# The path to magnetic fusion energy and the Princeton Plasma Physics Lab.

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U.S. DEPARTMENT OF ENERGY | Office of Science

PPPL

# Outline

- Introduction and motivation
- ITER
- Issues and Challenges
- PPPL research strategy

# Fusion Requires High Temperature Plasmas

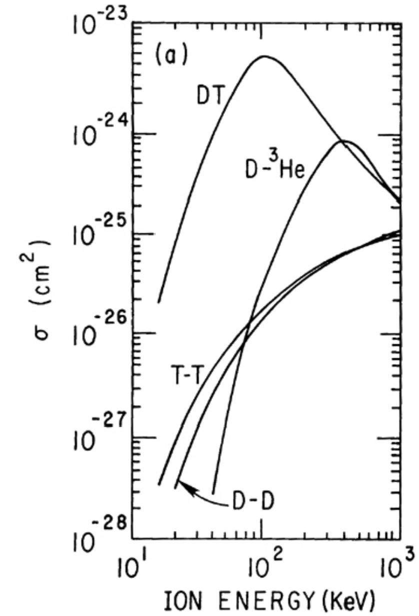
- D + T → α (3.5 MeV) + n (14.1 meV)
  highest cross section at lowest energy

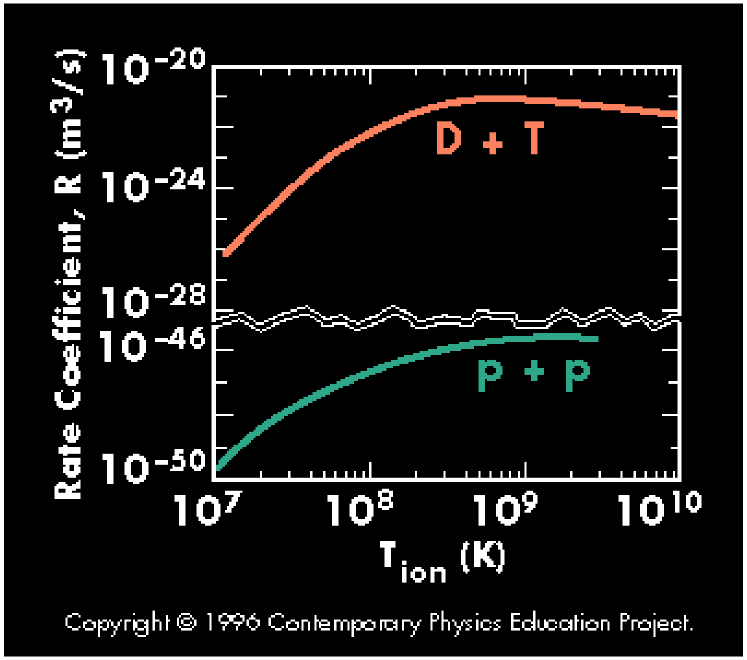
- For thermal distributions, reaction rate peaks ~ $T$ = 800 MºC ( ~70 keV)

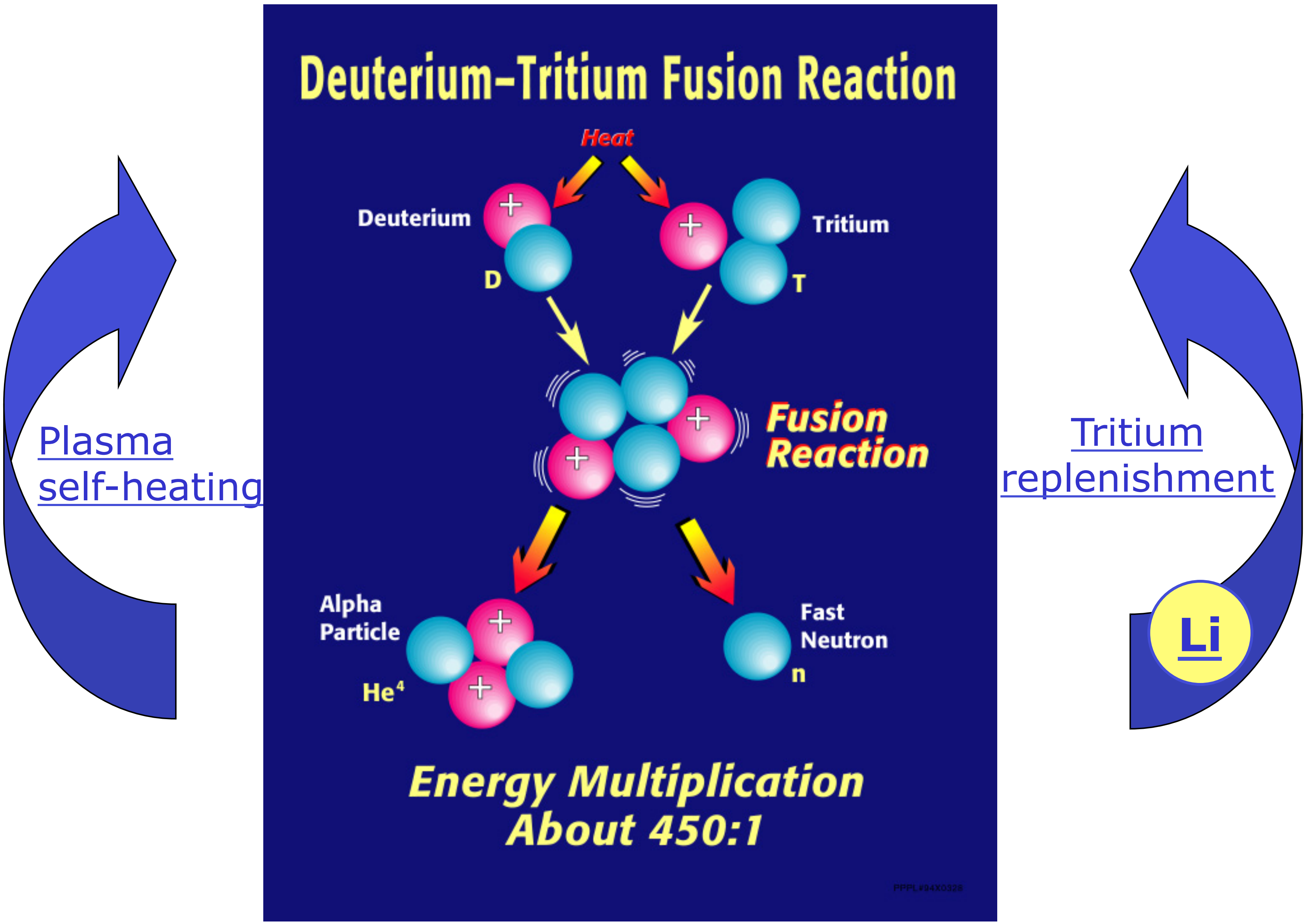
- Peak energy gain for $T$ ~ 170 MºC ( ~ 15 keV)

  There, reaction rate $n_D n_T \langle \sigma v \rangle \propto n^2 T^2 \propto p^2$
  ⇒ want to maximize pressure

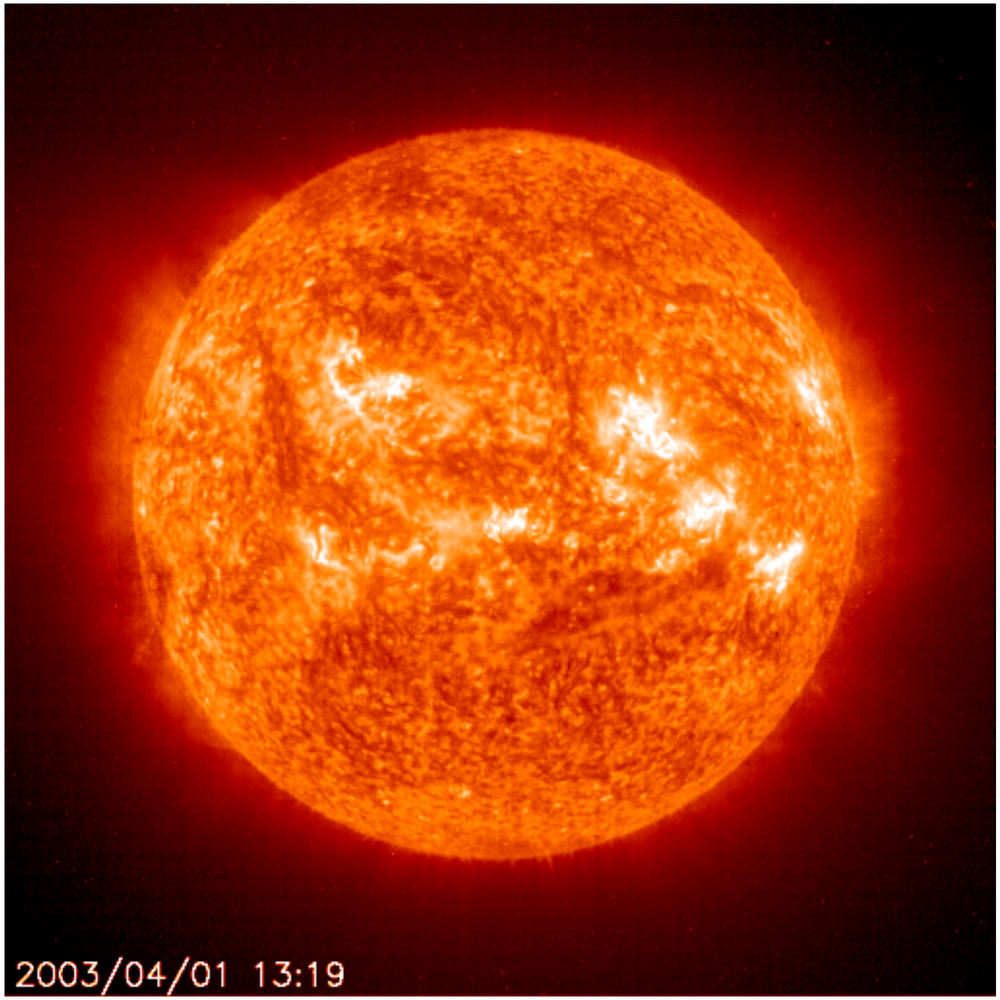
- For self-heated plasma
  fusion heating rate (α) = energy losses
  ⇒ $n\,\tau_E > 2\times 10^{20}$ (m$^{-3}$ sec$^{-1}$) for T = 20 keV
  $\tau_E$ is the energy confinement time
  (J.D. Lawson, 1957)




Deuterium–Tritium Fusion Reaction
Heat
Deuterium
D
Tritium
T
Fusion Reaction
Alpha Particle
He4
Fast Neutron
n
Energy Multiplication About 450:1
Plasma self-heating
Tritium replenishment
Li

# Fusion Plasma




10 million degrees

Fusion power density in sun ~ 300 Watt/cubic meter,

In fusion laboratory plasma ~10 MWatt/cubic meter

# Why fusion?

- Nearly inexhaustible

  Deuterium from water, Tritium from lithium+neutron

- Available to all nations

  reduced conflict over resources

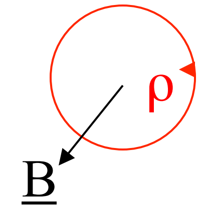
- Clean

  no greenhouse gases, no acid rain

- Safe

  no runaway reactions or meltdown;
  only short-lived radioactive waste

# Magnetic Confinement




- For straight magnetic field lines, charged particle motion ⊥ to B is constrained

$$m\frac{d\overline{v}}{dt} = q(\overline{E} + \overline{v} \times \overline{B}) + C$$

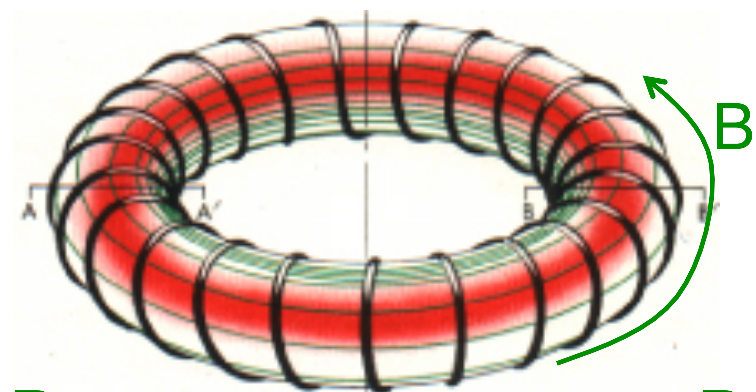
← collisions

to gyroradius $\rho = m v_\perp / qB$

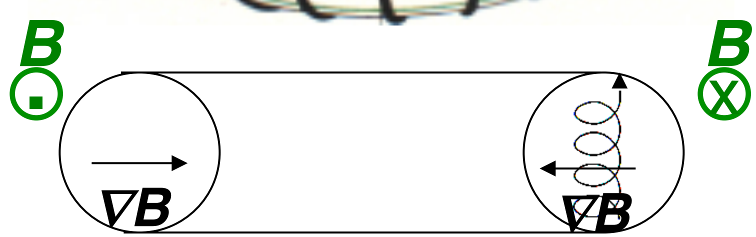
for 10 keV, $10^{20}$ m$^{-3}$
B = 1 T
$\rho_i \sim 1$ cm
$\lambda \sim 10$ km

⇒ collisional diffusion $D_\perp \sim \lambda^2 \nu_{coll} \rightarrow \rho^2 \nu_{coll}$
magnetic moment $\mu = m v_\perp^{\ 2} / 2B$

- Only successful way to confine motion ∥ to B is to bend B into a torus



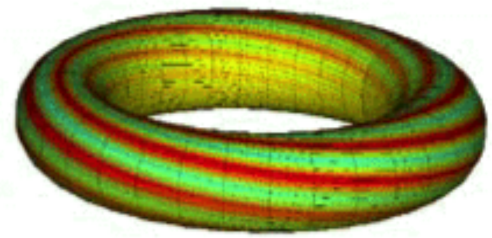

- $|B| \propto 1/R$
  Additional force = $-\mu \nabla B$ causes single particles to drift vertically




$$v_D = \mu\, \mathbf{B} \times \nabla \mathbf{B} / ZqB^2$$

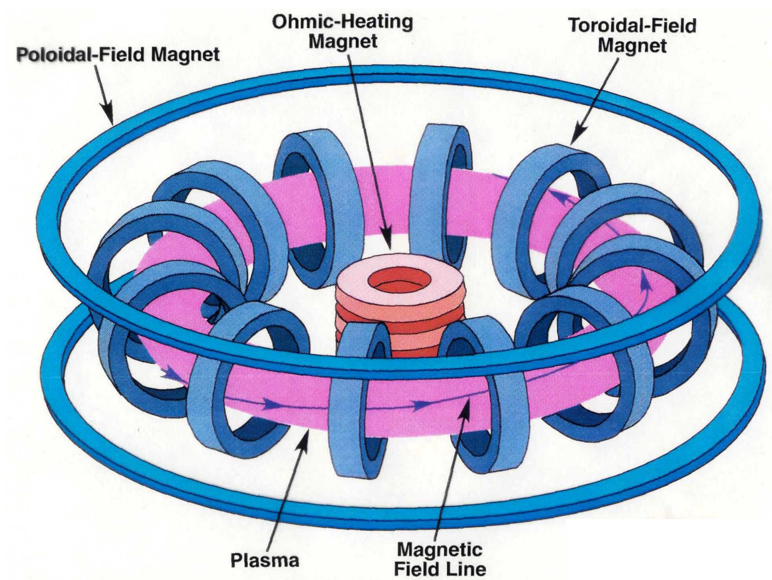
# Helical Magnetic Confinement

- Most successful strategy: use helical $\underline{B}$ with field lines on nested magnetic surfaces

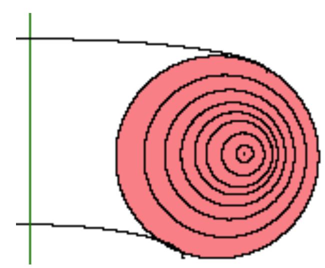


- During parallel motion along $\underline{B}$, $\boldsymbol{B} \times \nabla \boldsymbol{B}$ compensates at top and bottom of torus

