"US Program and Process"

or

Why the Restructured Program "Science Focus & Energy Goal" is the Best Way Forward

Michael E. Mauel
Columbia University

Presented to NRC Burning Plasma Assessment Committee
January 18, 2003

➲ **Reinforce and expand upon your recommendation:**

"A **strategically balanced fusion program**, including meaningful U.S. participation in ITER and **a strong domestic fusion science program**, must be maintained, recognizing that this will eventually require a substantial augmentation in fusion program funding…"

We need a Knowledge Base of Plasma Science, Fusion Science, and Fusion Technology to reach Our Goal of Economically and Environmentally Attractive Fusion Energy Source

- Advance plasma science
  ➠ Fundamental Understanding
- Explore fusion concepts and fusion technologies
  ➠ Optimization of the Fusion System
- Pursue fusion energy and fusion technology as a partner in the international effort
  ➠ Create and Understand Burning Plasma and Develop Fusion Materials and Technology

Our "science focus" supports new ideas, attracts and encourages young scientists, and contributes to and benefits from the larger science community.

A burning plasma experiment opens a new frontier in our research but should not cause change in program mission or strategy.

Outline

- **The events and reasoning leading to the 1995 Restructured Fusion Energy Science Program**
  - Parallels (and differences!) exist between early 90’s and today
  - Today’s fusion strategy combines both **energy AND science** goals, and (I believe) this strategy should not change with a burning plasma experiment
- **Optimizing fusion system through a portfolio approach**
  - Plasma behavior depends upon magnetic topology Different topologies have behaviors both common and different necessary for understanding
  - Source of innovation that drives optimization and attractiveness of energy goal
  - Links fusion research to the related and fundamental sciences
- **Some examples of energy AND science of the US “core program” (However, I am unable to cover IFE and technology programs.)**
- **Closing remarks**

Historical Context (I)

- **Bush Administration (July, 1991) announces National Energy Strategy calling for demonstration of fusion energy in about 35 years.**

- **FEAC (1992) concludes DEMO by 2025 requires a "robust national program" supported by a "national commitment to the goal of fusion". Additionally…**
  - The [balanced] national program should have three elements:
    - Vigorous research base in theoretical, computational, and experimental plasma physics, in fusion technology, materials, and reactor systems studies
    - [Full] operation of existing confinement facilities
    - Addition experiments for confinement-concept improvement research, for studies of long-pulse plasma behavior, and for the testing of candidate reactor materials
  - *Funds needed:* 5% real increase above 338M$93/year ***plus*** an increment for ITER construction and the international program.

Historical Context (II)

- **Desire to move forward with burning plasma experiment conflicted with budgetary constraints…**
  - Record 1992 budget deficit > $300B, "Contract with America", calls heard to reduce or dismantle DOE, 1993 Penny-Kasich (defeated), …
- **Resulting in premature efforts to narrow fusion research and force an "either energy/or science" decision…**
  - S.646: International Fusion Energy Act of 1993 (altered in conference)
    - Purpose: redirect and refocus the Department's magnetic fusion energy program in a way that will lead to ITER by 2005…and operation of a fusion DEMO by 2025…. Eliminate those components not directly contributing to ITER or to DEMO. Provide for reducing the program to $50M/year in the event that the [ITER] program is terminated.
  - Dr. Martha Krebs (*Science,* 1994):
    "The fusion program is in a period of major transition from a program focused on research to one focused on engineering development, from a laboratory and university base to an industry base, from a domestic program to an international program."

Historical Context (III)

- **Many voices called for reason and balance in fusion and plasma science research:**
  - Overwhelming community response against S.646: UFA, Fusion Coalition, …, and call for a balanced fusion program.
  - Prager/UFA: "We wish to sound a clear alarm… The proposed [energy] restructuring would severely retard progress in fusion." The famous three points: "(1) ITER is a major milestone, but it will likely not by itself provide sufficient information to proceed to a practical reactor. (2) Additional research of equal importance is essential. (3) The time scale for fusion demands a strong and innovative research effort in addition to ITER."
- **1995 NRC Report calls for reinvigoration of plasma science, for coordinated support of basic plasma science, and for aggressive support of academic research.**
- **1995 PCAST strongly supports fusion and defines key priorities as**
  - **Strong core program** in plasma science and fusion technology (domestic)
  - Ignition and burn experiment (international)
  - Low activation materials program (international)

Elements of Restructured Program

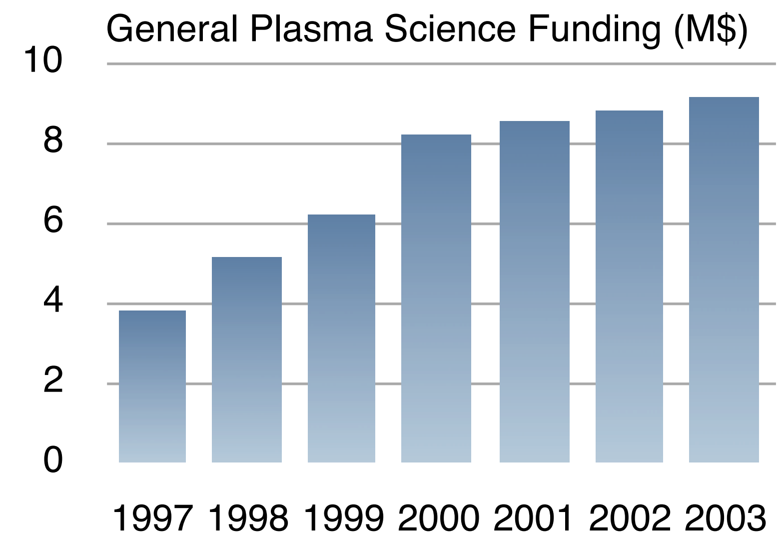
- New mission formalizes fusion's traditional strength:
  Advance the knowledge base needed for attractive fusion
- Three policy goals define a domestic science and technology program that ***broadly impacts the nation today*** and that contributes to ***the longer-term international energy goal***:
  - Advanced plasma science (and act as a steward for basic plasma science)
  - Develop fusion science, technology, and confinement innovations as the central domestic theme and strength
  - Pursue fusion energy and technology as a partner in the international effort
- "Science Focus and Energy goal"
- Robust:
  - Mission does not change with funding level, but (obviously) …
  - Sets no time schedule without a source of sufficient international funds

New Strategy Resulted in Real Change

- Significant direct support for general plasma science and university infrastructure.
- Encouragement of *two-way interactions with related fields* of science and engineering.
- Establishment of *national teams* to coordinate expertise to investigate key questions using *theory and computation, small and large experiments, new plasma control tools, …*
- Facilitate workshops to develop consensus; promote "Idea forums."
- Competitively review initiatives for new experiments, new research, and *opportunities (i.e. $$) for new ideas.*
- ***Many new starts (!)***: 14+ small, "high risk/high benefit" exploratory experiments and three new larger programs (ST, RFP, and Stellarator) having experiments capable of investigations with "fusion relevant" parameters.

