
The Future of Energy on Ea
is the Energy of the
FUSION

U.S. Fusion Energy Sciences Program

Presented to the

Secretary of Energy Advisor Board
Task Force on Fusion Energy

By

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Associate Director
for Fusion Energy Sciences
Office of Science
Department of Energy

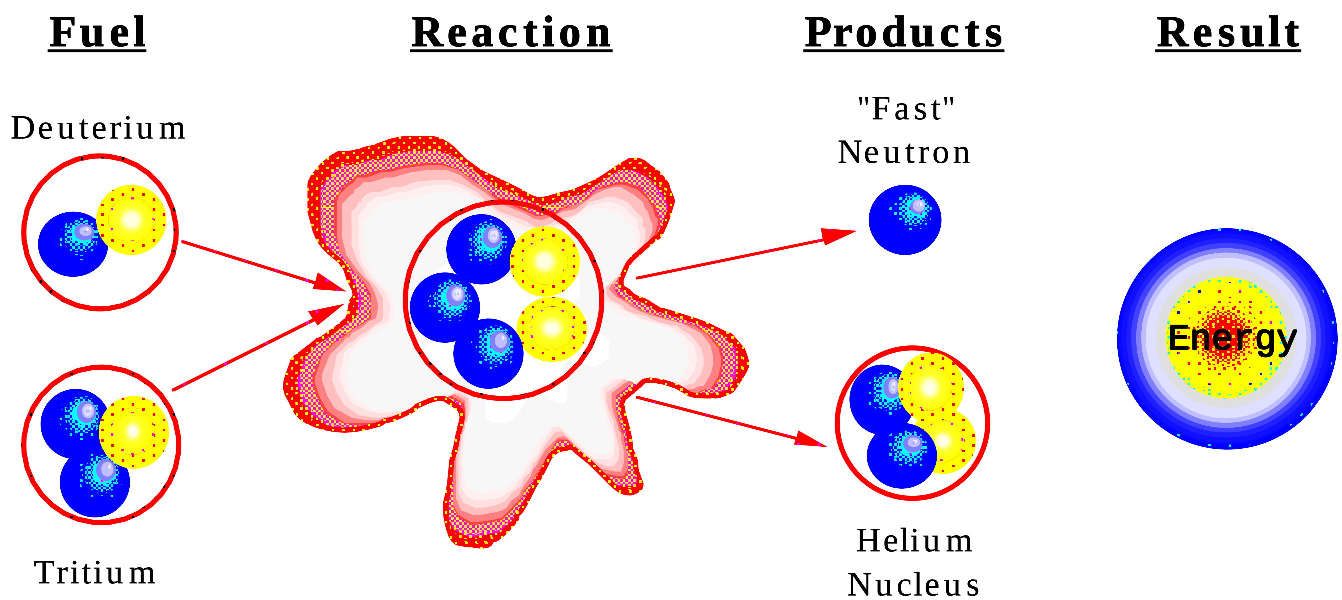
March 29, 1999

Why Develop Fusion Energy?

Fusion is a unique energy option with:

- o Secure inexhaustible fuel reserves
  - Fuel obtained from seawater
  - One pound of fusion fuel = 25,000 barrels of oil
- o Multiple end uses
  - Electricity
  - Fissile fuel
  - Tritium production
- o Attractive environmental and safety features
  - No long-lived reaction products
  - Radioactive structure is relatively easy to manage
  - No combustion pollutants are produced
  - No possibility of runaway reaction
- o Ancillary Benefits, such as, advances science and technology/spinoffs/education

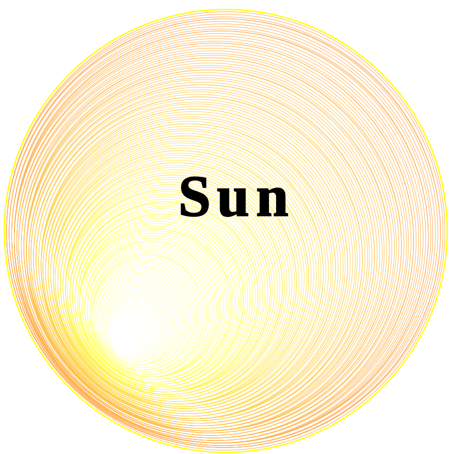
The Fusion Process



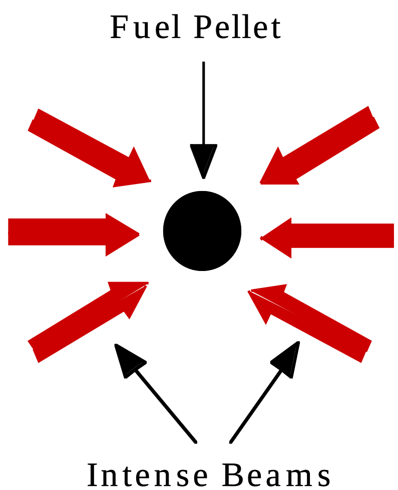
Tritium and Deuterium are "heavy" forms of Hydrogen

Three Confinement Approaches

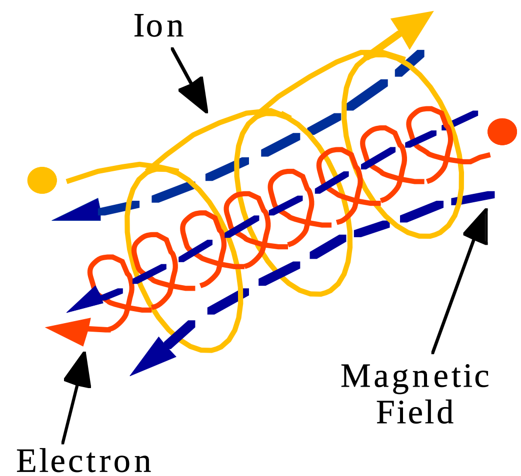
Gravitational



Inertial



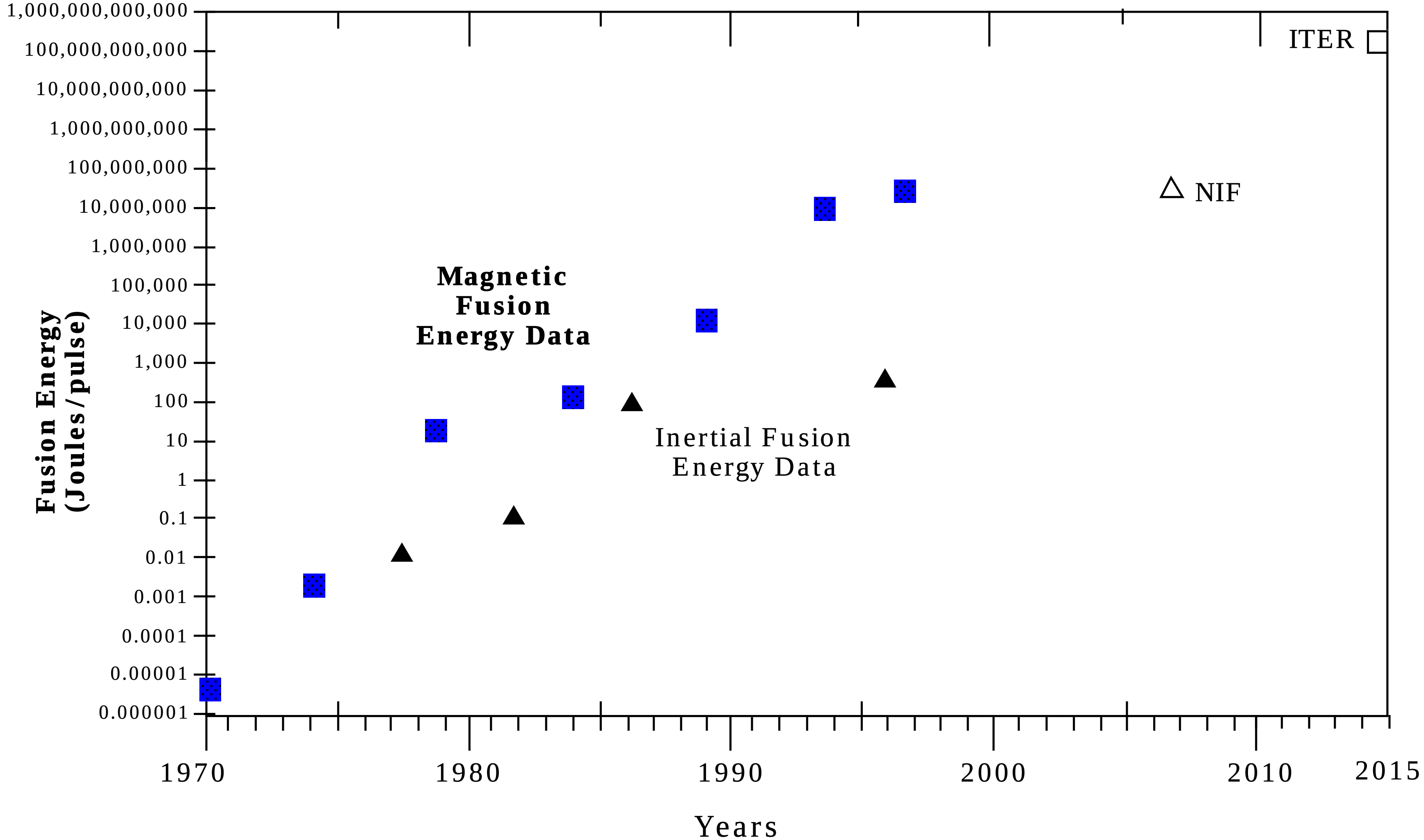
Magnetic



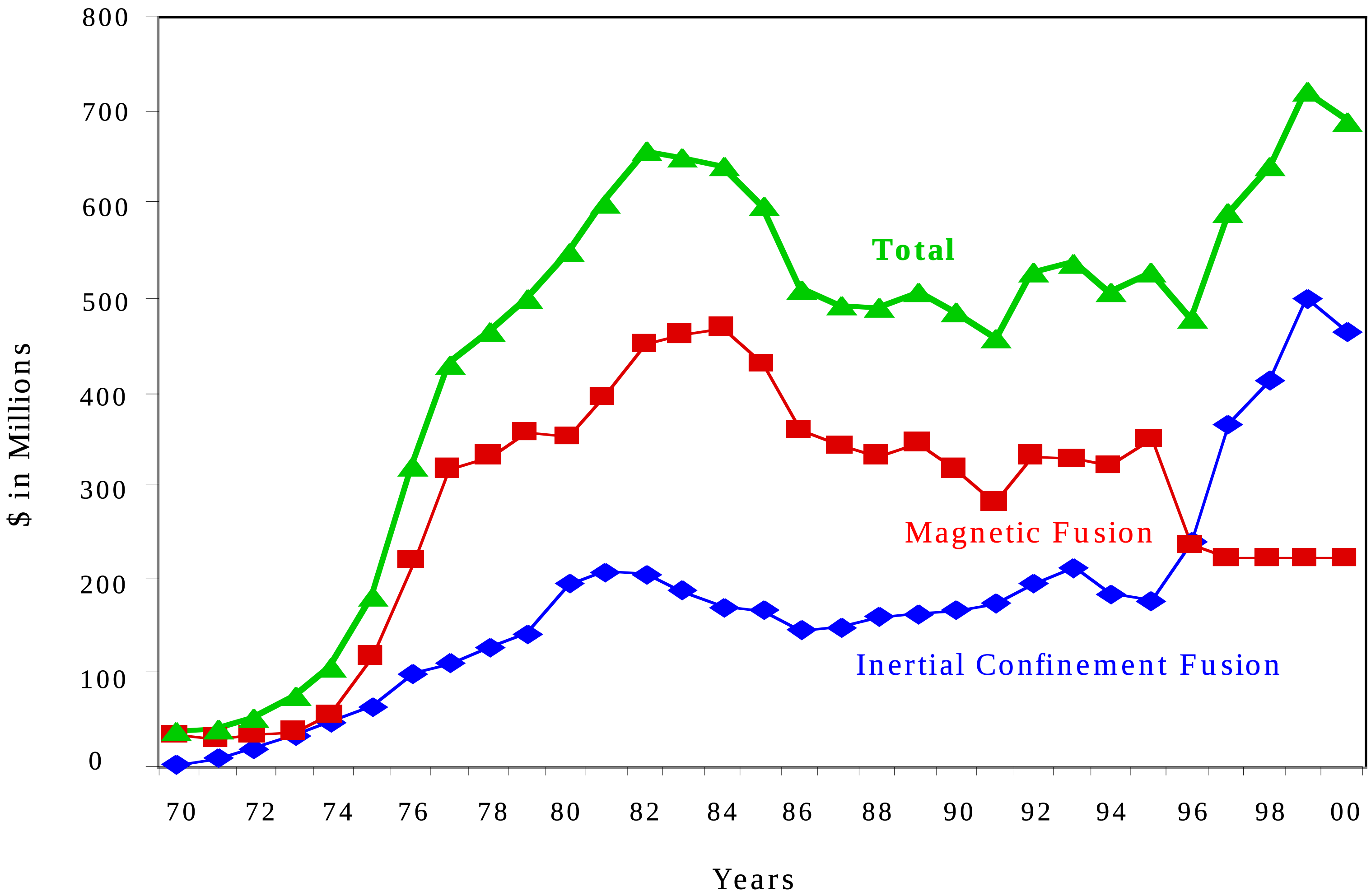
Plasma - The 4th State of Matter

(Picture not available)

