Operational Limits in Tokamaks

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Introduction

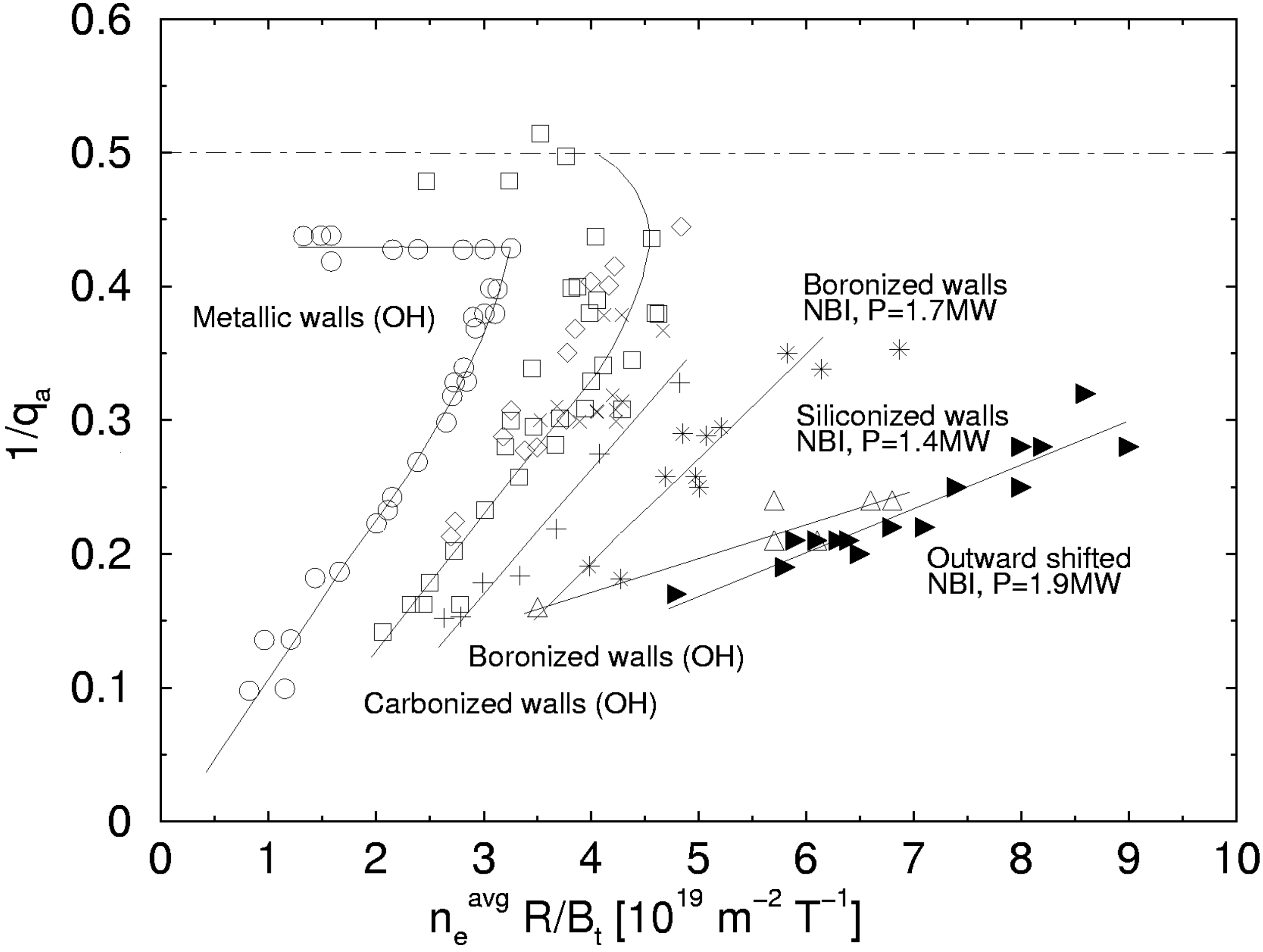
Optimisation of Tokamak Performance

$$P_{fusion} \propto \langle p^2 \rangle V \propto \beta^2 B^4 V$$

$$\beta \equiv \frac{\langle p \rangle}{B^2/(2\mu_0)}$$

Increase in tokamak performance constraint by **operational limits** (= instabilities)

Hugill Diagram



[J Rapp et al. 1999 *Proc. 26th EPS,* Maastricht, ECA **23J** 665]

Example: Beta + Density Limit + Disruption

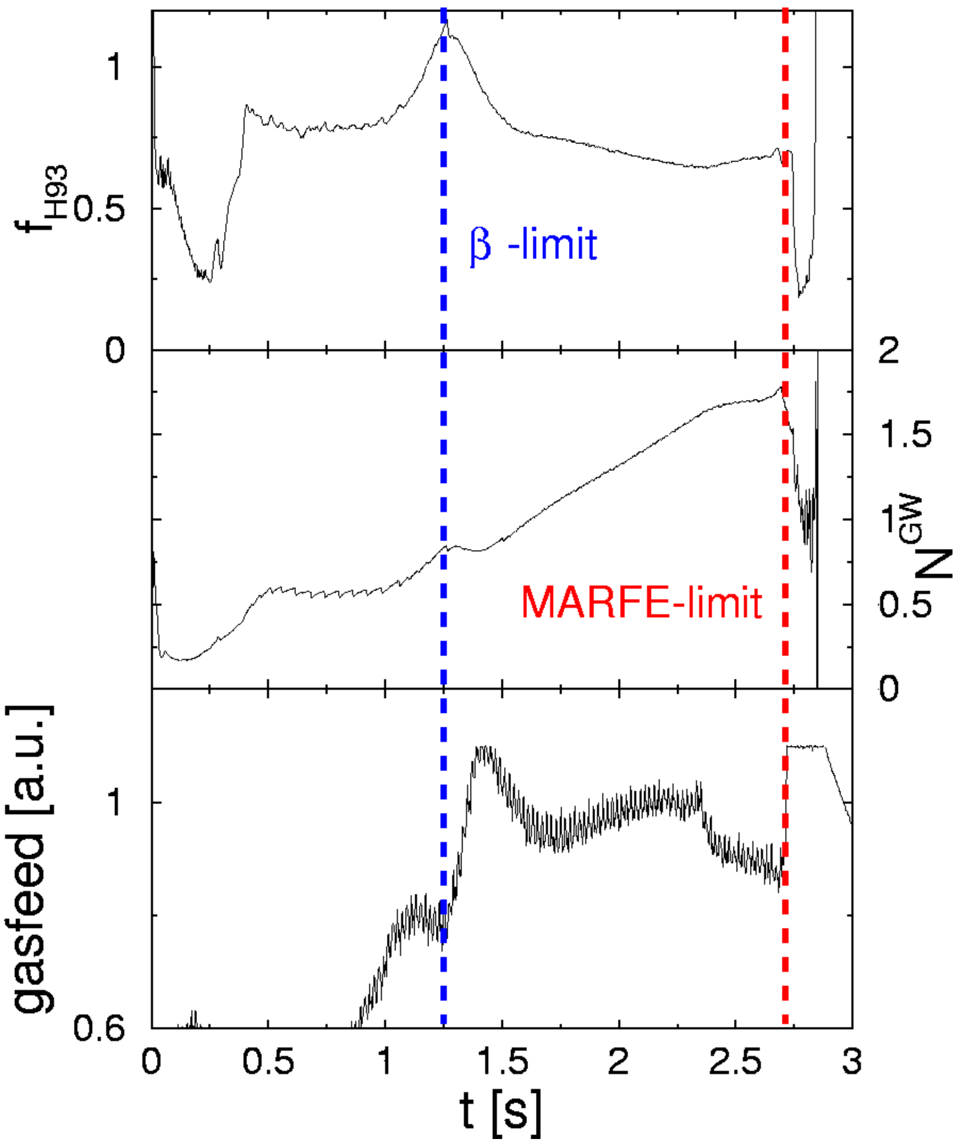
Electron density is continuously ramped up (strong gas fuelling)

Good confinement before *t* = 1.26 s

Confinement degradation caused by onset of an (neoclassical) tearing mode (NTM, *practical* beta limit)

N^{GW} ~ 2 due to good wall conditioning (fresh siliconisation)

