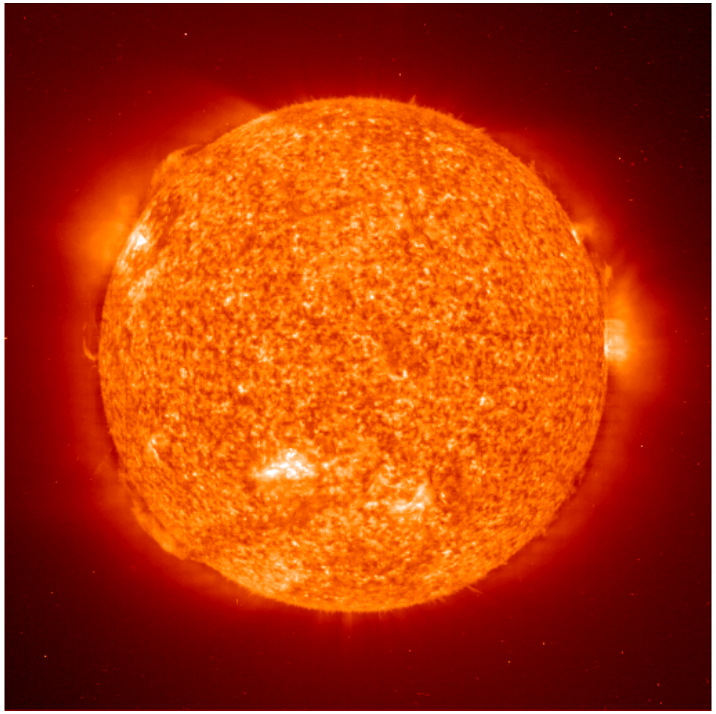
ASDEX Upgrade

Max-Planck-Institut für Plasmaphysik

ITER Physics Issues



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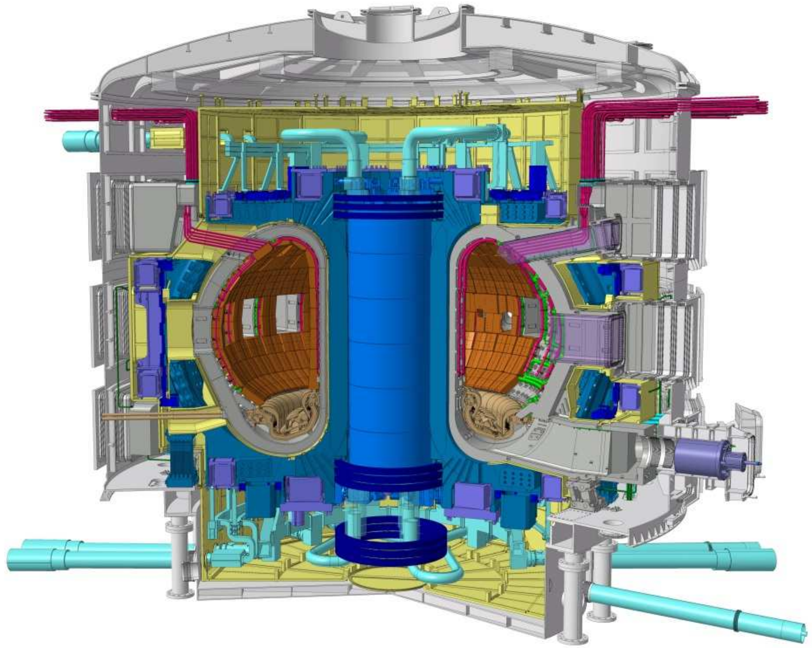

DPG Advanced Physics School
‚The Physics of ITER'
Bad Honnef, 22.09.2014

What will be ‚the physics of ITER'?

Q=10 operation (self-heated plasma)

- heat insulation (energy transport)
- magnetohydrodynamic (MHD) stability
- exhaust of heat and particles
- self-heating by α-particles

Q=5 steady state operation

- self-sustainment of plasma current

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Energy Transport in Fusion Plasmas

Global Gyrokinetic Simulation of
Turbulence in
ASDEX Upgrade

GENE

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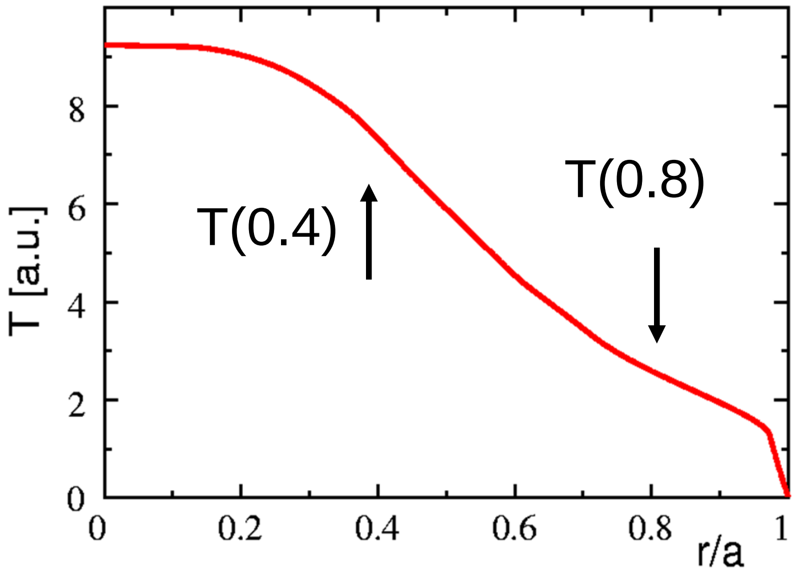
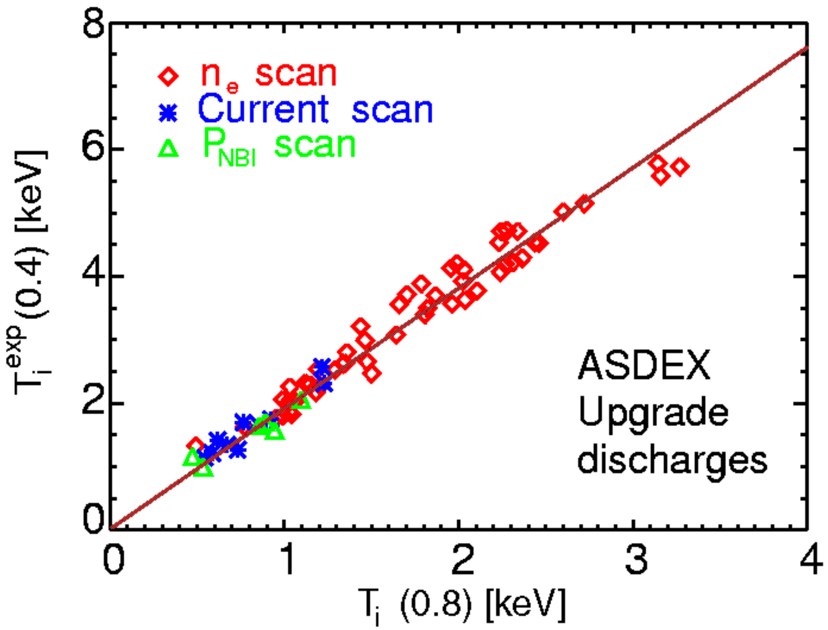
Anomalous transport determined by gradient driven turbulence

- linear: main microinstabilities giving rise to turbulence identified
- nonlinear: turbulence generates 'zonal flow' acting back on eddy size
- (eddy size)^2 / (eddy lifetime) is of the order of experimental χ–values

Energy Transport in Fusion Plasmas





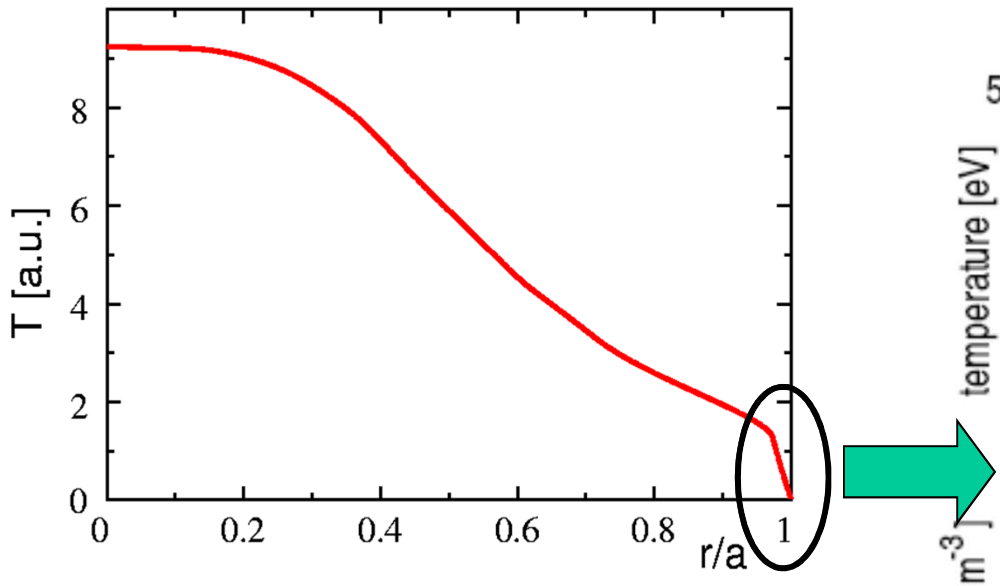
Anomalous transport determined by gradient driven turbulence

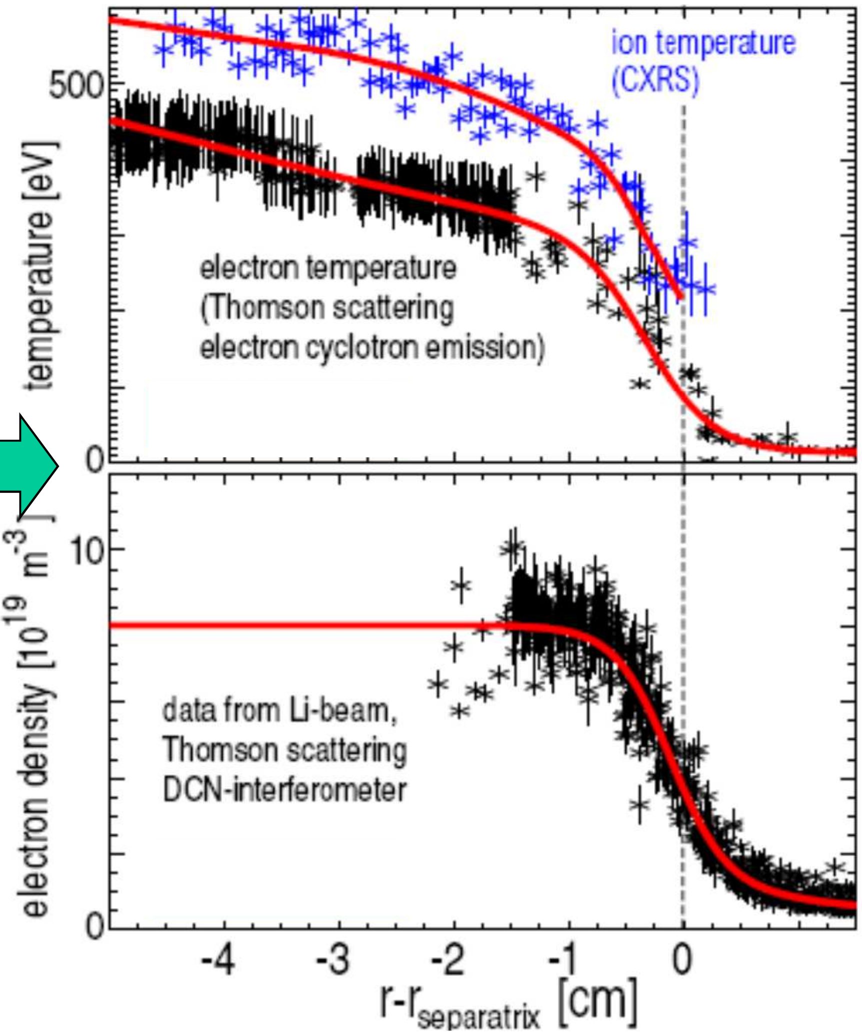
- temperature profiles show a certain ‘stiffness’
- ‘critical gradient’ phenomenon – χ increases with P_{heat} (!)

$\Rightarrow$ increasing machine size will increase central *T* as well as τ_E

N.B.: steep gradient region in the edge governed by different physics!

