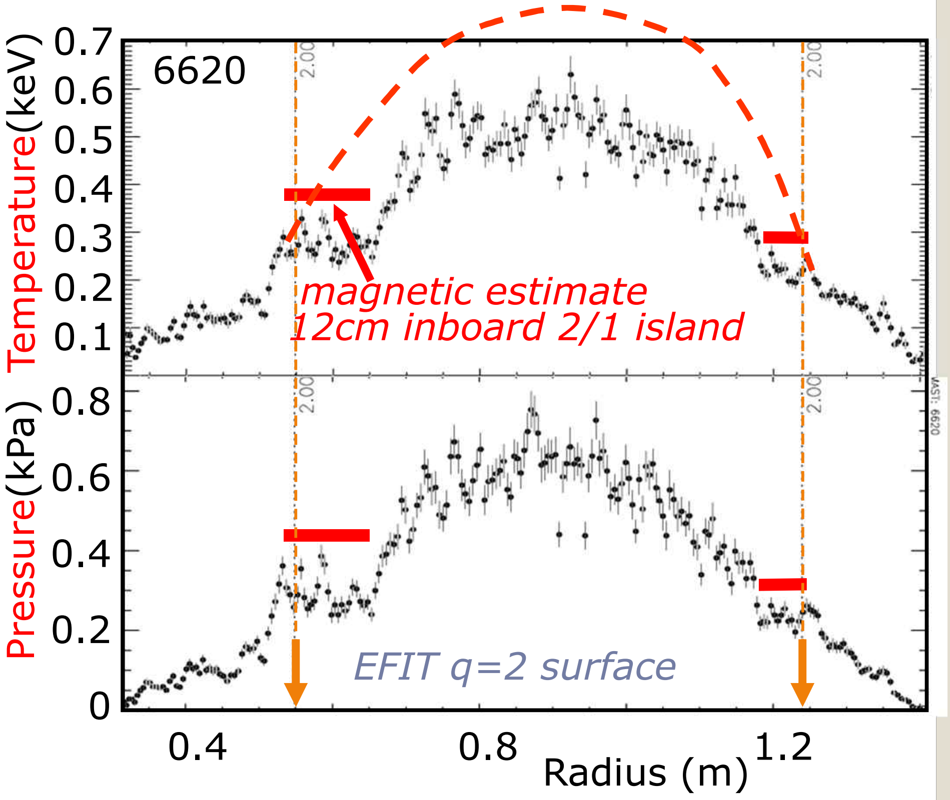
$$\beta_t(\%) = \beta_N \frac{I_\phi}{aB_\phi}$$

Neoclassical Tearing Mode (NTM)



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

Neoclassical Tearing Mode (NTM)