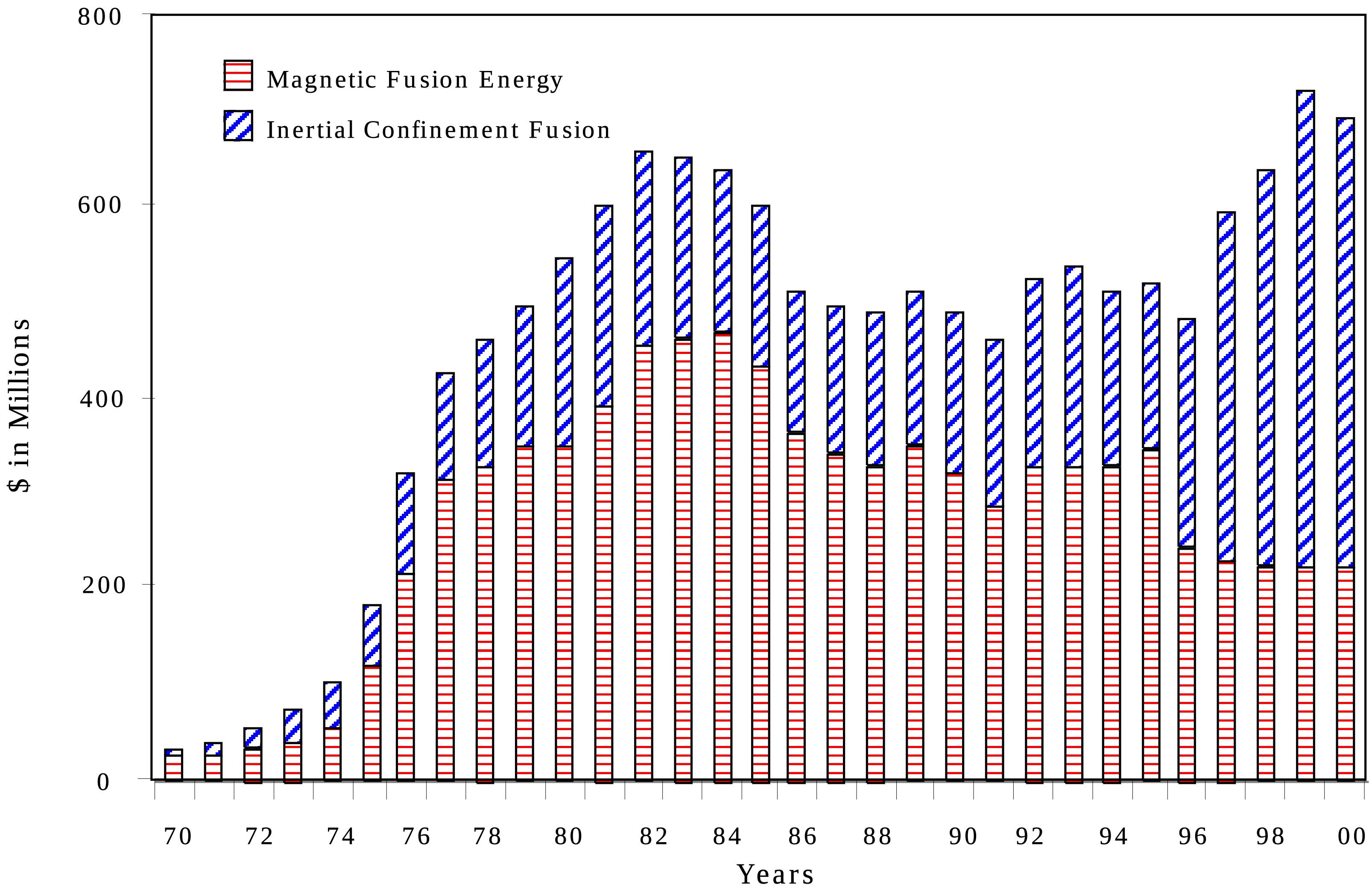
Progress in Fusion Energy Research



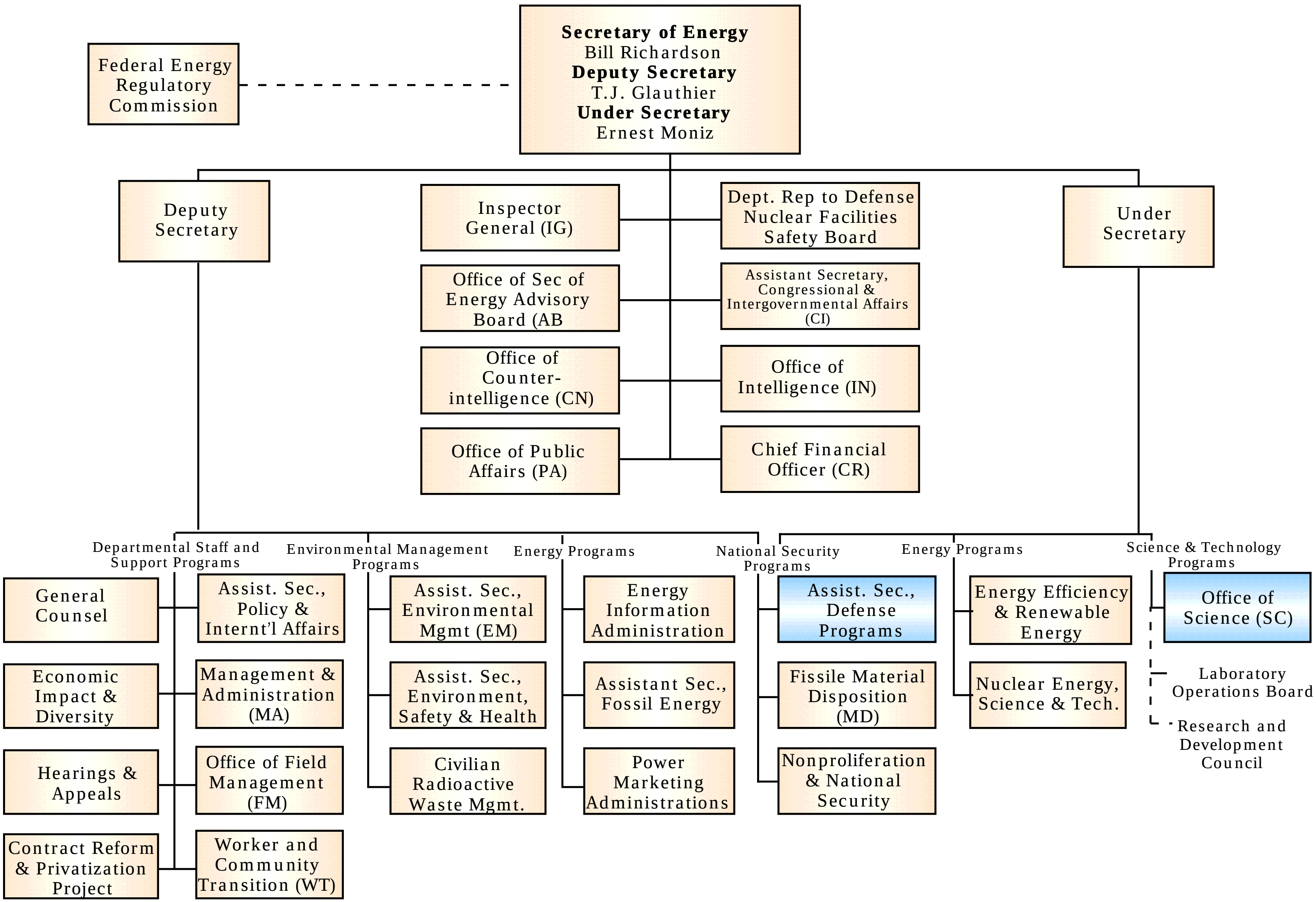
U.S. Fusion Budget History



U.S. Fusion Budget History



U.S. Department of Energy



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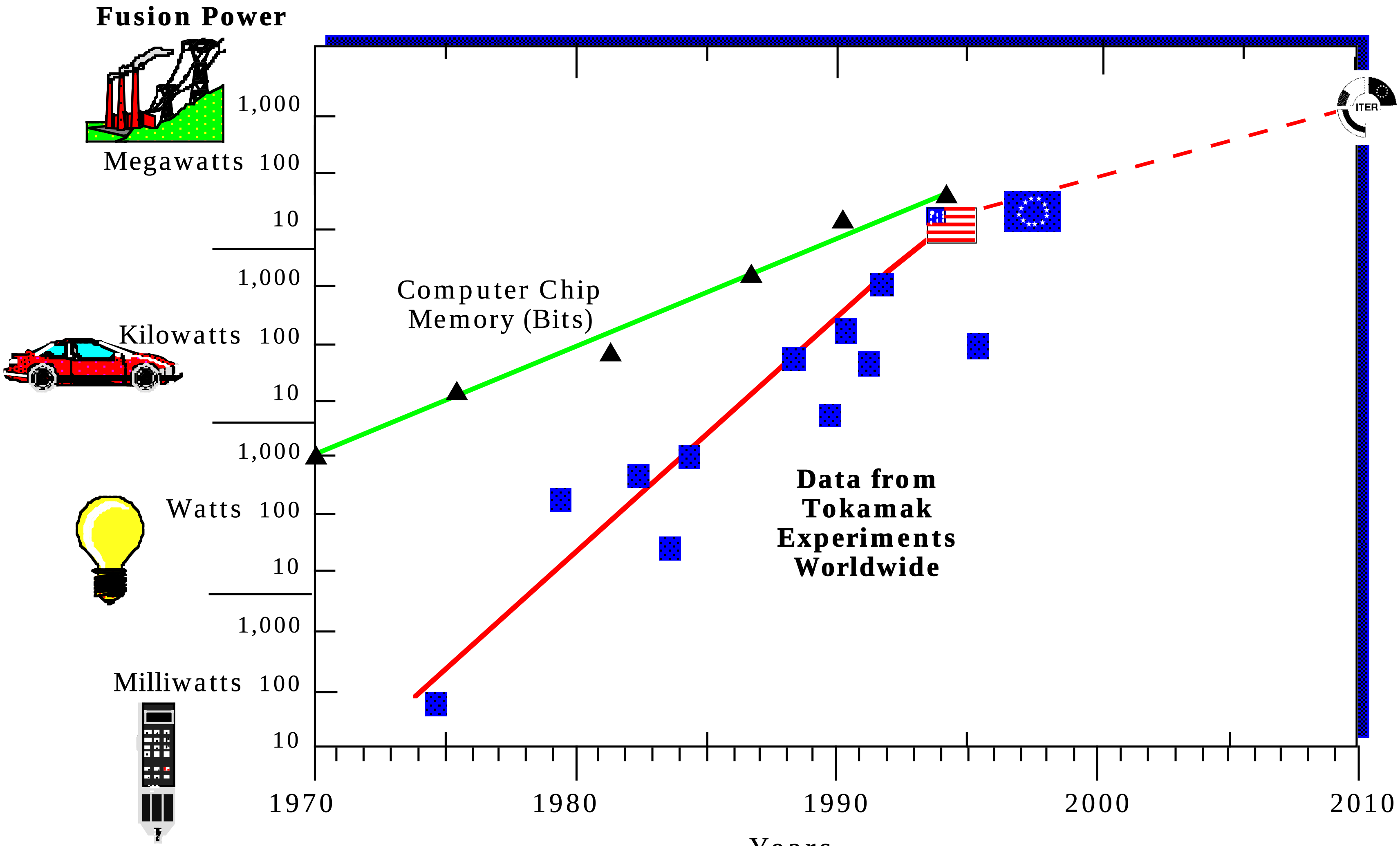
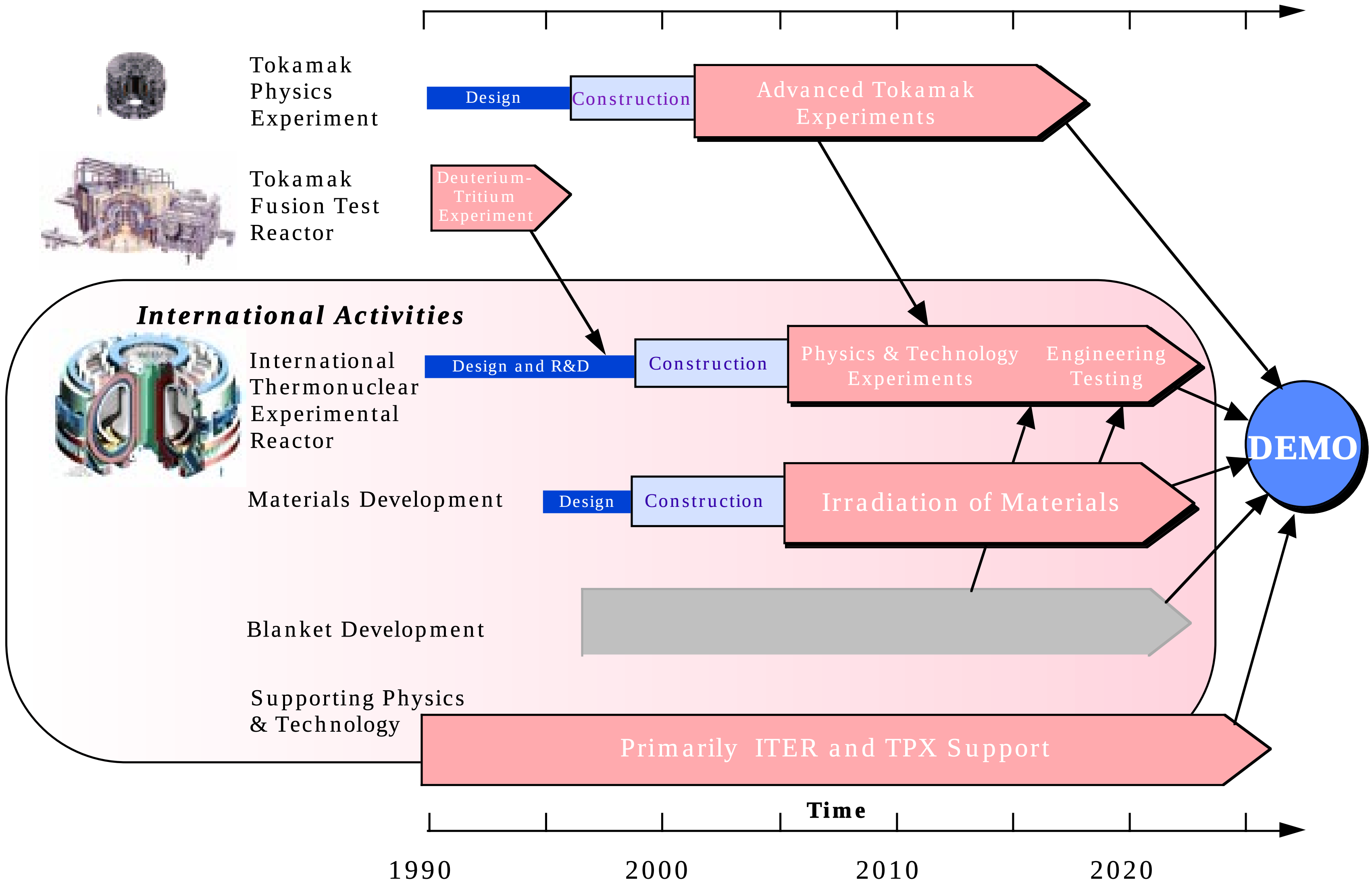
Magnetic Fusion Energy