The H-mode: a transport barrier in the edge



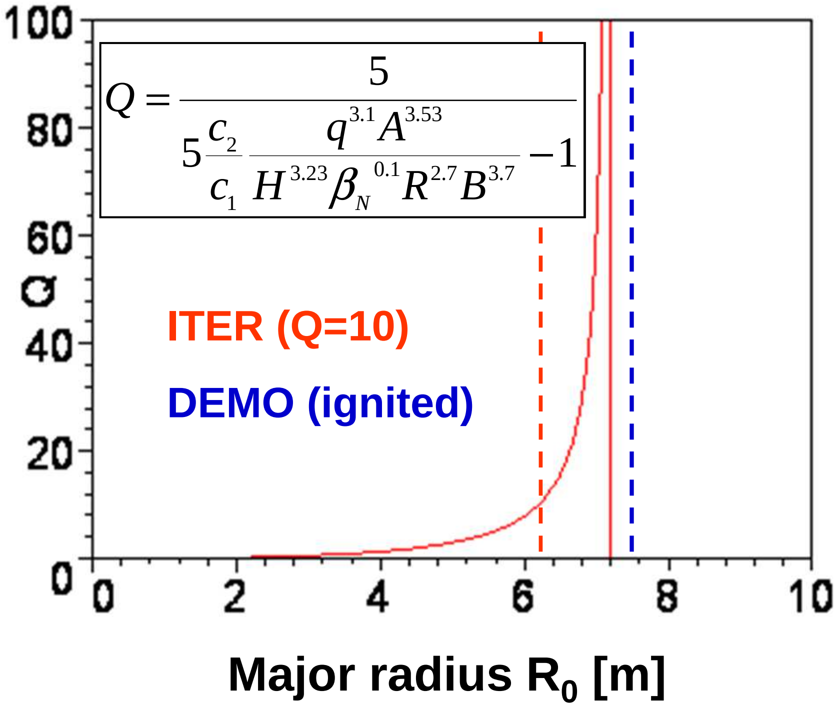


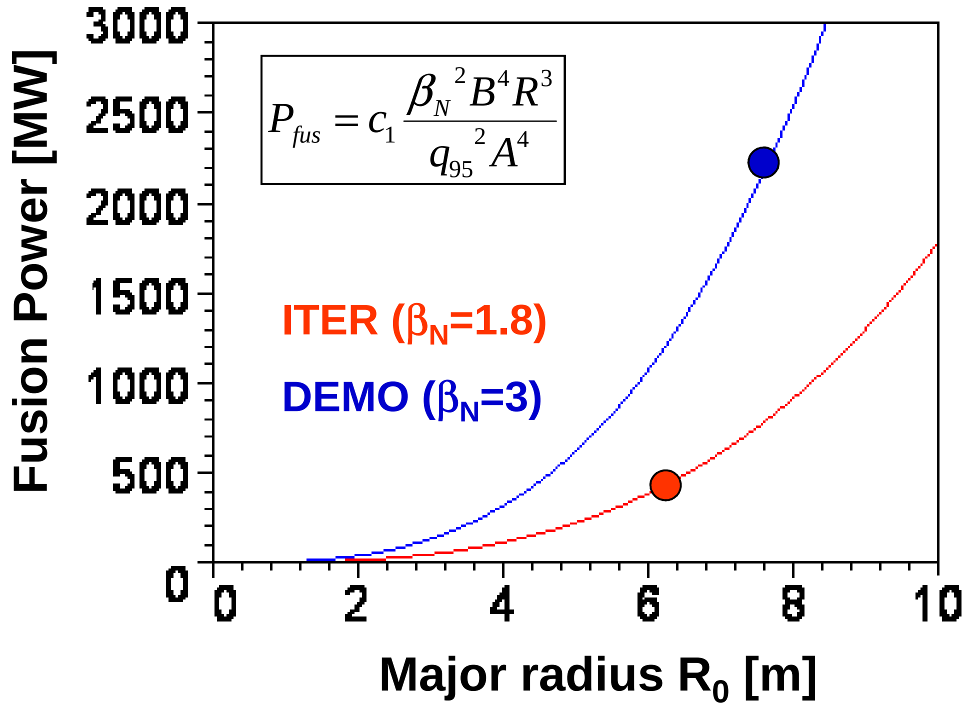
Turbulence suppression by sheared rotation in the plasma edge

- steep edge gradients of T and n
- profile stiffness: T higher in whole plasma core

H-Mode is standard operational scenario foreseen for ITER

Anomalous transport determines machine size





- ignoition (self-heated plasma) predicted at R = 7.5 m
- at this machine size, the fusion power will be of the order of 1 GW

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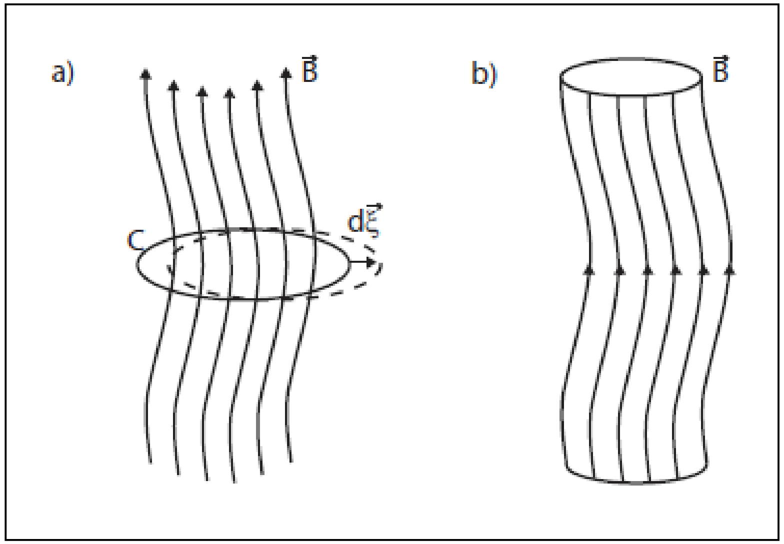
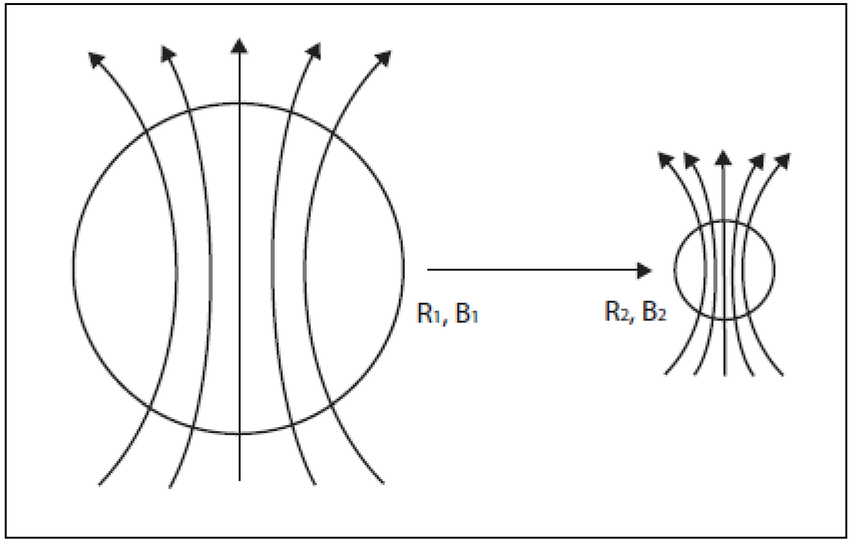
Ohm’s law and the ‘frozen fieldlines’

Concept of ‘flux tubes’:



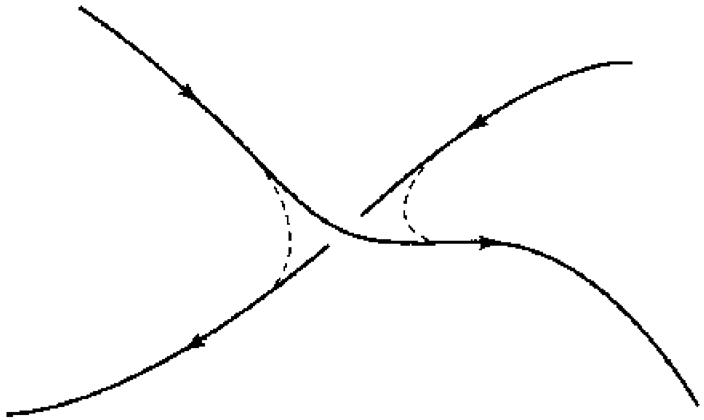


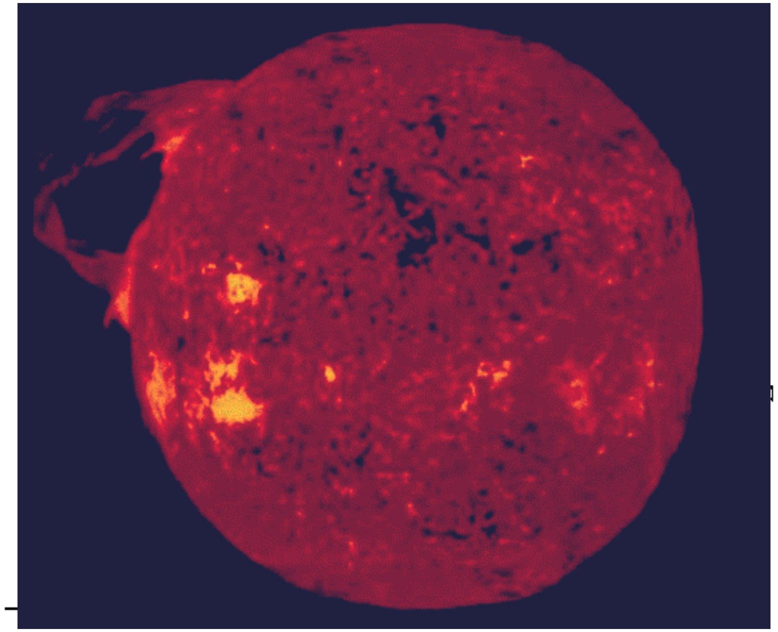
- in ideal MHD, plasma and field lines move together (Alfvén time scale, fast)
- flux tubes move with fluid and cannot intersect – topology conserved
- example: collapse of a neutron star

Reconnection in a hot fusion plasma

Due to high electrical conductivity, magnetic flux is frozen into plasma

$\Rightarrow$ magnetic field lines and plasma move together





A change of magnetic topology is only possible through reconnection

- opposing field lines reconnect and form new topological objects
- requires finite resistivity in the reconnection region

Example: Coronal Mass Ejection (CME) from the sun

Reconnection in a hot fusion plasma

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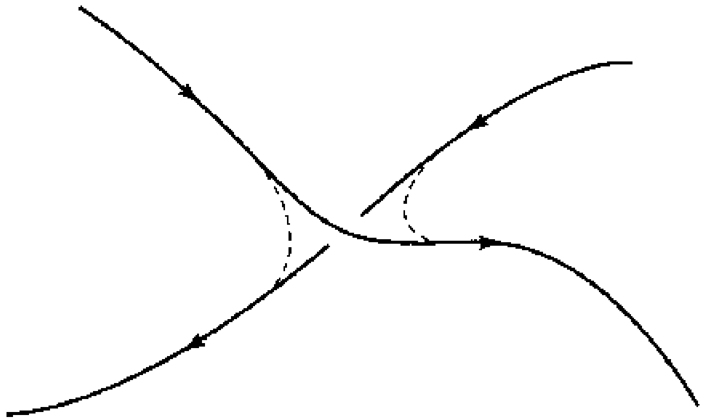

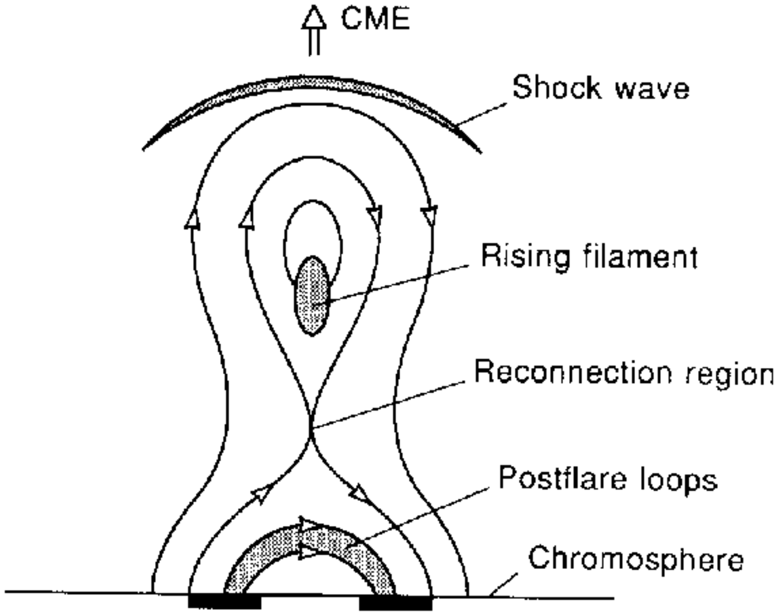

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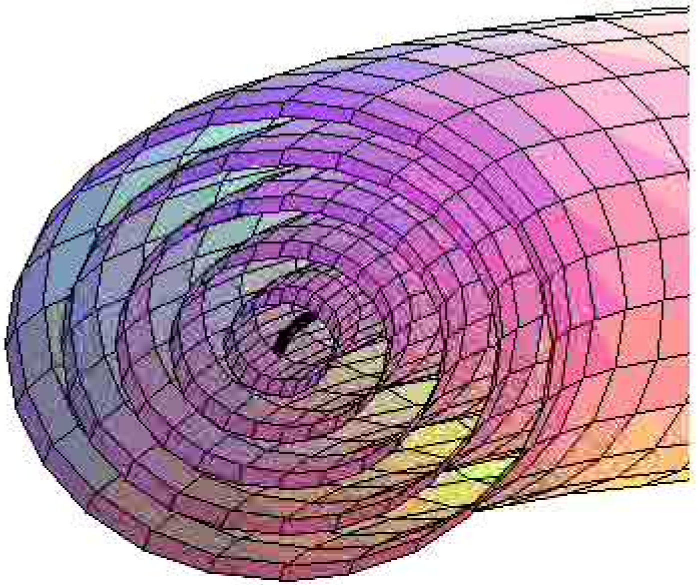
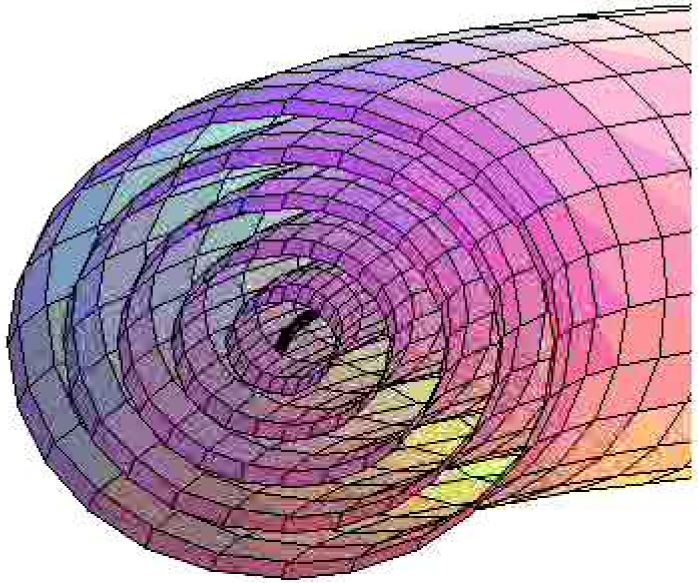
Ideal and resistive MHD instabilities





