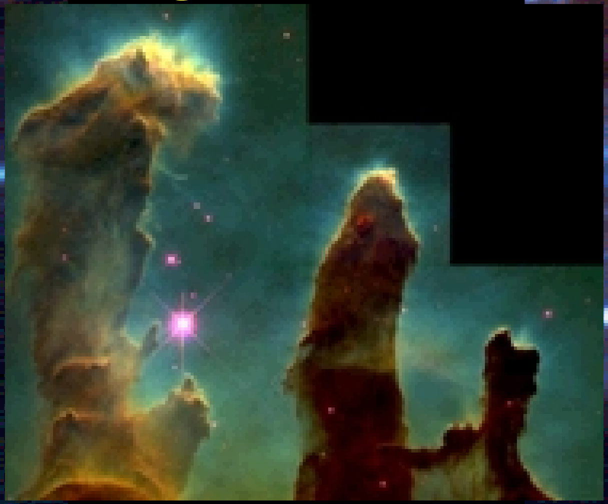
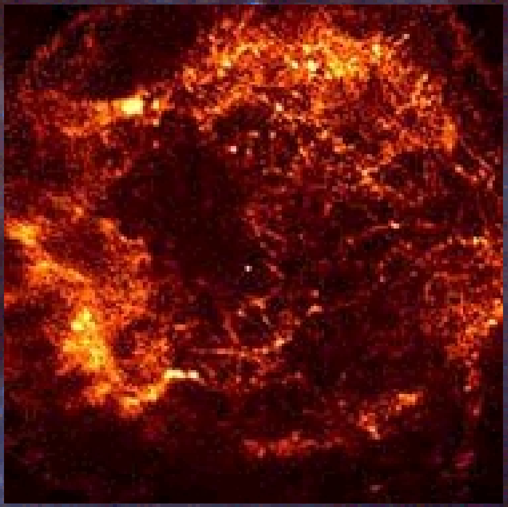
Fusion and Plasma Physics are at the Core of Nature's Most Powerful Self-Driven Systems

Eagle Nebula



HST

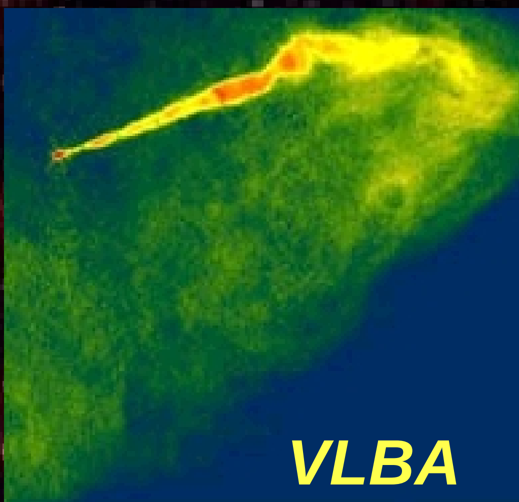
Cassiopia A

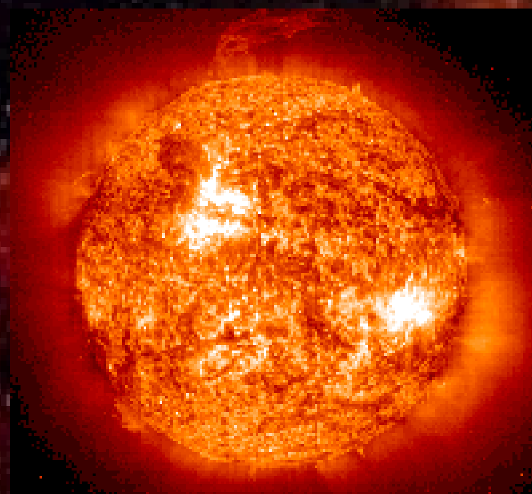


CHANDRA

Can we Solve the Mystery of Producing a Stationary Self-Driven Fusion FIRE??

Galactic Jet - M87





SOHO

CHANDRA

Confining a Fusion Fire

A Grand Challenge for Science and Technology

Dale Meade

Princeton University

Presented at

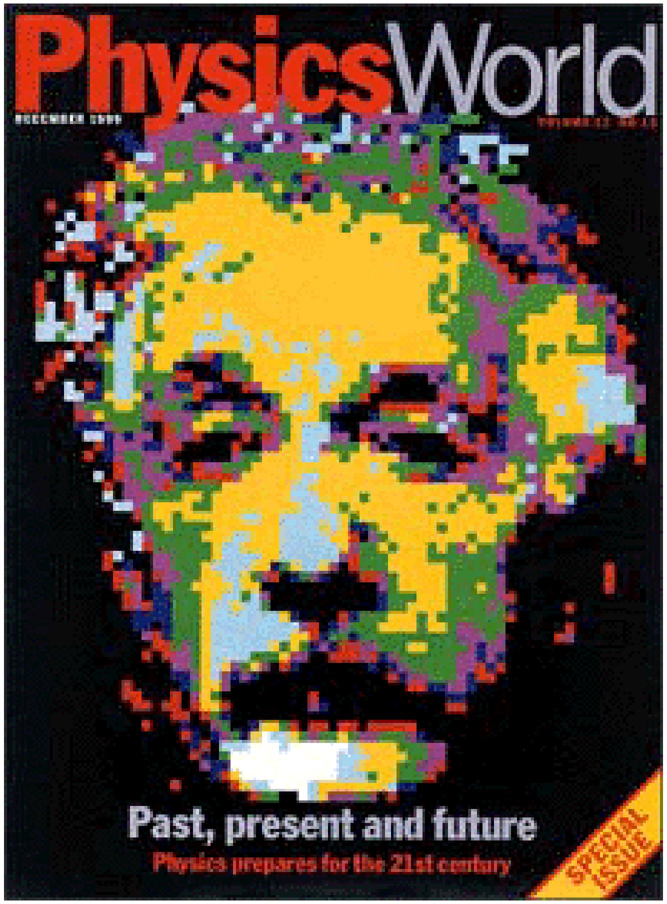
Department of Physics

University of Wisconsin, Madison

http://fire.pppl.gov **March 31, 2000** **http://www.cpepweb.org**

Fusion is an Outstanding Physics Challenge and is Connected to Other Outstanding Challenges

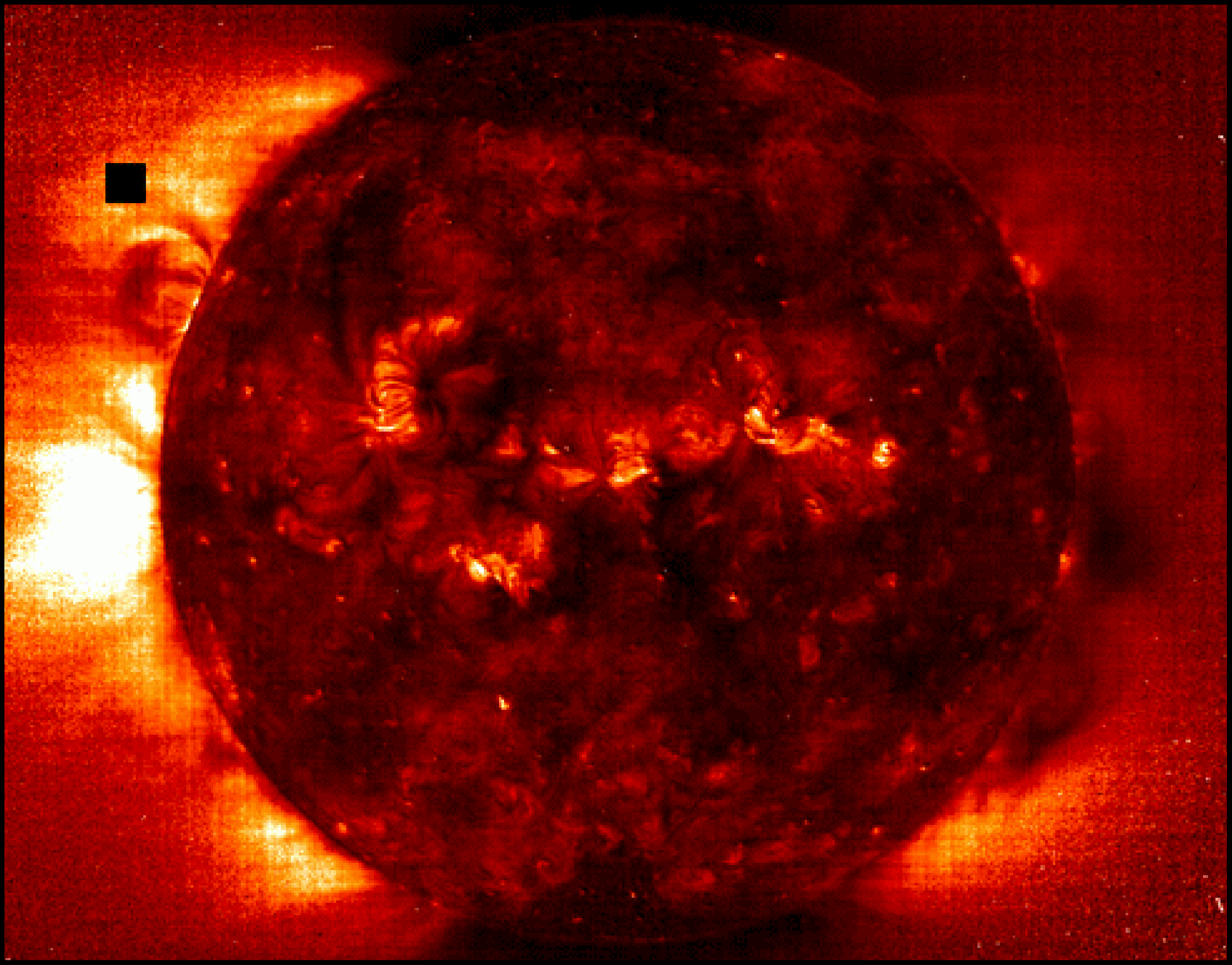
December 1999



Ten Outstanding Physics Challenges

- Quantum gravity presents the ultimate challenge to theorists
- Explaining high-T_c superconductors
- Unstable nuclei reveal the need for a complete theory of the nucleus
- Realizing the potential of fusion energy
- Climate prediction is heavy weather
- Turbulence nears a final answer
- Glass physics: still not transparent
- Solar magnetic field poses problems
- Complexity, catastrophe and physics
- Consciousness: the physicists view

