# Diversified International Portfolio for Magnetic Fusion

# and FIRE

**Dale M. Meade**

**for the FIRE Study Team**

**Overview**
**2002 Fusion Summer Study**
**Snowmass, CO**

**July 8, 2002**

http://fire.pppl.gov

# Outline

- Fusion Goals
- Critical Issues for Fusion
- Strategy for a Road Map
- FIRE
  - Goals
  - Characteristics
  - Issues/Challenges

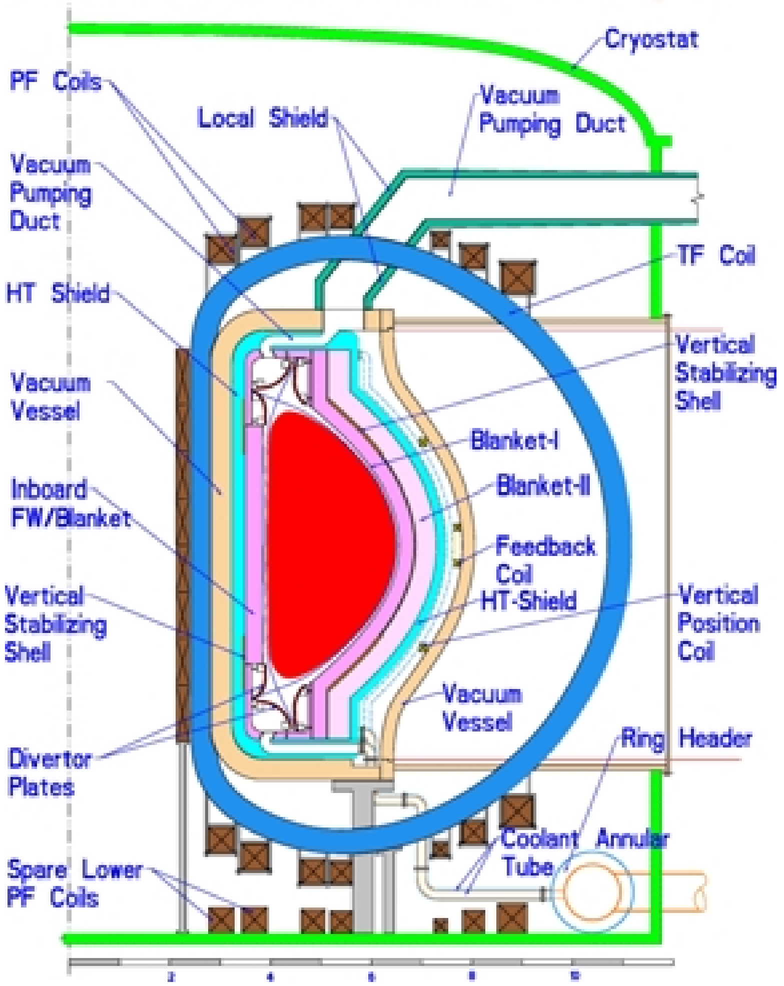
- Plans for the Future

# The Key Features for an Attractive Fusion Power Plant have been Identified

## Desired Characteristics

- Power gain $Q \geq 25$
  $n\tau_E T_i > 6 \times 10^{21}\ \mathrm{m}^{-3}\ \mathrm{s\ keV}$
- Power density $\geq 6\ \mathrm{MWm}^{-3}$
  high beta = $p_{plasma}/p_{mag} > 5\%$
- Wall Loading $> 3\ \mathrm{MW\ m}^{-2}$
- Steady state
  bootstrap current > 90%
- High availability
  First Wall Materials > 150 dpa
- Safety and Environment
  low activation materials
  no evacuation

Cross Section of ARIES-AT Power Core Configuration



**Pfusion = 1.7GW, Pe = 1 GW**

# Critical Issues to be Addressed in the Next Stage of Fusion Research

- **Advanced Toroidal Physics**
  - develop and test physics needed for an attractive MFE reactor
  - couple with burning plasma physics

- **Boundary Physics and Plasma Technology** (coupled with above)
  - high particle and heat flux
  - couple core and divertor
  - fusion plasma - tritium inventory and helium pumping

- **Burning Plasma Physics** (coupled with above)
  - strong nonlinear coupling inherent in a fusion dominated plasma
  - access, explore and understand fusion dominated plasmas