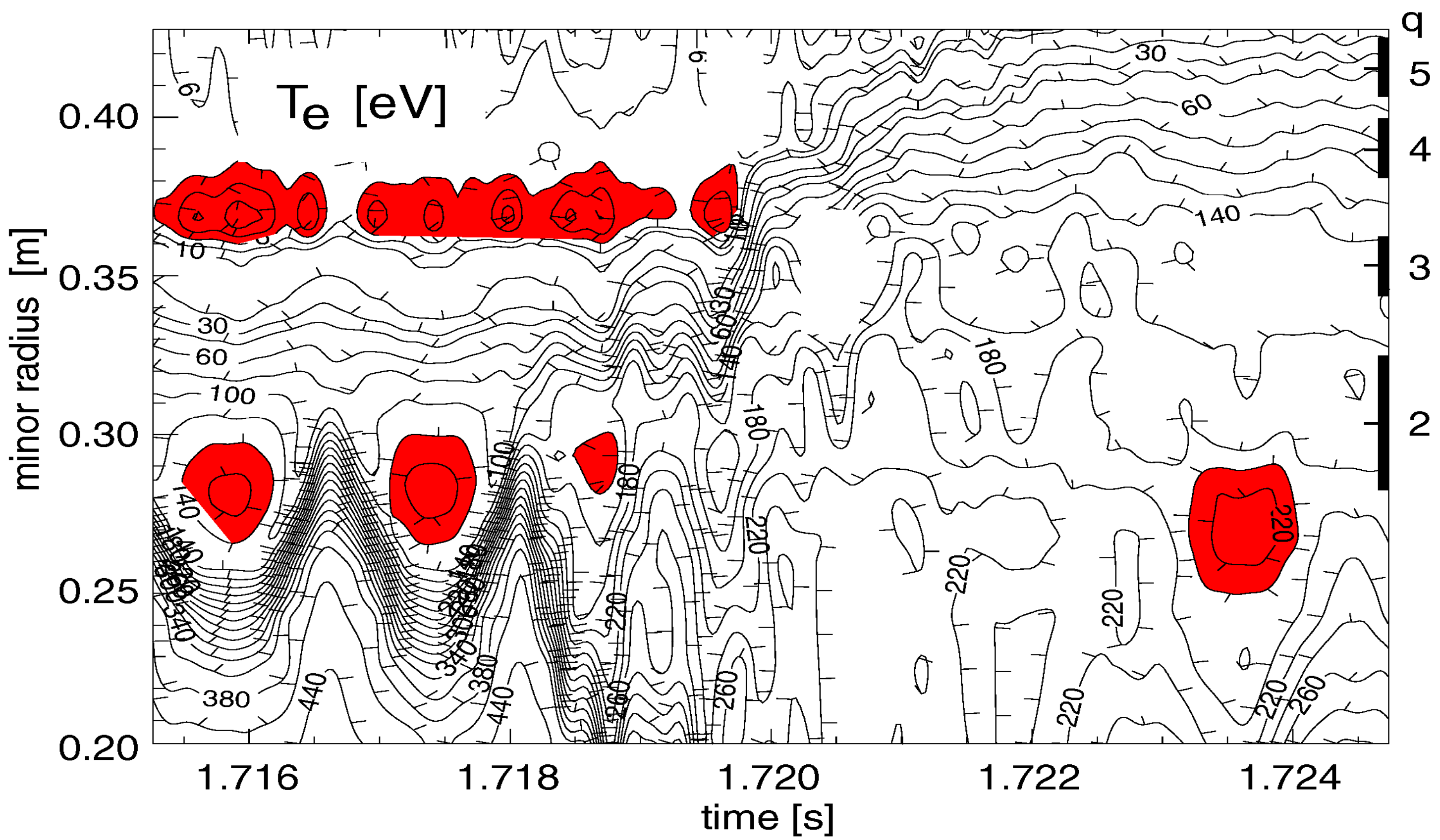
Ideal MHD: $\eta = 0$

- flux conservation
- topology unchanged

Resistive MHD: $\eta \neq 0$

- reconnection of field lines
- topology changes

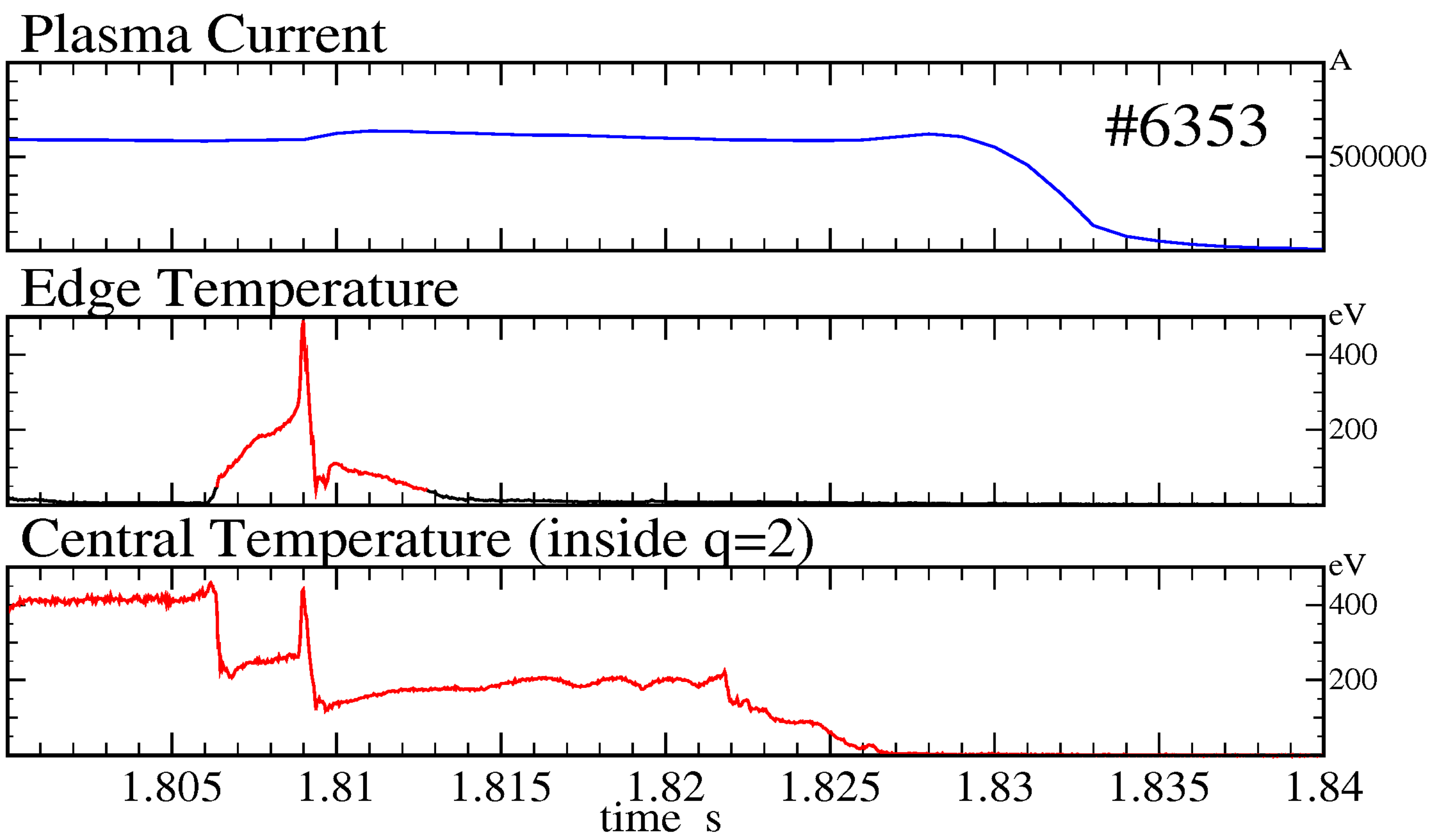
Magnetic islands impact tokamak discharges



coupling between island chains (possibly stochastic regions)

⇒ sudden loss of heat insulation ('disruptive instability')

Disruptive instability limits achievable density

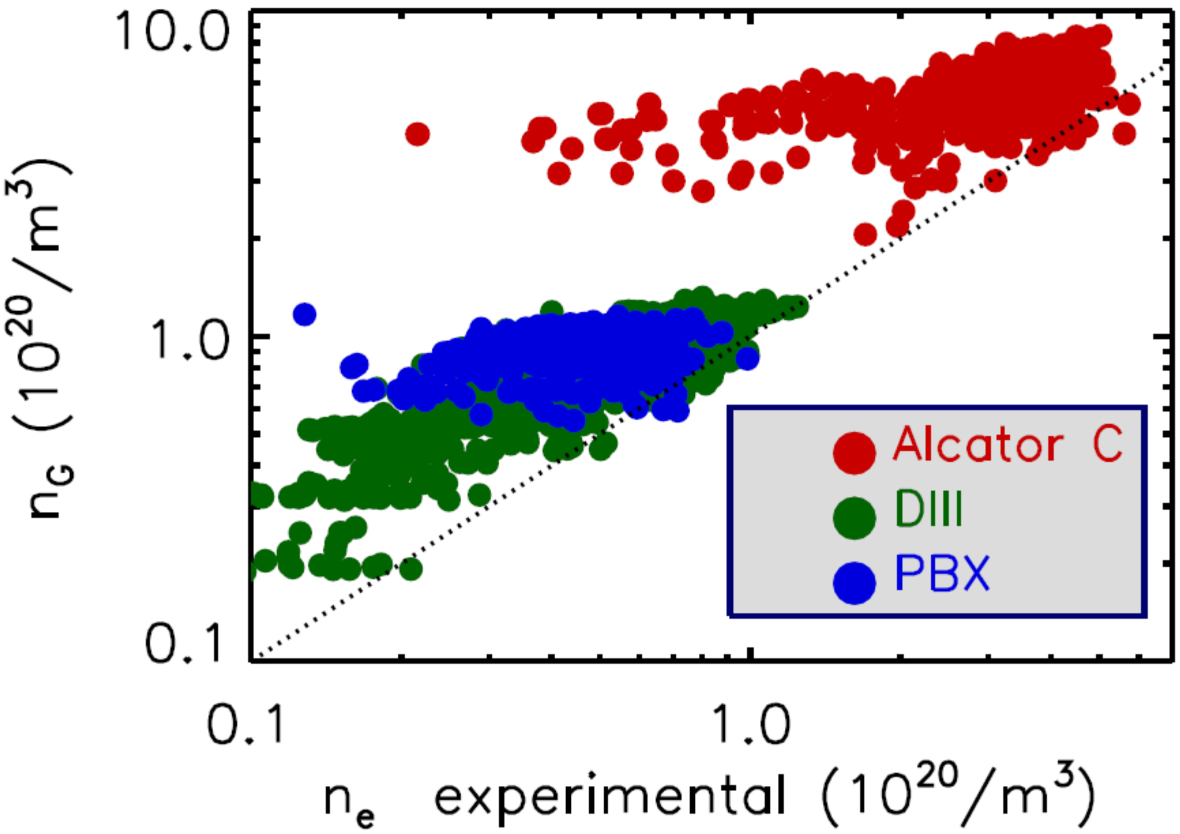


High density clamps current profile and leads to island chains

excessive cooling, current can no longer be sustained

disruptions lead to high thermal and mechanical loads!

