MAGNETIC FUSION ENERGY: STATUS AND OPPORTUNITIES

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PRESENTATION TO:
SECRETARY OF ENERGY ADVISORY BOARD
TASK FORCE ON FUSION ENERGY

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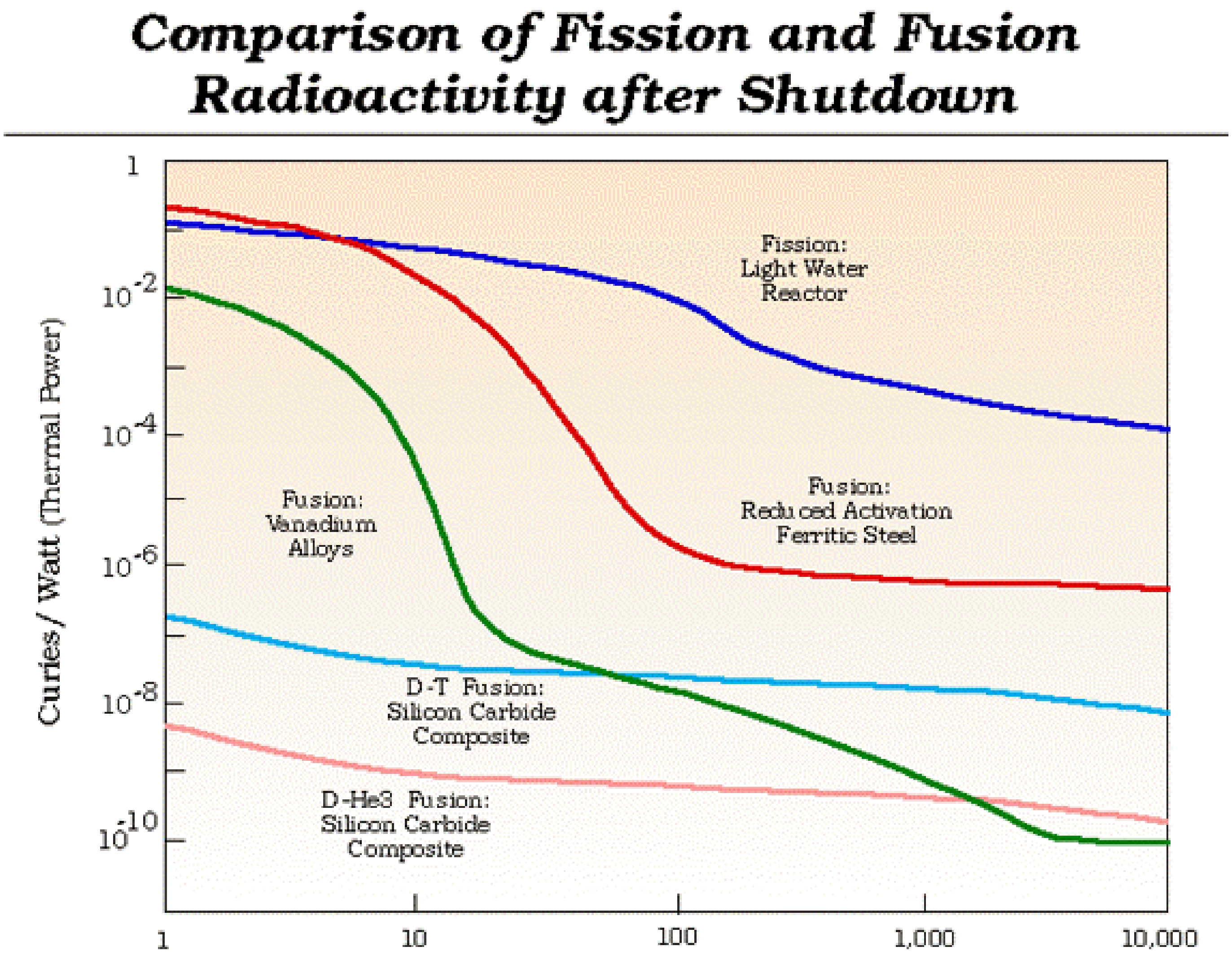
OUTLINE

- Fusion, Why and When?
- The Plasma Science of Magnetic Fusion
- The Magnetic Fusion Energy Portfolio
- Science and Technology Spin-offs
- Summary and Recommendations

WHY FUSION ENERGY?

- **ABUNDANT FUEL, AVAILABLE TO ALL NATIONS**
  - DEUTERIUM AND LITHIUM
- **ENVIRONMENTAL ADVANTAGES**
  - NO CARBON EMISSIONS
  - LOW RADIOACTIVITY
- **CAN'T BLOW UP, CAN'T MELT DOWN**
  - < 5 MINUTES OF FUEL IN PLASMA
- **LOW RISK OF NUCLEAR MATERIALS PROLIFERATION**
- **CONCENTRATED RELATIVE TO SOLAR, WIND, ETC.**
  - MINIMAL LAND USE
- **Not subject to daily, seasonal or regional weather variation.**
  - NO NEED FOR MASSIVE ENERGY STORAGE
  - NO NEED FOR LONG DISTANCE TRANSMISSION

Environmental Attractiveness of Fusion

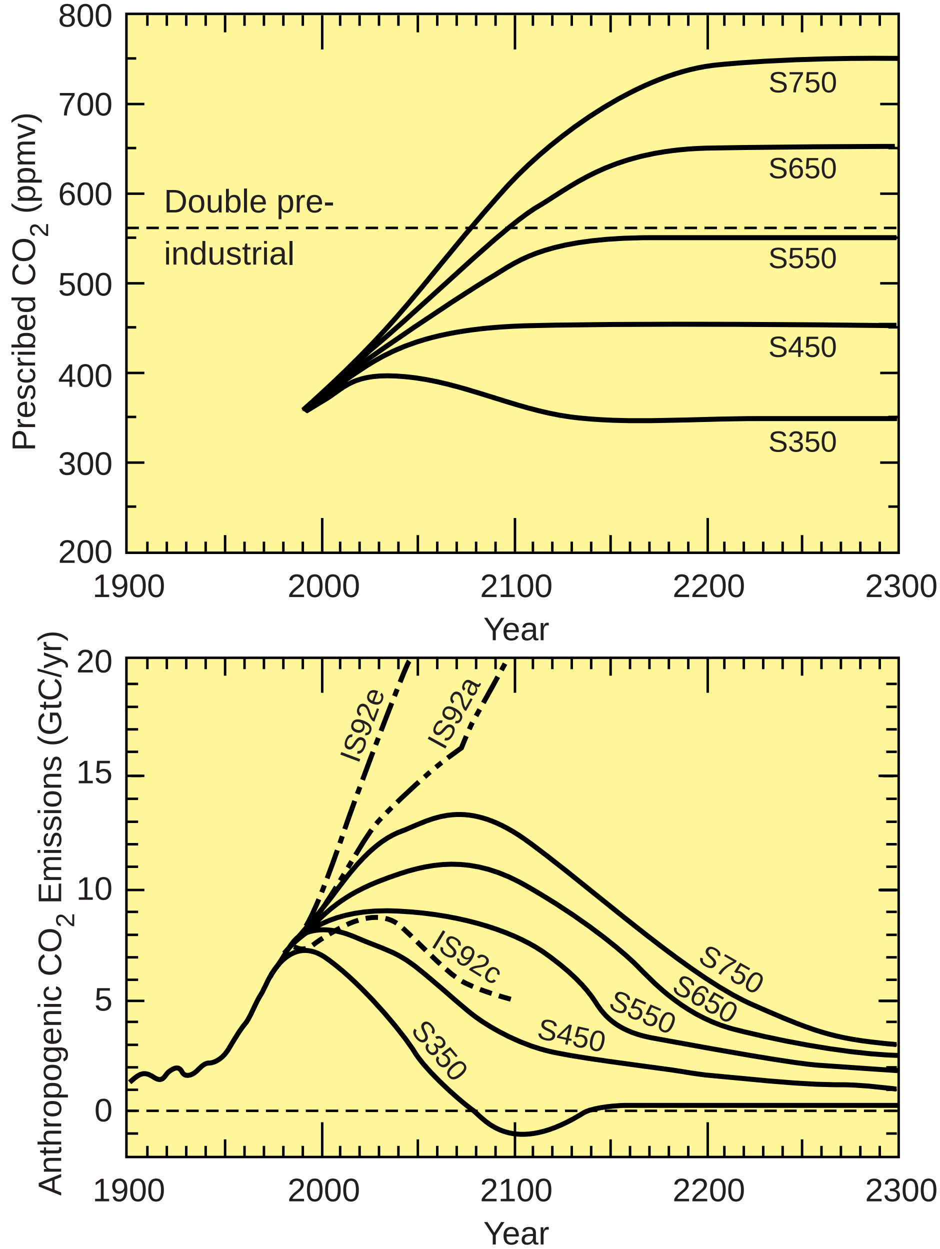


Magnetic Fusion Energy

Japan and Europe Are Pressing Forward Aggressively with Magnetic Fusion Energy

- **Japan and Europe have less energy resources than U.S., and greater concern about dependence on foreign energy supplies.**
  - **Japanese MFE Budget ~ 1.5 x U.S.**
  - **European MFE Budget ~ 2.5 x U.S.**
- **Japan and Europe are continuing the ITER Engineering Design Activity.**
- **Japan and Europe each are operating or constructing:**
  - **A ~$1B class tokamak experiment**
  - **A ~$1B class superconducting stellarator experiment.**
- **The U.S. now has no device in the ~$1B class.**

A Different Kind of Energy Economy will be Needed in the Future

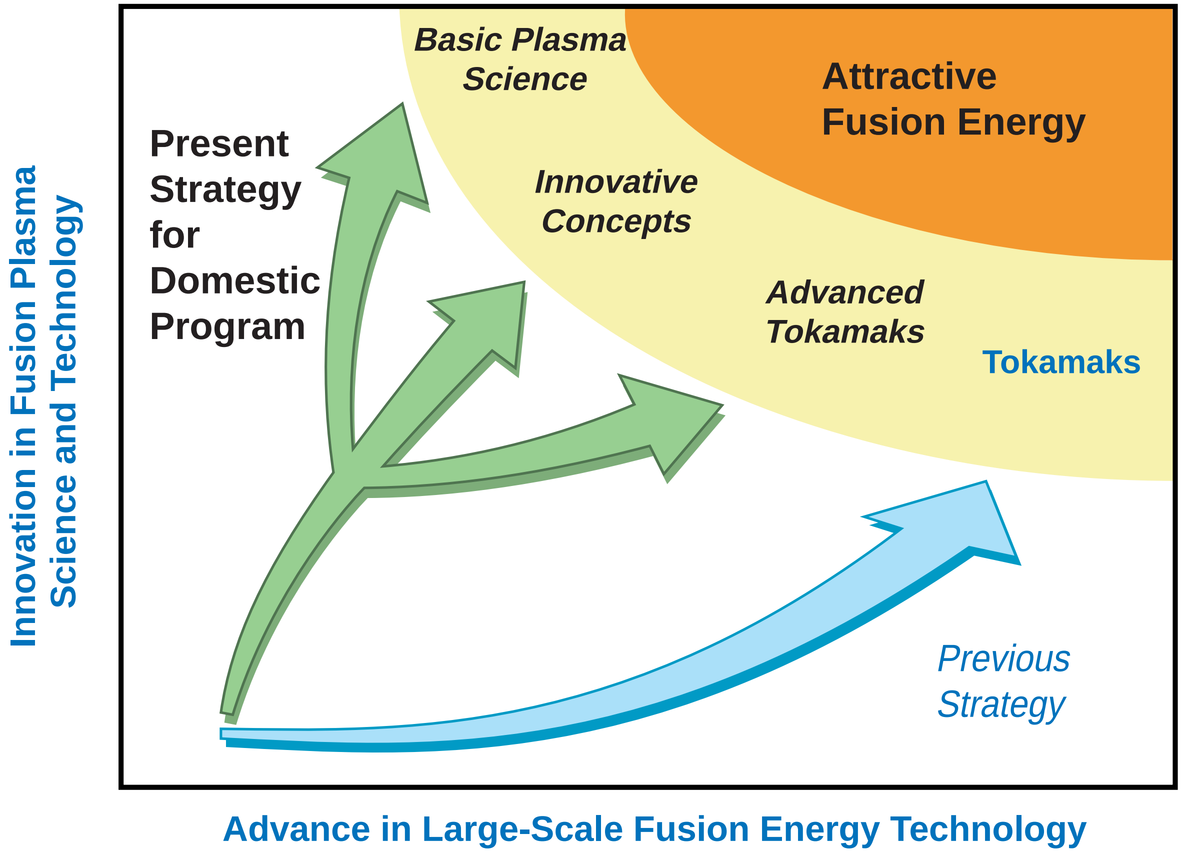


- **3x more energy**
- **3x less CO_2 emissions**

' Climate Change 1994, IPCC

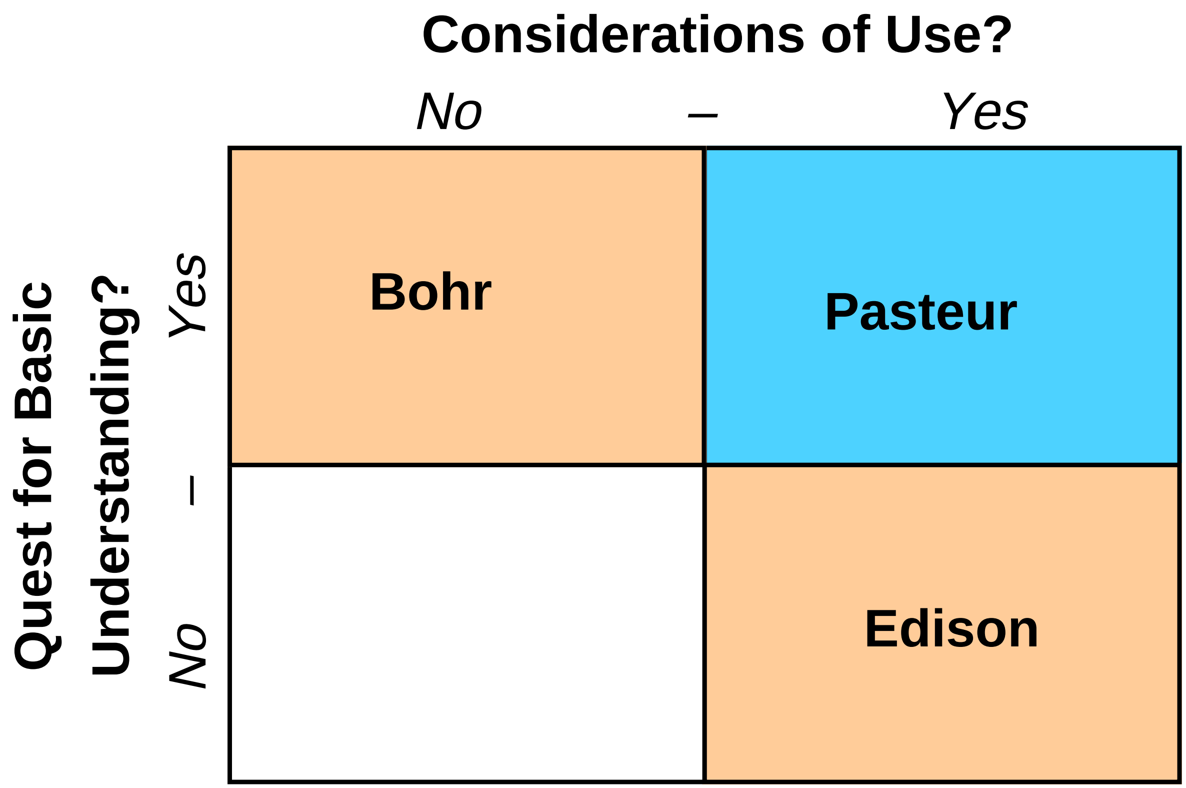
PPPL#98GR008

New Fusion Program Strategy



- Portfolio of innovative concepts, including inertial fusion energy
- Broader scientific areas of inquiry

Fusion Energy Science Sits in *Pasteur's Quadrant*



The Grand Challenge:
Excellent basic scientific understanding enabling the innovations that will make fusion energy practical.

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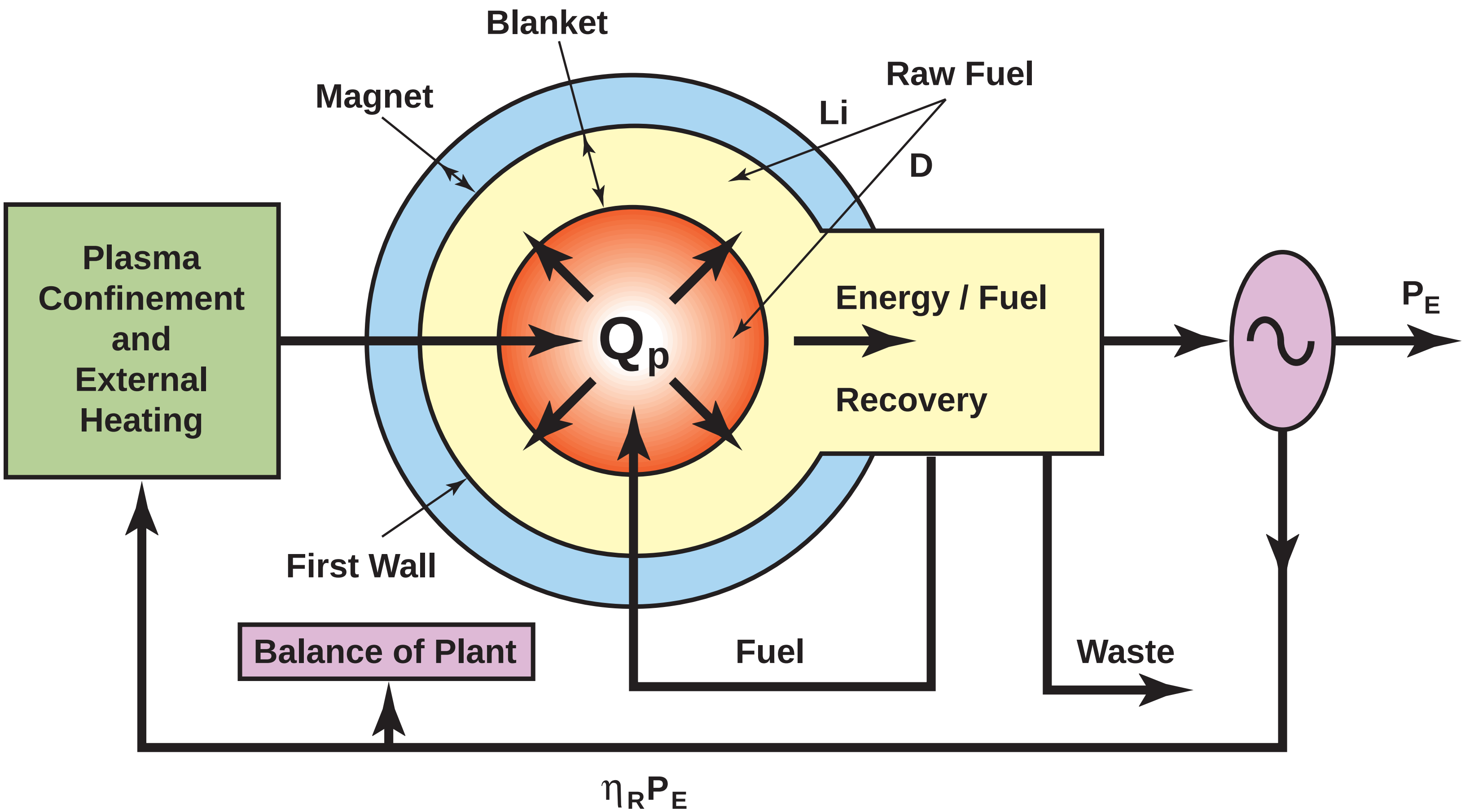
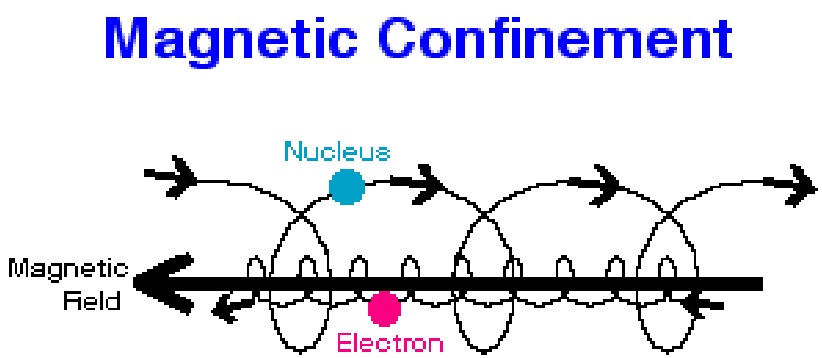
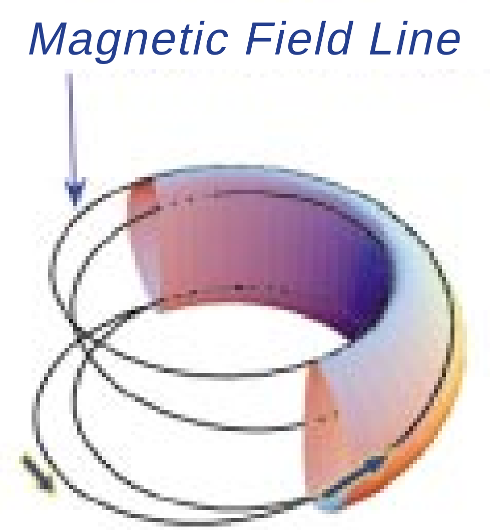
Schematic of MFE Power Plant