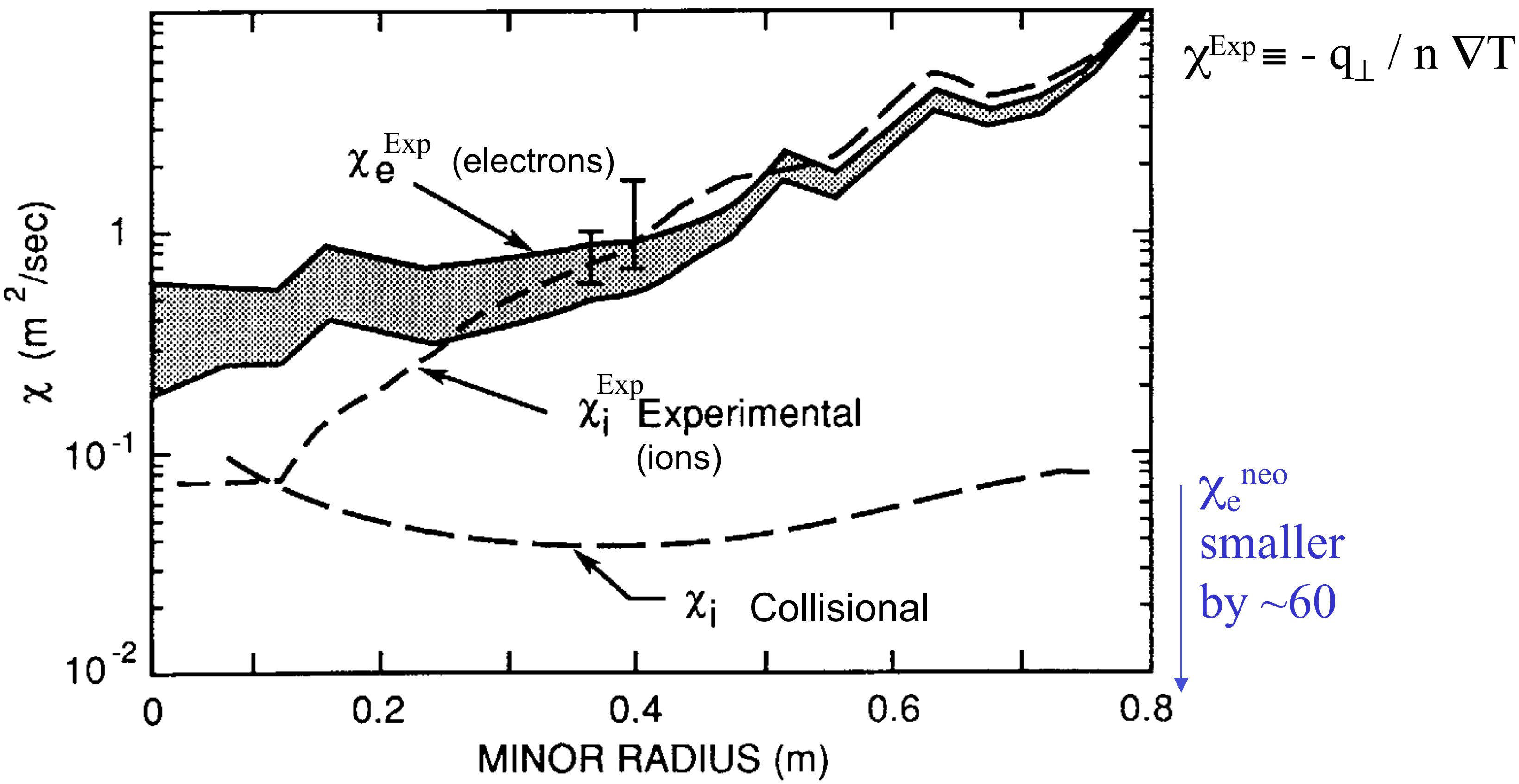
- Simplest strategy: make system toroidally symmetric: e.g. Tokamak
  - generate helical field using external coils + induced plasma current
  - Helicity of B parameterized as "magnetic rotational transform" = # transits short way / # long-way




symmetry ⇒ $p_\phi$ conserved,
⇒ particle orbits confined.
⇒ $\underline{B}$ field lines confined to nested toroidal surfaces
Issue: how to sustain current?



# Tokamaks: Very successful, but Loss of Energy Faster than Prediction

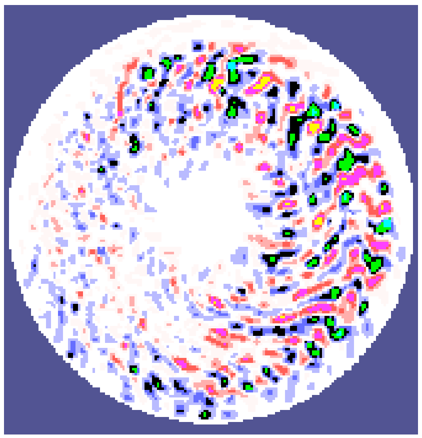



- Tokamaks have achieved fusion parameters: T~ 500 MºC ! $\tau_E$> 1 sec
  Have produced up to 17 MW of fusion power (gain $\lesssim$ 1)
- Additional processes: turbulence driven by huge thermal gradients
- Better than no magnetic field by >$10^6$

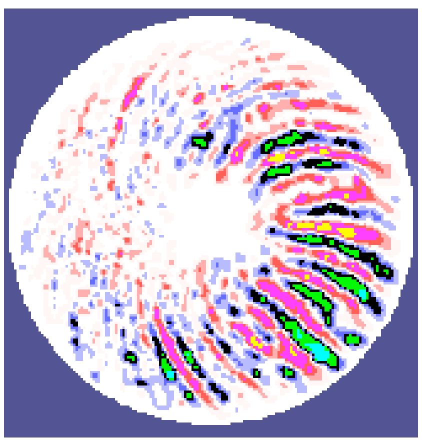
# Turbulence Suppressed By Sheared Flow

## Simulations predict turbulent eddies disrupted by strongly sheared plasma flow

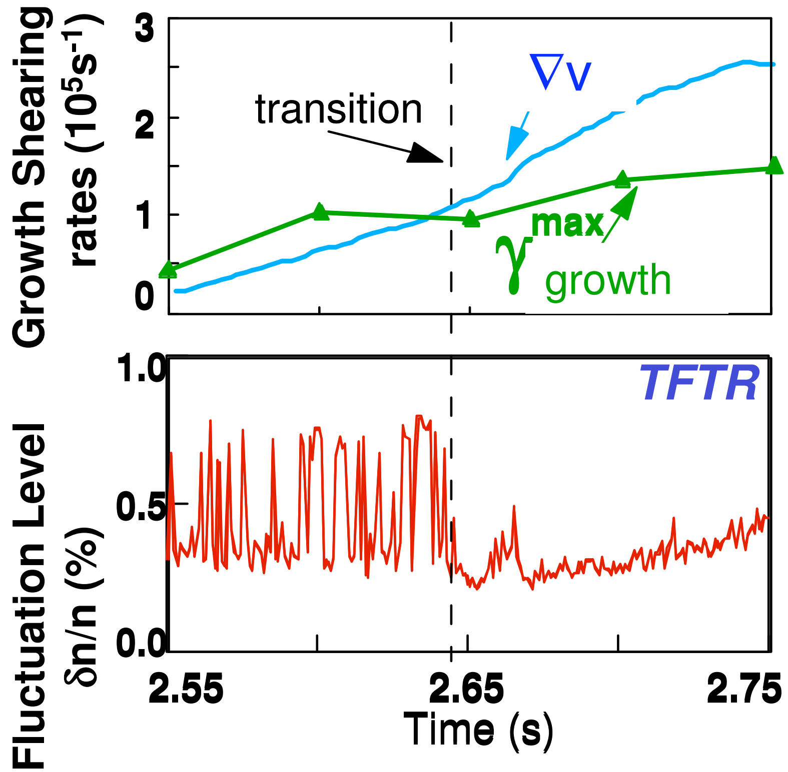
With Flow



Without Flow



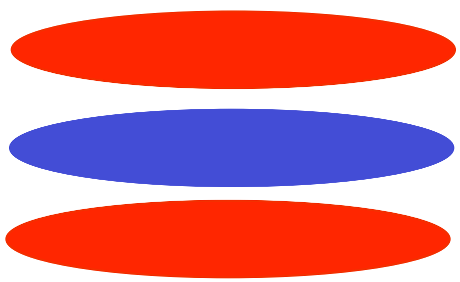
## Turbulent fluctuations are suppressed when shearing rate exceeds growth rate of most unstable mode




- Ion Transport reduced to collisional level !
- Turbulence generated self-generated flows crucial for saturation

# Sheared Flows can Reduce or Suppress Turbulence

Most Dangerous Eddies:
Transport long distances



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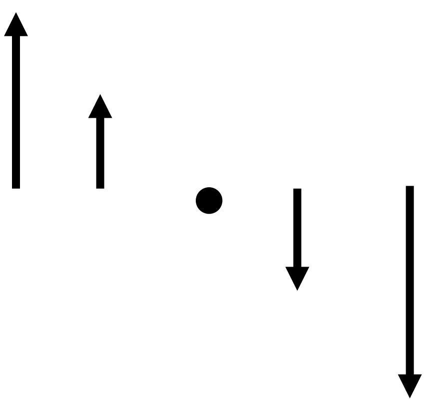
Sheared Flows



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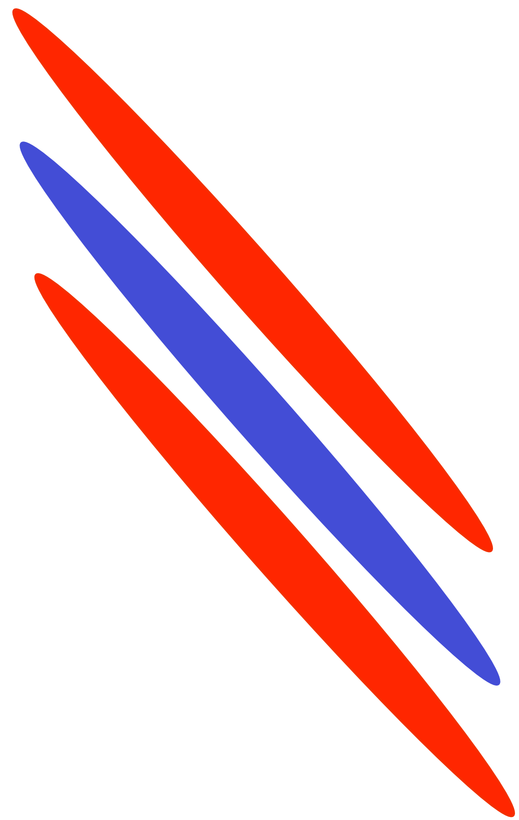
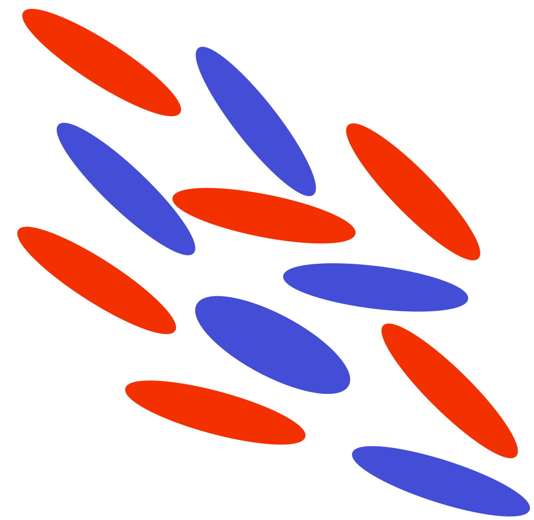
Sheared Eddies
Less effective