Fusion Does Work at Large Size



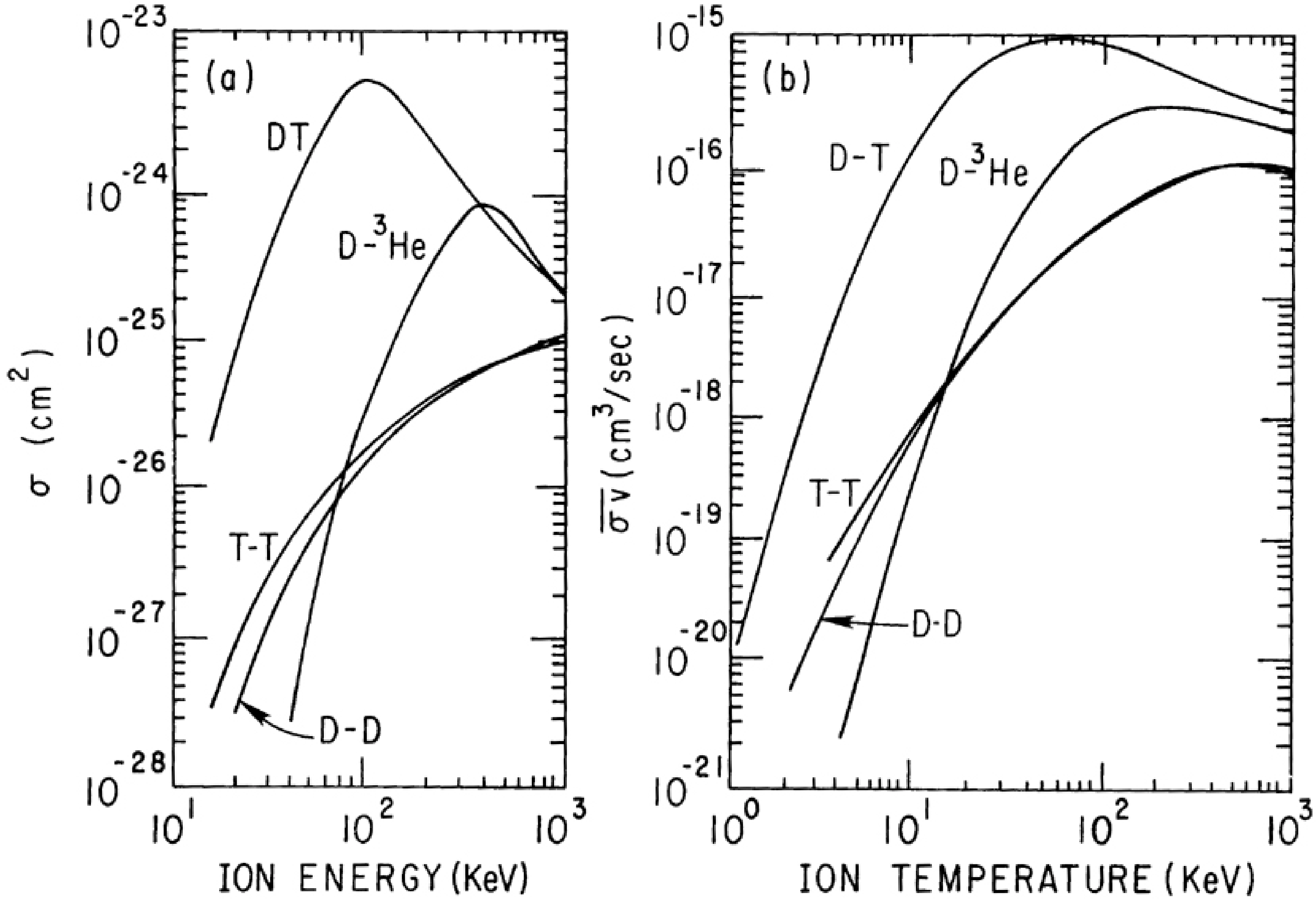
SOHO

Why is it so difficult in the lab?

Relevant Reactions for Fusion in the Laboratory

$D^{+} + D^{+}$	––>	$^{3}He^{++}$ (0.82 Mev)	+	n^{0} (2.5 MeV)
	––>	T^{+} (1 MeV)	+	p^{+} (3 MeV)
$D^{+} + {}^{3}He^{++}$	––>	$^{4}He^{++}$ (3.6 MeV)	+	p^{+} (14.7 MeV)
$D^{+} + T^{+}$	––>	$^{4}He^{++}$ (3.5 MeV)	+	n^{0} (14.1 MeV)
$Li^{6} + n$	––>	^{4}He (2.1 MeV)	+	T (2.7 Mev)

Fusion Cross Sections and Reaction Rates

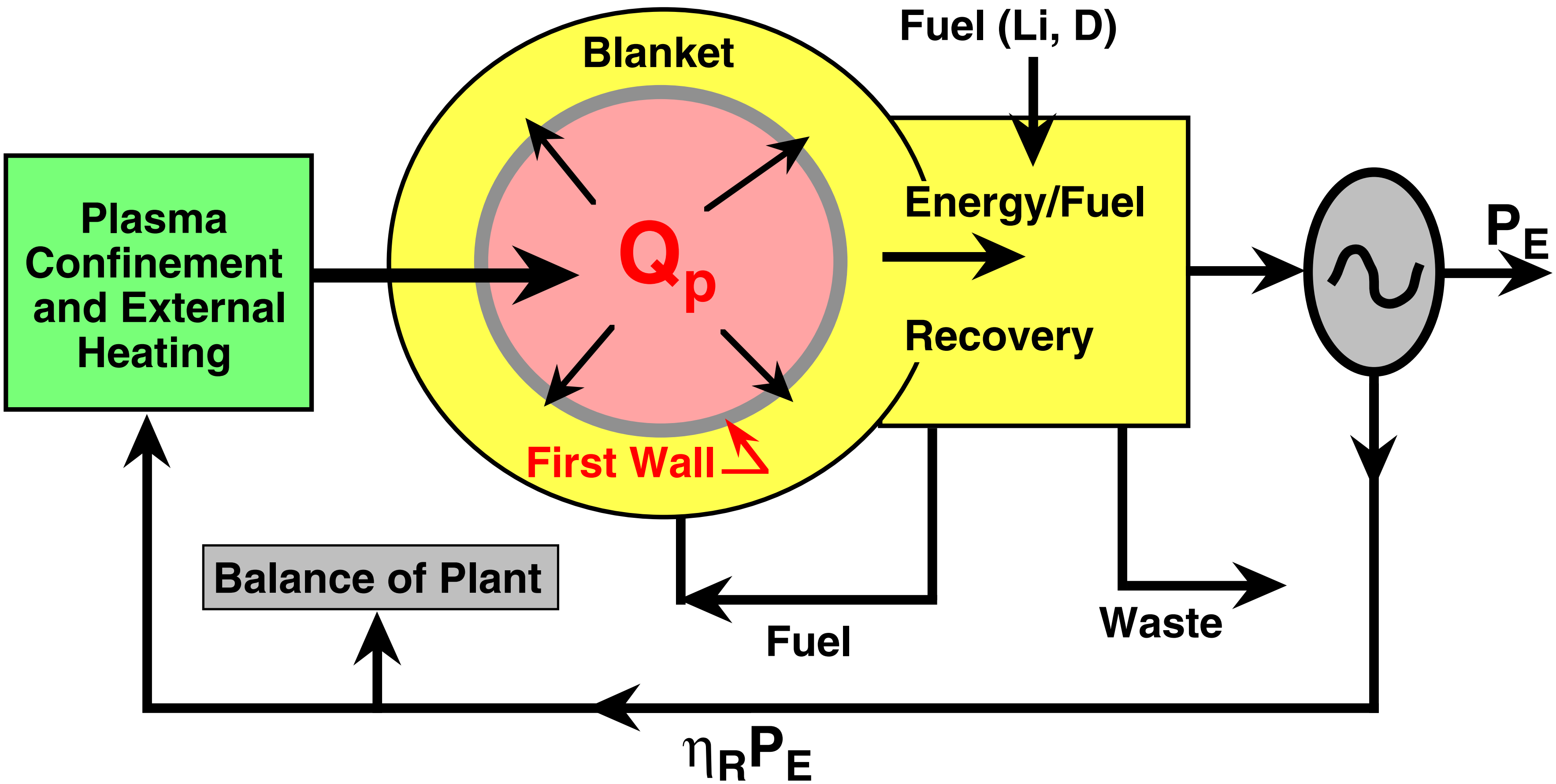


For Example:

$P_{DT} = n_D\, n_T \langle\sigma v\rangle (U_\alpha + U_n)$

$= 5.6 \times 10^{-7} \langle\sigma v\rangle n_D\, n_T$ watts m^{-3}, note: $\langle\sigma v\rangle \sim T^2$ @ 10 keV

The Grand Challenge, Science and Technology for Fusion



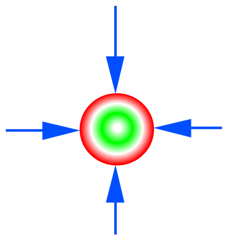
Key Plasma Performance Metrics

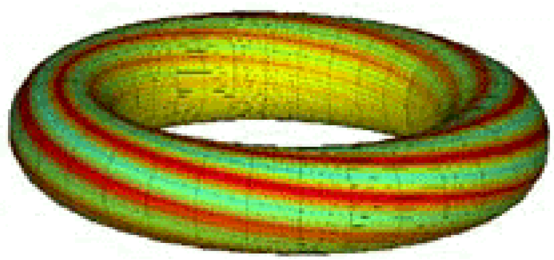
- Fusion Gain (Q_p)
- Fusion Energy Density
- Duty Cycle/Repetition Rate

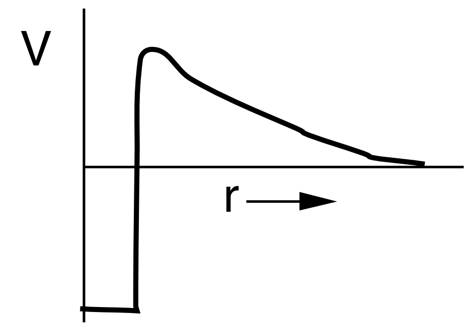
Key Engineering Metrics

- First Wall Lifetime
- Availability/Reliability
- Environment and Safety
- System Costs

There are Three Principal Fusion Concepts







Spherical Inertial

gravitational

transient compression

drive (laser-D/I, beam)

radial profile

time profile

electrostatic

Toroidal Magnetic

surface of helical B lines

twist of helix

twist profile

plasma profile

toroidal symmetry

Reactivity Enhancement

muon catalysis

polarized nuclei

others?

Plasma Requirements for a Burning Plasma

Power Balance

$$P_{aux\text{-}heat} + n^2 \langle\sigma v\rangle U_\alpha V_p/4 - C_B T^{1/2} n_e^2 V_p = 3nkTV_p/\tau_E + d(3nkTV_p)/dt$$

where: $n_D = n_T = n_e/2 = n/2$, $n^2 \langle\sigma v\rangle U_\alpha V_p/4 = P_\alpha$ is the alpha heating power, $C_B T^{1/2} n_e^2 V_p$ is the radiation loss, $W_p = 3nkTV_p$ and $\tau_E = W_p/(P_{aux\text{-}heat} - dW_p/dt)$ is the energy confinement time.

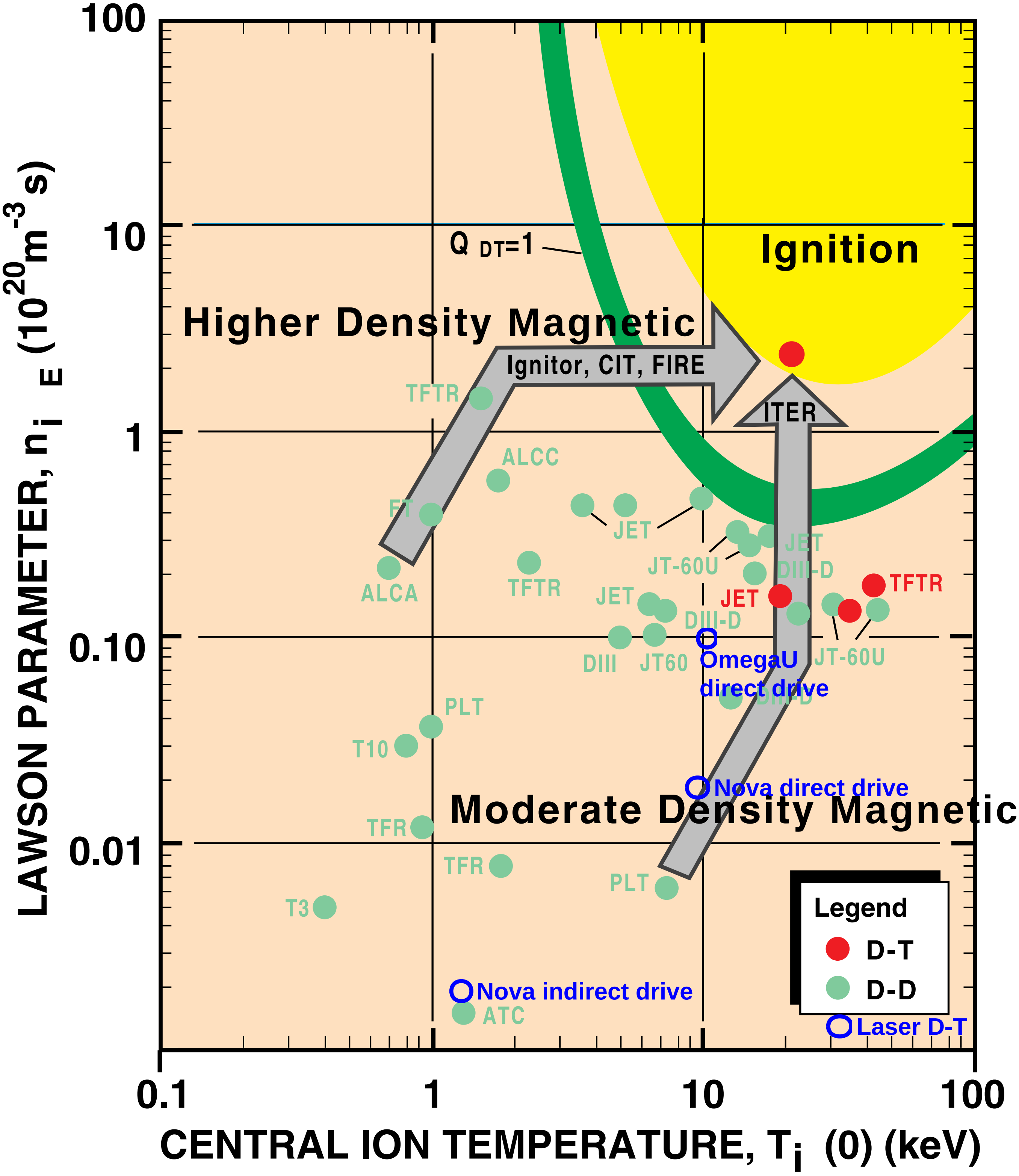
In Steady-state:

$$n\tau_E = \frac{3kT}{\langle\sigma v\rangle U_\alpha (Q+5)/4Q - C_B T^{1/2}}$$

where $Q = P_{fusion}/ P_{aux\text{-}heat}$

$Q = 1$ is Plasma Breakeven, $Q = \infty$ is Plasma Ignition

Status of Laboratory Fusion Experiments



#97GR041.ntau-98 FIRE

Comparison of Typical Plasma Parameters for Inertial and Magnetic Fusion

	Inertial	Magnetic
T_i (keV)	10	10
n (m^{-3})	6×10^{30}	3×10^{20}
τ_E (sec)	10^{-10}	2
radius (m)	10^{-4}	1

Why is Confinement a Challenge for Magnetic Fusion?