Magnetic Fusion Energy

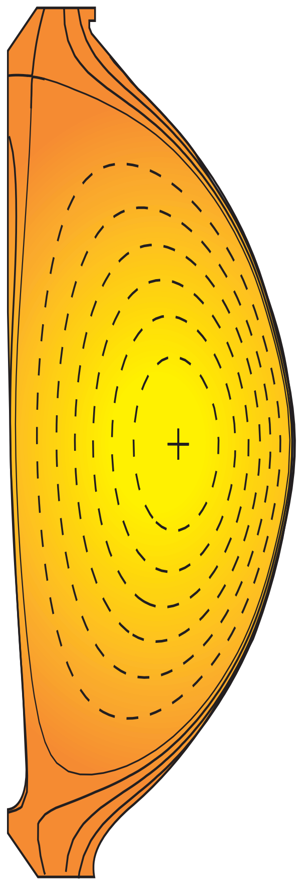
Toroidal Confinement





PLASMA SCIENCE AREAS IN MFE

- Macroscopic Stability
- Wave-particle Interactions
- Transport and Microturbulence
- Plasma-wall Interactions



FUSION POWER IS DETERMINED BY MACROSCOPIC STABILITY

- **Plasma stability is largely determined by**

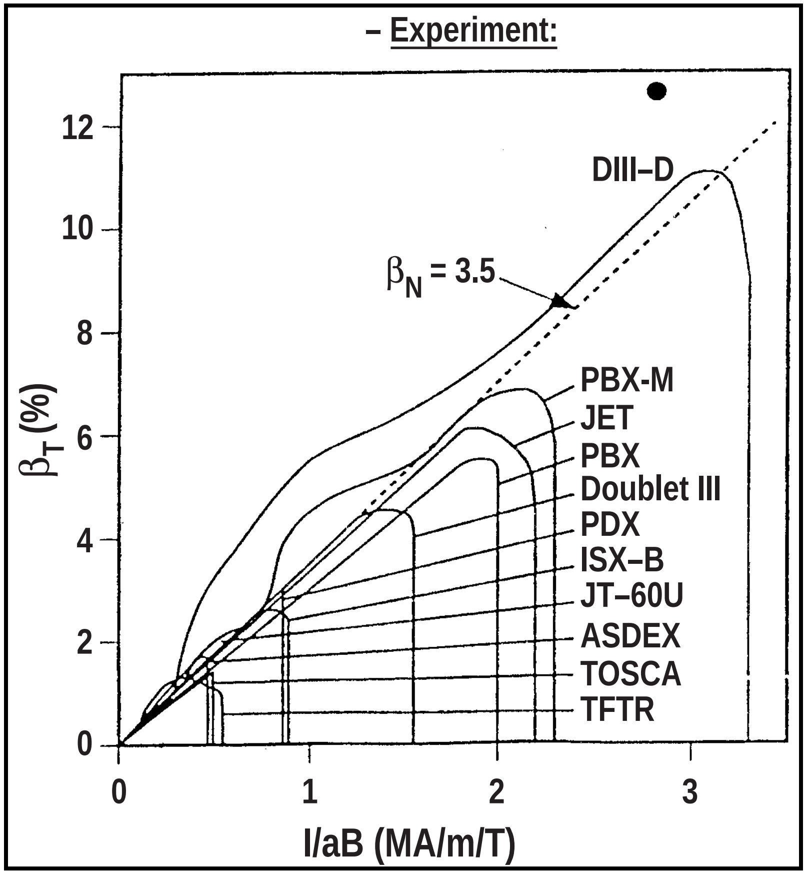
$$\beta \equiv \frac{2nT}{B^2/2\mu_0}$$

- **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.***

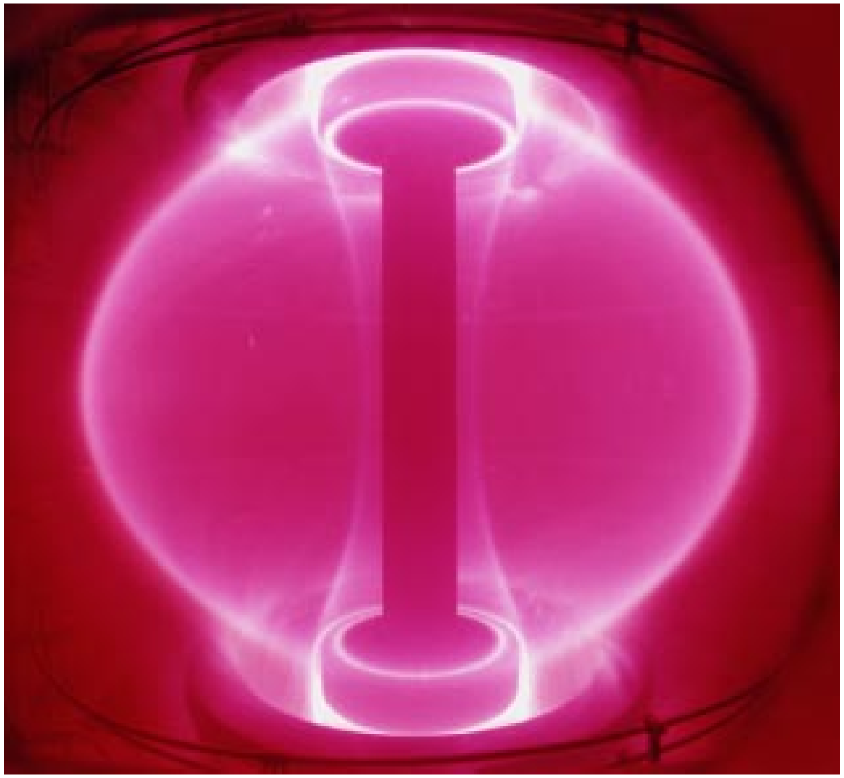
Ideal MHD Theory Provides Accurate Guidance on Operational Boundaries in Tokamaks



- **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".**

Small Spherical Torus in U.K. Reached Record (~40%) Average Toroidal β_t

NEW RECORD β ACHIEVED IN START



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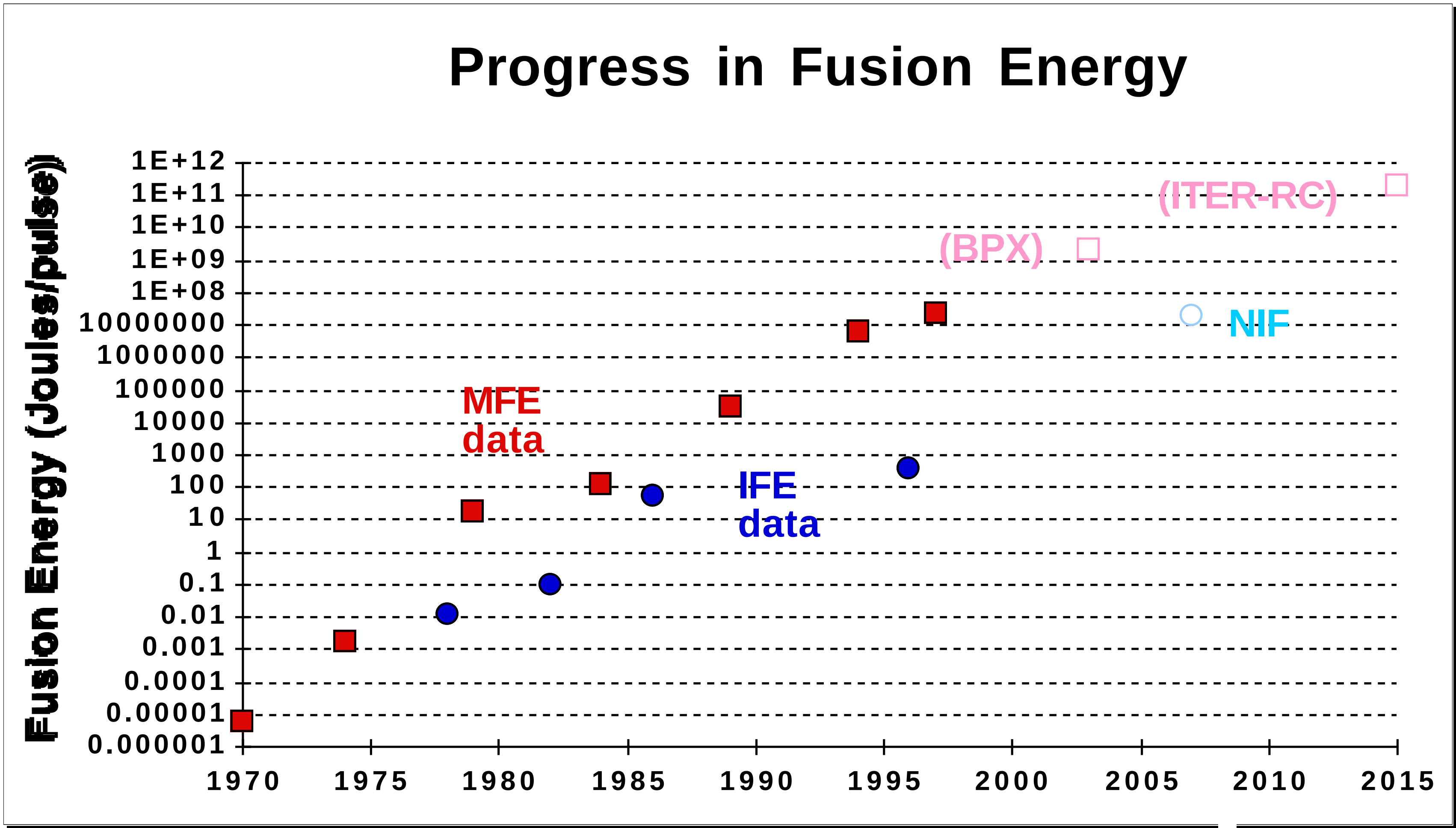
We Know we can Make Fusion Energy – The Challenge Now is to Make it Practical



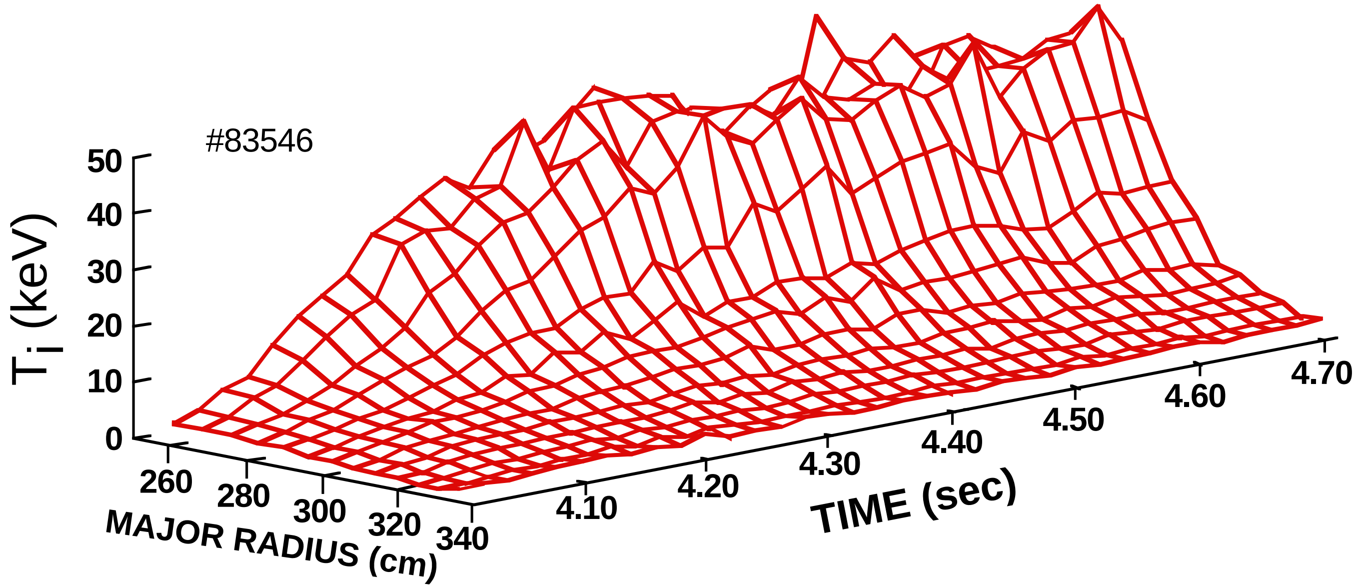
WAVE-PARTICLE INTERACTIONS ARE CRITICAL FOR PLASMA SUSTAINMENT

- **Plasma heating and current-drive**
  - **By beams of energetic neutral atoms**
  - **By radio-frequency waves**

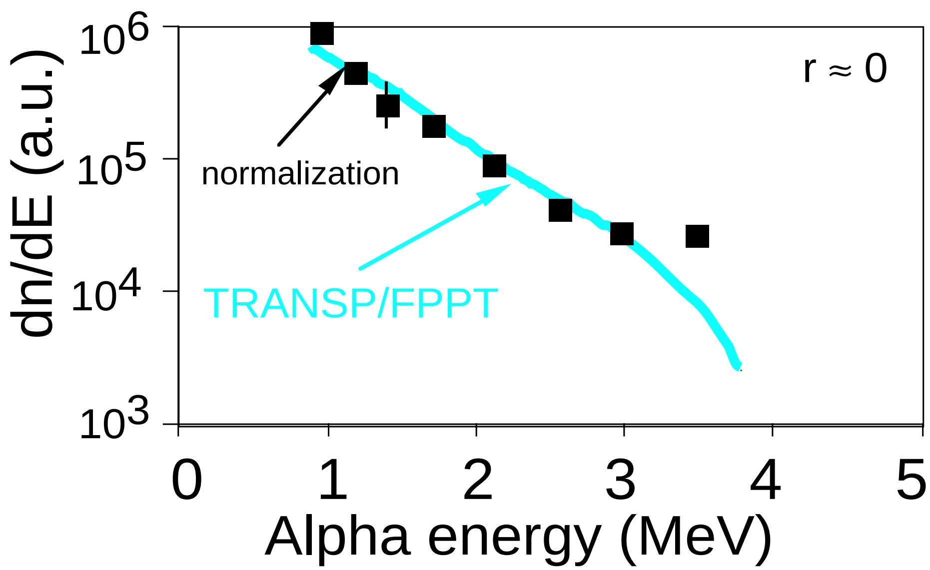
- **Plasma self-heating by α particles**

- ***Discovery of the "bootstrap" current has revolutionized toroidal systems.***

PLASMA HEATING BY NEUTRAL ATOM INJECTION IS EFFECTIVE AND WELL UNDERSTOOD

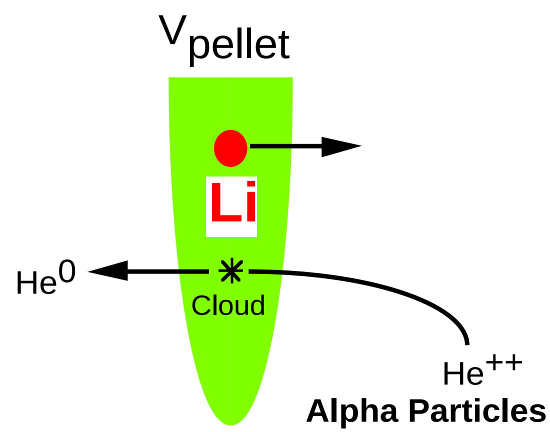


Confined Alphas in the Plasma Core Show Classical Slowing Down Spectrum



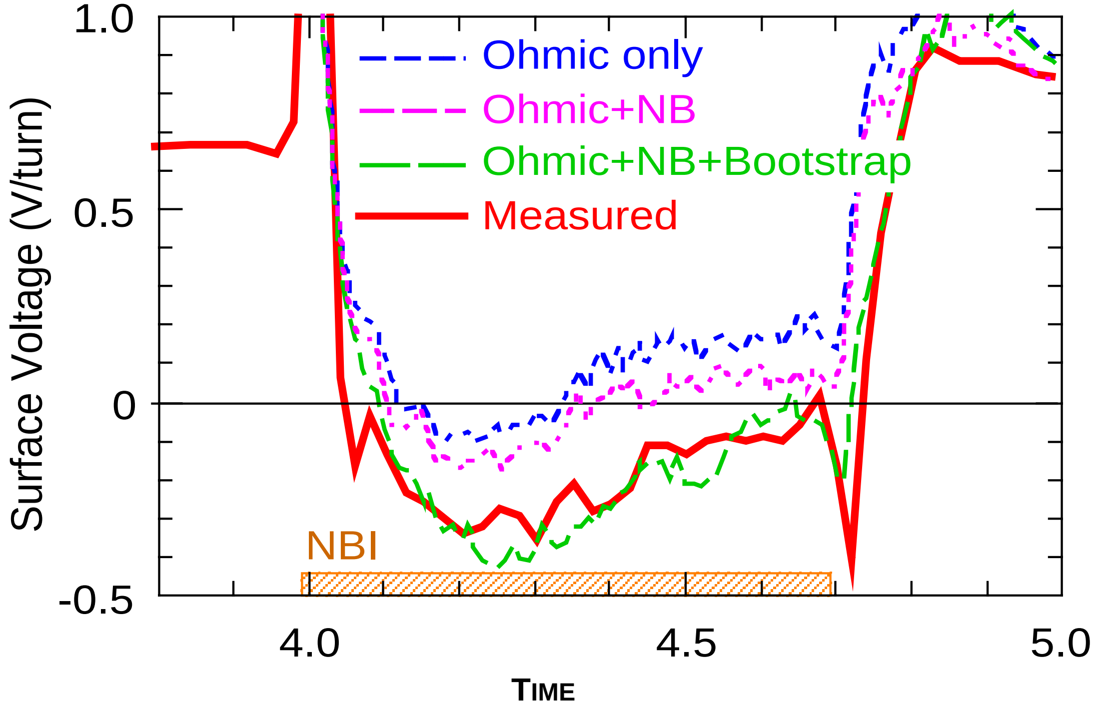
Double Charge Exchange Technique

$He^{++} + Li^{+} \Rightarrow He^{0} + Li^{3+}$



- **TRANSP calculation includes:**
  - orbit trajectories
  - classical slowing down
  - time dependence of alpha production