Disruption after MARFE onset



Radiation Limits

Radiation Processes and Radiation Instabilities

- Bremsstrahlung

$$P_{br} \sim Z^2 n_e n_Z T_e^{1/2}$$

Balanced by heating power

- Cyclotron radiation

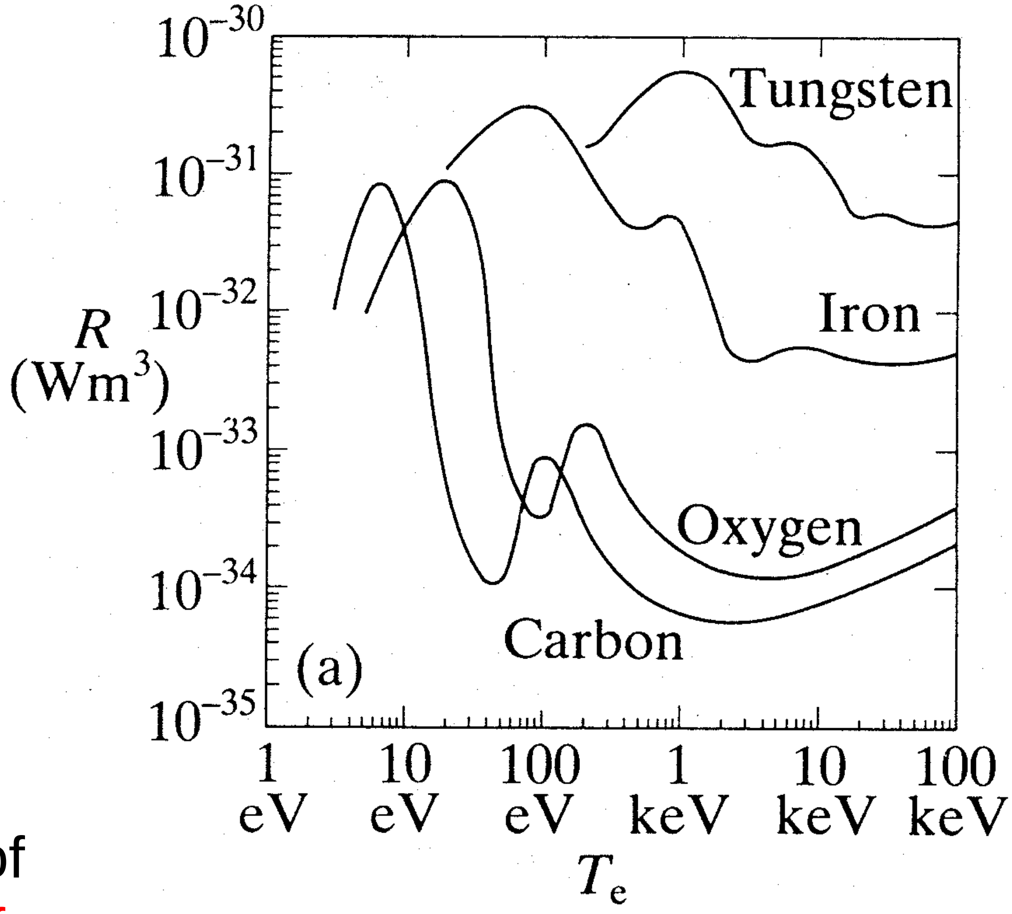
$$P_c = e^4 / (3\pi\varepsilon_o m_e^3 c^3)\, B^2 n_e T_e$$

Re-absorption, plasma is optical thick at fundamental frequency

- Line radiation

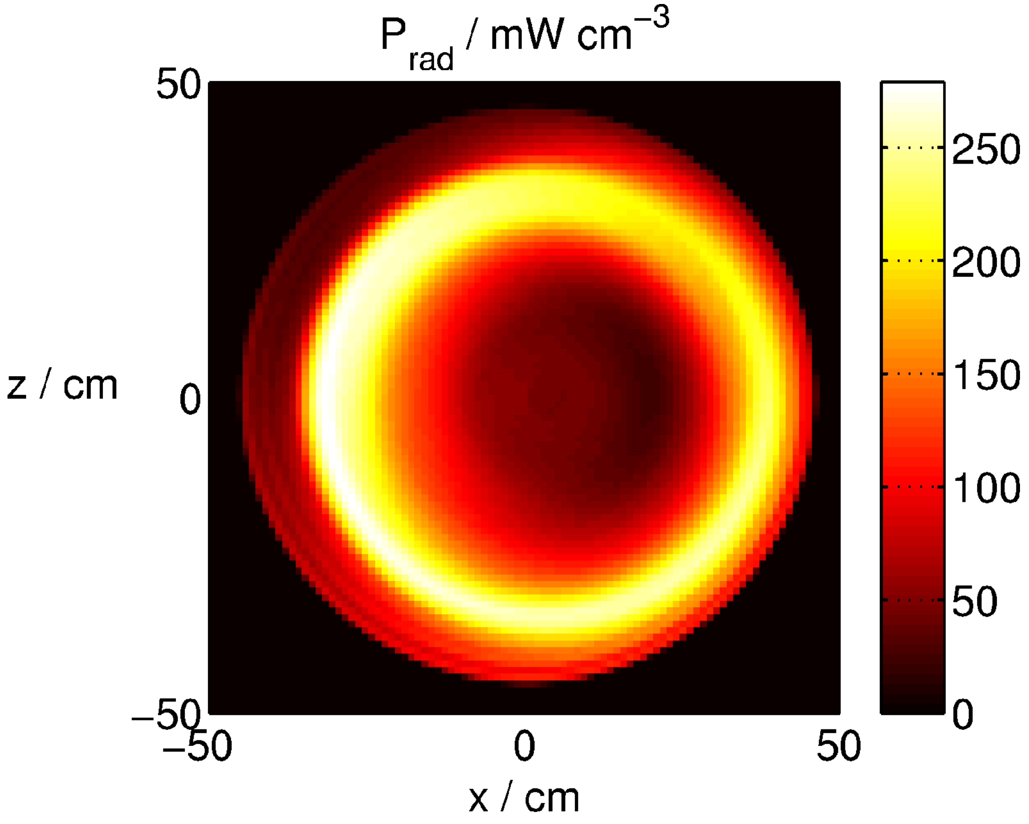
$$P_R = R(T_e)\, n_e n_I$$

Instability can develop due to shape of radiation function: radiation → drop of T_e → enhanced radiation ...



[figure from: J Wesson 1987 *Tokamaks*, Clarendon Press, Oxford;
data from: P E Post et al 1977 *Atomic Data and Nuclear Data Tables* **20** 397]

Density Limit - Radiative Collapse



- Poloidally symmetric radiation from the edge
- Line radiation from low-Z impurities
- Edge temperature drops with increasing edge density ⇒ radiation increases
- Density limit defined by

