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SMR 1331/19

AUTUMN COLLEGE ON PLASMA PHYSICS

8 October - 2 November 2001

The Structure of the US Fusion Energy Science Program - What Scientific Questions are We Trying to Address?

R.J. Goldston

Princeton University, Plasma Physics Lab.
Princeton, U.S.A.

These are preliminary lecture notes, intended only for distribution to participants.

The Structure of the US Fusion Energy Science Program – What Scientific Questions are We Trying to Address?

Rob Goldston, Director
Princeton Plasma Physics Laboratory

October 15, 2001

Fusion Plasma Science is in Pasteur's Quadrant

Prof. Donald Stokes, Dean, Princeton Woodrow Wilson School

Considerations of Use?

Quest for Basic Understanding?	No	Yes
Yes	Bohr	Pasteur
No		Edison

Tight coupling of understanding and innovation.

Strong commitment to *both!*

PPPL Mission Statement

The DOE Princeton University Plasma Physics Laboratory is *a Collaborative National Center* for plasma and fusion science. Its primary mission is to develop *the scientific understanding and the key innovations* which will lead to an attractive new energy source.

Associated missions include conducting *world-class research* along the broad frontier of plasma science and technology, and providing the *highest quality of scientific education.*

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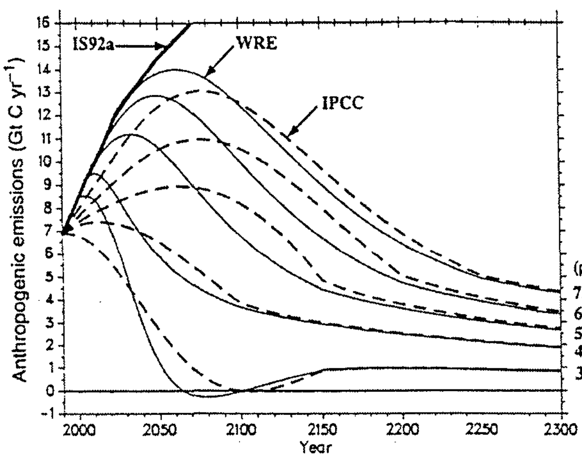
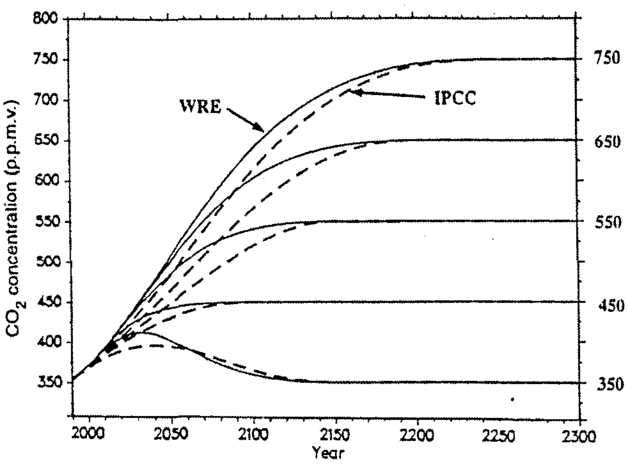
CO_2 Accumulation is a 100 to 200 Year Process





If CO_2 is a problem, non-carbon emitting sources must provide about half of the world's power by 2100.

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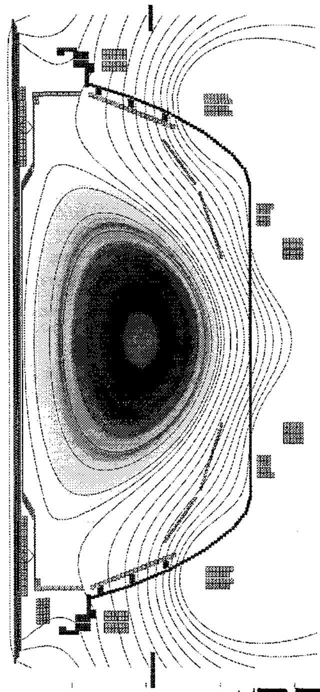
Plasma Science Challenges
NRC Plasma Science Committee

- Macroscopic Stability
  - What limits the pressure in plasmas?
    - Geomagnetic substorms, Chandra data
- Wave-particle Interactions
  - How do hot particles and plasma waves interact in the nonlinear regime?
    - Coronal heating, laser amplification
- Microturbulence & Transport
  - What causes plasma transport?
    - Astrophysical accretion disks
- Plasma-material Interactions
  - How can high-temperature plasma and material surfaces co-exist?
    - Materials processing



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Fusion Plasma Science is Addressed through a "Portfolio Approach"

- Scientific synergy – Common physics
  - Ideas from one configuration help others.
  - Hybrid configurations emerge.
  - Provides rigorous test of plasma science understanding.
- Breadth – Complementarity
  - Range of configurations avoids common roadblocks.
  - Broadens science and technology impact of fusion science.
- Leverage – > $1B/year International Program
  - Opportunities to access advanced scientific facilities abroad.

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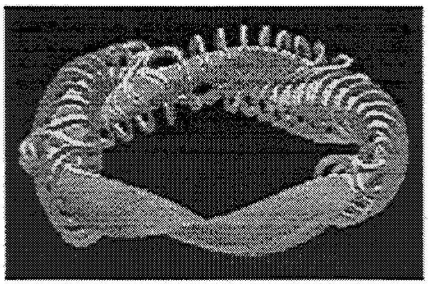
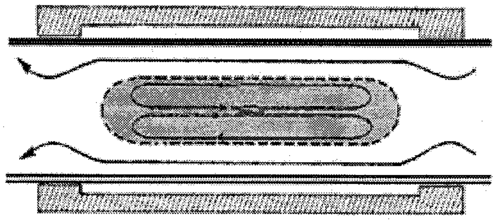
The Portfolio of MFE Configurations

