# FIRE

## A Next Step Option for Magnetic Fusion

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**for the FIRE Team**

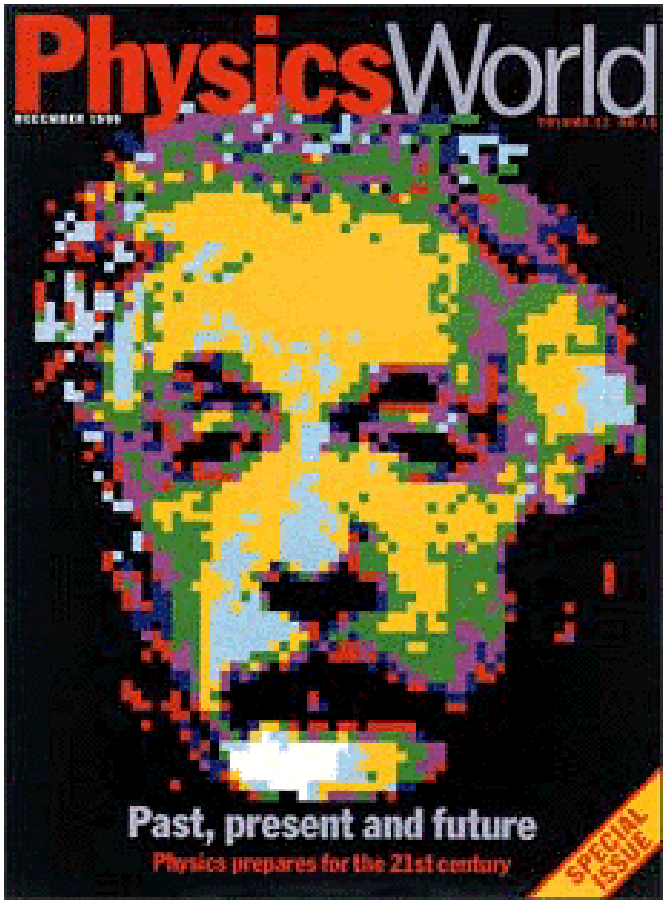
**Presented at**
**Argonne National Laboratory**
**Argonne, IL**

**April 17, 2001**

http://fire.pppl.gov

# Fusion is an Outstanding Physics Challenge and is Connected to Other Outstanding Challenges

**December 1999**




**Ten Outstanding Physics Challenges**

- Quantum gravity presents the ultimate challenge to theorists
- Explaining high-$T_c$ superconductors
- Unstable nuclei reveal the need for a complete theory of the nucleus
- Realizing the potential of fusion energy
- Climate prediction is heavy weather
- Turbulence nears a final answer
- Glass physics: still not transparent
- Solar magnetic field poses problems
- Complexity, catastrophe and physics
- Consciousness: the physicists view

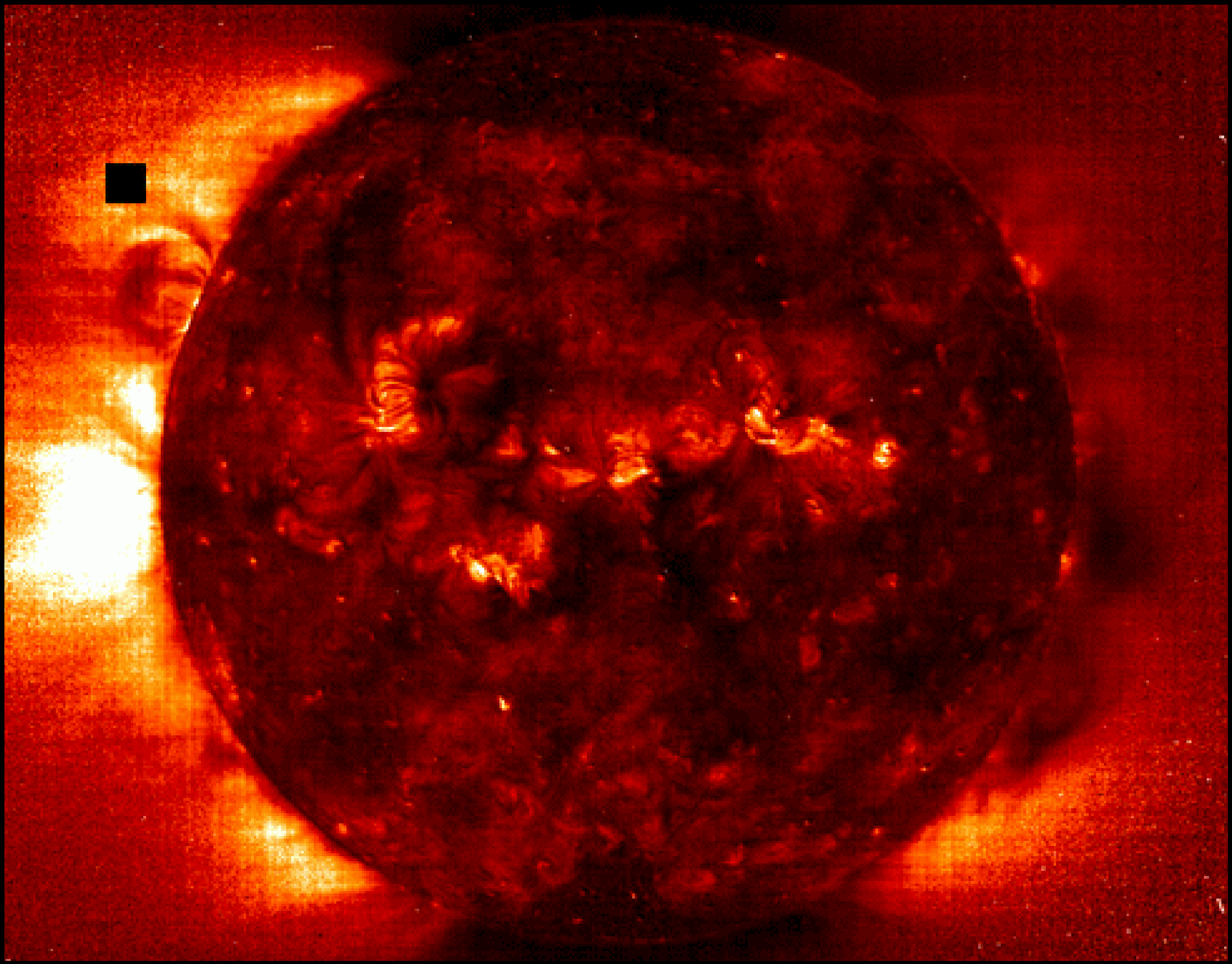
# Outline

- **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**

# 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."

# Plasmas Burn  at Large Size



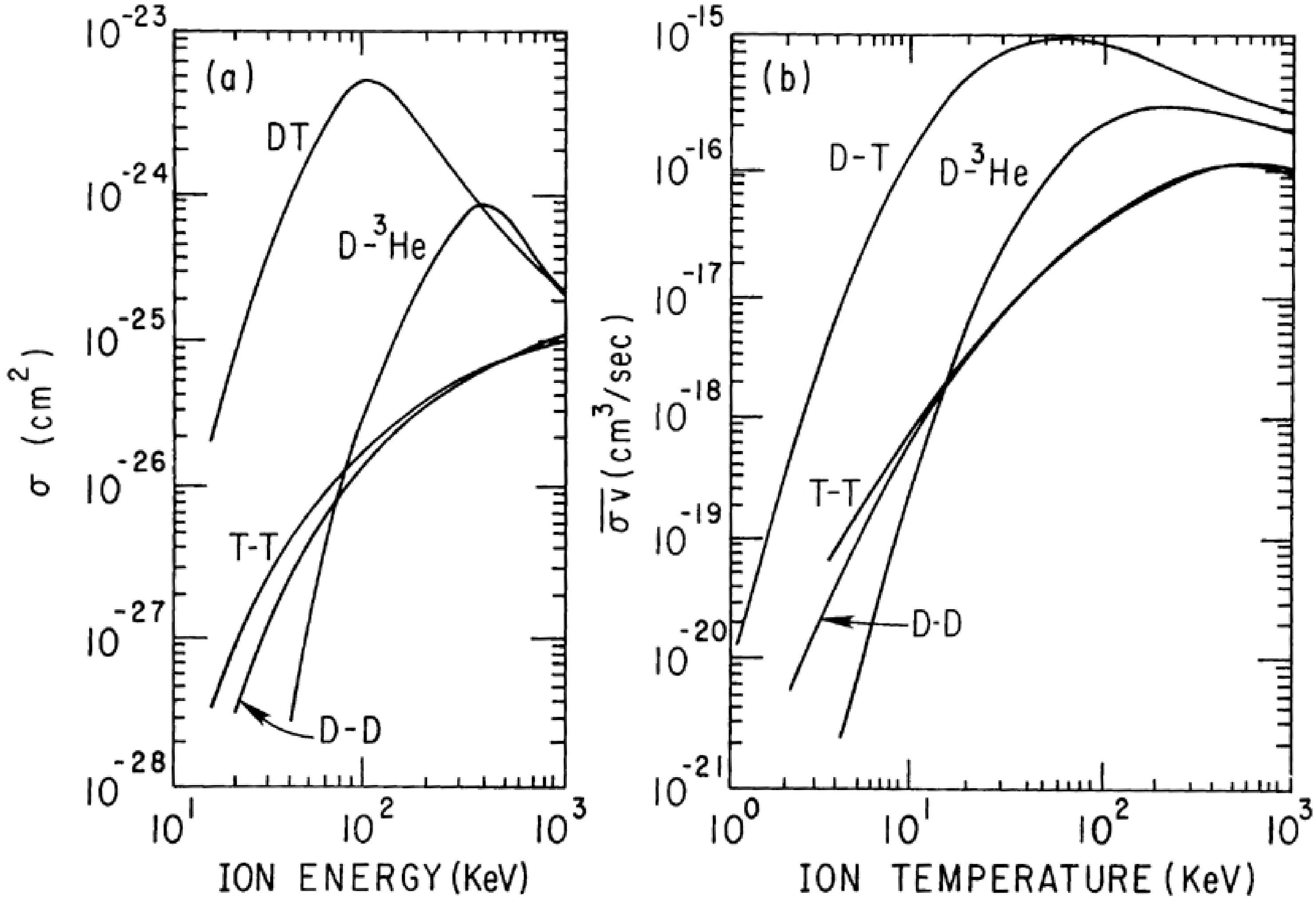
## Why is it so difficult in the lab?

SOHO

# 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 Cross Sections and Reaction Rates

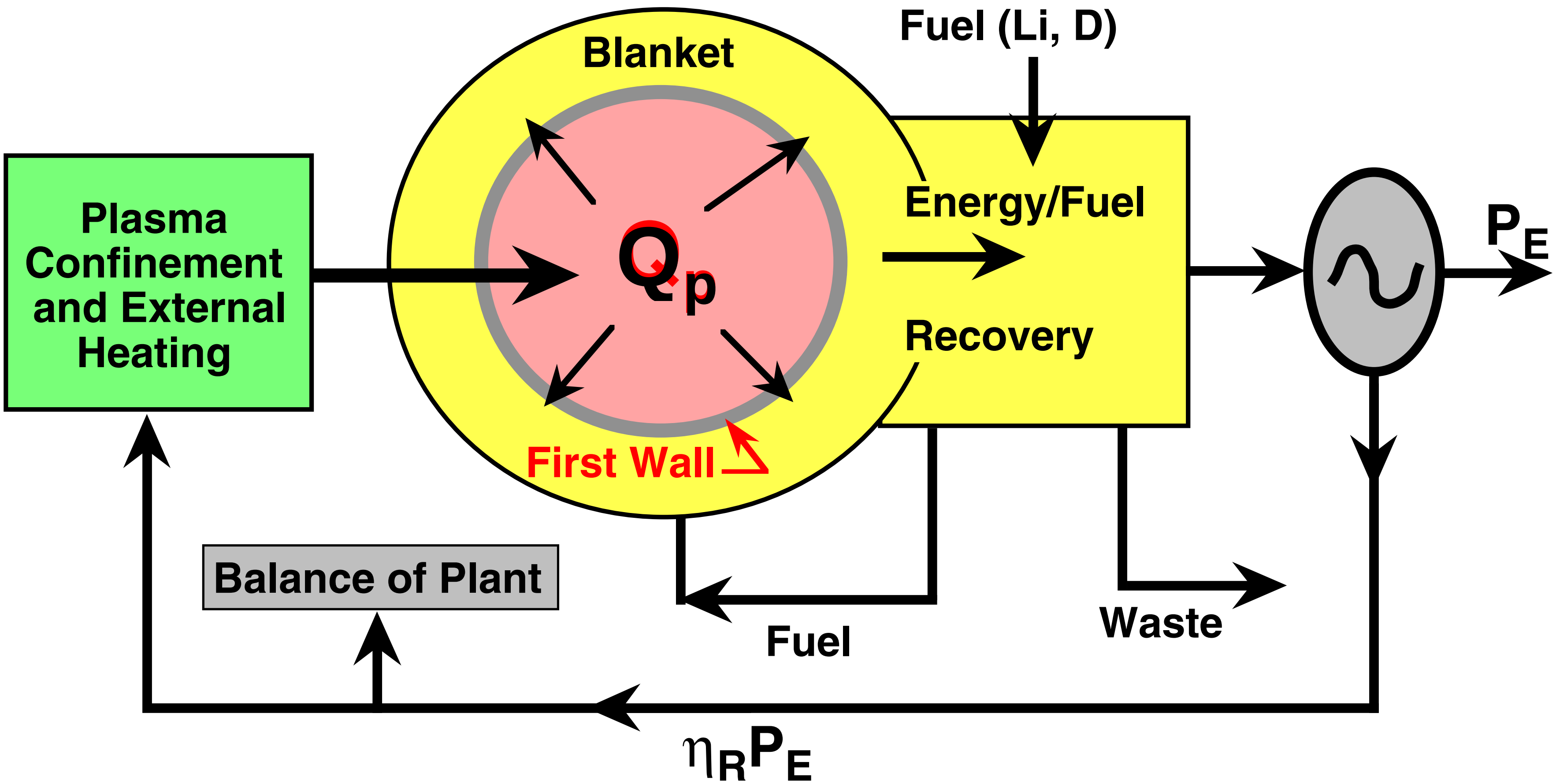



**For Example:**

$P_{DT} = n_D\, n_T <\sigma v> (U_\alpha + U_n)$

$= 5.6 \times 10^{-7} <\sigma v>\, n_D\, n_T$ watts $m^{-3}$, note: $<\sigma v> \sim T^2$ @ 10 keV