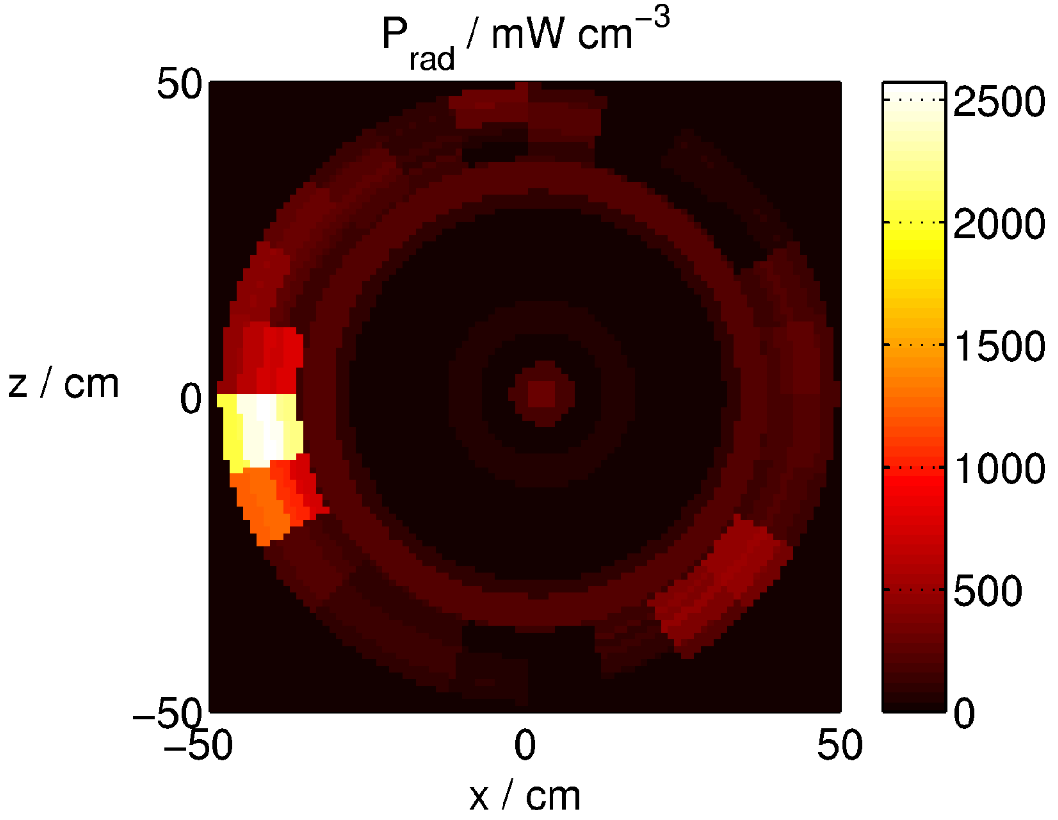
$$P_{\text{rad}} = P_{\text{heat}}$$

$$n_e^{crit} \propto \left(P_{heat} / \left(Z_{eff} - 1\right)\right)^{1/2}$$

⇒ Density limit can be enhanced by high heating power and reduction of impurities in the plasma

Density Limit - MARFEs

*MARFE ≡ **M**ultifaceted **A**symmetric **R**adiation **F**rom the **E**dge*



MARFE occurs on the high field side (HFS) of the torus

T_e ~ few eV

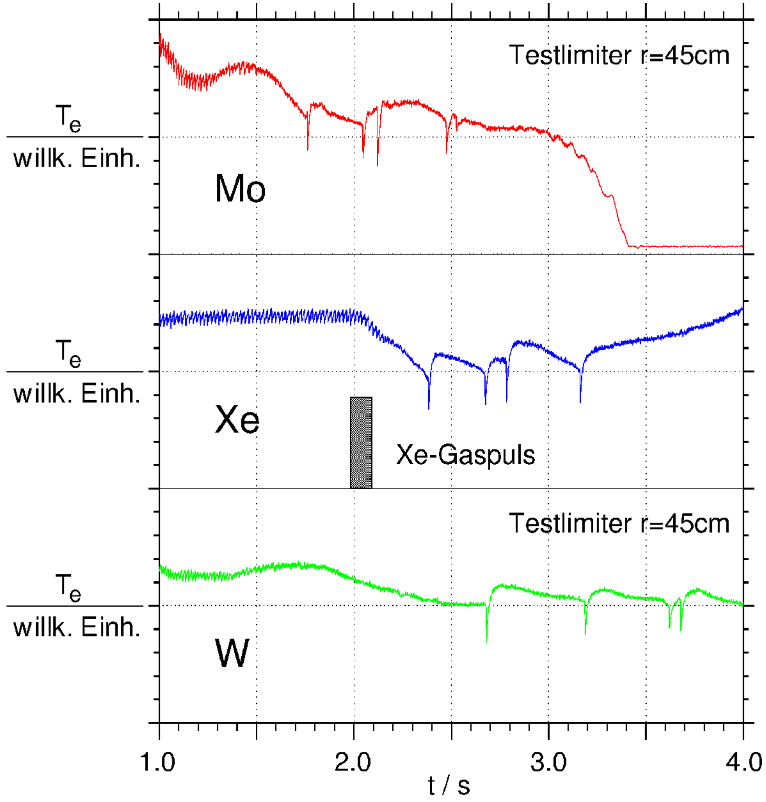
n_e ~ several 10^{20}m^{-3}

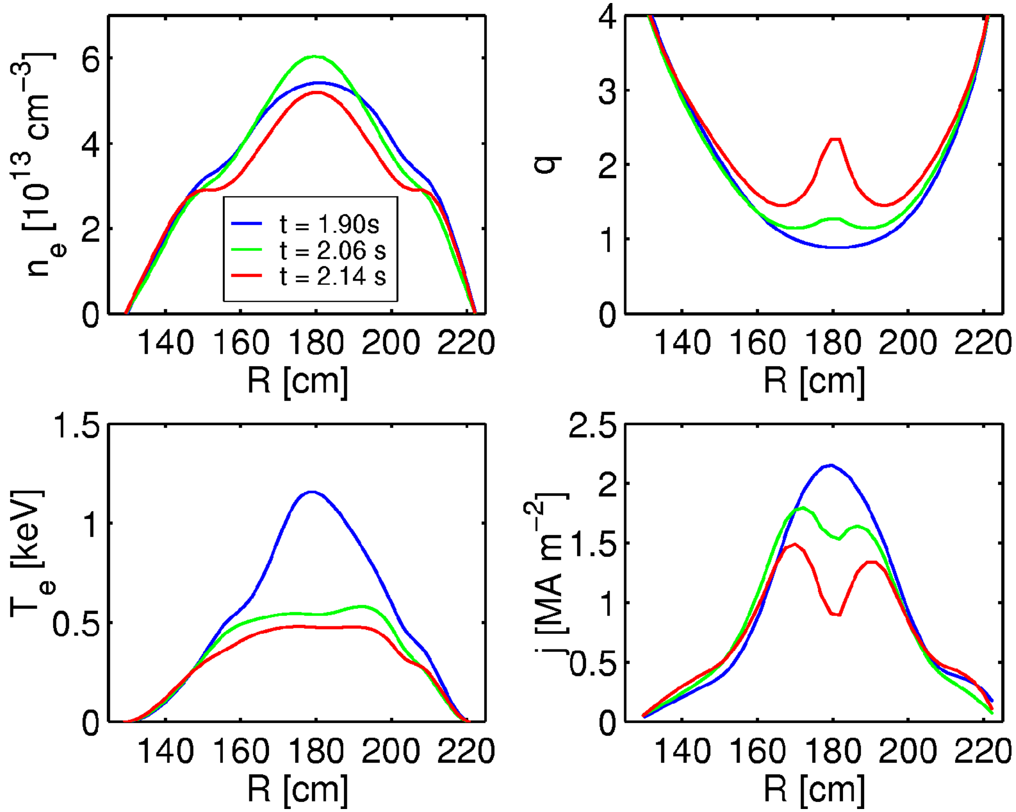
Onset of MARFE is connected to influx of recycling particles from the wall

Greenwald limit: $\overline{n}_e \sim \kappa \overline{j}$

⇒ Increase of the density limit with controlled displacement of the plasma column, i.e. reduced recycling possible

High-Z Impurity Accumulation





Cooling of the plasma centre by radiation

⇒ Drop in temperature, flat profile, loss of neo-classical temperature screening ($\propto T'$)