Disruptive instability limits achievable density



$n_G = I_p/(\pi a^2)$

Empirical ‚Greenwald-limit' describes well maximum density

- seems to be linked to a change in edge transport at $n \sim n_G$
- can be overcome if density profile shape is varied (peaked)

Ideal MHD instabilities limit achievable pressure

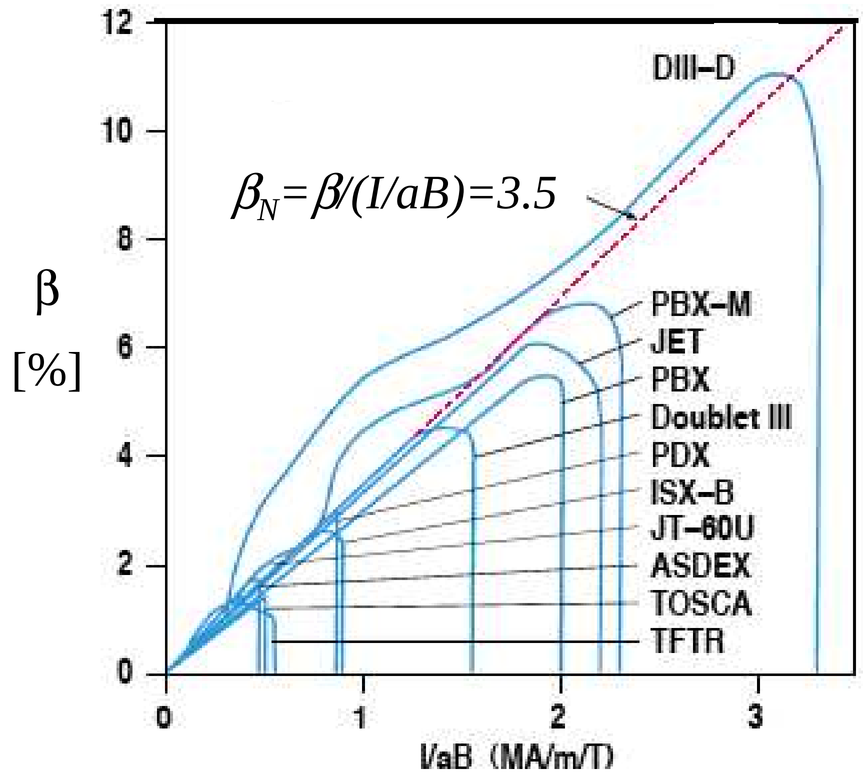
Optimising *nT* means high pressure and, for given magnetic field, high dimensionless pressure $\beta = 2\mu_0 \langle p \rangle / B^2$

This quantity is ultimately limited by ideal instabilities

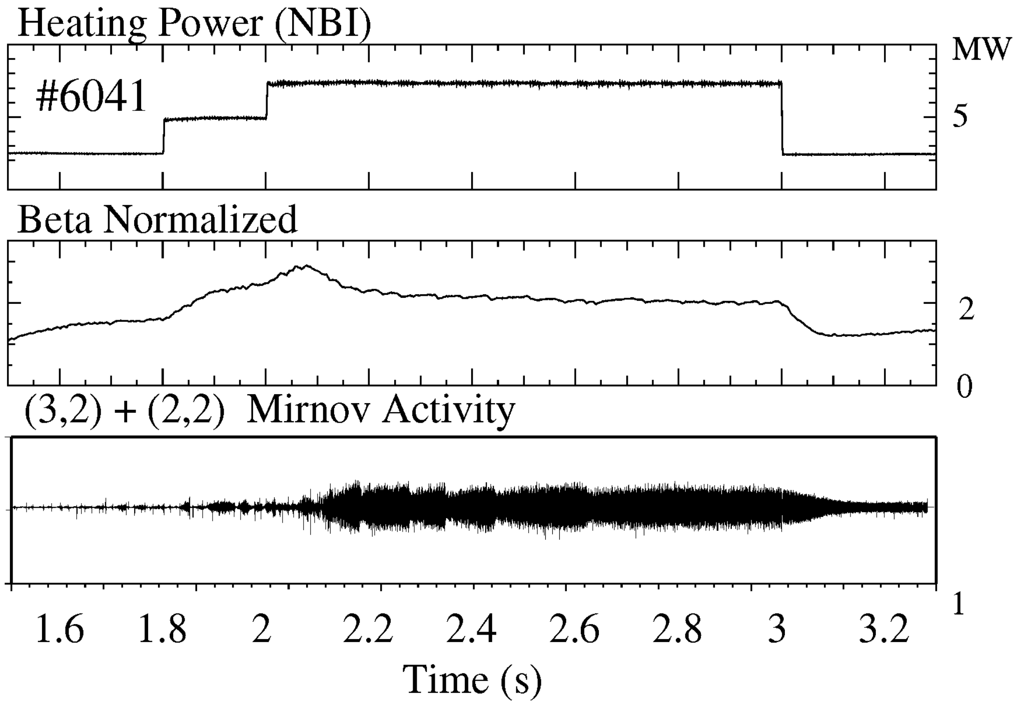
'Ideal' MHD limit (ultimate limit, plasma unstable on Alfvén time scale ~ 10 μs, only limited by inertia)

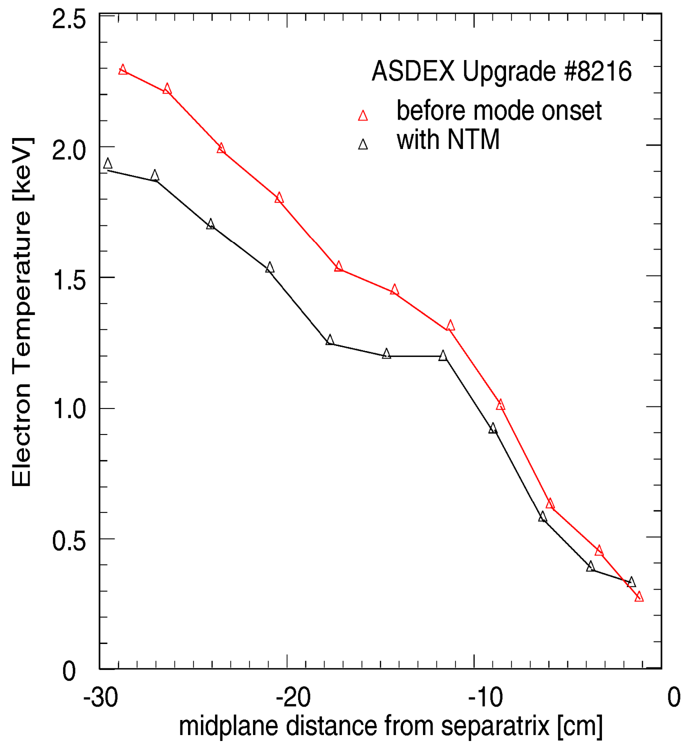
- 'Troyon' limit $\beta_{max} \sim I_p/(aB)$, leads to definition of $\beta_N = \beta/(I_p/(aB))$

- at fixed *aB*, shaping of plasma cross-section allows higher $I_p \rightarrow$ higher β



Resistive β-limit: Neoclassical Tearing Modes (NTMs)





Neoclassical tearing modes can occur well below ideal limit

- ‚practical β-limit' in ITER standard scenario (ELMy H-mode)
- note: can also lead to disruptive temination (especially at low q)

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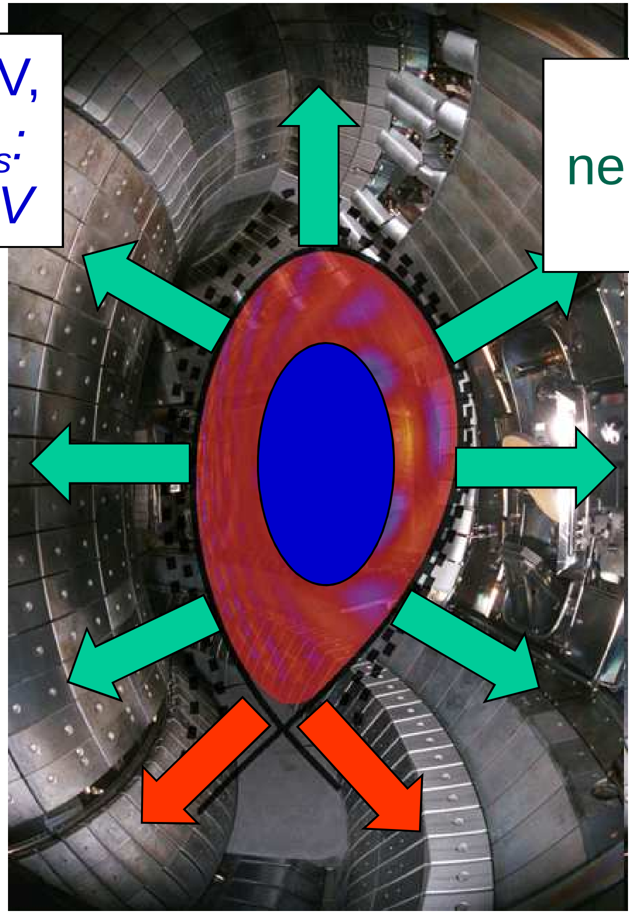
Fusion Reactor Energetics

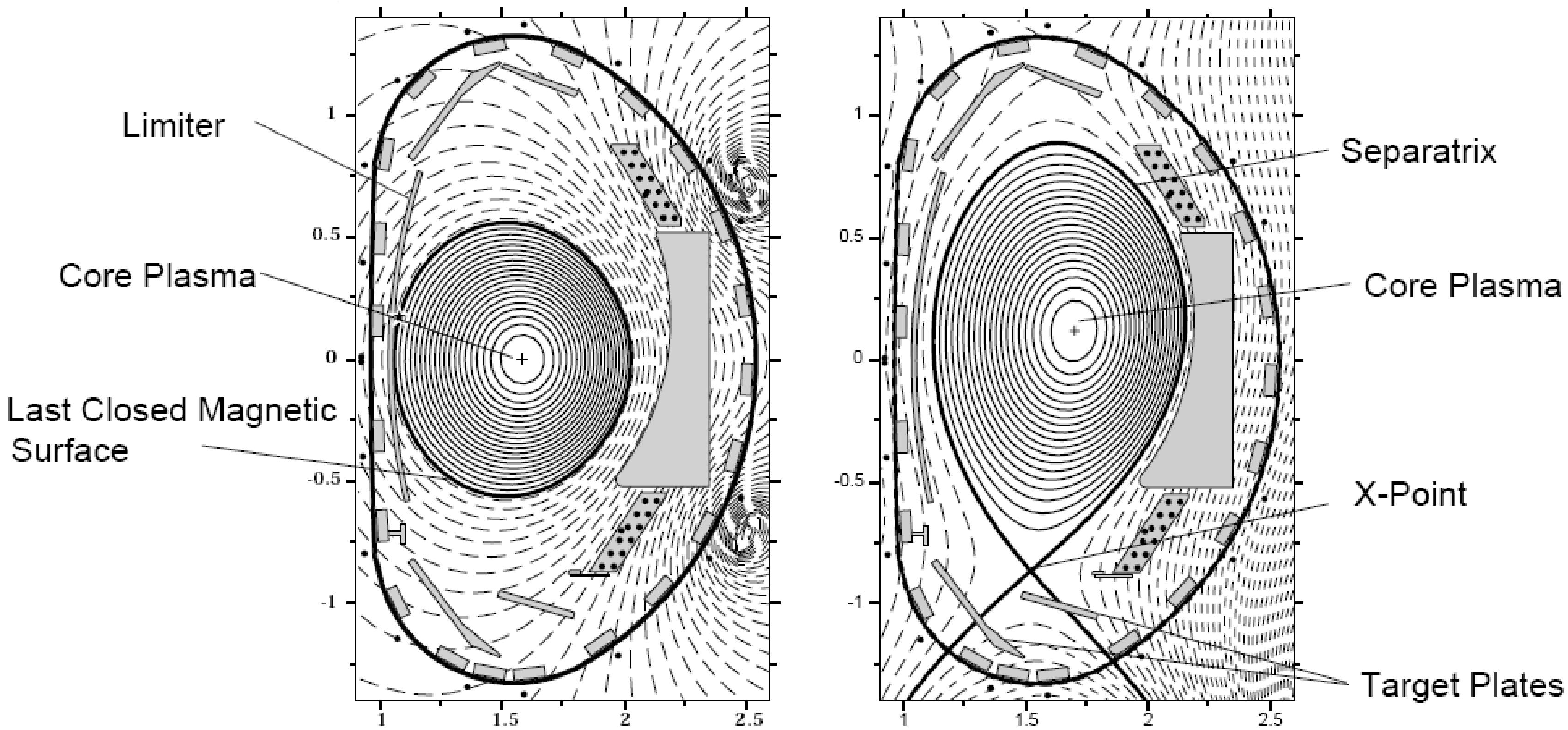
Core plasma @ T=25 keV, $n=10^{20}$ m^{-3} produces P_{fus}:
$D+T = He + n + 17.6$ MeV



$4/5*P_{fus}$ escape as neutrons and hit the first wall (typically 1 MW/m^2)

