FRONTIERS IN MAGNETIC FUSION PHYSICS

by
T.S. Taylor

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GENERAL ATOMICS

281–03/TST/wj

OUTLINE

- Burning plasma science
  - Science from a burning plasma (Navratil)
  - Ensuring the success of ITER (BPX)
  - Providing the greatest benefit from ITER (BPX)
- Fusion science
  - Transport
  - “Science of the boundary”
  - Portfolio of configurations
- Configuration optimization
  - Advanced Tokamak
  - Spherical Torus
  - Stellarator
  - Reverse Field Pinch

KEY SCIENTIFIC ISSUES IN SUPPORT OF BURNING PLASMAS (ITER)

— Contribute to the Success of ITER —

- Feedback control of neoclassical tearing modes
- Development of high confinement operatonal scenarios with reduced ELMs or no ELMs
  - Pedestal
- Develop divertor solutions for a range of plasma operation
- Tritium retention with carbon facing components
  - Remove tritium from co-deposited carbon
  - Replace carbon with tungsten
- Disruption avoidance or mitigation

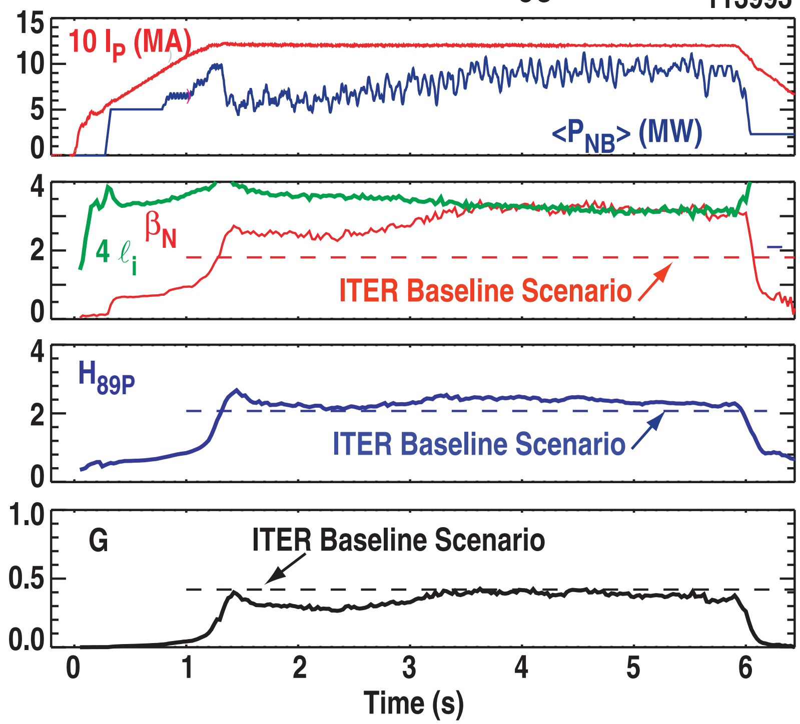
KEY SCIENTIFIC ISSUES IN SUPPORT OF BURNING PLASMAS (ITER)

— Gaining a Greater Benefit from ITER —

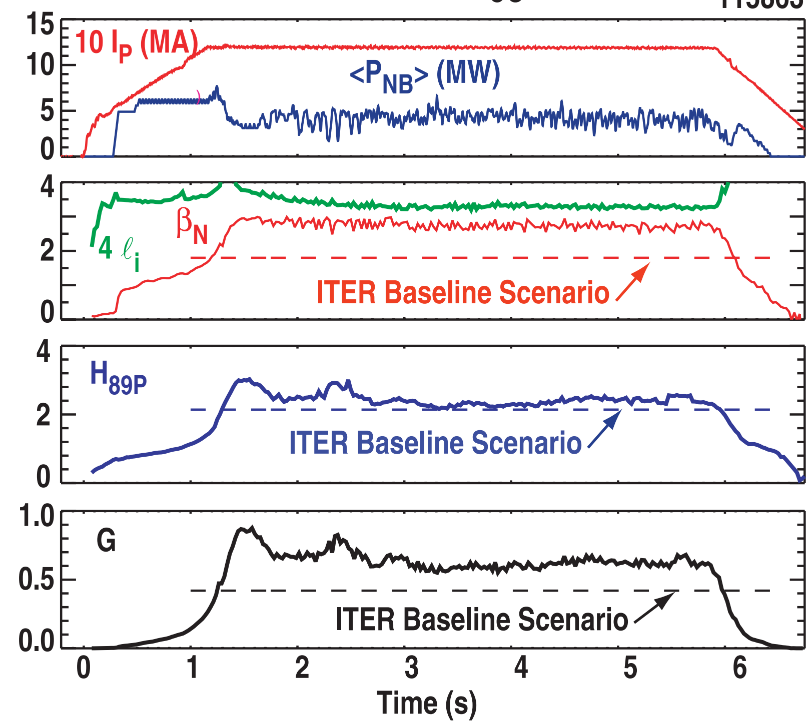
- Developing hybrid and steady-state advanced operating regimes for ITER
- Resistive wall mode control for reliable high beta operation
- Understanding limits to the density and extending reliable operation to high density
- Turbulent transport understanding and control
  - Pedestal
- Diagnostic development for key physics measurements on ITER

