Fusion Reactor Technology 2
(459.761, 3 Credits)

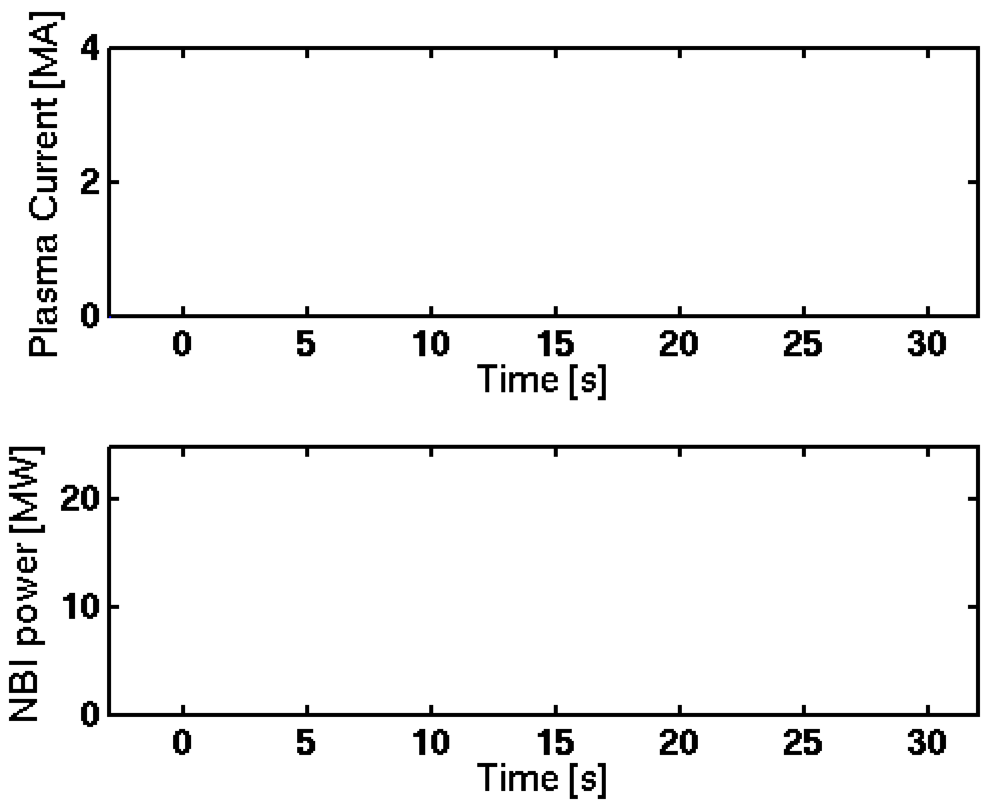
Prof. Dr. Yong-Su Na

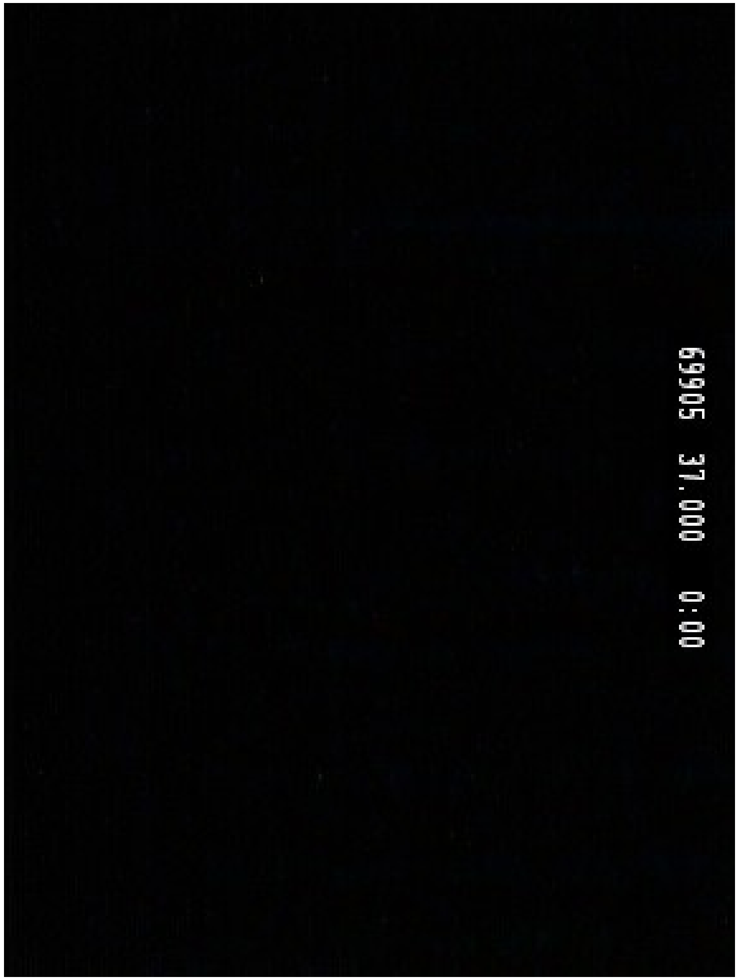
(32-206, Tel. 880-7204)

Tokamak Operation Scenario

JET pulse 69905 (B_T = 3.1 T)

Plasma Initiation	Current Ramp-up	High Power Phase	Plasma Quench

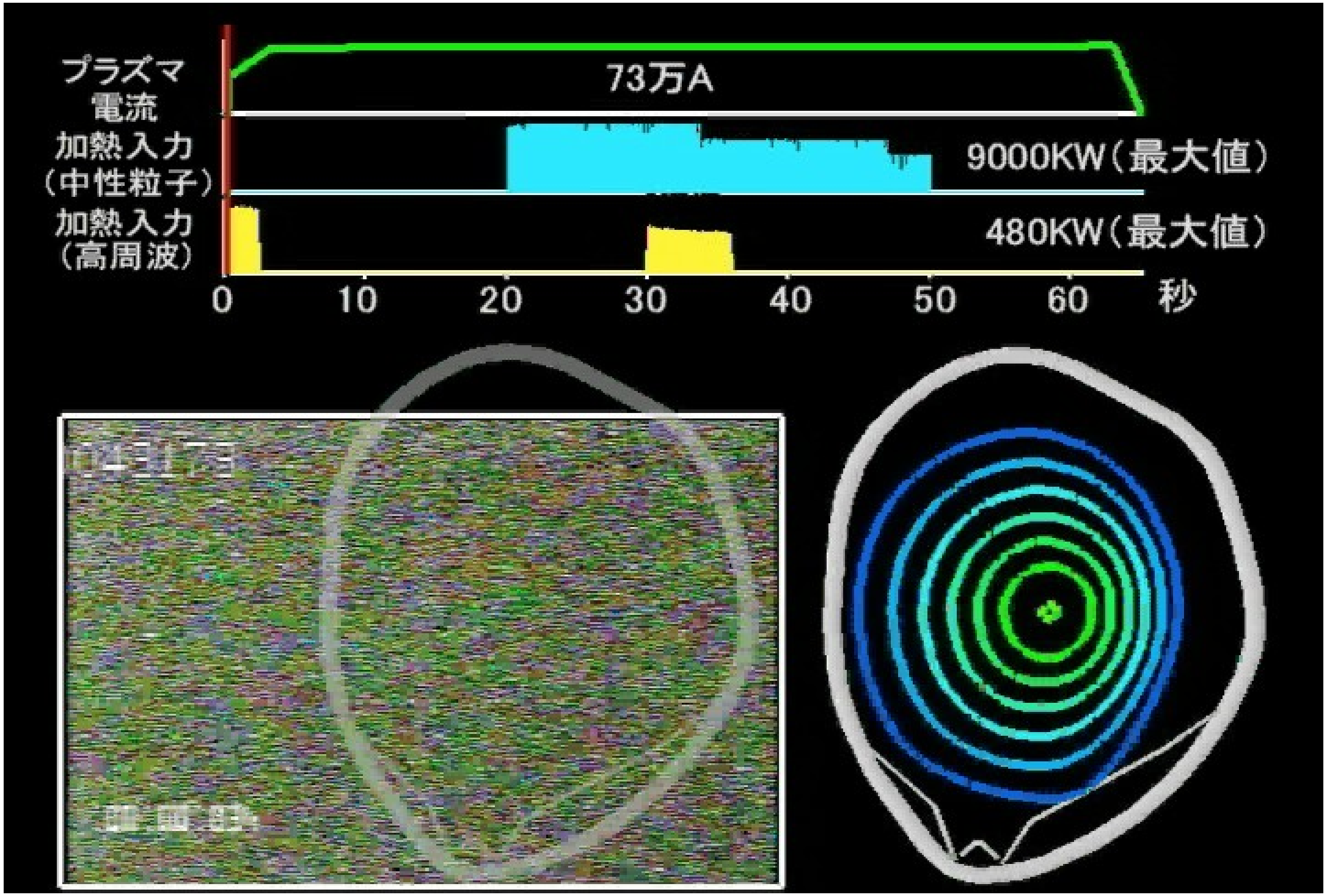




Scenario: sequence of actions making a plasma discharge.

Tokamak Operation Scenario

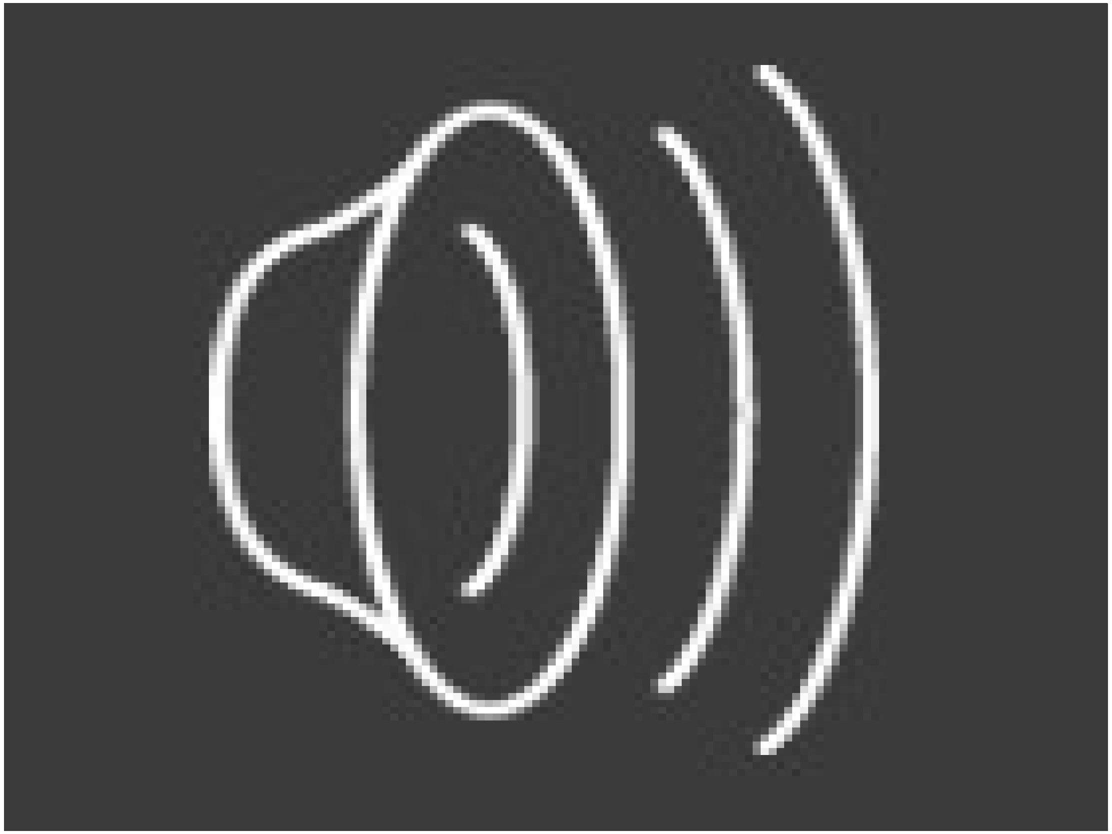
JT-60U



S. Ide et al. NF 45 S48 (2005)

Advanced tokamak operation

- **Conventional H-mode operation**



ITER 15MA baseline H-mode operation (S.H. Kim, PPCF 51)

- **Hybrid (advanced inductive) operation**
  - High confinement (H_{98}=1.2~1.4)
  - High non-inductively driven current & long-pulse
  - However it requires a flat q profile at the core region
- **Steady-state operation**
  - Very high confinement (H_{98} >1.4, ITBs)
  - Almost fully non-inductive operation
  - However it requires a reversed q profile to be favourable for forming/sustaining ITBs.

❖ **Advanced tokamak operation requires an active plasma profile control**

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

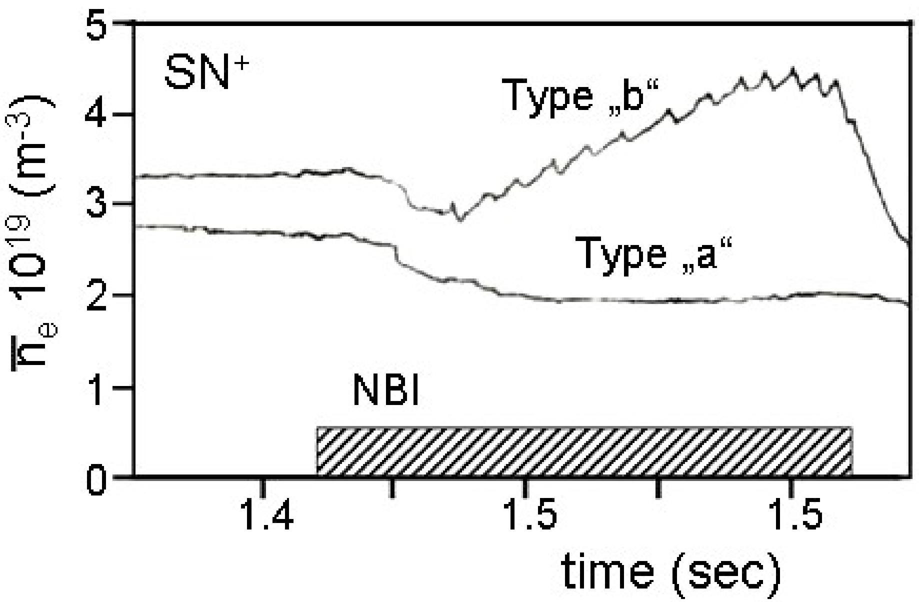
(Received 6 August 1982; revised manuscript received 1 October 1982)

