Fusion Development Path Panel

Preliminary Report

Summary for NRC BPAC Panel
(Focus on MFE)

Professor Robert J. Goldston for
the FESAC Development Path Panel

January 17, 2003

Charge for Preliminary Report

- "… I would like FESAC to develop a **plan with the end goal of the start of operation of a demonstration power plant in approximately 35 years.** The plan should recognize the capabilities of all fusion facilities around the world, and include both magnetic fusion energy (MFE) and inertial fusion energy (IFE), as both **MFE and IFE** provide major opportunities for moving forward with fusion energy."

- "The report would be most helpful if it could be done in two phases. Building as much as possible on previous work of FESAC, the first phase would be a **preliminary report, completed by December 1, 2002,** which would both provide a **general plan** to achieve the aforementioned goal and identify those **significant issues that deserve immediate attention.** As a second phase, I would like by March 2003, or earlier, a more detailed plan upon which budgeting exercises can be based."

Panel Members

- Mohamed Abdou, University of California, Los Angeles
- Charles Baker, University of California, San Diego
- Michael Campbell, General Atomics
- Vincent Chan, General Atomics
- Stephen Dean, Fusion Power Associates
- Robert Goldston (Chair), Princeton Plasma Physics Laboratory
- Amanda Hubbard, MIT Plasma Science and Fusion Center
- Robert Iotti, CH2M Hill
- Thomas Jarboe, University of Washington
- John Lindl, Lawrence Livermore National Laboratory
- Grant Logan, Lawrence Berkeley National Laboratory
- Kathryn McCarthy, Idaho National Engineering Laboratory
- Farrokh Najmabadi, University of California, San Diego
- Craig Olson, Sandia National Laboratory, New Mexico
- Stewart Prager, University of Wisconsin
- Ned Sauthoff, Princeton Plasma Physics Laboratory
- John Sethian, Naval Research Laboratory
- John Sheffield, ORNL – UT Joint Institute for Energy and Environment
- Steve Zinkle, Oak Ridge National Laboratory

Outline

- Principles
  - Definition of Demo
  - Portfolio Management Philosophy
  - External Linkages
- Illustrative General Plan
  - Panel’s Assessment
- Significant Issues that Deserve Immediate Attention
  - MFE Burning Plasma
  - Domestic Research – MFE & IFE
- Conclusions

Principles: Definition of Demo

The goal of the plan is operation of a US demonstration power plant (Demo), which will enable the commercialization of fusion energy. The target date is about 35 years. Early in its operation the Demo will show net electric power production, and ultimately it will demonstrate the commercial practicality of fusion power. It is anticipated that several such fusion demonstration devices will be built around the world. In order for a future US fusion industry to be competitive, the US Demo must:

a. be safe and environmentally attractive,
b. extrapolate to competitive cost for electricity in the US market, as well as for other applications of fusion power such as hydrogen production,
c. use the same physics and technology as the first generation of competitive commercial power plants to follow, and
d. ultimately achieve availability of ~ 50%, and extrapolate to commercially practical levels.

Principles: Portfolio Management (a)

The plan recognizes that difficult scientific and technological questions remain for fusion development. A diversified research portfolio is required for both the science and technology of fusion, because this gives a robust path to the successful development of an economically competitive and environmentally attractive energy source. In particular both Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE) portfolios are pursued because they present major opportunities for moving forward with fusion energy and they face largely independent scientific and technological challenges. The criteria for investment, in order to optimize cost-effectiveness, are:

a. **Quality**

- • Excellence and innovation in both science and technology are central.
- ii. Development of fundamental plasma science and technology is a critical underpinning.
- iii. The US must be among the world leaders in fusion research for the US fusion industry to be competitive.

Principles: Portfolio Management (b,c)

b. **Performance**:

- i. The plan is structured to allow for cost-effective staged investments based upon proven results. Decision points are established for moving approaches forward, as well as for “off-ramps”.
- ii. Technically credible alternative science and technology pathways that are judged to reduce risk substantially or to offer substantially higher payoff (“breakthroughs”) are pursued.
  - It is not a requirement, however, that every pathway be funded at the level needed for deployment in 35 years.
- Inevitably later elements of the plan are less well defined at this time than earlier ones; a goal of earlier elements is to help define later ones.

c. **Relevance**:

- i. Technical credibility
- ii. Environmental attractiveness
- iii. Economic competitiveness

Principles: External Leverages

The plan recognizes and takes full advantage of external leverages.

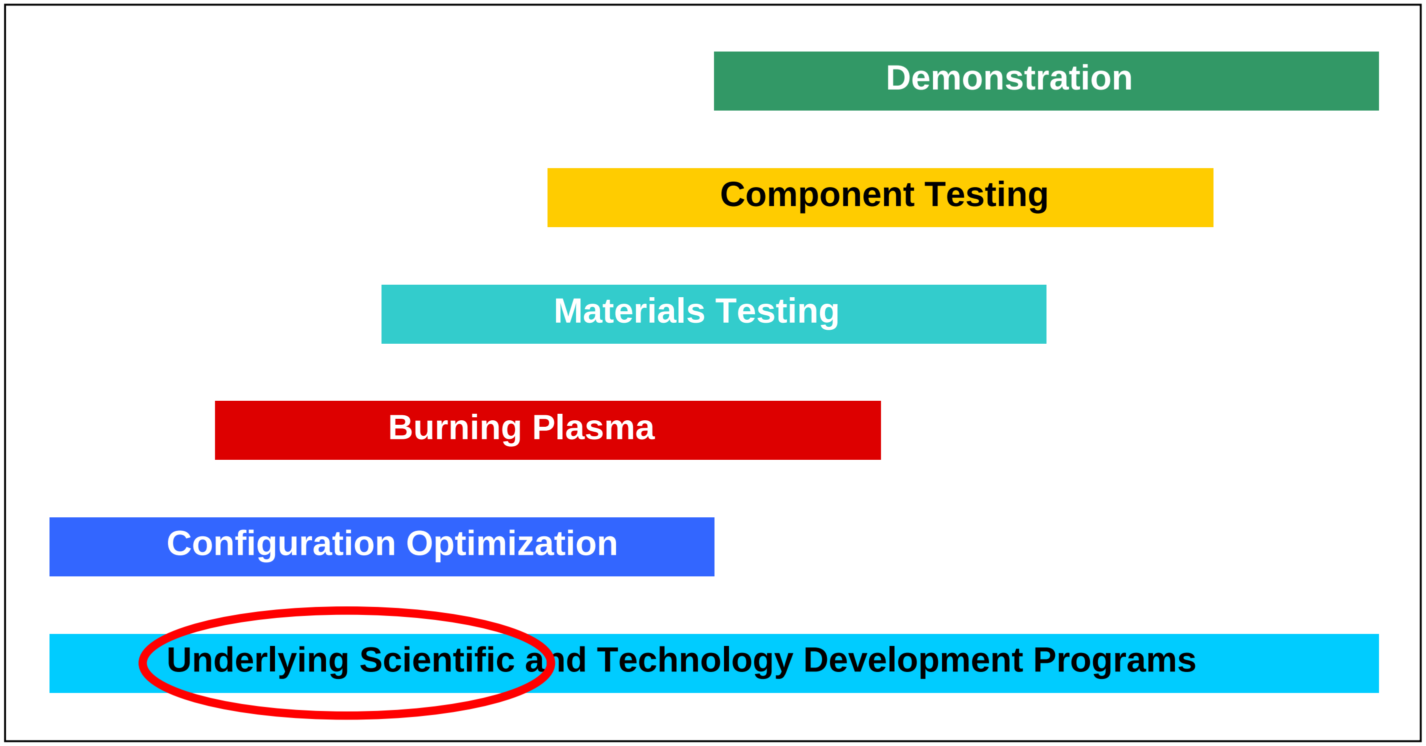
a. The plan depends upon the international effort to develop fusion energy, positioning the U.S. to contribute to this development and ultimately to take a leadership position in the commercialization and deployment of fusion energy systems.

b. The plan takes full advantage of developments in related fields of science and technology, such as advanced computing and materials nanoscience.

c. The high quality of the science and technology developed for fusion gives rise to opportunities for broader benefits to society. Thus connections to other areas of science and technology are actively pursued.

d. For Inertial Fusion Energy, the plan takes full advantage of advances supported by the US National Nuclear Security Administration (NNSA) in the area of Inertial Confinement Fusion (ICF).