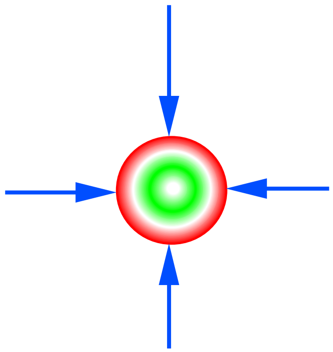
# The Grand Challenge, Science and Technology for Fusion

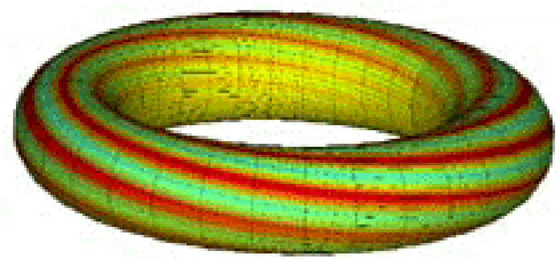


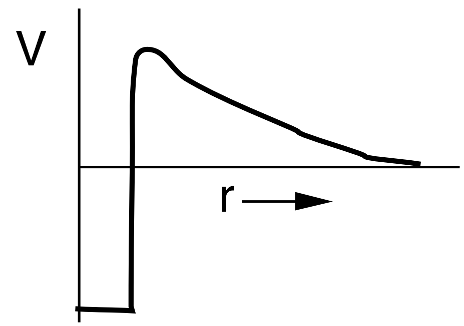

**Key Plasma Performance Metrics**
- Fusion Gain ($Q_p$)
- Fusion Energy Density
- Duty Cycle/Repetition Rate

**Key Engineering Metrics**
- First Wall Lifetime
- Availability/Reliability
- Environment and Safety
- System Costs

# There are Three Principal Fusion Concepts








<u>Spherical Inertial</u>

gravitational

transient compression

drive (laser-D/I, beam)

radial profile

time profile

electrostatic

<u>Toroidal Magnetic</u>

surface of helical B lines

twist of helix

twist profile

plasma profile

toroidal symmetry

<u>Reactivity Enhancement</u>

muon catalysis

polarized nuclei

others?

# Plasma Requirements for a Fusion-Dominated Plasma

**Power Balance**

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

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 $\tau_E = W_p/(P_{aux\text{-}heat} - dW_p/dt)$ is the energy confinement time.

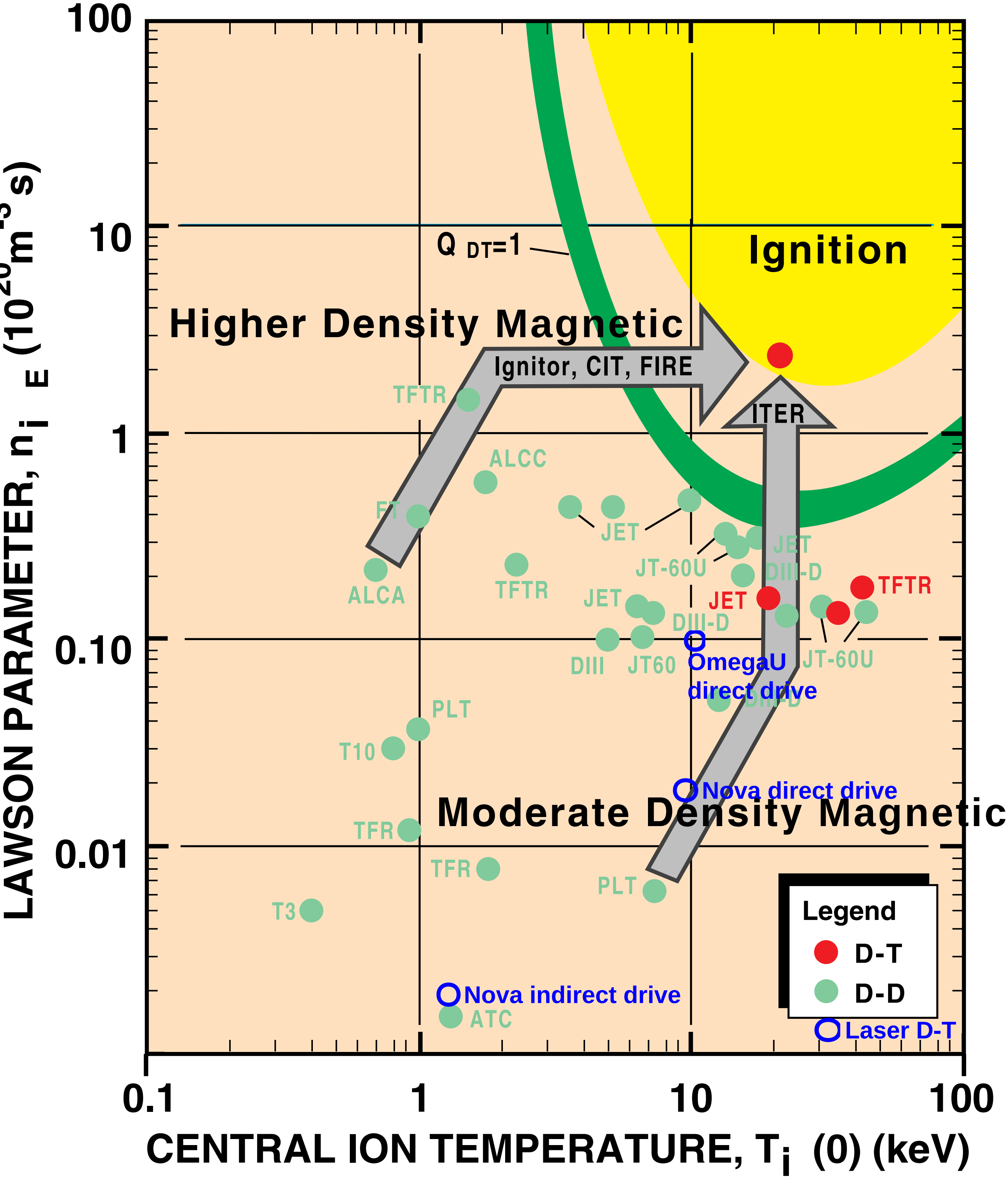
**In Steady-state:**

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

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

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

# Status of Laboratory Fusion Experiments




#97GR041.ntau-98 FIRE

# International Thermonuclear Experimental Reactor (ITER)

<u>Parties</u>

US (left in 1998)

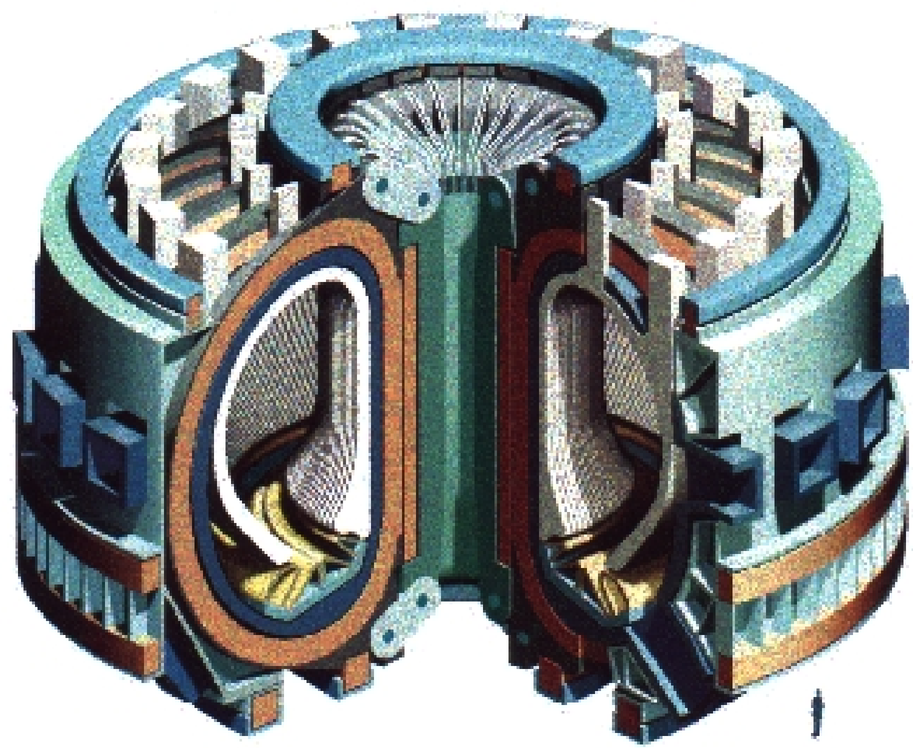
Japan

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** | | | | |

- **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.**

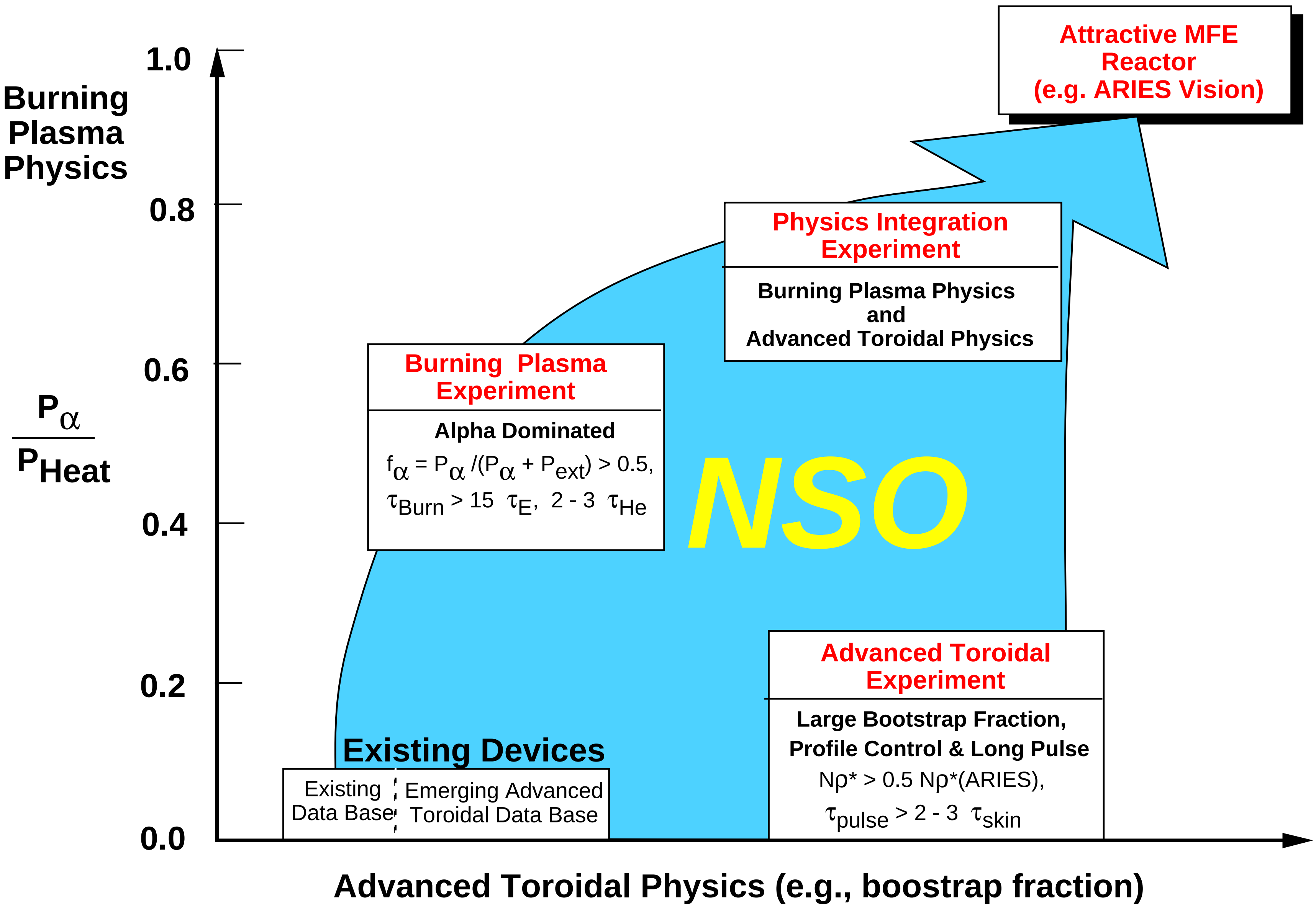
# Fusion Science Objectives for a Major Next Step Magnetic Fusion Experiment

