New Trends in Fusion Research

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CERN Academic Training Programme

11-13 October 2004

Credits and acknowledgments

EFDA, CRPP, MIT-PSFC, PPPL, LLNL, SNL, IFE Forum, US-DoE,

ILE Osaka, ESA, NASA, LLE, UCB, UKAEA, ….. with

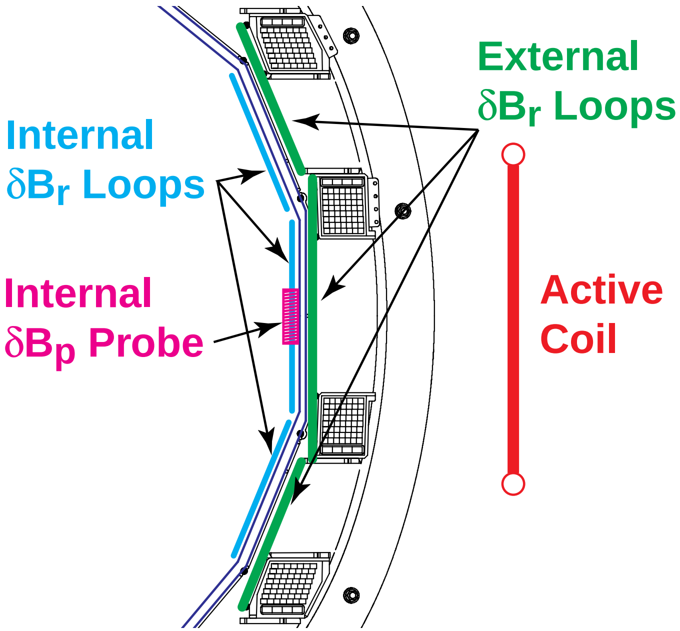
apologies to the many authors from whom I have 'stolen' viewgraphs

Lay-out of Lecture 3

- *Magnetic fusion physics challenges (cont.)*
  - Macroscopic equilibrium and stability
    - Resistive MHD instability
    - Example of a basic problem related to MHD in tokamaks and in space: magnetic reconnection
  - Plasma wall interaction
    - Main issues
    - The divertor concept

Resistive MHD Instabilities: ex. of active control

Active magnetic feedback with sensors and power supplies stabilizes Resistive Wall Modes in rapidly rotating plasmas.

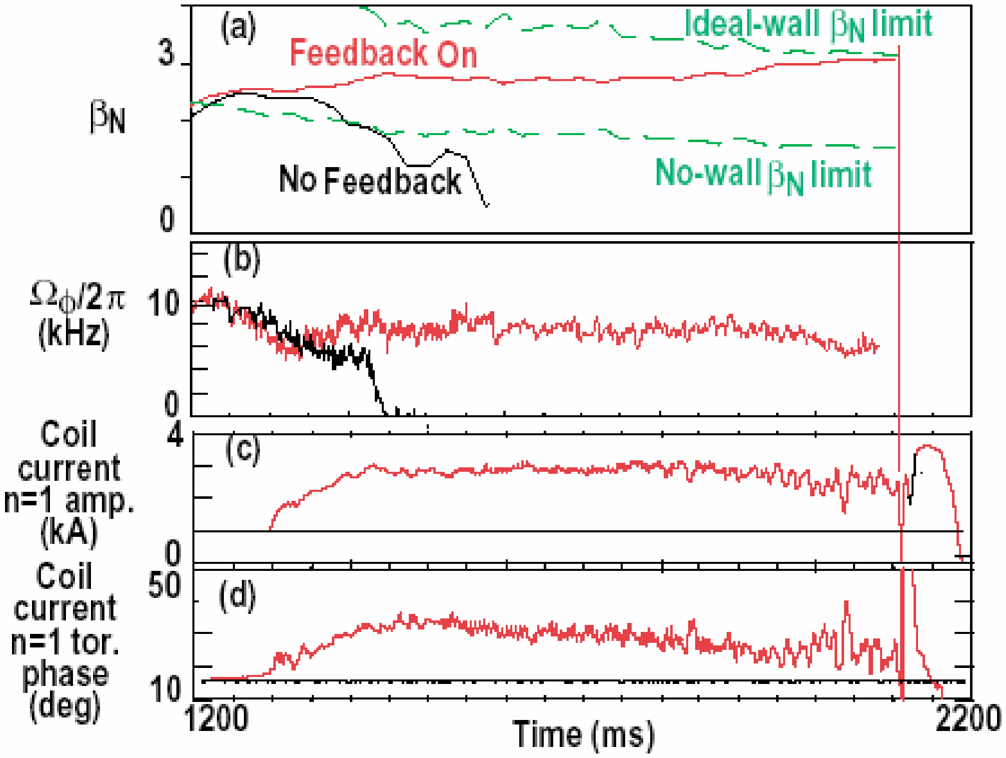


External δB_r Loops

Internal δB_r Loops

Internal δB_p Probe

Active Coil

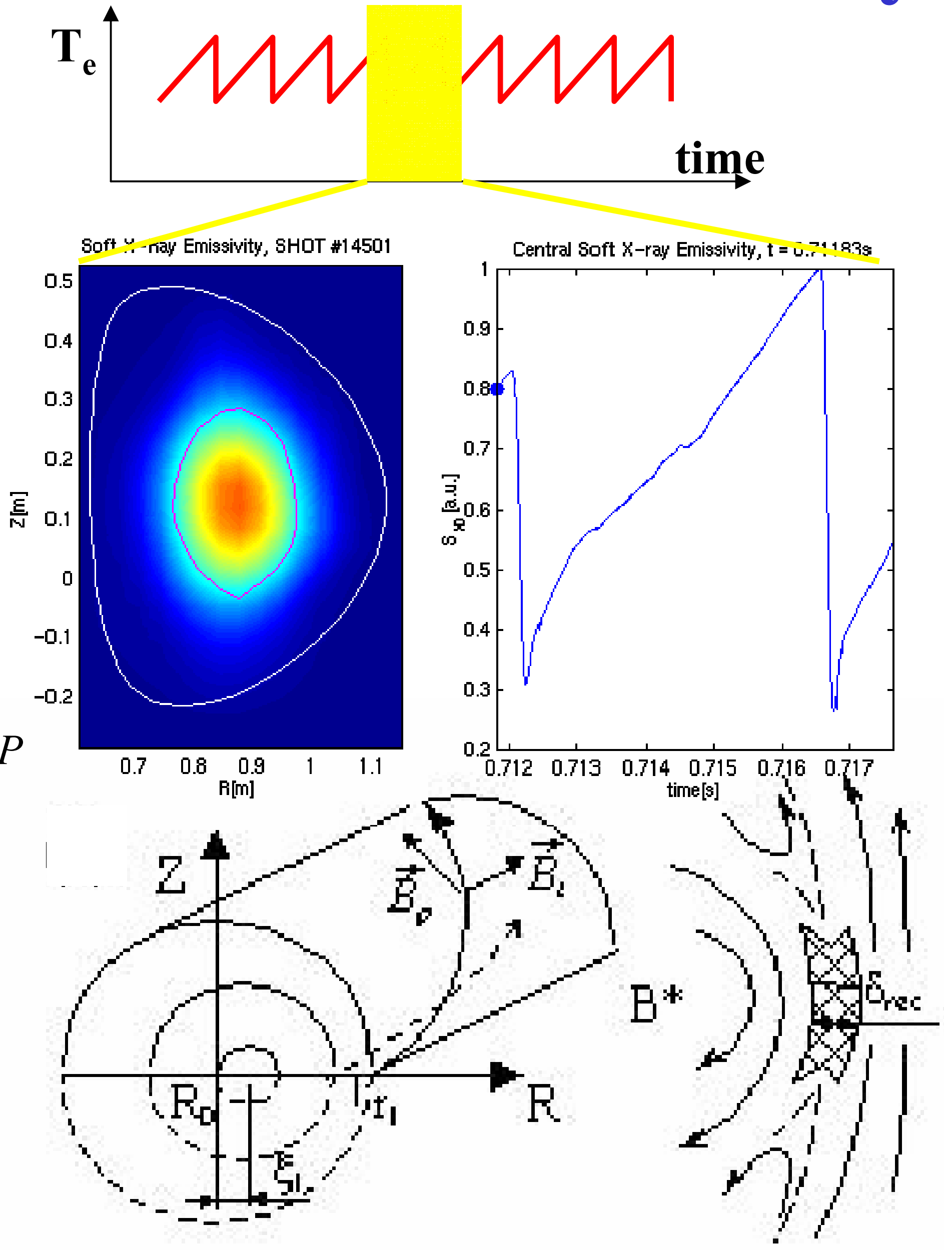


DIII-D tokamak, GA

Ideal or resistive? The sawtooth instability

- Sudden, very fast losses of energy and particles in core
- Ex.: X-ray emissivity

(~T_e, n) evolution in TCV

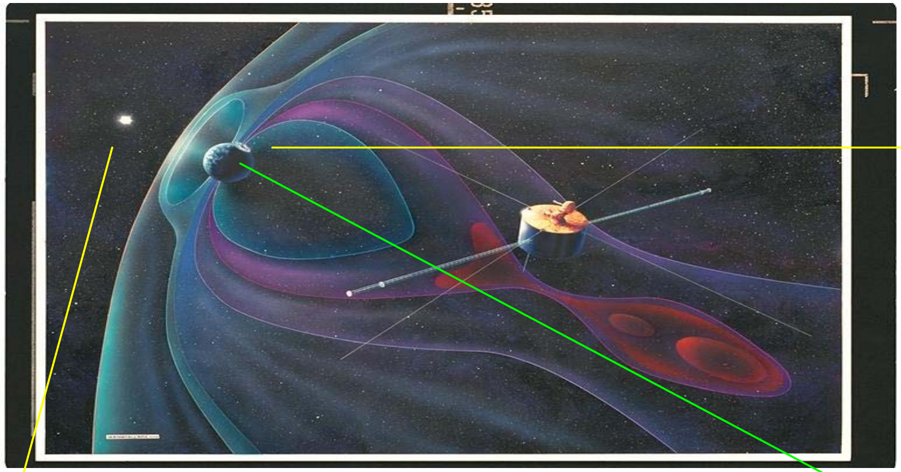


Courtesy of I.Furno, CRPP

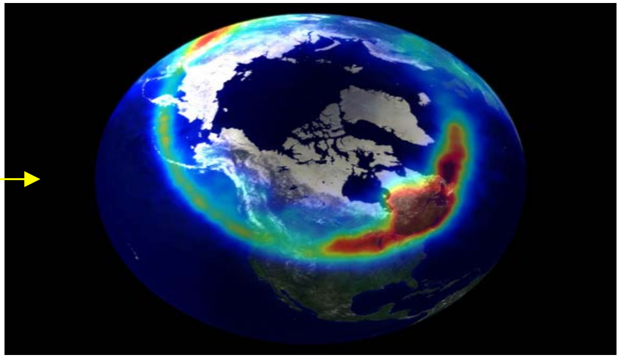
- Instability →local breaking of magnetic structure