STEADY-STATE *AT* SCENARIOS AND STATIONARY "hybrid" SCENARIOS ARE DEVELOPING THE BASIS FOR ITER LONG PULSE DISCHARGES (≳4000 s, ~500 W)

Without Sawteeth q_{95} = 4.4



With Sawteeth q_{95} = 3.2



ITER projection	Without Sawteeth	With Sawteeth
	$\beta_N = 3.2$	$\beta_N = 2.6$
	$H_{98y2} = 1.6$	$H_{98y2} = 1.4$
	$Q_{Fus} \approx 10$	$Q_{Fus} \approx \infty$
	$\tau_{DUR} = 4500$ s	

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FRONTIER ISSUES IN PLASMA AND FUSION SCIENCE

- Goals for attractive fusion energy
  - Maximize the plasma pressure
  - Maximize the plasma energy confinement
  - Minimize the power needed to sustain the plasma configuration
  - Simplicity and reliability

  leads to physics research in

  - Plasma turbulence and turbulent transport
  - Stability limits to plasma pressure
  - Stochastic magnetic fields, reconnection, and self-organized systems
  - Plasma confinement with different magnetic field symmetry
  - Control of sustained high pressure plasmas
  - Energetic particles in plasmas
  - Plasma behavior when self-sustained by fusion (burning)
  - Flow and transport on open field lines and the plasma interaction with material surfaces

from NRC Report on Burning Plasmas

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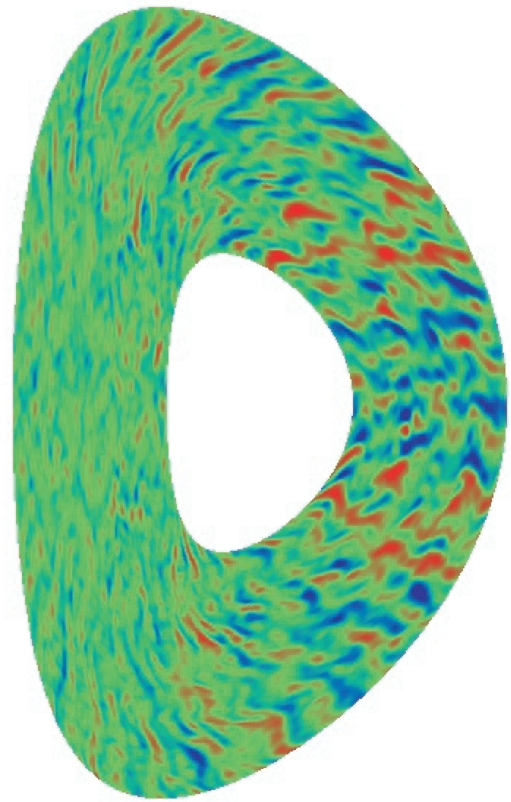
from NRC Report on Burning Plasmas

UNDERSTANDING TURBULENT TRANSPORT IS A GRAND CHALLENGE FOR PLASMA AND FUSION SCIENCE

— How Does Energy Leak Out of the Plasma ? —

FESAC/IPPA 3.1.1 Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems

- **For the first time, codes contain essential physics needed for meaningful comparison with experiment**
  - Kinetic ions and electrons at finite beta
  - Complete two dimensional geometry
  - Finite gyroradius
  - Profile variation (q, T_e, T_i, E×B flow...)
  - Self-consistent E×B shear flow



