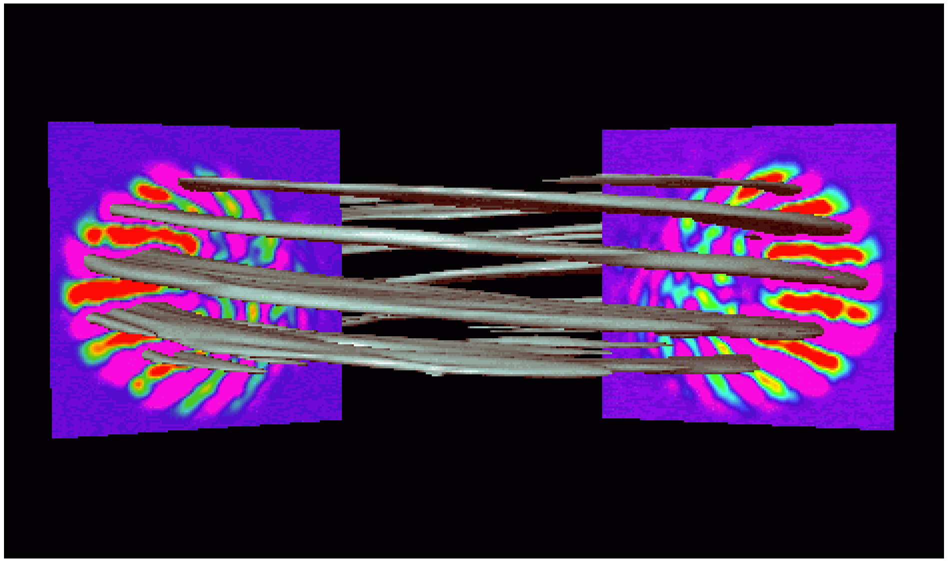
Turbulence and Transport

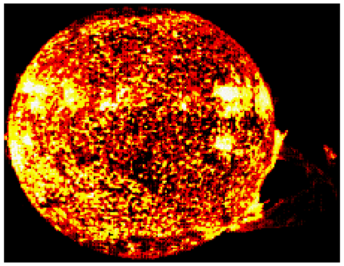
The Secrets of Magnetic Confinement

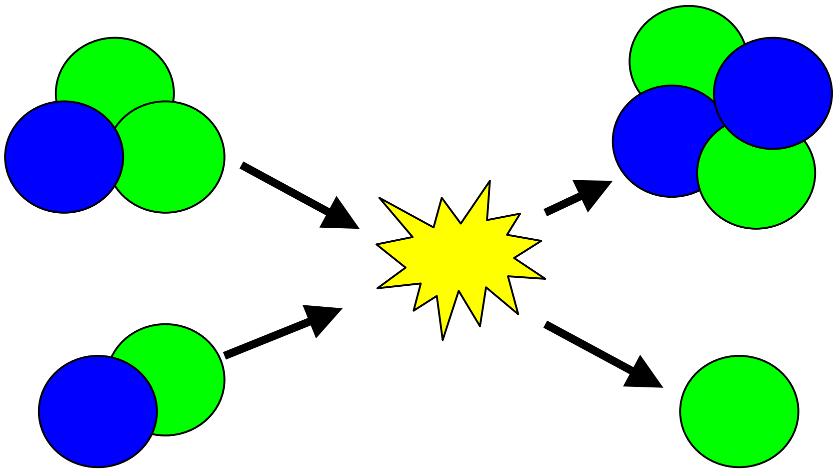


Martin Greenwald - MIT Plasma Science and Fusion Center

Oberlin College, March, 2002

THE FUSION REACTION POWERS THE STARS AND PRODUCES THE ELEMENTS OF THE PERIODIC TABLE



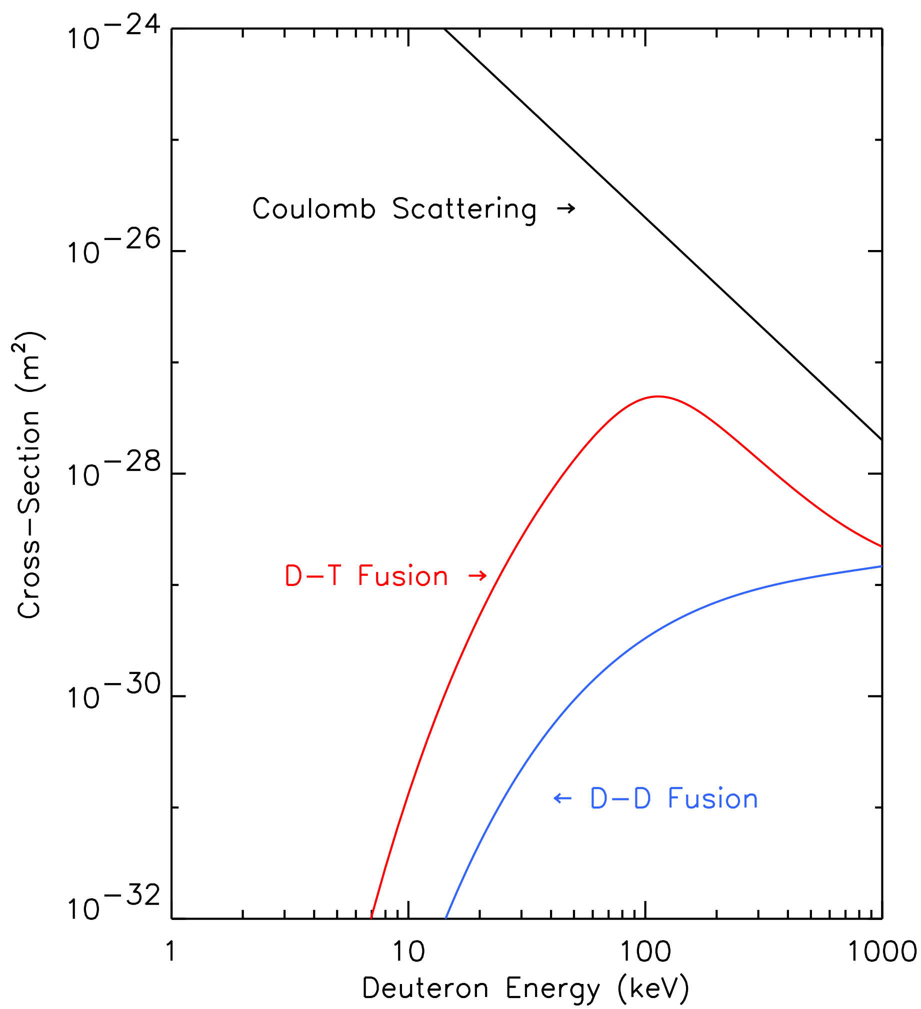


- For 50 years, scientists and engineers at laboratories around the world have been working to exploit the fusion reaction as a practical energy

- The promise is for an environmentally friendly method for generating electricity with an inexhaustible fuel supply.

THE CURVES OF THE FUSION REACTION AND FOR ELASTIC SCATTERING LEAD US DIRECTLY TO THE STUDY OF CONFINED PLASMAS

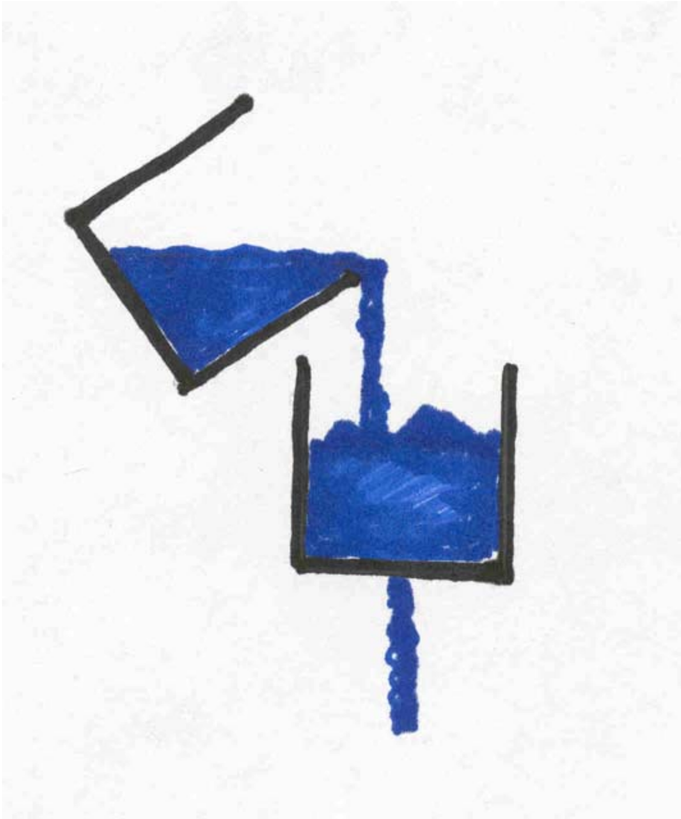
- Even at the optimum energy, the nuclei are much more likely to scatter elastically than to fuse
- Nuclei must be confined for many interaction times.
- Multiple scatterings thermalize the constituent particles.
- At the energies involved (10-100 keV), matter becomes fully ionized ⇒ **plasma.**



90% OF THE (VISIBLE) UNIVERSE IS MADE OF PLASMA

WHAT PRECISELY DO WE MEAN BY THE TERM "CONFINEMENT" ?