The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges

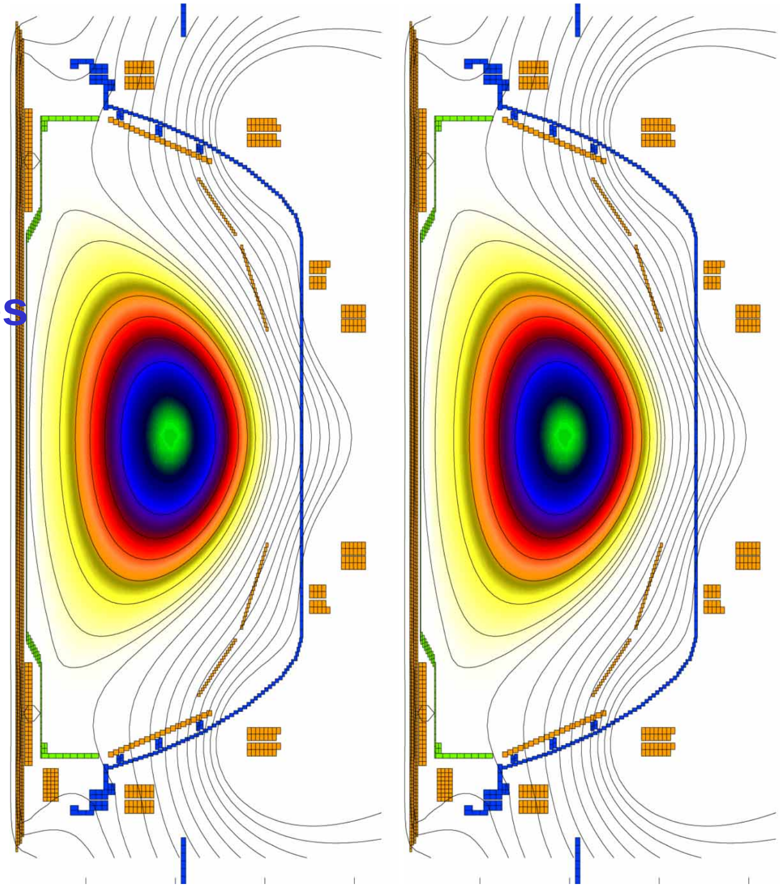


Overlapping scientific and technological challenges define the sequence of major facilities needed in the fusion development path. Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experiments, materials development and plasma and fusion power technologies precede and then underlie research on the major facilities.

Plasma Science Challenges

NRC Plasma Science Committee

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



Gyrokinetic Simulations of Plasma Microinstabilities

simulation by

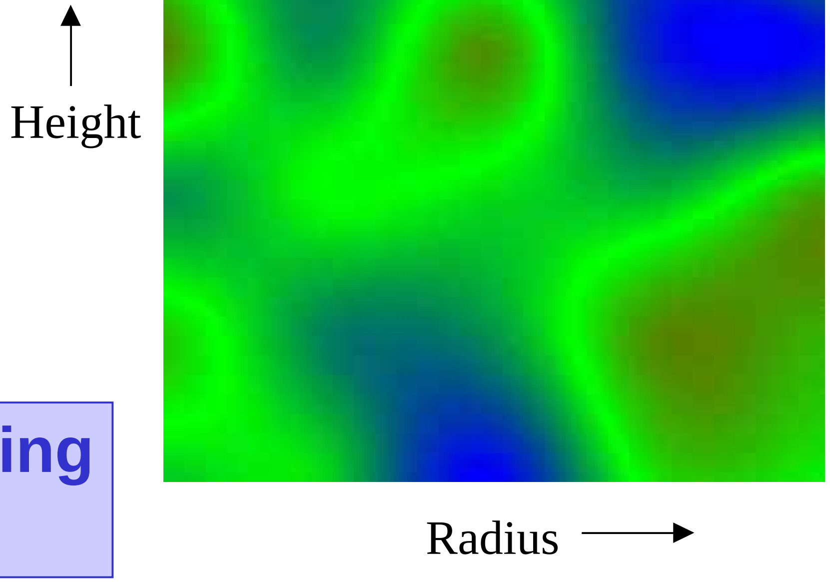
Zhihong Lin et al.

Presidential Early Career Award
for Scientists and Engineers, 2000

Direct Measurements of Turbulence Supports Shear Flow Model

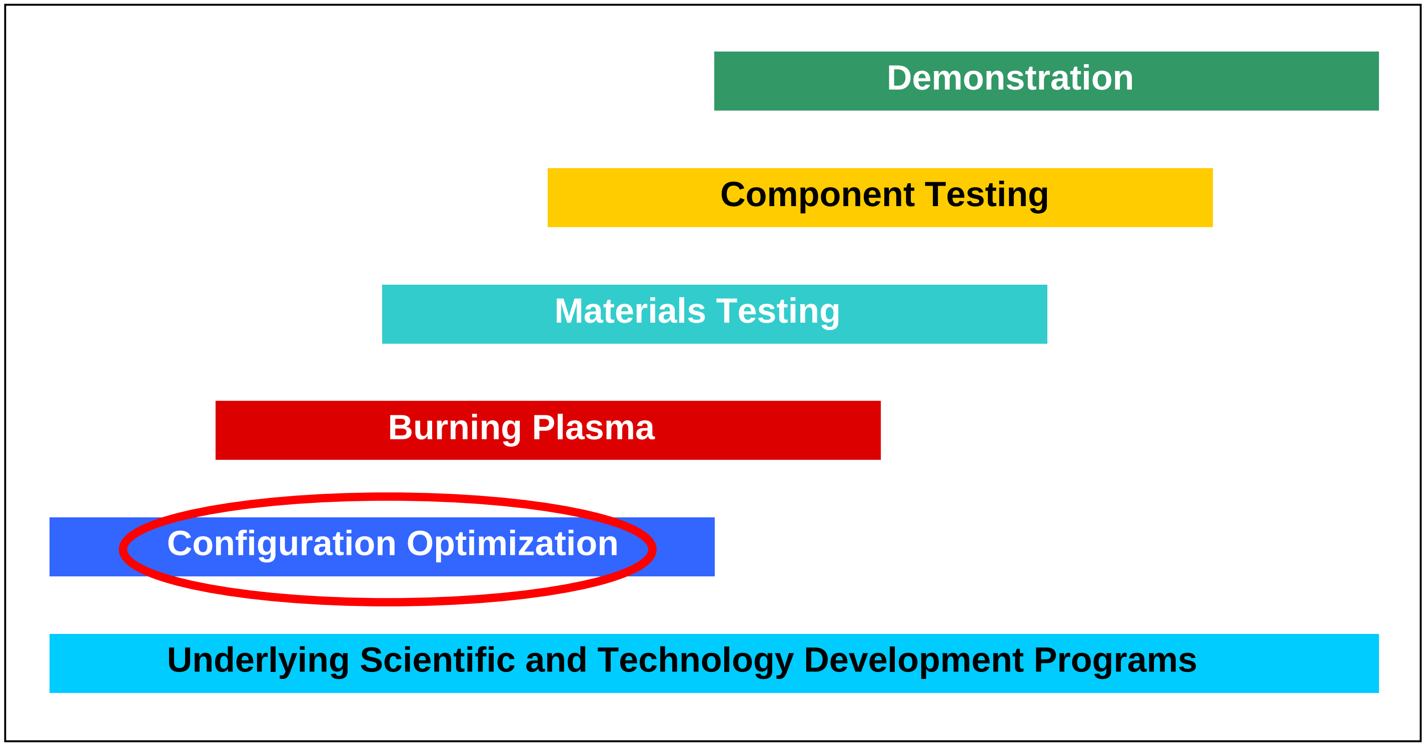
- **Movies of turbulent fluctuations in plasma density via beam emission spectroscopy.**
  - **University of Wisconsin**
- **From DIII-D advanced tokamak experiment**
  - **Varied flow speed across plasma results in tearing of structures**
    - *Red = high density*
    - *Green = average density*
    - *Blue = low density*

(Frame rate: 1,000,000 /sec)



Goal: Fundamental understanding for practical fusion energy.

The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges



Demonstration

Component Testing

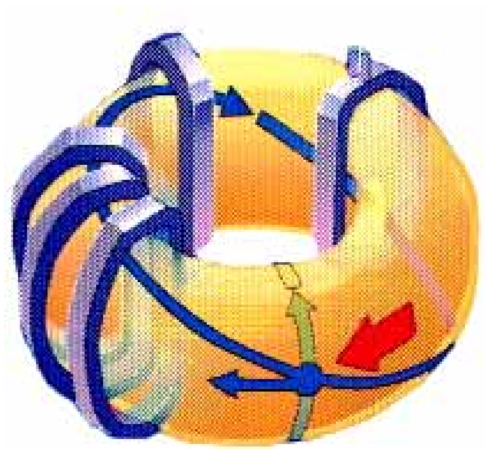
Materials Testing

Burning Plasma

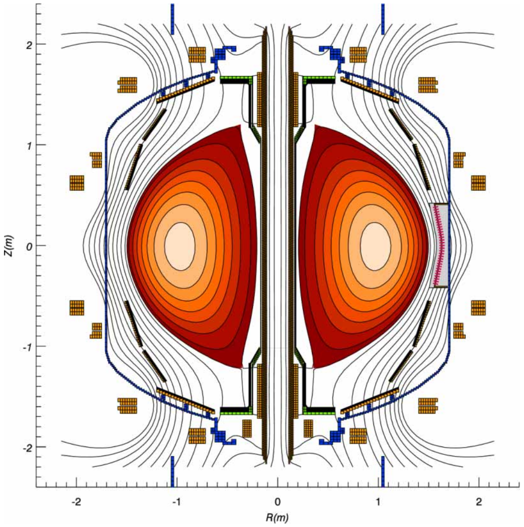
Configuration Optimization

Underlying Scientific and Technology Development Programs

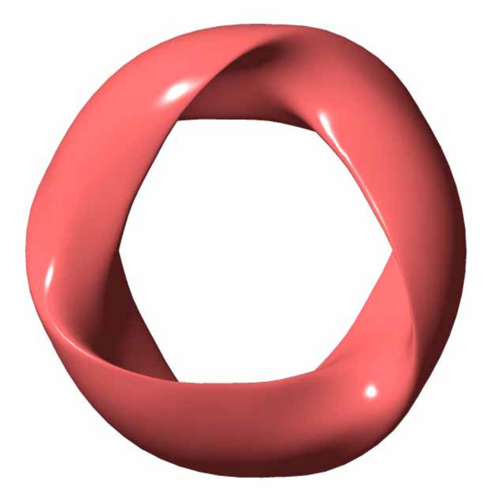
Advanced Plasma Configurations Address Key Fusion Issues: Steady state, Power per cost, Disruptions



Advanced Tokamak
Active instability control and driven steady-state.