Fusion SciDAC Computing Initiative

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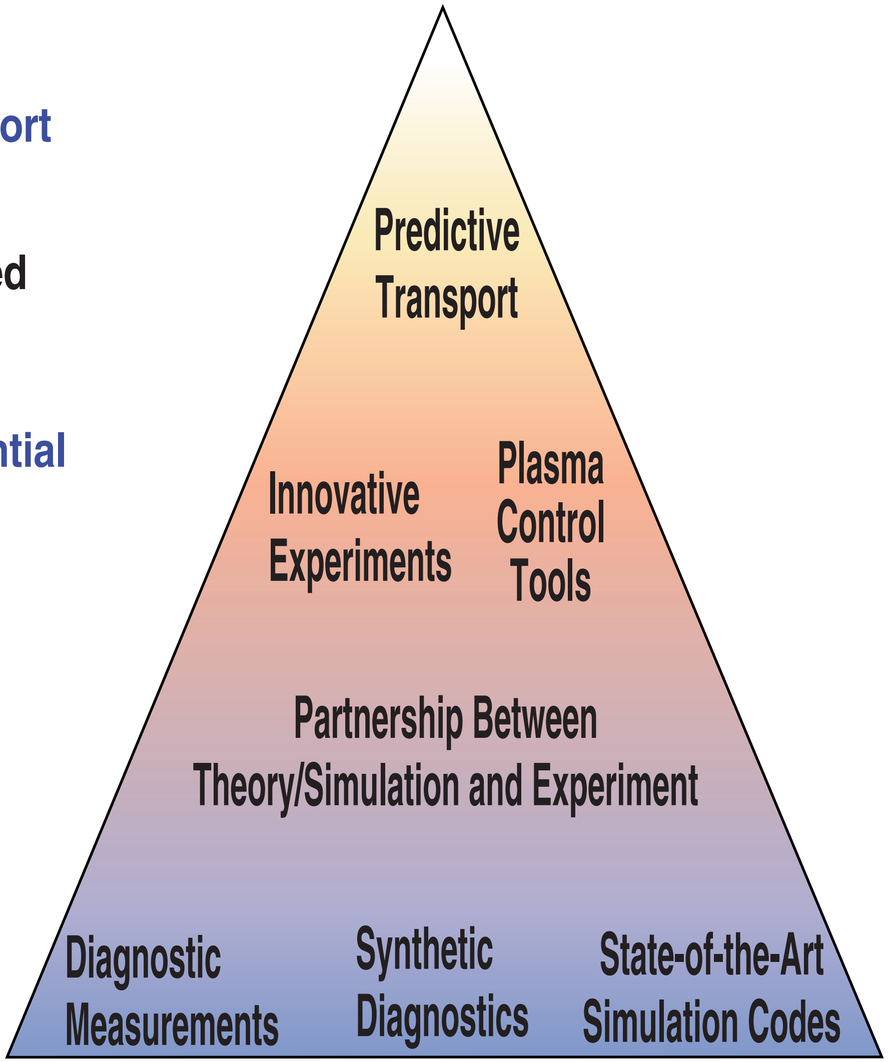
THE TIME IS NOW FOR A FOCUSSED EFFORT ON UNDERSTANDING TURBULENT TRANSPORT

- A community-wide effort led by the transport task force (TTF)
  - Draft community white paper prepared
- New diagnostics measurements are essential for comparing experiment to theory
  - Community diagnostic white paper written
- Many confinement scenarios abound to test different aspects of transport