A D-T reactor at a fuel density of 10^{20} m^{-3} requires

τ_E ~ 1 second , T_i ~ 10 keV

T_e ~ 10 keV v_{te} ~ 6×10^7 m/s

Assume a container with

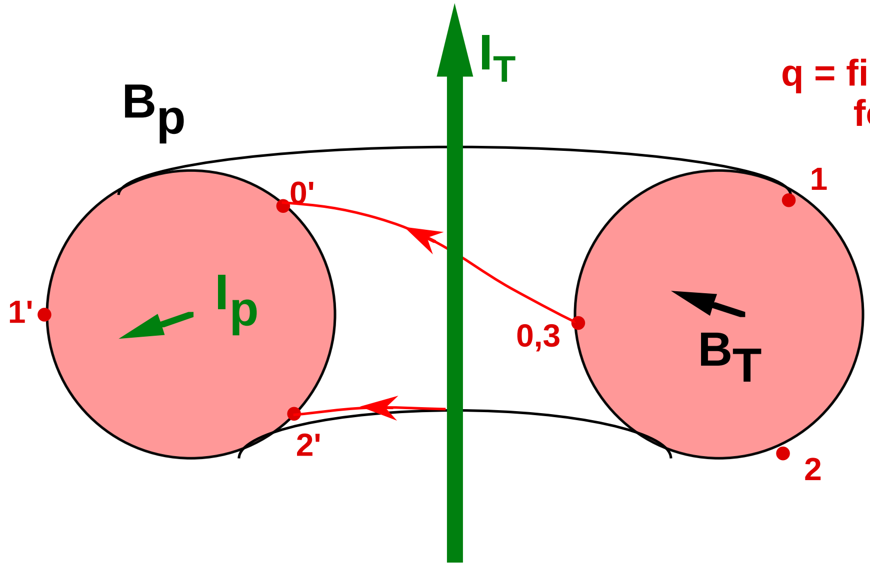
radius ~ 1 m (typical radius for a magnetic bottle)

Then the number of bounces

$N \sim v_{te} / r \sim 6 \times 10^7$

~ 30 coulomb collisions under typical conditions

Toroidal Magnetic Chamber (Tokamak)



q = field line cycles long way (toroidally) for one one cycle short way(poloidally)

q > 1 tokamak configuration

Ip produced by inductive drive or pressure driven boostrap current.

Axisymmetric Magnetic Configuration

- axial current, I_T , produces toroidal magnetic field, B_T
- toroidal current, I_p , produces vector potential, A_ϕ and poloidal field, B_p

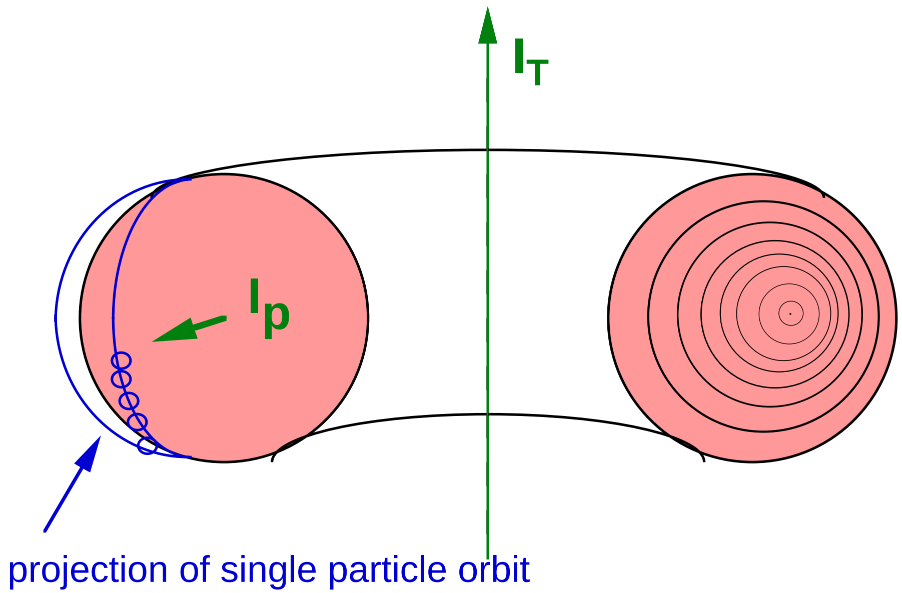
Axisymmetry ensures that:

- magnetic field lines lie in nested magnetic surfaces given by $\psi = 2\pi R A_\phi$
- charged particles are confined to within δ of magnetic surface due to conservation of canonical angular momentum

$$2mH = p_R^2 + p_Z^2 + \frac{(p_\phi - eRA_\phi)^2}{R^2} + e\Phi(R,Z)$$

$$\delta \sim mv/eB_p$$

Toroidal Magnetic Confinement



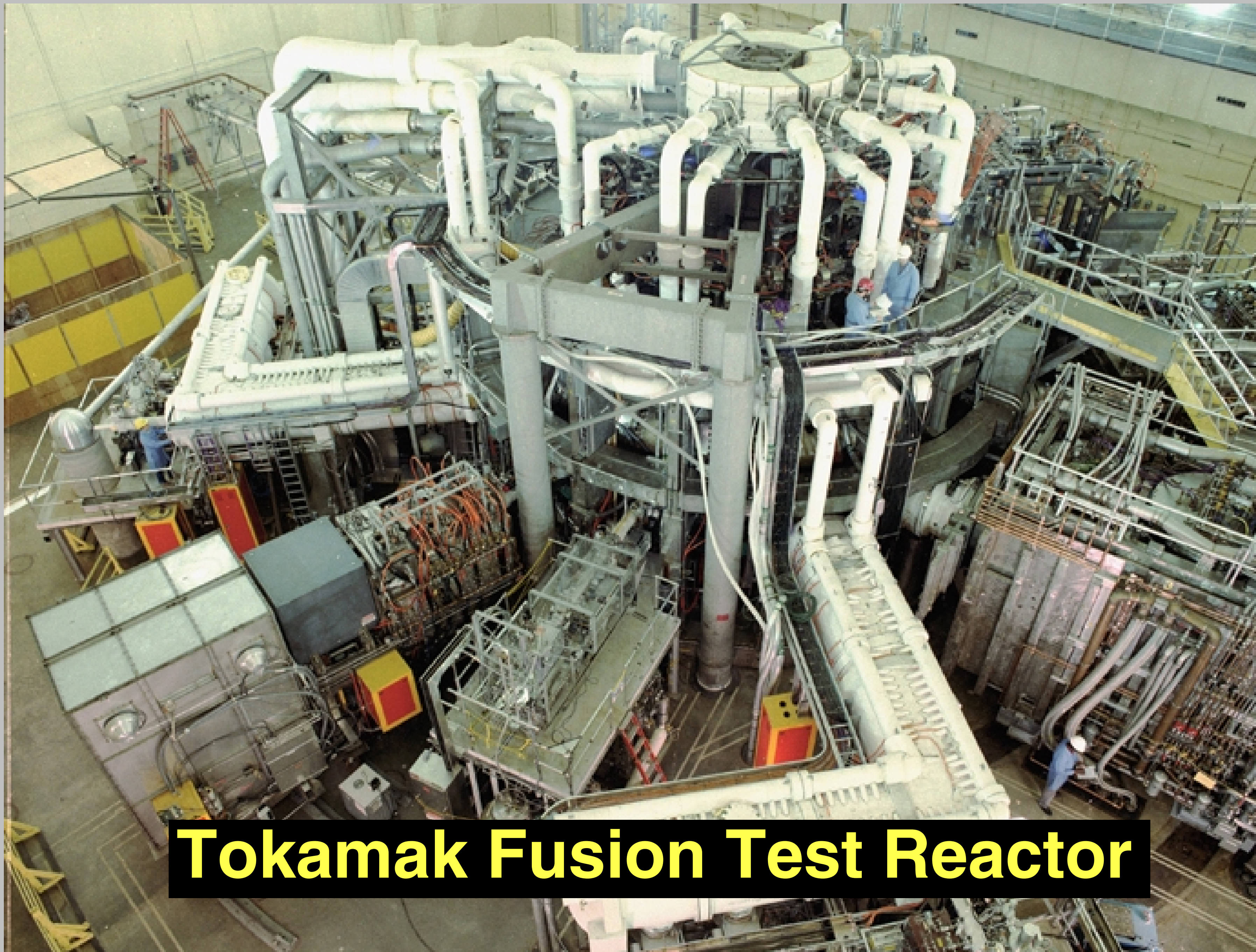
Nested Magnetic Surfaces (ψ = constant)

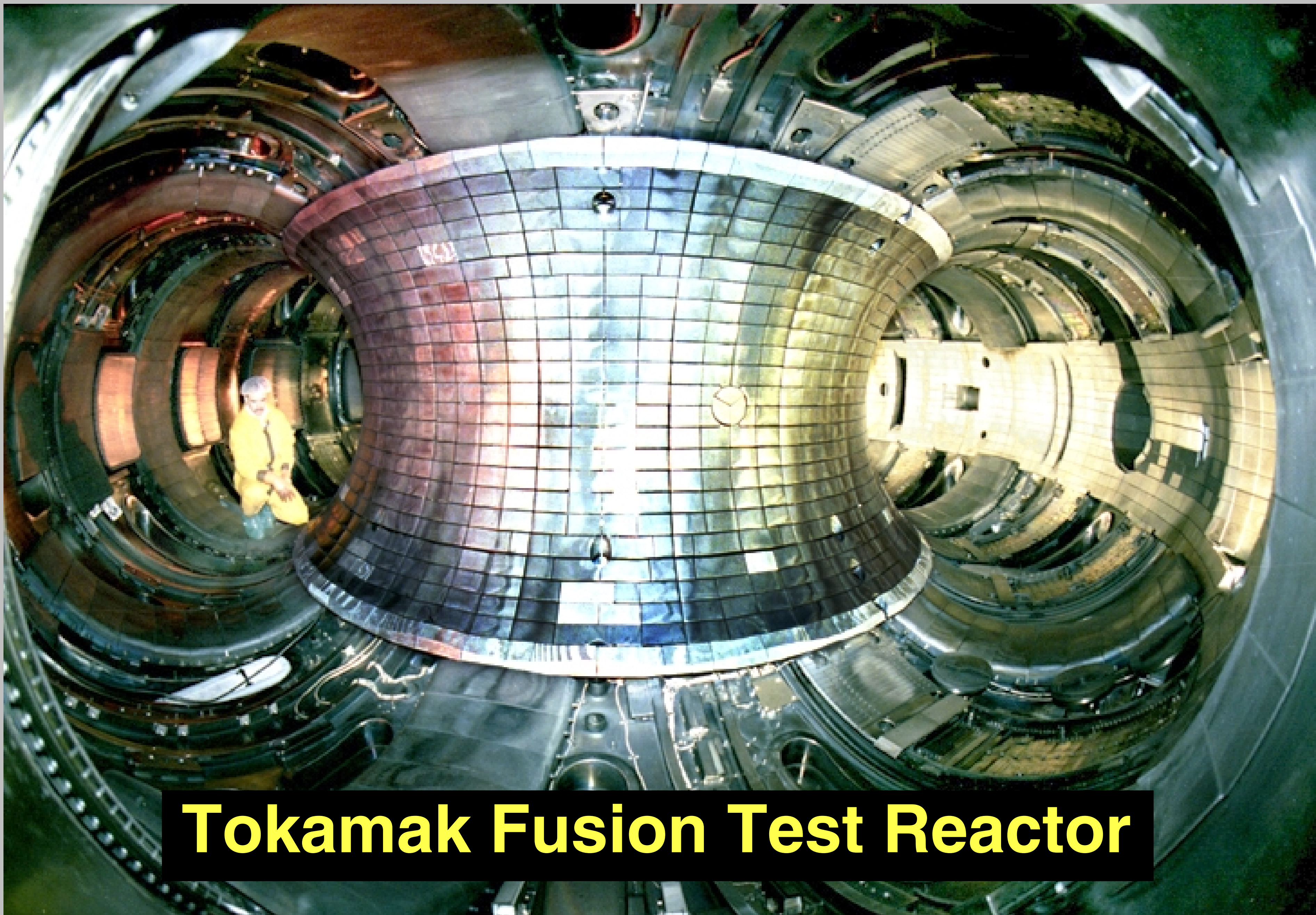
Plasma pressure = f(ψ)