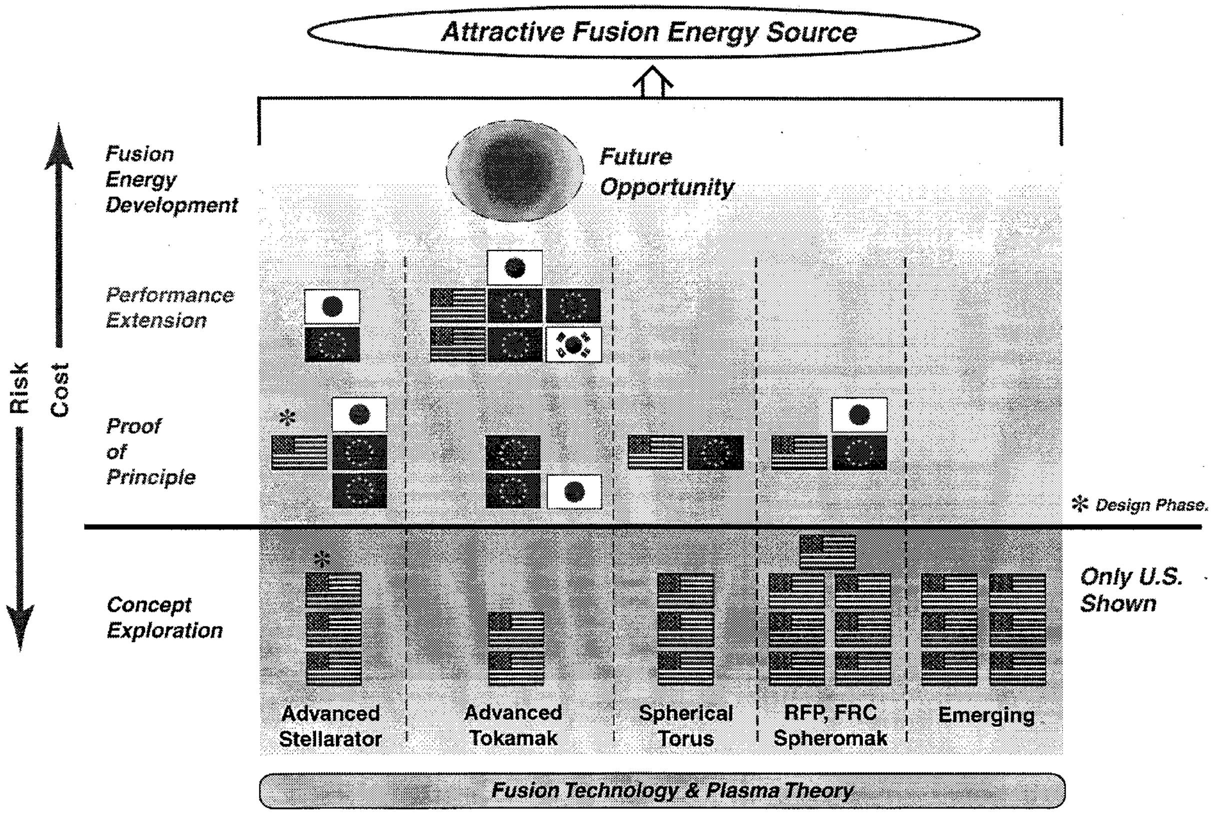
Externally Controlled **Self-Organized**





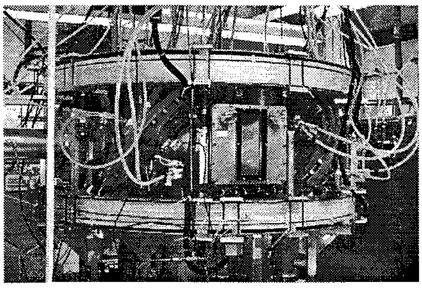
Example: Stellarator	**Example: FRC**
Coils link plasma	Coils do not link plasma
Magnetic fields from external currents	B from internal currents
Toroidal field >> poloidal field	Poloidal B >> Toroidal B
Large R/a	R/a $\rightarrow$ 1.0
More stable, better confinement	Higher power density

The Magnetic Fusion Energy Portfolio

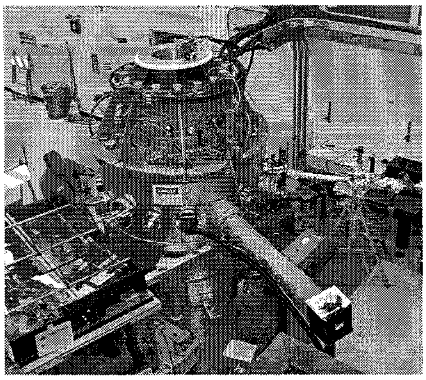


Facilities both operating and under construction.

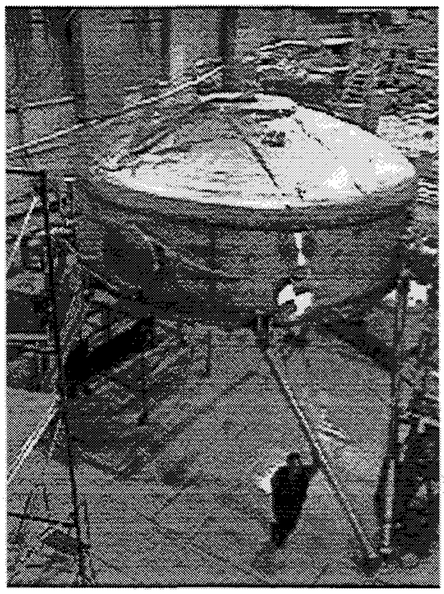
Innovative Confinement Concepts Expand the Range of Stability Studies



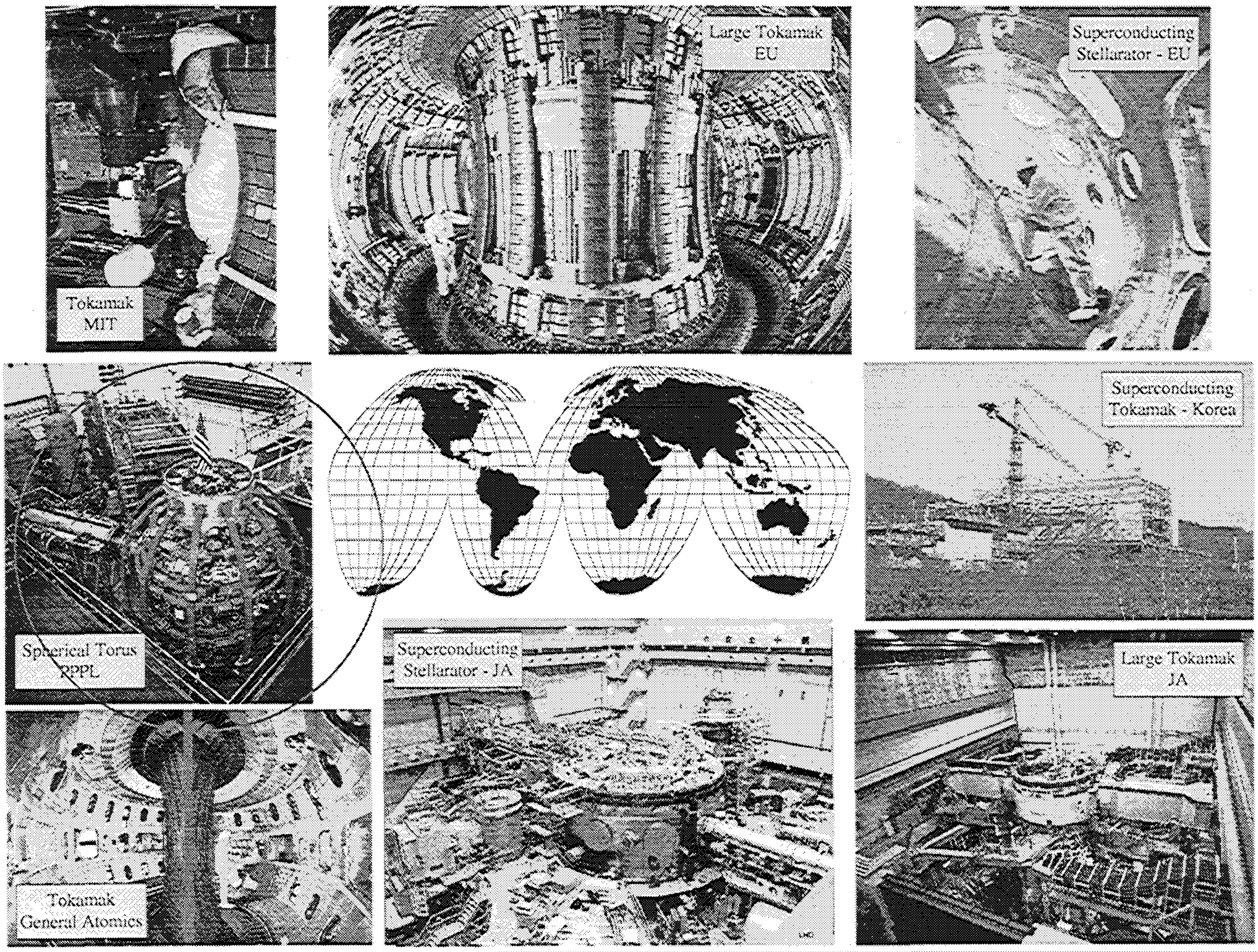
Compact Auburn Torsatron to become Compact Toroidal Hybrid
Auburn University, Auburn Alabama



