New Trends in Fusion Research

Ambrogio Fasoli

Centre de Recherches en Physique des Plasmas

Ecole Polytechnique Fédérale de Lausanne

and MIT –USA

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

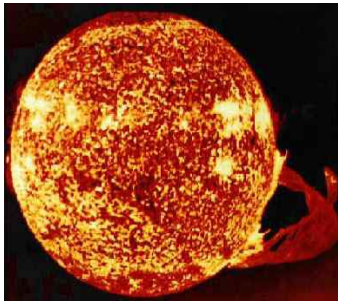
MIT PSFC CRPP EPFL EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Lay-out of Lecture 4

- *Magnetic fusion physics challenges (cont.)*
  - *Plasma wall interaction (cont.)*
    - *Main issues and the divertor concept*
    - Ex. of ongoing research: controlling edge instabilities
    - Choice of materials
  - Transport and turbulence
    - Non-collisional transport
    - How to limit the turbulence and its effect on transport?
  - Advanced tokamak operation: a promising route?
    - High gain, quasi steady-state

Fusion plasma *physics* challenges

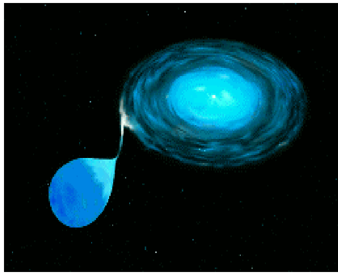
- Large power density and gradients ($10 MW/m^3 \approx 30'000 \times$ sun's core), anisotropy, no thermal equilibrium
  - Macro-instabilities and relaxation processes



solar flares, substorms

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

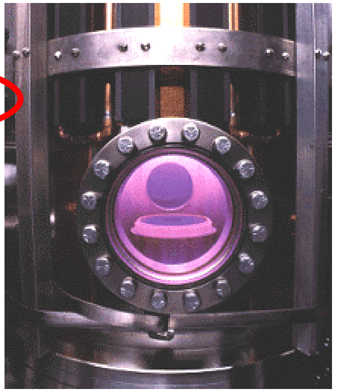
coronal heating



- Turbulent medium
  - Non-collisional transport and losses

accretion disks

- Plasma-neutral transition, wall interaction



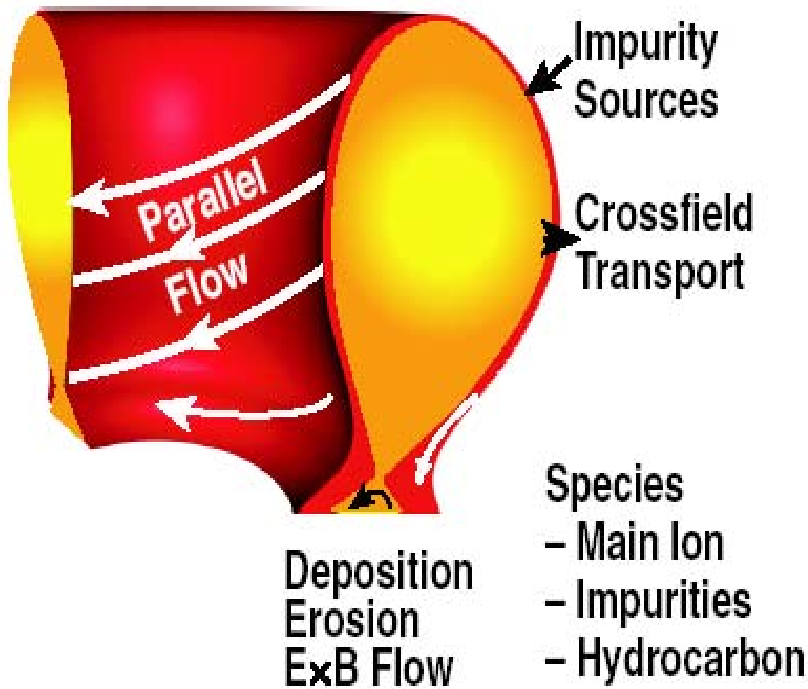
plasma manufacturing

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

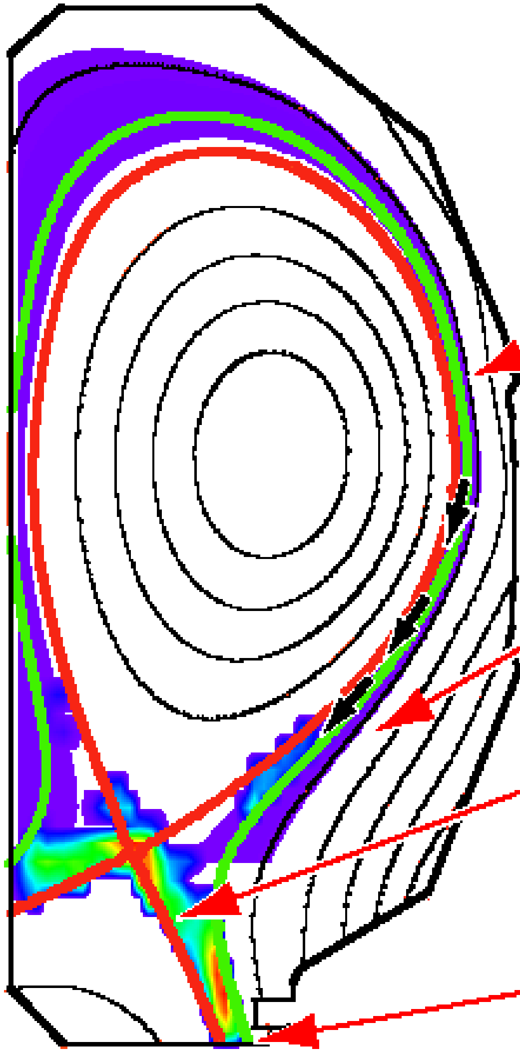
Plasma wall interaction issues

- Withstand power fluxes
  - Limit erosion, melting
    - Steady-state
    - *During transient edge instabilities*
- Keep the plasma pure
- Minimise T retention
- Exhaust power and particles

→the divertor concept
  - Separates plasma surface interactions from confined plasma



Main elements of divertor principle are included in 2-D codes (steady-state)

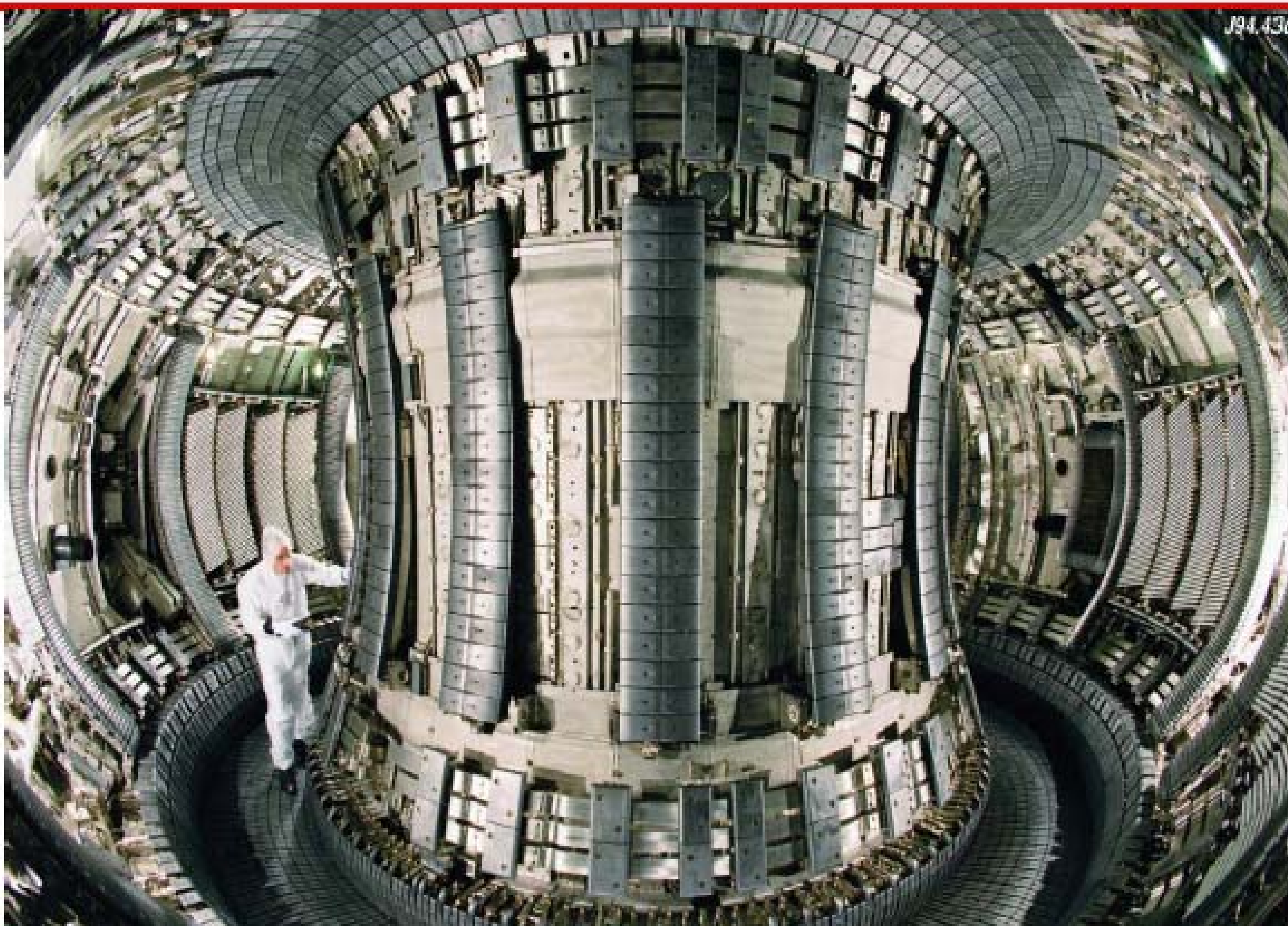


- Strong parallel transport
  Fluid drifts
  Actual flux surface geometry
- Non-equilibrium radiation rates
  2-D flow patterns
- Neutral recycling
  Recombination
  Detailed divertor structures
- Erosion of surfaces
  Ablation during intense heat pulses

