New Trends in Fusion Research

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apologies to the many authors from whom I have 'stolen' viewgraphs

MIT PSFC CRPP EPFL EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

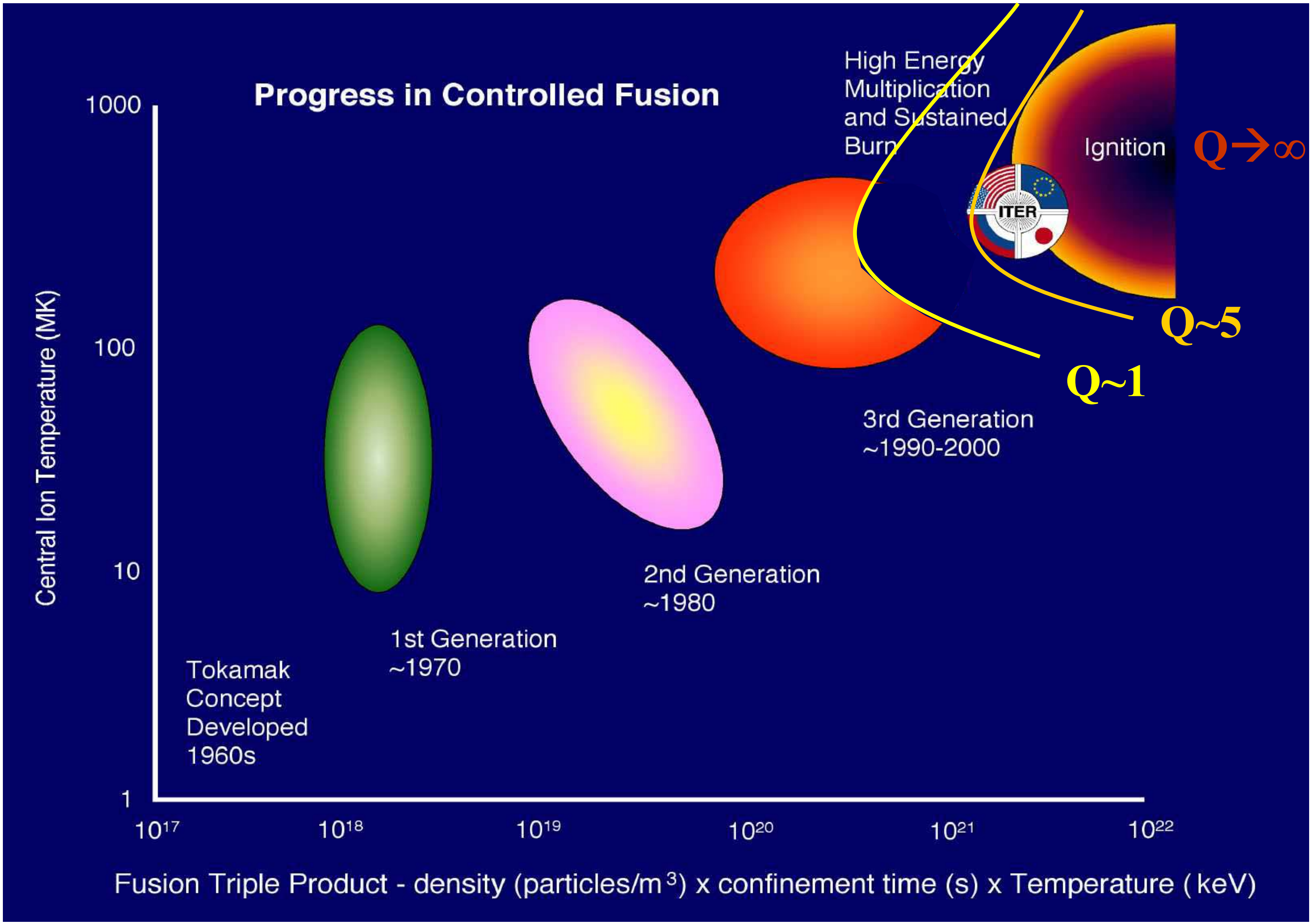
Lay-out of Lecture 2

- *Magnetic fusion basics*
- *Different magnetic confinement schemes*
- *Plasma heating, control and fuelling*
- *The JET tokamak*

movie

- Magnetic fusion physics challenges
  - Macroscopic equilibrium and stability
    - Ideal MHD
    - Ideal MHD stability limits
    - Disruptions

Progress in magnetic fusion

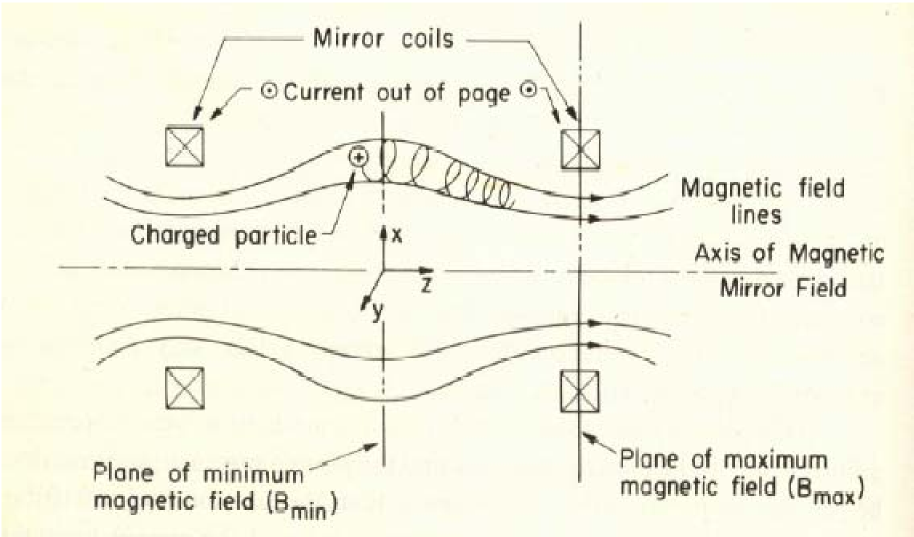


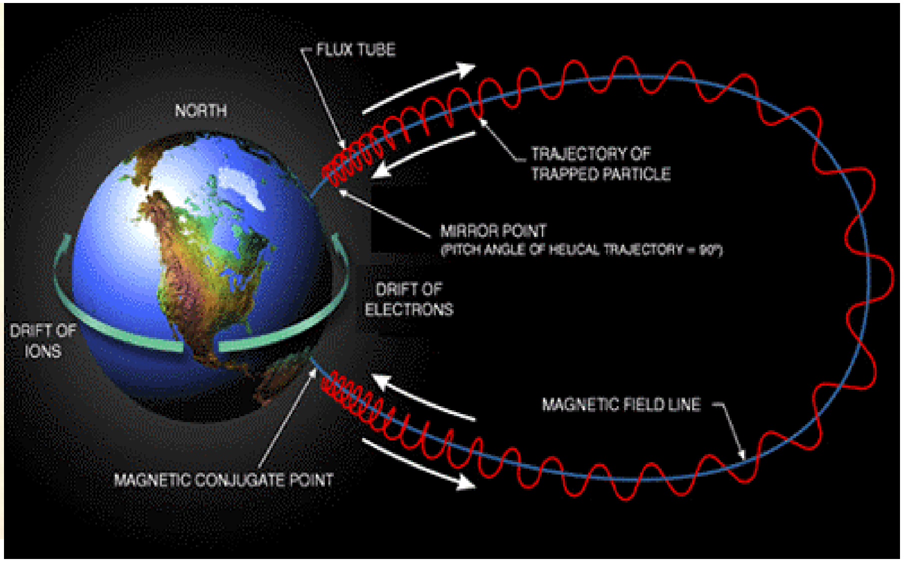
Magnetic mirror

- Conservation of magnetic moment (adiabatic invariant)

$$\mu = \tfrac{1}{2} m v_\perp^2 / B = E_\perp / B$$

  - If B increases, $E_\perp$ increases; but $E_{tot} = E_{||} + E_\perp = \text{const.}$ → $E_{||}$ decreases
  - At some point, particle cannot penetrate further into increasing B: $v_{||}$ →0 and changes sign: 'mirroring'
  - Equivalent to a force on guiding center $\langle F_{||} \rangle = -\mu \partial B / \partial z$
  - Particles with $|v_{||}|/|v_\perp| > [B_{max}/B_{min} - 1]^{1/2}$ are lost: *loss cone* in v-space