A simple analogy: water leaking out of a bucket

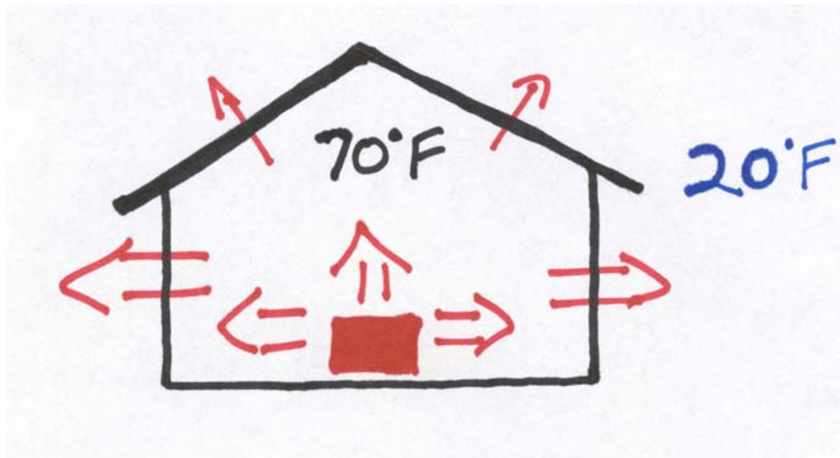


At steady-state, define confinement time as:

$$\tau\,(\sec) \equiv \frac{Volume\ of\ water\ (gallons)}{Source\ rate(gallons\,/\sec)}$$

ENERGY CONFINEMENT

A slightly better analogy for fusion energy: Heating a building



$$\tau_E(\text{sec}) \equiv \frac{Total\ stored\ energy\ (Joules)}{Heating\ rate\ (Watts)}$$

- Our goal is to get to the required temperature with the least amount of heating power.

CONFINEMENT REQUIREMENTS FOR FUSION

THE LAWSON CRITERION

$$Fusion\ Power = n_D\, n_T \cdot Rate\ per\ ion \cdot Energy\ per\ reaction$$

$$Fusion\ Power \propto n^2 F(T)$$

$$Loss\ Power = Confinement\ Loss + Radiation\ Loss$$

$$Loss\ Power = \frac{3nT}{\tau_E} + n^2 R(T)$$

In steady state, Fusion Power = Loss Power $\Rightarrow$ ***(Scientific Breakeven)***

- This is a quantitative statement of the requirements for good confinement and high temperature.

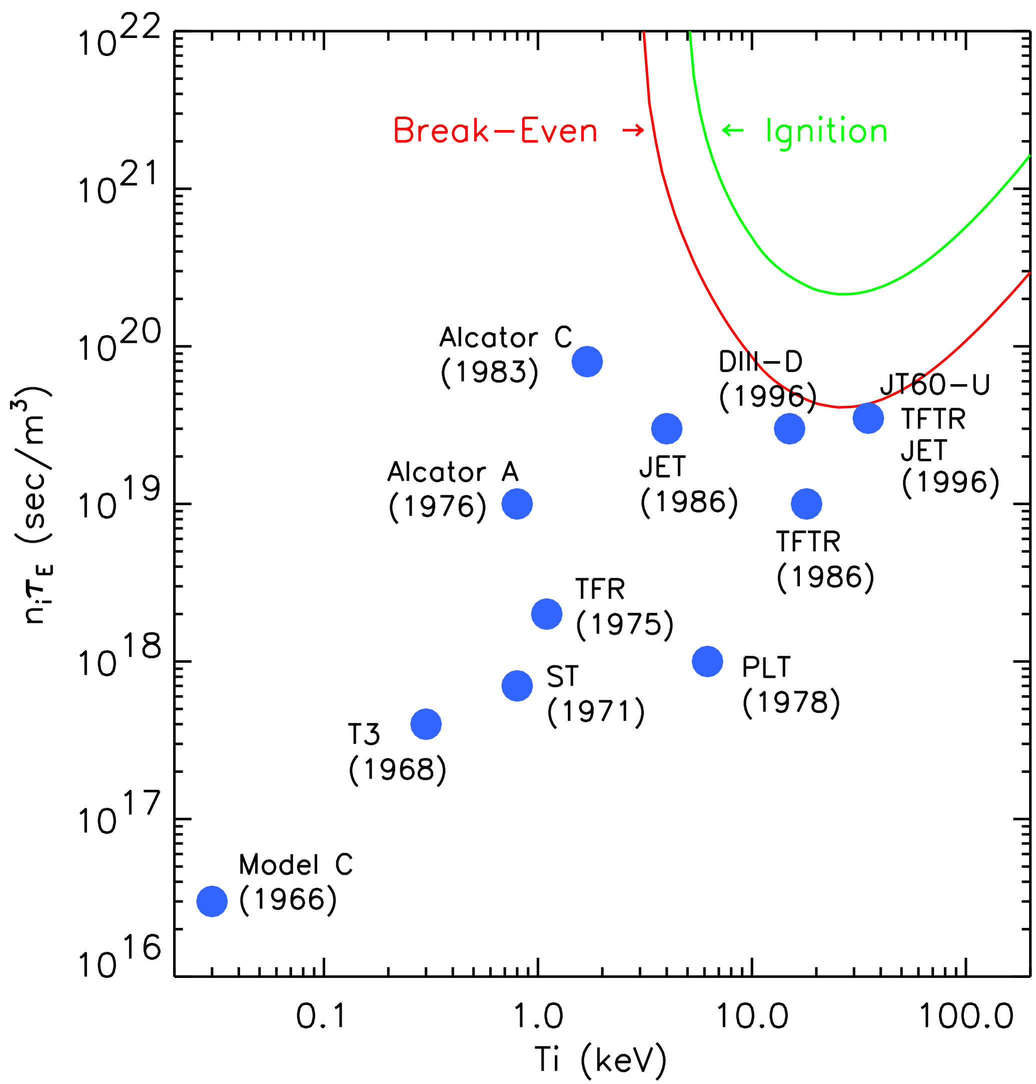
$$n^2 F(T) = \frac{3nT}{\tau_E} + n^2 R(T)$$

$$n\tau_E F(T) = 3T + n\tau_E R(T)$$

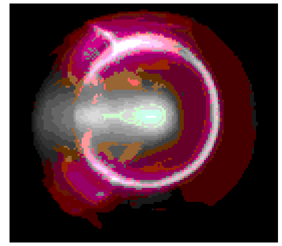
$$n\tau_E = \frac{3T}{F(T) - R(T)} = G(T)$$

DESPITE THE CHALLENGES, PROGRESS HAS BEEN SIGNIFICANT

- Over the last 35 years fusion yield has increased by about 10^7. **A doubling time of about 18 months!**
- We have roughly another factor of 100 in performance to go.
- We also need to go from pulses to steady state.

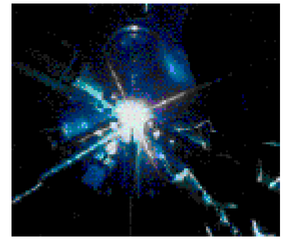


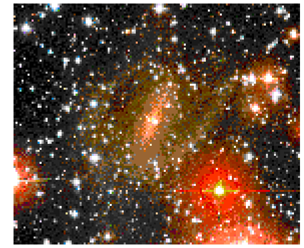
HOW DO WE DO IT?



Magnetic Confinement

Inertial Confinement





Gravity

1 Gravitational Confinement

- In a dense gravitational well, even fast particles are trapped
- Works well for stars
- Who can afford to build a star?

2 Inertial Confinement

- Heat and compress plasma to ignition plasma before constituents fly apart.
- Works for the H-bomb
- "Micro" explosions to be tested with NIF (Defense Program)

