Status and Opportunities in Magnetic Fusion

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for the FIRE Team

Presented at
Savannah River Site
Aiken, S. C.

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http://fire.pppl.gov

Outline

- **Requirements for Fusion**
- **Objectives for a Next Step Fusion Experiment**
- **The High Field Approach to Burning Plasmas**
- **Physics Aspects**
- **Other Considerations** (Cost, timing, etc)
- **Summary**

A Window of Opportunity for Energy R&D

- Increased awareness on the importance of a secure energy supply
  - National Energy Policy Report -The NEPD Group recommends that the President direct the Secretary of Energy to develop next-generation technology—including hydrogen and fusion.
  - HR-4 - to provide for security and diversity in the energy supply
- Link between economic growth and stable/affordable energy
- Global Climate Change and pressure from other nations for U. S. participation in CO_2 emission reduction.

Need to be ready when the window opens

Status of Fusion(2001)

- Good progress in the 1980s through the mid 1990s
  - controlled fusion conditions achieved
    > 400 million °C or > 40 keV
  - significant fusion power/energy produced

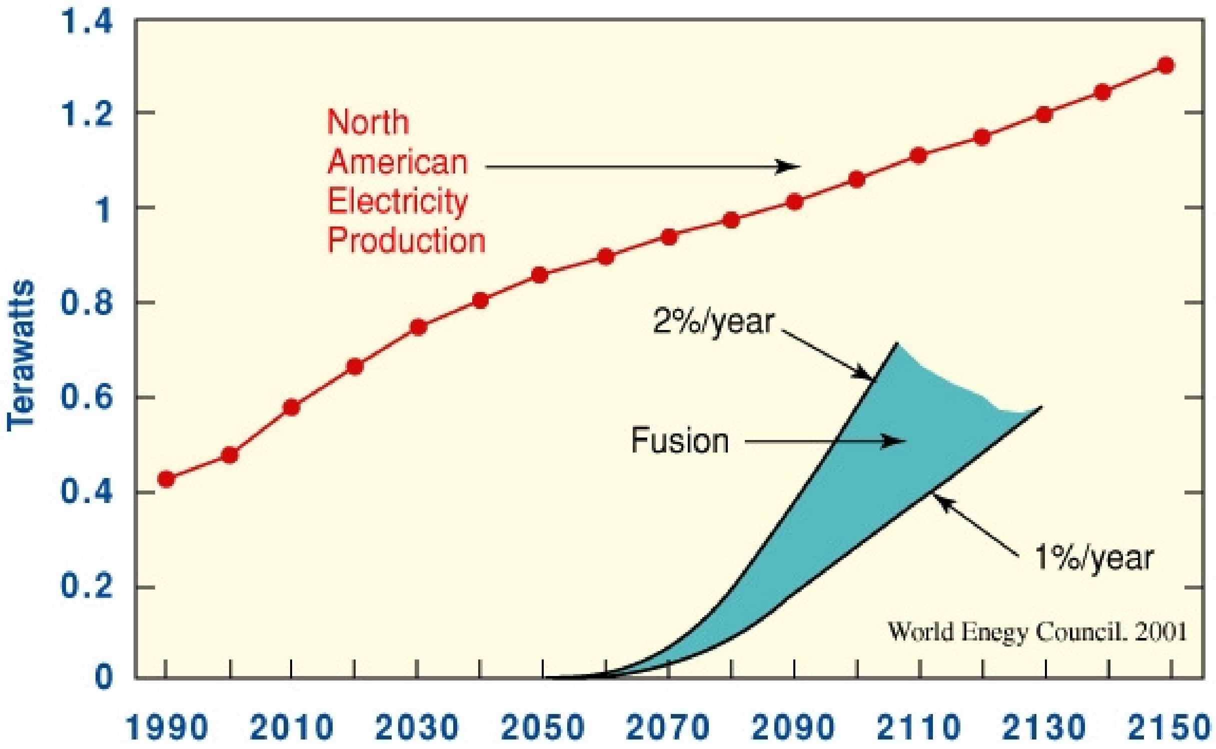
1.7 MW	JET Europe	1991
11 MW	TFTR US	1994
16 MW	JET Europe	1997
~~20 MW~~	~~TFTR US~~	~~1998,~~ proposed not accepted, incremental

- Testing of burning plasmas in Magnetic Fusion on Hold (Fusion Test Ban) since 1997. Searching for lower cost more innovative alternatives.
- Inertial fusion has two major fusion test facilities under construction

National Ignition Facility	US	$3.2 B	Ignition in 2010
Laser Megajoule	EU	> $ 2B	Ignition in 2010

- A test facility is needed in magnetic fusion to extend science understanding, develop technology and establish technical credibility of magnetic fusion.

Fusion Could Contribute to an Energy Portfolio, If We got started on a Burning Plasma Experiment Soon!



- Consistent with resource availability
  - Materials, fuel, low-level waste repositories
- Conservative deployment rate
  - *c.f.,* French nuclear fission was deployed at a rate of 7% of total electricity production / year
- Similar picture could hold in the developing world
  - Most population growth is in cities, where concentrated power sources will be needed. A possible U.S. export market.

Burning Plasma Physics is Widely Accepted as the Primary Objective for a Next Step in Fusion Science

- Grunder Panel (98) and Madison Forum endorsed Burning Plasmas as next step.
- NRC Interim Report (99) identified "integrated physics of a self-heated plasma" as one of the critical unresolved fusion science issues.
- The Snowmass Fusion Summer Study (99) endorsed the burning plasma physics objective, and that the tokamak was technically ready for high-gain experiment. A burning plasma experiment should also have advanced tokamak capability.
- SEAB (99) noted that "There is general agreement that the next large machine should, at least, be one that allows the scientific exploration of burning plasmas" and if Japan and Europe do not proceed with ITER "the U. S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost." ….. "In any event the preliminary planning for such as machine should proceed now so as to allow the prompt pursuit of this option."
- NRC/FuSAC (00) - "The US scientific community needs to take the lead in articulating the goals of an achievable, cost-effective scientific burning plasma experiment, and to develop flexible strategies to achieve it, including international collaboration."

Recent Events

Energy Authorization Bill (HR 4) passed by the House on August 1, 2001 directs DOE to submit a plan for a U.S. Burning Plasma Experiment to Congress by July 2004.

FESAC Endorses Recommendations of Burning Plasma Panel on August 2.

National Research Council is preparing a proposal to review burning plasma physics as required by HR 4 and recommended by FESAC.

Preparations are beginning for a Snowmass Summer Study 2002 that will emphasize burning plasmas.

Panel Recommendation Fully Endorsed by FESAC August 2, 2001

3. *The US Fusion Energy Sciences Program should establish a proactive US plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment. If the opportunity for international collaboration occurs, the US should be ready to act and take advantage of it, but should not be dependent upon it. The US should implement a plan as follows to proceed towards construction of a burning plasma experiment:*

- Hold a “Snowmass” workshop in the summer, 2002 for the critical scientific and technological examination of proposed burning plasma experimental designs and to provide crucial community input and endorsement to the planning activities undertaken by FESAC. Specifically, the workshop should determine which of the specific burning plasma options are technically viable, but should not select among them. The workshop would further confirm that a critical mass of fusion scientists believe that *the time to proceed is now* and not some undefined time in the future.

- Carry out a uniform technical assessment led by the NSO program of each of the burning plasma experimental options for input into the Snowmass summer study.

- Request the Director of the Office of Energy Sciences to charge FESAC with the mission of forming an “action” panel in Spring, 2002 to select among the technically viable burning plasma experimental options. The selected option should be communicated to the Director of the Office of Science by January, 2003.

- Initiate a review by a National Research Council panel in Spring, 2002, with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by Fall, 2003. This is consistent with a submission of a report by DOE to congress no later than July, 2004.

- Initiate an outreach effort coordinated by FESAC (or an ad-hoc body) to establish an appreciation and support for a burning plasma experiment from science and energy policy makers, the broader scientific community, environmentalists and the general public. This effort should begin now.

Relevant Reactions for Fusion in the Laboratory

$D^{+} + D^{+}$ ––> ${}^{3}He^{++}$ (0.82 Mev) + n^{0} (2.5 MeV)

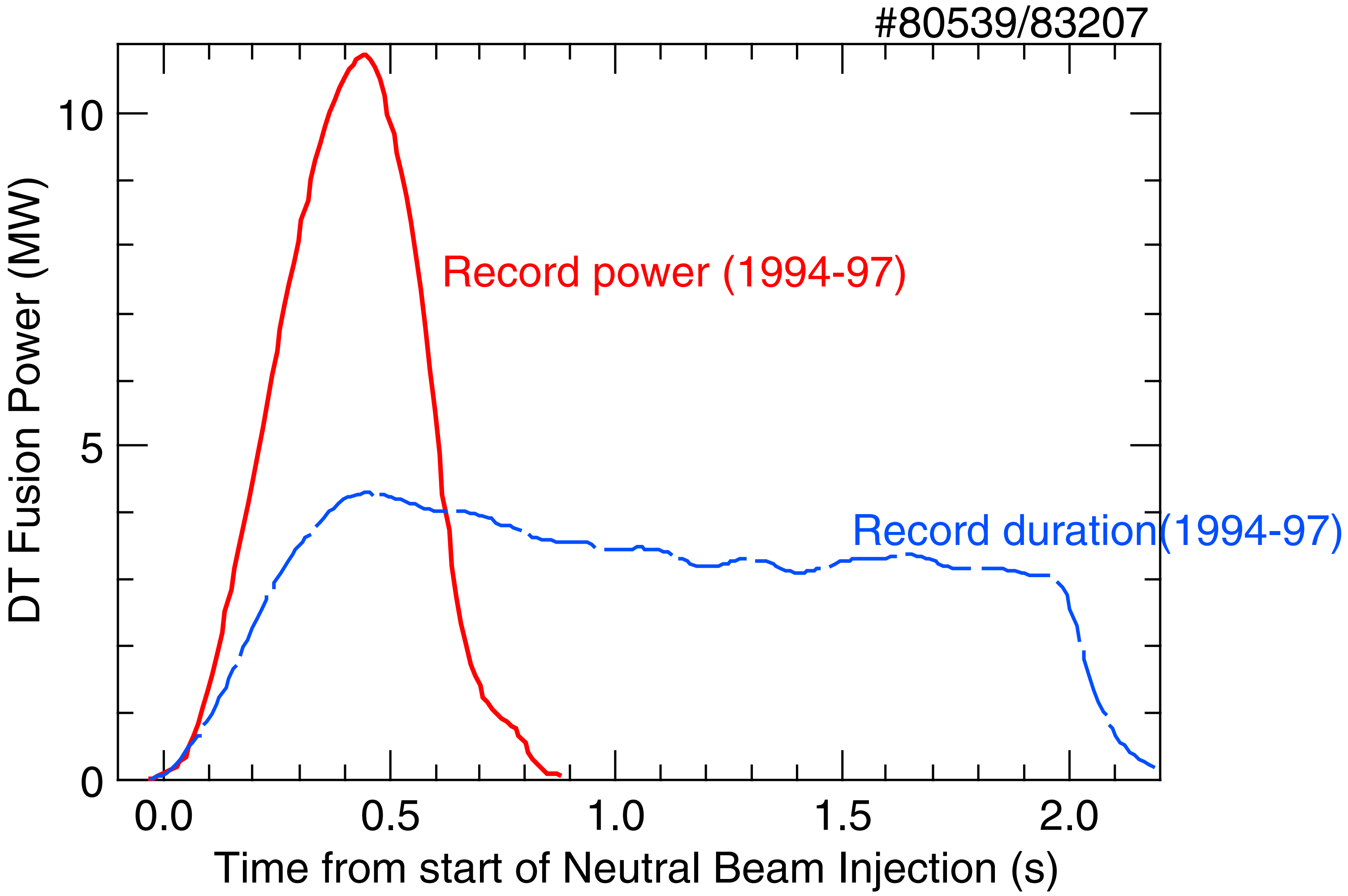
––> T^{+} (1 MeV) + p^{+} (3 MeV)