Magnetic reconnection

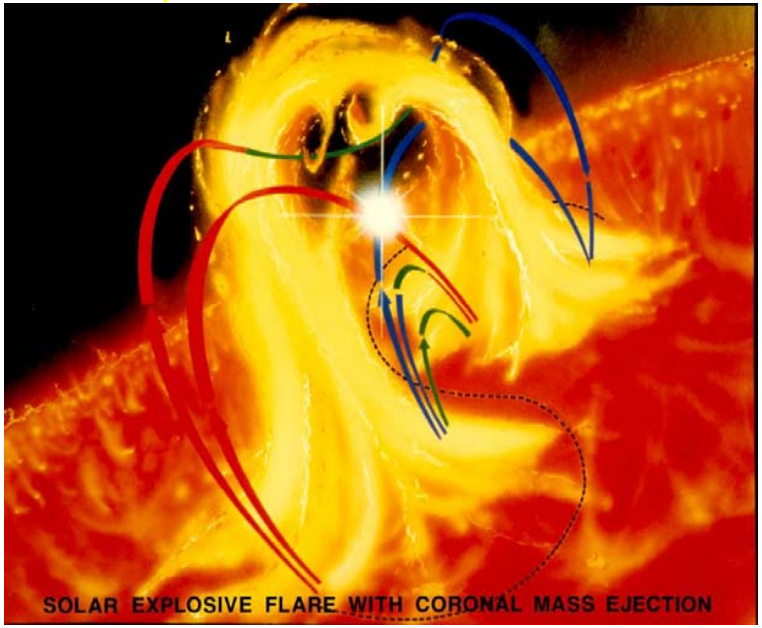
Change in B-field topology in the presence of plasma



Sun: flares,
coronal
mass
ejections



Earth: substorms, aurora

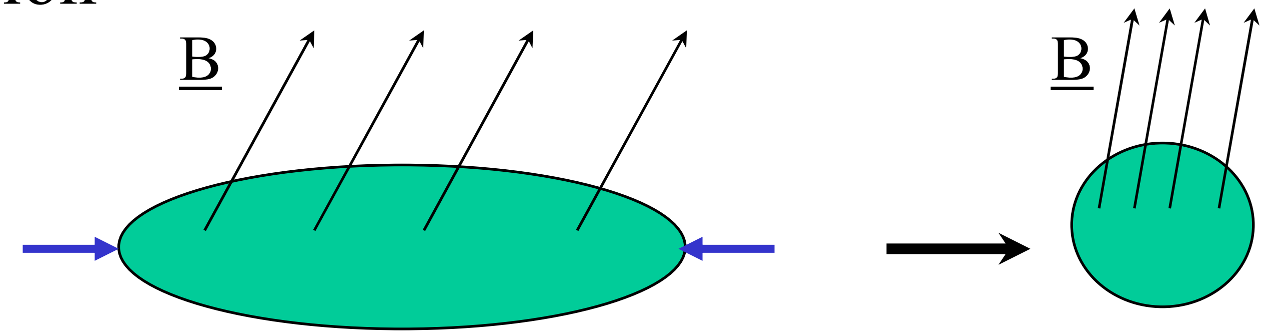


Fusion:

internal
relaxations
(*strong
guide field*)

Plasma as a charged fluid

- Resistivity η = 0: plasma and B frozen together, no reconnection



- Resistivity η ≠ 0: $\mathbf{E}+\mathbf{v}\times\mathbf{B}=\eta\mathbf{j}$ → **B** can diffuse wrt plasma

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \mathbf{v} \times \mathbf{B} - \frac{\eta}{\mu_0}\nabla^2\mathbf{B} = 0$$

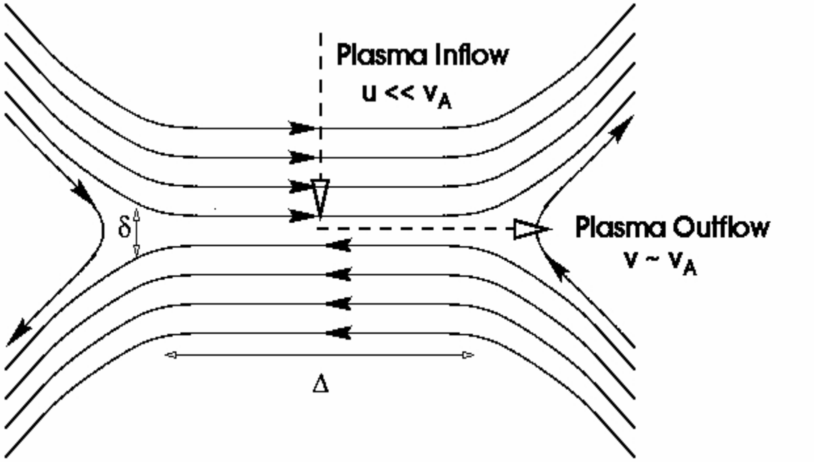
$t_R = \mu_0 L^2/\eta$ resistive time

Reconnection is an open question

	resistive time t_R	observed reconnection time
tokamaks	~1-10 s	10-100 μs
solar flares	$\sim 10^4$ years	~20 min
substorms	~infinite	~30 min

- If B^2-energy is converted to plasma flow
  - $v \sim v_A = B/(\mu_0 mn)^{1/2}$ Alfvén speed; but $t_A = L/v_A$ is far too short to explain observations
- Which L? Model local geometry
  - Ex. Sweet-Parker model

$t_{SP} \sim (t_R t_A)^{1/2}$ still far too long!



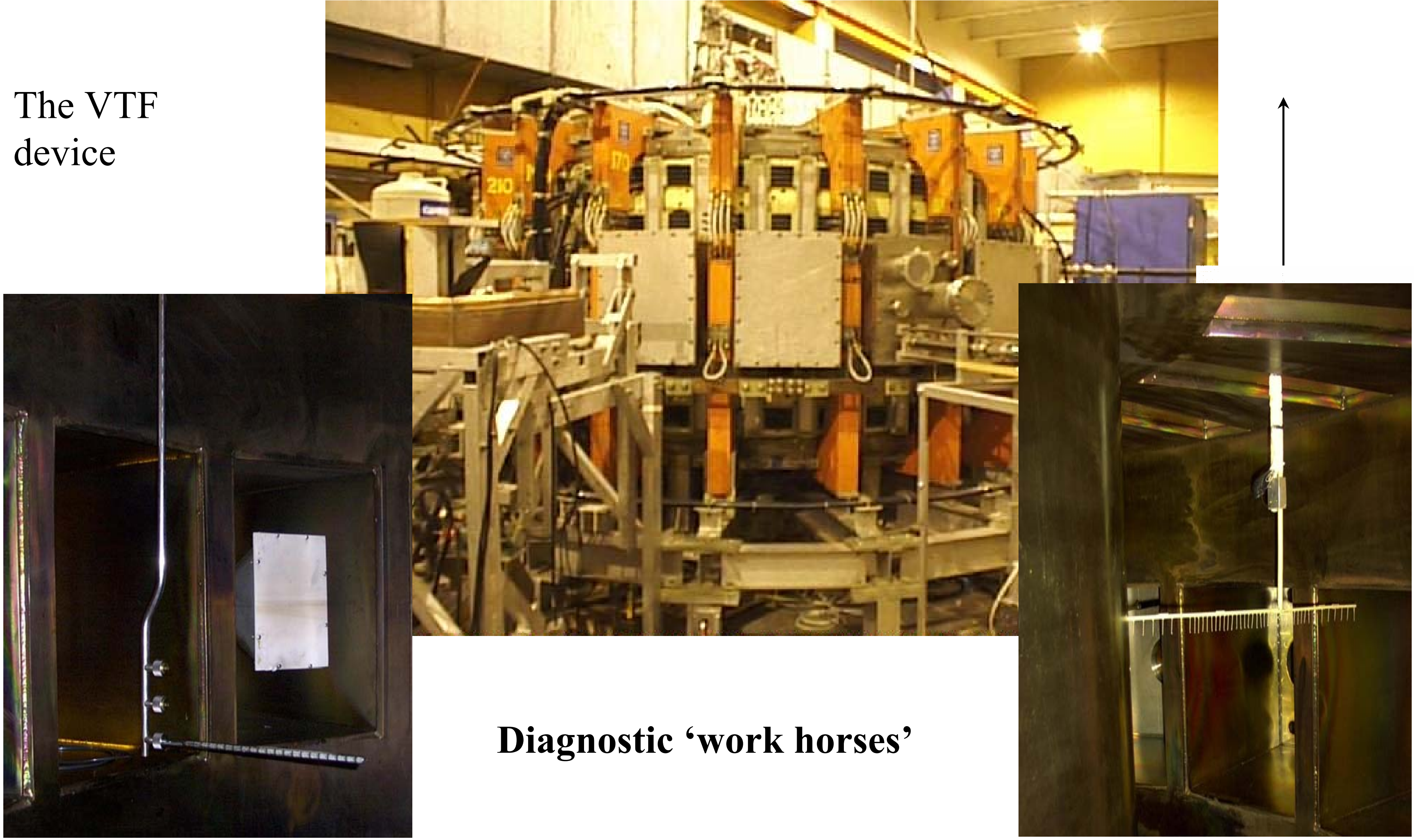
Examples of addressed questions on reconnection

- Can fast collisionless reconnection be observed?
- Intermittent vs. steady-state reconnection?
- Origin of fast time scale, mechanism breaking frozen-in law?