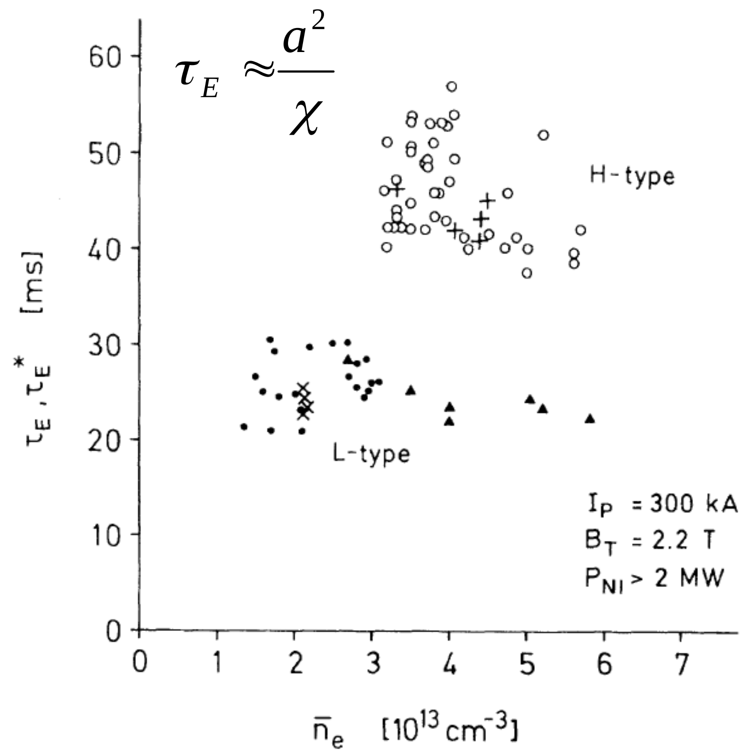
A new operational regime has been observed in neutral-injection–heated ASDEX divertor discharges. This regime is characterized by high β_p values comparable to the aspect ratio A ($\beta_p \leqslant 0.65A$) and by confinement times close to those of Ohmic discharges. The high-β_p regime develops at an 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

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

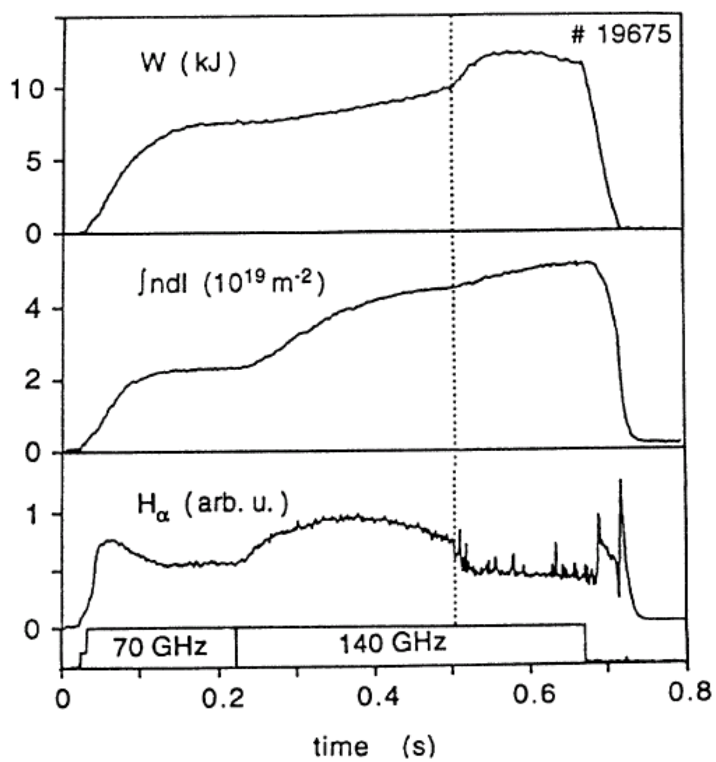


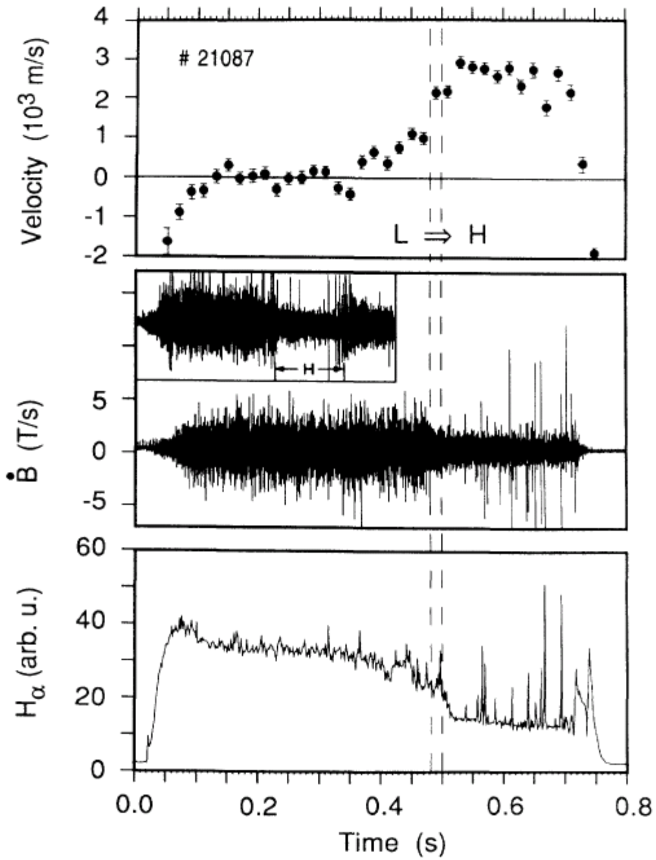


H-mode

- Established in stellarators as well

Wendelstein 7-AS

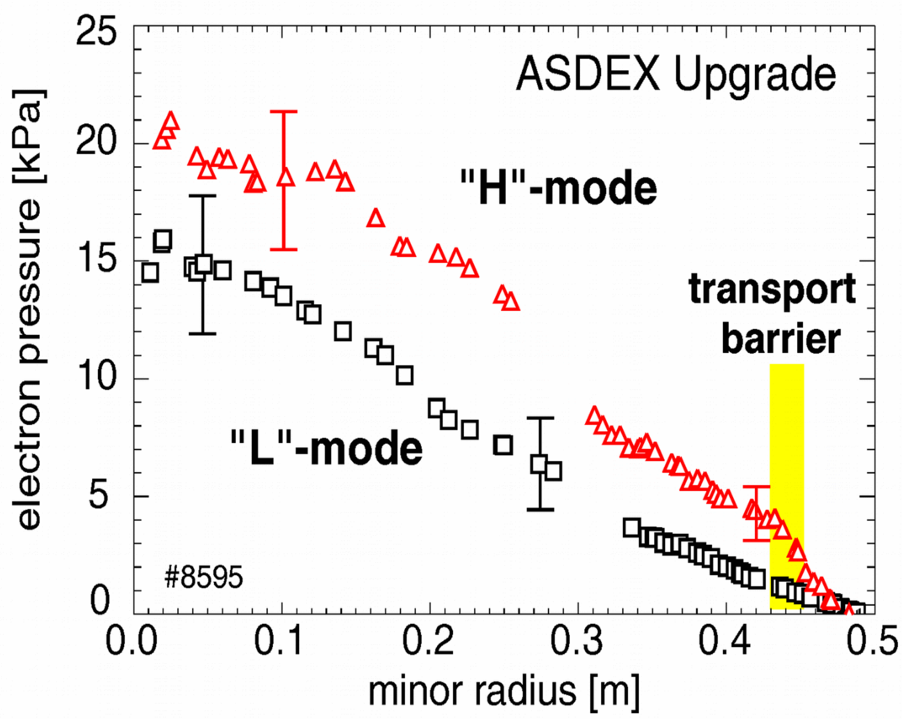




*V. Erckmann et al, Physical Review Letters **70** 2086 (1993)*

H-mode

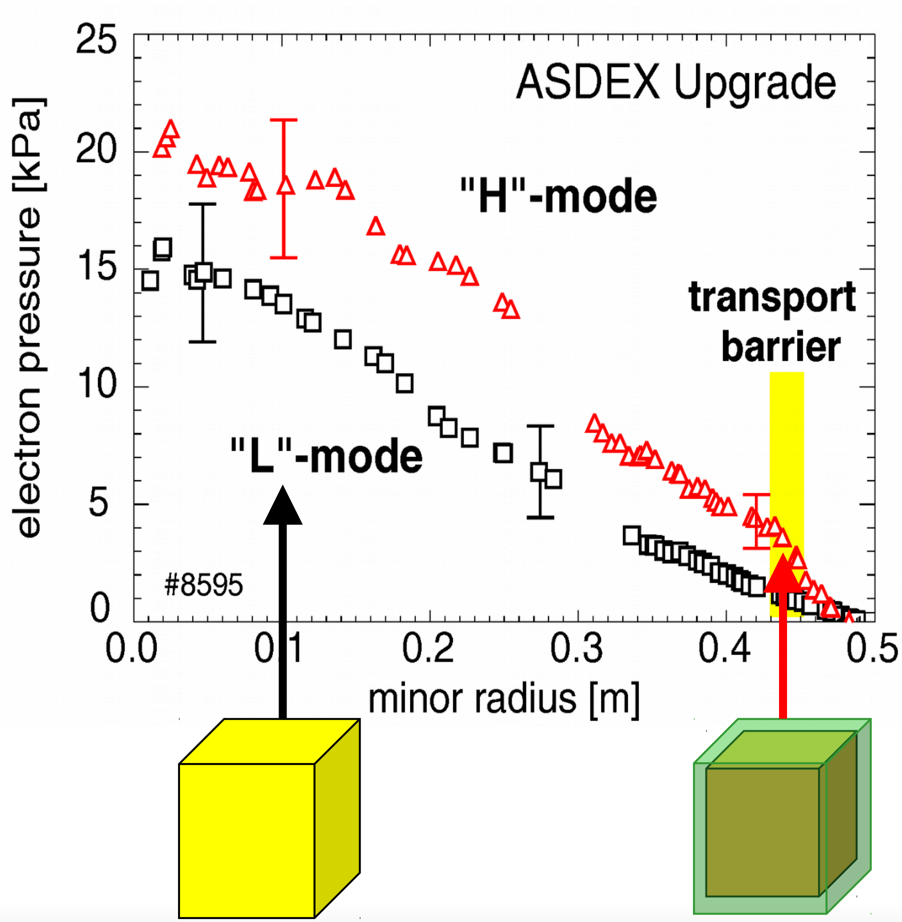
- 1982 IAEA F. Wagner et al. (ASDEX, Germany)
- Transition to H-mode: State with reduced turbulence at the plasma edge
- Formation of an edge transport barrier: Steep pressure gradient at the edge



Hoover dam

H-mode

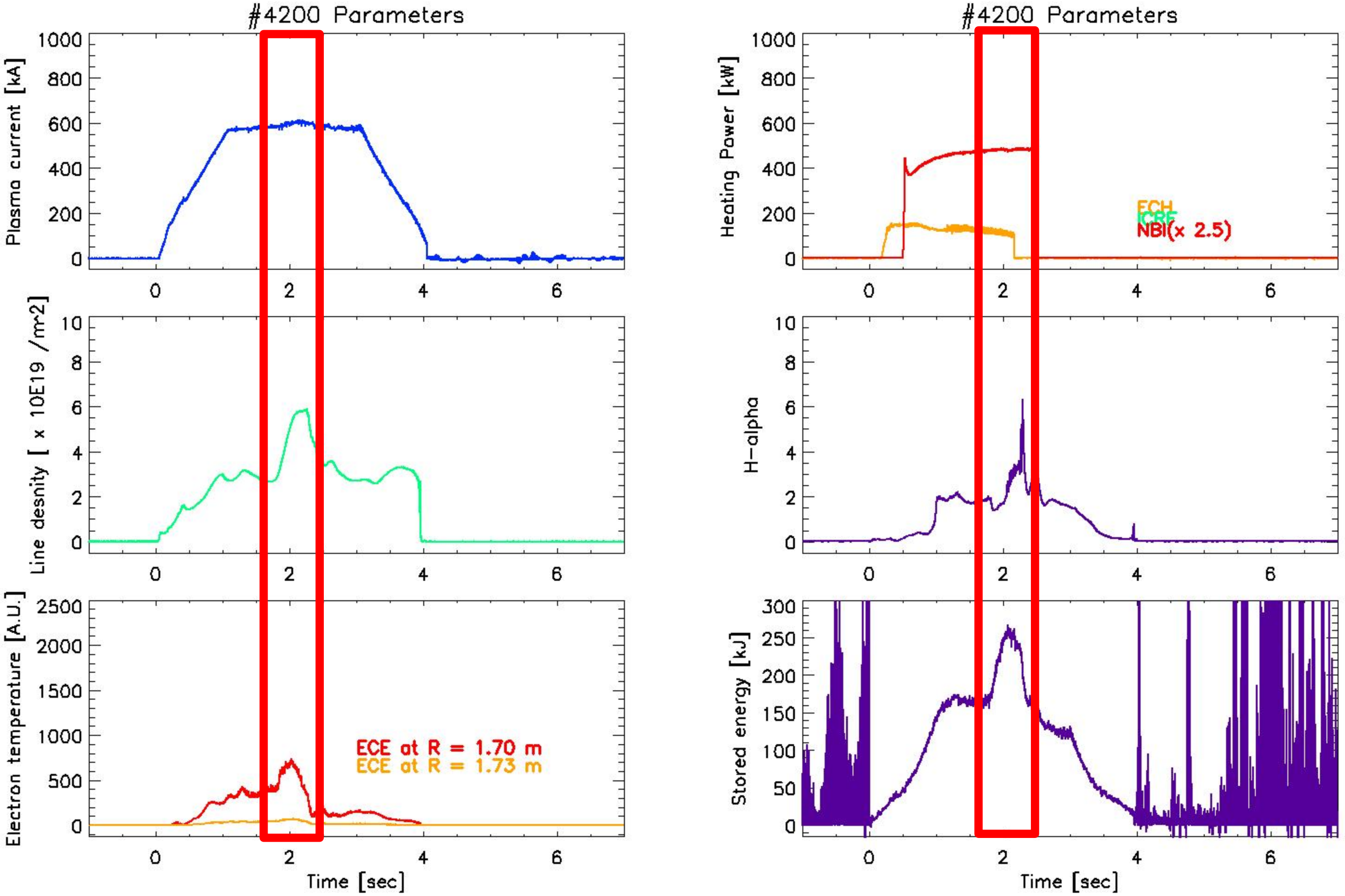
- 1982 IAEA F. Wagner et al. (ASDEX, Germany)
- Transition to H-mode: State with reduced turbulence at the plasma edge
- Formation of an edge transport barrier: Steep pressure gradient at the edge