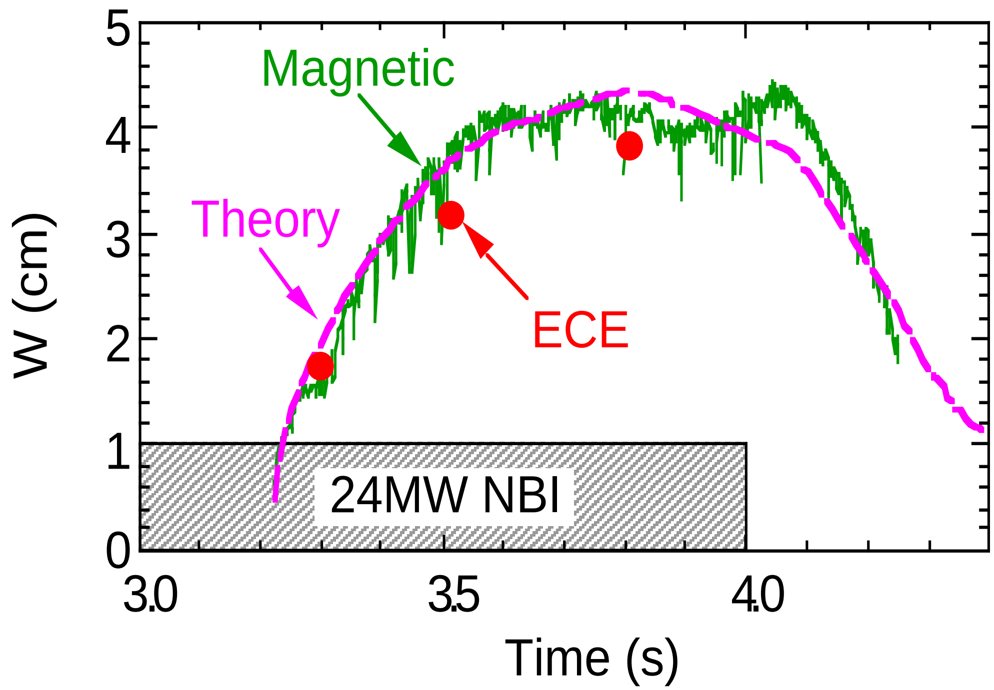
NEOCLASSICAL THEORY PREDICTION OF BOOTSTRAP CURRENT CONFIRMED



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

Magnetic Fusion Energy

Theory Successfully Predicts Island Widths for Low m/n Neoclassical Modes



- **Inhomogeneities in bootstrap current can be self-reinforcing.**
- **In stellarators, bootstrap current can be self-stabilizing.**

Fusion Gain is Determined by Transport and Microturbulence

- **Fusion power density**

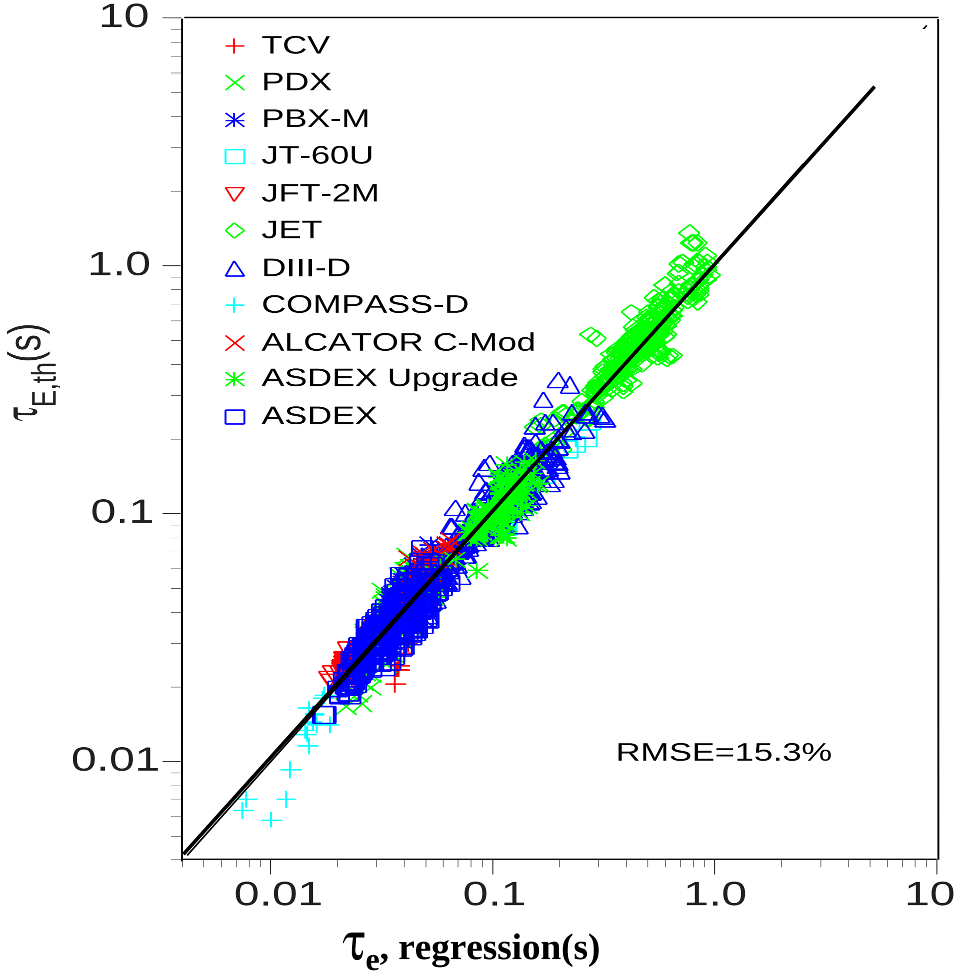
$$p_{fus} = E_{fus} n_d n_t \langle \sigma_{fus} v \rangle \sim n^2 T^2$$

- **Heat loss**

$$p_{loss} \cong \frac{3nT}{\tau_E}$$

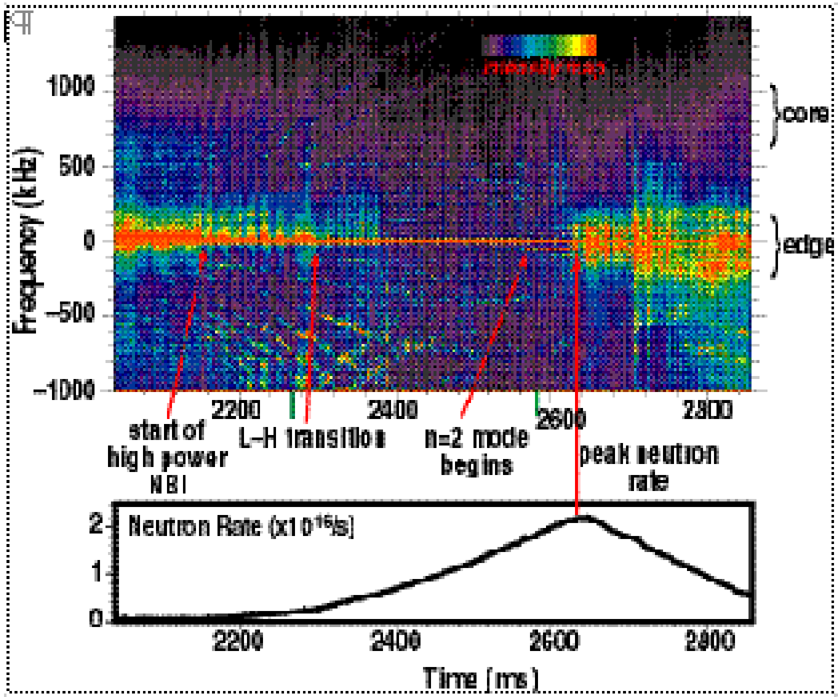
- ***Turbulence should not let heat out faster that it can be produced.***

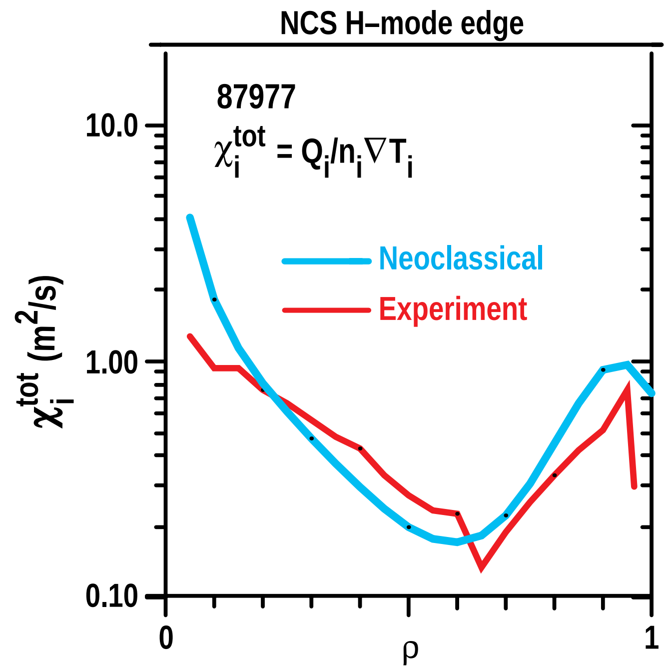
CONFINEMENT IS PREDICTABLE



Magnetic Fusion Energy

Ion Turbulence can be Eliminated

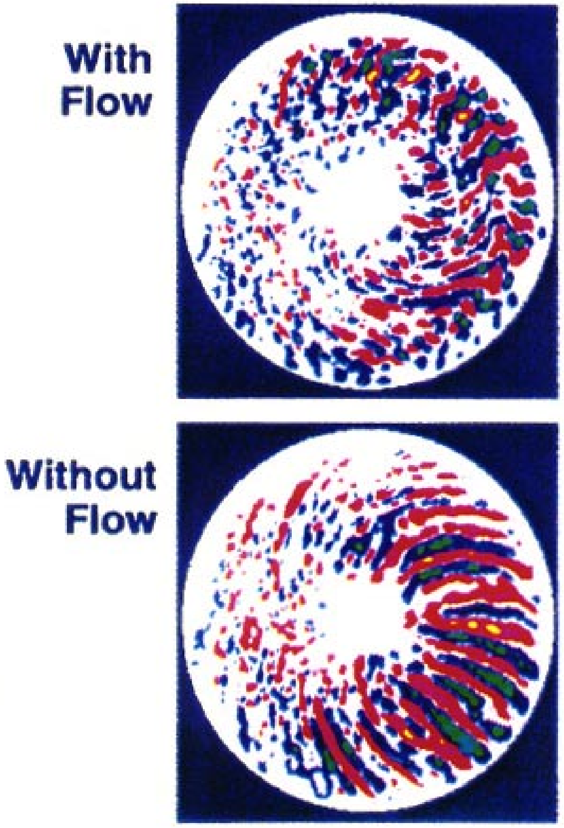




SHEARED FLOW CAUSES ENHANCED CONFINEMENT

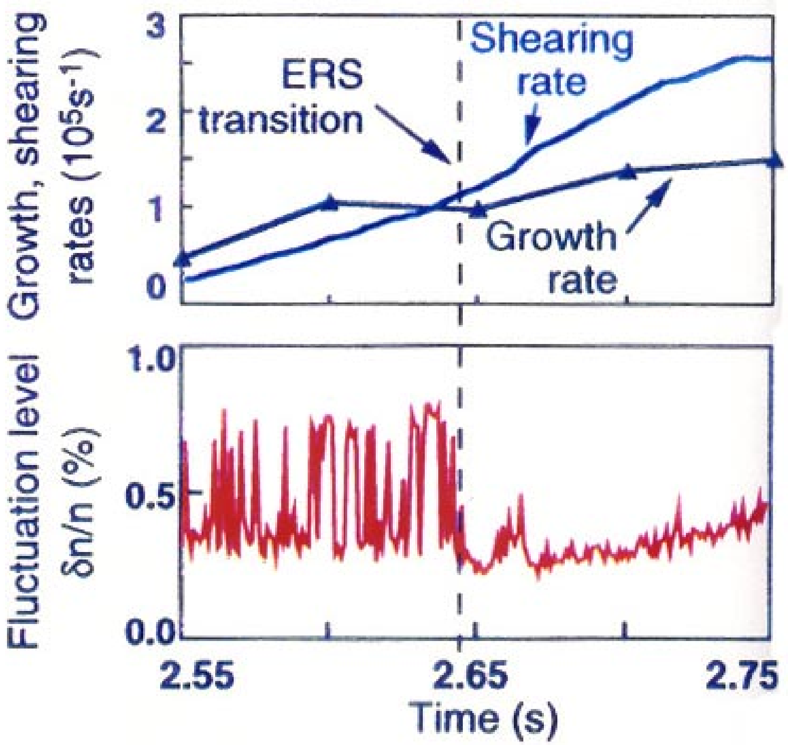
Gyrokinetic Theory

- Simulations show turbulent eddies disrupted by strongly sheared plasma flow



Experiment

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



PLASMA-WALL INTERACTIONS ARE CRITICAL TO FUSION POWER DENSITY

- **20% of DT fusion power is emitted as radiation and particle flow to the first wall.**

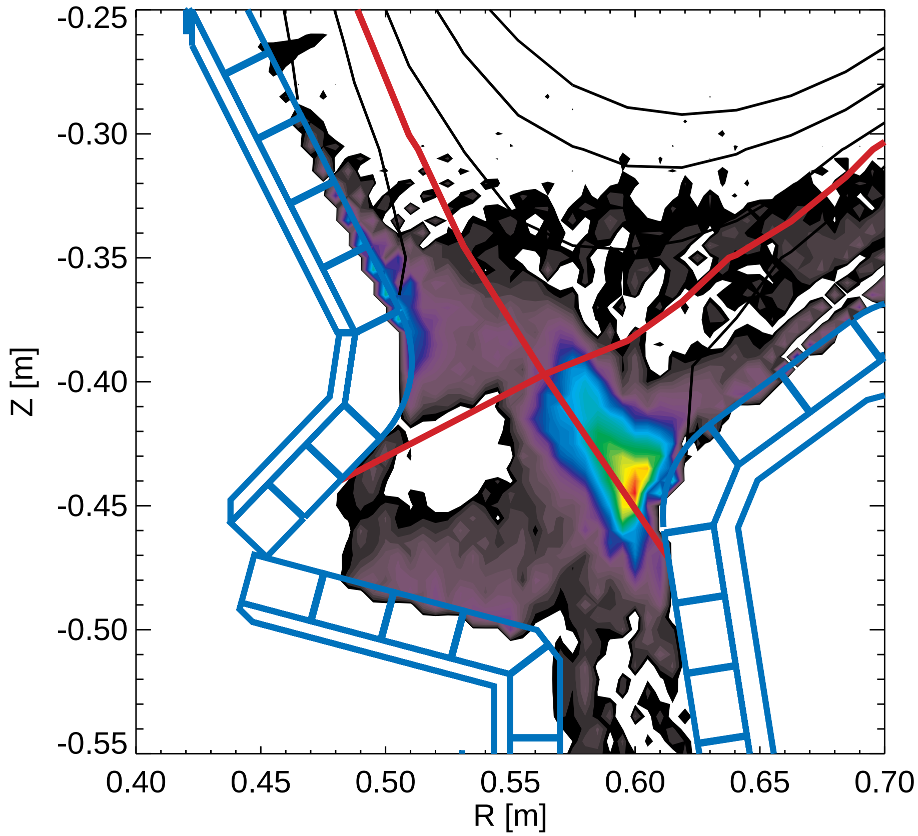
- **The heat and particle flows are concentrated in space by plasma divertors, and in time by plasma disruptions.**

- ***Major advances have been made recently in learning to control plasma-wall interactions.***

MAGNETIC DIVERTOR CHANNELS BOTH HEAT AND PARTICLES

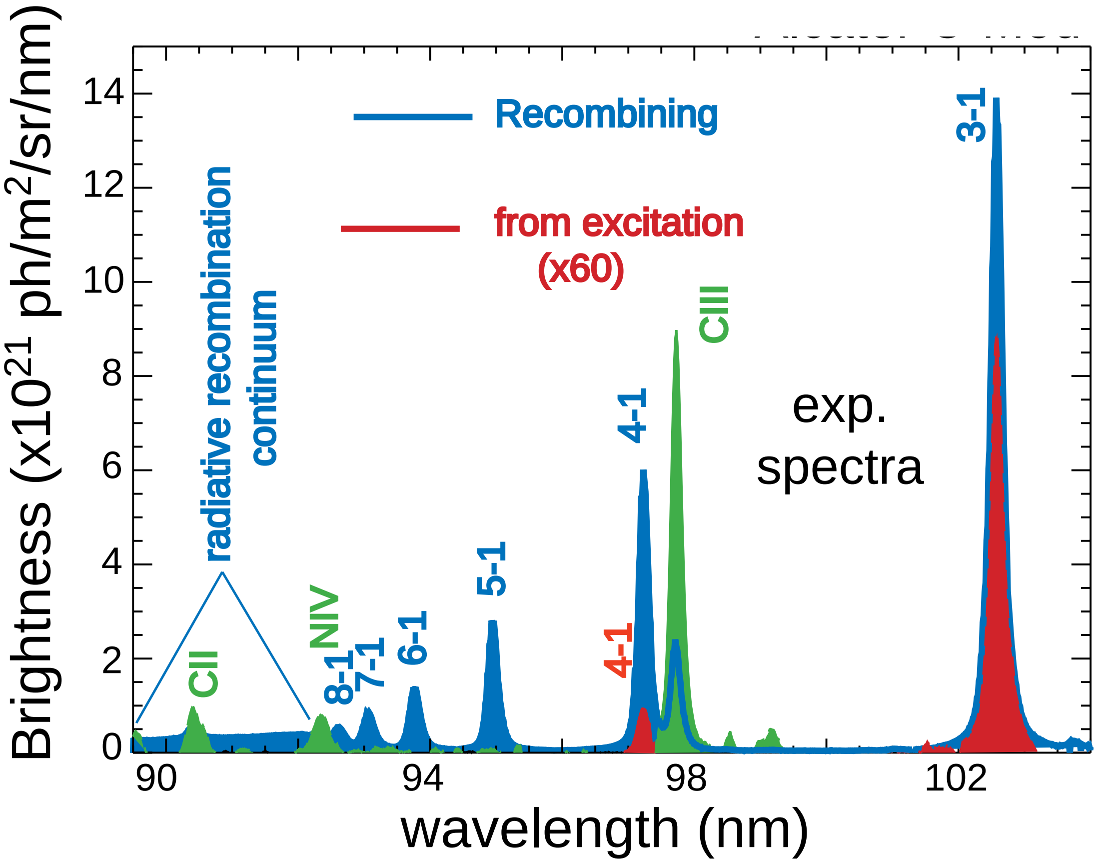
- **Directs heat flux away from plasma boundary.**