VTF reconnection experiment at MIT

Study plasma response to driven reconnection

The VTF
device



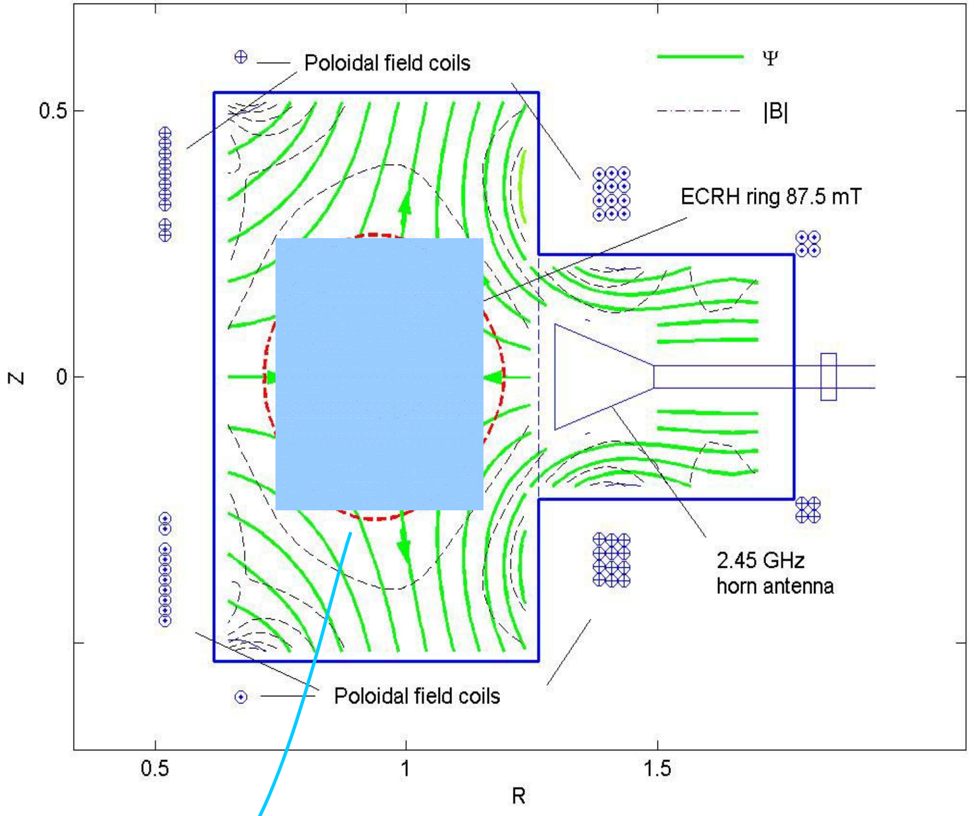
Diagnostic ‘work horses’

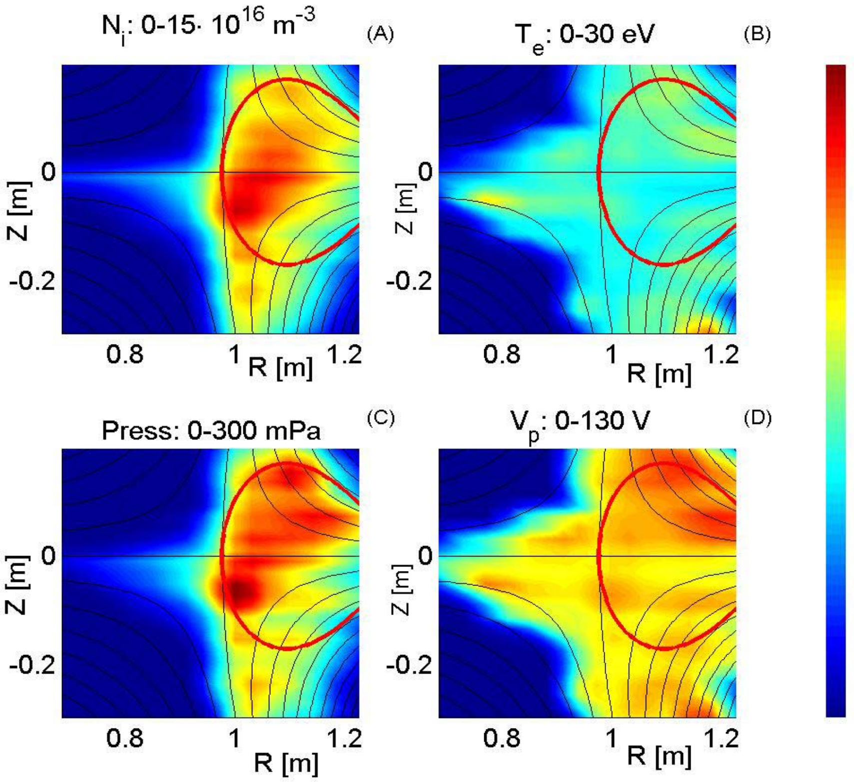
40-channels B-probe

45 heads L-probe

VTF configuration

- $\lambda_{mfp} >> L$, $\tau_{coll} > \tau_{orbit}, t_A; \rho_i << L$
- Plasma production by ECRH separate from reconnection drive