**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 ($\beta$-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.

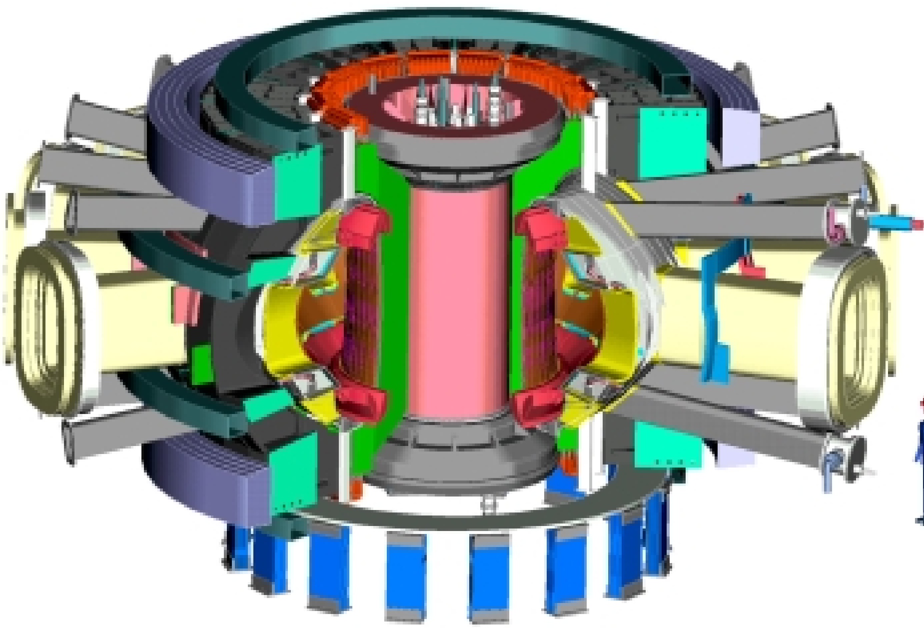
# Stepping Stones for Resolving the Critical Fusion Plasma Science Issues for an Attractive MFE Reactor




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

# Fusion Ignition Research Experiment
# (FIRE)

http://fire.pppl.gov



## Design Goals

- R = 2.0 m, a = 0.525 m
- B = 10 T, (12T)*
- $W_{mag}$= 3.8 GJ, (5.5T)*
- $I_p$ = 6.5 MA, (7.7 MA)*
- $P_{alpha} > P_{aux}$, $P_{fusion} < 200$ MW
- Burn Time ≈18.5s (≈12s)*
- Tokamak Cost ≤ $0.3B

  Base Project Cost ≤ $1B

* Higher Field Mode

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

# 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**

# Basic Parameters and Features of FIRE Reference Baseline

| | |
|---|---|
| R, major radius | 2.0 m |
| a, minor radius | 0.525 m |
| $\kappa_{95}$, elongation at 95% flux surface | ~1.8 |
| $\delta_{95}$, triangularity at 95% flux surface | ~0.4 |
| $q_{95}$, safety factor at 95% flux surface | >3 |
| Bt, toroidal magnetic field | 10 T with 16 coils, 0.34% ripple @ Outer MP |
| Toroidal magnet energy | 3.7 GJ |
| Ip, plasma current | ~6.5 MA (7.7 MA at 12 T) |
| Magnetic field flat top, burn time | 26 s at 10 T in dd, 18.5s @ Pdt ~ 200 MW) |
| Pulse repetition time | ~3hr @ full field and full pulse length |
| ICRF heating power, maximum | 30 MW, 100MHz for $2\Omega_T$, 4 mid-plane ports |
| Neutral beam heating | None, may have diagnostic neutral beam |
| Lower Hybrid Current Drive | None in baseline, upgrade for AT phase |
| Plasma fueling | Pellet injection (≥2.5km/s vertical launch inside mag axis, possible 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 | 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 |

**Higher Field Mode B = 12T and Ip = 7.7MA with a 12 second flat top has been identified.**
**Also enhanced performance option B = 10T, Ip = 7.7 MA with 20 s burn with R = 2.14m**

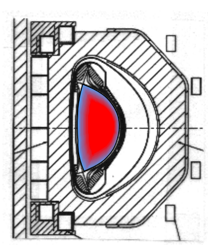
# FIRE would have Access for Diagnostics and Heating

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

$P_{fusion}$
= ~ 200 MW

Volume
= 18 $m^3$

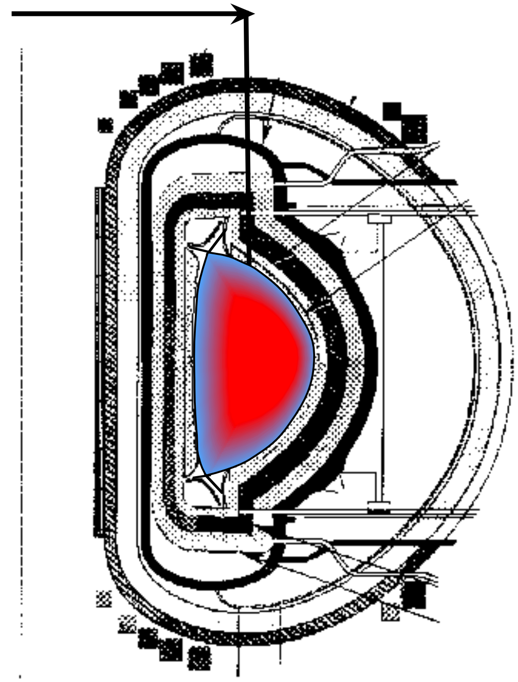
R = 2 m   B = 10 T



FIRE

~ 3X

R = 5.2 m   B = 6 T



ARIES-AT The "Goal"

$P_{fusion}$
= 1755 MW

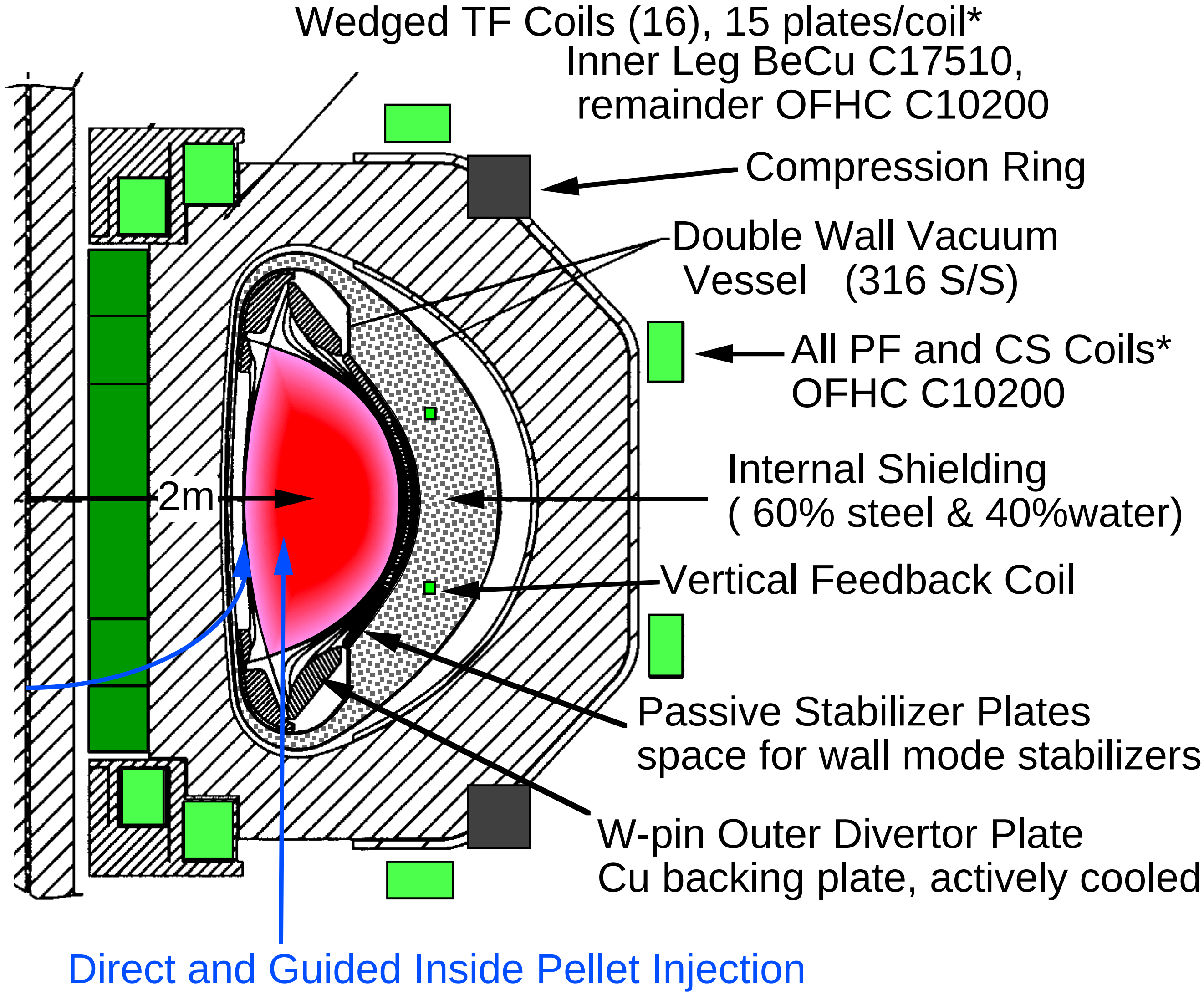
Volume
= 330 $m^3$

| | FIRE | ARIES-AT |
|---|---|---|
| Fusion Power Density ($MW/m^3$) | 12 | 5.3 |
| Neutron Wall Loading ($MW/m^2$) | 3 | 3.5 |
| Divertor Challenge (Pheat/R) | 25 | ~70 |
| Power Density on Div Plate ($MW/m^2$) | ~25 $\rightarrow$ 5 | ~5 |
| Burn Duration (s) | ~20 | steady |