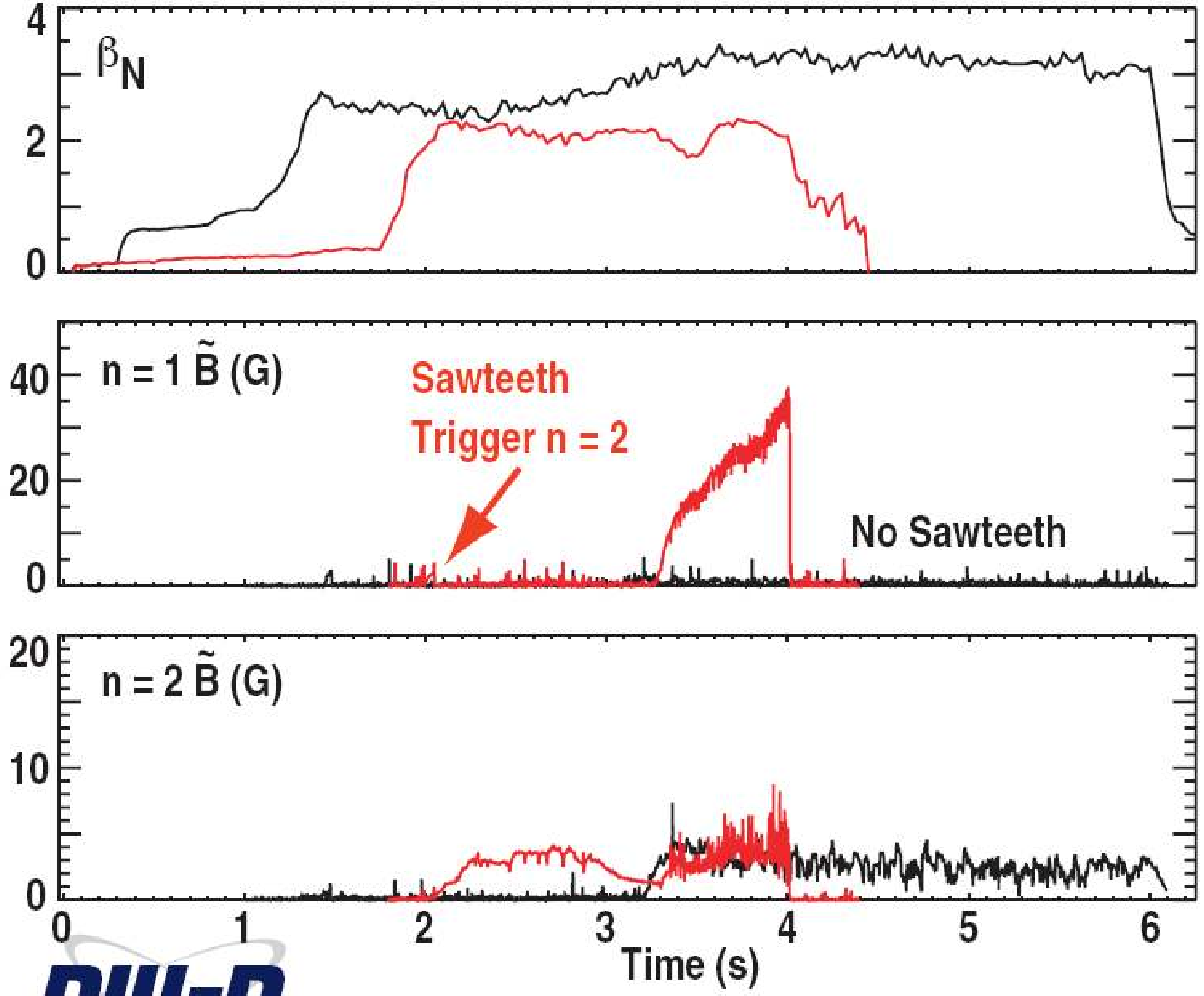


magnetic estimate
12cm inboard 2/1 island

EFIT q=2 surface

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

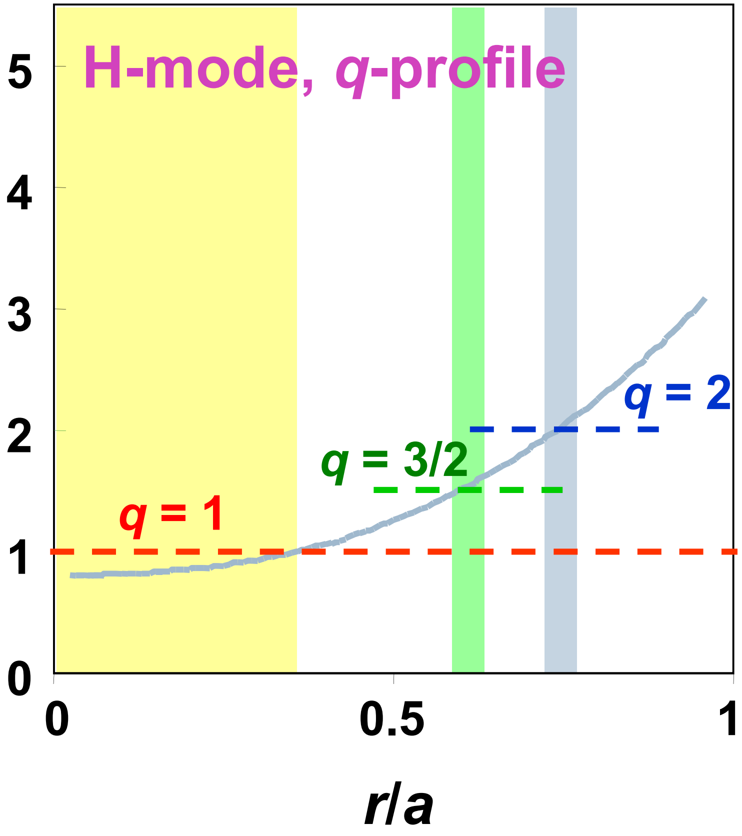
Neoclassical Tearing Mode (NTM)

