The next step in fusion energy: ITER and the challenge of predicting its behavior

D. B. Batchelor

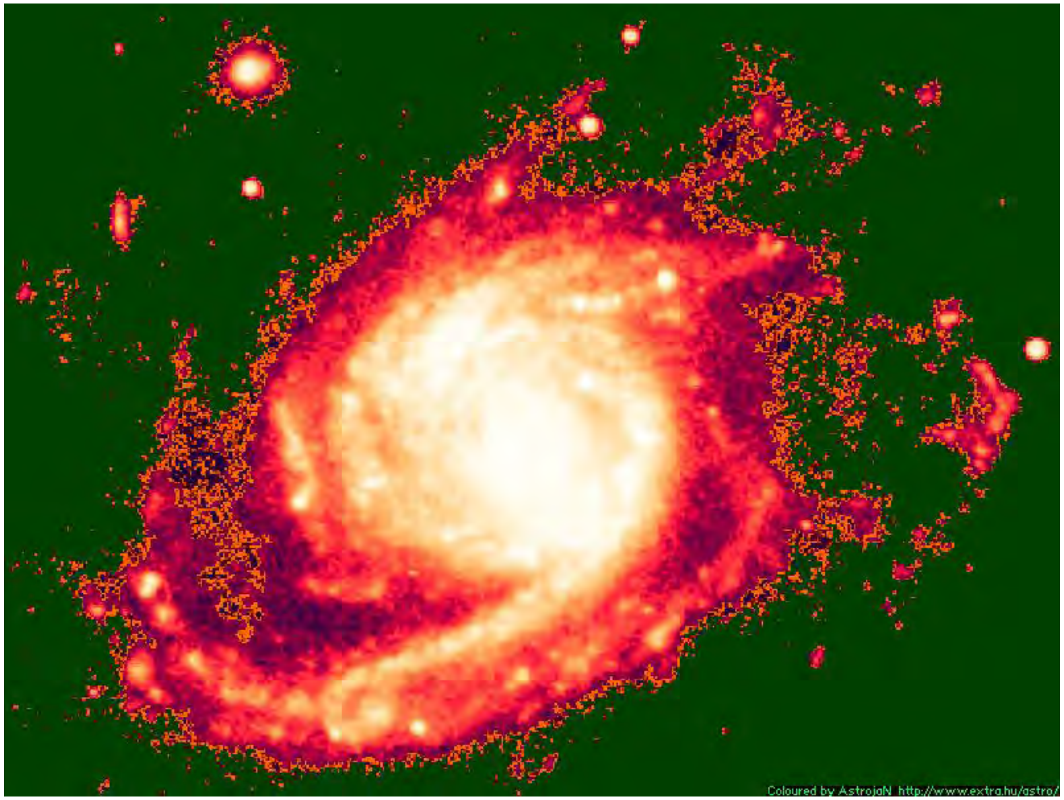
Oak Ridge National Laboratory

ASCAC Meeting

August 8-9, 2006

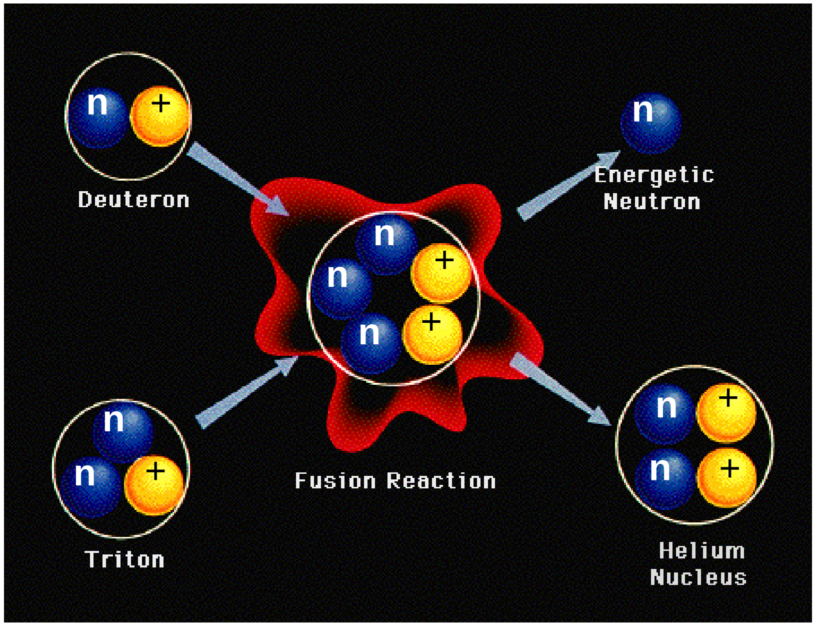
- **Three minute introduction to magnetic confinement fusion**
- **ITER – the next big step**
- **The role of simulation in fusion research**
- **An overview of fusion simulation today**
- **Where to go from here**

Nuclear fusion is the process of building up heavier nuclei by combining lighter ones.



It is the process that powers the sun and the stars, and that produces the elements.

The simplest fusion reaction – deuterium and tritium



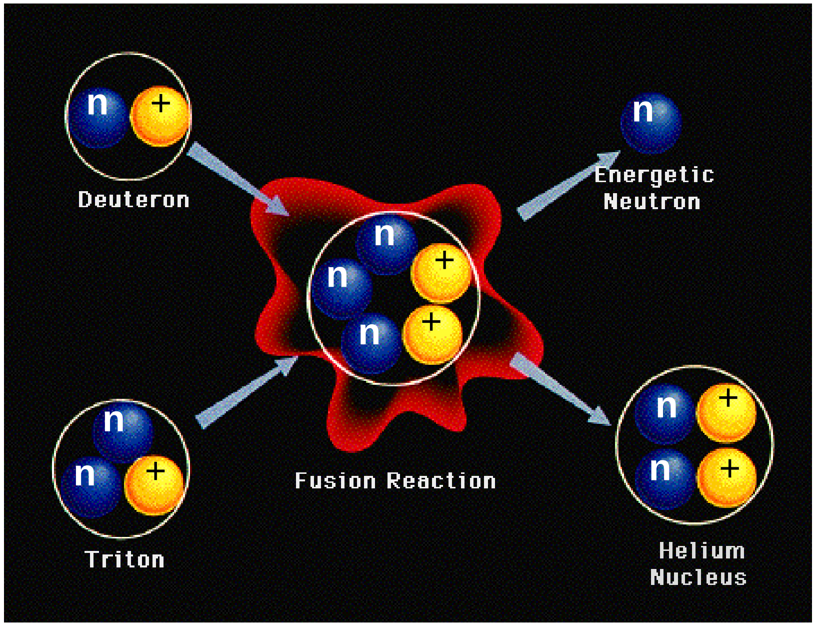
E_n = 14MeV

deposited in heat exchangers containing lithium for tritium breeding

E_α = 3.5 MEV

deposited in plasma, provides self heating

The simplest fusion reaction – deuterium and tritium



E_n = 14MeV

deposited in heat exchangers containing lithium for tritium breeding

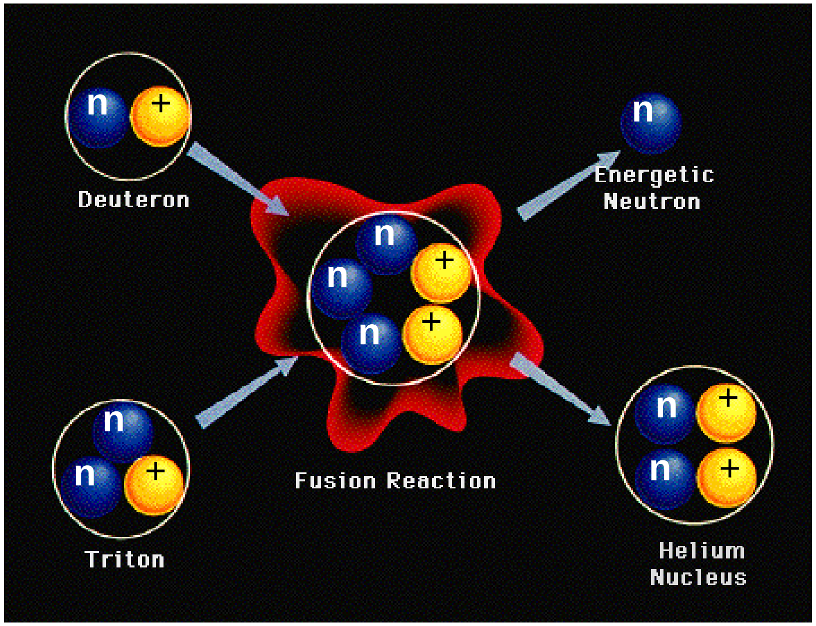
E_α = 3.5 MEV

deposited in plasma, provides self heating

About 1/2% of the mass is converted to energy ($E = mc^2$)

Remember this guy?