Sustained Spheromak Plasma Experiment
Lawrence Livermore National Laboratory



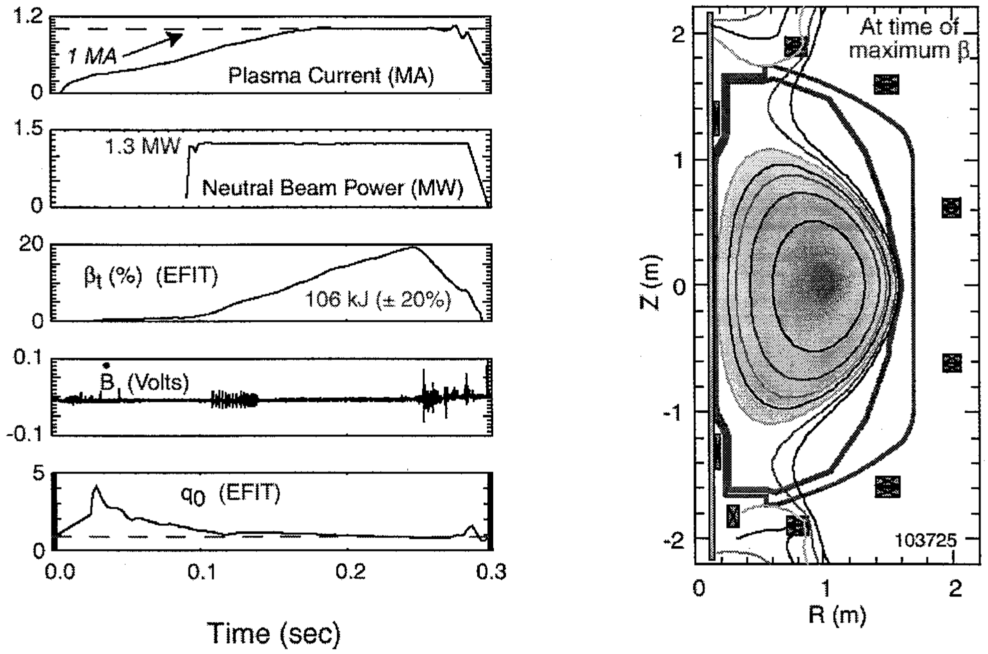
Levitated Dipole Experiment
Columbia University/Massachusetts Institute of Technology



High-β_t With Good Confinement

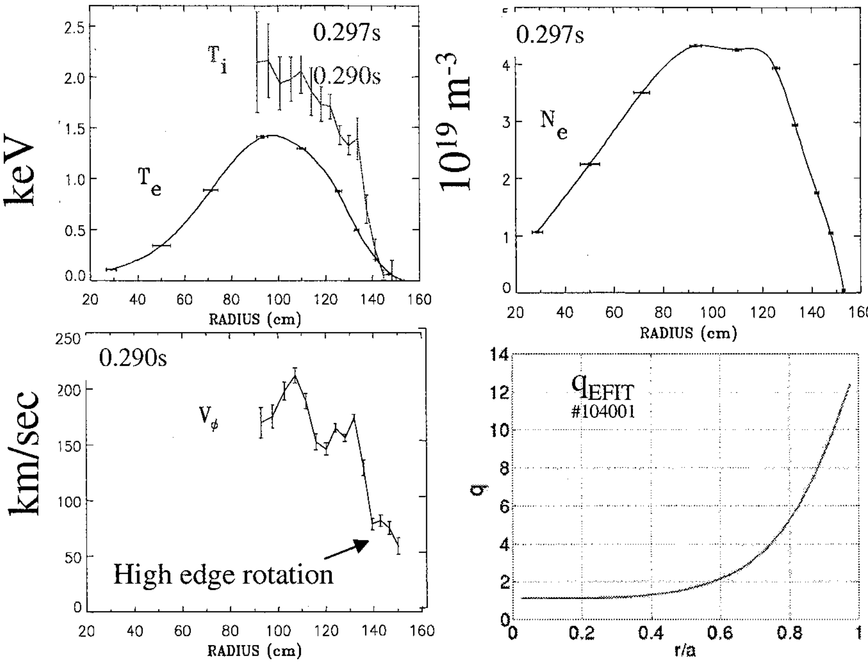
NSTX

$\beta_t = 2\mu_0\langle p\rangle / B_0^2 = 19.7\%$, $\beta_n = 3.9$, $B_0 = 0.3$ T, $q_\psi = 7.5$



NSTX is Beginning to Study Transport at High β and High Mach Number

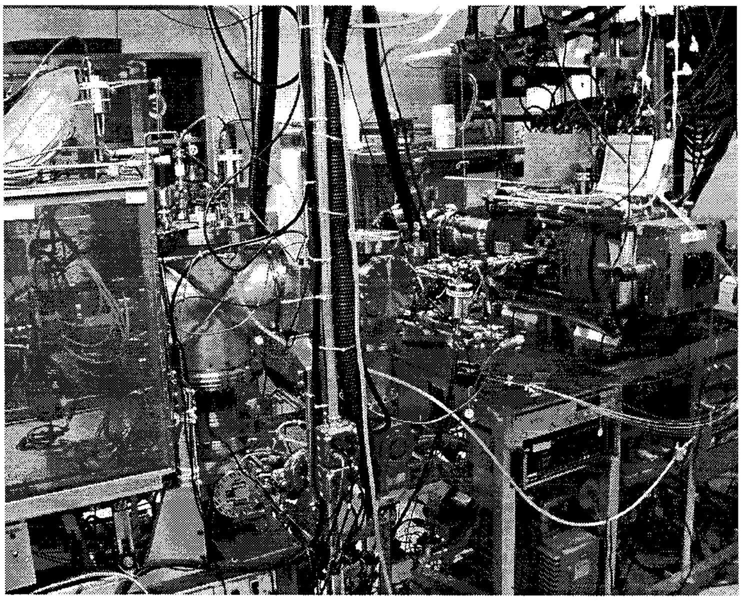
- **Broad T_i profile (compared to T_e)**
- **Large T_i - T_e**
- **High V_ϕ in core & edge**