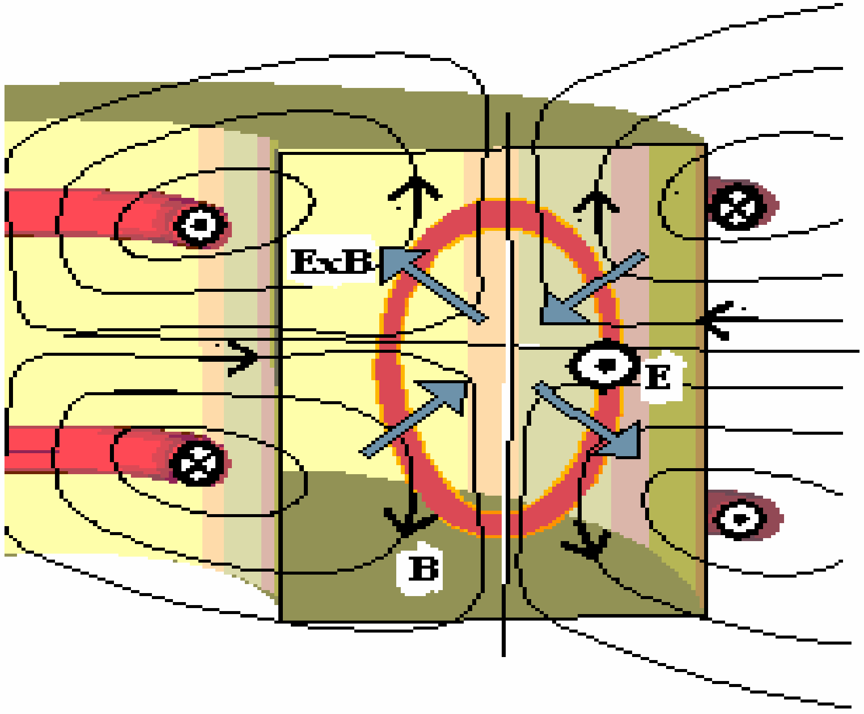


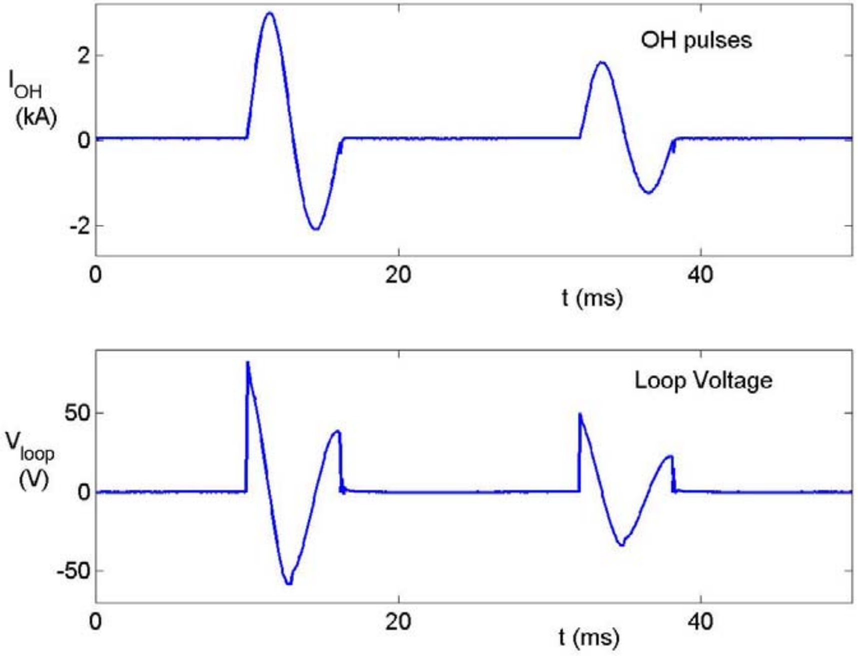


Ex. of target plasma profiles

$B_{cusp} = 50mT$, $B_{guide} = 87mT$; $P_{ECRH} \sim 30$ kW

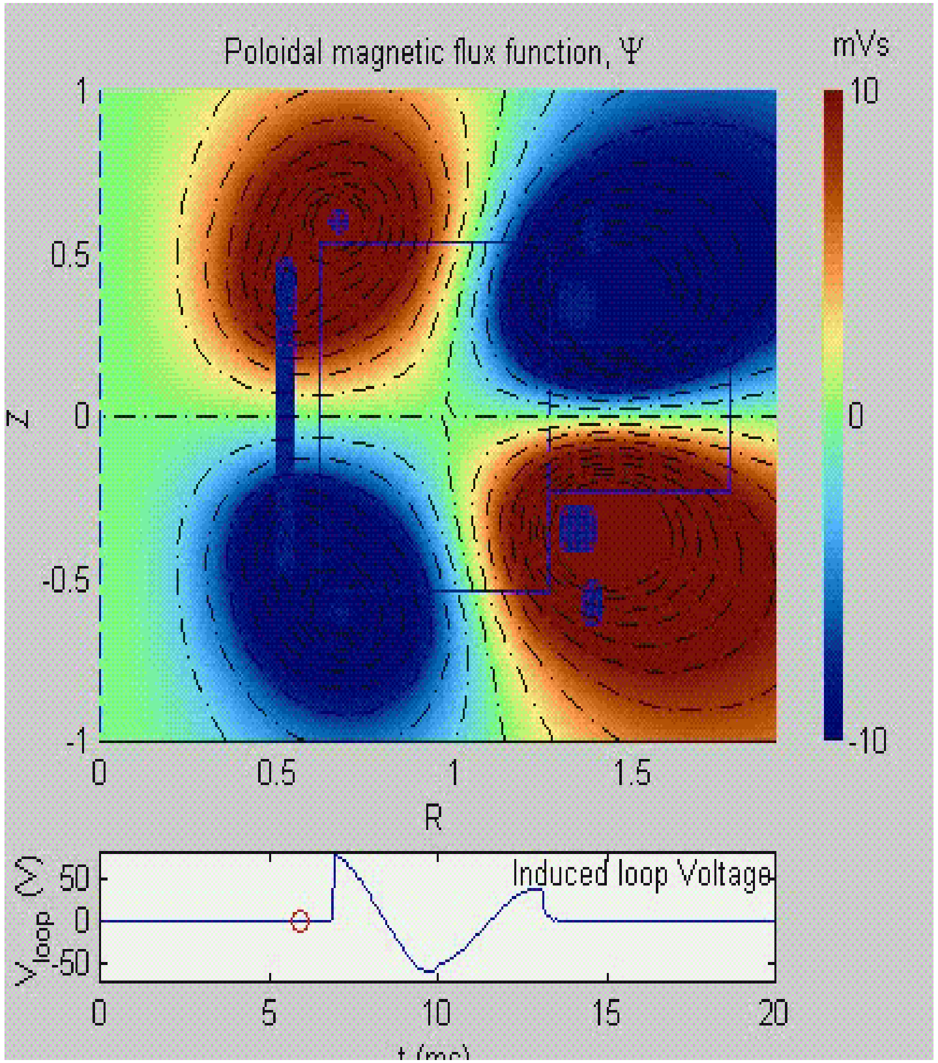
Reconnection drive





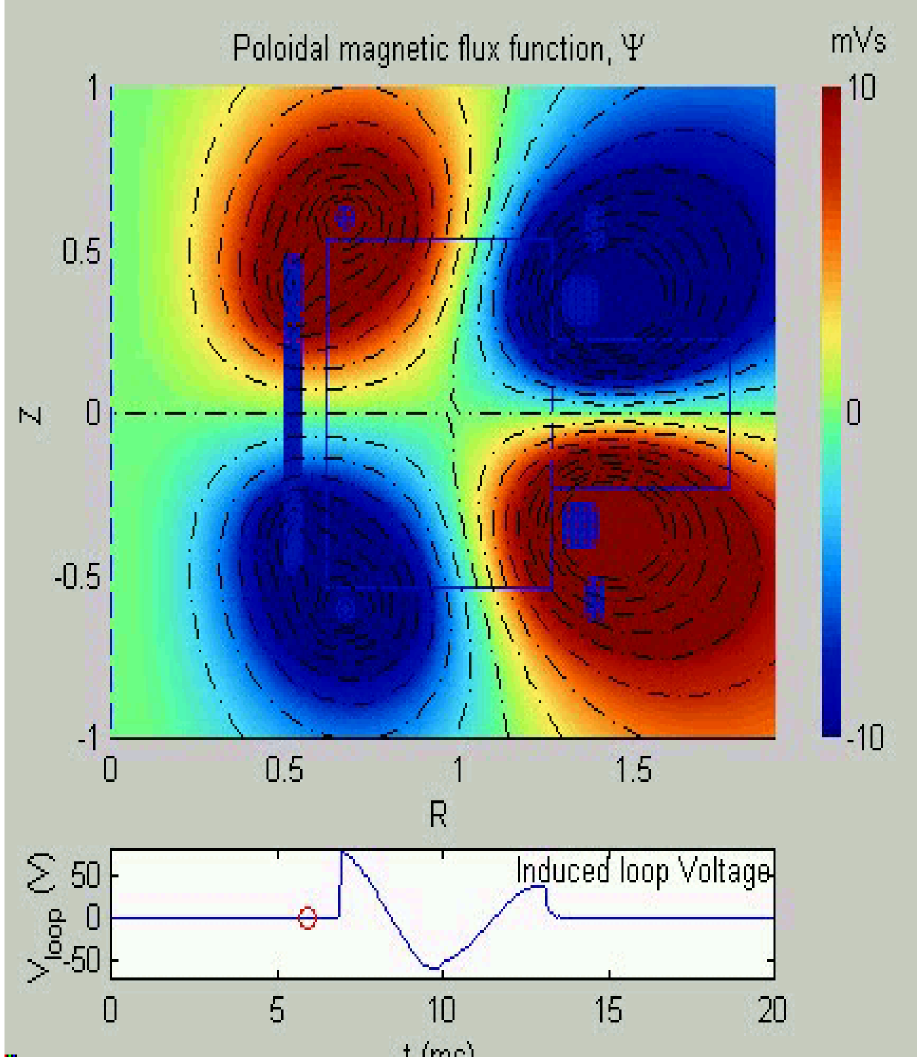
- Ohmic coils driven by LC resonant circuit
- Flux swing ~ 0.2 V-s, duration ~ 6 ms ($>>t_{reconnection}$)
- $V_{loop} \sim 100$ V, $v_{ExB} \sim 2$km/s $\sim v_A/10$

Calculated poloidal flux during reconnection drive



No reconnection

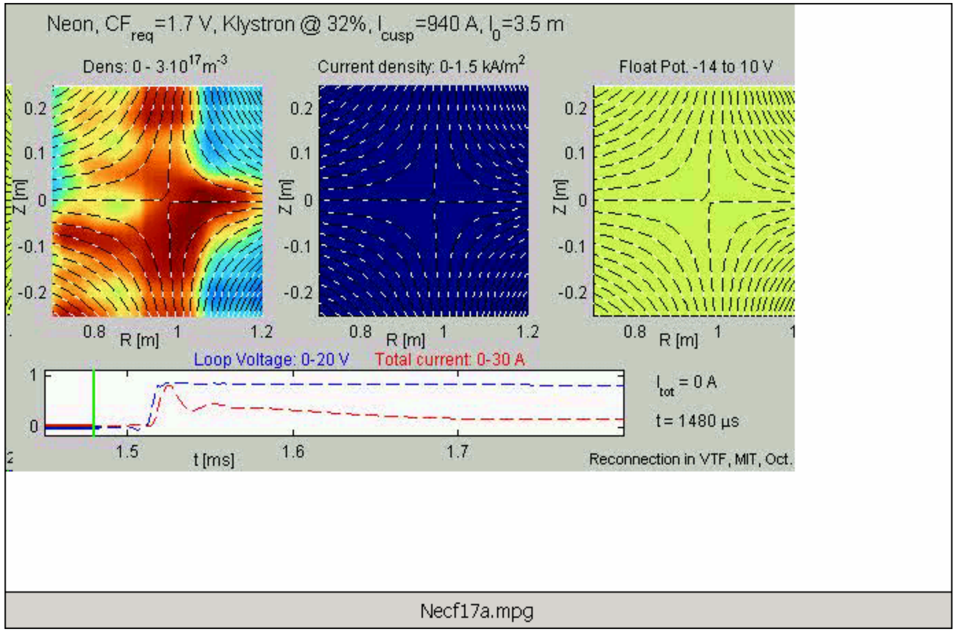
as in ideal MHD



Fast reconnection

as in vacuum

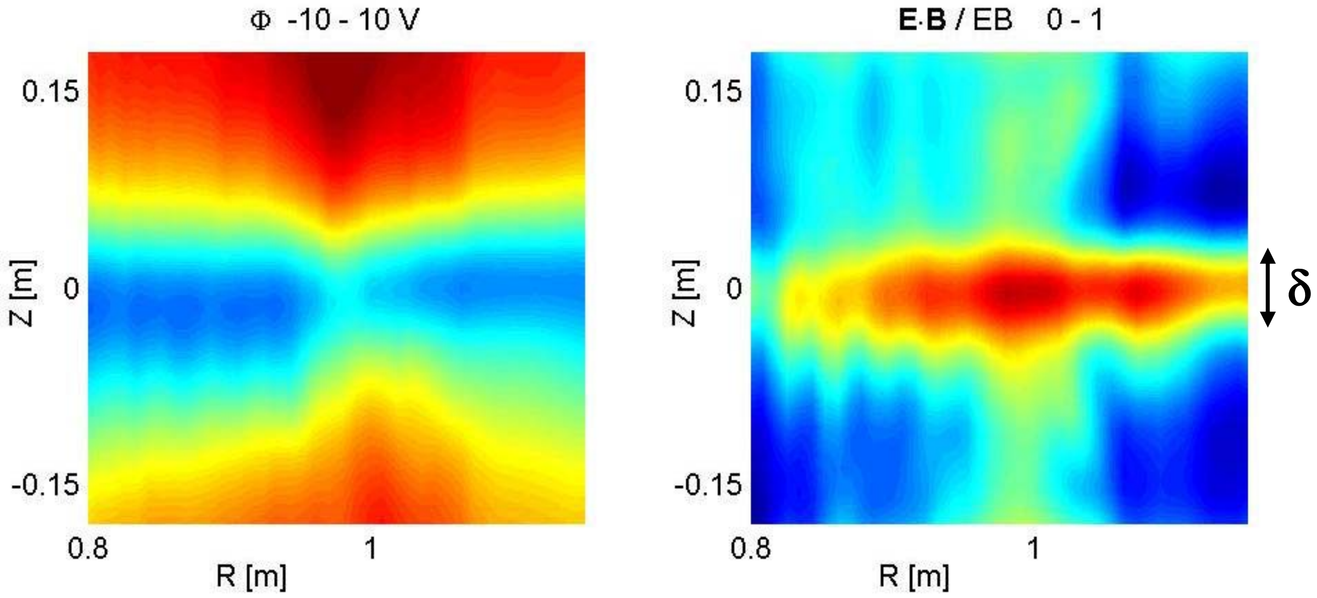
Measured response to driven reconnection



What breaks the *frozen-in* law?