q = q(ψ)

Toroidal Asymmetry can cause plasma loss

- small magnetic field perturbations can have large effect at resonant surfaces
- particle collisions (would allow present tokamaks to be near ignition)
- plasma instabilities (main limit in present fusion devices)


Tokamak Fusion Test Reactor

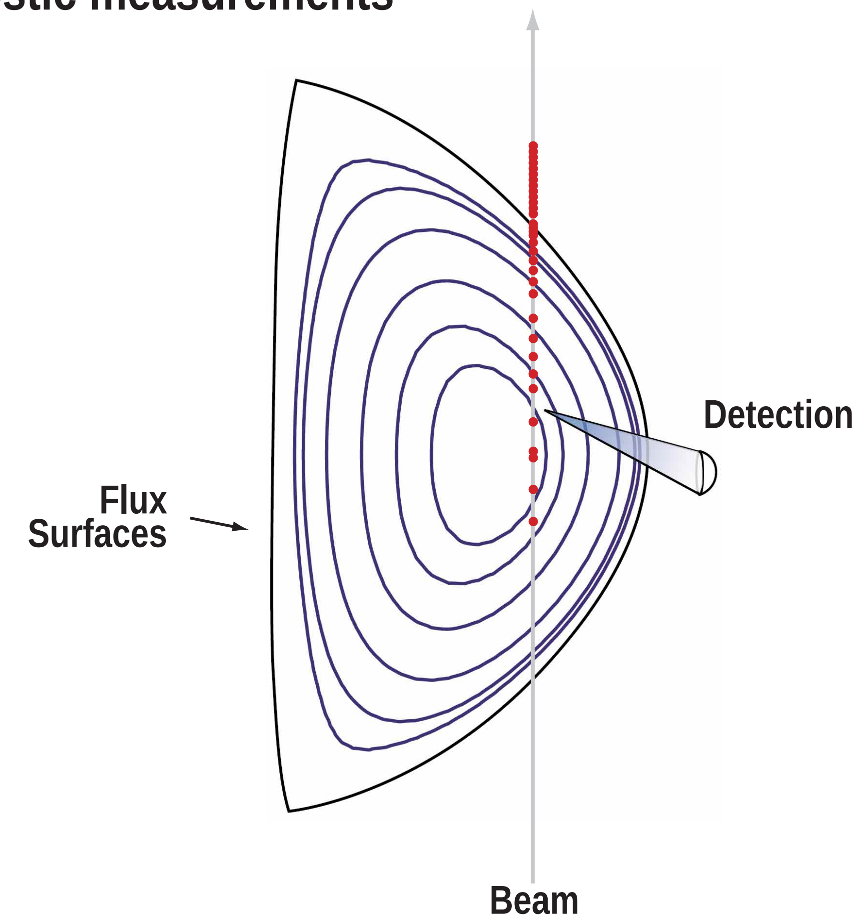

Tokamak Fusion Test Reactor

Comprehensive Diagnostic Systems have been Developed to Investigate Fusion Plasmas

Spatially and Time Resolved

— Typically ~50 diagnostic measurements

- Equilibrium magnetics
- Core profile diagnostics
  n_e, n_i, T_i, T_e, Z_{eff}, Z_i, v
- Internal magnetic field profile, B_θ, q
- Core and edge turbulence $\tilde{n}_e$, $\tilde{T}_e$
- Edge and divertor T_e, n_e, Z_e, radiation, neutral pressure



095–99 (modified DMM)

Plasma Instabilities Limit Fusion Plasma Confinement

Small-Scale Electrostatic Turbulence (fluctuating electric field, E)

$\mathbf{v} = \mathbf{E}\mathrm{x}\mathbf{B}/B^2$, ions and electrons both drift across the magnetic field preserving charge neutrality

$> \ _i$ instability wavelength ~ ion gyro-radius

$\sim v \ _{correlation}$ random walk step size

Small-Scale Magnetic Turbulence (fluctuating magnetic field, B)

$\mathbf{v} = v_{thermal}\ \mathbf{B}/B$, mainly loss of electron energy

Large-Scale Large-Amplitude Magnetic Instability

plasma pressure sufficient to distort even tear the magnetic field, similar to solar flares. Can cause total loss of plasma in a tokamak.

Fusion Power is Determined by Macroscopic Stability

- **Plasma stability is largely determined by**

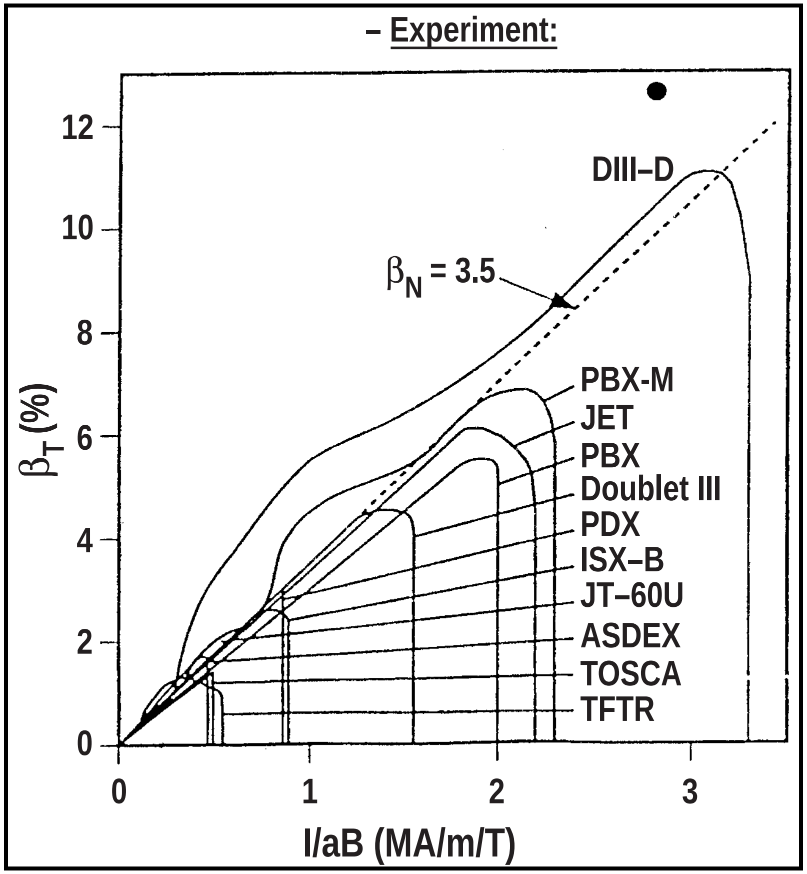
$$\beta \equiv \frac{2nT}{B^2/2\mu_0}$$

- **Fusion power**

$$p_{fus} = E_{fus} n_d n_t \langle \sigma_{fus} v \rangle \sim n^2 T^2 \sim \beta^2 B^4$$

- ***Denser, hotter plasma makes more fusion.***

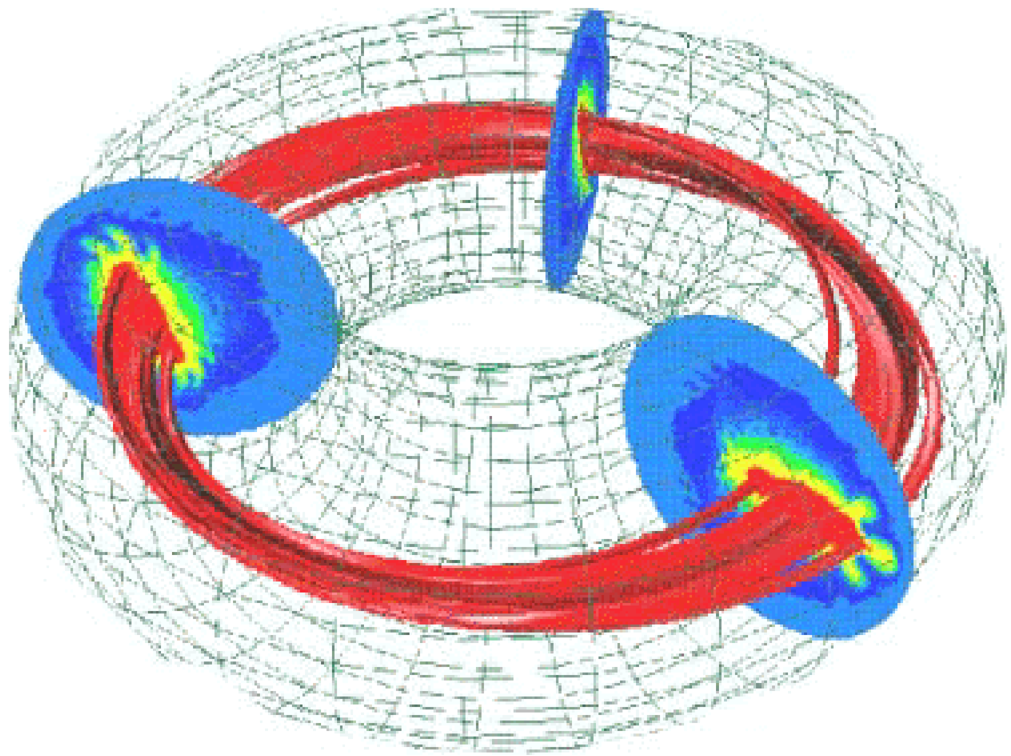
Ideal MHD Theory Provides Accurate Guidance on Operational Boundaries in Tokamaks



- **Plasma shaping enables increasing I/aB and the β-limit.**
  - **Elongation - κ**
  - **Triangularity - δ**
  - **Inverse aspect ratio**
    ε = a/R