# FIRE Incorporates Advanced Tokamak Innovations

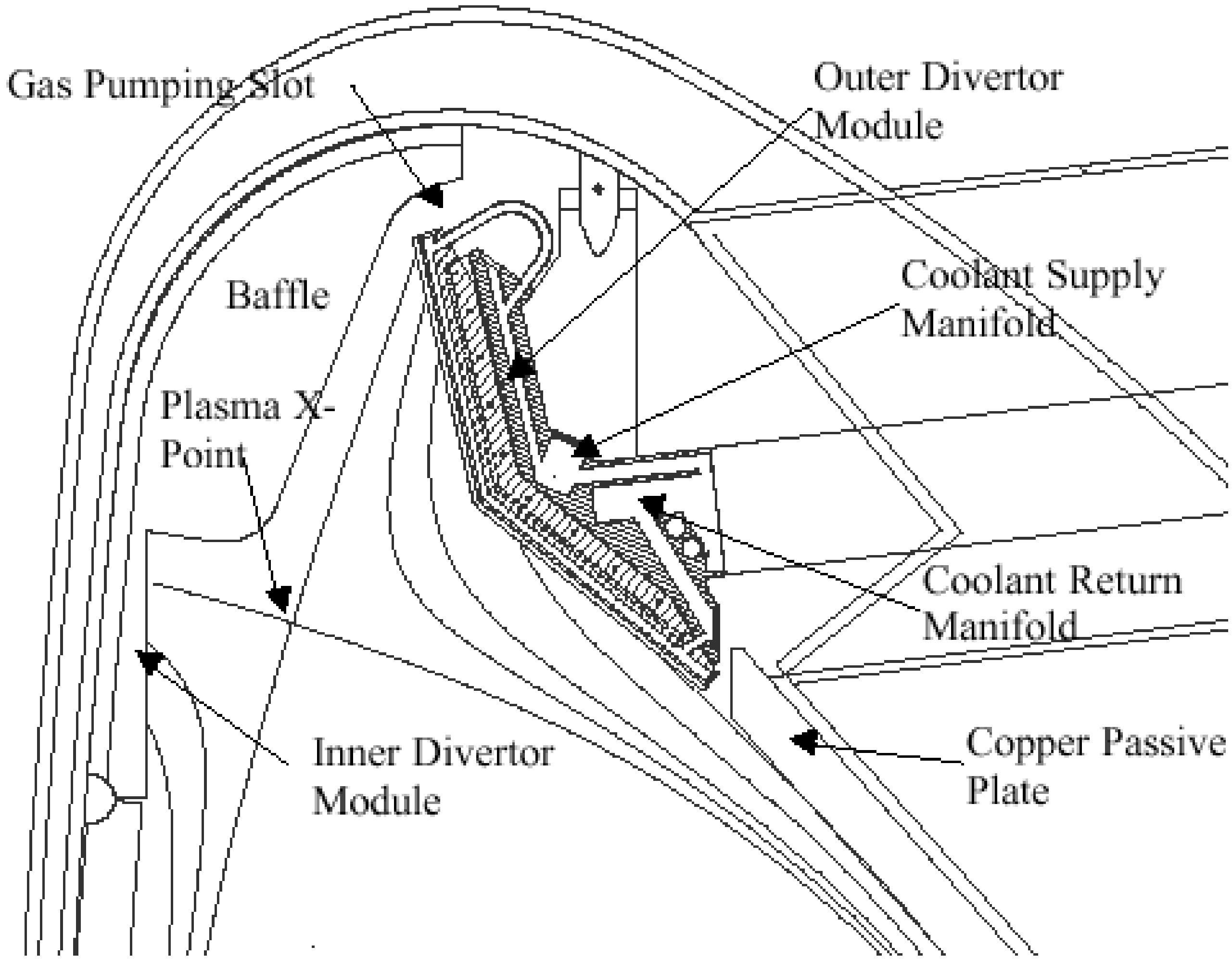
**AT Features**

- DN divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



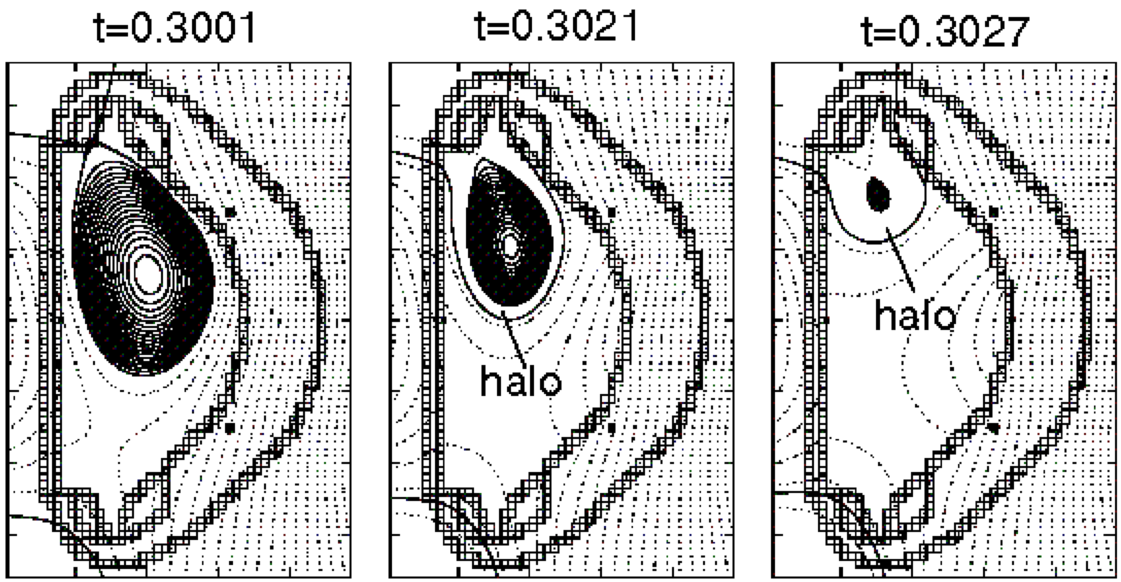

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

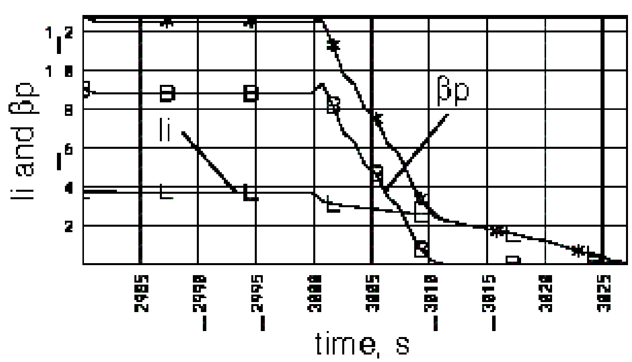
# FIRE's Divertor Must Handle Attached(25 MW/m2) and Detached(5 MW/m2) Operation

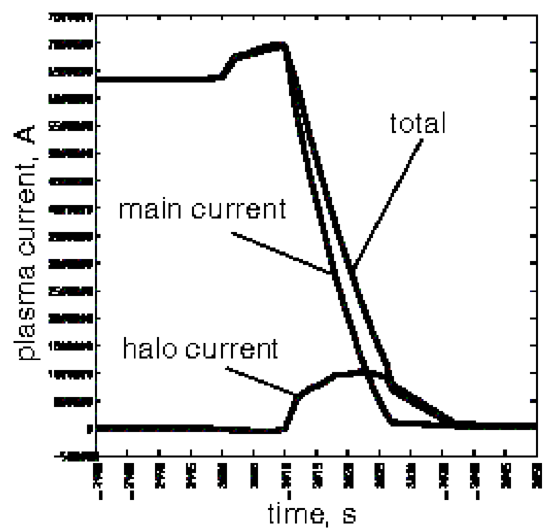


# FIRE Must Handle Disruptions

VDE Simulation with 3 MA/ms Current Quench



## Recent Innovations have Markedly Improved the Technical Basis for a Compact High Field Tokamak Burning Plasma Exp't.

Tokamak experiments (1989-1999) have developed enhanced confinement modes that scale (e.g.,ITER-98H) 1.3 times higher than the 1989 CIT design assumption.

Alcator C-Mod - the prototype for Compact High Field tokamaks has shown:

- Confinement in excess of 1.4 times the 1989 design guidelines for CIT and ~1.15 times the recent ITER-98H design guidelines.
- Successful ICRF heating at high density in shaped diverted plasmas.
- Successful detached divertor operation at high power density.

**VDEs and halo currents have made internal hardware design more difficult.**

D-T experiments on TFTR and JET have shown:

- Tritium can be handled safely in a laboratory fusion experiment!!!
- D-T plasmas behaved roughly as predicted with slight improvements in confinement in plasmas with weak alpha-heating.

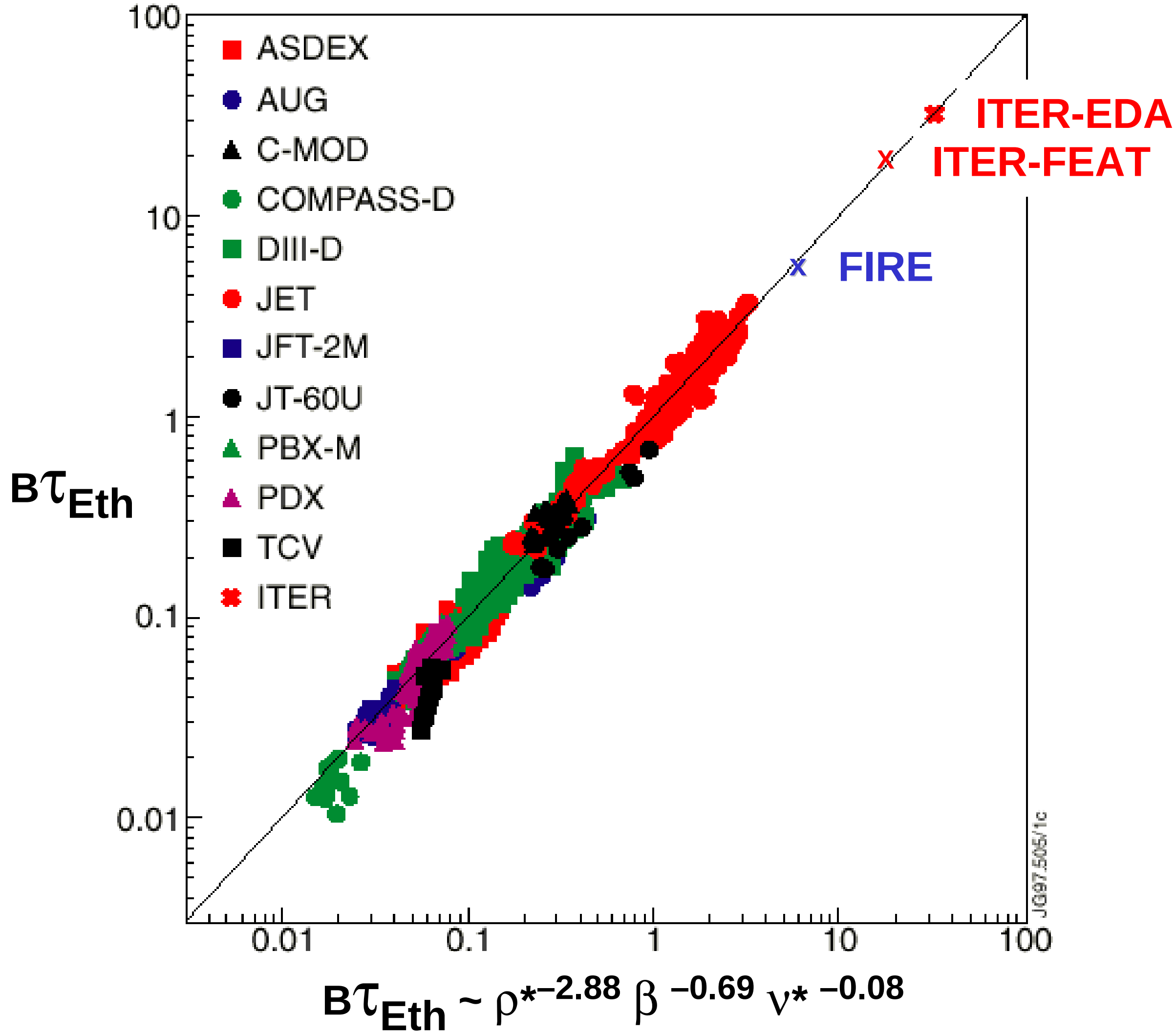
Engineering Innovations to increase capability and reduce cost

- Improved coil and plasma facing component materials, improved 3-D engineering computer models and design analysis, advanced manufacturing.

# FIRE is a Modest Extrapolation in Plasma Confinement

| Dimensionless Parameters |
| --- |
| $\omega_c \tau$<br>$\rho^* = \rho/\mathbf{a}$<br>$\nu^* = \nu_c/\nu_b$<br>$\beta$ |

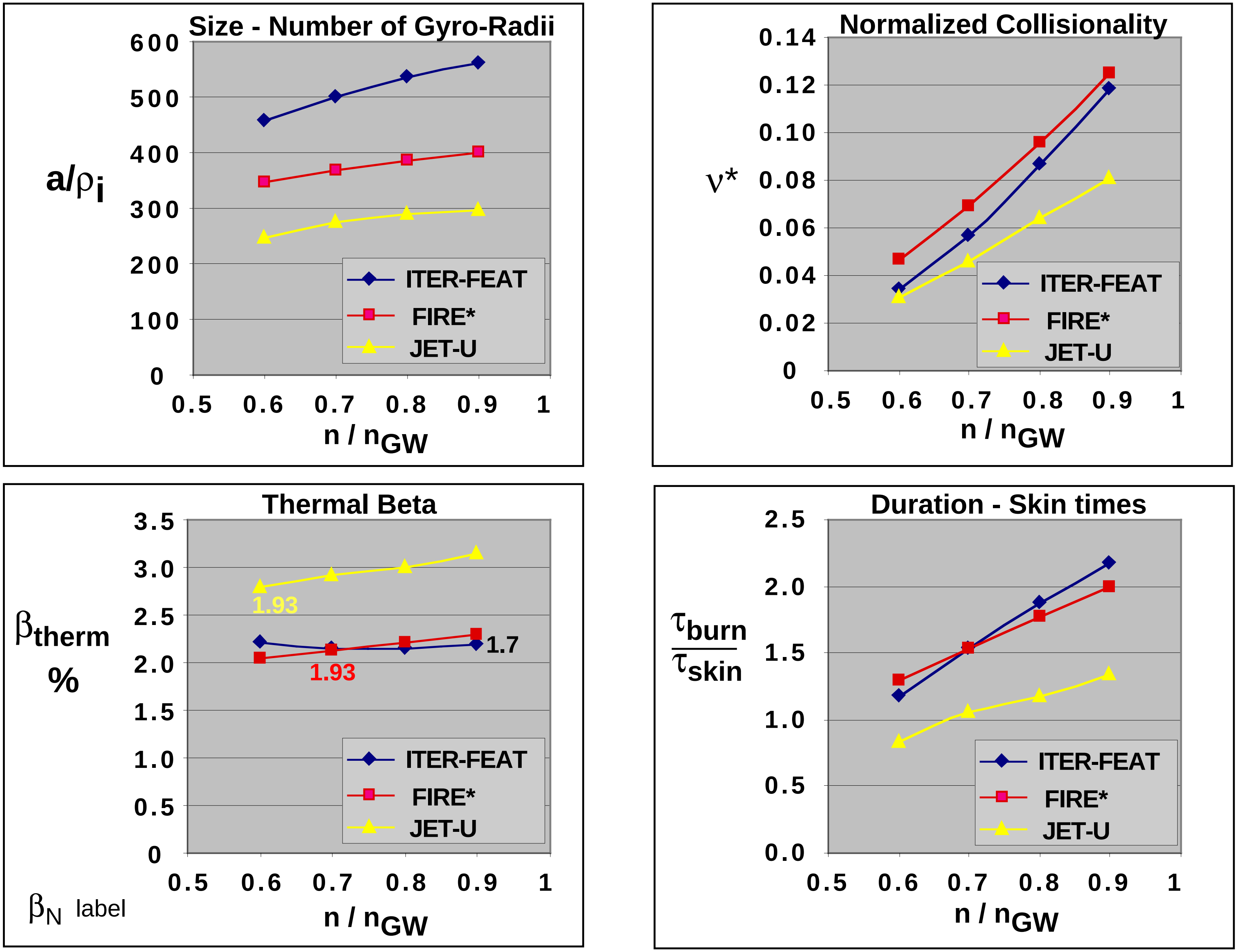
| Similarity Parameter |
| --- |
| $B\ R^{5/4}$ |