Hoover dam

H-mode

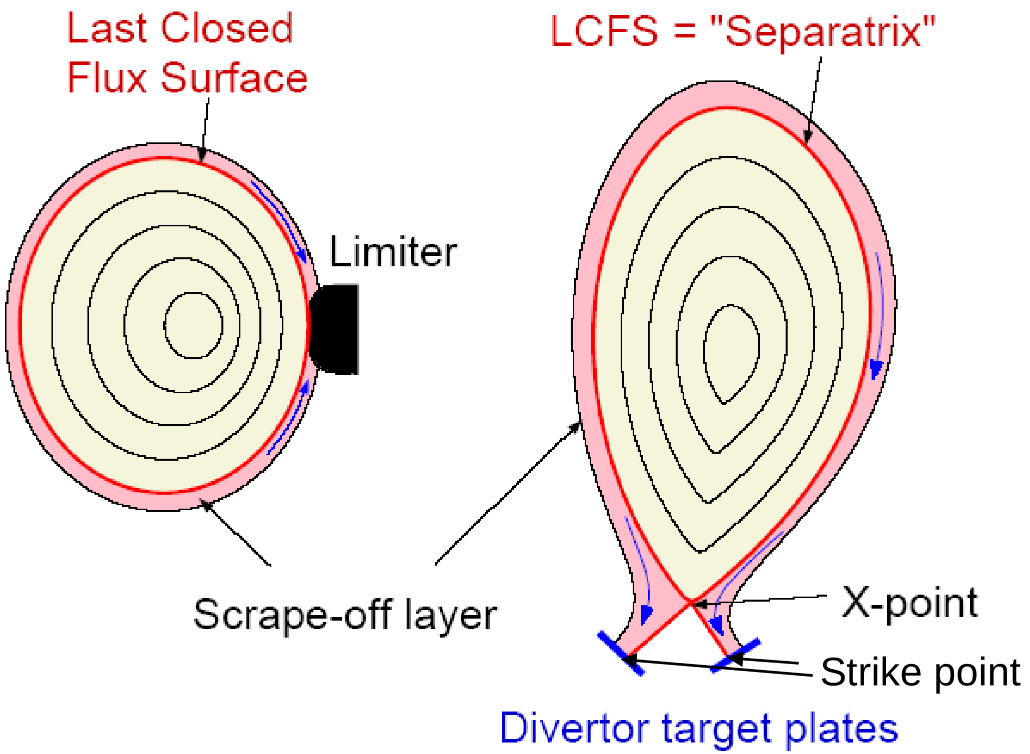
- **First H-mode Transition in KSTAR (November 8, 2010)**



- 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?

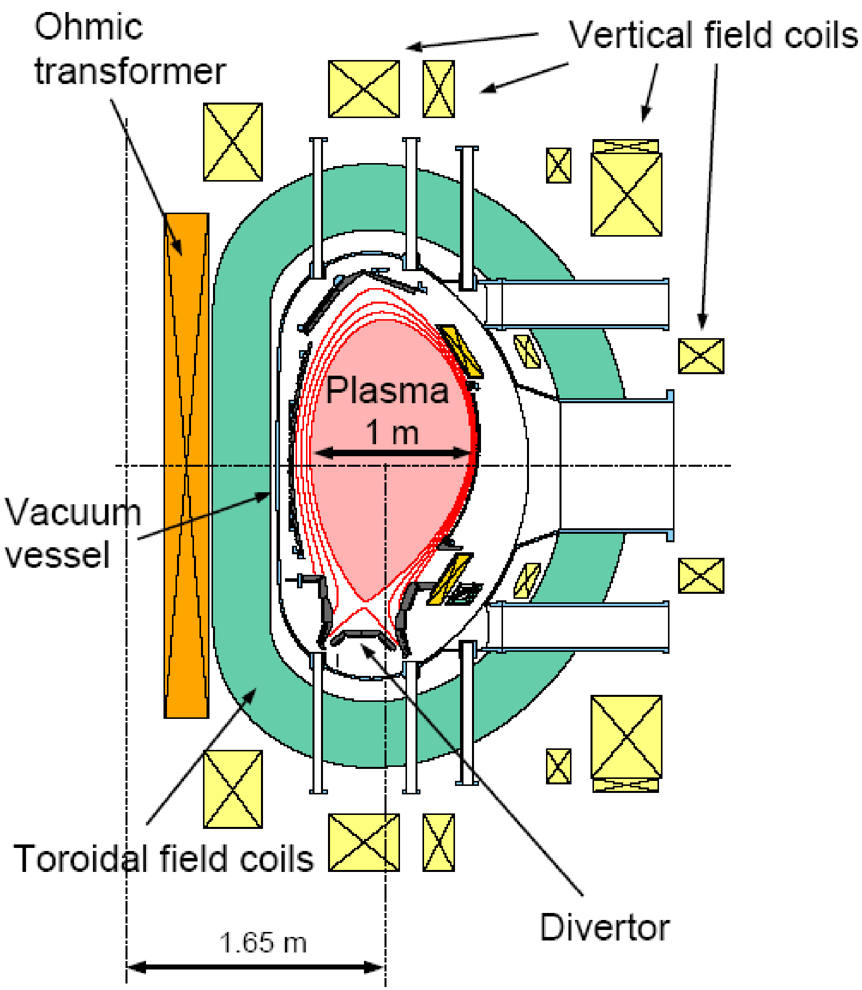
- **Separation of plasma from wall by a limiter and a divertor**

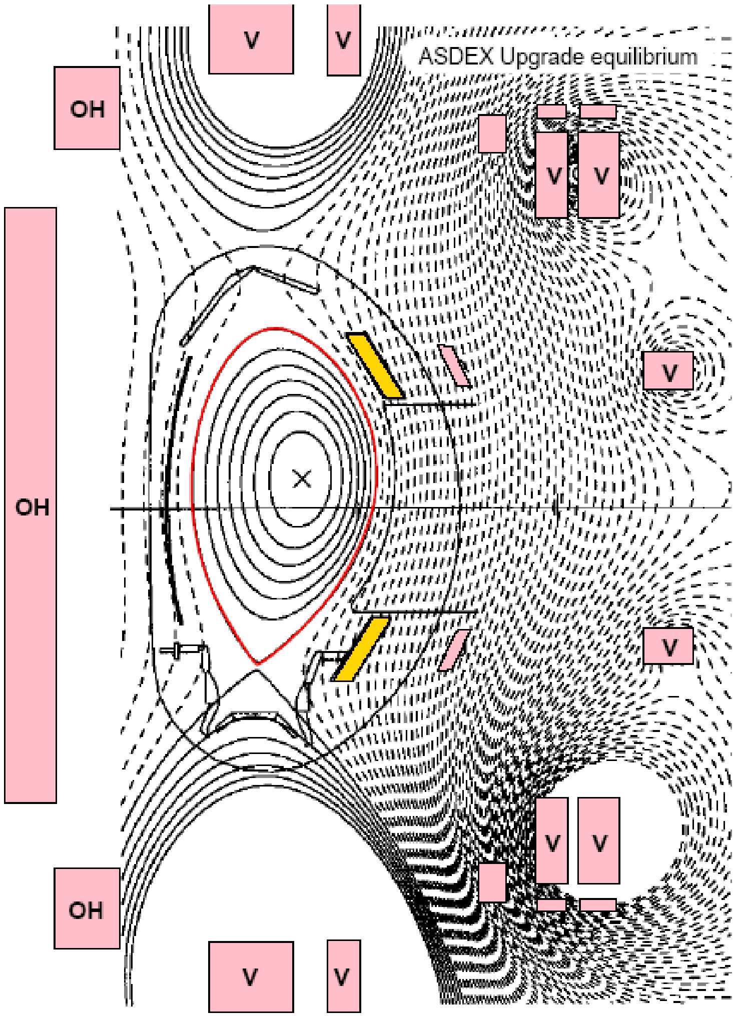


- Advantage of the divertor configuration

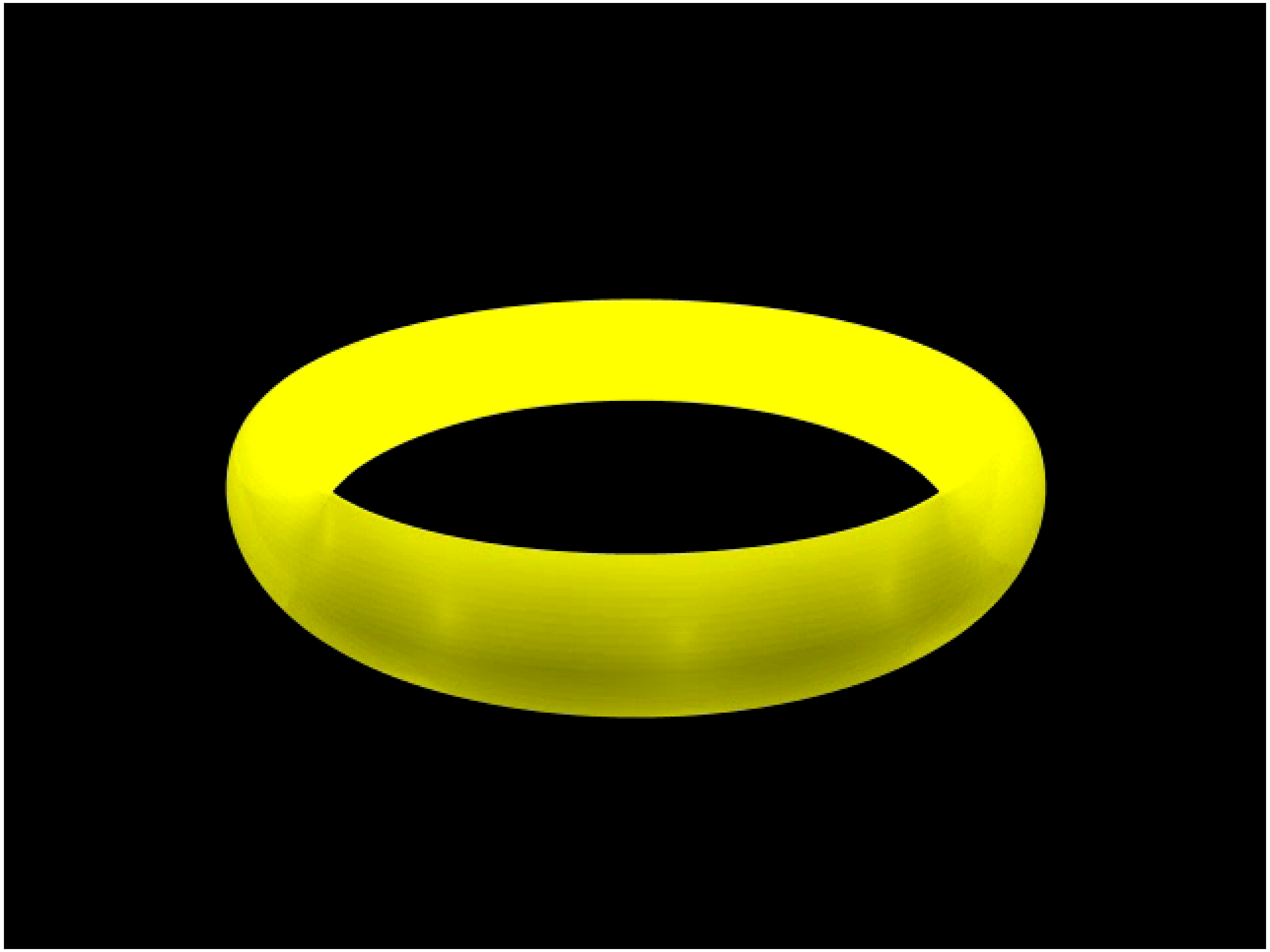
- First contact with material surface at a distance from plasma boundary
- Reducing the influx of ionized impurities into the interior of the plasma by diverting them into an outer „SOL“

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

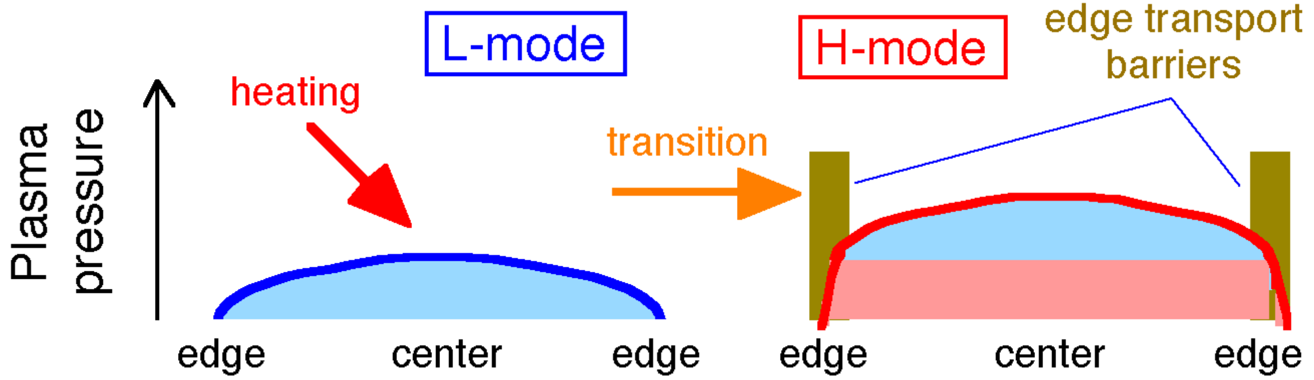
H-mode: How to?

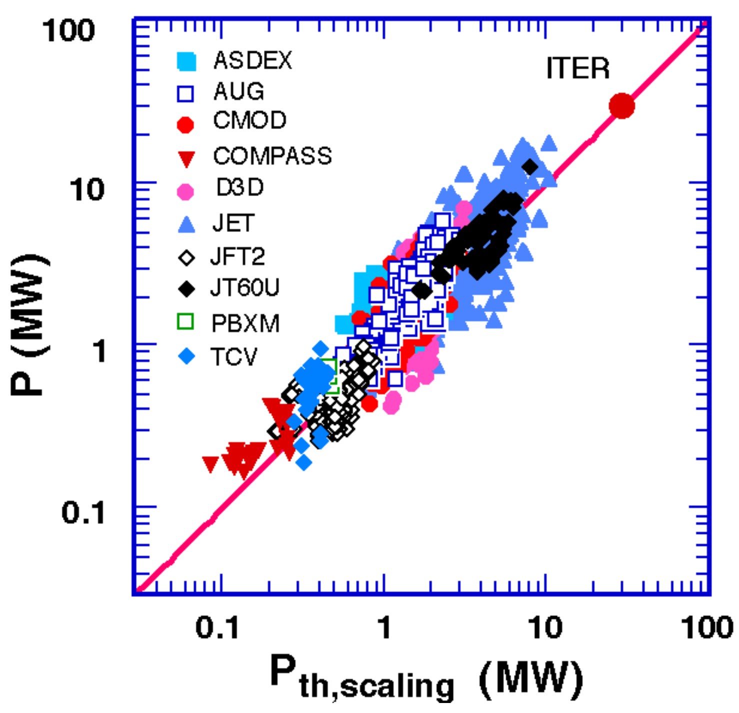


H-mode: How to?