$D^{+} + {}^{3}He^{++}$ ––> ${}^{4}He^{++}$ (3.6 MeV) + p^{+} (14.7 MeV)

$D^{+} + T^{+}$ ––> ${}^{4}He^{++}$ (3.5 MeV) + n^{0} (14.1 MeV)

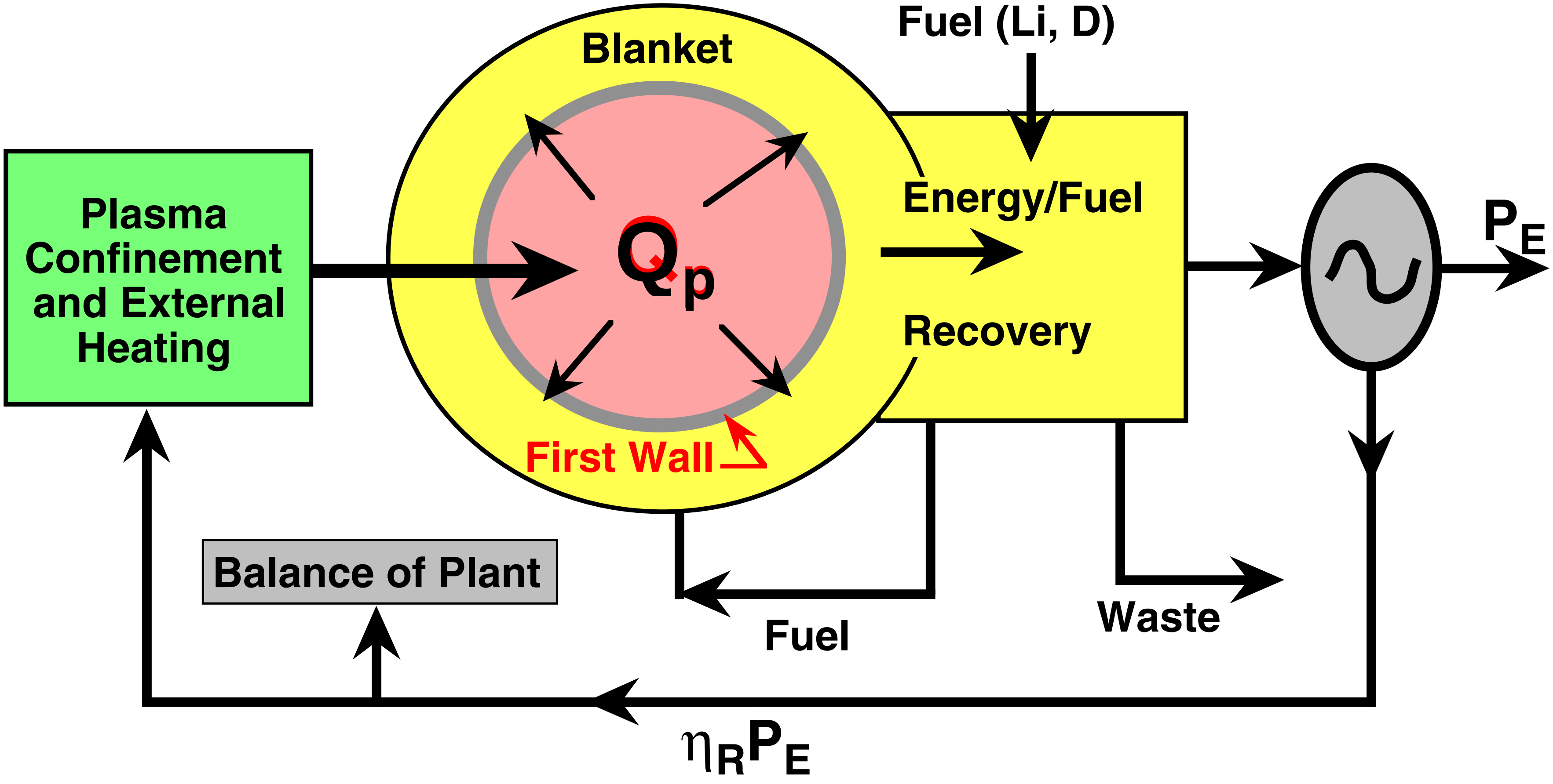
$Li^{6} + n$ ––> ${}^{4}He$ (2.1 MeV) + T (2.7 Mev)

Fusion Power Production in TFTR



“used” 100g of SRS tritium over 3 years

The Grand Challenge, Science and Technology for Fusion



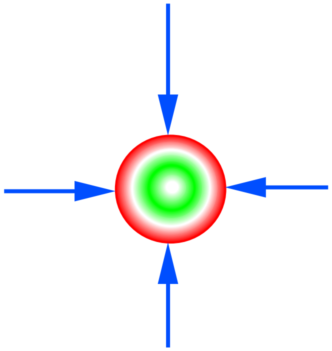
Key Plasma Performance Metrics

- Fusion Gain (Q_p)
- Fusion Energy Density
- Duty Cycle/Repetition Rate

Key Engineering Metrics

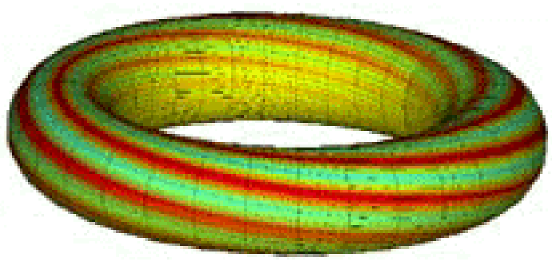
- First Wall Lifetime
- Availability/Reliability
- Environment and Safety
- System Costs

There are Three Principal Fusion Concepts



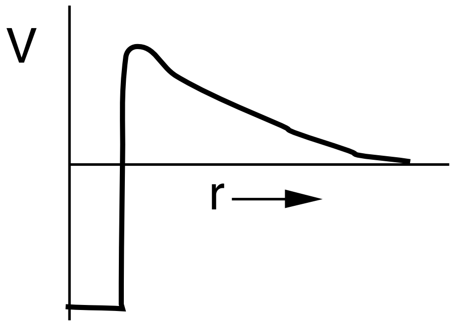
Spherical Inertial

- gravitational
- transient compression
  - drive (laser-D/I, beam)
  - radial profile
  - time profile
- electrostatic



Toroidal Magnetic

- surface of helical B lines
  - twist of helix
  - twist profile
  - plasma profile
  - toroidal symmetry



Reactivity Enhancement

- muon catalysis
- polarized nuclei
- others?

Plasma Requirements for a Fusion-Dominated Plasma

Power Balance

$$P_{\text{aux-heat}} + n^2 \langle\sigma v\rangle U_\alpha V_p/4 - C_B T^{1/2} n_e^2 V_p \quad = \quad 3nkTV_p/\tau_E + d(3nkTV_p)/dt$$

where: $n_D = n_T = n_e/2 = n/2$, $n^2 \langle\sigma v\rangle U_\alpha V_p/4 = P_\alpha$ is the alpha heating power, $C_B T^{1/2} n_e^2 V_p$ is the radiation loss, $W_p = 3nkTV_p$ and $\tau_E = W_p/(P_{\text{aux-heat}} - dW_p/dt)$ is the energy confinement time.

In Steady-state:

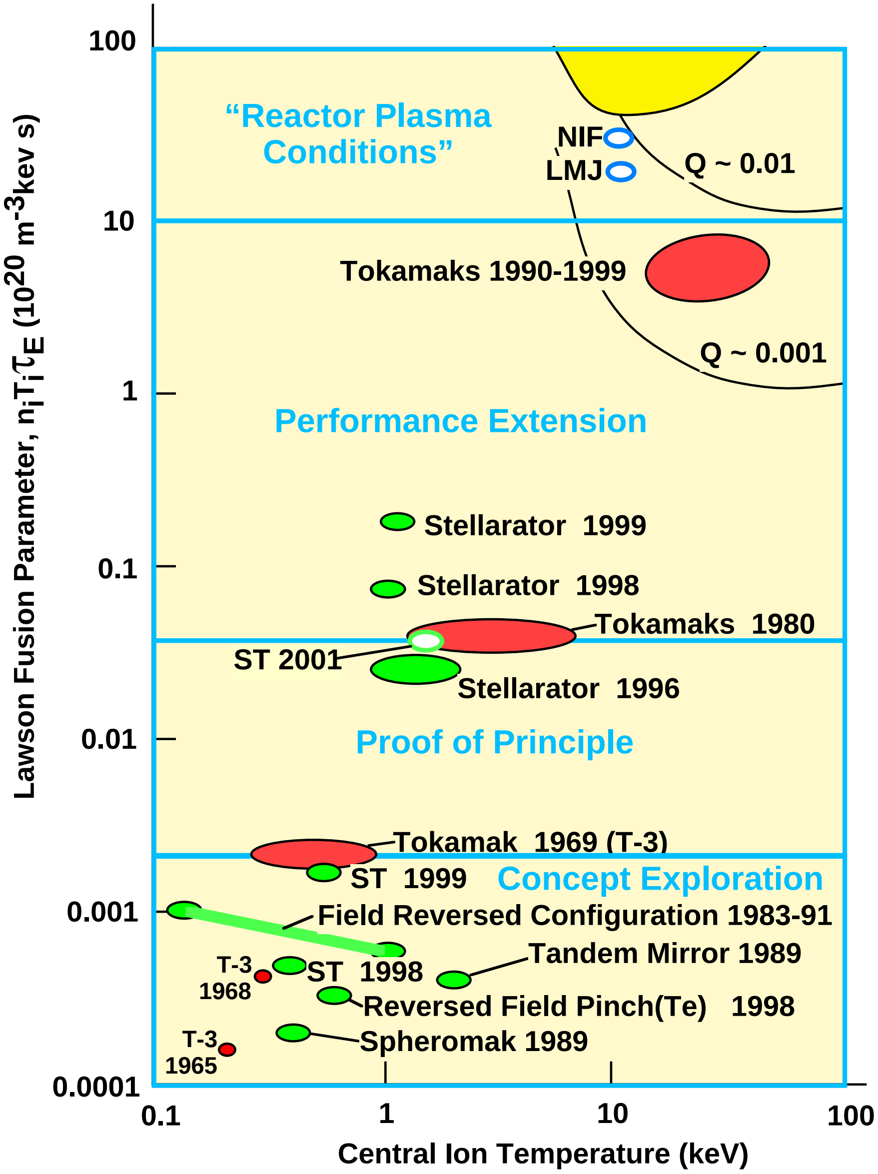
$$\boxed{n\tau_E = \frac{3kT}{\langle\sigma v\rangle U_\alpha (Q+5)/4Q - C_B T^{1/2}}}$$