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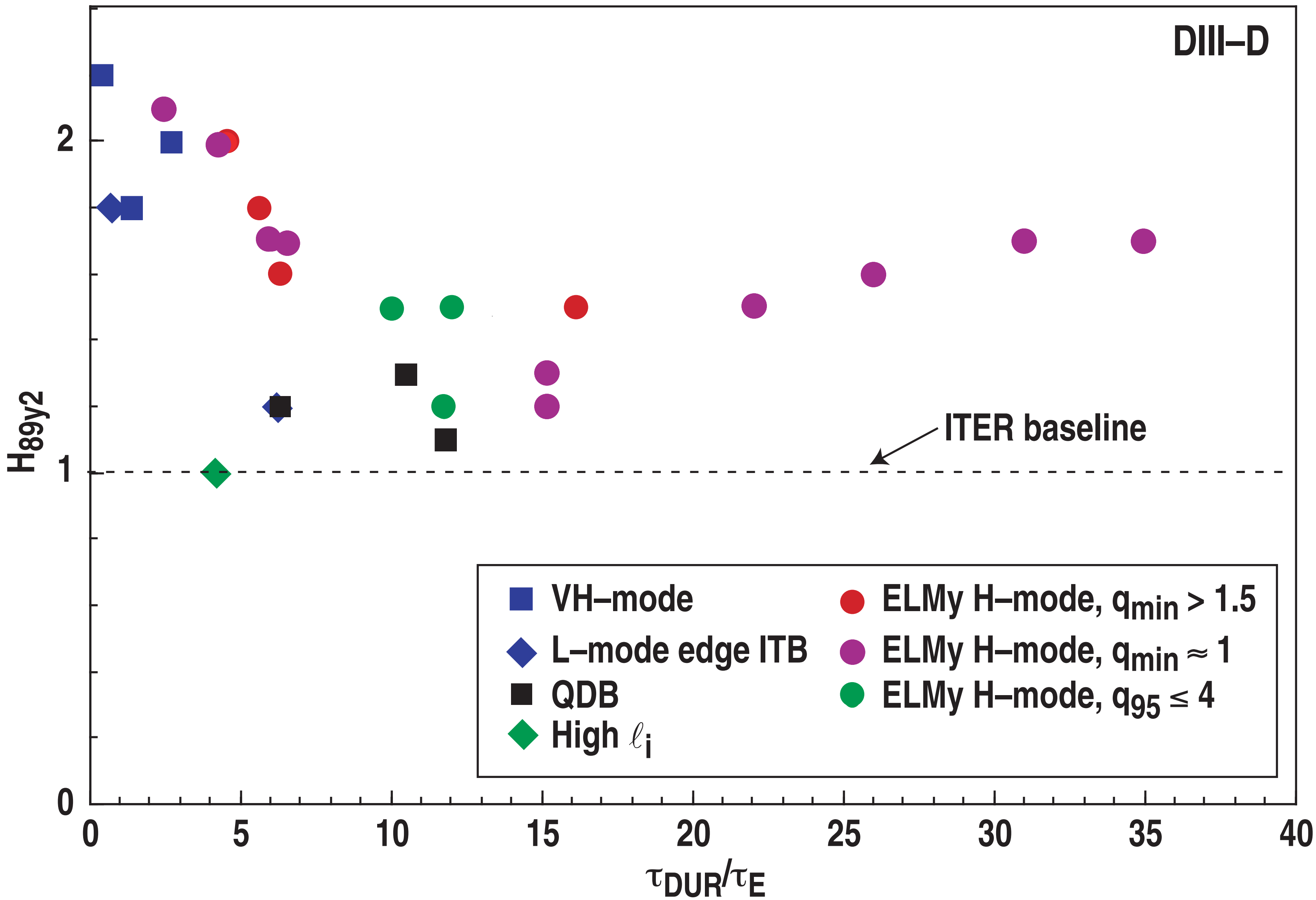
HIGH CONFINEMENT REGIMES ABOUND



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THE NEED TO UNDERSTAND TRANSPORT AND CONFINEMENT SPANS CONFIGURATION SPACE

- The size of next step devices is largely set by confinement considerations
  - Proof of principle ⇒ performance enhancement
  - Performance enhancement ⇒ BPX, CTF, . . .

$$\frac{P_\alpha}{P_{Loss}} \approx nT\tau$$

$$\tau = H\tau_G$$

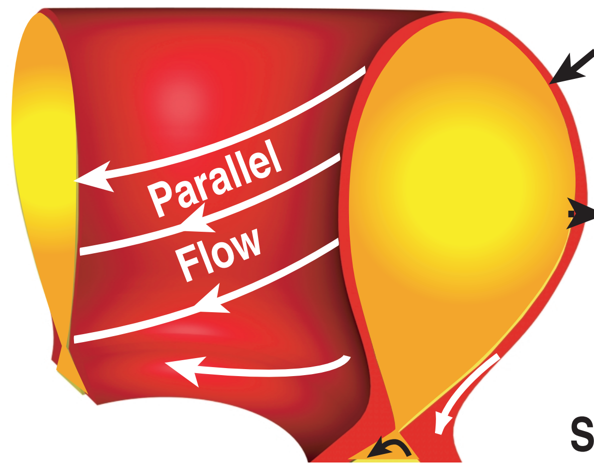
$$\tau_G = \sqrt{V/P}\; R/aI$$

$$\frac{P_\alpha}{P_{Loss}} \approx (HI\, R/a)^2 \approx \left[H\,(akB/q)\right]^2$$