The simplest fusion reaction – deuterium and tritium



E_n = 14MeV

deposited in heat exchangers containing lithium for tritium breeding

E_α = 3.5 MEV

deposited in plasma, provides self heating

- **About 10 KeV of kinetic energy is required to overcome the Coulomb barrier to obtain nuclear reaction**
- **The nuclear interaction has short range whereas the Coulomb interaction is long range**
- **The fusion reaction rate of an energetic T in a D target is much less than the energy loss rate due to Coulomb scattering**

⇒ YOU CAN'T GET NET ENERGY GAIN BY USING AN ACCELLERATOR, SHOOTING INTO A COLD TARGET

We *can* get net energy production from a *thermonuclear* process

- **We heat a large number of particles so that the temperature is ~ 10KeV ⇔ 100,000,000°**
  ⇒ PLASMA

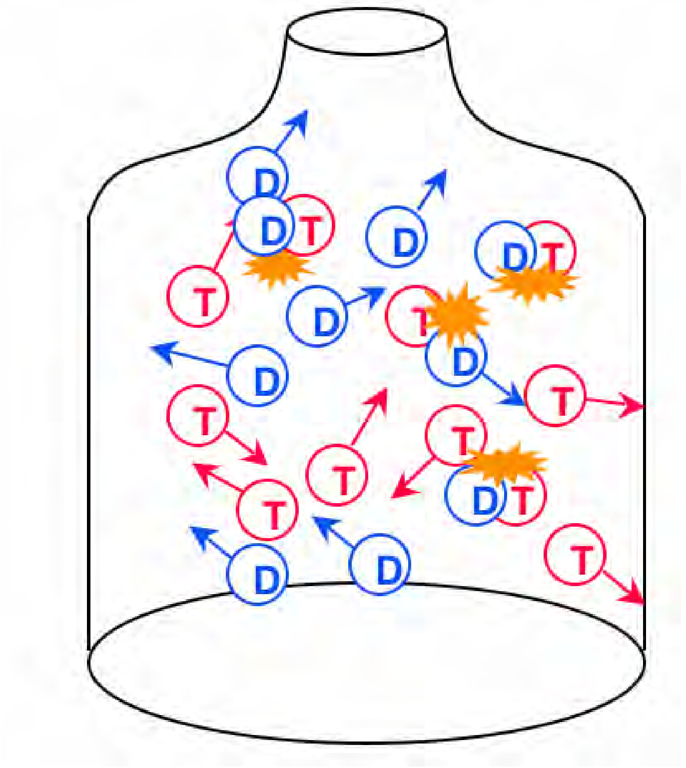
- **Then we hold the fuel particles and energy long enough for many reactions to occur**

$$Q = \frac{P_{fusion}}{P_{heating}} \Rightarrow \begin{cases} = 1 \rightarrow \text{break even} \\ > 20 \rightarrow \text{energy feasible} \\ \infty \rightarrow \text{ignition} \end{cases}$$

Lawson *breakeven* criterion:
high particle density – *n*
long confinement time – τ
at high enough temperature – T

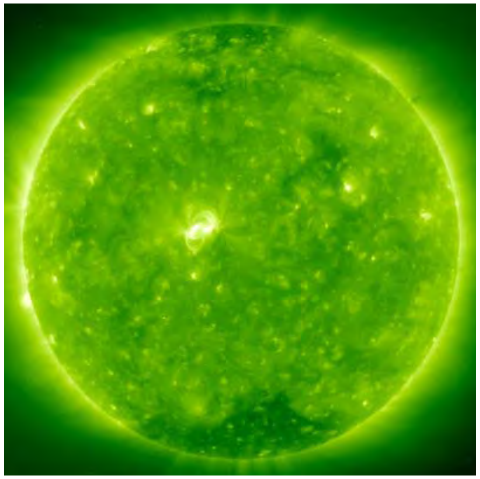
$$n_e \tau_E > 10^{20}\ \mathrm{m^{-3}s}$$

Nuclear thermos bottle



What can we really use for our nuclear thermos bottle?

The plasma is hotter than the sun.
We certainly can't use a material!



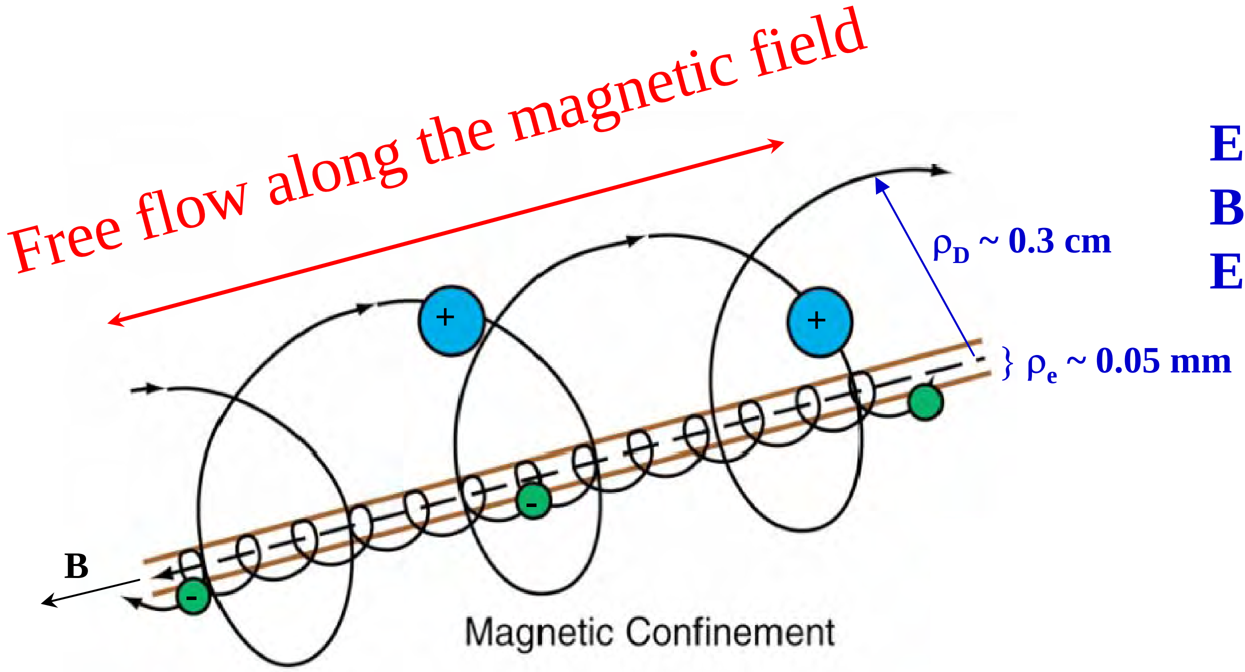
- **Gravitational confinement → it works for the sun**

- **Inertial confinement → it works for H bombs, and maybe for laser fusion**

Magnetic confinement →

Very hot plasmas can be confined using strong magnetic fields

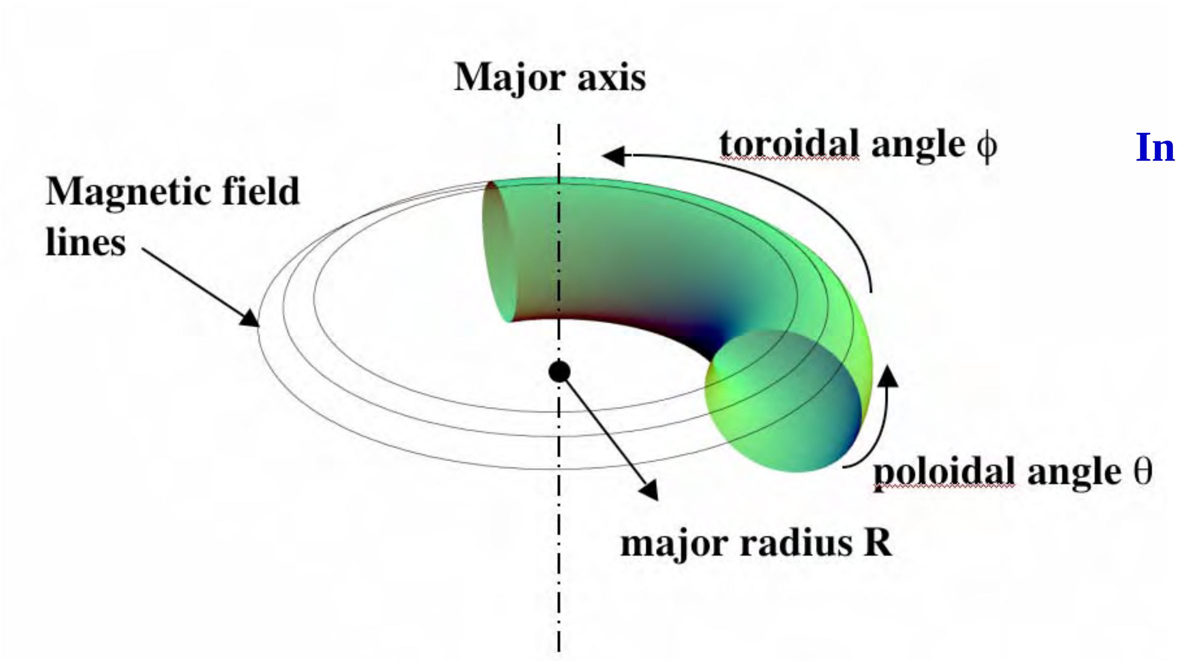
A magnetic field confines charged particles in the direction perpendicular to the field into nearly circular orbits

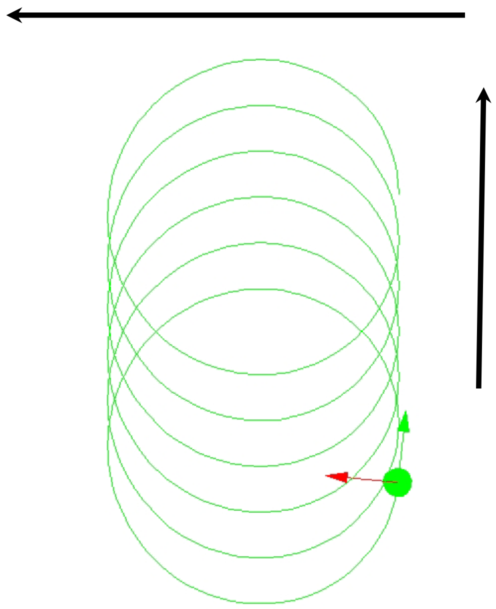


Example:
B = 5 Tesla
E = 10 KeV

To get confinement along the field we bend the field lines into a torus

Unfortunately a simple toroidal magnetic field doesn’t provide confinement – particles drift away from magnetic field lines



