Magnetic Confinement Fusion Science
Status and Challenges

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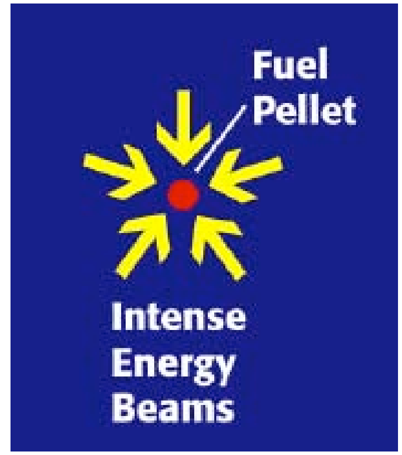
Two approaches to fusion

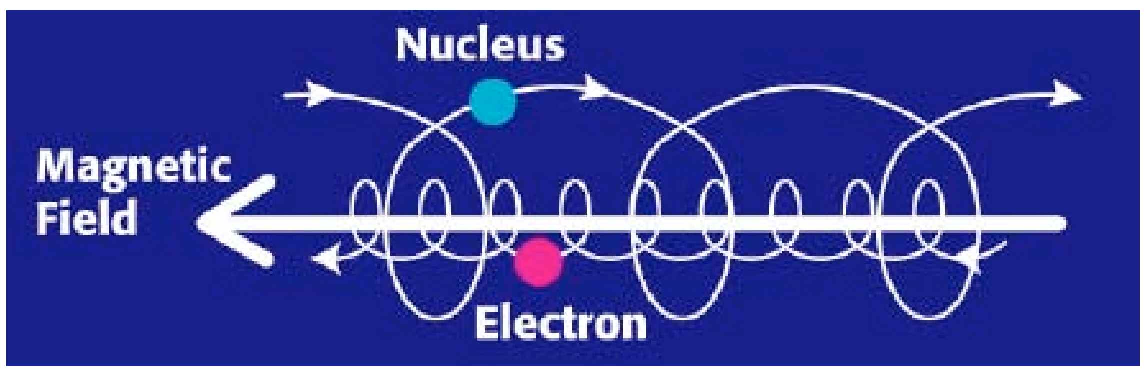
Inertial confinement

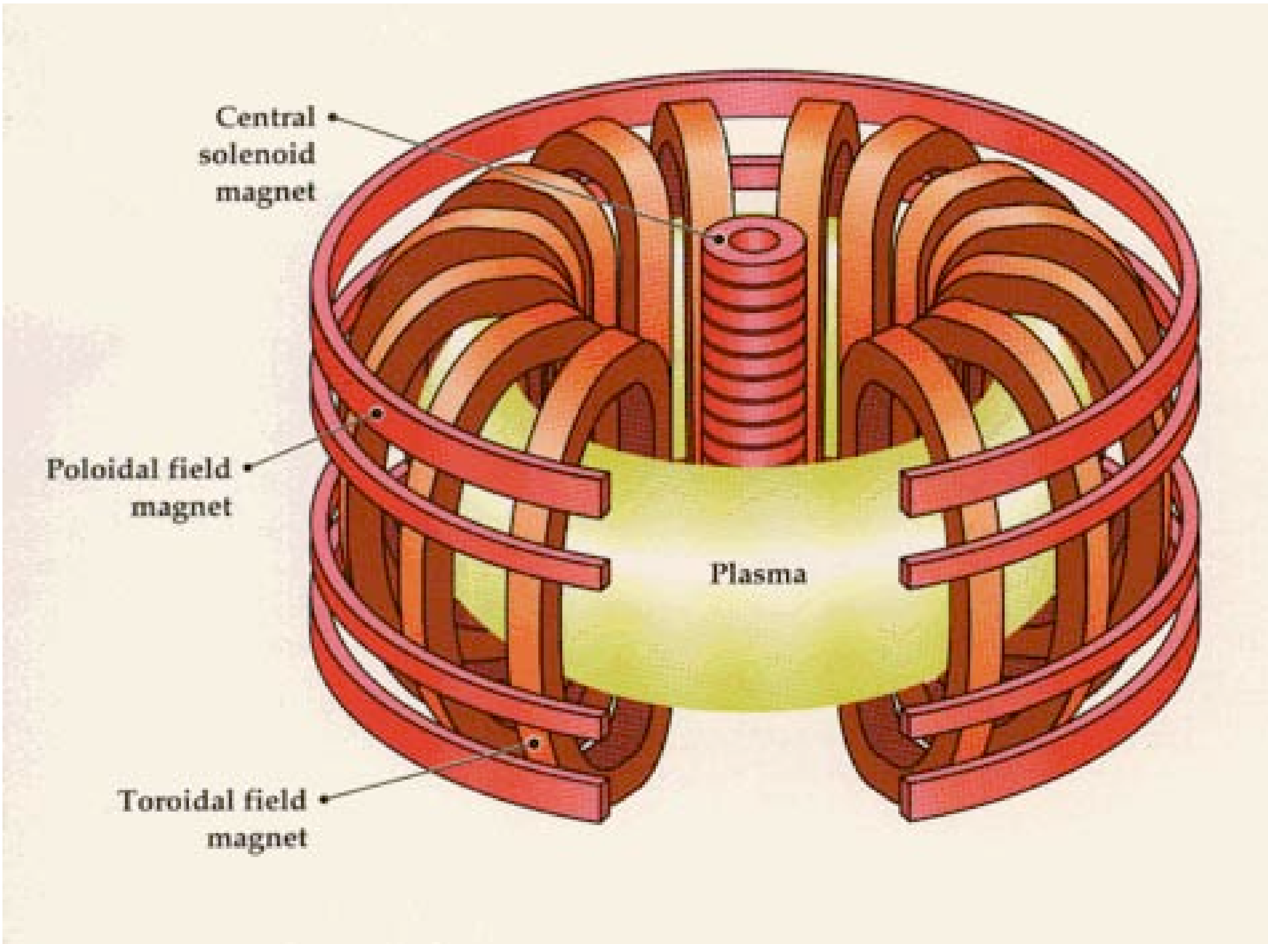
extremely dense, short-lived



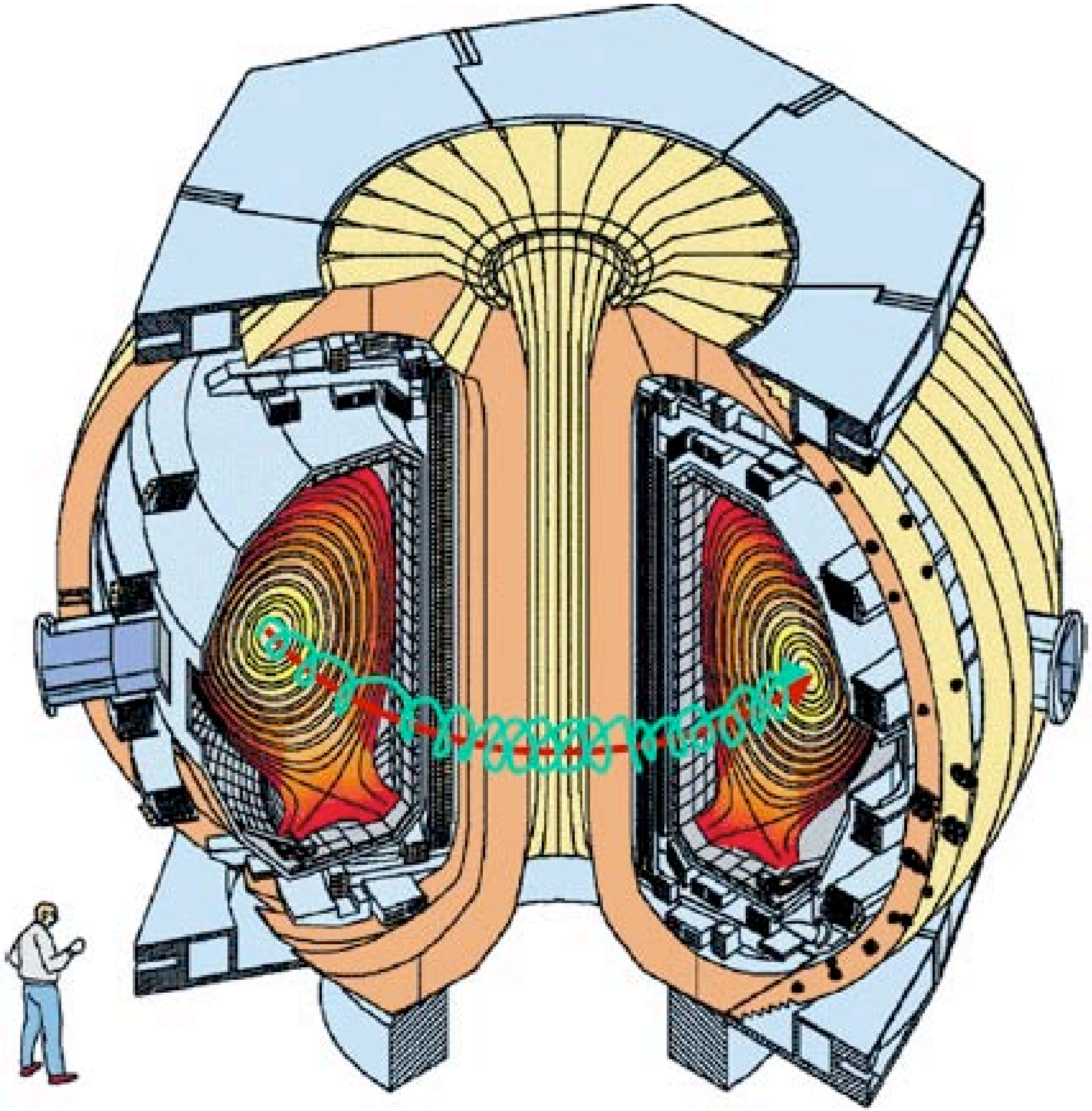
Magnetic confinement

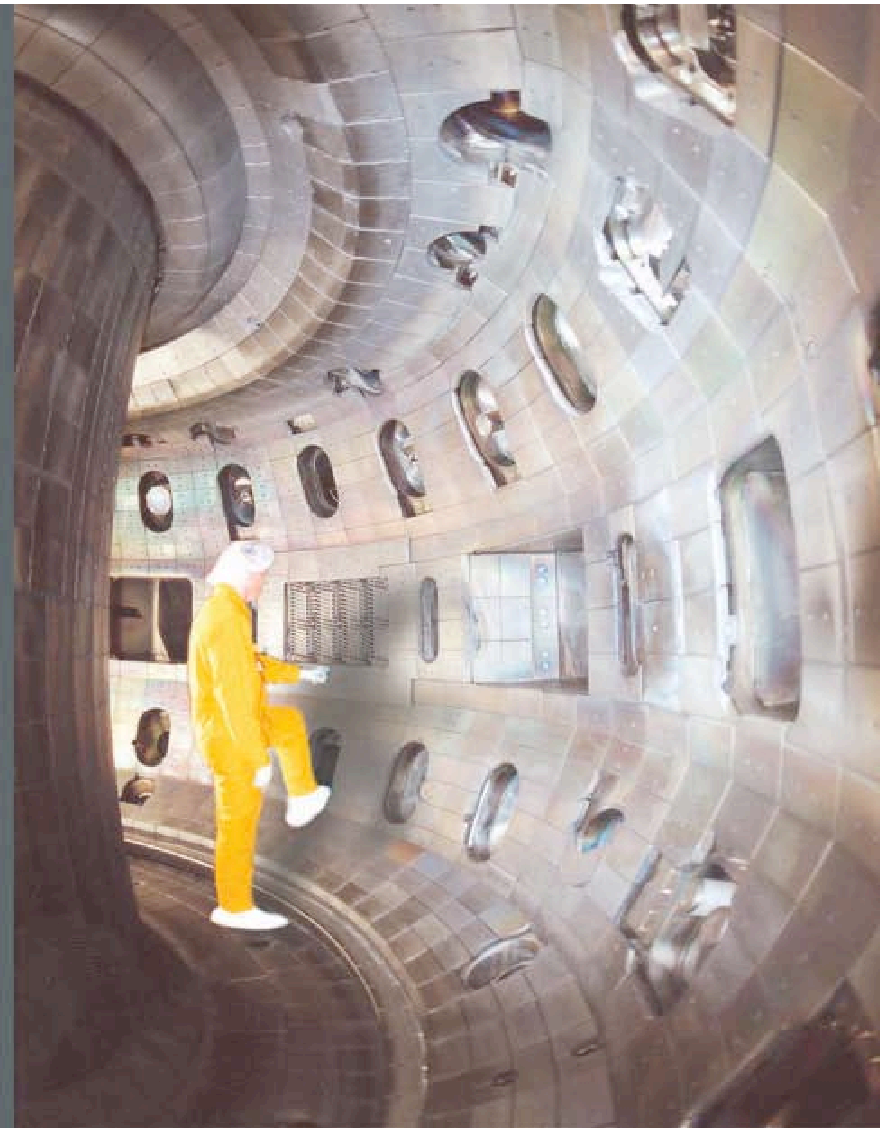
relatively dilute, long-lived




Central
solenoid
magnet
Poloidal field
magnet