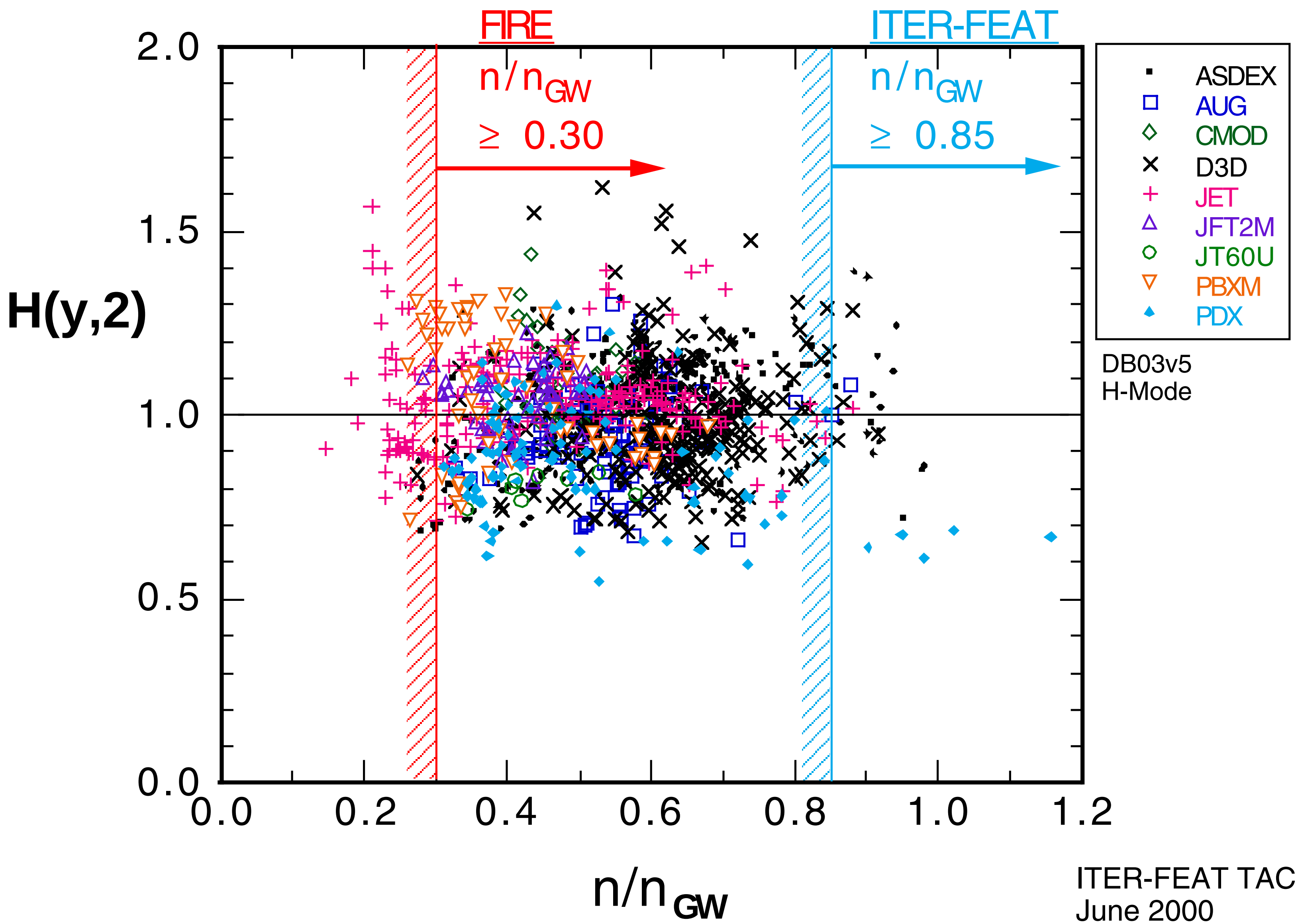

Kadomtsev, 1975

# Dimensionless Parameters for Potential Next Step D-T Plasmas

**ITER-FEAT (15 MA): Q = 10, H = 0.95, FIRE*(7.7 MA): Q = 10, H = 1.03, JET-U (6 MA): Q = 0.64, H = 1.1**

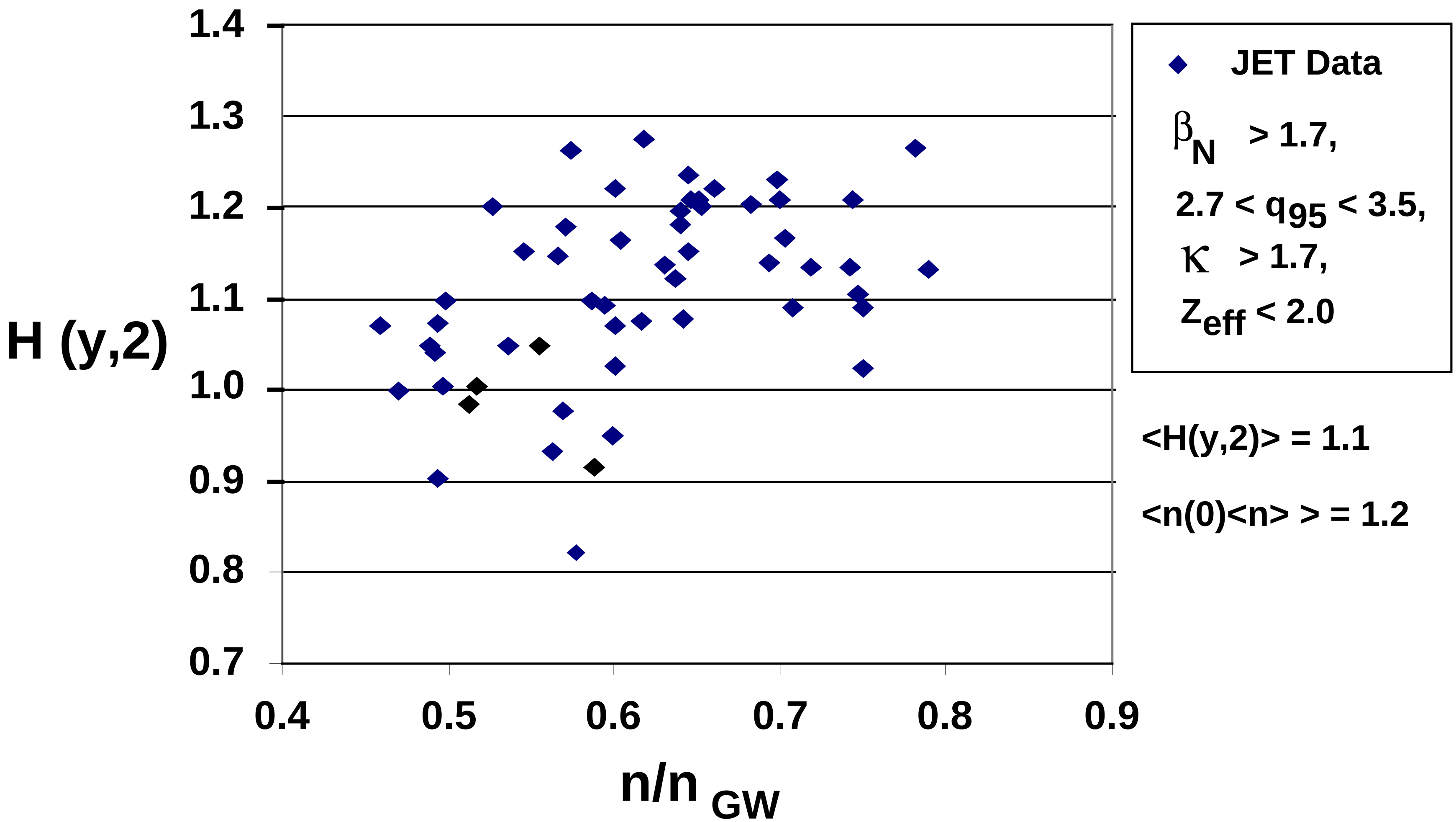


# FIRE can Access Most of the Existing H-Mode Database



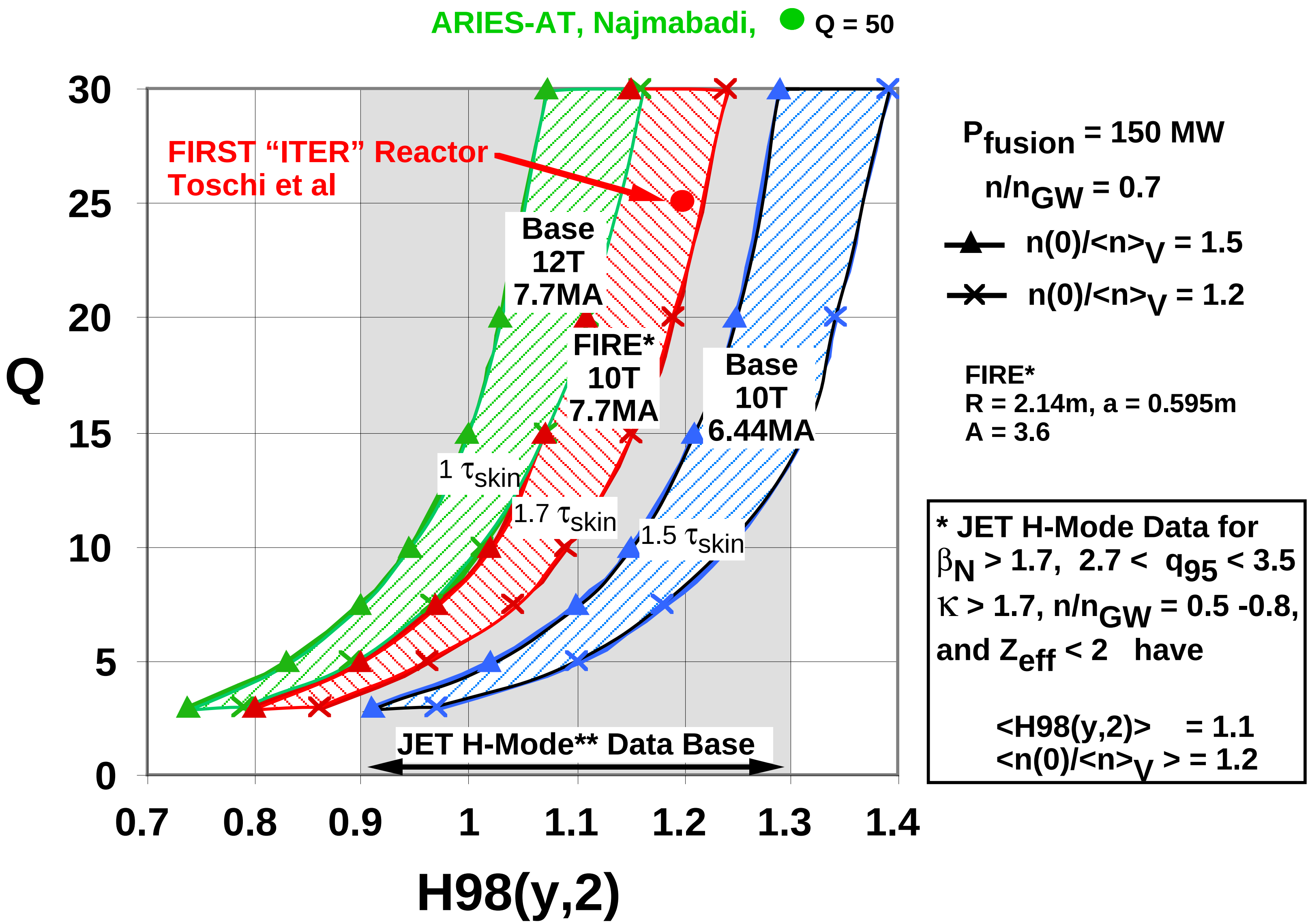

ITER-FEAT TAC Meeting
June 2000

# JET H-Mode Data Selected for FIRE-like Parameters

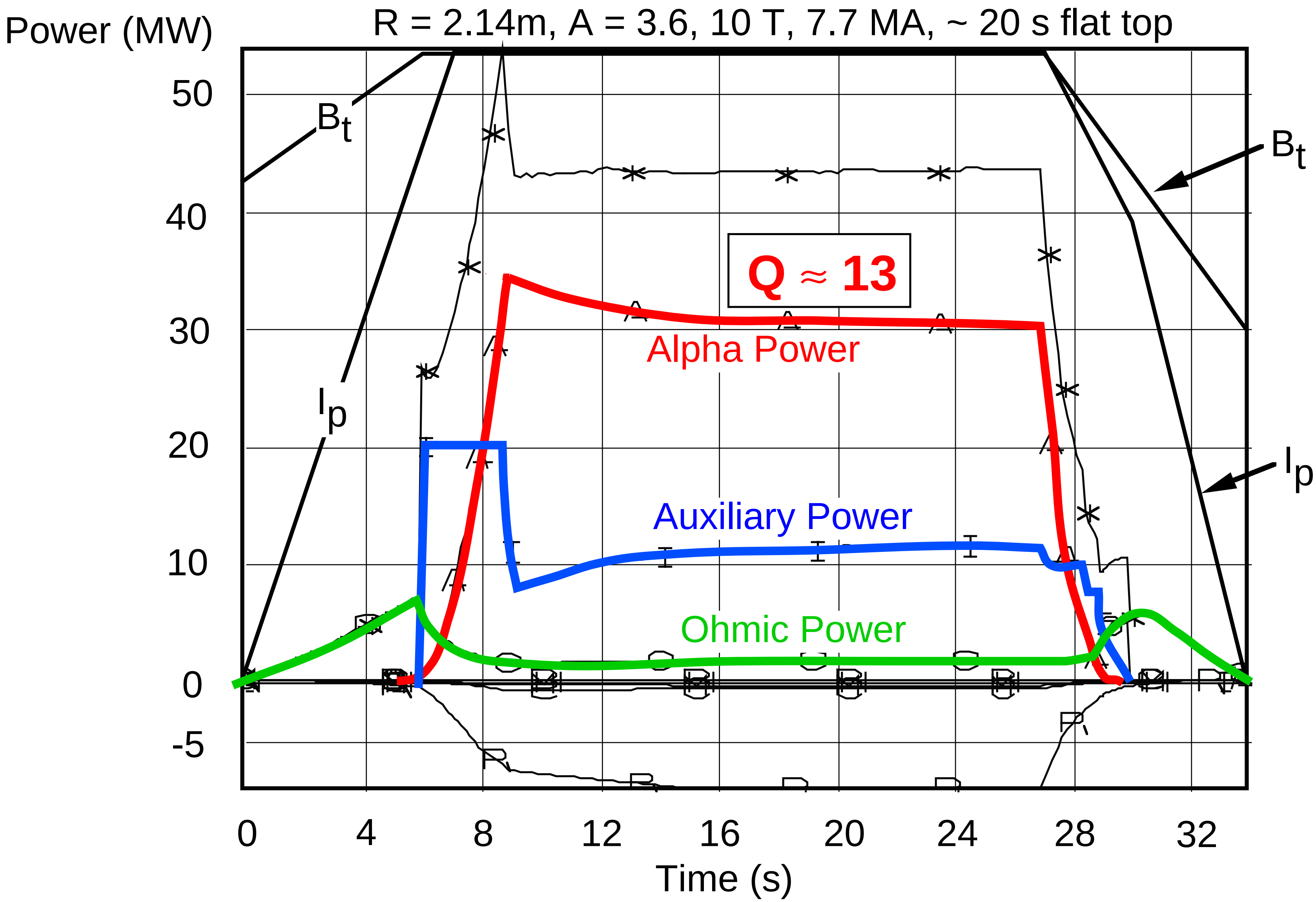