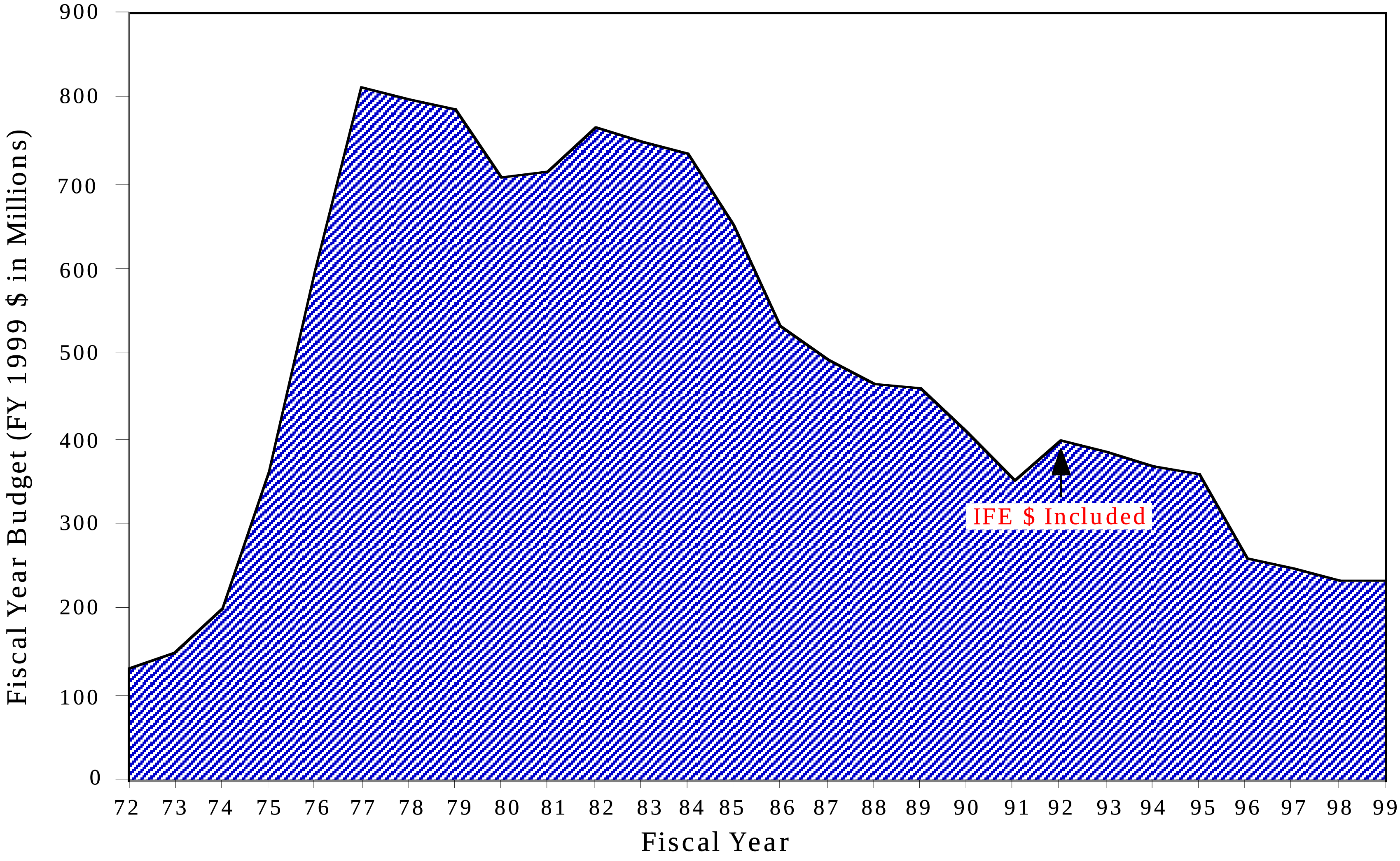
Progress in Magnetic Fusion Research



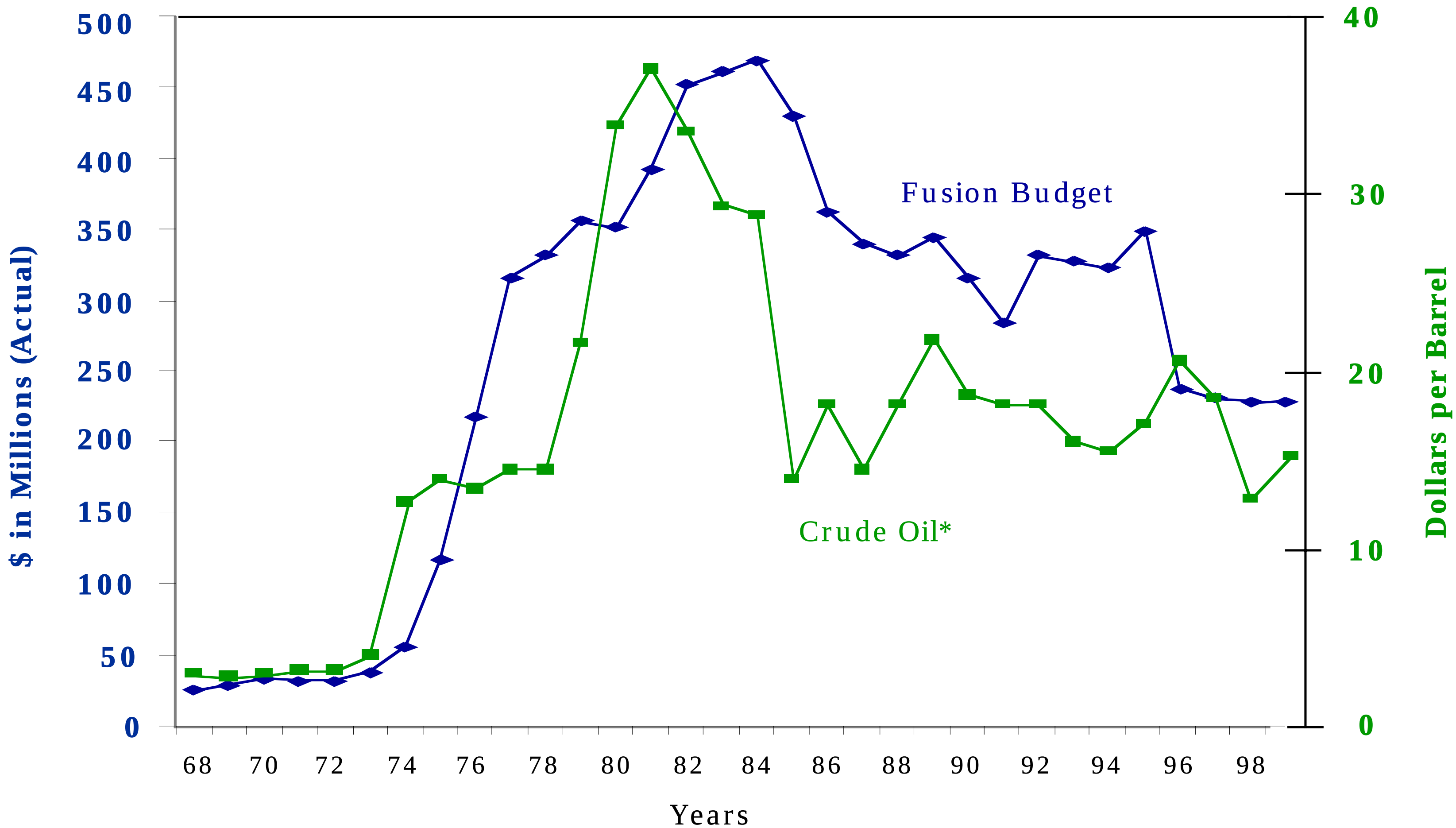
U.S. Magnetic Fusion Strategy (1991-1996)



U.S. Fusion Energy Sciences Budget History



U.S. Fusion Budget Vs. the Price of Crude Oil



*In Actual $'s from Energy Information Administration/Annual Energy Review 1998, Table 9.1, Crude Oil Price Summary, Refiners Acquisition Costs, Imported, Nominal, Web site: eia.doe.gov/p...w/monthly.energy/mer9-1

1/20/99

FY 1996 Congressional Direction

- Reduce budget from \$366 million request to \$244 million
- Restructure strategy, content, near to mid-term objectives
- Emphasize fusion science, concept improvement and alternative approaches, and development of materials
- Recognize increasing importance of international cooperation as a means of building major facilities

U.S. Fusion Energy Sciences Program Mission and Goals

Program Mission

"Acquire the knowledge base needed for an economically and environmentally attractive fusion energy source."

Program Goals

I. Understand the physics of plasmas

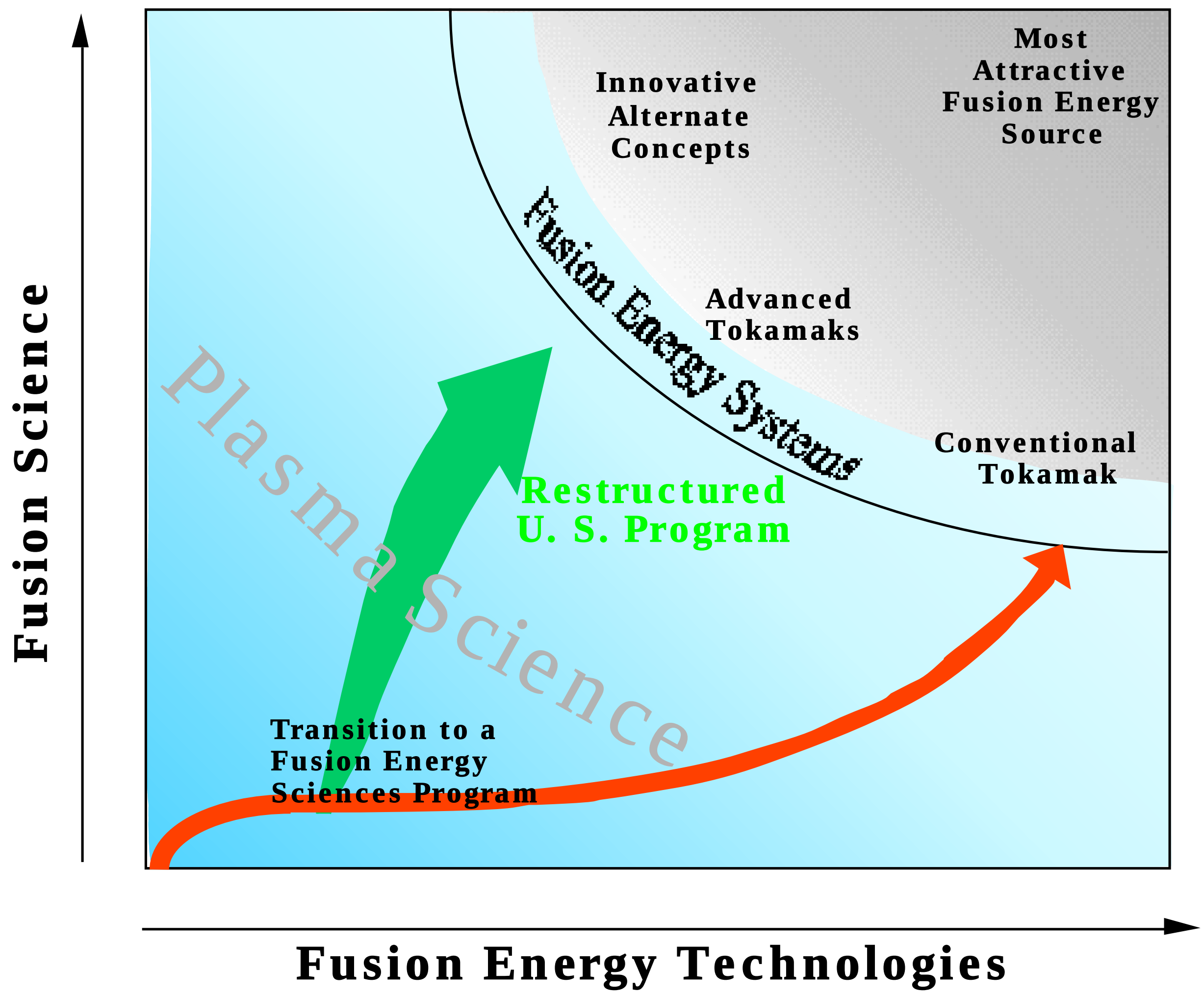
II. Identify and explore innovative approaches to fusion science and technology

III. Explore the science and technology of energy producing plasma, as a partner in an international effort

U.S. Fusion Energy Sciences Program
Five Year Objectives

- Substantial progress in scientific understanding and optimization of toroidal plasmas, with tokamaks the most mature of several related configurations (I, II)
- Strengthened general plasma science and education efforts, with connections to other scientific communities (I)
- Significant improvement in integrated modeling, based on theoretical understanding and the experimental experience base and exploiting anticipated advances in large-scale computation (I)
- Active explorations evaluating a variety of innovative fusion approaches, including the scientific and technological bases for an IFE heavy-ion driver (II)
- Marked progress in the scientific understanding necessary for evaluating technologies and materials required under conditions of high plasma heat flux and neutron wall load (II)
- Membership in an international collaboration to study burning plasma physics and develop related fusion technologies (III)

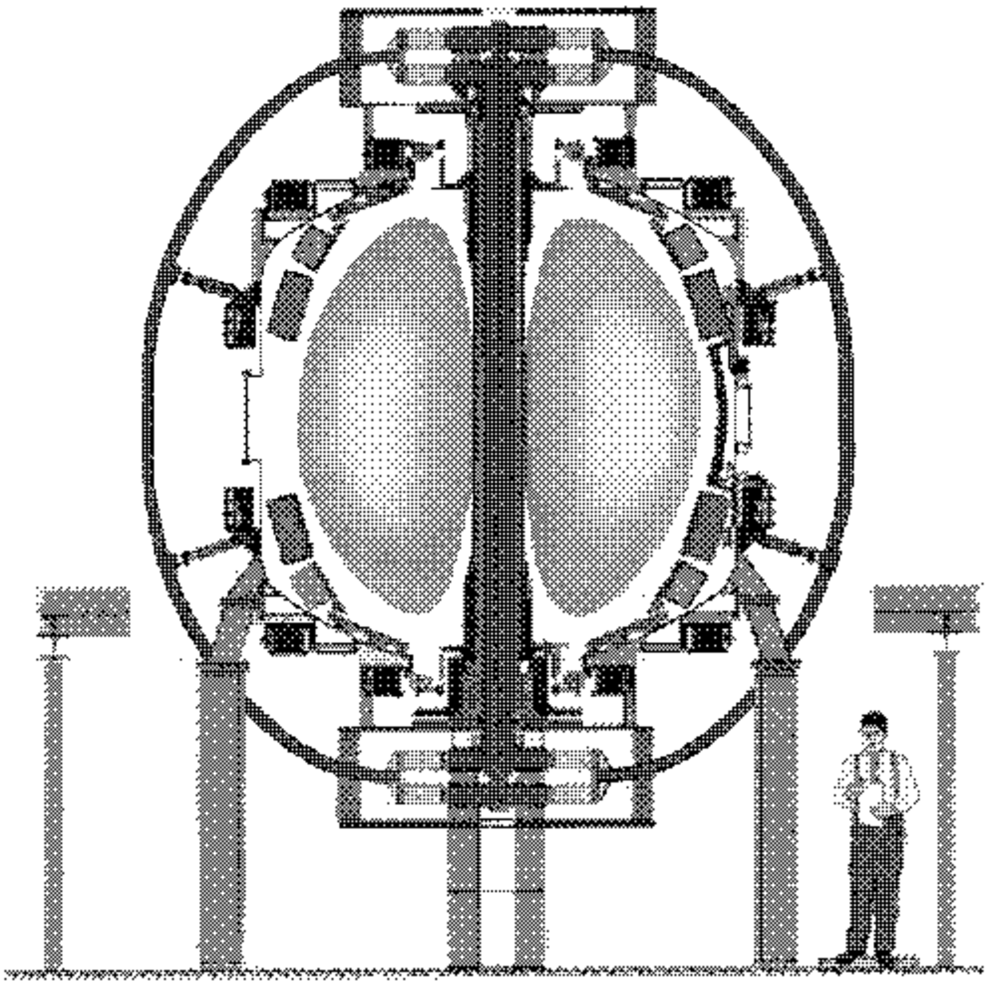
Restructuring of the U.S. Fusion Energy Sciences Program



New Fusion Energy Sciences Program

- o Increased breadth of concepts being funded
  - Initiated work on National Spherical Torus Experiment
  - Initiated Innovative Concepts grant competition
  - Increased funding for existing exploratory experiments
- o DIII-D, C-MOD and NSTX have become national facilities
- o Assumed stewardship role for field of plasma science
  - Initiated Basic Plasma Science and Engineering Program with NSF
  - Initiated Plasma Science Junior Faculty Development Program
- o Restructured U.S. technology program to emphasize domestic program needs (that may also meet ITER needs)
- o Identified lower cost options to meet ITER objective
  - Conducting orderly close-out of financial participation in reduced cost ITER

National Spherical Torus Experiment (NSTX)

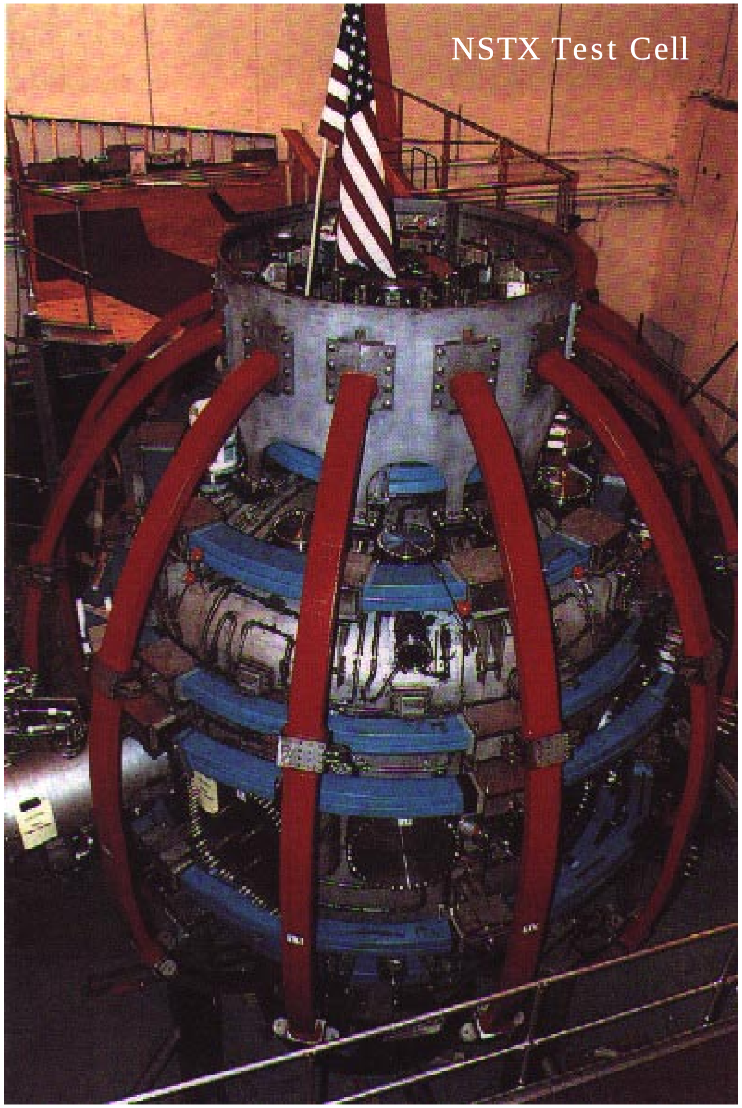


Features:

- A physics experiment
- National Research Team
- FY 2000 Targets
  1 MA current
  >0.5 S pulse length
  4 MW RF power
- Highly efficient containment of plasma energy β~30-40%
- Self-generated confinement current (up to 90%)
- First plasma--February 1999