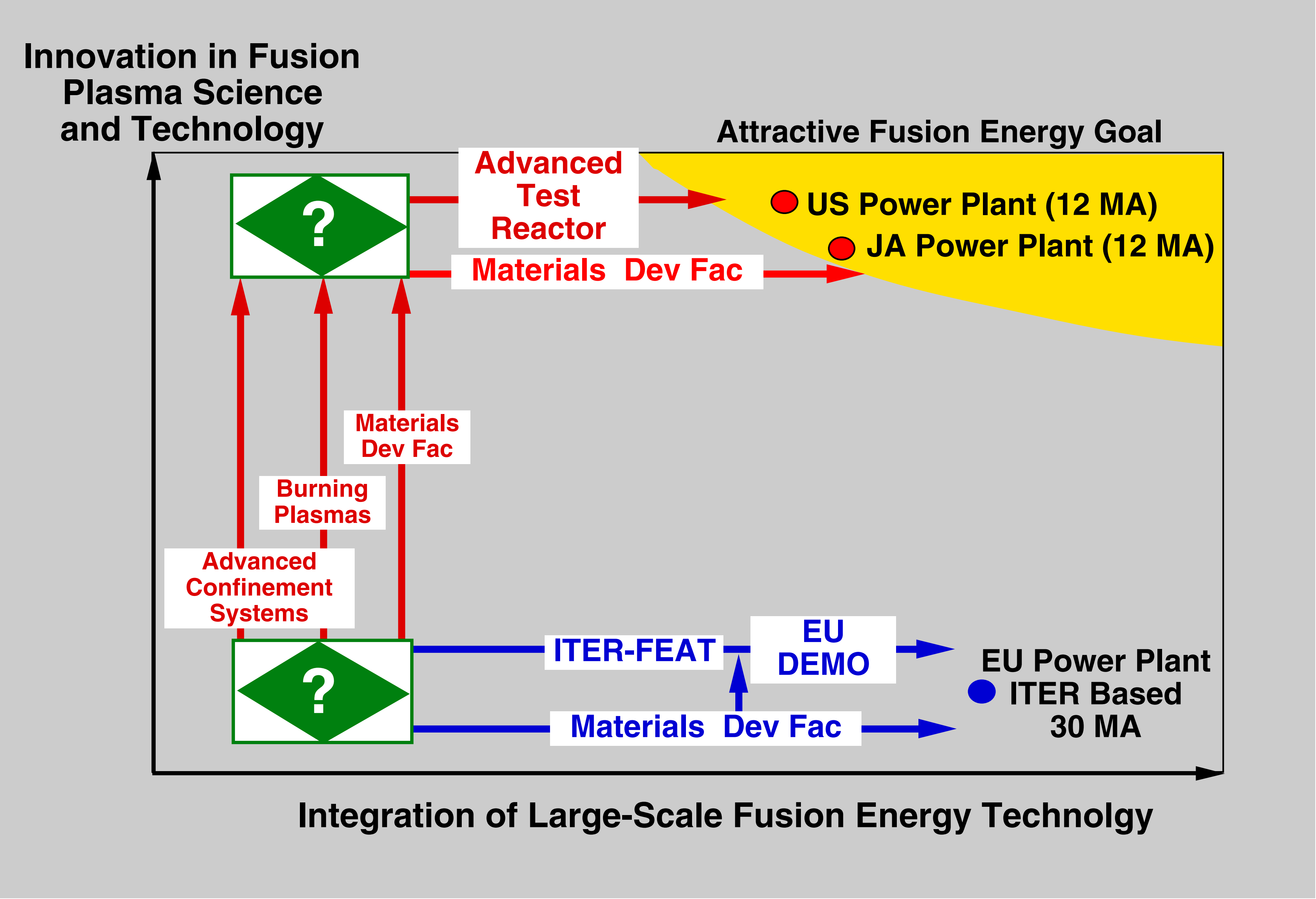
- **Neutron-Resistant Low-Activation Materials**
  - high fluence material testing facility using “point”neutron source