Plasma
Toroidal field
magnet

The tokamak





Fusion energy requires

- Heating the plasma

  to 100 million degrees

- Confining the plasma

  energy replacement time ~ 1 second
  for density ~ 10^{15} cm^{-3}

- Extracting energy from the plasma

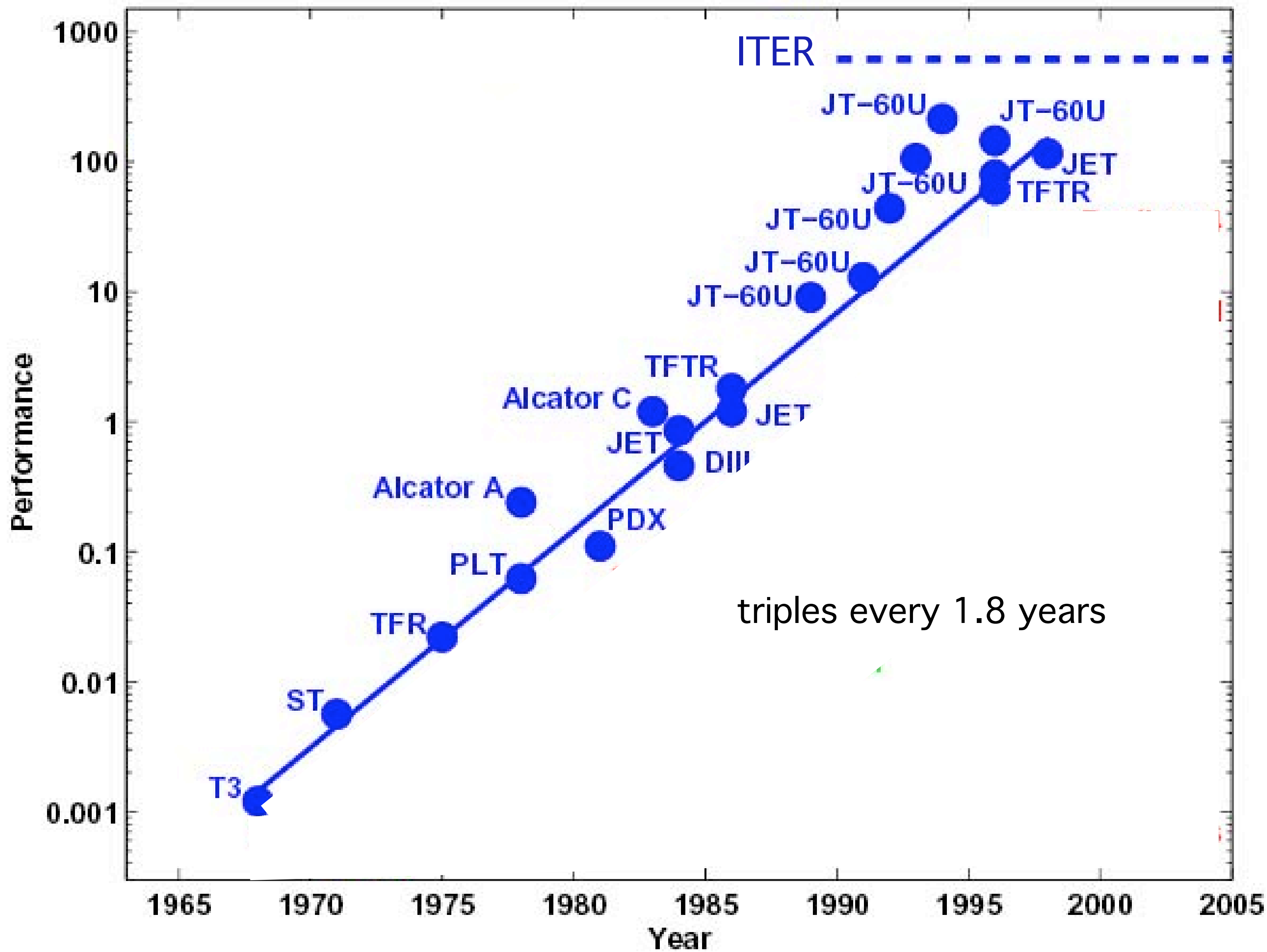
  co-existence of hot plasma and material surface progress in confinement is measured by

fusion triple product =

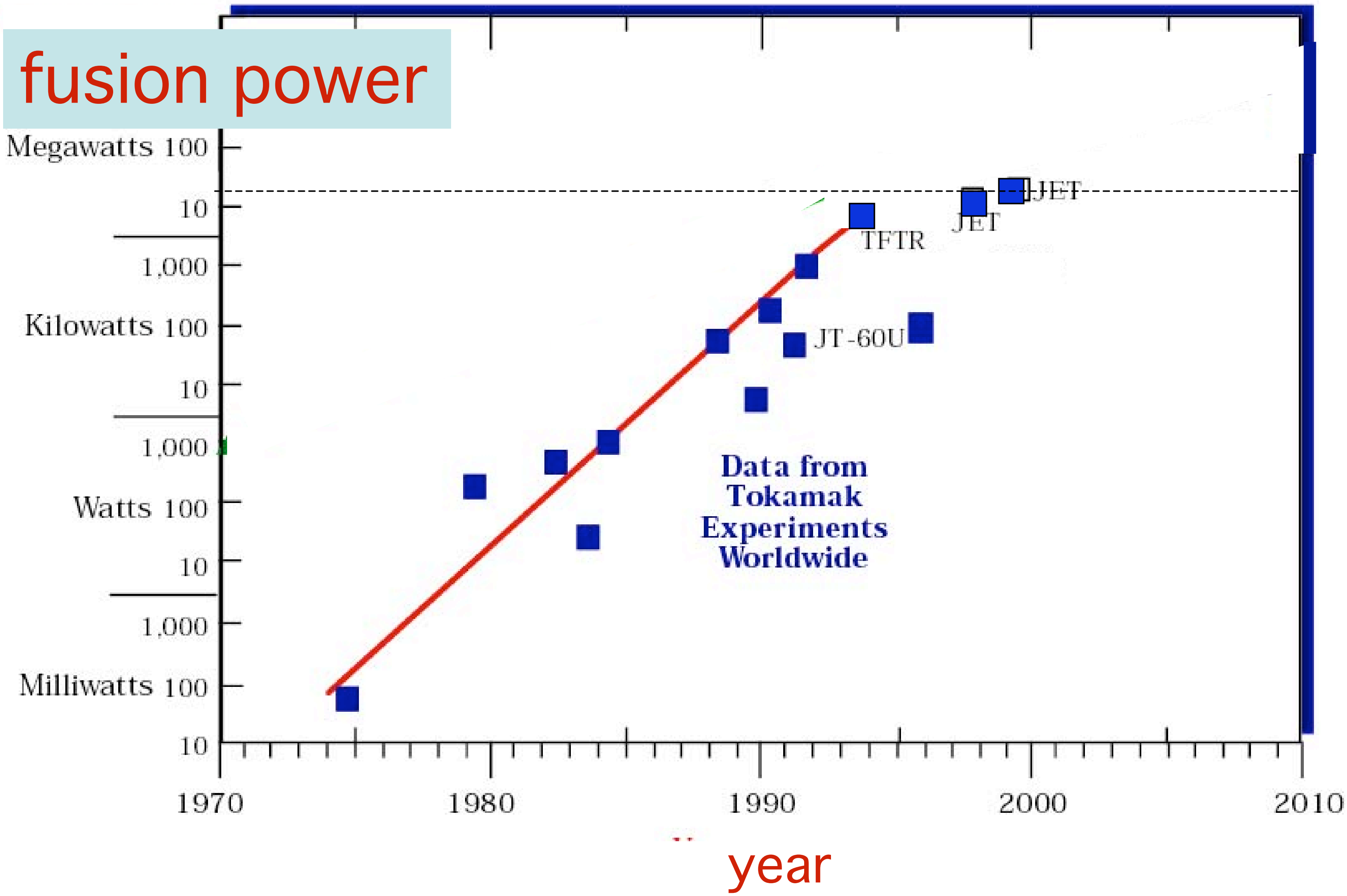
(density)(temperature)(energy replacement time)