- **Role of wall condition**

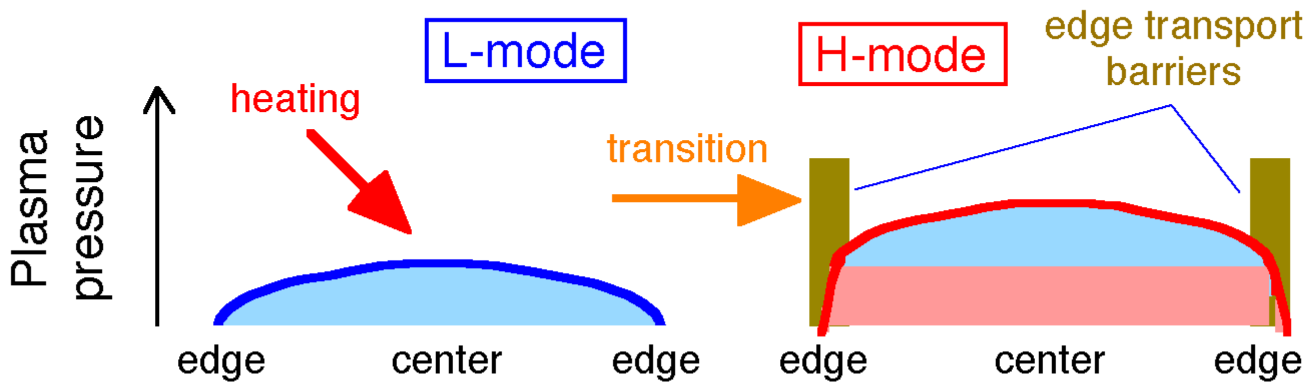
H-mode: How to?

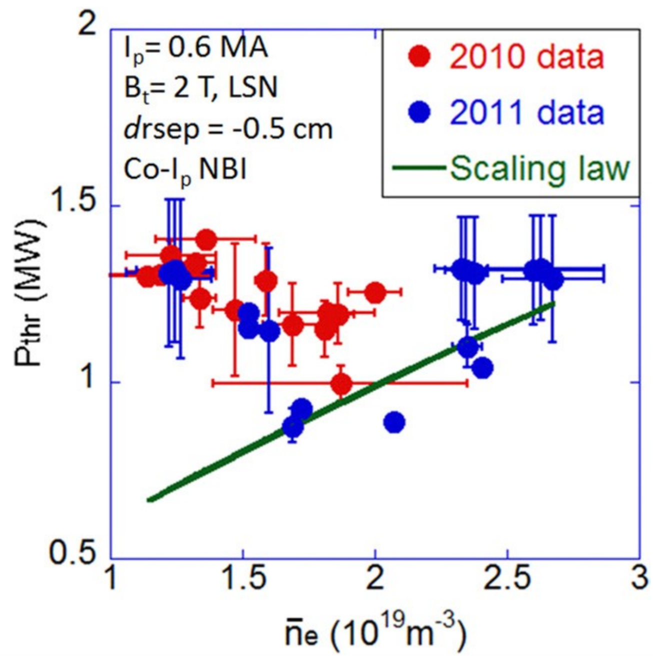




$$P_{th} = 2.84 M^{-1} B_t^{0.82} n_{20}^{0.58} R^{1.0} a^{0.81}$$

H-mode: How to?





KSTAR

$$P_{th} = 0.0488\pm0.0028\,n_{e20}^{0.717\pm0.035}B_t^{0.803\pm0.032}S^{0.941\pm0.019}$$

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

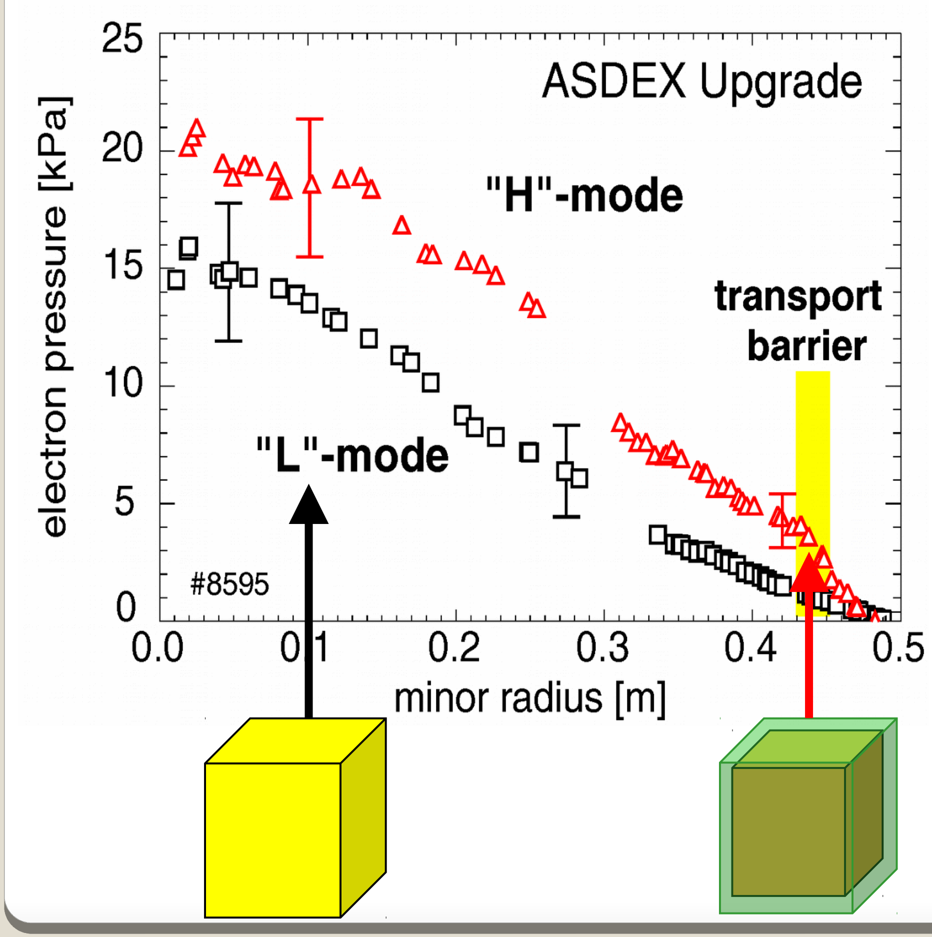
Note. Dependency of S taken from multi-machine comparison not from single machines

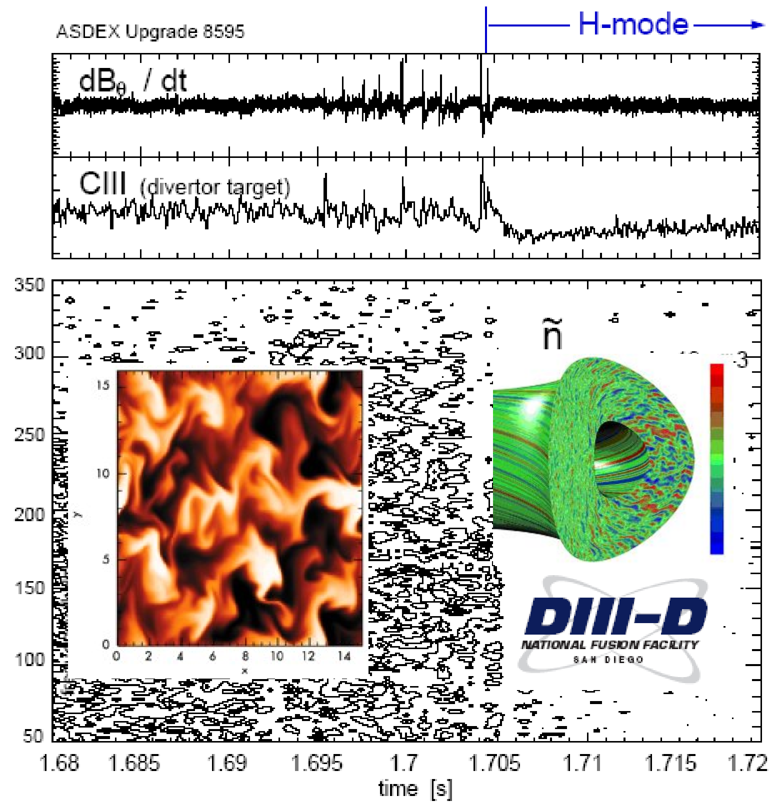
$$P_{loss} = P_{OH} + P_{NBI}^{inj} - P_{NBI}^{loss} + P_{EC}^{inj} - dW_{tot}/dt$$

J-W. Ahn, H.-S. Kim et al., Nucl. Fusion 52 114001 (2012)

H-mode: Why?

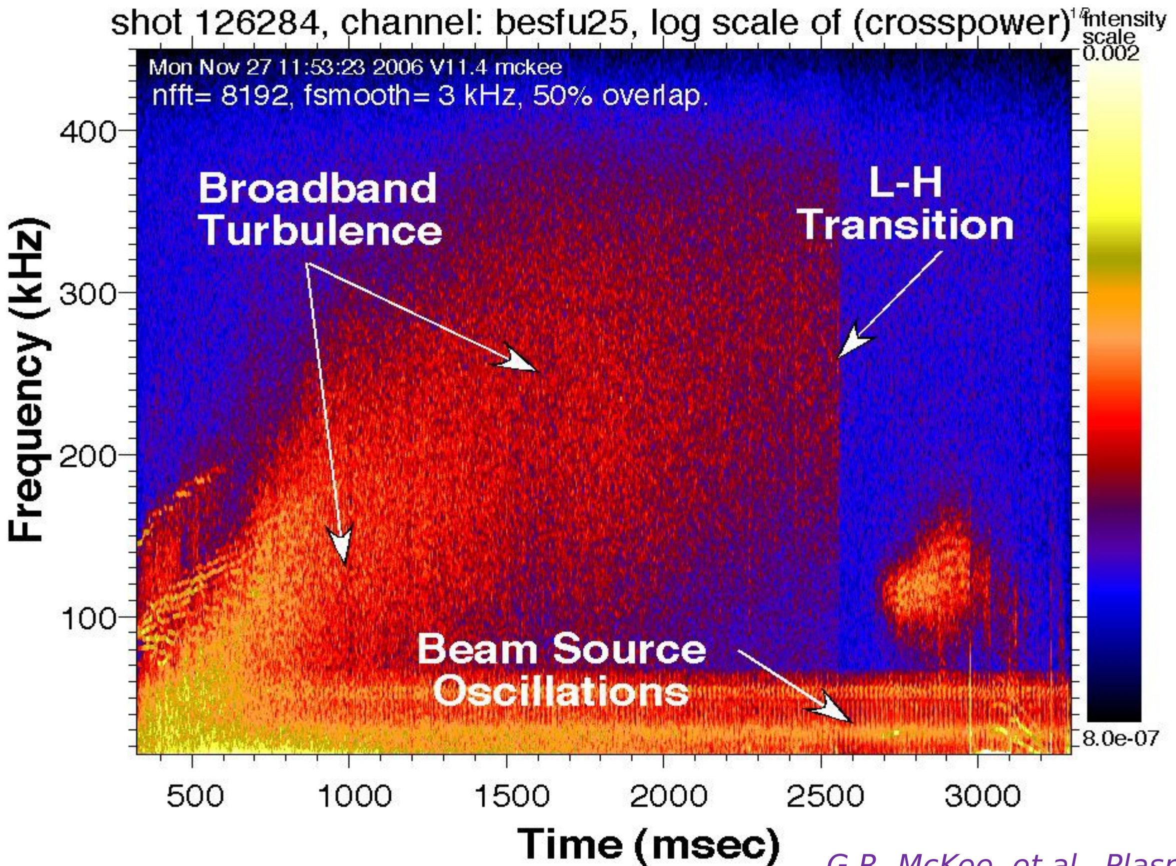
- 1982 IAEA F. Wagner et al. (ASDEX, Germany)
  - Transition to H-mode: State with reduced turbulence at the plasma edge
  - Formation of an edge transport barrier: Steep pressure gradient at the edge





H-mode: Why?

- 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

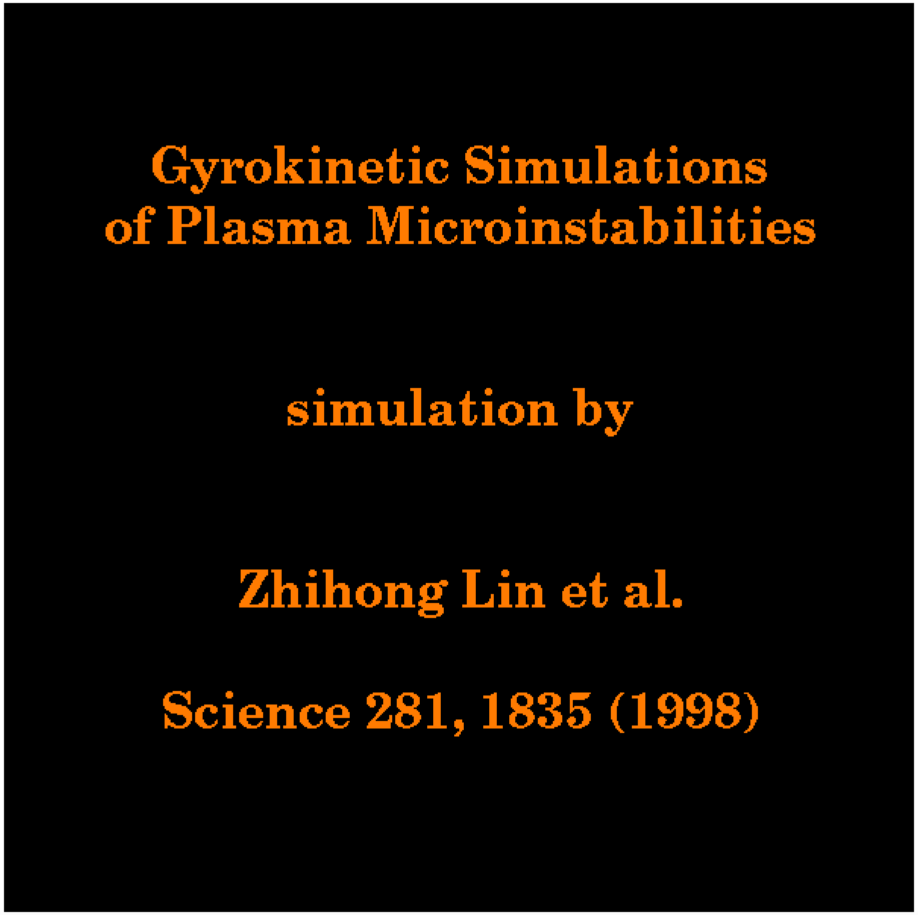


Density fluctuations at $r/a = 0.65$ measured by beam emission spectroscopy

G.R. McKee, et al. Plasma Fusion Res. 2 S1025 (2007)

H-mode: Why?