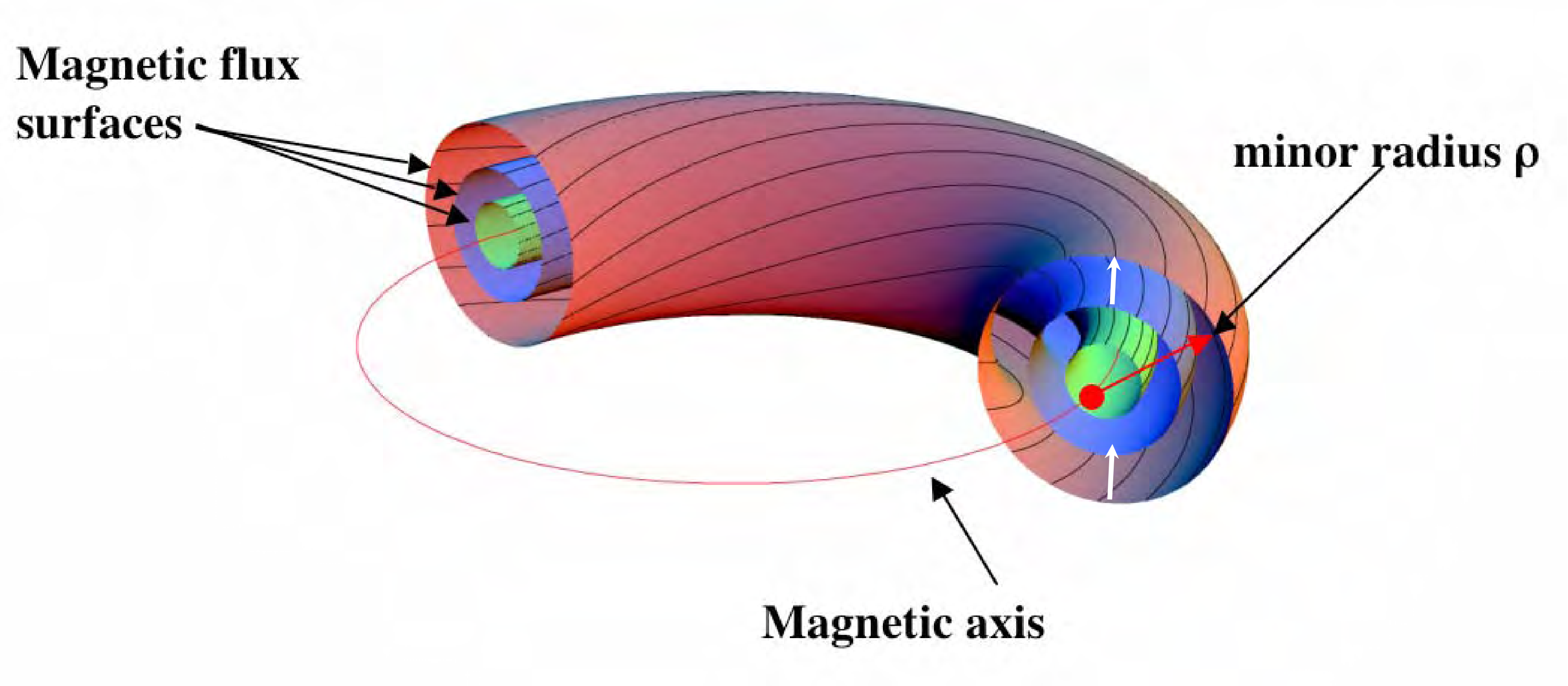


Increasing magnetic field strength

Drift velocity

∇B drift due to 1/R $\Rightarrow$ electrons $\uparrow$, ions $\downarrow$

So we add a magnetic field component winding the short way around → poloidal field

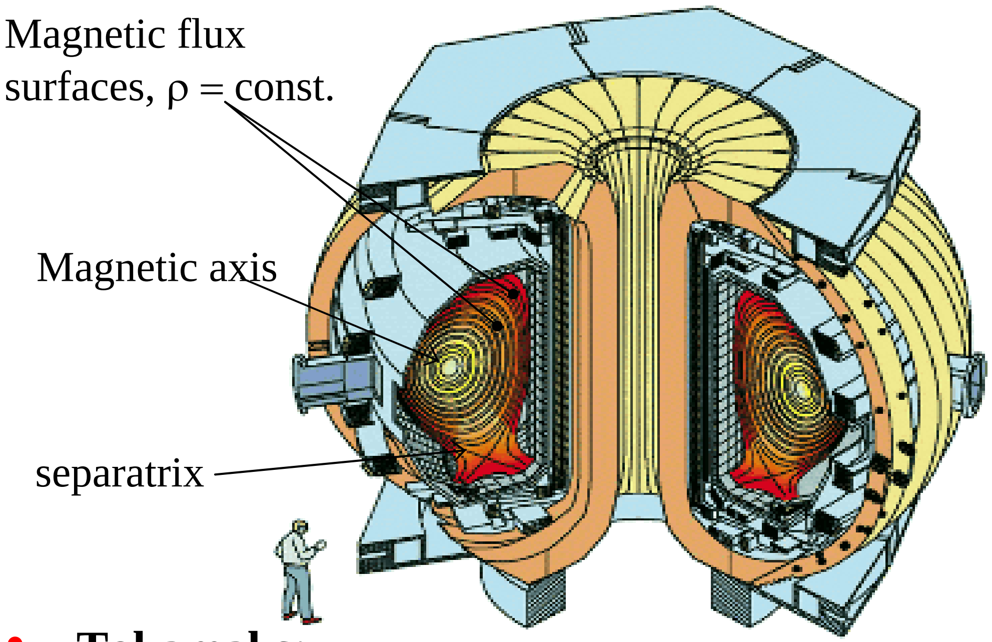


- **Magnetic field lines lie on closed, nested surfaces – flux surfaces, Ψ = const.**
- **Vertical ∇B drift averages to zero as particle follows field around poloidally**

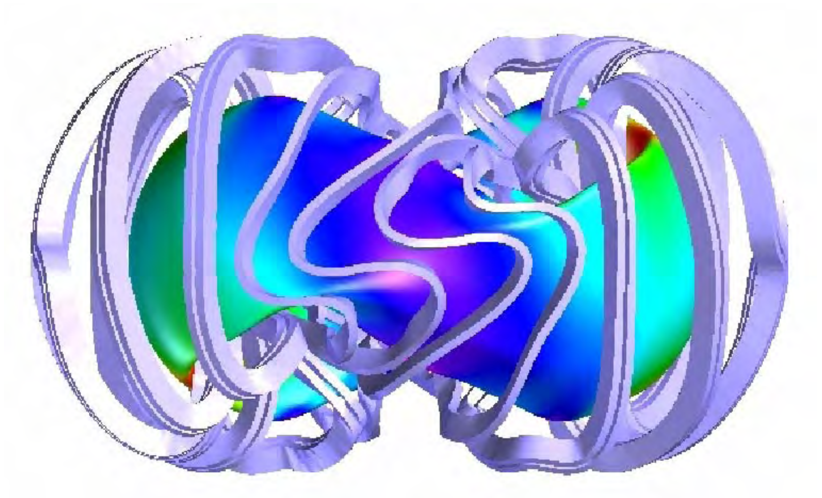
An *ideal* magnetic field with closed magnetic surfaces can hold *single* charged particles forever

Required poloidal magnetic field is produced either by large internal plasma current (tokamak) or external coils (stellarator)

Tokamak, axisymmetric



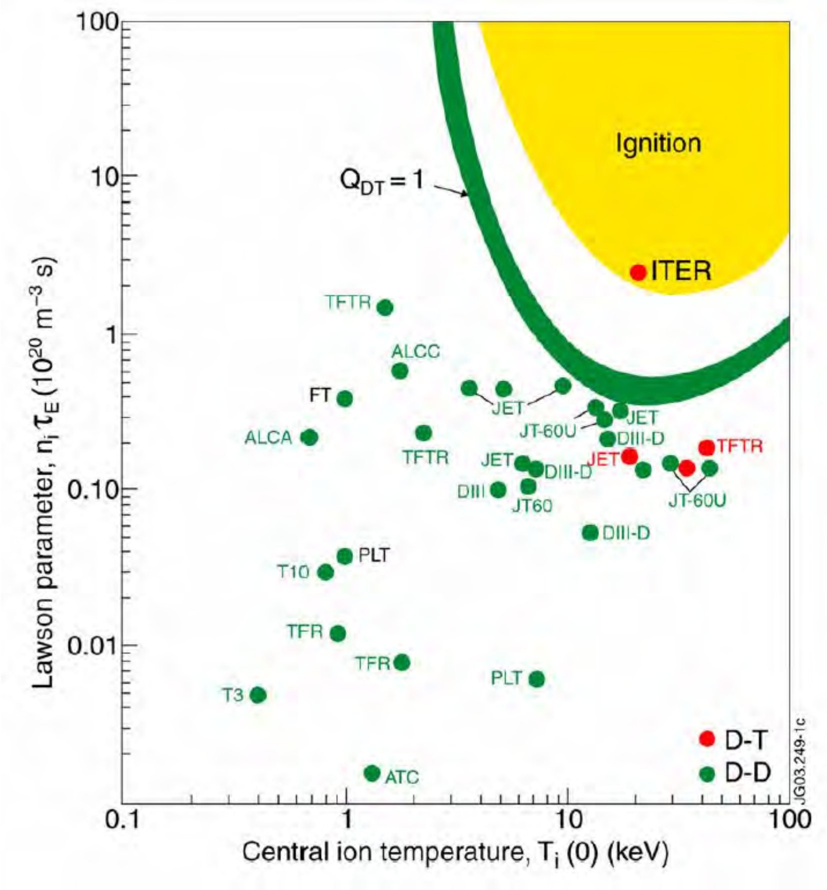
Compact Stellarator non-axisymmetric!!