- **Permits pumping of neutral helium ash.**



NEUTRAL PARTICLE CONCENTRATION AIDS ASH REMOVAL & HEAT REDUCTION

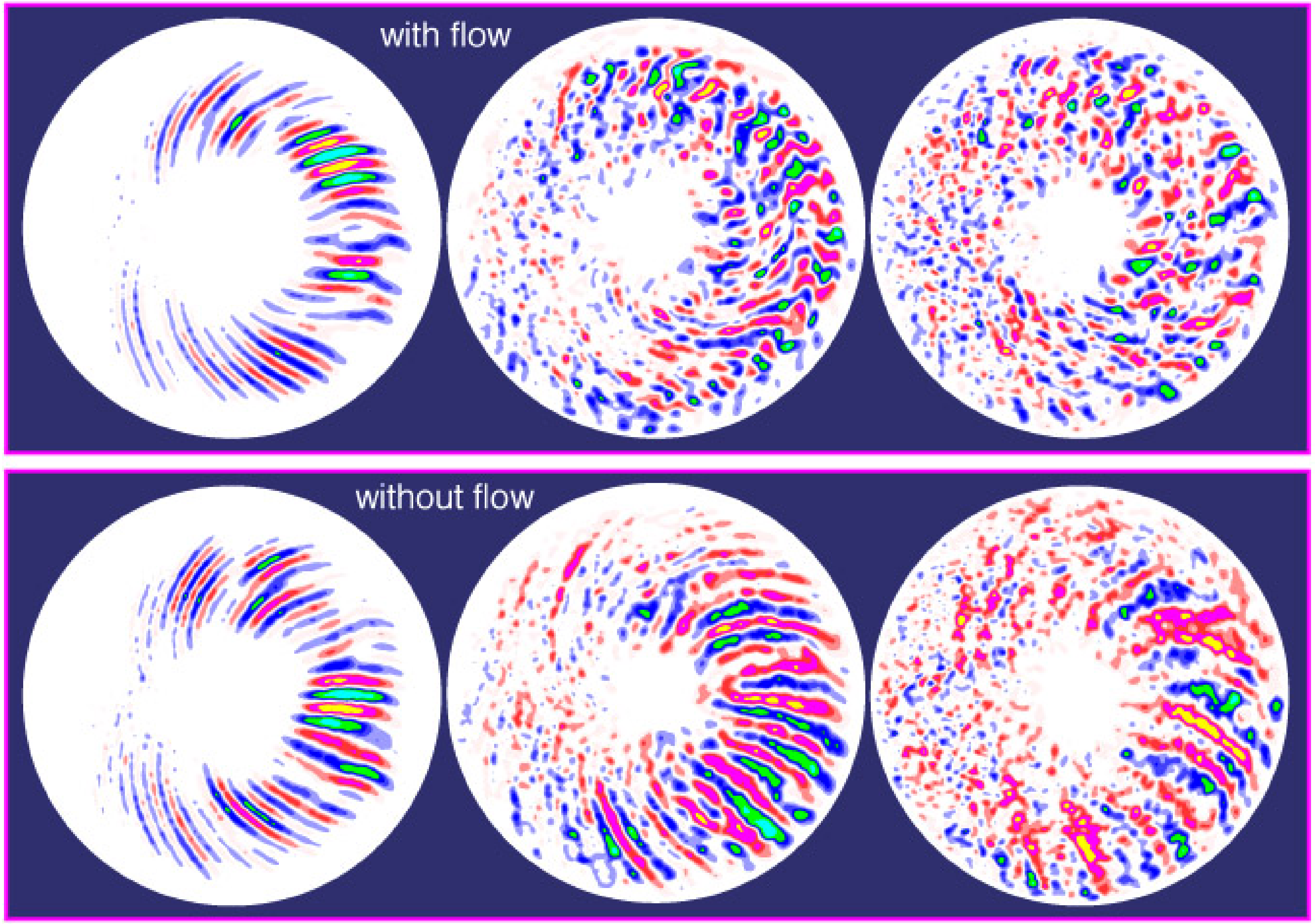
- **Plasma is extinguished by recombination.**
- **Heat flux is greatly reduced.**
- **Disruption mitigation is an active research area.**



The Role of Computation

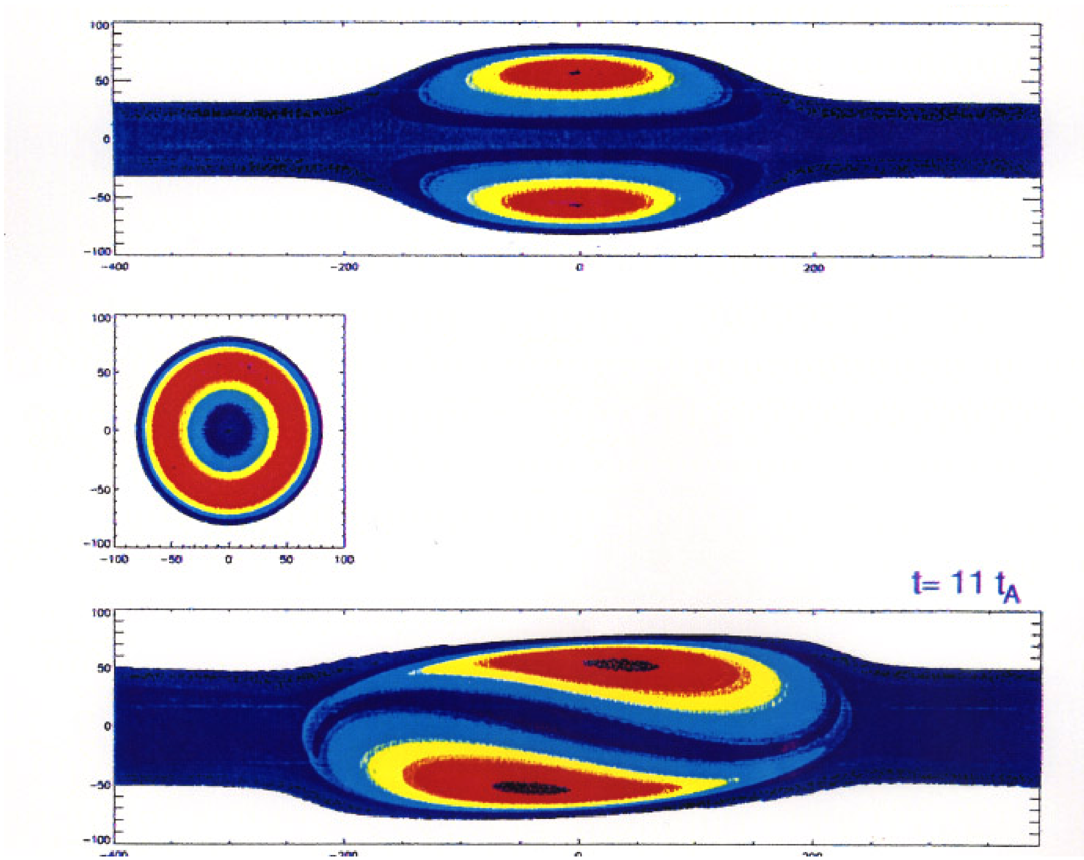
- **Plasma physics is governed by Maxwell's equations and the Lorentz force equation.**
- **Powerful Particle-in-Cell (PIC) codes examine microturbulence and transport.**
- **Powerful fluid codes examine macrostability.**
- **Advanced simulation will accelerate the cycle of theoretical understanding and experimental innovation.**

Realistic Simulations Enabled by New MPP

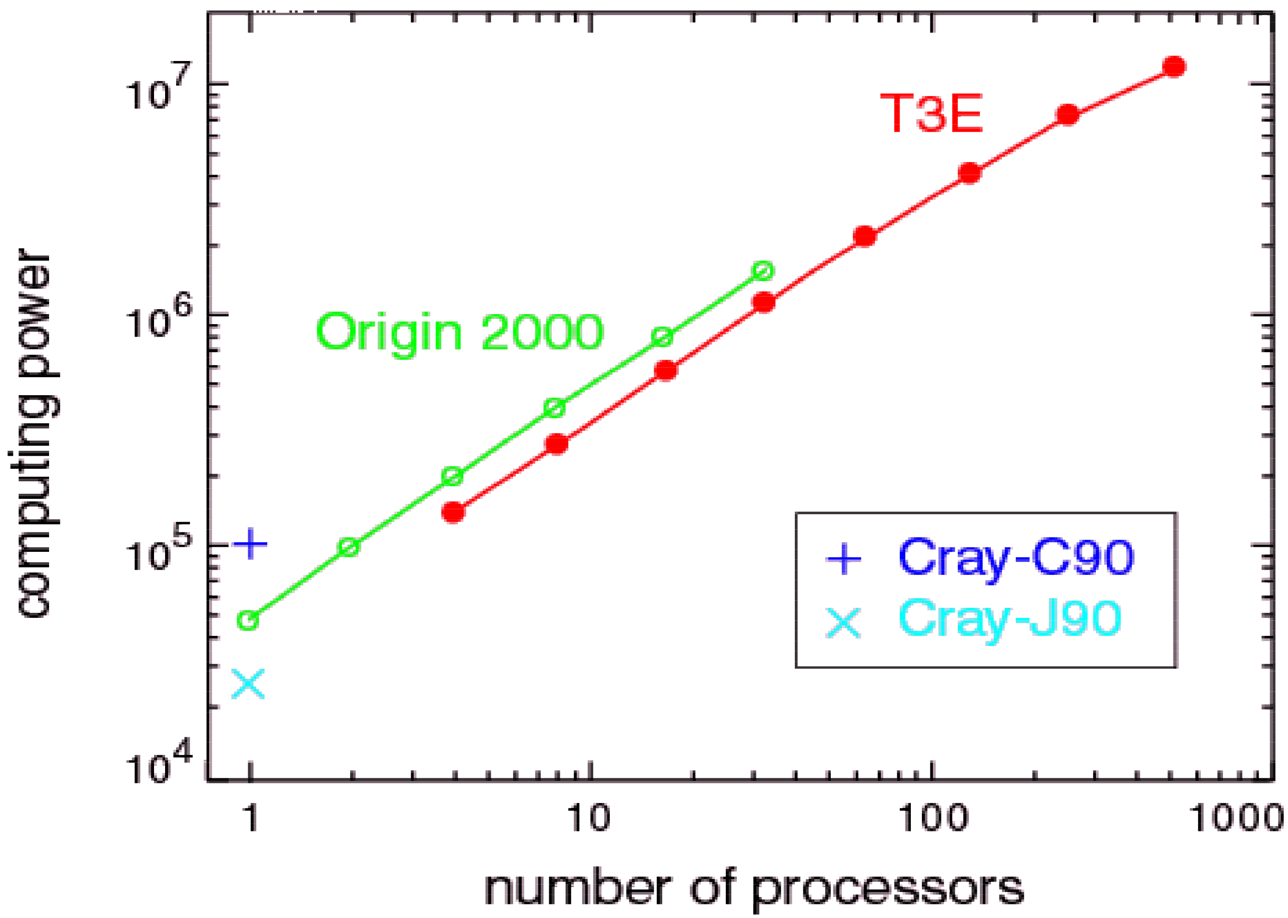


3D nonlinear gyrokinetic simulations: flow suppression of turbulent transport

MHD Simulation of n=1 Tilting Instability in FRC



PIC Codes Scale Well to Massive Parallelism



- Y-axis: the number of particles which move 1 step in 1 second

OUTLINE

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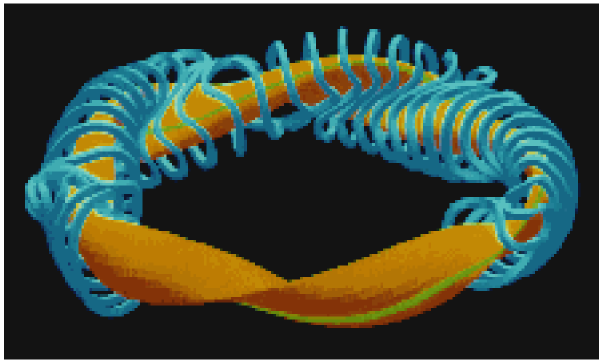
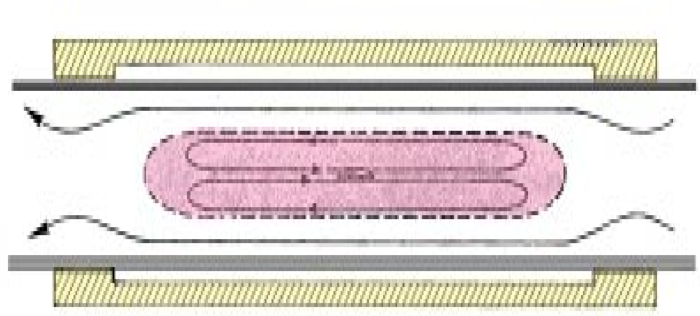
KEY IDEAS BEHIND THE PORTFOLIO APPROACH

- **Strong scientific synergy – Commonality**
  - Ideas from one configuration help others
  - Hybrid configurations emerge
- **Breadth – Complementarity**
  - Avoids common roadblocks
  - Broadens Science and Technology spin-offs
- **Leverage off >$1B/year International Program**

MFE CONFIGURATIONS IN THE PORTFOLIO

Externally Controlled ↔ **Self Organized**





Example: Stellarator
Coils link plasma
Magnetic fields from external currents
Toroidal field >> poloidal field
Large R/a
More stable, better confinement

Example: FRC
Coils do not link plasma
B from internal currents
Poloidal B >> Toroidal B
R/a $\rightarrow$ 1.0
Higher power density

STAGES OF DEVELOPMENT

- **Concept Exploration**
  Ideas are given their first test, at a small scale.

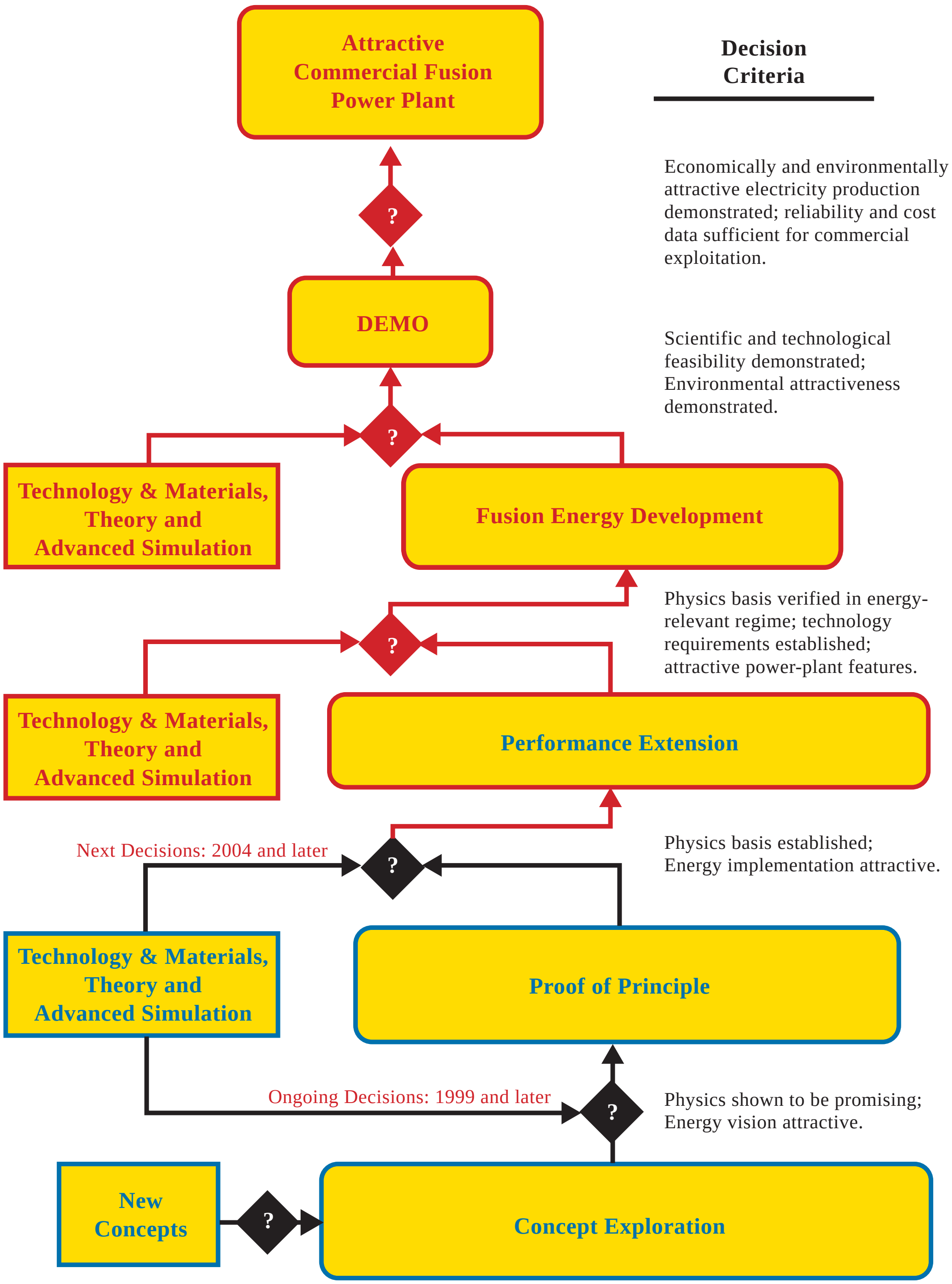
- **Proof of Principle**

First integrated tests of confinement, stability, sustainment, plasma-wall interactions.

- **Performance Extension**

Plasma parameters approach power plant conditions – test scaling, new physics.