_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

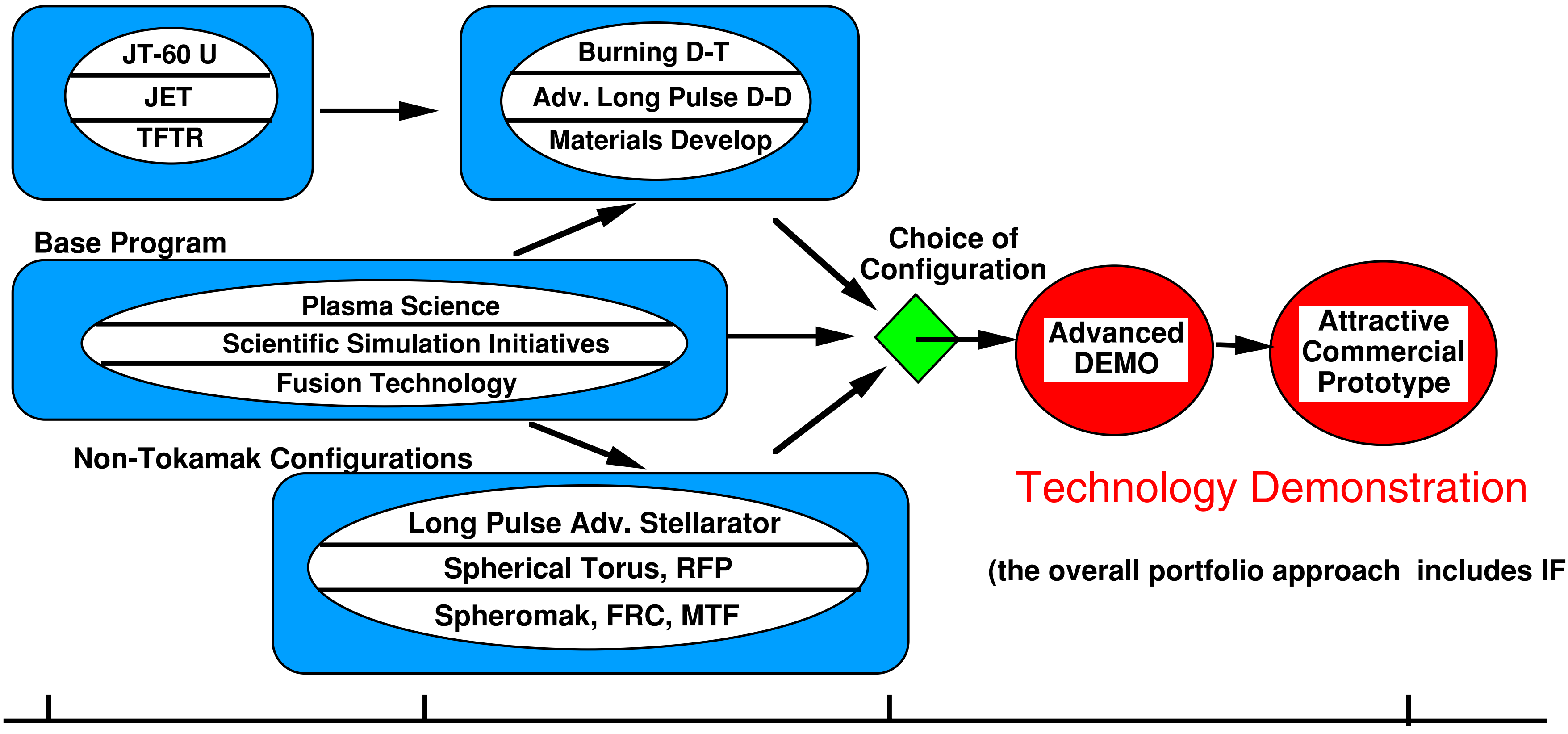
  - high fluence component testing facility using volume neutron source

- Superconducting Coil Technology does not have to be coupled to physics experiments - only if needed for physics objectives