where $Q = P_{\text{fusion}}/ P_{\text{aux-heat}}$ Palpha/(Palpha + Paux-heat) = Q / (Q + 5)

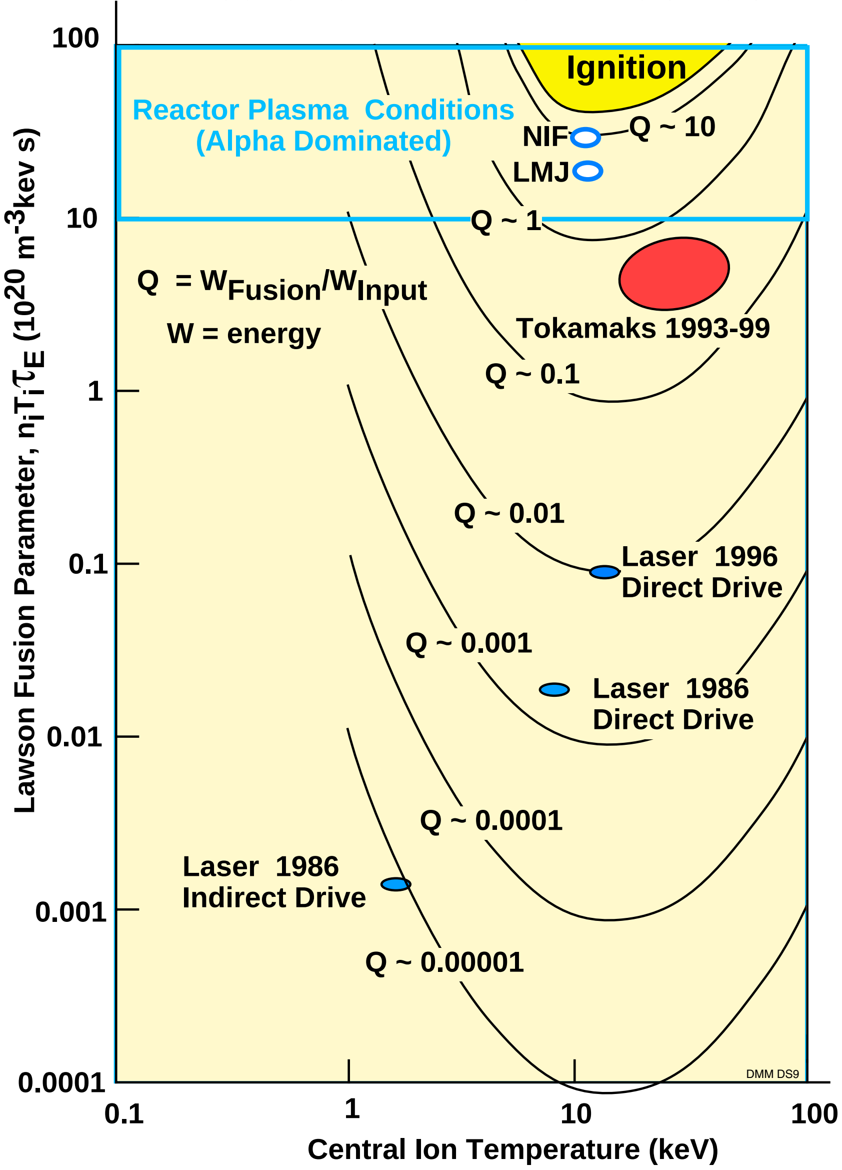
$Q = 1$ is Plasma Breakeven, $Q = \infty$ is Plasma Ignition

The Tokamak is Technically Ready for Burning Plasma Experiment

Deuterium Plasmas



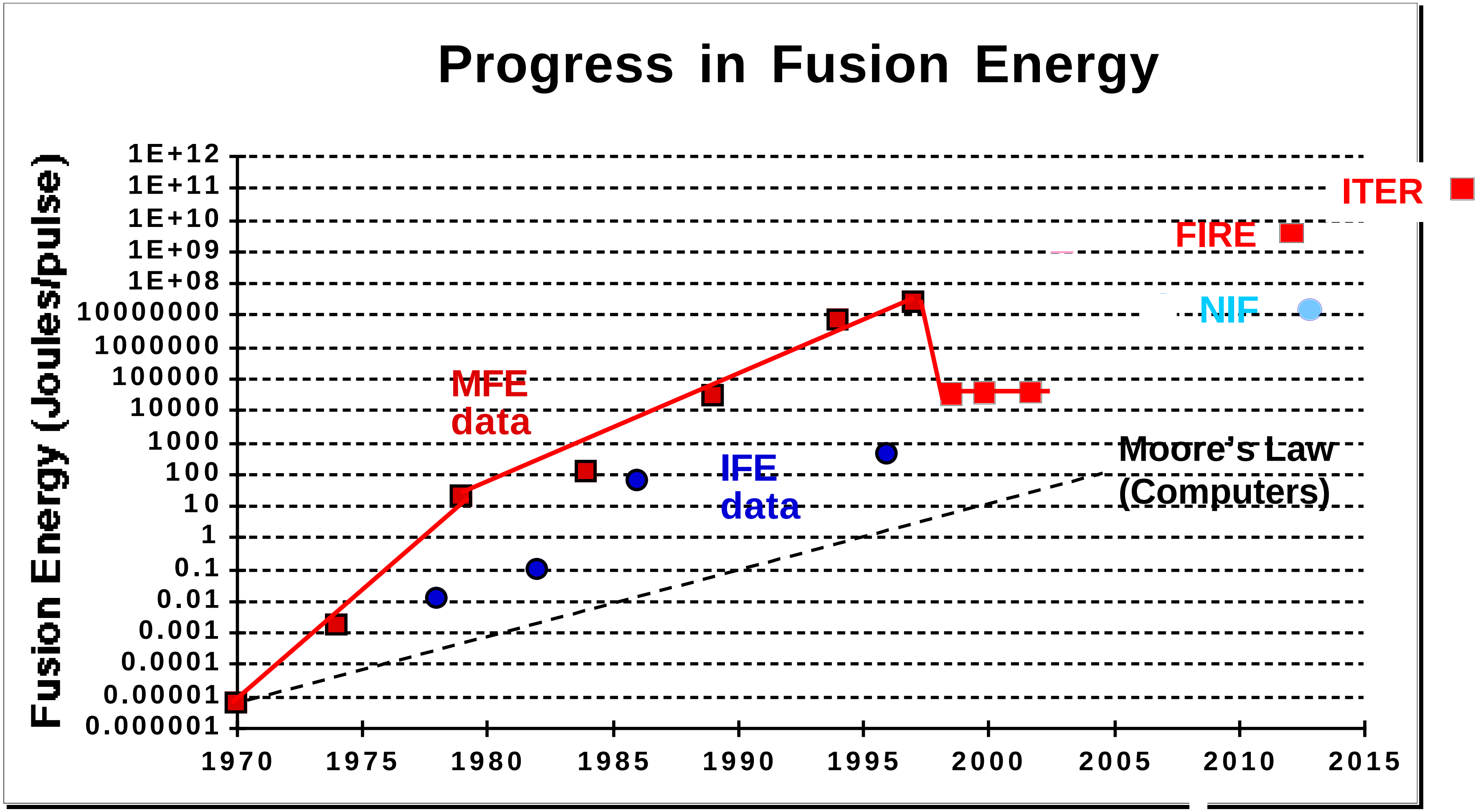
Deuterium - Tritium Plasmas



The tokamak is sufficiently advanced to permit the design, construction and initiation of a next step burning plasma experiment within the next decade that could address the fusion plasma and self-heating issues for magnetic fusion.

Fusion Energy was Making Good Progress.

But has Stalled Awaiting a Burning Plasma Experiment



International Thermonuclear Experimental Reactor (ITER)

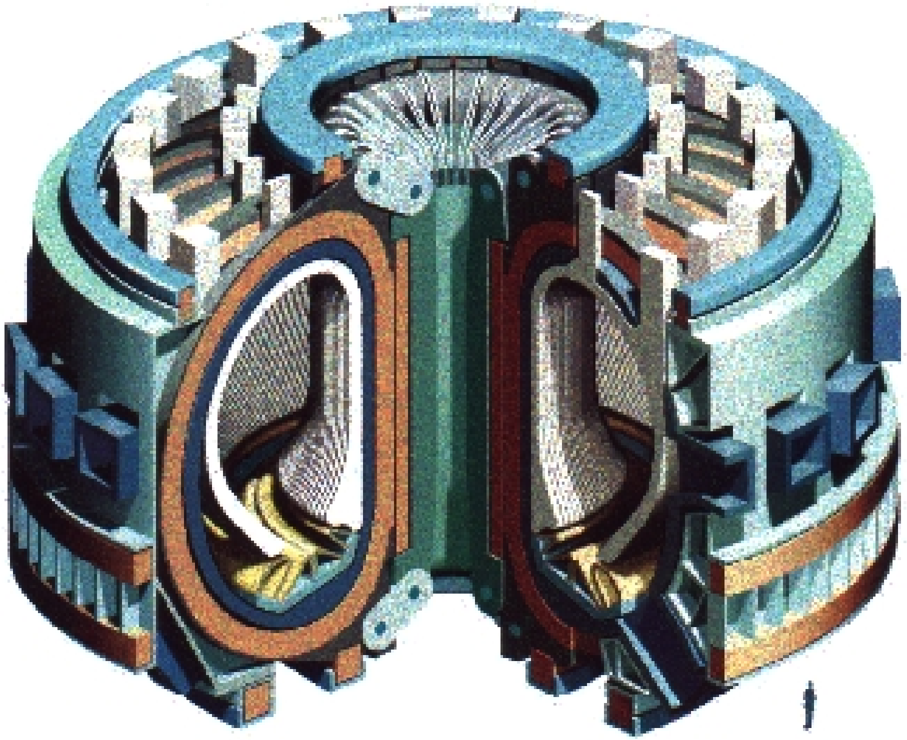
Parties

US (left in 1998)

Japan

Europe

Russia



P_{fusion} ~ 1,500 MW
for 1,000 seconds

Cost ~ $10 B

Japan, Europe and Russia are continuing to work on a reduced size version with a goal of reducing the cost to ~$5B.

Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

NSO/FIRE Community Discussions

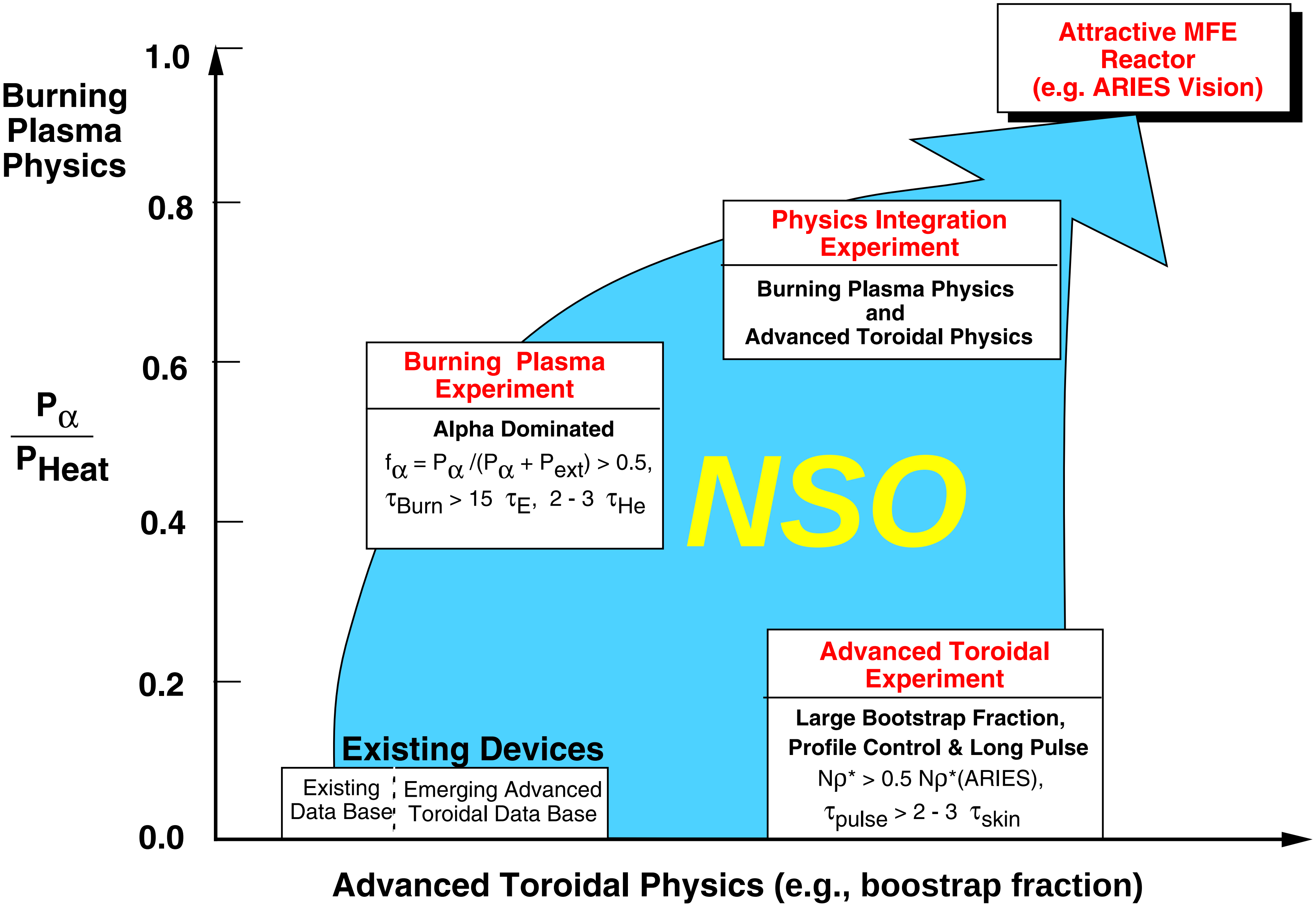
A Proactive NSO/FIRE Outreach Program has been undertaken to solicit comments and suggestions from the community on the next step in magnetic fusion.

- Presentations have been made and comments received from:

SOFT/France	**Sep 98**	**IAEA/Japan**	**Oct 98**	**APS-DPP**	**Nov 98**
FPA	**Jan 99**	**APEX/UCLA**	**Feb 99**	**APS Cent**	**Mar 99**
IGNITOR Wkshp	**May 99**	**NRC/NAS**	**May 99**	**GAT**	**May 99**
LLNL	**May 99**	**VLT-PAC**	**Jun 99**	**MIT PSFC**	**Jul 99**
Snowmass	**Jul 99**	**PPPL/SFG**	**Aug 99**	**VLT-PAC**	**Jun 99**
VLT-PAC	**Jun 99**	**MIT PSFC**	**Jul 99**	**U. Rochester**	**Aug 99**
NYU	**Oct 99**	**PPPL/SFG**	**Aug 99**	**U. Wis**	**Oct 99**
FPA	**Oct 99**	**SOFE**	**Oct 99**	**APS-DPP**	**Nov 99**
U. Maryland	**Dec 99**	**DOE/OFES**	**Dec 99**	**VLT PAC**	**Dec 99**
Dartmouth	**Jan 00**	**Harvey Mudd**	**Jan 00**	**FESAC**	**Feb 00**
ORNL	**Feb 00**	**Northwest'n**	**Feb 00**	**U. Hawaii**	**Feb 00**
Geo Tech	**Mar 00**	**U. Georgia**	**Mar 00**	**PPPL**	**Mar 00**
Naval Postgrad S	**Mar 00**	**U. Wis**	**Mar 00/Apr00**	**EPS/Budapest**	**Jun 00**
IPP/Garching	**Jun 00**	**CEA/Cadarache**	**Jun 00**	**JET-EFDA**	**Jun 00**
NSO-PAC	**Jul 00**	**SOFT/Spain**	**Sep 00**	**IAEA/Italy**	**Oct 00**
Int'l DB/Frascati	**Oct 00**	**CRPP/Lausanne**	**Oct 00**	**ANS/TOFE**	**Oct 00**
APS/DPP-ICPP	**Oct 00**	**VLT-PAC**	**Dec 00**	**UFA BP Wkp**	**Dec 00**
NSO-PAC2	**Jan 01**	**MIT IAP**	**Jan 01**	**Columbia U.**	**Jan 01**
DOE OFES	**Feb 01**	**LANL**	**Apr 01**	**SANL PP/FE**	**Apr 01**
ANL	**Apr 01**	**APS Wash.**	**Apr 01**	**EPS/Madeira**	**Jun 01**

- **The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. Over 19,000 visitors from around the world have logged on to the FIRE web site since the site was initiated in July, 1999.**

Stepping Stones for Resolving the Critical Fusion Plasma Science Issues for an Attractive MFE Reactor



Attractive MFE Reactor
(e.g. ARIES Vision)

Physics Integration Experiment

Burning Plasma Physics
and
Advanced Toroidal Physics

Burning Plasma Experiment

Alpha Dominated

$f_\alpha = P_\alpha /(P_\alpha + P_{ext}) > 0.5$,

$\tau_{Burn} > 15\ \tau_E$, 2 - 3 τ_{He}

Existing Devices

Existing Data Base	Emerging Advanced Toroidal Data Base

Advanced Toroidal Experiment

Large Bootstrap Fraction,
Profile Control & Long Pulse

$N\rho^* > 0.5\ N\rho^*$(ARIES),

$\tau_{pulse} > 2 - 3\ \tau_{skin}$

The “Old Paradigm” required three separate devices, the “New Paradigm” could utilize one facility operating in three modes or phases.

Fusion Science Objectives for a Major Next Step Magnetic Fusion Experiment

Explore and understand the strong non-linear coupling that is fundamental to fusion-dominated plasma behavior (self-organization)

  - Energy and particle transport (extend confinement predictability)
  - Macroscopic stability (β-limit, wall stabilization, NTMs)
  - Wave-particle interactions (fast alpha particle driven effects)
  - Plasma boundary (density limit, power and particle flow)
- Test/Develop techniques to control and optimize fusion-dominated plasmas.
- Sustain fusion-dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effects of profile evolution due to alpha heating on macro stability, transport barriers and energetic particle modes.
- Explore and understand various advanced operating modes and configurations in fusion-dominated plasmas to provide generic knowledge for fusion and non-fusion plasma science, and to provide a foundation for attractive fusion applications.