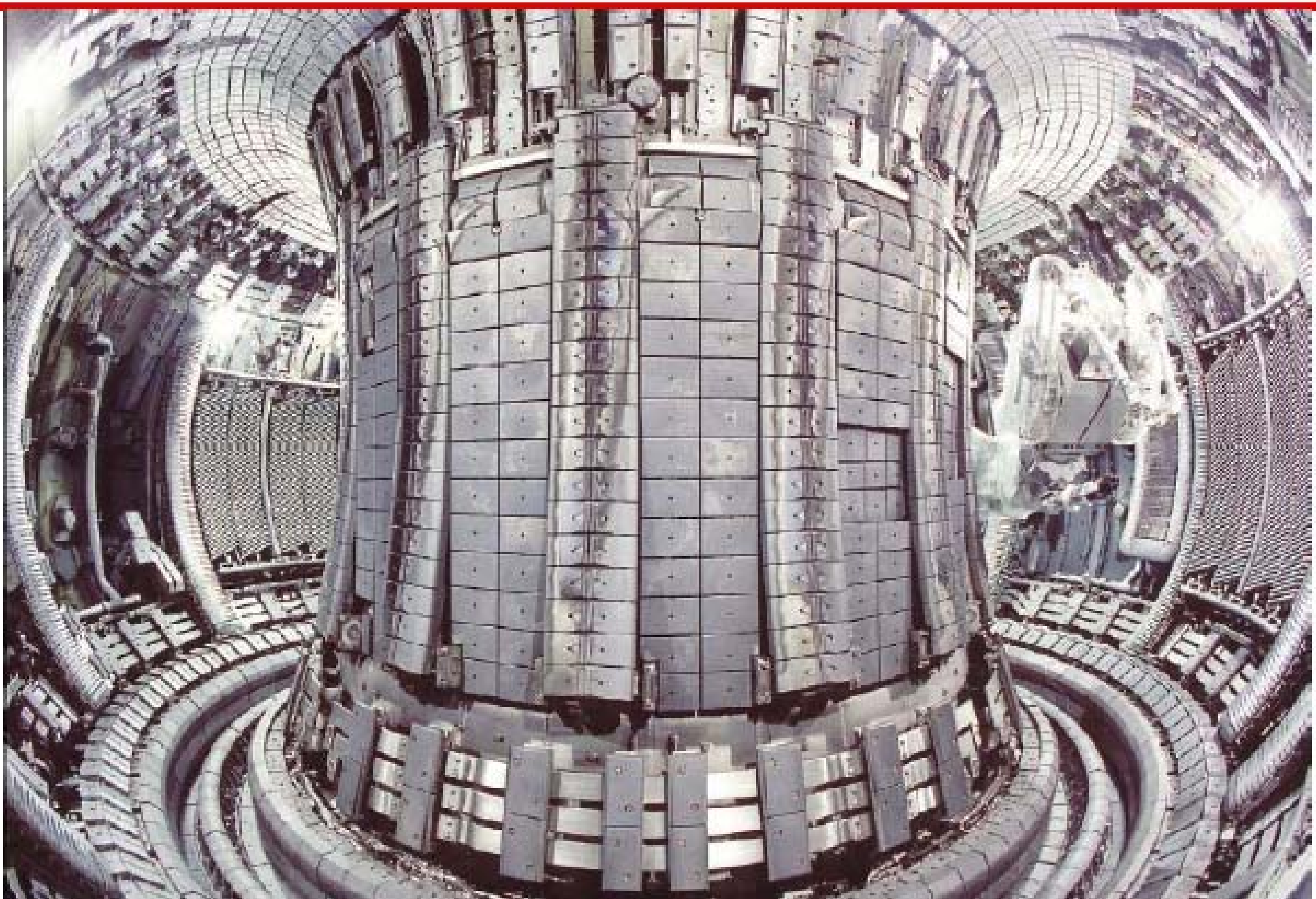
JET vessel in 1991

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

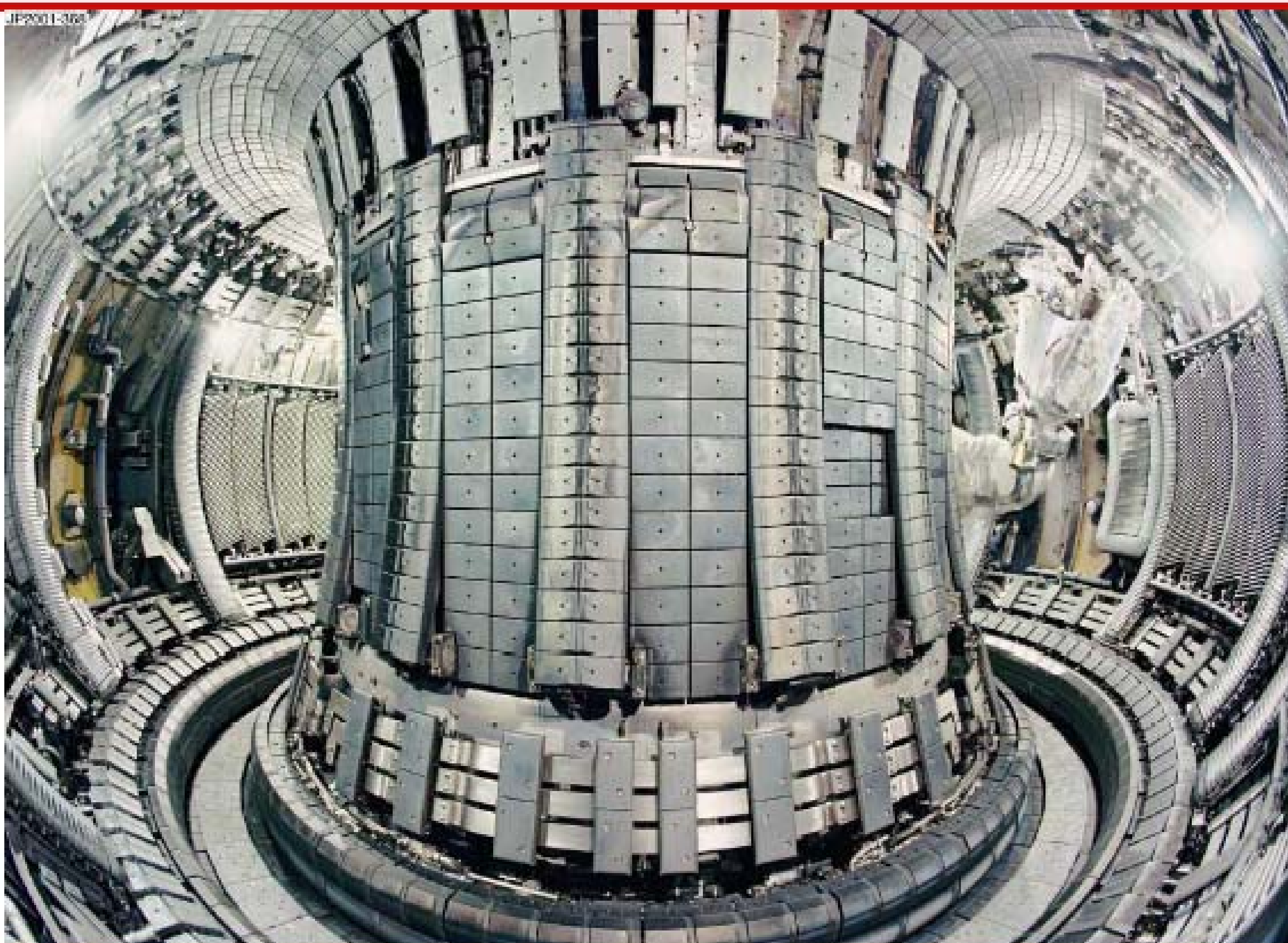
JET vessel with Mark I divertor in 1994



JET vessel with Mark IIGB divertor in 1998

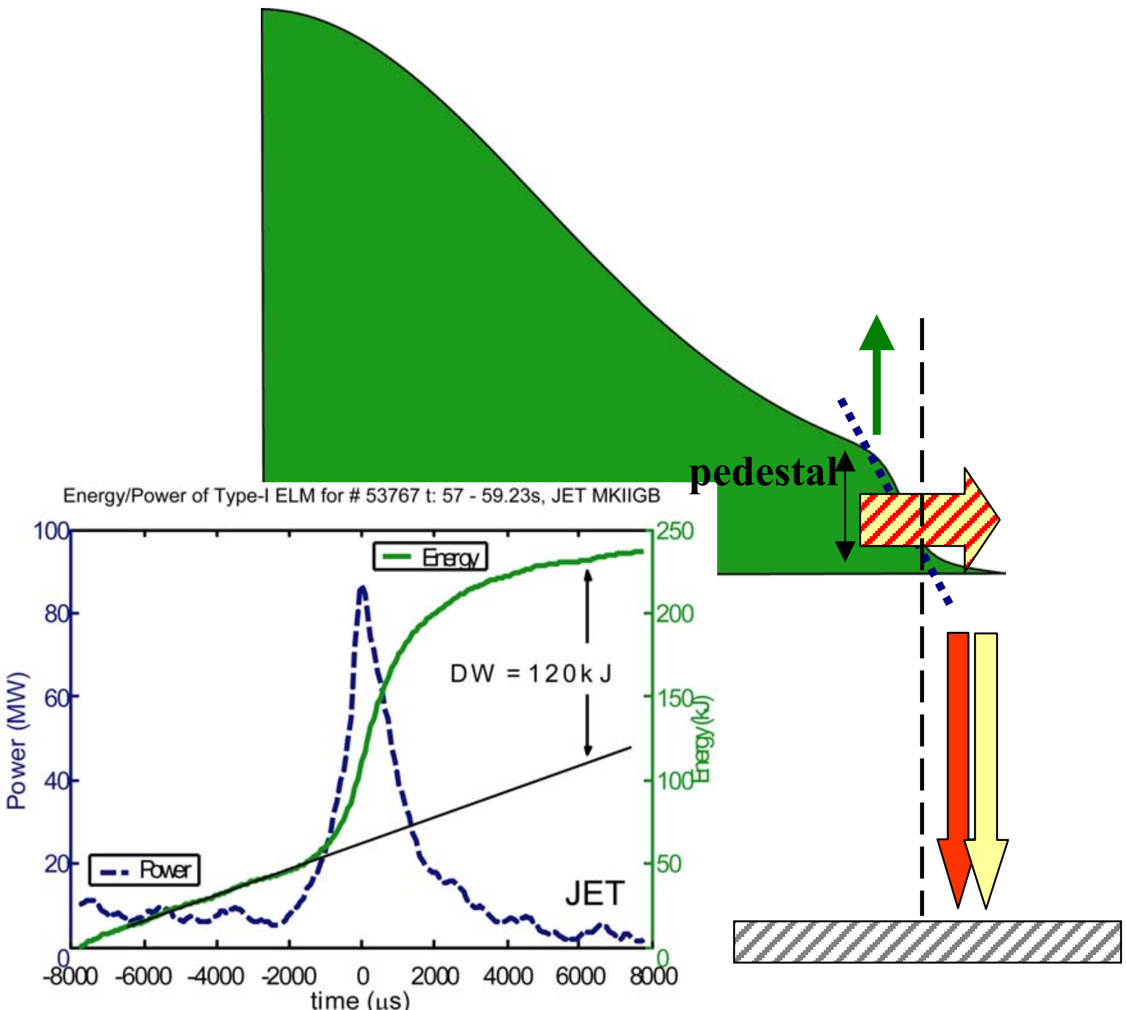


JET vessel with Mark IISRP divertor in 2002



The problem of transient edge instabilities

Transient transport



Eich, 2003

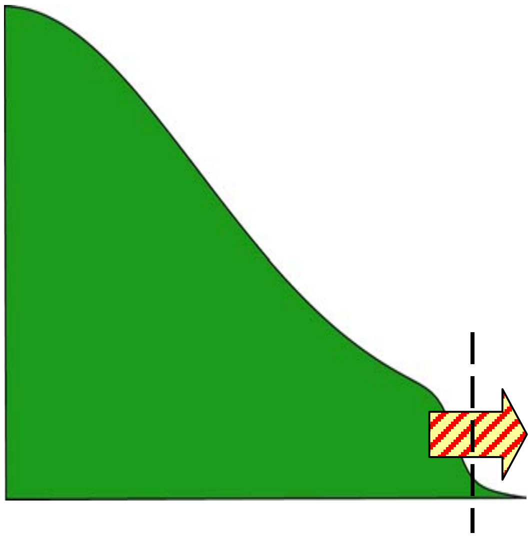
- $P_{FUS} \propto p_{ped}^2$ - high pedestal very desirable

Kinsey 2003

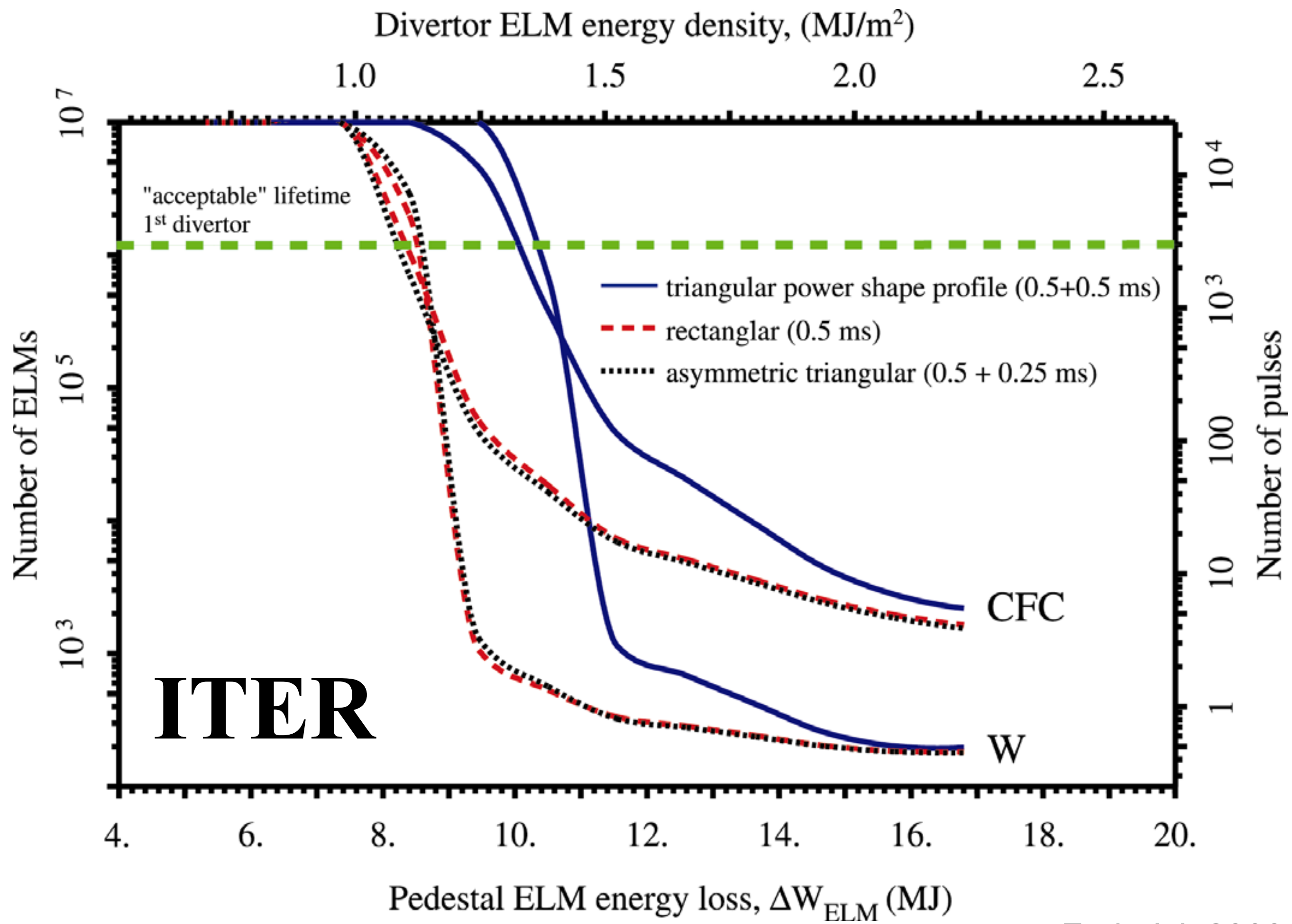
- Pedestal maintained close to marginal stability to MHD instabilities *(peeling-ballooning modes)*
- Collapses intermittently, releasing power and particles beyond separatrix
- Edge Localised Modes, ELMs

Slides from G.Counsell, IKAEA

Transient transport

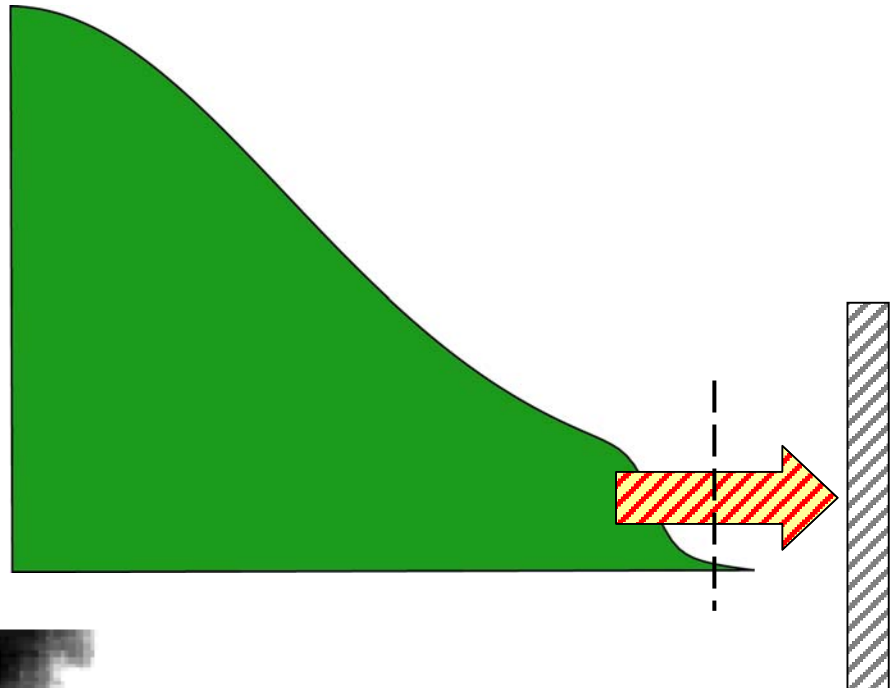


- Materials physics sets limit on allowable ΔW_{ELM}

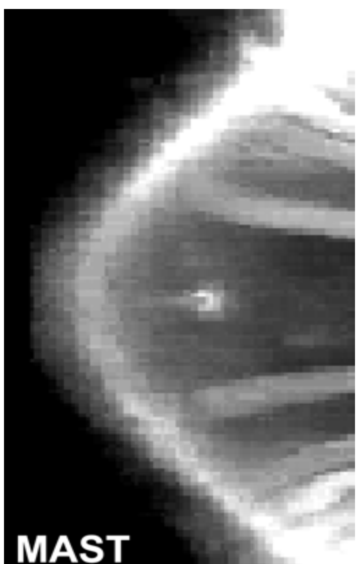


Federici, 2003

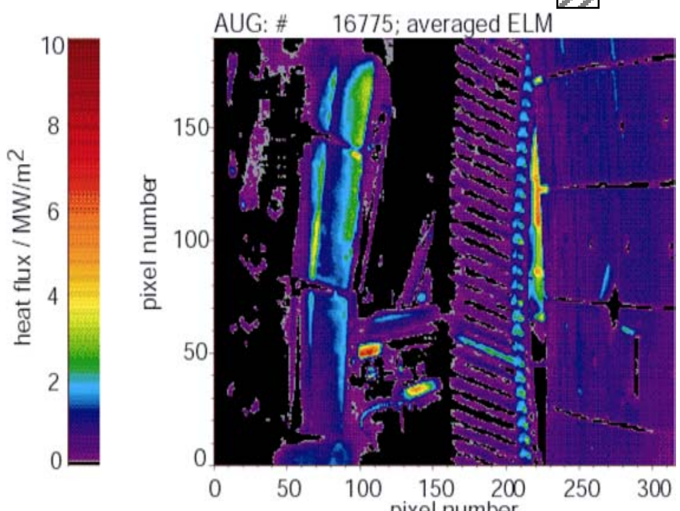
Transient transport



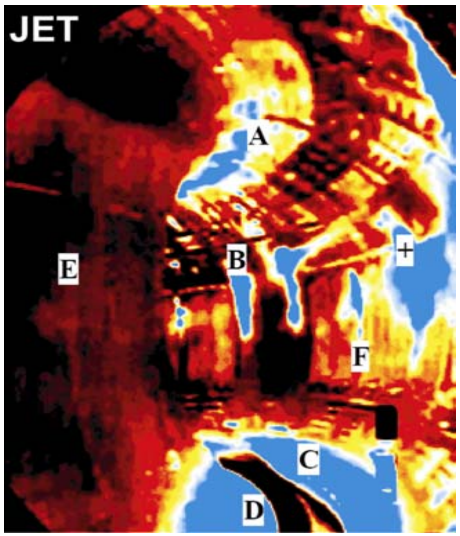
- Some ELMs (Type I) also deposit energy & particles on first wall
- 10-50% ELM energy arrives at wall



Counsell, 2000

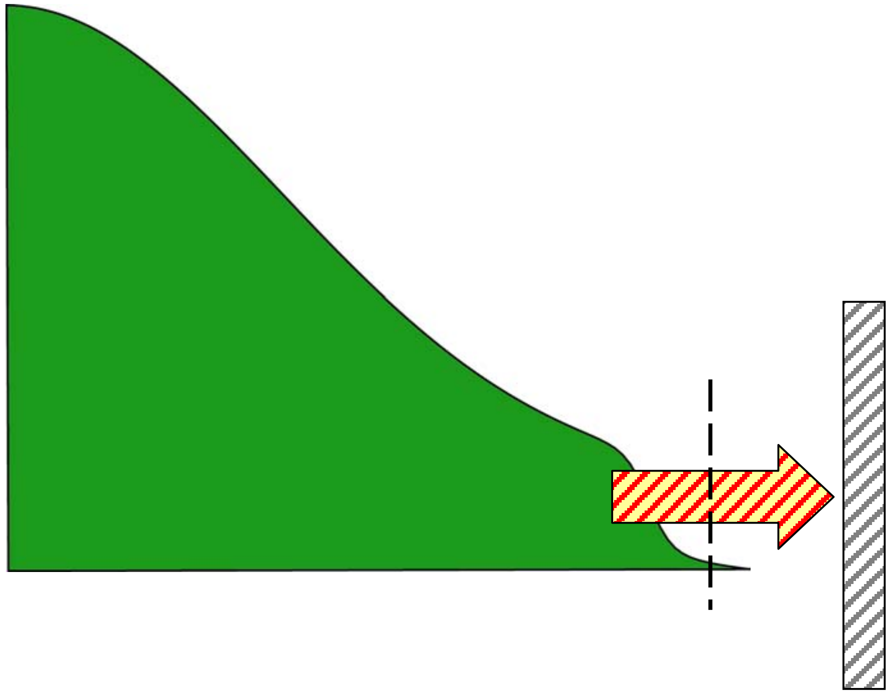


Herrman, 2003

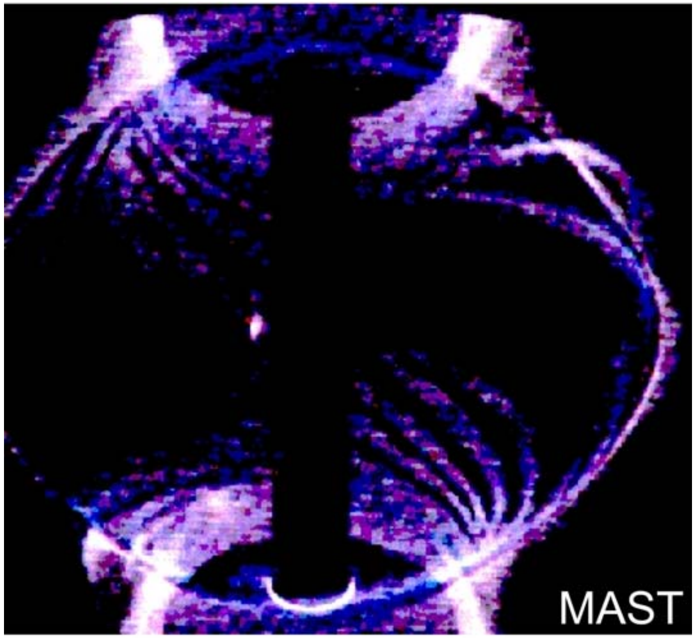


Ghendrih, 2003

Transient transport



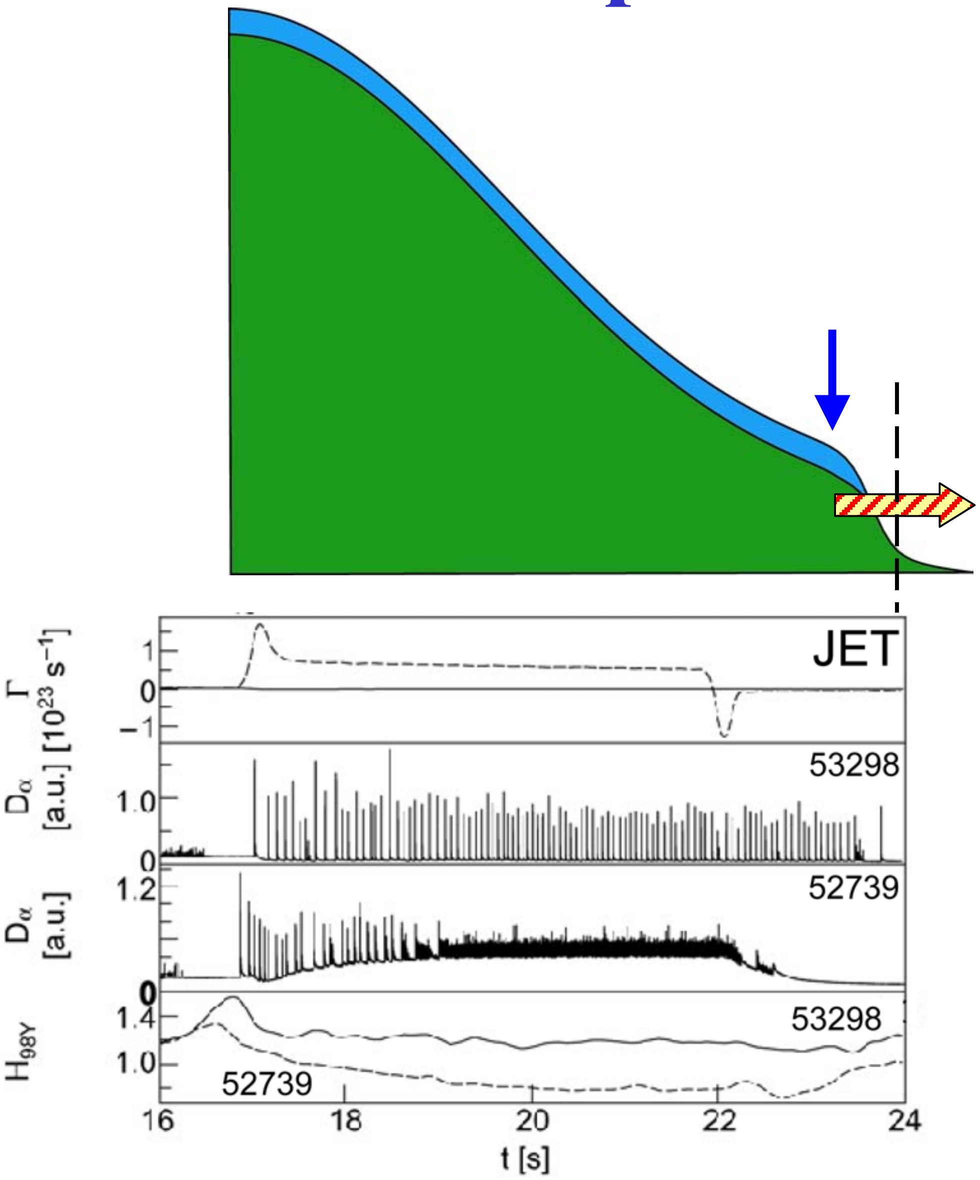
- Type I ELMs (at least) now also deposit energy & particles on first wall
- 10-50% ELM energy arrives at wall
- Localised deposition due to ELM structure