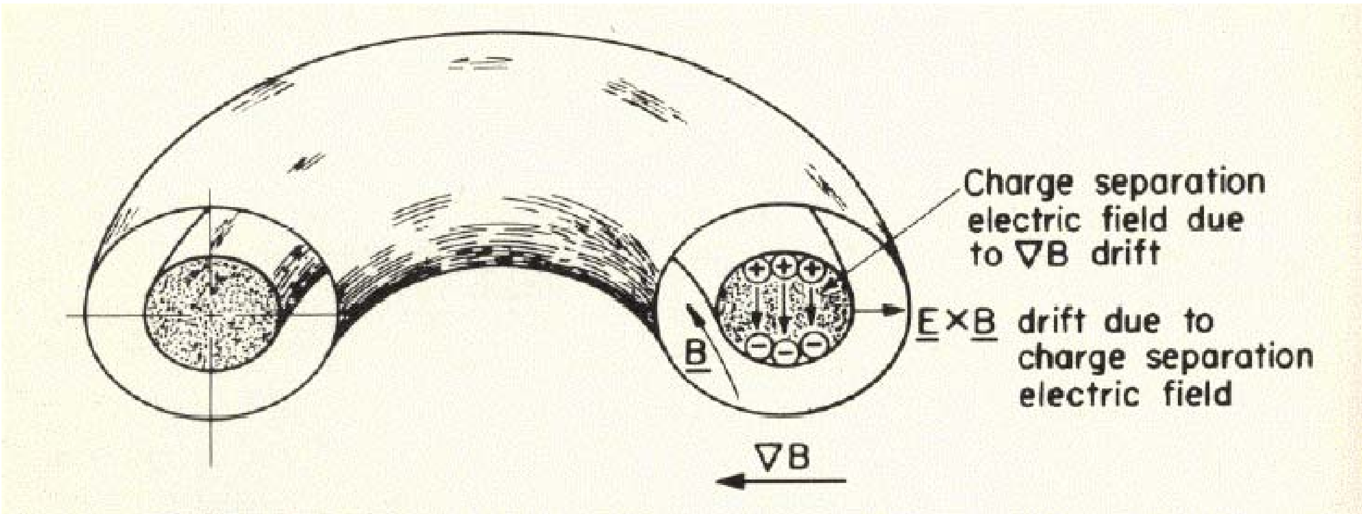


Particle drifts in toroidal machine

- Guiding center approximation
- Generic drift with force $\mathbf{F}$: $\mathbf{v}_D = \mathbf{F}\times\mathbf{B}/(qB^2)$

  E.s. force: $\mathbf{v}_{ExB} = \mathbf{E}\times\mathbf{B}/B^2$ (charge independent)
- If B is not uniform and B-field lines are curved: gradB and curvature drifts

$$\mathbf{v}_D = (\tfrac{1}{2}v_\perp^2 + v_\parallel^2)\mathbf{B}\times\nabla\mathbf{B}/(\Omega B^2) \quad \text{(charge dependent, } \Omega = qB/m)$$



The need for additional plasma heating

$$\eta = \frac{\sqrt{2}}{\pi^{3/2}} \frac{m_e^{1/2} Z e^2 \ln\Lambda}{12\varepsilon_0^2 T_e^{3/2}} \propto T_e^{-3/2}$$

Heating by current ('ohmic heating') becomes less and less effective at high T_e
The increase in energy per unit volume is

$$\frac{dE_k}{dt} = \eta J^2$$

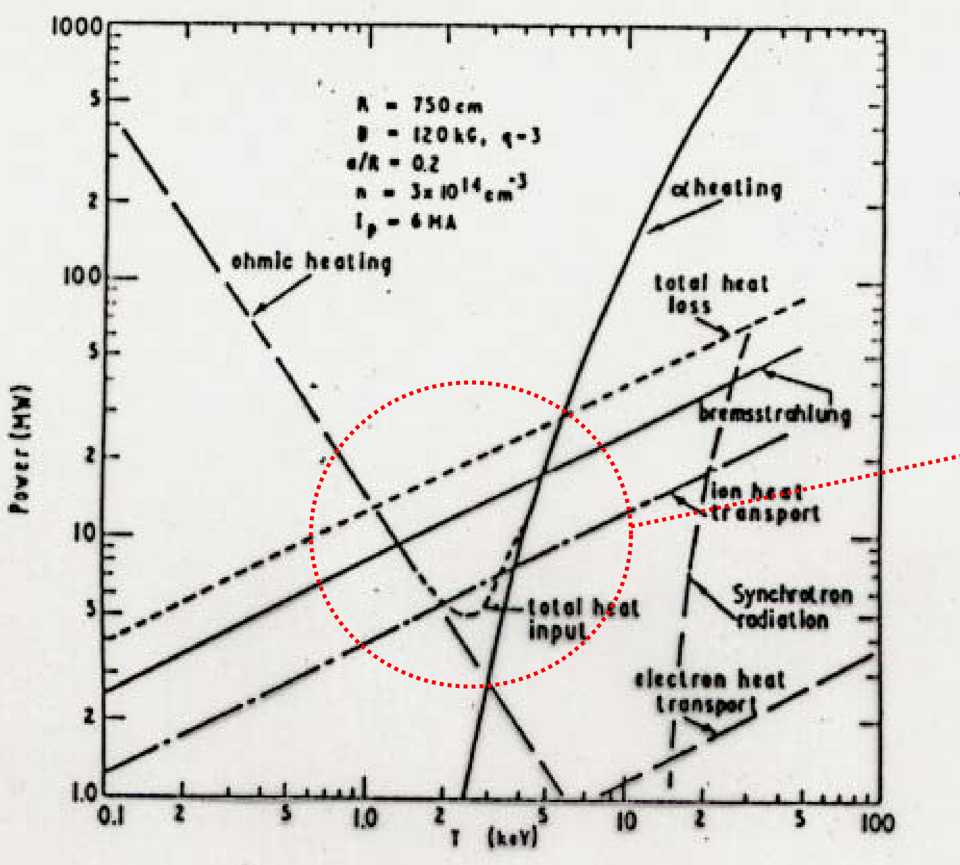


FIG. 1. Power balance — reactor case. For this case parameters typical of those used for reactor design studies at Culham have been used. For this graph neo-classical heat losses are assumed.

Need to fill in 'gap' between ohmic heating region and a-heating, where losses dominate