- **Violation of I/aB or β limits results in sudden "disruptions".**

Simulation of a Plasma Disruption Driven by High Plasma Pressure

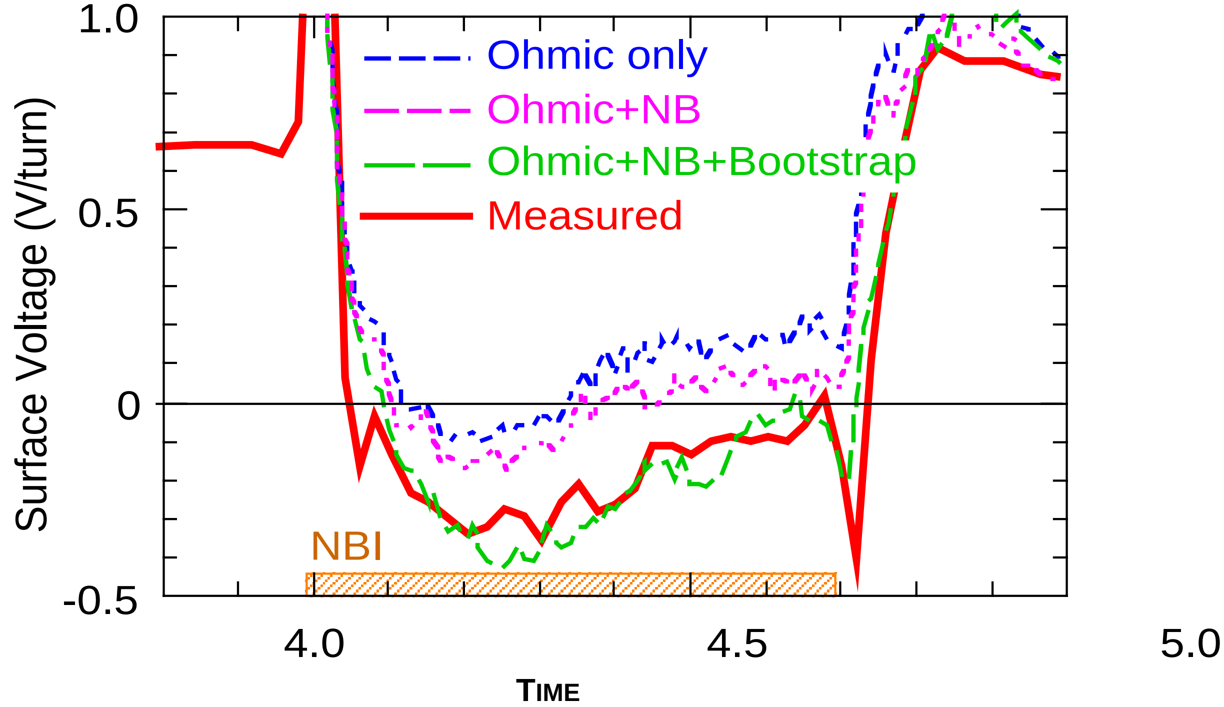


Nonlinear 3-D Fluid Computation

WAVE-PARTICLE INTERACTIONS ARE CRITICAL FOR PLASMA SUSTAINMENT

- **Plasma heating and current-drive**
  - **By beams of energetic neutral atoms**
  - **By radio-frequency waves**
- **Plasma self-heating by α particles**
- **Discovery of the self-driven "bootstrap" plasma current has revolutionized toroidal systems.**

Neoclassical Theory Prediction of Self-Driven Plasma Current Confirmed*

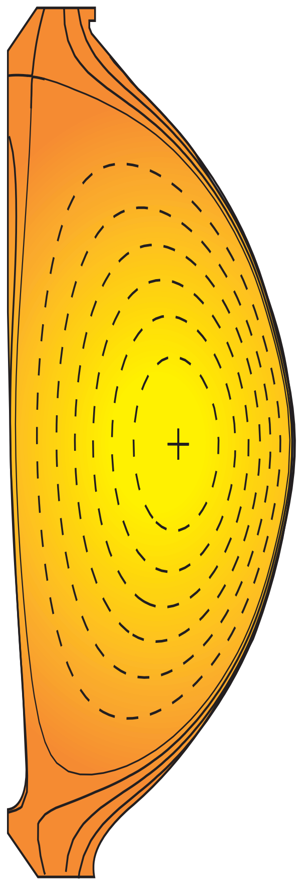


- **PLASMA SURFACE VOLTAGE IS WELL MODELED BY INCLUDING BEAM-DRIVEN AND SELF-DRIVEN (BOOTSTRAP) CURRENTS.**
- **ENABLED DESIGN OF ADVANCED TOKAMAK, SPHERICAL TORUS, AND STELLARATOR.**

*** seminal experiments were done on the Wisconsin Levitated Octupole**

Plasma Science Areas in Magnetic Fusion

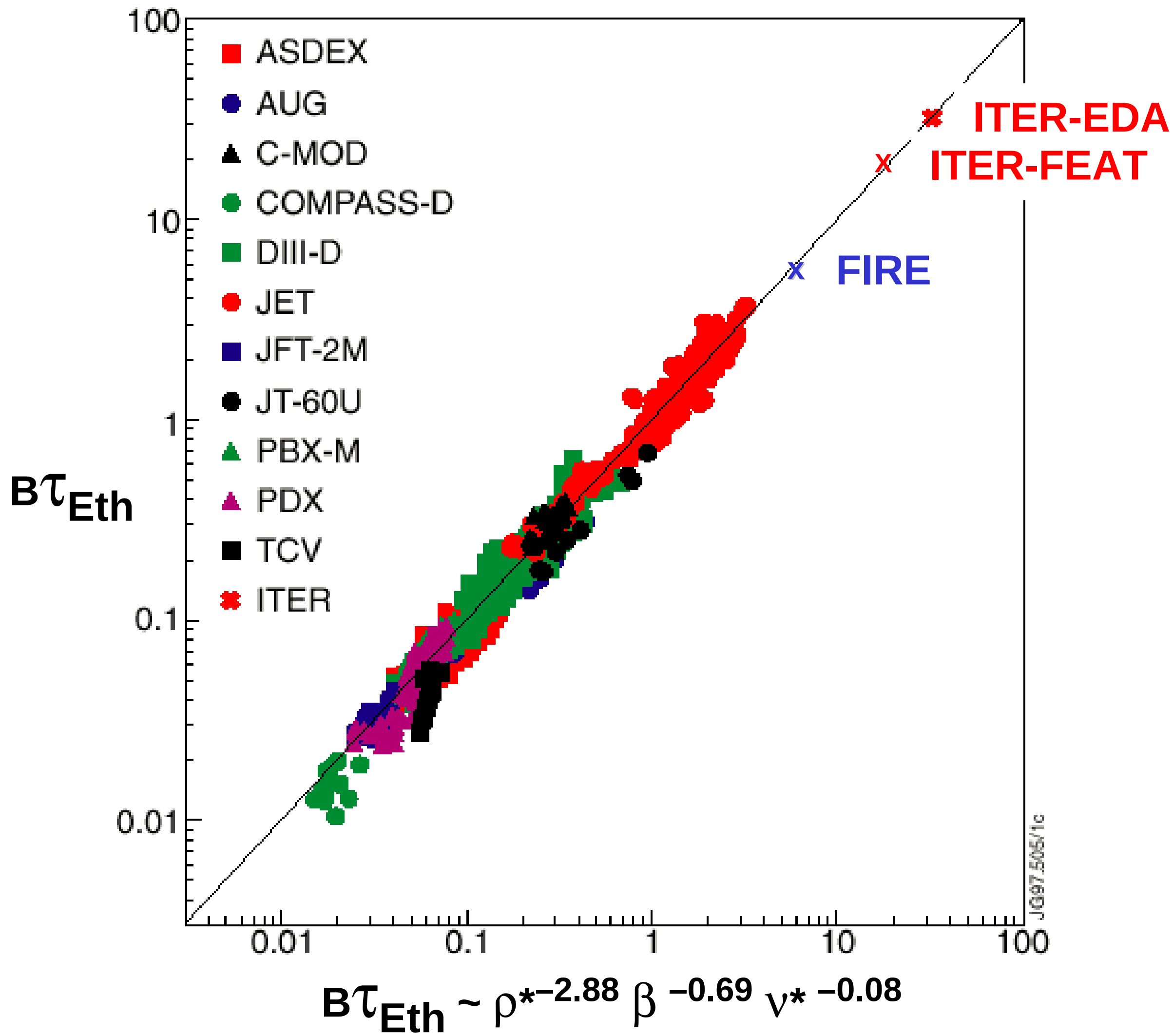
- Macroscopic Stability
- Wave-particle Interactions
- Transport and Microturbulence
- Plasma-wall Interactions
- Self-heated Plasmas



Wind Tunnel Experiments on Plasma Confinement

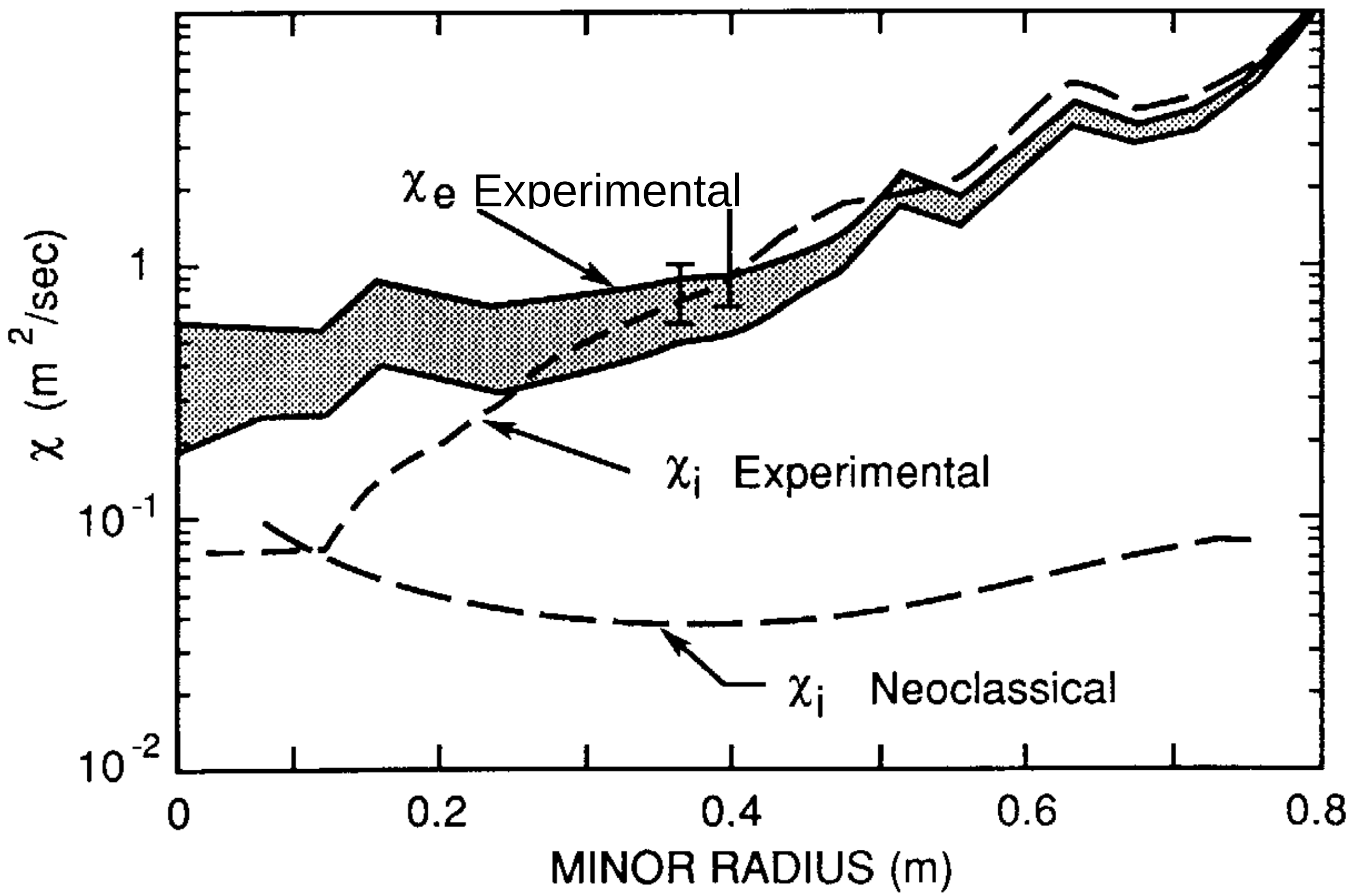
Dimensionless Parameters
$\omega_c \tau$ $\rho^* = \rho/a$ $\nu^* = \nu_c/\nu_b$ β