3 Magnetic Confinement

Takes advantage of the motion of charged particles in a magnetic field

MAGNETIC CONFINEMENT

Gyro-radius

$$\rho = \frac{mV_\perp c}{qB} \propto \frac{\sqrt{mT}}{B}$$

Gyro-frequency, $\omega_c = \frac{eB}{mc}$

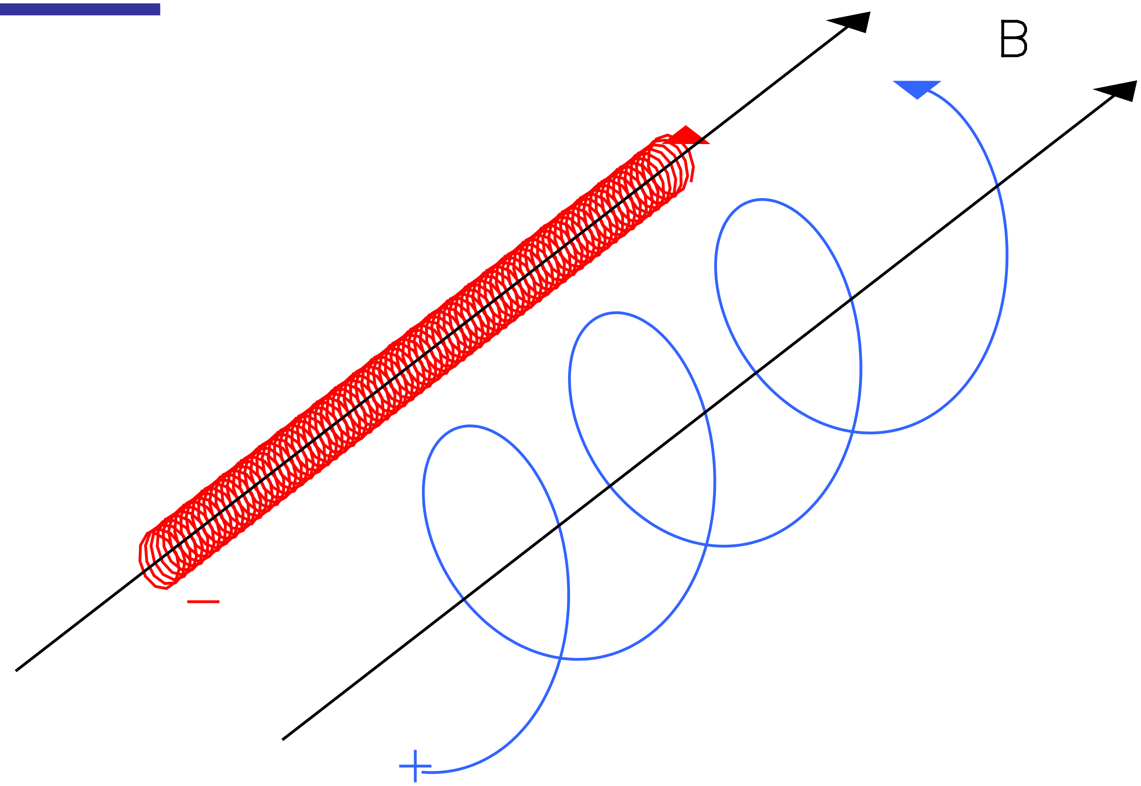
At B = 5T, T = 10keV

ρ_e = 0.067 mm

ρ_i = 2.9 mm

$\omega_e = 8.8 \times 10^{11}$ rad/sec

$\omega_i = 4.8 \times 10^{8}$ rad/sec



Ionized particles are deflected by the Lorentz force and bent into circular orbits.

DIFFUSION/HEAT CONDUCTION

- Elastic collisions cause particles to move off field lines; energy is transferred (transported) in these collisions too.
- The process resembles a random walk with a step of size Δx taken every Δt seconds

$$Diffusion\ Coefficient \equiv D = \frac{\Delta x^2}{\Delta t}$$

$$\Delta t = \frac{1}{\nu}; \quad \nu \equiv collision\ \ frequency$$

- Characteristic relaxation time for a diffusive process, $\tau \propto \frac{L^2}{D}$

For a magnetic fusion plasma:

Δx = ρ_i

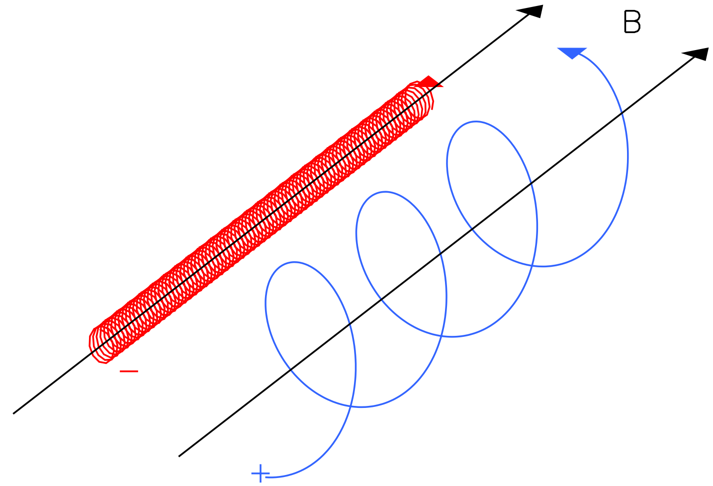
D ~ 10^{-3} m^2/sec

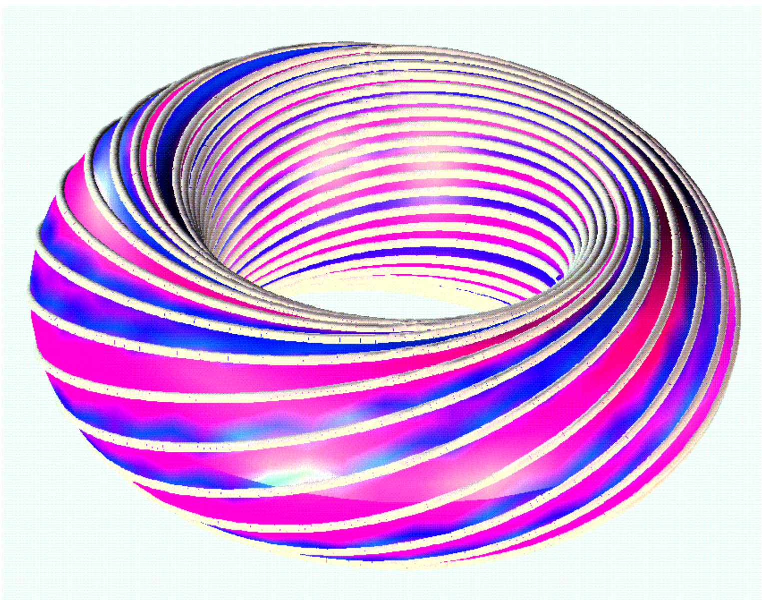
So for L = plasma radius ~ 1 meter,

τ ~ 1000 sec

(more than good enough)

IN THE SIMPLE EXAMPLE SHOWN, THERE IS NO CONFINEMENT AT ALL PARALLEL TO THE MAGNETIC FIELD.

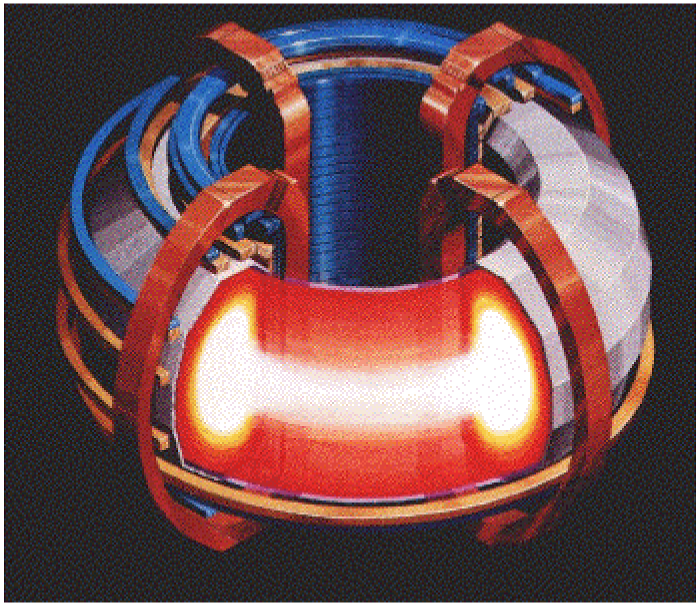




- For a practical device, the end losses must be eliminated

- **Voila! Eliminate the ends.**

MOST FUSION EXPERIMENTS START HERE: WITH TOROIDAL PLASMAS.

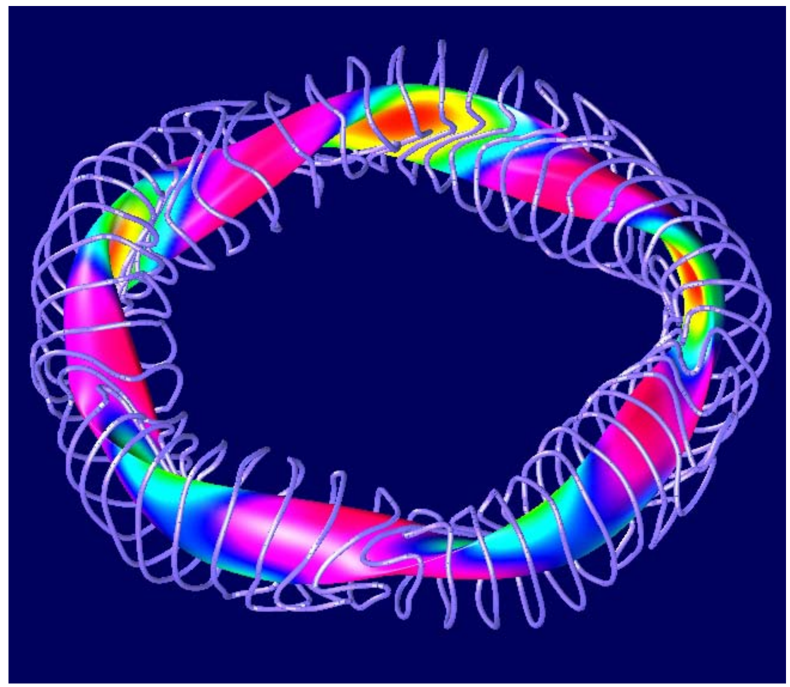


Tokamak

(toroidalnaya kamera magitnaya katushka)

Stellarator - *Wendelstein 7AX*

(Under construction in Greifswald Germany)