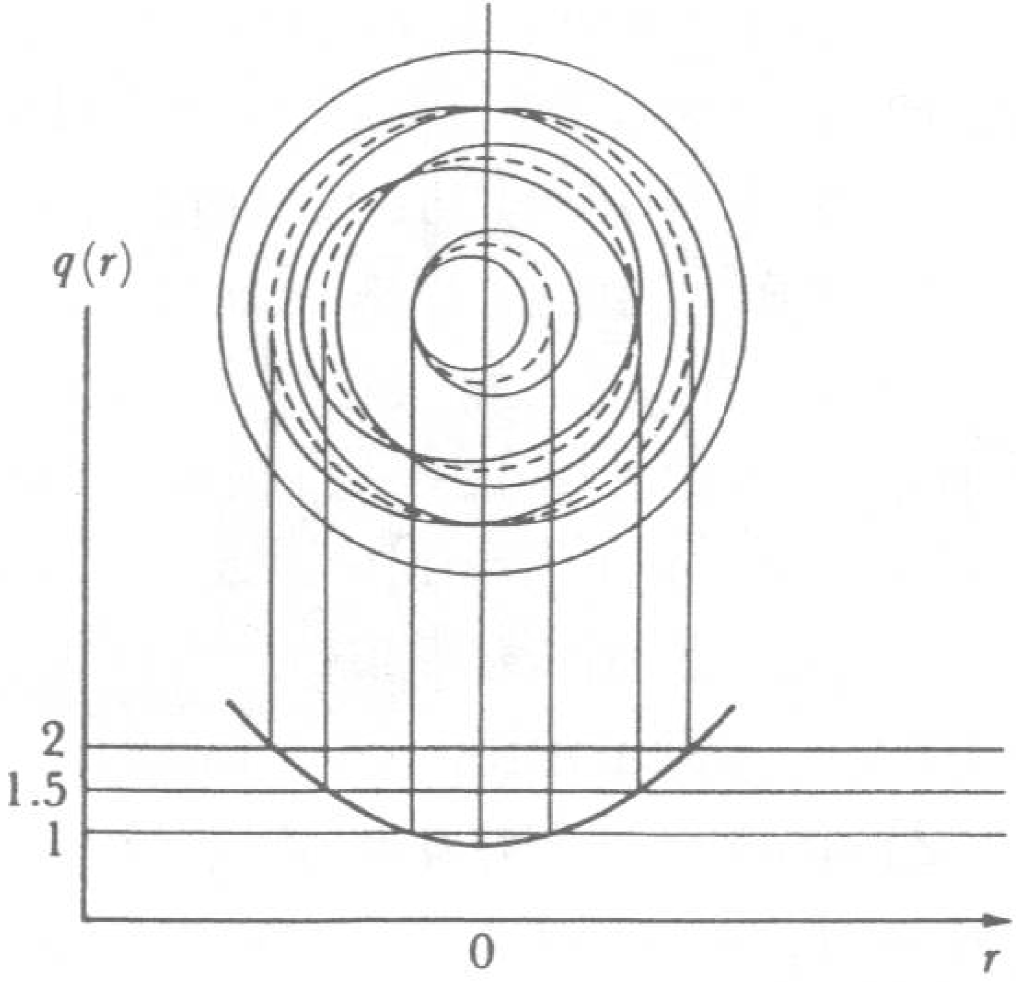


DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

H–mode: Limitations

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

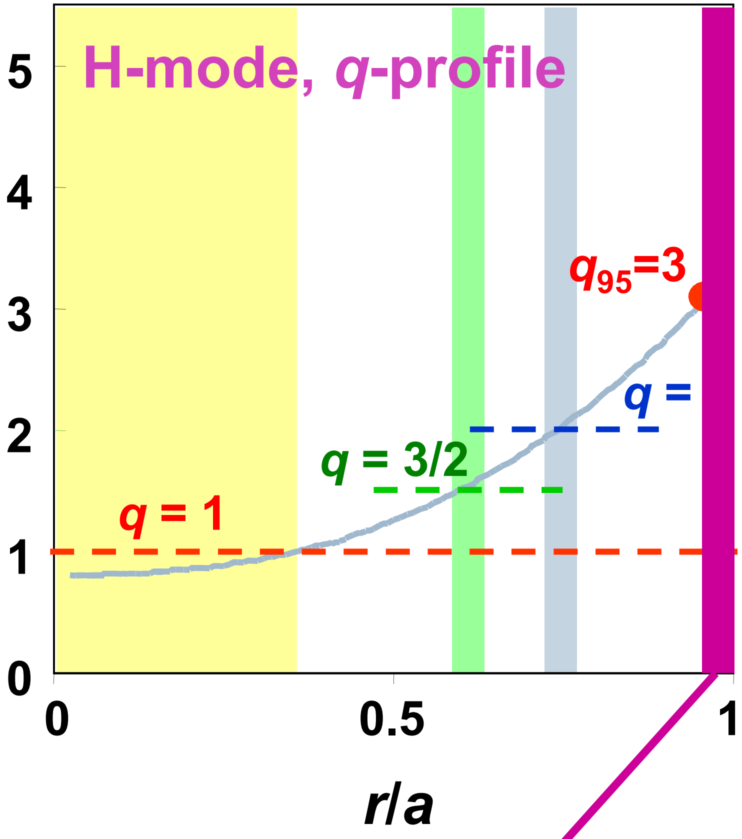




K. Miyamoto, "Controlled Fusion and Plasma Physics" Taylor & Francis (2007)

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.