Spherical Torus and Reversed Field Pinch
High fusion power at low magnetic field.

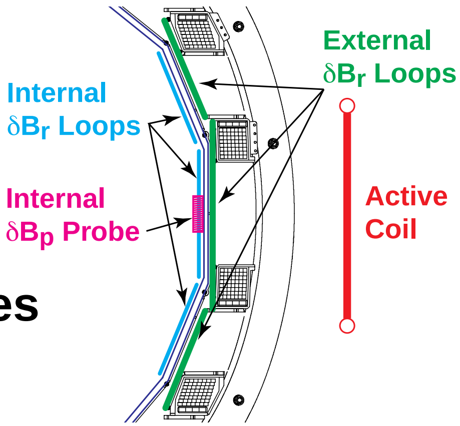


Compact Stellarator
Passive stability and steady-state operation.

Goal: Combine domestic innovation with ITER science and technology for **practical fusion energy.**

Tokamaks: Active Control of MHD Instabilities

Active magnetic feedback with sensors and power supplies stabilizes Resistive Wall Modes

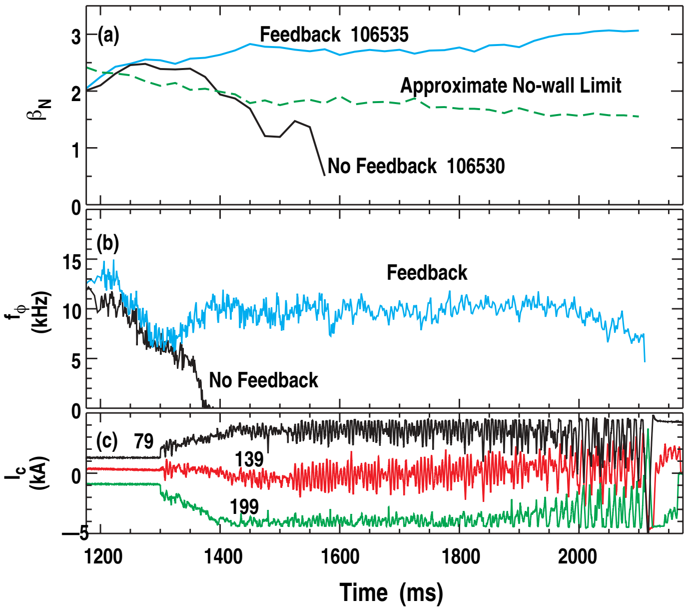


Internal δB_r Loops

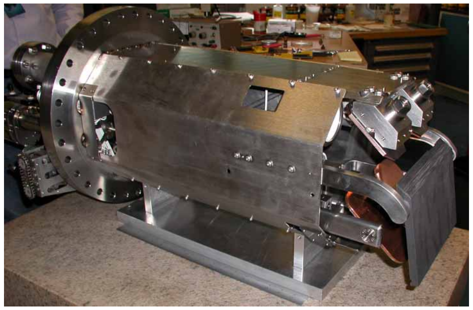
Internal δB_p Probe

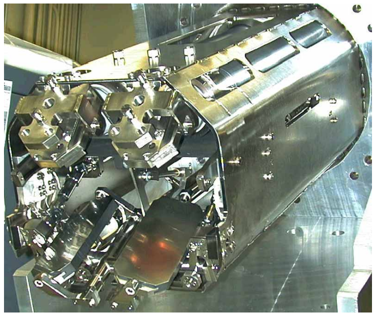
External δB_r Loops

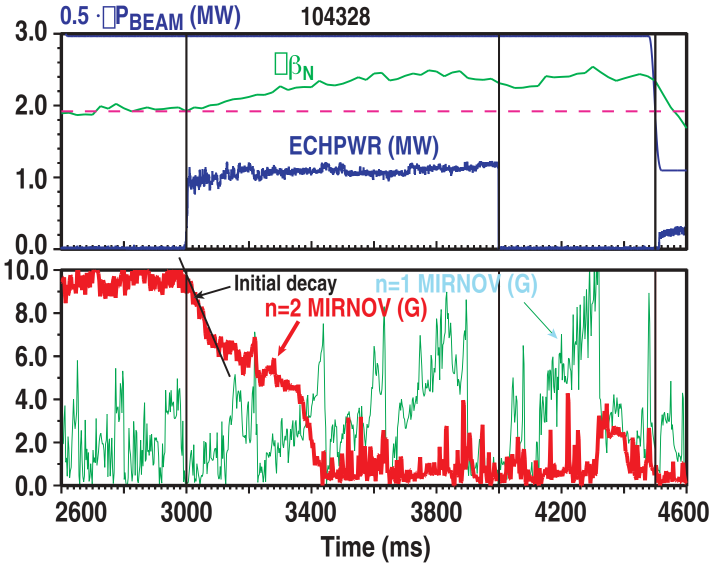
Active Coil

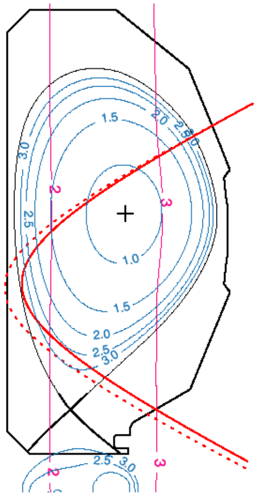


Steerable ECH/ECCD launchers allow stabilization of Neoclassical Tearing Modes

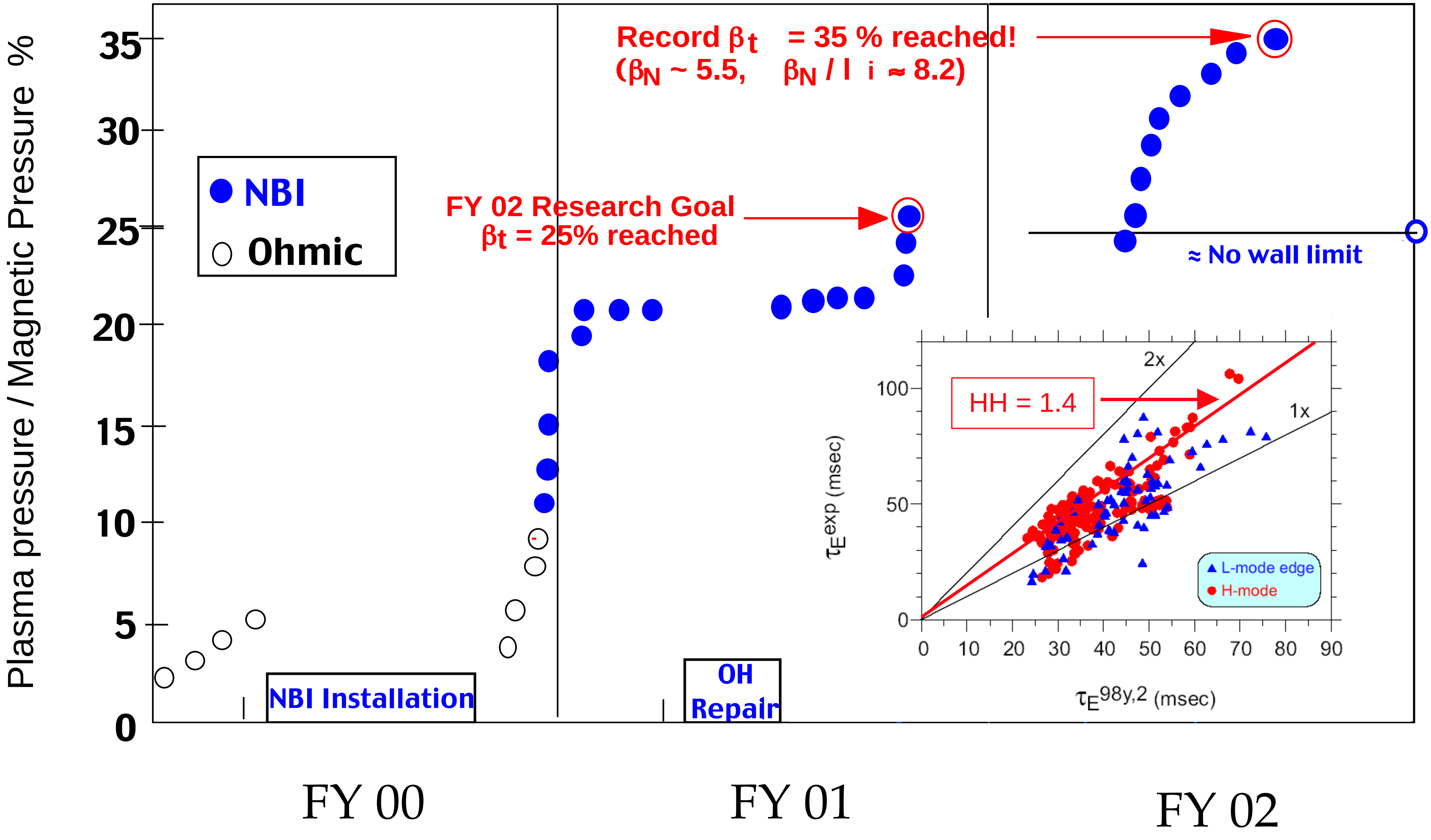








National *Spherical Torus* Experiment is Delivering Remarkably High Performance