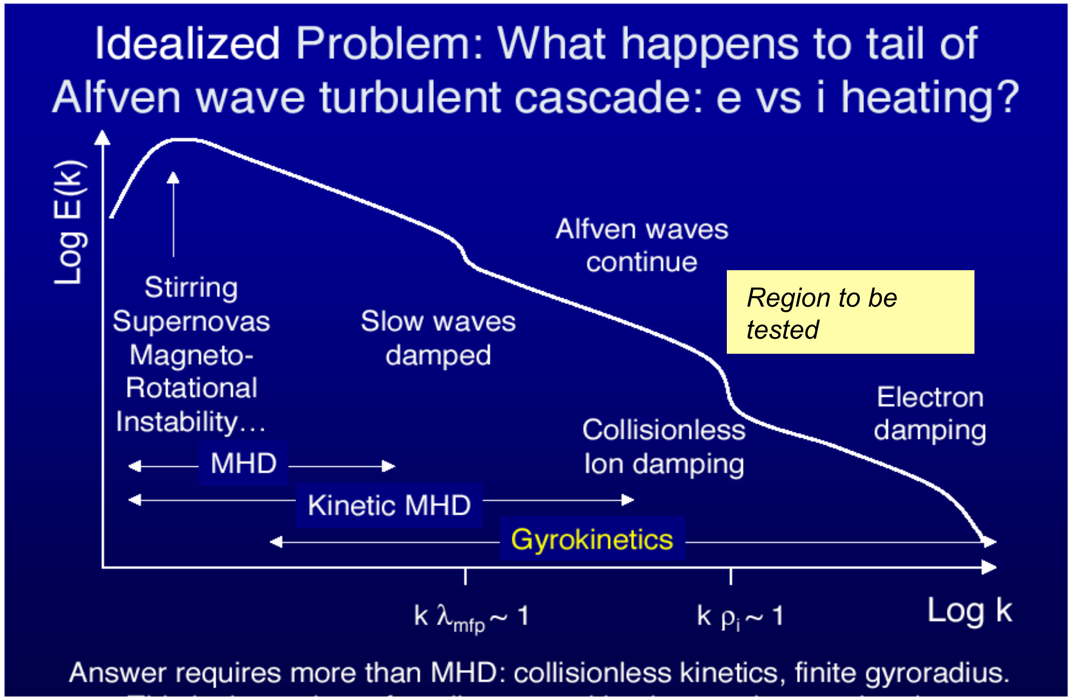


Break up from secondary instabilities

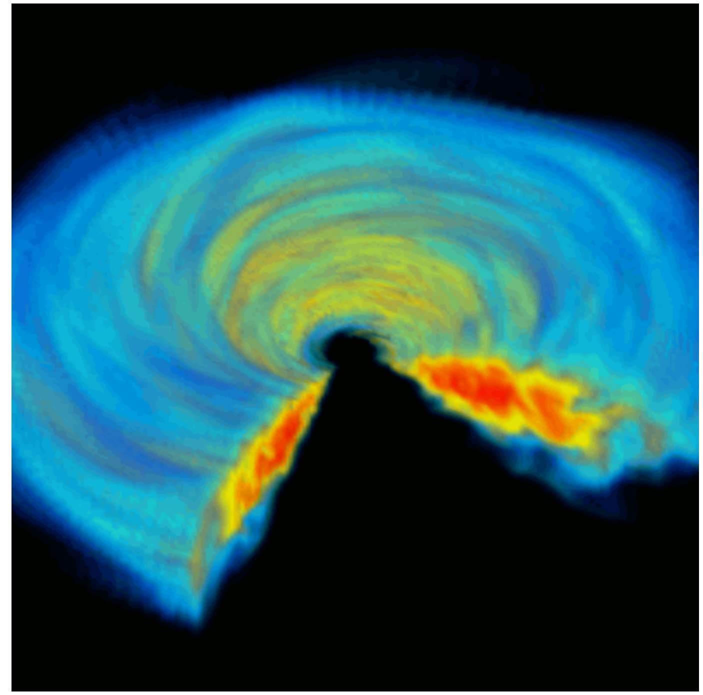


$$\omega_{E\times B} \equiv \nabla v_{E\times B} \sim \gamma$$

# Gyrokinetic Analysis of Turbulence Has Broad Scientific Importance



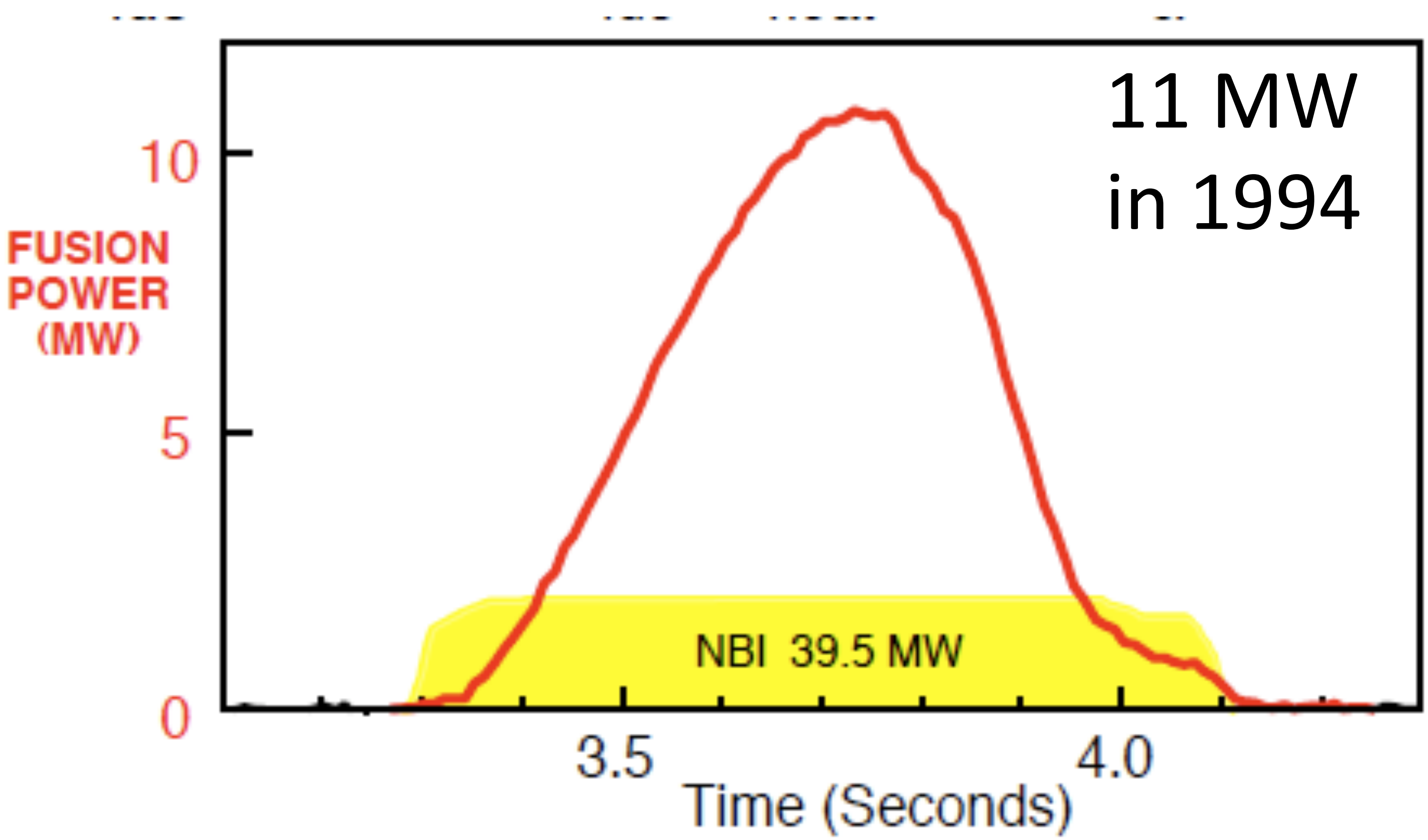

Hawley, Balbus, Stone



MHD simulation of accretion disk

- **Astrophysics turbulence dynamics: cascading of MHD turbulence to small ion scales is of fundamental importance (only electrons radiate…).**
- **Fusion's gyrokinetic formalism can be applied to astrophysical turbulence, w/ applications to shocks, solar wind, accretion disks.**
- **Laboratory plasmas provide validation of formalism.**

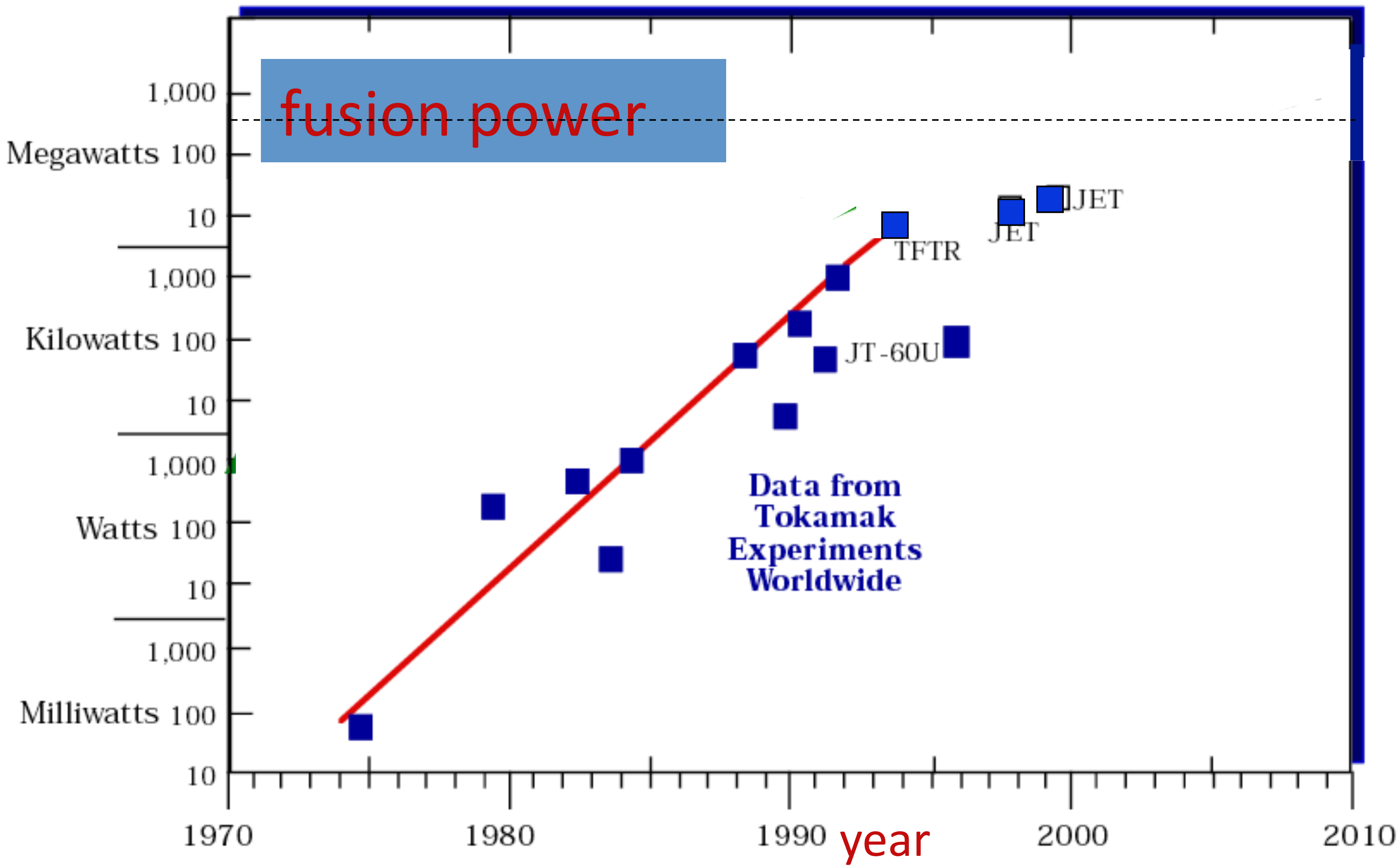
# Experiments produced substantial fusion energy




TFTR, PPPL

- Enough for ~3000 houses
- JET (EU) produced 16MW for ~1 sec. in 1997

# huge advance in fusion power




*Recent progress in fusion power limited by lack of facilities, not science*

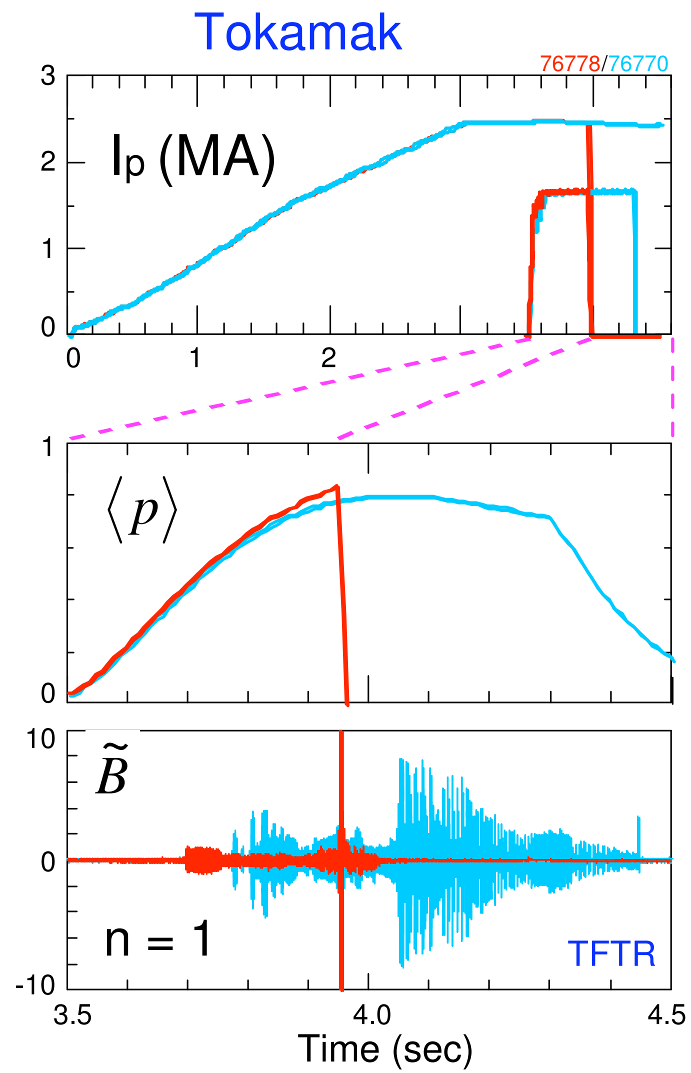
# Tokamak Pressure Limits Set by Instabilities

Tokamak pressure limit extensively studied

- Determined by instabilities
  - Ideal-like instabilities $\rightarrow$ disruptions
  - Saturated instabilities: degraded confinement
- Instabilities often involve plasma current

  Can cause strong changes to confining magnetic fields $\rightarrow$ Disruptions

- Onset of instabilities in good agreement with theory




$$\delta W = \frac{1}{2}\int dr^3 \left\{ \frac{|\delta B|^2}{\mu_o} + \frac{B^2}{\mu_o}|\nabla \bullet \xi_\perp + 2\xi_\perp \bullet \kappa|^2 + \gamma p |\nabla \bullet \xi|^2 - J_{||}(\xi_\perp \times b)\bullet \delta B - 2(\xi_\perp \bullet \nabla p)(\kappa \bullet \xi_\perp) \right\}$$

current limit pressure limit

# Next Step:  Burning Plasmas in ITER

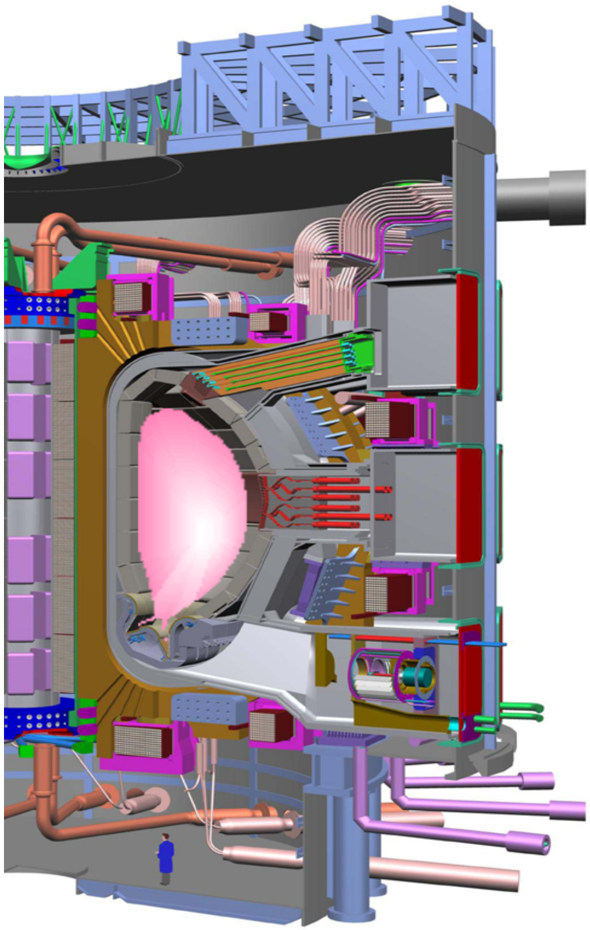
**Partnership of US, China, EU (45%), India, Japan, Russia, S.Korea;**

**Located in France.  US contributions managed by ORNL, PPPL, SRNL.**

**ITER goals: 500 MW for >500s,**
**power gain Q > 10**

**Understanding of:**

- Sustaining hot burning plasma by fusion reactions.
- confinement of reactor-scale plasma
- high gain dynamics



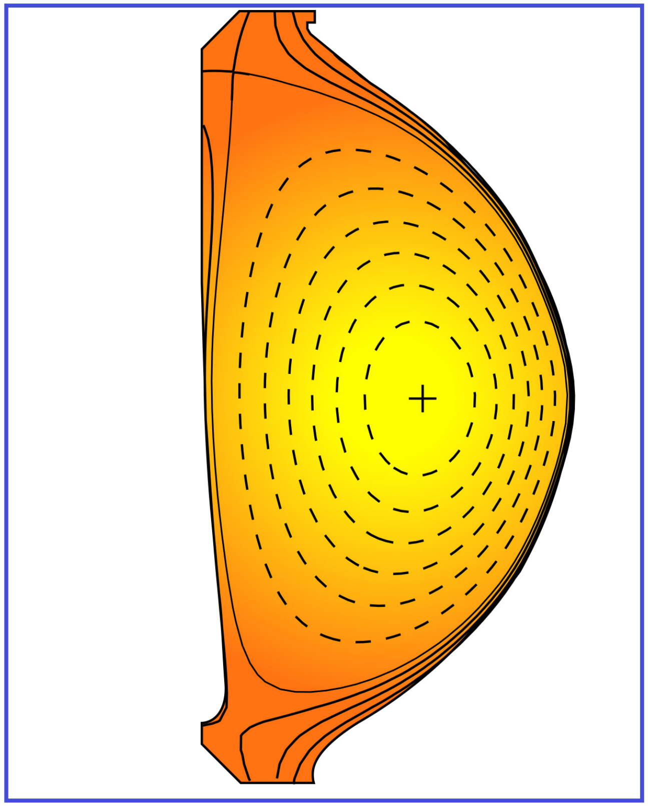
ITER (~2020)

## ITER site preparation in France

Plan for 2020 Operation

# ITER will Study Wide Range of Physics
## In the Burning Plasma Regime

**Partnership of EU, Japan, China, India, S.Korea, US**



- **Stability:** Extend the understanding of pressure limits to much larger scale plasmas.
- **Energetic particles:** Study strong heating by fusion $\alpha$-particles, in new regimes where multiple instabilities are can overlap.
- **Turbulence:** Extend the study of turbulent plasma transport to much larger plasmas, providing a strong test of fundamental physics scaling of turbulence.
- **Plasma-materials:** Extend the study of plasma-materials interactions to much higher power, much greater pulse length.

**Today:** Fusion power 11-17 MW for ~1 second, gain of < 1
**ITER:** 500 MW for 10 minutes, gain > 10
**Power Plant:** 2500 MW, continuous, gain > 25, ~ same size
No disruptions.