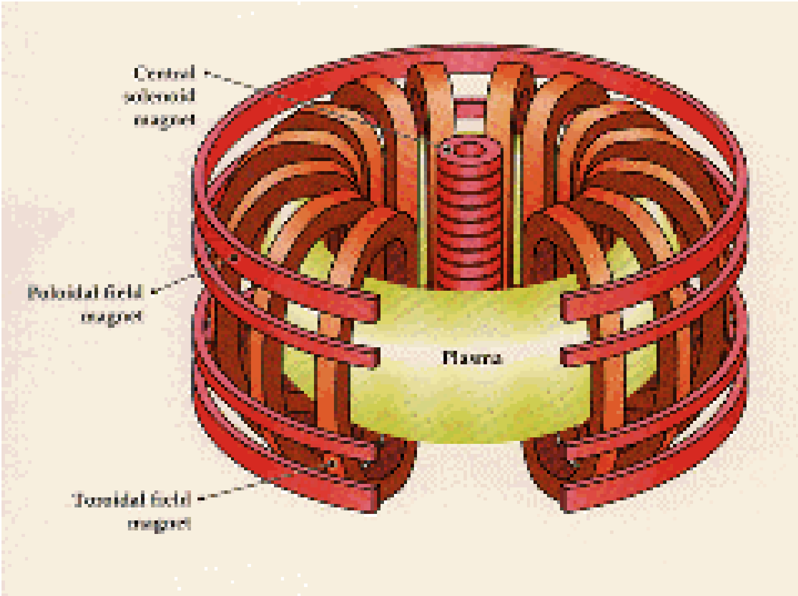
Roadmap to Attractive Fusion Power — A Portfolio Approach —



Magnetic Fusion Energy

The Tokamak is the Most Advanced Configuration in MFE

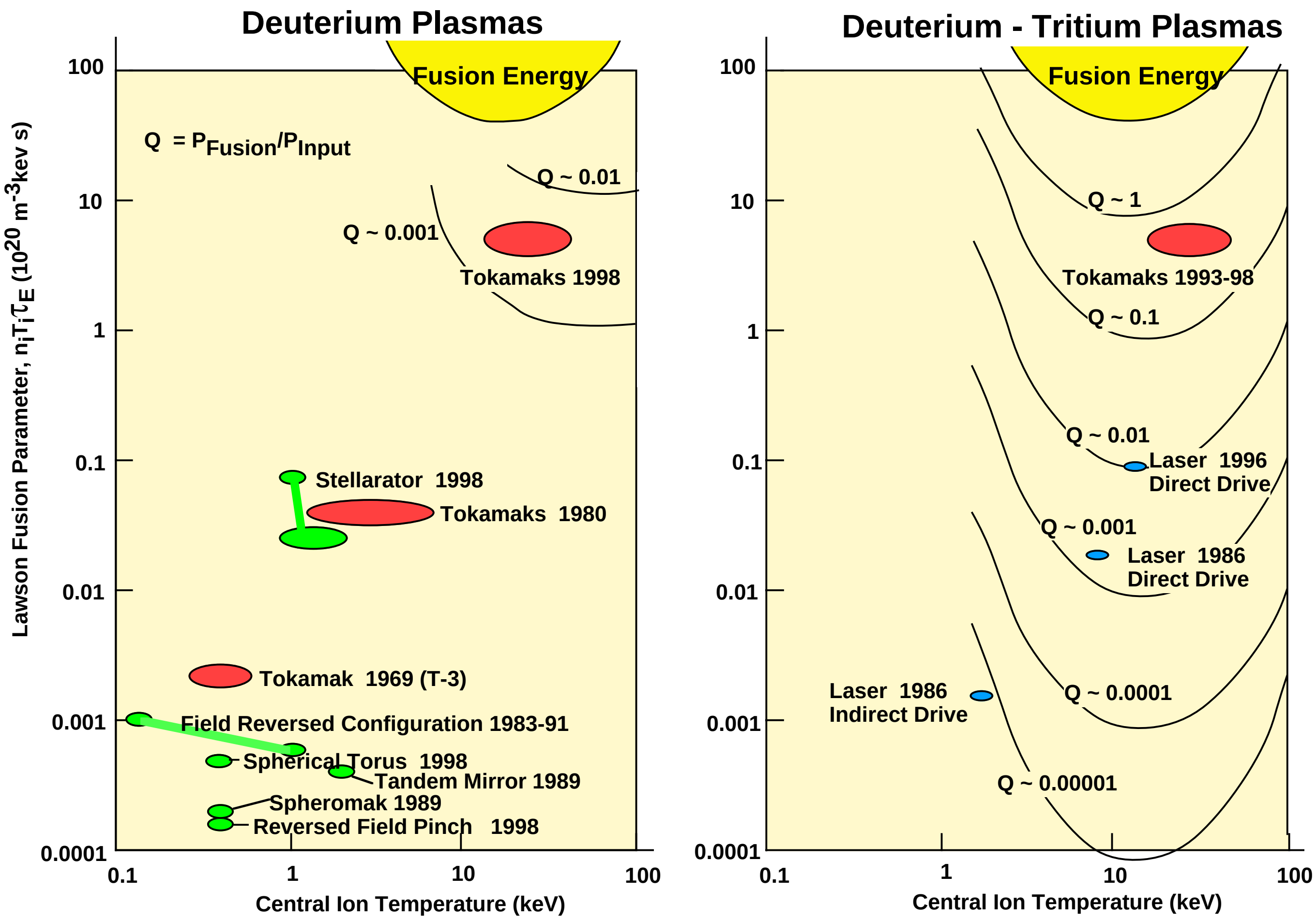
- Stable operation
- Good confinement
- Excellent database supporting other MFE configurations.



Issues:

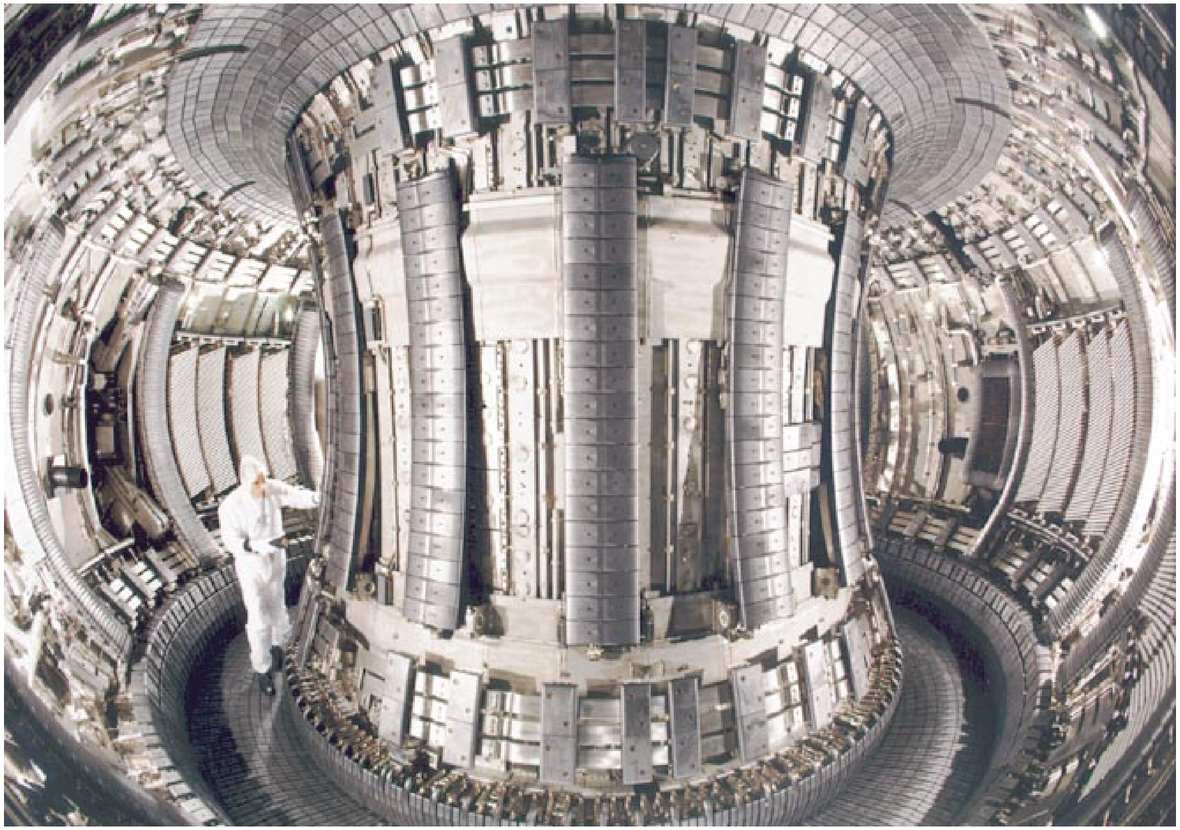
- Modest power density
- Continuous operation impractical
- Disruptions

Progress in Tokamak Performance Has Been Dramatic



Magnetic Fusion Energy

Joint European Torus (JET)



Magnetic Fusion Energy

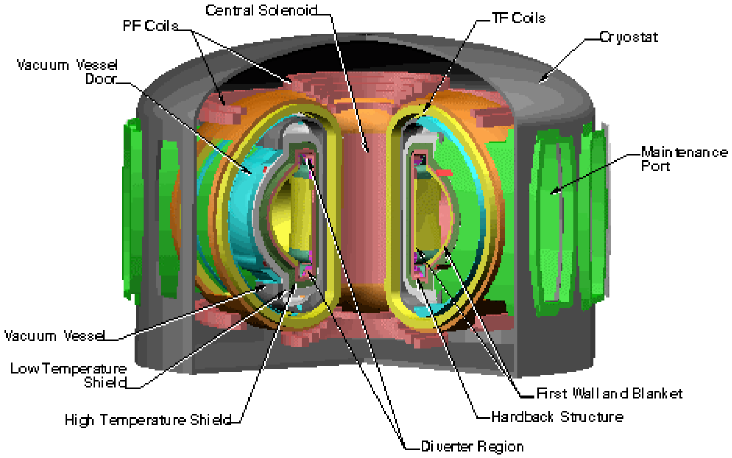
THE ADVANCED TOKAMAK RESOLVES KEY TOKAMAK ISSUES

- **Features:**
  - **High bootstrap current reduces power requirement for steady-state current drive.**
  - **Hollow current profile allows high-beta stability to short-wavelength modes.**
- **Areas of research:**

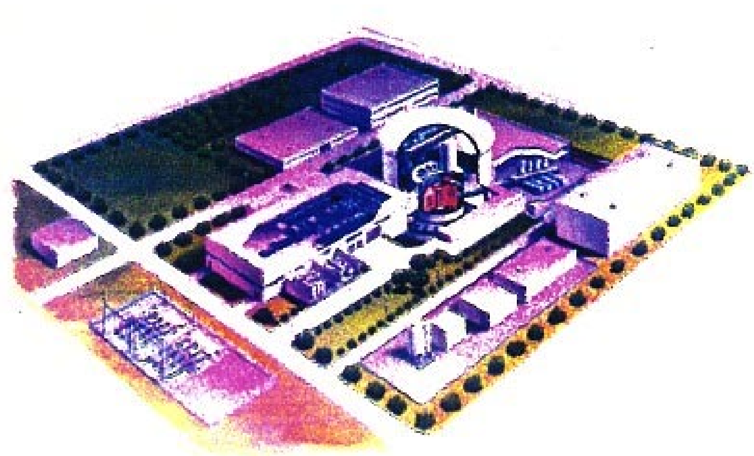
- **Stability to long-wavelength modes.**
- **Current and pressure profile control.**

The Advanced Tokamak Leads to an Attractive Fusion Power Plant

- **THE ARIES –RS SYSTEM STUDY**

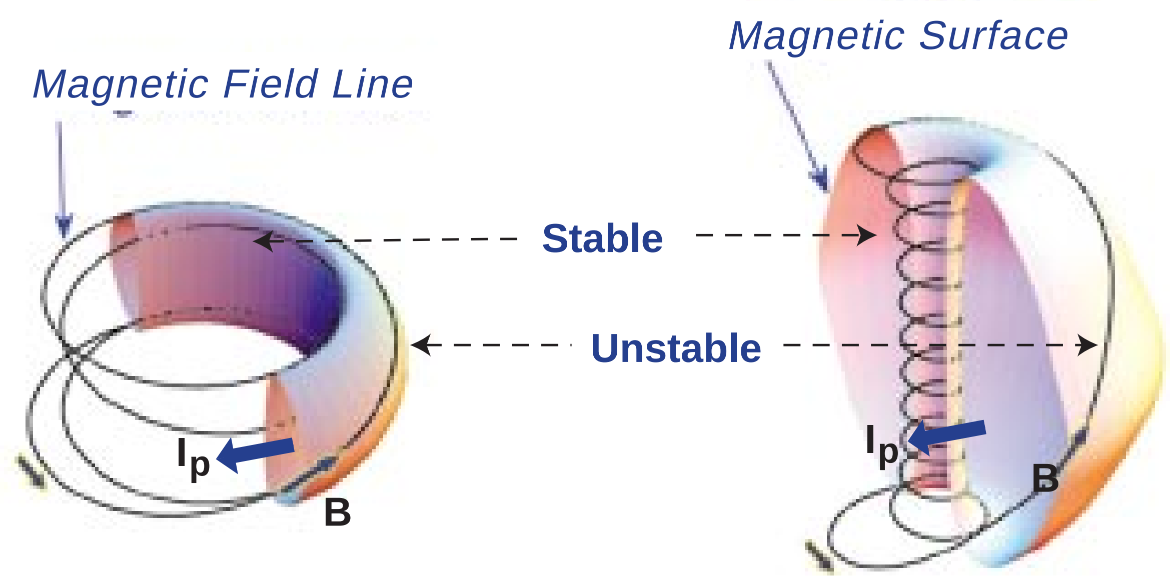


- **THE JAPANESE SSTR SYSTEM STUDY**



- **ATTRACTIVE FEATURES**
  - **COMPETITIVE COST OF ELECTRICITY**
  - **STEADY-STATE OPERATION**
  - **MAINTAINABILITY**
  - **LOW-LEVEL WASTE**
  - **PUBLIC AND WORKER SAFETY**

ST Maximizes the Good-Curvature Field Line Length over the Bad-Curvature Field Line



Tokamak

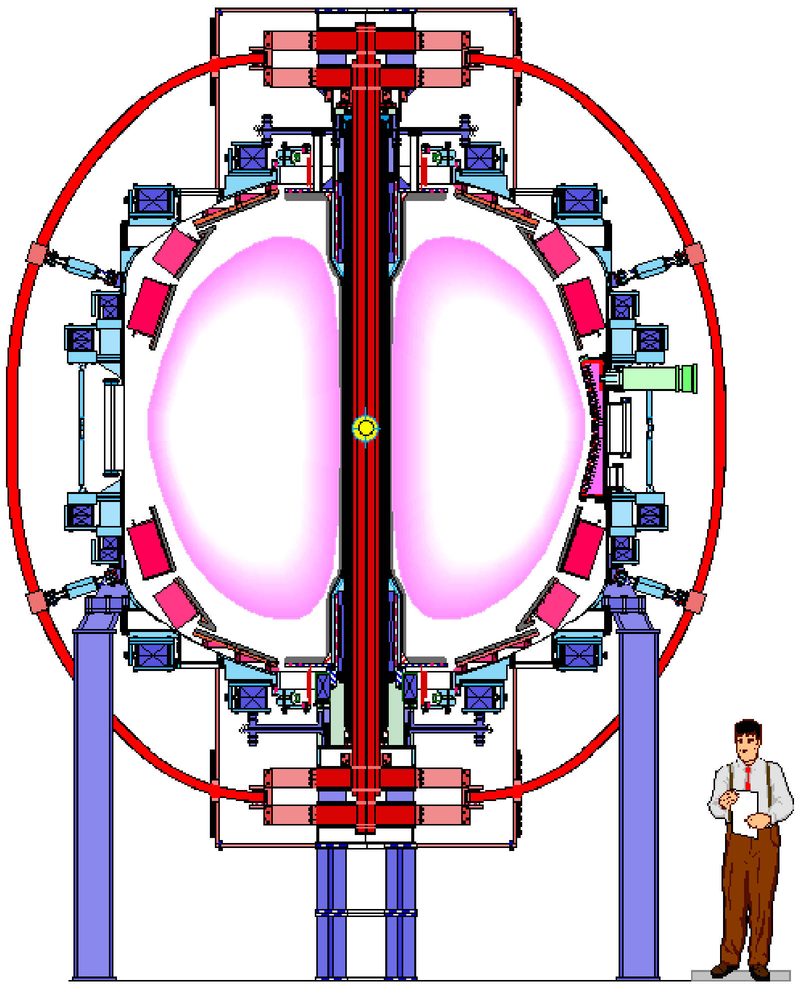
(A = 4, κ= 2, q = 4)

Spherical Torus

(A = 1.25, κ= 2, q = 12)

This leads to very high β and widens ST parameter domain.

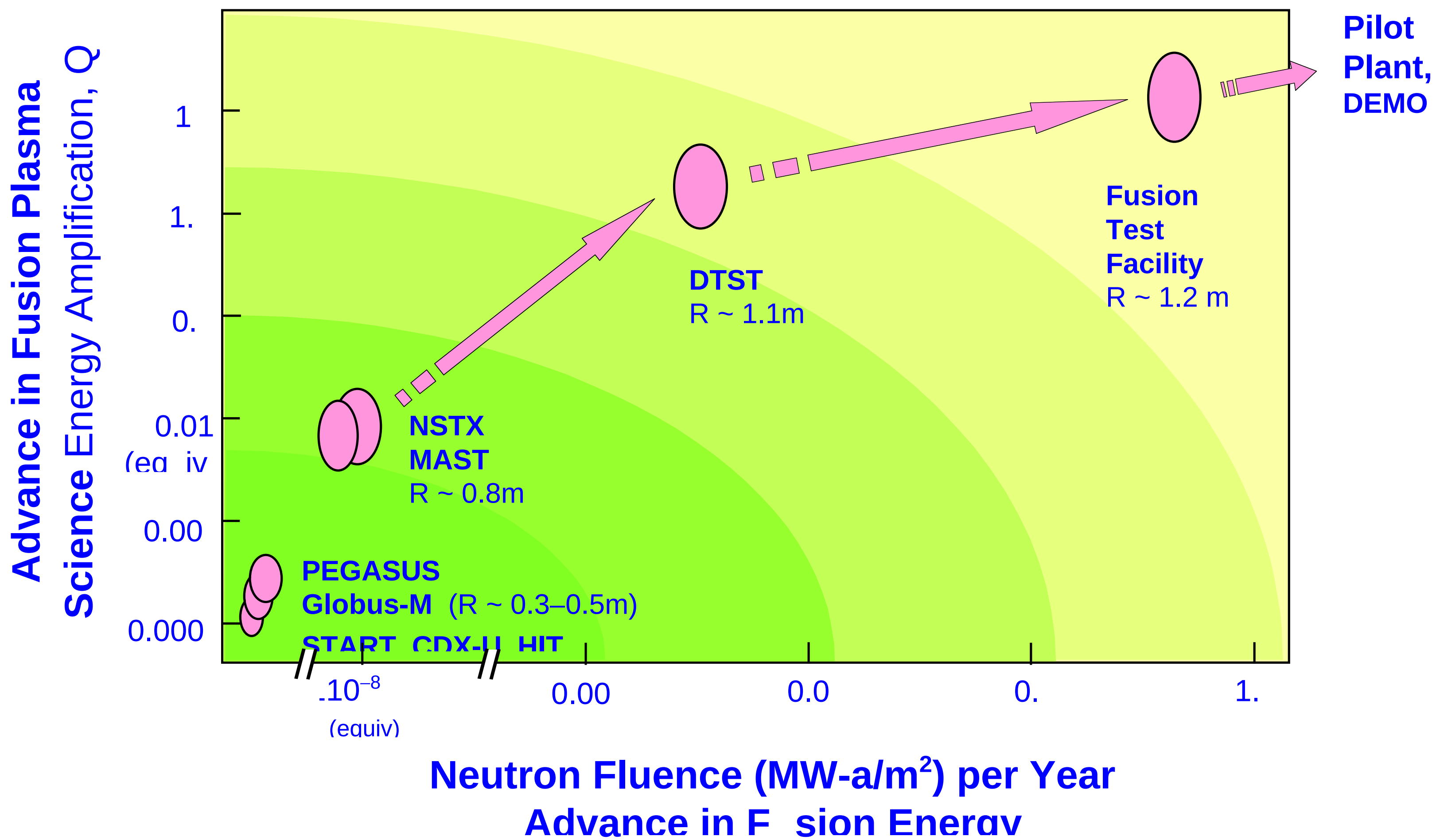
A World-Class Innovative Fusion Experiment