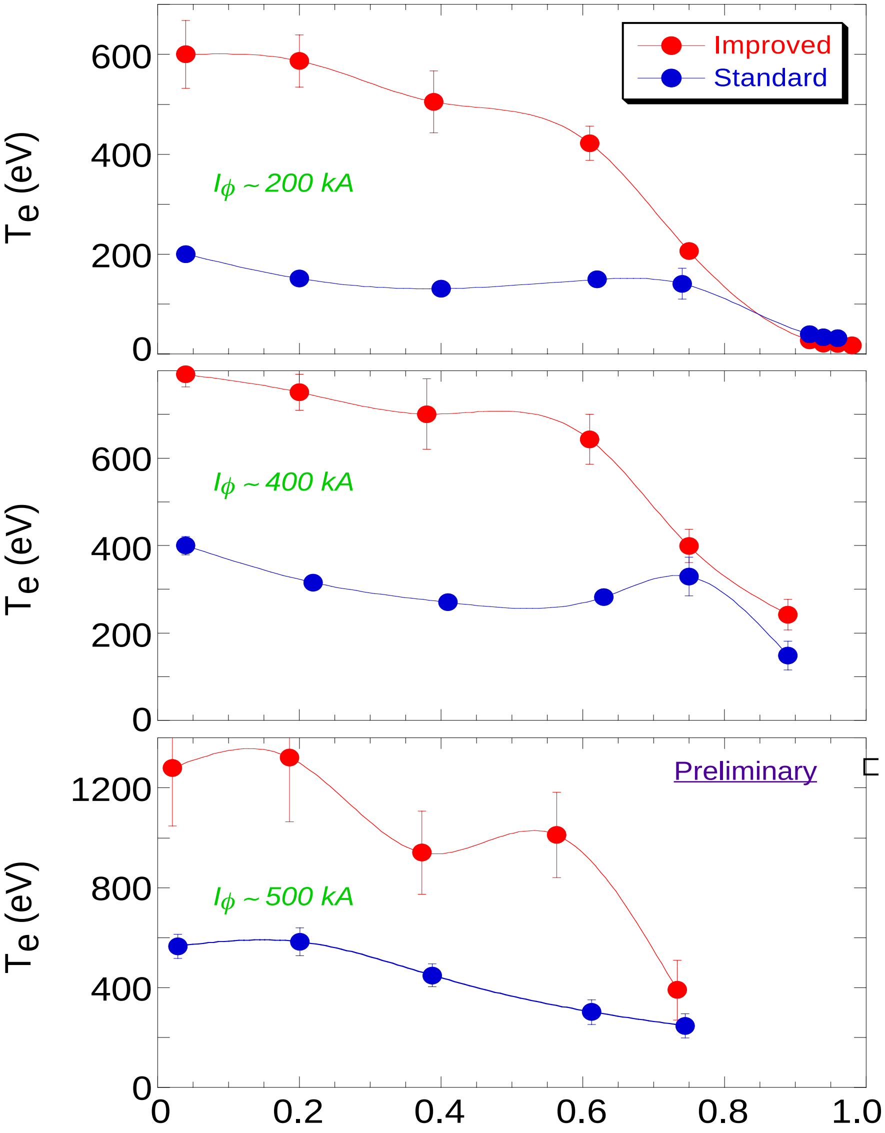
Record β_t = 35 % reached! (β_N ~ 5.5, $\beta_N / l_i \approx 8.2$)

FY 02 Research Goal β_t = 25% reached

≈ No wall limit

HH = 1.4

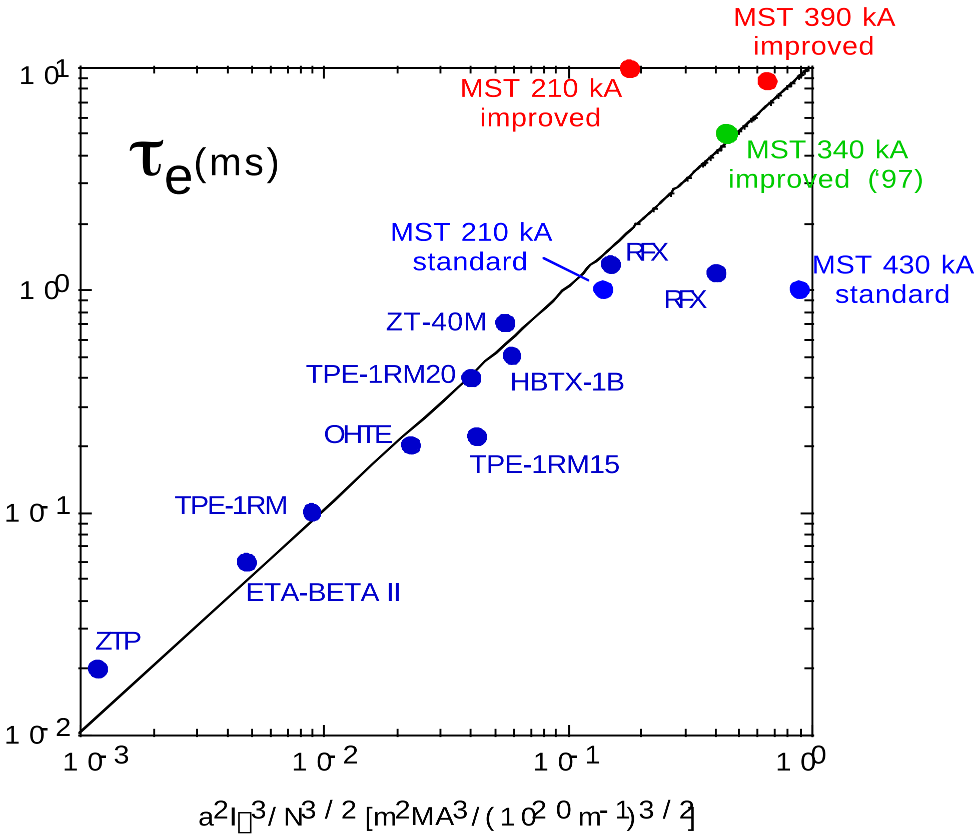
Dramatic Increase of Te with j(r) Control in RFP



β_{tot} ~ 12%

for

200 kA PPCD



Compact Stellarator offers Passive Stability and Steady-State Operation

Goal:
Stable, steady-state operation with excellent plasma confinement and low power for plasma sustainment and control. No RWM's, no NTM's, no rotation drive, no feedback!

Technique:
Use massively parallel computing to optimize 3-dimensional shaping.

Cost: $73.5M as spent
PPPL - ORNL construction project.
In President's FY2003 budget.
Critical Decision - 1 approved.

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

Australia, Austria, Japan, Germany, Russia, Switzerland, Ukraine

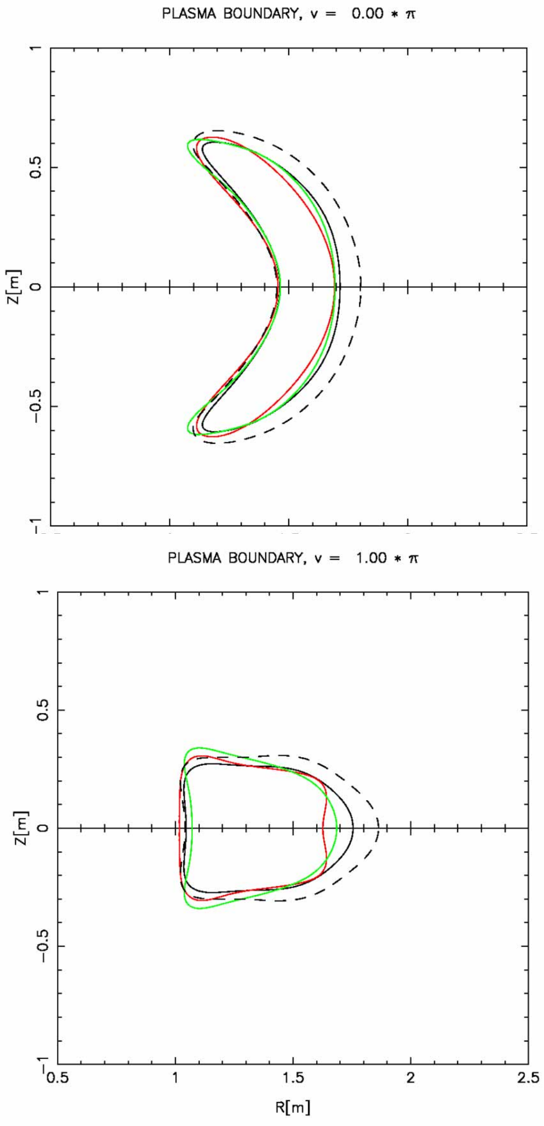
Equilibrium Maintained even with Loss of I_P or β