Neutral Beam Injection

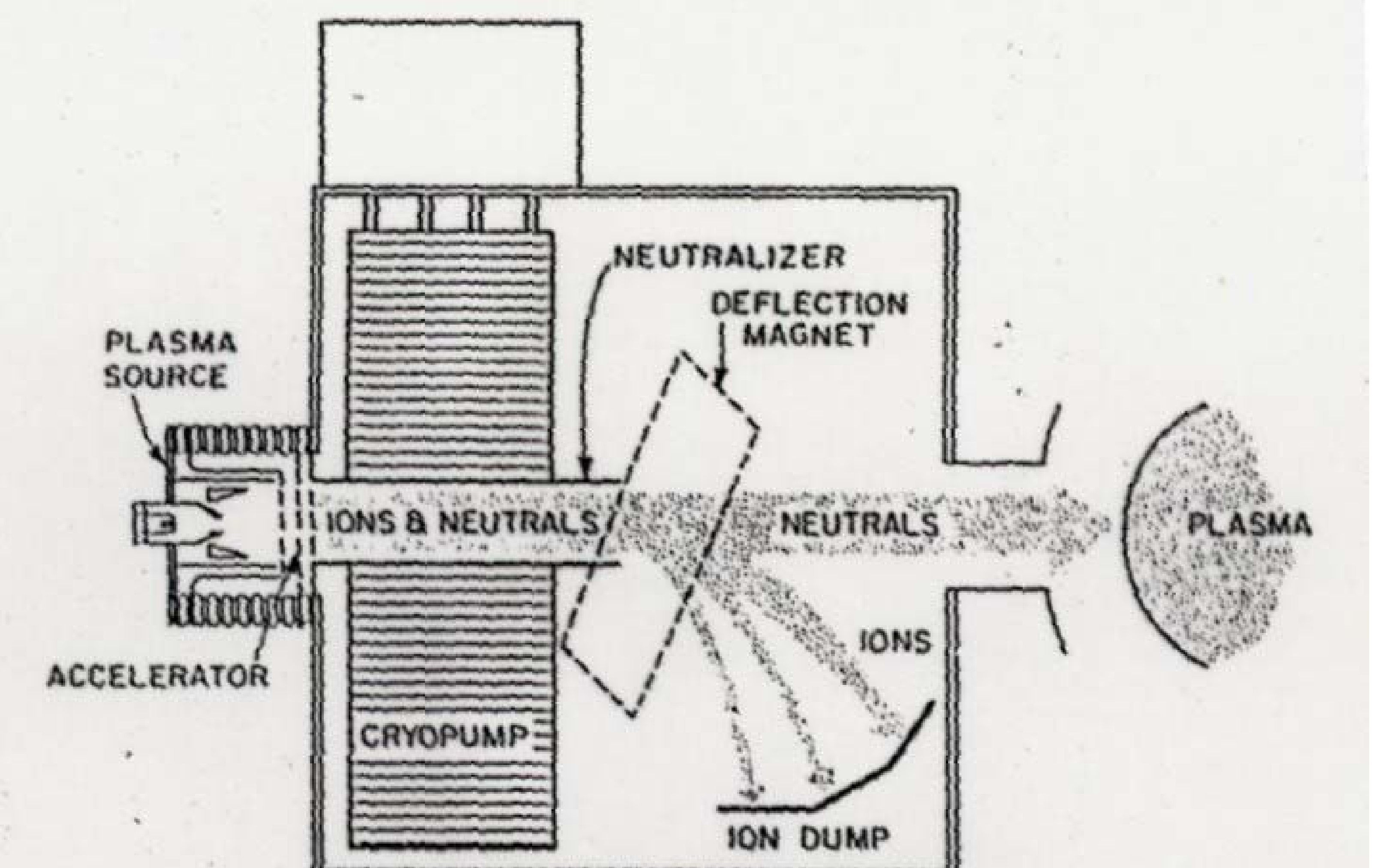


FIGURE 6.5. Schematic illustration of a neutral-beam injection system (from Reference 32).

NBI: neutralisation efficiency

- Neutralisation efficiency goes down for high energies: for large, dense plasmas we need to develop negative ion beams

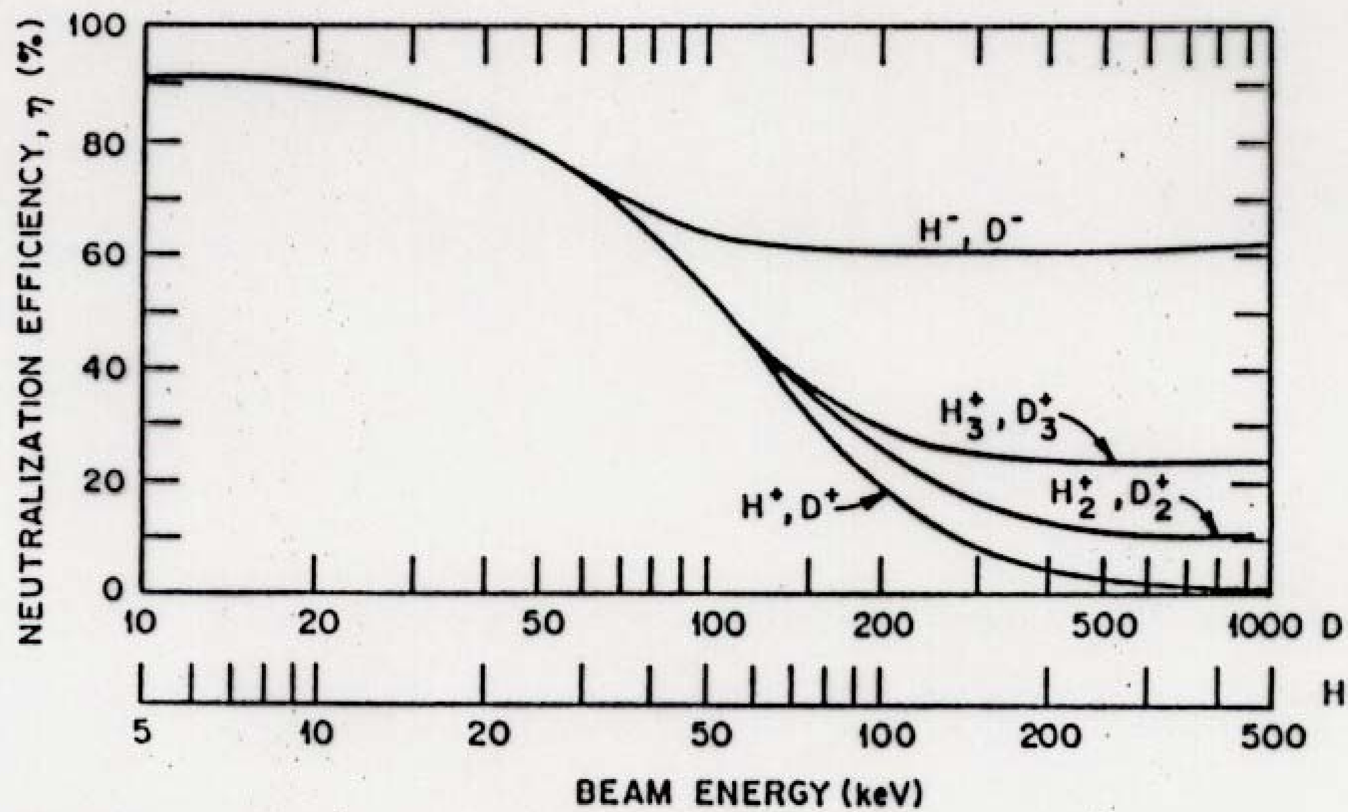
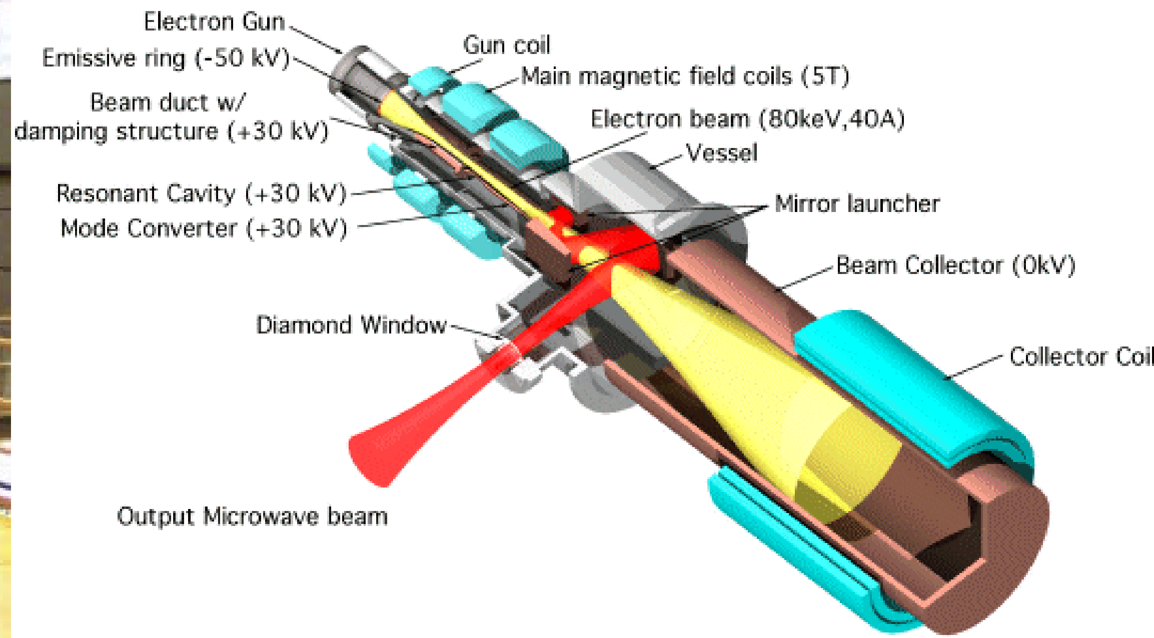


FIGURE 6.6. Neutralization efficiency for different beam energies; efficiency equals power in neutral atoms out divided by power in ion beam entering neutralizer cell.