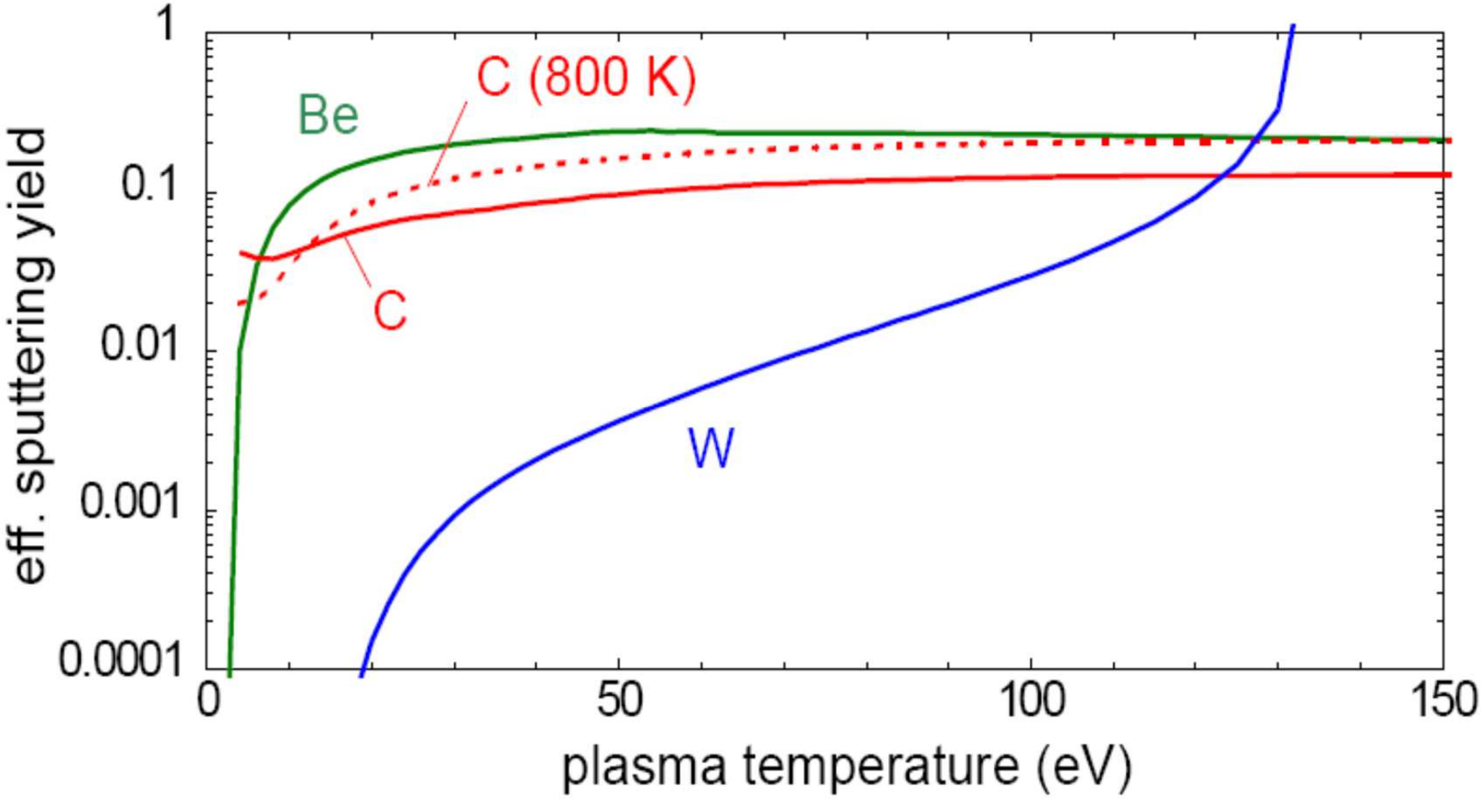
$1/5*P_{fus} + P_{ext}$ escape in charged particles along B-field lines and hit the wall in a narrow band (without further mitigation, 100 MW/m^2 !)

Plasma wall interface – from millions of K to 100s of K



- plasma wall interaction in well defined zone further away from core plasma
- allows plasma wall contact without destroying the wall materials
- provides particle control (retention of impurities, pumping of He ash)

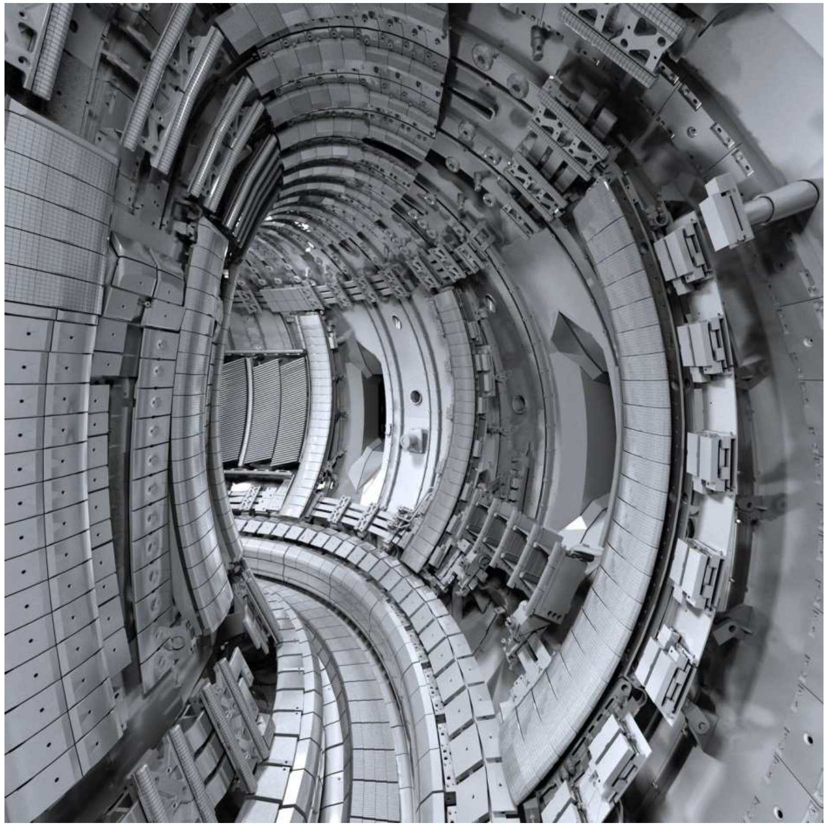
The perfect wall material: Low-Z or High-Z?

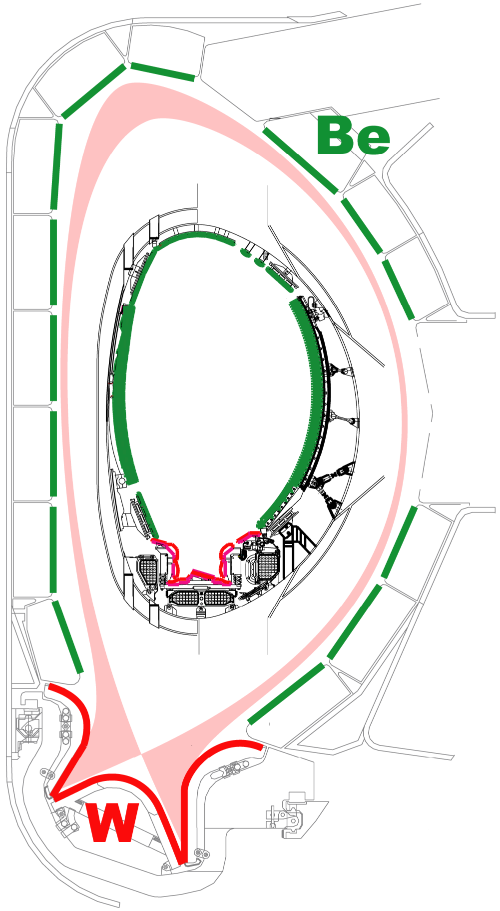


High-Z materials (W, Mo) promise low erosion rates and fuel retention

• if edge temperature is low enough…

Tokamak operation with metal wall



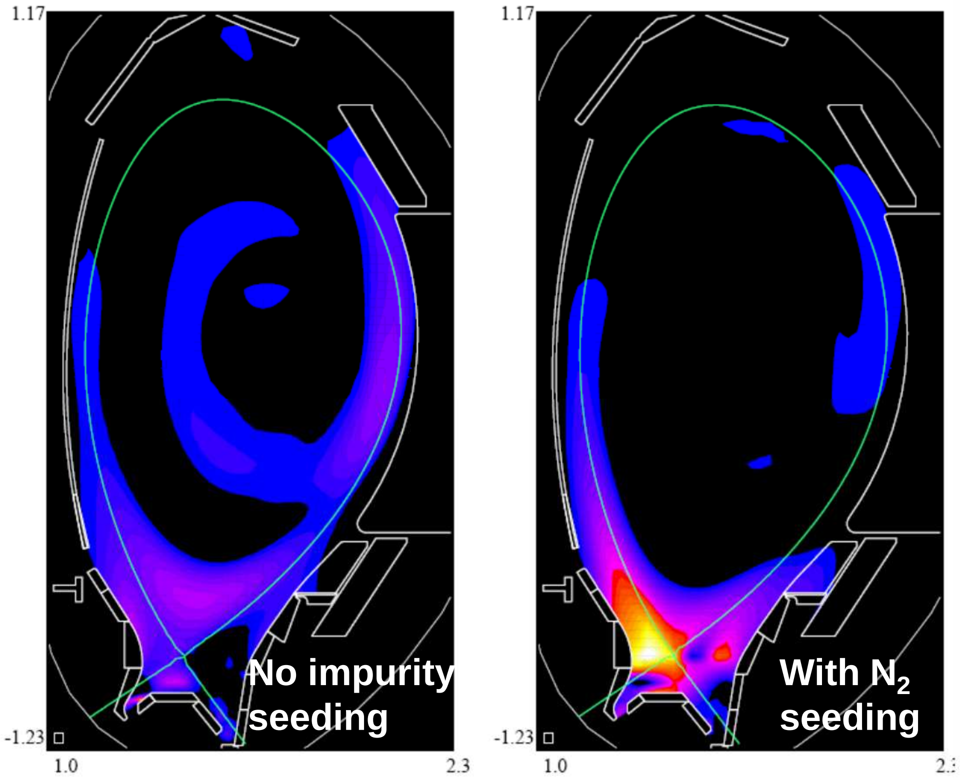


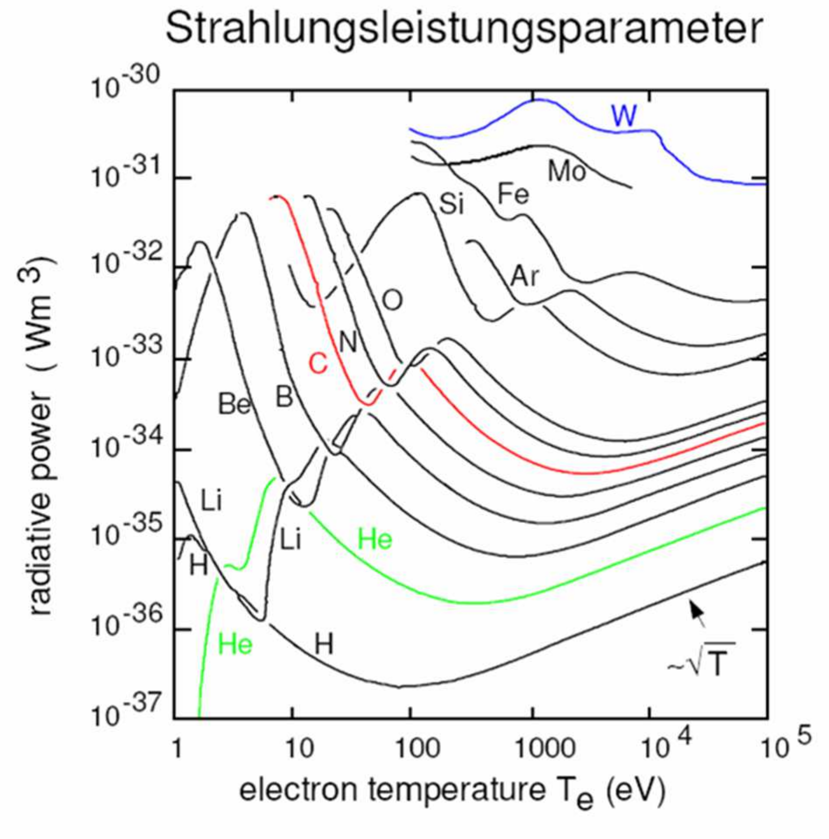
Divertor allows use of W under reactor relevant plasma conditions

- capitalises on low divertor temperatures that lead to negligible erosion
- needs special care to avoid excessive W content in plasma