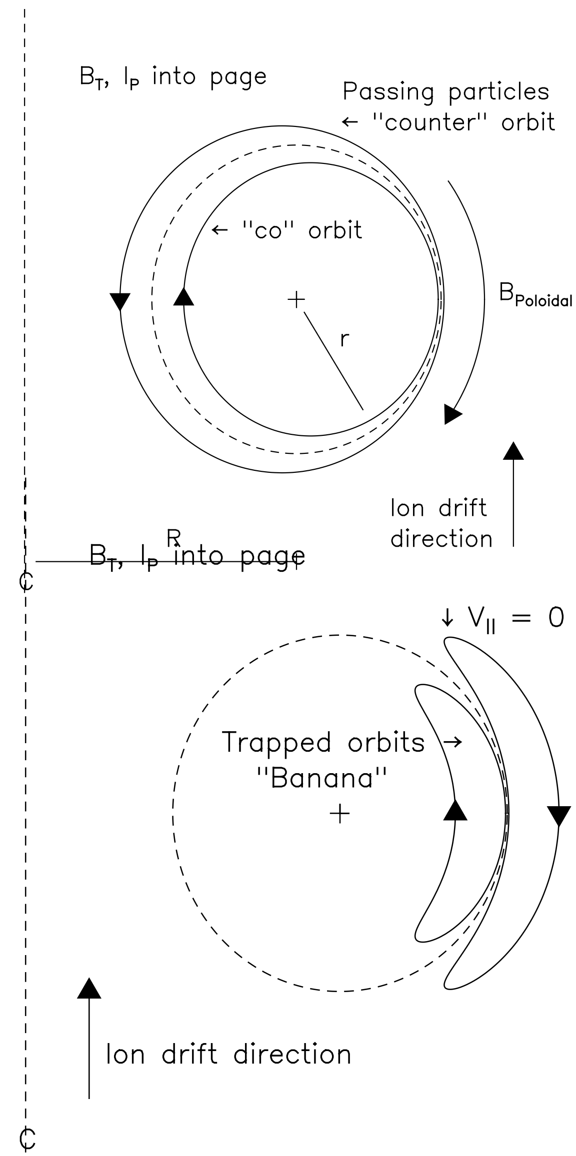
PARTICLE ORBITS ARE MORE COMPLICATED IN A TOROIDAL SYSTEM

Ions and electrons drift off of magnetic field lines due to:

Magnetic Field Curvature $$V_D = \frac{mV_{\parallel}^2}{qBR}$$

Magnetic Field Gradients $$V_D = \frac{mV_{\perp}^2 \nabla B}{qB^2}$$

Electric Fields $$V_D = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$



Classical (Collisional) vs Anomalous Transport

We could live easily with classical conductive losses, **even with the toroidal effects**.

For a plasma about 2 meters in diameter:

$D \sim 5 \times 10^{-2}\ m^2/sec$

$\tau \sim 20$ sec (still more than enough)

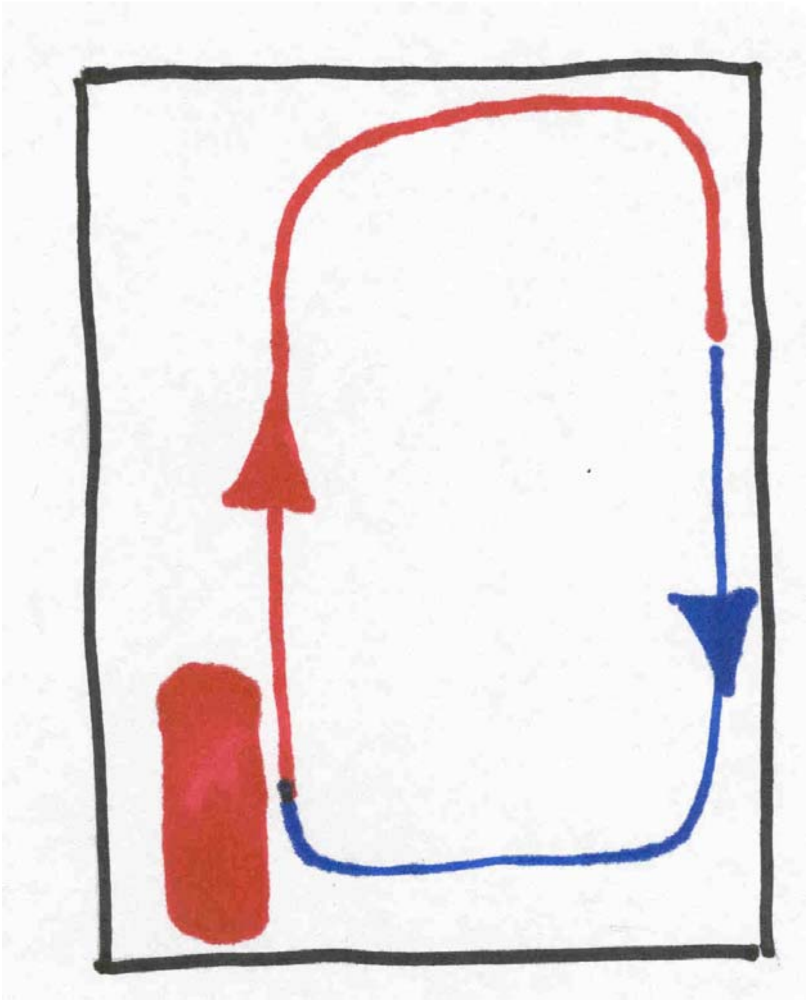
In experiments, losses are typically **much** higher.

- The search for source of these anomalous losses has been an important part of controlled fusion research .
- It presents one of the most challenging problems of classical physics.
- To begin, consider the difference between conduction and convection.

CONVECTION - Heat Transfer in Fluids

Air is a very poor conductor of heat
Theoretically it is 4 orders of magnitude worse than typical solids.
So why do we wear coats, why insulate our houses???

- The **only** purpose of insulation (down/fiberglass) is to break up convection currents
- To make the convection process less efficient at carrying heat



WHERE DOES CONVECTION COME FROM IN PLASMAS??

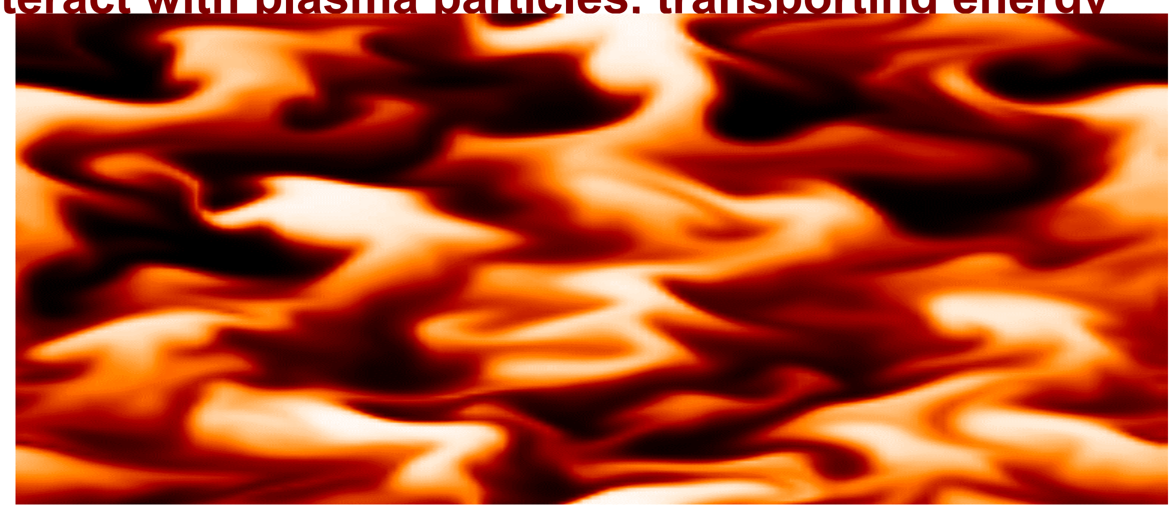
Plasmas support all sorts of wave motion

The system is far from thermodynamic equilibrium (strong gradients)

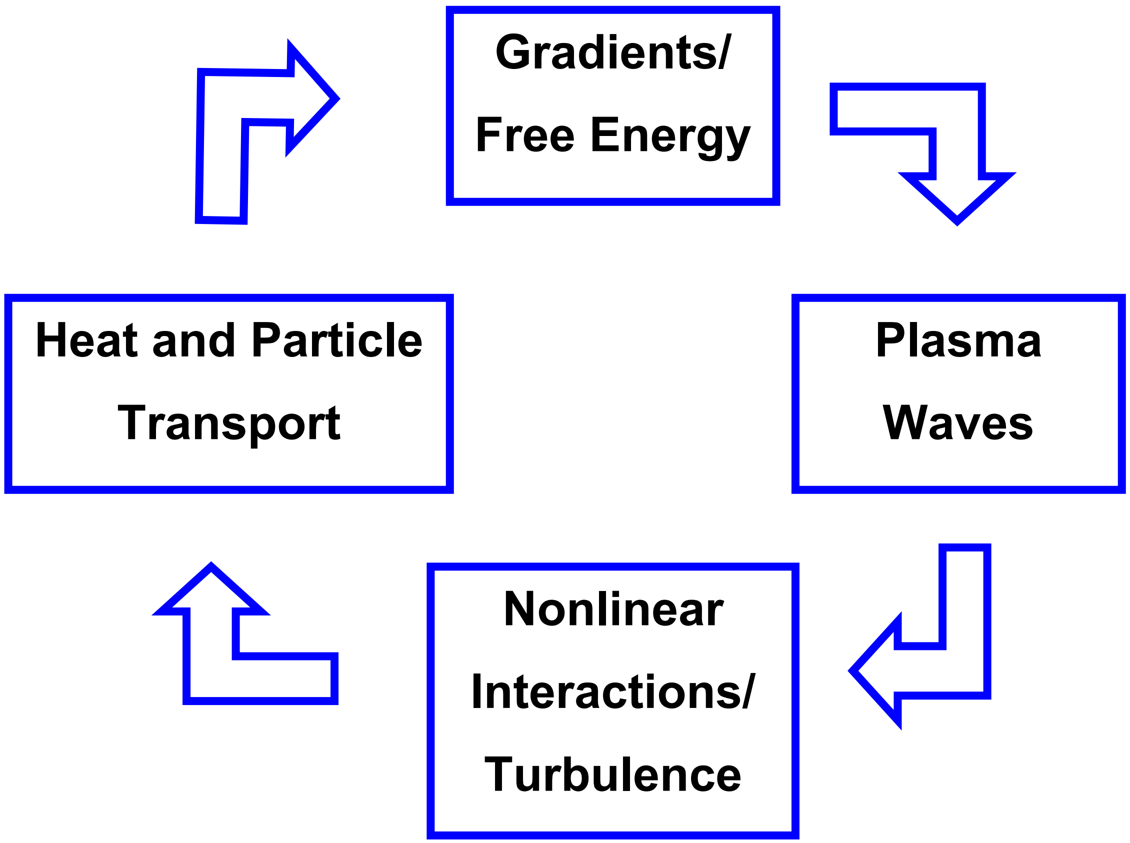
Waves grow by tapping free energy in temperature and density gradients

As they grow, the waves modify the plasma (non-linear physics - compare to waves breaking at the shore)

Waves evolve and interact with plasma particles, transporting energy and particles.