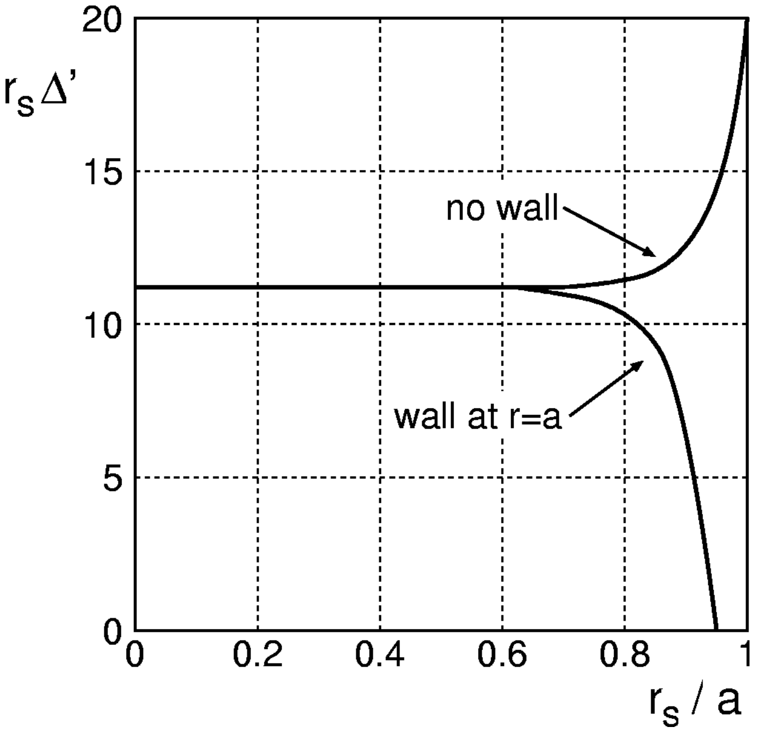
⇒ Increase of accumulation rate

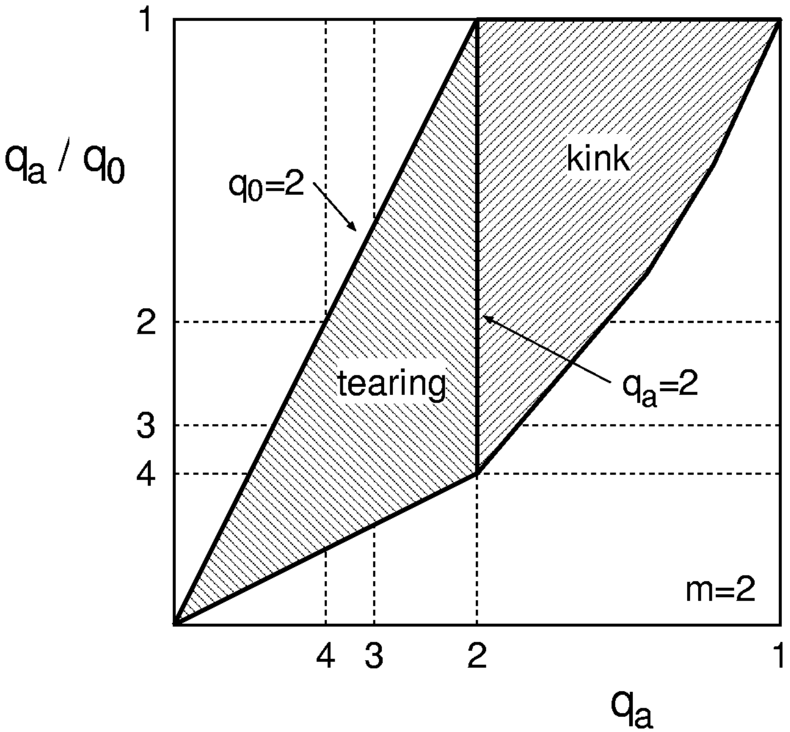
⇒ Displacement of the plasma current, reversed magnetic shear in the centre

⇒ Double tearing modes, internal disruptions

MHD Stability Limits

q_a Limit





[figures from: J Wesson 1987 *Tokamaks*, Clarendon Press, Oxford]

m=2 *tearing mode* when resonant q=2 surface is *inside* the plasma

Kink instability if resonant surface lies *outside*

$$q_a = 5\, a^2\, B_t / (R\, I_p) > 2 \qquad \text{(cylindrical)}$$

Plasma current has upper limit for a given toroidal magnetic field

Ideal Beta Limit („Troyon Limit“)

Maximum beta depends on pressure profile, current profile, and plasma shape (elongation, triangularity)

$$\beta_t = 2\mu_0 \langle p \rangle / B_t{}^2$$

Numerical calculations with respect to ballooning modes, Mercier limit, and *n* = 1 kink modes with optimised pressure and current profiles (Troyon 1984)

n = 1 kink mode limits the achievable beta:

$$\beta_t{}^{\max} = C I_p / \left(a B_t \right)$$

Normalised beta:

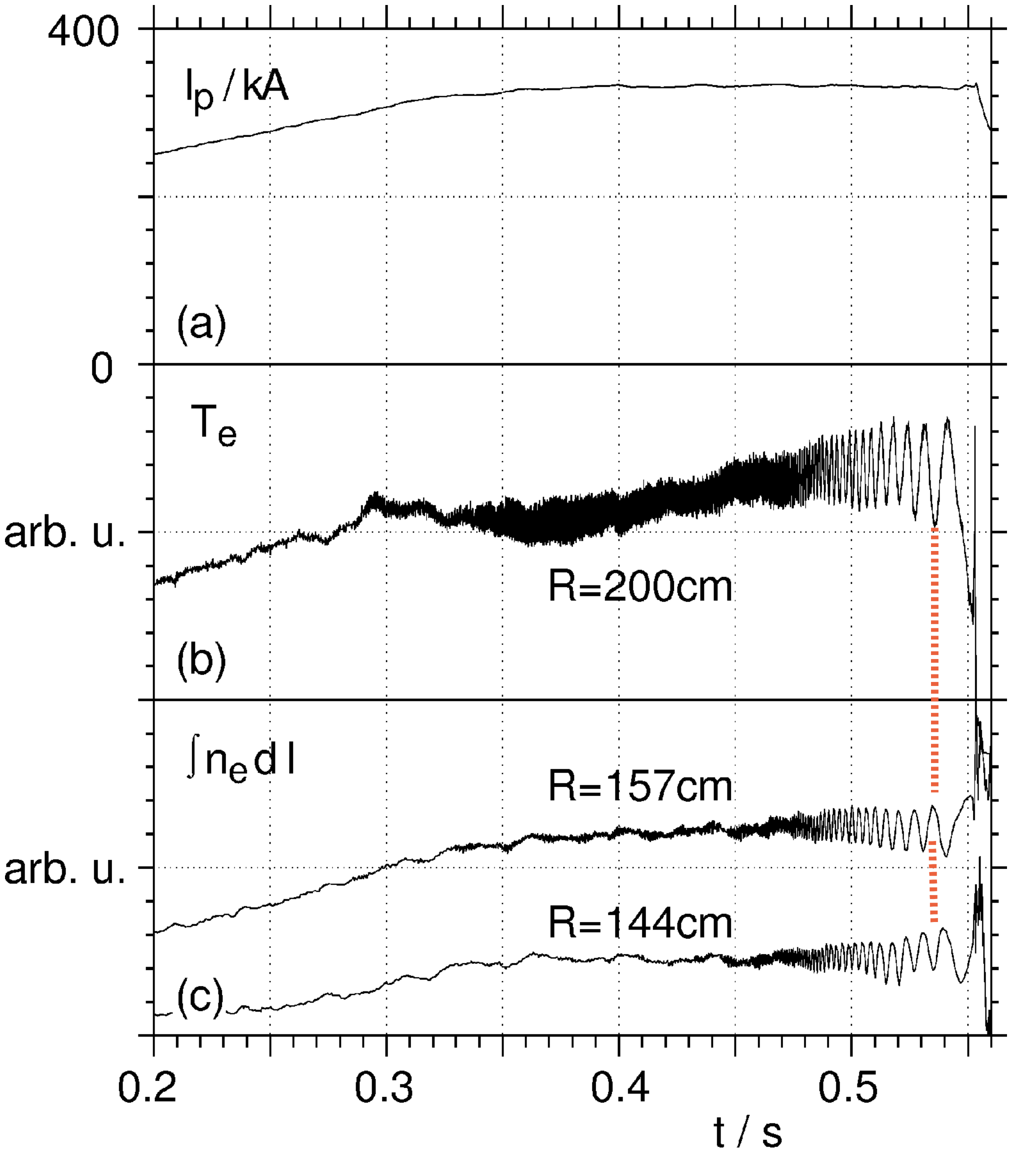
$$\beta_N{}^{\max} = \beta_t{}^{\max} [\,] / \left(I_p / a B_t \right) \approx 2.8$$

For circular shape and large aspect ratio:

$$\beta_p{}^{\max} = 0.14 \left(R/a \right) q_a$$

Beta limit *transiently* reached, in *stationary* discharges below ideal prediction

Tearing Modes



Tearing instability is driven by radial current profile gradients

Growth of tearing modes determined by *tearing parameter,* mode is unstable if $\Delta' > 0$

$$\Delta'(w) = \frac{1}{B_r}\left(\frac{\partial B_r}{\partial r}\right)\Bigg|_{r_s+w/2}^{r_s-w/2}$$

Size of magnetic island

$$\frac{dw}{dt} \cong \frac{\eta}{2\mu_0}\Delta'(w)$$

Growth time

$$\gamma^{-1} \approx \tau_R{}^{3/5}\tau_A{}^{2/5}$$

Double Tearing Modes (DTM)