# Innovation First or Large-Scale Technology Integration First ??



# Diversified International Porfolio for Magnetic Fusion



**Second Phase**

Scientific
Feasibility

**Third Phase**

Fusion Science and Technolgy
Feasibility

**Fourth Phase**

Electric Power
Feasibility

**Commercialization Phase**

Economic
Feasibility

**Three Large Tokamaks**

- JT-60 U
- JET
- TFTR

**Several Large Facilities**

- Burning D-T
- Adv. Long Pulse D-D
- Materials Develop

**Base Program**

- Plasma Science
- Scientific Simulation Initiatives
- Fusion Technology

**Non-Tokamak Configurations**

- Long Pulse Adv. Stellarator
- Spherical Torus, RFP
- Spheromak, FRC, MTF

**Choice of Configuration**

**Advanced DEMO**

**Attractive Commercial Prototype**

Technology Demonstration

**(the overall portfolio approach includes IFE)**

**1985** **2005** **2020** **2050**

**Reduced Technical Risk**

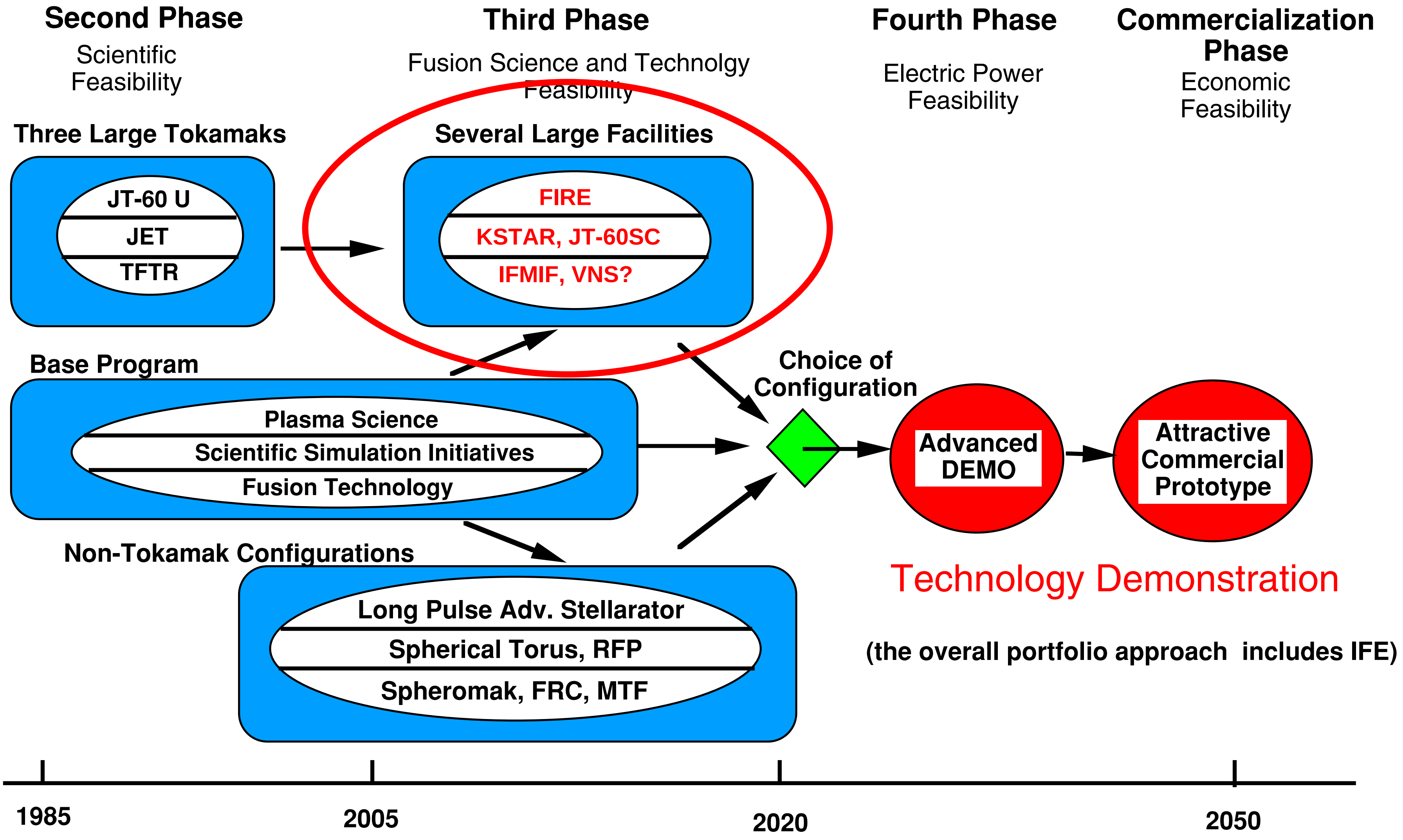
**Increased Technical Flexibility**

**Streamlined Management Structure**

**Faster Implementation**

**Better Product/Lower Overall Cost**

# A "Lower Cost More Efficient Path" to Fusion Energy



**Second Phase**

Scientific Feasibility

**Third Phase**

Fusion Science and Technolgy Feasibility

**Fourth Phase**

Electric Power Feasibility

**Commercialization Phase**

Economic Feasibility

**Three Large Tokamaks**

- JT-60 U
- JET
- TFTR

**Several Large Facilities**

- FIRE
- KSTAR, JT-60SC
- IFMIF, VNS?