TEC = $21,100,000 Begin Operations, July 1999

National Spherical Torus Experiment



Torus is located at Princeton Plasma
Physics Laboratory, Princeton, New Jersey

Innovative Confinement Concepts Development

Definitions

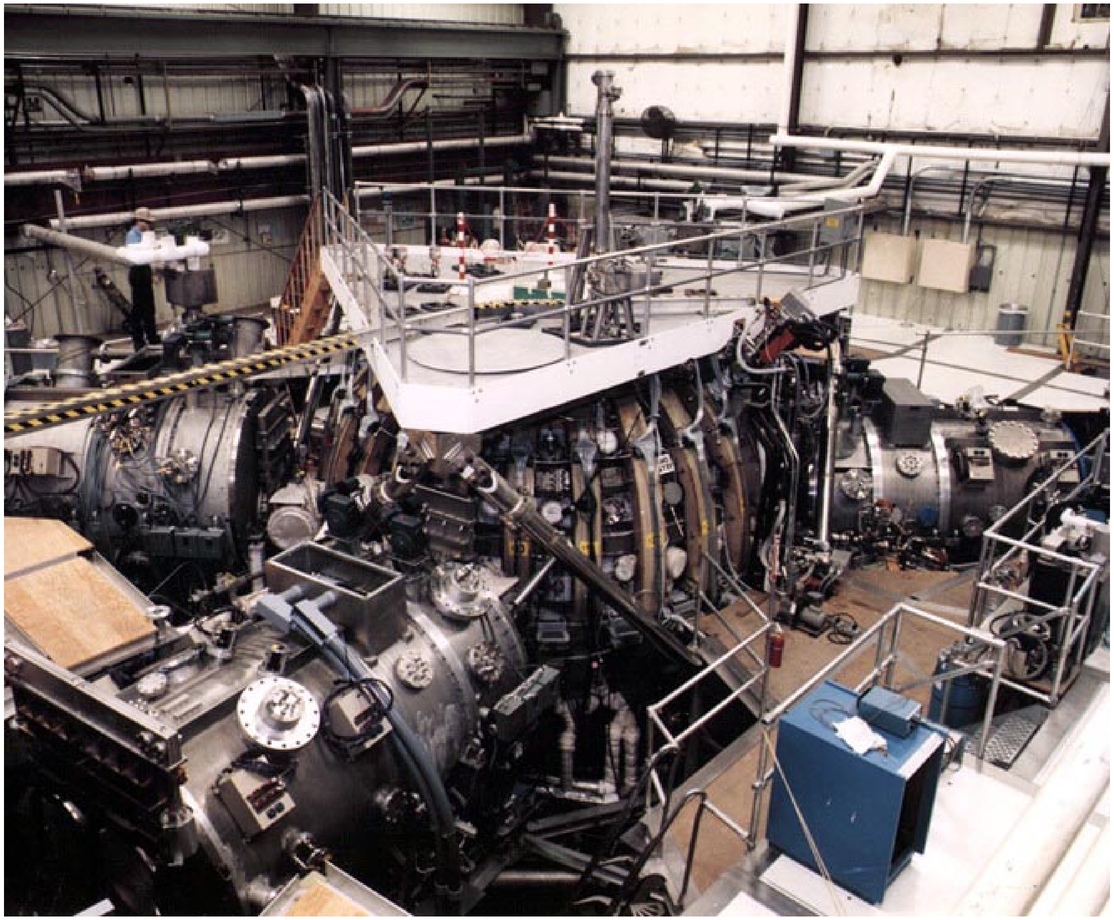
- o Development plan recommended by FESAC (July 22, 1996 report)
  - \- Postulated five stages of development; scientifically a continuum
    - -- Concept exploration
      - --- Innovation and basic scientific understanding
    - -- Proof-of-Principle
      - --- Development of integrated and broad understanding to provide confidence in evaluation of potential of concept for fusion energy applications
    - -- Proof of Performance and Performance Extension
      - --- Exploration at or near fusion relevant regime
    - -- Fusion energy development
      - --- ITER
    - -- Fusion Demonstration Power Plant

Innovative Confinement Concepts

- o Advanced tokamak
- o Magnetic concepts other than tokamak
  - \- Important for:
    - -- Intrinsic scientific value
    - -- Potential to discover concepts that would make attractive fusion power sources
  - \- 14 experimental programs
  - \- Located primarily at universities

DIII-D Tokamak

General Atomics



High pressure with good confinement

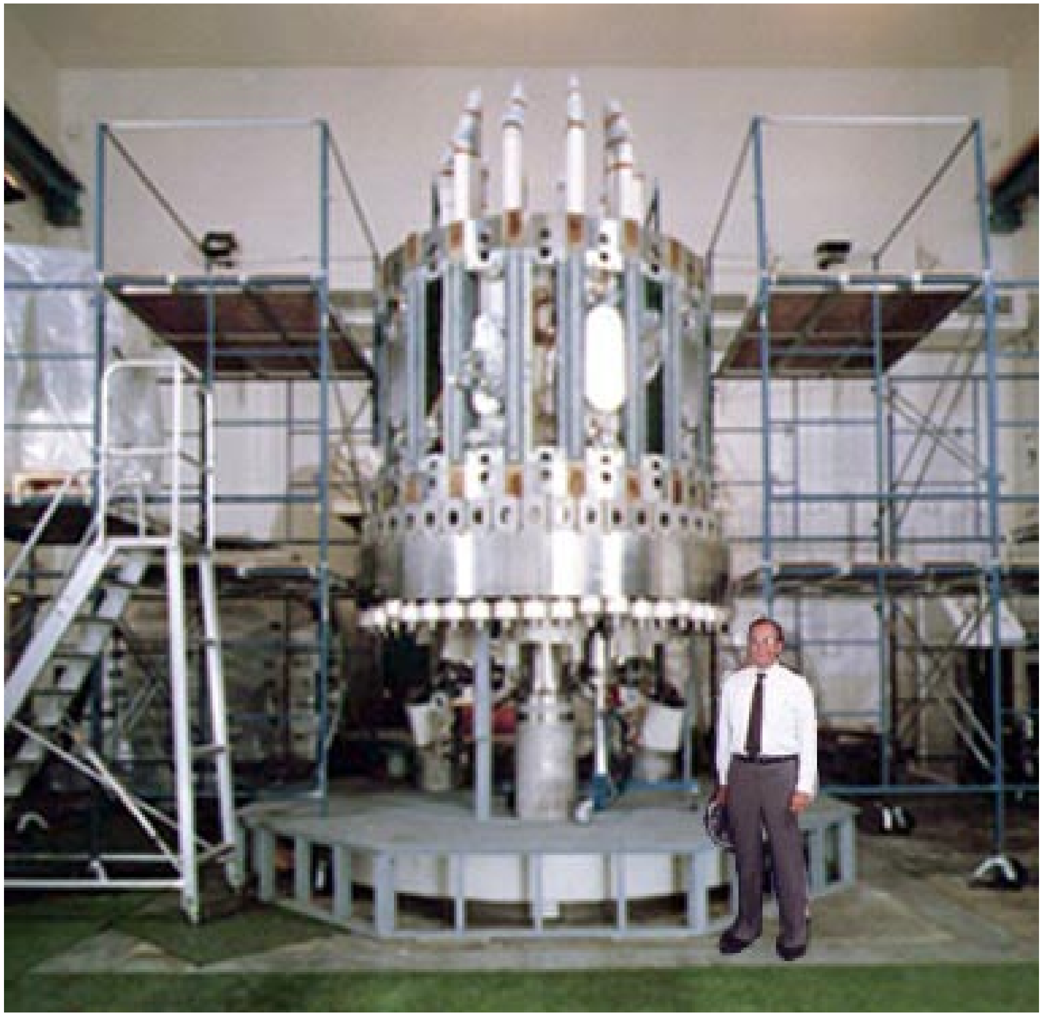
Heating and non-inductive current-drive techniques

Particle and power handling

Parameters:

Magnetic Field	2.2 T
Plasma Current	2.5 MA
Heating Power	24 MW
Pulse Length	5 Sec

Alcator C-MOD



Very high magnetic fields allow for compact size

Fusion grade plasmas can be generated at modest cost

Unique/flexible divertor configuration combined with excellent diagnostics allows in depth understanding of particle/power exhaust in tokamaks

Supportive of ignition/burning plasma physics experiments in compact copper machines

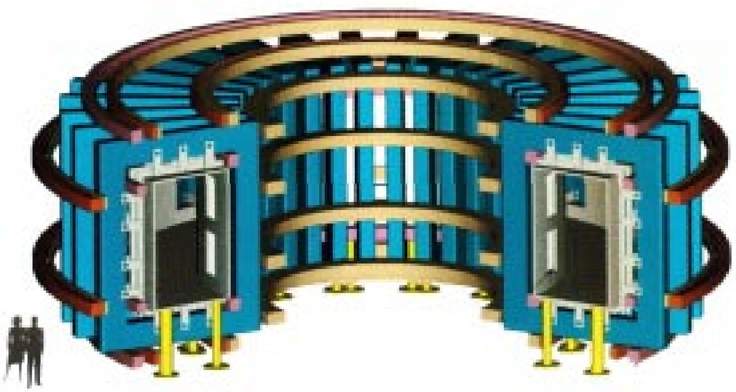
Parameters:

Toroidal Field	9 T
T.F. Flat-top	5 s at 5 T
Plasma Current	1.5 MA
Heating Power (ICRF)	8 MW

University-Scale Tokamaks

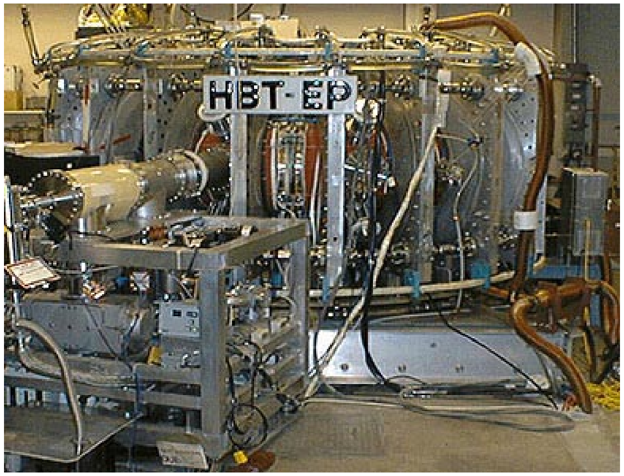
Electric Tokamak at UCLA

- Large scale, low field
- Poloidal rotation via ICRF
- Aimed at elimination of neoclassical transport losses and enhanced plasma pressure



HBT-EP at Columbia

- Movable close-fitting conducting shell
- Active feedback control
- Targeted at control of external kink instability



Diagnostics Development

- Exploration of novel measurement techniques
- Specialized instruments employed on various facilities for comparision of data

Theory Program Overview

Goal: Provide the predictive scientific understanding needed to develop an attractive fusion energy source

- o Develop analytic theories of basic physical phenomena in fusion plasmas
- o Construct and validate models of fusion plasma performance

Recent Progress:

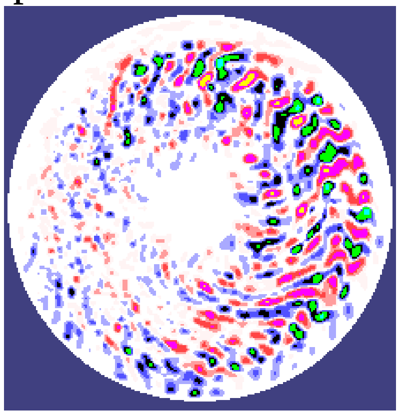
- o Physics of core and edge transport barriers in toroidal devices
- o Development of advanced toroidal operating regimes
- o Credible models of edge plasma/divertor performance
- o Theoretical explanation of non-linear manifestations of alpha particle driven instabilities
- o Improved models of turbulence and transport in tokamak

Turbulent Fluctuations Suppressed When ExB Shearing Rate Exceeds Maximum Linear Growth Rate of Instabilities