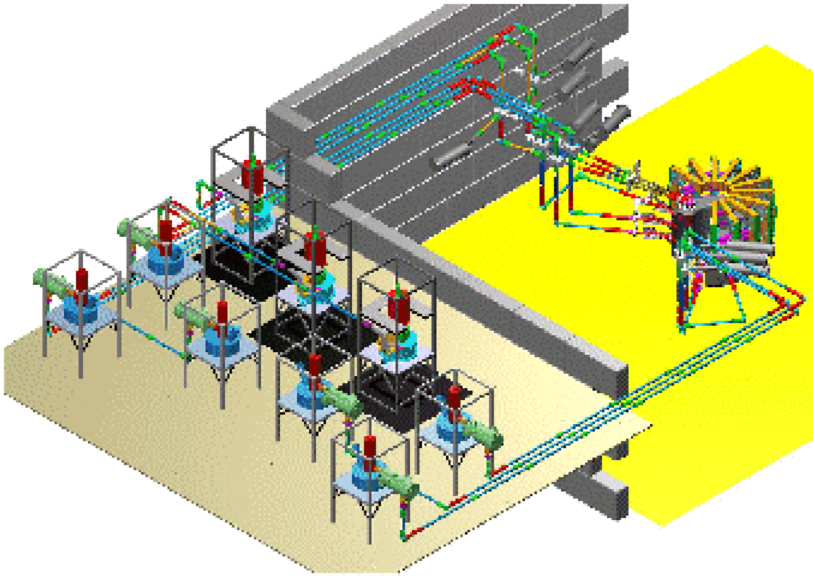
Example of a modern ECRH system TCV - Lausanne

- The sources: gyrotron tubes

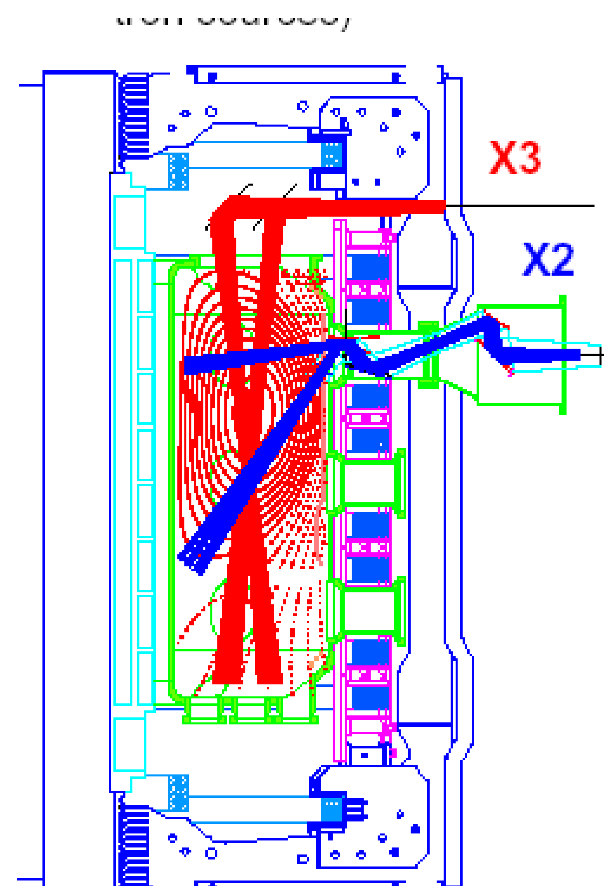
0.5MW, 2s, 6 at 82.7GHz and 3 at 118 GHz



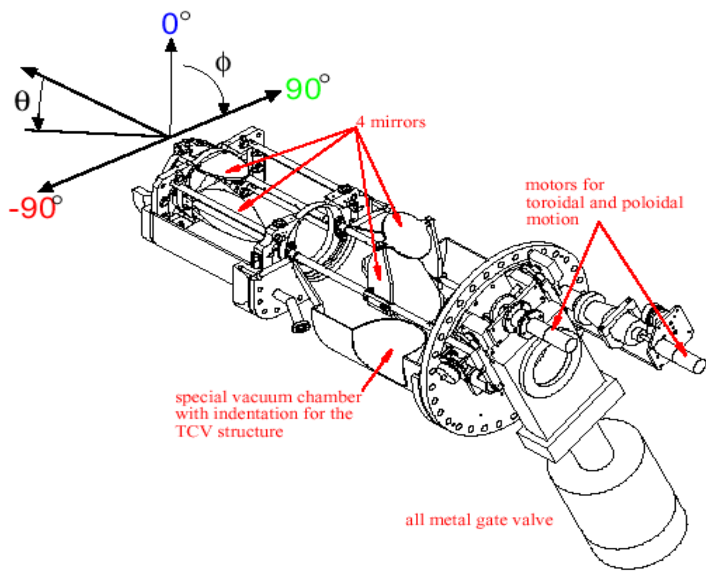
Example of a modern ECRH system TCV - Lausanne



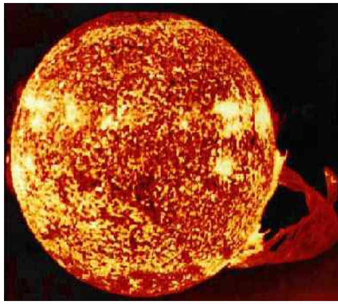
- Steering and injection into tokamak



Beams can be steered poloidally and toroidally



Fusion plasma *physics* challenges

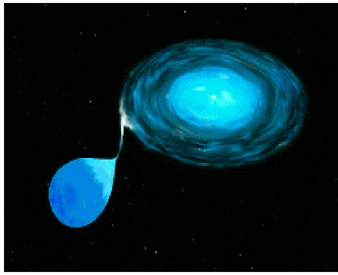


- Large power density and gradients ($10 MW/m^3 \approx 30'000 \times$ sun's core), anisotropy, no thermal equilibrium
  - Macro-instabilities and relaxation processes

solar flares, substorms

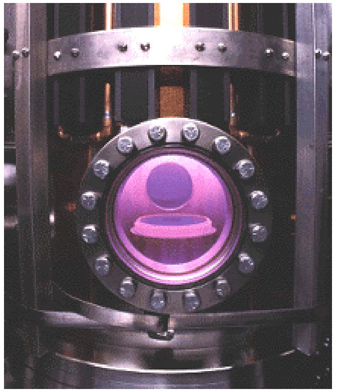
- Dual fluid/particle nature
  - Wave-particle interaction (resonant, nonlinear)