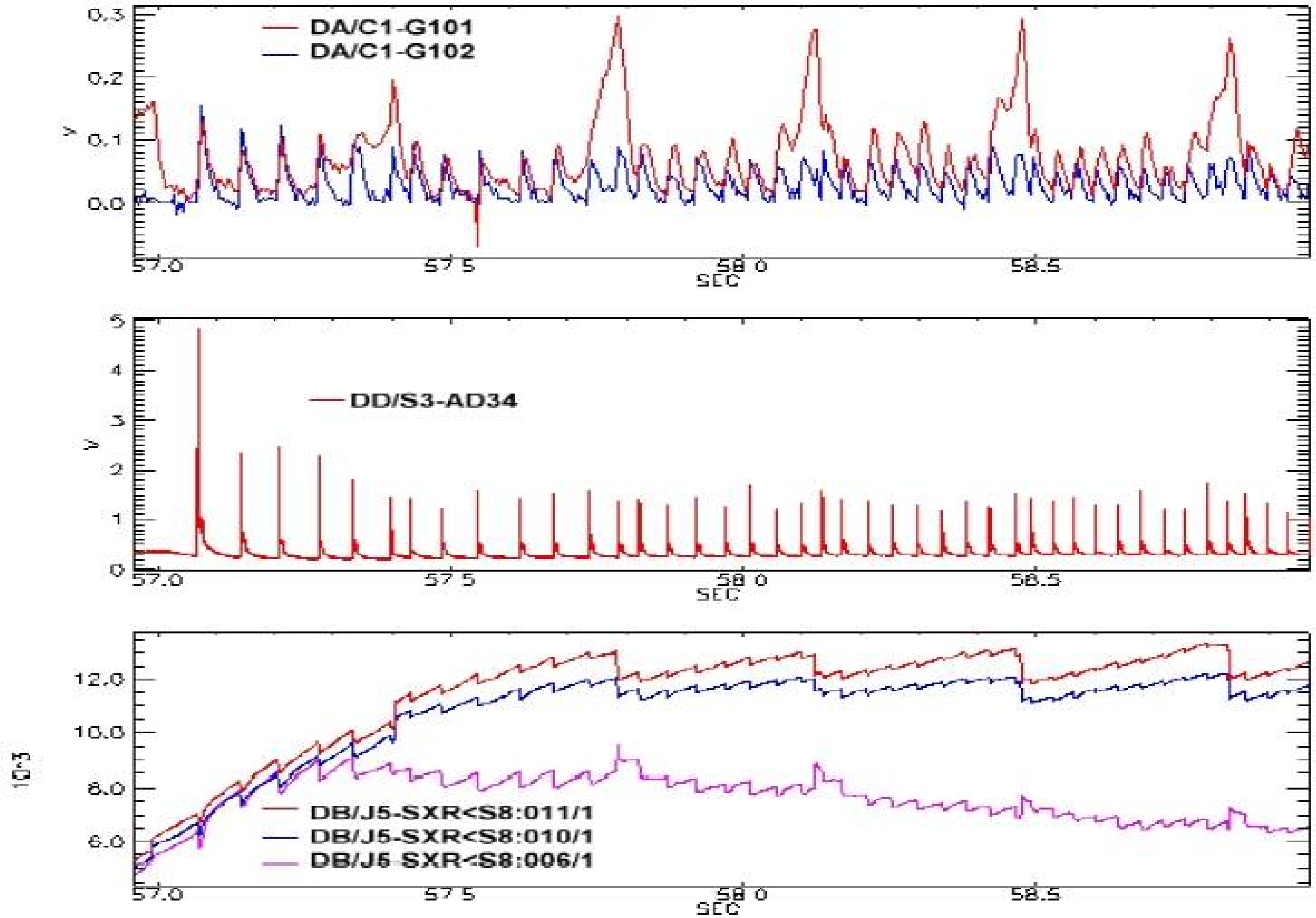
- ITER work point is chosen conservatively: $\beta_N \leq 1.8$!

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

Edge Localised Mode (ELM)