**Base Program**

- Plasma Science
- Scientific Simulation Initiatives
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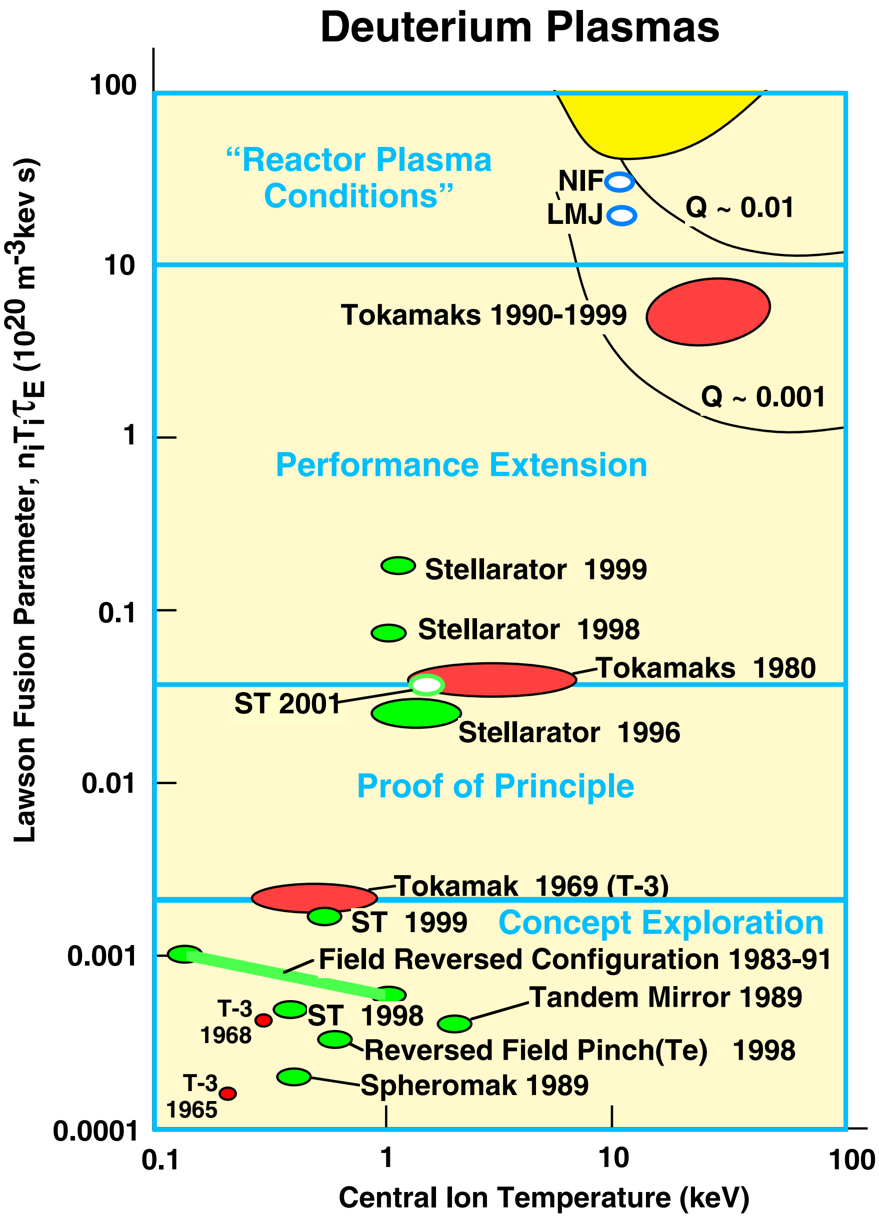
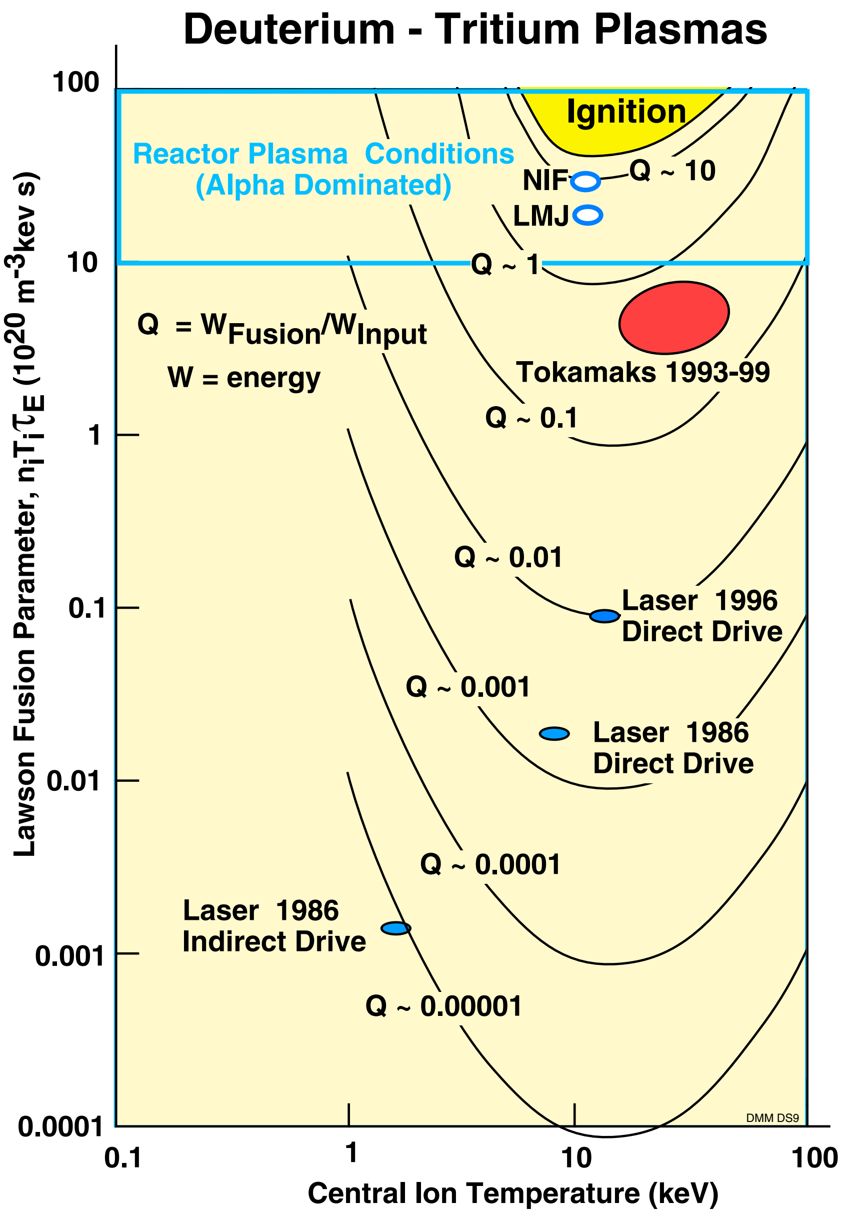
# Magnetic Fusion is Technically Ready for a High Gain Burning Exp't