Kirk, 2003

Could lead to melting of first wall (e.g. Be)

Methods to control ELMs? An open field of research



Ways ahead:

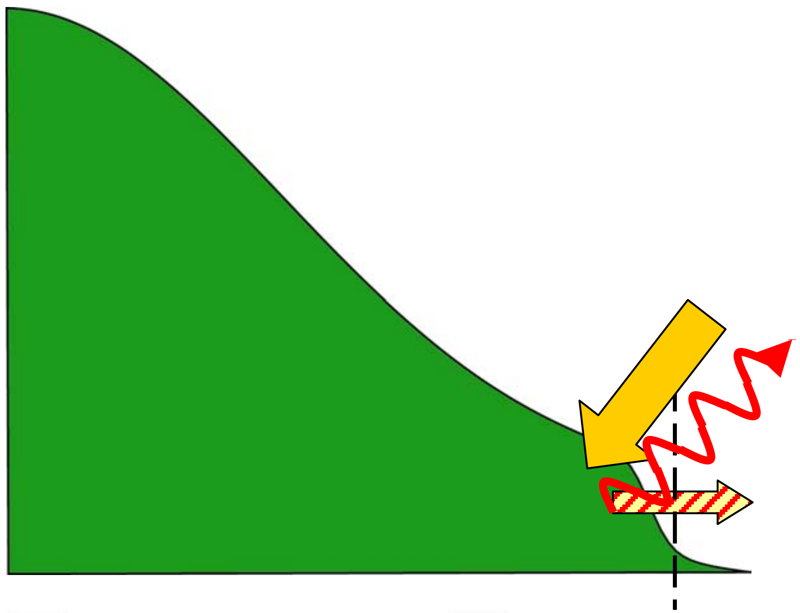
- Reduce the pedestal height and gradient
- Move from coupled peeling-ballooning to peeling modes

⇒ Different type of ELMs *(Small Type III)*

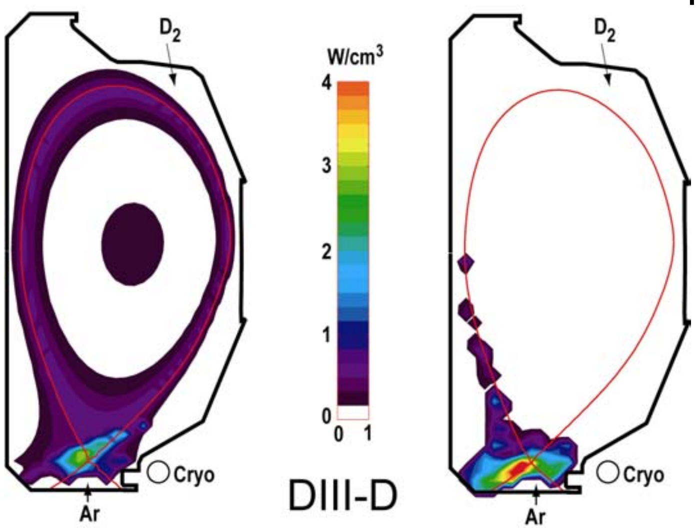
- Gas puffing is a simple way to achieve this

Problem - reducing pedestal height also reduces core performance

Transient transport



Jackson, 2002



Ways ahead:

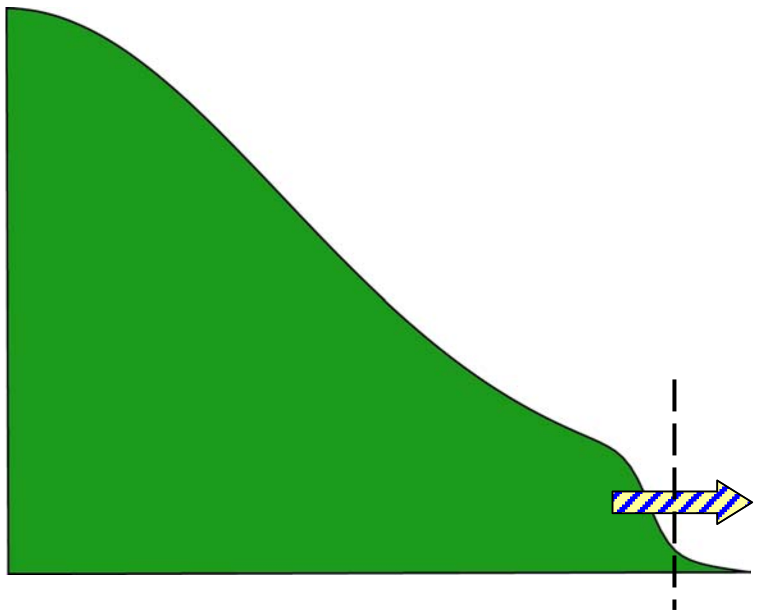
- Add impurity species to edge plasma
- Increased radiation reduces conducted edge losses

⇒Impurity seeded regimes

Potential problem -

- In some experiments (e.g. JET), confinement usually is reduced by impurity seeding

Transient transport



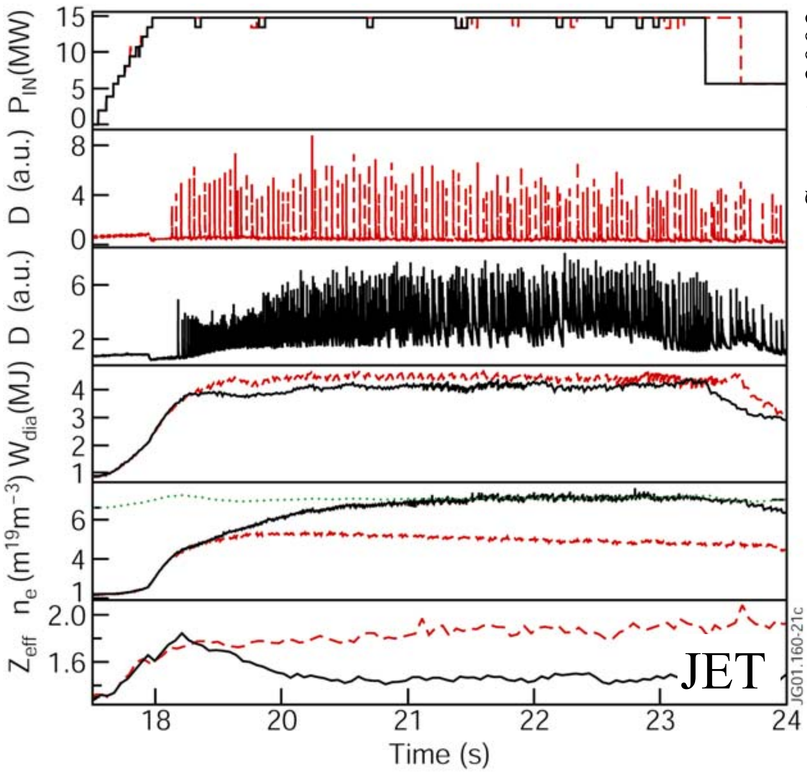
Problem -

- Very narrow operating space
- 'Formula' different on each device

Ways ahead:

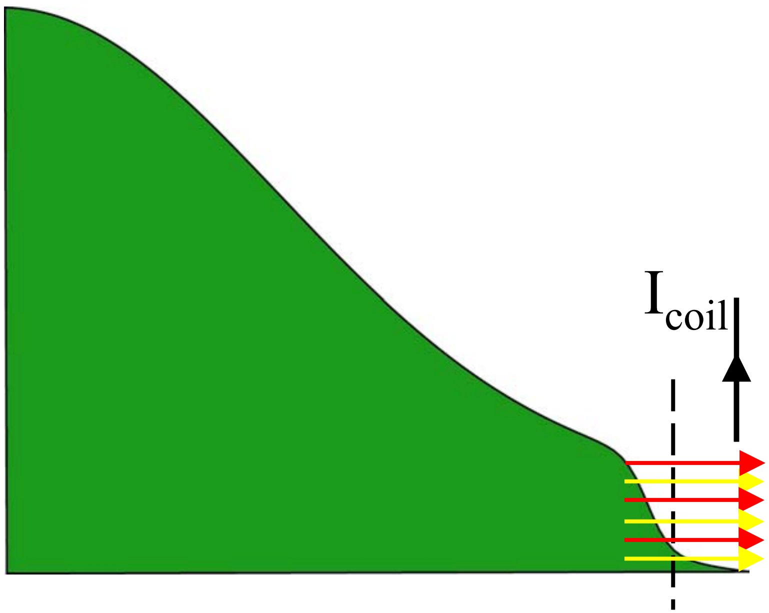
- 'Alternative' small ELM regimes with high confinement

•Obtained at high triangularity, relatively low current, high density



Sartori, 2002

Transient transport



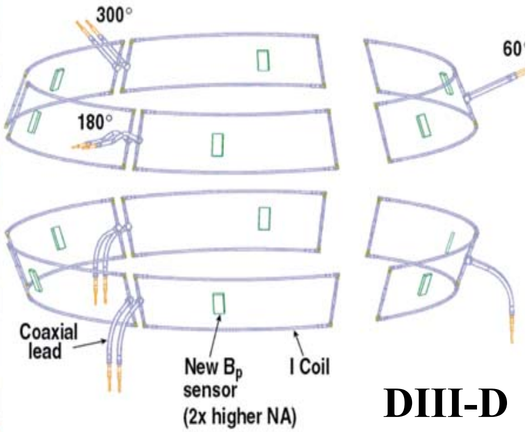
Ways ahead:

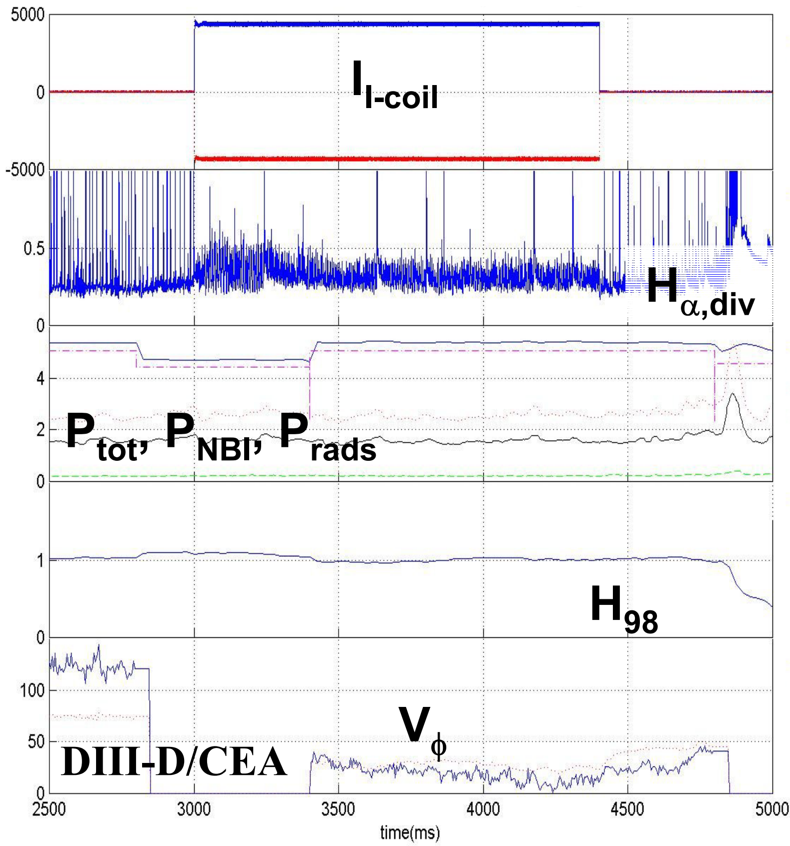
- 'Ergodise' edge plasma using perturbations from external coils

⇒ Stochastic boundary control

I-coil segment (carbon tiles removed)

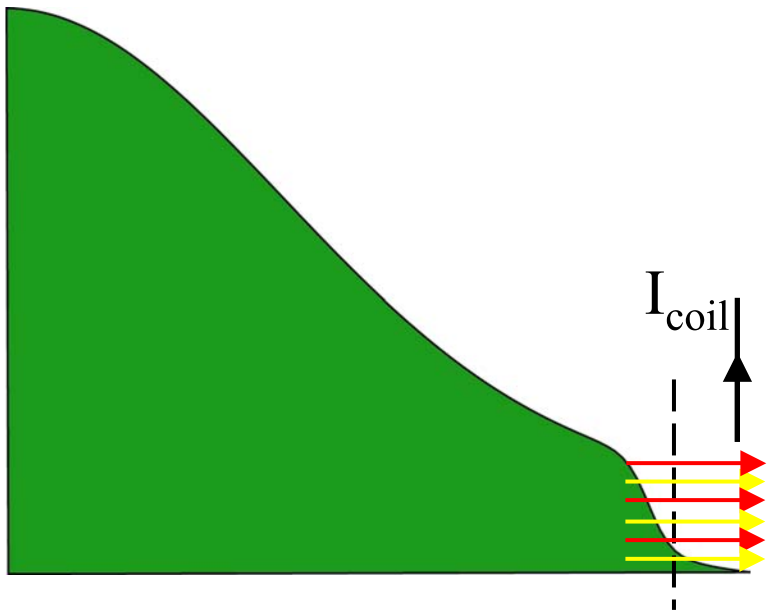
Moyer, 2003

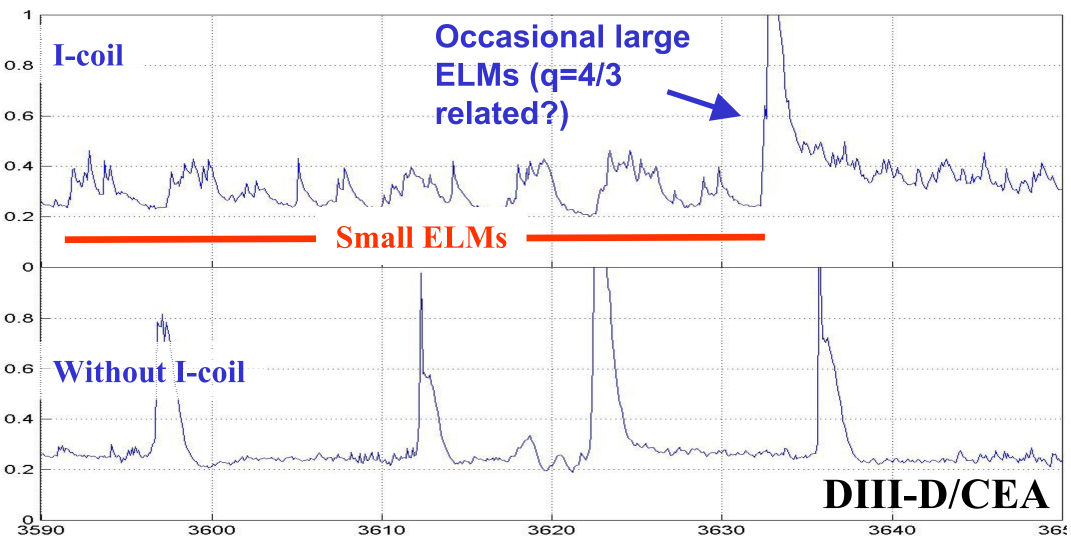




Thomas, 2003

Transient transport





Thomas, 2003

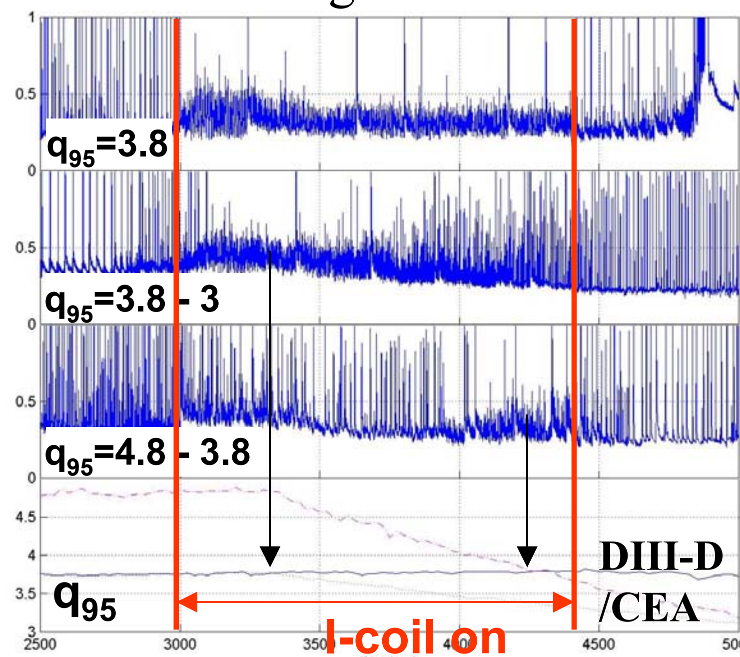
Ways ahead:

Stochastic boundary control

- Resonant perturbation demonstrated
- Small ELMs

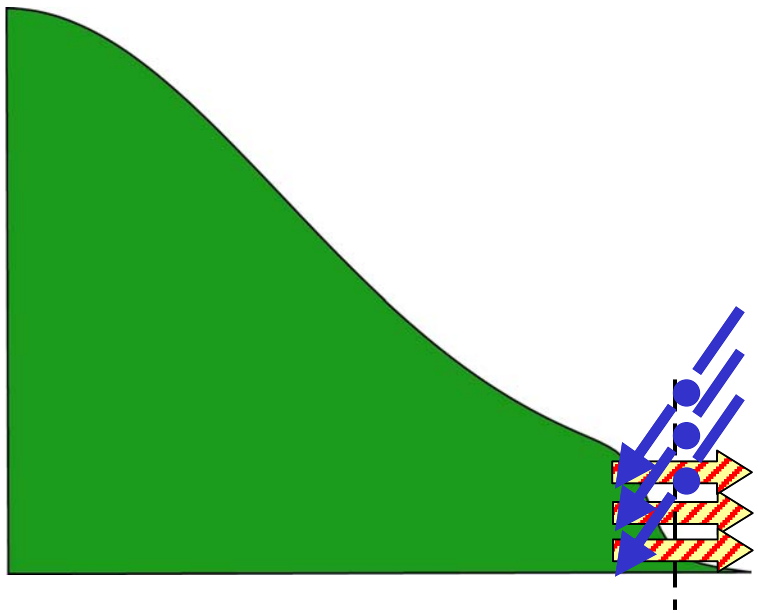
Problem:

- Very early days, none identified as yet
- Some large ELMs



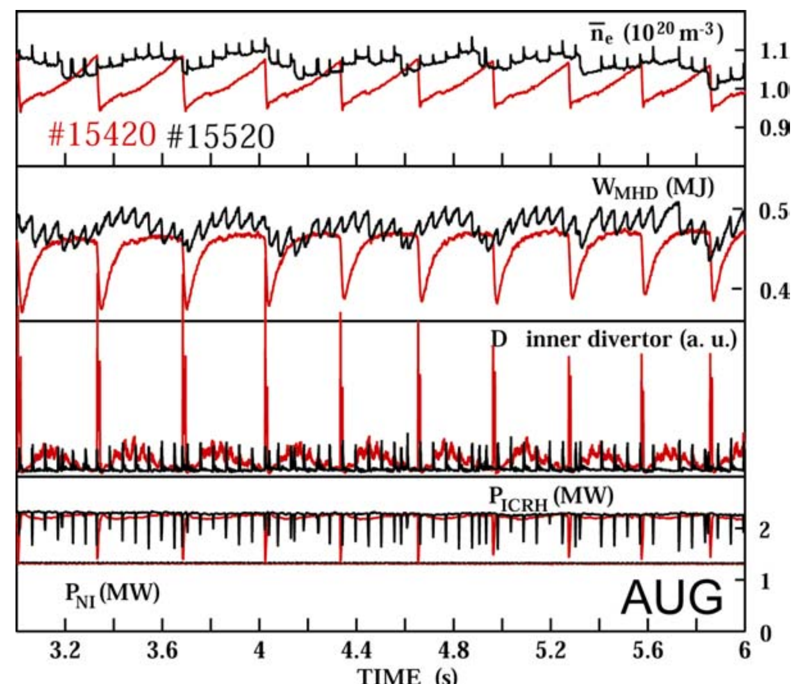
Thomas, 2003

Transient transport



Ways ahead:

- Control the ELM frequency by multiple shallow pellet injection
- Actively increasing ELM frequency reduces ΔW_{ELM}
- No apparent impact on confinement
- Can small pellets penetrate deep enough in a reactor?



Lang, 2003

What material for first wall and divertor?

- Experience with C from present day experiments

Long term fuel (T) retention

JET	**10%**
TFTR	**13%**

Equivalent ITER T limit (350g) would be reached in less than 50 shots

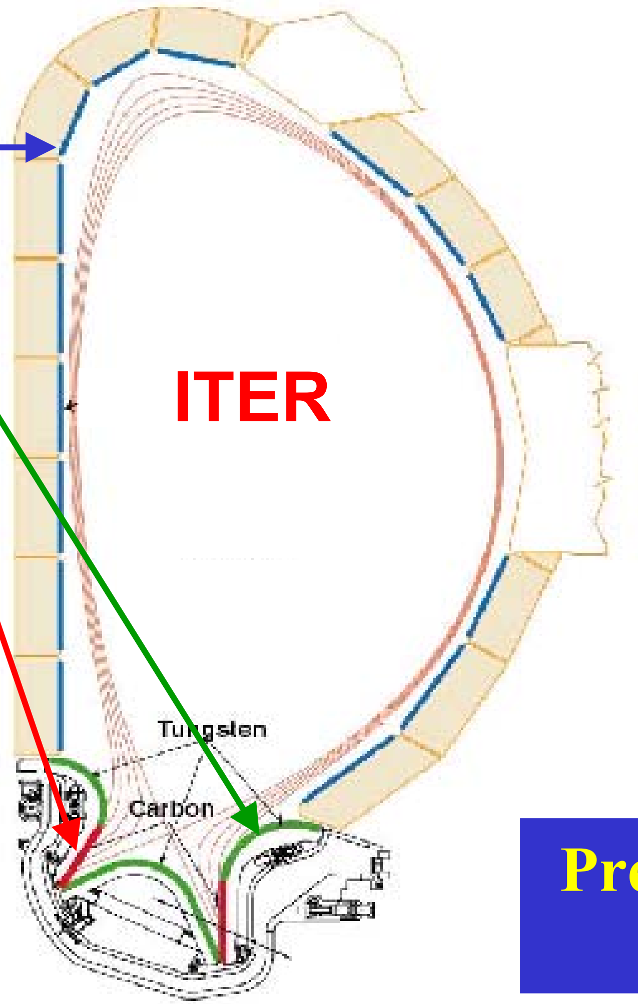
- Present understanding: Tritium is retained by co-deposition with carbon, on the plasma facing sides or on remote areas
- Full C walls would give unacceptable retention of T
  - Unless new techniques to remove co-deposited T are found

What material for first wall and divertor?

700m² Be first wall
- Low Z
- Oxygen getter

100m² Tungsten
- low erosion

50 m² Graphite CFC
- no melting

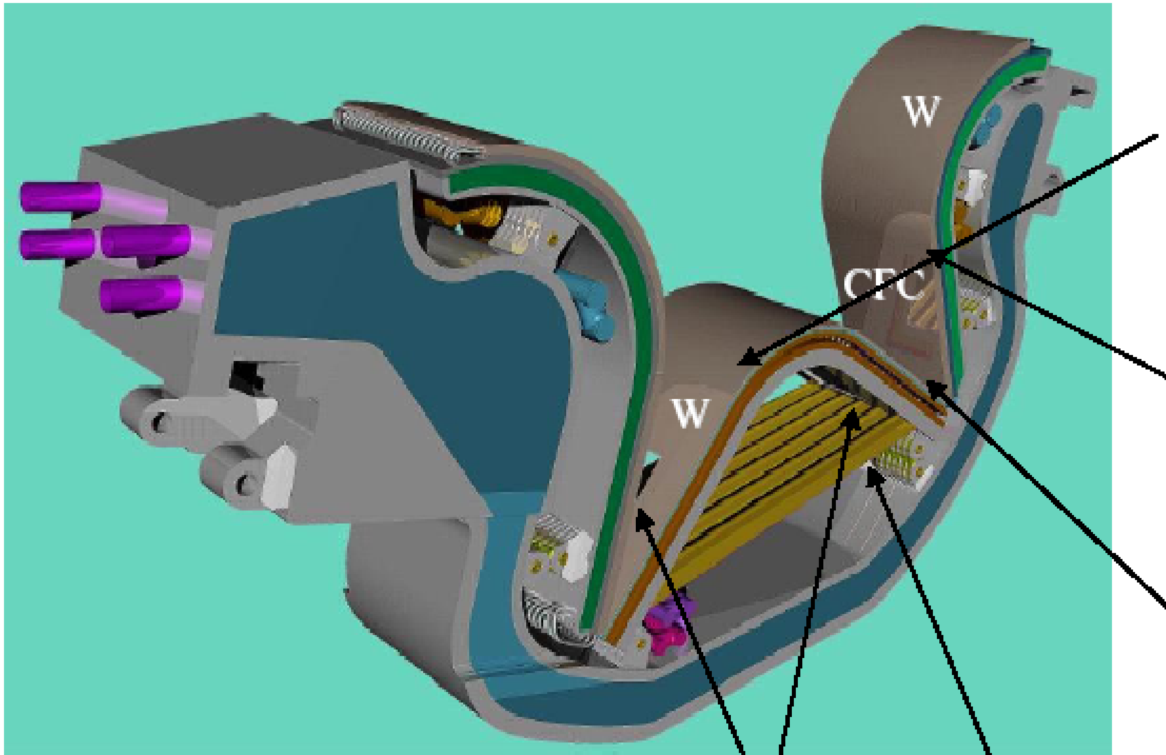


Present ITER wall material choice

Details of ITER divertor geometry

Divertor Geometry

ITER



Dome provides protection for the pumping region components and contributes to baffling neutrals from re-entering the main plasma.

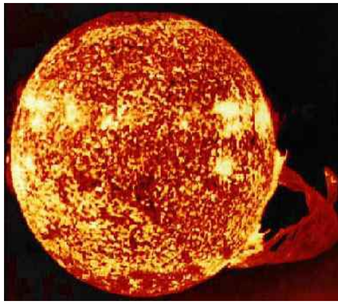
The target is highly inclined to the field lines this reduces the heat flux at the strike point.

The protection plates at the lower end of the private region PFC together with the vertical targets form a closed "V" at the apex of each channel which aids detachment.

Openings allow free re-circulation of neutrals from inboard to outboard which gives detachment to be achieved in the outer channel without the need for excessive gas puffing.

Exhaust gas Pumped through slots in liner

Fusion plasma *physics* challenges

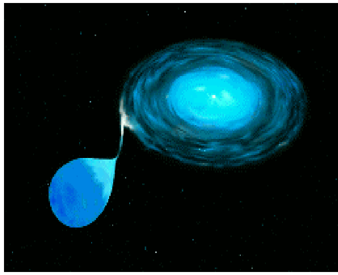


- Large power density and gradients ($10 MW/m^3 \approx$ 30’000×sun’s core), anisotropy, no thermal equilibrium
  - Macro-instabilities and relaxation processes

solar flares, substorms

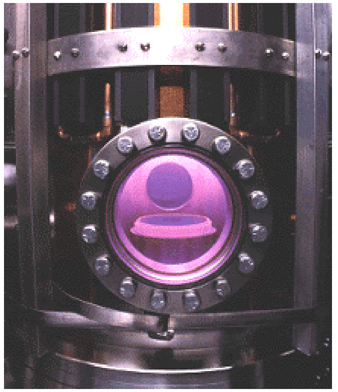
- Dual fluid/particle nature
  - Wave-particle interaction (resonant, nonlinear)

coronal heating



- Turbulent medium
  - Non-collisional transport and losses

accretion disks



- Plasma-neutral transition, wall interaction

plasma manufacturing

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

Turbulence and non-collisional transport

- Confinement time $\tau_E \sim (\text{size})^2/\chi$; $\chi \sim (\text{step size})^2 \times \nu$
- Collisional (*classical*) theory:
  - ν = Coulomb collision frequency
  - (step size) = particle orbit size: what is it in a tokamak

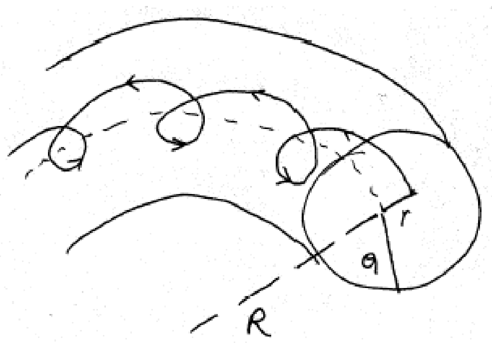
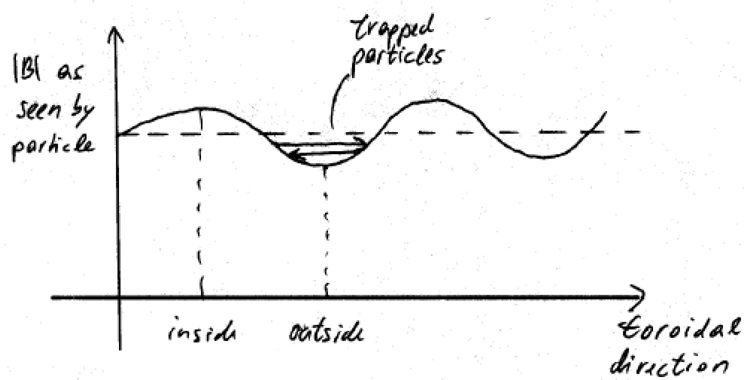
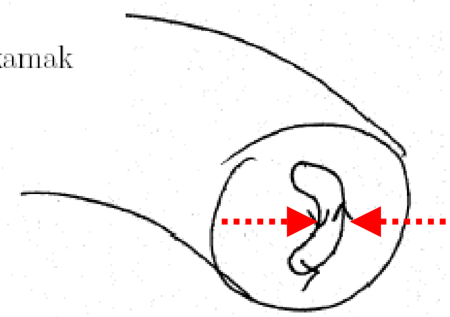


Figure 7: Helicoidal field lines in a tokamak



rapped particles



Size$\sim\rho_L q(2a/R)$

Figure 9: 'Banana' shaped orbits of trapped particles

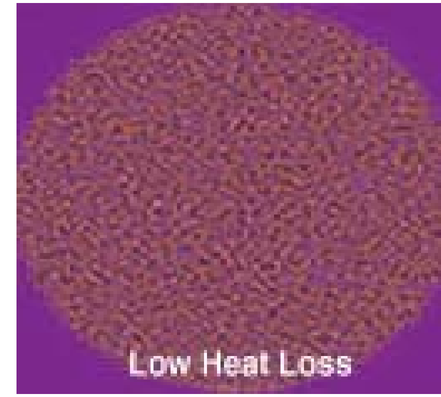
Turbulence and non-collisional transport

- But $\tau_E^{meas} << \tau_E^{coll}$ → *anomalous* transport
- Anomalous transport is caused by *drift wave* micro-turbulence, generated by pressure gradients
  - Drift waves: universal instabilities associated with pressure gradients

$$\omega^* = k_y v_\mathrm{d} \qquad v_\mathrm{d} = \frac{T}{m\Omega}\frac{1}{n}\frac{dn}{dx} \equiv \frac{T}{m\Omega}\frac{1}{L_n}$$

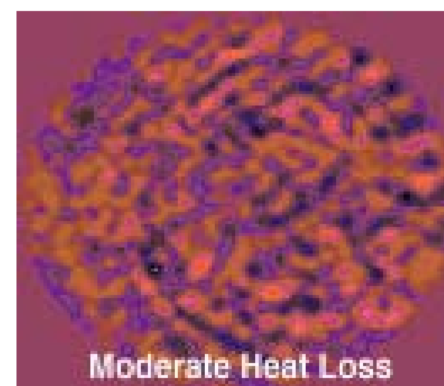
Effect of drift waves on transport

- Waves give 'kicks' (E×B) to particles→ transport
- Step size ~ λ, ν ~ (correlation time)$^{-1}$
- But small λ → weak transport: cannot explain observation!