3D

Non-monotonic *q* profiles

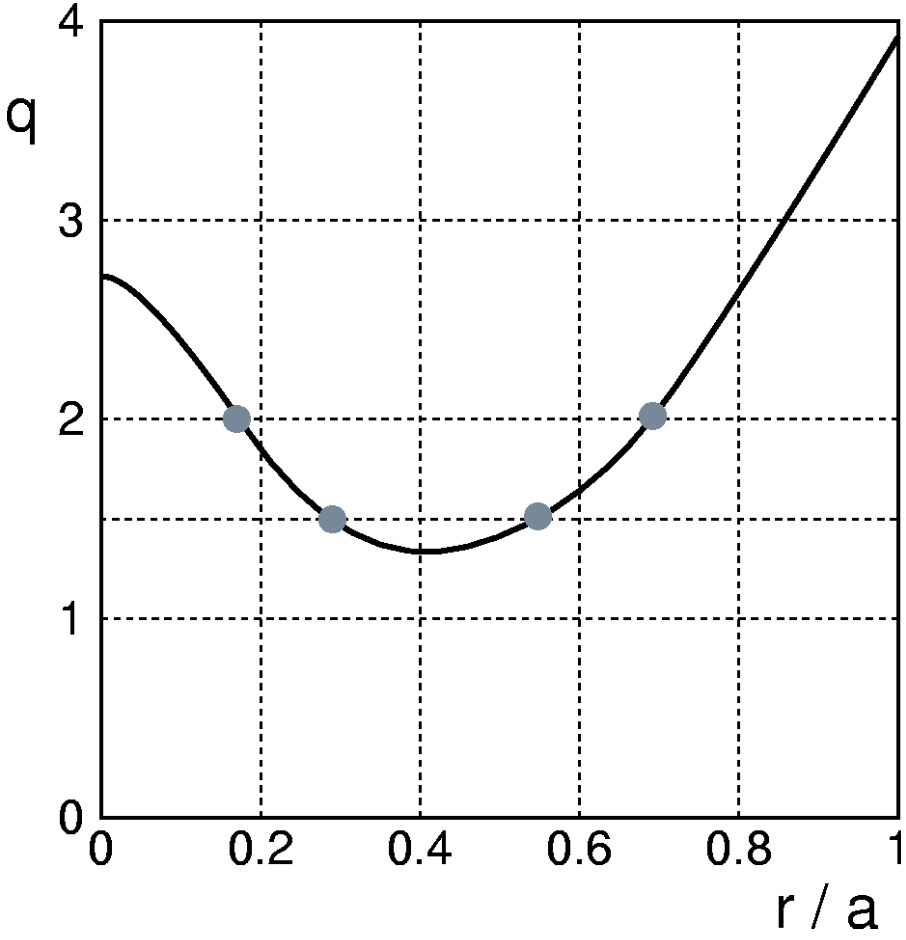
Off-axis current drive

Impurity accumulation during plasma start-up

Reversed magnetic shear attractive for tokamak Operation

Transport barriers

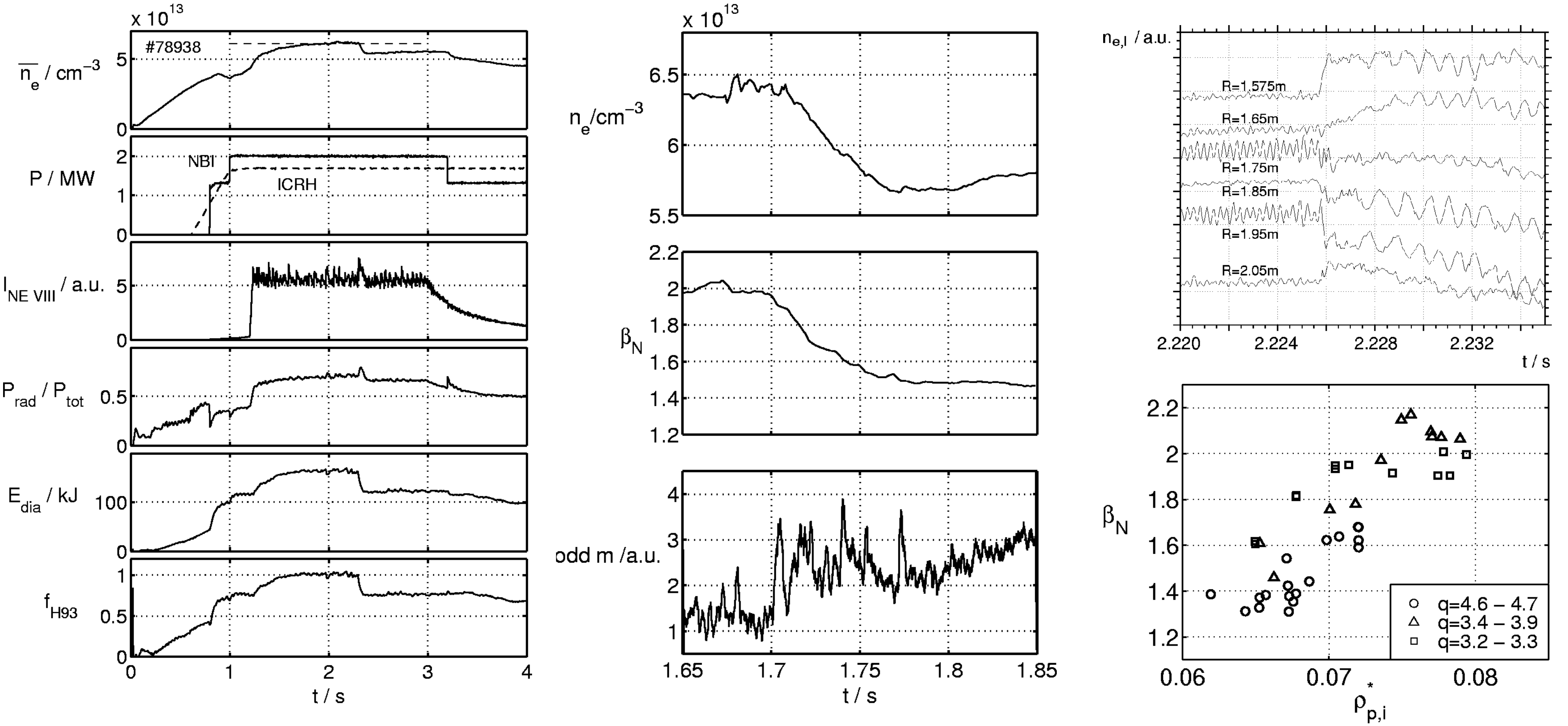
Non-inductive current



DTMs: large spatial extension; rapid growth; mode coupling / overlap; minor and major disruptions; off-axis sawteeth

Neo-classical Tearing Modes (NTM)

3D



- Confinement drop is correlated to the onset of a 3/2 neo-classical tearing mode
- $\Delta' < 0$, a so-called seed island is required, sawtooth crash triggers mode
- β_N scales approx. linear with the poloidal ion gyro radius → low threshold in ITER

Locked Modes

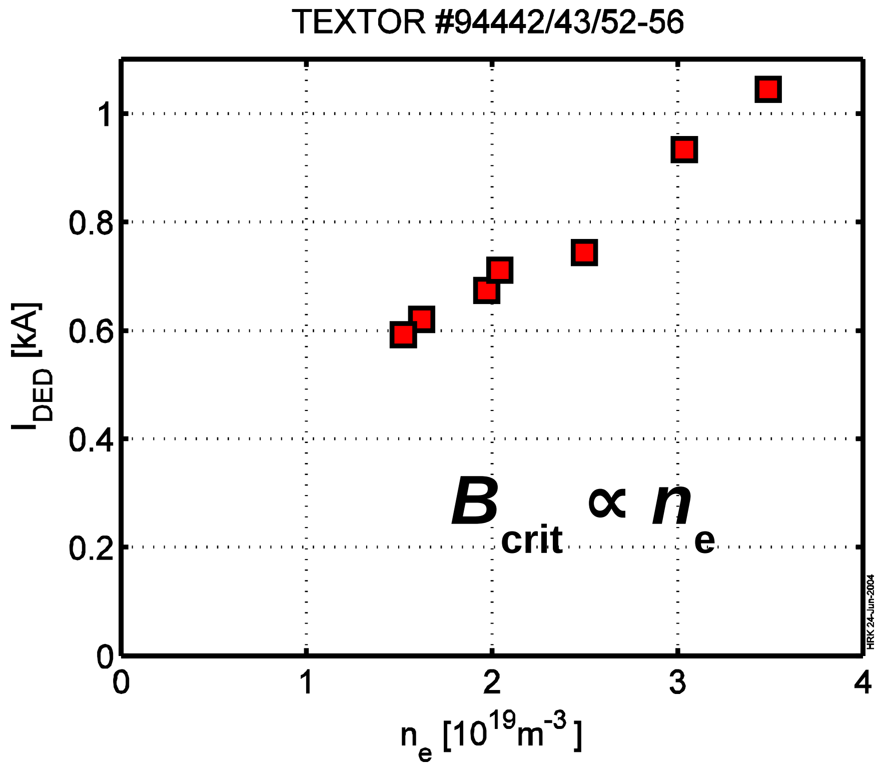
- Stationary magnetohydrodynamic perturbation
- Plasma rotation