Growing Support for General Plasma Science

- Funds for general plasma science increasing (Goal = 12.9M$, 5%)
- NSF/DOE Partnership
- 18 young faculty awards (theory, simulation, experiment, space, basic, astrophysics, HEDP)
- Peer review for all research programs
- New initiatives for theory and simulation
- Working for new plasma science centers

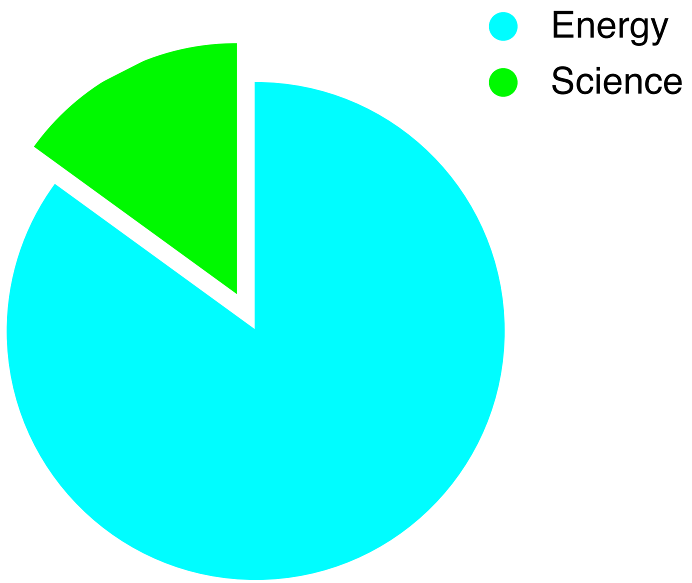


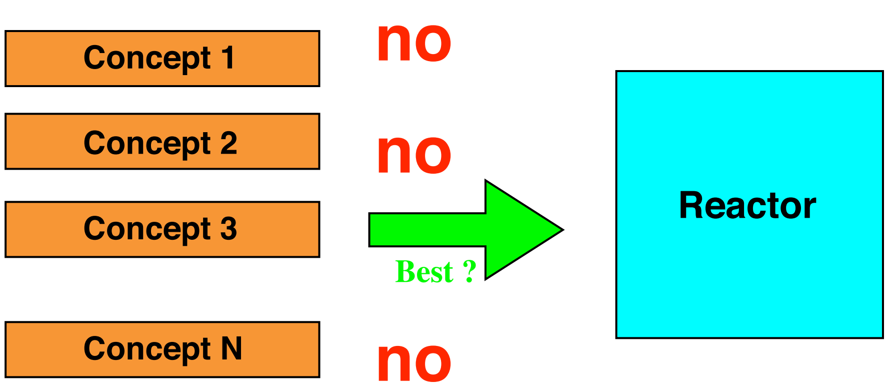
18 New Faculty Awards:

1997	Scott Parker (Colorado), Andrew Ware (Montana), Bruno Bauer (Nevada-Reno), Michael Brown (Swarthmore), Earl Scime (West Virgina)
1998	Matthew Stoneking (Lawrence), Richard Fitzpatrick (Texas)
1999	Christopher Watts (Auburn), George Tynan (UCSD)
2000	David Newman (Alaska), Ambrogio Fasoli (MIT), Eric Blackman (Rochester)
2001	Benjamin Chandran (Iowa), Thomas Killian (Rice), Eric Held (Utah State)
2002	Troy Carter (UCLA), Thomas Pederson (Columbia), Carl Sovinec (Wisconsin)

New Paradigms Describe Fusion Energy Science R&D

Old

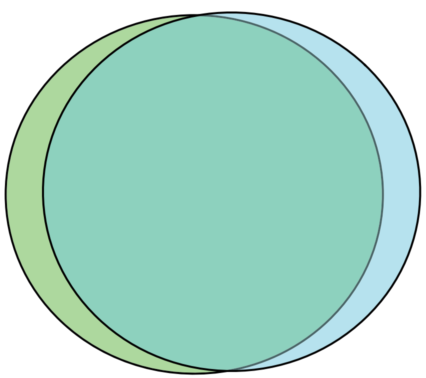




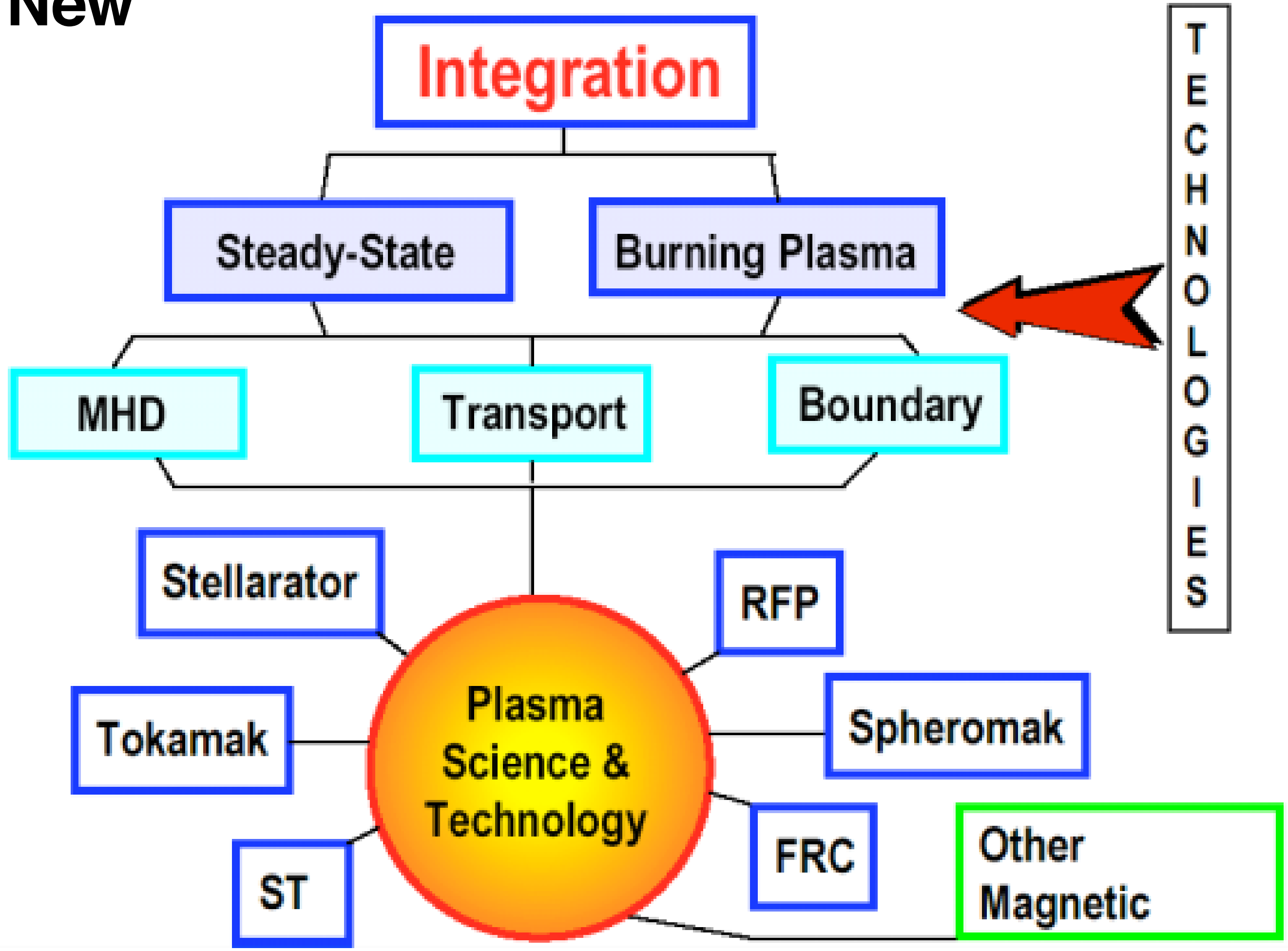
Judge fusion concepts for "reactor relevance"
Focus quickly through process of elimination