# ITER will develop fusion-energy technology

- **Superconducting magnets**
- **First wall materials**
- **Remote handling**
- **Tritium breeding blankets (at modest neutron fluence)**

# Princeton Plasma Physics Laboratory

- 436 FTE employees
- 20 postdocs
- 38 graduate students

~ 250 visiting scientists
(40 resident)

$92M (FY 10)

Founded 1951

U.S. DEPARTMENT OF ENERGY | Office of Science

PRINCETON UNIVERSITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

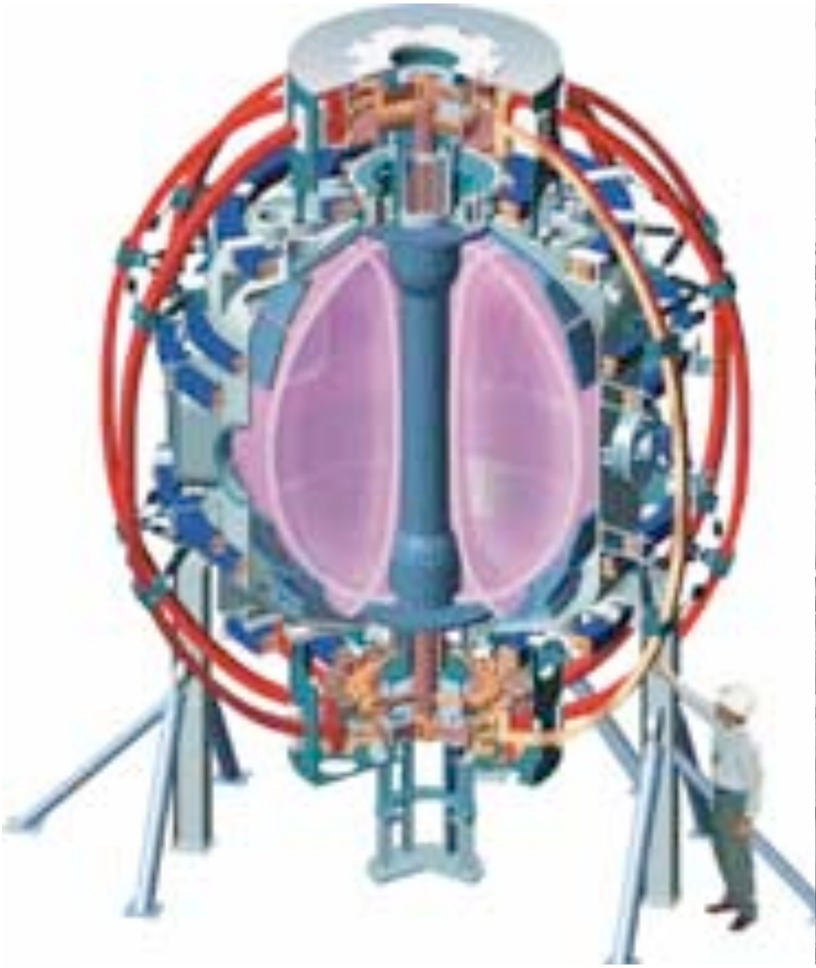
# PPPL Strategic Initiatives

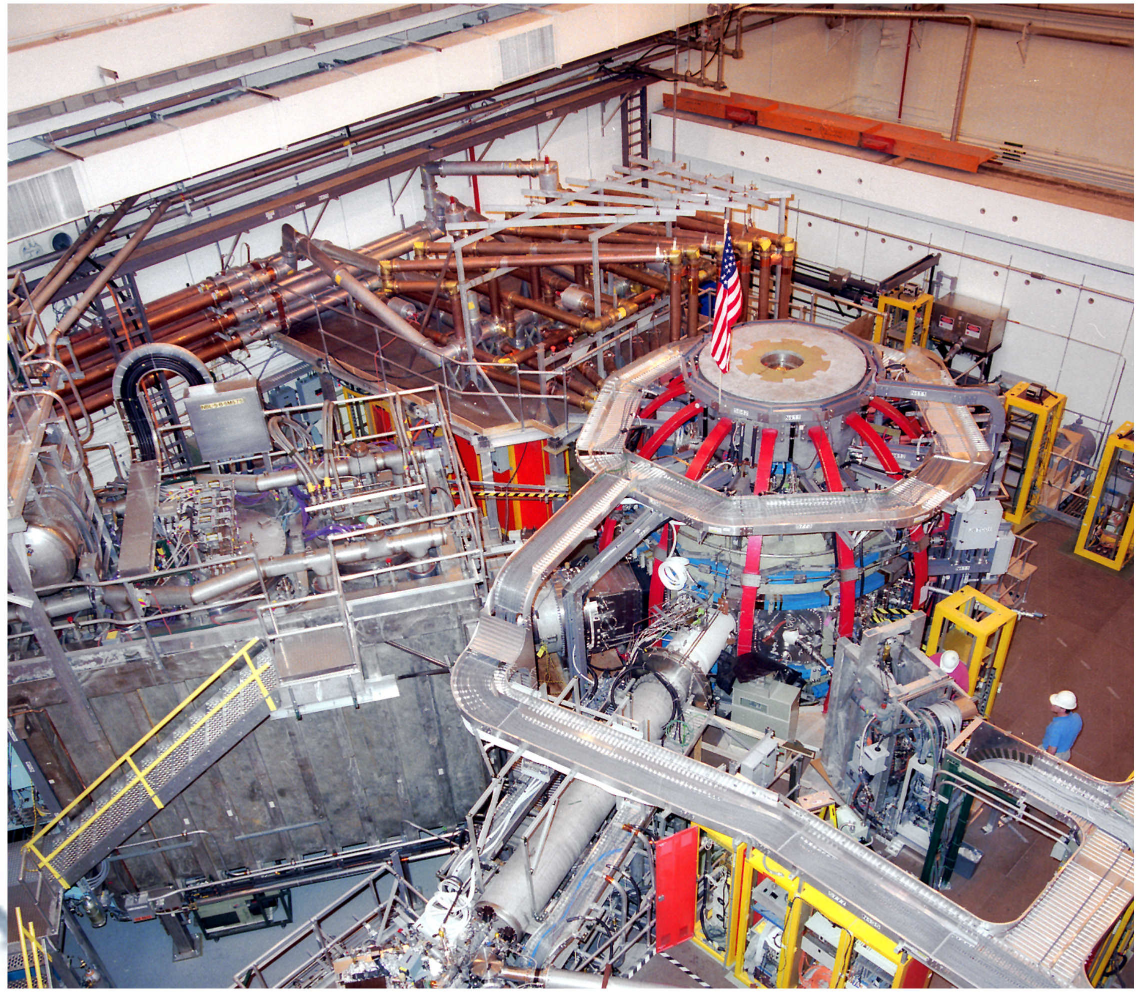
- Develop magnetic fusion energy
  - Advance the spherical tokamak for multiple fusion applications
  - Explore the physics and engineering science of plasmas producing fusion power (ITER & beyond)
  - Use 3D magnetic fields for steady-state, disruption-free plasma confinement
  - Develop integrated predictive models of burning plasmas
  - Develop methods to control the plasma-material interface

- Establish a center of excellence in plasma astrophysics

- Develop plasma science and related applications

# National Spherical Torus Experiment





- Extremely compact tokamak; increased curvature & shearing
- Lower magnetic field strength required
- Increased efficiency,  cost effectiveness

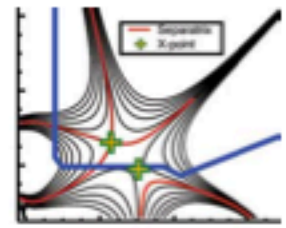
# NSTX Mission Elements

- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)

ST-FNSF

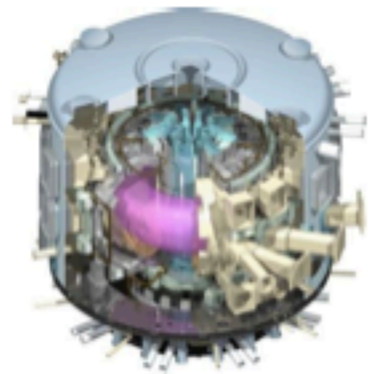
- Develop solutions for plasma-material interface

Lithium



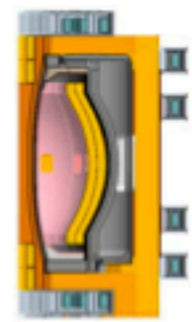
“Snowflake”

- Advance toroidal confinement physics for ITER and beyond



ITER

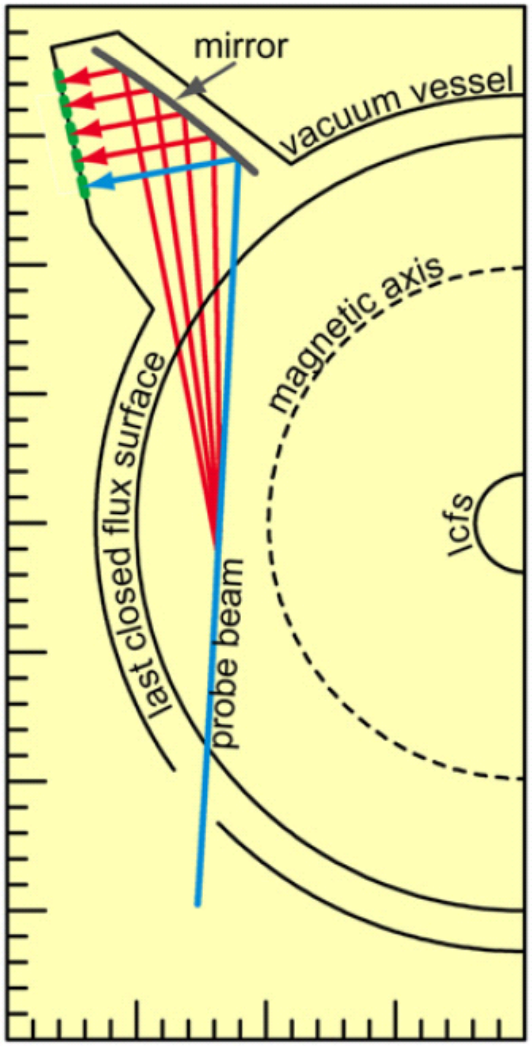
- Develop ST as fusion energy system



ST Pilot Plant

# NSTX Can Study Electron-scale Turbulence

Short wavelength electron turbulence measured by microwave scattering (accessible due to NSTX weak magnetic field)

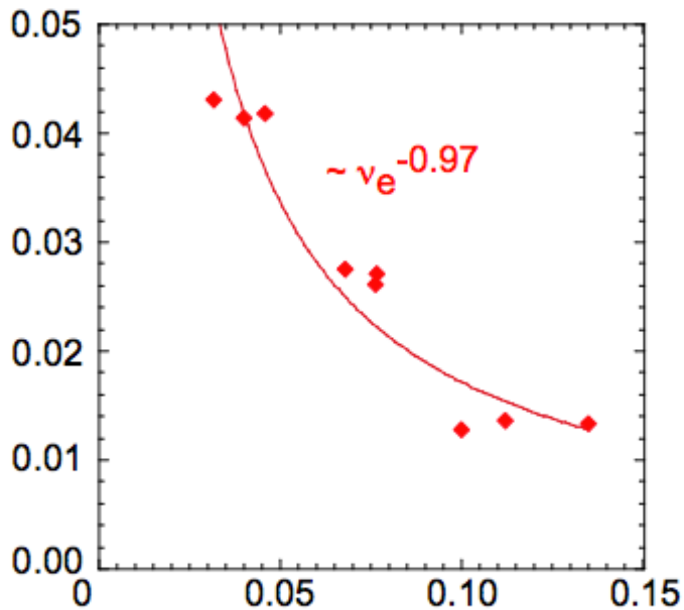



- Properties consistent with theory based on turbulence via electron temperature gradient, but
- Measured fluctuations increase with temperature (contrary to confinement scaling)
- Theory based on larger-scale ion turbulence scales as in experiment

# Confinement and turbulence

- Why does the spherical tokamak scale differently with temperature than the tokamak?

Confinement time (normalized)




← hotter collision frequency

Favorable scaling,

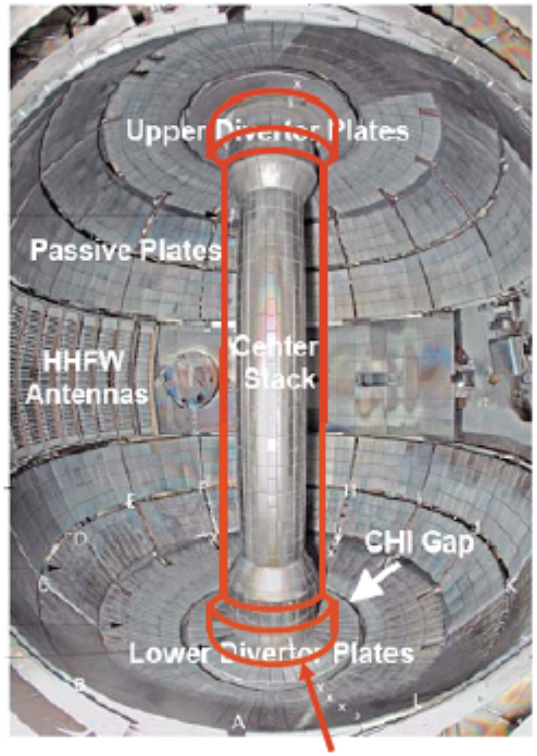
~ independent of collision frequency in the tokamak

Why the difference? Will it persist?

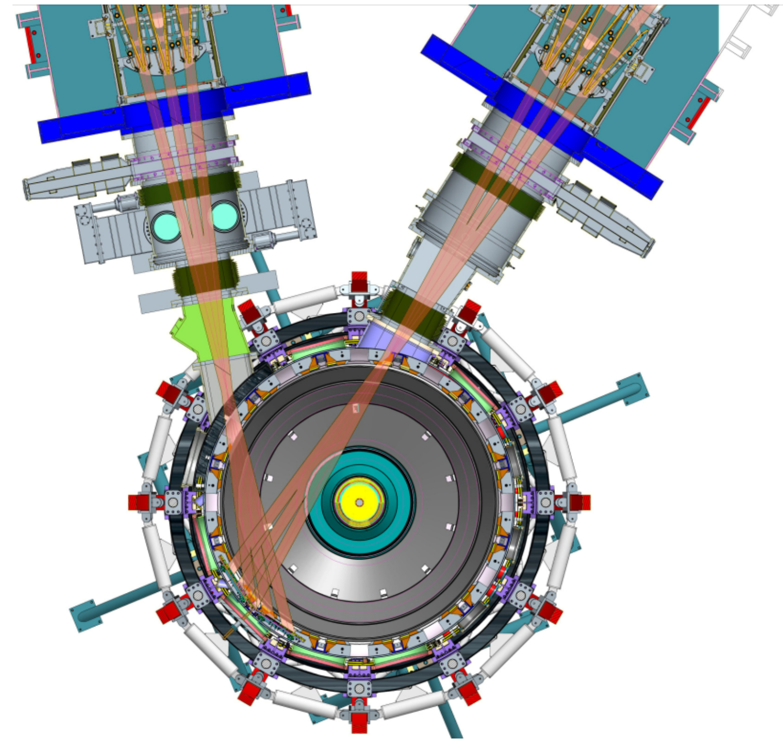
- What determines electron turbulence and transport in toroidal plasmas? (Important for ITER confinement)

# NSTX-Upgrade

*new center stack*




*second neutral beam*



Double the current, double the heating power, quintuple the plasma duration

↓

big boost to all NSTX science missions

(parameters closer to burning plasma conditions)

# The plasma-material interface challenge

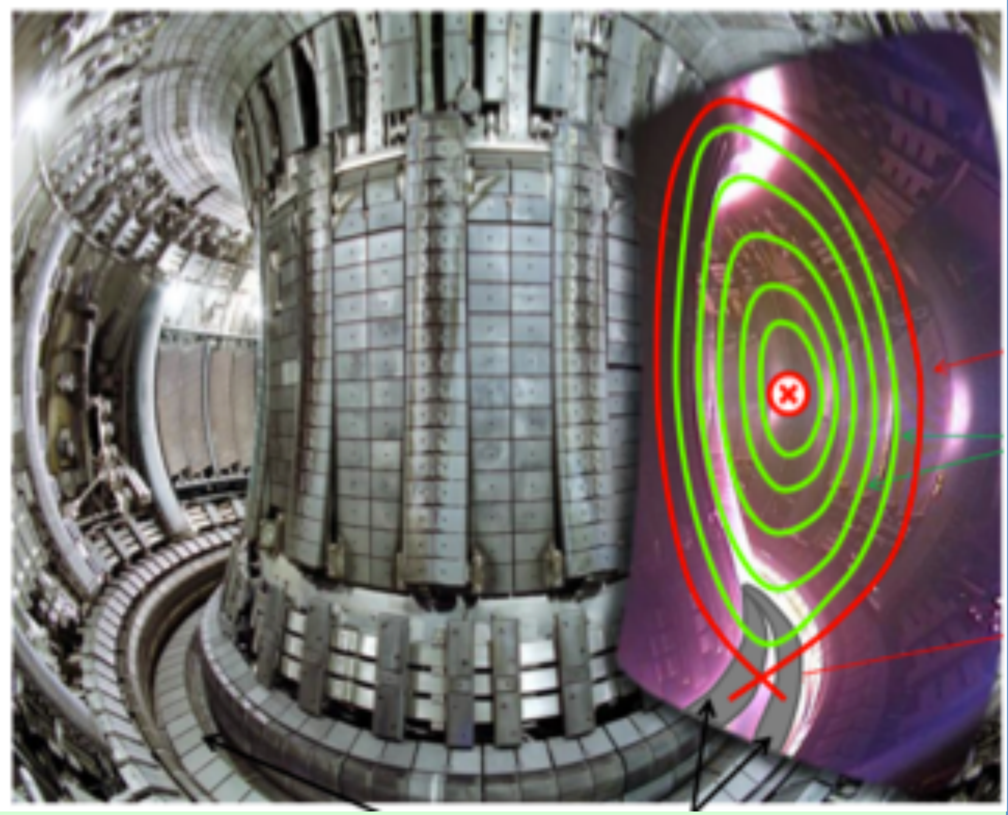
- Materials to survive intense fluxes (10 MW/m$^2$, and beyond)
- Plasma survival in presence of material influence