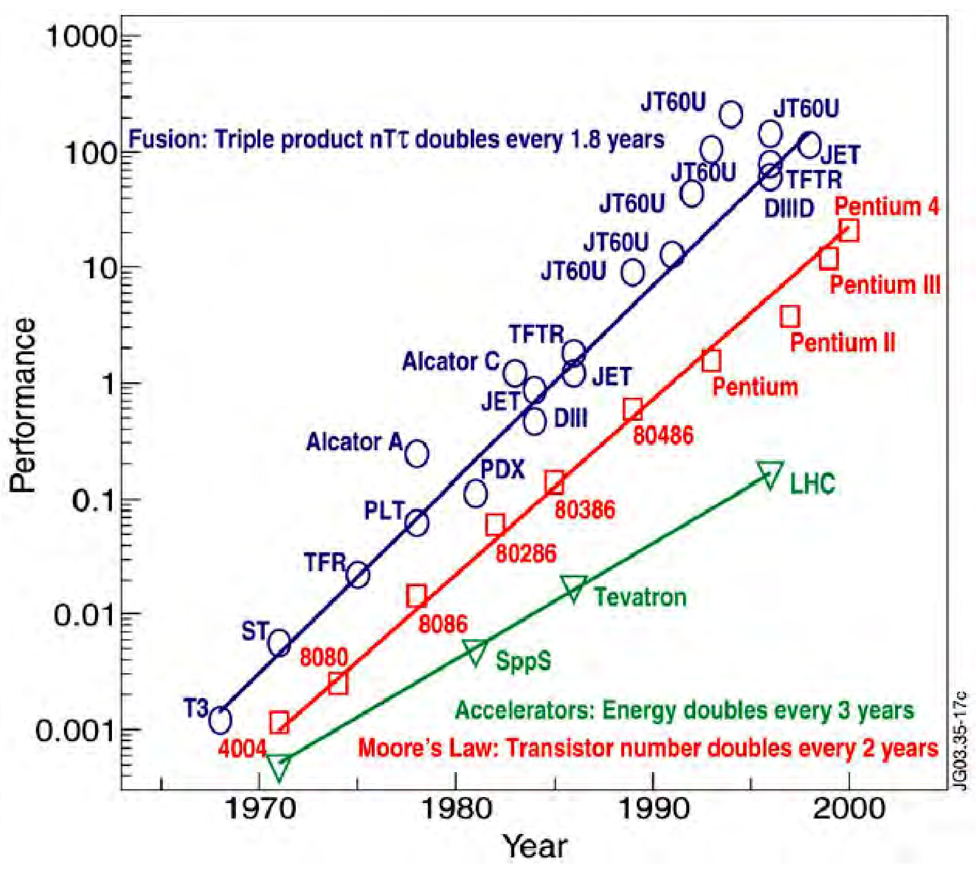


- **Tokamaks:**
  - **Axisymmetric ⇒ very good plasma confinement**
  - **Large internal current a problem ⇒ Instability source, Inductive drive → pulsed, non-inductive drive expensive**

- **Stellarators:**
  - **Non-axisymmetric ⇒ not so good plasma confinement**
  - **Small internal current ⇒ Inherently steady state, less susceptible to current driven instability**

Where are we now? Present fusion experiments are at the “scientific breakeven” level of performance





Why do we care? – Advantages of fusion energy

- **Inexhaustible supply of fuel – .01% of water is Deuterium**
- **No greenhouse gas combustion products – CO2, NoX, etc**
- **Relatively small radioactivity hazard – byproduct is helium,** **There is an inventory of radioactive tritium and activated steel in the reactor device. Essentially no biologically active waste such as strontium or iodine.**
- **No possibility of nuclear runaway/meltdown – safe for location near population centers**
- **Existing distribution infrastructure**

Electricity supply for one family / year with 0.08g D and 0.02 g Li

Deuterium extracted from ordinary water

Tritium produced from lithium + fusion neutron

So, what is the next step?

Understand the physics of "burning" fusion plasmas

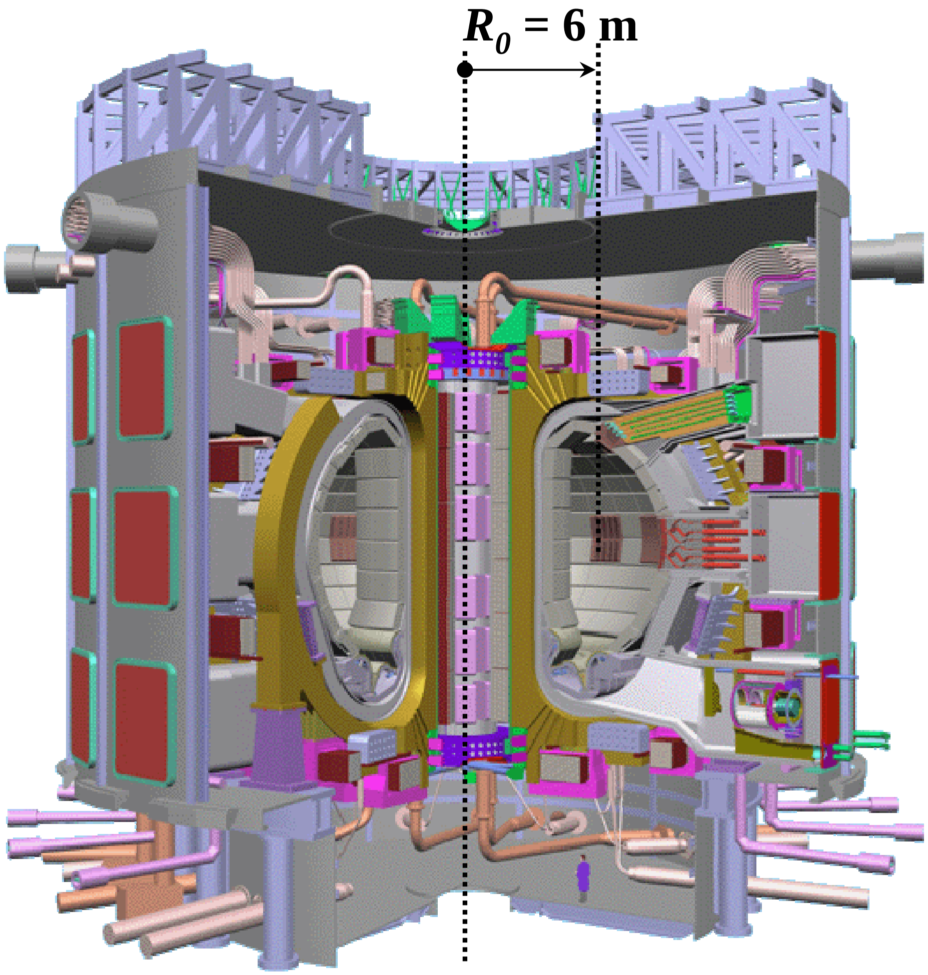
- **Plasma self-organization – most of the plasma heating will be from internal fusion reactions rather than external sources**
- **Control of burning plasmas with external sources – inductive fields, electromagnetic waves, particle beams …**
- **Develop long pulse, or steady, plasma operating states**

Develop and demonstrate technologies for fusion reactors

- **Demonstrate availability and integration of essential nuclear fusion technologies**
- **Test tritium breeding concepts**
- **Test fusion materials in reactor-like environment**

ITER will take the next steps to explore the physics of a "burning" fusion plasma

An international effort: Japan, Europe, US, Russia, China, Korea, India



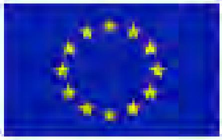
- **Fusion power ~ 500MW**
- **$I_{plasma} = 15$ MA, $B_0 = 5$ Tesla**
  T ~ 10 keV, τ_E ~ 4 sec
- **Large – 30m tall, 20kTons**
- **Expensive > \$5B+**
- **High level negotiations under way on roles and contributions**
- **First burning plasmas ~2018**

Latest news ***http://www.iter.org***

ITER Evolution

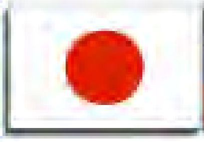
Conceptual / Engineering Design Activities 1988-2001

4



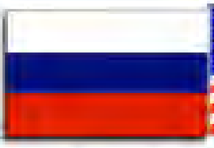
European Union (1988-)

2



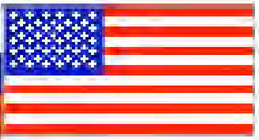
Japan (1988-)

1



USSR/Russian Federation (1988-)

1



United States (1988-1998, 2003-)

Coordinated Activities / Transitional Arrangements (2001-)

1

China (2003-)

1

South Korea (2003-)

1

India (2005-)

ITER engages the governments of over 50% of the world's population

---

ITER – Originally an acronym for International Thermonuclear Experimental Reactor

means "The Way" in Latin

ITER Status – Site is Cadarache, France, adjacent to CEA

Kaname Ikeda (Director General, Dec-2005)

- Nuclear engineer
- Leader in Japanese space and nuclear fuel programs
- Ambassador to Croatia

- **Licensing 2008**
- **Construction/commissioning 2008 - 2016**
- **Research 2016 - 20206**

Role of Simulation in Fusion Research

Basic theory requires simulation – i.e. large scale computation

- **Needed to find the consequences of any theory in a real situation**
- **Needed to validate (or invalidate) a theory by experimental comparison**

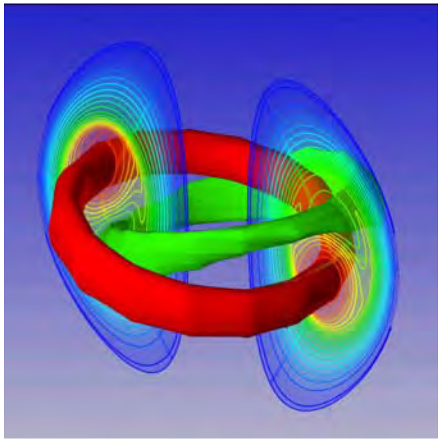
Simulation directly supports experiments

- **Facility design**
- **Plasma scenario development**
- **Experimental (shot) design**
- **Experiment interpretation**

Understanding the basic theory requires simulation

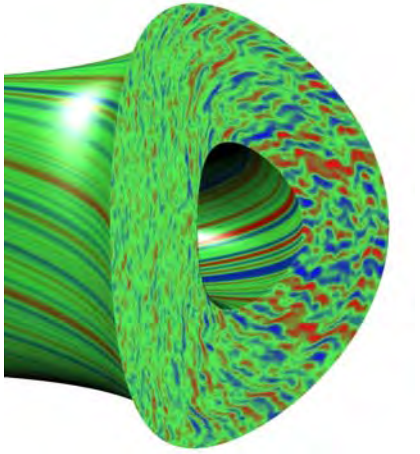
Hydromagnetic force balance of plasma pressure supported by J×B force

- MHD equilbrium
- Macroscopic fluid instability
- Current and magnetic field evolution