- **Total loss of I_P or β only causes a small shift in equilibrium (few cm), for fixed coil currents.**

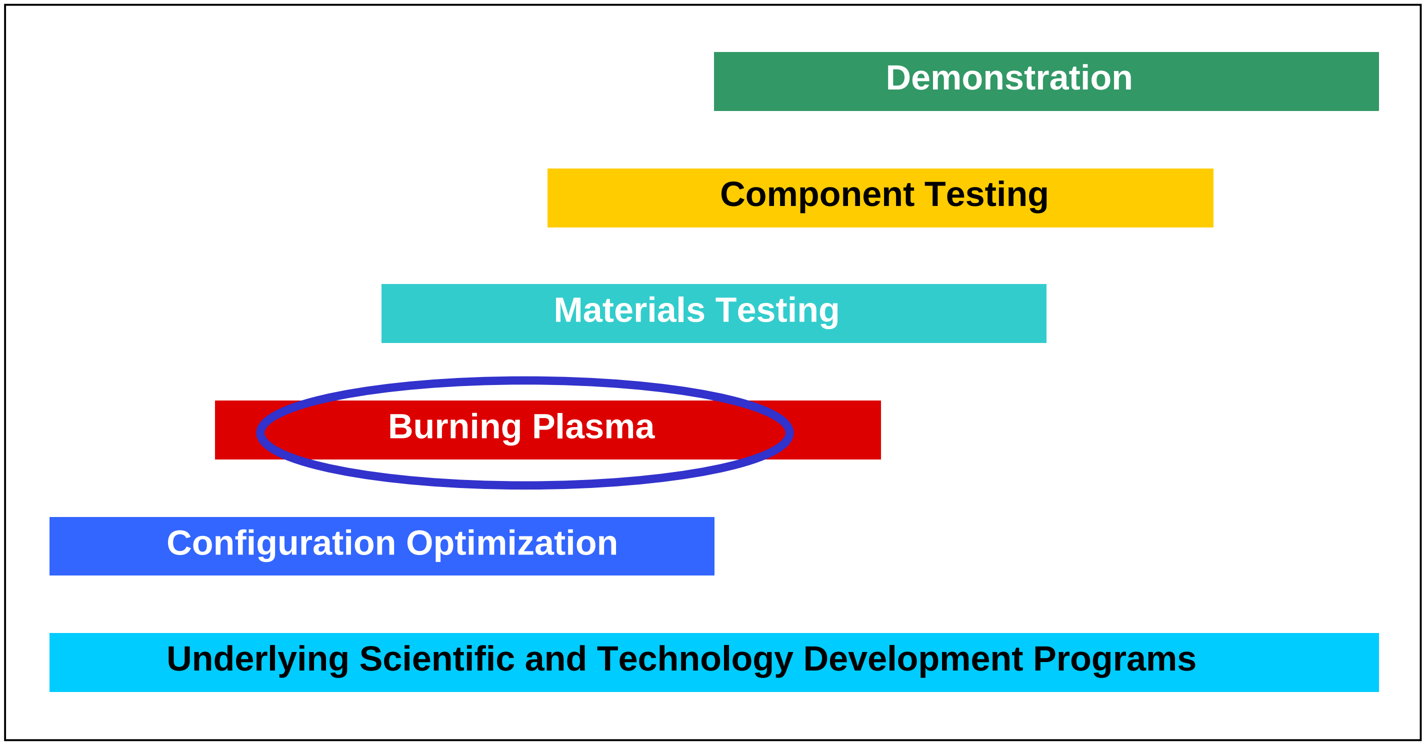
- **For comparable tokamak disruption, loss of $\beta \Rightarrow$ radial shift of ~ 30cm. Similar shift for ~ 20% drop in I_P.**

- **NCSX disruptions will not lose equilibrium, should give unique insight into disruption dynamics.**

- **Positional stability is a very attractive feature in a power-plant plasma.**



The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges



Demonstration

Component Testing

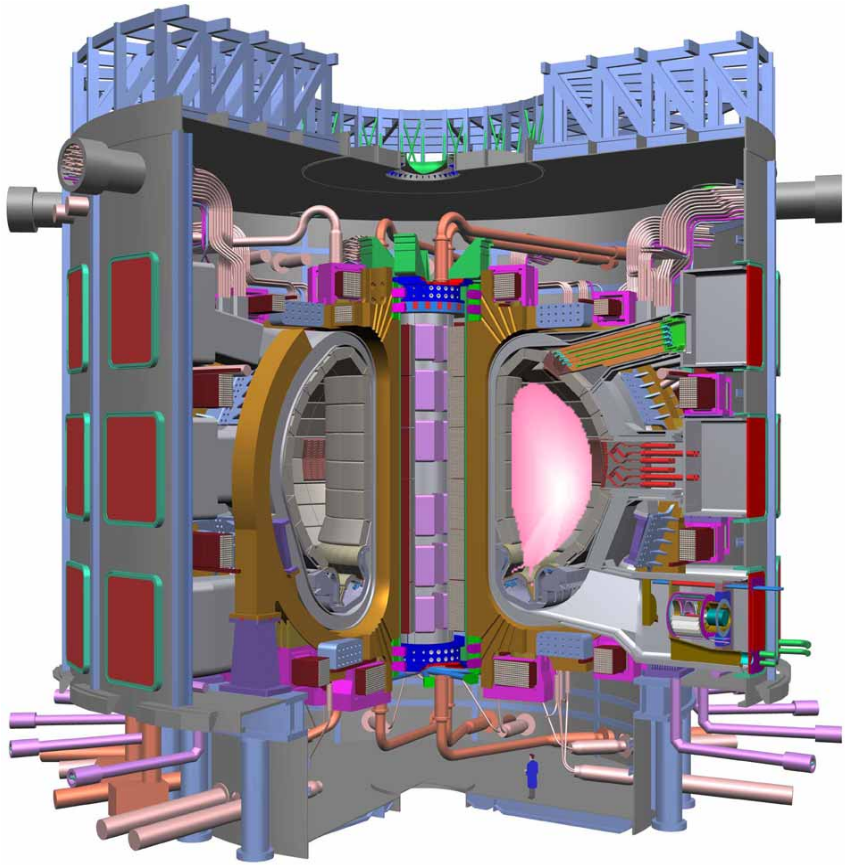
Materials Testing

Burning Plasma

Configuration Optimization

Underlying Scientific and Technology Development Programs

ITER Provides a Collaborative Opportunity to Create a Sun on Earth



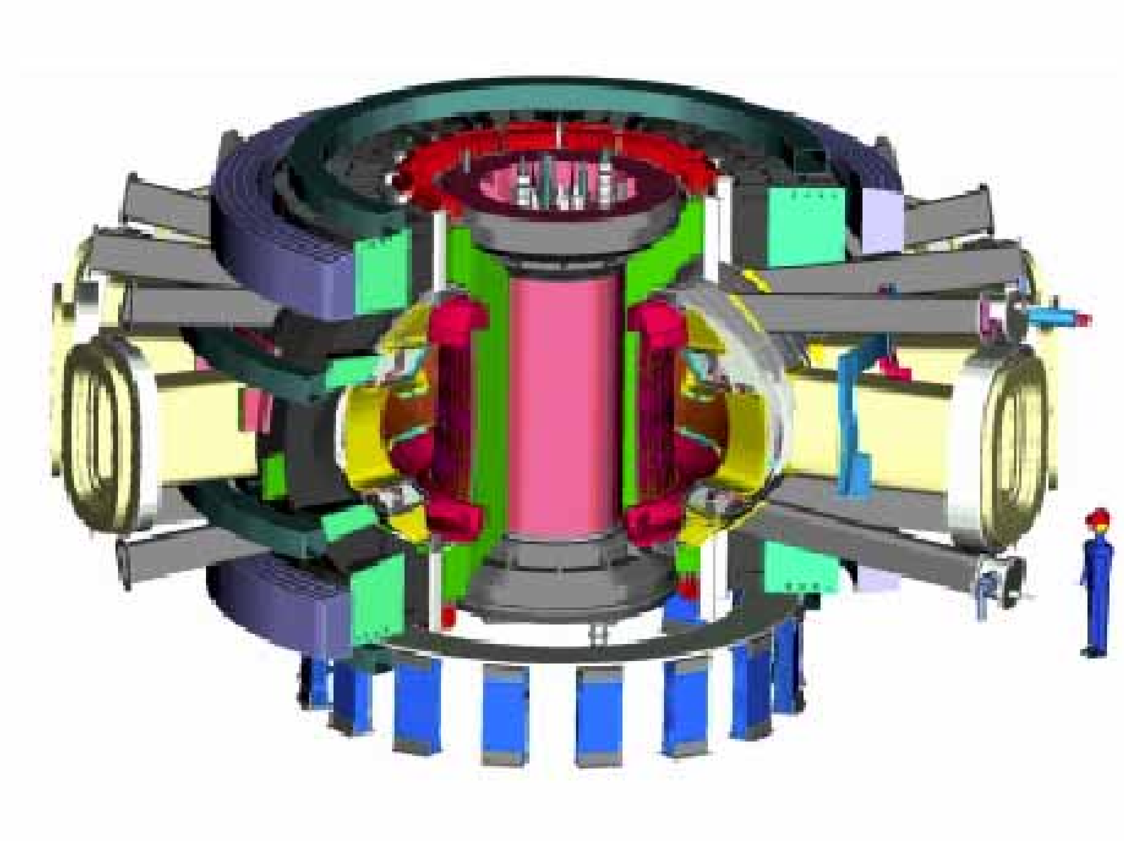
Fusion Science Benefits:
Extends fusion science to larger size, burning (self-heated) plasmas – for very long pulses.