This approach discussed at IAEA(Sorrento) and at the International Confinement Database meeting (Frascati).

# Projections of FIRE Compared to Envisioned Reactors

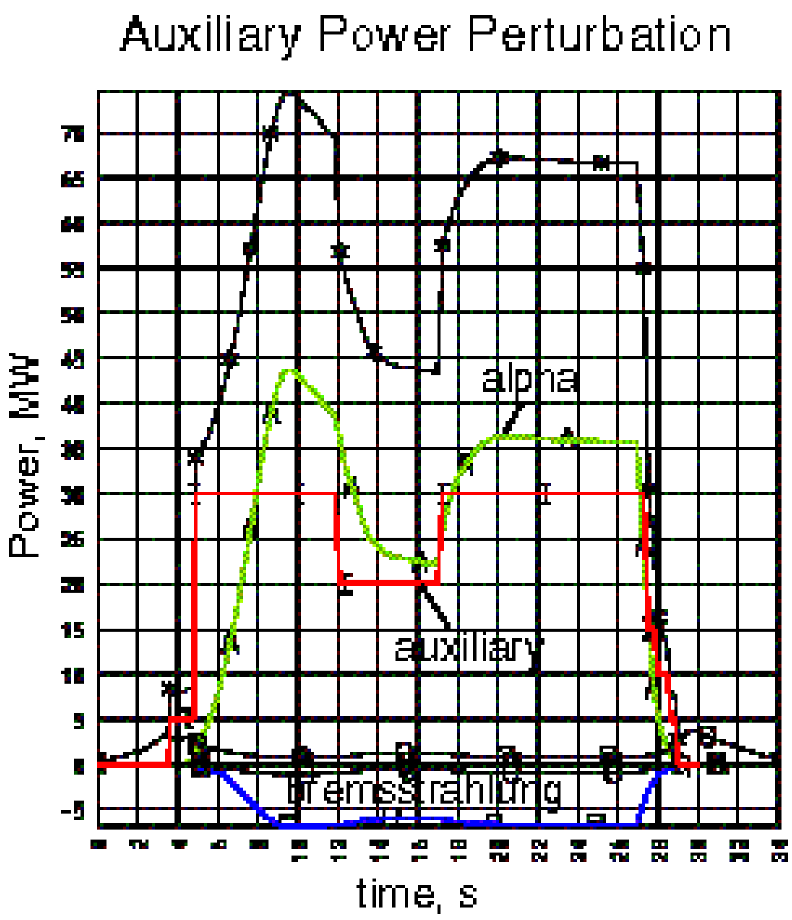


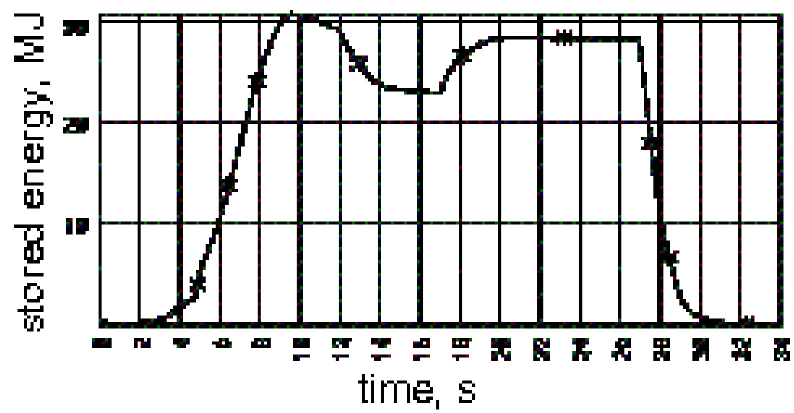
# 1 1/2-D Simulation of Burn Control in FIRE* (TSC)

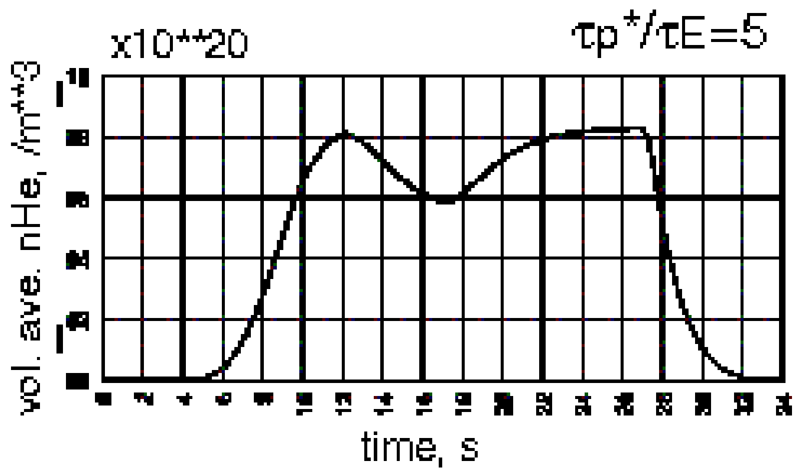



- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and $n/n_{GW}$ = 0.67
- Burn Time ≈ 18 s ≈ 21 $\tau_E$ ≈ 4 $\tau_{He}$ ≈ 2 $\tau_{skin}$

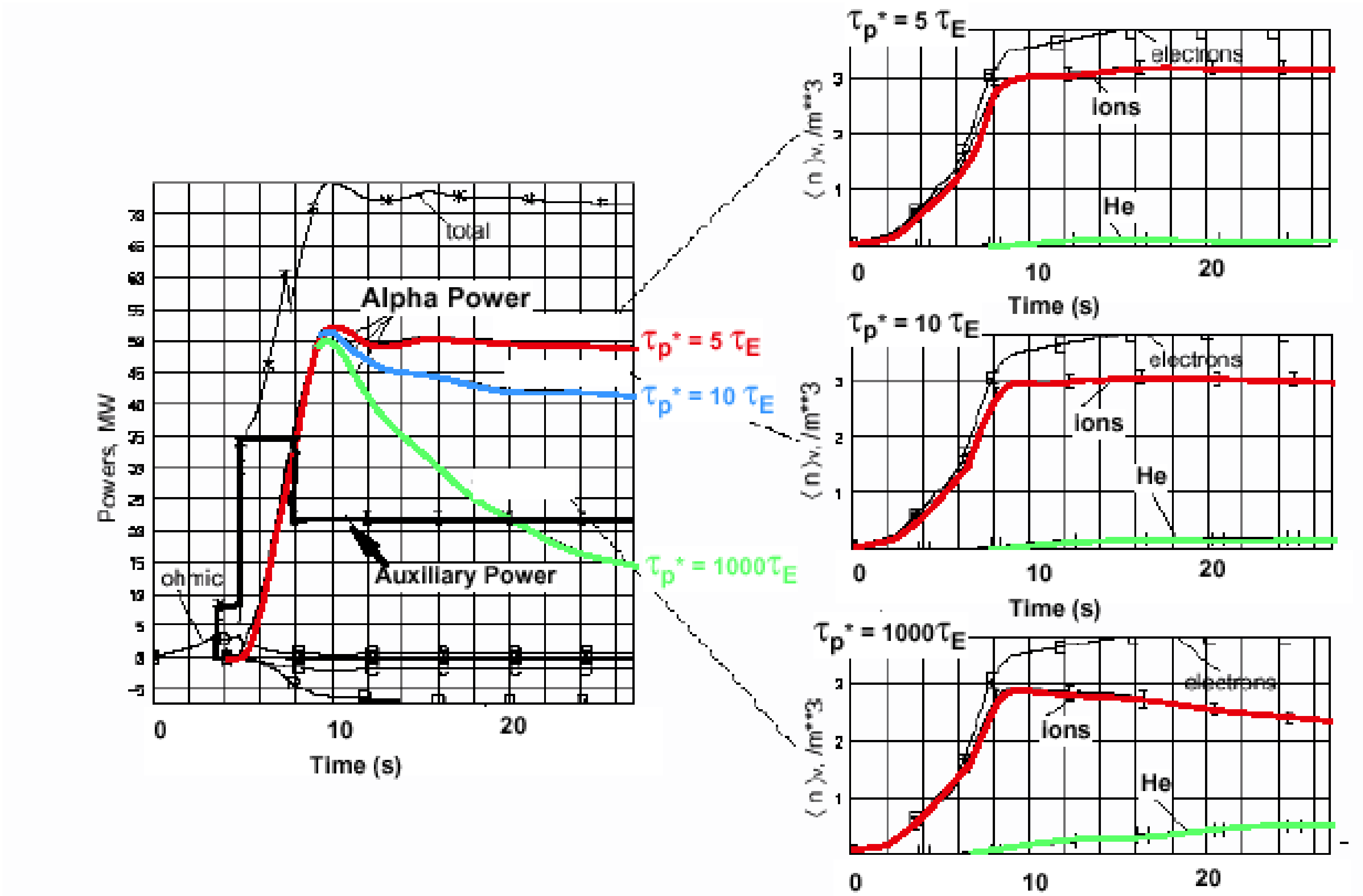
# Plasma Response to $P_{aux}$ Modulation