($10^{21} m^{-3}$) (10^{8}K) (1 second)

Progress of fusion triple product



Huge advance in plasma parameters



- Progress accomplished through research in fundamental plasma physics and technology
- Challenges and opportunities remain

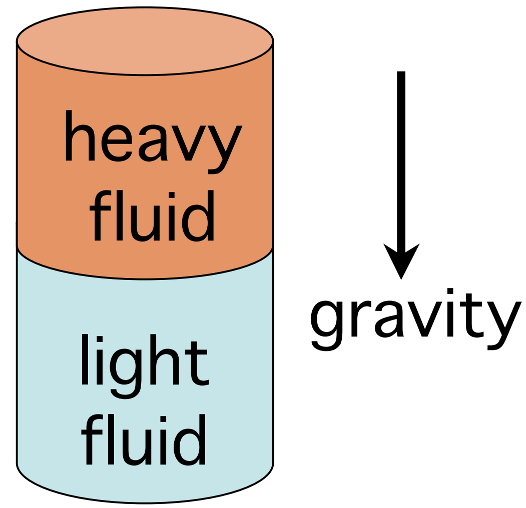
Scientific issues for fusion

(not exhaustive)

- Maximize the plasma pressure
- Control plasma turbulence and energy transport
- Control plasma disruptions
- Develop new magnetic configurations
- Control the plasma-wall interaction
- Develop new materials
- Produce a burning plasma

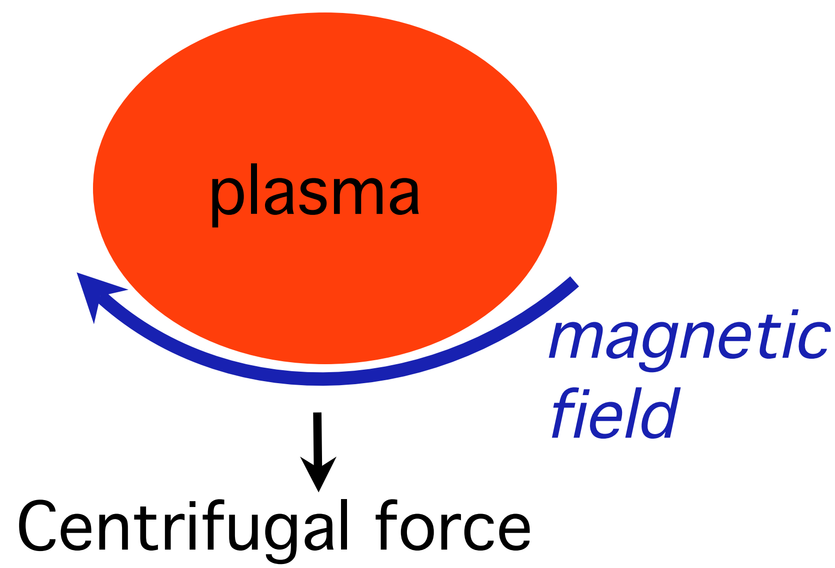
Pressure-driven instability

Rayleigh-Taylor instability in fluid, driven by gravity

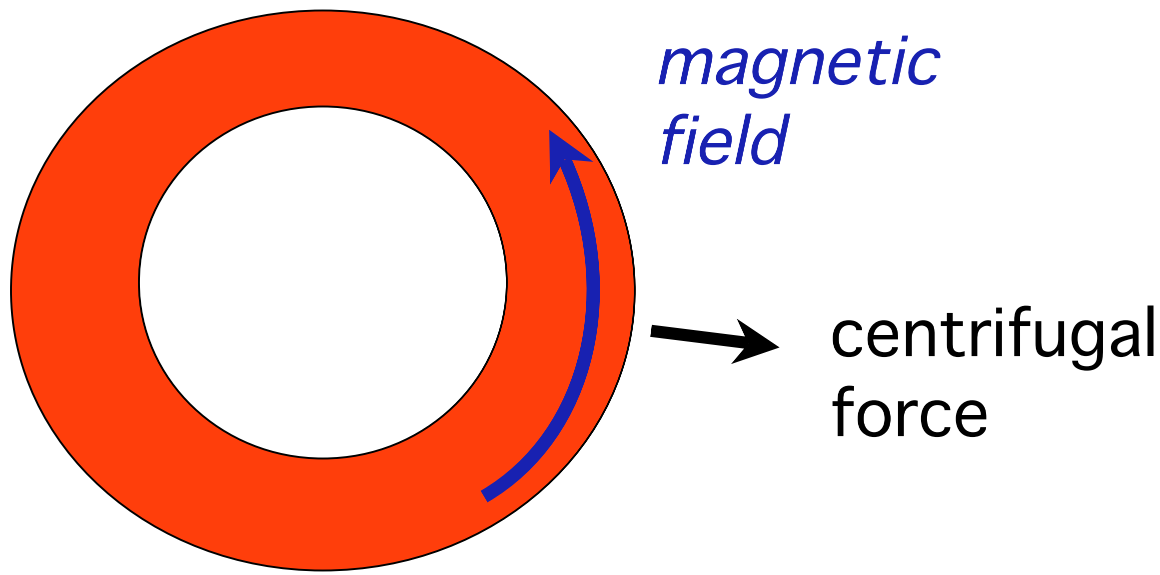


plasma instability,

driven by centrifugal force of particles moving along curved magnetic field



Centrifugal force in a torus



Stability theory is highly developed

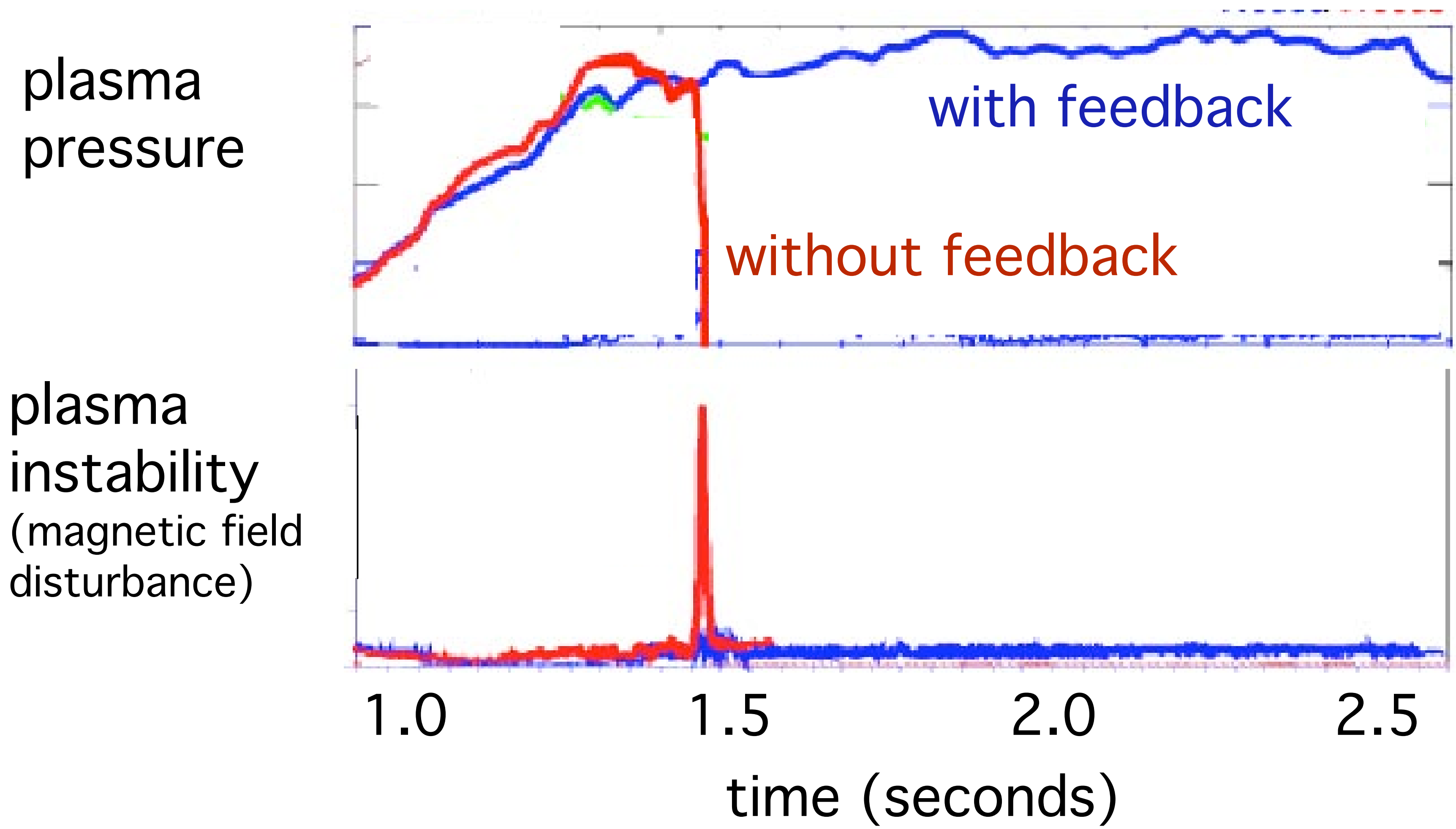
- Stability depends upon
  - magnetic curvature, twist, shear
  - plasma rotation
  - location of conducting boundaries