Baseline Parameter

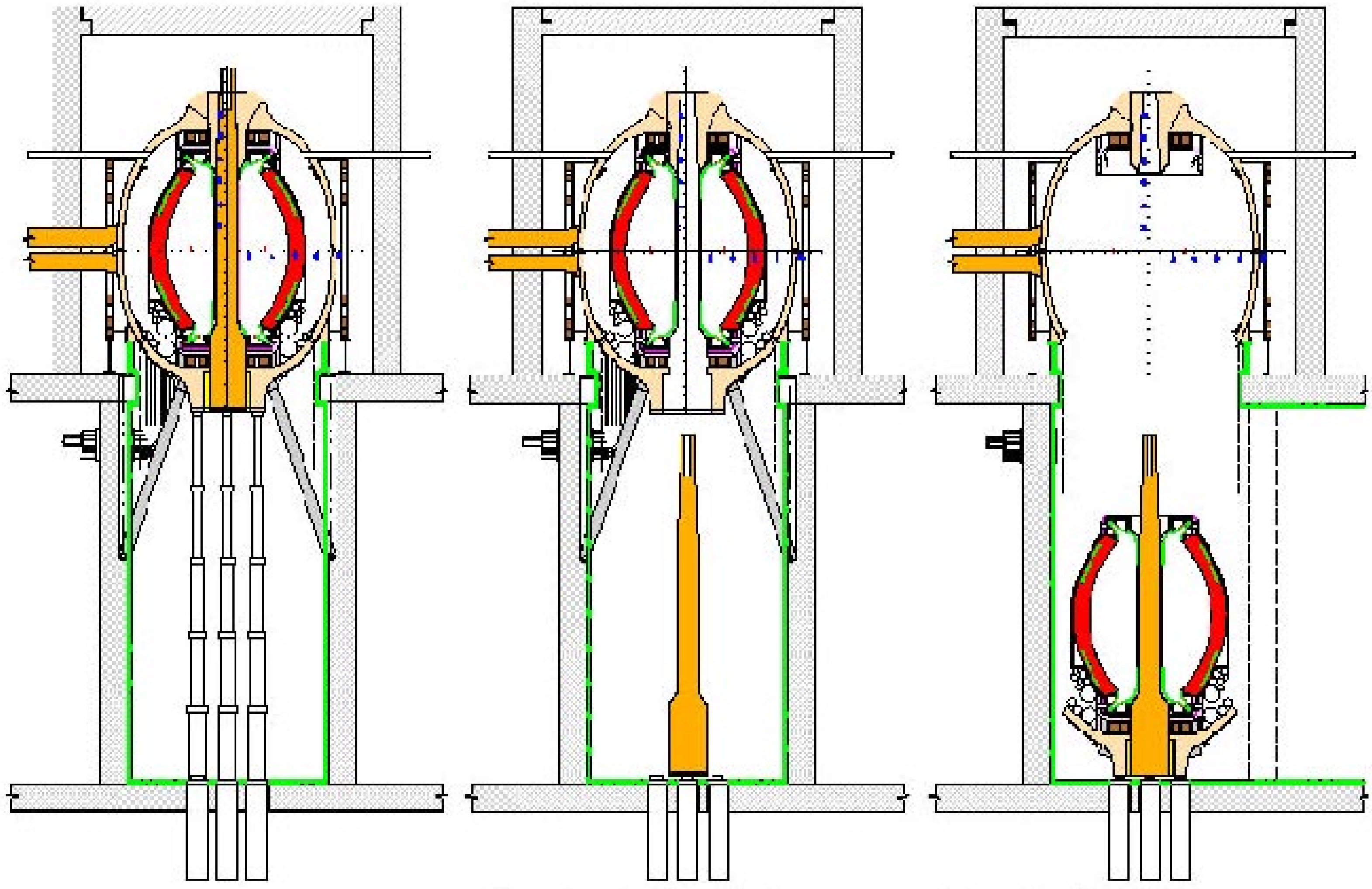
- Major radius
  ≤ 85 cm
- Minor radius
  ≤ 68 cm
- Plasma current
  1 MA
- Toroidal field
  0.3–0.6 T
- Heating and current drive
  11 MW
- Flat-top time
  5–1.6 s

ST Can Advance Fusion Science and Technology Using Small-Size Devices

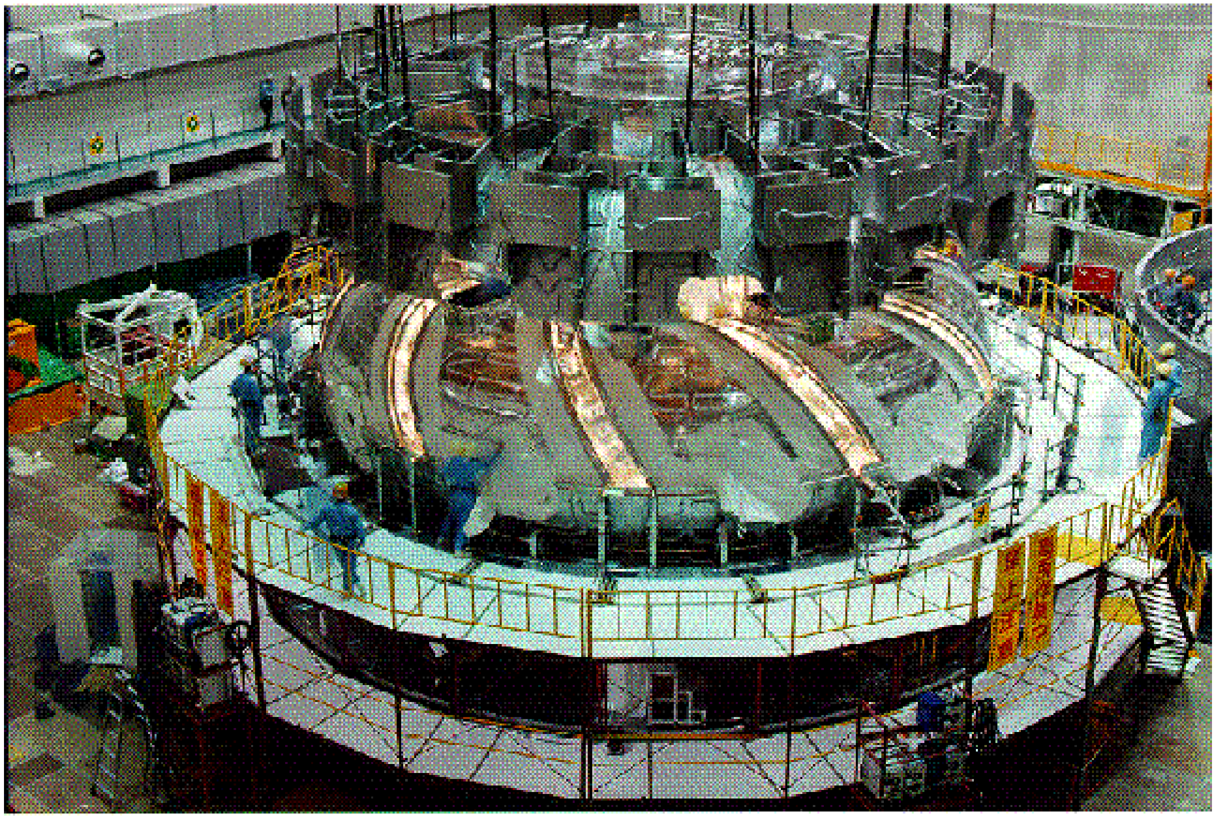


Magnetic Fusion Energy

ARIES-ST Elevation View Showing Maintenance Paths



Japanese LHD Stellarator Has Begun Operation



U.S. Program: Compact Stellarators

- **REVOLUTION IN THEORETICAL UNDERSTANDING PLUS TOKAMAK EXPERMENTAL RESULTS ALLOWS NUMERICAL DESIGN OF ATTRACTIVE STELLARATOR CONFIGURATIONS.**

- EXCELLENT PLASMA CONFINEMENT.
- HIGH β STABILITY.
- DESIGN TO STABILIZE TROUBLING INSTABILITIES.

  E.G. KINK AND NEOCLASSICAL TEARING – MODES.

- **CAN COMBINE PHYSICS ADVANCES OBSERVED IN TOKAMAKS WITH STELLARATOR FLEXIBILITY $\rightarrow$ MORE COMPACT DESIGNS.**

- CURRENT STELLARATORS HAVE HIGH ASPECT RATIOS, R/A ~8 – 11.
- CAN GET R/A ~ 2 – 4 USING BOOTSTRAP CURRENT.

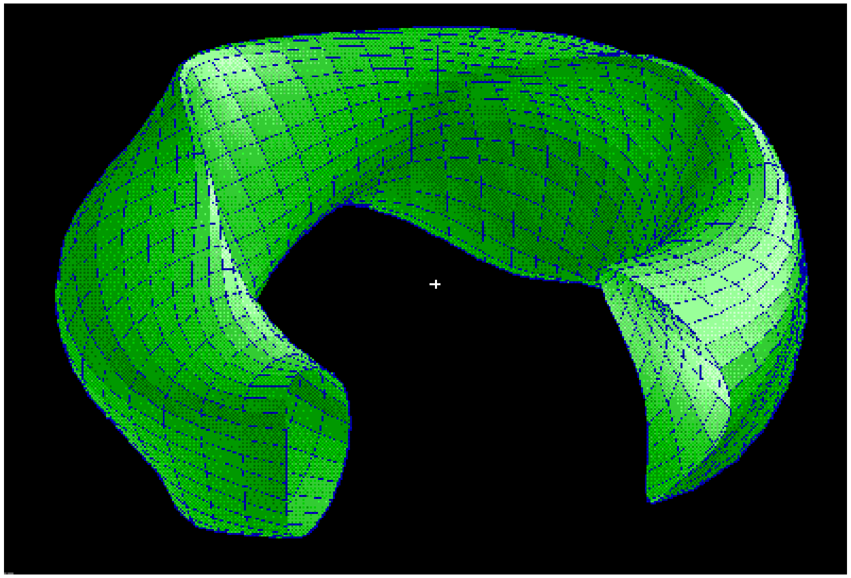
  $\Rightarrow$REDUCE SIZE AND COST OF EXPERIMENTS, REACTORS.

NCSX: NATIONAL COMPACT STELLARATOR EXPERIMENT

- R/<A> = 3.4,

- THEORETICALLY:
  $\beta \geq$ 4% STABLE TO BALLONING, NEO-TEARING.

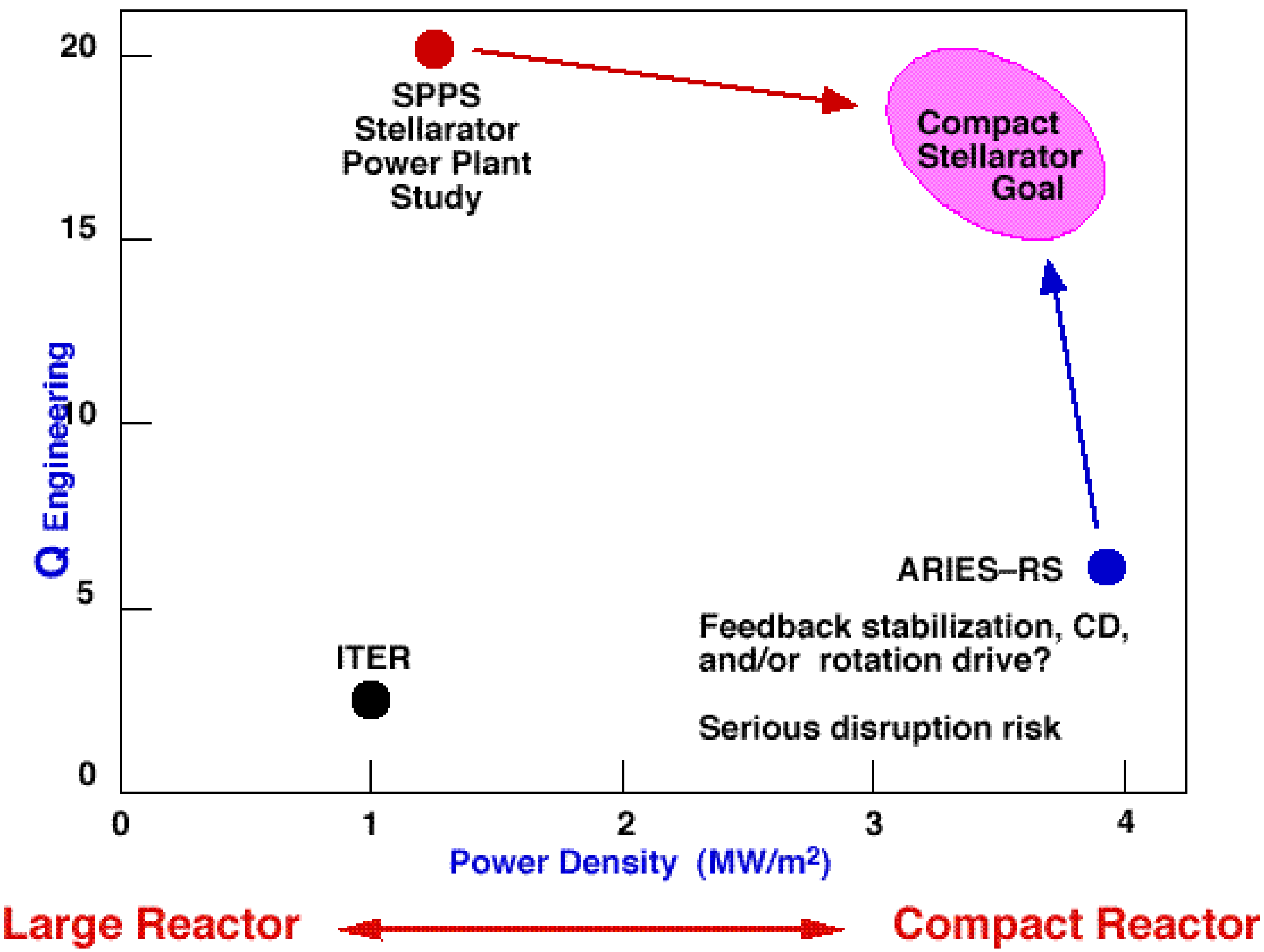
  STABLE TO EXTERNAL KINK WITHOUT CONDUCTING WALL, ROTATION, OR FEEDBACK $\Rightarrow$ SIMPLER.



- EXPERIMENT: TEST STABILITY, IMMUNITY TO DISRUPTIONS.

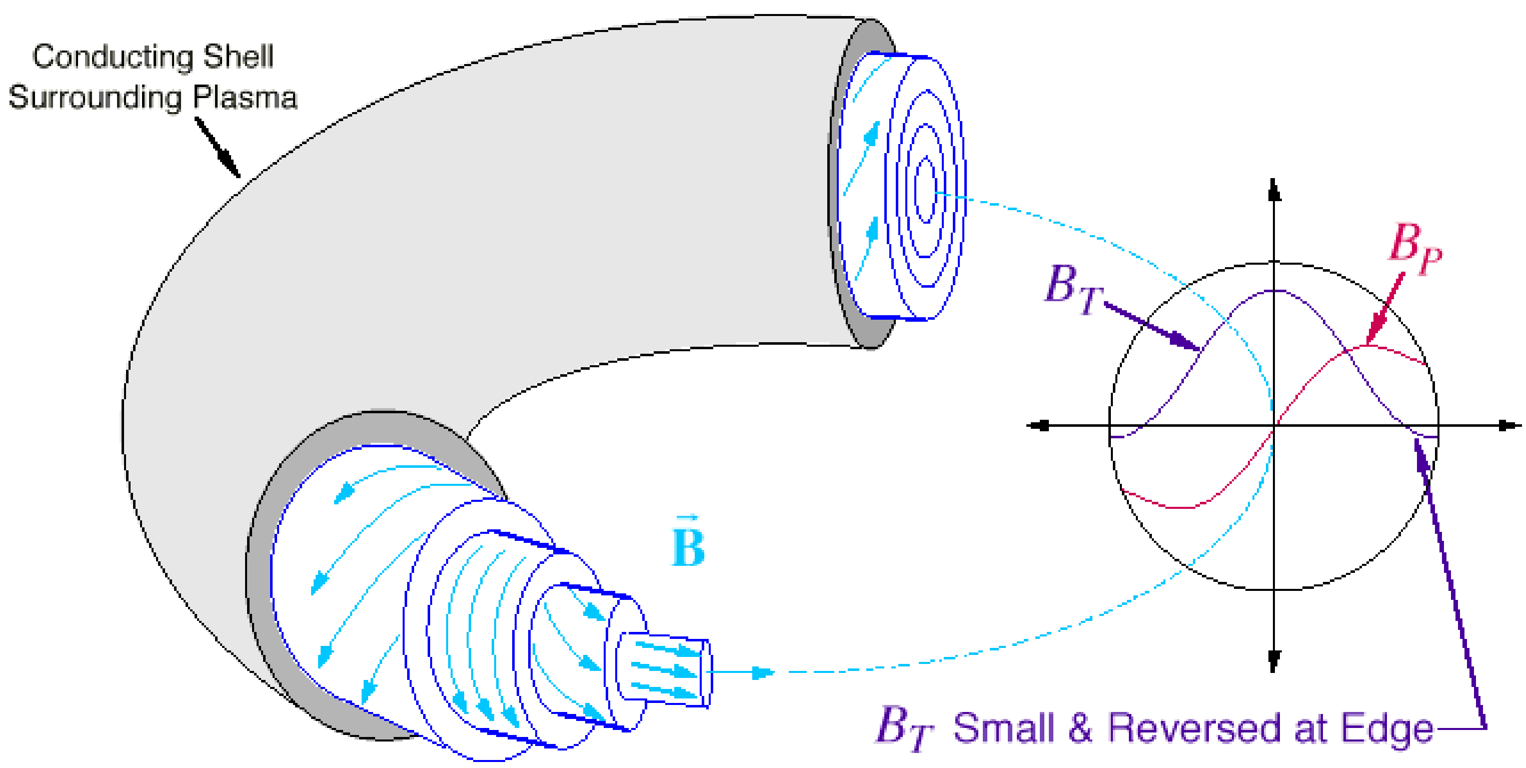
- PROPOSAL: BUILD RE-USING COMPONENTS OF AN EXISTING TOKAMAK.