R. Bell, B. LeBlanc

Motional Stark Effect Measurements of Field Angle Revolutionized Stability Studies

- Motional Stark Effect depends on v x B $\Rightarrow$ E.
  - Linear effect in D_0 beam injected into plasma.
- Allows measurement of B field tilt $\Rightarrow$ q profile.
  - Can get E_r and $|B|$ as well as tilt $\Rightarrow$ rotation & pressure profiles.
- Developed on PBX-M at PPPL by FP&T; revolutionized stability studies.
  - Laser induced flourescence being developed for stronger signal in NSTX and other low field / high β devices.



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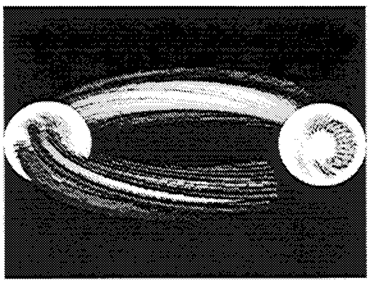
New Approach to Diagnosis and Understanding of Turbulence

GTC simulation:

Z. Lin



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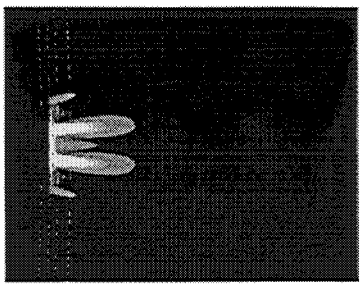
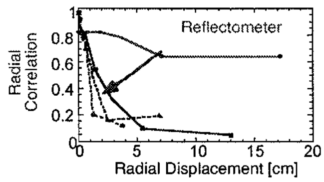
Parallelized simulation of μ-wave reflection:

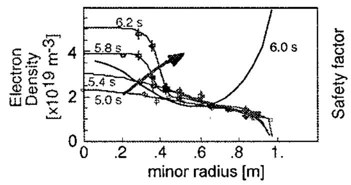
E. Valeo, R. Nazikian



System size ~ 200 λ x 100 λ

Data Interpretation (JT-60U)



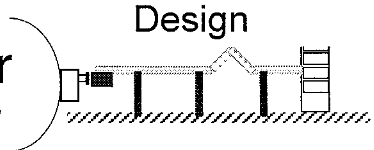


R. Nazikian et al., IAEA 1998

Experimental Design

Textor

Germany



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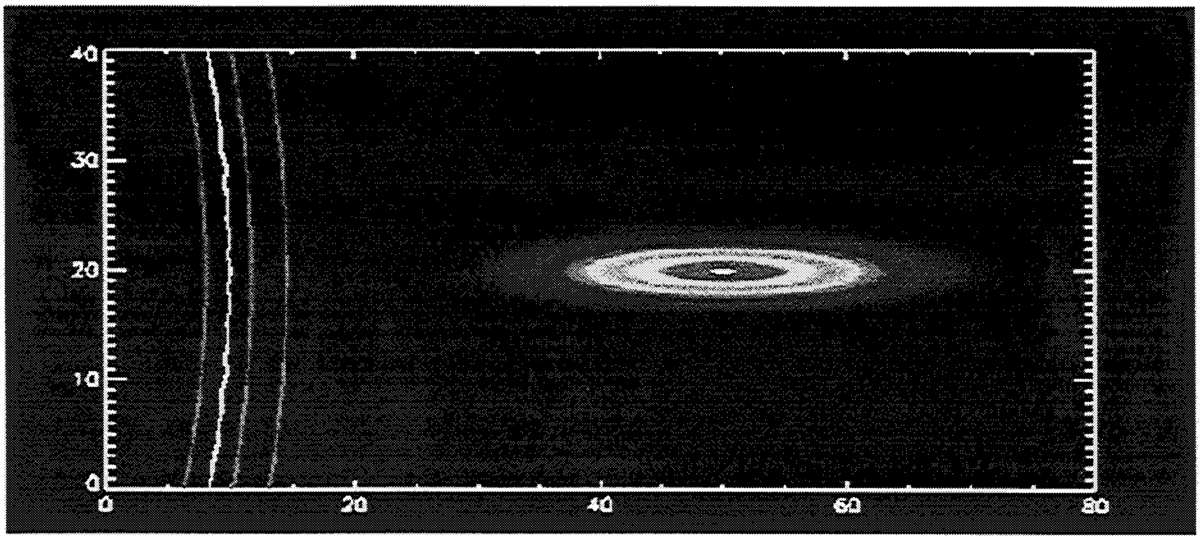
Simulation of Microwave Imaging Experiment



- Strong Theory / Experiment Collaboration

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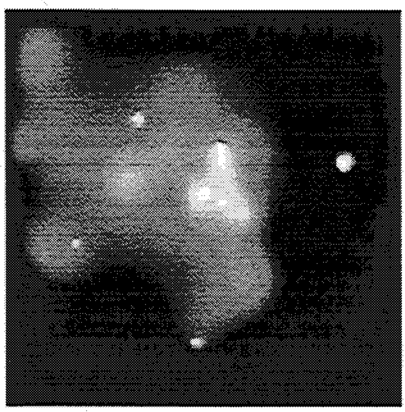
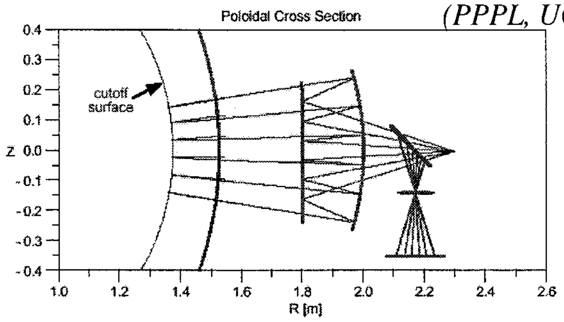
Opportunity: Physics link with Astrophysics via High Beta Turbulence

- Turbulence in accretion disks, active galactic nuclei may be amenable to codes developed for fusion.
- Benchmark turbulence codes at high beta in NSTX.
- Requires qualitative advance in plasma measurement:
  - diagnostics: spatial, low k, high k resolution
- Key collaborators: U Maryland, UC Berkeley, UC Davis, PPPL