A plasma physics and materials science challenge

In tokamaks,
heat exhaust magnetically
channeled to special plates

width of exhaust plume is key
challenge for material survival

ITER will use tungsten



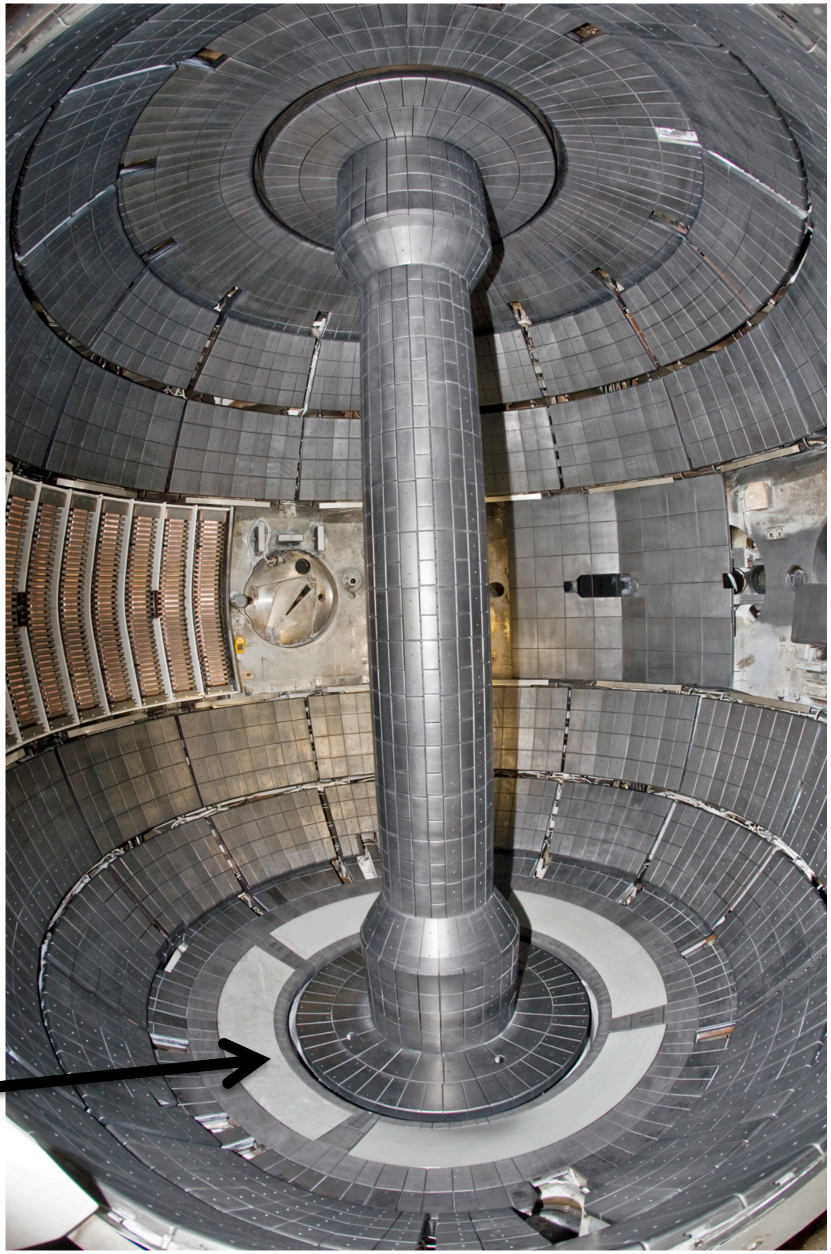
# Liquid lithium boundary

- The materials benefit

  no erosion, neutron damage, heat overload (if flowing), self-regenerating

- The plasma confinement benefit

  highly absorbing, no cold gas in-flux, reduced transport



Liquid lithium plate

# Liquid lithium boundary

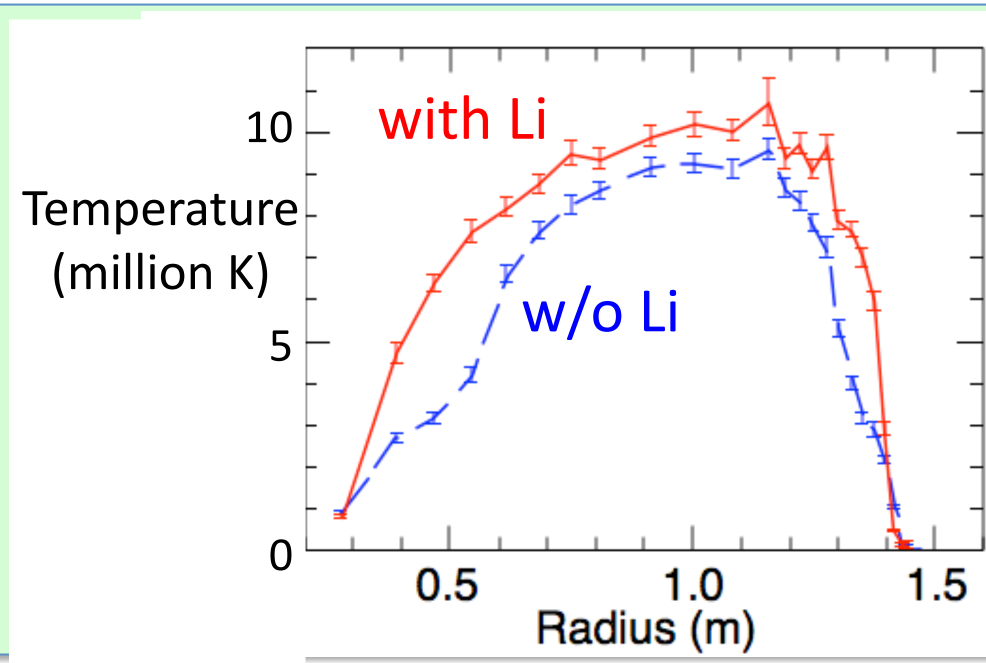
- The materials benefit

  no erosion, neutron damage, heat overload (if moving), self-regenerating

- The plasma confinement benefit

  highly absorbing, no cold gas in-flux, reduced transport

NSTX
Solid lithium coating improves confinement

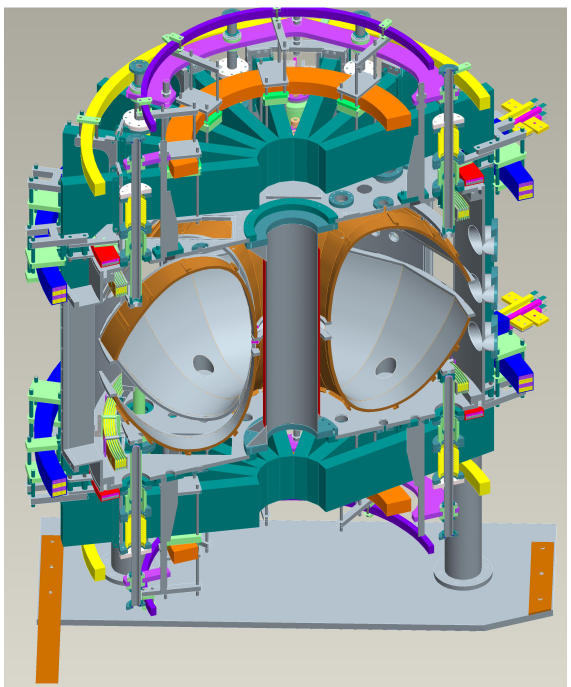


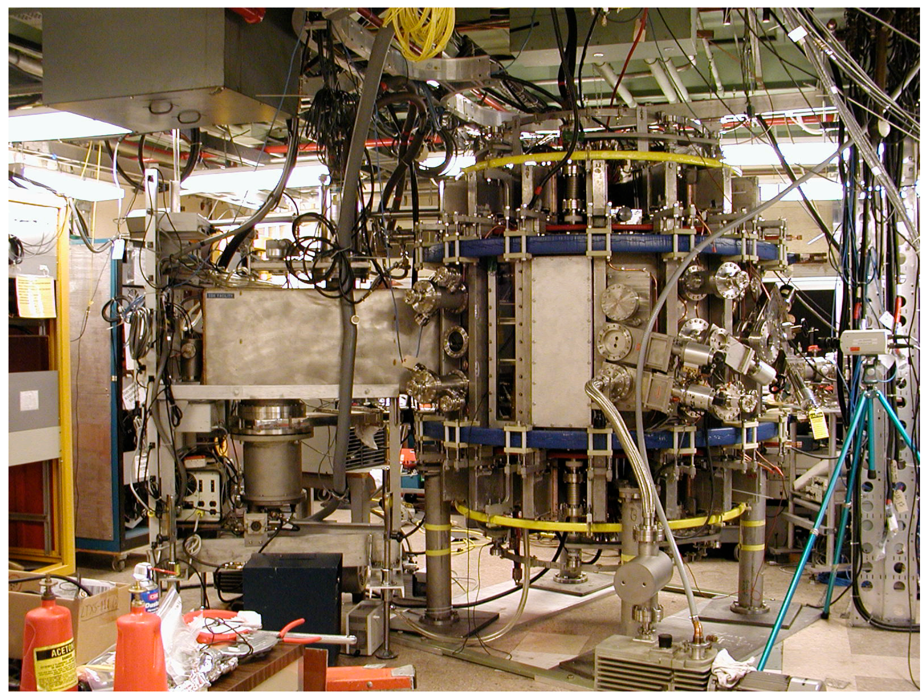
# Broader Plasma-Material Interface program

- NSTX: liquid lithium, magnetic channeling, source of high heat flux

- Lithium Tokamak Experiment (LTX)

  exploratory tokamak with full liquid lithium surface coverage

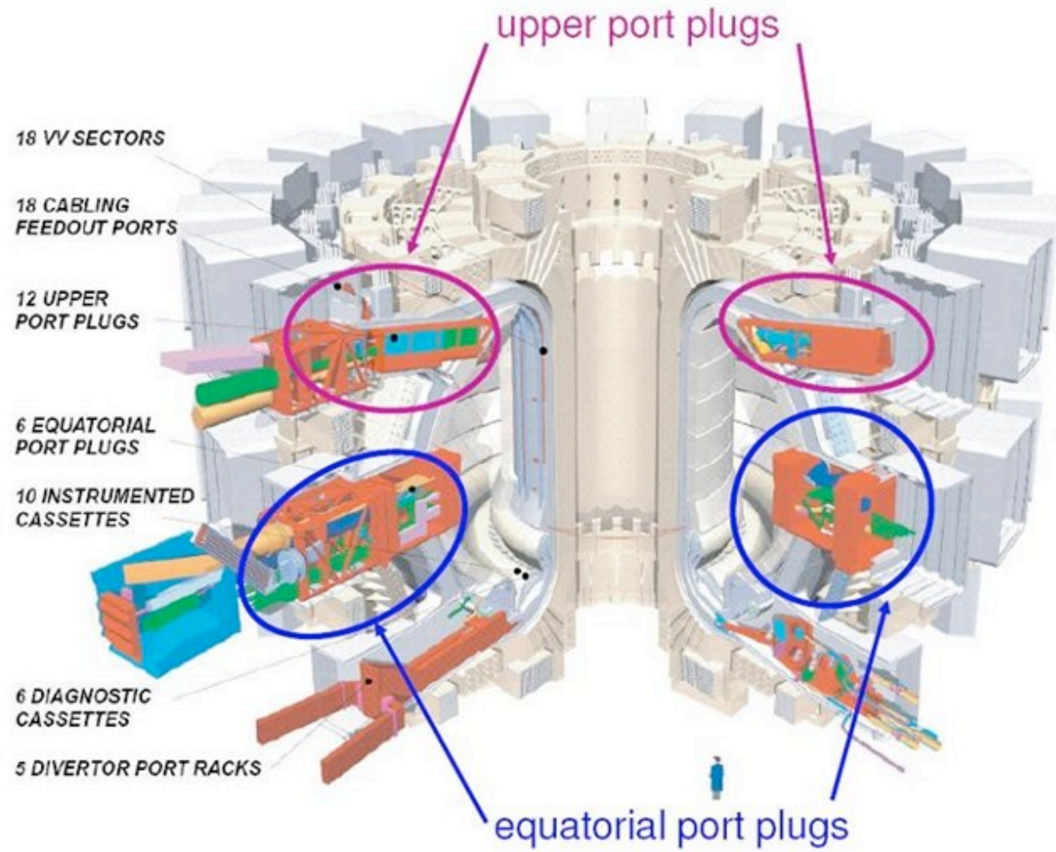




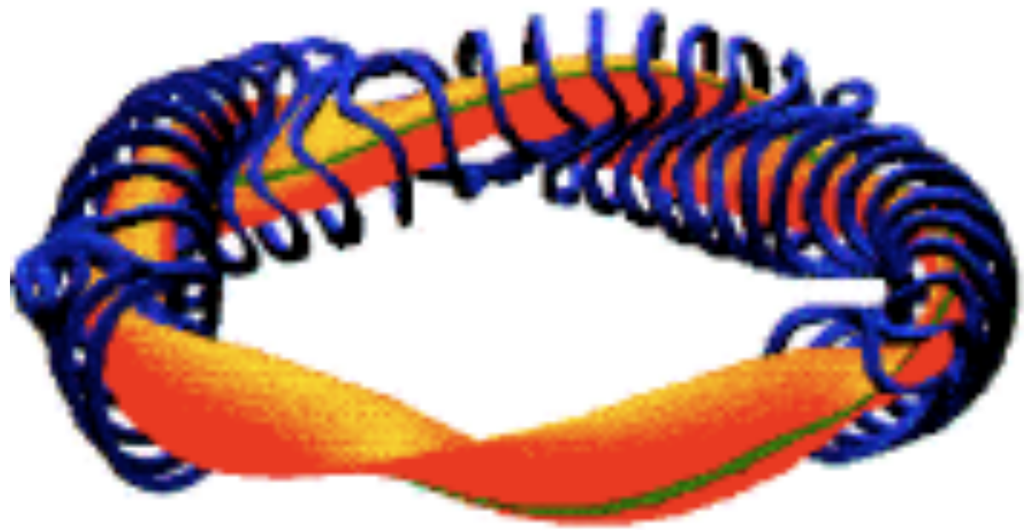
Started liquid lithium operation in FY 11

# PPPL responsibilities for ITER Construction

- Design/management of steady-state electric power network
- Management of US diagnostics contribution
- Design of diagnostic port plugs
- Conceptual design of in-vessel coils
- Various specific design tasks



# 3D Magnetic Shaping Provides Solutions



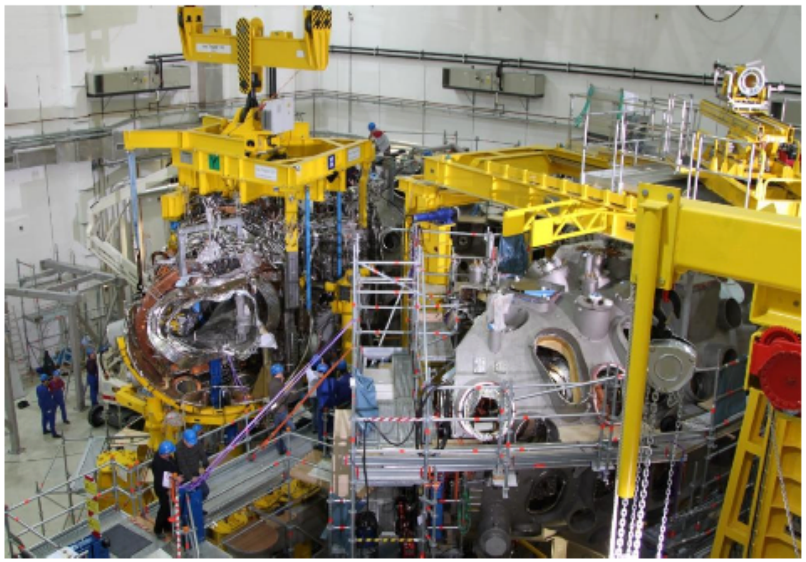
With 3D magnetic cage, carefully optimized, plasma is