The Compact Stellarator Could Combine the Best Features of Tokamaks and Stellarators

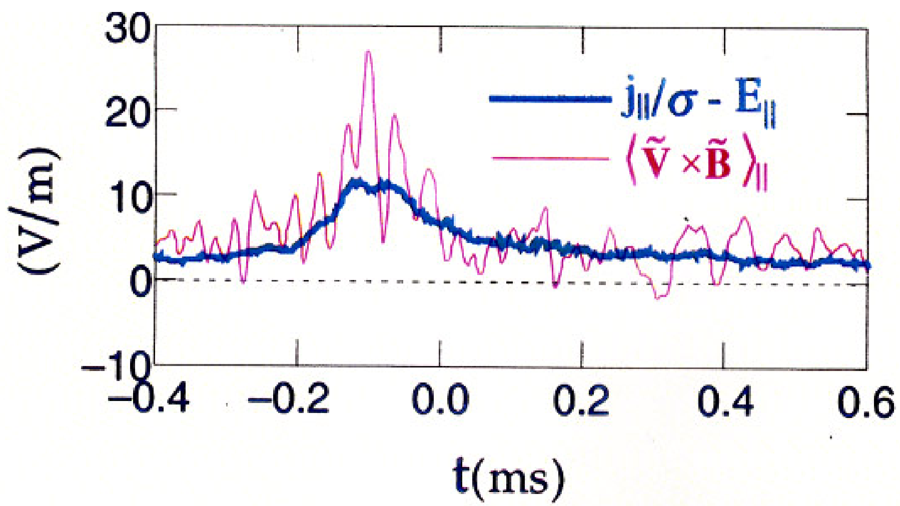


Reversed Field Pinch (RFP) Magentic Configuration

- toroidal field $B_T \approx$ poloidal field B_P
- large "magnetic shear" (field line twists >90° from center to edge)



Magnetic Fluctuations Drive Poloidal Current in a Reversed Field Pinch



Parallel Ohm's Law: $E_{||} + \langle \tilde{\mathbf{V}} \times \tilde{\mathbf{B}} \rangle_{||} = j_{||}/\sigma$

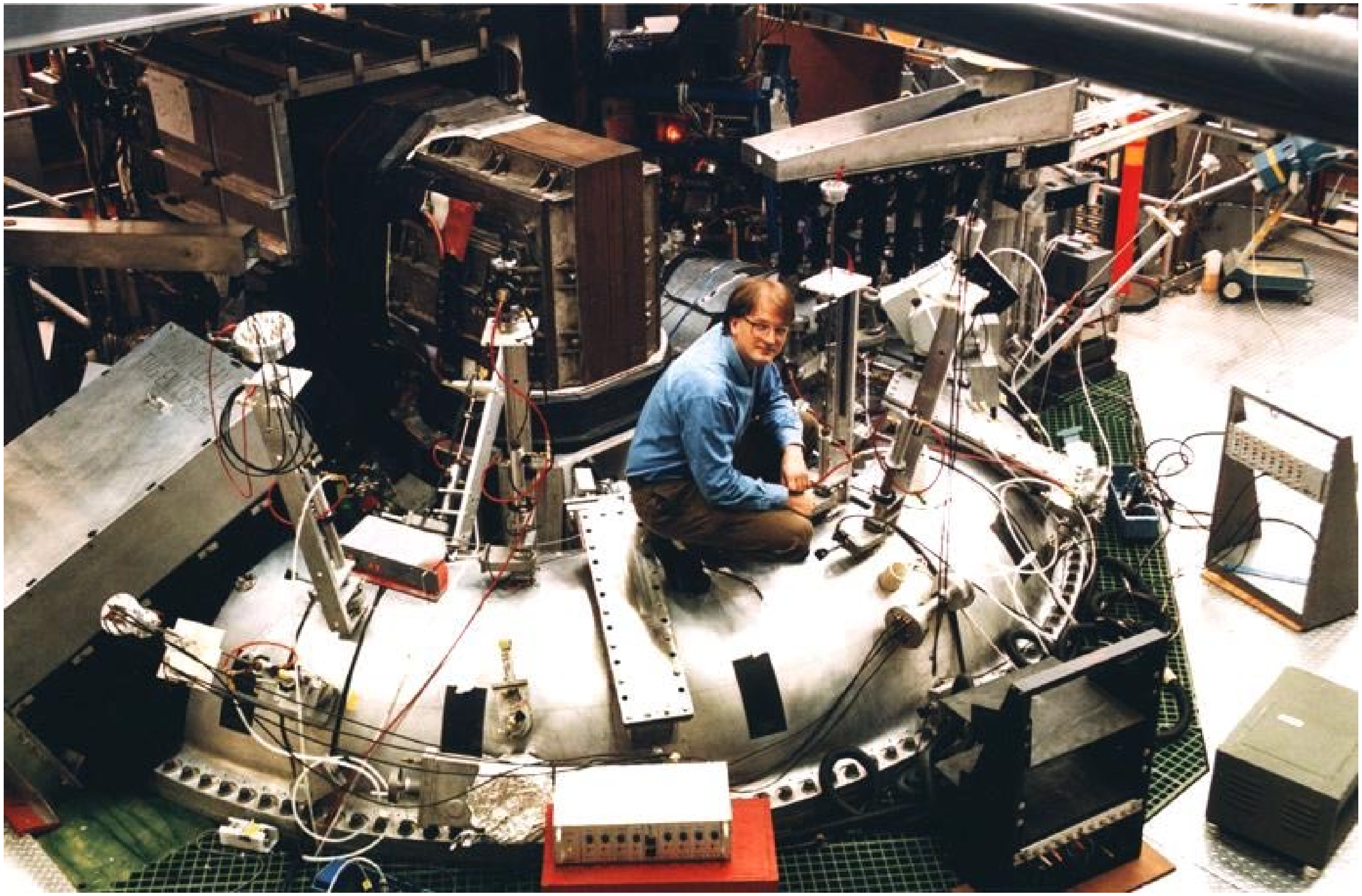
the dynamo term

Good agreement is obtained between theory and experimental measurements of the dynamo mechanism.

The Reversed Field Pinch

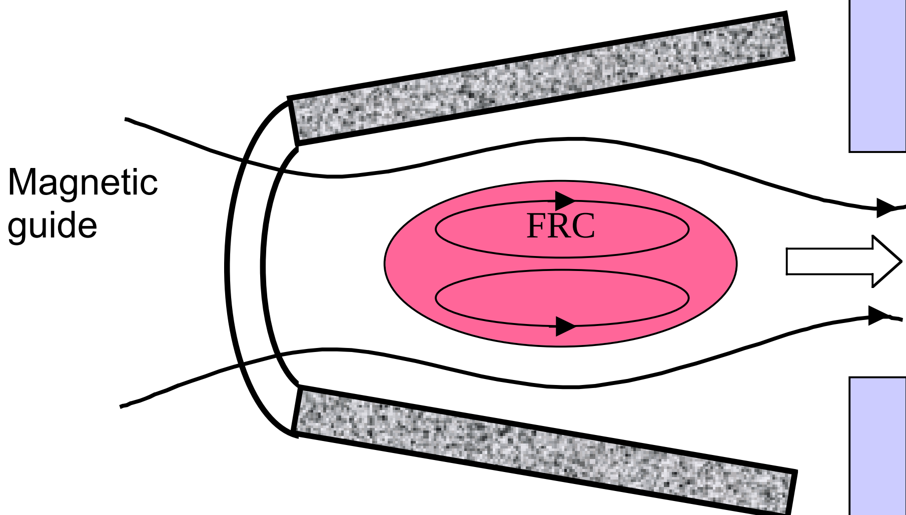
- **Key power plant advantage:**
  - **Weak magnetic field**
  - **(RFP ≈ tokamak with field reduced 10x)**
- **Physics consequence:**
  - **Strong magnetic turbulence**
  - **Large energy transport**
- **Possible solution:**
  - **Eliminate energy source for turbulence**
  - **Control current profile**
- **Initial results encouraging**
  - **Five fold confinement gain**
- **Proposal to increase diagnostics, current drive, plasma heating: concept exploration→ proof of principle**

Reversed Field Pinch

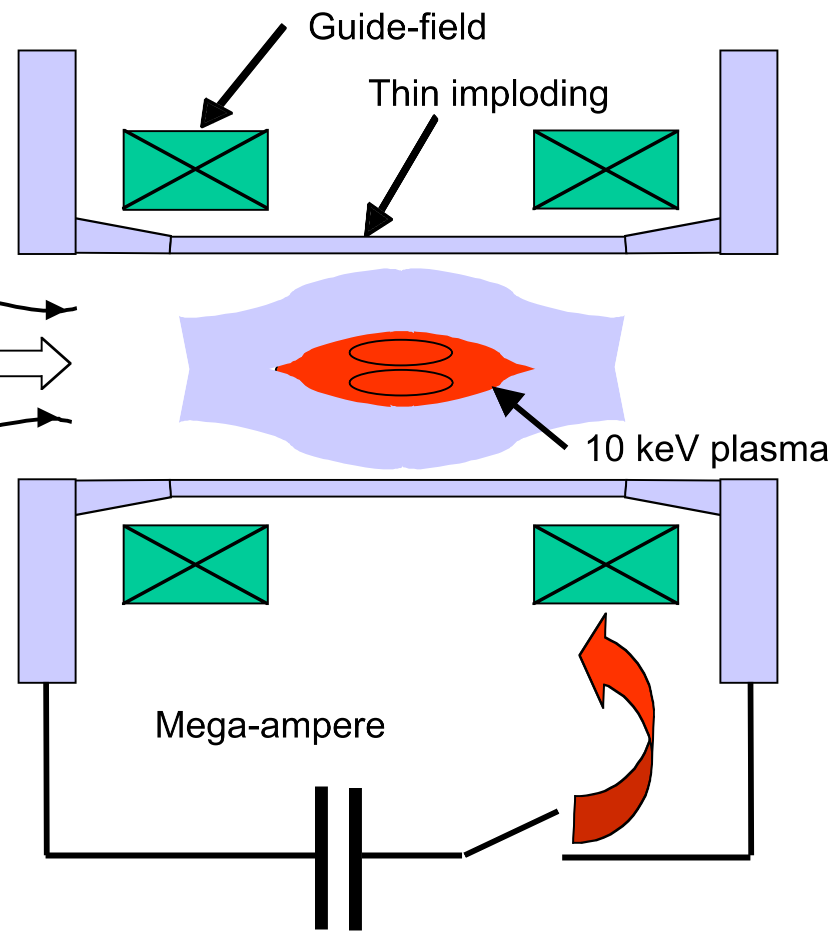


Elements of MTF

Plasma preheater and injector



Liner implosion system



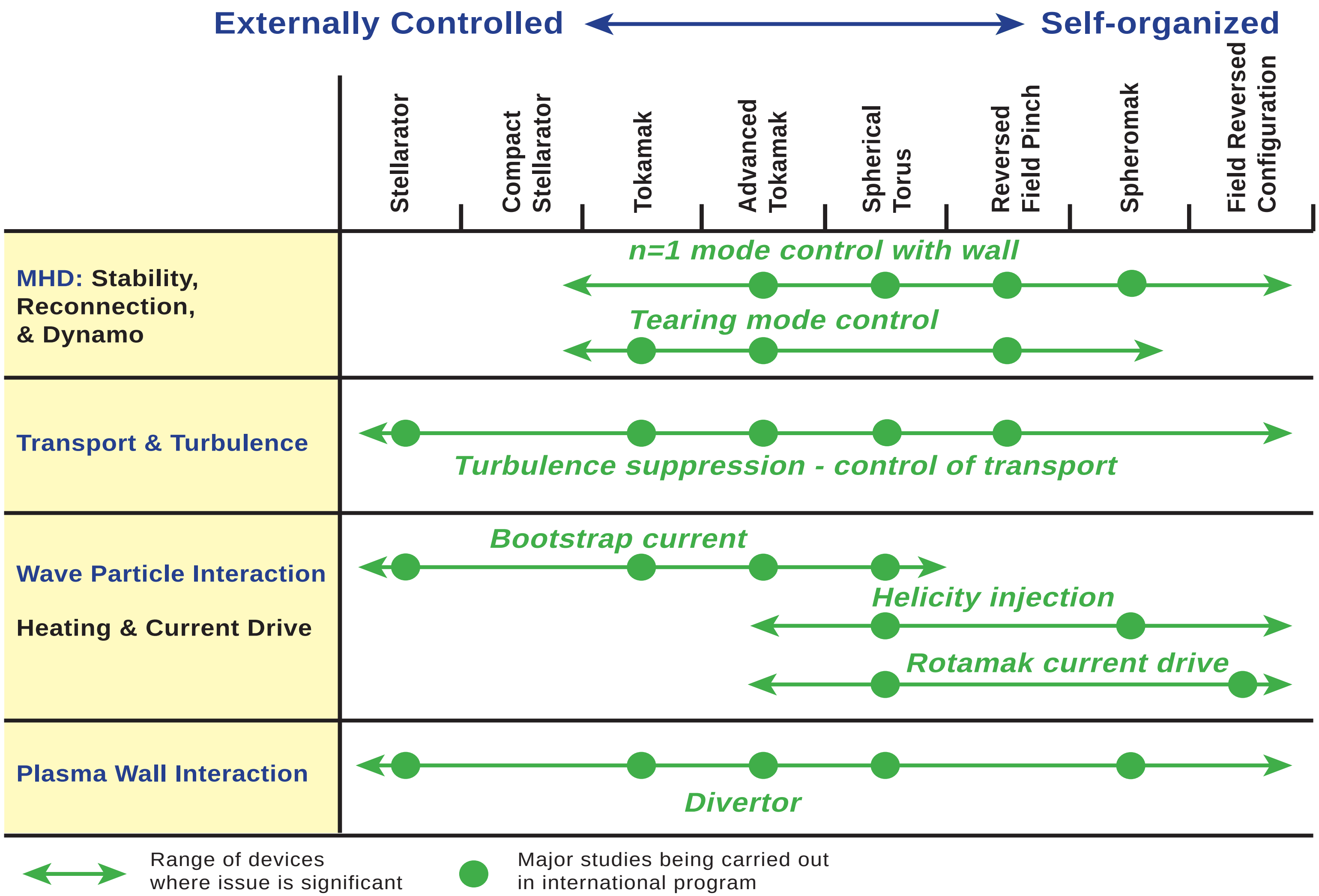
Typical parameters:

	Initial	Final
n	10^{17} cm^{-3}	10^{20} cm^{-3}
T	300 eV	10 keV
B	100 kG	10 MG

Magnetized Target Fusion Offers Significant Yield at Low Cost

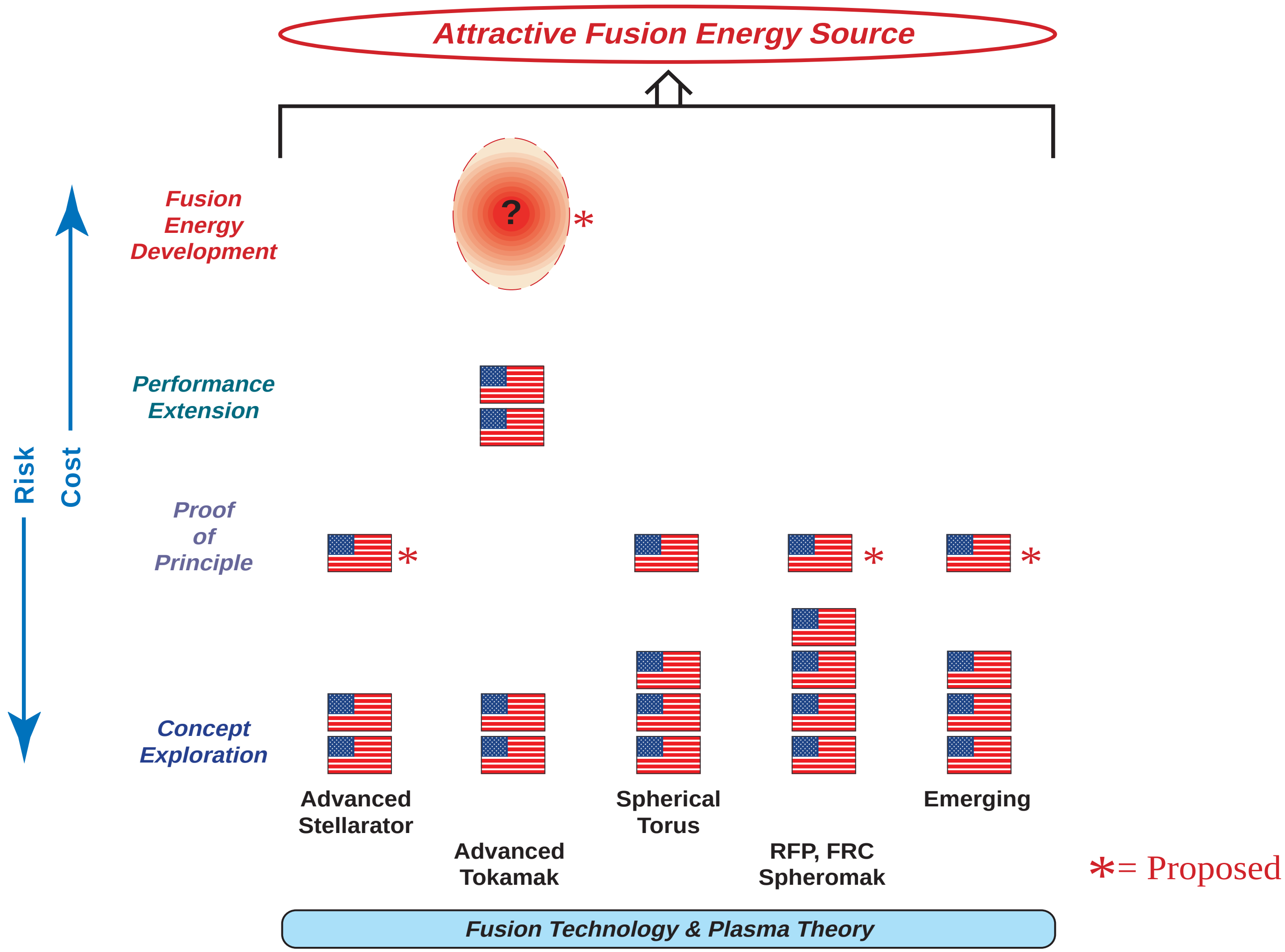
- Fuel density and time scale are intermediate between MFE and IFE; magnetic field is high.
  ⇒ Smaller than MFE, lower power than IFE.
- Can use pulsed-power Defense facilities that exist or are under construction.
  ⇒ \$B class facilities are not required for Q=1.
- Broadens scientific boundaries of MFE and IFE.
- Issues include stand-off and rep-rating, ultimate gain limitations in the absence of a "hot-spot."