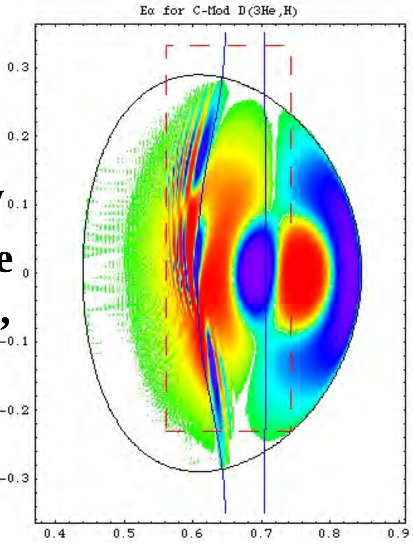
Kinetic stability and transport

- Micro-stability
- Turbulence and turbulent transport
- Long mean-free-path collisional transport
- Fusion heating



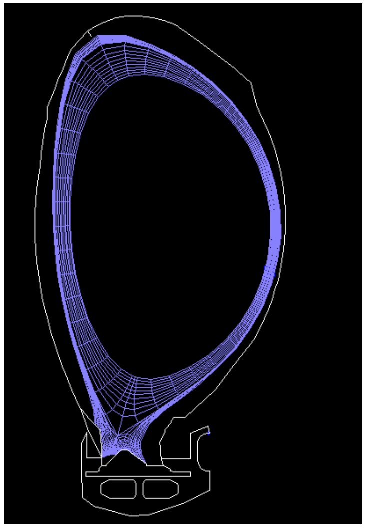
Injection of high-power waves or particle beams, magnetic flux

- Plasma heating
- Externally driven current or plasma flow
- Wave processes – mode conversion, absorption, reflection
- Non-Maxwellian particle distributions

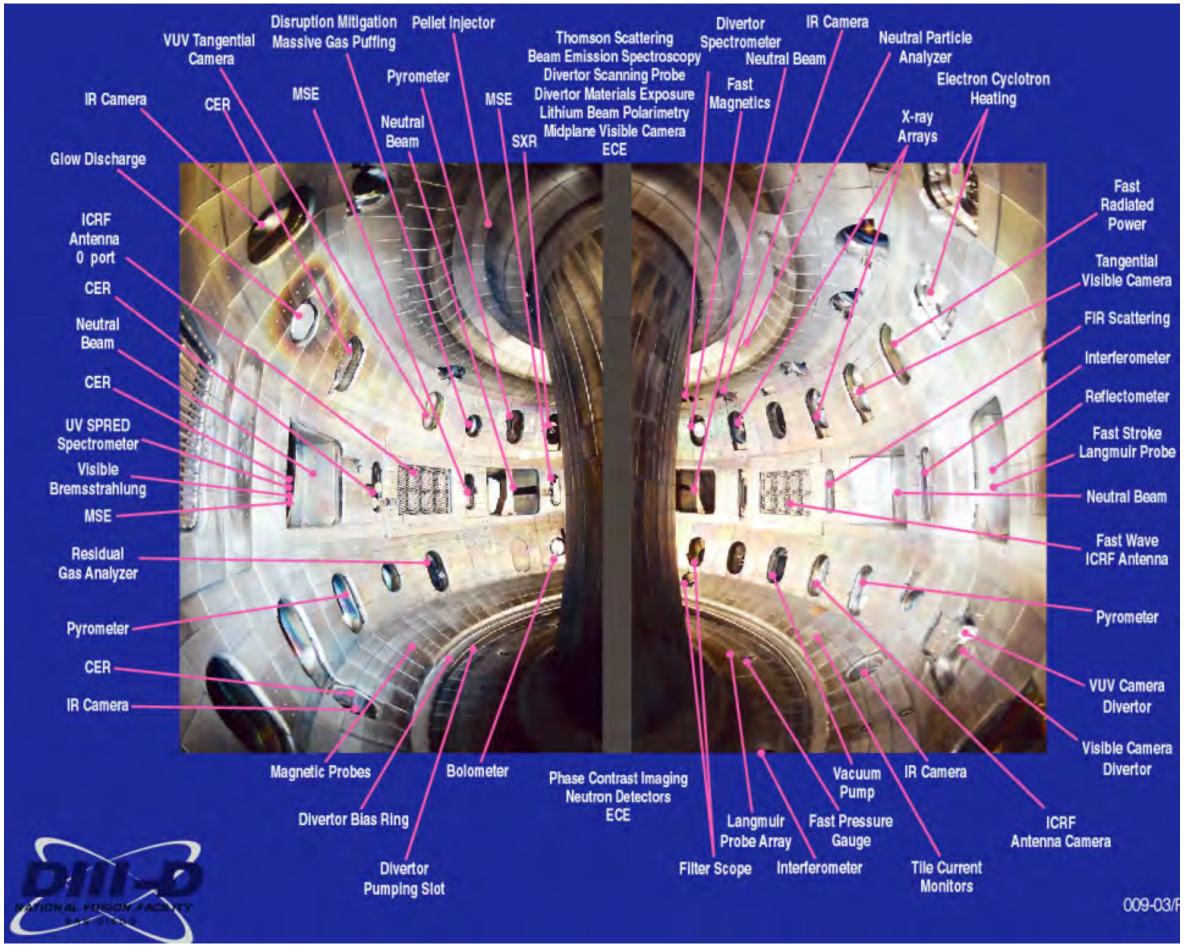


Plasma/edge interactions

- Atomic physics processes
- Transition closed → open flux surfaces
- Transport on open field lines
- Turbulence
- Plasma/material interactions



Simulation and modeling are essential elements in interpreting results of fusion experiments

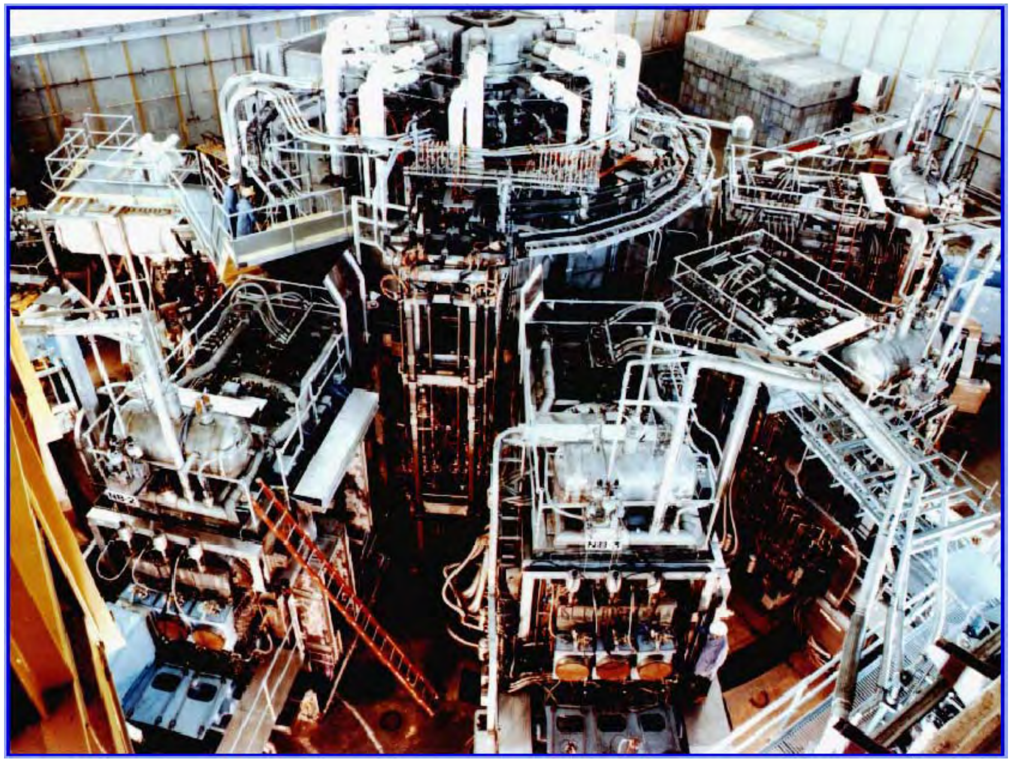


- Diagnostics of hot plasmas rely on interpretation of radiation and particles that come out of the plasma – inversion requires simulation
- Many of the phenomena cannot be measured directly

Operating and research costs on large devices are comparable to construction – for ITER could be $1M/DAY

Tokamak Fusion Test
Reactor (TFTR)
PPPL (1982-1997† R.I.P.)

Scale TFTR << Scale ITER



Simulation is required to plan and design experiments

- **What effects are expected?**
- **Can required plasma conditions be produced?**
- **Can expected phenomena be observed/measured with available diagnostics?**