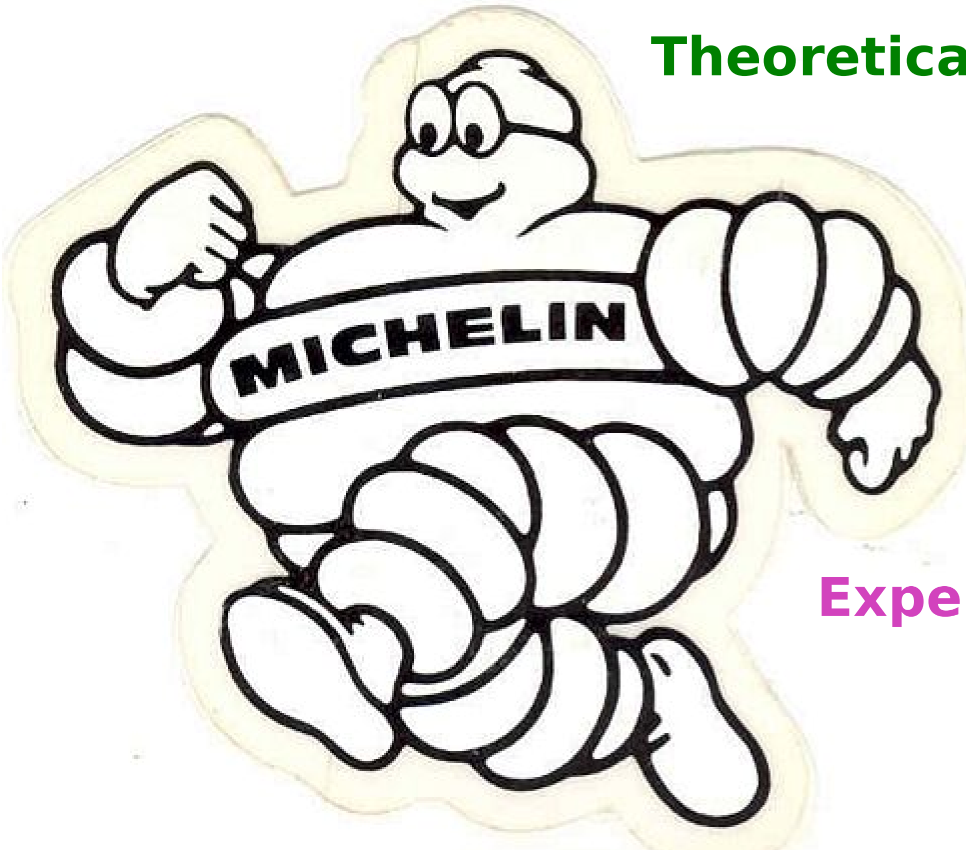
- 1982 IAEA F. Wagner et al. (ASDEX, Germany)
  - Transition to H-mode: State with reduced turbulence at the plasma edge
  - Formation of an edge transport barrier: Steep pressure gradient at the edge



H-mode: Why?

Theoretical physics

H-mode: Why?

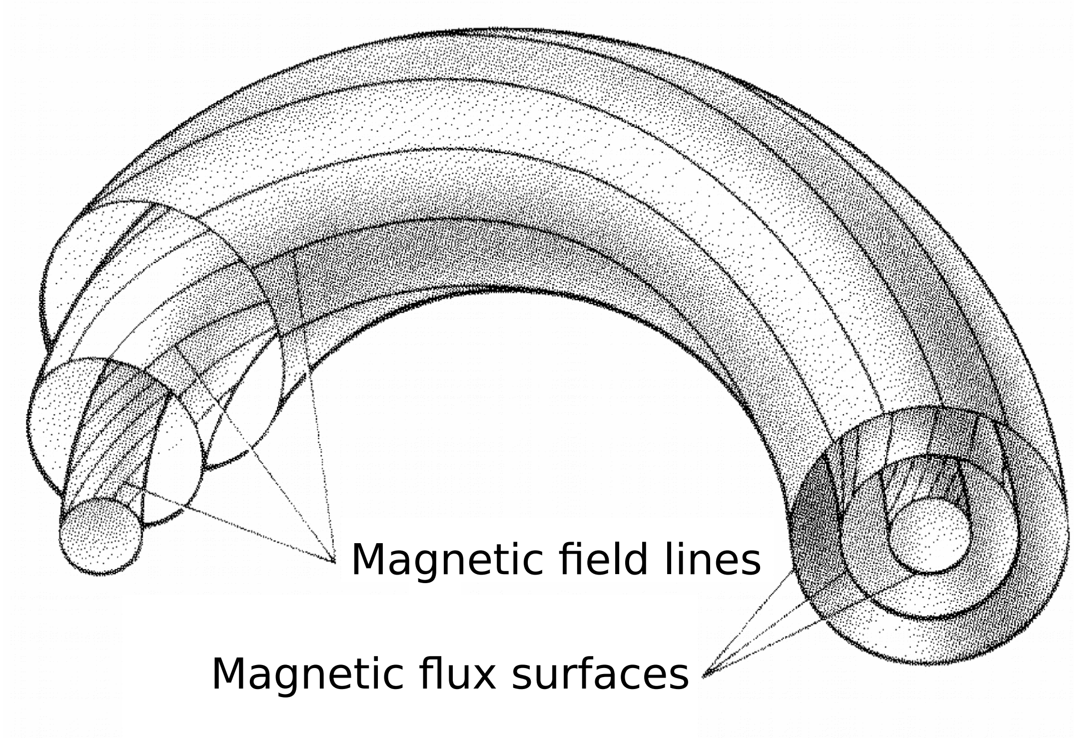


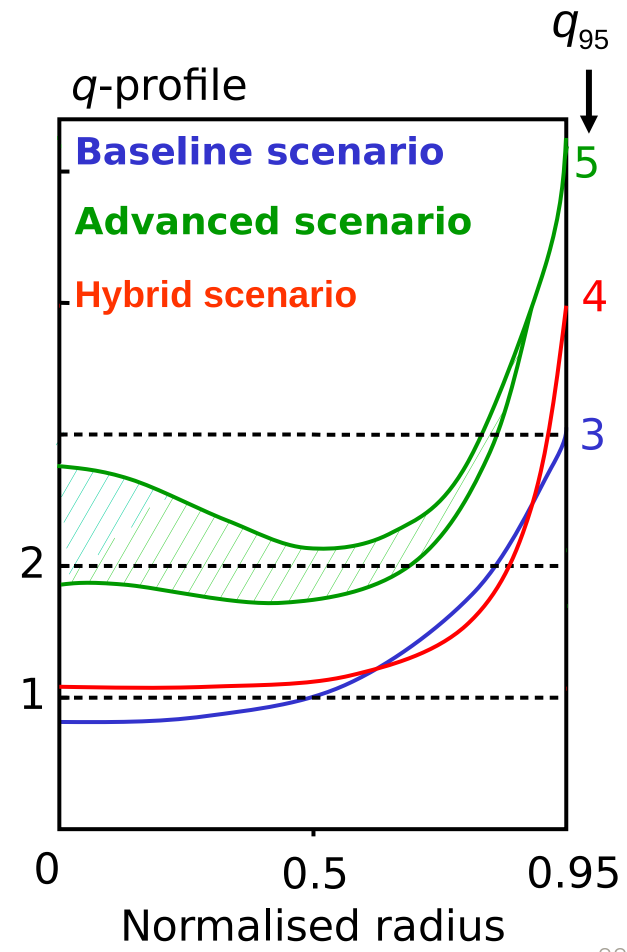
Theoretical physics

Experimental physics

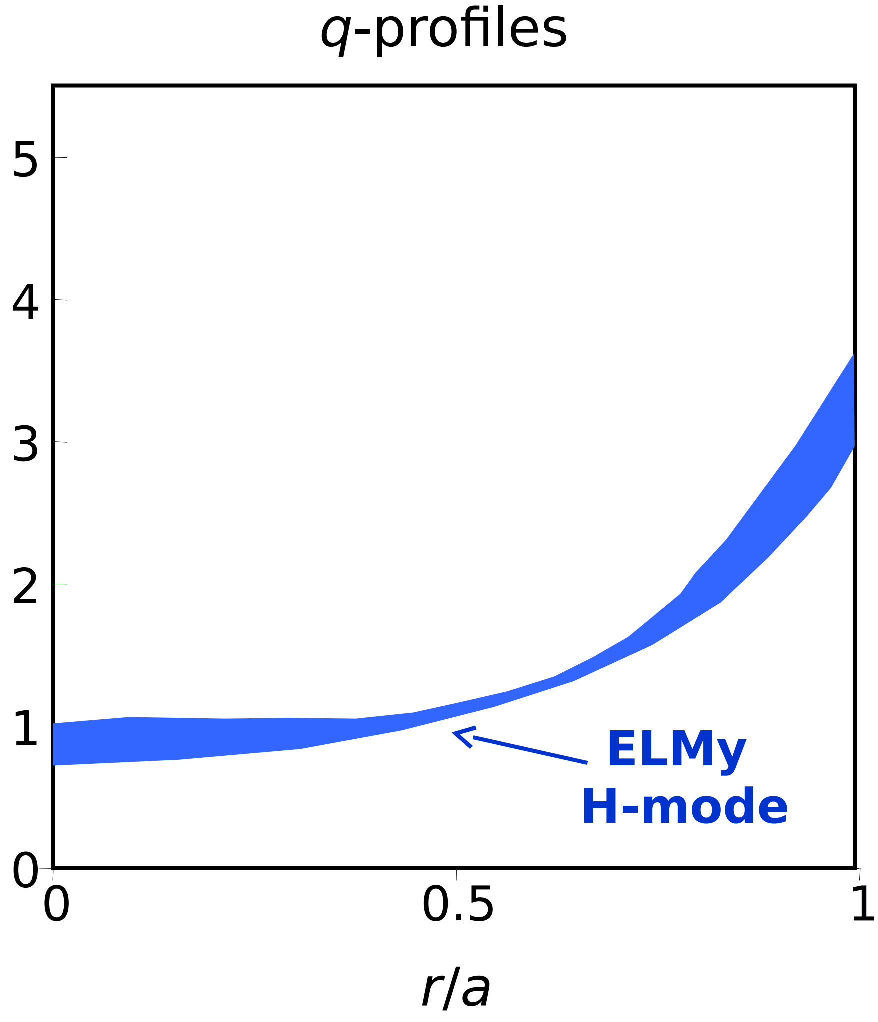
Basic Tokamak Variables

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

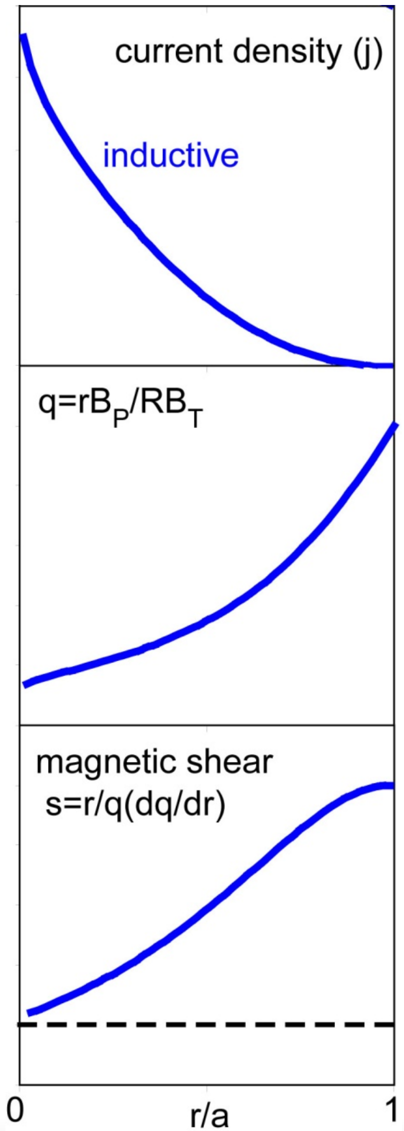


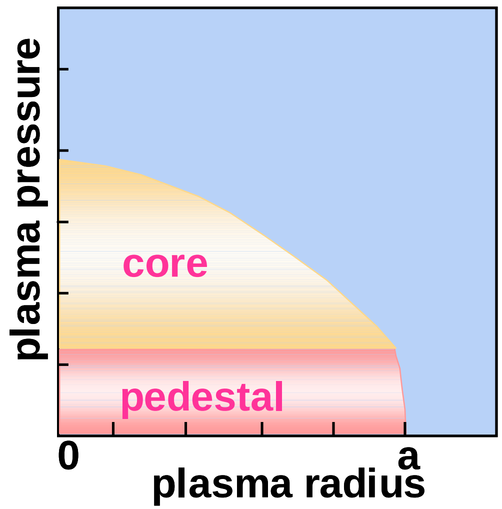


Tokamak Operation Modes



Conventional Operation Mode – H-mode

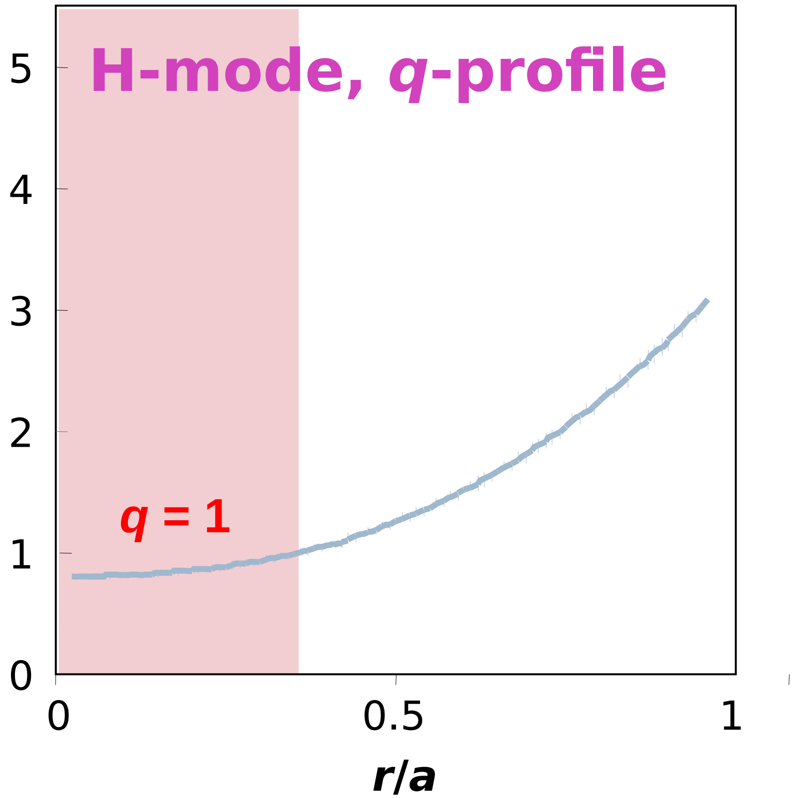




- Mild pressure gradient with steep edge pedestal
- Naturally peaked current profile
- Monotonic *q*-profile
- Positive magnetic shear