Science Topics *vs.* Configurations



Magnetic Fusion Energy

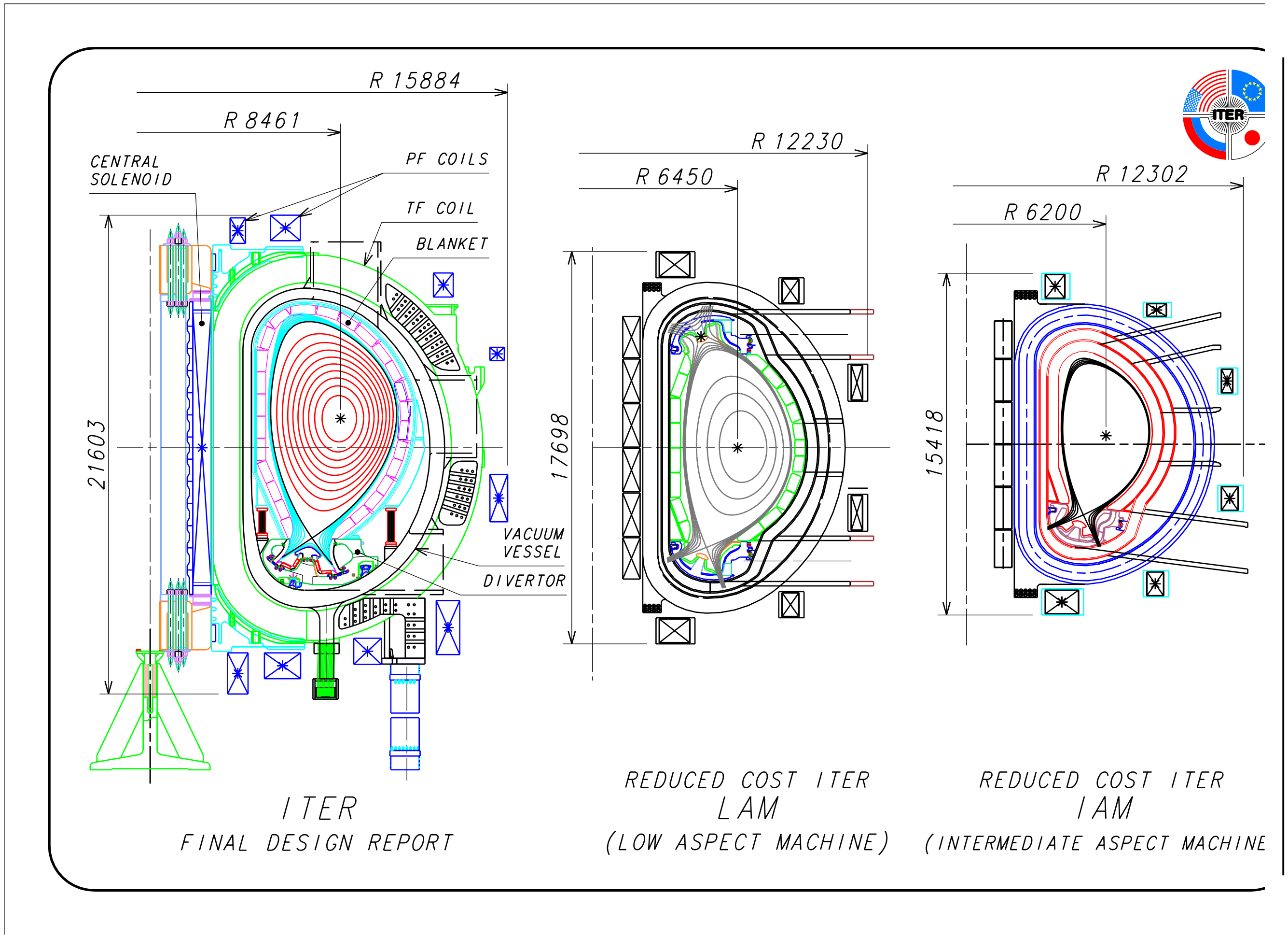
Present and Proposed U.S. MFE Portfolio



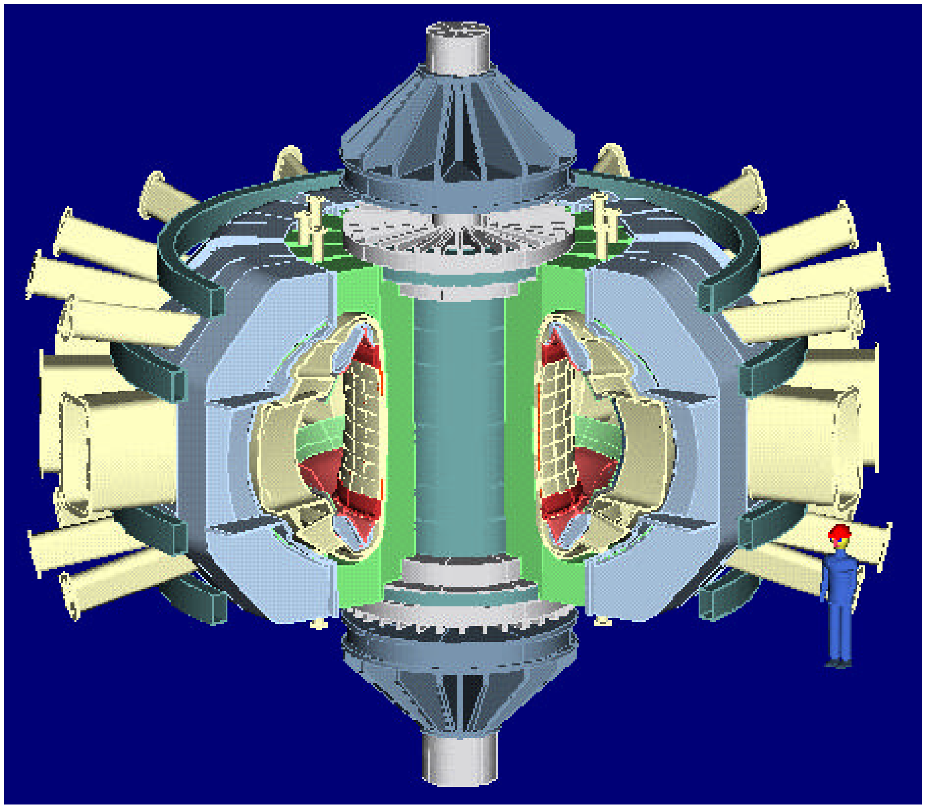
The Tokamak / AT is Technically Prepared for a High-Gain Test

- **The 3 ITER partners could decide (yes/no) on construction any time between 2001 – 2003.**
- **The U.S. should consider requesting LHC-like participation if the decision is yes.**
- **The U.S. should prepare alternative international approaches if ITER will not go forward.**

THE REDUCED-COST ITER HAS ADVANCED TOKAMAK FEATURES



A LIMITED-PULSE ADVANCED TOKAMAK BURNING PLASMA DEVICE SHOULD COST ~ $1B



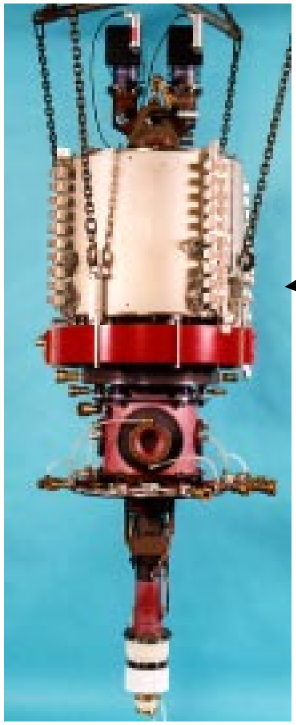
Design Goals

- R = 2.0 m, a = 0.525 m
- B = 10 T,
- I_p = 6.5 MA
- P_{fusion} ~ 220 MW
- Q ~10, τ_E ~ 0.55s
- Burn Time ~ 10s
- Total Project cost ~ $ 1B

ENABLING TECHNOLOGIES FACILITATE EXPERIMENTAL RESEARCH

- **Experimental research paced by availability of tools.**

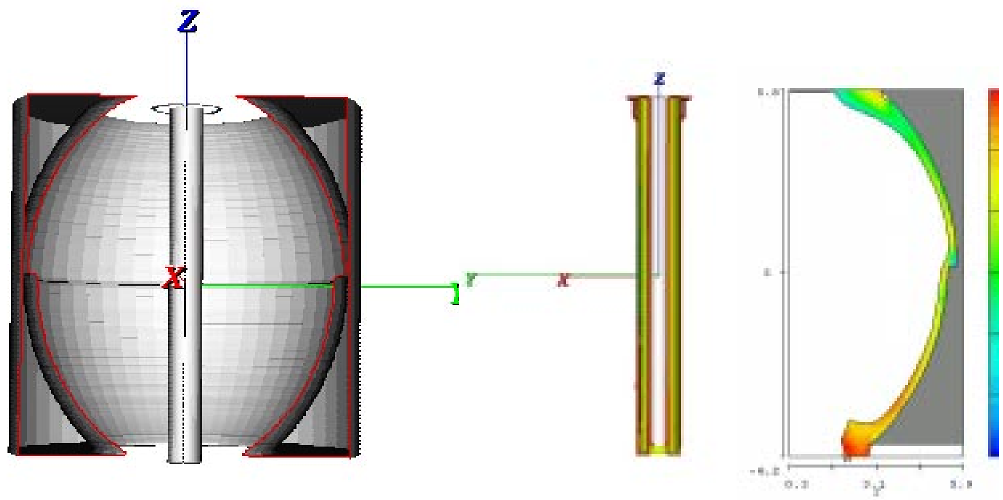
- **Some key areas:**
  - **Plasma heating and current drive**
  - **Fueling**
  - **Power handling**
  - **Plasma diagnostics**



1MW 110 GHz gyrotron with CVD diamond window for long-pulse electronic cyclotron resonance heating, developed through U.S. MFE Program

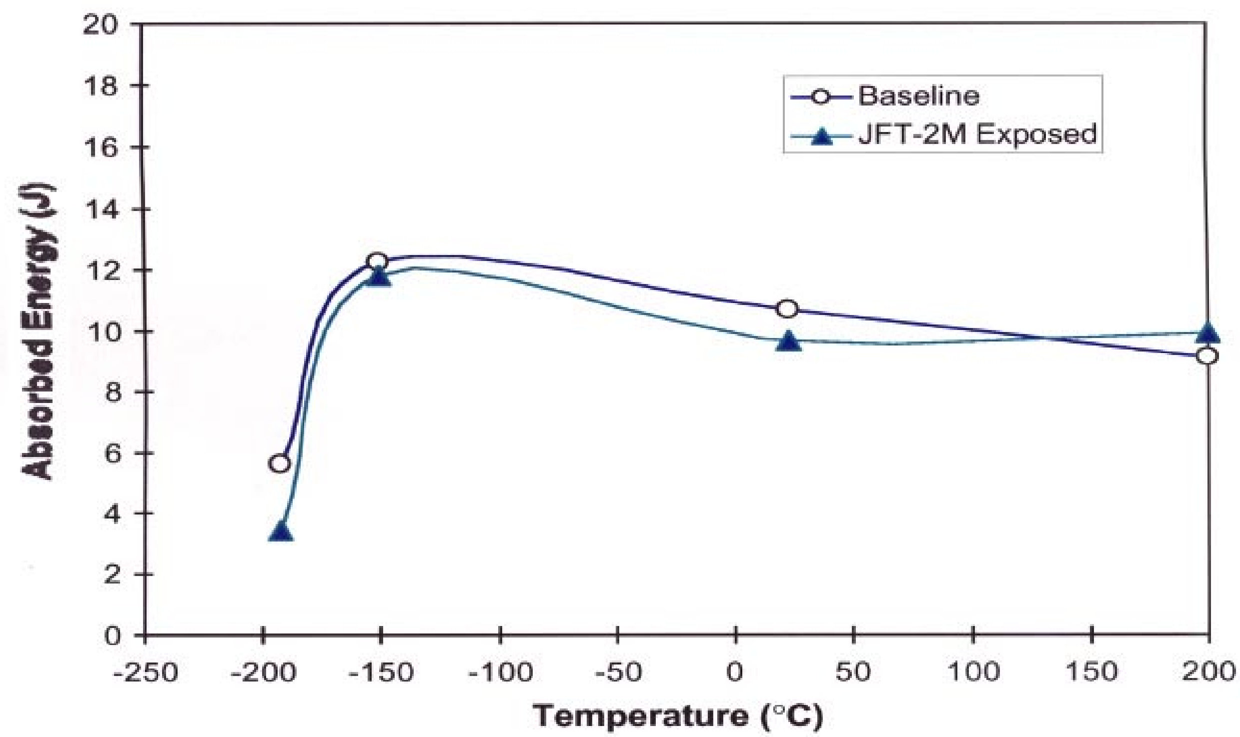
FUSION TECHNOLOGIES POINT TO INNOVATIVE APPROACHES

Flowing Liquid Wall Spherical Torus



- Flowing liquid walls may permit very high fusion power density.
- Wall-protection reduces need for low-activation structural materials.

Materials Development for Fusion

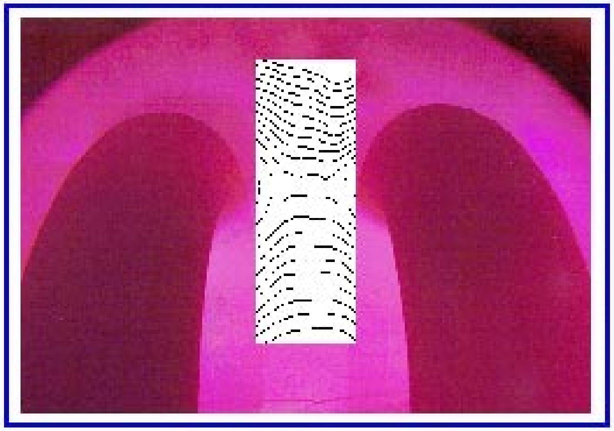


- **IMPACT PROPERTIES OF VANDIUM ALLOY ARE UNAFFECTED BY EXPOSURE TO TOKAMAK ENVIRONMENT.**

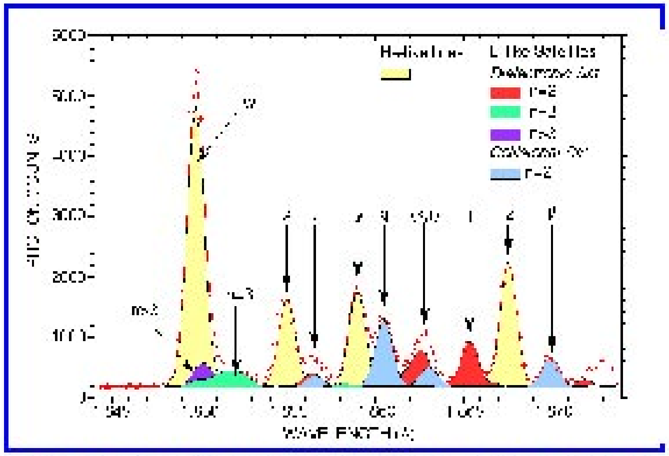
OUTLINE

- Fusion, Why and When?
- The Plasma Science of Magnetic Fusion
- The Magnetic Fusion Energy Portfolio
- Science and Technology Spin-offs
- Summary and Recommendations

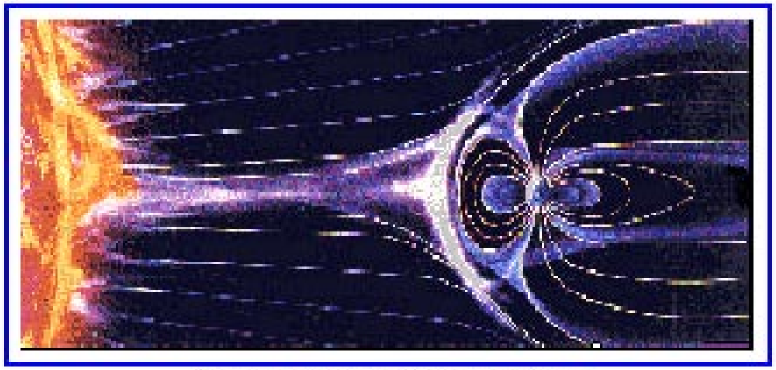
Some Science Spinoffs of Fusion



MAGNETIC RECONNECTION

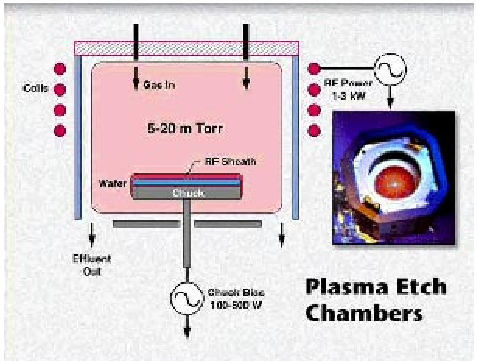


ATOMIC PHYSICS OF LINE RADIATION—IRON SPECTRUM
X-RAY CRYSTAL SPECTROMETER

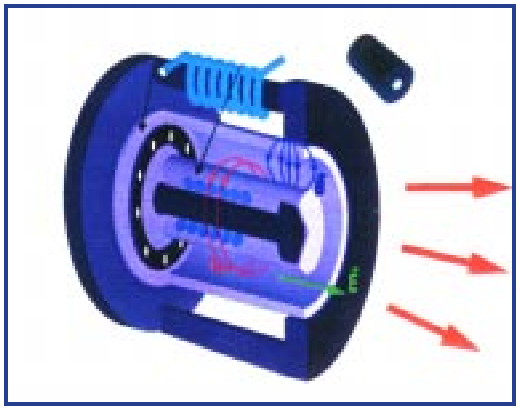


STUDY OF SOLAR WIND EFFECTS

Some Technology Spinoffs of Fusion



CHIP PROCESSING

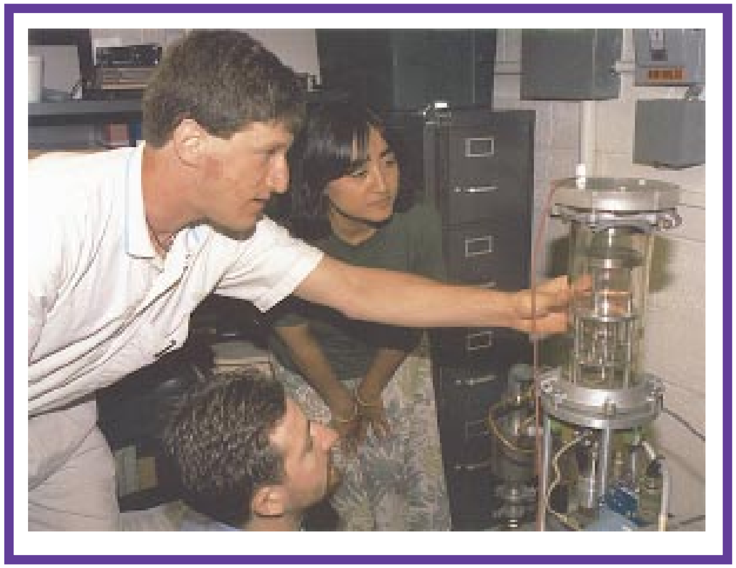


HALL THRUSTER

FLAT PANEL DISPLAY

ARC FURNACE

Education



Graduate Education

- 35 Research Universities involved in fusion research.
- Estimate >750 Ph.D's awarded.

- Science outreach to K-12 teachers and students nationally.
- National Undergraduate Fellowship Program 30 students/yr.

OUTLINE

- **Fusion, Why and When?**
- **The Plasma Science of Magnetic Fusion**
- **The Magnetic Fusion Energy Portfolio**
- **Science and Technology Spin-offs**
- **Summary and Recommendations**

SUMMARY OF STATUS

- **Dramatic advances have been made in all areas of fusion Plasma Science:**
  - **Macroscopic Stability**
  - **Wave-particle Interactions**
  - **Transport and Microturbulence**
  - **Plasma-wall Interactions**

- **A portfolio of synergistic and complementary confinement experiments is in place.**

2003 – 4 Will Present Opportunities

- The decision could be taken to construct an Advanced Tokamak burning-plasma experiment.

- The Spherical Torus could advance to Deuterium – Tritium Performance Extension.

- The new Proof of Principle experiments may show attractive paths forward.

- Existing Concept Exploration experiments may be ready to move to Proof of Principle.

To Prepare for Decisions in 2003-04 will Require Additional Funds

- **All existing facilities are underutilized.**
- **New PoP experiments require funding.**
- **Scientific Simulation (funded by SSI?),
Fusion Technology and Materials,
International Collaboration,
General Plasma Science and Technology.**
- **This new fusion roadmap provides the programmatic basis for increased support for fusion energy research.**

Conclusions and Recommendations

- **MFE research is making excellent progress, based on a synergistic portfolio approach.**
- **There are important opportunities for investment in MFE (and IFE).**
- **A budget increase to $300M/year**

  + $40M in MFE

  + $40M in IFE

  would prepare both programs to move forward aggressively, if the Nation so chooses, in 2003-4.

"The road to useful power from fusion may be a long one, but the commanding importance of the goal continues to arouse strong commitments."

"…the effort is to reach that plateau which the theorists have held out to us of high confinement under high temperature and relatively undisturbed conditions. … I have the impression that the promised land is virtually within sight. And on that basis one can be intelligently optimistic about the future, as I think many of us are."

Dreams, Stars, and Electrons, 1997
Lyman Spitzer, Jr.
Jeremiah Ostriker