From Chandra; our galaxy's core, 0.5 - 10 keV x rays

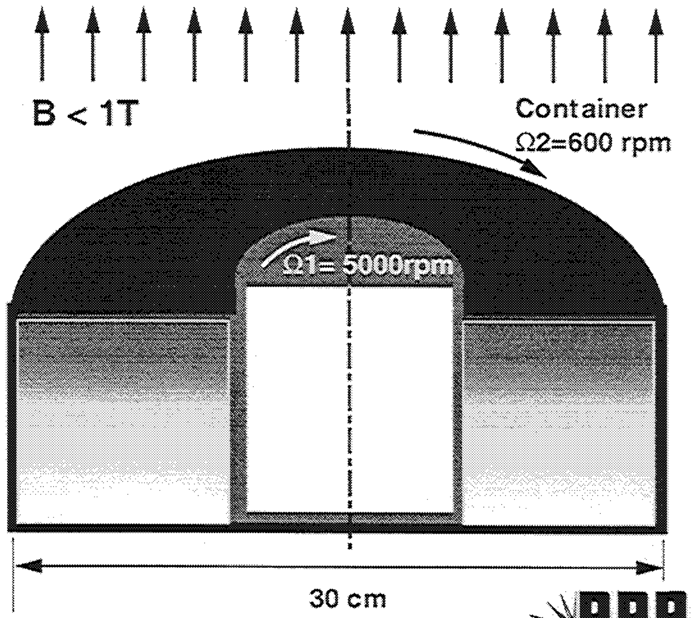


Imaging Reflectometry (PPPL, UC Davis)

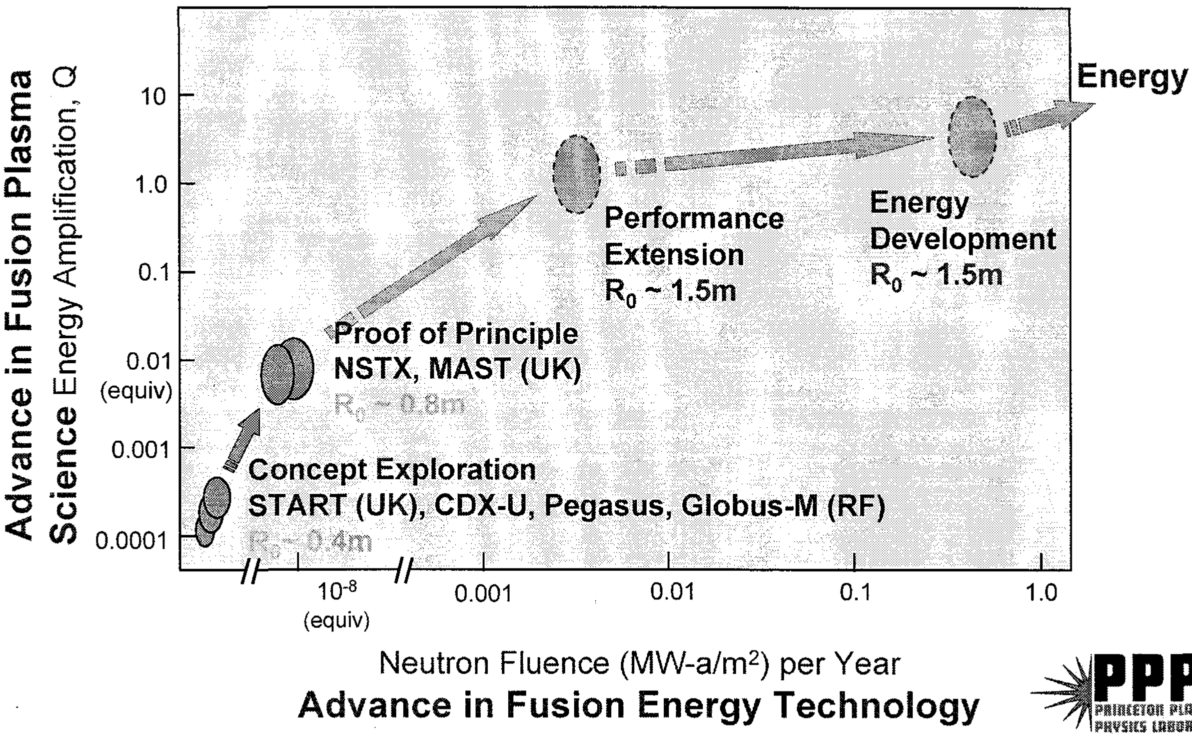
A Proposed Experiment to Study Magnetorotational Instability Important to Accretion Disk Physics

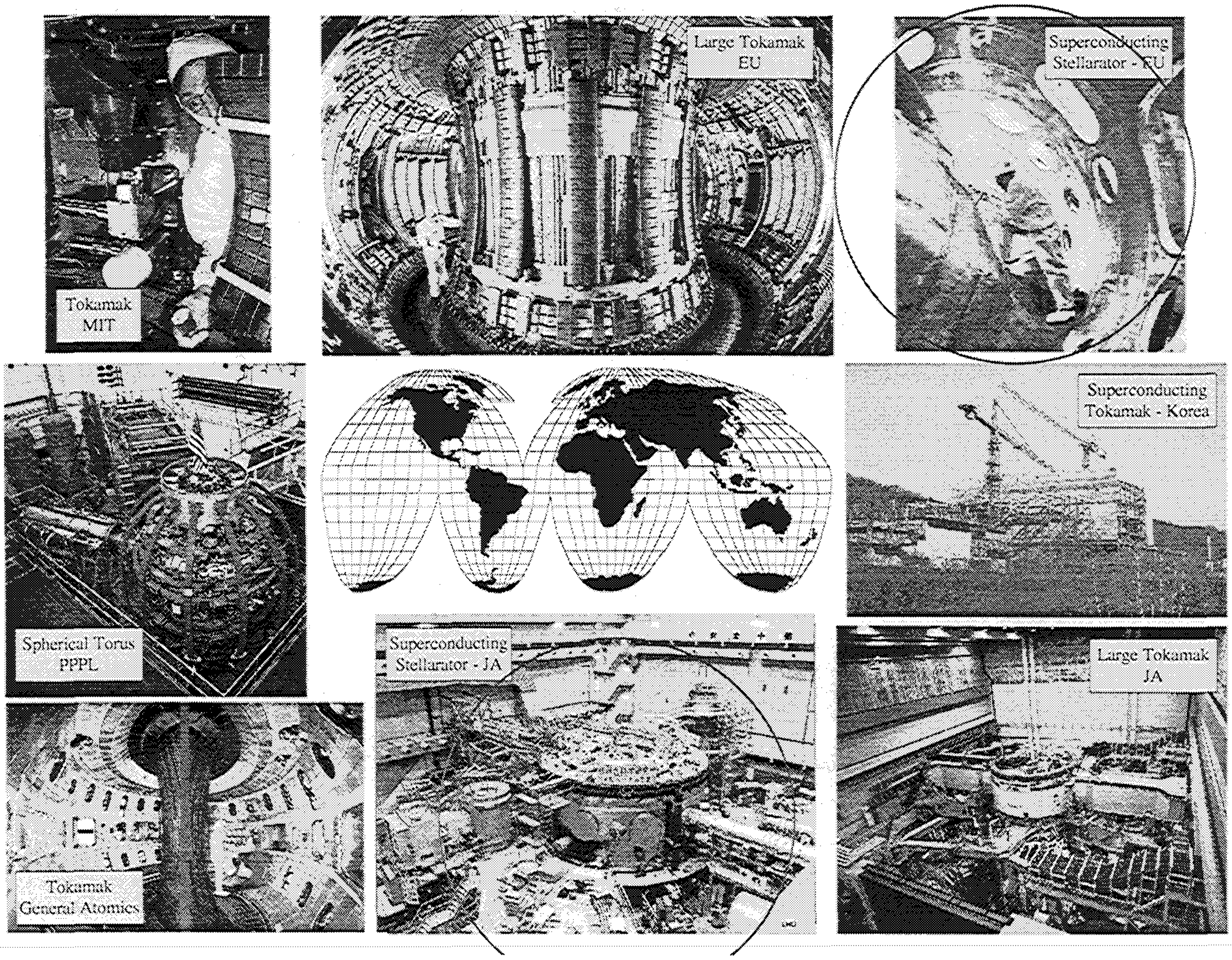
H. Ji (PPPL) , J. Goodman (PU), A. Kageyama (NIFS), E. Shoshan (Rutgers)