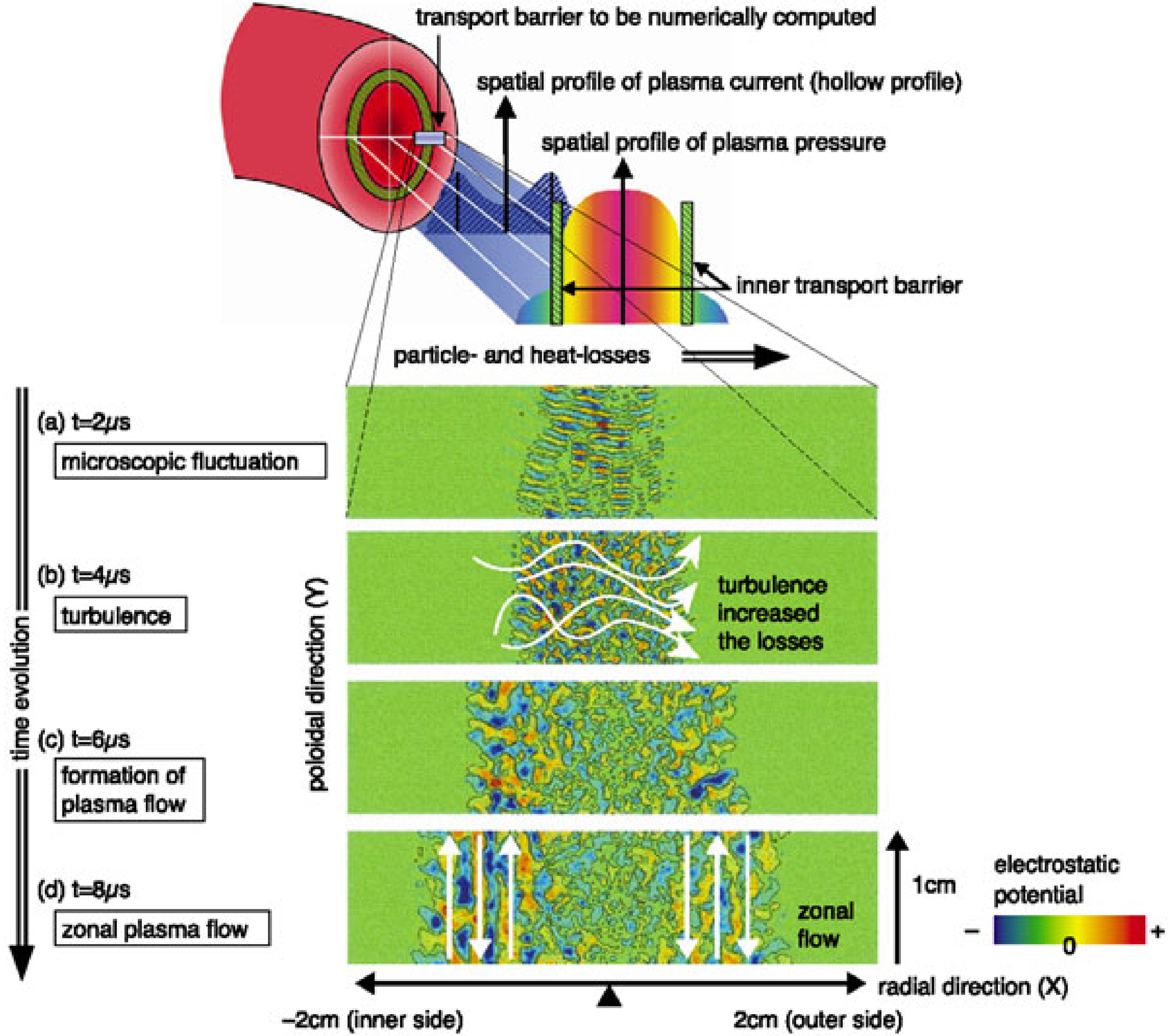
- Theory: Nonlinear evolution of turbulence leads to radially extended structures which are responsible for large transport

- Possible cure: Shear flows driven by radial electric fields break these structures, reducing radial correlations, diffusivity, turbulence amplitude

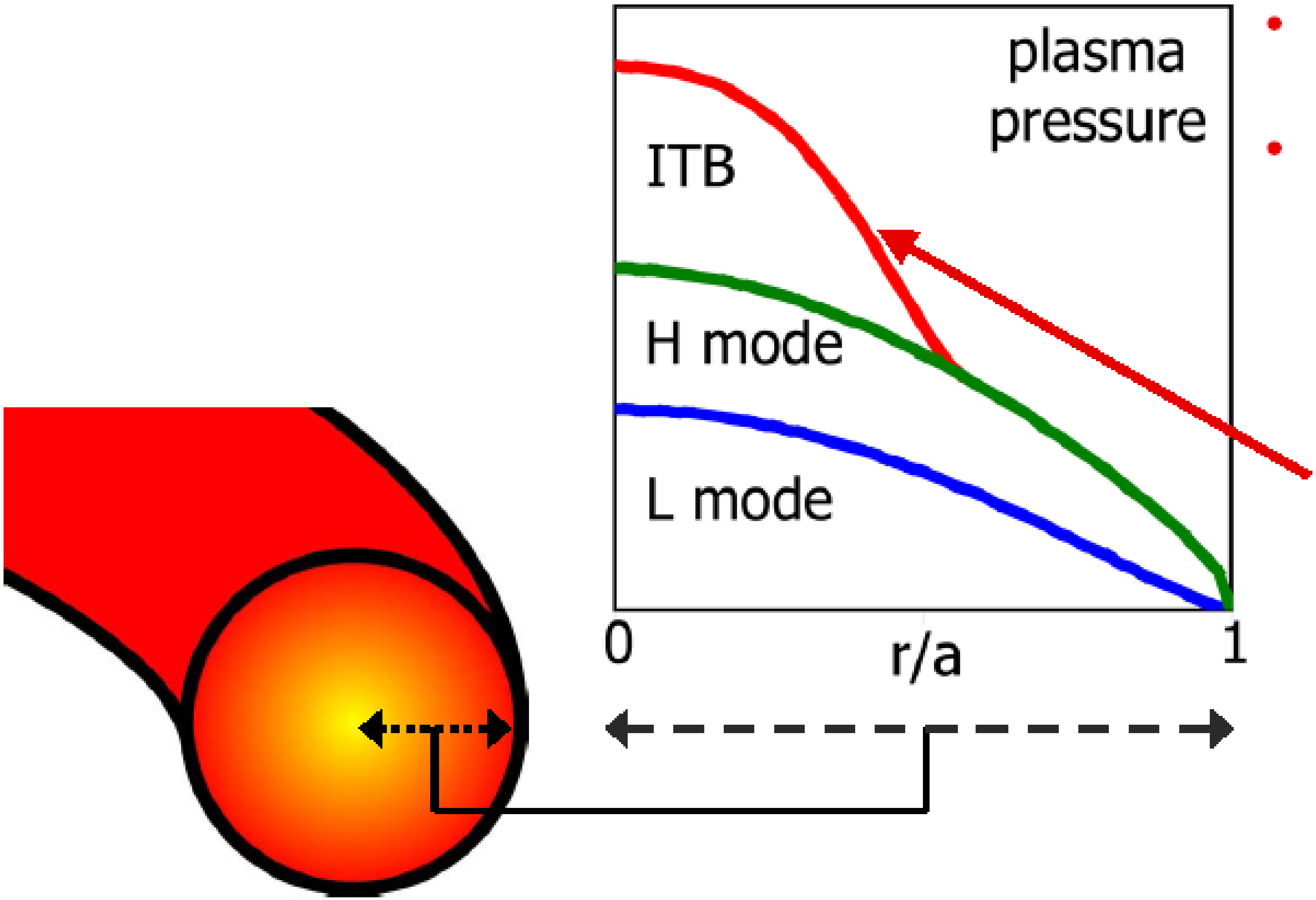


Courtesy of B.Nevins, DoE SciDac initiative

Sheared flows cause enhanced confinement?



Transport barriers



- H mode
- ITB plasma

- Reduced turbulence and improved insulation in core region

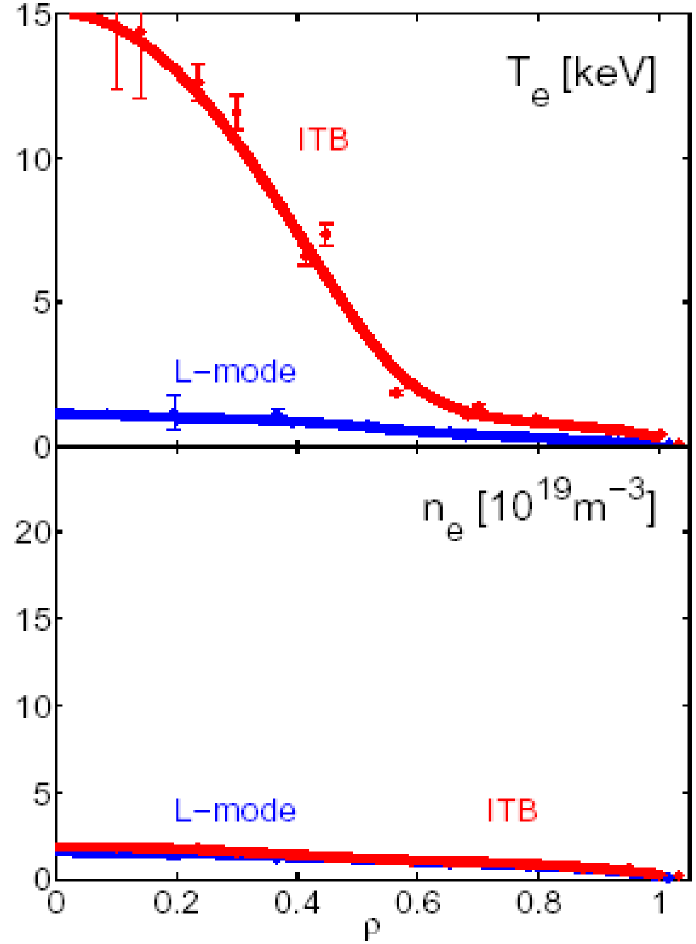
Steep internal pressure gradient

Observed enhanced confinement

– Several tokamaks see indications of reduction of turbulence in the presence of *strong* shear flows (compared to growth rate of most unstable mode)

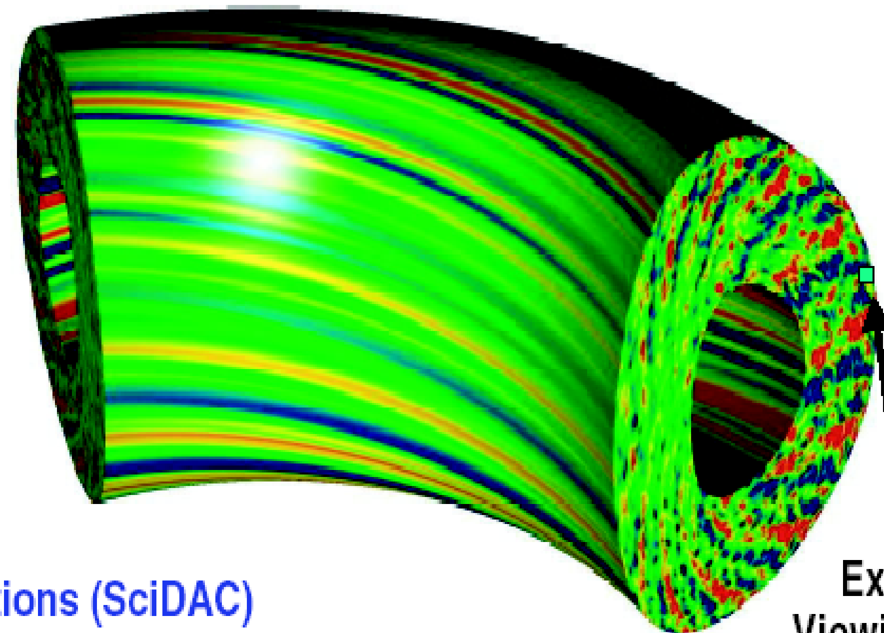
- Reduction of turbulence can lead to 'internal transport barriers'
  - **Ex. electron ITB on TCV with strong (~3MW) ECRH**

Y.Martin et al., EPS '03



WE ARE CONFRONTING NEW CHALLENGES IN PHYSICS MEASUREMENTS

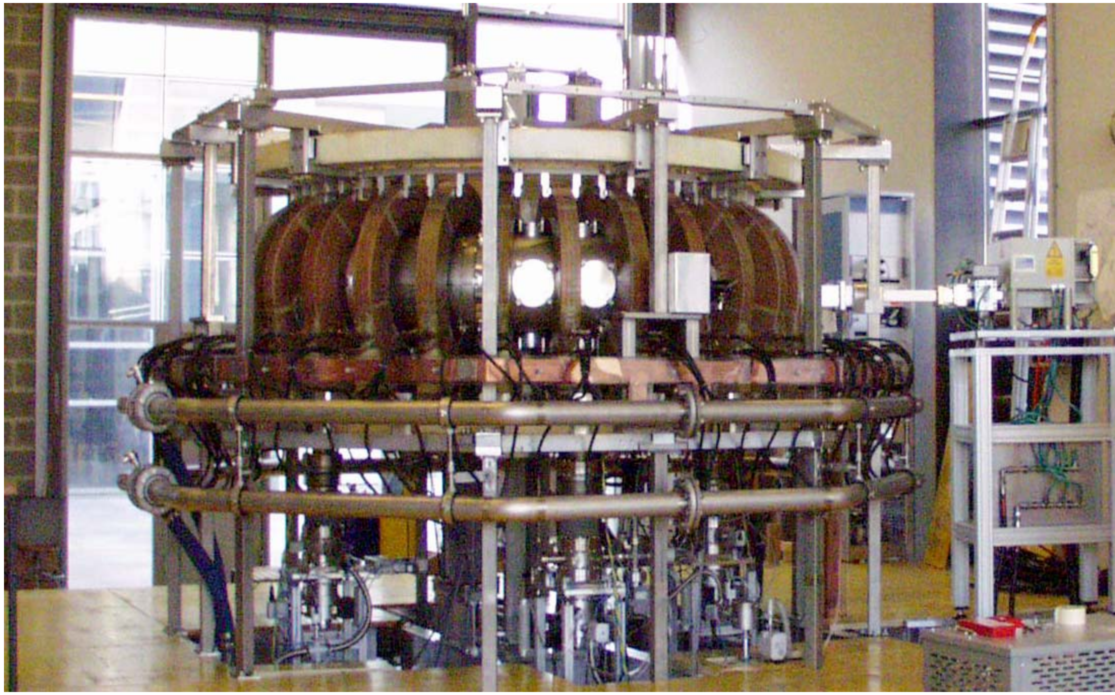
R.Goldston, PPPL Director, Review of Plasma Science and Fusion program by US National Academy of Sciences, '02



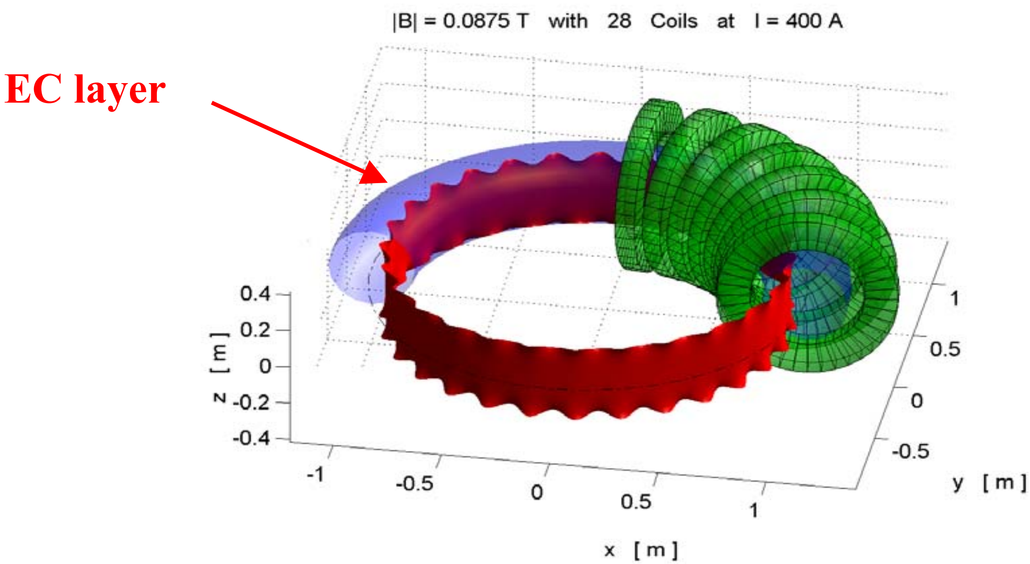
- More complex, non-linear simulations (SciDAC)
- Need new generation of diagnostics
  - Measure new parameters
  - New Physical scale (ion ⇒ electron gyroradius)
  - New Temporal scale
  - Increase Spatial Coverage
- Will require new technology such as imaging, lasers, etc.

→Motivation for a specialised device

The TORPEX device at CRPP

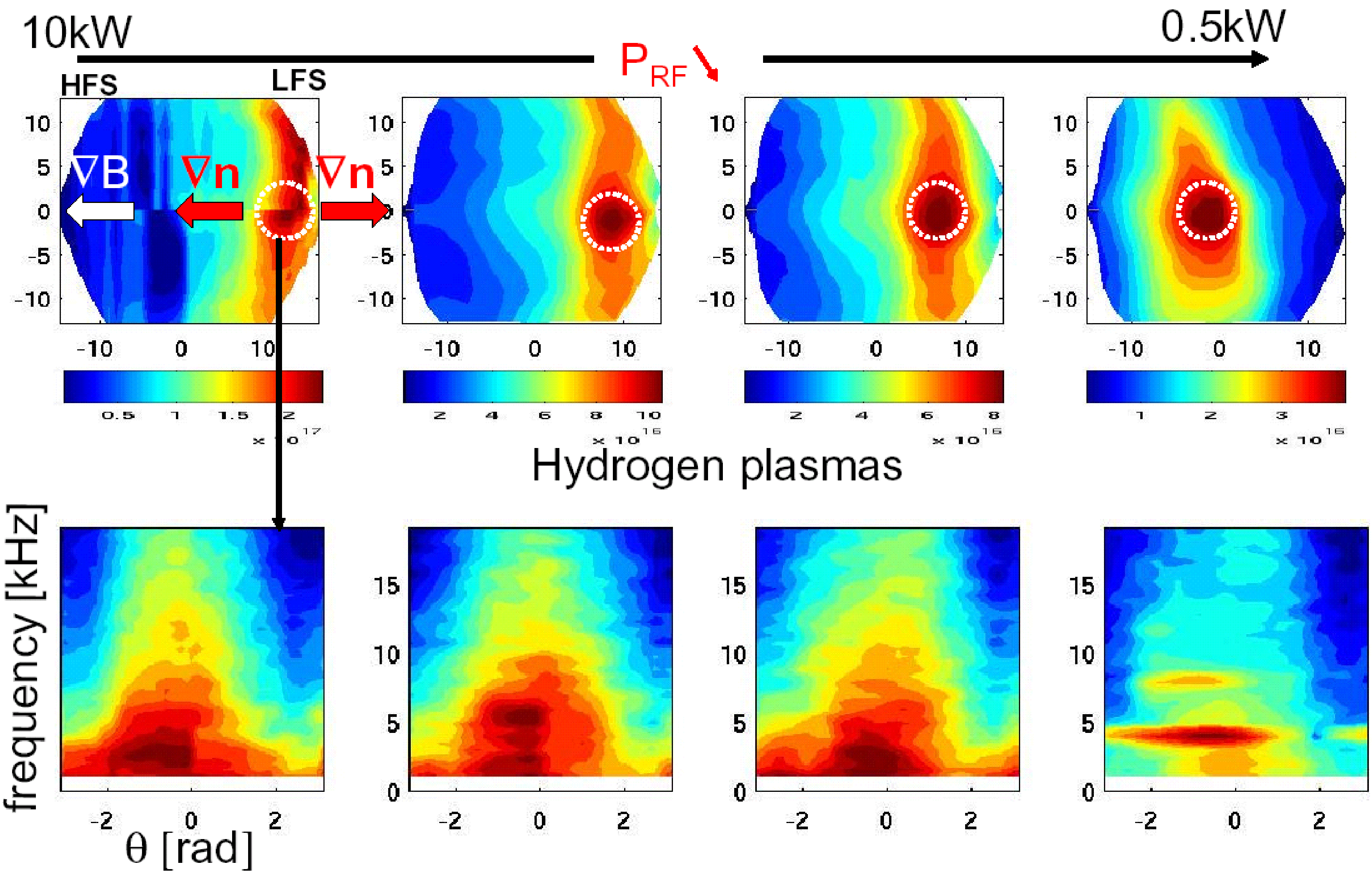


Major radius	1m
Minor radius	0.2m
Magnetic field	$B<0.1T$
Pulse duration	50-200ms
Neutral gas pressure	10^{-4}-10^{-5}mbar
Injected power@2.45GHz	$P_{RF}<50kW$
Plasma density	$n \sim 10^{17} m^{-3}$
Electron temperature	$T_e \sim 10eV$
Gas	Ar, H, N, …