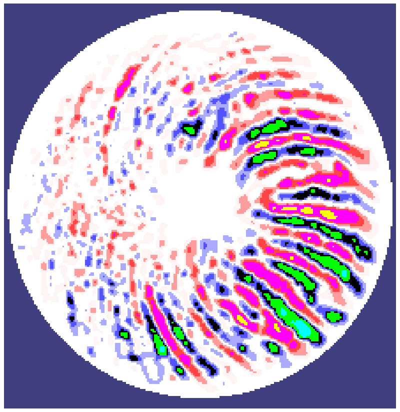
Gyrokinetic Theory

Simulations show turbulent eddies disrupted by strongly sheared plasma flow

With Flow

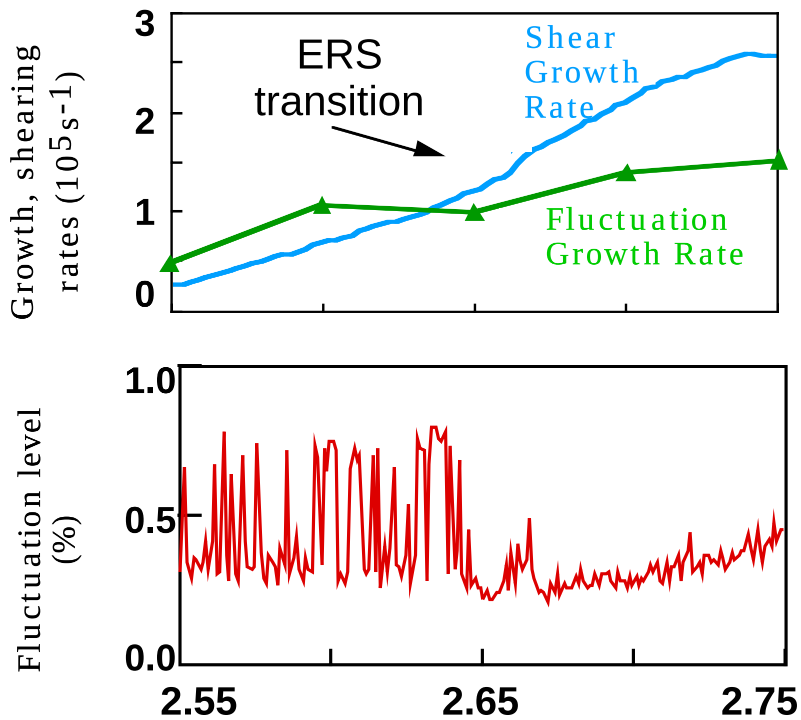


Without Flow

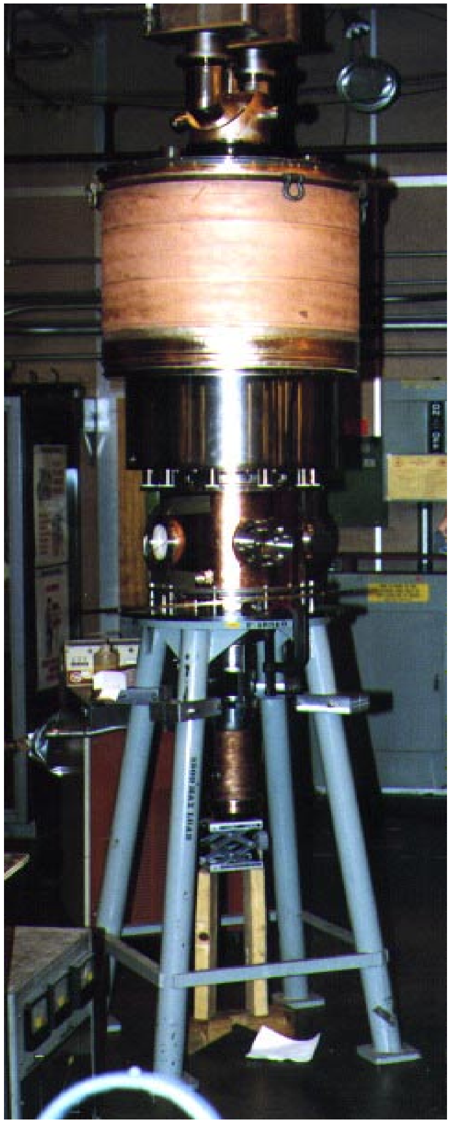


Experiment

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



110 GHz Gyrotron Program



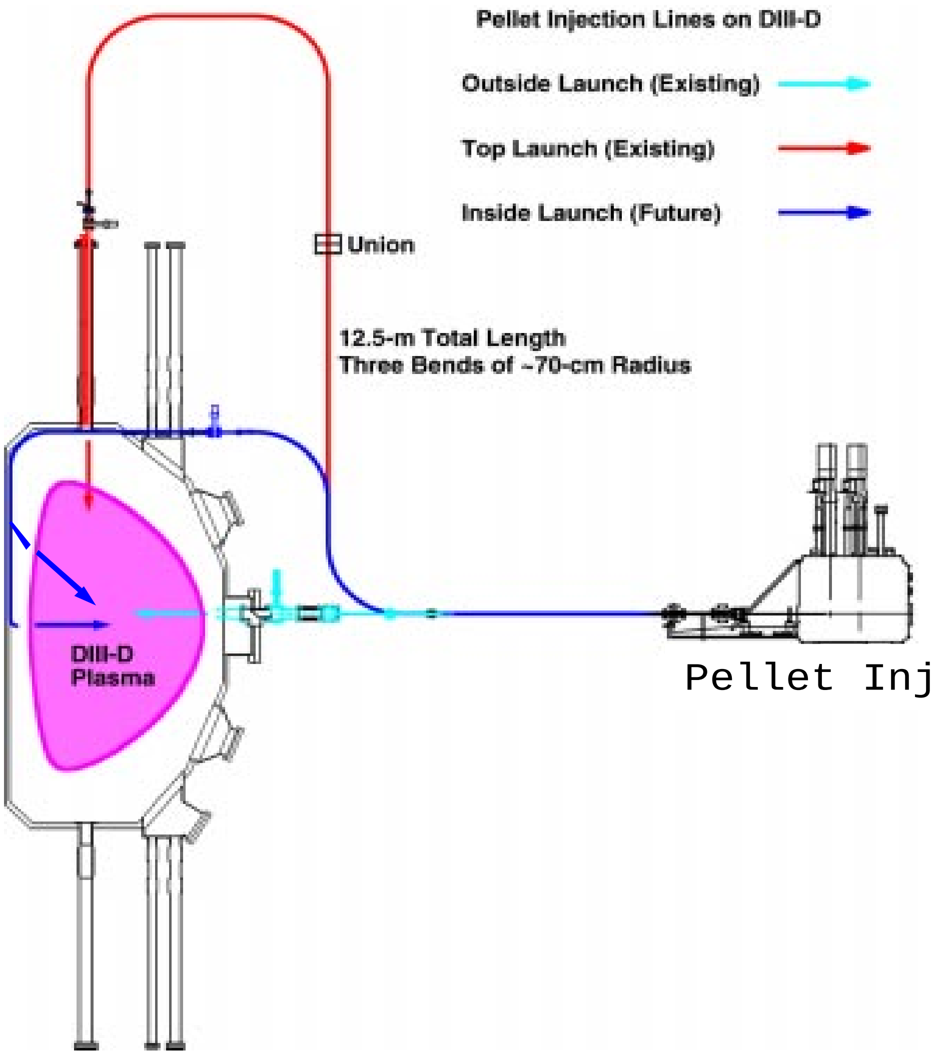
100 GHz Tube

Continuous power level of 200 kW

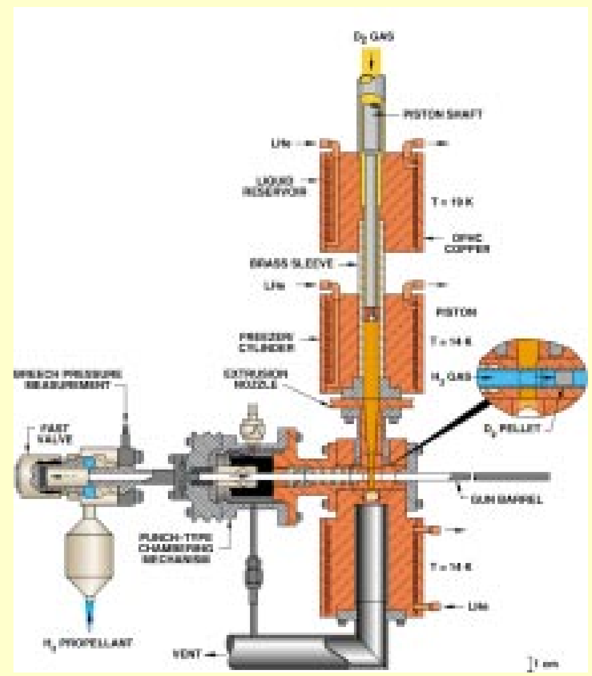
Pulsed operation at power level
of 1 MW (in 1 second pulses.)

Operation at 1 MW
for 10 seconds is
being tested with
diamond window

Pellet Injection on DIII-D



Schematic View of Pellet



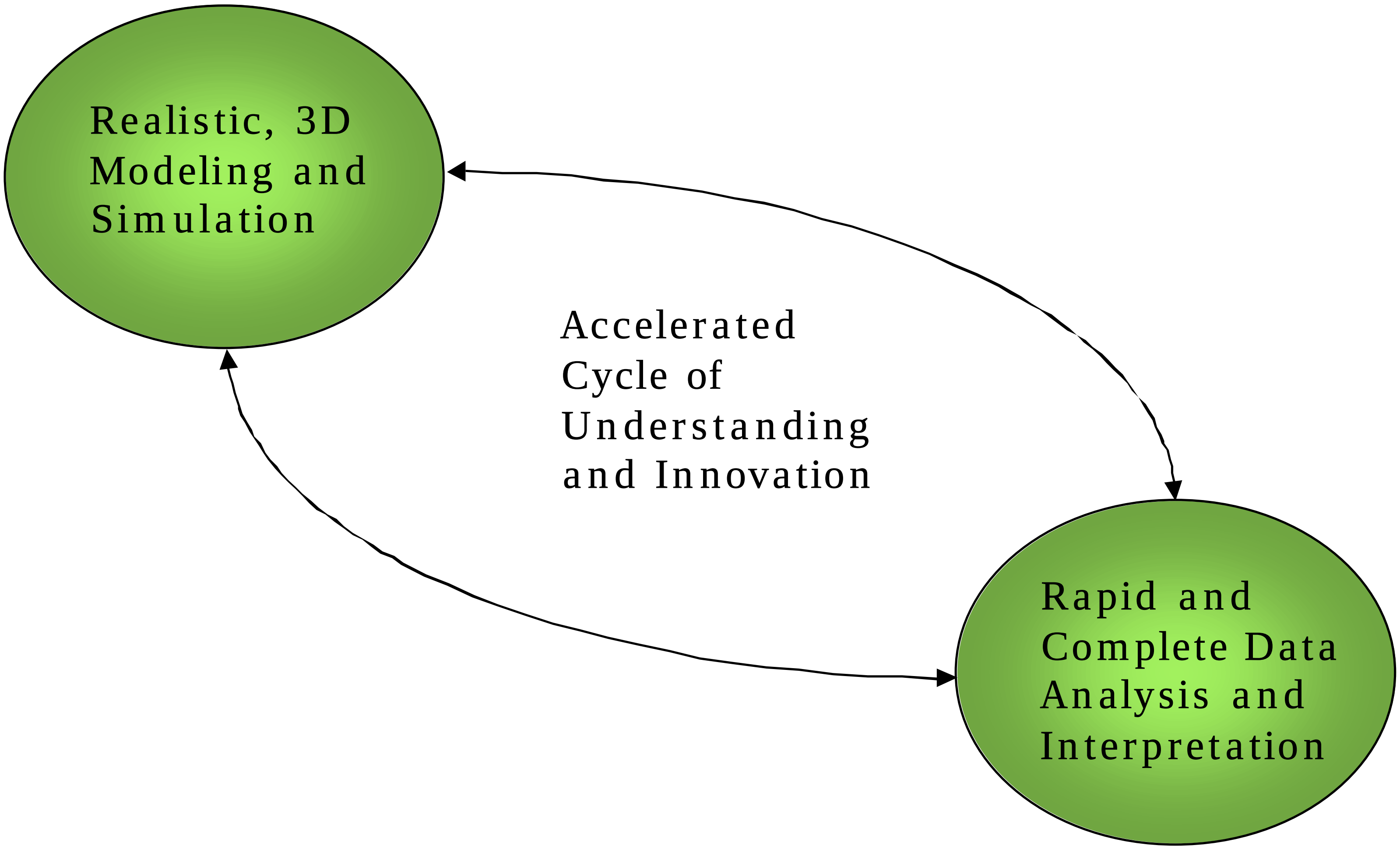
Scientific Simulation Initiative

DOE's Part of the Information Technology
for the Twenty-first Century Initiative

Objective: To develop and deploy advanced computing technologies, to solve scientific and engineering problems of extraordinary complexity

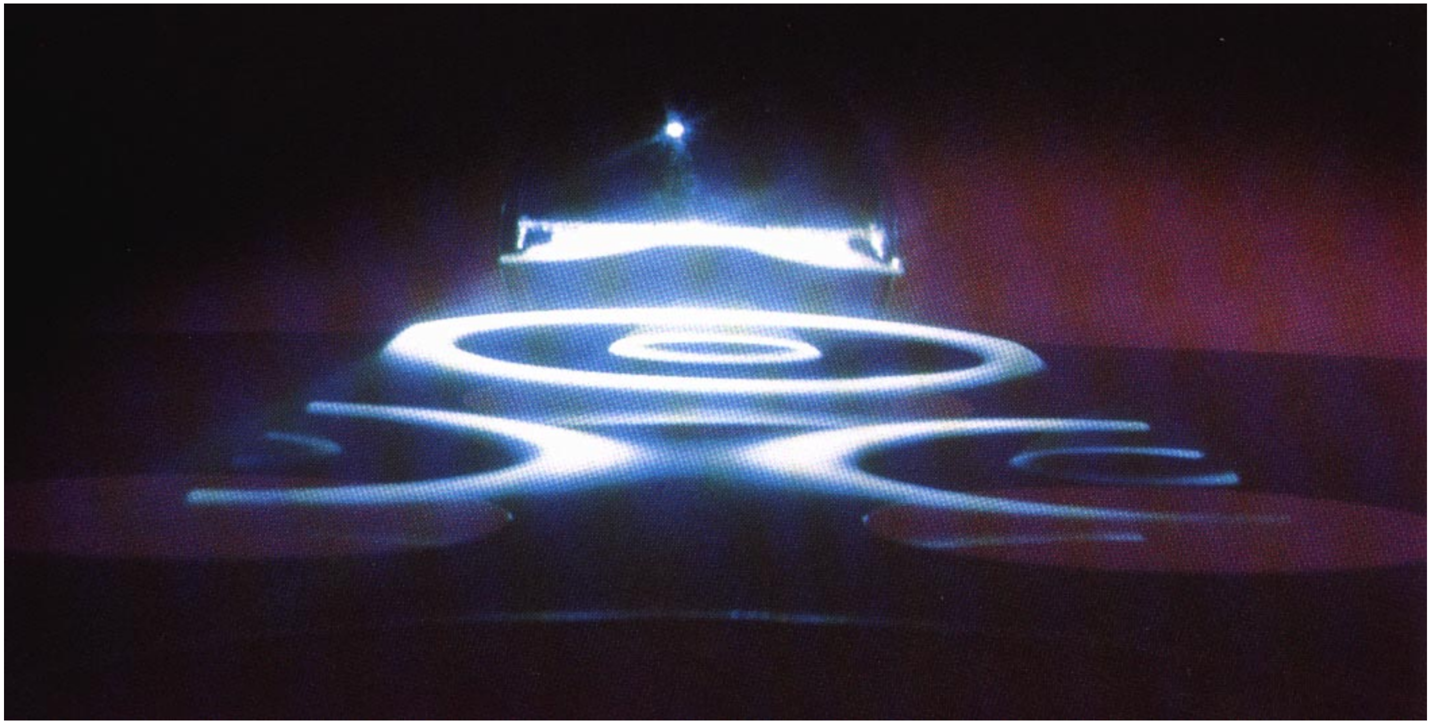
- o Target Applications: Global Systems, Combustion Simulation, and Basic Science
- o Proposed FY 2000 Budget: $70 Million
- o Fusion is one of five basic science areas seeking $2-3 million of FY 2000 funding (two will be funded)

Overall Objectives for the Fusion SSI



General Plasma Science

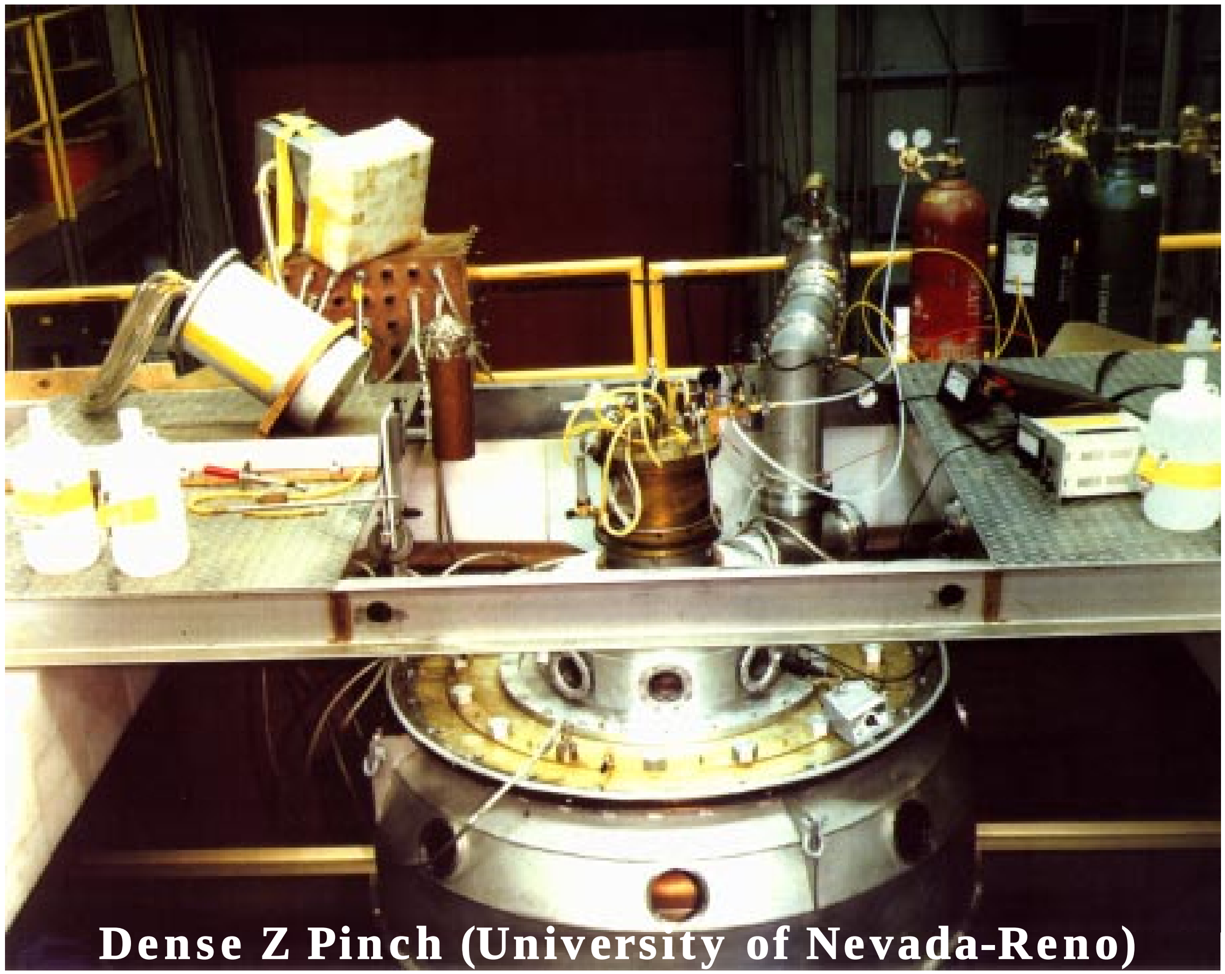
General Plasma Science programs are located primarily at universities and cover a broad space of plasma science and technology. Most grants are funded under a NSF/DOE partnership.



Silicon Wafers
undergoing plasma processing in a "plasma reactor"

General Plasma Science

There are presently seven Plasma Physics Science Junior Faculty Development Awards. The program will be continued in FY 1999.



Dense Z Pinch (University of Nevada-Reno)

Enabling Technologies Program

Carries out the research that enhances technology capabilities and fosters the innovation needed to advance fusion science.