coronal heating



- Turbulent medium
  - Non-collisional transport and losses

accretion disks

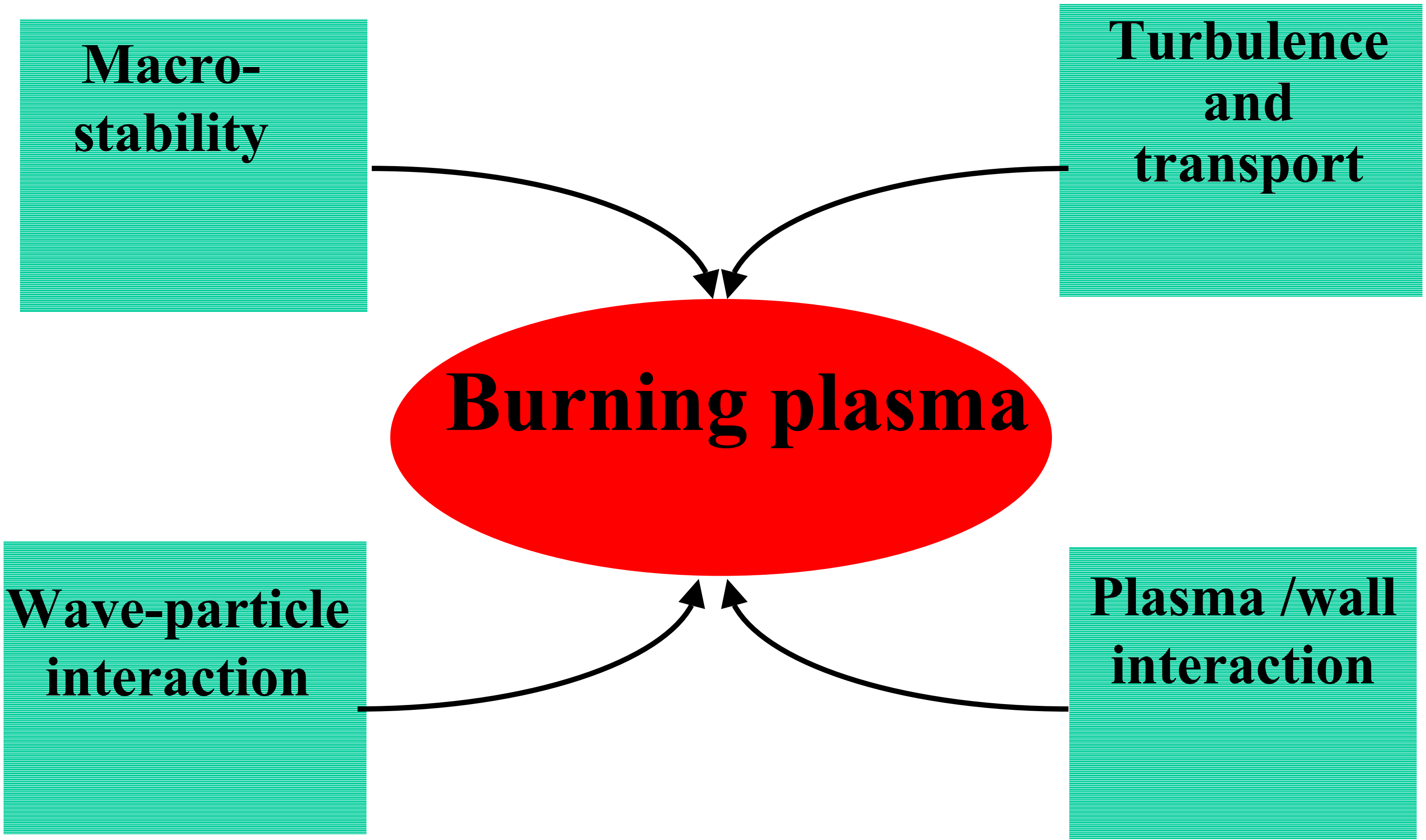


- Plasma-neutral transition, wall interaction

plasma manufacturing

Huge range in temporal ($10^{-10} \rightarrow 10^{5}$ s) and spatial scales ($10^{-6} \rightarrow 10^{4}$ m)

Progress in key areas is leading to next step burning plasma experiment



Macroscopic stability: the MHD model

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0; \qquad \nabla \cdot \mathbf{J} = 0; \tag{19}$$

$$\rho \frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t} = \mathbf{J} \times \mathbf{B} - \nabla p; \qquad \mathbf{E} + \mathbf{u} \times \mathbf{B} = \begin{cases} 0 & \text{“ideal” MHD} \\ \eta \mathbf{J} & \text{“resistive” MHD} \end{cases}; \tag{20}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(p\rho^{\gamma}) = 0; \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J}; \tag{21}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}; \qquad \nabla \cdot \mathbf{B} = 0; \tag{22}$$

Here

$$\frac{\mathrm{d}}{\mathrm{d}t} \equiv \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \tag{23}$$

is the convective derivative. Variables are ρ (*mass* density), $\mathbf{u}$ (fluid velocity), $\mathbf{J}$, p, $\mathbf{E}$, $\mathbf{B}$. We have 16 equations, of which 14 are independent, and 14 unknowns. The MHD approximation describes phenomena that are

- Macroscopic ($L \gg \rho_L$)
- Relatively slow ($\tau \gg \Omega_{ci}^{-1}$; $m_e \frac{d}{dt} \to 0$)
- But fast enough that $u \gtrsim v_{\mathrm{th}i}$

Note that the charge density does not appear, as we consider quasi–neutrality, and that the electric field in the Lorentz force and in the displacement current (in Ampères law) has been neglected.

MHD plasmas: flux freezing and B-field diffusion (1)

In hot plasmas $\eta \to 0$. An important consequence is that magnetic flux is 'frozen' into the plasma. The field lines and the flux tubes associated with them acquire an important physical meaning as if they were real objects.

To estimate over how much time flux can be frozen in plasma, let us consider Ohm's law with $\eta \neq 0$ (resistive MHD). We are interested in the time variation of $\mathbf{B}$ in the plasma

$$\frac{\partial \mathbf{B}}{\partial t} \overset{\text{Faraday}}{=} -\nabla \times \mathbf{E} \overset{\text{Ohm}}{=} -\nabla \times \left\{ -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} \right\}. \tag{24}$$

Assume $\eta \cong$ constant and consider Ampère's law $\mathbf{J} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{\eta}{\mu_0} \nabla \times (\nabla \times \mathbf{B}) =$$

$$= \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{\eta}{\mu_0} (\nabla(\nabla \cdot \mathbf{B}) - \nabla^2 \mathbf{B}) = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\text{convection}} + \underbrace{\frac{\eta}{\mu_0} \nabla^2 \mathbf{B}}_{\text{diffusion}}. \tag{25}$$

MHD plasmas: flux freezing and B-field diffusion (2)

So $\mathbf{B}$ varies in plasma because it is 'transported' by it (convective term) or because it diffuses through it (diffusion term). To estimate the relative importance of the two terms, consider the scale length $L \equiv |\nabla|^{-1}$. Thus

$$\frac{\left|\frac{\eta}{\mu_0}\nabla^2\mathbf{B}\right|}{|\nabla \times (\mathbf{u} \times \mathbf{B})|} \sim \frac{\frac{\eta}{\mu_0}\frac{B}{L^2}}{\frac{uB}{L}} = \frac{\eta}{\mu_0 u L} \equiv R_\mathrm{m}^{-1}, \tag{26}$$

where $R_\mathrm{m} = \mu_0 u L/\eta$ is the magnetic Reynolds number.* In most plasmas of interest $R_\mathrm{m} \gg 1$. The characteristic time for the diffusion of $\mathbf{B}$ in plasmas is

$$\tau = \left(\frac{\eta}{\mu_0 L^2}\right)^{-1} = \frac{R_\mathrm{m} L}{u} \tag{28}$$

and in general is macroscopic, e.g. in the JET tokamak ($L \cong 1$ m, $T_e = 10$ keV, $\eta = 5 \cdot 10^{-5} \times T_{e\,[\mathrm{eV}]}^{-3/2} \ln\Lambda \sim 7.5 \cdot 10^{-10}\ \Omega\mathrm{m}$)

$$\tau \sim 1700\ \mathrm{s}. \tag{29}$$

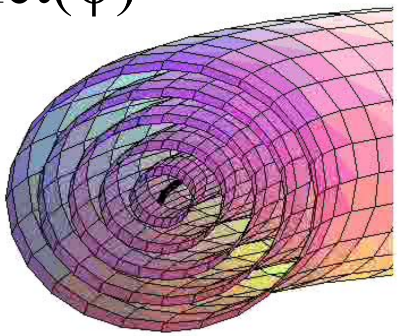
MHD equilibrium

- MHD equations with d/dt=0: $\mathbf{j}\times\mathbf{B} = \nabla p$
- Consequences