Additional cooling by impurity seeding

Bolometry of total radiated power

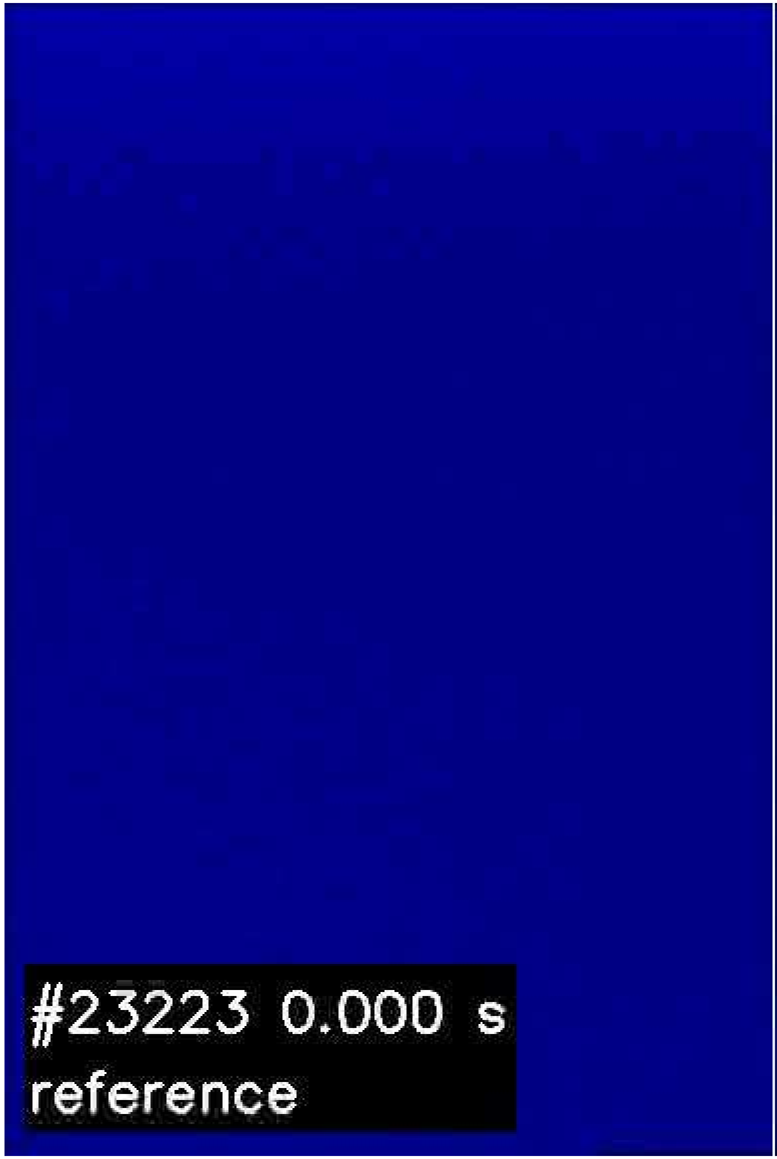


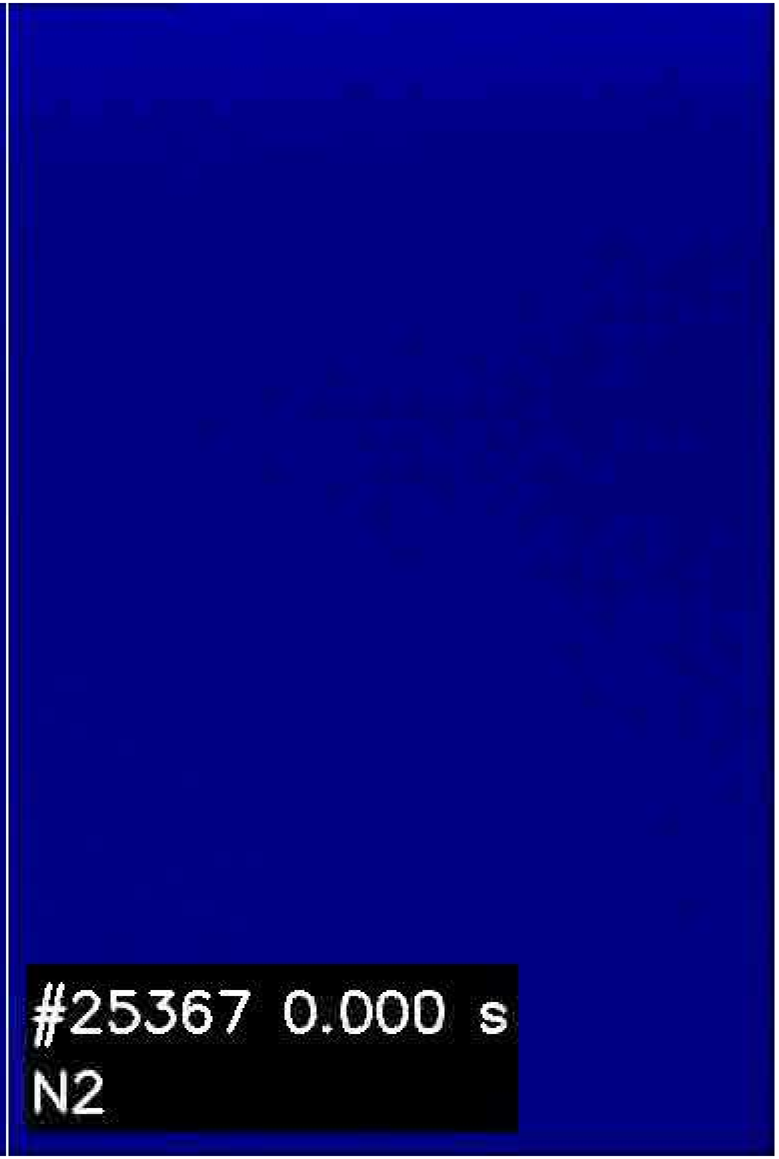


Injecting adequate impurities can significantly reduce divertor heat load

- impurity species has to be ‘tailored’ according to edge temperature
- edge radiation beneficial, but core radiation (and dilution) must be avoided

Additional cooling by impurity seeding





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The next step: studying α-heating

Core plasma parameters sufficient to generate significant fusion power

- study plasmas with significant self-heating by α-particles in ITER
- needs $P_\alpha = 1/5\ P_{fus} >> P_{ext}$, so it necessarily is closer to a reactor

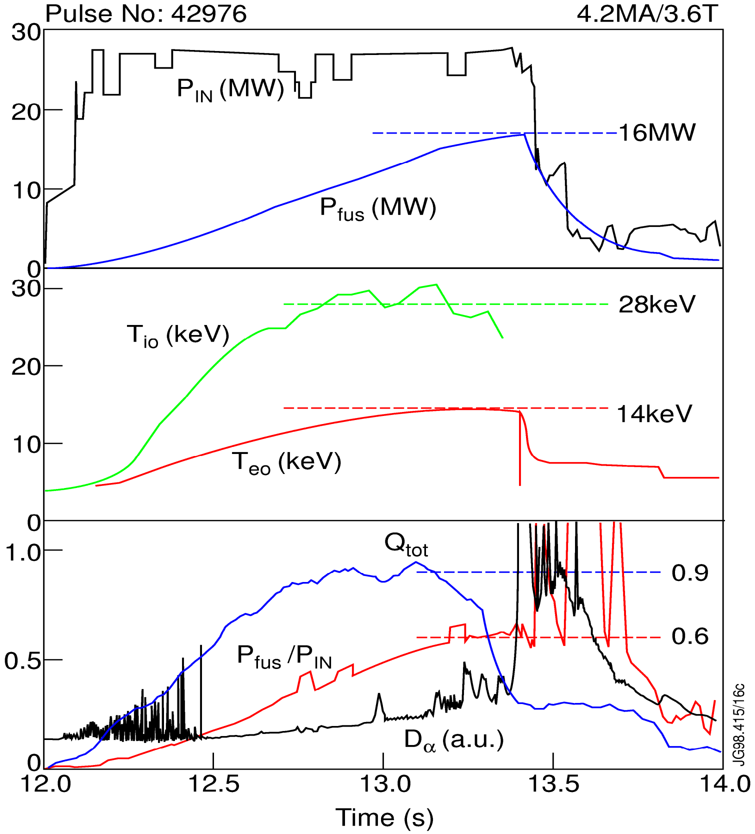
We expect to see qualitative new physics:

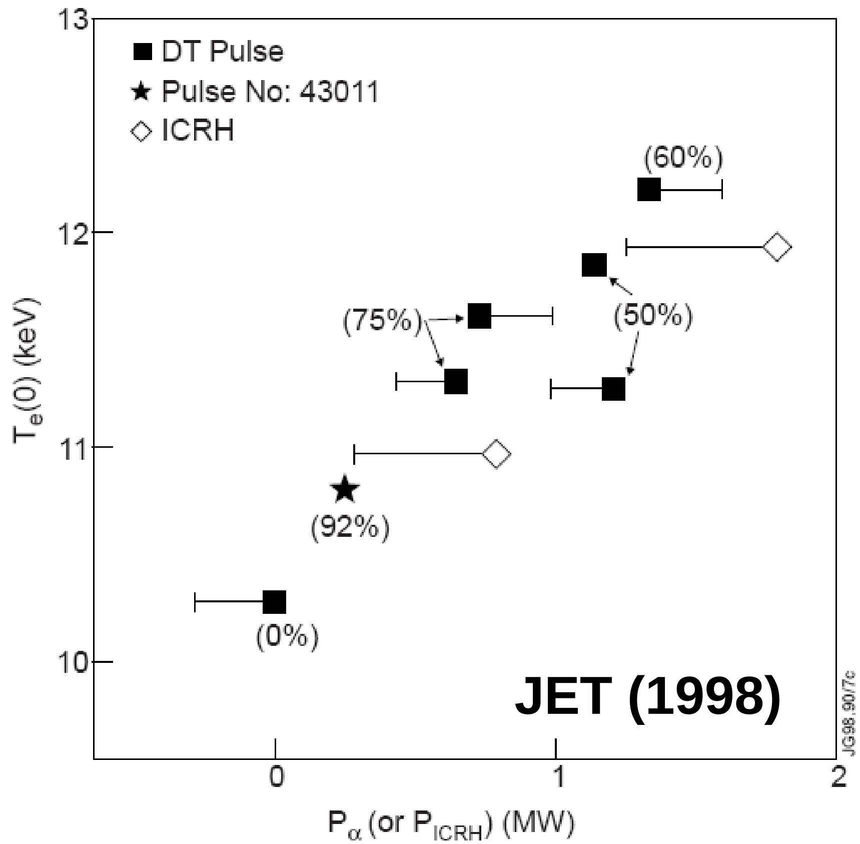
- self-heating nonlinear ($P_{fus} \sim n^2T^\gamma$ *and* $T \sim P_{fus}{}^\delta$) - interesting dynamics
- suprathermal population of α-particles can interact with plasma waves

We can have a ‘preview’ in present day machines

- pilot D-T experiments (JET (EU), TFTR (US))
- suprathermal ions generated by heating systems simulate α-particles

Previous D-T experiments

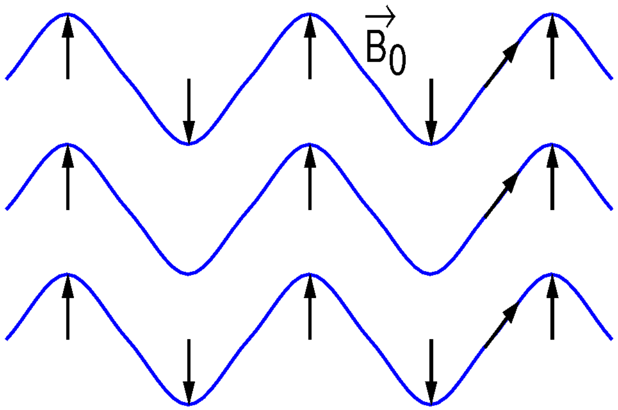




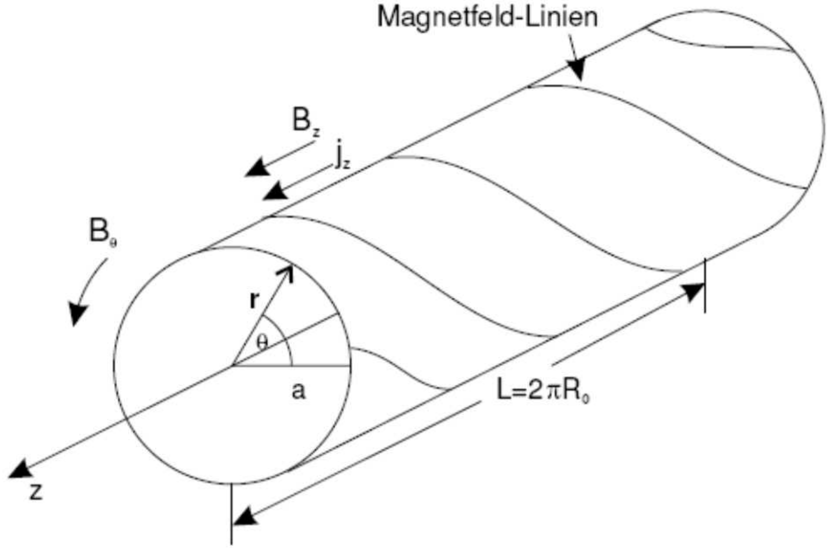
First D-T experiments at low P_α/P_{tot} have demonstrated α-heating

- ‚classical' (=collisional) slowing down would guarantee efficient α-heating
- question: can we expect this also when P_α is the dominant heating?