# Divertor Pumping Needed for Plasma Burn




Adjust divertor pumping to control helium ash

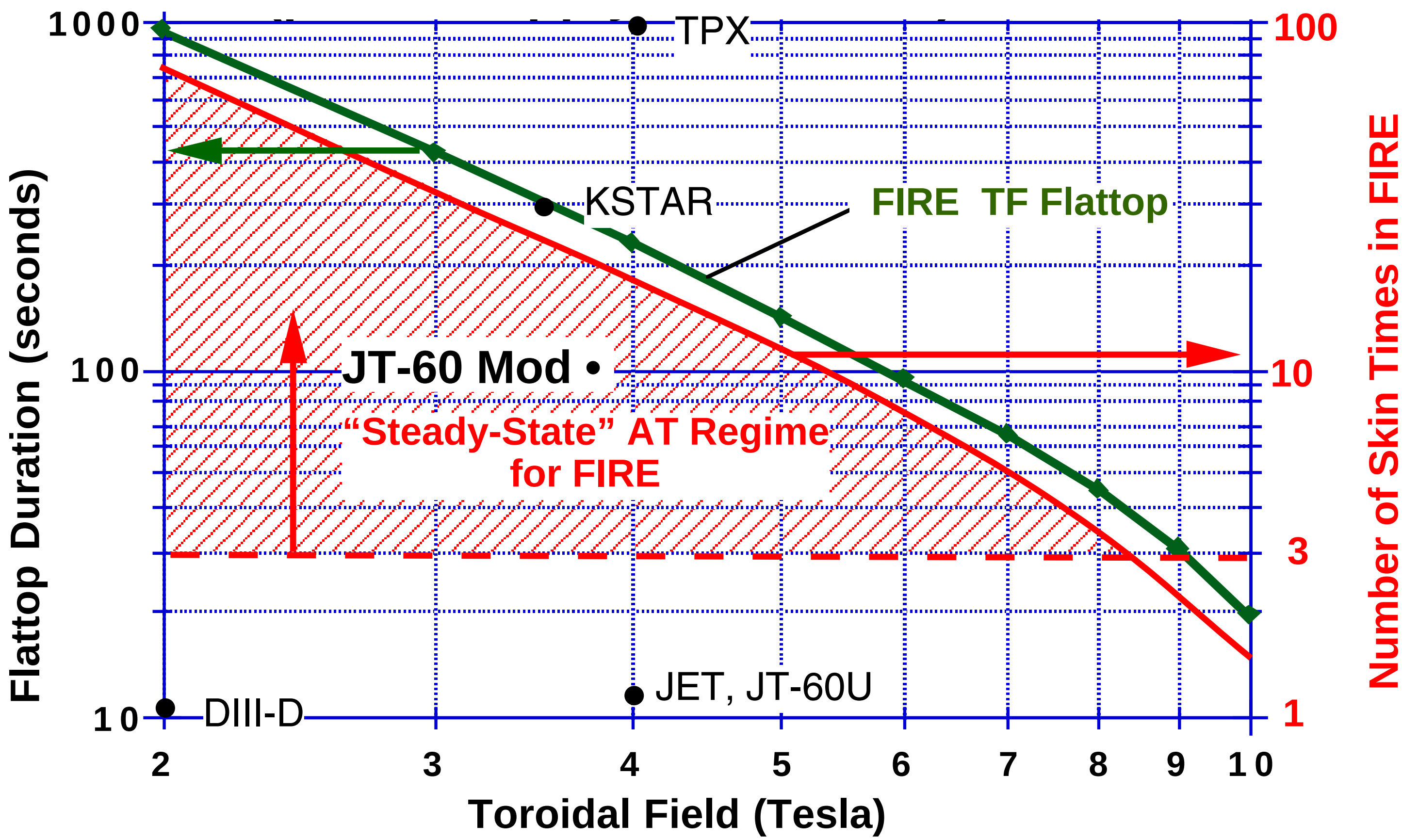
TSC/Kessel/21-q.ps

# FIRE Has Several Operating Modes Based on Present Day Physics

- Reference: ELMing H-mode
  - B=10 T, Ip=6.5 MA, Q=5, t(pulse)=18.5 s
- High Field: ELMing H-mode
  - B=12 T, Ip=7.7 MA, Q=10, t(pulse)=12 s
- AT Mode: Reverse Shear with fbs>50%
  - B=8.5 T, Ip=5.0 MA, Q=5, t(pulse)=35 s
- Long Pulse DD: AT Mode and H-mode
  - B=4 T, Ip=2.0 MA, Q=0, t(pulse)>200 s

FIRE can study both burning AND long pulse plasma physics in the same device

# FIRE could Access "Long Pulse" Advanced Tokamak Mode Studies at Reduced Toroidal Field.




Note: FIRE is ≈ the same physical size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT .

**The combination of JET-U, JT-60 Mod, KSTAR and FIRE could cover the range fromsteady-state non-burning advanced-tokamak modes to "quasi-equilibrium" burning plasmas in advanced tokamak modes.**