The *frozen-in* law is violated where **E•B**≠0, *diffusion region*

Experimental measurement



Generalized Ohms law:

$$\mathbf{E}+\mathbf{v}\times\mathbf{B}=\cancel{\eta\,\mathbf{j}}+\frac{1}{ne}(\cancel{\mathbf{j}\times\mathbf{B}}-\boxed{\nabla\cdot\mathbf{p}_e})+\cancel{\frac{m_e}{ne^2}\frac{d\,\mathbf{j}}{dt}}$$

Would give $\delta \sim c/\omega_{pe}$

too small ($<10^3$) & can't explain phase

far too small with strong guide field, would give $\delta \sim c/\omega_{pi}$

Only off-diagonal terms (toroidal symmetry) → orbit effects

Results on addressed reconnection questions

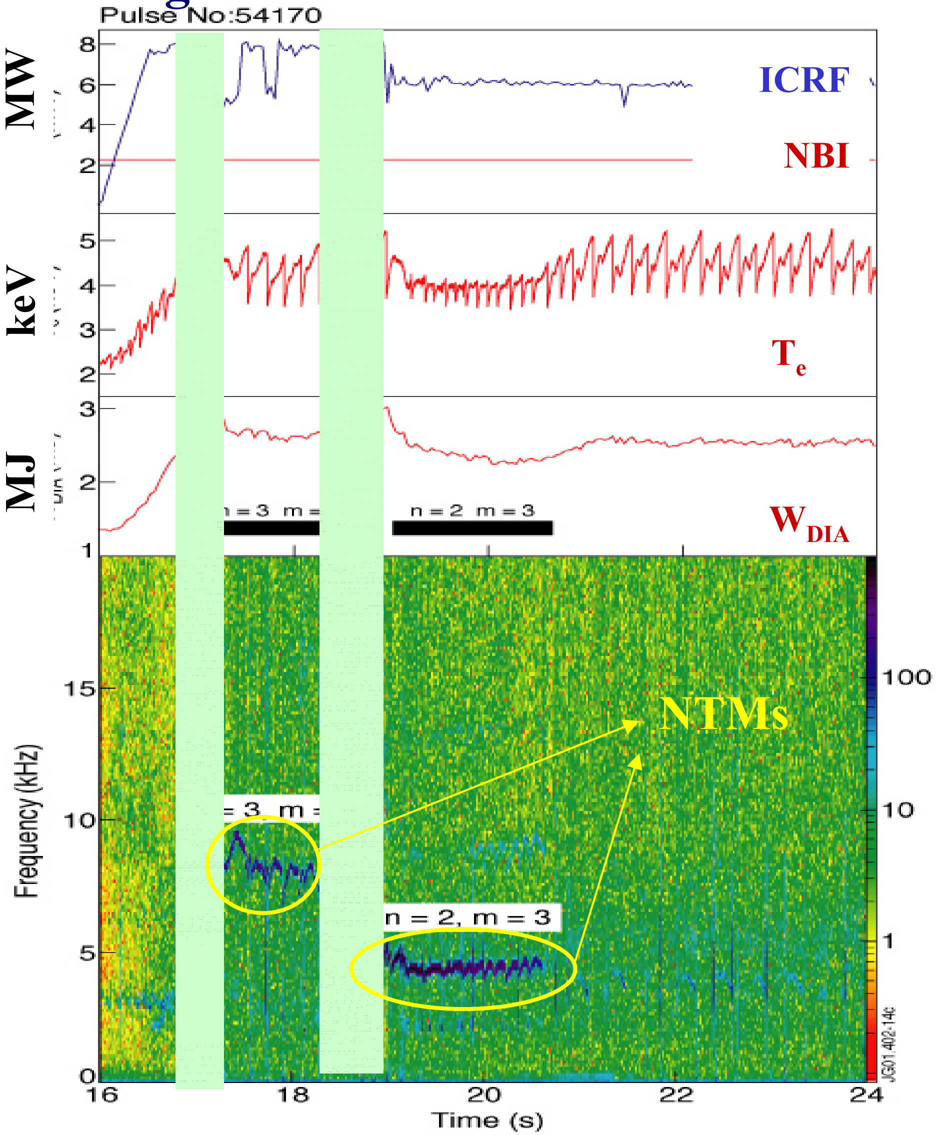
- *Can fast collisionless reconnection be observed?*
  - **Yes, was directly measured in the lab**
    - **Highly anomalous current: can’t even define resistivity as E/J≠constant**
- *Can reconnection be intermittent with a steady drive?*
  - **Yes: no steady-state, dynamical evolution of j(r) and potential**
    - **Ion polarisation current explains observed reconnection dynamics**
- *Origin of fast time scale for reconnection, mechanisms behind breaking of frozen-in flux?*
  - **$\nabla\cdot p_e$ (off-diagonal), kinetic effects, particle orbits**

Back to tokamak problems:

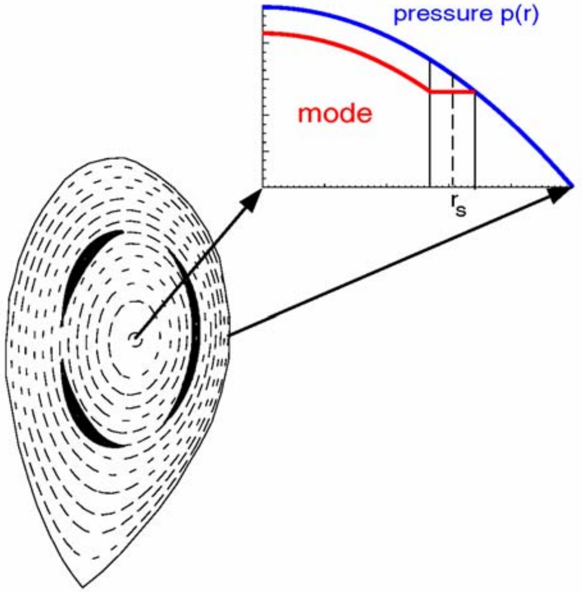
coupling betwen sawteeth and NTM instability

- Small sawteeth are benign
  - Redistribution only local
- α's (or other fast particles, e.g. created by ICRH) increase sawtooth period
  - Sawtooth crash, when eventually comes, is much larger, and triggers other resistive instabilities (*NTM*) that tear B-field structure over large region, degrading confinement

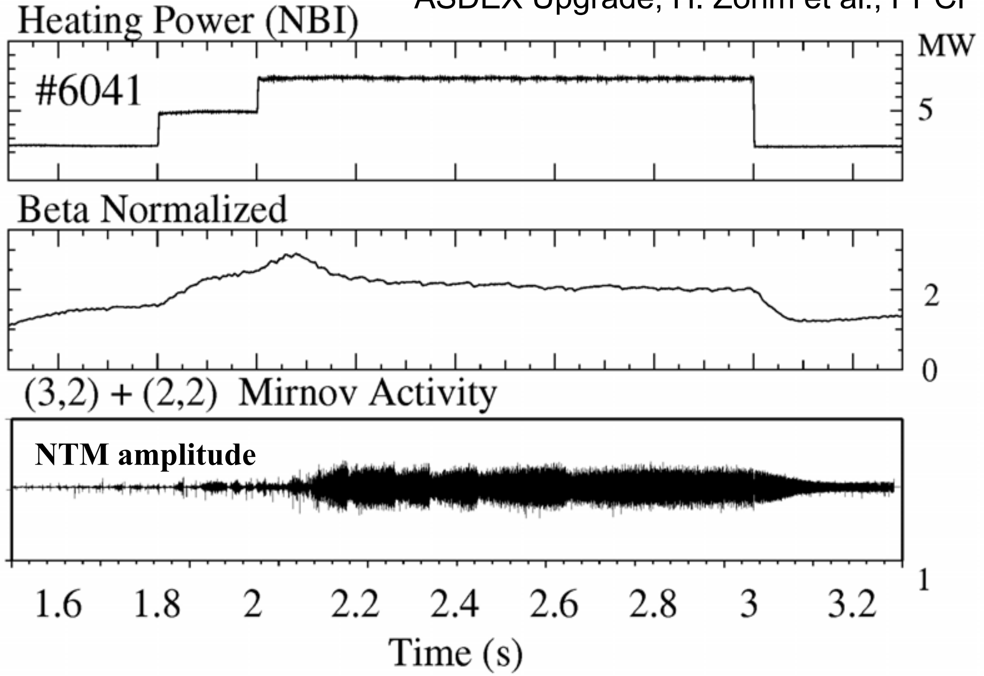
Ex. of NTM triggered crashes of large ICRH-stabilised sawteeth