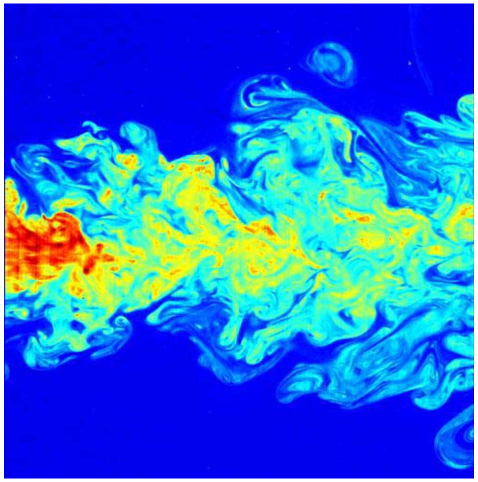


PROFILES AND CONVECTIVE TRANSPORT EVOLVE SELF-CONSISTENTLY



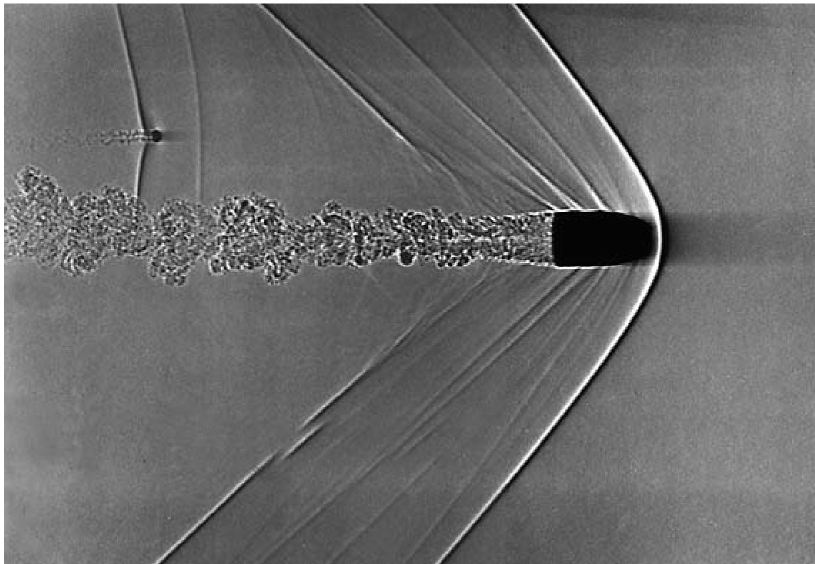
TURBULENCE

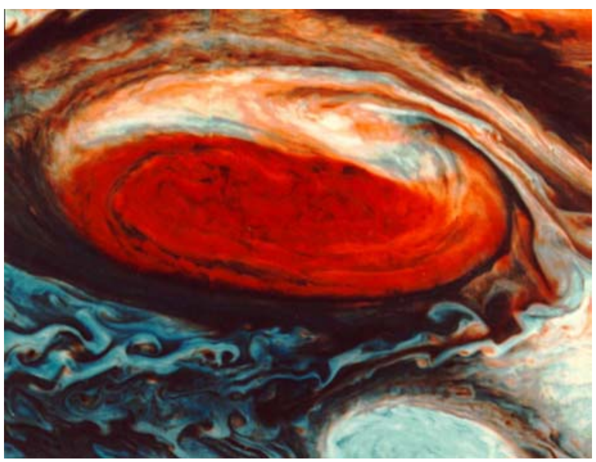
- Turbulence is a ubiquitous phenomenon in nature.
- It is generated as a spontaneous way of releasing the free energy associated with gradients.
- As waves grow, they modify the medium in which they propagate
- This non-linear interaction leads to "chaotic" behavior, turbulence
- It breaks the symmetry of the physical system and involves multiple time and space scales..



Turbulence is a Grand challenge of physics

TURBULENCE OCCURS OVER A WIDE RANGE OF SCALES

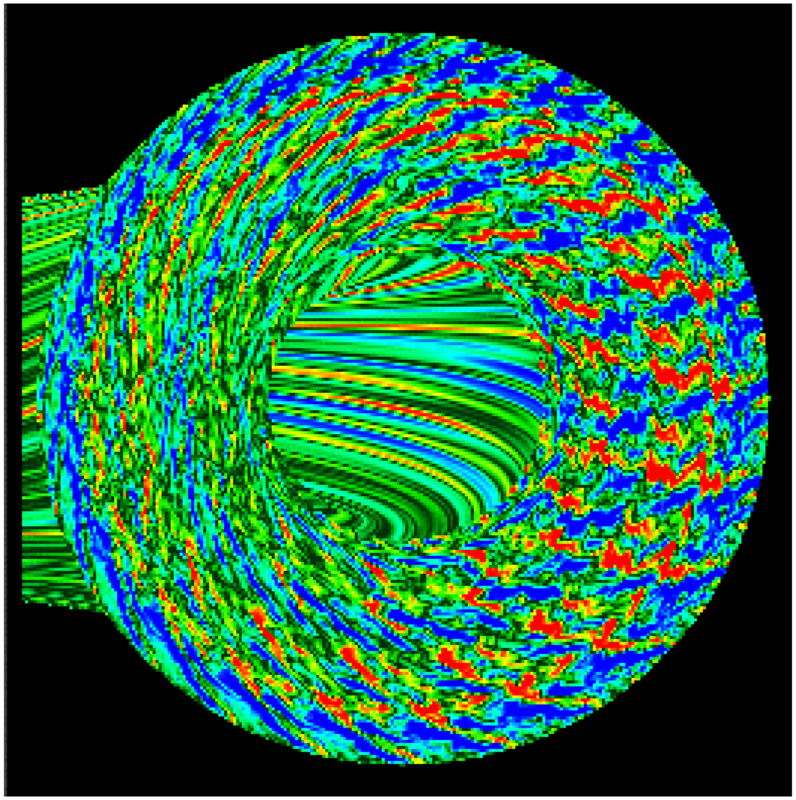




PLASMA TURBULENCE AND TRANSPORT CAN BE SIMULATED BY LARGE COMPUTER CODES

- Plasmas can be described with a set of fluid equations (MHD) plus Maxwell’s equations

- Or with a full “kinetic” treatment which looks at the evolution of the system in six dimensional “phase space” (position + velocity)