Similarity Parameter
$B\,R^{5/4}$



Kadomtsev, 1975

Measured Transport is Much Larger than Neoclassical Transport



- q / n T

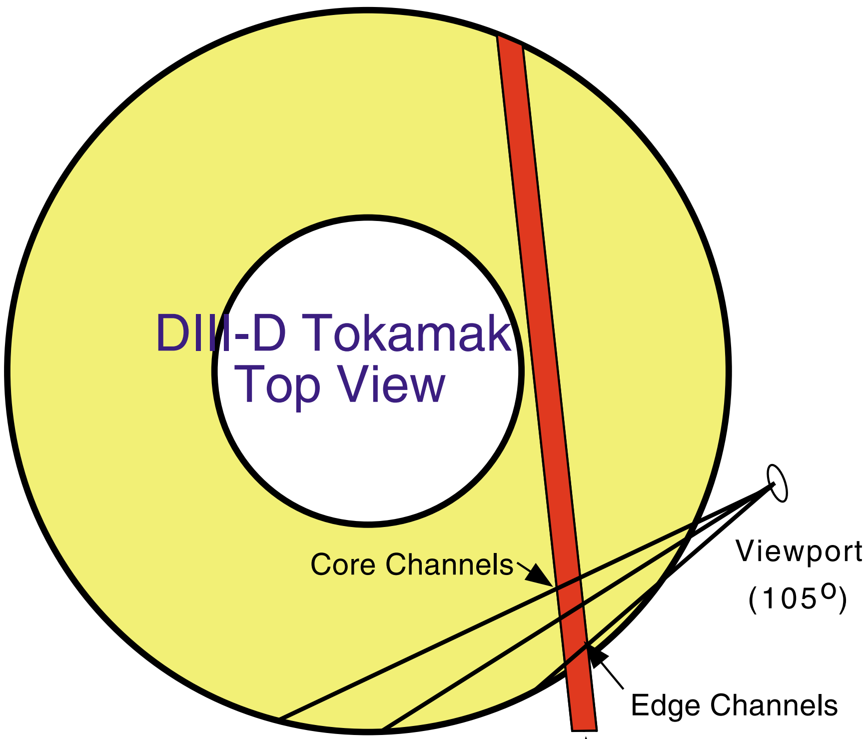
e neo
smaller
by ~60

- Wrong profile, scaling with B and collisionality
- Better than no magnetic field by 10^6
- Additional processes: turbulence

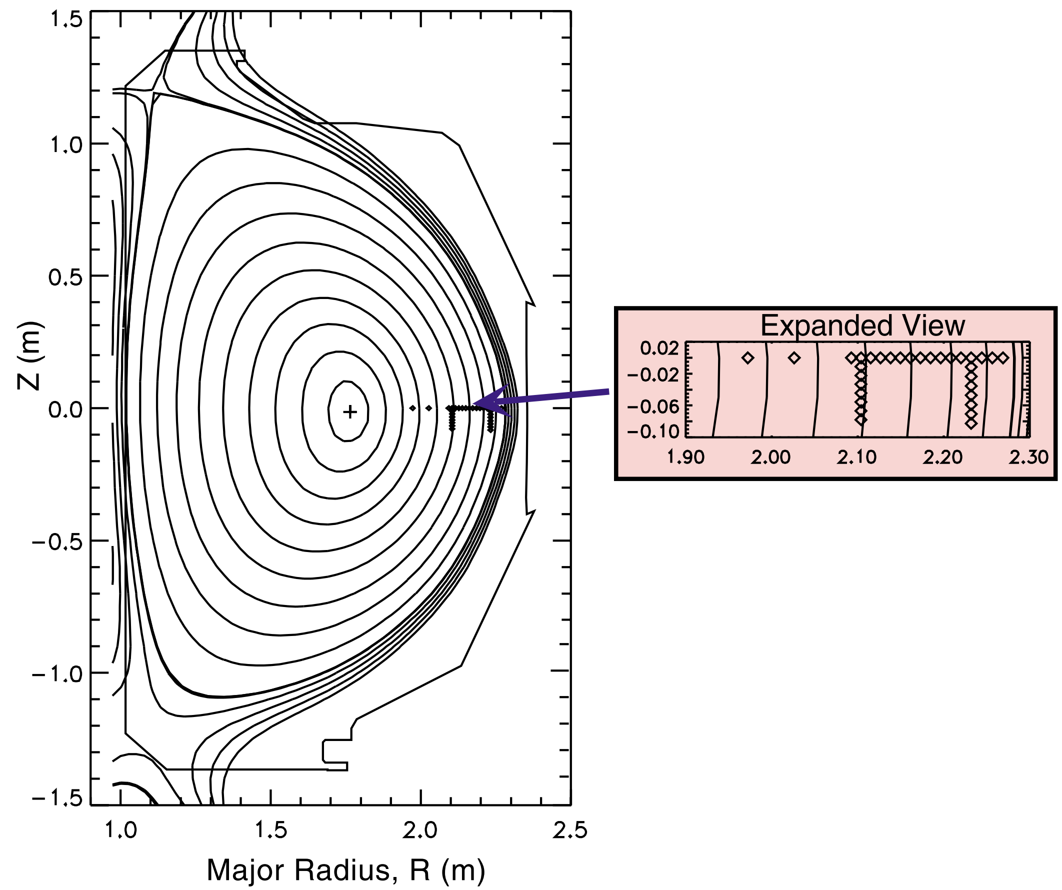
Localized Turbulence Measured via BES

- Beam Emission Spectroscopy: measure local density turbulence from fluctuations in light emitted from injected neutral H^0 beam:

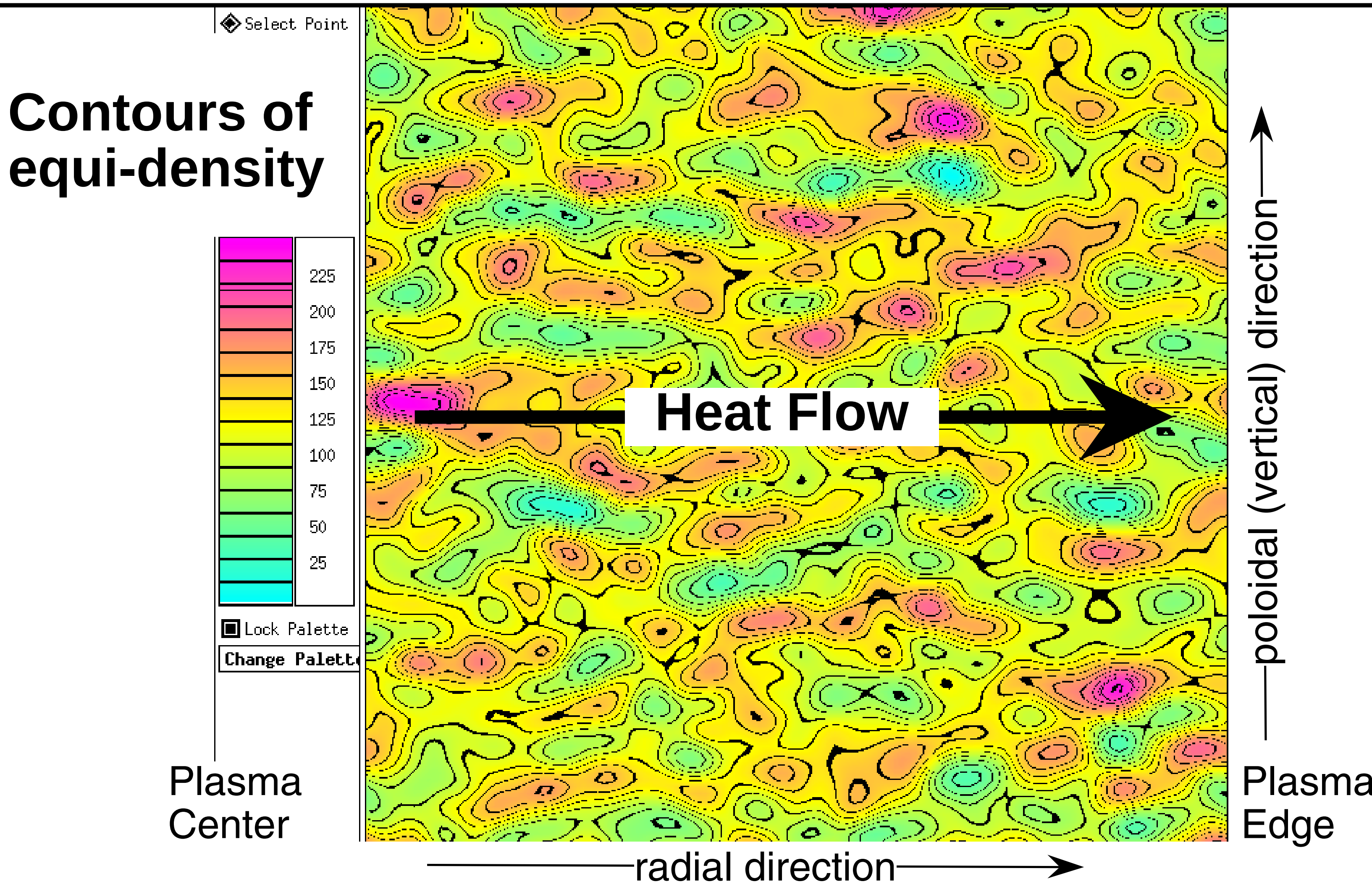
BES Viewing Geometry



Poloidal Cross Section



Measured Turbulent Eddies in TFTR



- $\delta n/n \sim 0.1\,\%$, $\delta T_i/T_i \sim$ 3-4 $\delta n/n$, $\lambda \gg \rho_i$, $\lambda_{radial} \gg \lambda_{poloidal}$
- **Consistent with simulations of ion temperature gradient (ITG) instabilities**

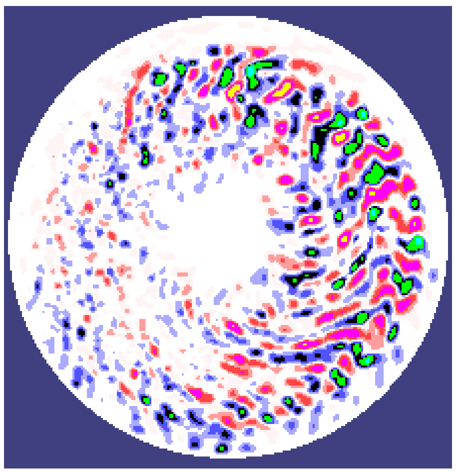
Turbulent Fluctuations Suppressed When E×B Shearing Rate Exceeds Maximum Linear Growth Rate of Instabilities