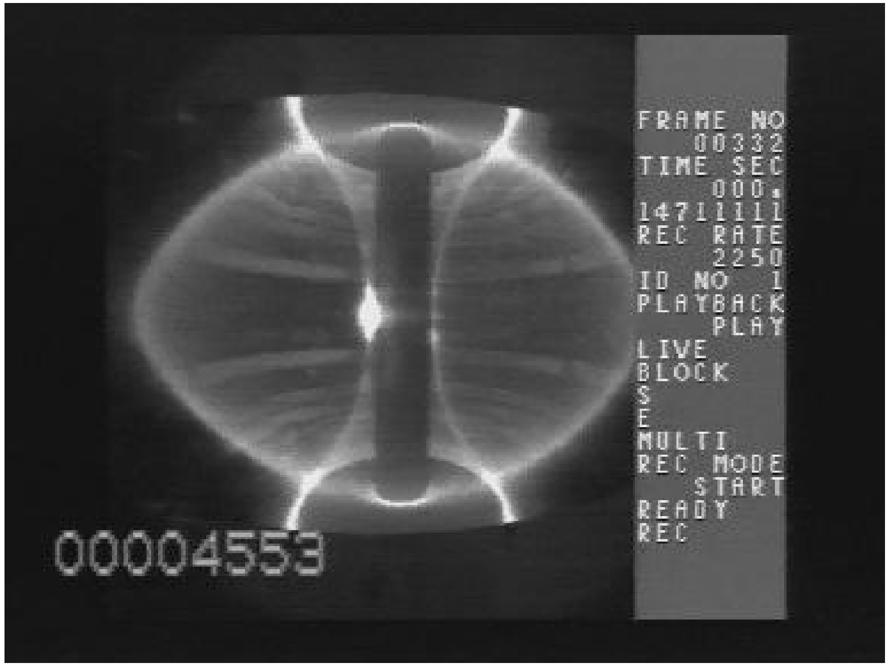
- Example of sawteeth and ELMs

JET, Pulse 52022



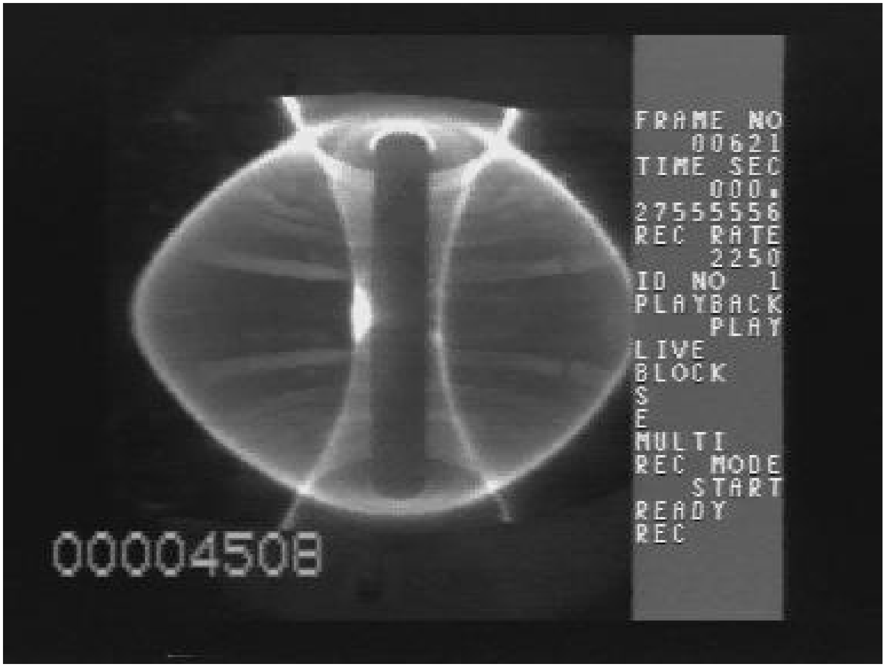
Edge Localised Mode (ELM)