New Paradigms Describe Fusion Energy Science R&D

Energy AND Science



New



Study fusion concepts to develop required “knowledge base” Complementarity and Commonality in Concepts

Science Focus Receives Broad Support

- **1999 Snowmass: "Opportunities and Directions in Fusion Energy Science" examined "key issues" and how to address them for *all* elements of the fusion program.**
    - Science: Pursue the challenging yet realistic goal of developing comprehensive predictive models well-tested against experiment
    - MFE: Strong complementary and commonality between confinement configurations needed to answer key physics questions

- **2000 NRC FuSAC:**

  "Increasing our scientific understanding of fusion-relevant plasmas should be **a central goal** of the U.S. fusion program on a par with the goal of developing fusion energy technology…"

    - Scientific Progress and the Development of Predictive Capability (Ch. 2)
    - Plasma Confinement Configurations (Ch. 3)

  *Recommends a roadmap for fusion showing the path to answer fusion's **major science questions** and the relationship between these questions and development of concepts within the portfolio.*

Two over-arching themes have emerged from the MFCWG discussions

Across Magnetic Concepts and Across Scientific Disciplines

- Physics Understanding and Predictive Capability to Develop the Scientific Basis for Fusion Energy
  - Allows (fosters) commonality across concepts and levels of development
  - Transferability of physics learned from one magnetic concept to another
  - Rapid development of concepts (possibly skipping a level)
  - Opportunity to reduce the cost of fusion energy development

    Optimal design of experiments/facilities— rapid development
- Development and employment of plasma control tools
  - Scientific Understanding
  - Performance optimization
  - Innovative technological and scientific solutions

    ⇒ Partnership between technology & physics

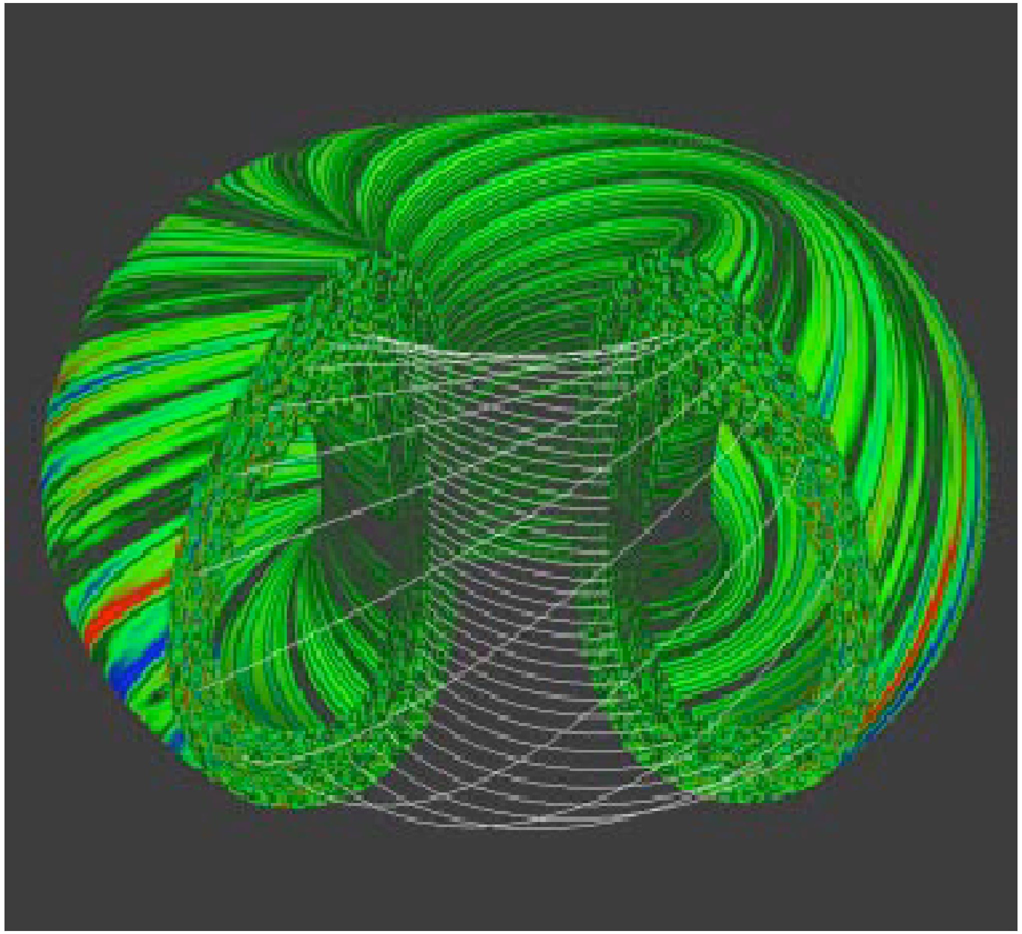
Goal 1: Comprehensive transport models

- Pursue the challenging, yet realistic goal of developing comprehensive predictive transport models, based on physically reasonable assumptions and well-tested against experiments

- Several models reproduce core T(r) with 15-30% RMS accuracy in some regimes. More comprehensive simulations needed for a wider variety of regimes and more accuracy.

- Relatively complete simulations are becoming feasible (with non-adiabatic electrons, electromagnetic fluctuations, realistic geometry, edge recycling ...).

[Added: Diagnostics capable of required resolution]



Numerical Tokamak Turbulence Project

Burning Plasma Experiment is part of a Science AND Energy Fusion Program

- **2002 Snowmass**

“The study of burning plasmas…is at the frontier of magnetic fusion energy science [and] the next major step in magnetic fusion research…, essential to **the science focus and energy goal** of fusion research.”

“The study of burning plasma will be carried out as part of a program that includes advancing fundamental understanding, theory and computation, and optimization of magnetic confinement configurations.”

“A **strong base science and technology program is needed** to advance essential fusion science and technology and to participate effectively in, and to benefit from the burning plasma effort. … The [portfolio] would benefit from a tokamak BP.”

- **FESAC Burning Plasma Plan**

“A burning plasma program is needed as a crucial scientific element…”

“A burning plasma experiment would be an integral part of the fusion energy sciences research program. … ”

“A strong core science and technology goal is essential to the success of the burning plasma effort, as well as the overall development of fusion energy.”

Necessity for a Portfolio Approach to MFE

- Fundamental element of plasma confinement is the magnetic flux tube. Confinement results when fields are wrapped onto a torus (magnetic surface), connected as closed rings, or plugged with parallel electric fields. Typically, all three types of flux tubes coexist within a confinement configuration.