SCIENCE OF THE BOUNDARY: A KEY SCIENCE ISSUE FOR THE FUTURE

— the Forgotten SCIENCE —

- Interesting and complex
  - — Cross field and parallel transport
  - — Ions, neutrals, impurities, molecules
  - — Parallel flow (sonic), and E×B flow



- Key elements
  - — Heat removal — "limitation?" in power plants and CTF
  - — Particle control, He ash removal
  - — Control of impurities
  - — Plasma fueling
  - — Impact on core
    - ▲ Confinement
    - ▲ Density limits

- ITER — renewed interest and priority

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PORTFOLIO OF CONFIGURATIONS CONTRIBUTES TO RESOLUTION OF KEY SCIENTIFIC ISSUES

- **Experimental test bed for understanding key elements of theory and models**
  - Shaping (or aspect ratio) (stellerator, tokamak, ST, spheromak)
  - Toroidal field strength (ratio of B_T to B_P) (tokamak, ST, RFP)

- **Example: Stability limits to plasma pressure (Resistive Wall Modes)**
  - Advanced Tokamak and Spherical Torus
    - ➢ Wall stabilization required for high β_N, pressure driven kinks
    - ➢ Solutions: Plasma flow or active feedback
  - Reversed Field Pinch and Spheromak
    - ➢ Wall stabilization required for current driven kinks ($\beta \geq 0$)
    - ➢ Solutions: Plasma flow or active feedback
  - Phenomena and solutions are similar

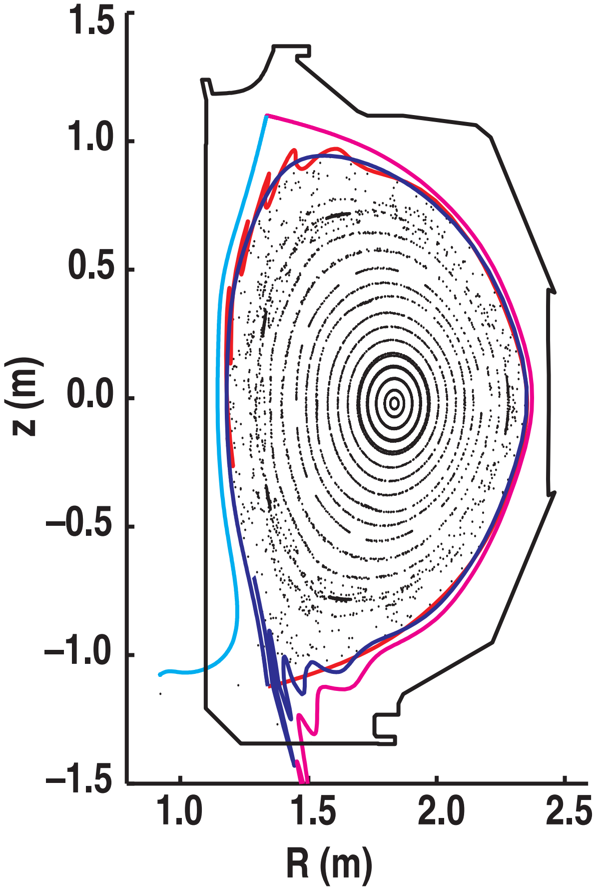
    $\Longrightarrow$ Cross configurational predictive capability likely