Enabling Technology

- ITER tasks have been the focus through FY 1998

- In FY 1999, transition begins to broaden portfolio of activities serving the domestic program and our interests for international collaborations

- Transition will be completed in FY 2000; Enabling Technology will emphasize those technologies that enable experiments, domestically and internationally, to achieve their full scientific research potential

Enabling Technology

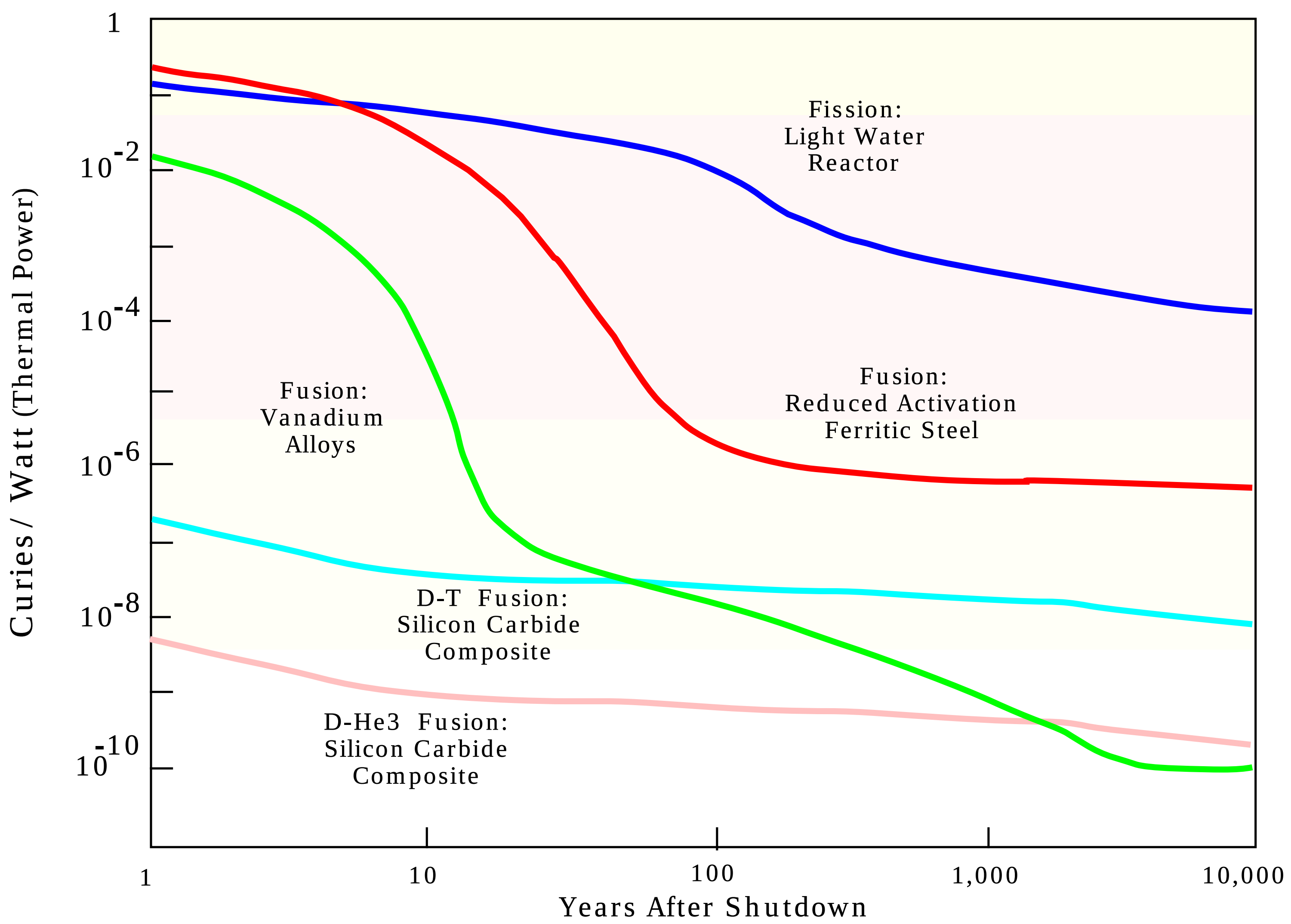
Materials Research

- Explore innovations in materials needed in the long term to advance fusion science and to achieve fusion's potential as an attractive energy source

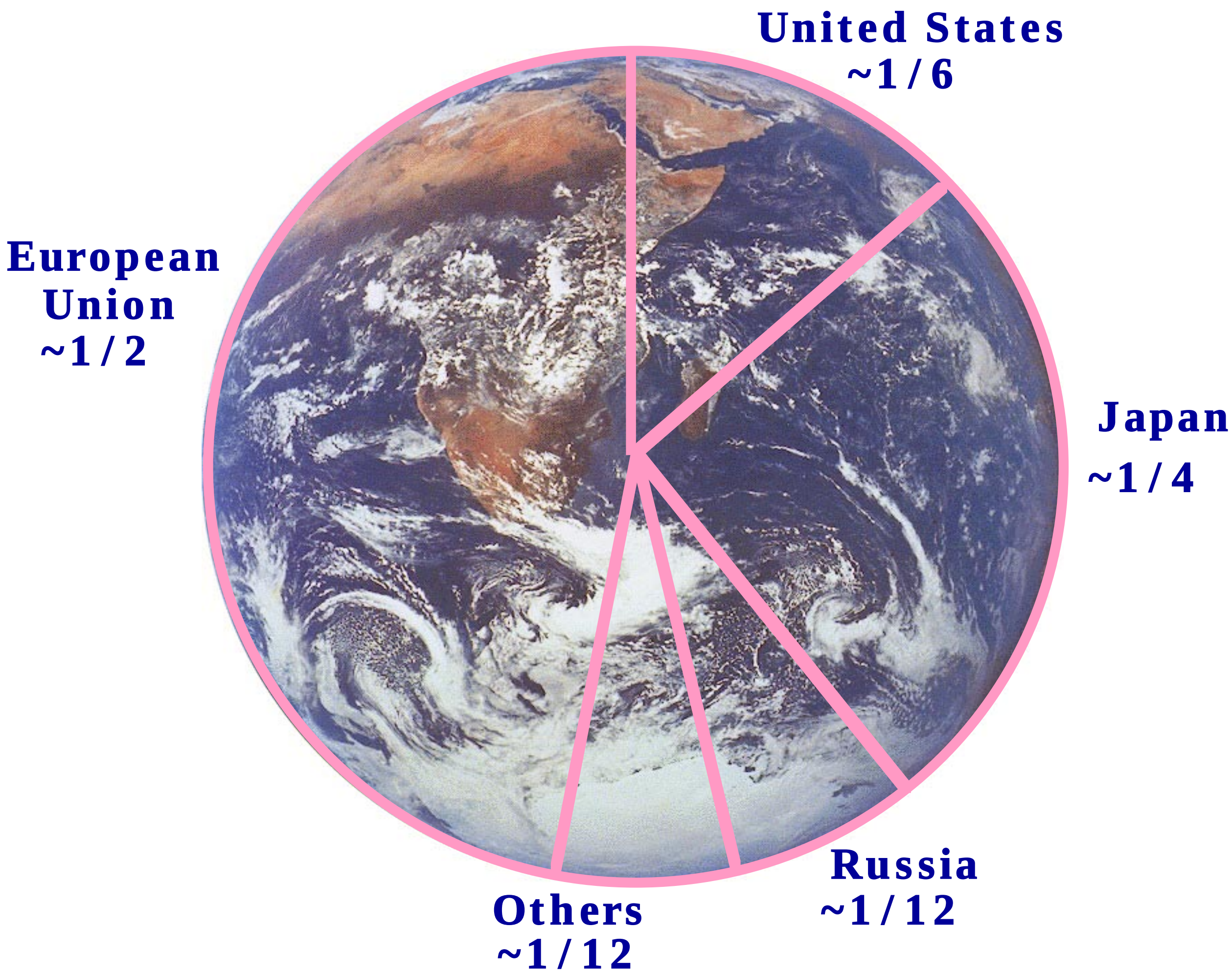
  - Focus on low-activation structural materials (vanadium alloys, ferritic steels, and silicon carbide composites) for high power density fusion devices

  - Smaller complementary efforts on non-structural materials research are also being pursued (coolants, insulators, coatings, tritium breeders and plasma facing materials)

Comparison of Fission and Fusion Radioactivity After Shutdown



World Magnetic Fusion Effort (1999)



International Collaboration -- ITER Status

- U.S. participated with EU, Japan, and RF for 6 years through 7/98, but Congress did not approve U.S. participation in the 3 year extension

- Other 3 Parties are proceeding with reduced-cost, reduced objective design (about half of original ITER cost, i.e. $5B in today's dollars) without U.S.

- New design incorporates many advanced tokamak features; retains significant, integrated, performance capability of Q=10, power of 500 MW, pulse of 500 seconds with potential for ignition and/or steady state Q=5

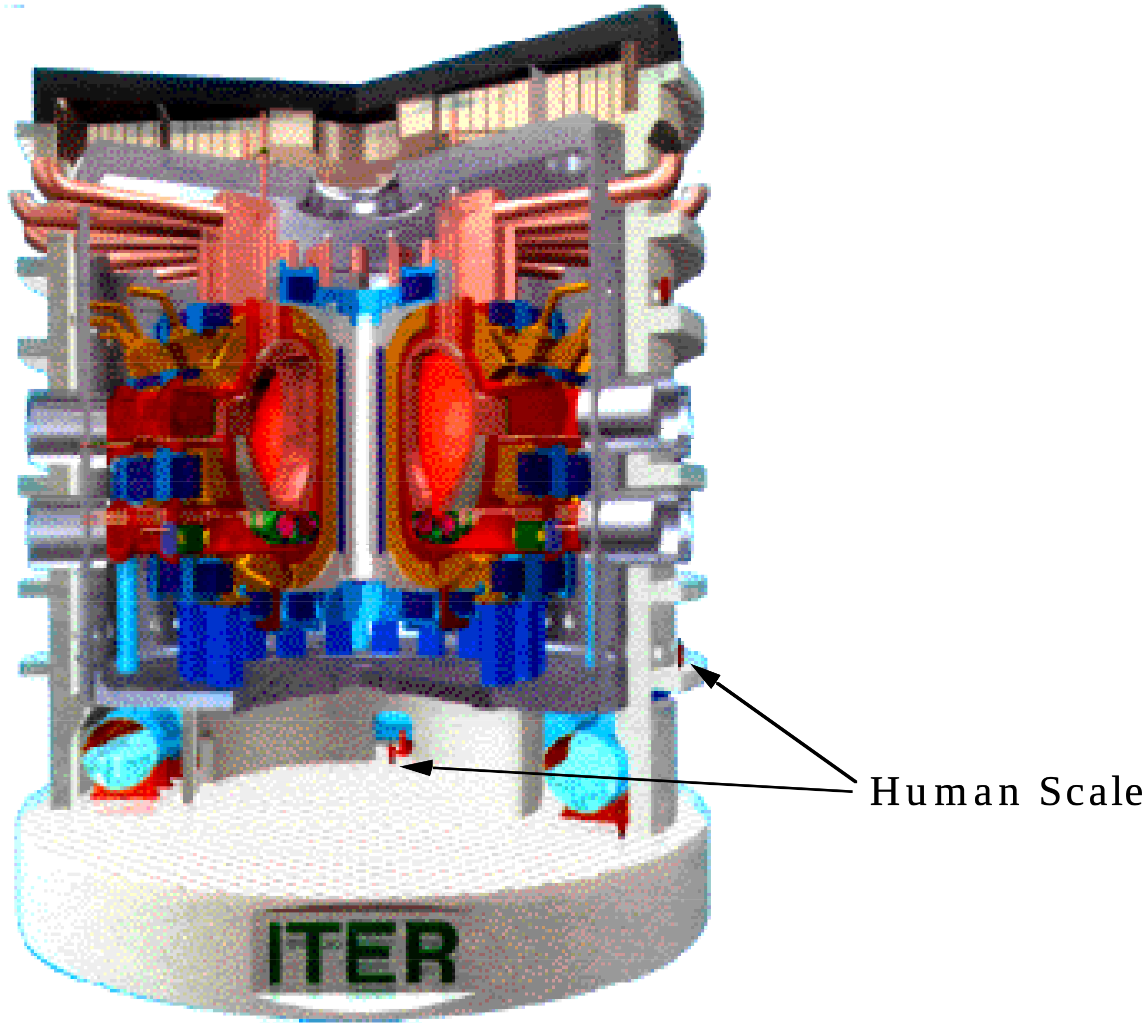
- Decision on readiness to proceed with construction is planned for late 2000

- Recent Special Working Group of all 4 Parties concluded, "World program in fusion is scientifically and technically ready to take the important ITER step."

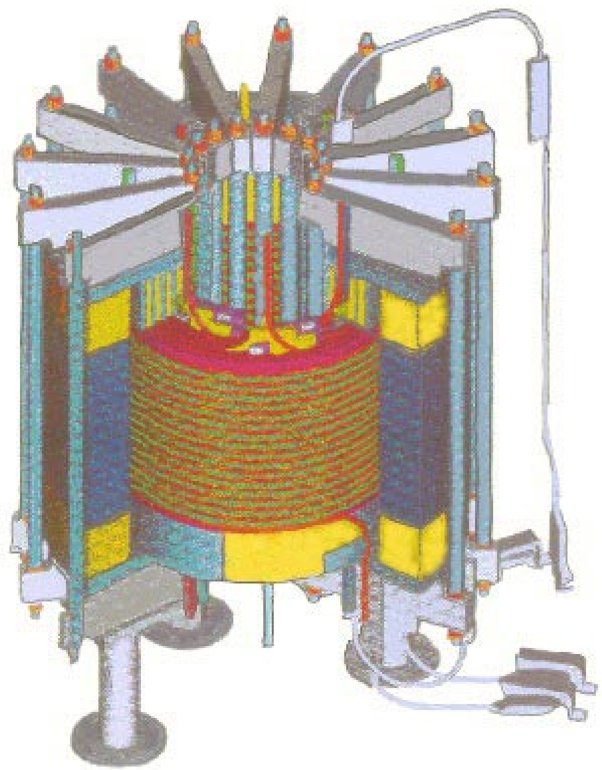
- U.S. plans to contribute to physics on voluntary basis and complete major commitments to build 40 ton CS Magnet Model Coil and Divertor Cassette and participate in their operational tests.

- If other 3 Parties proceed with construction, U.S. would want to reconsider its involvement in ITER program

International Thermonuclear Experimental Reactor



Central Solenoid Magnet Model Coil



Snapshot of International Collaborations not available here. See
http://wwwofe.er.doe.gov/More_HTML/international.html

Next Step Options Studies

- ITER design activities were redirected in FY 1999 to Next Step Option Studies (NSO)
- NSO is a national team effort conducted at about 1/3 the funding level of U.S. ITER home team design activity
- Design studies emphasize plasma behavior at high energy gain and long duration, with initial focus on a burning plasma experiment
- Assessment of advanced physics burning plasma experiment to be completed by fall 1999

Progress Toward New International Agreement on Fusion Science

- Secretary called for new agreement in Vienna (9/22)
- U.S. proposed Fusion Program Leader forum
  - Presented to EU, JA, and RF in November
  - Fusion energy science and fusion energy development elements
- Annual forum would enable Leaders, for first time to:
  - Review progress in collaborative activities
  - Evaluate/improve effectiveness of major collaborations
  - Consider possible enhancements of joint efforts
  - Involve Leaders of other fusion programs as well
- EU ready, in principle, to reach agreement while JA/RF, focused on ITER revalidation, considering our proposal

Inertial Fusion Energy

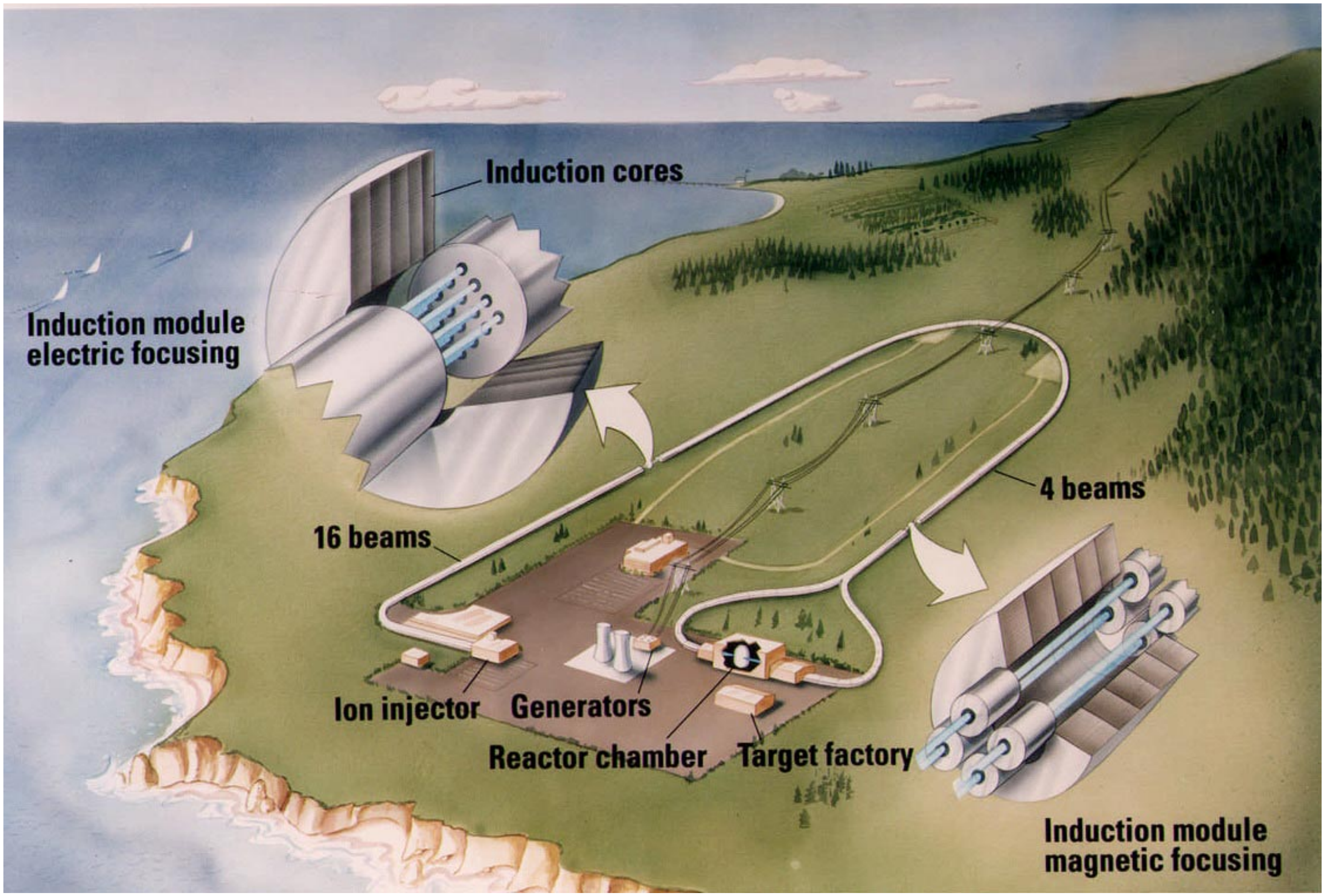
Inertial Fusion Energy

- DP program conducting target physics using NOVA, OMEGA, and NIKE; National Ignition Facility under construction