- Plasma produced by RF power
  $f=2.45GHz \sim f_{ce}=eB/m_e$
- Field configuration:
  $B_{toroidal} + B_{vertical}$

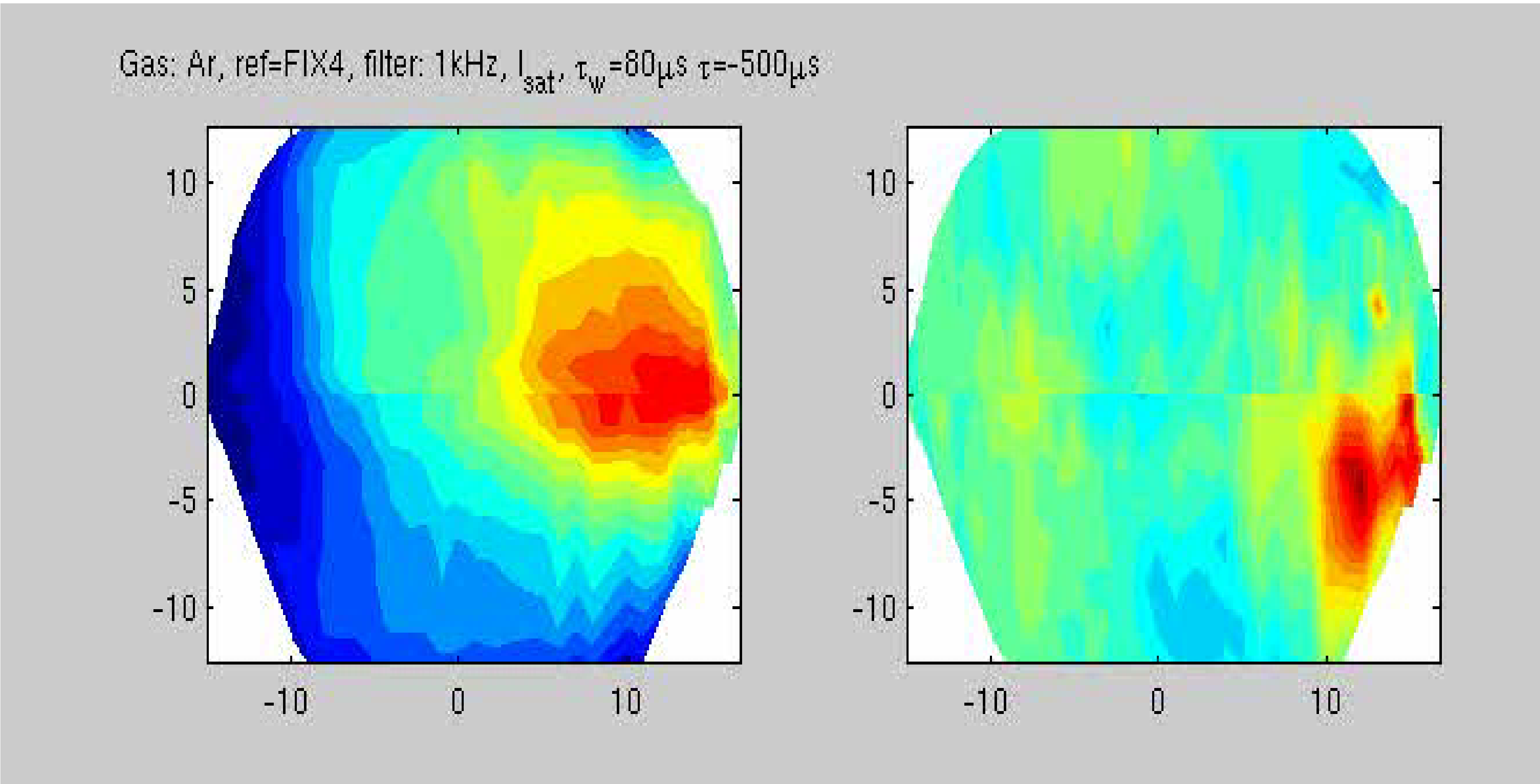
Relation between profiles and wave spectra



Interchange instability: **∇n and ∇B co-linear**

Reconstruction of ‘structure’ dynamics in drift wave turbulence

Conditional average sampling of density fluctuations



Density

Density fluctuation structures f > 1kHz

Open questions on turbulence and transport

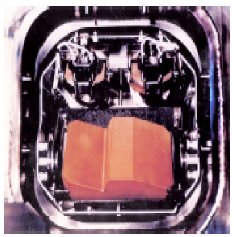
- Development of drift waves from linear to turbulence
  - Control of gradients
- Self-generated macro-structures
  - Mechanisms for creation and growth
- Related transport
  - Diffusive, ‘large’ events, statistics, universality
- Ways to reduce turbulent transport
  - Shear flows imposed from outside (waves, external E-field,…)

***Advanced tokamak* concept**

- Can fusion power / cost be improved ?
  - Improve β-value ($P_{fus} \propto \beta^2 B^4$) and confinement
    - Tailor discharge to increase β
    - Reduce transport by strong rotation and shear
- Can a tokamak be turned into a steady-state (or very long pulse) device?
  - ***Need ways to generate 'non-inductive' current***

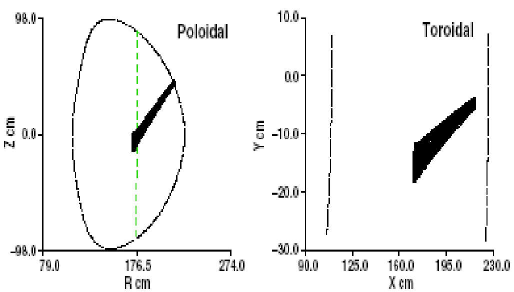
Localised current drive by Electron Cyclotron waves

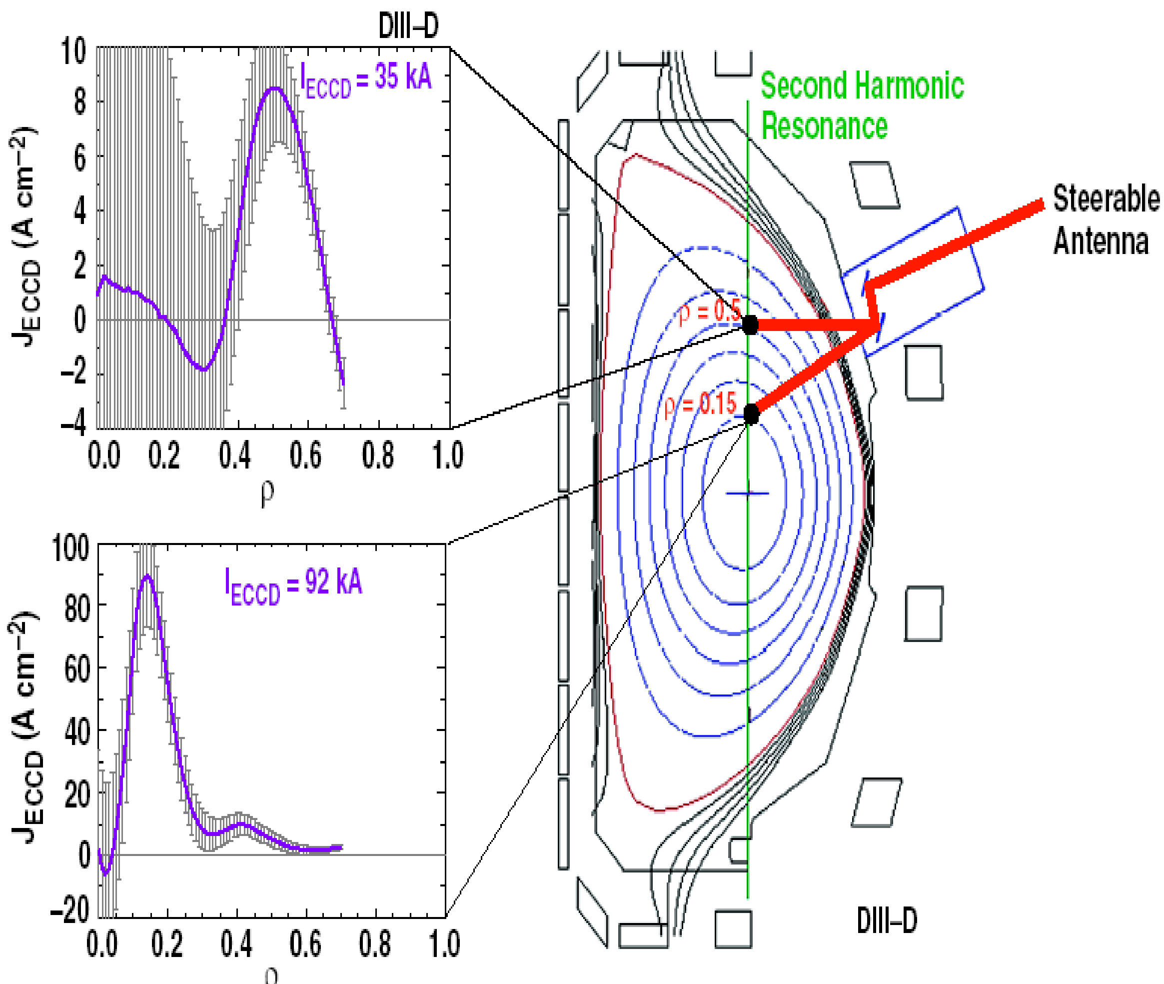
- Waves propagate in vacuum, so antenna can be far from the plasma



DIII–D

- Inside the plasma the waves propagate up to a critical density (related to the plasma frequency) and are absorbed near the cyclotron resonance or its harmonics

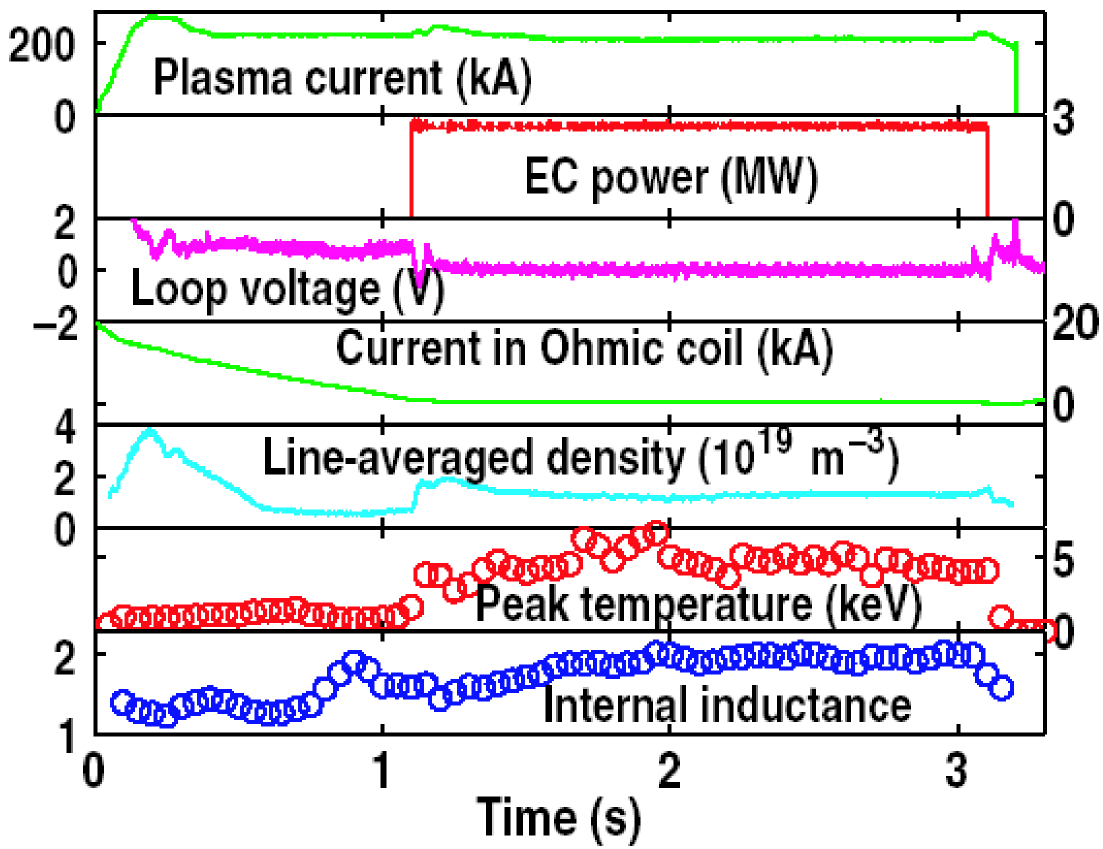




Fully ECCD driven discharge in TCV

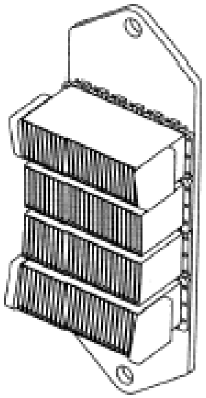
Fully non-inductive discharges

210 kA sustained in steady state by 2.7 MW co-ECCD



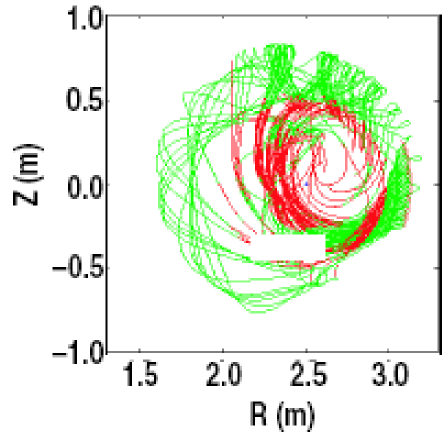
IRn/P (10^{20} A-M^{-2}-W^{-1}) =
7.3×10^{-3}

Lower hybrid current drive ($\Omega_i<\omega<\Omega_e$)



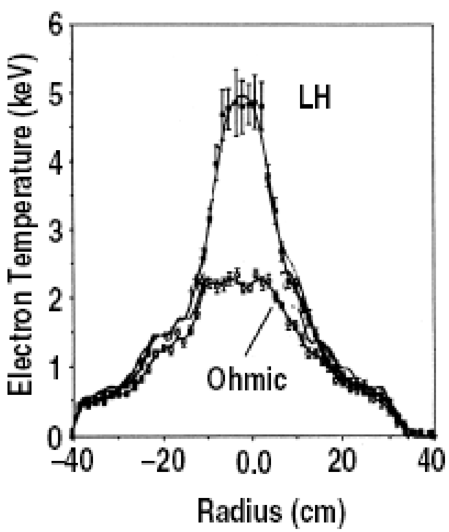
Lower Hybrid **coupling** requires $n_{||} > 1$
(Brambilla, SWAN)

Phased array or waveguides

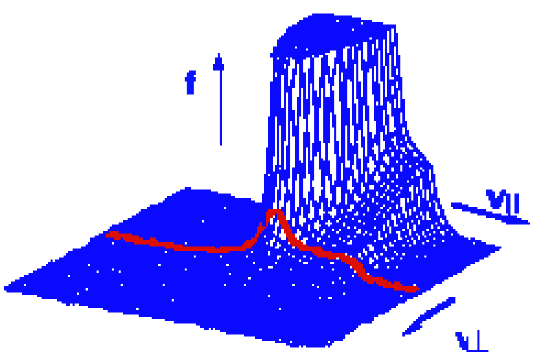


Ray tracing: the accessible waves cross the plasma and can undergo several reflections at the edge before being absorbed.