# A Series of Advanced Tokamak Regimes Aimed at the Ultimate ARIES-AT can be studied with Alpha Heating.

## Steps to ARIES-AT

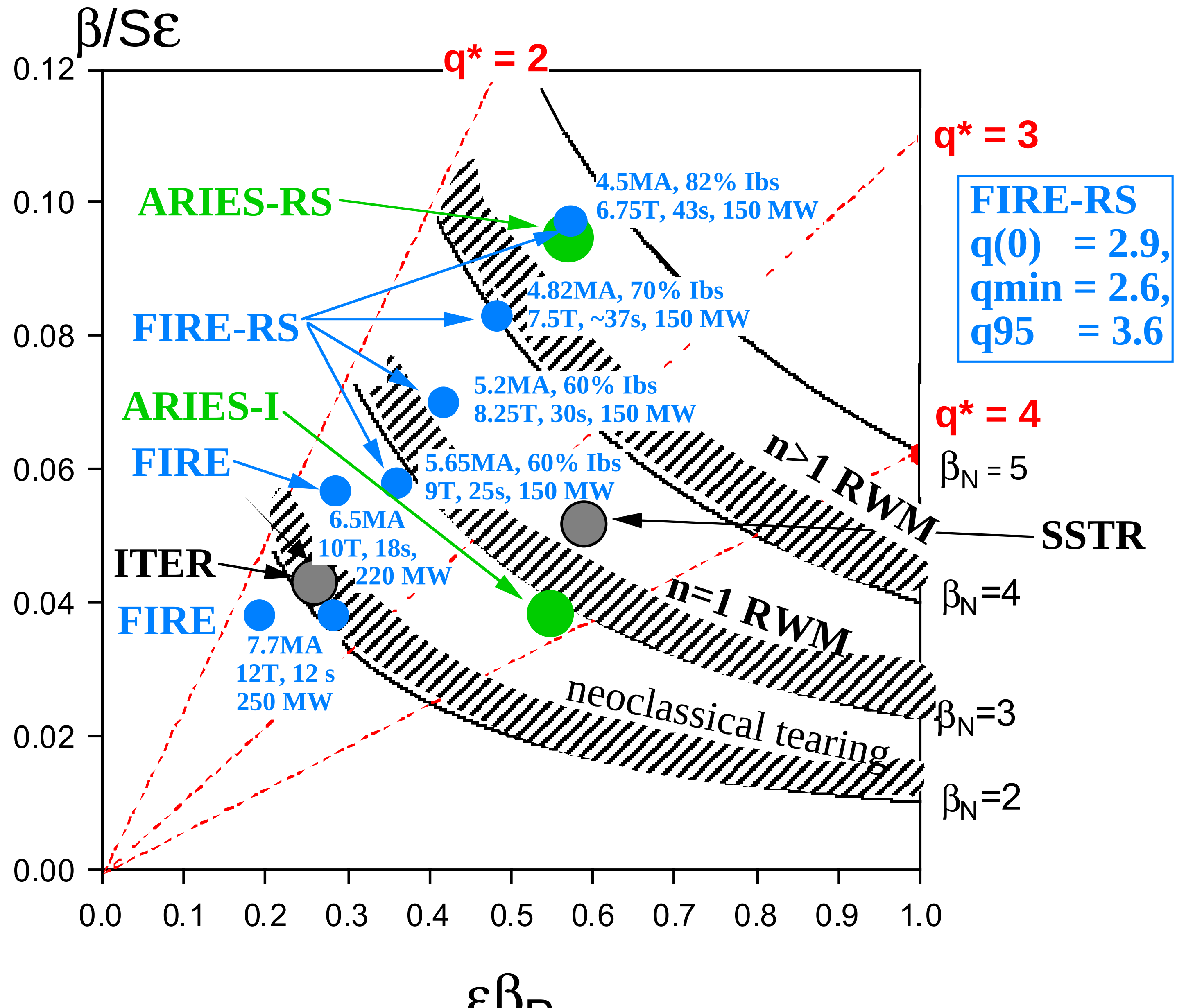
1) stabilize NTM's

2) stabilize n=1 RWM

3) stabilize n>1 RWMs

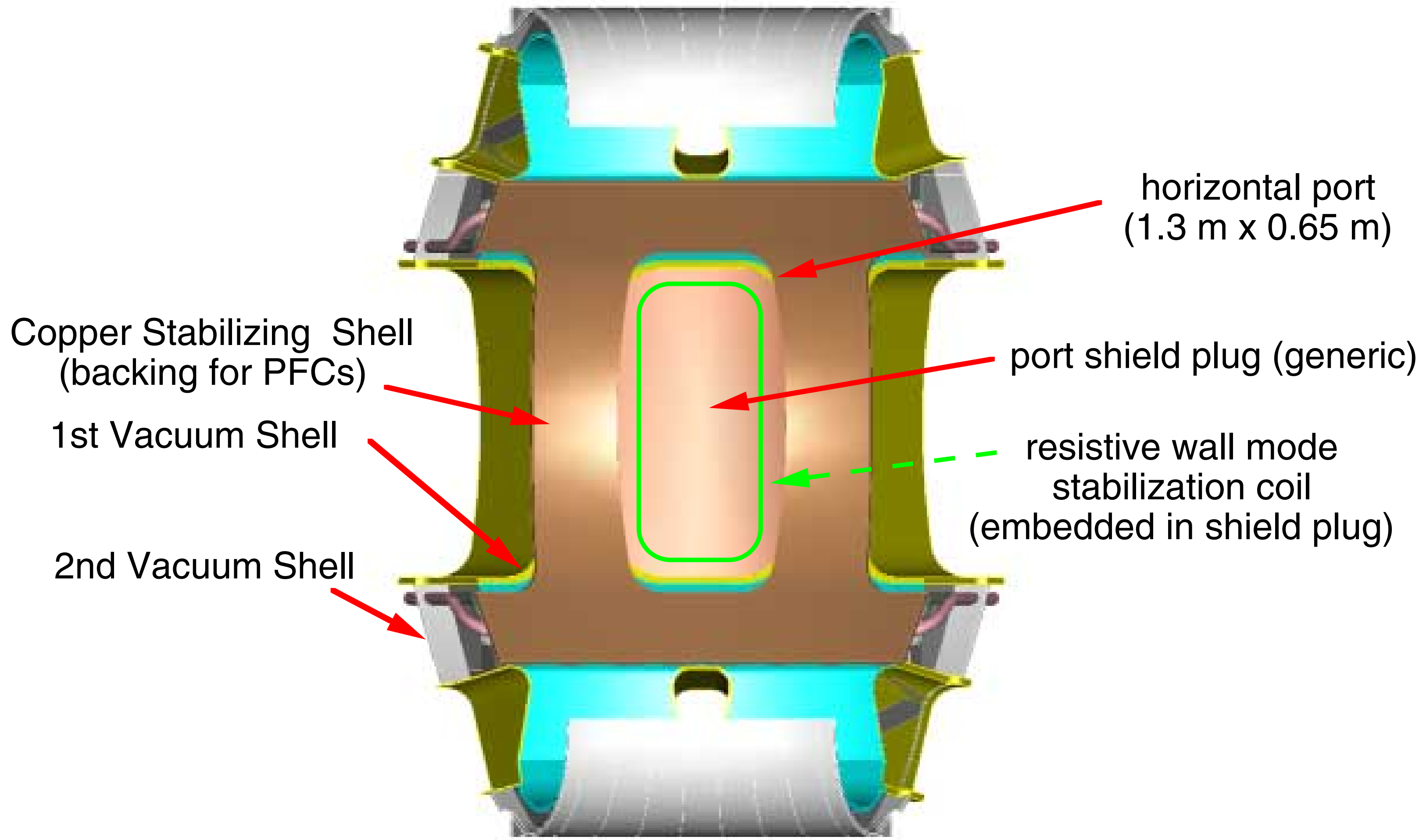
*each step with higher $f_{bs}$

**each step with more profile control



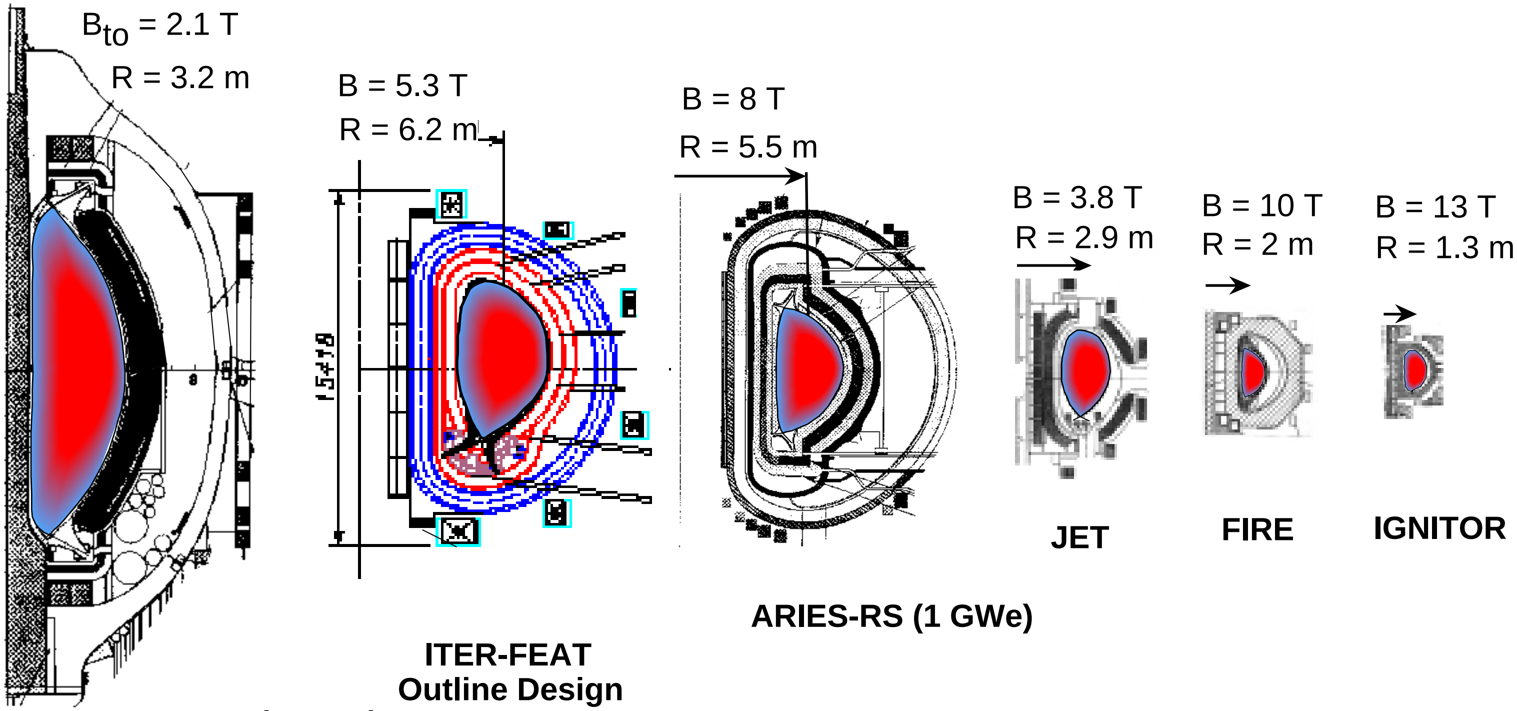
# FIRE is Evaluating Methods to Stabilize Resistive Wall Modes

view of hoizontal port front looking from plasma side




Concept under development by J. Bialek, G. Navratil, C.Kessel et al

# Potential Next Step Burning Plasma Experiments and Demonstrations in MFE




| 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

# FIRE Power Requirements for BeCu or CuTF Coils

| | 10T (20s flattop) | | 12T (12s flattop) | |
|---|---|---|---|---|
| BeCu | Peak Power (MW) | Peak Energy (GJ) | Peak Power (MW) | Peak Energy (GJ) |
| TF | 490 | 11.5 | 815 | 11.5 |
| PF | 250 | 2.2 | 360 | 3.7 |
| RF | 60 | 1 | 60 | 0.6 |
| $\sum$ | 800 | 14.7 | 1235 | 15.8 |
| Grid | 550 (TF&RF) | 12.5 | 600 (TFbase) | 10.9 |
| MG | 250 (PF) | 2.2 | 635 (TFsupp&PF&RF) | 4.9 |

| | 10T (45s flattop) | | 12T (25s flattop) | |
|---|---|---|---|---|
| Cu | Peak Power (MW) | Peak Energy (GJ) | Peak Power (MW) | Peak Energy (GJ) |
| TF | 267 | 12.6 | 345 | 13.2 |
| PF | 250 | 5 | 360 | 4.6 |
| RF | 60 | 2.3 | 60 | 1.3 |
| $\sum$ | 577 | 19.9 | 765 | 19.1 |
| Grid | 577 (All Systems) | 19.9 | 404 (TF&RF) | 14.5 |
| MG | 0 | 0 | 360 (PF) | 4.6 |

# Preliminary FIRE Cost Estimate (FY99 US$M)

| | Estimated Cost | Contingency | Total with Contingency |
|---|---|---|---|
| 1.0 Tokamak Core | 252.2 | 75.2 | 323.0 |
| 1.1 Plasma Facing Components | 65.0 | 17.0 | |
| 1.2 Vacuum Vessel/In-Vessel Structures | 35.2 | 9.7 | |
| 1.3 TF Magnets /Structure | 113.8 | 37.2 | |
| 1.4 PF Magnets/Structure | 28.4 | 8.5 | |
| 1.5 Cryostat | 1.8 | 0.5 | |
| 1.6 Support Structure | 7.5 | 2.2 | |
| 2.0 Auxiliary Systems | 134.6 | 39.3 | 173.9 |
| 2.1 Gas and Pellet Injection | 7.1 | 1.4 | |
| 2.2 Vacuum Pumping System | 13.0 | 2.0 | |
| 2.3 Fuel Recovery/Processing | 7.0 | 1.0 | |
| 2.4 ICRF Heating | 107.4 | 34.9 | |
| 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 | 88.3 | 21.8 | 110.1 |
| 8.0 Project Support and Oversight | 100.1 | 15.0 | 115.1 |
| 9.0 Preparation for Operations/Spares | 16.2 | 2.4 | 18.6 |
| **Preconceptual Cost Estimate (FY99 US$M)** | **960.9** | **236.9** | **1193.5** |

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

This estimate is work in progress and will be reviewed in the winter 2000.

October 13, 2000

## 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

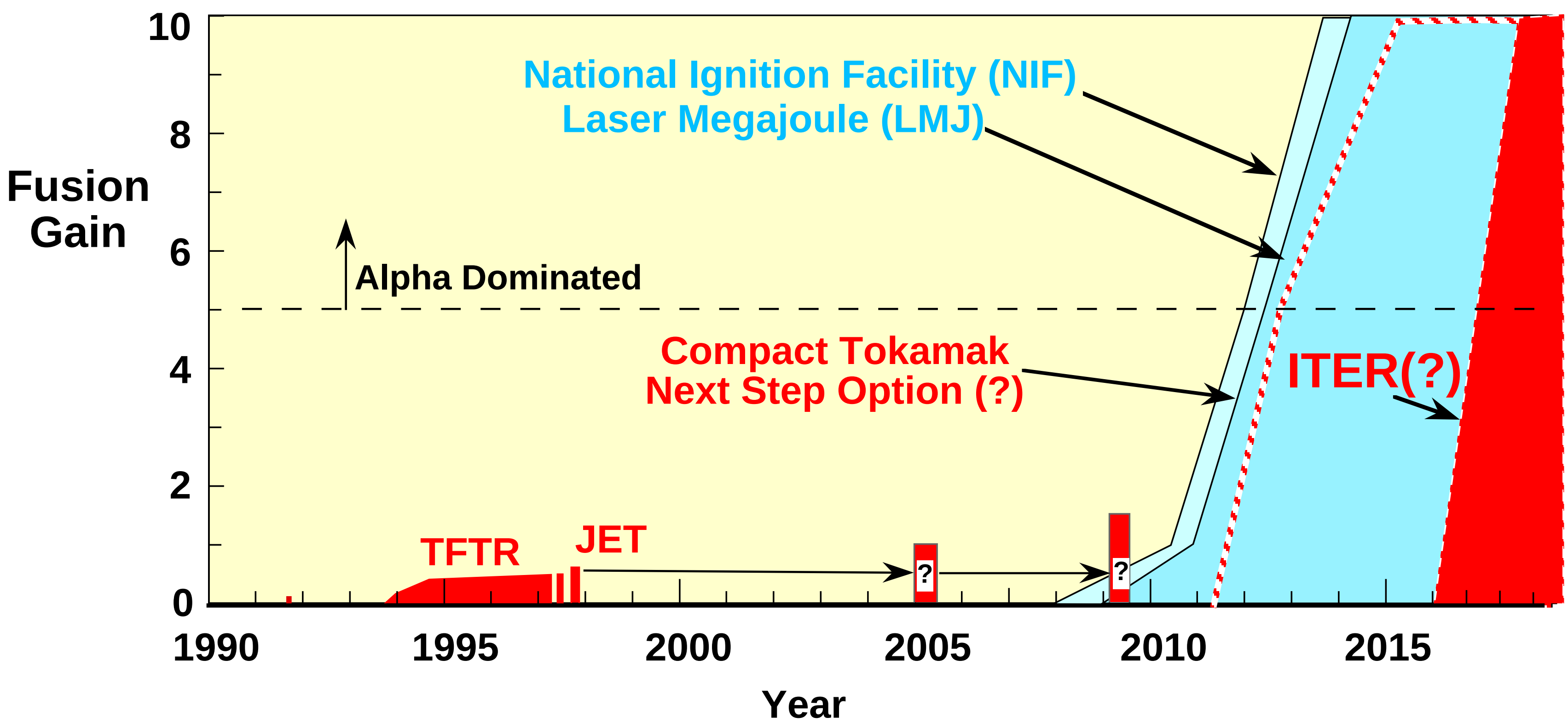
- **Tritium Inventory**

  5 g to 25g (in process inventory)

- **Cryogenic Plant**

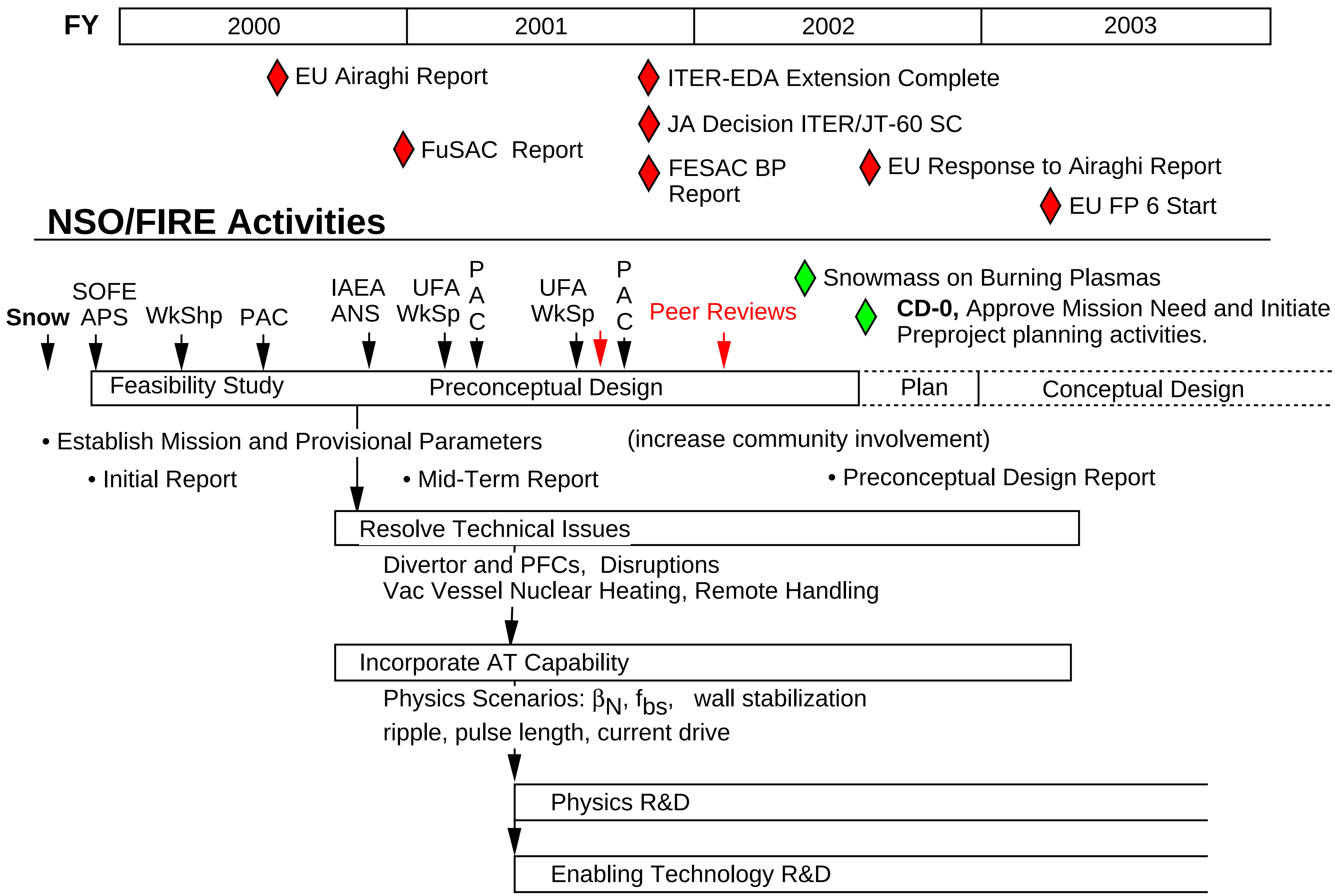
  2 kW refrigerator, 600 kgallon LN storage

# 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



# 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.

- 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