We must Burn to Learn

Contributors to the FIRE Design Study

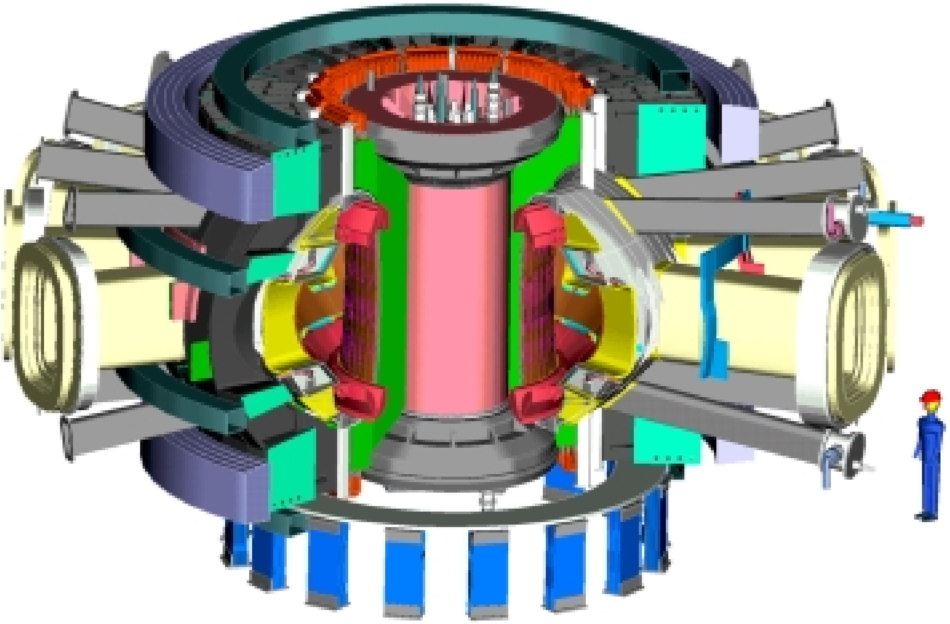
FIRE is a design study for a major Next Step Option in magnetic fusion and is carried out through the Virtual Laboratory for Technology. FIRE has benefited from the prior design and R&D activities on BPX, TPX and ITER.

Advanced Energy Systems
Argonne National Laboratory
DAD Associates
General Atomics Technology
Georgia Institute of Technology
Idaho National Engineering Laboratory
Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Sandia National Laboratory
Stone and Webster
The Boeing Company
University of Illinois
University of Wisconsin

Fusion Ignition Research Experiment

(FIRE*)

http://fire.pppl.gov



Design Features

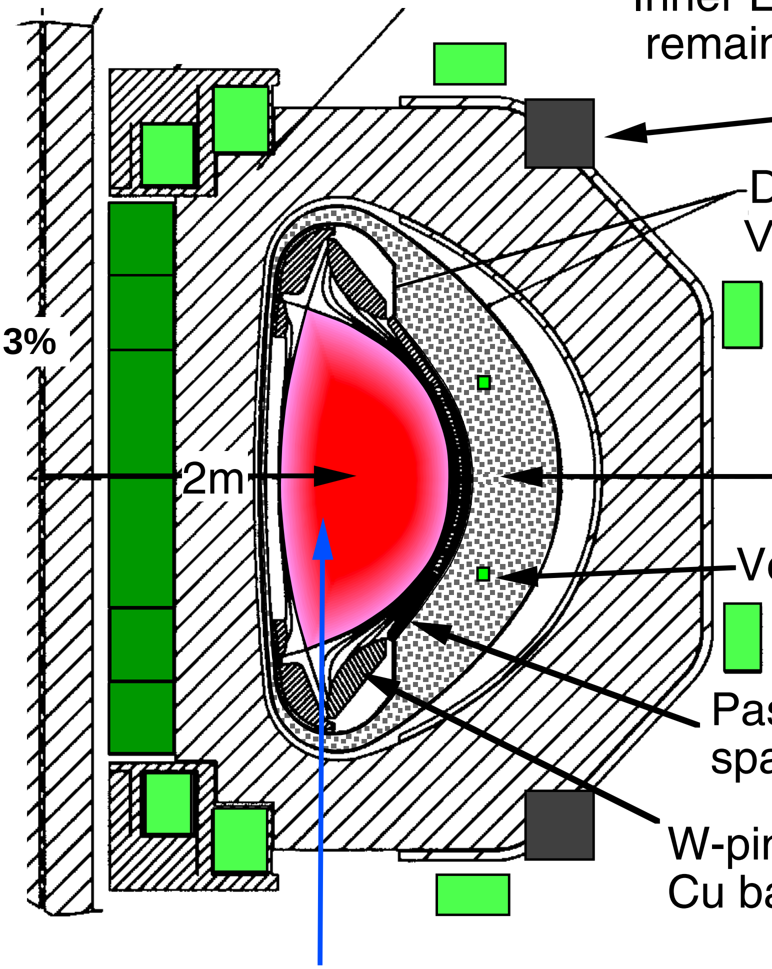
- R = 2.14 m, a = 0.595 m
- B = 10 T
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA
- $P_{aux} \leq$ 20 MW
- Q $\approx$ 10, P_{fusion} ~ 150 MW
- Burn Time $\approx$ 20 s
- Tokamak Cost $\approx$ \$375M (FY99)
- Total Project Cost $\approx$ \$1.2B at Green Field site.

Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.

FIRE Incorporates Advanced Tokamak Innovations

AT Features

- DN divertor
- strong shaping
- very low ripple **< 0.3%**
- internal coils
- space for wall stabilizers



Wedged TF Coils (16), 15 plates/coil*
Inner Leg BeCu C17510,
remainder OFHC C10200

Compression Ring

Double Wall Vacuum
Vessel(316 S/S), Be First Wall

All PF and CS Coils*
OFHC C10200

Internal Shielding
(60% steel & 40%water)

Vertical Feedback and Error
Field Correction Coils

Passive Stabilizer Plates
space for wall mode stabilizers

W-pin Outer Divertor Plate
Cu backing plate, actively cooled

Direct and Guided Inside Pellet Injection

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

Basic Parameters and Features of FIRE*

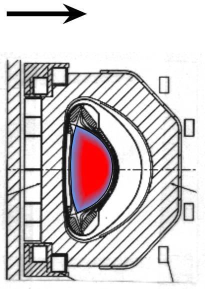
R, major radius	2.14 m
a, minor radius	0.595 m
κx, κ95	2.0, 1.77
δx, δ95	0.7, 0.55(AT) - 0.4(OH)
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.3% ripple @ Outer MP
Toroidal magnet energy	5.8 GJ
Ip, plasma current	7.7 MA
Magnetic field flat top, burn time	28 s at 10 T in dd, 20s @ Pdt ~ 150 MW)
Pulse repetition time	~3hr @ full field and full pulse length
ICRF heating power, maximum	20 MW, 100MHz for $2\Omega_T$, 4 mid-plane ports
Neutral beam heating	Upgrade for edge rotation, CD - 120 keV PNBI?
Lower Hybrid Current Drive	Upgrade for AT-CD phase, ~20 MW, 5.6 GHz
Plasma fueling	Pellet injection (≥2.5km/s vertical launch inside mag axis, guided slower speed pellets)
First wall materials	Be tiles, no carbon
First wall cooling	Conduction cooled to water cooled Cu plates
Divertor configuration	Double null, fixed X point, detached mode
Divertor plate	W rods on Cu backing plate (ITER R&D)
Divertor plate cooling	Inner plate-conduction, outer plate/baffle- water
Fusion Power/ Fusion Power Density	150 - 200 MW, ~10 MW m-3 in plasma
Neutron wall loading	~ 3 MW m-2
Lifetime Fusion Production	5 TJ (BPX had 6.5 TJ)
Total pulses at full field/power	3,000 (same as BPX), 30,000 at 2/3 Bt and Ip
Tritium site inventory	Goal < 30 g, Category 3, Low Hazard Nuclear Facility

FIRE is being Designed to Test the Physics and In-Vessel Technologies for ARIES-AT