Neoclassical Tearing Modes



ASDEX Upgrade, H. Zohm et al., PPCF 96



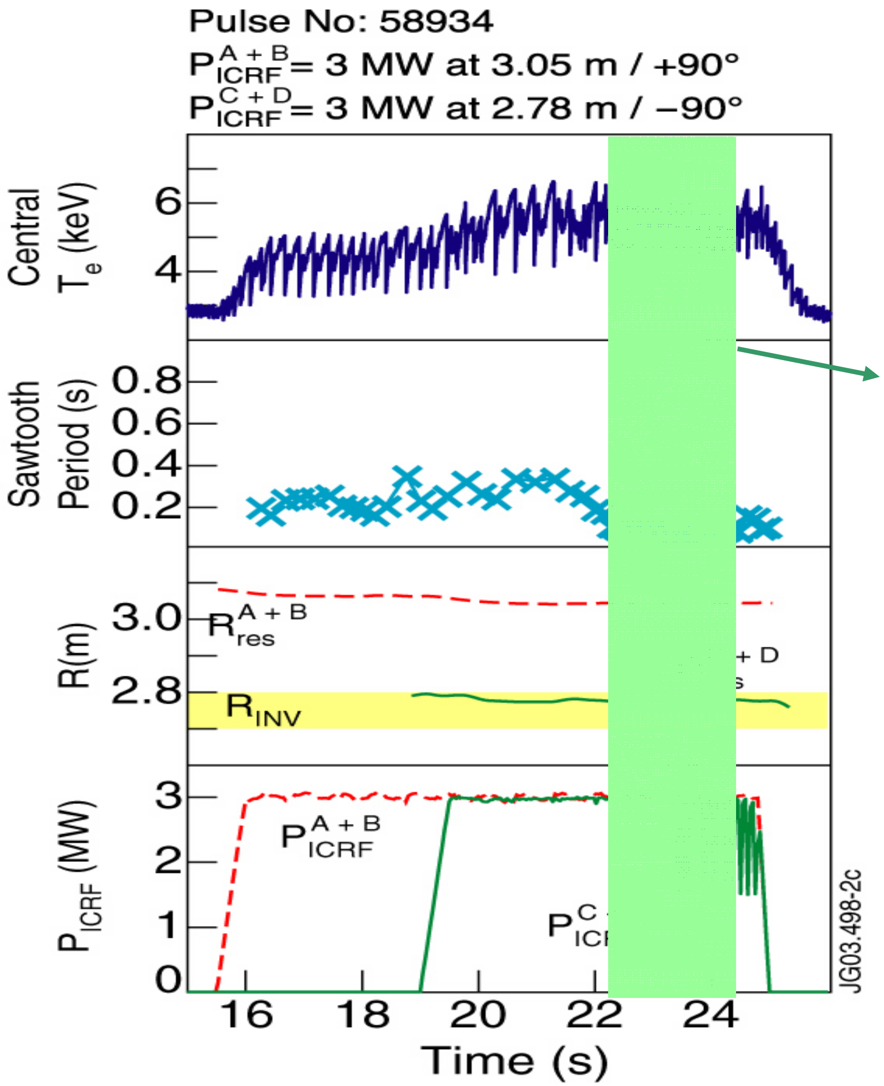
- Once seeded, island is sustained by lack of local current
- Two ways to tackle the NTMs

  1) Avoid them by controlling sawteeth (i.e. keep their period short) using ICRH

  2) Replace missing current to actively stabilise mode

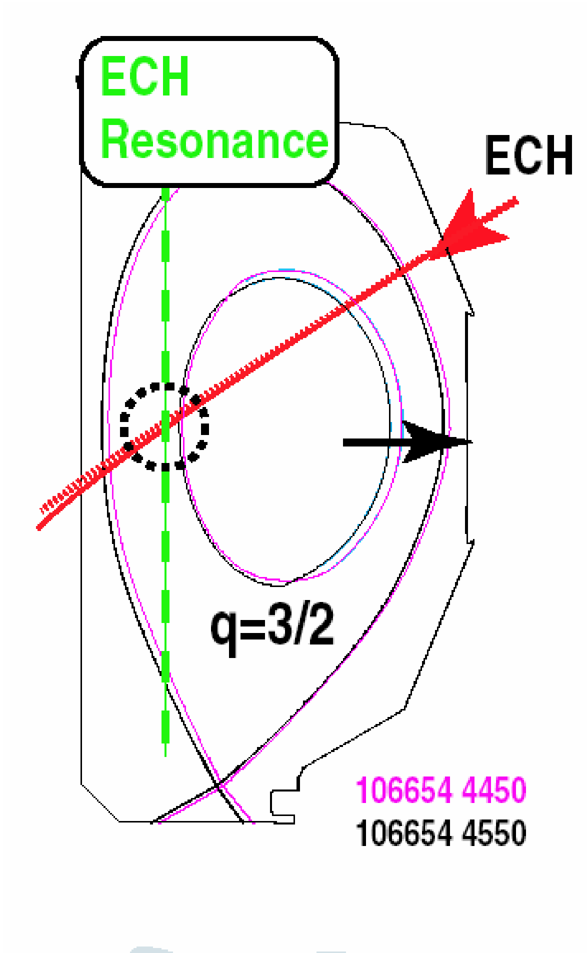
Avoiding NTMs

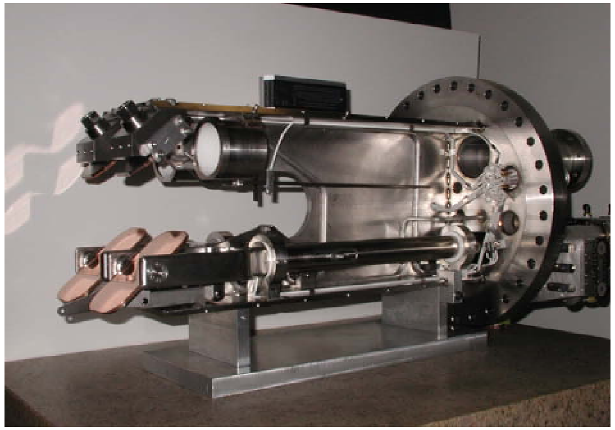
Use ICRH to modify current profile locally and de-stabilise (i.e. reduce period of) sawteeth



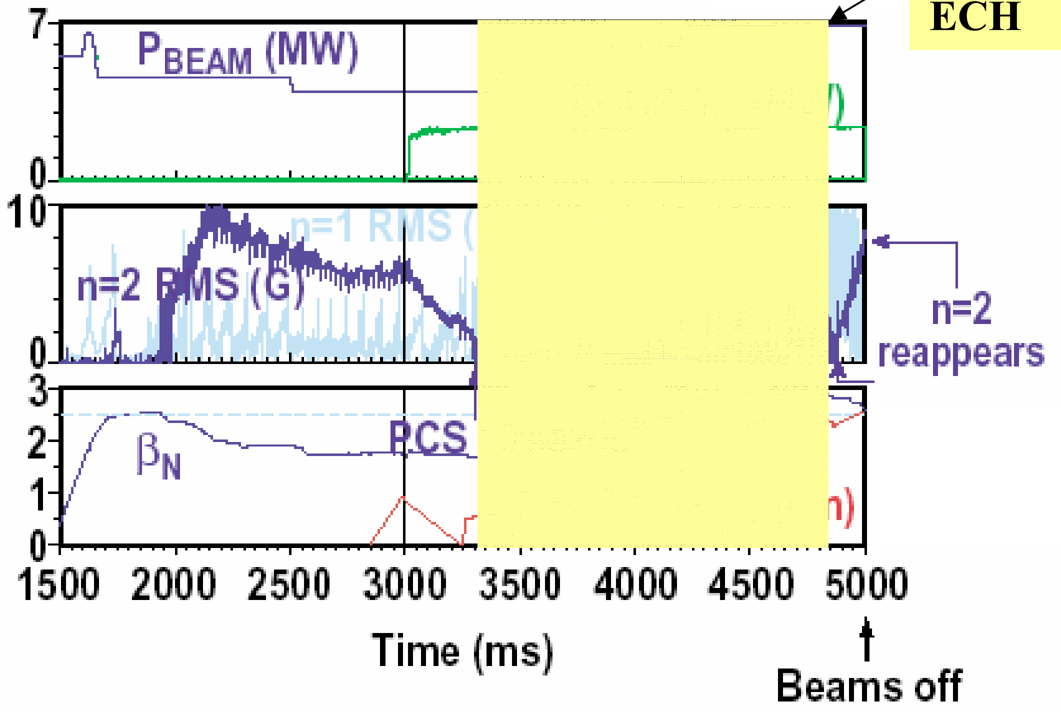
De-stabilisation of fast particles stabilised sawtooth by ICRH:
avoid large build-up of ∇p and subsequent large crash, hence avoid triggering NTM instabilities

Precisely directed microwaves can stabilise NTMs



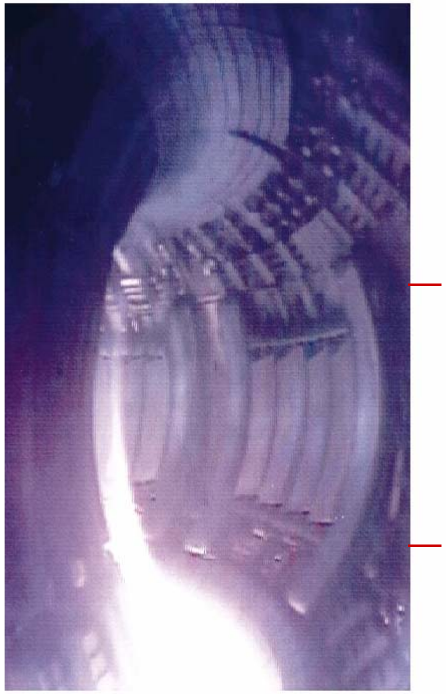


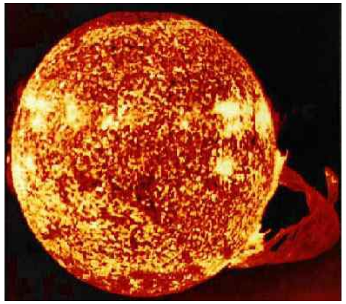
Steerable ECH/ECCD launchers allow local injection of current and NTM stabilization