TFTR

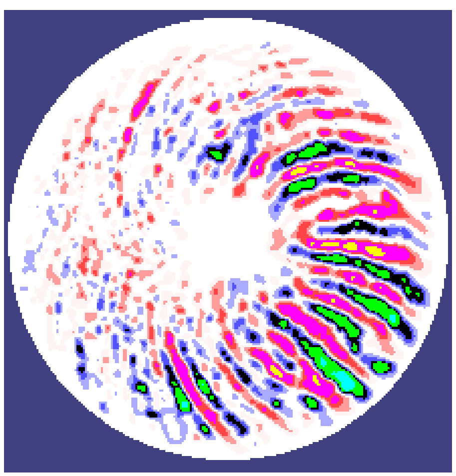
Gyrokinetic Simulations

- Turbulent eddies disrupted by strongly sheared plasma flow

With Flow



Without Flow

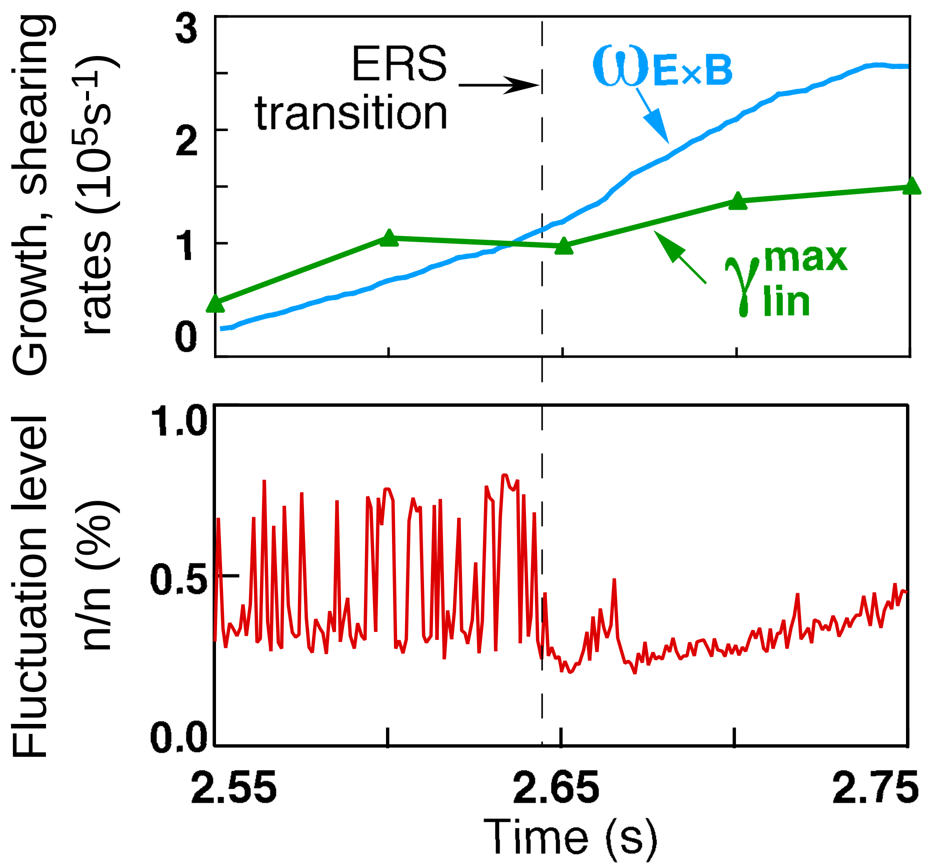


W. Lee, Z. Lin, E. Mazzucato, E. Synakowski, M. Beer

Z. Lin *et al*, Science **281** (1998) 1817

Experiment

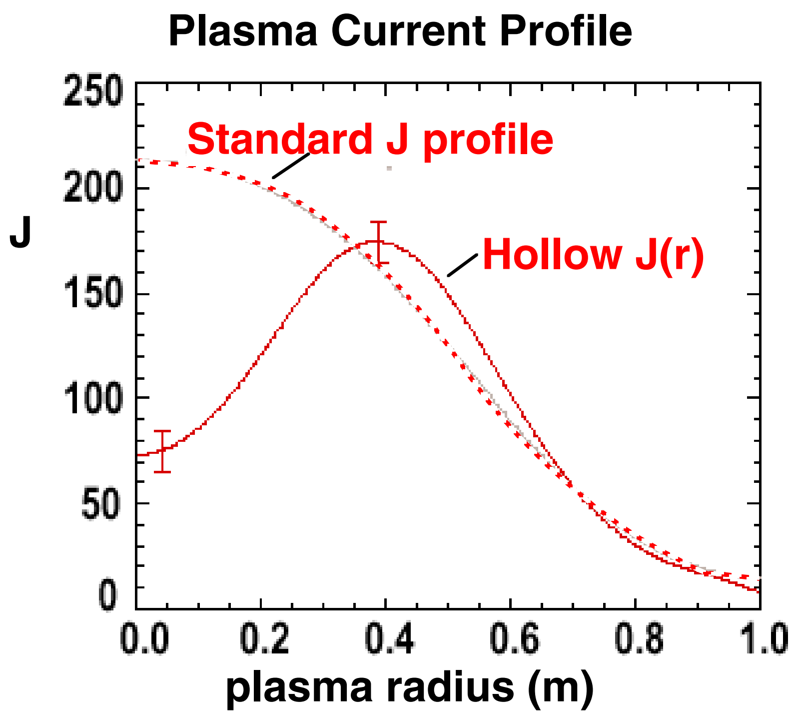
- Bursts of fluctuations are suppressed when **E B** shearing rate exceeds growth rate of most unstable mode



E. Mazzucato *et al*, PRL **77** (1996) 3145

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Plasma Current Profile Control and the Bootstrap Current are Crucial for the Advanced Tokamak

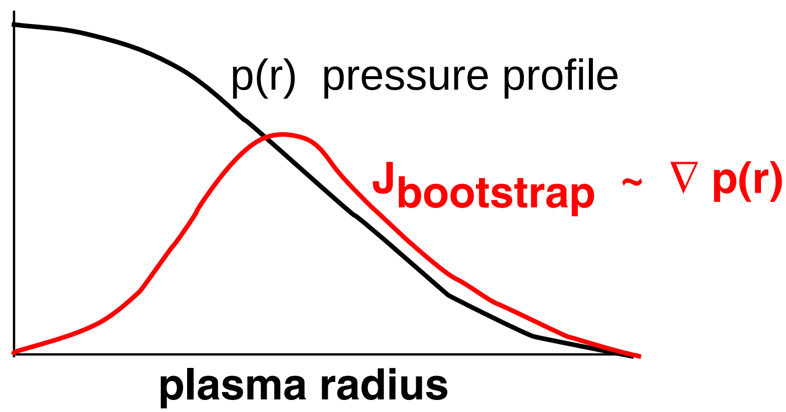


Hollow J(r) produces a reversed shear (relative twist) in the B lines;

dq(r)/dr < 0, standard > 0

This configuration is predicted to have :

- reduced turbulence
- higher stable pressure
- better alignment of bootstrap current with required current
  - potentially steady-state



The Advanced Tokamak is a strongly coupled system, especially when self-heated.

Physics Requirements for Next Step Experiments

Study Physics of Fusion Plasmas (transport, pressure limits, etc.)

Same plasma physics if $\rho^* = \rho/a$, $\nu* = \nu_c/\nu_b$ and β are equal

Requires $BR^{5/4}$ to be equal to that of a fusion plasma

Study Physics of Burning Plasmas (self heating, fast particle stability, etc)

Alpha heating dominant, $f_\alpha = P_\alpha/P_{heat} = Q/(Q+5)$

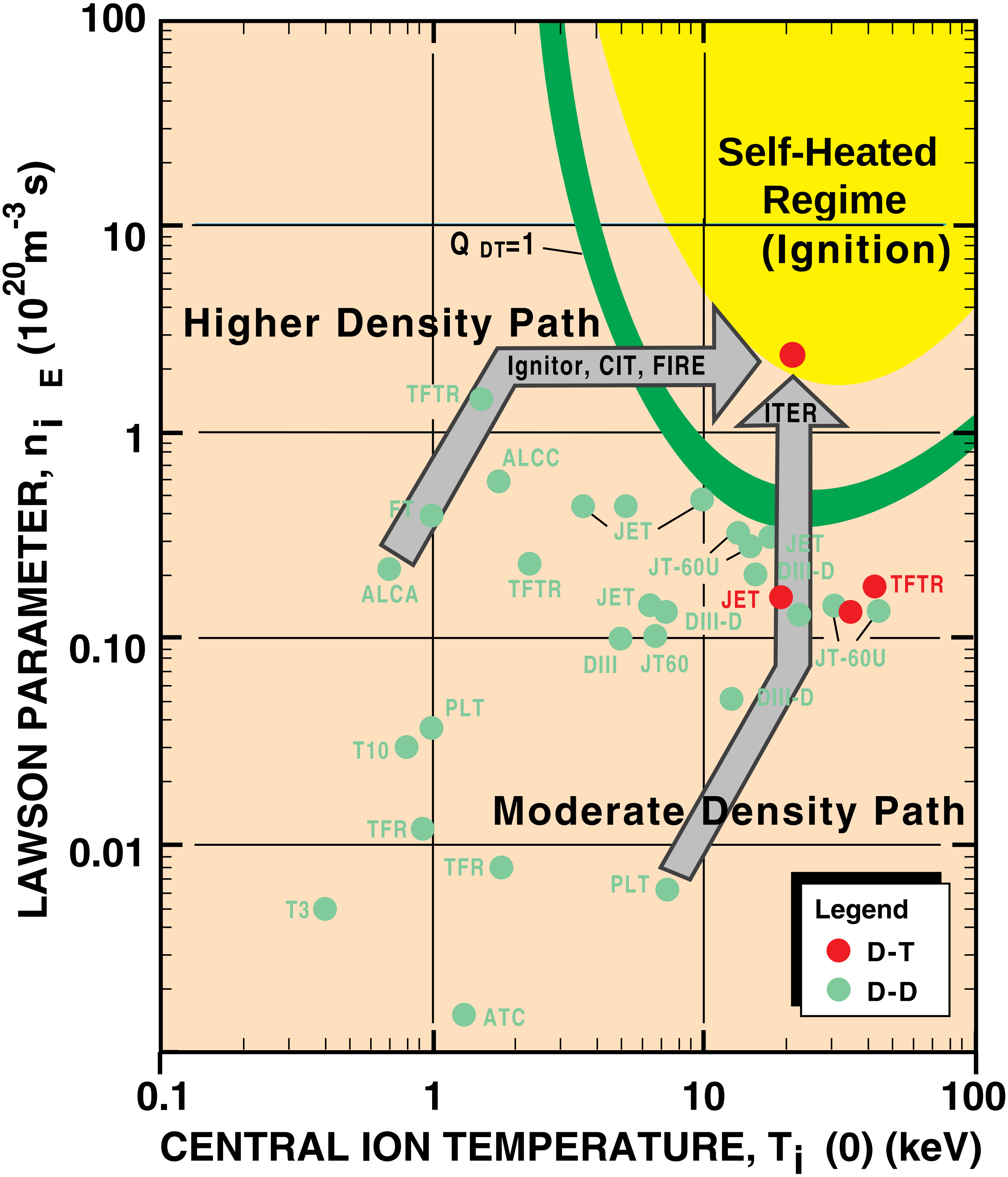
Q = function of $n\tau_E T$, e.g., Lawson diagram

$n\tau_E T = B \times \text{function}(\rho^*, \nu*, \beta)$ is true in general

$n\tau_E T = B \times (BR^{5/4})$, if τ_E is given by ITER98H empirical scaling at fixed beta

Alpha particle confinement requires $Ip(R/a) \geq 9$, $Ip(R/a) \sim BR$

Magnetic Fusion Pathways to Self-Heating

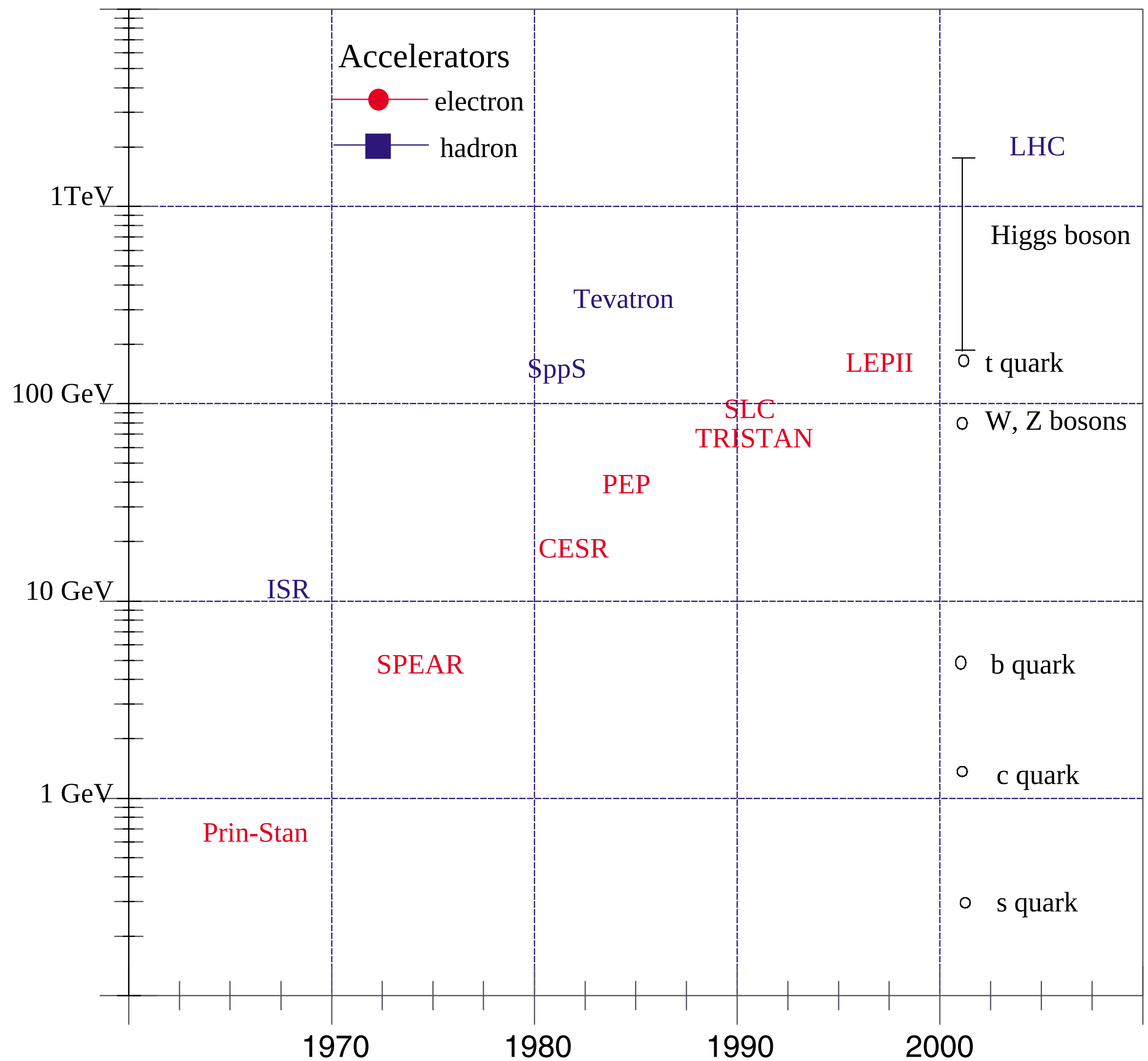


#97GR041.ntau-98 FIRE

High Energy Physics Accelerators Enable Discovery

HEP facilities plotted by discovery reach in mass vs. year

Also shown are some important discoveries and the expected range for the Higgs



International Thermonuclear Experimental Reactor (ITER)