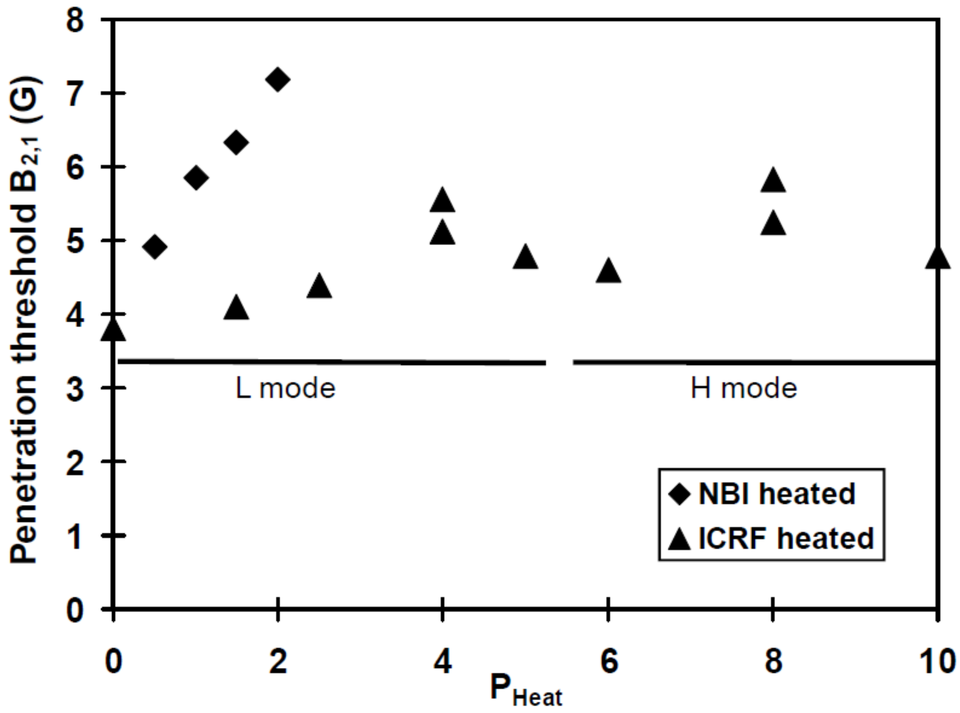
  Diamagnetic drift $\omega_e^* = m / (e\, n_e\, B\, r)\, p'$

  Radial electric field $v_\phi = E_r / B_\theta$

  Toroidal rotation due to momentum transfer (NBI)
- Slowing down of mode rotation due to friction forces
- Mode locks to wall (rotation stops)
- Locked mode enhances transport / leads to disruption
- Detection with specially designed magnetic diagnostic or from profile (T_e, n_e) measurements
- Momentum transfer and sheared rotation counteract mode locking

Error Fields

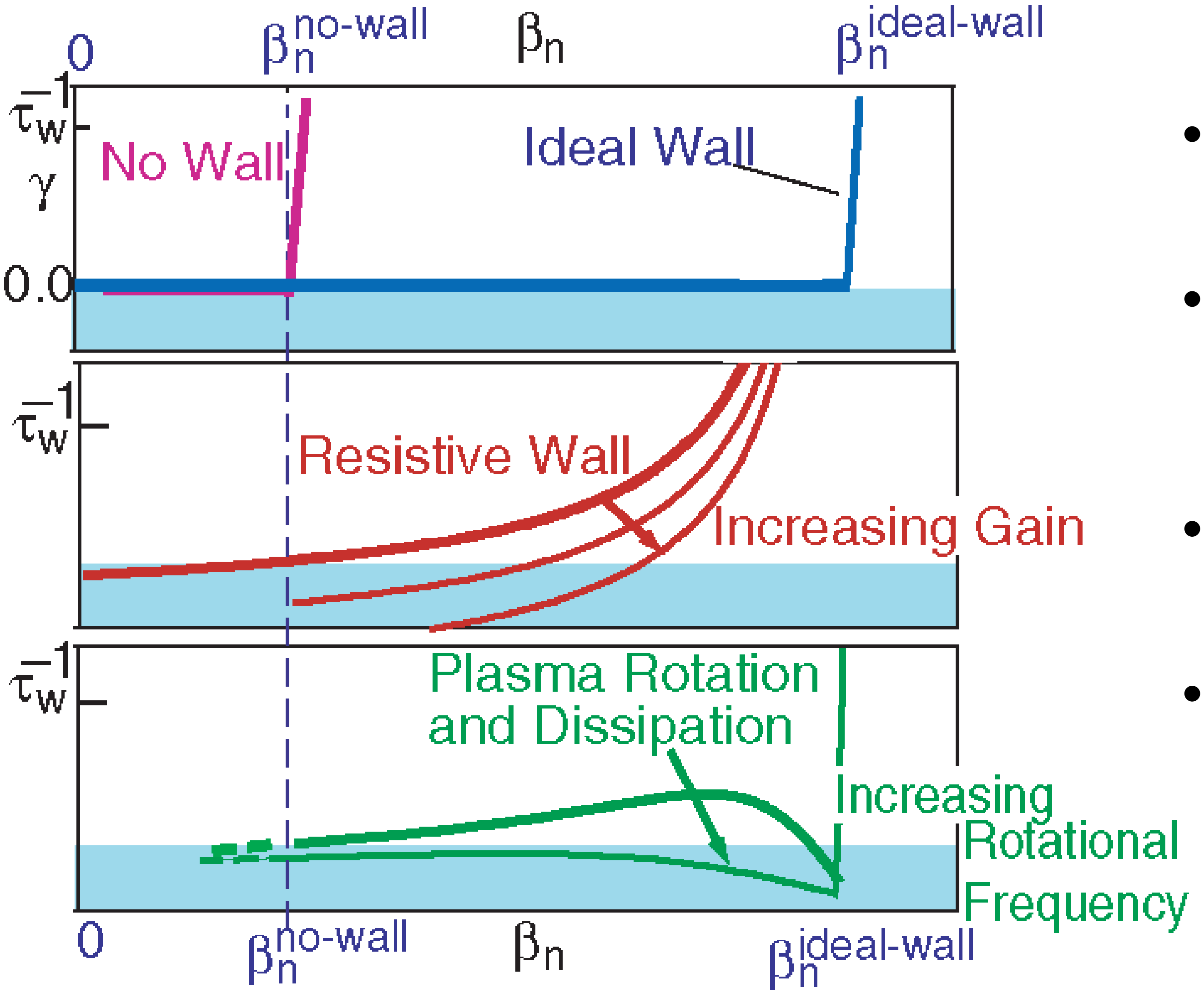




[R Buttery et al. 2000 *Nuclear Fusion* **40** 807]

- Non-axisymmetric error fields originate from non-ideal coil alignments and current feeders
- Locked modes (m/n=2/1) are excited above a critical field threshold
- Threshold depends on density, toroidal field, configuration, plasma rotation, beta, …
- Critical error fields are in the order $B_r/B_t \approx 10^{-5}$ .. 10^{-4}
- External error field correction coils are needed to cancel the intrinsic error field

Resistive Wall Modes (RWM)



[M Okabayashi et al. 2002 *PPCF* **44** B339]

- Beta limited by global external kink mode
- Passively stabilized by ideal conducting close fitting wall
- Resistive wall reduces growth rate
- **Active feedback** (using saddle coils) and **plasma rotation** enhance beta limit

Vertical Instability of Elongated Plasmas

- Axisymmetric instability with toroidal mode number n = 0
- Vertically elongated plasmas are unstable with respect to vertical displacements (VDEs)
- Vertical stability of a circular, large-aspect ratio plasma is determined by the field index (stable if *n* > 0)

$$n = -\frac{R}{B_v}\frac{dB_v}{dR}$$

- Vertical instability has a large growth rate (inertial time scale)
- Stabilisation by a conducting shell around the plasma (reduces growth rate to resistive time scale) or by active feedback using (external) coils (growth rates up to ~4000 s^{-1} can be controlled, TCV 2000)
- Maximum elongation is limited by vertical instability