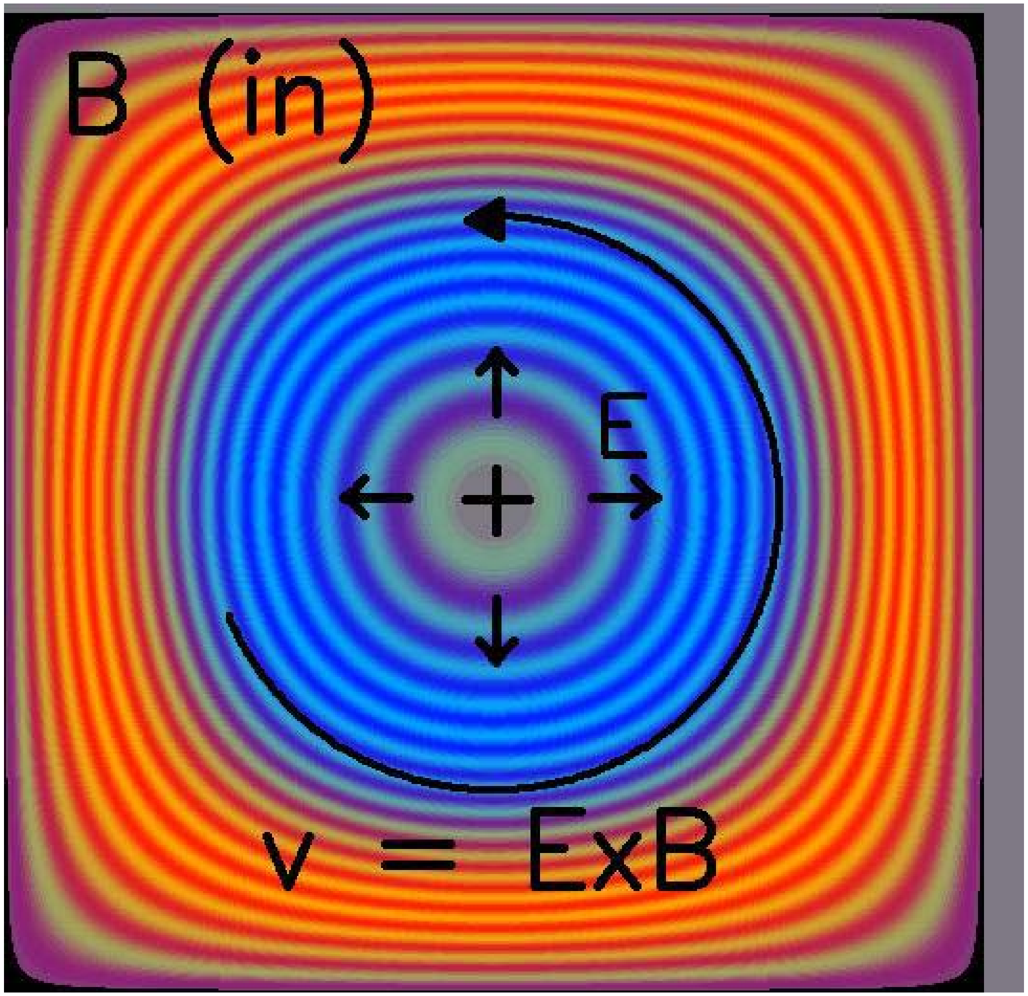


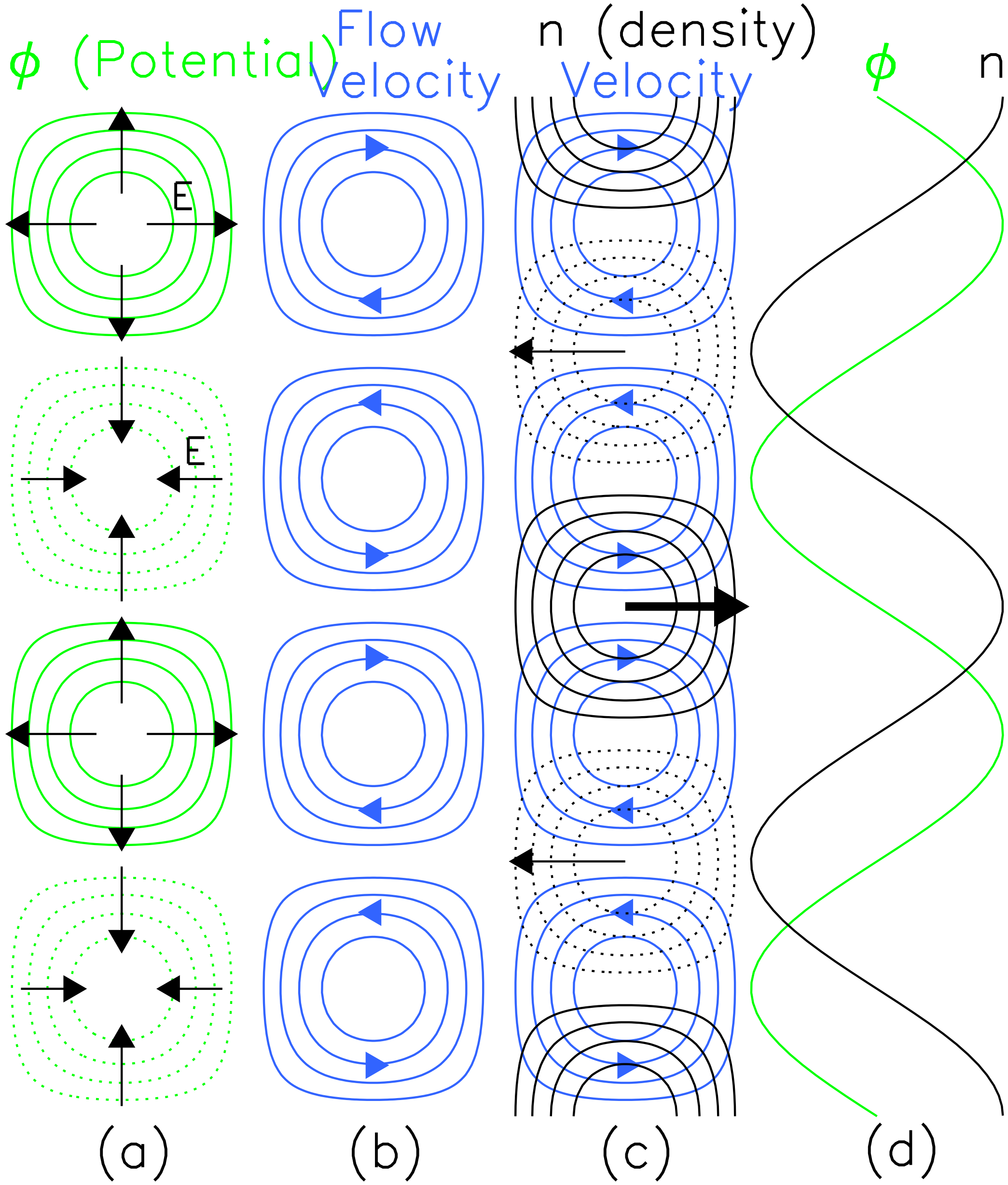
- In magnetized plasmas, turbulence features are small in cross section, but extend along the magnetic field lines

HOW DOES TURBULENCE LEAD TO TRANSPORT?

- The waves that seem to cause the most transport are a little like ordinary sound waves **but**…..they have an important electric component
- That is, the electrons, being lighter, move faster and separate slightly from the ions
- The result are localized regions of excess + and - charge, + and - potential

ExB drift causes the plasma to whirl around regions of high or low potential.





ϕ (Potential)
Flow
Velocity
n (density)
Velocity
ϕ
n
E
E
(a)
(b)
(c)
(d)

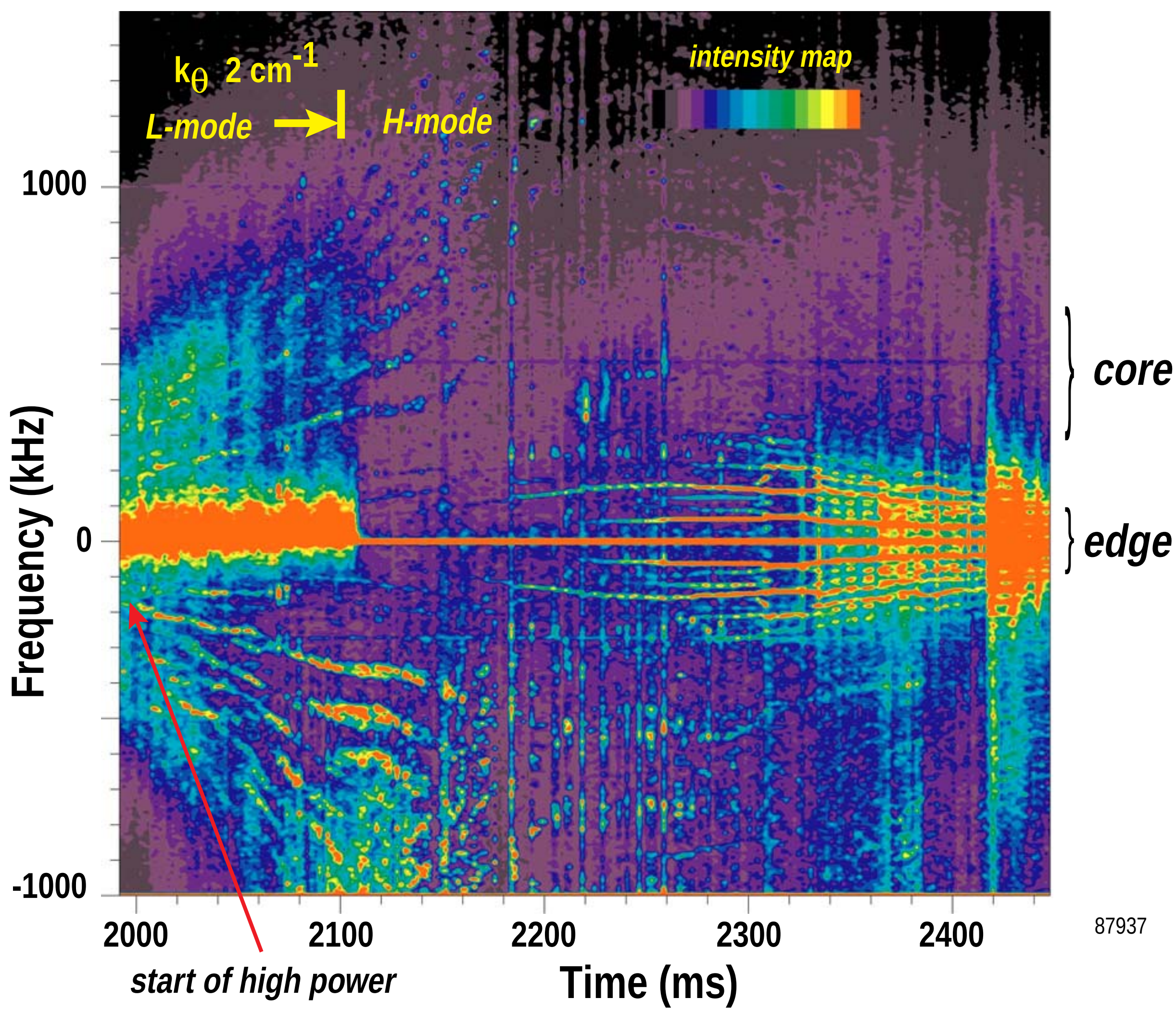
FLUCTUATIONS ARE SUPPRESSED THROUGHOUT THE ENTIRE PLASMA DURING HIGH PERFORMANCE H-MODE

- Core fluctuations are gradually reduced after the application of high neutral beam power.