- **Mechanisms of fast accretion / angular momentum transport in accretion disks has been a long standing problem in astrophysics**
- **Magnetorotational instability (MRI) is an important candidate mechanism in MHD, but never realized in laboratory**
- **Rotating gallium disk experiment could create MRI and study its relations with other important MHD physics, such as dynamo.**
- **Experiment with water is starting to test hardware and fluid stability**



ST Development may be an Attractive Element of the World Program





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**
- **We expect this connection to continue**

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Gyro-averaging Allows a New Form of Symmetry

- **Hamiltonian formulation of Alfvén gyro-averaged drift equations:**

$$H = \rho_\parallel^2 B^2 / 2 + \mu B$$

$$\vec{v}_{gc} = \rho_\parallel(\vec{B} + \nabla \times \rho_\parallel \vec{B}) / (1 + \rho_\parallel \hat{b} \cdot \nabla \times \hat{b})$$

- **Expressions for magnetic fields in canonical coordinates:**

$$\vec{B} = q \nabla \psi_p \times \nabla \theta - \nabla \psi_p \times \nabla \zeta$$

$$\vec{B} = g(\psi_p) \nabla \zeta + I(\psi_p) \nabla \theta + \delta(\psi_p, \theta) \nabla \psi_p$$

$$J = \nabla \psi_p \cdot (\nabla \theta \times \nabla \zeta); \quad B^2 J = I + gq$$

- **Theorems by Boozer et al. show you can construct magnetic field configurations which have H symmetric (|B| symmetric) in canonical coordinates, but non-symmetric in configuration space.**

- **For compact stellarators - of special interest is toroidal symmetry.**
  - Symmetry and compactness of the tokamak.
  - Stability and steady-state operation of the stellarator.

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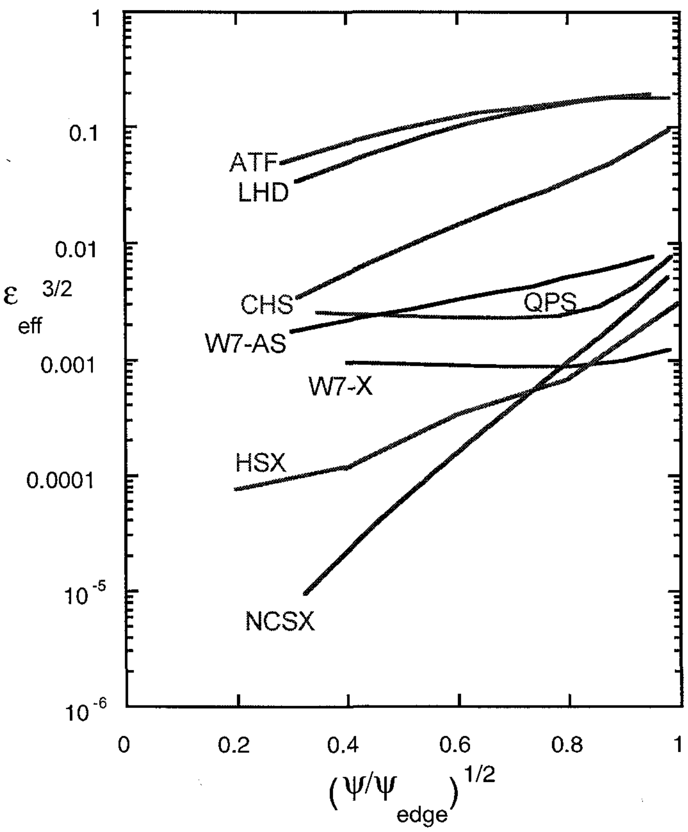
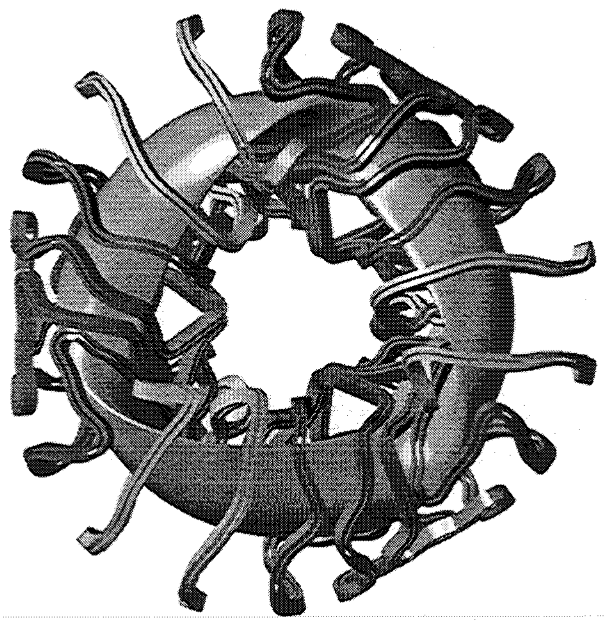
New Stellarators Test Quasi-Symmetries and Disruption Immunity

- Natural plasmas are asymmetric
- Asymmetrical neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- Low (adjustable) flow-damping
  - manipulation of flows for flow-shear stabilization
  - zonal flows like in tokamaks, but can be turned on and off
- Test quasi-axisymmetry and MHD physics at low ν_* and high β.