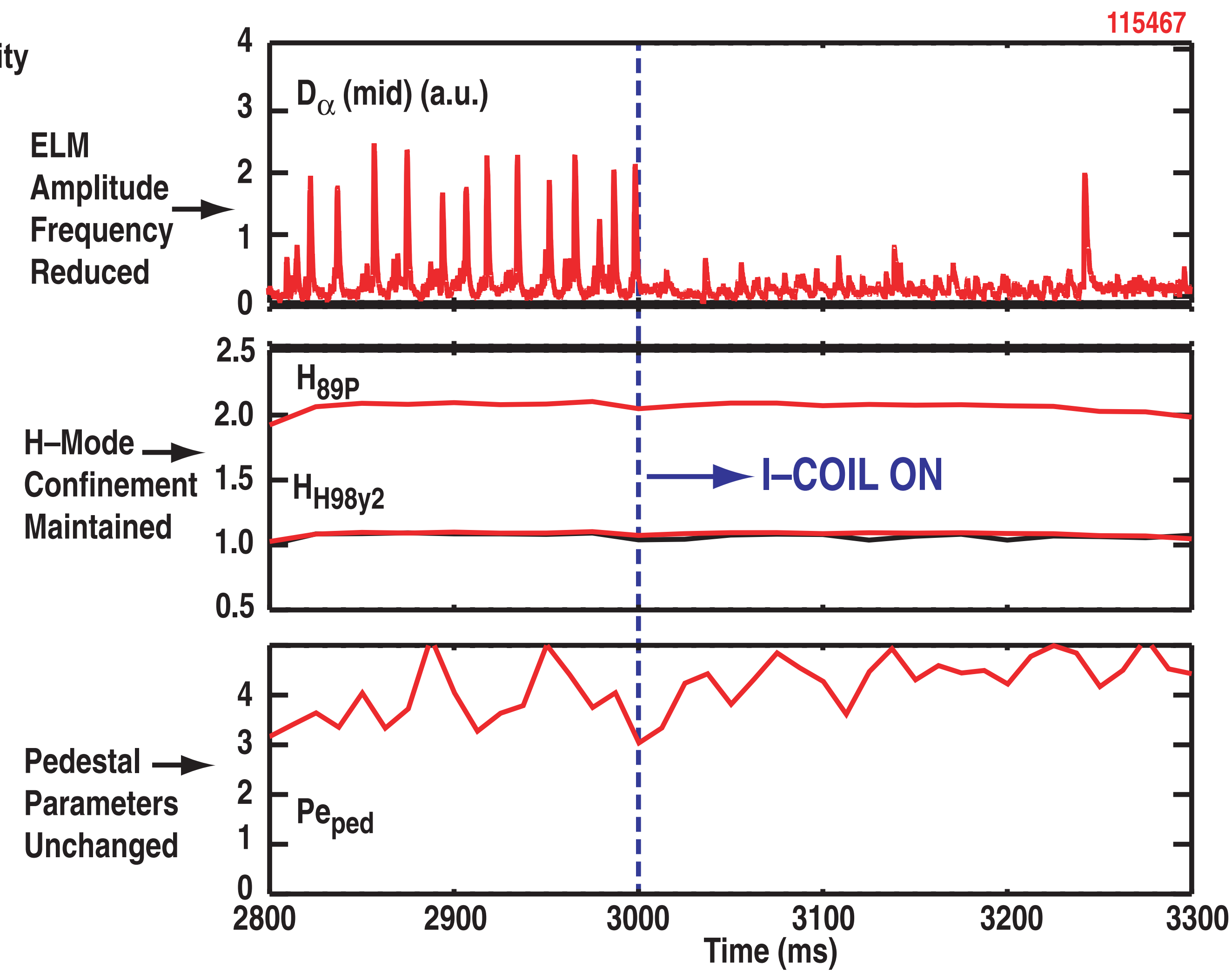
- **Example: stochastic magnetic fields**
  - RFP, Tokamak, Stellerator, ...

STOCHASTIC MAGNETIC BOUNDARY SUPPRESSES ELMs WITHOUT DEGRADING CONFINEMENT

— Possible ELM solution for ITER —

Six international participants
Four, from Stellarator community





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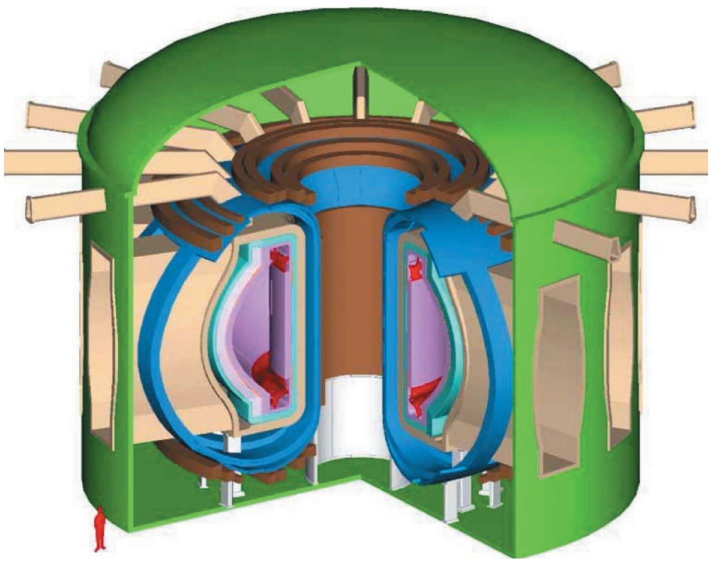
CONFIGURATION OPTIMIZATION
FRONTIER PHYSICS FOR STEADY-STATE ADVANCED TOKAMAK