- steady-state (no need to drive current in plasma)
- free of disruptions (no current-driven instabilities)
- high gain (no power needed for current drive)

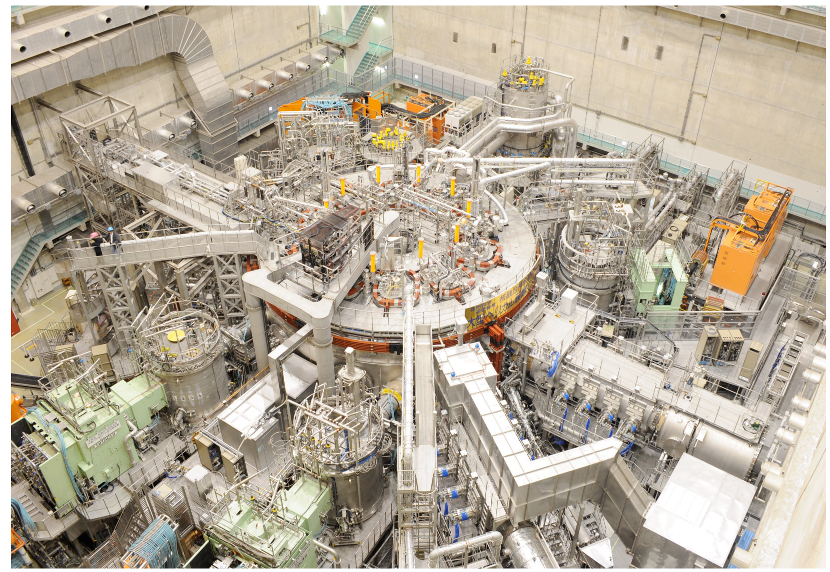
# PPPL Leading International Partnerships on 3D

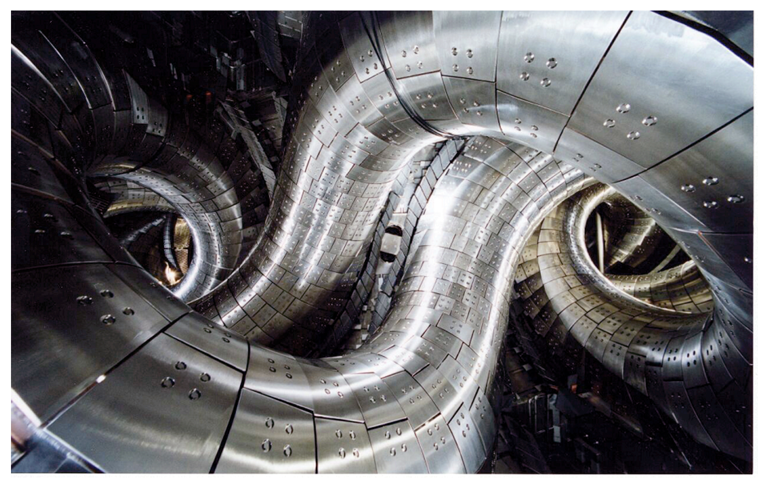
- Large International Facilities, none in US

W7-X (Germany)



LHD (Japan)

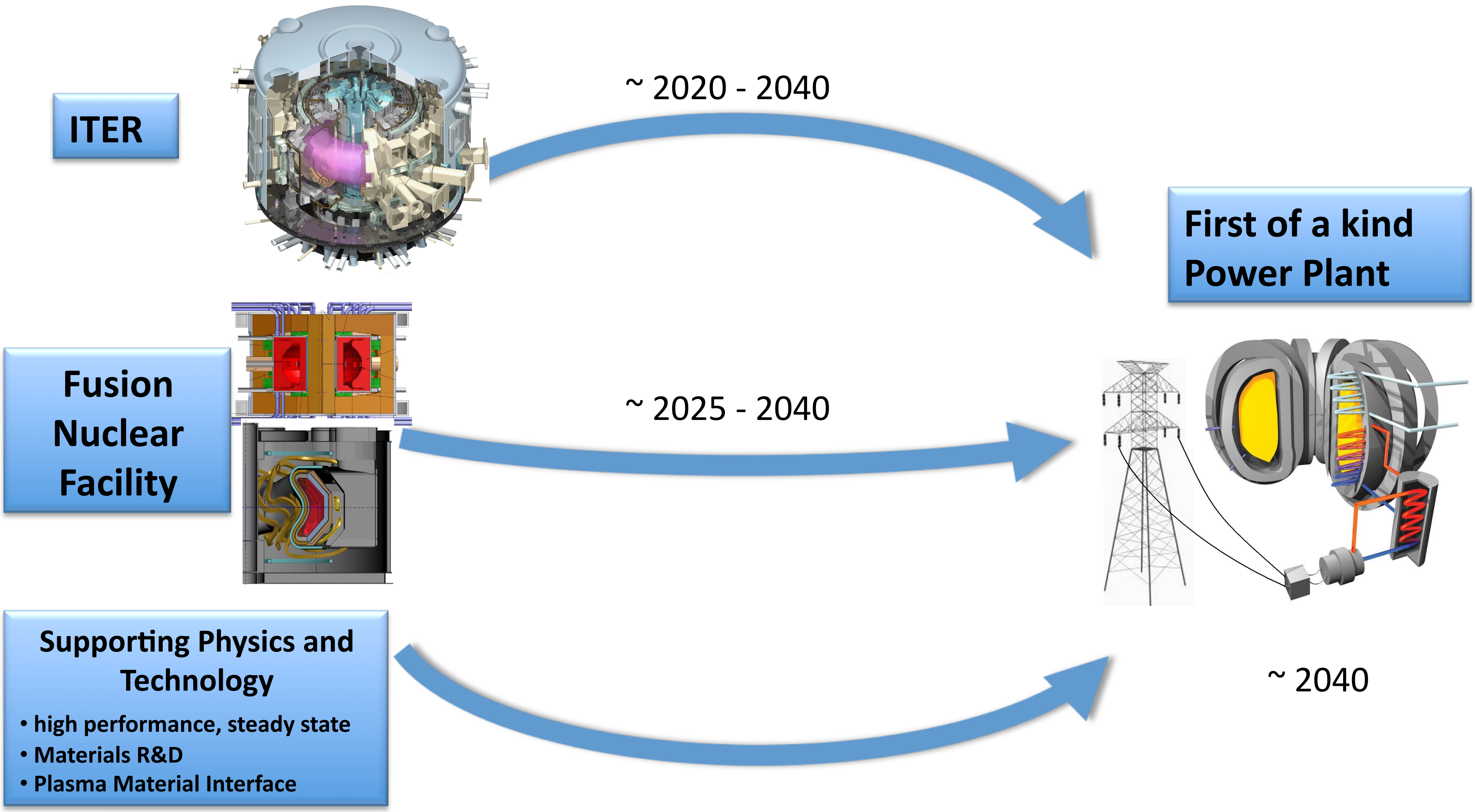




W7X: trim coils, diagnostics, divertor physics/eng'g, machine assembly

LHD: diagnostics, 3D plasma analysis, transport

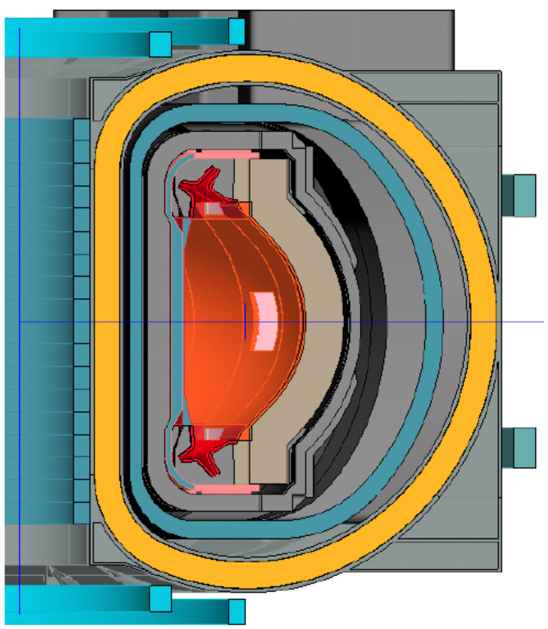
# The road to fusion power



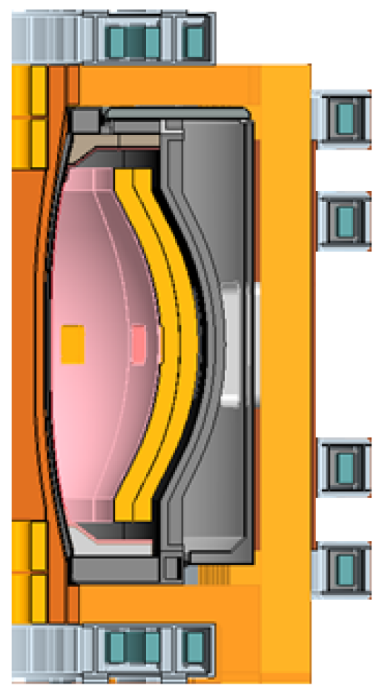
# Conceptual designs are being developed in the US and the World

## Fusion Pilot Plant designs

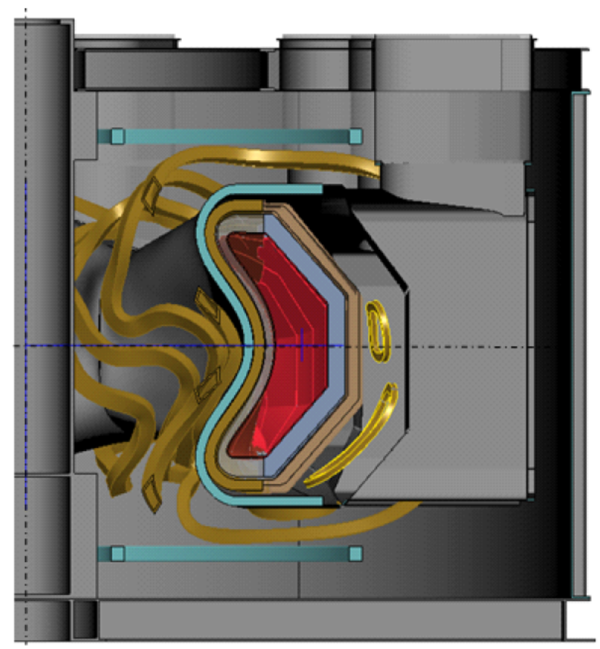
- Address fusion nuclear technology issues, and
- Generate net electricity (requires achieving high efficiency)
- Demonstrate reliable, robust operation and maintenance