Technology Benefits:
Fusion-relevant technologies.
High duty-factor operation.

Contributes to Spherical Torus, Reversed Field Pinch and Compact Stellarator, as well as to Advanced Tokamak.

US has had major impact on device design
500 – 700 MW thermal fusion power
400sec – 1 hr pulse length, duty factor ~25%

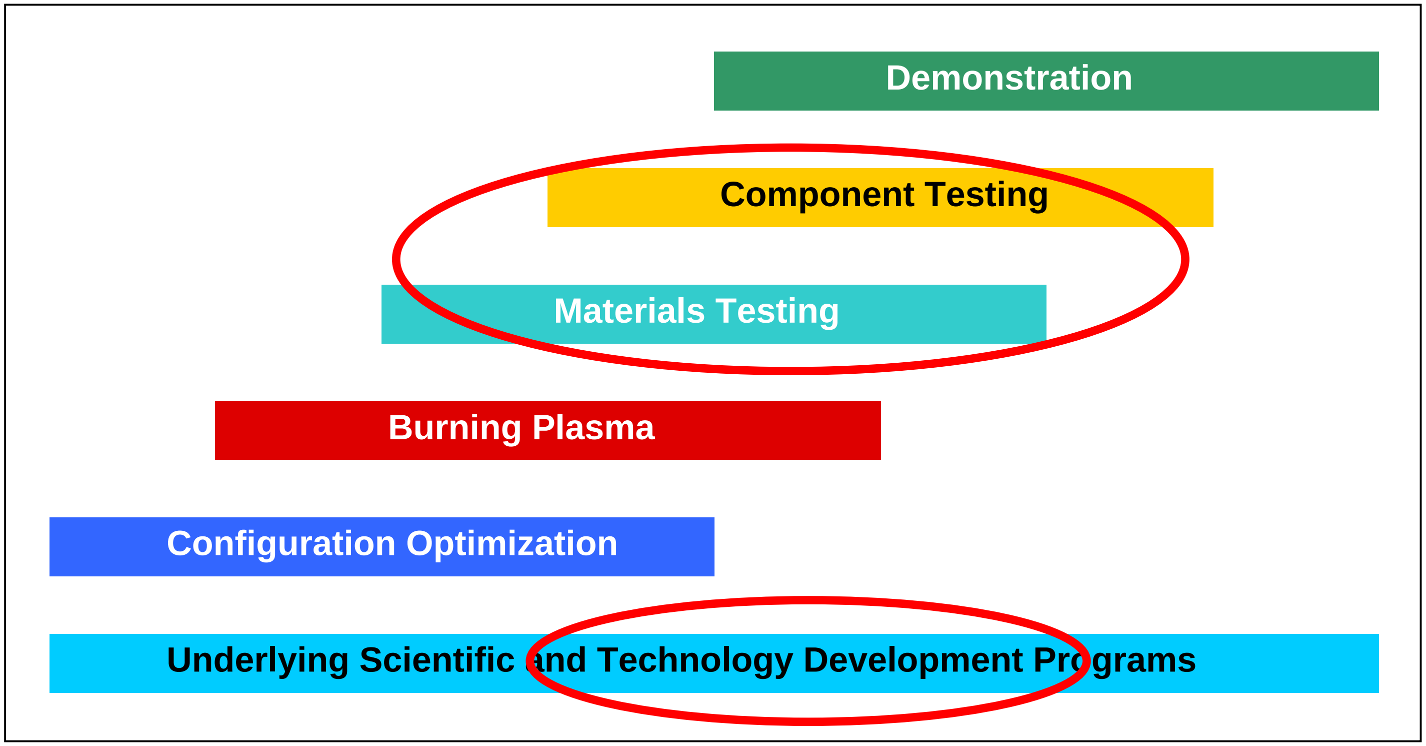
FIRE Emphasizes Burning Plasma Physics Issues



P_{fusion}	200MW
Burn Duration	20 sec
Duty factor	0.25%
Major Radius	2.14m
Minor Radius	0.58m
Cost ($FY2003)	$1.37B
	(FIRE Team estimate)

Would also contribute to fusion portfolio.

The Fusion Development Path is Defined by a Set of Overlapping Scientific and Technological Challenges



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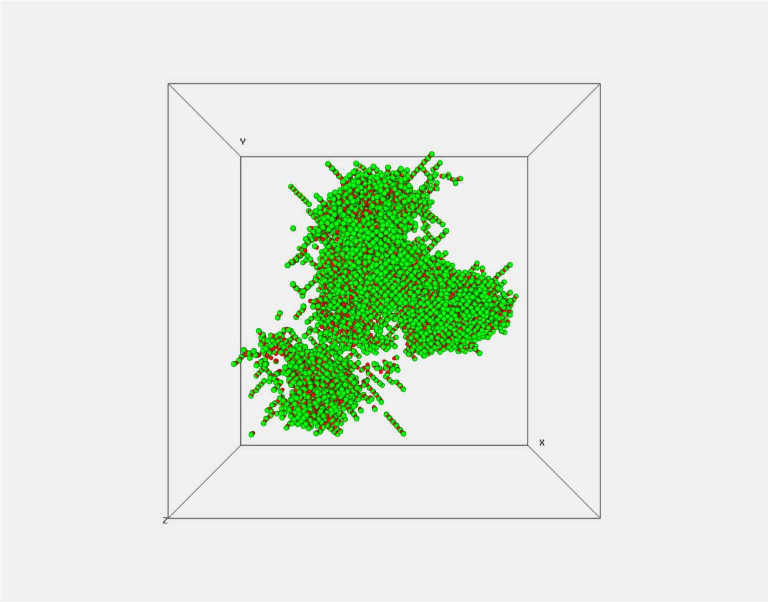
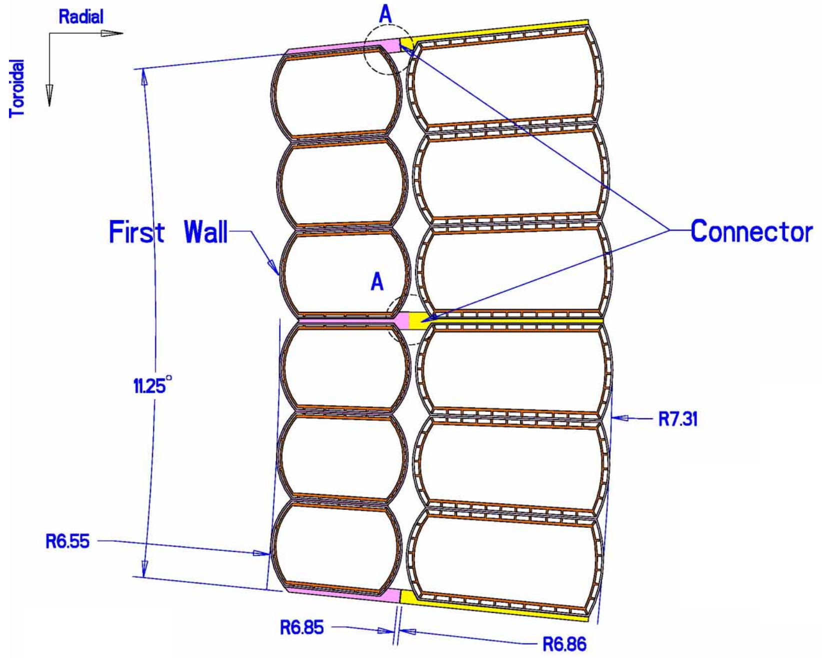
Nanoscience and New Designs are Advancing Fusion Materials and Technologies



Molecular Dynamics calculation of atomic displacements. Ferritic steels are looking very attractive.