Goal: Steady-state, f_{NI} = 100%, high f_{BS}
High beta, β_T, β_p, β_N
High confinement, τ_E, H

ARIES–AT



- **Self-consistent integrated scenarios**

  "Can self-consistent high bootstrap fraction, high confinement, and high β discharges be sustained for durations greater than the current redistribution time?"

- **Controlled high β plasmas**

  ⇒ Resistive wall mode stabilization
  - Rotation
  - Active feedback without rotation

  "Can β approaching the ideal wall limit be stably obtained in low rotation plasmas?"

- **Control of the profiles**
  - Current profile
  - Pressure profile, transport

  "Can current profiles and pressure profiles be obtained and maintained consistent with high bootstrap fraction and high β?"

- **Transport/confinement: extrapolation to the next step**

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CONFIGURATION OPTIMIZATION
FRONTIER PHYSICS FOR THE SPHERICAL TORUS

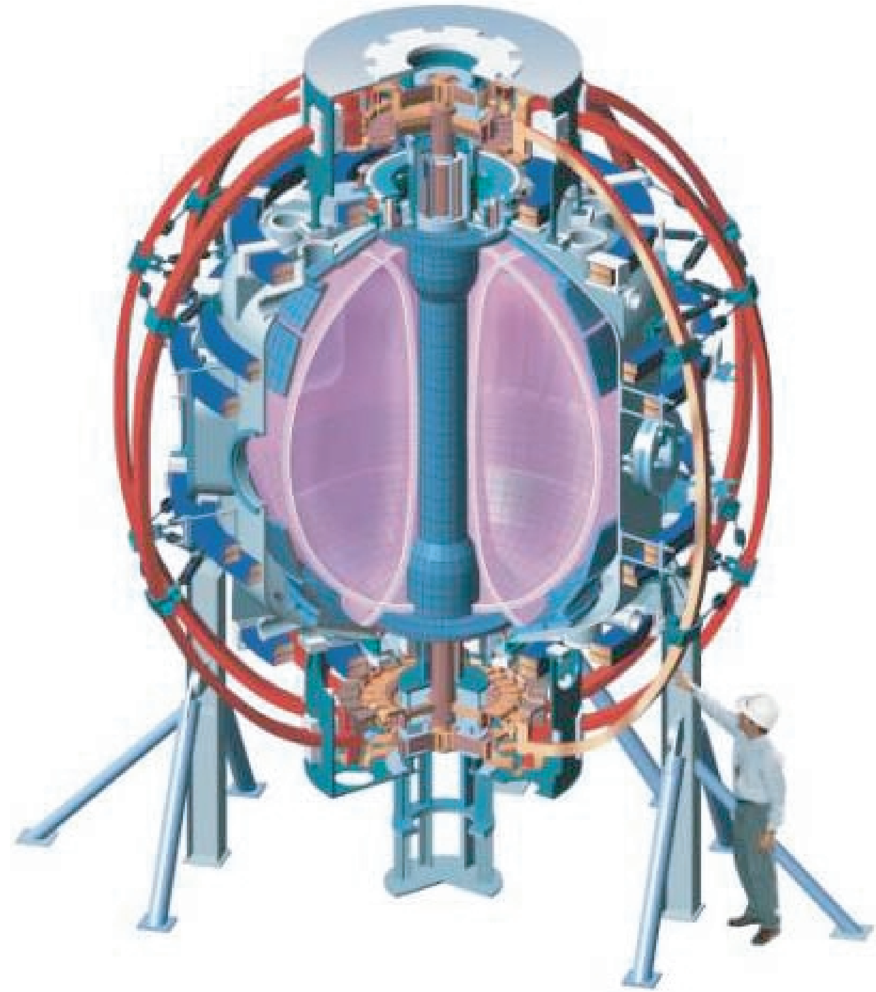
- All of those for the Advanced Tokamak

- Confinement and confinement scaling

  - Especially $\tau(\beta)$ as $\beta \to 1$

  "How does turbulence and transport vary at high pressure?"