MAST
MEGA-AMPERE SPHERICAL TOKAMAK

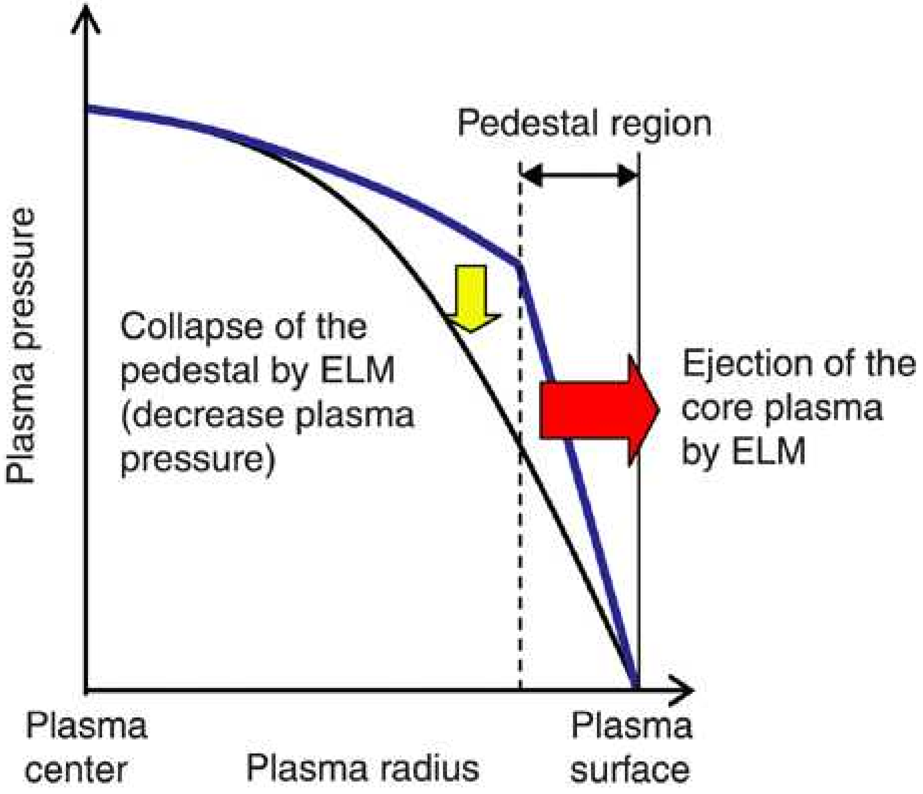


Edge Localised Mode