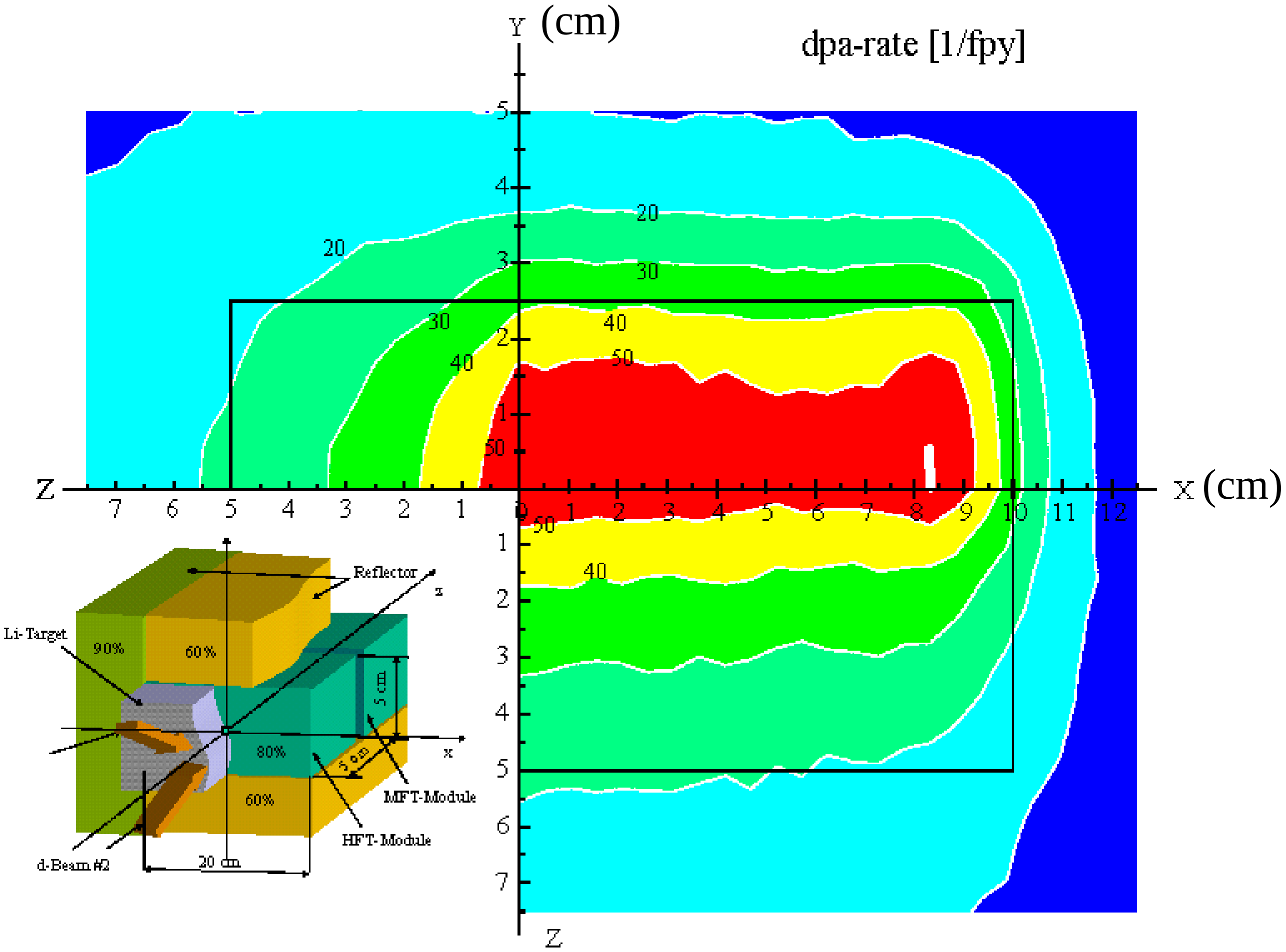
Simplified blanket designs allow high electrical efficiency and low radioactivity.

Goal: Convert fusion power to electricity with high efficiency and low radioactivity.

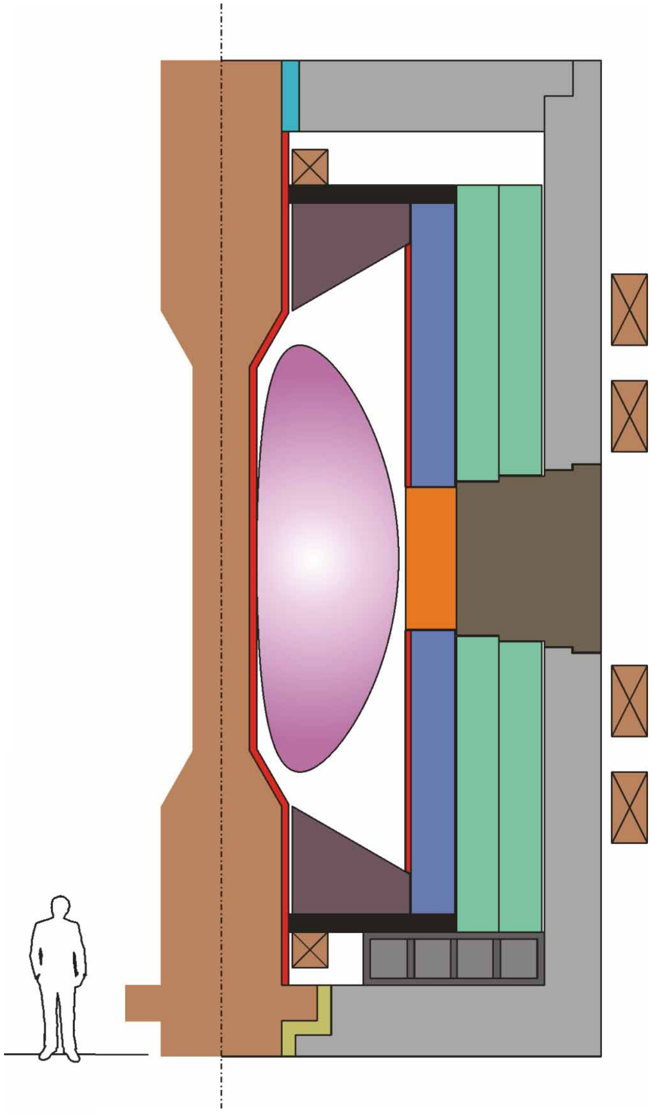
International Fusion Materials Irradiation Facility

A D-Li stripping neutron source to test fusion materials at realistic He/dpa ratios

1/4 of 5x20cm
Target zone
> 50 dpa ~
> 5 MW/m^2



Single Turn TF Coil Can Lead to an Attractive Spherical-Torus-Based Component Test Facilitiy



R = 1.2m, a = 0.8m

Mission: to quality components for high duty factor operation in Demo

Wall Loading at Test Modules (MW/m²)	1.0	3.0
HH (ITER98pby2)	1.4	1.8
Applied toroidal field (T)	2.4	2.2
Plasma current (MA)	12.6	11.4
Normalized beta (β_N)	4.1	7.0
Toroidal beta (β_T, %)	26.8	45.1
n/n_{GW} (%)	17	52
Q (using NBI H&CD)	2.4	5.8
Fusion power (MW)	72	214
Number of radial access ports	7	7
Radial access test area (m²)	12.8	12.8
P_{Heat}/R (MW/m)	37	67
Tritium burn rate (kg/full-power-year)	4	12
Total facility electrical power (MW)	286	272
Fraction of neutron capture (%)	81.6	81.6
Local T.B.R. for self-sufficiency	1.23	1.23

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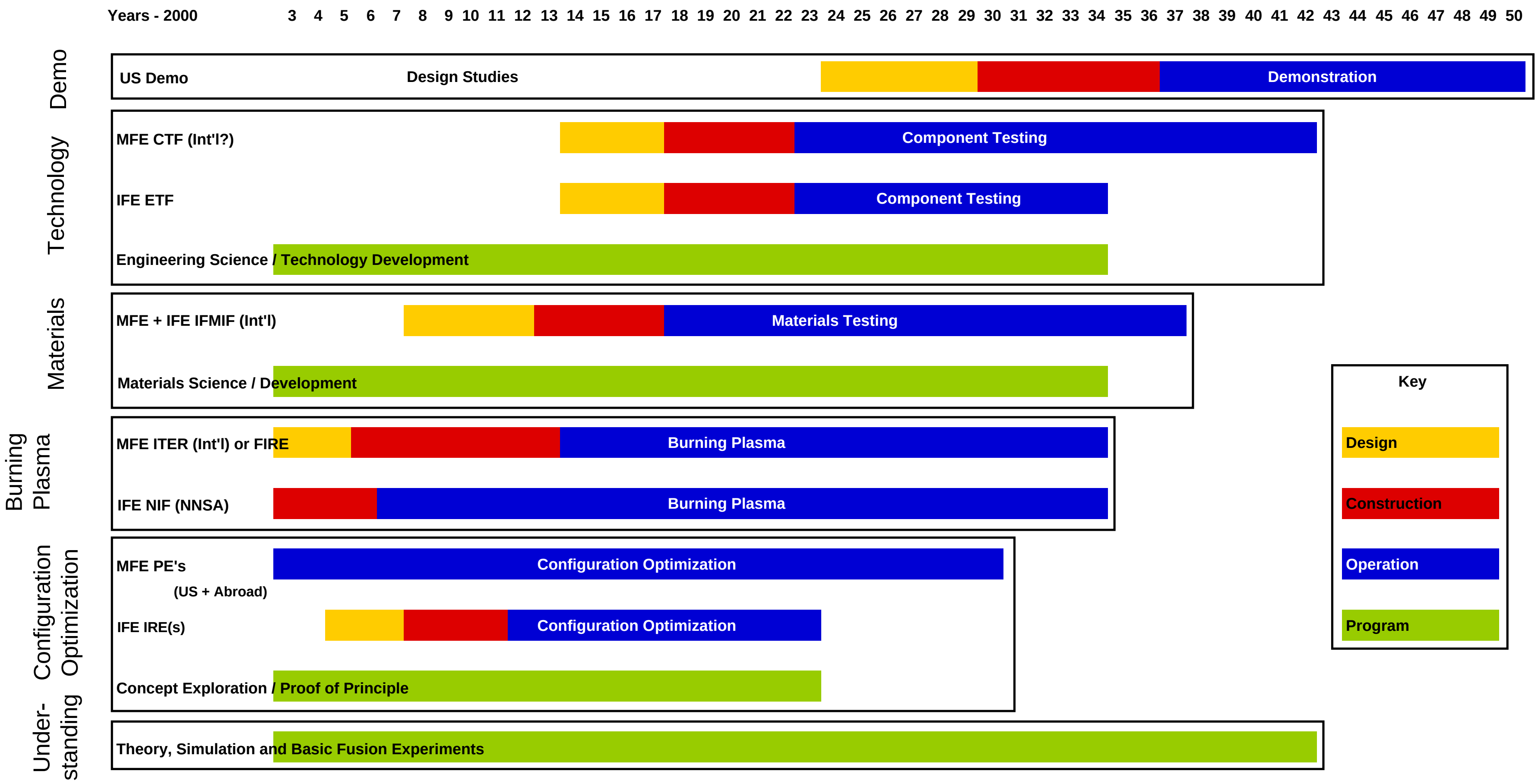
Illustrative General Plan