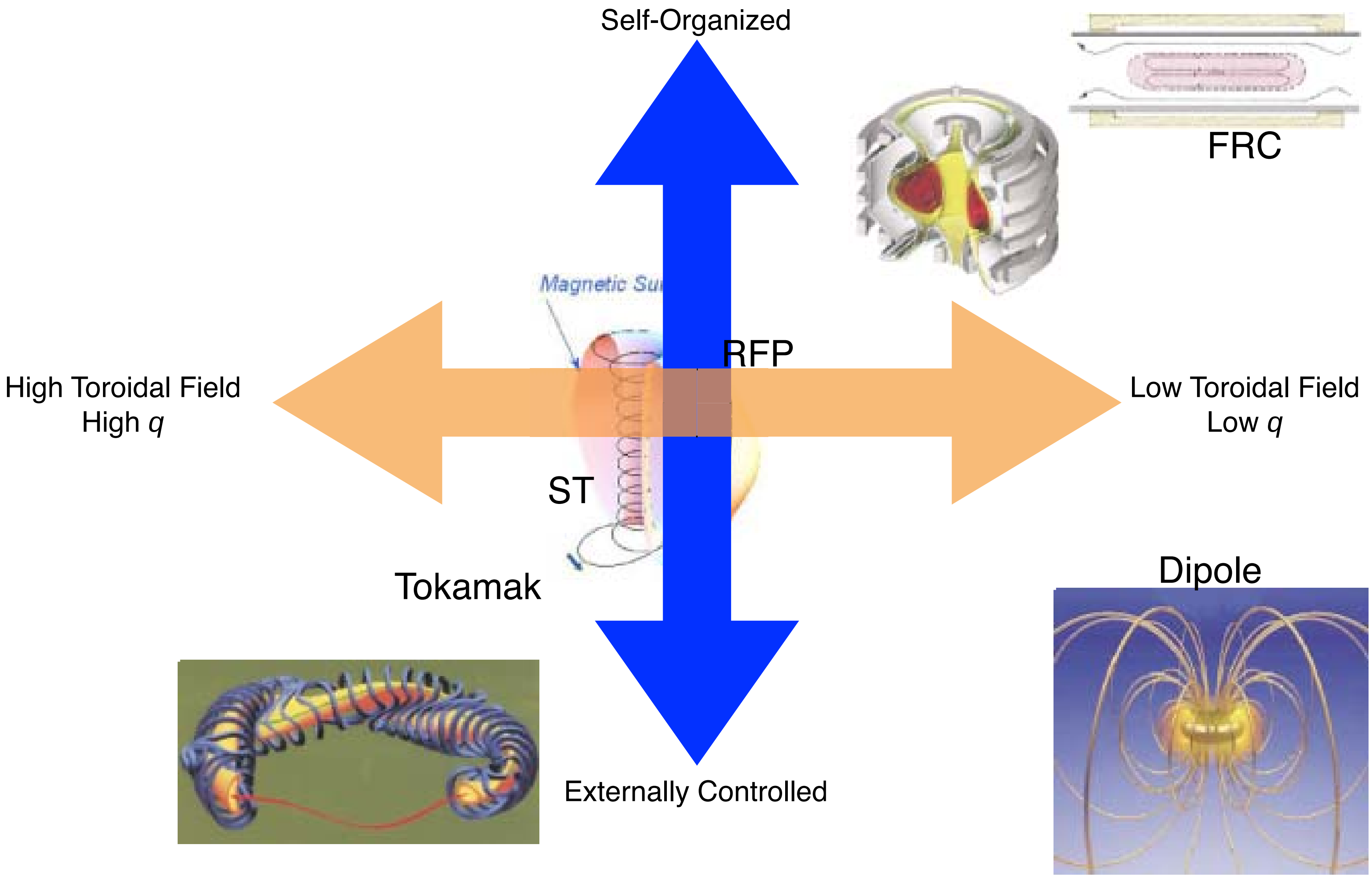
- Dynamics of a flux tube depends sensitively on the topological arrangement of the magnetic field (*e.g.* rotational transform, curvature, average magnetic well, symmetry). Furthermore, confined plasma requires self currents that alter the magnetic configuration.

- The portfolio approach aims to develop a predictive understanding between the the (challenging!) study

- Burning plasma physics as a science step (as well as an "energy step") aims to predict the result of self-heating on any confinement configuration.

- The logic for a tokamak BP experiment is not based on our selection of the tokamak as the final or most desirable fusion concept. (It's based on readiness.)

Magnetic Configurations



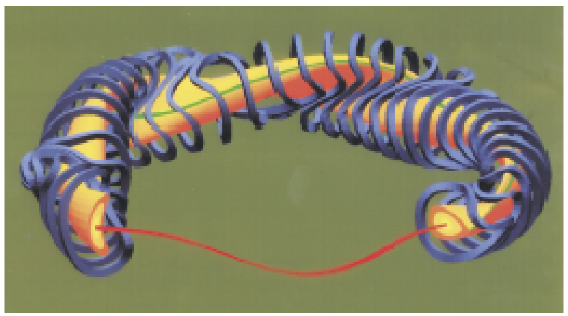
Different Configurations Test Complementary Regimes

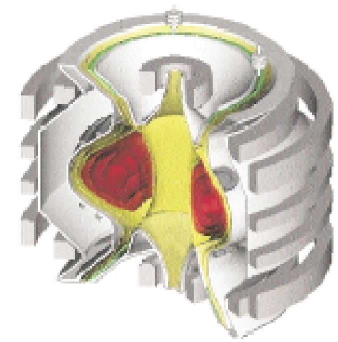
Example: Helical Lines Nested Surfaces

Externally-Imposed Fields
$B_T/B_p >> 1$; $q > 1$

Self-Organized Fields
$B_T/B_p \leq 1$; $q < 1$

Stellarator | Tokamak | RFP | **Spheromak**





Stellarator:

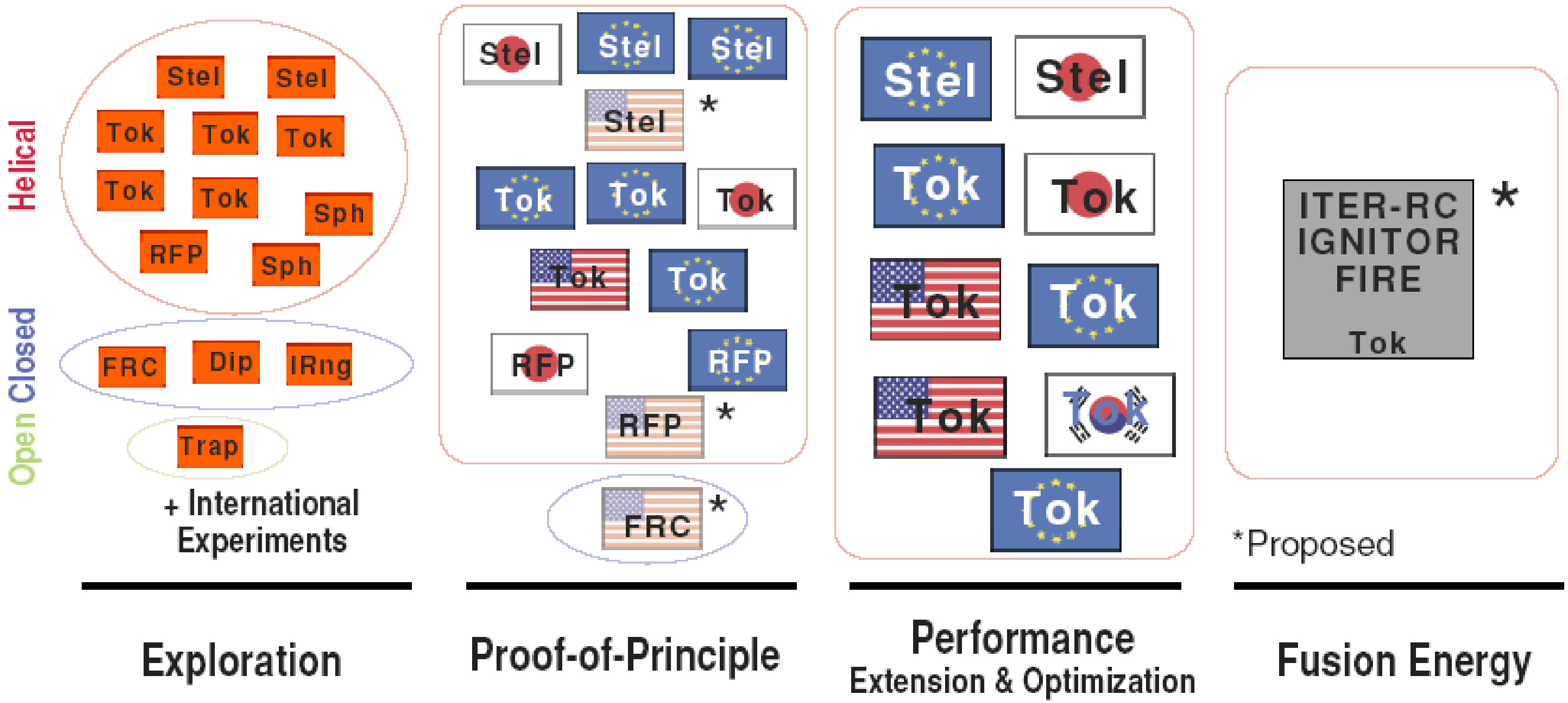
(–) Large applied field ($B^2/2\mu_0 >> P$);
(++) Robustly stable magnetic topology;
(+) Does not require wall stabilization;
(++) Strong fields produce good confinement;
(++) Steady state;
(+) Relatively simple startup;
(– –) Coils link plasma;
(– –) Relatively low power density;
(–) Superconducting magnets;
(–) Divertor flux trapped within coils;
(–) Large aspect ratio, large size; ...