- Edge fluctuations cease at the L-H transition.
  - Low fluctuation levels everywhere in the plasma during H-mode.

- Narrow band features at low frequencies indicate increasing MHD at high beta approaching end of high performance phase at 2417 ms..

Contour Plot of Scattered Fluctuation Spectra Evolution



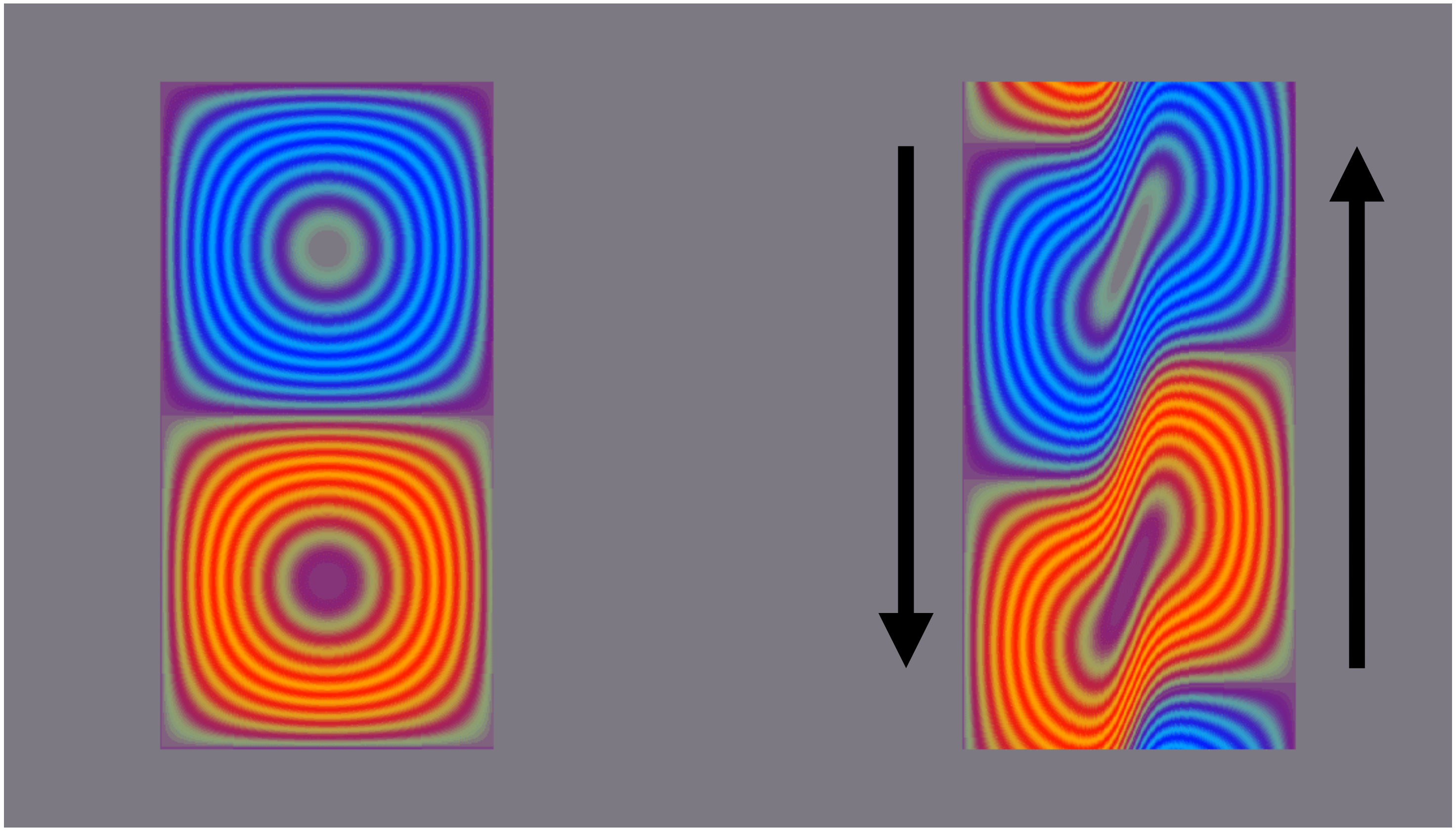
263-96/24 [Rettig, 2F05]

UCLA Electrical Engineering

GENERAL ATOMICS

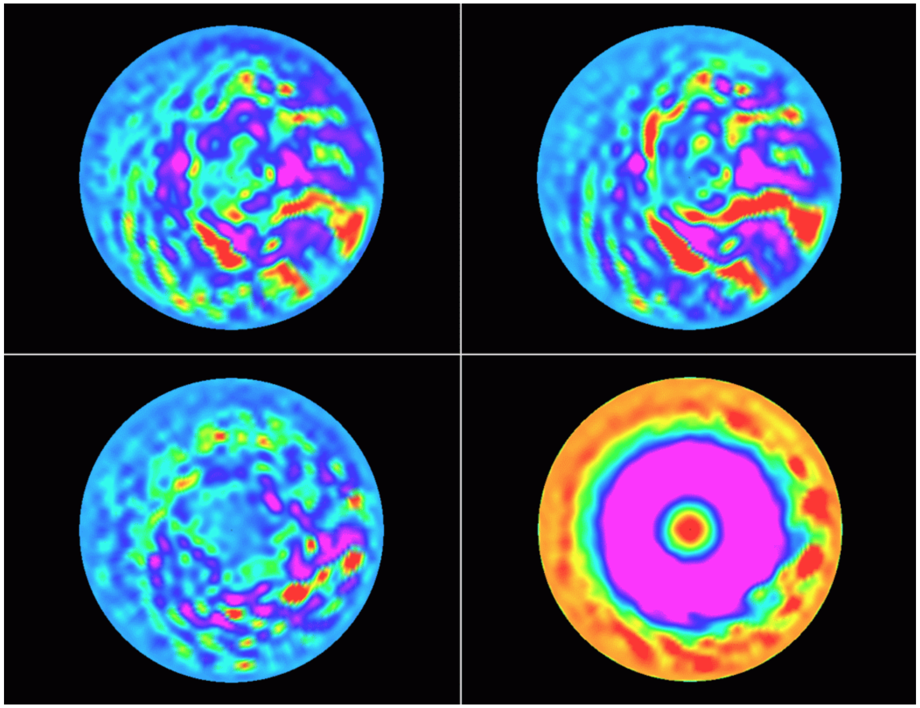
HOW CAN WE REDUCE TURBULENT TRANSPORT ?

Experiments show regimes of dramatically improved confinement:

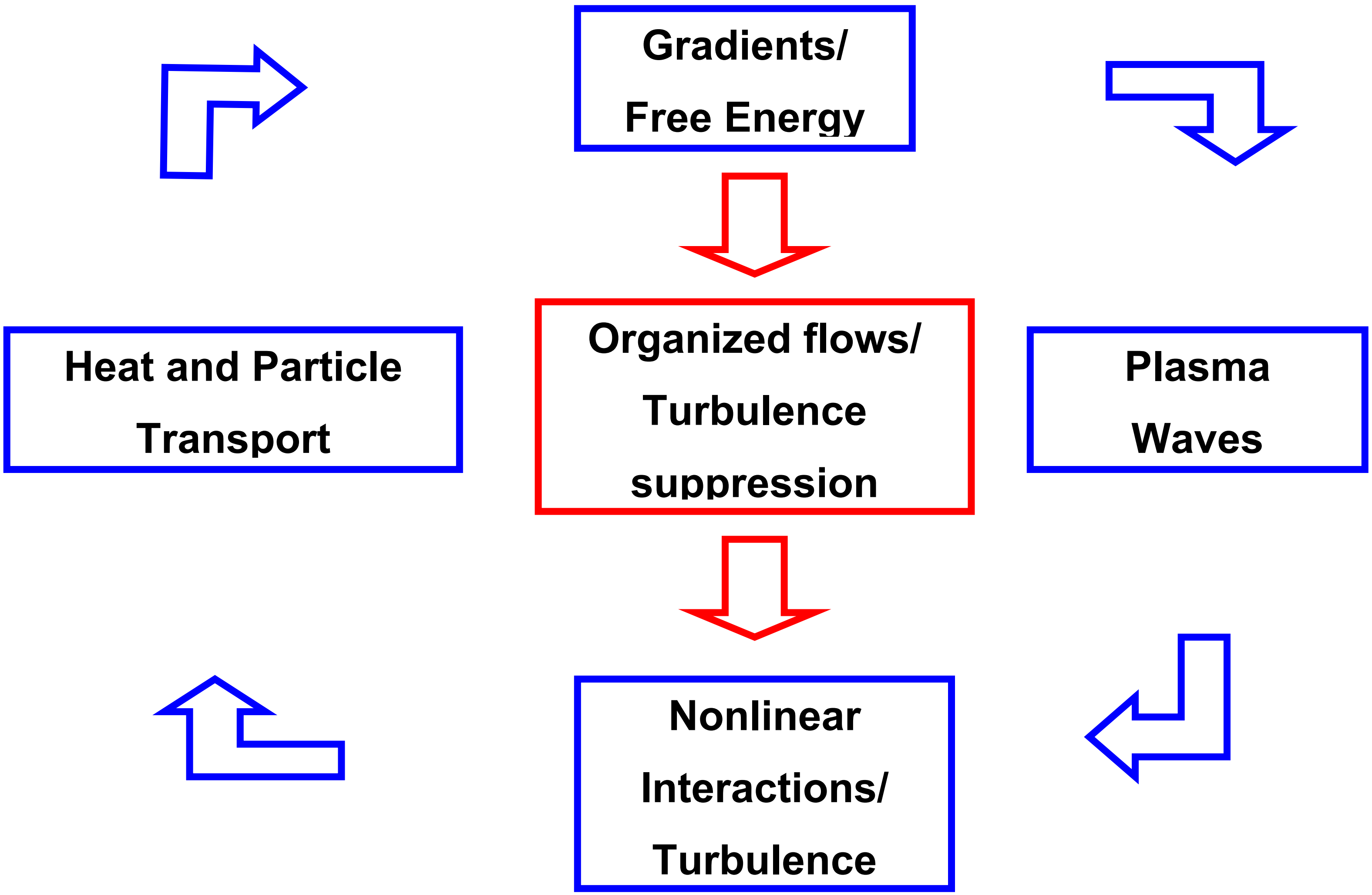


Theory suggests that the improved confinement is due to **self-organized flows.**