More defined ↔ Less defined



Includes both programs and facilities.
No costing at this time.

Panel’s Assessment

The Panel has done a preliminary examination of the components of the plan, both their individual duration and the linkages between them, and has concluded that these are consistent with the operation of a Demo on the desired timescale. Achievement of this timescale requires that appropriate funding is provided so that the schedule for the design, construction and operation of facilities is technically driven. Furthermore in some cases design must begin before all information is in hand, and the decision to construct a facility must then be taken promptly when confirmatory information becomes available.

It is the judgment of the Panel that the plan illustrated here can lead to the operation of a demonstration fusion power plant in about 35 years and enable the commercialization of fusion power. It should be recognized … that significant scientific and technological challenges remain for the development of fusion as a practical energy source, necessitating a portfolio approach. Furthermore, while costing of the plan is a task for the Panel’s Final Report, it is clear that substantial additional resources will be needed to implement this plan. In particular, in order to initiate this plan, funding for fusion energy research including both MFE and IFE needs to begin to ramp up in FY2004.

Significant Issues that Deserve Immediate Attention - I

MFE Burning Plasma

The MFE portion of the plan depends fundamentally on US participation in a magnetically confined burning plasma experiment. It is time critical for the US to move forward with the burning plasma recommendations of FESAC. This is a dual-path strategy including both the ITER and FIRE options, that begins with US participation in the ITER negotiations with the aim of becoming a partner in the undertaking and continuing preparation for a FIRE conceptual design activity. The sooner the US joins ITER negotiations the larger will be US leverage on critical decisions. There are matters of urgent concern to the US, such as cost-control, project management, research decision-making and – of course – its own benefits and obligations.

Significant Issues that Deserve Immediate Attention - II

Domestic Research – MFE & IFE

Materials science and fusion chamber and power technology development work needs to be accelerated for both MFE and IFE. The Engineering Validation phase of the International Fusion Materials Irradiation Facility must begin expeditiously.

MFE facilities devoted to configuration optimization (from concept exploration to performance extension) need to be adequately utilized and innovative new such facilities need to be constructed at a cost-effective pace. The enabling technology program needs to provide necessary plasma control tools to support these experiments, and new opportunities in theory and advanced computing need to be pursued. Preparations for a burning plasma experiment need to be started.

The IFE portion of the plan, including elements that are currently distributed between the Office of Science and the NNSA, needs to be adopted as a significant mission with appropriate emphasis within the DOE. Within IFE, the heavy ion beam program needs to begin design of a next-step proof-of-principle experiment. The z-pinch approach to IFE and fast ignition research need to be pursued more aggressively. The development of laser fusion energy has been supported through the high-average-power laser program. This activity is of critical importance to the laser IFE development path, and needs to be supported on a continuing basis.

The recommendation by the NAS/NRC to strengthen connections to other areas of science and technology needs to be implemented.

Conclusion

Dramatic scientific and technological advances have been achieved over the last decade, from the understanding and control of turbulence in magnetically confined plasmas to the demonstration of the positive impact of improved symmetry control in inertial confinement. This strengthened scientific understanding of fusion systems, bolstered by the application of advanced computing, provides enhanced confidence that practical fusion systems can be realized. Increased concern about the impact of human activity on the global ecosystem points to the need for new broadly available, non-polluting energy sources such as fusion. In addition, escalating international tensions underscore the importance of long-term national energy security.

A commitment now to expend the additional resources to develop fusion energy within 35 years is timely and appropriate.

(Recommend you invite IFE community to speak with you.)

What Options Exist if an Accelerated 35-year Plan is not part of the DOE Program?

Professor Rob Goldston, Director
DOE Princeton University Plasma Physics Laboratory

January, 2003

The FESAC Burning Plasma Strategy is the Correct Approach

- Join ITER negotiations now with the aim of becoming a partner.
  - Contribute to high-tech construction.
  - Propose and implement science experiments.
  - Have equal access to experimental and engineering data.
  - Increase the domestic core program in parallel with the burning plasma initiative.
    - Need to advance fundamental understanding, configuration optimization, materials and technology in parallel with burning plasma.
    - This is consistent with the observation that new jobs are needed to attract young scientists and engineers to fusion research.
    - My opinion: Over the next 5 years a domestic program increase approximately equal to the U.S. burning plasma initiative is needed for a strategically balanced program.

- Maintain FIRE as an option, if ITER does not go forward.
  - Strongly encourage international participation.

ITER is a Major Step Forward, but it is *not* a Model of a Power Plant

	ITER	ARIES – RS
R, a	6.2 m, 2.0 m	5.52 m, 1.38 m
B_T, RB_T	5.3 T, 33 Tm	7.98 T, 44 T
Normalized Beta	2.0	4.84
Fusion Power	500 MW	2170 MW
Neutron Wall Load	0.57 MW/m^2	3.96 MW/m^2
Disruption Damage	Some acceptable	Essentially none
Heat Loading, P_{heat}/R	24 (MW/m)	93 (MW/m)
Bootstrap Fraction	50 % in s.s. mode	88 %
Recirculating Power	> 100 % in s.s. mode	17 %
Material	Stainless steel	Low activation

Innovation is needed to make fusion practical and cost-effective, particularly for the U.S. market.

What Should be done in the Case of Very Limited Incremental Funding for Fusion Research?

- Increases for participation in a burning plasma should still be balanced with increases in domestic research, in order to maintain strategic balance.

- If overall increases are very limited, the U.S. role in ITER will consequently have to be very limited as well.

- There are critical things to be done outside of ITER:
  Research innovation needs to lead to devices well below the size/cost of ITER that generate high power continuously, without damaging disruptions.
  $5B for 500 MW_{th} is far too expensive for a practical power plant.

- If the domestic program is not strengthened as we join ITER, we will be supporting the Europeans and Japanese to sell us (expensive) fusion power plants.

- If the domestic program is strengthened, the U.S. can be strategically positioned to provide the innovations which will make fusion practical and cost-effective, particularly for the U.S. market.

What if the World is not able to move Forward with a Burning Plasma Experiment?

- It is possible that the international process will not be able to come to closure on financial arrangements for ITER.
- It is possible that the U.S. will not be financially able to lead a successful effort to construct FIRE.
  - With demise of ITER, it will be difficult for the international community to make a transition to supporting FIRE.
  - (Previous notes about the strategic need to strengthen the domestic program of science and innovation hold in the FIRE case as well.)
- Under these circumstances the best strategy for the U.S. is to press forward aggressively with the restructured program, focused on science and innovation.
  - With success in the various lines currently under investigation, a less expensive burning plasma may be possible in the future. For example, an R = 1.5m Spherical Torus could in principle make 750 MW of fusion power - but the science is not yet in place to move forward with such a device.
  - Continuing advances in materials and technology could lead to the possibility of constructing a burning plasma with lower activation materials.

Conclusions

- **The FESAC strategy is optimal:**
  - **Join ITER negotiations now with the aim of becoming a partner.**
    - **Contribute to construction.**
    - **Propose and implement science experiments.**
    - **Have equal access to experimental and engineering data,**
    - **Increase the domestic core program in parallel with the burning plasma initiative.**
  - **Maintain FIRE as an option, if ITER does not go forward.**
    - **Strongly encourage international participation.**
- **In the case where additional funding is limited, increases for participation in a burning plasma must be balanced with increases in domestic research.**
- **In the case where no burning plasma goes forward, the U.S. should continue its focus on science and innovation, leading to better options in the future.**

Key near term issue: ***Key Administration and Congressional decision-makers need promptly to assess the prospects for additional funding for fusion research, in order to inform U.S. ITER negotiators.***