Spheromak:

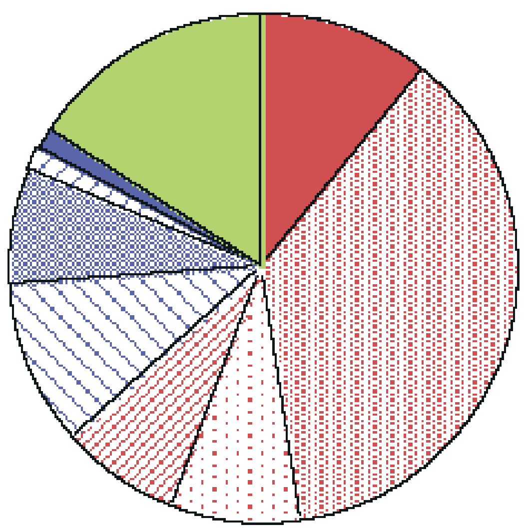
(++) Small applied field ($B^2/2\mu_0 \geq P$);
(– –) Magnetic topology requires sustaining significant plasma current;
(–) Requires wall stabilization;
(– –) Self-generated fields driven by magnetic turbulence;
(–) Relatively complex startup;
(++) Simple coils;
(++) Potentially high power density;
(+) Large divertor flux expansion;
(+) Small aspect ratio, small size; ...

(with "personal" judgements of potential value)

(1999) Today's Experimental Portfolio

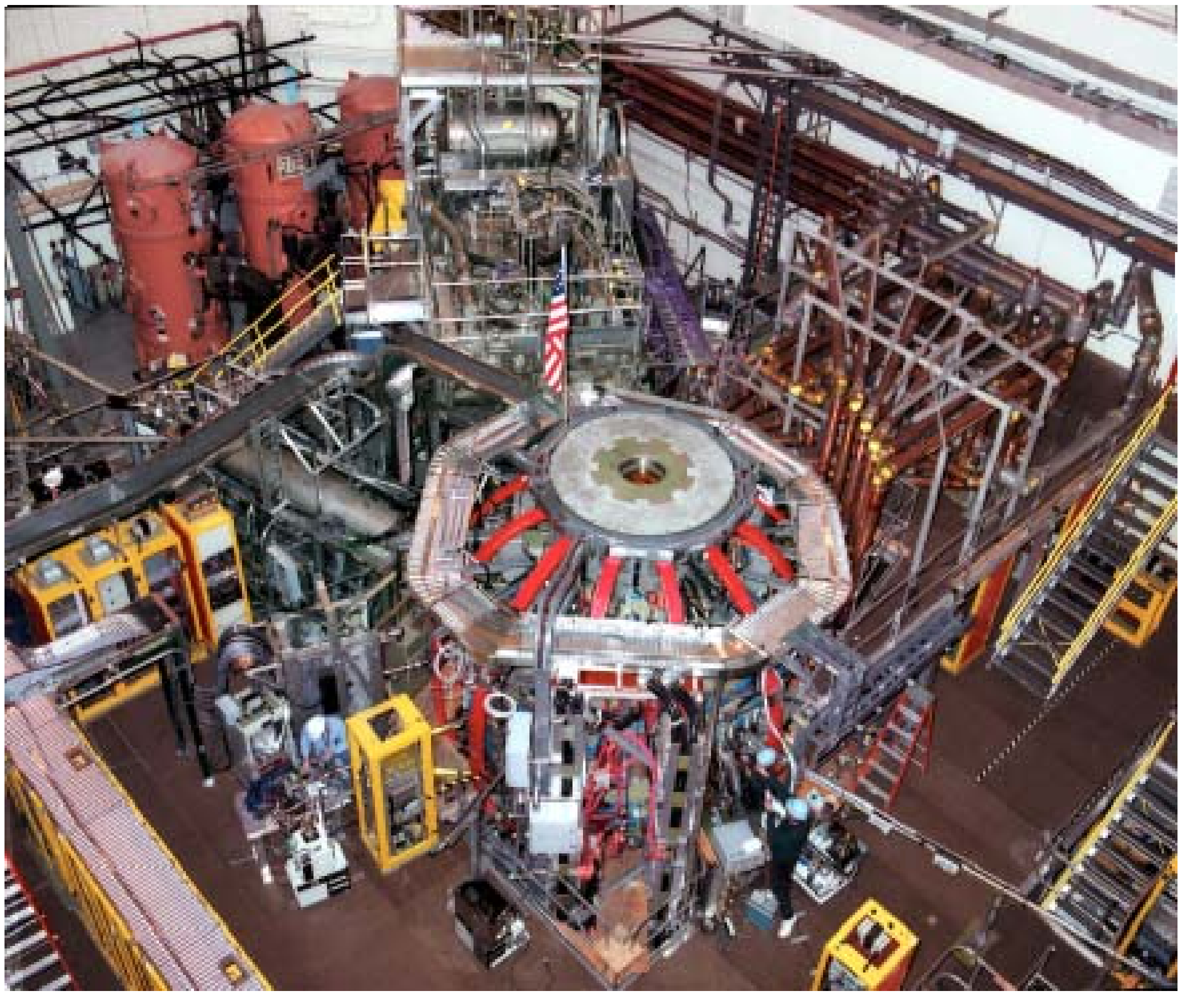


Nuclear Fusion Supplement 1991 World Survey of Activities in Control Fusion Research (IAEA, Vienna)