Scientific challenges of fusion simulation

Fundamental challenges to fusion simulation – physics, mathematics, computation

Basic description of plasma is 7D → *f*(x, v, t), evolution determined by non-linear Boltzman equation + Maxwell's equations

$$\frac{\partial f}{\partial t} + \mathrm{v}\cdot\nabla f + \tfrac{q}{m}\left[E + \mathrm{v}\times B\right]\cdot\nabla_{\mathrm{v}} f = C(f)$$

convection in space

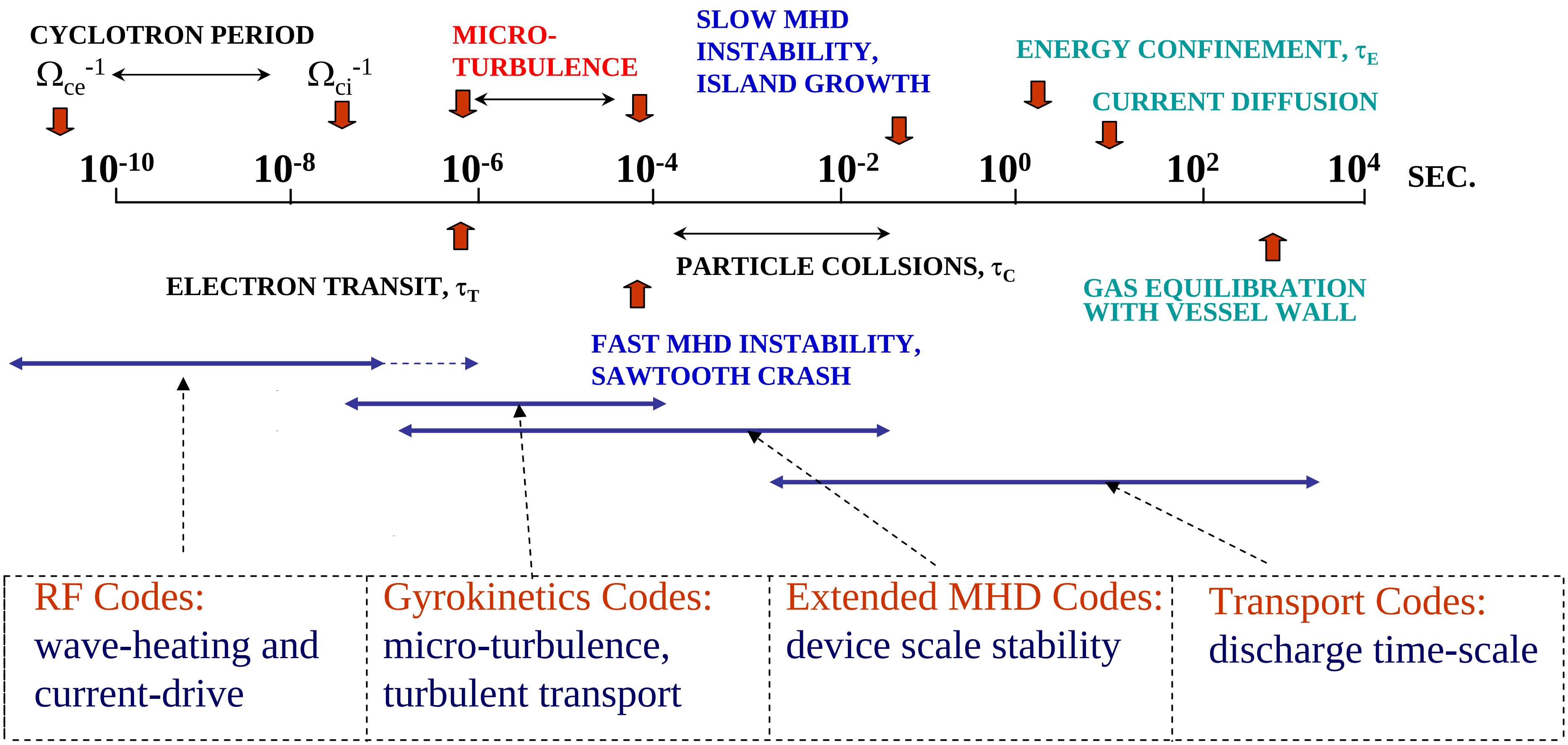
convection in velocity space

Collisional relaxation toward Maxwellian in velocity space

- **High dimensionality**
- **Extreme range of time scales – wall equilibration/electron cyclotron O(10^{14})**
- **Extreme range of spatial scales – machine radius/electron gyroradius O(10^{4})**
- **Extreme anisotropy – mean free path in magnetic field parallel/perp O(10^{8})**
- **Non-linearity**
- **Sensitivity to geometric details**

To deal with this there have been developed several classes of sub-disciplines in fusion physics each with related simulation codes

Fusion simulation disciplines have evolved to study different kinds of phenomena on different time scales



CYCLOTRON PERIOD

Ω_{ce}^{-1} Ω_{ci}^{-1}

MICRO-TURBULENCE

SLOW MHD INSTABILITY, ISLAND GROWTH

ENERGY CONFINEMENT, τ_E

CURRENT DIFFUSION

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} SEC.

ELECTRON TRANSIT, τ_T

PARTICLE COLLSIONS, τ_C

GAS EQUILIBRATION WITH VESSEL WALL

FAST MHD INSTABILITY, SAWTOOTH CRASH

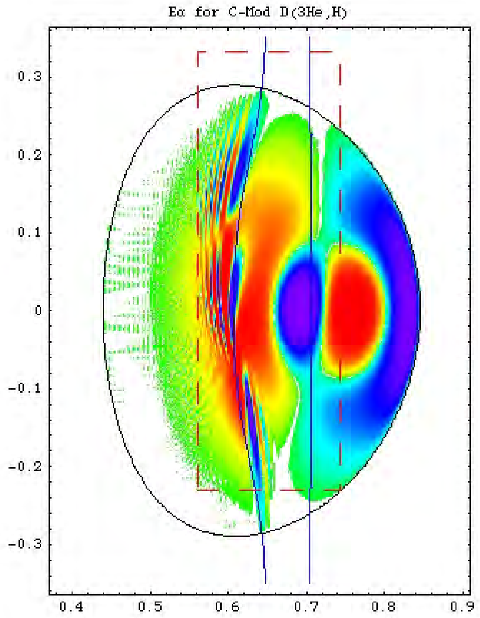
RF Codes: wave-heating and current-drive

Gyrokinetics Codes: micro-turbulence, turbulent transport

Extended MHD Codes: device scale stability

Transport Codes: discharge time-scale

RF codes solve for high power plasma waves used to heat and control fusion plasmas, $\tau < 10^{-7}$ sec



$$\nabla \times \nabla \times \mathbf{E} + \frac{\omega^2}{c^2}\mathbf{E} = \mathbf{J}_P \circ \mathbf{E} + \mathbf{J}_{ant} \quad : \quad + \text{boundary conditions}$$

$$\mathbf{J}_P(\mathbf{x},t) = e\int d^3 v \mathbf{v} f_1(\mathbf{x},\mathbf{v},t) \qquad f_1(\mathbf{x},\mathbf{v},t) = -\frac{e}{m}\int_{-\infty}^{t} dt' \mathbf{E}_1(\mathbf{x}'(\mathbf{x},\mathbf{v},t'),t') \cdot \frac{\partial f_0}{\partial \mathbf{v}'}$$

plasma wave current: an integral operator on E

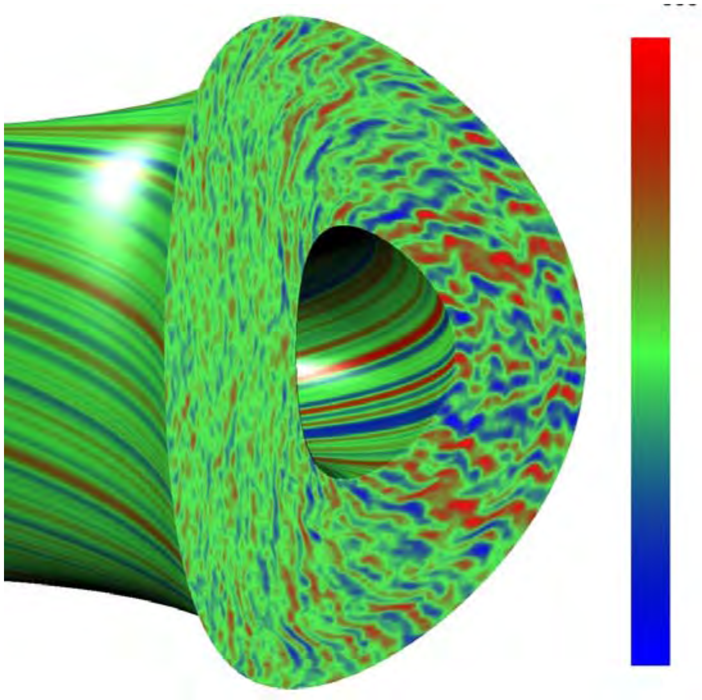
Plasma response is highly non-local – solve integral equation

Quasi-linear – average distribution function f_0 evolves slowly, described by Fokker-Planck equation

- **Objectives: understand heating of plasmas to ignition, detailed plasma control through localized heat, current and flow drive**

Microturbulence codes describe the small scale fluctuations that presently dominate transport of matter and heat in fusion plasmas, $\tau \sim 10^{-7} - 10^{-4}$ sec

$$\frac{\partial \tilde{h}_a}{\partial t} + \left(\mathbf{v}_{\chi a} + \mathbf{v}_{da} + v_{\parallel}\hat{\mathbf{b}}\right) \cdot \nabla \tilde{h}_a = -\mathbf{v}_{\chi a} \cdot \nabla f_{0a} - q_a \frac{\partial f_{0a}}{\partial W} \frac{\partial \tilde{\chi}}{\partial t} + \text{collisions} + \text{sources/sinks},$$



Gyrokinetic equation:

Direct solution of pde, or

Particle-in-cell (PIC)

- **Objectives: understand and cure rapid transport of energy and particles out of the system**

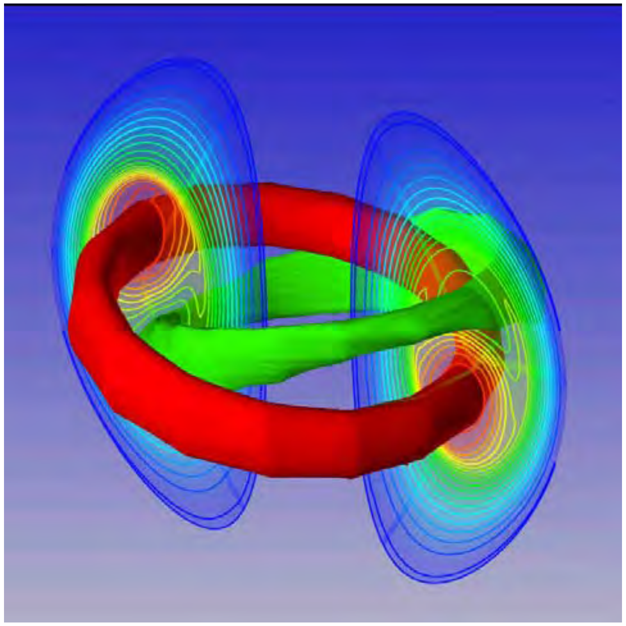
(X)MHD codes describe gross plasma motion in a fluid model with extensions to kinetic and non-ideal effects, $\tau \sim 10^{-6} - 10^{-1}$ sec