- All plasmas disassemble above a pressure limit

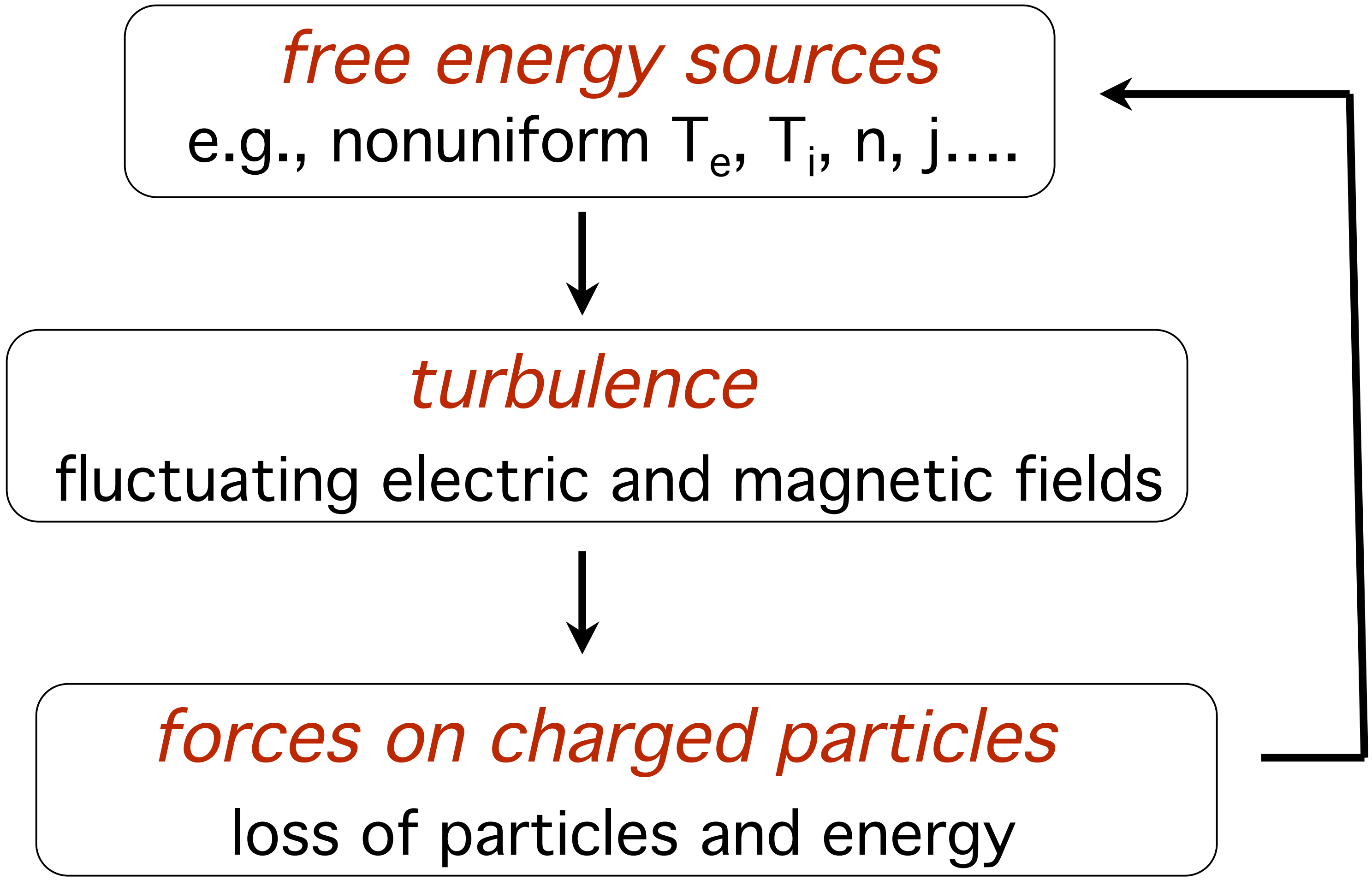
- Feedback techniques have been developed to attain high pressure

  (plasma pressure ~ 10% of magnetic pressure)

Maximizing pressure through feedback

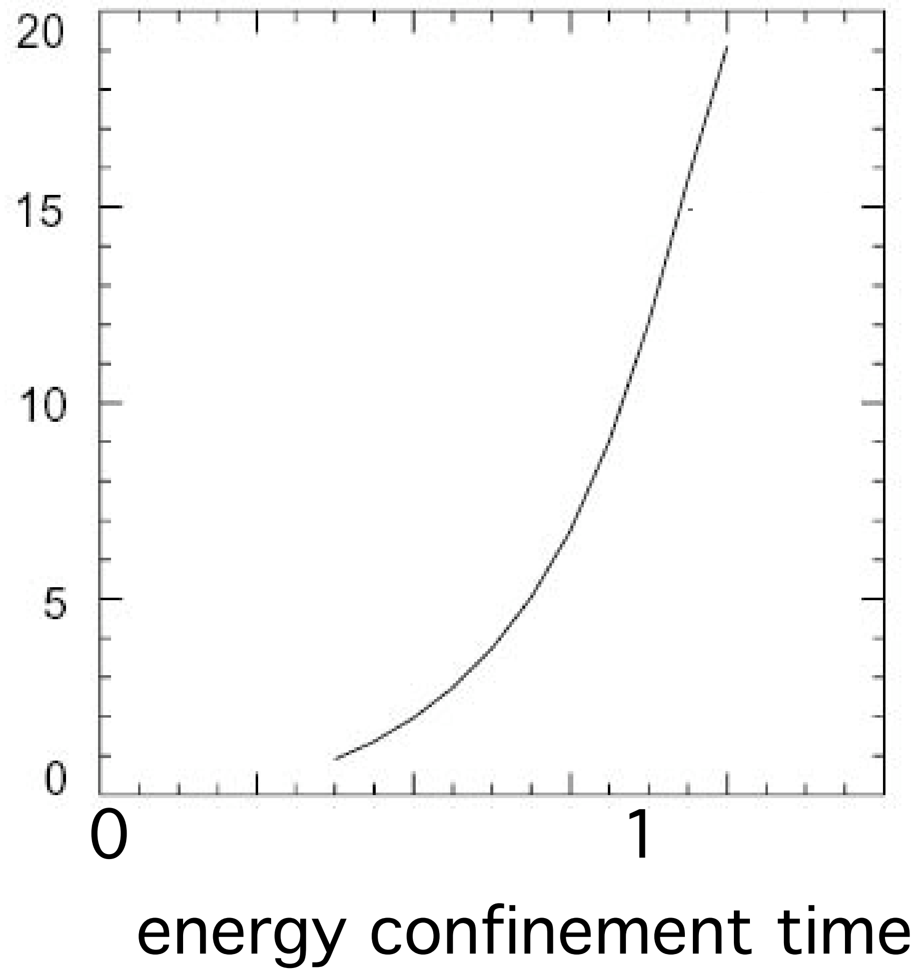


Turbulence and transport



fusion power gain depends strongly on confinement

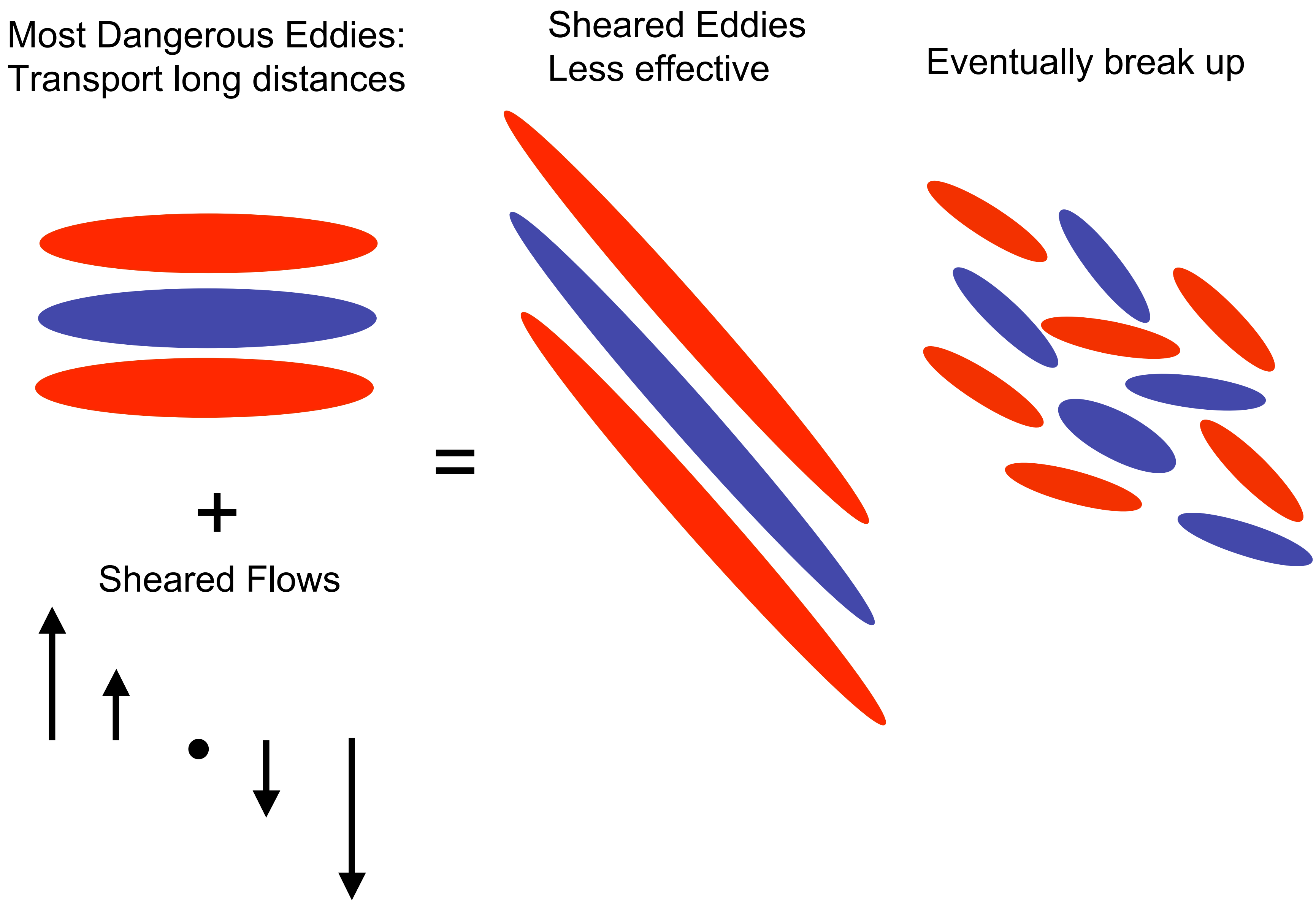
$$Q = \frac{\text{fusion power}}{\text{heating power}}$$



Plasma turbulence no longer considered unavoidable “force of nature”

- Fundamental understanding evolving
- Control techniques evolving
- Recent insight: sheared plasma flow can reduce turbulence