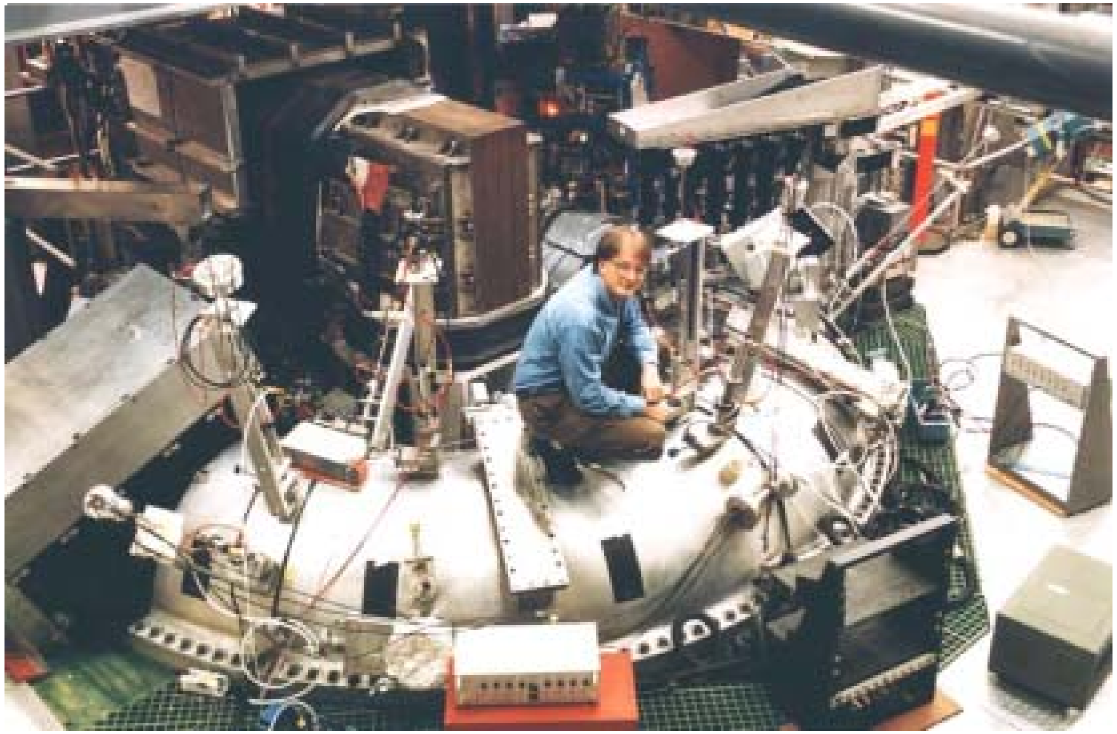
Stellarator	23 experiments in 6 countries
Tokamak	79 experiments in 25 countries
RFP	18 experiments in 5 countries
Spheromak	16 experiments in 6 countries
Other Pinch	23 experiments in 16 countries
FRC	16 experiments in 9 countries
E/I-Ring	3 experiments in 3 countries
Int Ring	3 experiments in 3 countries
Mirrors	23 experiments in 6 countries

NSTX Spherical Torus



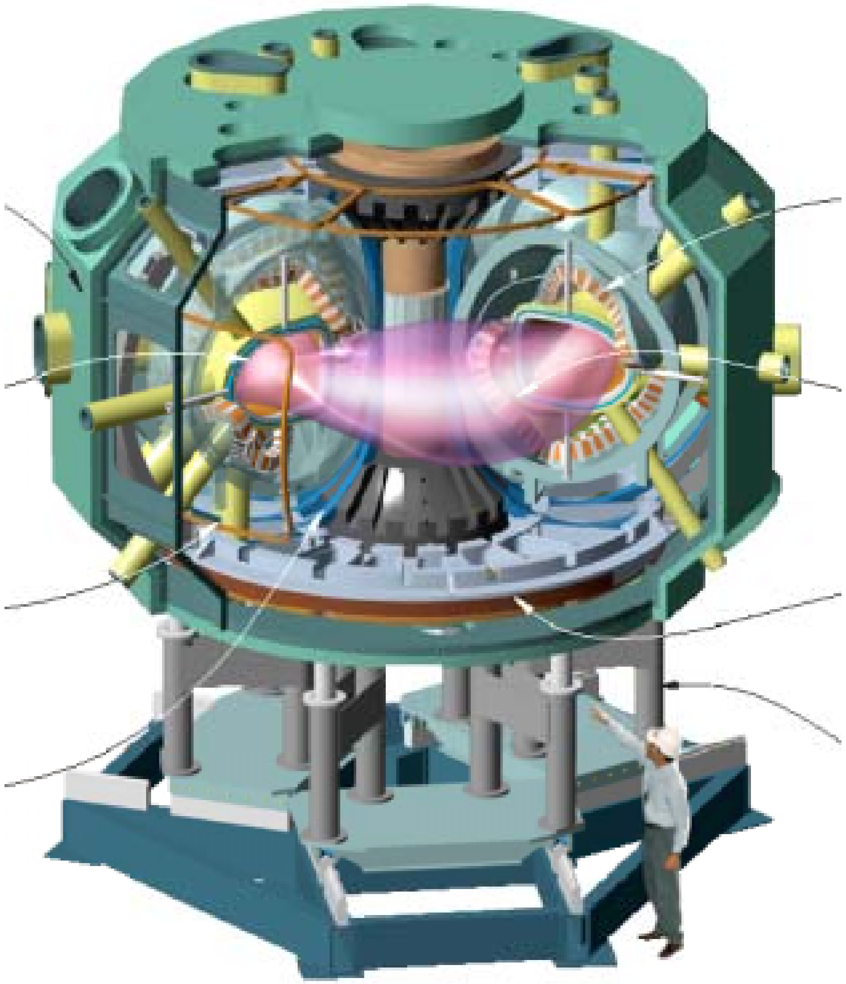
- Understand transport and stability at very high beta
- Explore potential for steady-state currents
- Explore noninductive startup
- Fusion benefits: compact, low-field, low-cost. Improved maintenance.

MST Reversed Field Pinch



- Reduce magnetic turbulence through current profile control
- Develop current-drive or effective pulsed scenarios
- Fusion benefits: Reduced costs from low toroidal field

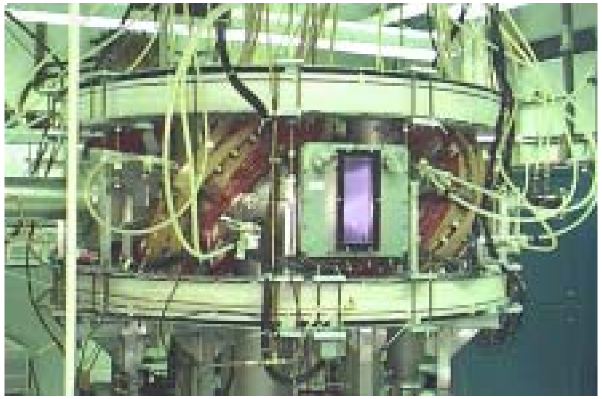
NCSX Compact Stellarator



- Systematic studies of rotational transform and shear effects on ideal, resistive and kinetic (fast-ion) instabilities.
- Adjustable transform
- Determine beta-limit and confinement at low-aspect ratio
- Fusion benefit:
  Stable, steady-state operation with good plasma confinement, low disruption loads, and low recirculating power for plasma sustainment and control.
- Benefits from tokamak experience.