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla\right)\mathbf{V} = -\nabla p - \nabla\cdot\Pi + \mathbf{J}\times\mathbf{B}$$

$$\left(\frac{\partial}{\partial t} + \mathbf{V}_\alpha\cdot\nabla\right)p_\alpha = -\gamma\, p_\alpha\nabla\cdot\mathbf{V}_\alpha + (\gamma-1)(Q_\alpha - \nabla\cdot\mathbf{q}_\alpha)$$

$$\mathbf{E} = -\mathbf{V}\times\mathbf{B} + \eta\mathbf{J} + \frac{1}{en}\mathbf{J}\times\mathbf{B} + \frac{1}{\varepsilon_0\omega_p^2}\left[\frac{\partial\mathbf{J}}{\partial t} + \nabla\cdot(\mathbf{J}\mathbf{V} + \mathbf{V}\mathbf{J}) + \sum_\alpha\frac{q_\alpha}{m_\alpha}(\nabla p_\alpha + \nabla\cdot\Pi_\alpha)\right]$$

$$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}\,, \qquad \nabla\cdot\mathbf{B} = 0$$



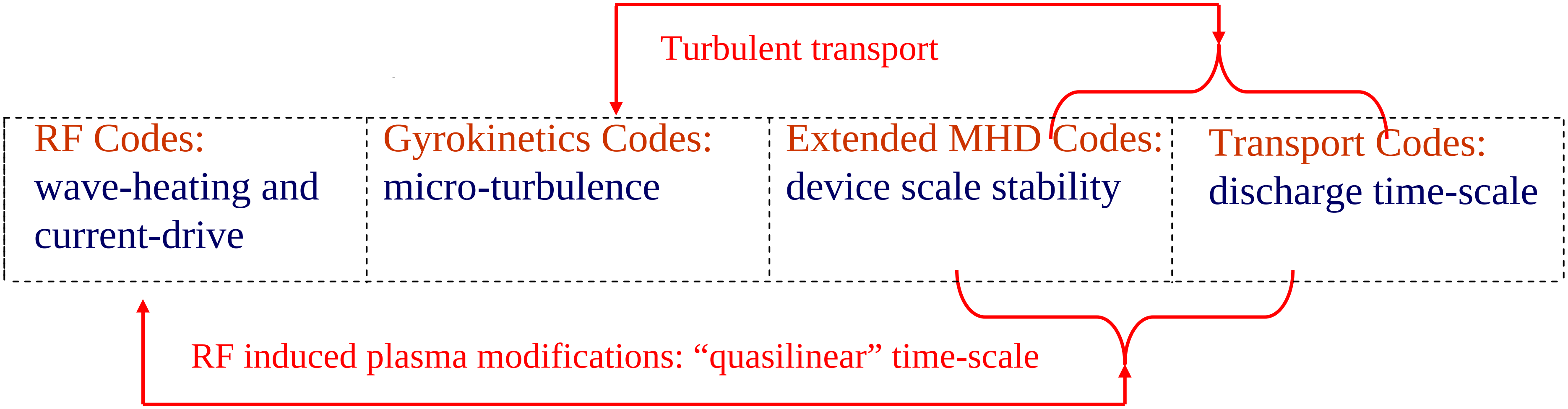
Snapshot of a 3D calculation of a reconnection event in a low-aspect ratio tokamak. Two iso-pressure surfaces are shown

- **Objectives: Understand global force balance, and large scale, fluid-like instabilities – sawtooth instabilities, very slowly growing neoclassical tearing modes**

Bringing it all together: Integrated modeling

We may have models for atmosphere, ocean, sea ice and biomass, but we can't hope to understand global warming until we determine how these systems interact.

Integrated Fusion Simulation – even when the time scales are well separated they can interact



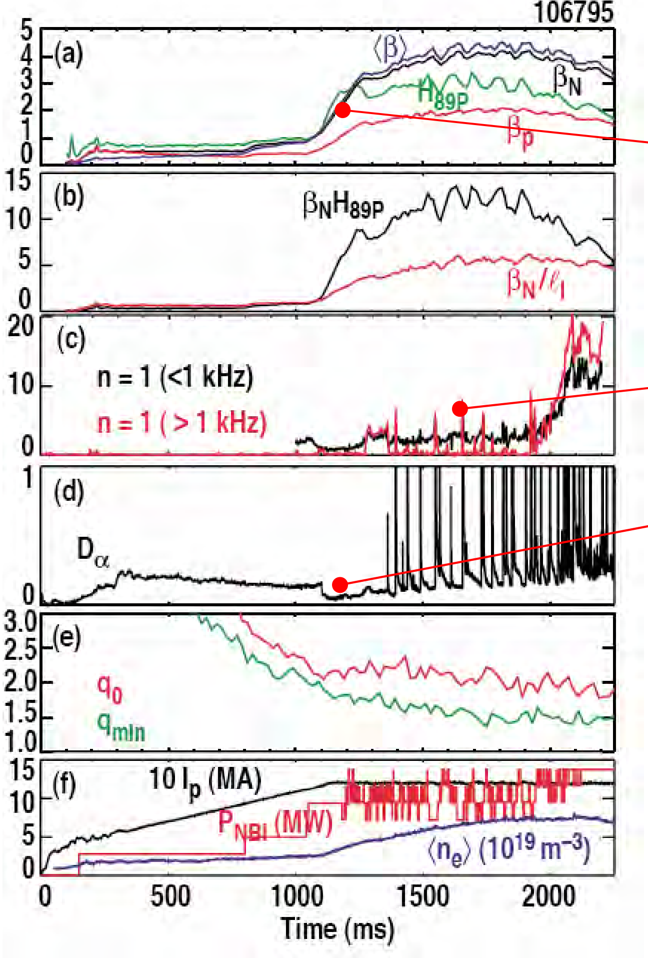
- **Unlike climate model components (atmosphere, land-mass, ocean, sea ice) which have a separating boundary, coupled fusion process can occur at the same time, in the same place, in the same chunk of plasma**

- **Being made thinkable by access to super-computers, and collaborations with computer science and mathematics expertise ⇒ SciDAC**

Surprise – in many circumstances we find sudden transitions to states with much improved plasma confinement – local transport barriers

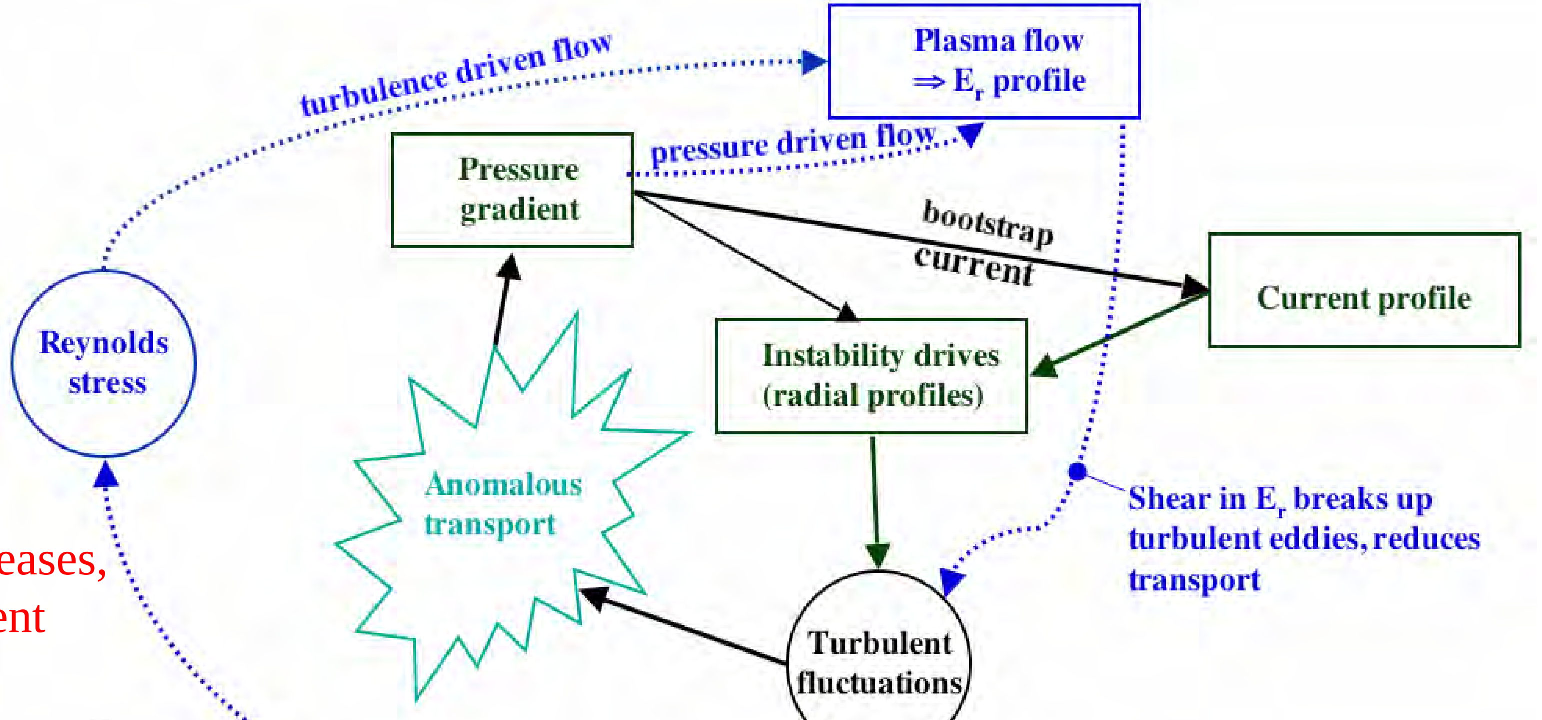
DIII-D Tokamak

K. Burrell *et al*



- **Rapid rise of plasma pressure**
- **Localized decreased levels of microturbulence**
- **Increased levels of bursts of MHD activity**
- **Drop of radiation at plasma edge, followed by radiation bursts correlated with MHD modes**
- **Appearance of sheared poloidal flow velocity in plasma**