Compact Stellarators will Address Key Issues of Fusion Plasma Science



- **Macroscopic Stability:**
  - **Disruptions - when, why, why not?**
    ⇒ High β, 3-D stability to kink, ballooning, neoclassical tearing, vertical displacement.
- **Microturbulence and Transport:**
  - **Is quasi-symmetry effective at high T_i? Challenge E_r shear understanding via ripple control.**
    ⇒ High T_i, flexible coil system
- **Wave-particle Interactions:**
  - **Do we understand 3-D fast ion resonances, *AE modes in 3-D?**
    ⇒ Good fast ion confinement
- **Plasma-boundary interaction:**
  - **Effects of magnetic stochasticity?**
    ⇒ High power, flexible coil system

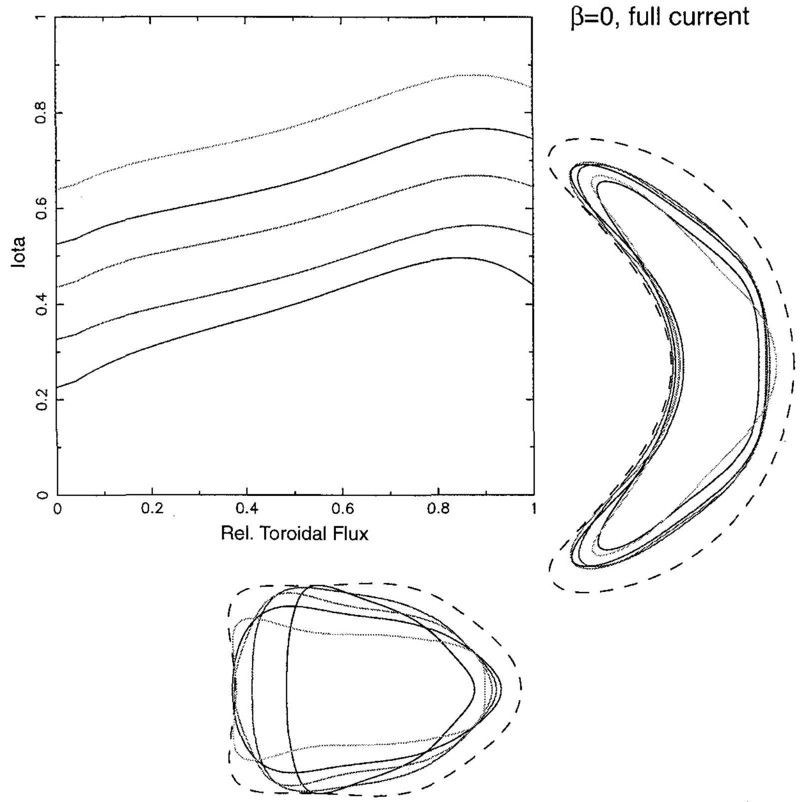
Auburn U., Columbia U., LLNL, NYU, ORNL, PPPL, SNL-A, U. Texas, UCSD, U. Wisconsin

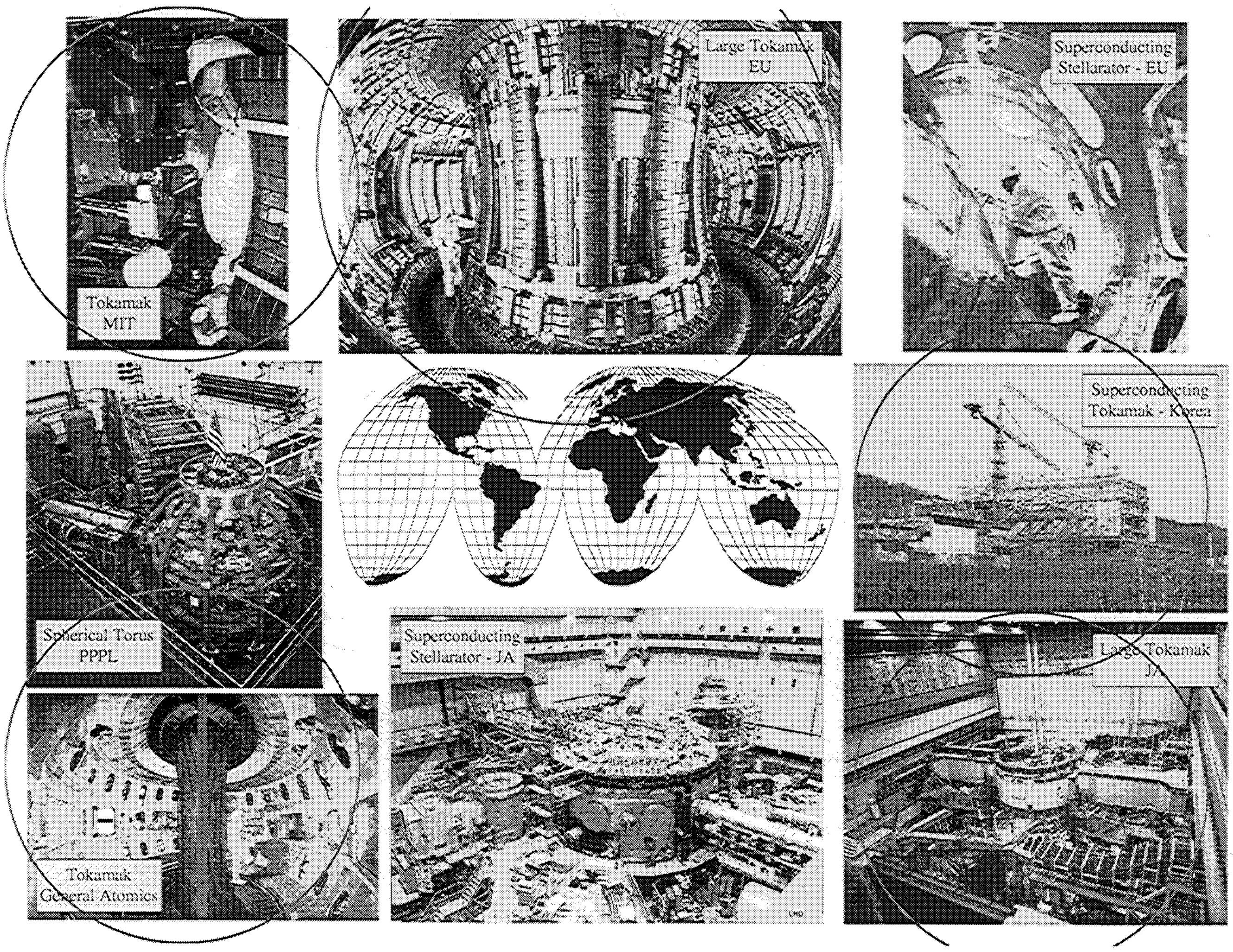
Australia, Austria, Japan, Germany, Russia, Switzerland!