  $\mathbf{B} \bullet \nabla p = 0$ →pressure is constant on magnetic surfaces

  $\mathbf{j} \bullet \nabla p = 0$ →current lies on magnetic surfaces

  →All quantities are flux functions: fct(ψ)



- Tokamak equilibrium is characterised by
  – Safety factor $q=\Delta\phi/2\pi$, $\Delta\phi$=toroidal angle covered by field line to come back at same position
    - If a<<R, $q \sim rB_{tor}/R_0B_{pol} \propto 1/I_p$
  – Normalised pressure $\beta=nT/(B^2/2\mu_0)$

MHD Stability in Tokamaks

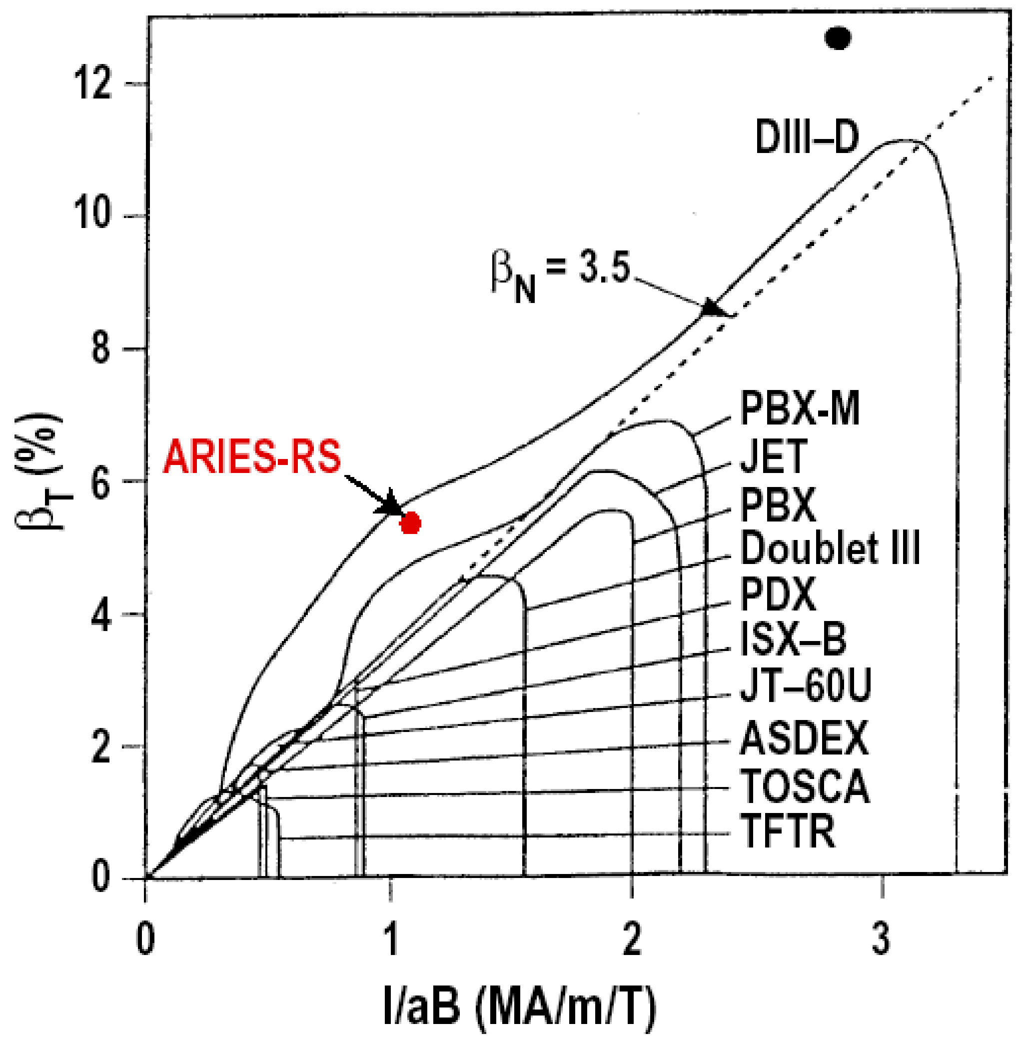
- Destabilising forces
  - Current gradients
  - Pressure gradients combined with *bad* curvature (Rayleigh-Taylor)
- Stabilising factors
  - B-field line bending and compression (field lines tends to stretch)
  - Good curvature
- Two classes of instabilities
  - Ideal MHD
    - $\eta=0$; fast time scale (μs): no hope for active control
  - Resistive MHD
    - $\eta\neq0$; longer time scale (ms): hope for active control

MHD stability imposes limits on optimisation of fusion parameters

- Current limit
  - Limits energy confinement time
    - $\tau_E \propto 1/q \sim I_p$ for fixed B-field
  - Can be improved by shaping the plasma
- Limit in normalised pressure $\beta \propto nT/B^2$
  - Limits fusion power for given B ($$$!)
    - $P_{fus} \propto \beta^2 B^4$
  - Can be improved by shaping the plasma
- Density limit
  - Limits fusion power
    - $P_{fus} \propto n^2 \langle \sigma v \rangle$
  - Not fully understood, can be improved by peak radial profiles

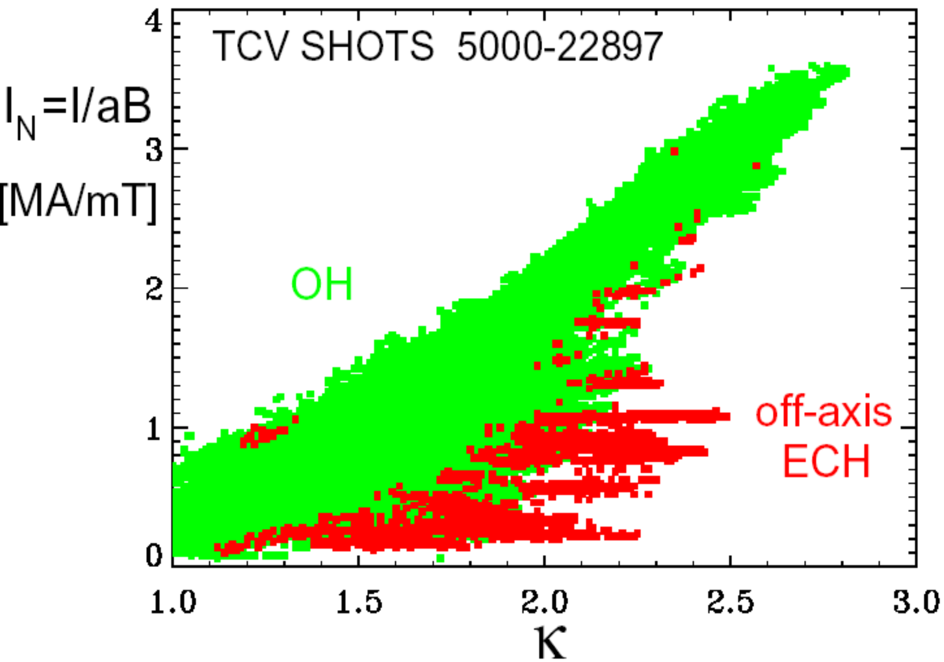
Ex. of ideal MHD stability limits

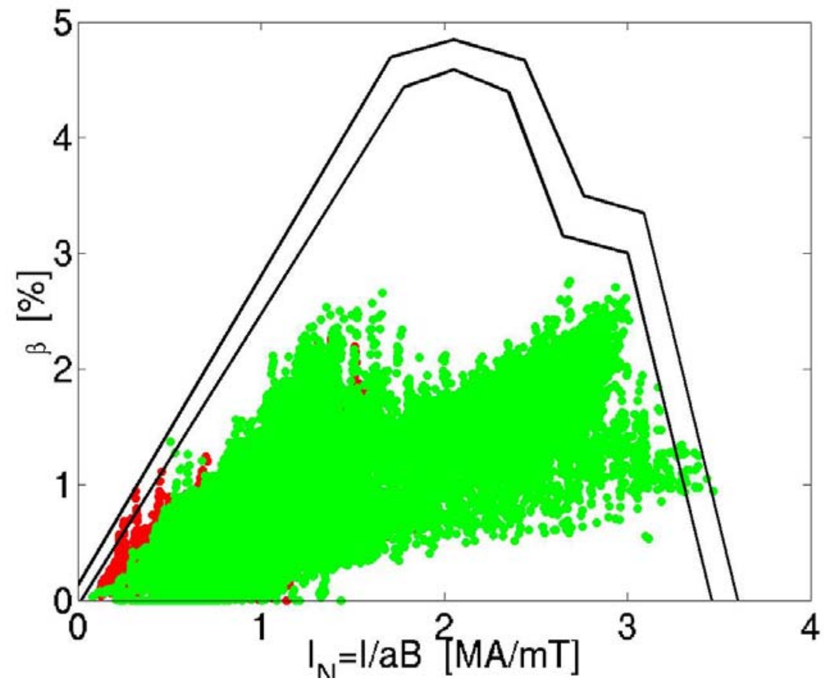
- Ex. limit in β and current



Ideal MHD limits in shaped plasmas

– TCV tokamak (Lausanne): extend stability domain using high elongation discharges