P_{fusion}
= ~ 150 MW

Volume
= 27 m^3

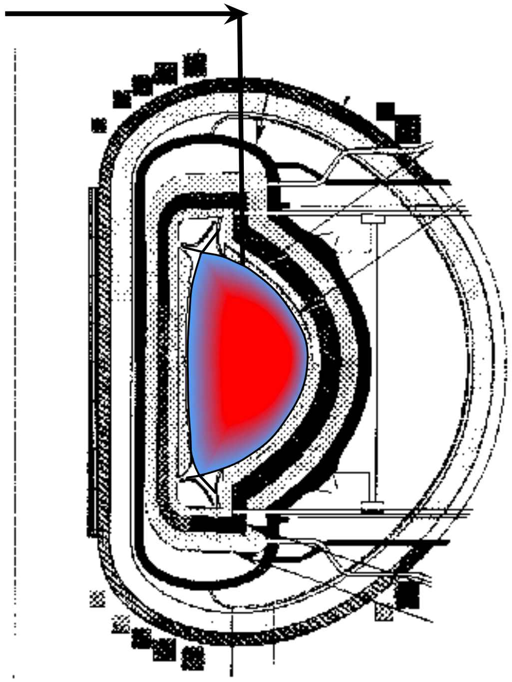
R = 2.14 m B = 10 T



FIRE

~ 3X

R = 5.2 m B = 6 T



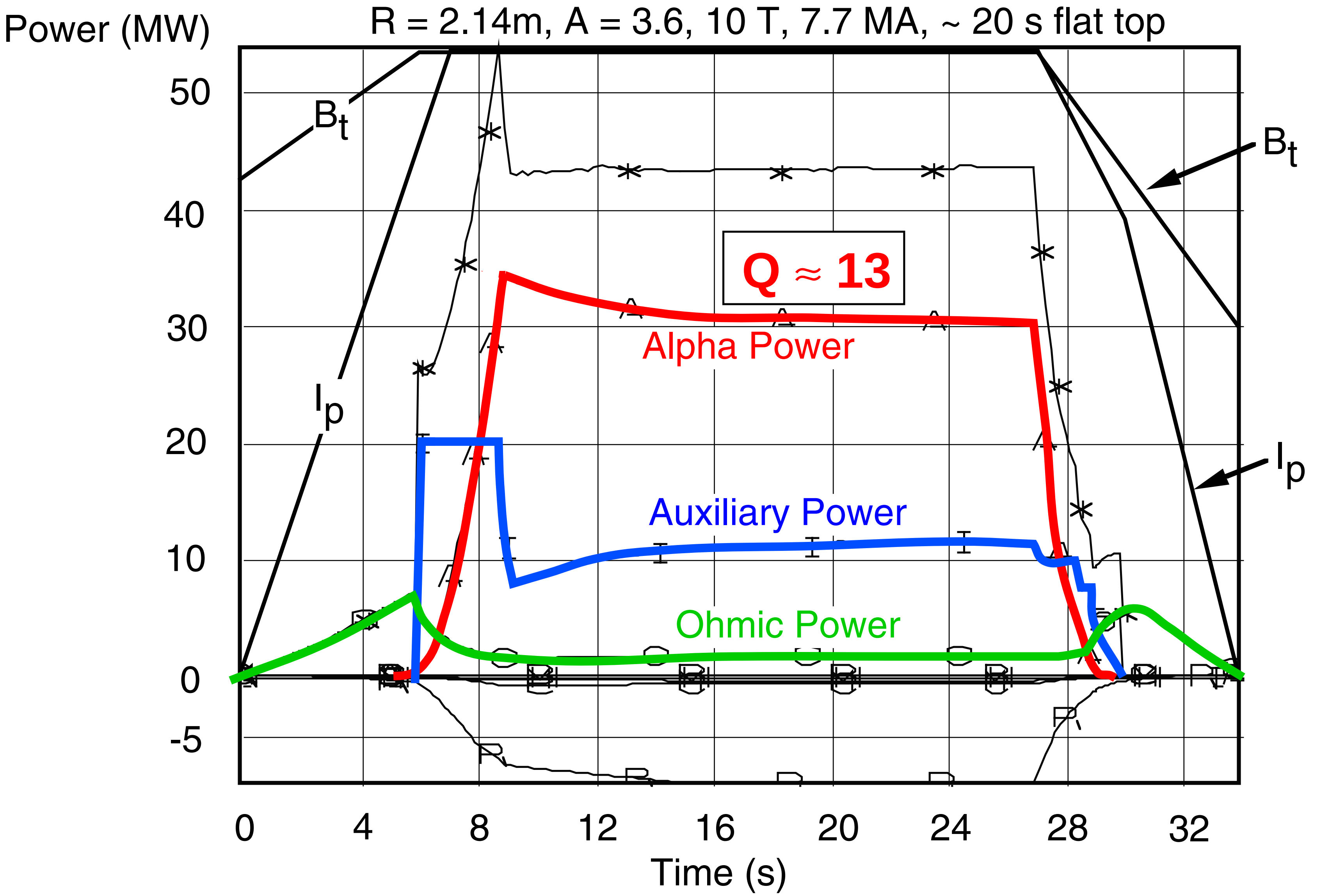
P_{fusion}
= 1755 MW

Volume
= 330 m^3

ARIES-AT The “Goal”

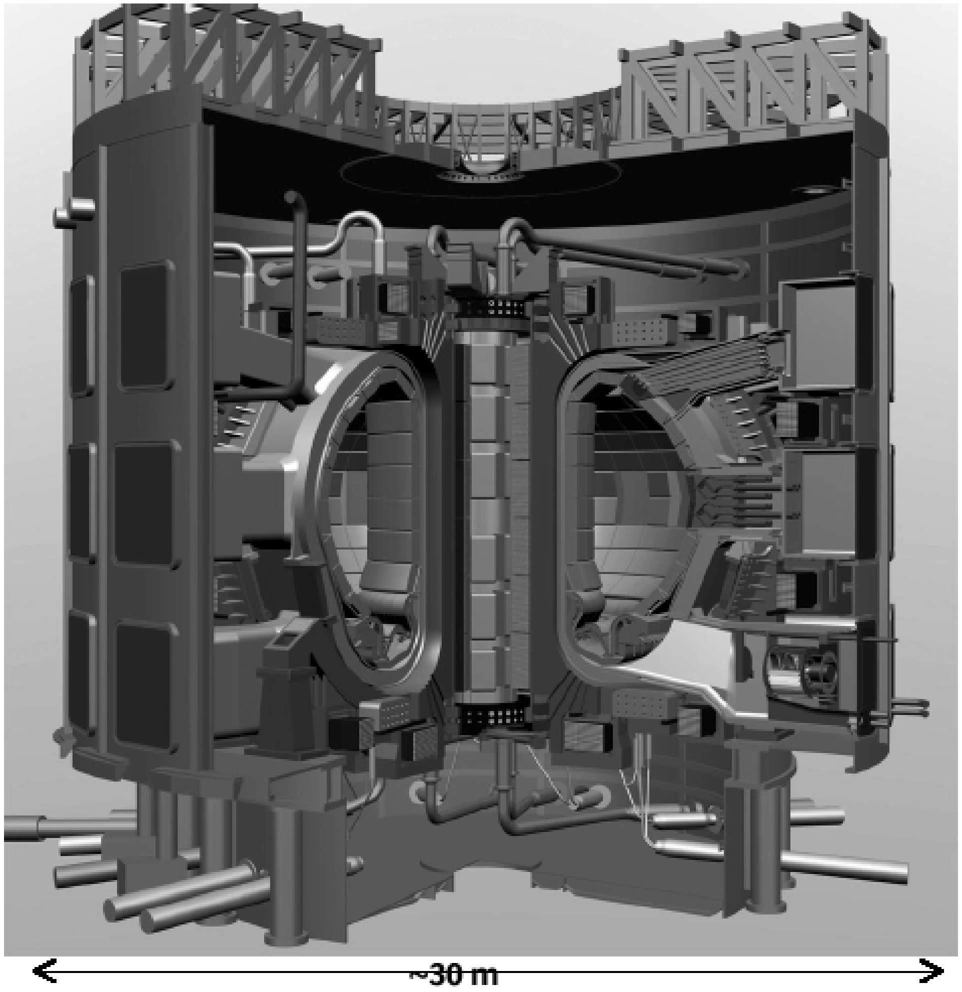
	FIRE	ARIES-AT
Fusion Power Density (MW/m^3)	5.6	5.3
Neutron Wall Loading (MW/m^2)	2.3	3.5
Divertor Challenge (Pheat/R)	25	~70
Power Density on Div Plate (MW/m^2)	~25 → 5	~5
Burn Duration (s)	~20	steady

1 1/2-D Simulation of Burn Control in FIRE* (TSC)



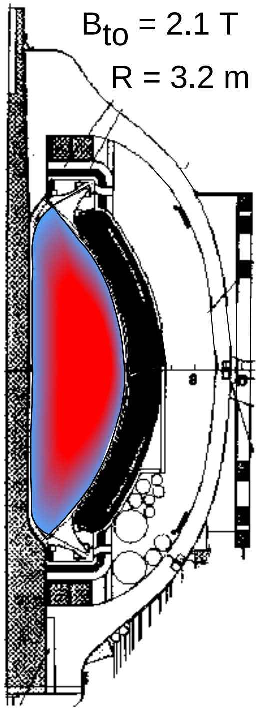
- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and $n/n_{GW} = 0.67$
- Burn Time ≈ 18 s ≈ 21 $\tau_E \approx 4\ \tau_{He} \approx 2\ \tau_{skin}$

ITER Addresses Both Burning Plasma and Technology Issues



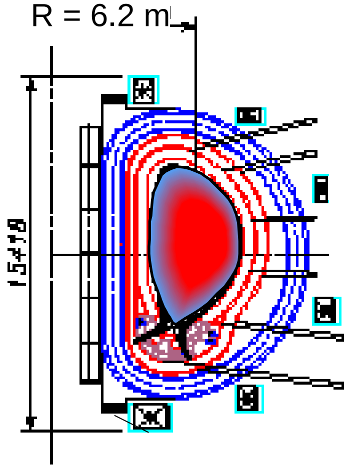
P_{fusion}	500MW
Q	10
Pulse	>400s
Major Radius	6.2m
Minor Radius	2.0m
Plasma Current	15MA
Toroidal Field	5.3T
Heating/Current Drive Power	73MW
Cost ($2000)	$4.6B (~ $8B US Cost methodology)

Potential Next Step Burning Plasma Experiments and Demonstrations in MFE


B_{to} = 2.1 T

R = 3.2 m

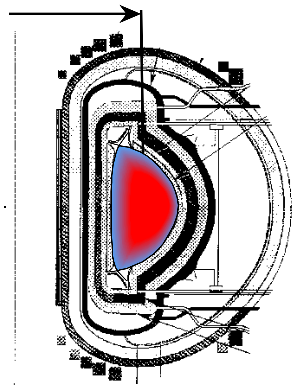
ARIES-ST (1 GWe)



B = 5.3 T

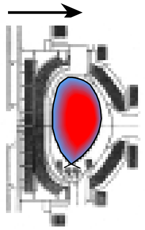
R = 6.2 m

**ITER-FEAT
Outline Design**


B = 8 T

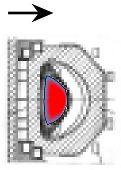
R = 5.5 m

ARIES-RS (1 GWe)


B = 3.8 T

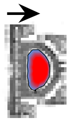
R = 2.9 m

JET


B = 10 T

R = 2 m

FIRE


B = 13 T

R = 1.3 m

IGNITOR

Cost Drivers	ARIES-ST	ITER-FEAT	ARIES-RS	JET	FIRE	IGNITOR
Plasma Volume (m^3)	810	837	350	95	18	11
Plasma Surface (m^2)	580	678	440	150	60	36
Plasma Current (MA)	28	15	11	4	6.5	12
Magnet Energy (GJ)	29	50	85	2	5	5
Fusion Power (MW)	3000	500	2200	16	200	100
Burn Time (s), inductive	steady	300	steady*	1	20	5

* assumes non-inductive current drive

Preliminary FIRE Cost Estimate (FY99 US$M)

	Estimated Cost	Contingency	Total with Contingency
1.0 Tokamak Core	266.3	78.5	343.8
1.1 Plasma Facing Components	71.9	19.2	
1.2 Vacuum Vessel/In-Vessel Structures	35.4	11.6	
1.3 TF Magnets /Structure	117.9	38.0	
1.4 PF Magnets/Structure	29.2	7.2	
1.5 Cryostat	1.9	0.6	
1.6 Support Structure	9.0	1.8	
2.0 Auxiliary Systems	135.6	42.5	178.1
2.1 Gas and Pellet Injection	7.1	1.4	
2.2 Vacuum Pumping System	9.6	3.4	
2.3 Fuel Recovery/Processing	7.0	1.0	
2.4 ICRF Heating	111.9	36.6	
3.0 Diagnostics (Startup)	22.0	4.9	26.9
4.0 Power Systems	177.3	42.0	219.3
5.0 Instrumentation and Controls	18.9	2.5	21.4
6.0 Site and Facilities	151.4	33.8	185.2
7.0 Machine Assembly and Remote Maintenance	77.0	18.0	95.0
8.0 Project Support and Oversight	88.8	13.3	102.2
9.0 Preparation for Operations/Spares	16.2	2.4	18.6
Preconceptual Cost Estimate (FY99 US$M)	**953.6**	**237.8**	**1190.4**

Assumes a Green Field Site with **No** site credits or significant equipment reuse.