NTM stabilised by ECH

Fusion plasma *physics* challenges



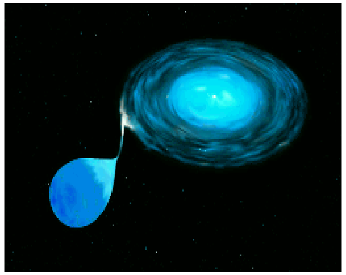


- Large power density and gradients (10MW/m^3 ≈ 30’000×sun’s core), anisotropy, no thermal equilibrium
  - Macro-instabilities and relaxation processes

solar flares, substorms

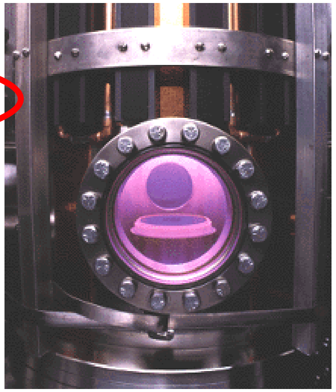
- Dual fluid/particle nature
  - Wave-particle interaction (resonant, nonlinear)

coronal heating



- Turbulent medium
  - Non-collisional transport and losses

accretion disks



- Plasma-neutral transition, wall interaction

plasma manufacturing

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

Plasma wall interaction issues

- Withstand power fluxes
  - Limit erosion, melting
    - Steady-state
    - *During transient edge instabilities*
- Keep the plasma pure
- Minimise T retention
- Exhaust
  - Power
    - Through solid surface in contact with fluid transfer medium
  - Particles
    - To avoid dilution in reactor ^{4}He ‘ashes’ must be removed

→the divertor concept

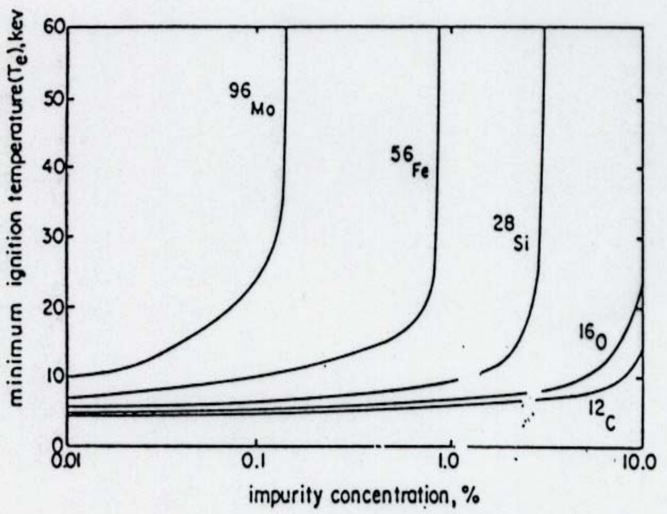
- Separates plasma surface interactions from confined plasma

The need for a *pure* plasma

- **Bremstrahlung radiation**

  $$P_b = A\, Z^2 n^2 T^{1/2}$$

- **Bremstrahlung limitation will move up for higher Z**



Minimum ignition temperature goes up with impurity concentration

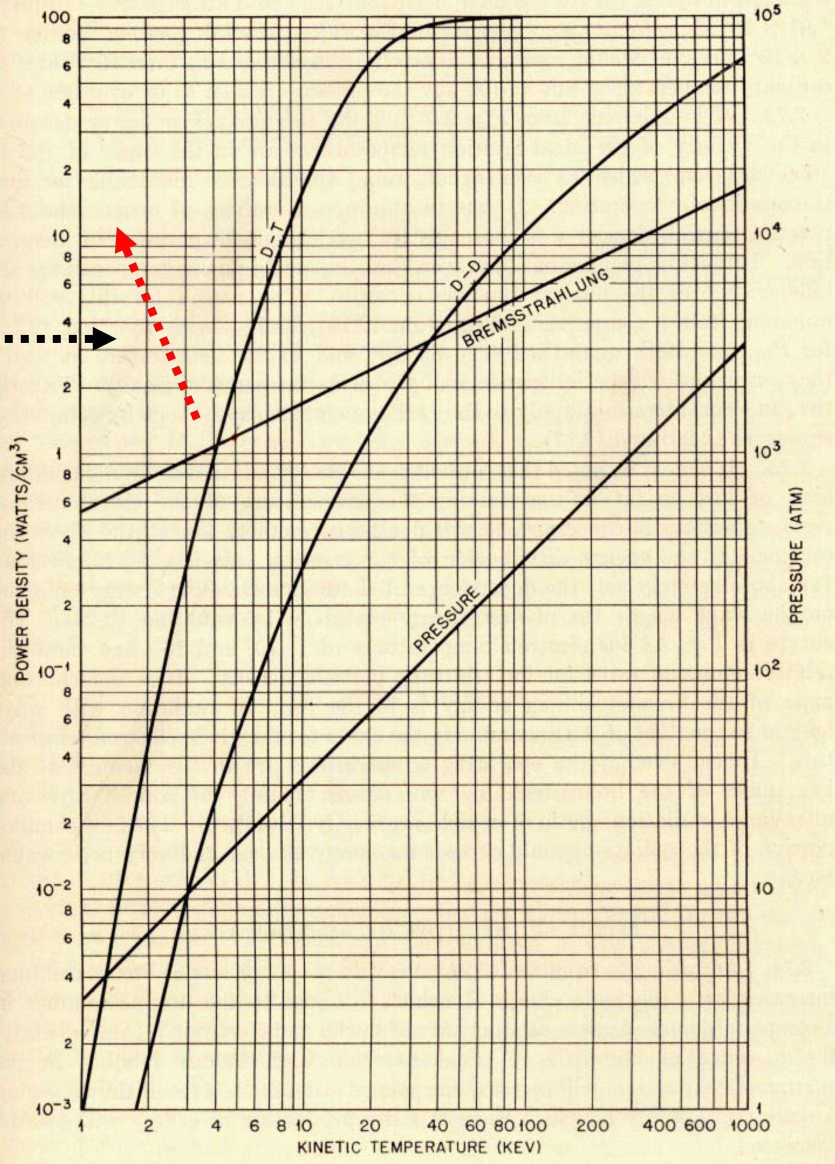


FIG. 2.9. Characteristics of thermonuclear reactions and the ideal ignition temperature.

The divertor concept

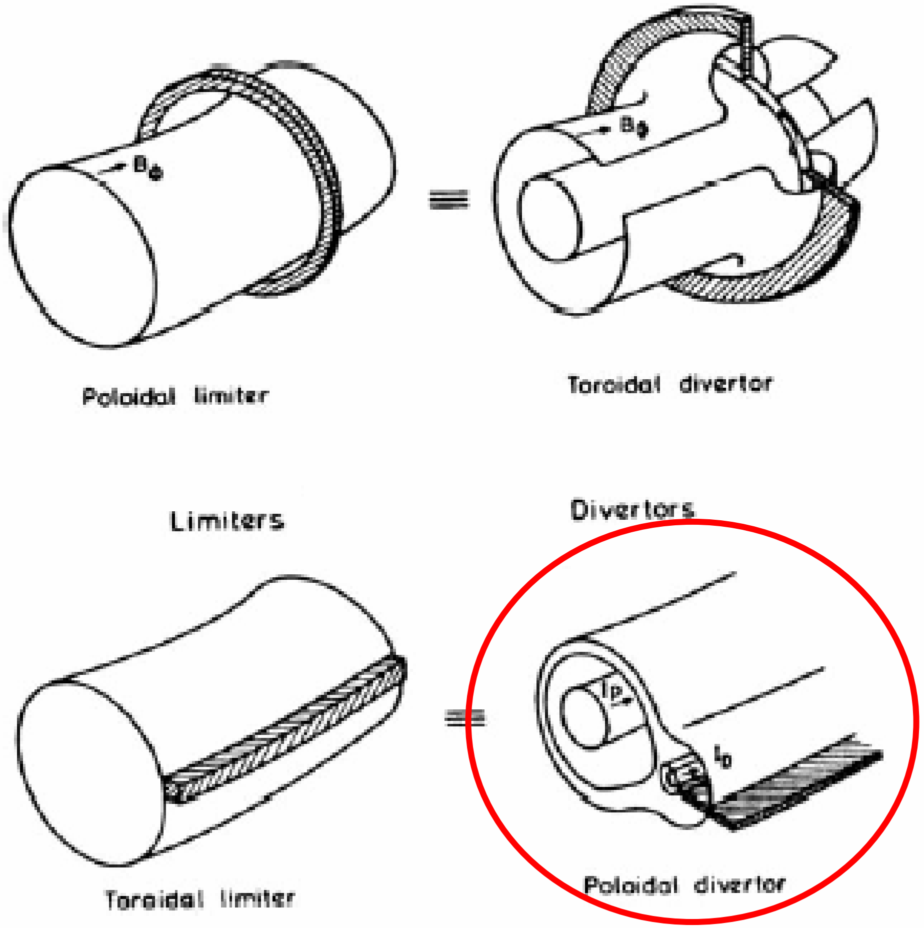
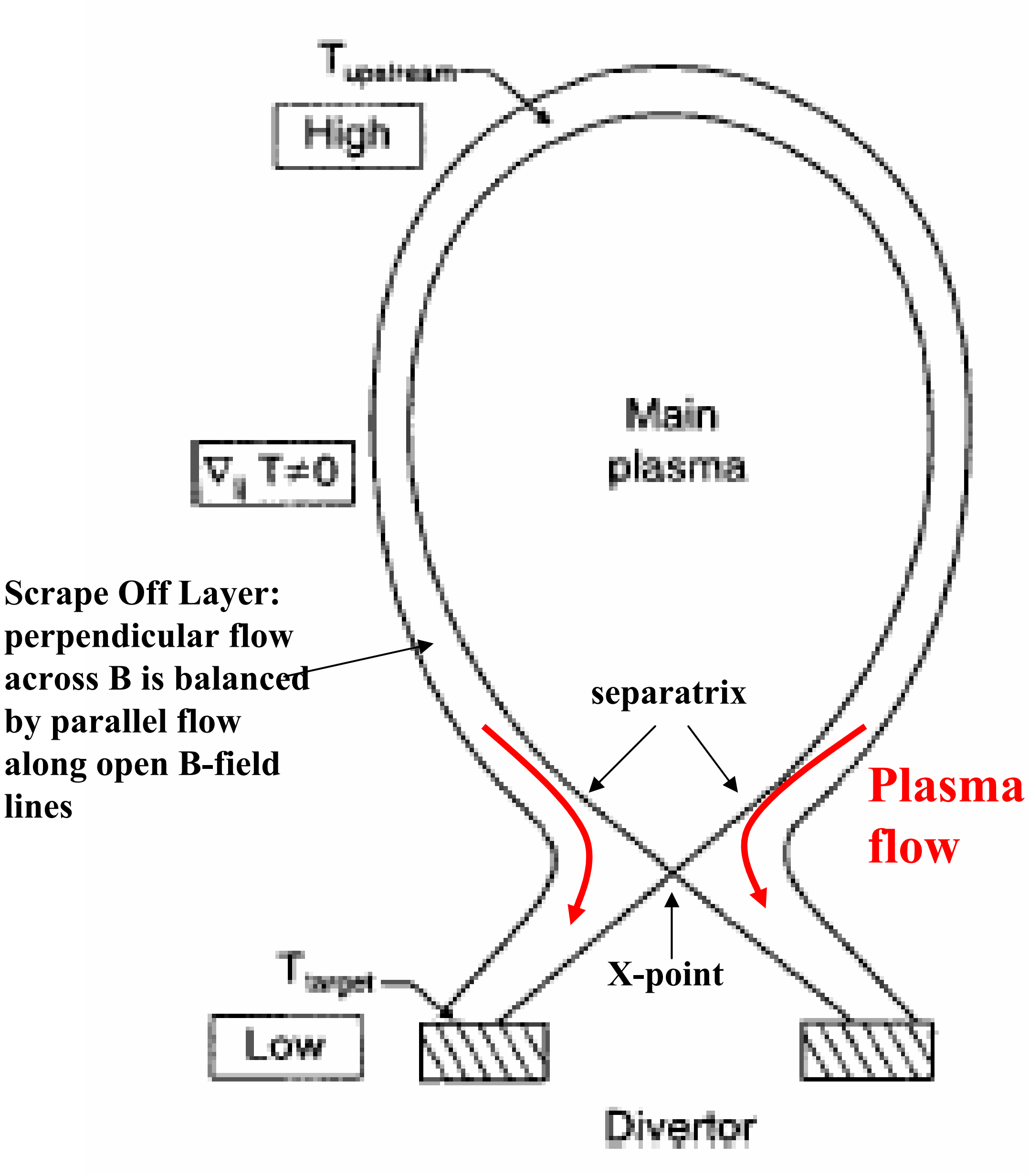