- ER developing components for energy applications, especially accelerator-based driver

- Developing international collaboration

An Inertial Fusion Power Plant Based on a Heavy-Ion Induction Linear Accelerator



Inertial Fusion Energy

- Inertial fusion energy has been reviewed often
  - Fusion Policy Advisory Committee (FPAC)--1990
  - Fusion Energy Advisory Committee (FEAC)--1993
  - Fusion Energy Sciences Advisory Committee (FESAC)--1996
- We regard the reports and recommendations highly, and expect them to remain relevant in a broad sense

Inertial Fusion Energy

- Questions of scientific merit and energy relevance were addressed positively

- The potential for inertial fusion energy is real

- The fusion program has had a mandate to pursue two independent approaches to fusion energy development, magnetic and inertial confinement fusion

Inertial ***Fusion Energy***

- Our strategy accepts target physics as the highest priority inertial fusion activity and that it is being developed as part of the weapons research program

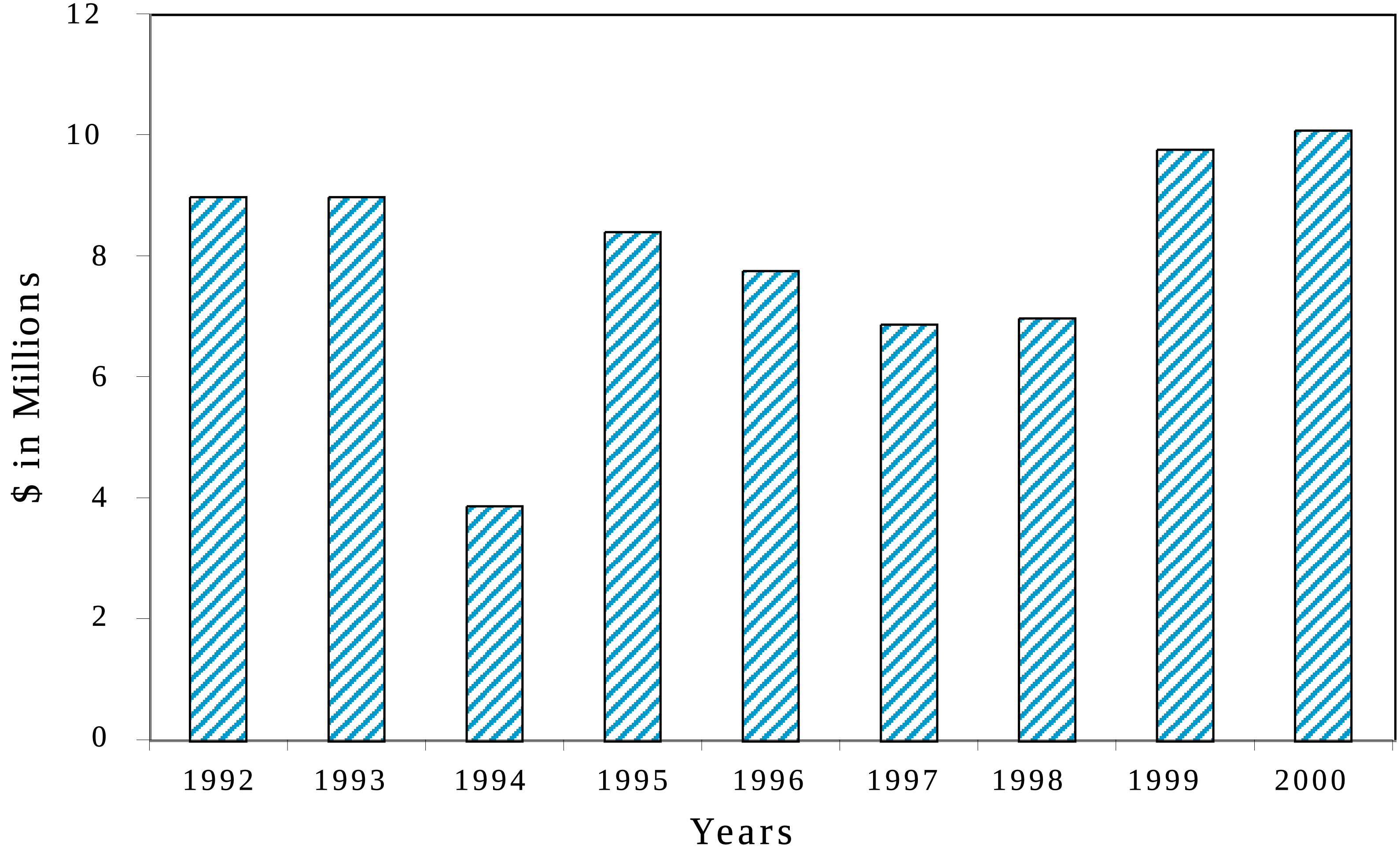
- The OFES role is to develop the "enabling technology" for inertial fusion energy

  - The highest IFE priority in the OFES program has been the development of heavy-ion accelerators as the most desirable drive for energy applications

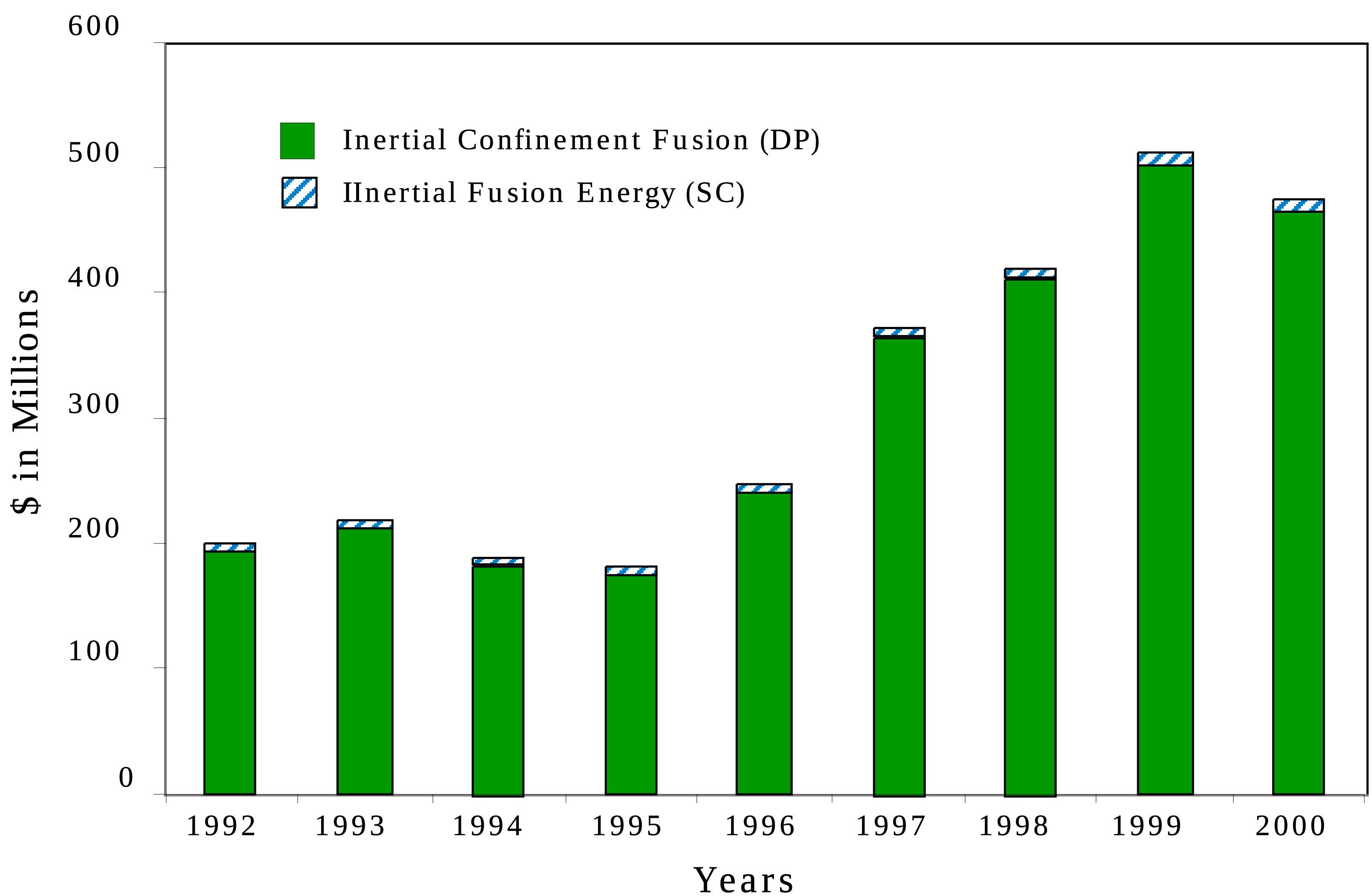
  - The IFE program has also included other efforts in IFE power systems studies and related technologies

  - Need to reassess potential of other drivers

Inertial Fusion Energy Budget

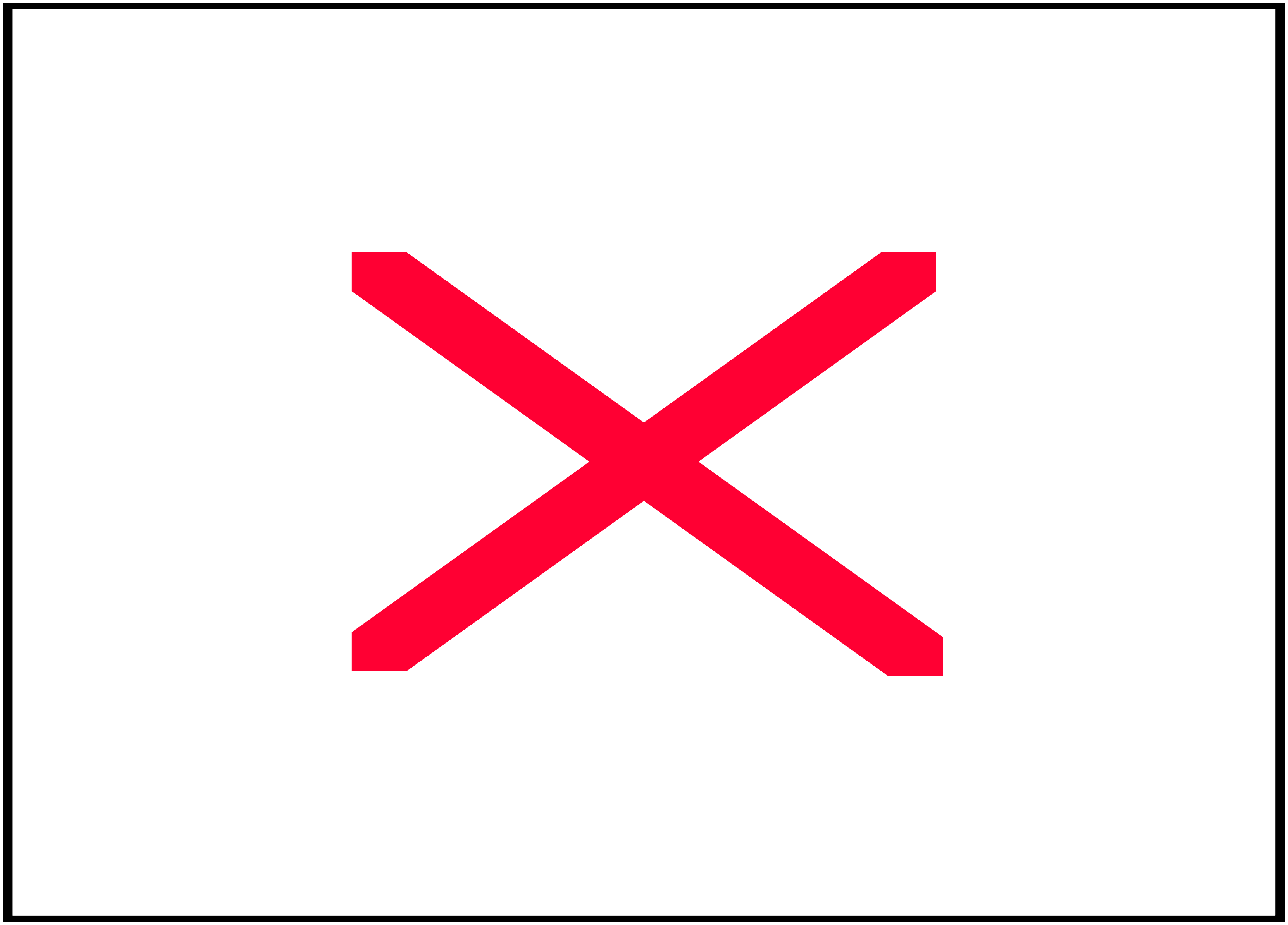


Total Inertial Fusion Budgets



Systems Studies Activities Addressing the Marketplace for Fusion

- o Strategic planning and forecasting
  - Assess fusion role in sustainable energy strategy
  - Determine how fusion can best fit
  - Initial focus on role of large fusion power stations, macro-economic models, and outreach
- o Fusion applications and test facilities design studies
  - Explore potential for non-electric applications
  - Evaluate potential for hydrogen production
  - Conceptual design for near-term applications

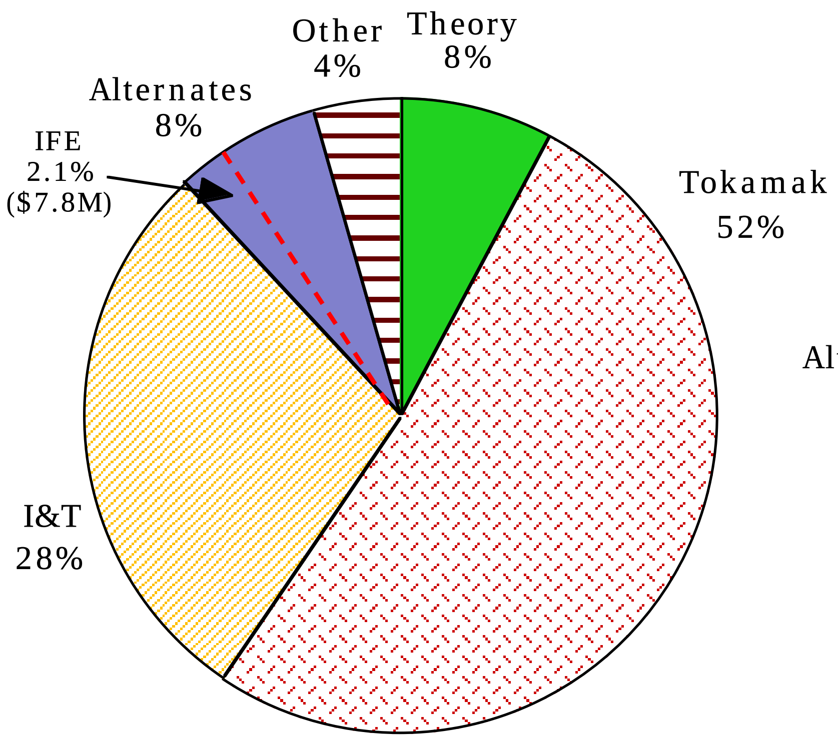


Optimism for Fusion in Long Term

- "Rehabilitation" of nuclear energy
- Environmental issues, such as climate change
- Global population growth and resource depletion issues