June 5, 2001

Site Characteristics for FIRE

- **Land Area**

  ~ 20 acres

- **Buildings**

  Test cell ~ 30m x 45 m x 17 m (high)

  Auxiliary Buildings - power, material handling, cryo, support

- **Power**

  ~ 600 MW from grid for ~ 20 s pulse every 3 hours

  ~ 200 MW and ~ 4.5 GJ from on site MG

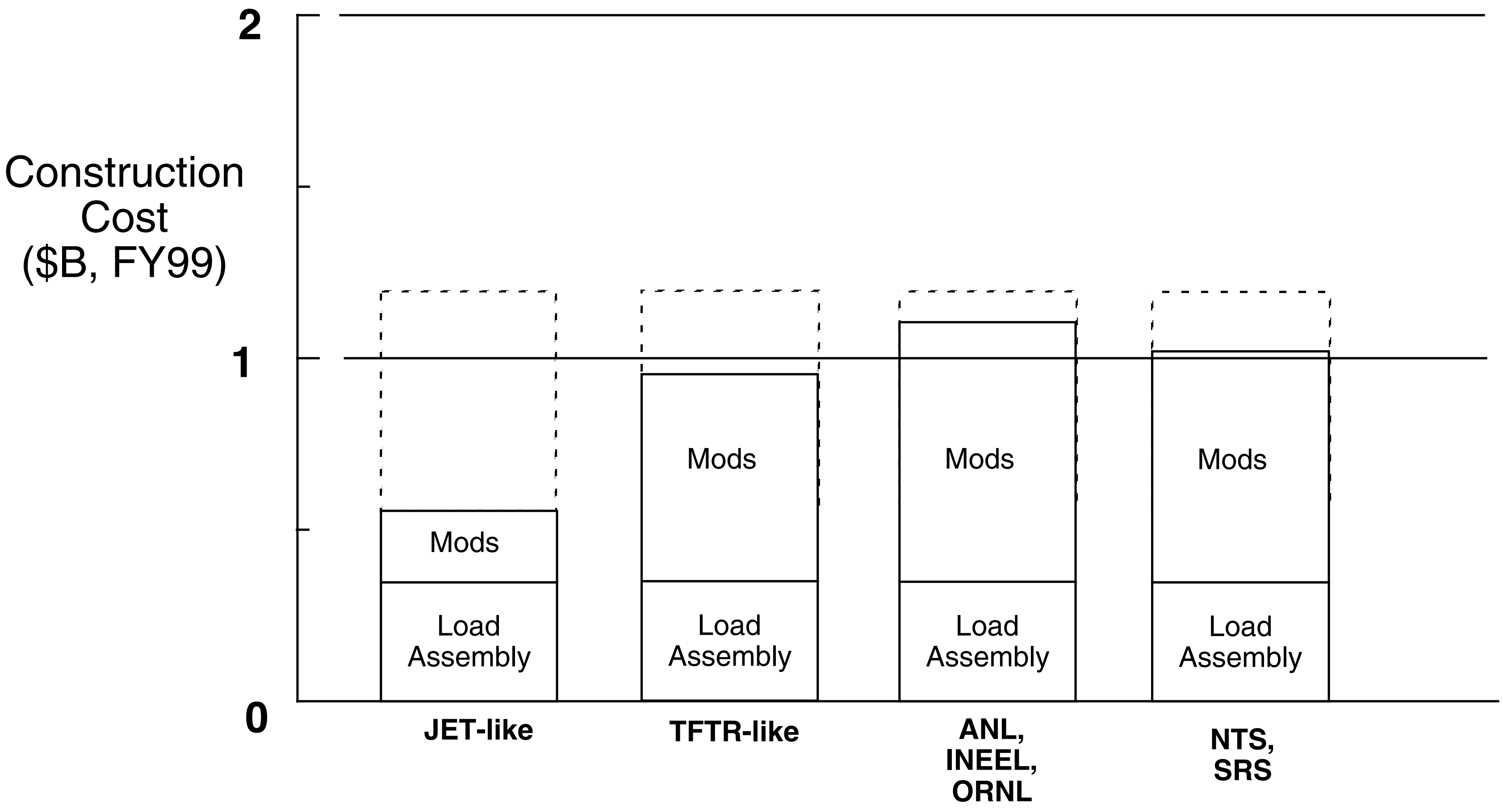
- **Tritium Inventory**

  5 g to 25g (in process inventory)

- **Cryogenic Plant**

  2 kW refrigerator, 600 kgallon LN storage

Site Credits could be Significant and Need to be Evaluated

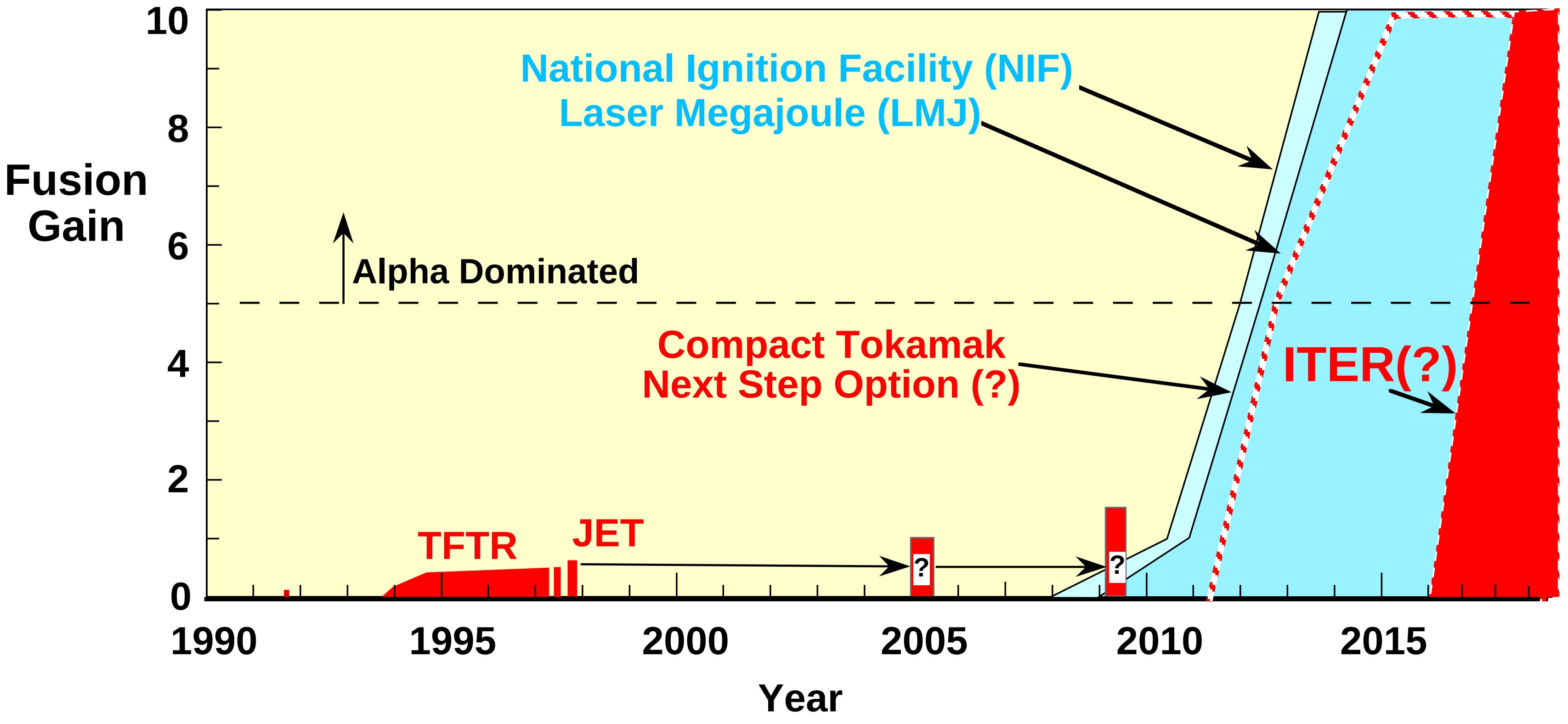


Lowest Cost Next Step **Potential for Future Growth**

1. Could the TFTR site ever be used for tritium again? We need to determine this very soon.

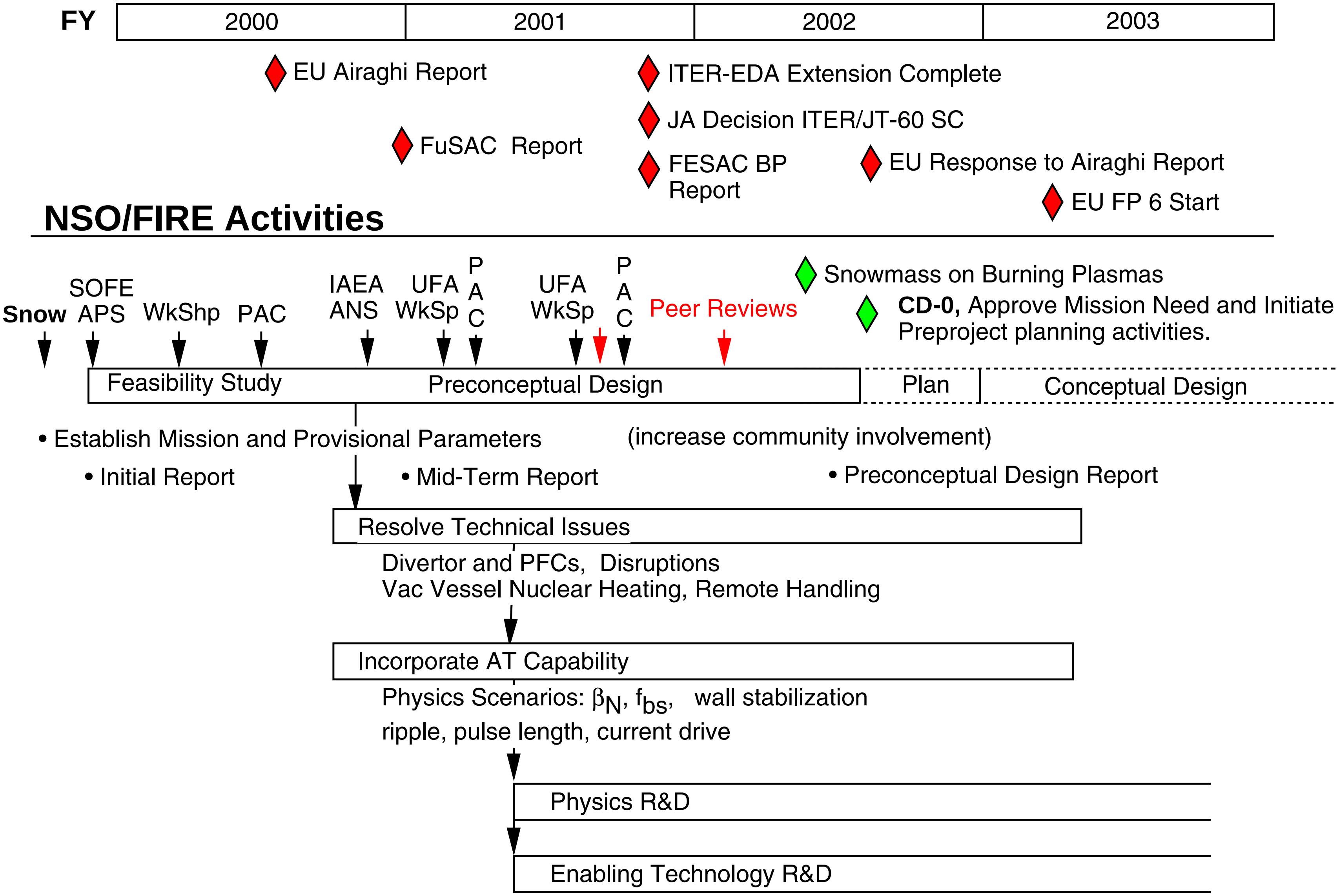
2. Defense Program sites may be special opportunities.