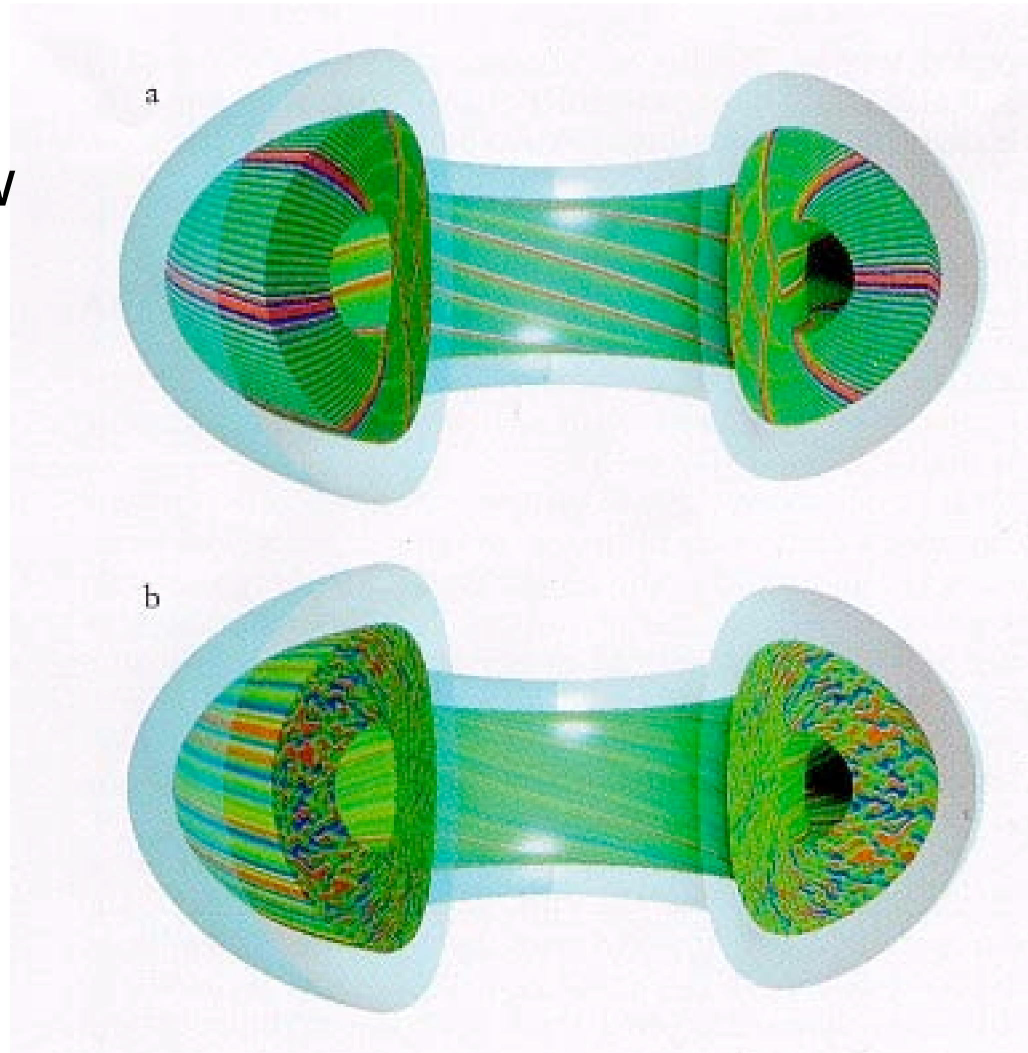
Sheared Flows can Reduce or Suppress Turbulence