Codes by: Cardinali, Bonoli, Ignat, Valeo, Harvey, Takase
(Figures from Giruzzi)



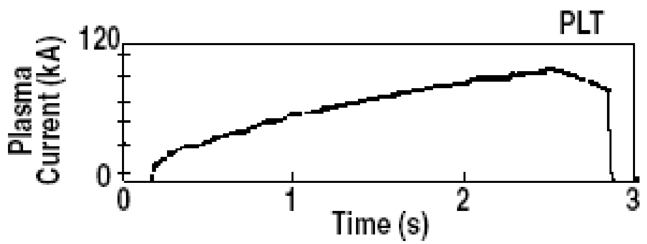
Electrons heated by LH (PLT)



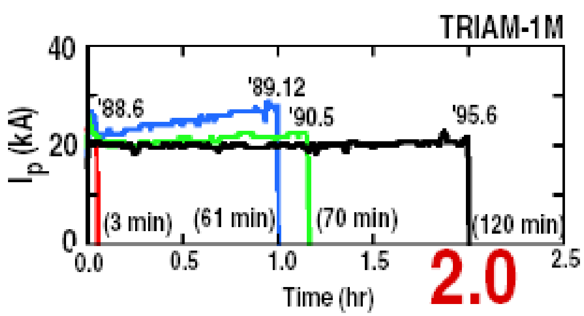
Damping of LH waves forms a parallel energetic electron tail in the distribution function via **Electron Landau Damping.** This asymmetry constitutes the non-inductive current (Fisch, Karney)

Lower hybrid current drive: results

- Plasma current initiated and ramped up by LHCD

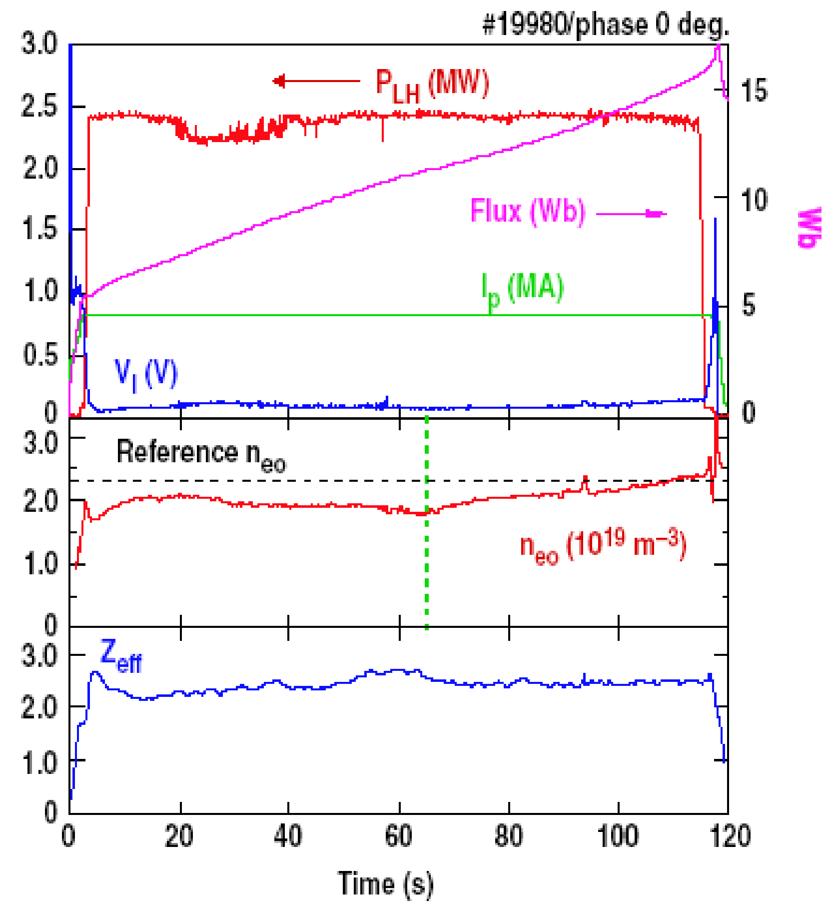


- Plasma current maintained in steady state:
  - JET; 3 MA, 4 s
  - TRIAM-1M; 20 kA, 2 hr

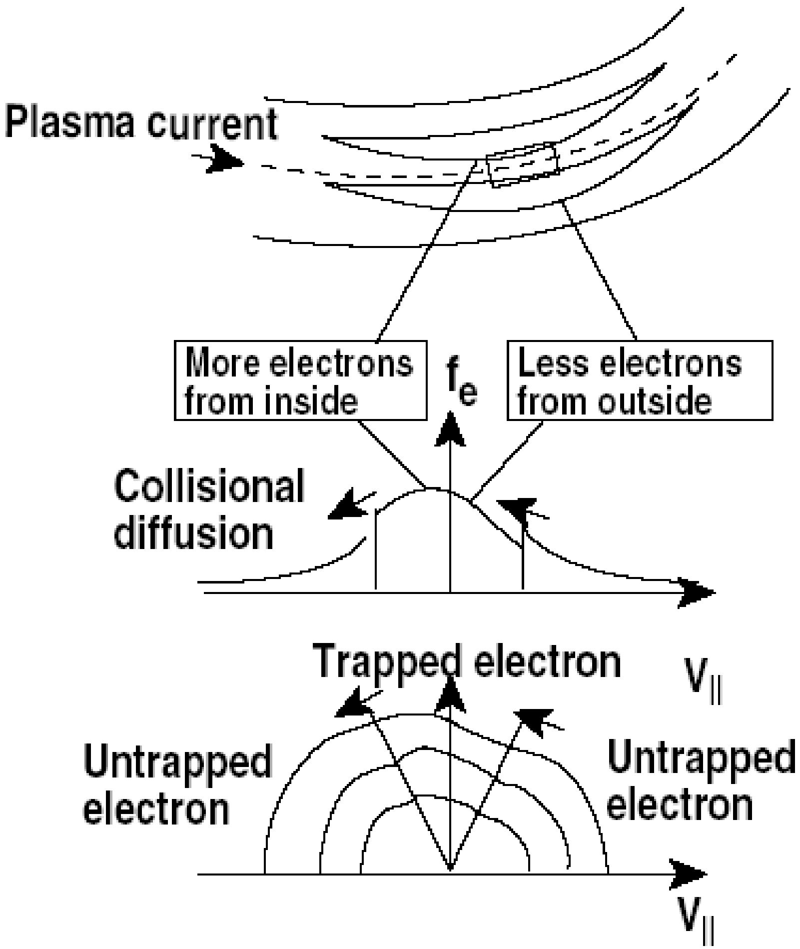


2.0 Hours!

- 2-minute-long discharge at I_p = 0.8 MA
- Injected energy = 290 MJ



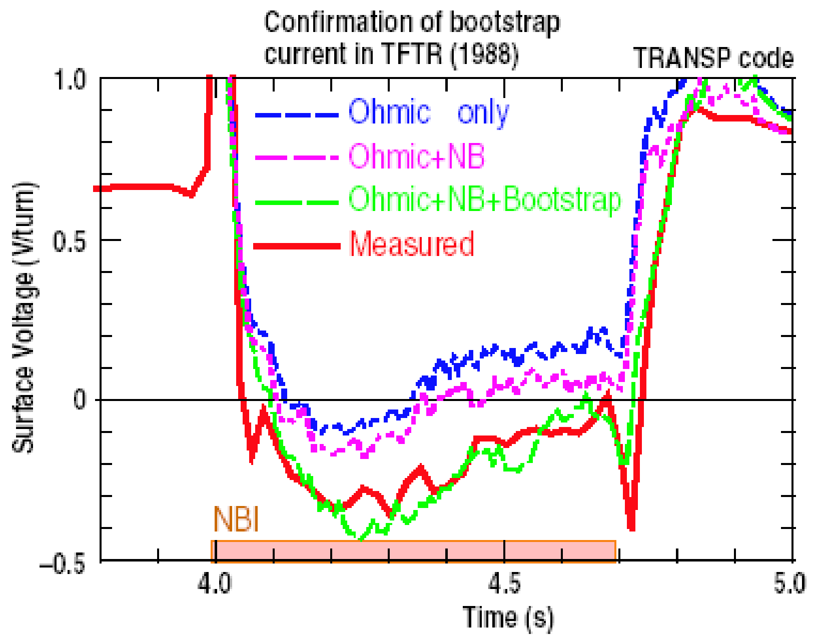
The self-generated *bootstrap* current



(Kikuchi, PPCF 37 (1995))

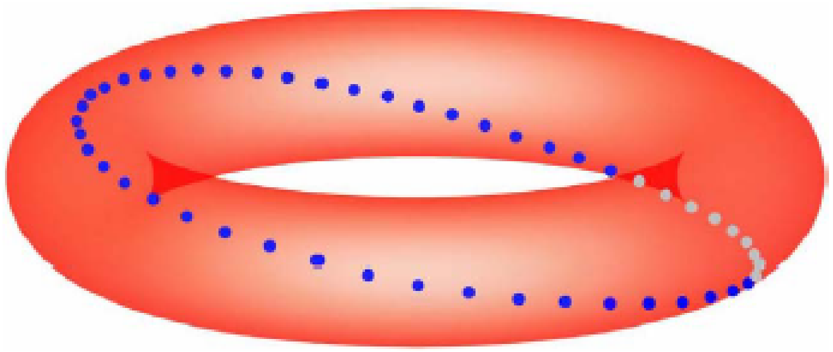
Needs a strong pressure gradient

- $J_{bs} \propto$ local pressure gradient

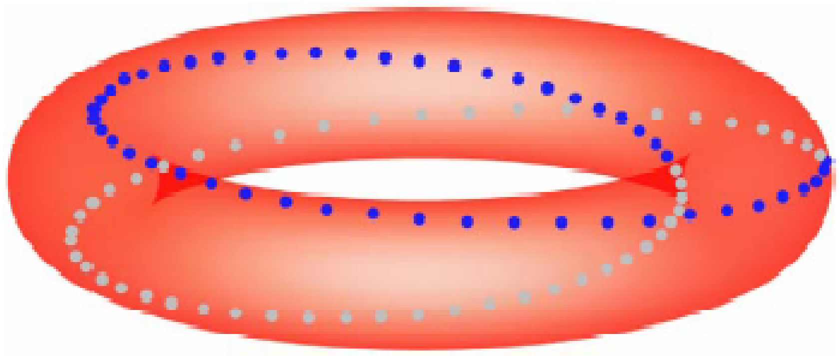


Reminder: the safety factor q

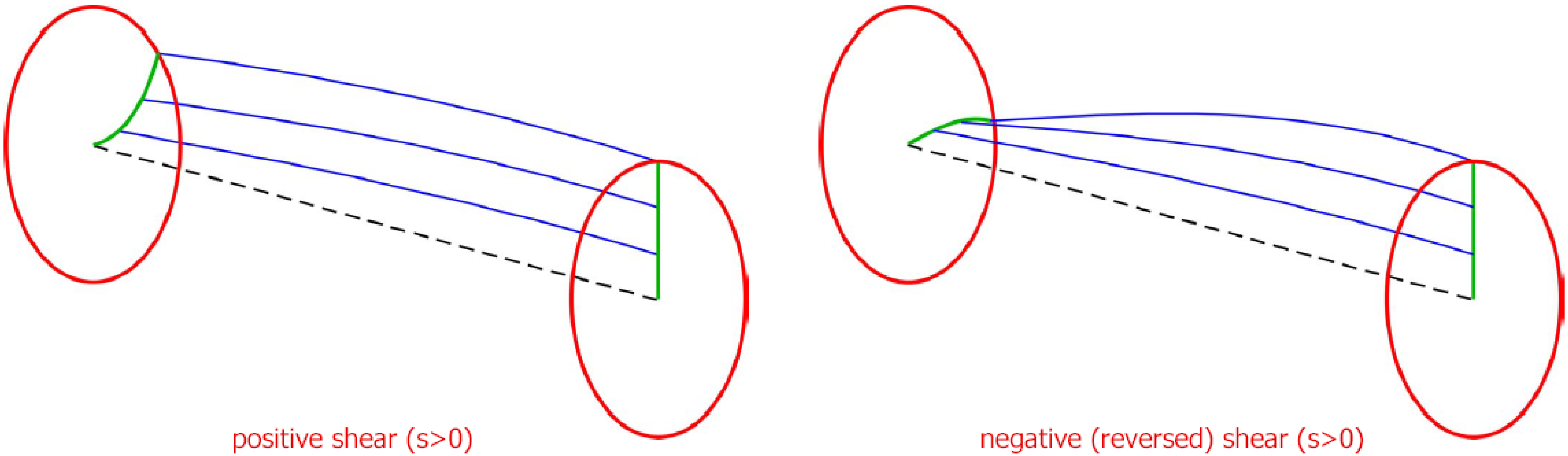
q = 1 field line



q = 2 field line

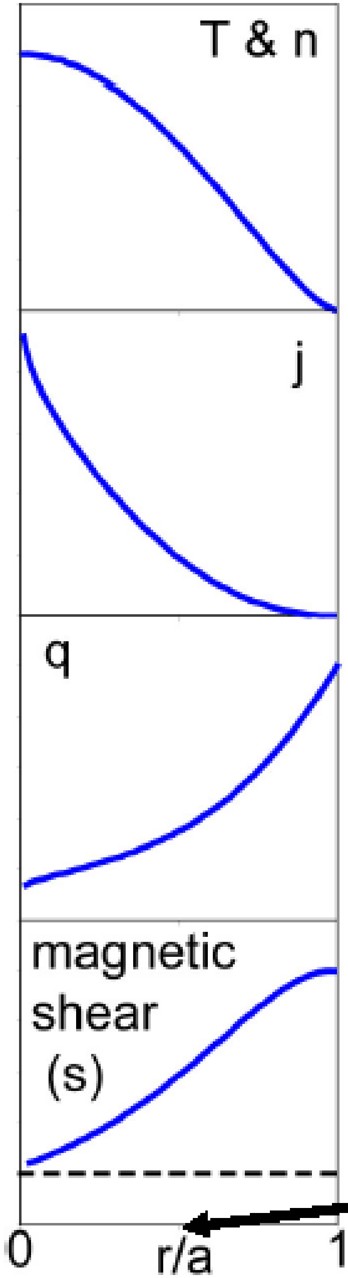


Magnetic shear = r/q(dq/dr)



- Role of negative shear region
  - Helps creating transport barrier in the core by producing strong (sheared) rotation

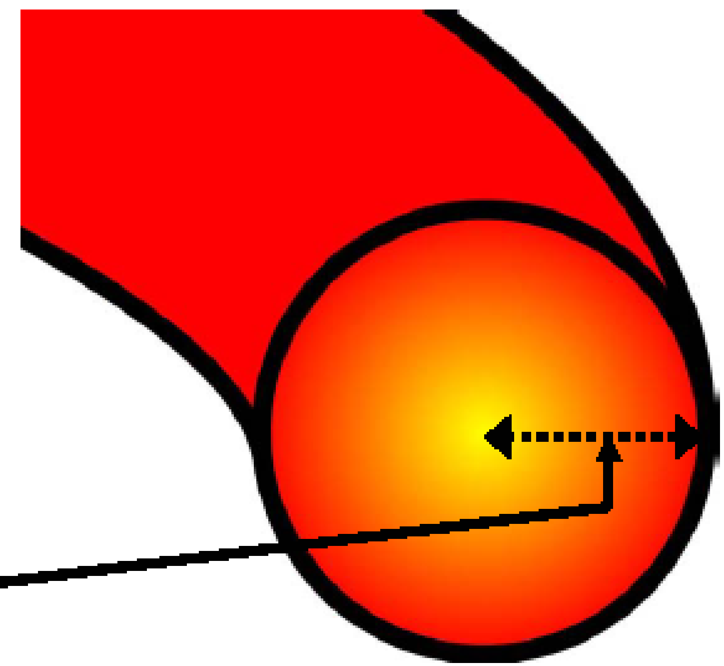
Typical magnetic topology



- Tokamak temperature and density profiles are typically peaked
- Toroidal electrical conductivity scales as $T_e^{1.5}$ (also orbit effects)
  'natural' current profile peaked → provided by inductive E-field
- q-profile is monotonic