H-mode: Limitations

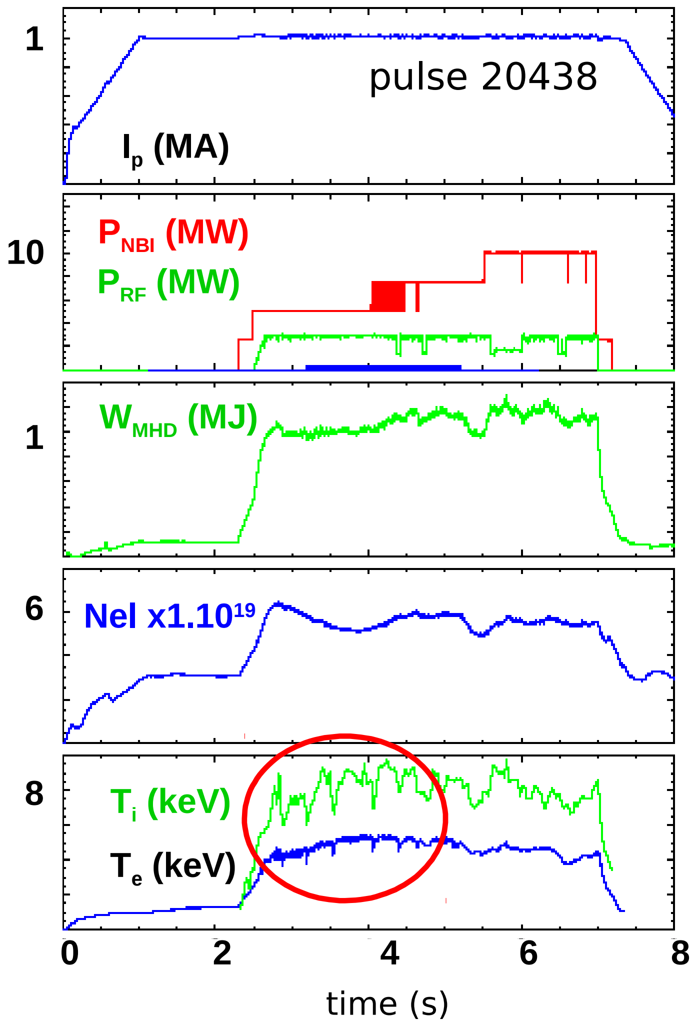
- Stability of H-mode plasmas related safety factor profile: $q(r)$

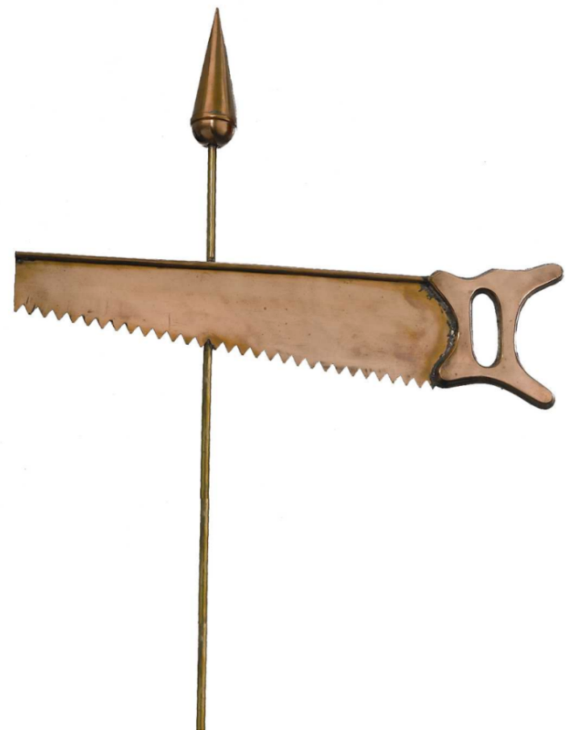


$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

Sawtooth

ASDEX Upgrade

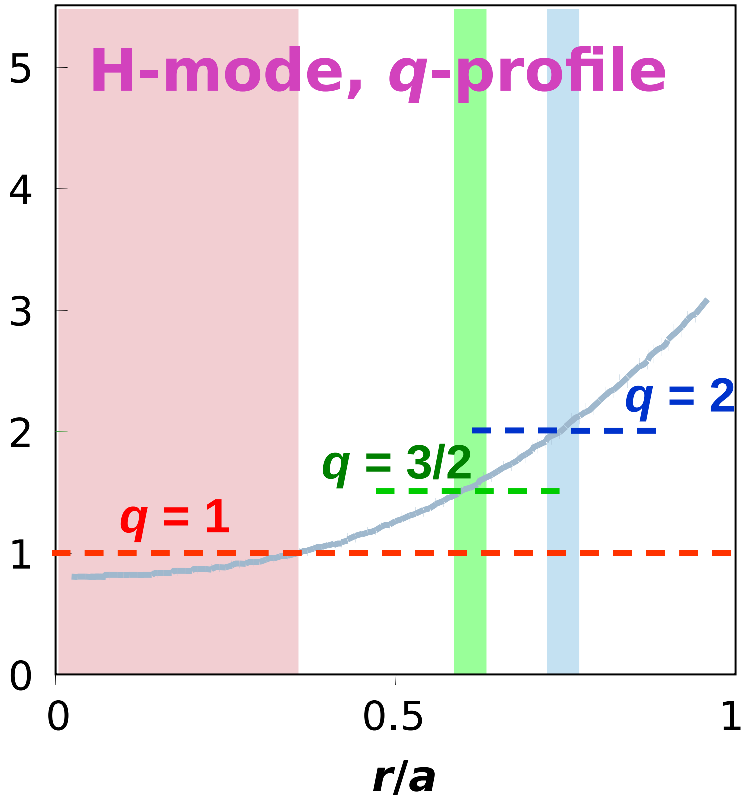




- nonlinear low-*n* internal mode
- internal (minor) disruption
- enhanced energy transport in the plasma centre

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

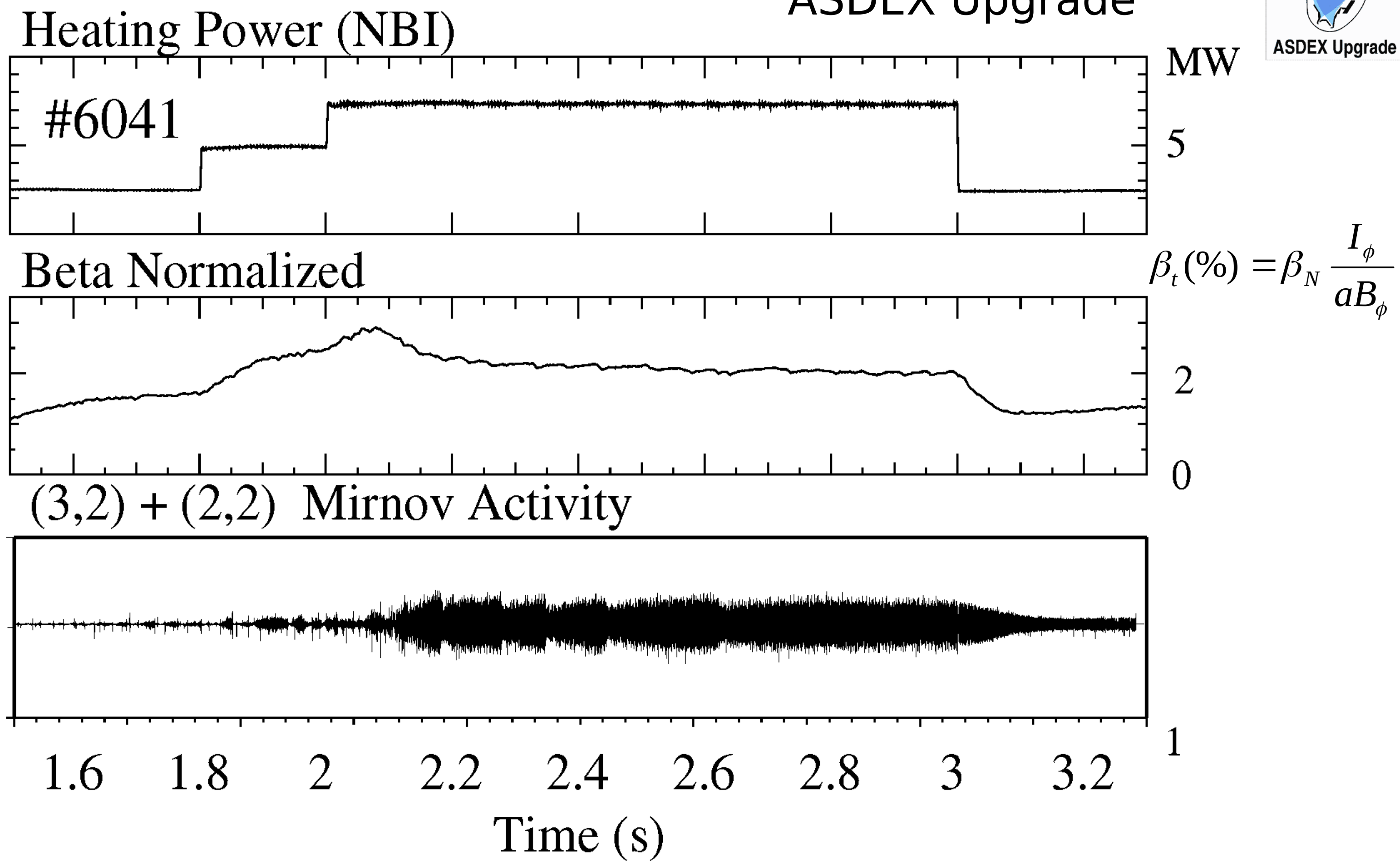
$q = 3/2$ and $q = 2$:

Neoclassical Tearing Modes (NTMs):

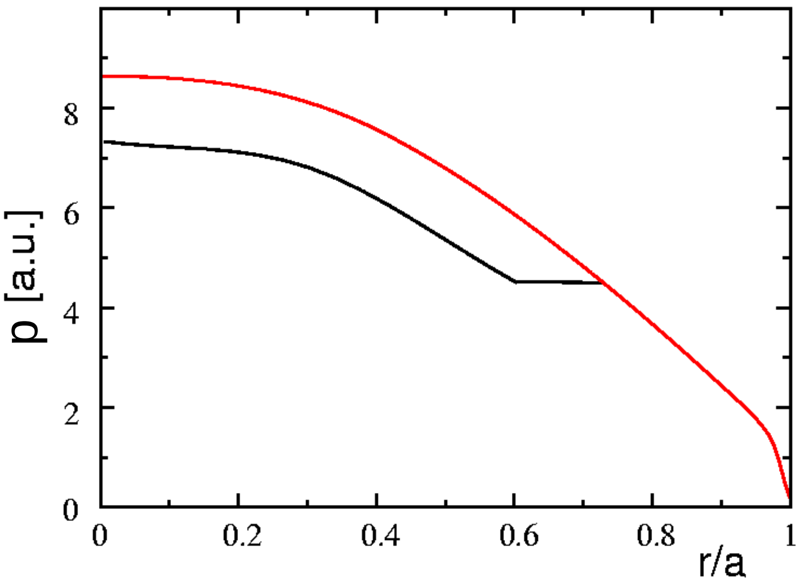
- limit the achievable $\beta \equiv 2\mu_0 p/B^2$
- degrade confinement (+ disruptions)
- often triggered by sawteeth

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

Neoclassical Tearing Mode (NTM)

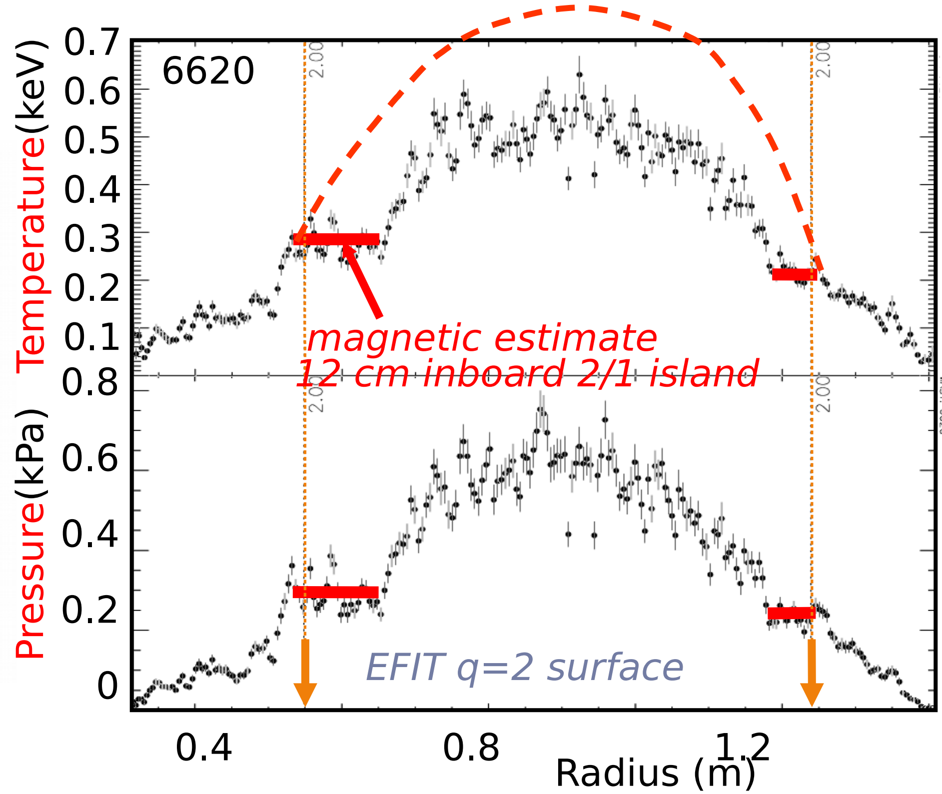


Neoclassical Tearing Mode (NTM)