"Smaller" Exploratory Experiments

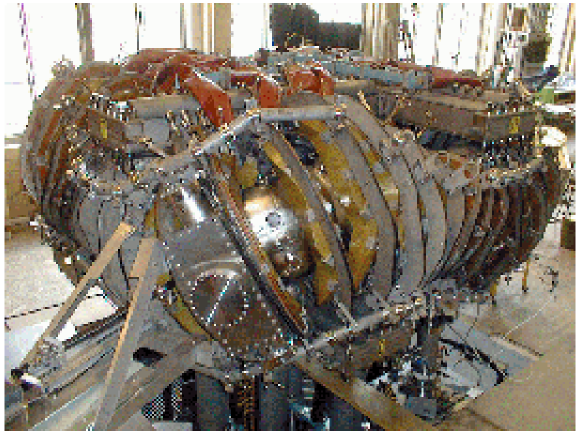
- Innovation and exploration: Search for new approaches with potential for "high benefit" to science and/or energy goals.
- Themes: Very compact size, reduced tritium fusion fuels, compatibility with novel technologies (liquid walls), high-leverage physics (strong flows)
- Open competitive selection process; often has strong educational components; often has focused research objective
- Can address key issues not possible in larger facilities.



Compact Torsatron (Auburn)

Includes Stellarators, Tokamaks, STs, RFP, Spheromak, Strong Flows, Novel Pinches, Dipole, FRC, …
(Facility Costs range from 1-5$M)

Helicity Injection Torus-II (Washington)



Helical Symmetry Experiment (Wisconsin)

Fusion Science "Success" Stories

- PCAST 1997 presentation
- NRC FuSAC 1999 presentation
- Last month's PRLs

"Typical" Examples from the Fusion Core Program

(PCAST 1997: Impact of small, focused experiments)

- **Understanding neoclassical bootstrap current**

  In 1971, theorist at the U.K. and U.S.S.R. predict pressure gradients of a collisionless plasma drive current.

  First seen in a toroidal octupole (Zarnstorff and Prager, *PRL* 1984); Observed next in TFTR (Zarnstorff, *et al.*, *PRL* 1988); and becoming essential for the steady-state advanced tokamak.

- **Understanding stability limits and confinement improvement**

  In 1981-84, as tokamaks were heated with high-power NBI, (1) global instabilities appeared causing rapid plasma flows to the walls, and (2) the cross-field leakage of energy and particles grew worse.

  Theory and experiments (ASDEX, 1982) motivated "specialty" experiments at Columbia (HBT, 1986), MIT (Versator, 1988), UCLA (CCT, 1989); Later, national team conducted experiments that modified both current and pressure profiles in DIII-D to simultaneously improve stability and create edge and central transport barriers (Lazarus, *et al. PRL* 1996). [*Added*: confinement improvements due to $\mathbf{E} \times \mathbf{B}$ flow shear seen in Heliotron-E (*PRL*, 1996) and RFP (*PRL*, 1998).]

- **Observations of planetary magnetospheres motivate new exploration of energy and particle confinement in dipole**

Using the Portfolio to Find Common Physics and National Teams

(FuSAC 1999)

VOLUME 82, NUMBER 18 PHYSICAL REVIEW LETTERS 3 MAY 1999

Empirical Similarity of Frequency Spectra of the Edge-Plasma Fluctuations in Toroidal Magnetic-Confinement Systems

Tokamaks (JET, JT-I) & Stellarators (WVII-AS, JT-IU)!

M. A. Pedrosa,[1] C. Hidalgo,[1] B. A. Carreras,[2] R. Balbín,[1] I. García-Cortés,[1] D. Newman,[2] B. van Milligen,[1] E. Sánchez,[1] J. Bleuel,[3] M. Endler,[3] S. Davies,[4] and G. F. Matthews[4]

[1]Asociación EURATOM-CIEMAT, 28040-Madrid, Spain
[2]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-8070
[3]Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85740 Garching, Germany
[4]JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, United Kingdom

VOLUME 82, NUMBER 19 PHYSICAL REVIEW LETTERS 10 MAY 1999

Direct Observation of the Resistive Wall Mode in a Tokamak and Its Interaction with Plasma Rotation

A. M. Garofalo,[1] A. D. Turnbull,[2] M. E. Austin,[3] J. Bialek,[1] M. S. Chu,[2] K. J. Comer,[4] E. D. Fredrickson,[5] R. J. Groebner,[2] R. J. La Haye,[2] L. L. Lao,[2] E. A. Lazarus,[6] G. A. Navratil,[1] T. H. Osborne,[2] B. W. Rice,[7] S. A. Sabbagh,[1] J. T. Scoville,[2] E. J. Strait,[2] and T. S. Taylor[2]

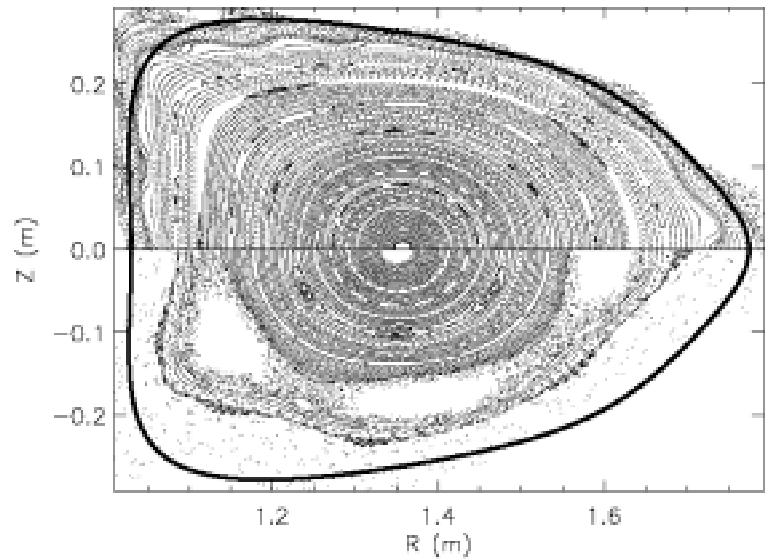
[1]Columbia University, New York, New York 10027
[2]General Atomics, San Diego, California 92186-5608
[3]The University of Texas at Austin, Austin, Texas 78712
[4]University of Wisconsin, Madison, Wisconsin 53706-1687
[5]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543
[6]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
[7]Lawrence Livermore National Laboratory, Livermore, California 94551-9900

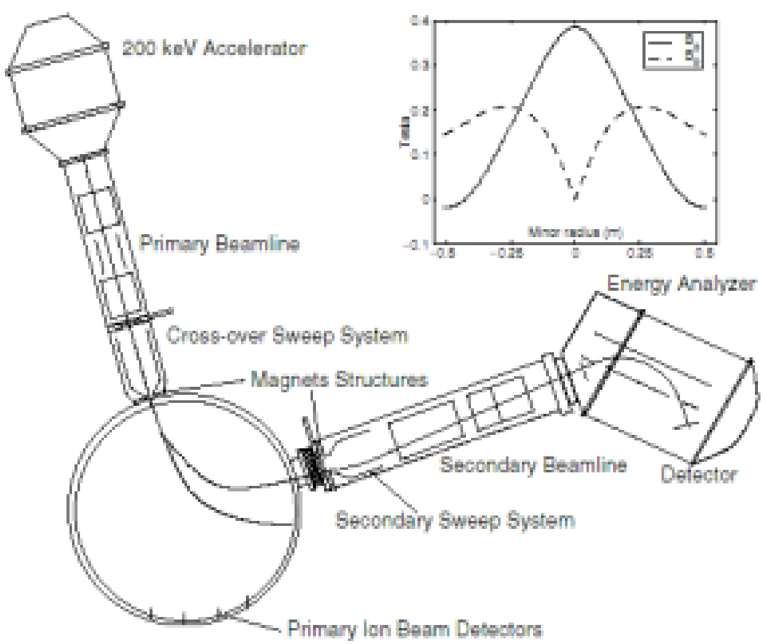
National Teams!