tokamak



compact tokamak



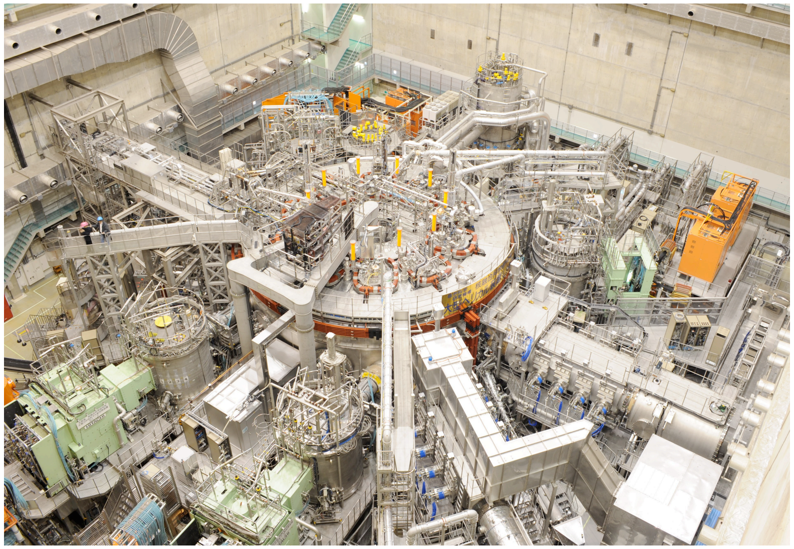
stellarator

# Magnetic fusion activity is Escalating across the world

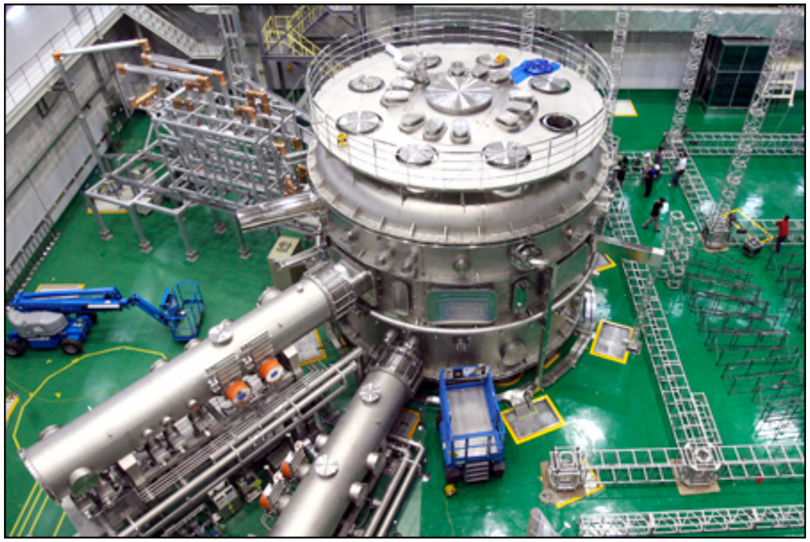
England: JET tokamak

China: superconducting tokamak EAST

Japan: superconducting stellarator

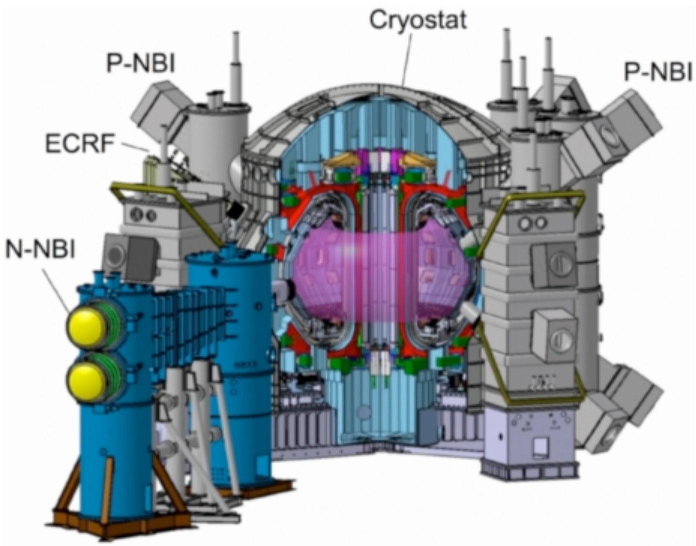


Korea: superconducting tokamak KSTAR

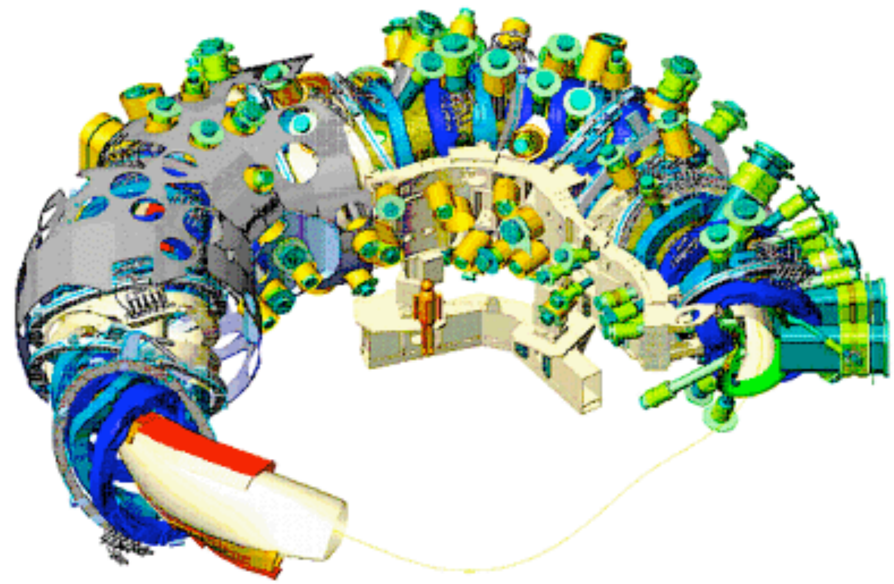


# Major facilities under construction

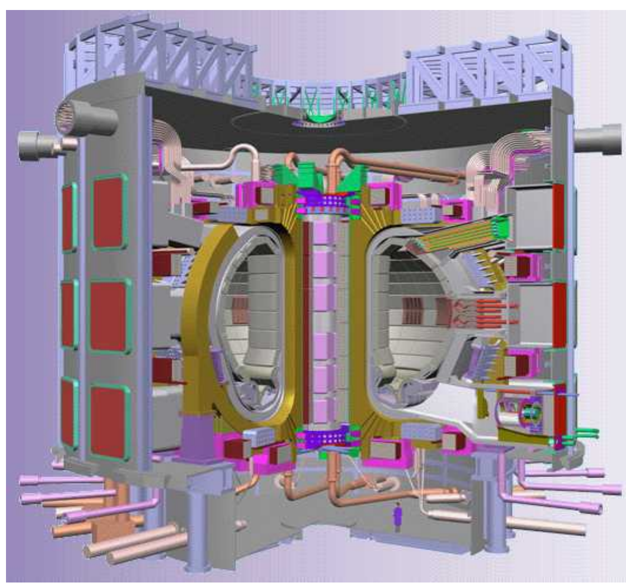
Japan: superconducting tokamak JT60-S




Germany: superconducting stellarator W7-X

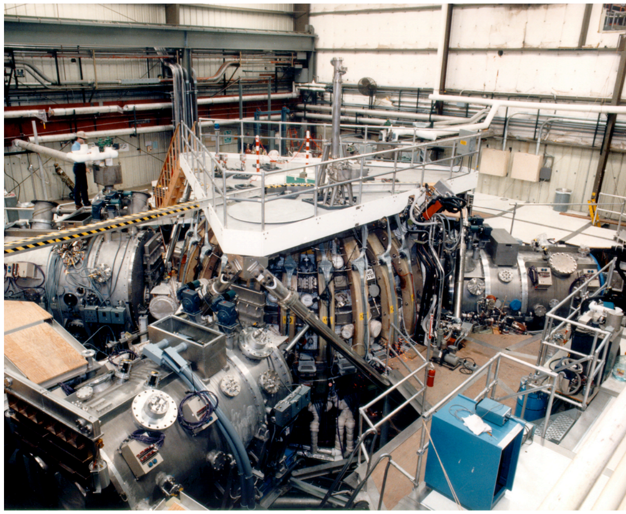


France: ITER



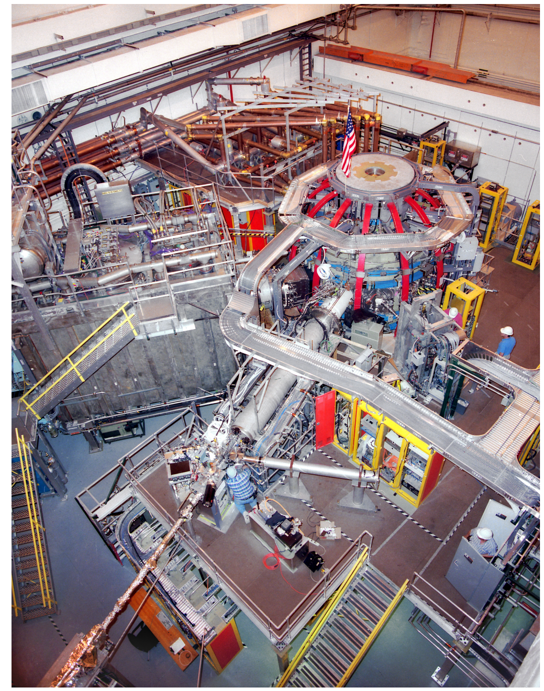
# The US operates a strong set of medium-scale experiments

General Atomics: DIIID tokamak



MIT: CMOD tokamak

PPPL: NSTX spherical tokamak



- These facilities advance critical issues for ITER and beyond
- However, the 6 major facilities overseas are more capable than the US facilities
- US contribution to the world fusion program is needed to meet the R&D challenges
- Reinvigoration of the US program is essential for US competitiveness in fusion

# Summary

- Fusion research is about to enter burning plasma regime.

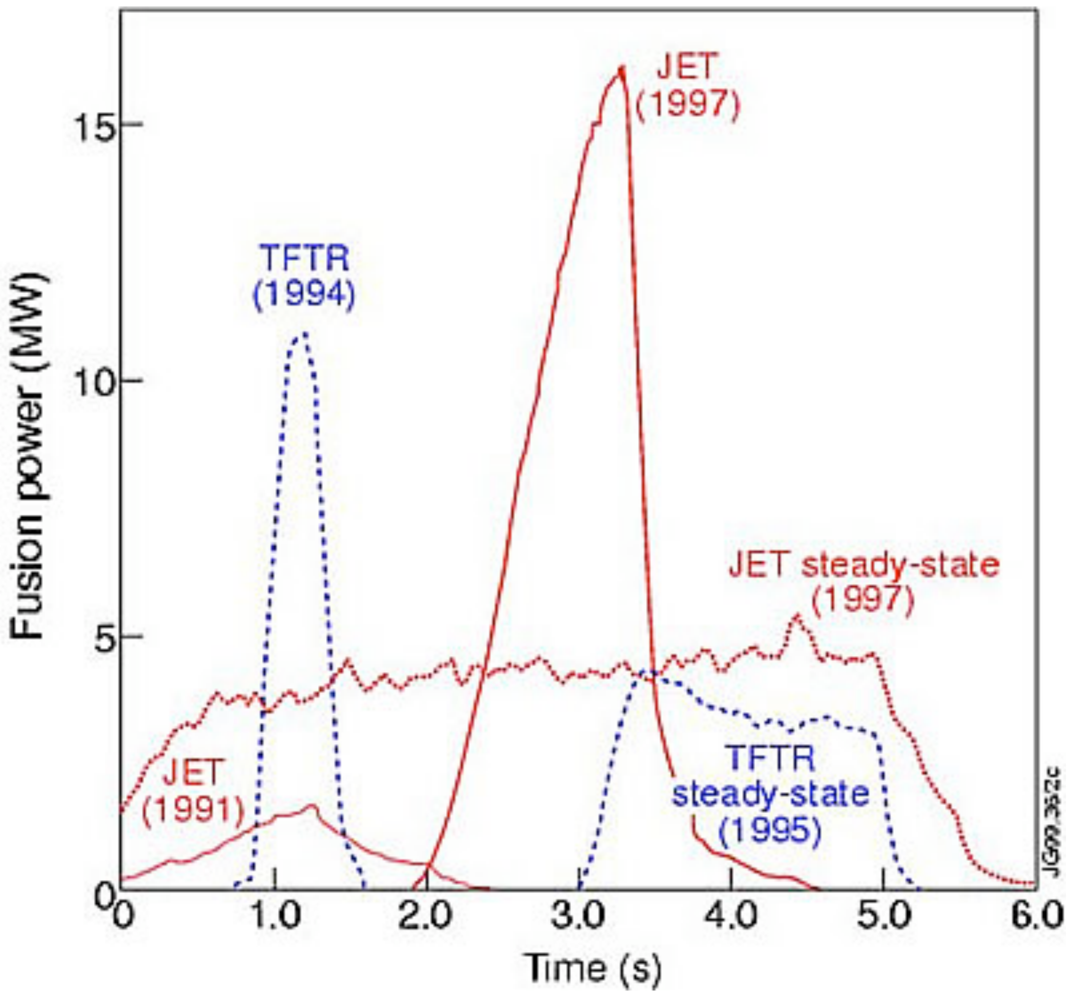
- Predictive understanding of high temperature plasma dynamics has been developed. ITER will validate in burning plasmas.

- Solutions to remaining challenges (steady-state, robust stability) are developing.

- World is aggressively pursuing fusion energy. US must invest to stay engaged.

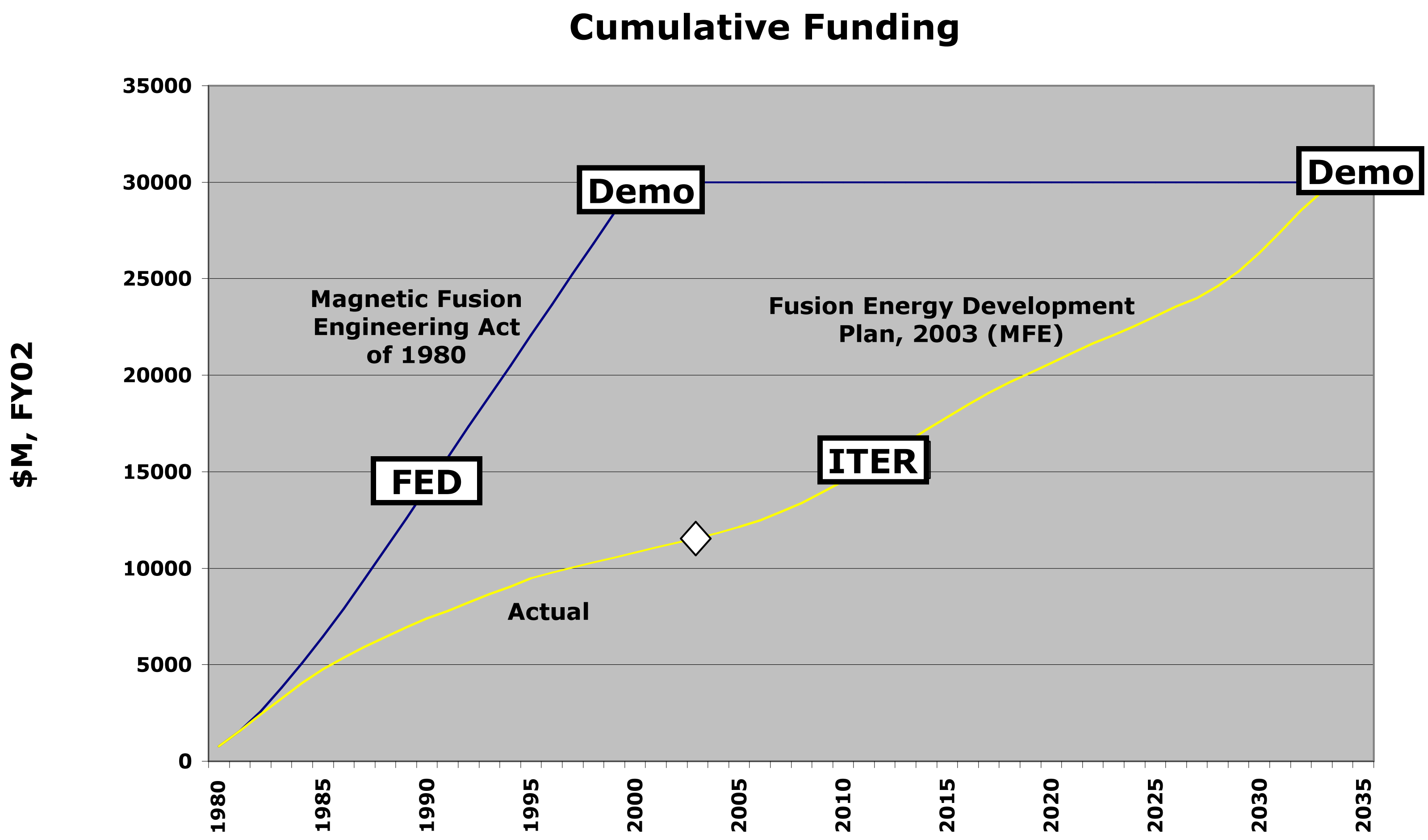
# 16 MW in 1997

~ 10 MJ




JET, UK

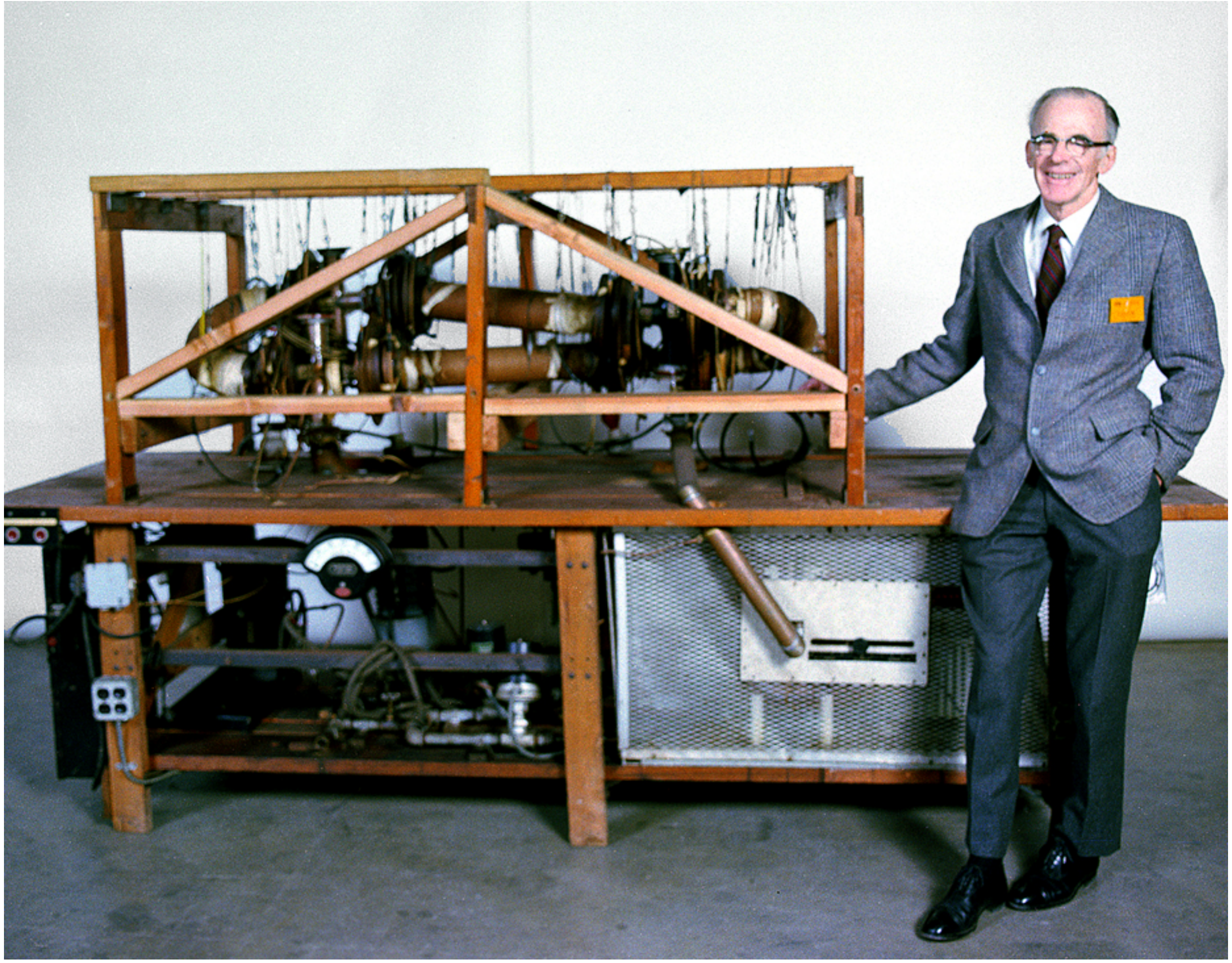
# The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