Violation of ideal MHD stability: disruptions

- Sudden loss of stability: the plasma and the current carried by it are lost over fast time scale

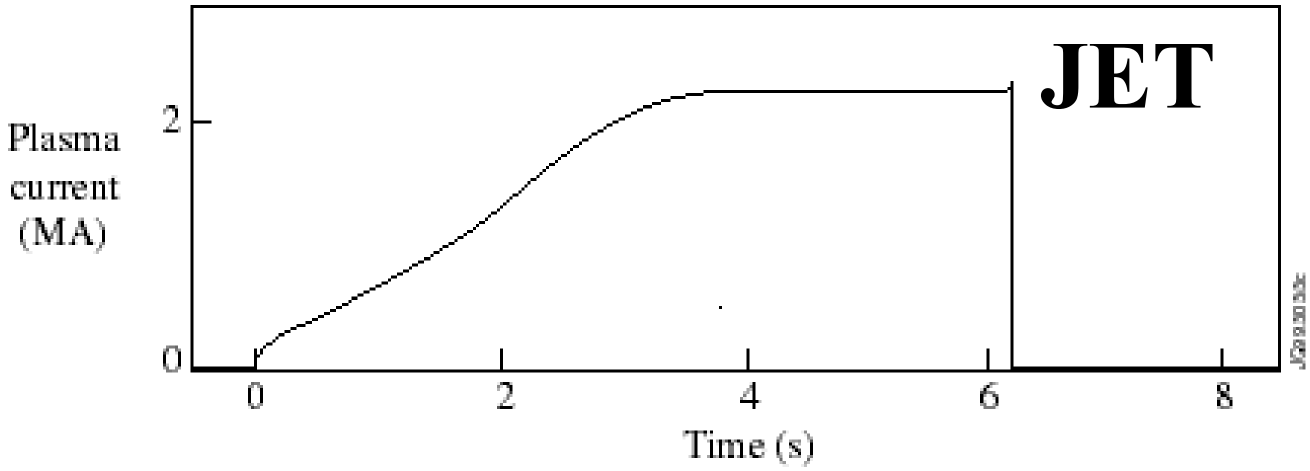
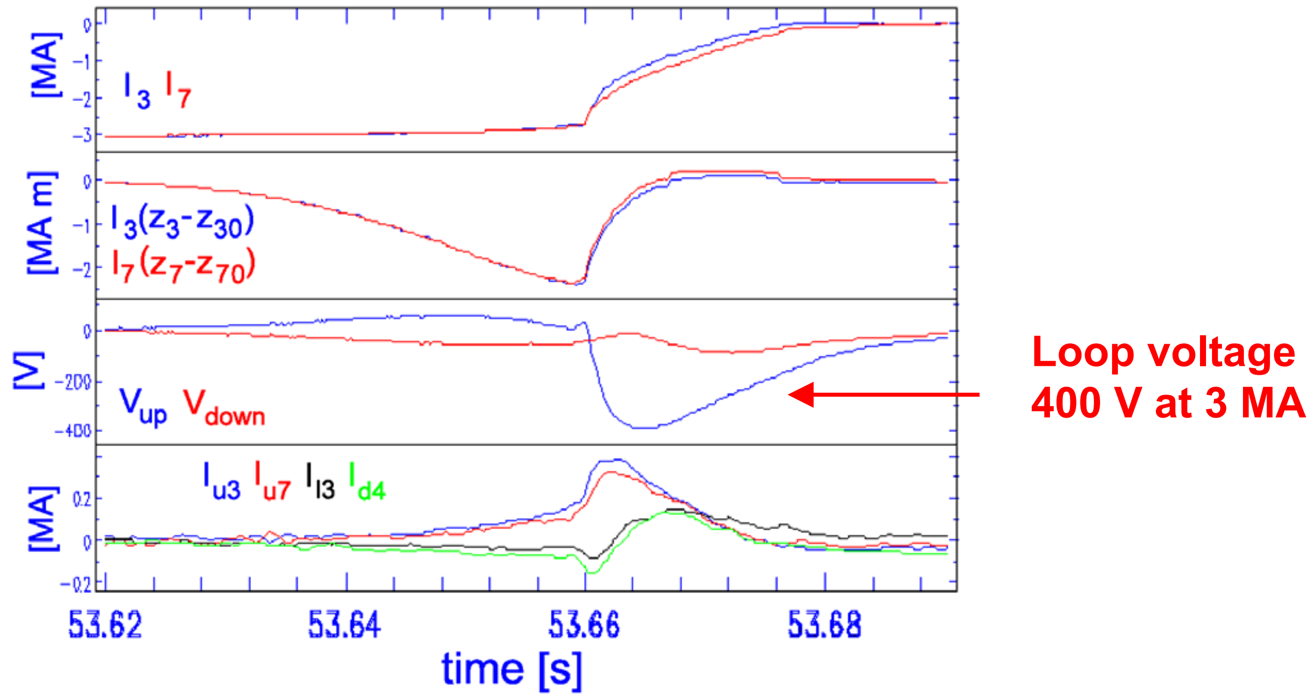


Figure 10.1. Time trace of the plasma current showing the abruptness of the current decay in a fast disruption.

Consequences of disruptions toroidal loop voltage…



… creating *Runaway* Electrons

- RE have too high energy to be slowed down by collisions ($\sigma \sim v^{-3}$), and keep being accelerated by residual E-field
- At very high energy confinement is lost and wall can be damaged

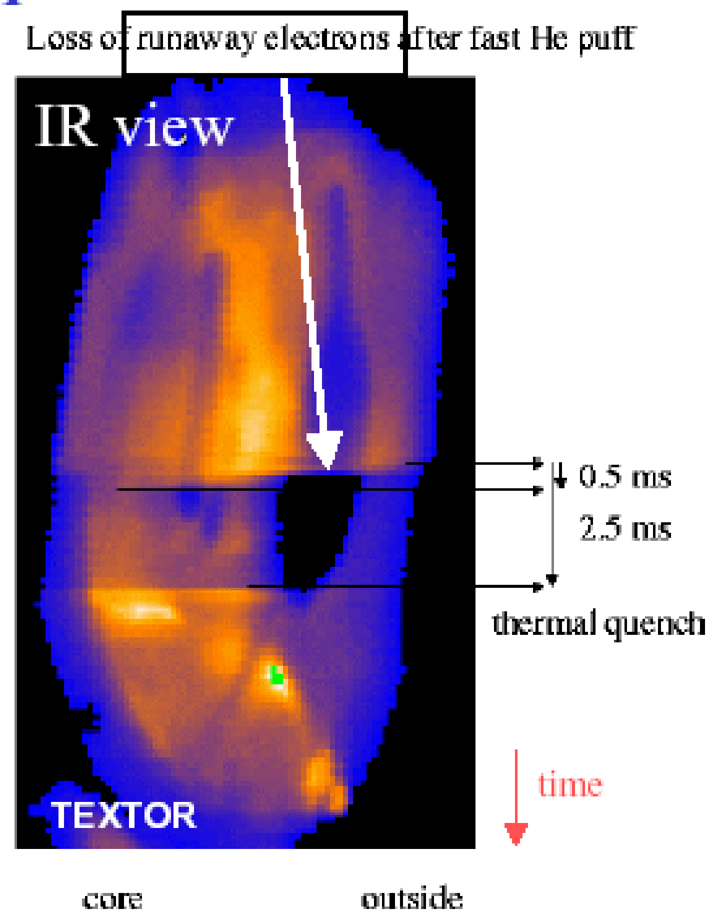
Disruption mitigation: TEXTOR tokamak

HELIUM PUFF

Prove runaway electron suppression

Runaway electrons start interacting with the injected helium within 0.5 ms of the opening of the valve.