Disruption



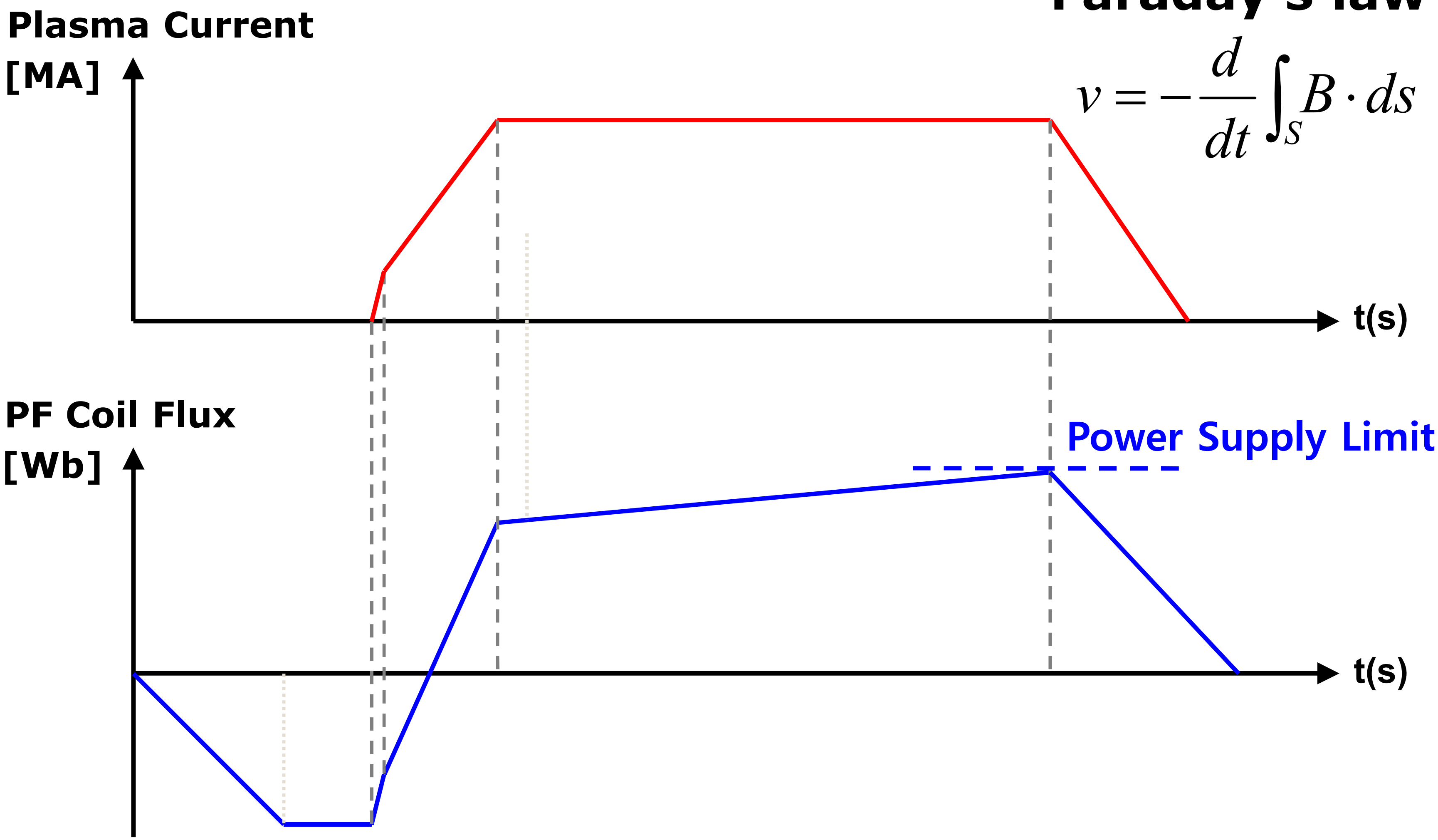
Edge Localised Mode (ELM)