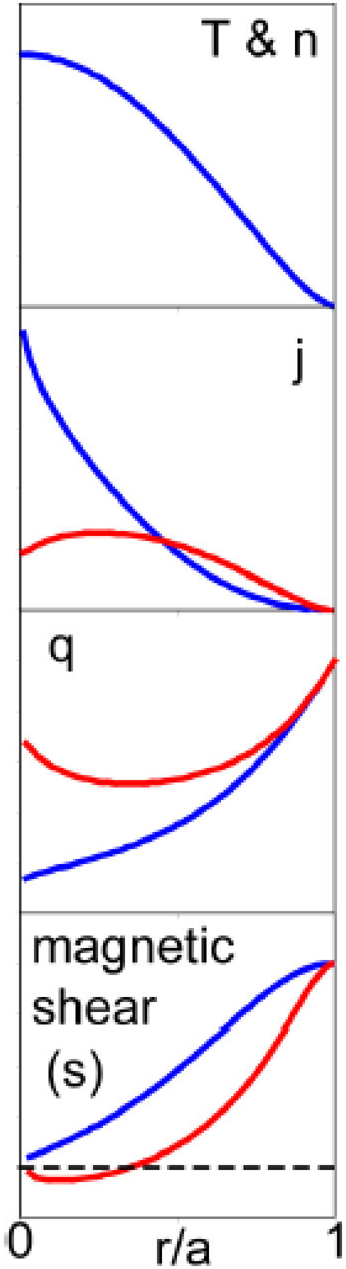
  $q \approx rB_T/RB_P$

  $\int B_p.dl = \mu_0 \int j.da$
- Magnetic shear is positive



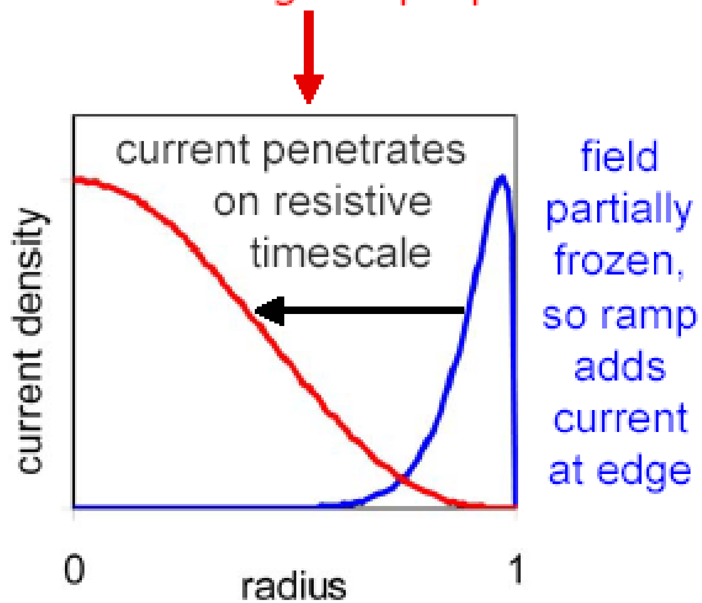
plasmas cross-section

Atypical magnetic topology

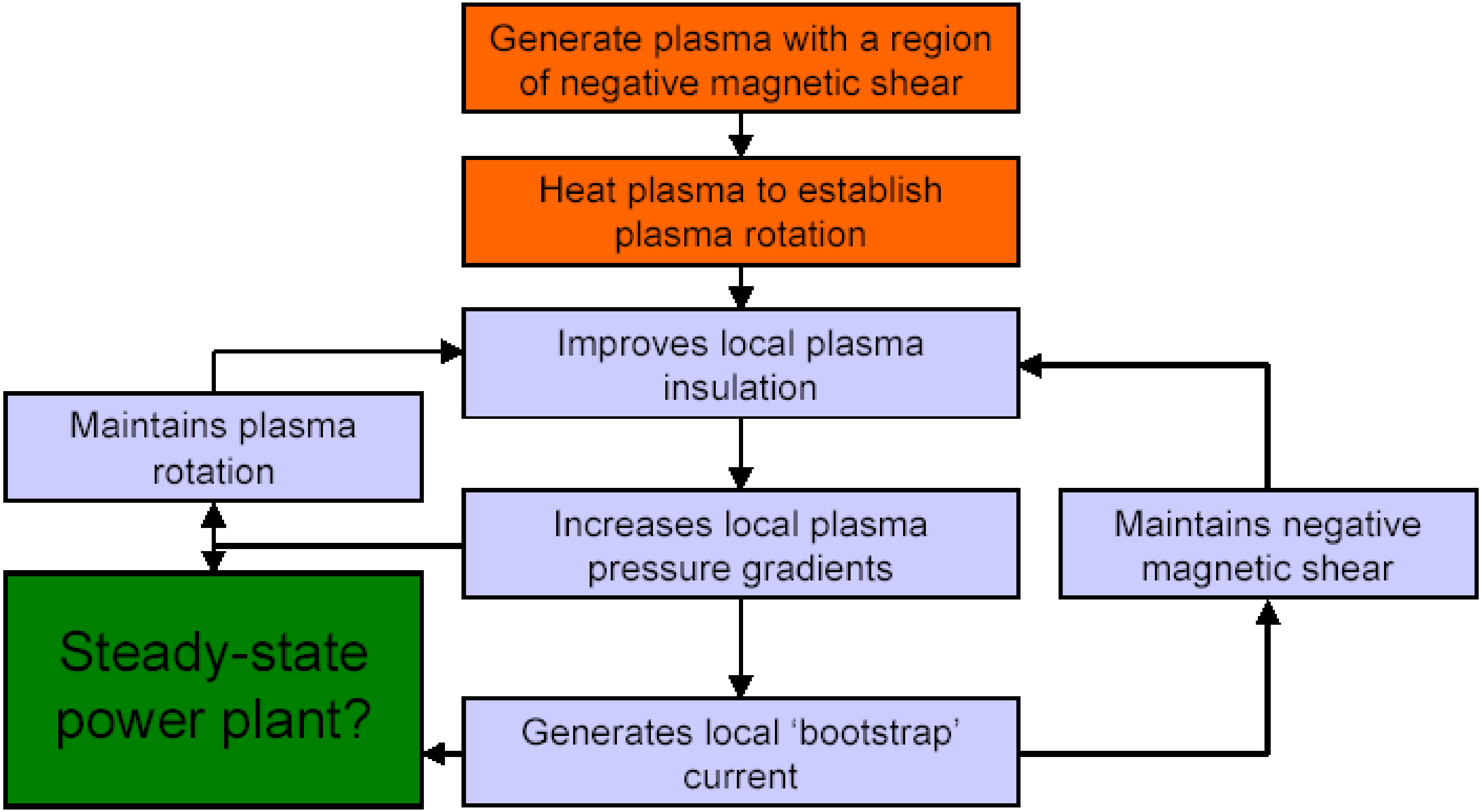


1. Non-inductive current can be driven on- or off-axis by:
   – Waves (electron cyclotron, ion cyclotron, lower hybrid)
   – Beams (injected high energy neutrals that ionise in the plasma)
2. Pressure driven bootstrap current is peaked off-axis due to orbits in the presence of a pressure gradient
3. Hollow inductive current profile possible during ramp-up

- q-profile can become non-monotonic
- Magnetic shear can be negative (reversed) in plasma core



Advanced tokamak regime



UKAEA Fusion

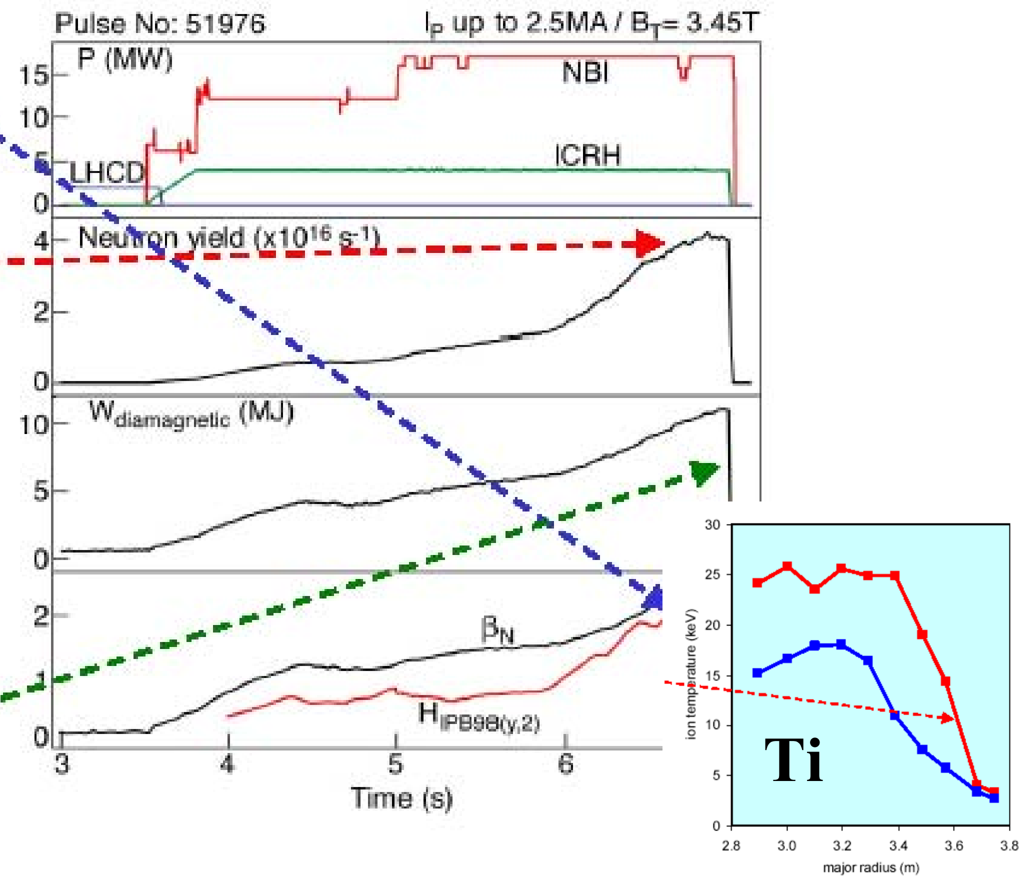
Advanced tokamak regime in JET

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

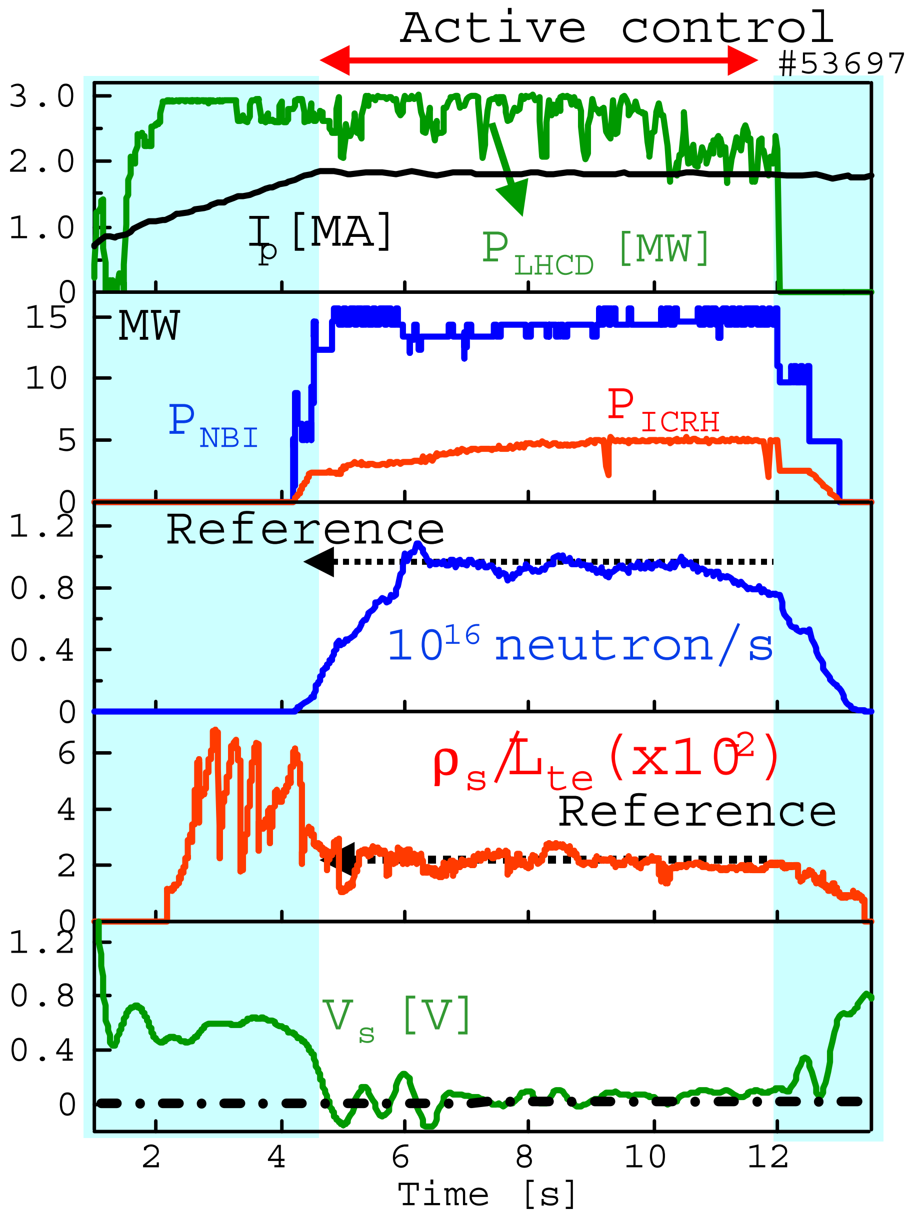
JET

Internal transport barriers (ITBs)

- Confinement can reach almost twice the ELMy H-mode value.
- High fusion yield:
  - This D-D plasma yield equivalent to about 8 MW fusion power in D-T.
  - JET's highest D-D fusion yield has been achieved with an ITB plasma.
- High Q ($\equiv P_{fusion}/P_{heating}$):
  - The D-T equivalent fusion yield would correspond to about Q≈0.4.
- Stability of these plasma is challenging:
  - This one disrupted at high pressure.
  - Real-time feedback being developed to control this regime.



Real-Time Control of ITBs in JET



JET: 1.8MA/3.4T

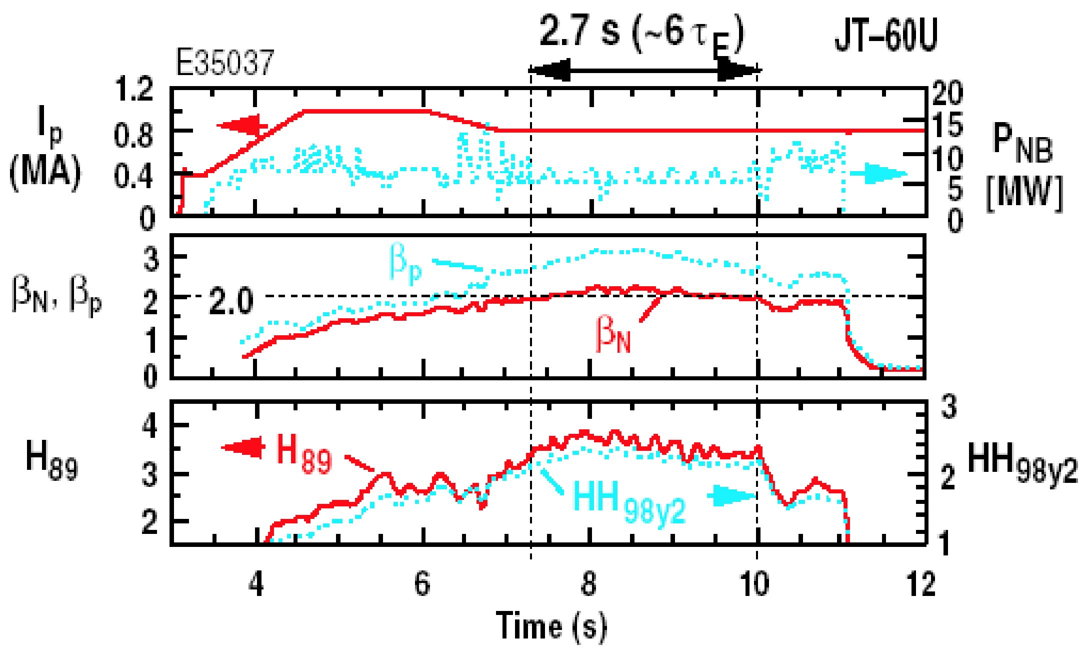
- ITB is controlled during at V_s~0 with 100% of non inductive current
- P_{LHCD} to slow down q(r,t)
- P_{NBI} controlled by Neutron
- P_{ICRH} controlled ρ_s/L_{te} at the ITB location
- More stable regime and mi impurity accumulation with RT control

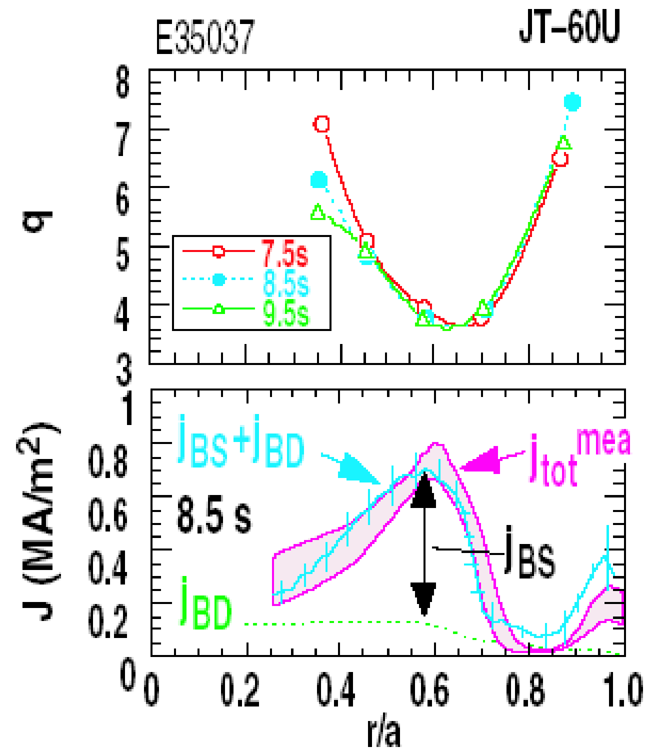
Mazon D et al 2002 PPCF 44 1087

Advanced tokamak regime

A HIGH PERFORMANCE PLASMA WITH FULL NON–INDUCTIVE CURRENT DRIVE AND 80% BOOTSTRAP FRACTION IN JT–60U

- H_{89}~3.5, HH_{98y2}~2.2, β_N~2, β_p~2.9, f_{BS}~80% for $6\tau_E$ with full non-inductive CD
- Current profile was largely determined by the bootstrap current, and was nearly stationary

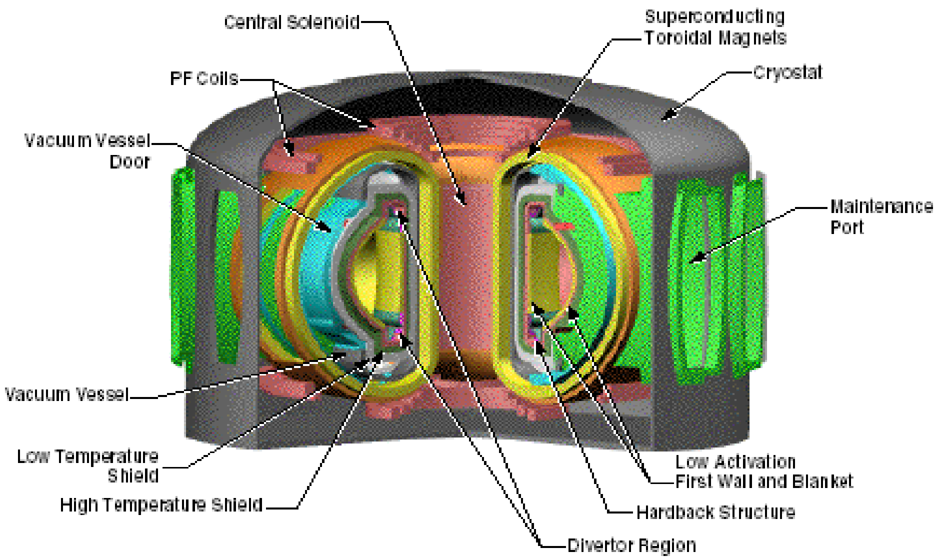




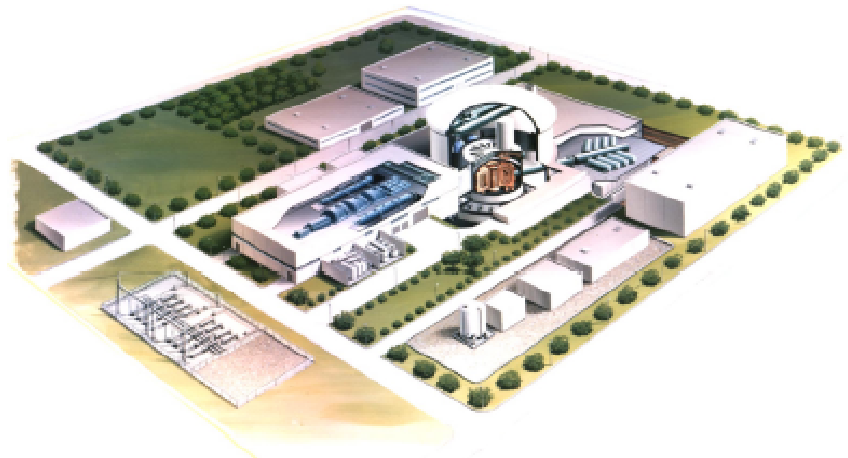
JT 60 also 80% bootstrap fraction

Optimisation of fusion power plant based on advanced tokamak concept

- The U.S. ARIES — RS system study



- The Japanese SSTR system study



- Attractive features
  - Competitive cost-of-electricity
  - Steady-state operation
  - Maintainability
  - Low-level waste
  - Public and worker safety

	Conventional	AT
Size, major radius (m)	8	5
COE ¢/kWhr	~13	~7
Power cycle	Pulsed	Steady state

$$\mathrm{coe} \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{P_e^{\,0.4}\,\beta_N^{\,0.4}\left(\frac{n}{n_{limit}}\right)^{0.3}}$$

The plasma transport matrix

- Similar transport mechanisms occur for heat and particles, and other plasma quantities, although some off-diagonal terms may play role