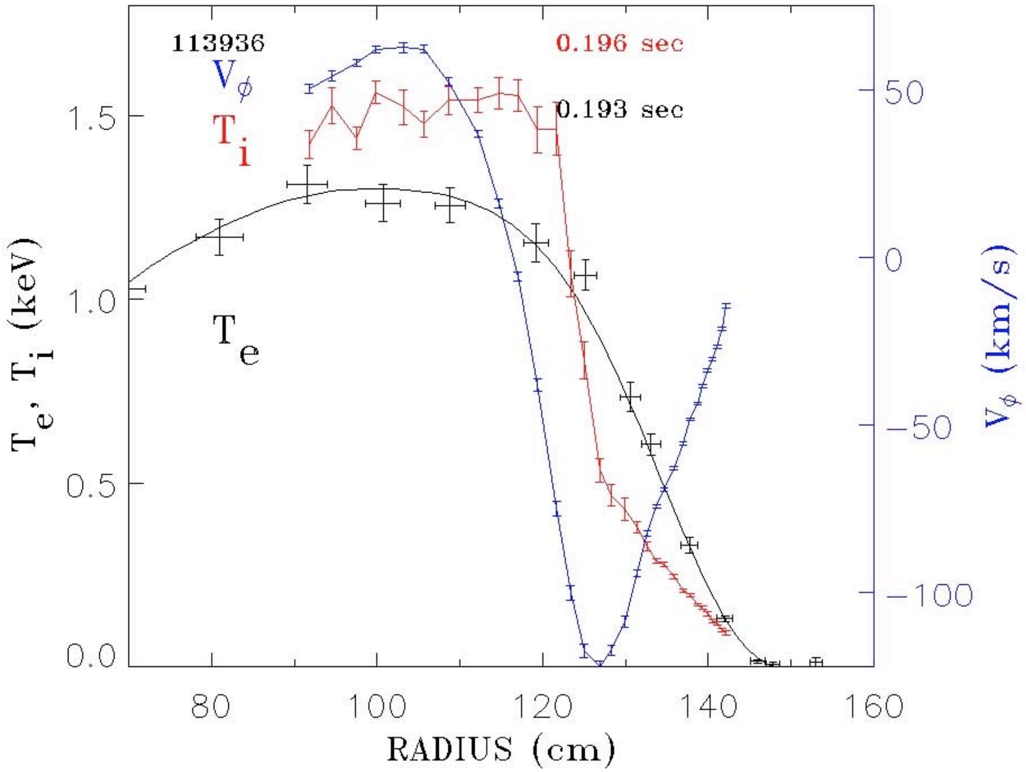
Computation of plasma turbulence

Without sheared flow

With sheared flow



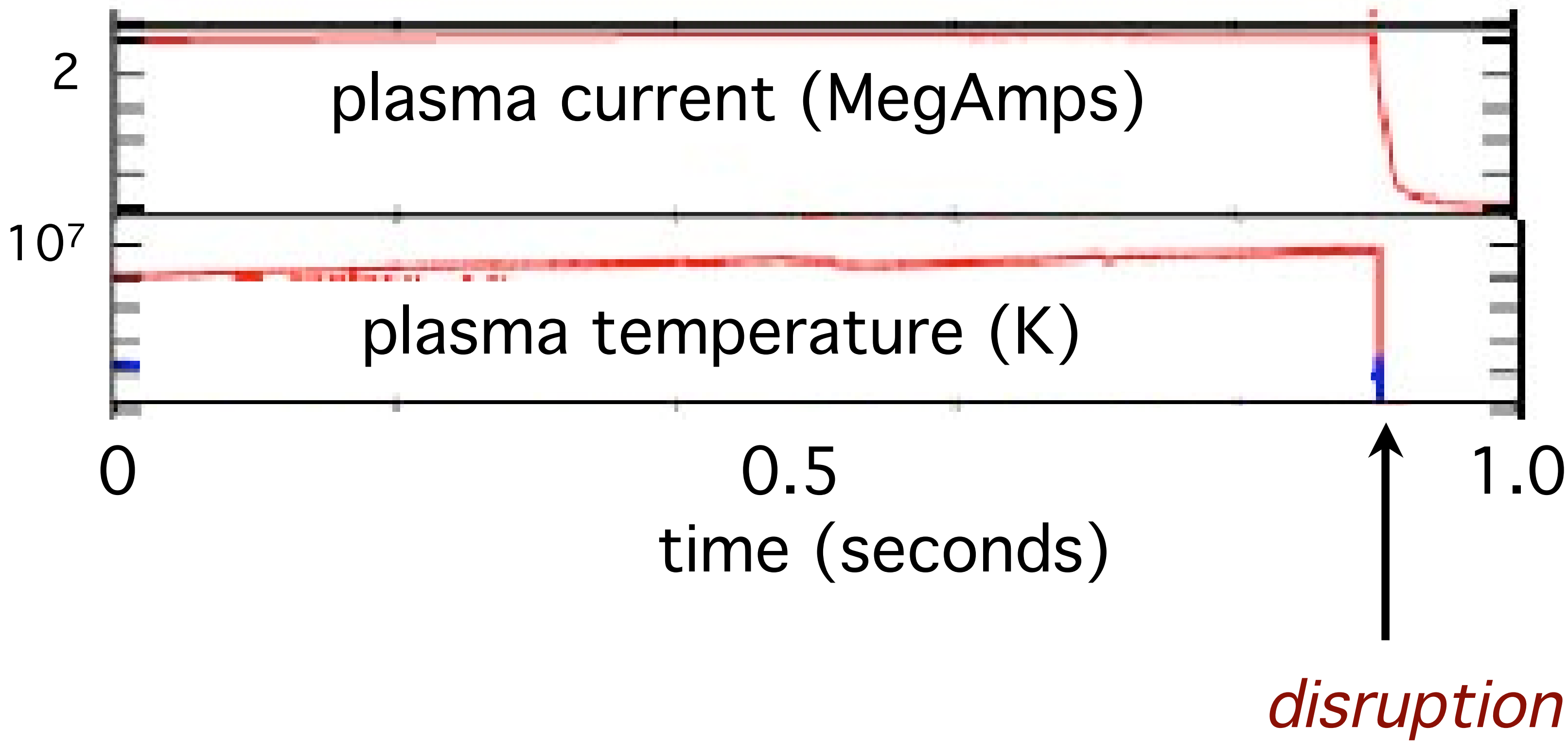
Ion transport barrier forms



Sheared flow and ion transport barrier forms spontaneously

Next frontiers: electron turbulence, magnetic turbulence

Disruptions

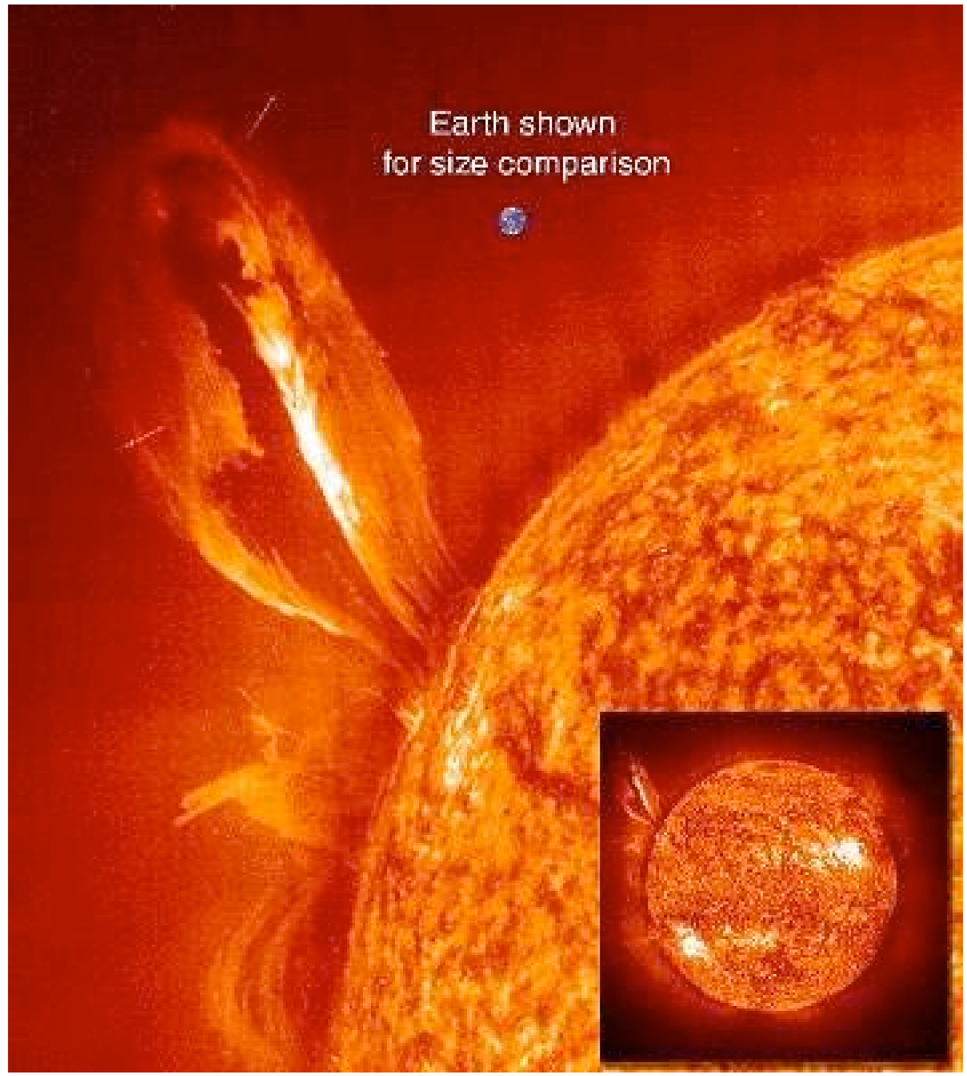


- localized heat flux (tens of GW/m² for 1 ms in ITER)
- Induced currents in structures (hundreds of tons)
- runaway electrons (tens of MA)

Disruptions arise from sudden rearrangement of magnetic field

physics similarities to solar flares

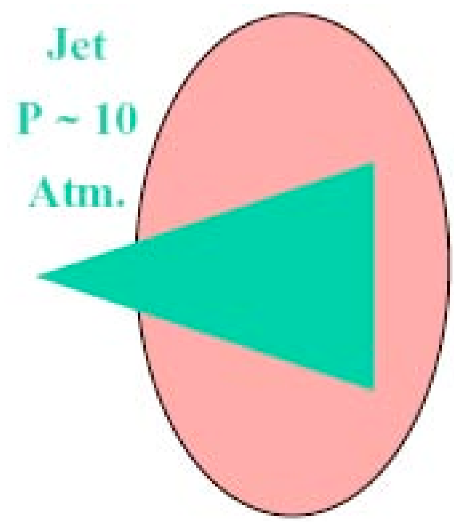
magnetic reconnection



A practical method for disruption control

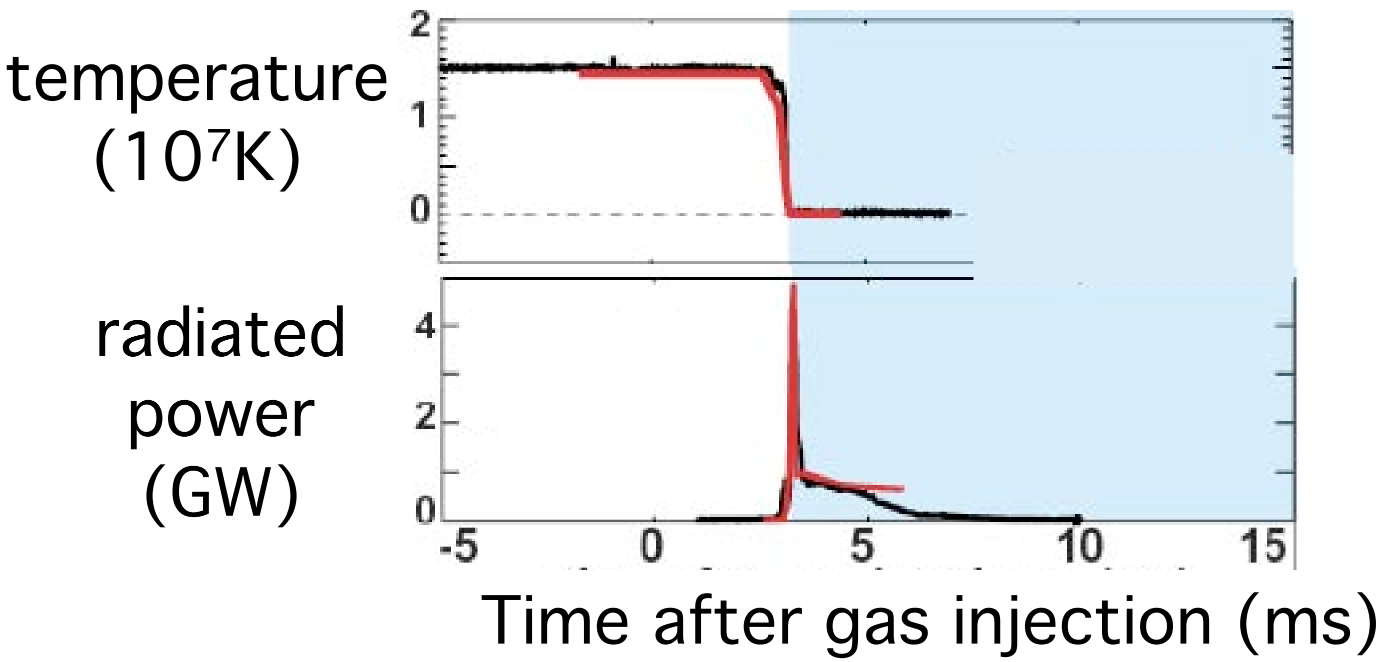
Permit disruption to occur,

Control its behavior by rapid injection of jet of neutral gas



Causes energy to be radiated isotropically,

No localized heat deposition



radiates nearly 100% of power in 200 microseconds,

power radiated isotropically - no local damage

Plasma confinement is an optimization problem with many physics and engineering variables

Physics variables

- Magnetic field curvature, twist, shear, symmetry
- Plasma flow
- Spatial structure of electron temperature, ion temperature, current density.....

Optimizing the magnetic configuration requires fundamental physics and invention

Configuration optimization is an essential partner to tokamak research

- For fundamental plasma physics and fusion energy science
- To evolve an improved fusion energy concept
- To contribute to scientific problems yet confronting the tokamak

The spectrum of magnetic configurations

weak —— *magnetic field* → *strong*

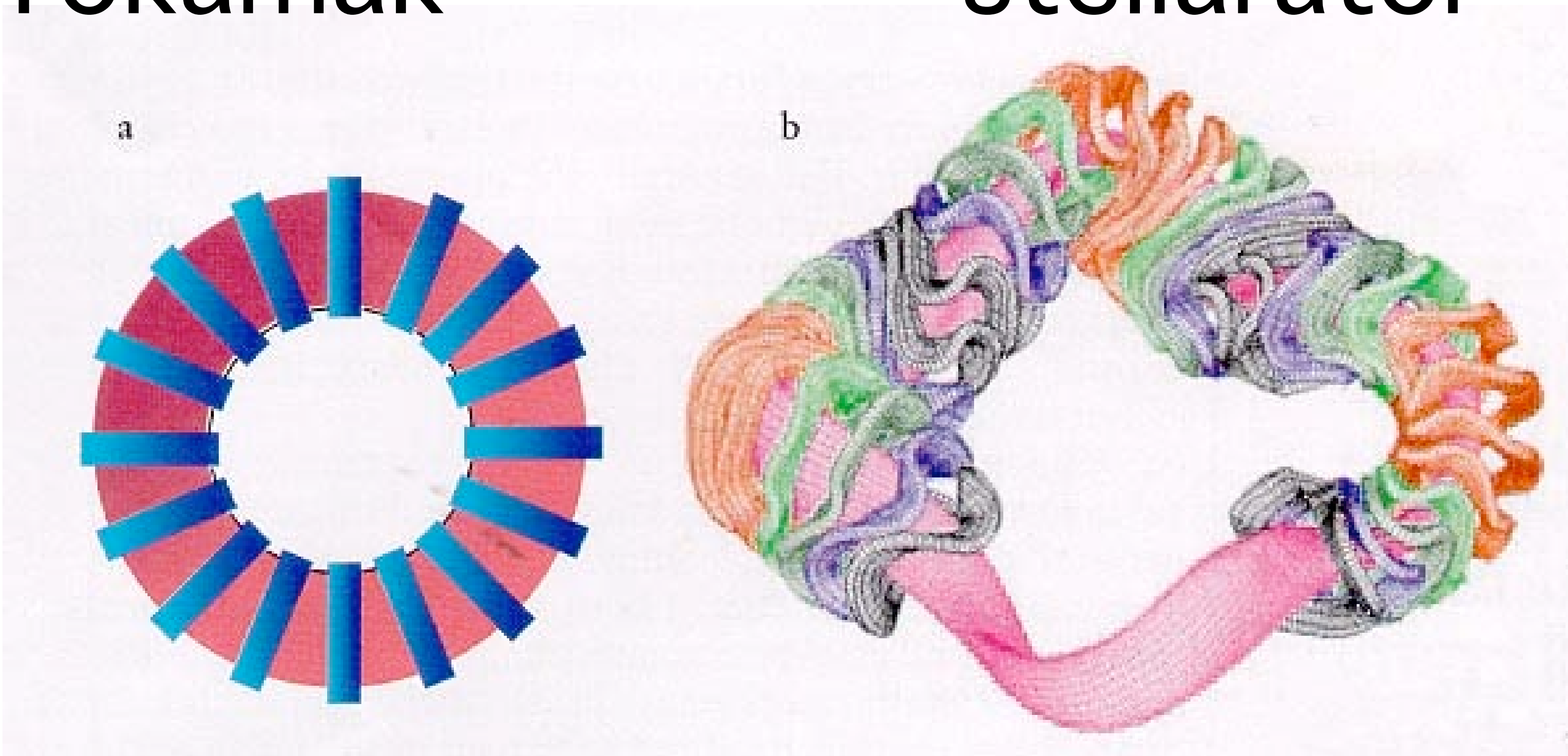
self-organized → *externally controlled*

emerging → *highly developed*

examples:

compact torus	*reversed field pinch*	*spherical tokamak*	*stellarator*

Tokamak stellarator



simple coils

symmetric around axis

current carrying

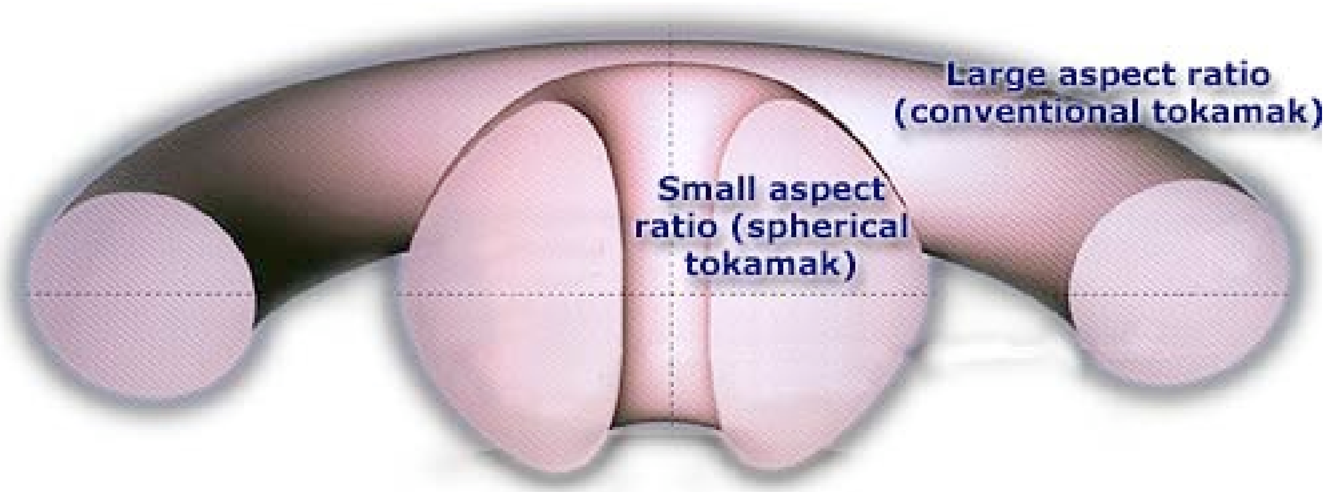
Complex coils

Helical symmetry within plasma

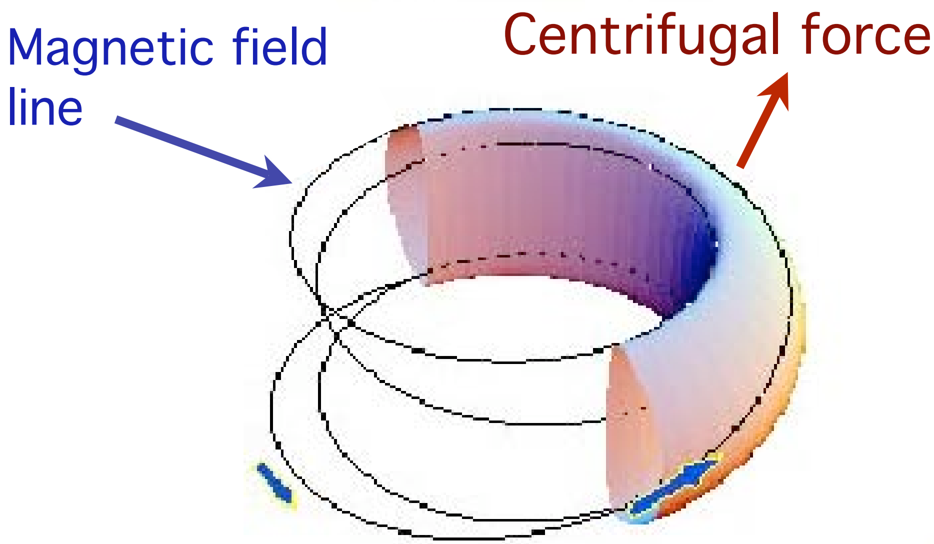
No need for plasma current

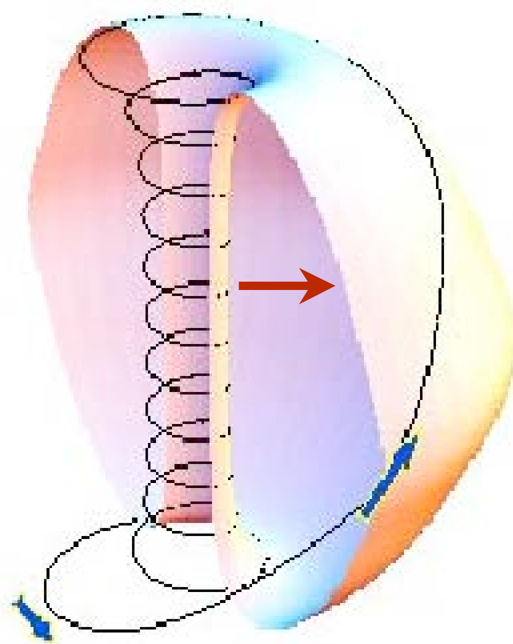
Steady-state, no disruptions

Reduce aspect ratio of tokamak



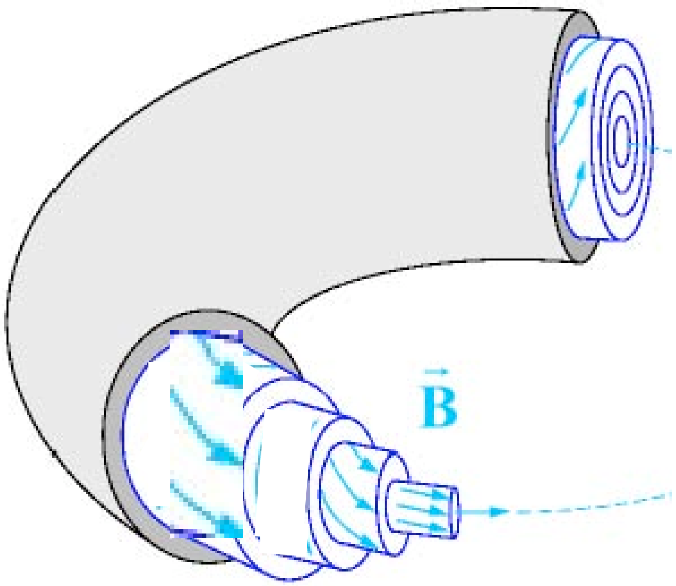
tokamak spherical tokamak





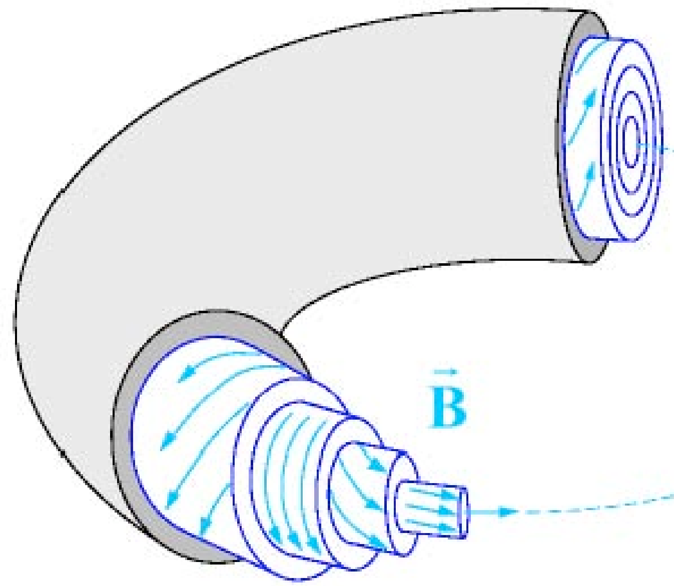
Instability from centrifugal force yields medium pressure