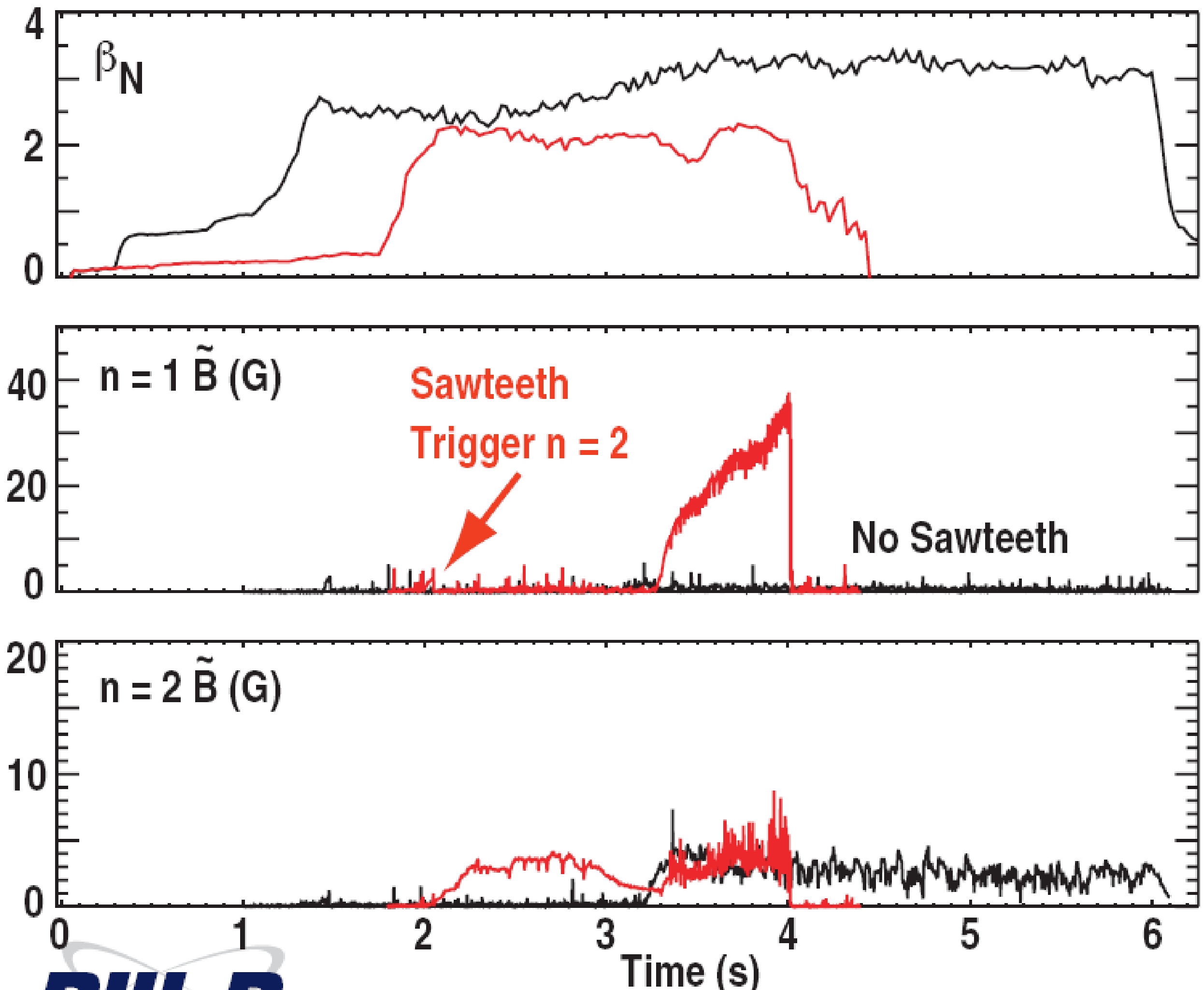
- Pressure flattening across magnetic islands due to large trans-
port
 coefficients along magnetic field lines

Neoclassical Tearing Mode (NTM)



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

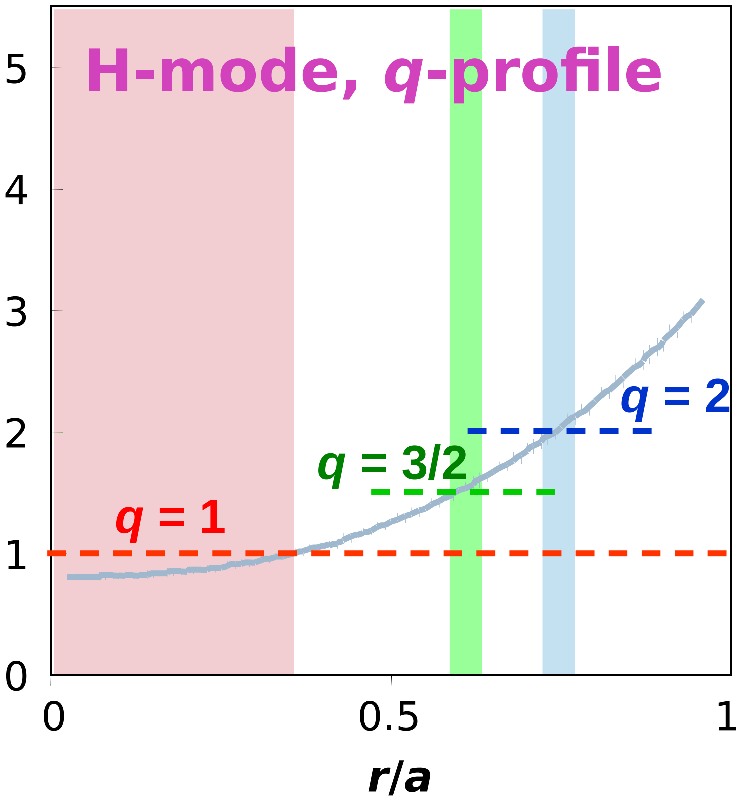
Neoclassical Tearing Mode (NTM)

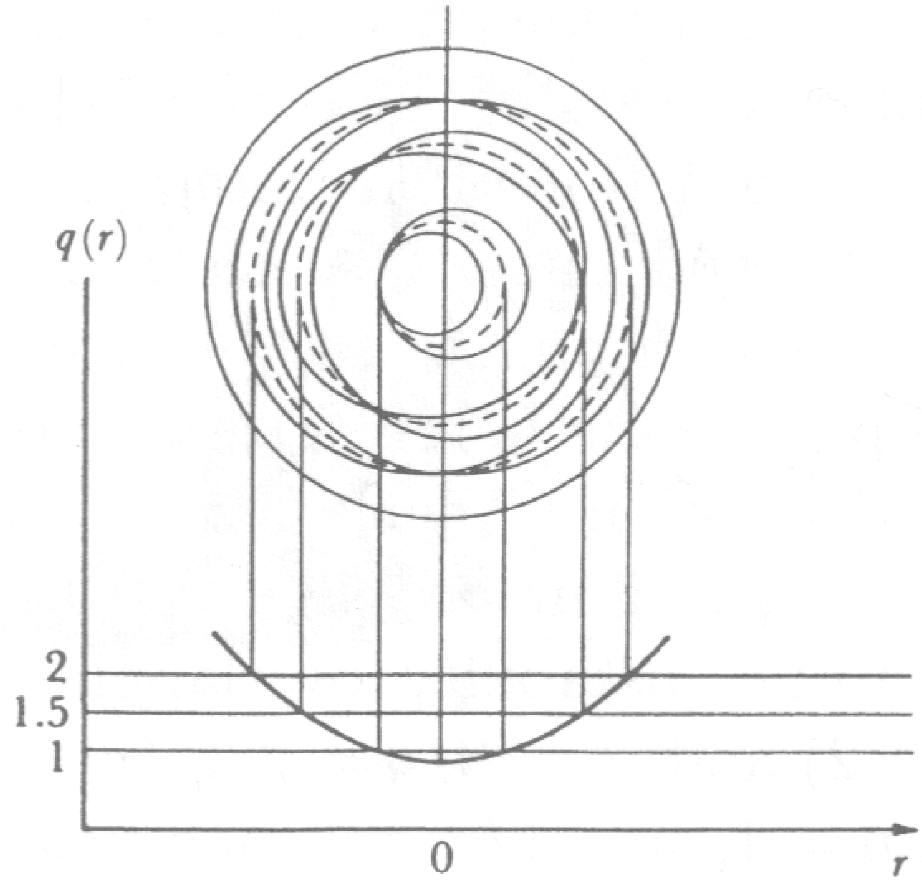


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

H-mode: Limitations

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

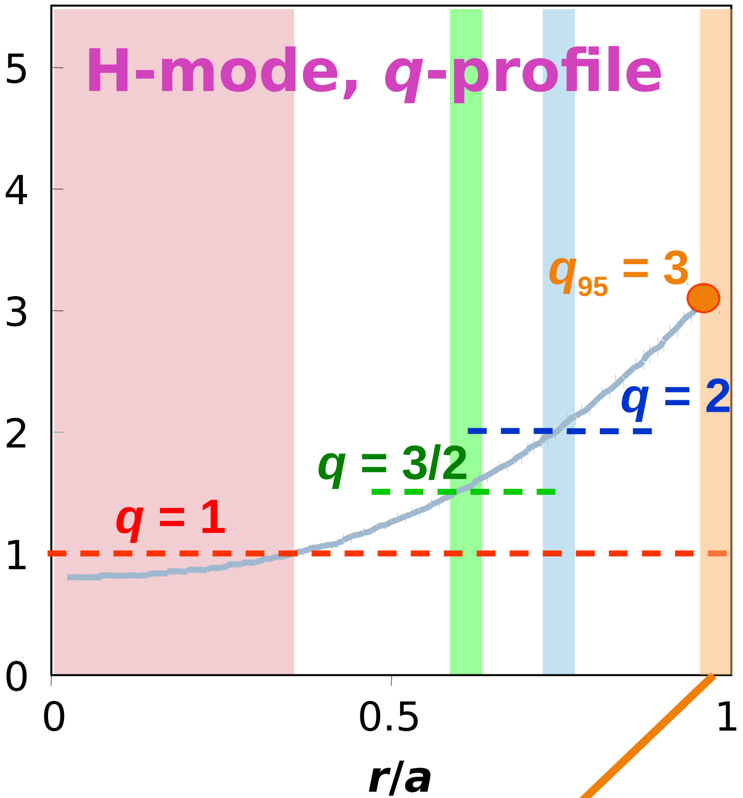




K. Miyamoto, "Controlled Fusion and Plasma Physics" Taylor & Francis (2007)

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

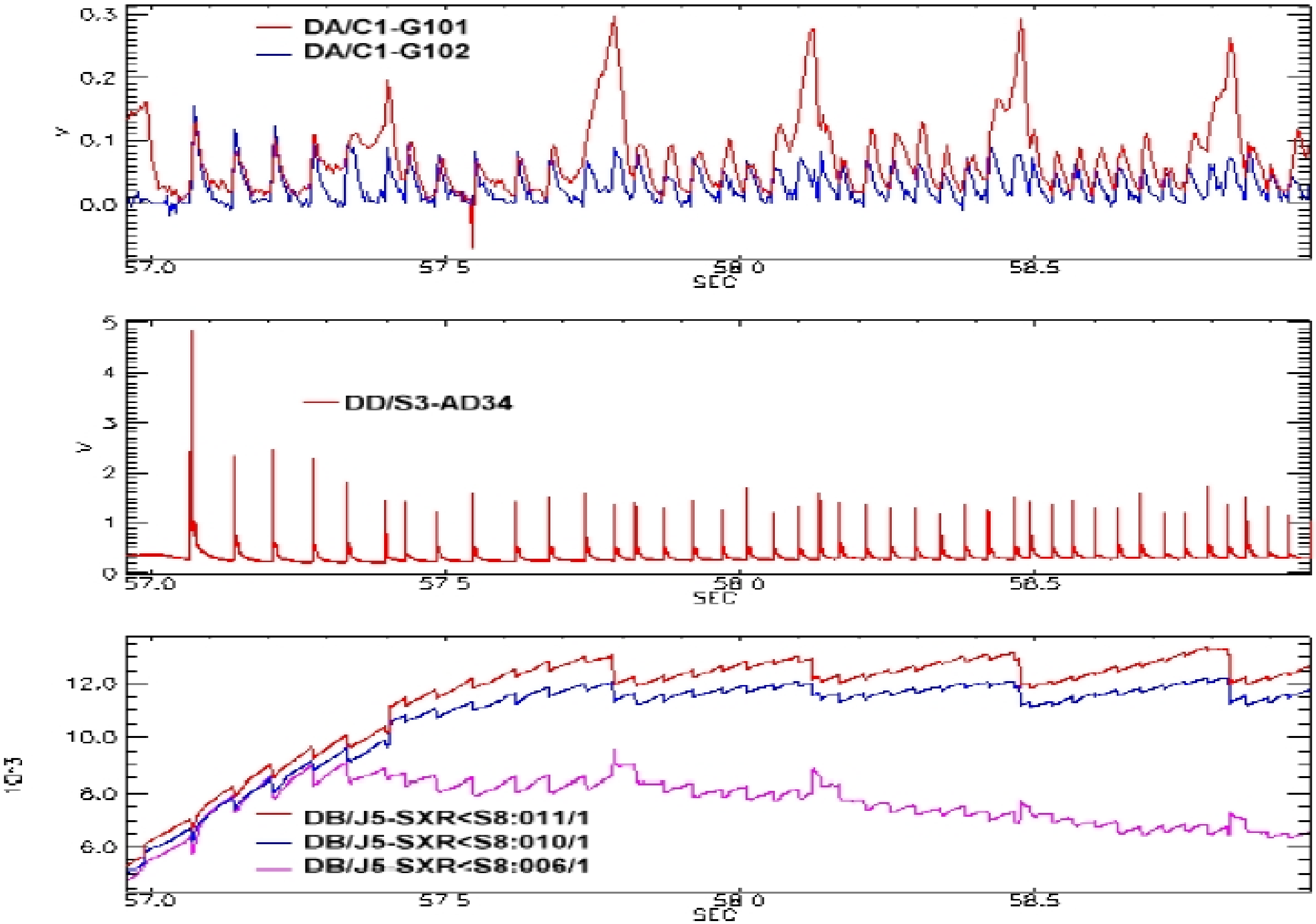
ITER work point is chosen conservatively: $\beta_N \leq 1.8$