Recent PRL's

(NRC BP 2002)

- "Eliminating Islands in High-Pressure Free-Boundary Stellarator …Solutions," PRL, 12-30-02.
- "Core Electrostatic Fluctuations and Particle Transport in a Reversed-Field Pinch," PRL, 12-30-02.
- "Observation of Coherent Sheared Turbulence Flows in the DIII-D Tokamak," PRL, 12-23-02.
- "Generation of Noninductive Current by Electron-Bernstein Waves in the COMPASS-D Tokamak," PRL, 12-23-02.
- "Comparison of a Low- to High-Confinement Transition Theory with Experimental Data from DIII-D," PRL, 12-23-02.





Some Last Words

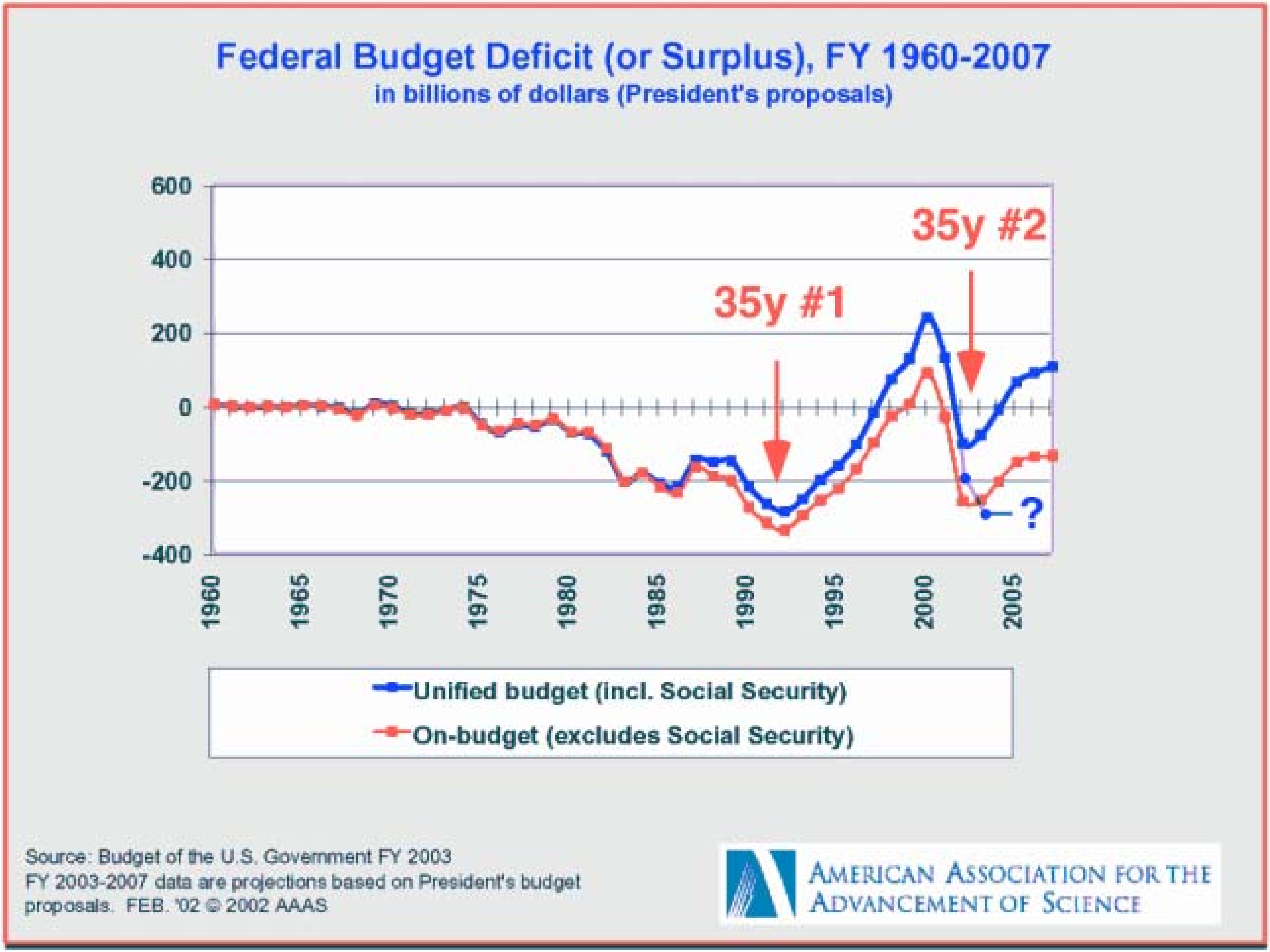
- Our progress improving *and understanding* confinement and stability of magnetized plasma has been truly spectacular.
- Much of this progress has resulted from the “core program,” including small and large experiments, sophisticated diagnostics and plasma control tools, research teams that focus collective expertise to answer challenging questions, theory and simulation, ….
- Fusion is not at the end of its learning curve.
- New ideas and discoveries will occur—essential to the attractiveness of both fusion energy as a power source and fusion energy science to students.
- A burning plasma experiment opens a new frontier in our research but does not change the program mission or strategy.
- Strong consensus for burning plasma next step as a frontier science should not be misinterpreted as acceptance of the tokamak as the best reactor. (We need a portfolio for energy too!)
- This importance of the core program increases as our national commitment to fusion energy grows. The value of the burning plasma program both contributes to and rests upon the knowledge and the scientific infrastructure generated by the core program.

Back to the Future?

- **Today, as was the case true before, fusion is at a crossroad…**
  - Opportunity exists to create and explore a burning plasma.
  - The world-wide need for clean, carbon-free energy is real.
  - The exciting prospect of net fusion power is motivating calls for "fast-track" energy development.
  - Fusion energy development remains **expensive** and requires additional breakthroughs that (I believe) are wholly likely.

- **But, this time, things are different…**
  - Wide acceptance of the "science focus" needed for fusion energy research.
  - By way of developing our "knowledge base", we have a proven record that knowledge innovation better fusion system.
  - We're older and wiser (?)

Growing Federal Deficits may have Negative Impacts on Science Funding



We must not abandon Science for Energy

Dr. J. Marburger (18 November 2002):

"The closer we are to a transition from a fusion science program to a fusion device engineering program, the easier it will be to create favorable economic conditions to accelerate the practical implementation of fusion power."

Response:

- *The burning plasma next step is at the* ***scientific frontier****. Transition to a fusion engineering program is only possible* ***after*** *the burning plasma experiment… so let's do the burning plasma step NOW!*

"We need to understand how a burning plasma program will potentially shift the focus and direction of the Fusion Energy Sciences Program and what aspects of the program will need to change."

Response:

- *The burning plasma program* ***opens new directions*** *and* ***expands*** *the focus of our research, but it is still too early to shift from science!*
- *Questions of the optimal fusion system will become more urgent as we proceed with a burning plasma experiment.*