Figure 13. Various limiter and divertor configurations: (1) the *poloidal ring limiter*, in the simplest case, is a circular annular plate of inner radius $r = a_{\text{plasma}}$, outer radius $r = a_{\text{wall}}$. (2) The *toroidal divertor* involves a diversion of the toroidal magnetic field near the edge, making for a configuration analogous to that of the *poloidal ring limiter*. (3) The *toroidal limiter* consists of a toroidally symmetric, protruding structure attached to the wall, mounted at the outside of the vessel, as shown here, or at the bottom, etc. (4) The *poloidal divertor* involves a diversion of the poloidal magnetic field near the edge, making for a toroidally symmetric configuration, analogous to the toroidal limiter [13].

The divertor concept



Scrape Off Layer: perpendicular flow across B is balanced by parallel flow along open B-field lines

- Long connection length parallel to B_{tot} (e.g. in ITER ~150m) reduces parallel power flux arriving to target
- Upstream T_e~0.5keV, must be reduced to ~5eV

→At 5eV $\sigma_{ionisation} < \sigma_{charge\ exchange}$

→Energy is transfered from ions to neutrals, which spread power deposition (*neutral cushion*)

→T is further reduced and e-i recombination occurs

→Plasma *detachment*

Observation of plasma *detachment*

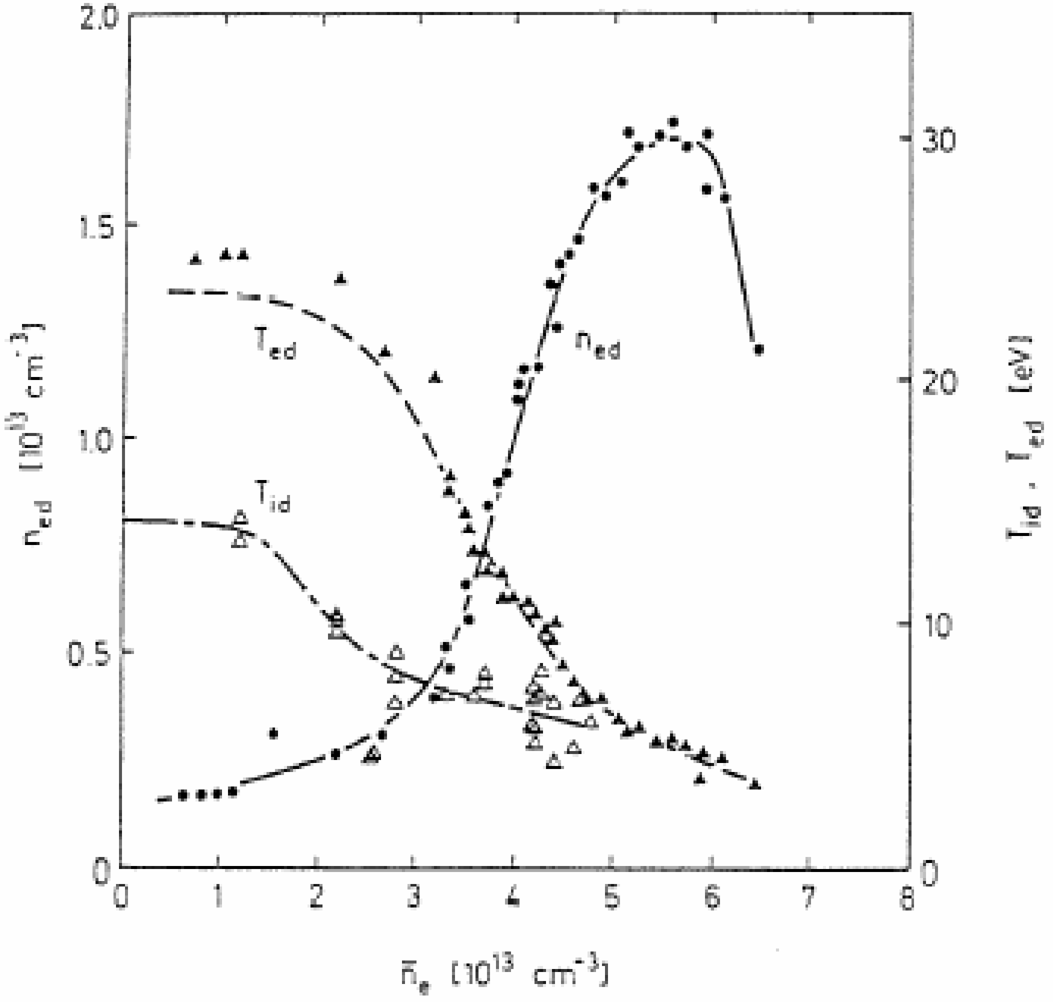
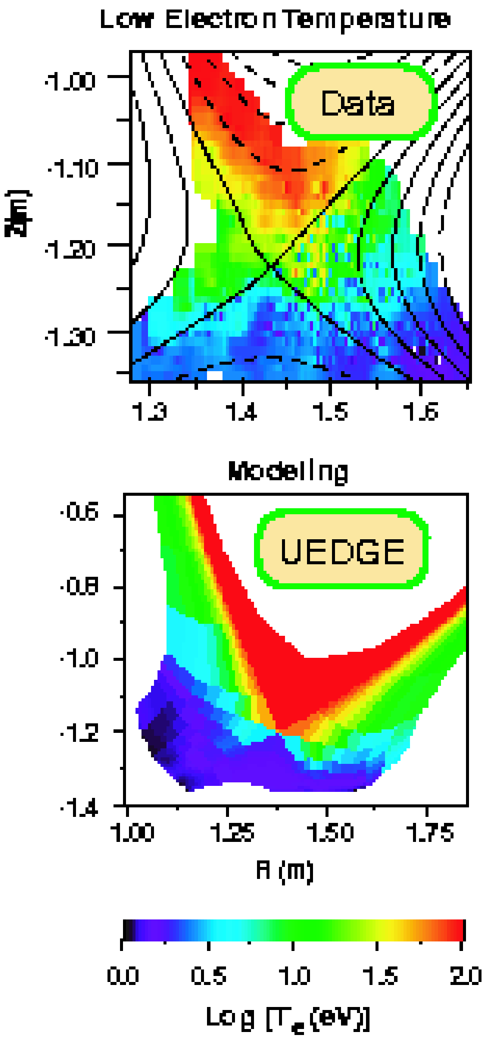


Figure 25. Divertor conditions in ohmic discharges in ASDEX as a function of $\bar{n}_e$ (Shimomura *et al* 1983, Wagner and Lackner 1986). Electron density n_{ed} and temperature T_{ed} from a Langmuir probe. Ion temperature T_{id} from C III line-width measurements.



DIII-D Thomson scattering T_e profile plot and UEDGE simulation showing extended region of cold (T_e < 2eV) recombining plasma

Ex. of different divertor geometries