National Compact Stellarator Experiment: Modular Coils have Flexibility for Physics Studies

- **Can externally control rotational transform and shear.**
- **Can adjust to avoid iota=0.5, or hit it in mid-radius.**
- **Can accommodate wide range of p, j profiles.**

- **Will allow systematic studies of rotational transform and shear effects on ideal, resistive and kinetic (fast-ion) instabilities.**





The World Advanced Tokamak Program aims at an Attractive Steady-State Operating Mode

- **An attractive steady-state tokamak power source requires:**
  - Relatively high beta (~ 5%)
    - Feedback and/or rotational stabilization of resistive wall kink modes
    - Feedback stabilization of neoclassical tearing modes
  - Strong self-sustained bootstrap current (~ 80%)
    - Pressure profile control
    - Current drive and current profile control
- **A strong international effort is underway to demonstrate the Advanced Tokamak mode:**
  - US: C-MOD, DIII-D
  - EU: JET, ASDEX-U
  - JA: JT-60U / JT-60SC
  - Korea: KSTAR

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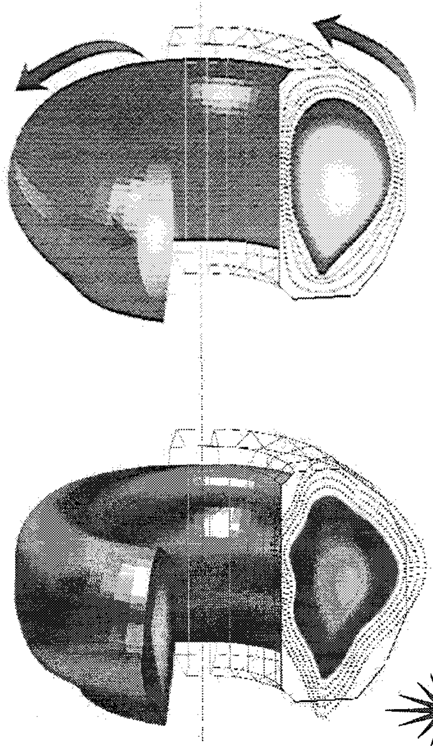
Rotation Stabilizes Plasma "Kinks" to Higher Pressure

- Strong plasma rotation was predicted to stabilize "kinks" to higher pressure.
- Columbia - Princeton - GA collaboration to test feedback control of kinks on DIII-D.
- Control of field errors allowed rotation to continue, stabilized kink to higher plasma pressure $\Rightarrow$ more fusion!
- Will be transferred to NSTX.



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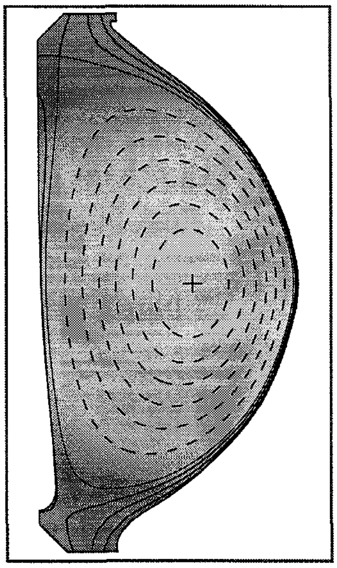
A Burning Plasma will Extend the Reach of Fusion Plasma Science

- Macroscopic Stability
  - Effects of lower collisionality, smaller gyro-radius.
- Wave-particle Interactions
  - Effects of intense, isotropic alpha particle concentrations.
- Microturbulence & Transport
  - Effects of lower collisionality, smaller gyro-radius.
- Plasma-material Interactions
  - Much more intense, longer-lasting interactions for study.
- Integrated demonstration of substantial fusion power production.
  - Relevant to a range of toroidal systems, esp.: Advanced tokamak, ST, Stellarator



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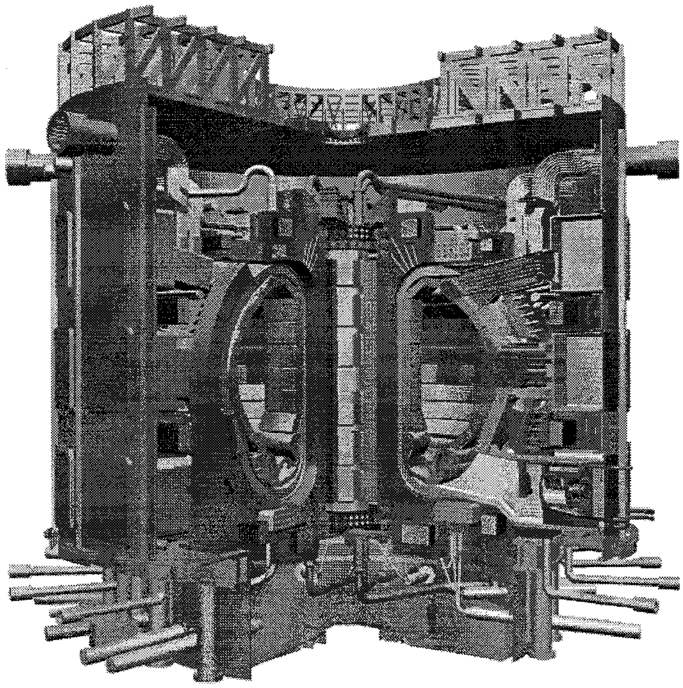
Iter Addresses Burning Plasma and Fusion Technology Issues



P_{fusion}	500MW
Q	10
Pulse	500 - 2500s
Major Radius	6.2m
Minor Radius	2.0m
Plasma Current	15MA
Toroidal Field	5.3T
Heating/Current Drive Power	73MW
Cost ($2000)	$4.6B

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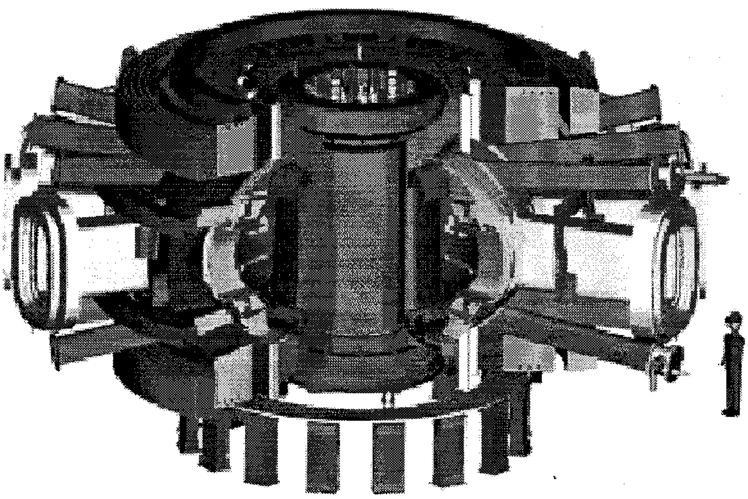
FIRE Emphasizes Burning Plasma Physics Issues



P_{fusion}	200MW
Q	10
Burn Duration	~20s
Major Radius	2.14m
Minor Radius	0.58m
Plasma Current	7.7 MA
Toroidal Field	10 T
Heating Power	30MW
Cost ($2000)	$1.25B

A more modest potential domestic step.

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Understanding, Innovation and Collaboration

- Continuing deepening and broadening of the science of plasmas is central to the innovations needed for the success of fusion energy research.
- Plasma science itself is a beautiful and deep contribution to world scientific culture.
- Strengthening collaboration between areas of plasma science and between plasma science and other areas is beneficial to all concerned.

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Not Science *vs.* Energy – Strong Commitment to Both!

- PPPL and the world fusion research community are committed to providing the world with an attractive new energy source.
- We are also committed to deepening and broadening the science of plasmas.
- The prospect is not a choice of "Science *vs.* Energy" but wonderful advances in both.

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