Alfven waves – continuum and gap modes



torsional (shear) Alfven wave



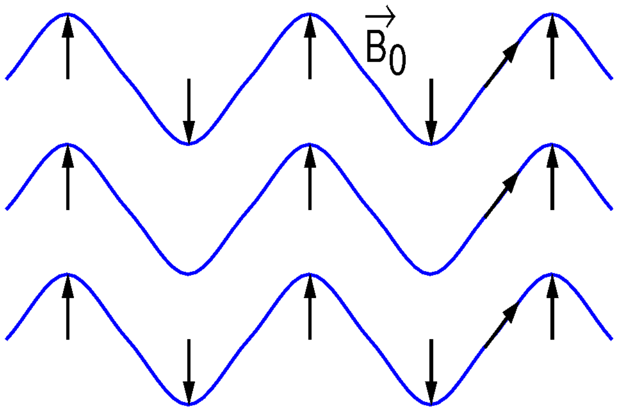
$$v_A = \frac{B}{\sqrt{\mu_0 m_i n}}$$

$$f(r,\theta,z) = \hat{f}(r)\exp(i(m\theta - nz/R_0))$$

B-field lines in a plasma can oscillate like a string of a guitar

- double periodic cylinder: $\omega = k_{//} v_A$ gives continuum structure

Alfven waves – continuum and gap modes



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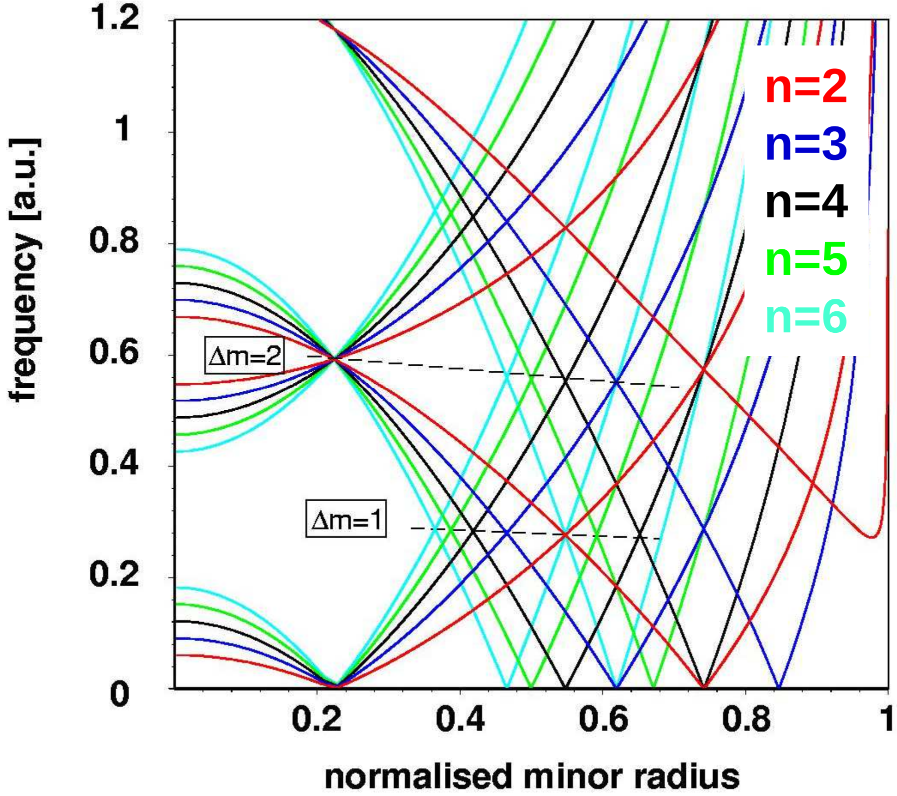
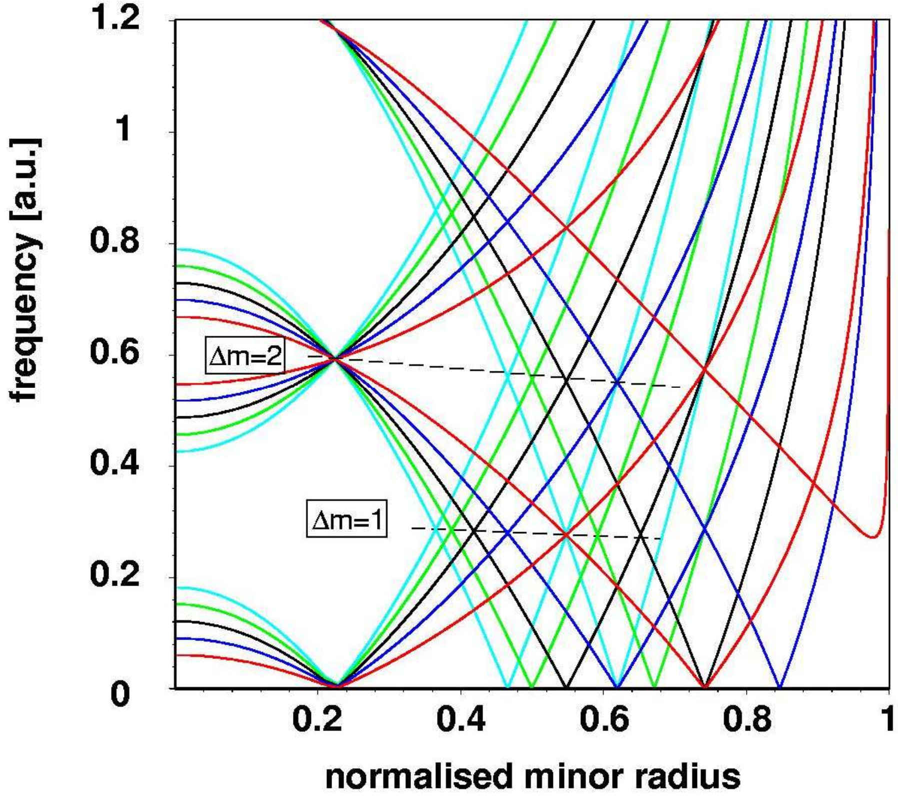
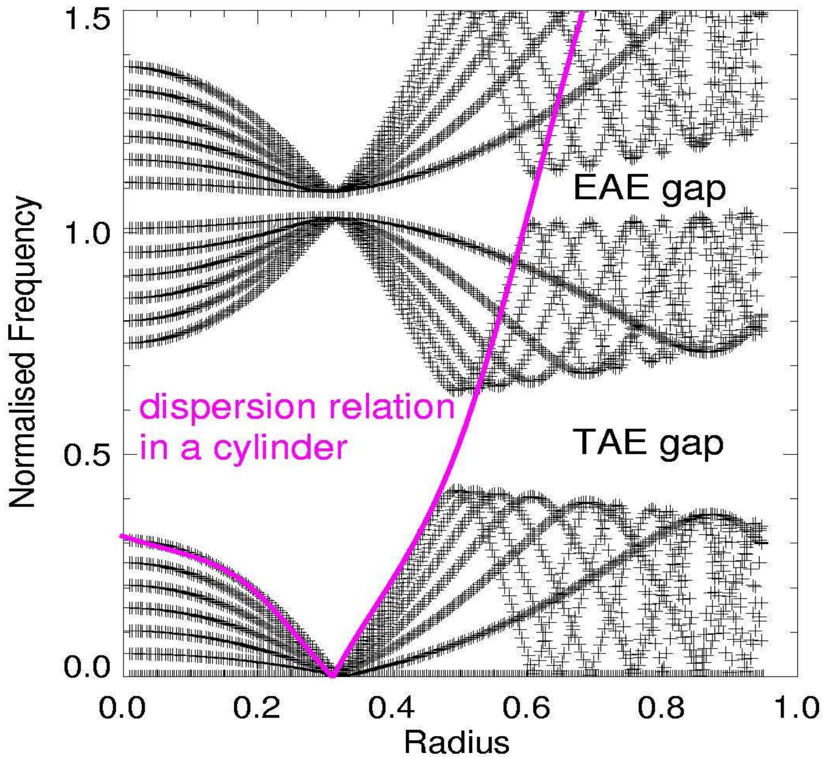


B-field lines in a plasma can oscillate like a string of a guitar

- double periodic cylinder: $\omega = k_{//} v_A$ gives continuum structure
- this leads to strong damping of the modes (radial variation of ω)

Alfven waves – continuum and gap modes

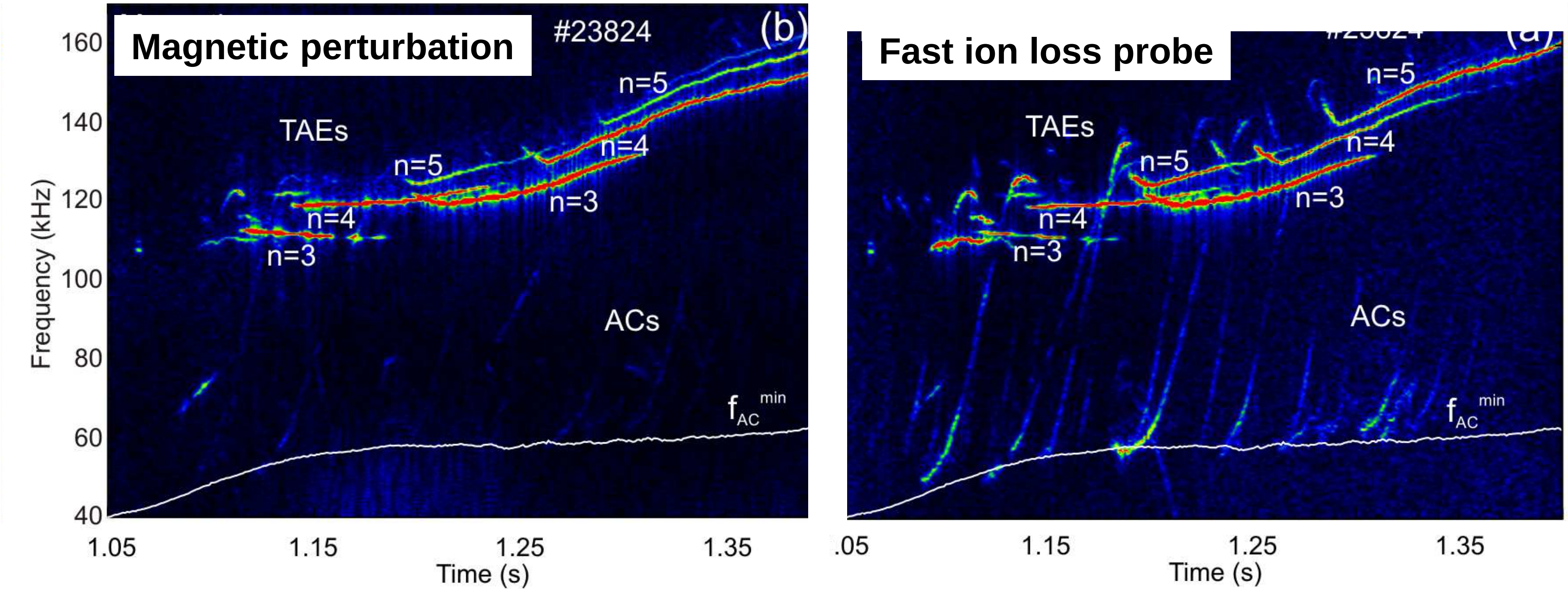




B-field lines in a plasma can oscillate like a string of a guitar

- double periodic cylinder: $\omega = k_{//} v_A$ gives continuum structure
- in a torus, gaps open that allow Alfven resonances to extend over radius

Excitation of Alfvén waves by Fast Particles



Suprathermal ions with $v \approx v_A$ can excite Alfvén waves which expel them

- in present day experiments, these ions come from heating systems
- in future reactors, this could expel α-particles that should heat the plasma!

Study of nonlinear interaction between waves/instabilities and suprathermal particles will be one of the main items of ITER physics

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Advanced tokamak – the problem of steady state

In ‘conventional’ operation, current in transformer (central solenoid) has to be ramped down contnuously to compensate ohmic losses

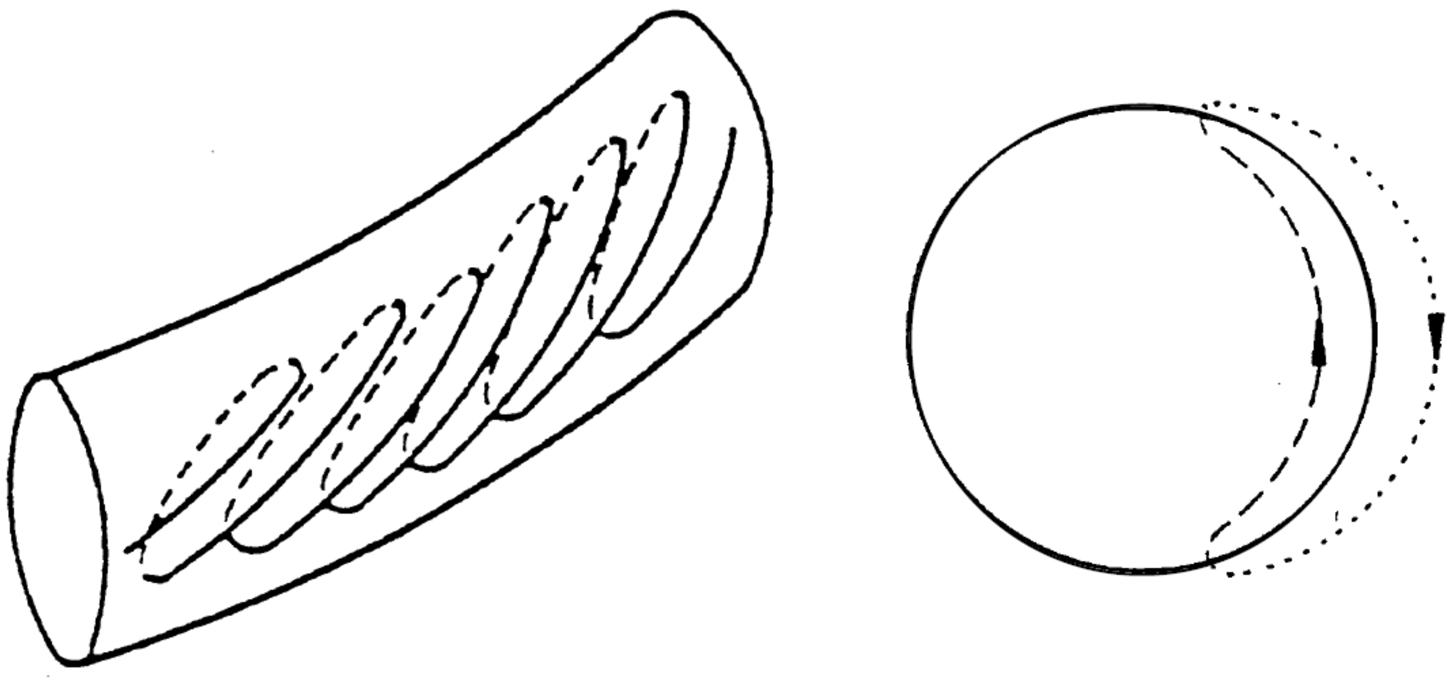
- these tokamak discharges are inherently pulsed

Advanced scenarios aim at stationary (transformerless) operation

- external CD has low efficiency around 0.1 A per W
- need a better idea to sustain plasma current in a tokamak

…the bootstrap current!