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

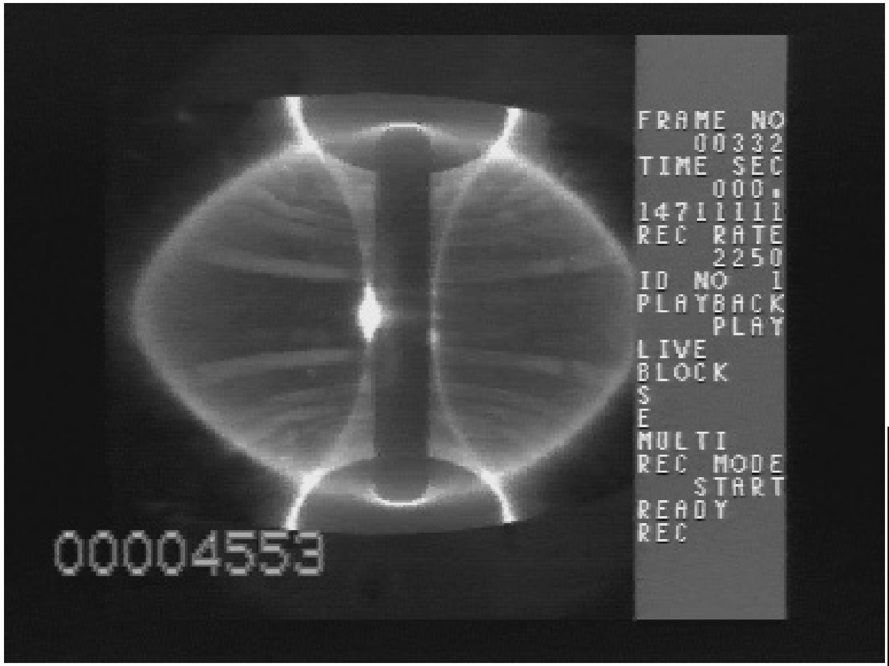


EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

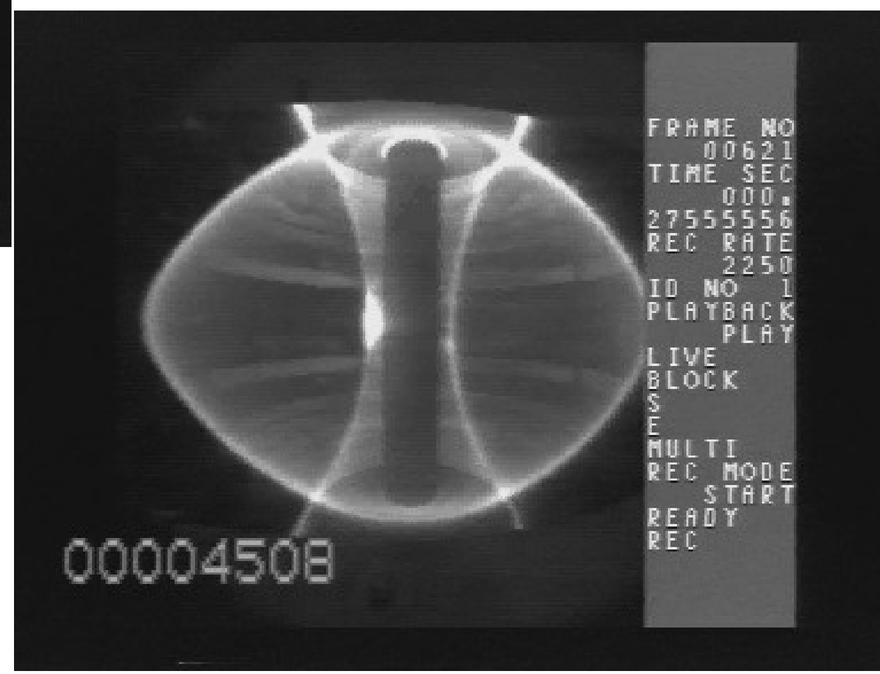
Edge Localised Mode (ELM)

MAST
MEGA-AMPERE SPHERICAL TOKAMAK

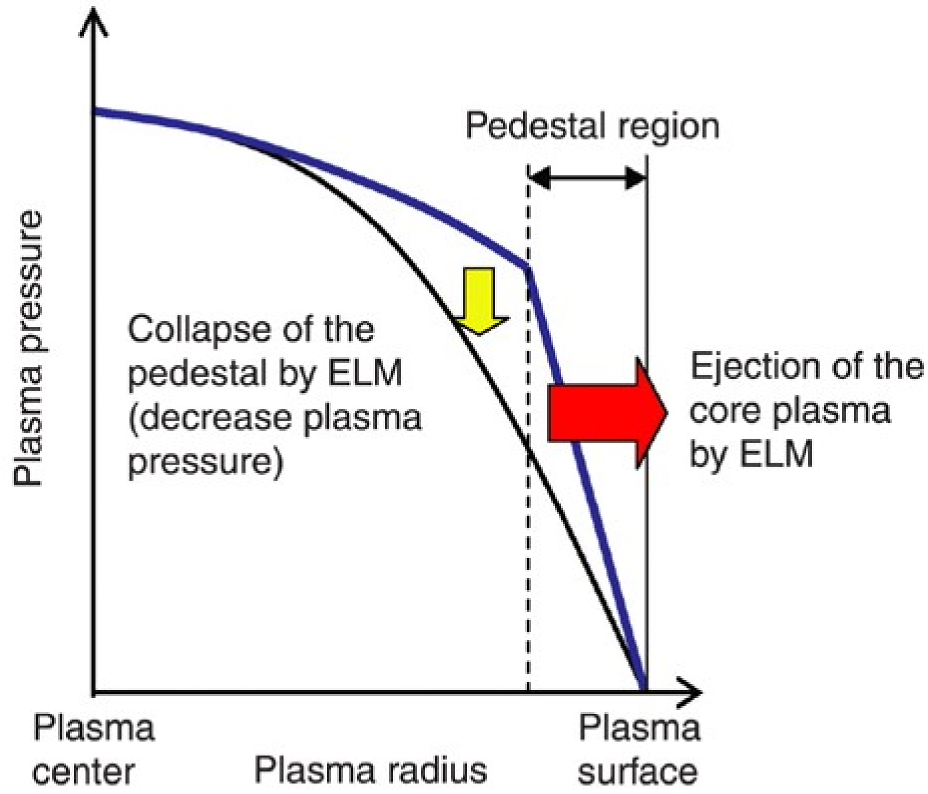


Edge Localised Mode

Disruption



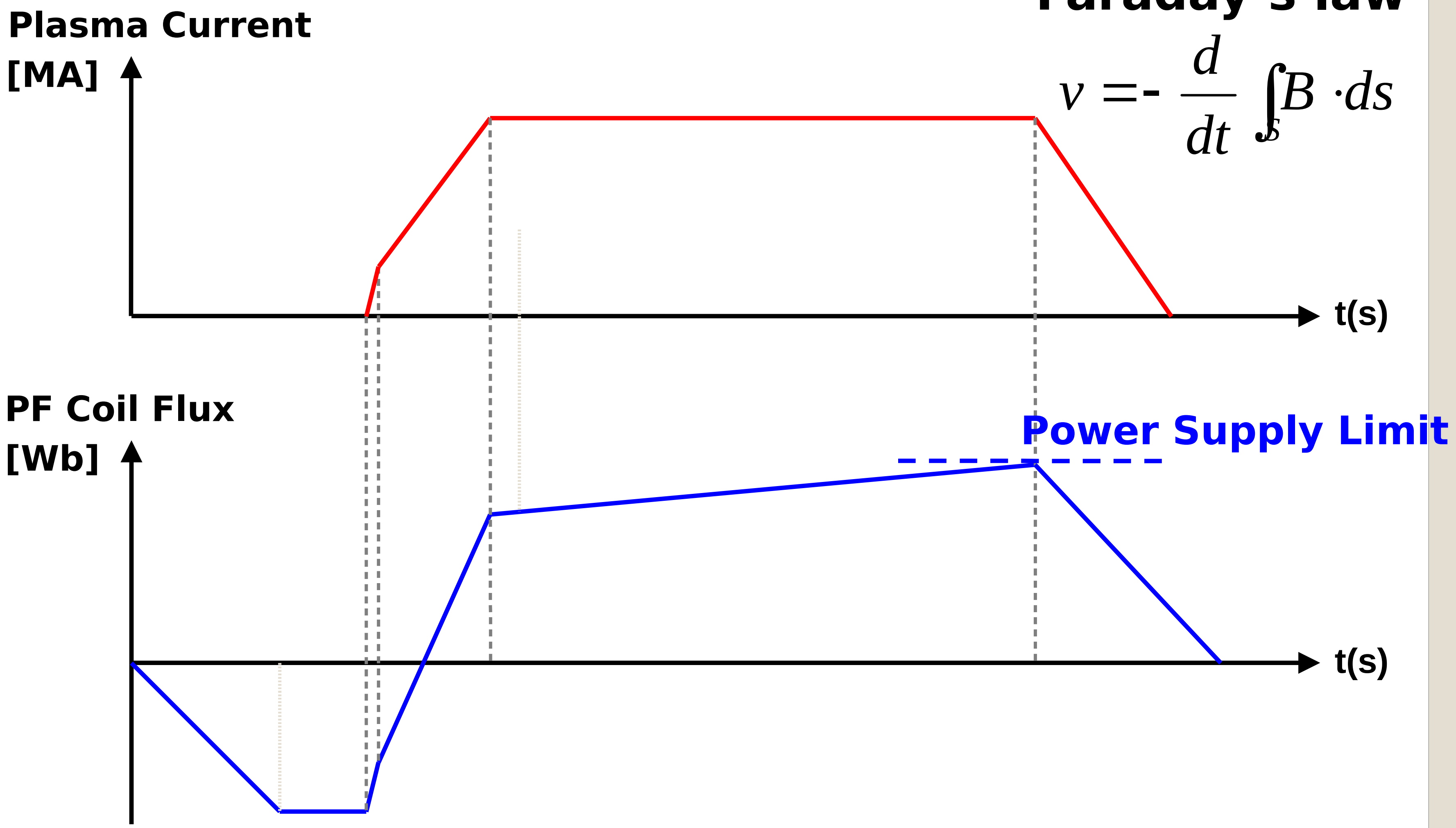
Edge Localised Mode (ELM)



H-mode: Limitations

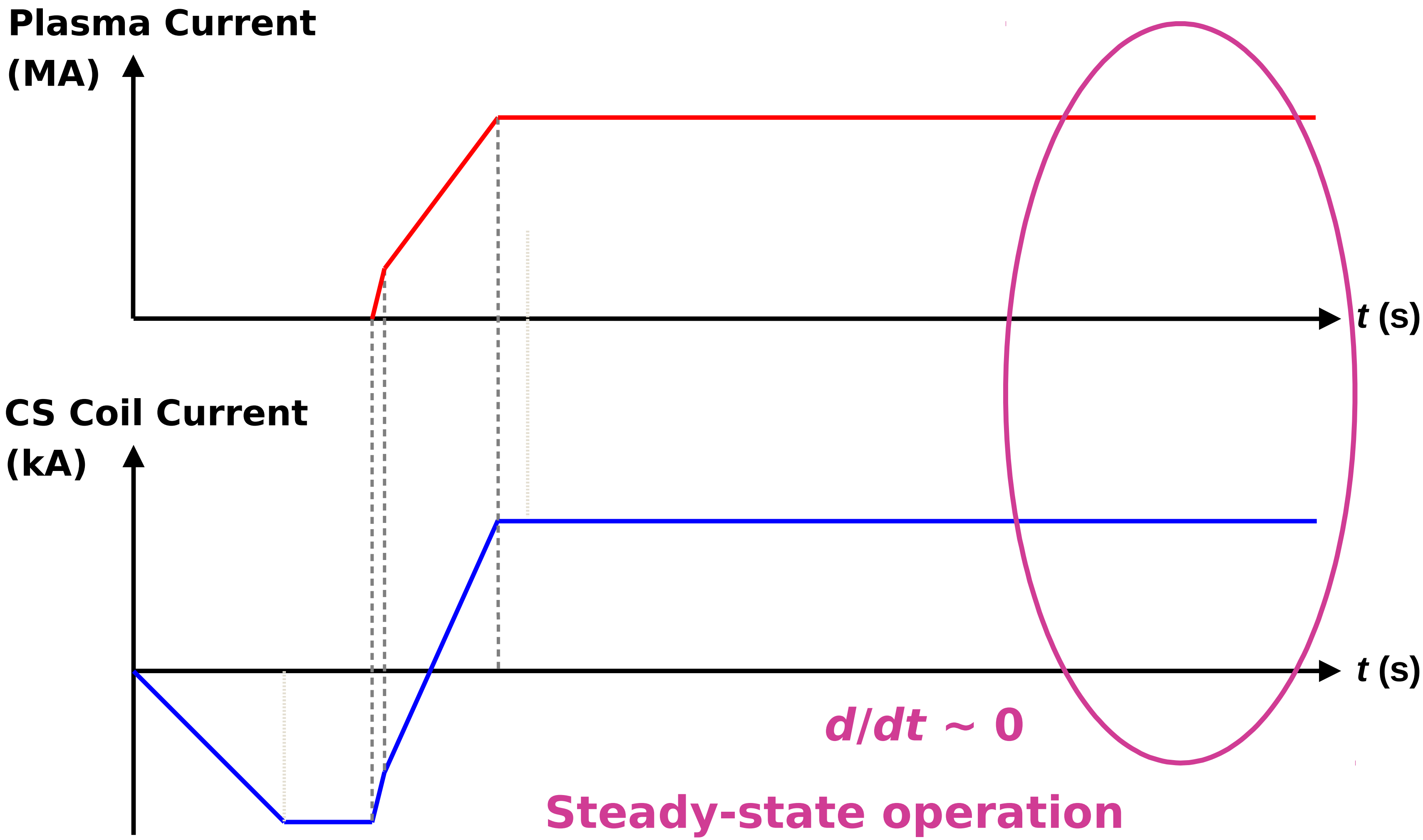
Faraday's law

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



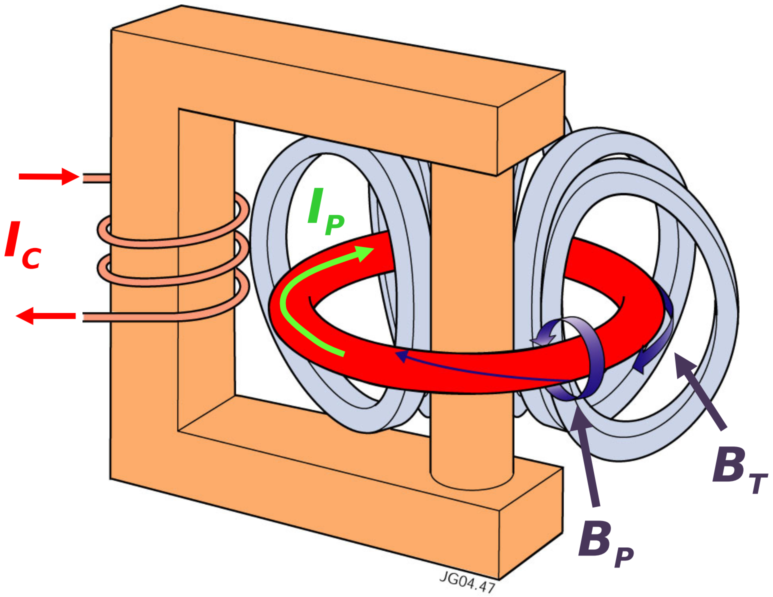
Inherent drawback of Tokamak!

Steady-State Operation



Steady-state operation
by self-generated and externally driven current

H-mode: Limitations



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**

$I_P = 0 \quad + I_{NI}$ **Non-inductive (steady-state) operation**

- **Conventional H-modes cannot reach steady state (producing continuous fusion power by fully non-inductive operation in a tokamak reactor).**

References

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

- A. C. C. Sips, 2001-, Seminars