Effect of centrifugal force weakened, yielding higher pressure tokamak



strong toroidal magnetic field

reversed field pinch

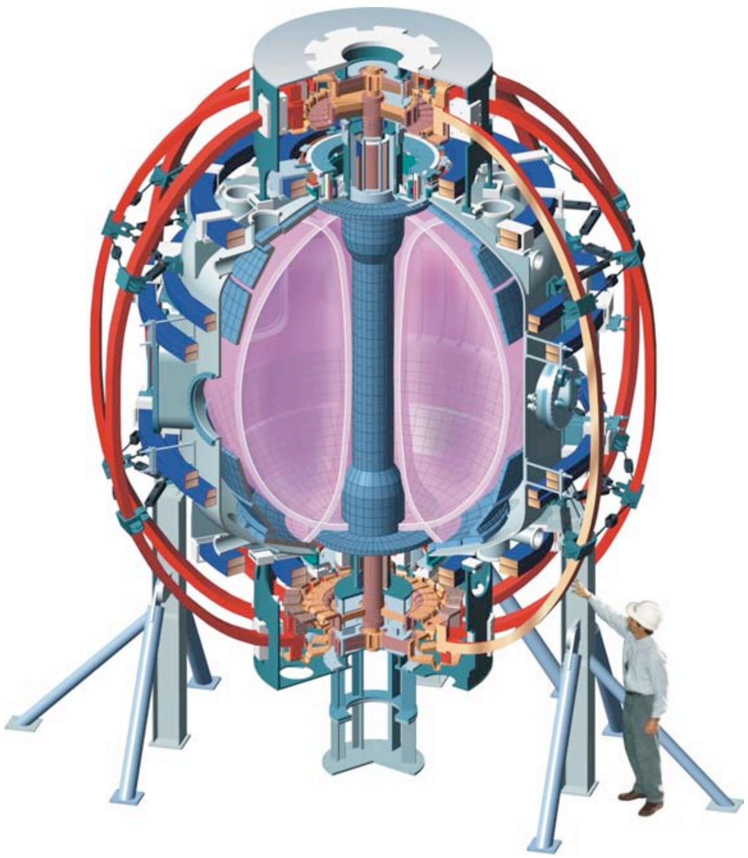


weak toroidal field

simplifies engineering

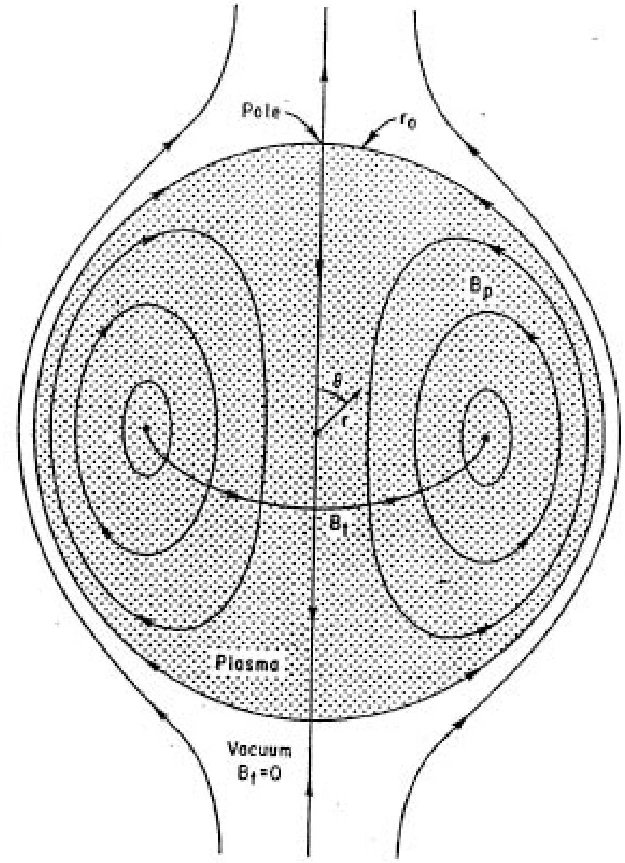
but weakens confinement

Spherical tokamak



Small hole in center

compact torus



No hole in center of torus

Very compact

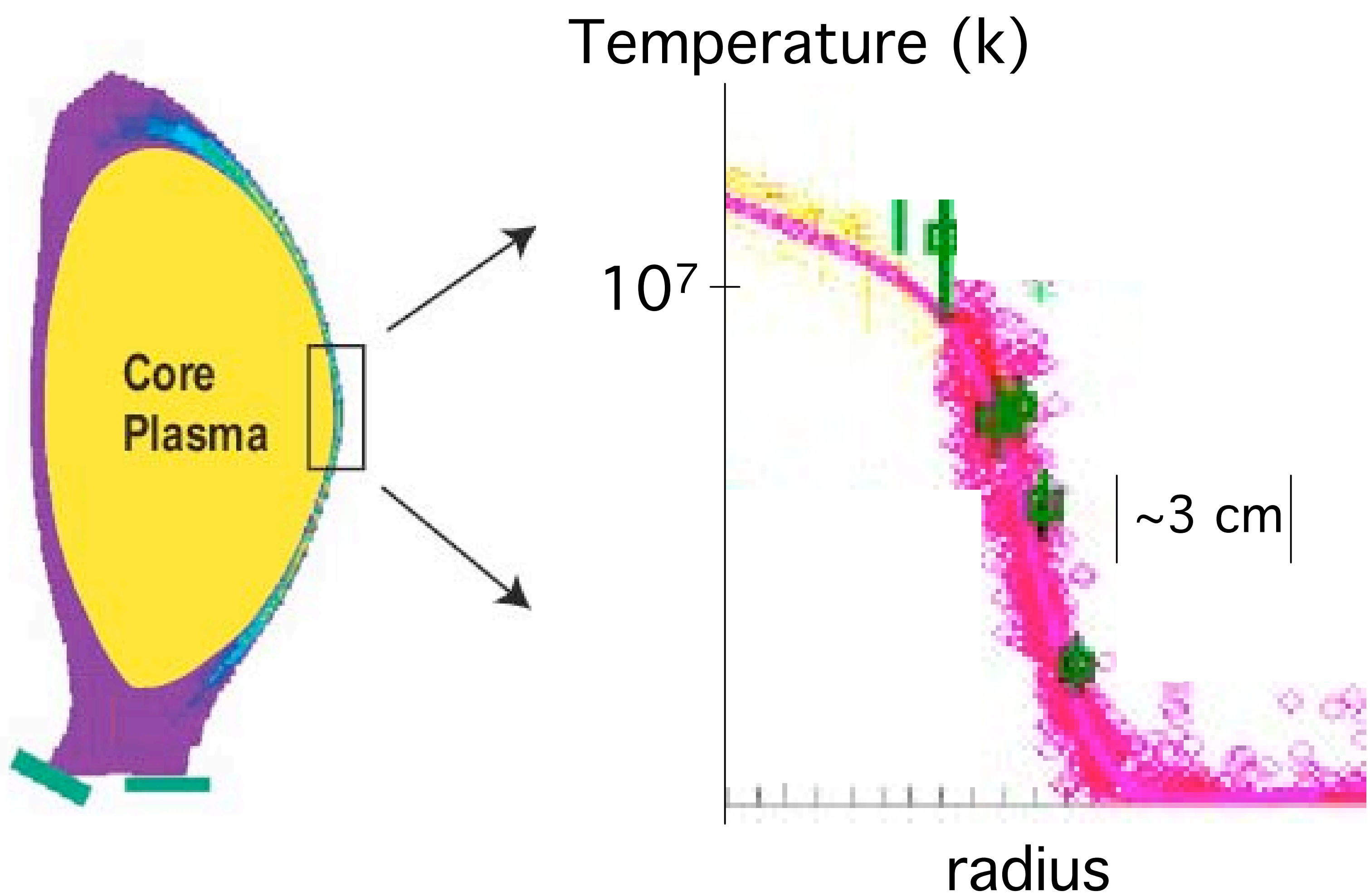
Stability under study

How to interface a 100 million degree plasma to a room temperature wall?

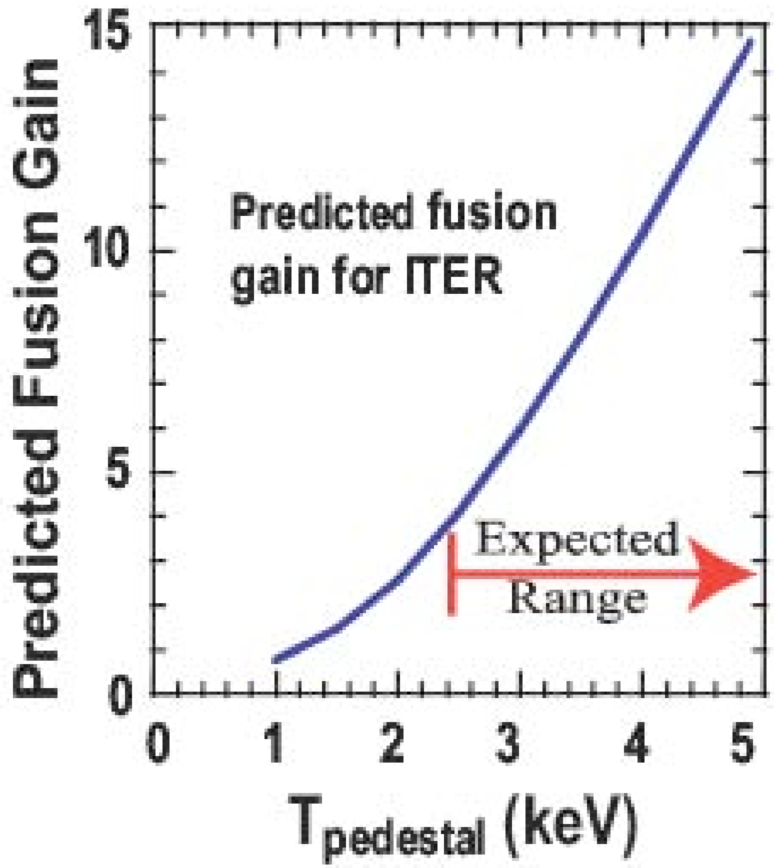
- Need to control the edge plasma

- Need new wall materials

A temperature pedestal forms at the plasma edge

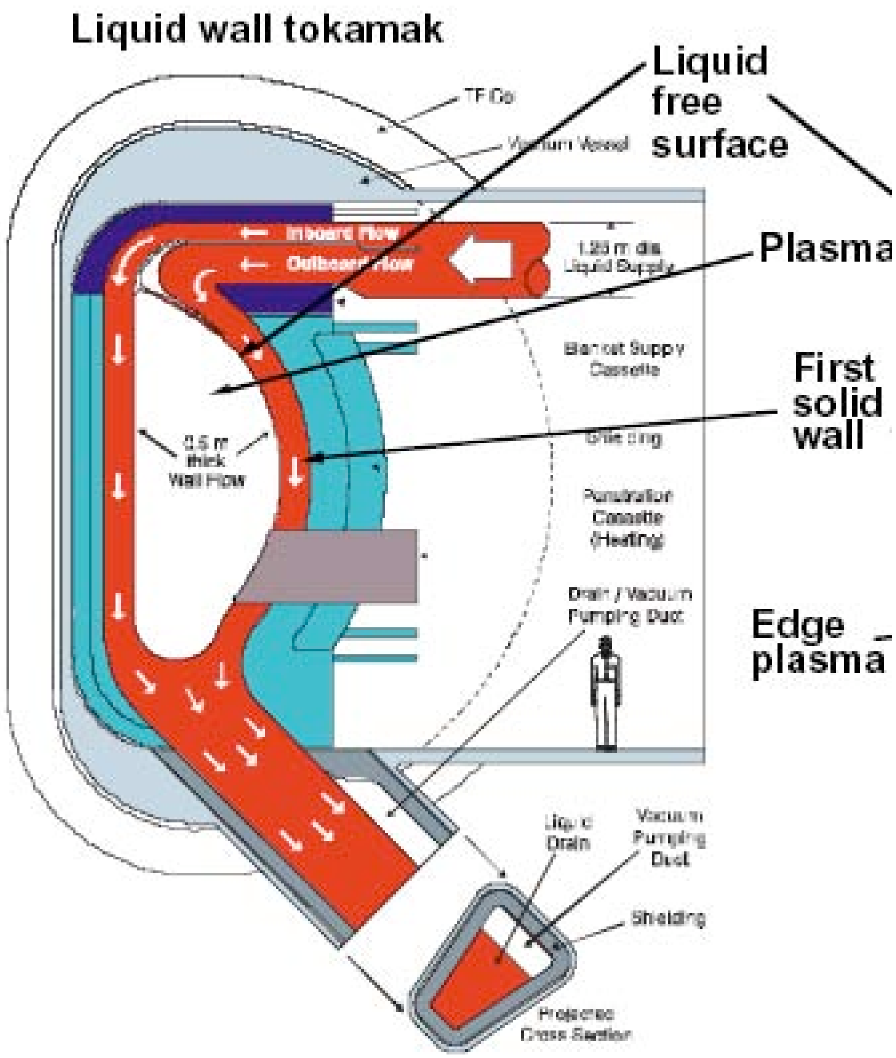


The temperature at the height of the pedestal is important



Structures developed to withstand a heat flux of 25 MW/m^2

Liquid walls for fusion



Scientific issues for fusion

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Conclusions

- Many scientific challenges remain

- Fusion energy science is highly advanced

We are ready to build a burning plasma experiment - a new frontier is fusion energy and plasma physics