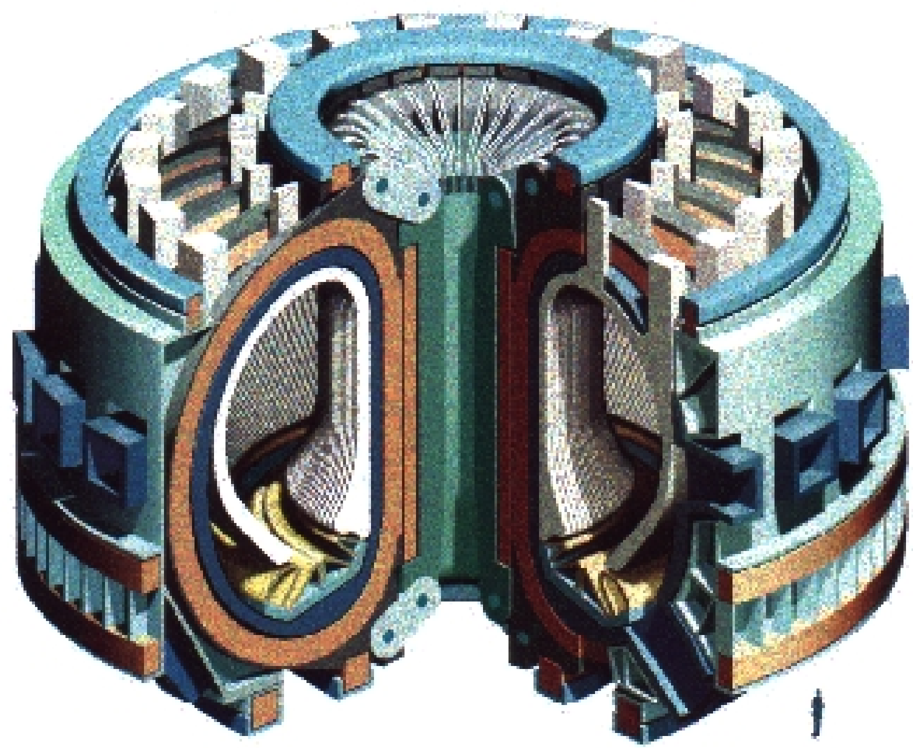
<u>Parties</u>

US (left in 1998)

Japan

Europe

Russia



P_{fusion} ~ 1,500 MW for 1,000 seconds

Cost ~ $10 B

Japan, Europe and Russia are continuing to work on a reduced size version with a goal of reducing the cost to ~$5B.

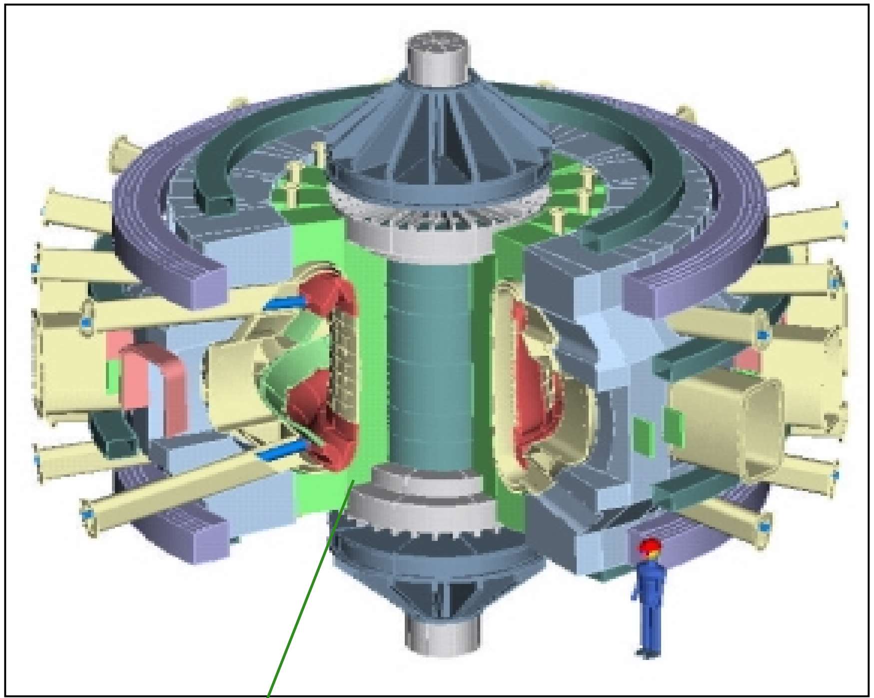
Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

The Rosetta Stone for Fusion

	Fusion Energy	Fusion Science
plasma physics	$n\tau_E T$	ρ^*, ν^*, β $(BR^{5/4})$
burning physics	$Q = P_{fus}/P_{aux\text{-}heat}$	$f_\alpha = P_\alpha/(P_{aux\text{-}heat} + P_\alpha)$
time	s, min, hr	τ_E, τ_{skin}, etc
flexibility	low	high
availability	high	low
technology	nuclear	enabling

Fusion Science and Fusion Energy have different languages, metrics, and missions.

Fusion Ignition Research Experiment (FIRE)



LN BeCu ("HTS")

Design Goals

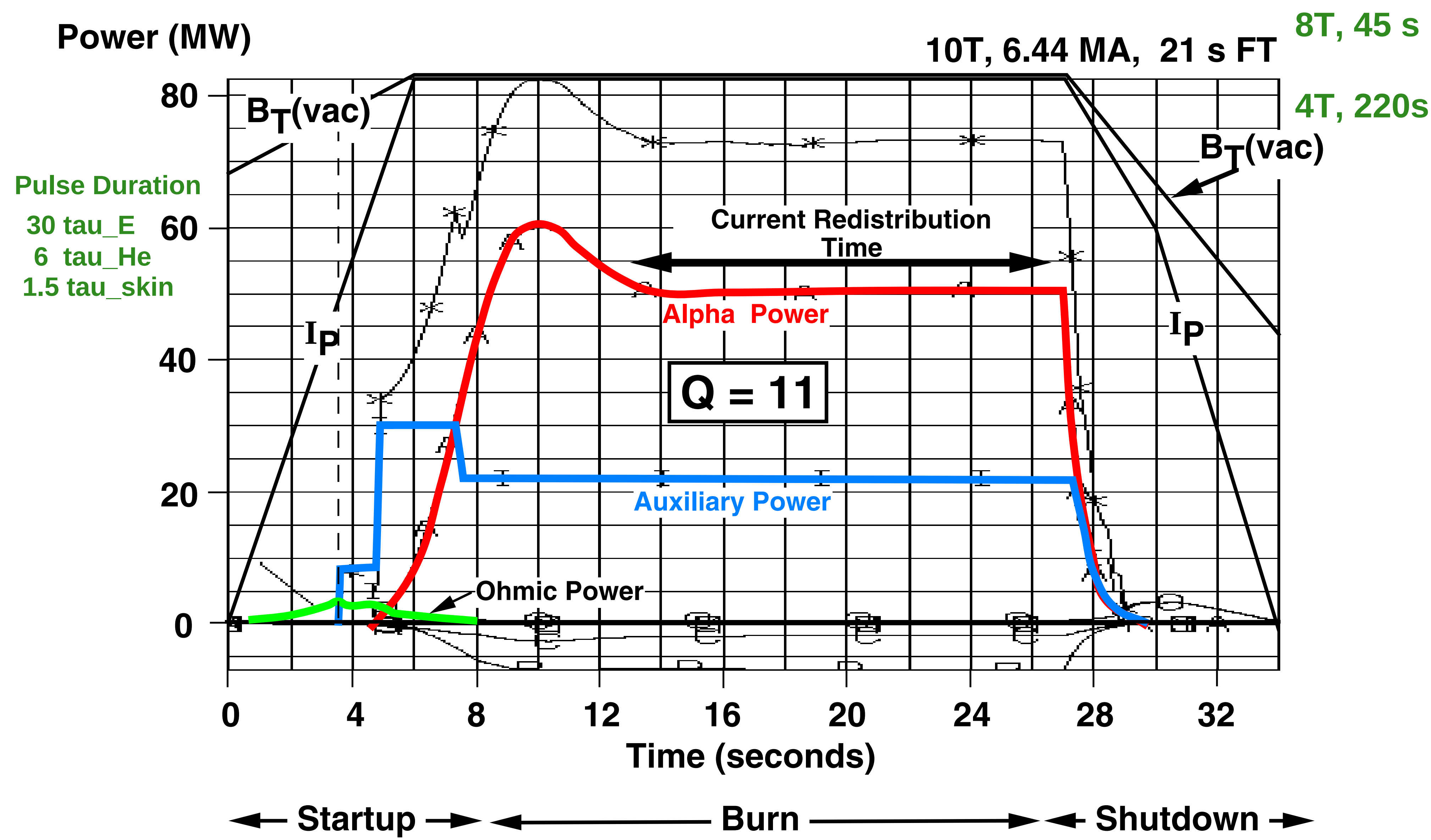
- R = 2.0 m, a = 0.525 m
- B = 10 T, (12T)*
- W_{mag}= 3.8 GJ, (5.5 GJ)*
- I_p = 6.5 MA, (7.7 MA)*
- $P_{alpha} > P_{aux}$, P_{fusion} ~ 220 MW
- Q ~ 10, τ_E ~ 0.55s
- Burn Time ~ 20s (12s)*
- Tokamak Cost ≤ $0.3B

  Base Project Cost ≤ $1B

* Higher Field Option

Attain, explore, understand and optimize alpha-dominated plasmas to provide knowledge for the design of attractive MFE systems.

1 1/2 -D Simulation* of Burn Control in FIRE



* The Tokamak Simulation Code (TSC) is one of several plasma simulation codes. **Click here http://w3.pppl.gov/topdac/**

Concluding Remarks

- The capability now exists to produce and control fusion plasmas for detailed investigation in the laboratory. However, fusion reactors based on the present state of knowledge are large and innovations are needed for an attractive reactor concept.

- Recent developments in plasma diagnostics and computer simulation of three-dimensional non-linear phenomena now allow detailed comparison of theory and experiment.

- New insight into the physical processes causing plasma transport could lead to an advanced toroidal configuration that would have a significant impact on the attractiveness of magnetic fusion.

- The FIRE compact high field tokamak could address many of the generic fusion science issues including: self-heated plasma physics, many of the long pulse advanced tokamak issues and could begin the study of self-heated self-organized plasmas in a $1B class experimental facility.

http://fire.pppl.gov

Laboratories to Explore, Explain and Expand the Frontiers of Science