- Plasma discharge initiation and sustainment without internal transformer



CONFIGURATION OPTIMIZATION FRONTIER PHYSICS FOR THE STELLARATOR

— Compact Stellarators —

- Transport and confinement
  - Improved confinement regimes?

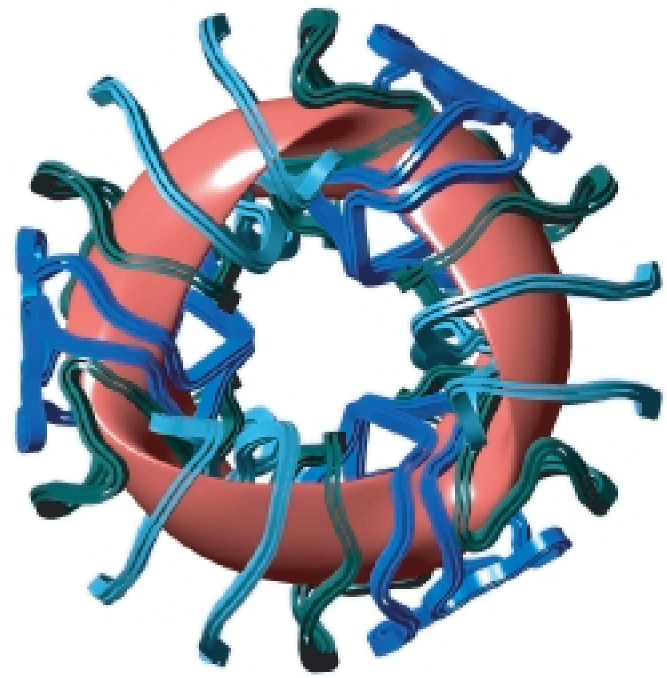
  "Is toroidal damping reduced and turbulence suppressed in stellarators with symmetry?"

- Equilibrium

  "Can plasmas with good (closed) 3-D flux surfaces be experimentally produced?"

- Current driven disruptive instability

  "Is the current driven disruptive instability avoided?"



NCSX Plasma and Coils

- Test MHD stability boundaries at high β

  "How does the pressure limit vary with 3-D shaping and differing contributions from plasma current?"

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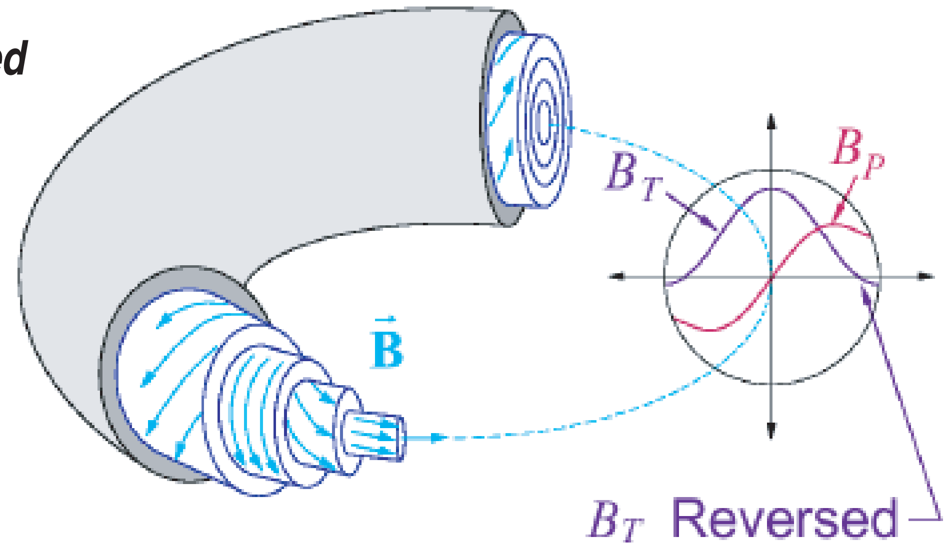
CONFIGURATION OPTIMIZATION
FRONTIER PHYSICS FOR REVERSED FIELD PINCH

- **Transport and confinement scaling**
  - In the presence of MHD

    "How does stochastic magnetic field transport particles, momentum?"
  - In the absence of large scale MHD

    "Can magnetic fluctuation induced transport be eliminated?"

    "What is the residual electrostatic transport?"



- **RFP sustainment**

  "Can the RFP equilibria be sustained without the dynamo using efficient current sustainment techniques?"