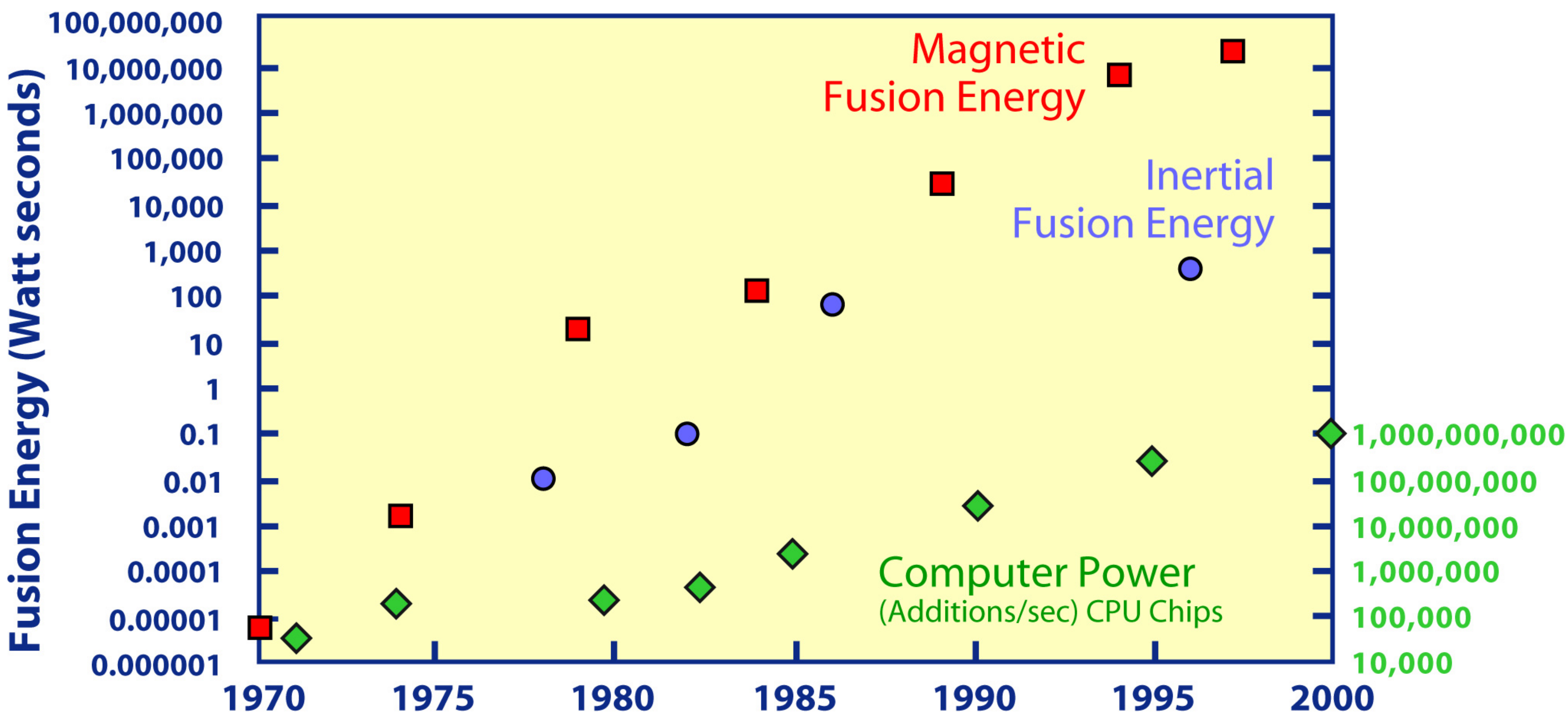

**Fusion Development is on Budget.**

# Different Approach: Stellarators

Model A Stellarator
ca. 1953
(with Prof. Lyman
Spitzer)

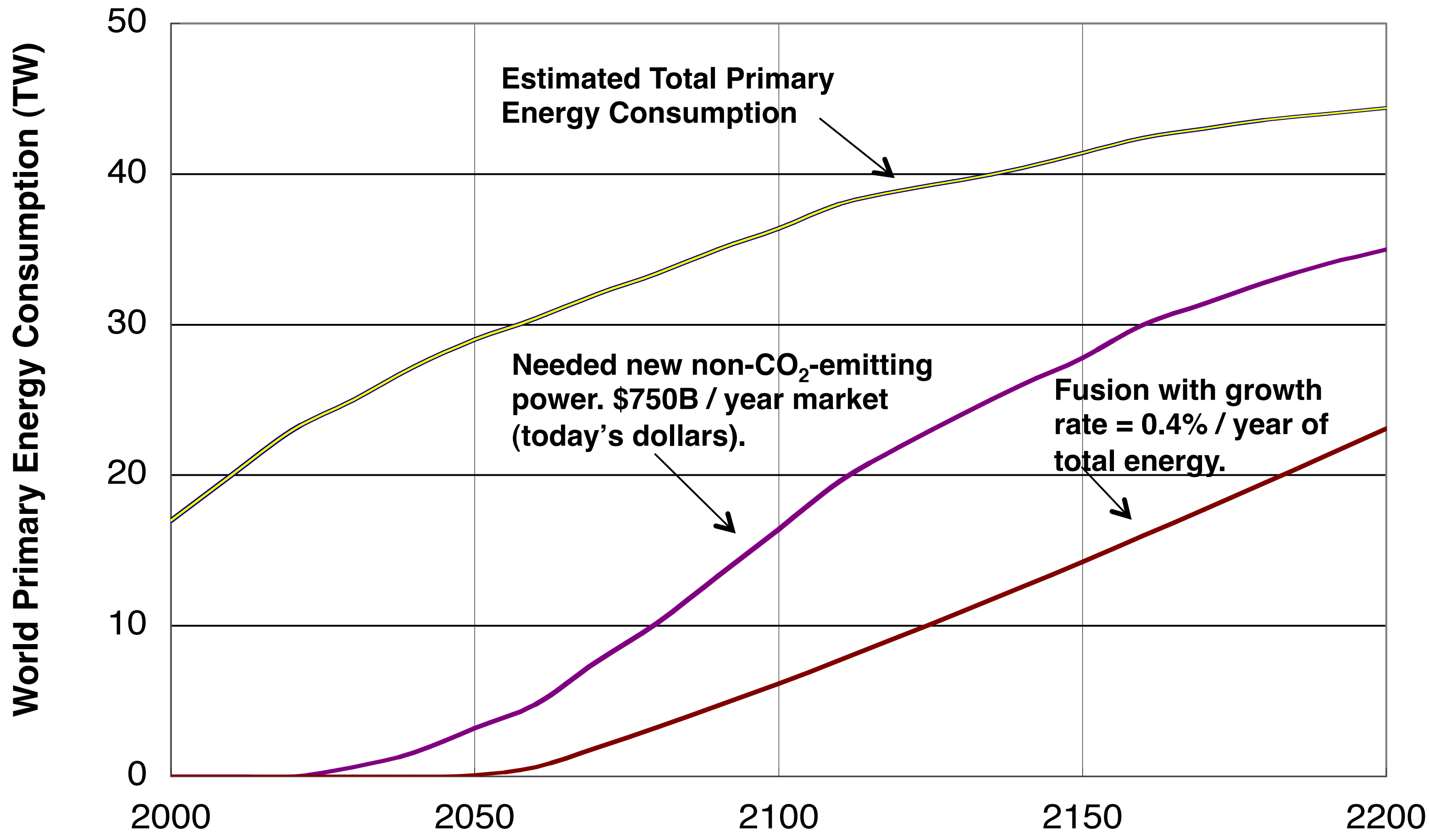


# Progress in Fusion has Outpaced Computer Speed




**Progress is paced by the construction of new facilities.**

# Fusion Can Deliver on a Reasonable Timescale

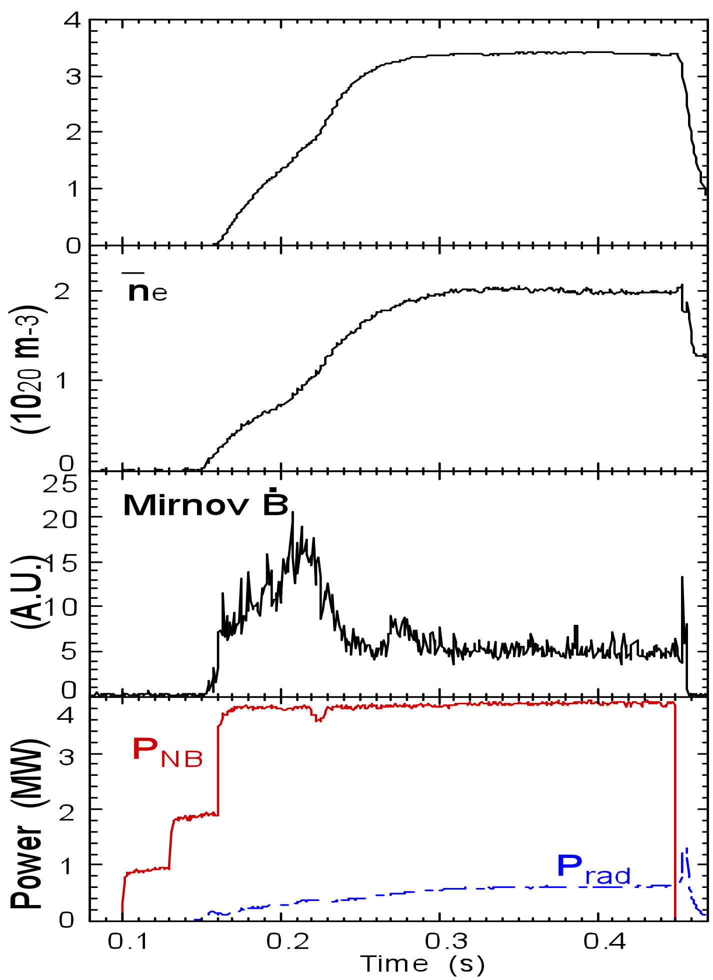


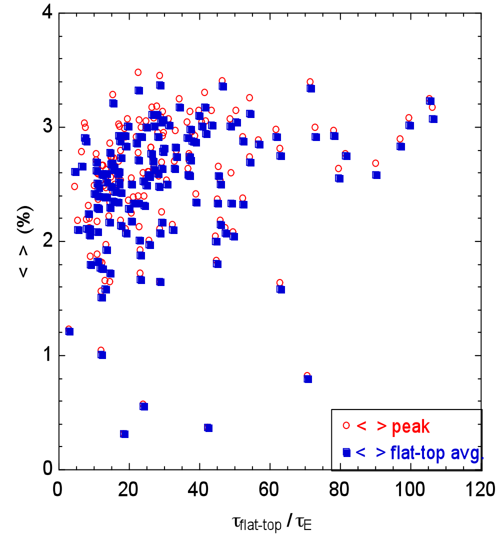

**ROI and Real Options analyses are very favorable.**

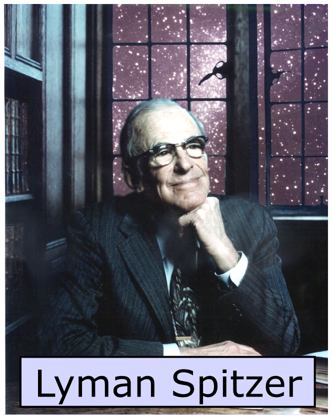
# Strong Connection Between Stellarators and Other 3D Plasma Physics Problems

- **Many other plasma problems are three-dimensional**
  - Magnetosphere; astrophysical plasmas
  - free-electron lasers; accelerators
  - perturbed axisymmetric laboratory configurations
- **Development of 3D plasma physics is synergistic, with stellarator research often driving new 3D methods.** Examples:
  - methods to reduce orbit chaos in accelerators based on stellarator methods [Chow & Carry, Phys. Rev. Lett. 72, 1196 (1994)]
  - chaotic orbits in the magnetotail analyzed using methods developed for transitioning orbits in stellarators [Chen, J. Geophys. Res. 97, 15011 (1992)]
  - astrophysical electron orbits using drift Hamiltonian techniques and magnetic coordinates developed for stellarators
  - tokamak and RFP resistive wall modes are 3D equilibrium issues
  - transport due to symmetry breaking was developed with stellarators

# U.S. Collaboration with German Stellarator Program Shows Quiescent high-β




**Stellarators make Long, Quiet Plasma Pulses**
**LHD in Japan: 54 minute discharges.**

# Plasma astrophysics

New report, initiated by PPPL, makes the case for plasma astrophysics

Describes 10 major questions in plasma astrophysics

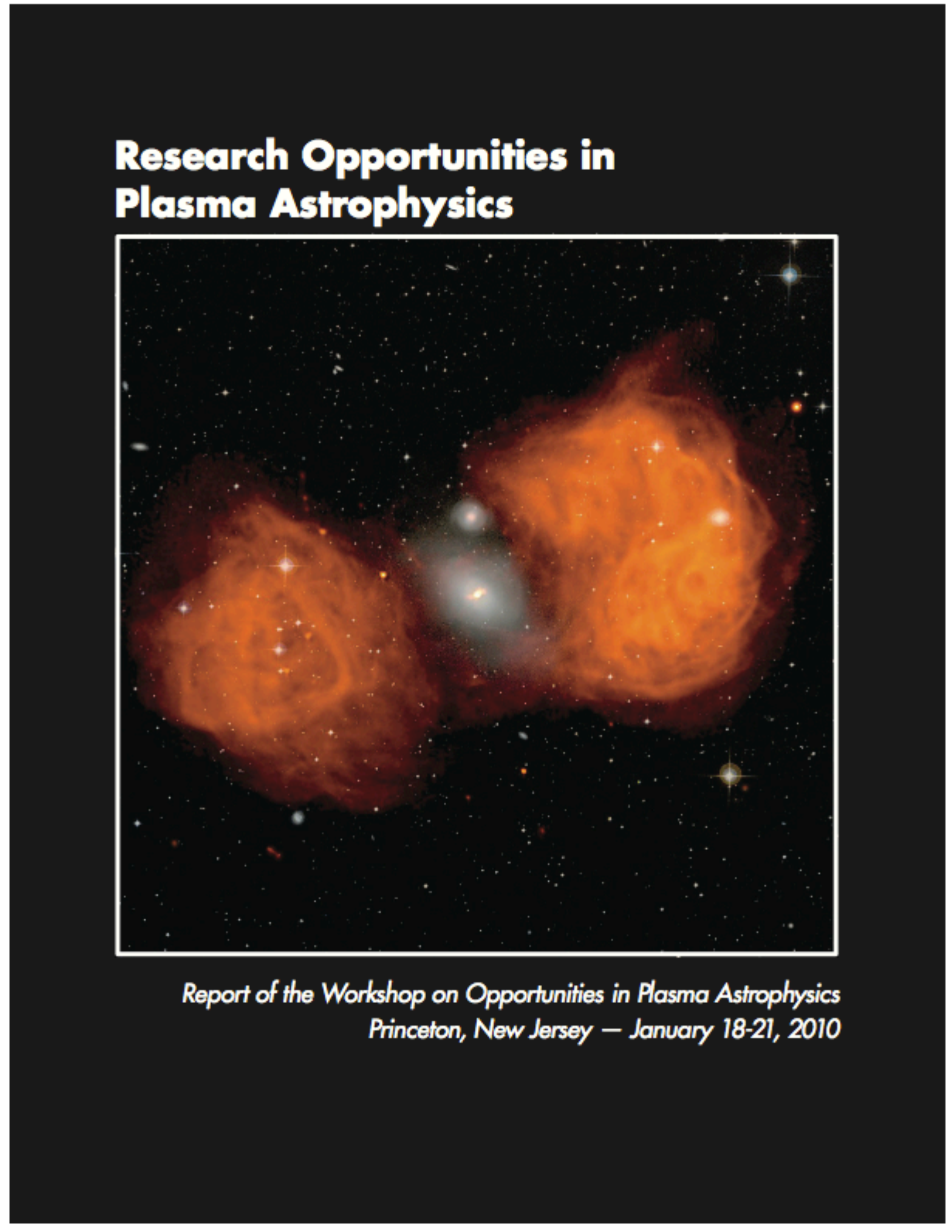
e.g.,

- What powers the most luminous sources in the universe?
- How do magnetic explosions work?
- Can magnetic fields affect cosmic structure formation?

Describes 10 plasma processes underlying astrophysical phenomena

e.g., reconnection, dusty plasmas, radiation hydrodynamics, angular ` momentum transport.....

Report being conveyed to funding agencies (DOE, NASA, NSF)



# Max Planck/Princeton center for plasma physics

- Proposed a joint research center between the Max Planck Society (Germany) and Princeton
- Selected topics in fusion and plasma astrophysics
- Germany: Institute for Plasma Physics (Garching, Greifswald)
  Institute for Astrophysics (Garching)
  Institute for Solar System Research (Lindau)
  US: PPPL
  Princeton Department of Astrophysical Sciences
- Approved in Germany (supporting 12 German postdocs), contingent on US funding
- Proposed to DOE (6.5 postdocs), NSF (3 postdocs, J. Stone), Princeton (funding 2.5 postdocs)