Timetable for "Burn to Learn" Phase of Fusion



- Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for ≥ 15 years.
- Compact High-Field Tokamak Burning Plasma Experiment(s) would be a natural extension of the ongoing "advanced" tokamak program and could begin alpha-dominated experiments by ~ 10 years.
- More than one high gain burning plasma facility is needed in the world program.
- The information "exists now" to make a technical assessment, and decision on MFE burning plasma experiments for the next decade.

Timetable for a Major Next Step in MFE



FY 2000 | 2001 | 2002 | 2003

◆ EU Airaghi Report

◆ FuSAC Report

◆ ITER-EDA Extension Complete

◆ JA Decision ITER/JT-60 SC

◆ FESAC BP Report

◆ EU Response to Airaghi Report

◆ EU FP 6 Start

NSO/FIRE Activities

Snow, SOFE APS, WkShp, PAC, IAEA ANS, UFA WkSp, PAC, UFA WkSp, PAC, Peer Reviews

◆ Snowmass on Burning Plasmas

◆ **CD-0,** Approve Mission Need and Initiate Preproject planning activities.

Feasibility Study | Preconceptual Design | Plan | Conceptual Design

- Establish Mission and Provisional Parameters

(increase community involvement)

- Initial Report
- Mid-Term Report
- Preconceptual Design Report

Resolve Technical Issues

Divertor and PFCs, Disruptions
Vac Vessel Nuclear Heating, Remote Handling

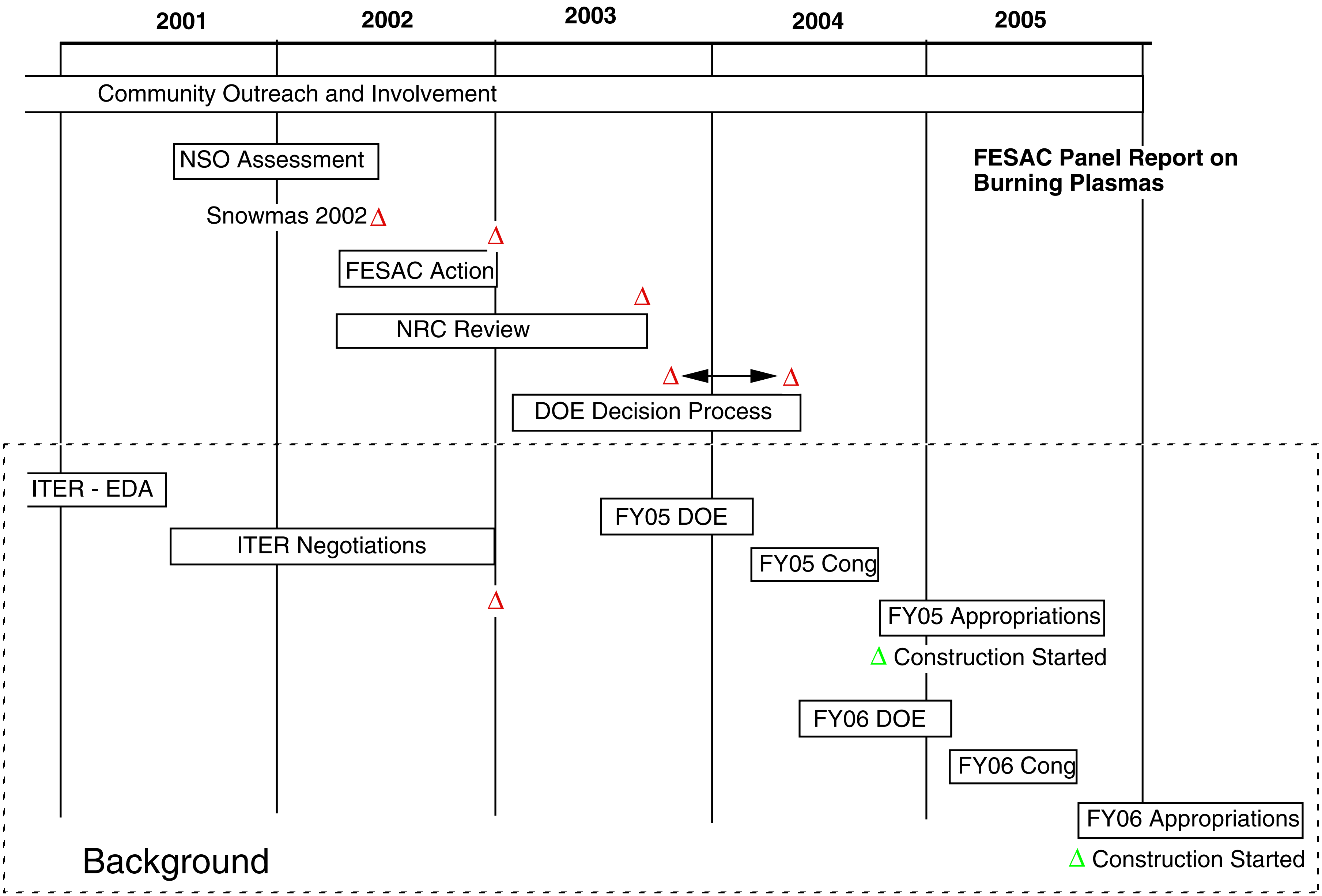
Incorporate AT Capability

Physics Scenarios: β_N, f_{bs}, wall stabilization
ripple, pulse length, current drive

Physics R&D

Enabling Technology R&D

Recommended US Plan for Burning Plasmas



2001 2002 2003 2004 2005

Community Outreach and Involvement

NSO Assessment

Snowmas 2002 Δ

FESAC Action

NRC Review

DOE Decision Process

FESAC Panel Report on Burning Plasmas

ITER - EDA

ITER Negotiations

FY05 DOE

FY05 Cong

FY05 Appropriations

Δ Construction Started

FY06 DOE

FY06 Cong

FY06 Appropriations

Δ Construction Started

Background

Major Conclusions of the FIRE Design Study

- Exploration, understanding and optimization of fusion-dominated (high-gain) burning plasmas are critical issues for all approaches to fusion.

- The tokamak is a cost-effective vehicle to investigate fusion-dominated plasma physics and its coupling to advanced toroidal physics for MFE. The tokamak is technically ready for a next step to explore fusion plasma physics.

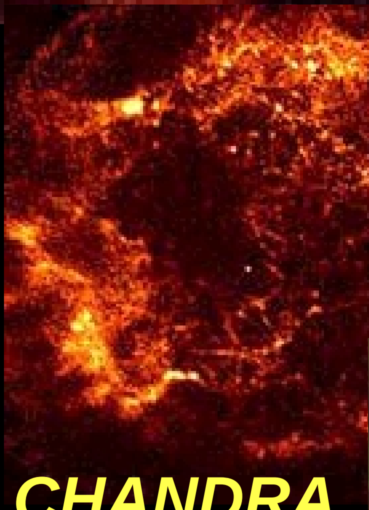
- The FIRE compact high field tokamak can address the important fusion-dominated plasma issues, many of the long pulse advanced tokamak issues and begin the coupling of fusion-dominated plasmas with advanced toroidal physics in a $1B class facility. A host site with significant credits is essential.

- The FIRE design point has been chosen to be a “stepping stone” between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.

- A plan is being developed for an Advanced Tokamak Next Step that will address physics, engineering and cost issues in FY 2000-2 with the goal of being ready to begin a Conceptual Design in 2003.

http://fire.pppl.gov

Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science



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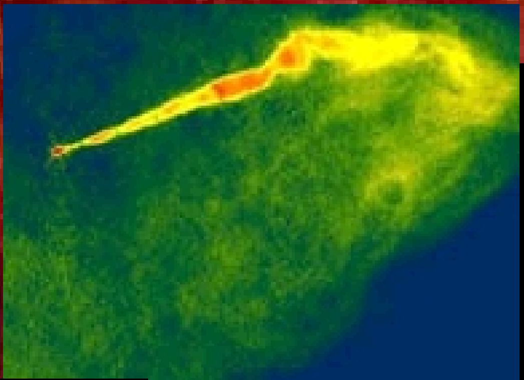
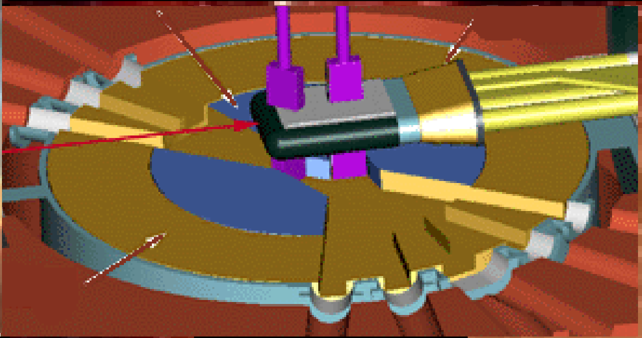
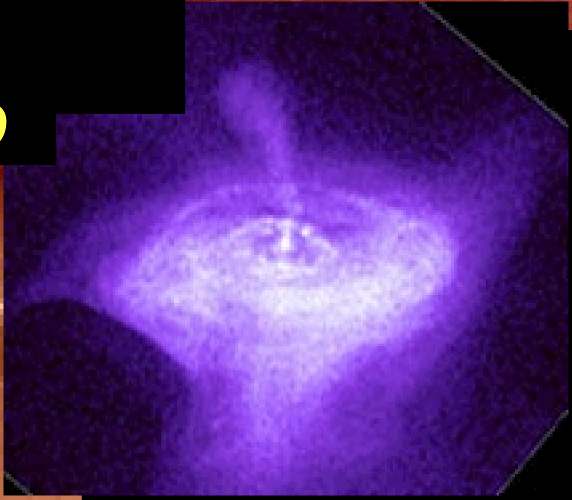


VLBA

HST (NGST)



SNS



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