HXR shows that no RE crashes on the wall at their original (high) energy.



KH Finken et al., Journal of Nuclear Materials **313-316** (2003) 1247

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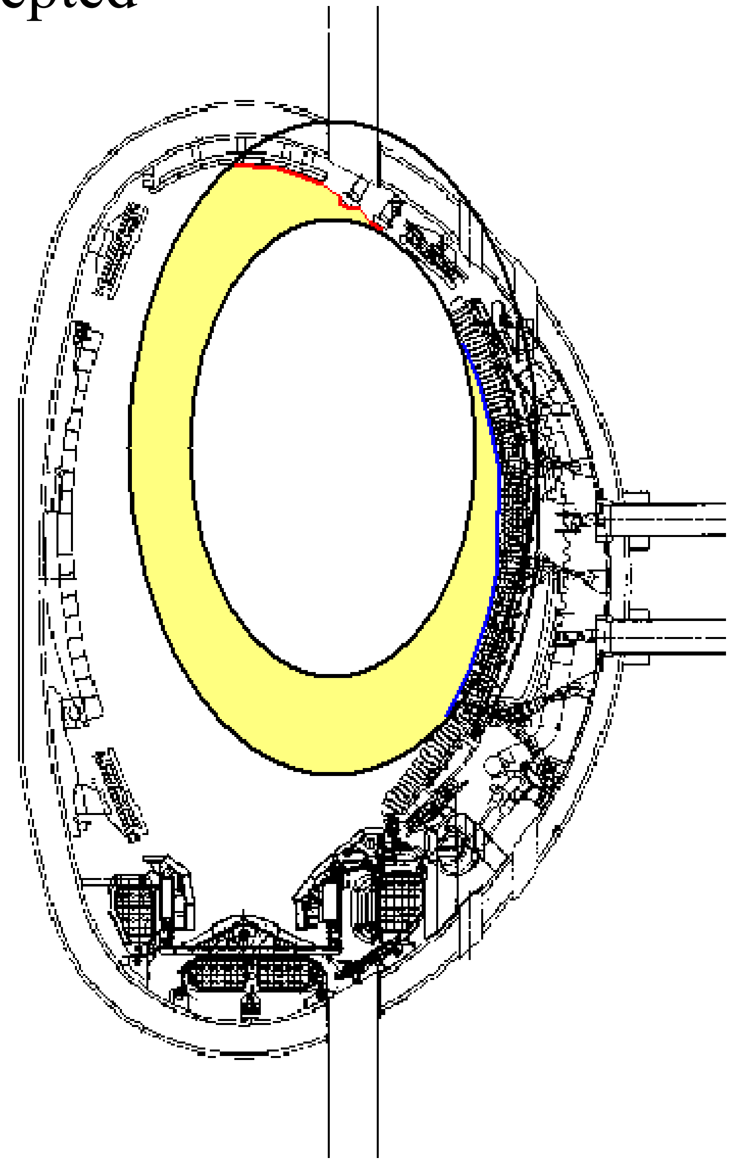
in der Helmholtz-Gemeinschaft

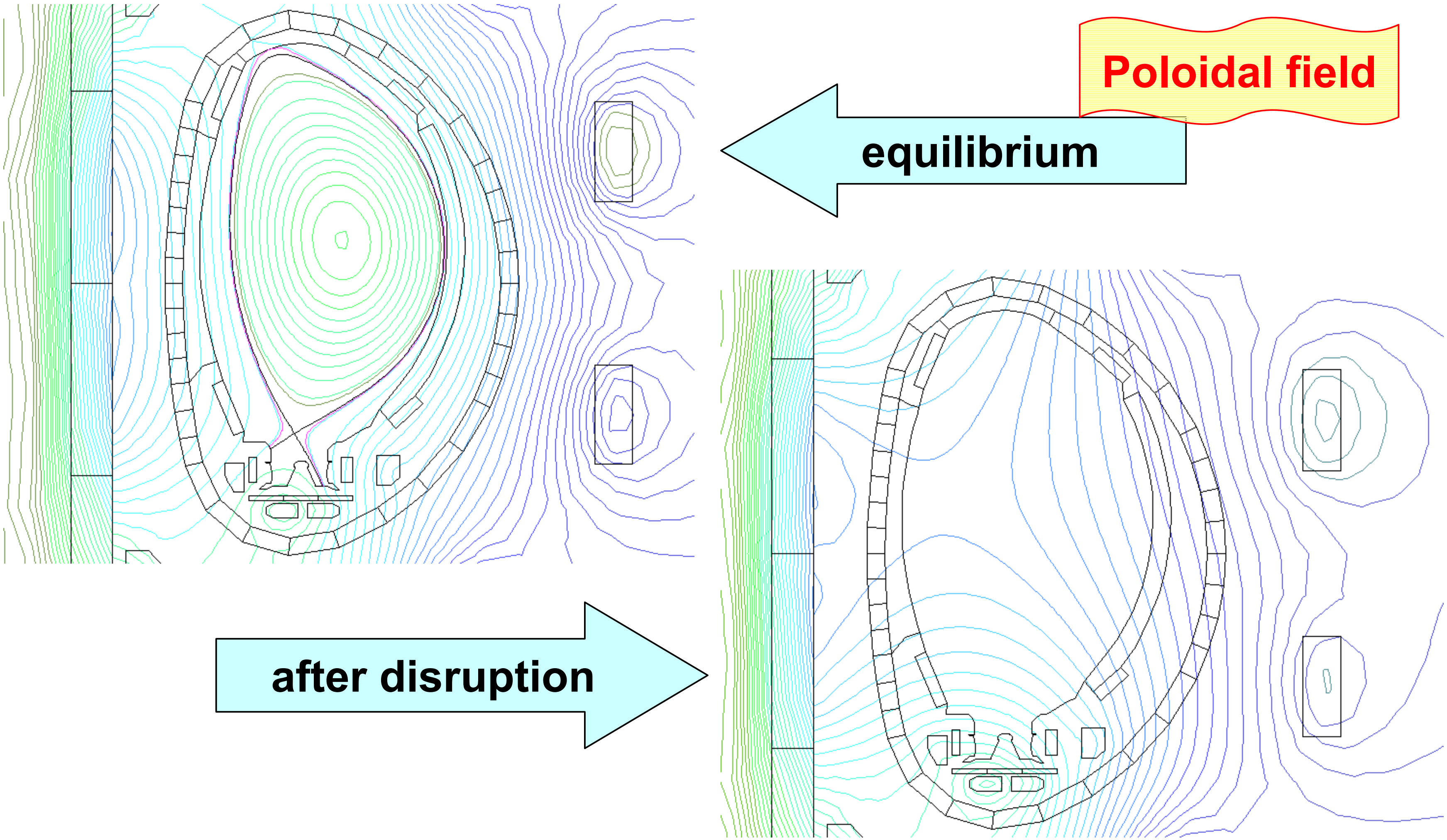
Consequences of disruptions: halo currents

- Currents flowing in plasma intercepted by conducting surfaces
- $I_{halo} \sim< 30\%\ I_{pmax}$



Consequences of disruptions: large dB/dt

E.g. in JET: dB/dt ~ 100T/s (radial, poloidal)



Must avoid paths for induced current