H-mode: Limitation

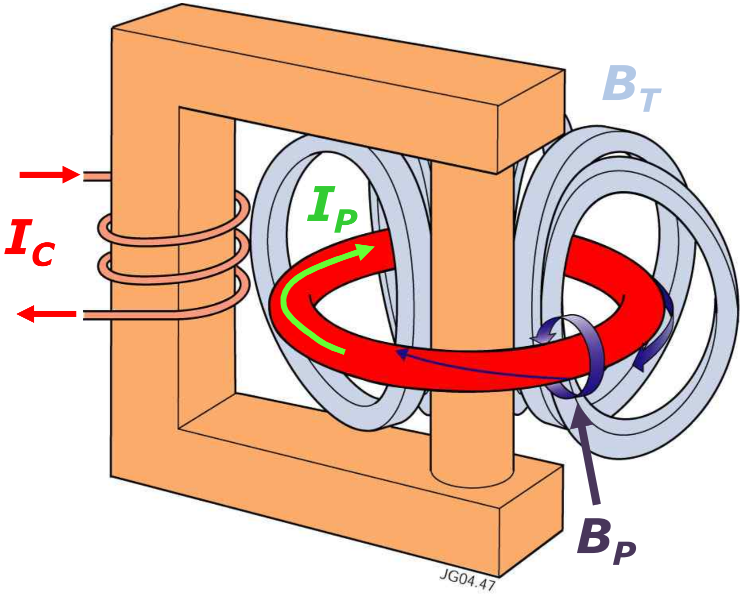
Faraday`s law

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



Inherent drawback of Tokamak!

H-mode: Limitation



Faraday‵s law

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

$$\frac{dI_C}{dt} \xrightarrow[\text{induction}]{\text{By}} I_{OH}$$

$I_P = I_{OH} + I_{NI}$ **Standard inductive operation**

$I_P = 0 + I_{NI}$ **Non-inductive operation**

steady state scenario: producing continuous fusion power in a tokamak reactor.

References

- E. Joffrin, “Advanced tokamak scenario developments for the next step”, 34th EPS Conference, Warsaw 2007
- A. C. C. Sips, Seminars