Disruptions

Runaway Electrons

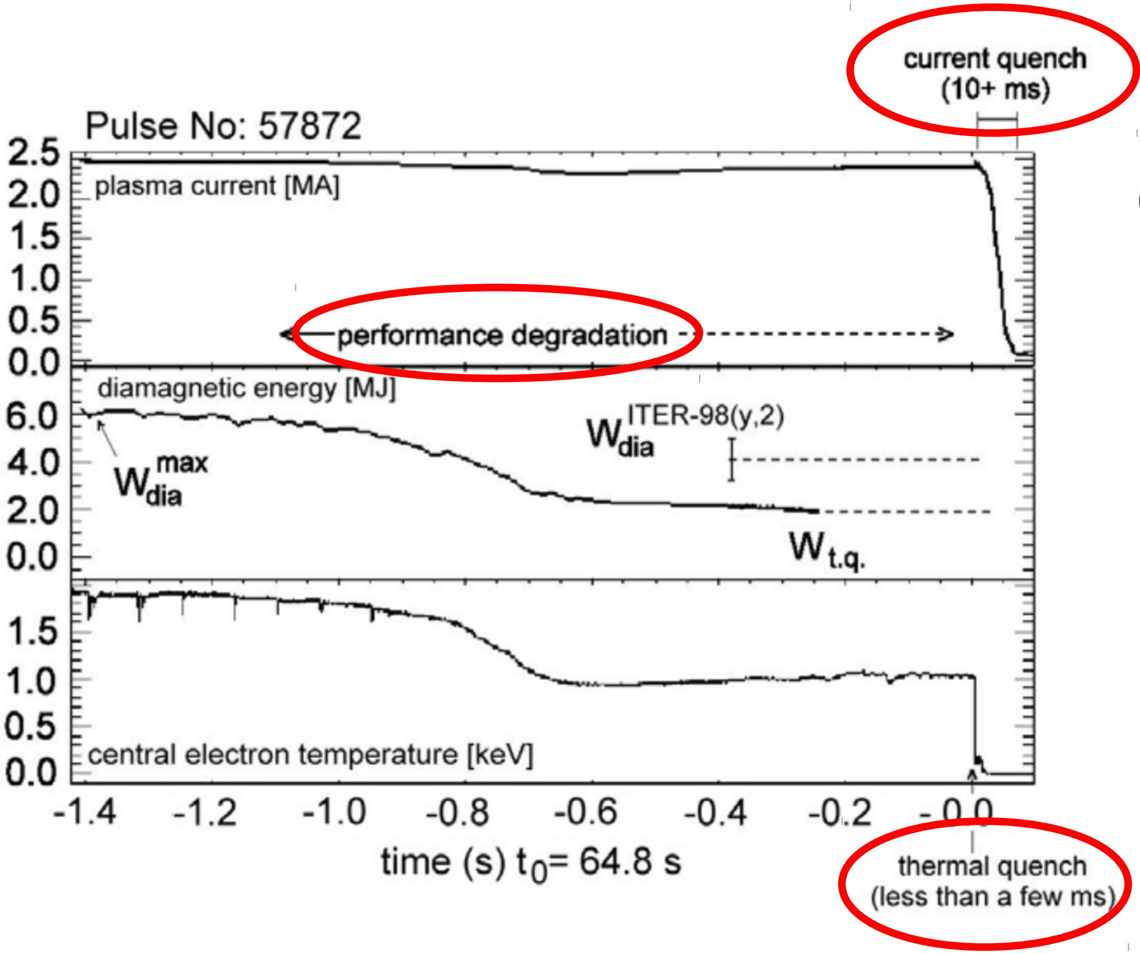
- Ohmic plasma current requires toroidal electric field
- Electrons are accelerated
- Drift velocity is balanced by collisional force → resistivity

$$Ee = m_e v_d / \tau_c$$

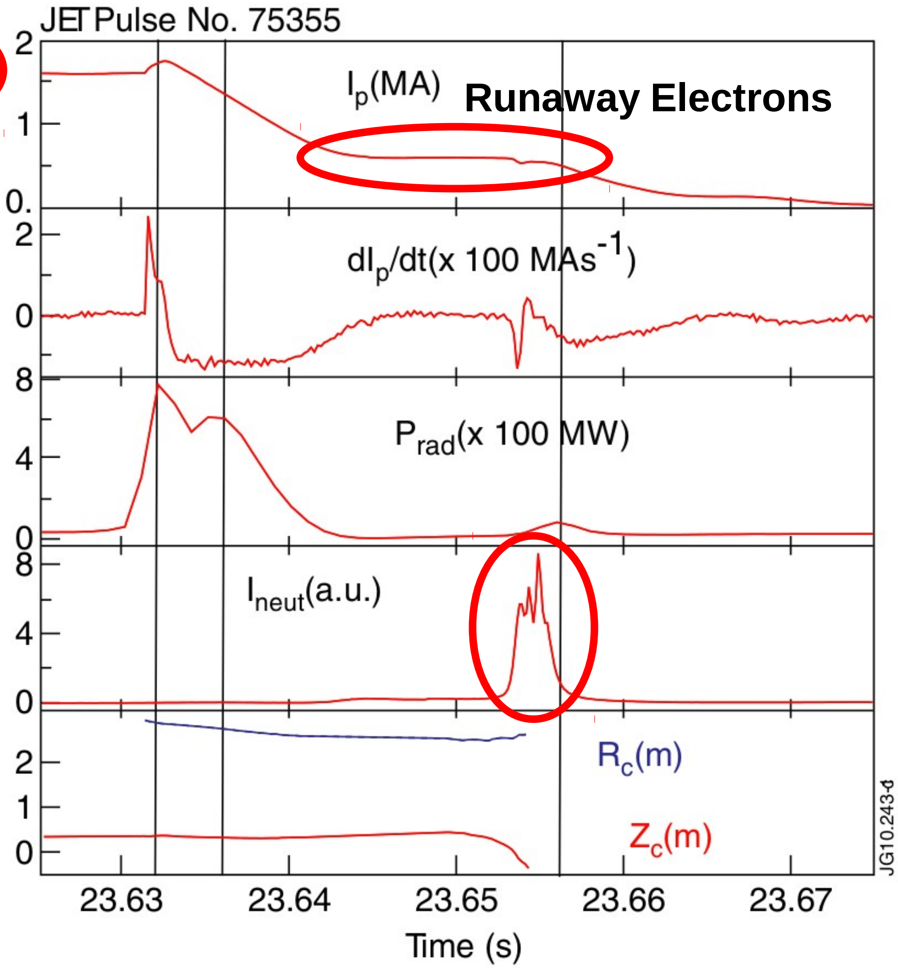
- Runaway occurs for electrons with $v_e >> v_{th}$ (collisional force $\propto 1/v_e^2$), and at low densities ($\tau_c \propto 1/n$)
- Non-maxwellian distribution function develops
- Large amounts of runaway electrons are created during disruptions
- High-energetic electrons may cause damage / evaporation of first wall