To understand this phenomenon requires coupled simulation of a number of complex, evolutionary processes



Plasma flow
⇒ E_r profile

Pressure gradient

Current profile

Instability drives (radial profiles)

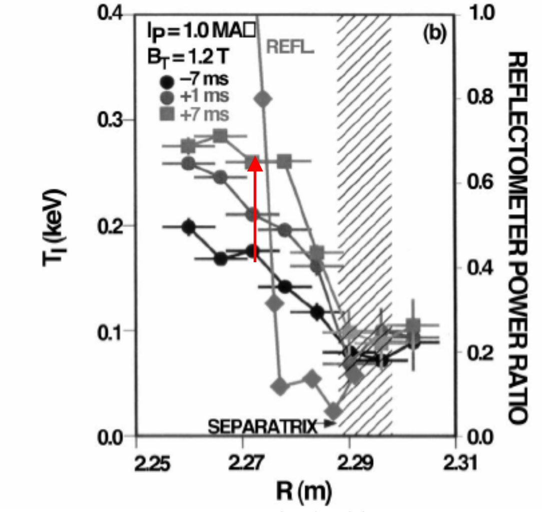
Reynolds stress

Anomalous transport

Turbulent fluctuations

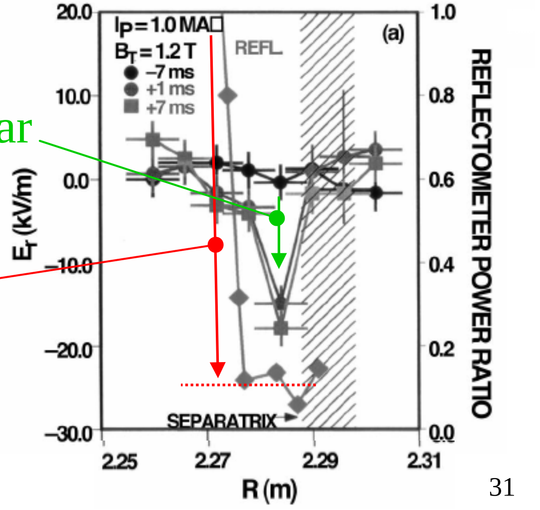
Shear in E_r breaks up turbulent eddies, reduces transport

Transport decreases, Pressure gradient increases

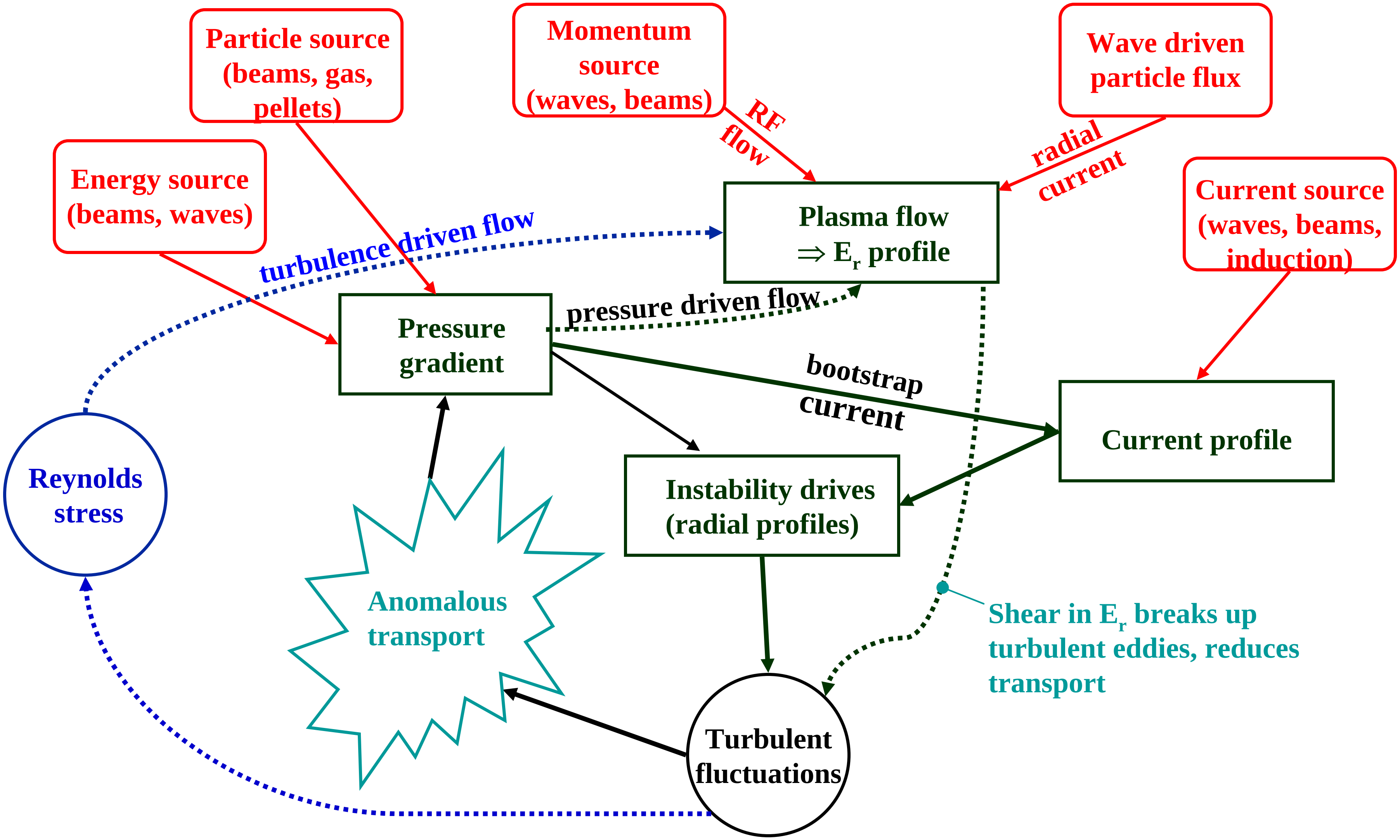


Strong electric field shear appears.

Turbulent fluctuation level drops in shear region.



For success we have not just to understand, but to <u>control</u> non-linearly coupled processes – we use external sources to probe and control



Comprehensive, coupled simulation is essential for programming the various control actuators

A comprehensive simulation capability is needed for fusion – requiring resources comparable to a major device construction

From Charge to the Fusion Energy Sciences Advisory Committee (FESAC): Roadmap for a joint initiative with the Office of Advanced Scientific Computing Research (OASCR). – James F. Decker, Acting Director, Office of Science (2001)

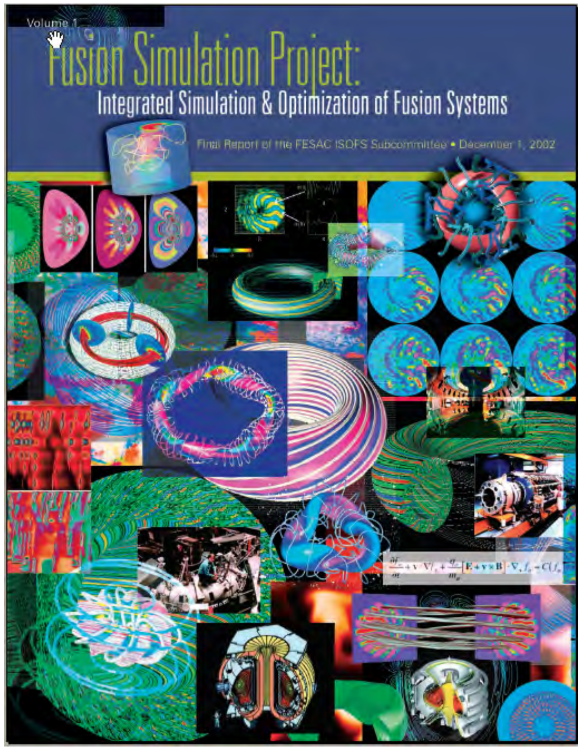
- "…develop a fully integrated capability for predicting the performance of externally-controlled systems including turbulent transport, macroscopic stability, wave-particle physics, and multi-phase interfaces."
- "The initiative should be planned as a 5-6 year program"
- "Rough estimates are that an integrated simulation initiative would require a total funding level of about $20 million per year, with funding for the plasma scientists provided by OFES and funding for the applied mathematicians, computer scientists, and computational resources provided by OASCR."

What came out was a proposed: Fusion Simulation Project (FSP)

"Ultimate (~ 15 yr) objective is to predict reliably the behavior of plasma discharges in a toroidal magnetic fusion device on all relevant time and space scales."

We have begun two pilot projects, under SciDAC aegis – "Focused Integration Initiatives"

- **Center for Simulation of Wave Interactions with MHD (SWIM)**
- **Center for Plasma Edge Simulation (CPES)**
- **Probably one more soon (SciDAC II)**
- **This document has been widely read around the world – similar, but less ambitious projects begun in Japan, Europe, (China)**



Volume 1

Fusion Simulation Project:

Integrated Simulation & Optimization of Fusion Systems

Final Report of the FESAC ISOFS Subcommittee • December 1, 2002

We have a significant comparative advantage to succeed in such an undertaking

- **World leading fusion theory and simulation capability**
- **Established, working partnerships with Mathematics and Computer Science**
- **Accessibility to supercomputing resources**

Concluding remarks

- **Numerical modeling has advanced to the stage that it plays an important role in understanding and predicting plasma behavior in existing experiments**
- **Full predictive modeling of fusion plasmas will require cross-coupling of many complex physics processes and solution over many space and time scales – this will be interesting**
- **New computers and algorithms make it possible to think about new levels of simulation**
- **Plans are being developed for and an integrated fusion simulation activity**
  ⇒ Fusion Simulation Project (FSP)
- **Full simulations of burning plasma experiments could be possible in the 10 year to 15 year time frame if an aggressive program is launched in this area**
- **A fusion simulator would have significant benefits to the fusion sciences program and to a "burning" plasma experiment – a cost effective way to ensure that the US has a significant science role in ITER**