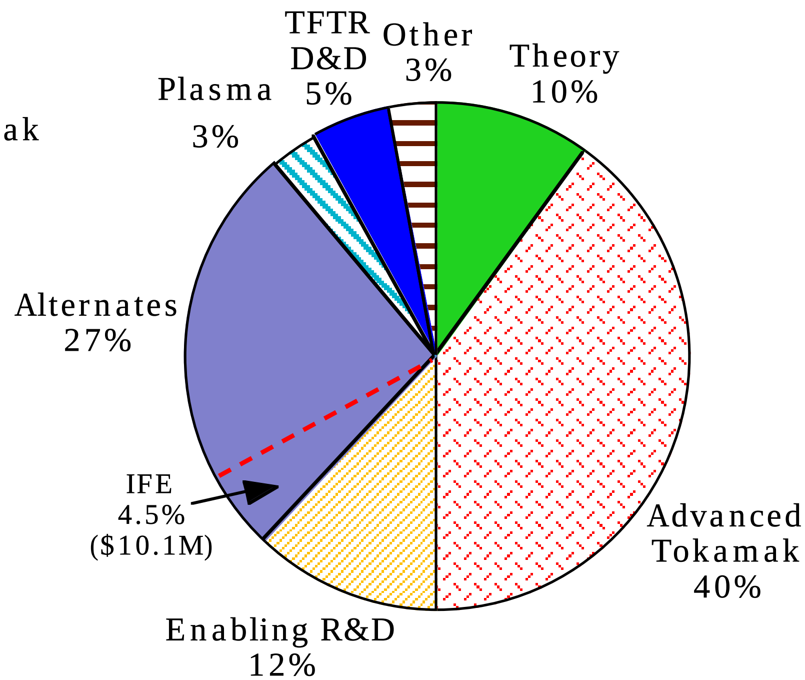
Restructuring Changes Fusion Energy Sciences Budget

FY 1996 President's Request



Total $366M

FY 2000



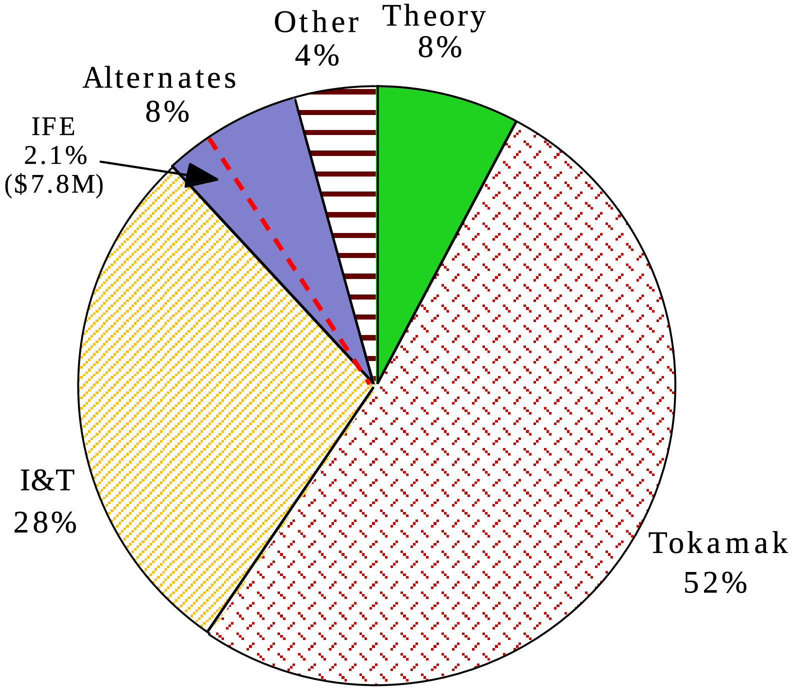
Total $222.6M

3/29/99

Restructuring Changes in Fusion Energy Sciences Budget

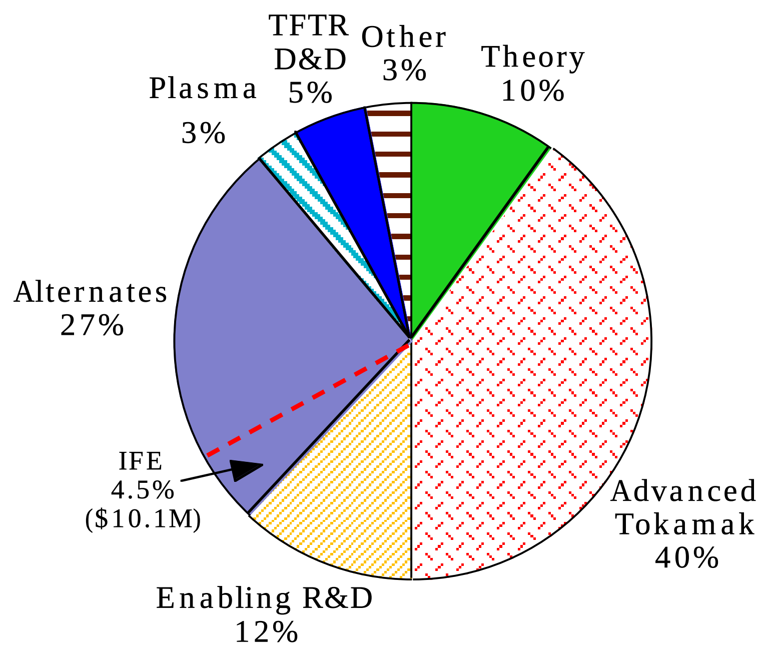
$ in Millions

FY 1996
President's Request



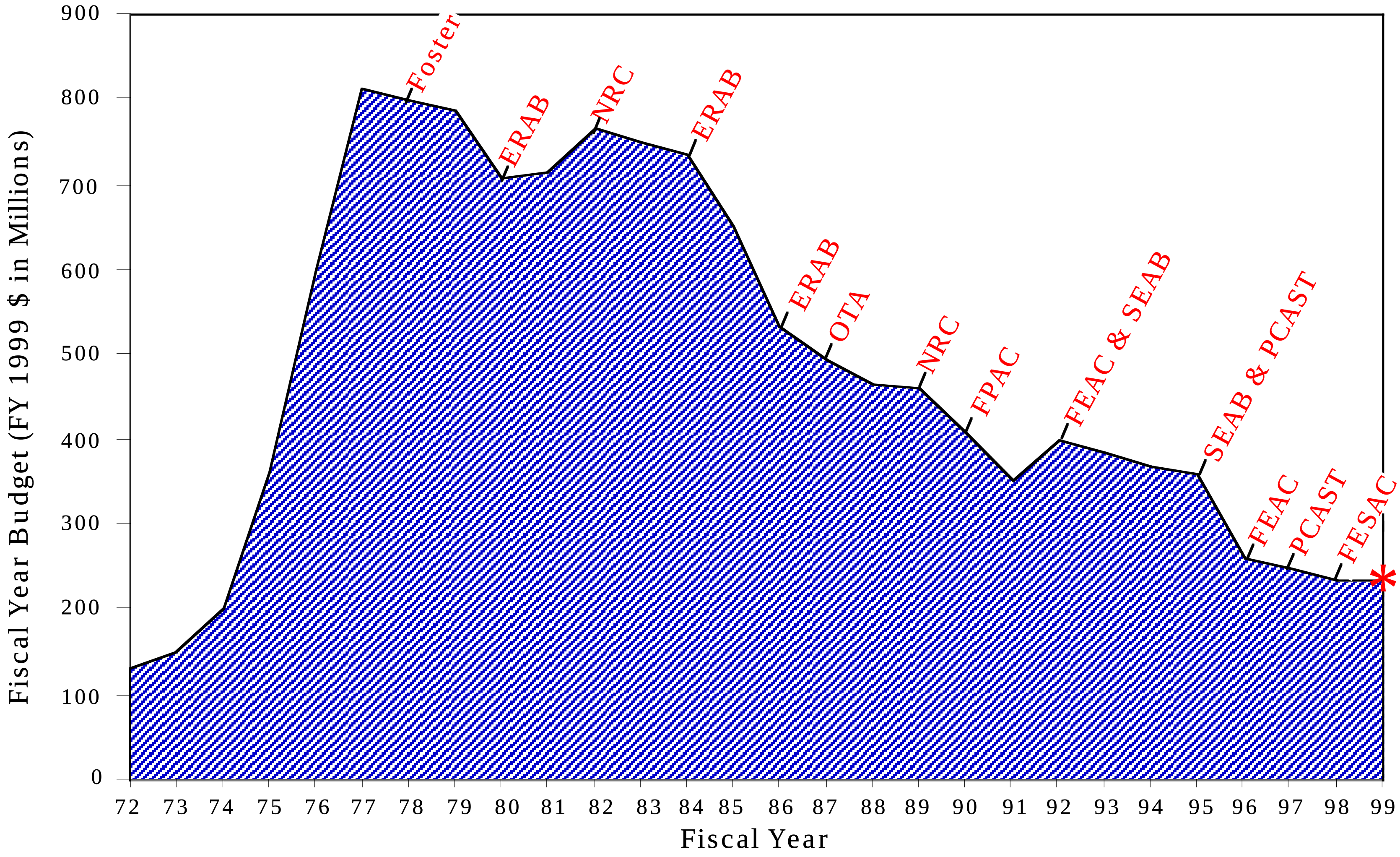
Total $366M

FY 2000



Total $222.6M

U.S. Fusion Energy Sciences Budget History and Dates of Major Fusion Program Reviews



*Reviews Scheduled for 1999: SEAB, NRC, FESAC, Fusion Summer Study

Fusion Program Reviews in 1999

- Four activities
  - Secretary of Energy Advisory Board (SEAB)
  - National Research Council (NRC)
  - Fusion Energy Sciences Advisory Committee (FESAC)
  - Fusion Summer Study

- Provide input to the development of a program plan for fusion energy sciences by the end of 1999
  - Paths for both energy and science goals
  - Address needs of both MFE and IFE
  - Address overlaps, international collaboration, funding constraints
  - Based on a "working" consensus

SEAB Review

- Response to Congressional request
- Review and provide recommendations on role of MFE and IFE in national fusion <u>energy</u> program
  - Appropriate balance among concepts
  - Relationship to international programs
  - IFE connection to stockpile stewardship
  - Broader science and educational goals
- Will affect content and timing of fusion energy program
- Report by May 1999

NRC Review

- o Assess scientific quality of fusion energy sciences program
  - Excellence of the research
  - Influence on other scientific areas
  - Role in higher education
  - Likelihood of providing fundamental insights and research directions
- o Review goals and strategy
- o Report by mid-September 1999

FESAC Review

- o Report on opportunities and requirements including technical requirements of fusion energy by February 1999

- o Lead Community assessment of restructured program

  - Recommend further redirection given flat budgets
  - Recommendations on P-o-P experiments
  - Recommendations on balance

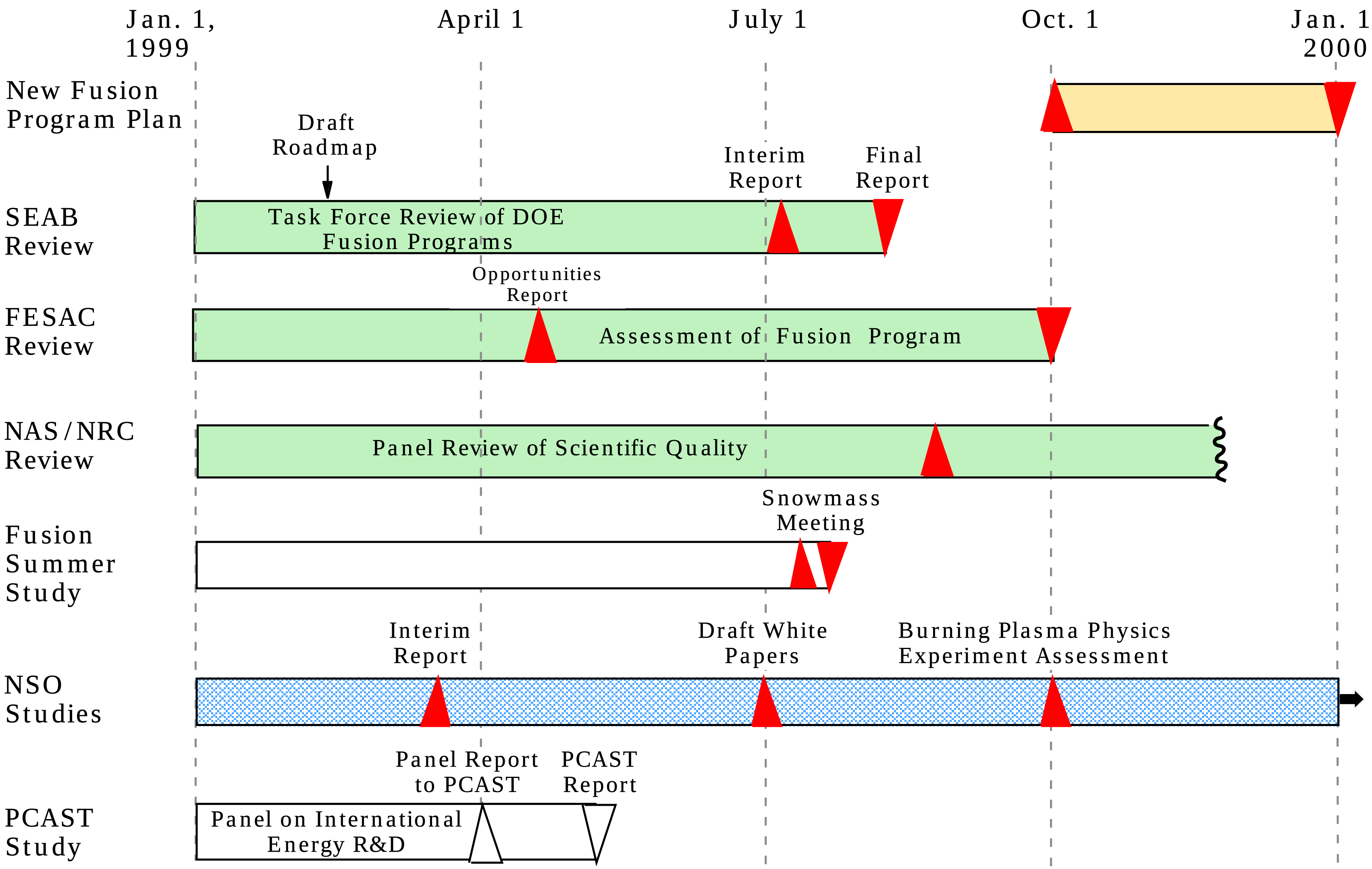
    -- Tokamak versus non-tokamak physics
    -- Magnetic versus inertial fusion energy

  - Recommendations on program content, emphasis, and balance
  - Complete by September 1999

Fusion Summer Study

- Examine opportunities and directions in fusion energy science for the next decade
- Develop scientific and technical basis for consensus on:
  - Key issues in plasma science, technology, energy, environment
  - Opportunities and potential contributions of existing and possible future facilities to reduce costs and increase economic and environmental attractiveness
- Chaired by Rich Hawryluk, Grant Logan, and Mike Mauel
- To be held at Snowmass, CO; July 11-23, 1999
- Details on http://www.pppl.gov/snowmass/

Fusion Review and Planning Activities for 1999



Summary Conclusions

- o The fusion program is not an ordinary science program--it has a specific energy vision as well

- o The review and planning activities this year will assess both aspects of the fusion program

- o The realities of budget constraints limit the size and scope of the fusion program

  - MFE is dependent upon international collaboration

  - IFE is dependent upon weapons research

- o Reviews and planning meetings will lay the foundation for future progress toward fusion science and energy goals

Backup

Criteria for the National Academy of Science Review

- **Excellence**: the quality of the science
- **Impact**: the influence that fusion research has had on other areas
- **Education**: the role fusion porgram in higher education
- **Stewardship**: how well the fusion program has sustained plasma science
- **Strengthening Foundations**: the likelihood of discovering fundamental insights that lead to promising new directions

National Research Council, 1995

“***Plasma science is the study of the ionized states of matter.***”

- “Plasma Science includes plasma physics but aims to describe a much wider class of ionized matter in which, for example, atomic molecular, radiation transport, excitation, and ionization processes, as well as chemical reactions, can play significant roles.”

- “The goal of plasma physics is to describe elementary processes in completely ionized matter”

- “Plasma science has played a major role in magnetic fusion research from its inception and, in many ways, the quest for controlled fusion has been critical in the development of modern plasma science.”

Science Research Activities in FY 1999

- o Continue to develop and validate computational models of plasma behavior and prepare fusion proposals for the Scientific Simulation Initiative

- o Several new innovative concept experiments will achieve full operational status in FY 1999:

  - The flow stabilized Z pinch (U. Wash)

  - Pegasus ST (U. Wisc)

  - HSX stellarator (U. Wisc)

  - Spheromak (LLNL

- o NSTX will be completed in April and will have a brief (6 week) run period to explore systems operation and benchmark initial diagnostics. The NSTX national team has been established