Disruption

3D



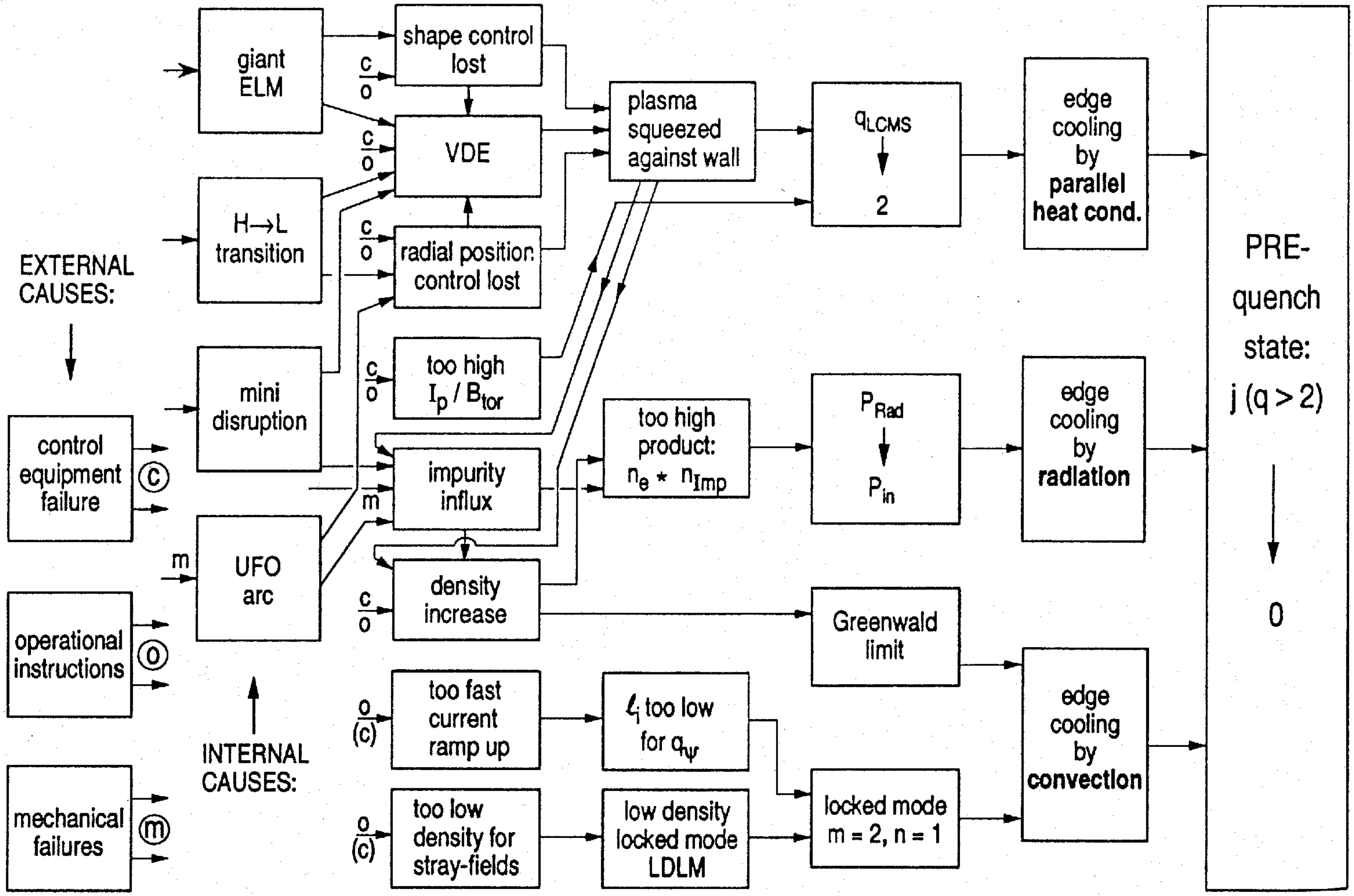
[V Riccardo et al 2005 *Nucl. Fusion* **45** 1427–1438]



Runaway Electrons

[A Loarte et al. 2011 *Nucl. Fusion* **51** 073004]

Disruption Causes



[F C Schüller 1995 *Plasma Phys. Contr. Fusion* **37** A135]

Two phases:

Energy quench

Current quench

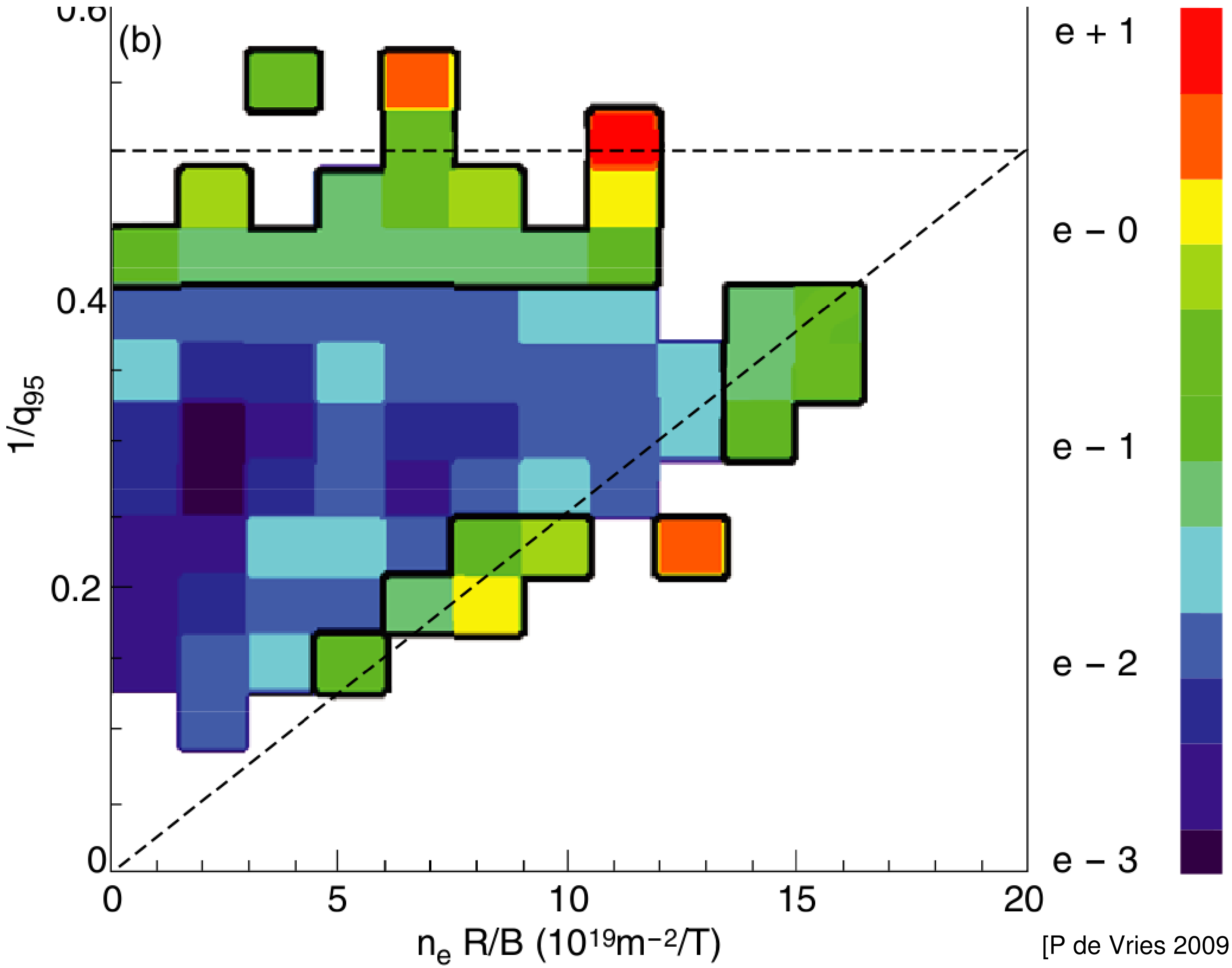
Fast time scale

L/R ~ ms

Plasma energy is released to wall

Strong forces due to eddy and *halo currents*

Disruptivity vs Operational Limits



[P de Vries 2009 *NF* **49** 055011]

Avoidance / Mitigation of Disruptions

- Goal: reduce forces on the vessel and prevent damage to first wall
- Avoidance of disruptions by
  - Real-time detection of disruption precursor and appropriate action
  - Detection of locked mode and controlled shutdown of the discharge
  - Operation in safe regime far from operational limits
- Mitigation of disruptions by
  - Detection of oncoming disruption with e.g. neural networks etc, and initialisation of *soft stop* (reduce plasma shaping, heating power, etc)
  - Heating to soften the current quench
  - Massive gas injection (He ... Ar) or pellet/dust injection to mitigate heat loads and forces, and to prevent runaway generation
- **Disruptions = Loss of plasma control**

Summary

- Tokamak operation and performance is constraint by operational limits
- Hard (disruption) and soft (confinement deterioration) limits exist
  - Radiative collapse / MARFEs
  - Impurity accumulation
  - External kink modes (q_a)
  - (Neo-classical) tearing modes, double tearing modes
  - Locked modes / error fields
  - Resistive wall modes
  - Vertical instability (VDEs)
- Stationary performance is limited by neo-classical tearing modes
- Mode stabilisation, error field correction, and prevention/amelioration of disruptions required to optimise performance in fusion experiments

⇒ A tokamak reactor needs active control of MHD stability