SELF ORGANIZED FLOWS



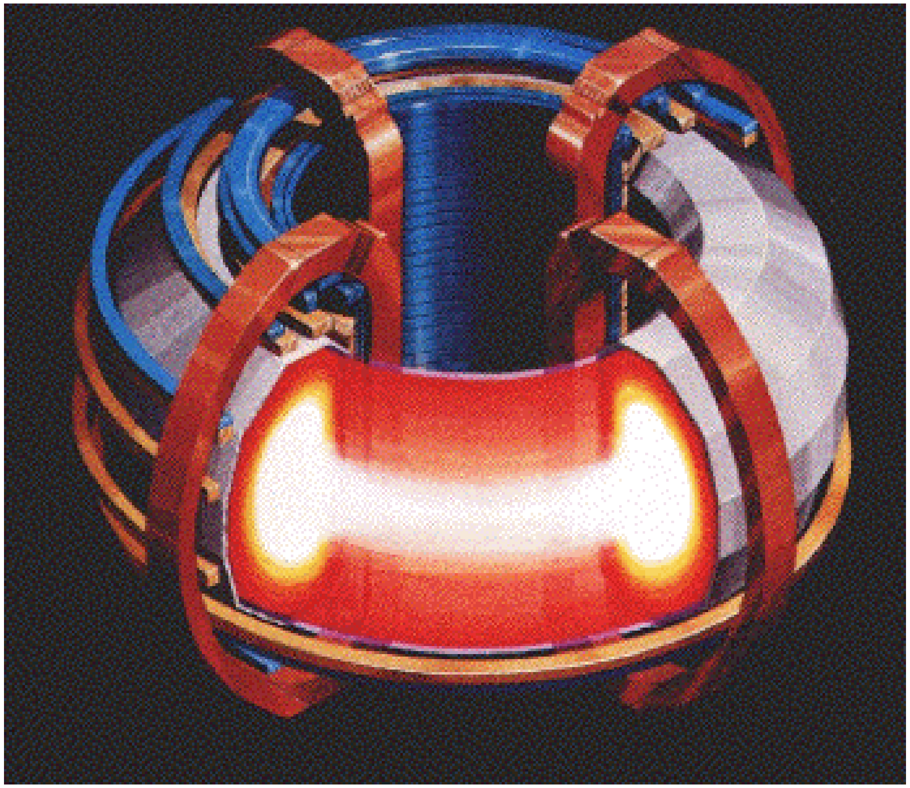
SHEAR FLOW PARADIGM



EXPERIMENTAL PROGRAM IN FUSION ENERGY

Two main missions

- Test physics basis
- Extend performance

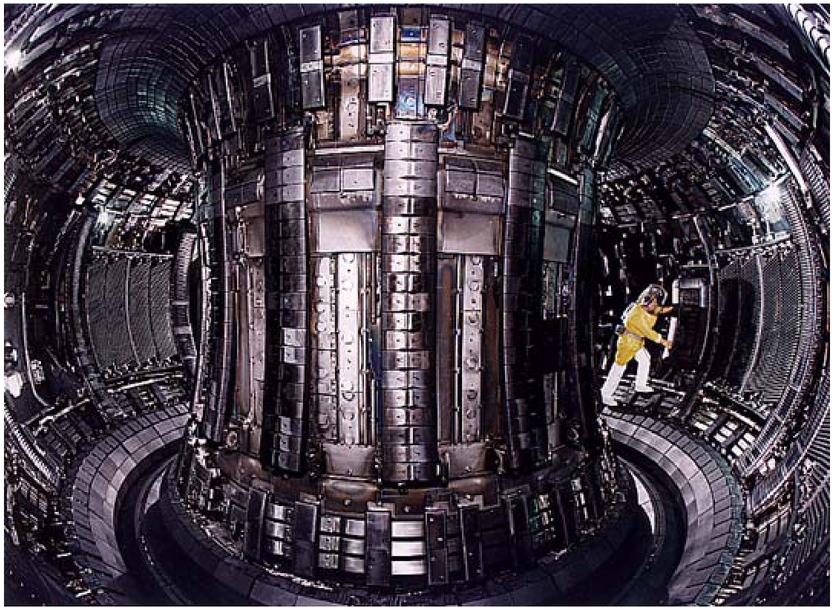


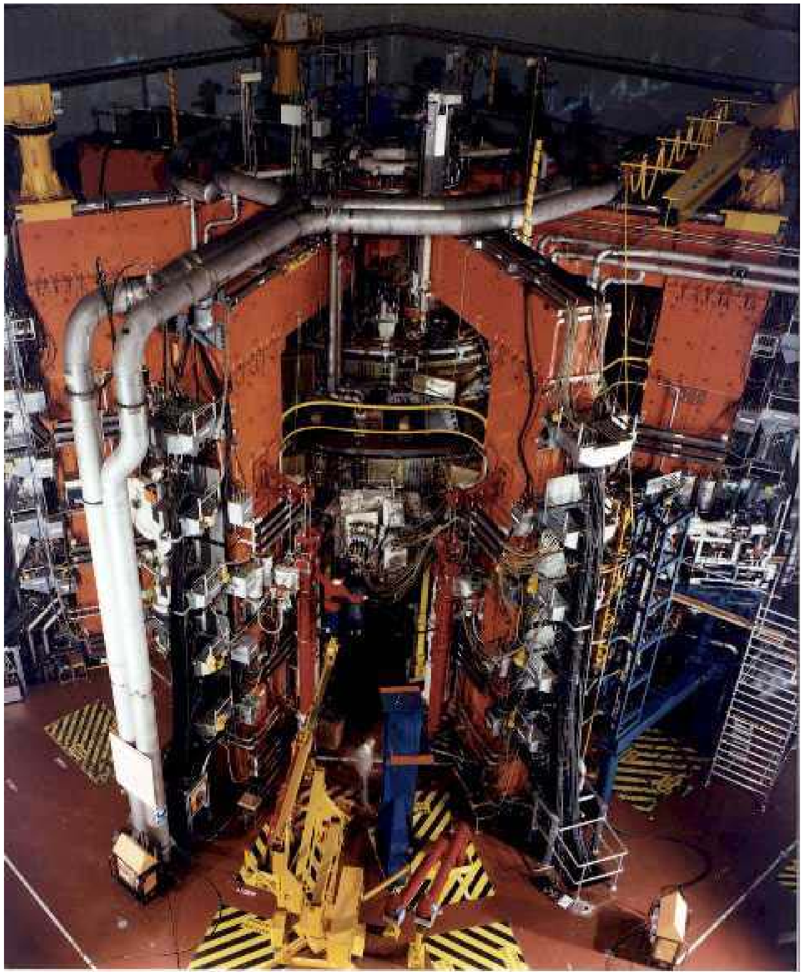
Challenges

- Large scale engineering
  - Magnet systems
  - Heating and fueling
  - Heat removal
- Diagnostics and interpretation
- Integration of diagnostic data into coherent view
- Comparisons with theory

EXPERIMENTS CAN BE SMALL – LABORATORY SIZED

TYPICAL" LARGE EXPERIMENT - JET (JOINT EUROPEAN TOKAMAK)





FACILITIES AND INFRASTRUCTURE CAN BE EXTENSIVE

EXPERIMENTS ARE LARGE COLLABORATIVE VENTURES

- 100's of scientists and students, dozens of institutions
- Run as national (international) facilities
- Of course many smaller experiments exist as well - these are increasingly run as collaborations as well.

- Moderately large data sets
- 100 MB to 1GB per shot (Virtually all must be visualized)
- 3,000-10,000 shots per year - multi-TB archives
- Many diagnostics - most complex, interactions are important
- Significant interpretation effort required
- Runtime requirements for interpretation and display
- Machine control - part of the experiment

SUMMARY

- Controlled fusion has the potential to provide virtually unlimited energy **if** we can solve the associated technical problems

- Confinement of heat and particles is one of the foremost of these problems

- In experiments, heat and particle transport are mostly driven by turbulence

- Great progress has been made in understanding the nature of this turbulence and the means to reduce it.

MUCH WORK REMAINS TO BE DONE, THE PROBLEM OF TURBULENT TRANSPORT IS AMONG THE GREATEST CHALLENGES IN PHYSICS

THE END