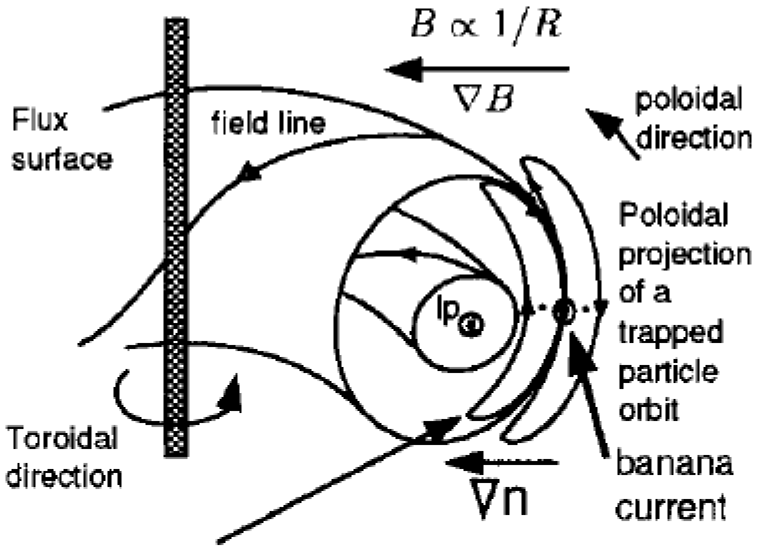
Particle orbits: banana orbits in tokamaks



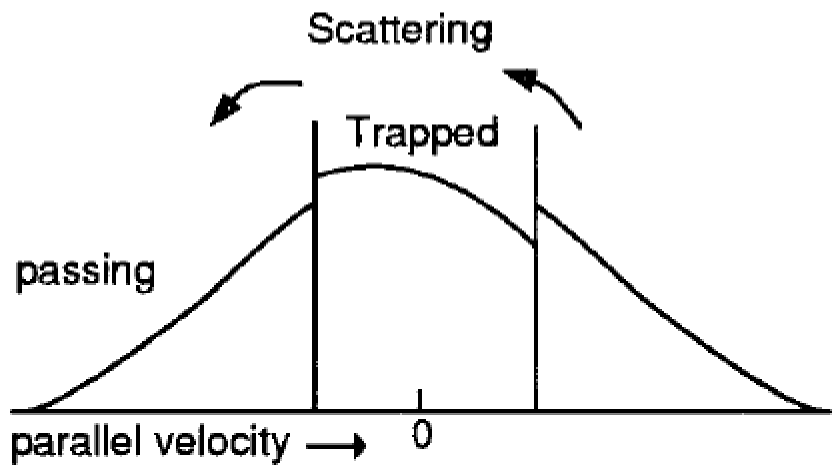
Due to the 1/R decay of a B-field in a torus, there is a magnetic mirror

- particles with low $v_{||}$ are trapped in this mirror, bounce back and forth
- poloidal projection of orbit resembles banana – ‚banana orbit‘

Bootstrap current



This orbit lies further inside more particles follow this orbit than the orbit further out.



Distribution function as a function of the parallel velocity for constant perpendicular velocity.

For finite pressure gradient, there is a net current of trapped particles along field lines

Distortion of distribution function due to trapped particles leads to a net current of passing electrons

banana current → bootstrap current

Advanced tokamak – the problem of steady state

Advanced scenarios aim at stationary (transformerless) operation

- external CD has low efficiency around 0.1 A per W
- internal bootstrap current high for high $j_{bs} \sim (r/R)^{1/2}\ \nabla p/B_{pol}$

  $\rightarrow f_{NI} \sim I_{bs}/I_p \sim p/B_{pol}^2 \sim \beta_{pol}$

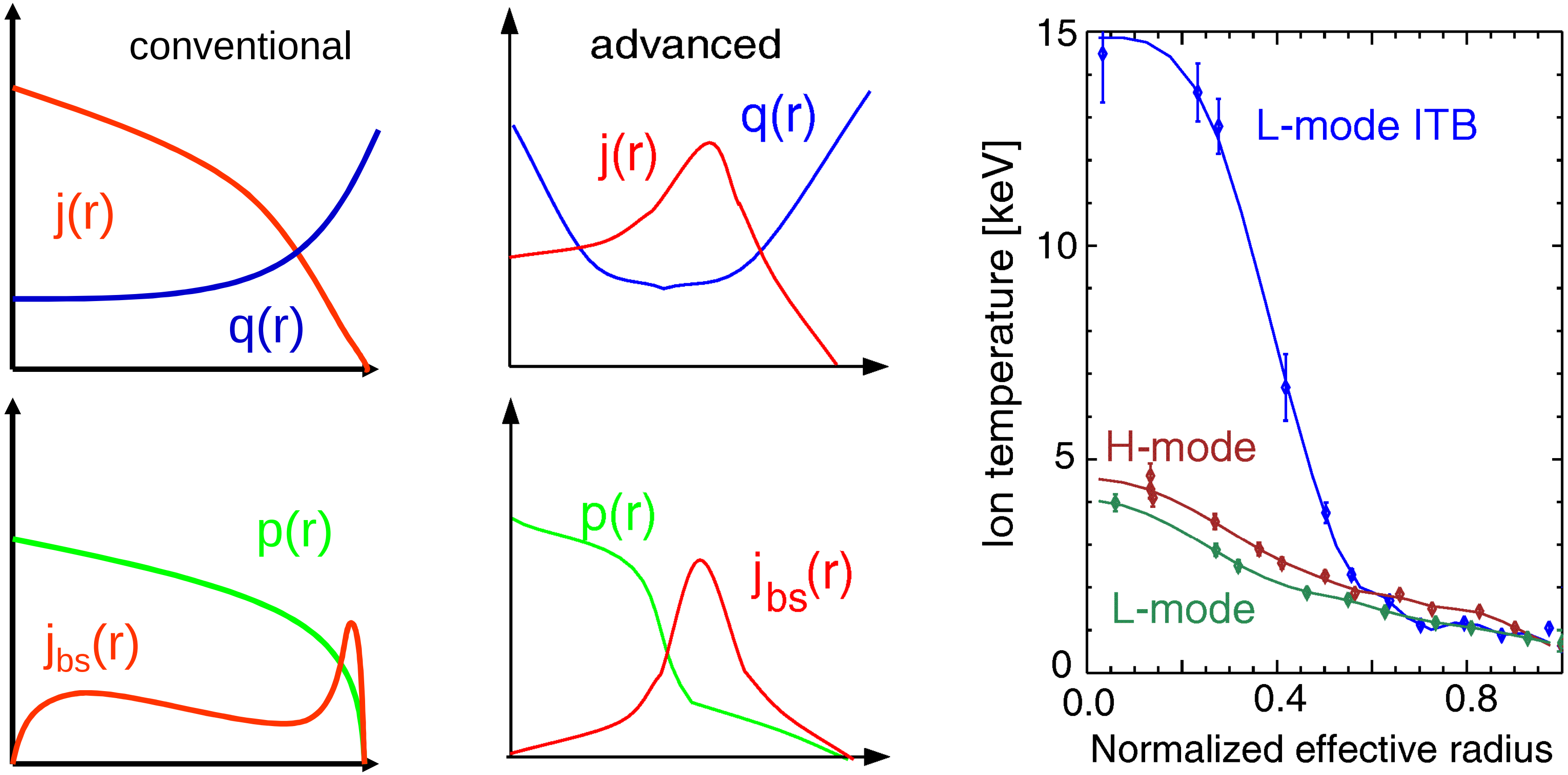
Recipe to obtain high bootstrap fraction:

- low B_{pol}, i.e. high q – elevate or reverse q-profile ($q=(r/R)(B_{tor}/B_{pol})$)
- high pressure where B_{pol} is low, i.e. peaked $p(r)$

Both recipes tend to make discharge ideal MHD (kink) unstable!

In addition, j_{bs} profile should be consistent with q-profile

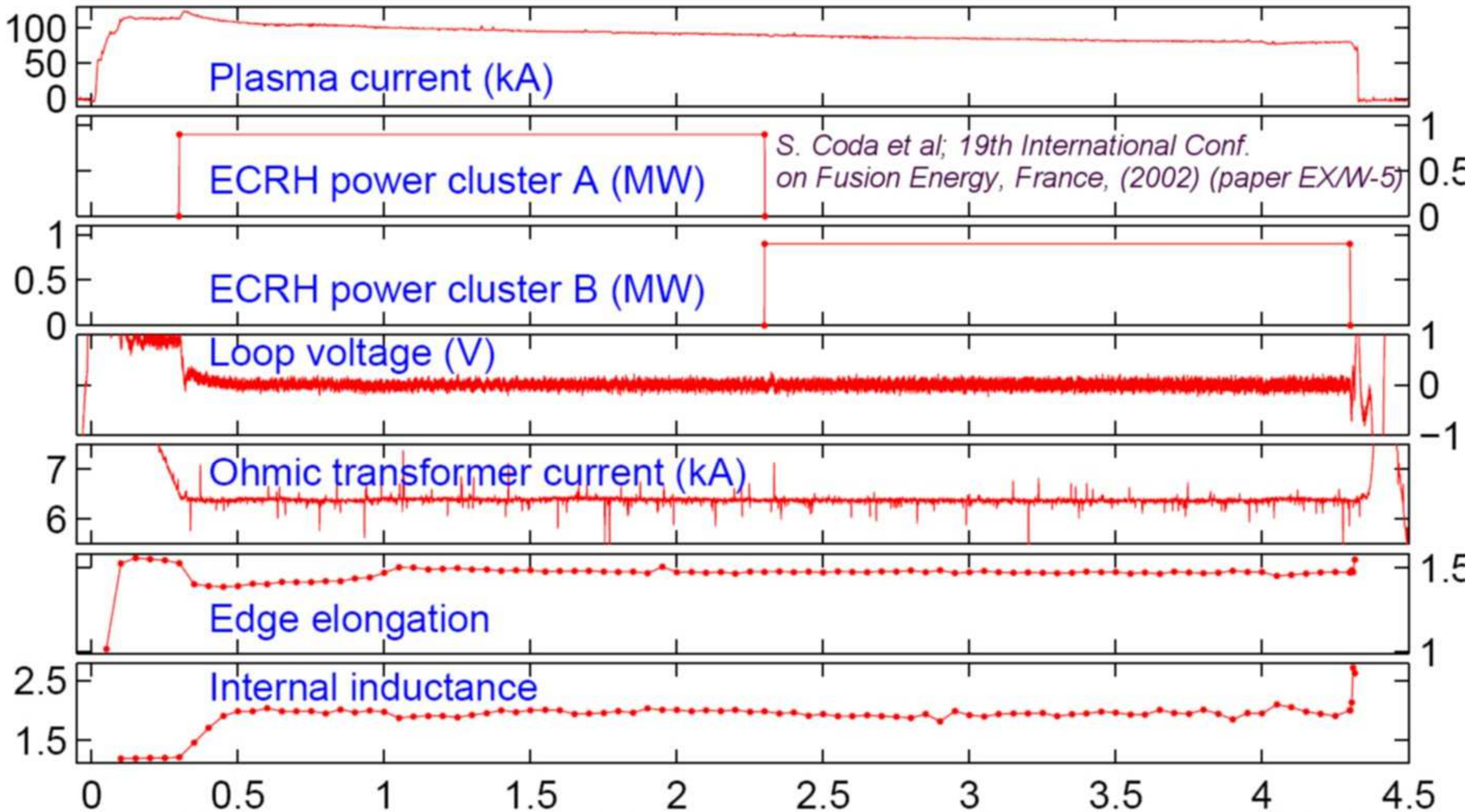
Advanced tokamak – the problem of steady state



A self-consistent solution is theoretically possible

- reversing *q*-profile suppresses turbulence – internal transport barrier (ITB)
- large bootstrap current at mid-radius supports reversed *q*-profile

Advanced tokamak – the problem of steady state



TCV discharge 20881 of record length (4.3 s), sustained by 0.9 MW ECCD

A 'proof of existence' exists – bit a long way to go….