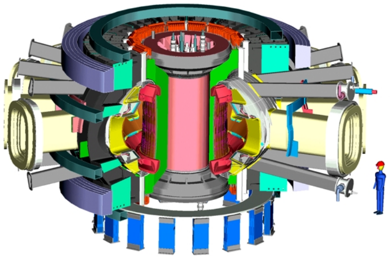




We are ready but this step is our most challenging physics step yet.

# Burning Plasma Physics - The Next Frontier

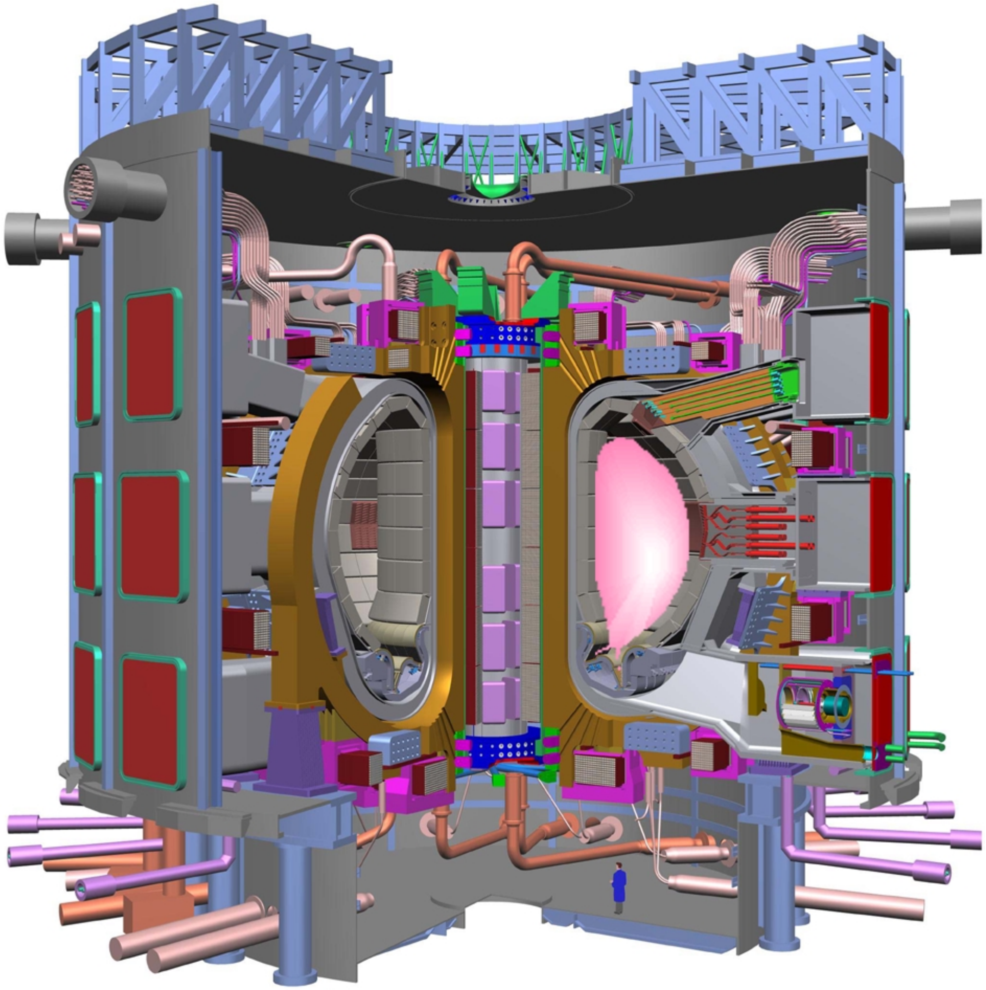
Three Options
(same scale)



**FIRE**

US Based
Diversified International Portfolio

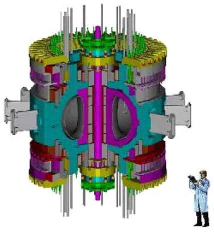
1,400 Tonne



**ITER-FEAT**

JA, EU or CA Based
International Partnership

19,000 Tonne



**IGNITOR**

Italian Based
International Collaboration

500 Tonne

# Next Step Option (FIRE) Program

## Organization

- National activity managed by the Virtual Laboratory for Technology with participation by more than 15 institutions.

## Purpose:

- to investigate and assess various opportunities for advancing the scientific understanding of fusion energy, with emphasis on plasma behavior at high energy gain and for long duration.

- tasks to be pursued include investigation of a modular program pathway, with initial emphasis on the burning plasma module (e.g., FIRE).

## Advisory Committee

- Members: Tony Taylor (Chair), Gerald Navratil, Ray Fonck, David Gates, Dave Hill, Wayne Houlberg, Tom Jarboe, Mitsuro Kikuchi, Earl Marmar, Raffi Nazikian, Craig Petty, Rene Raffray, Paul Thomas, James VanDam

- Extensive PAC Reports provide detailed recommendations for the FIRE activity to address. NSO-PAC reports are on FIRE (http://fire.pppl.gov).

# Participants in the FIRE Engineering 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 Science Objectives for a Major Next Step Burning Plasma 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.

# Advanced Burning Plasma Exp't Requirements

## Burning Plasma Physics

| | |
|---|---|
| Q | $\geq 5$, ~ 10 as target, ignition not precluded |
| $f_\alpha = P_\alpha/P_{heat}$ | $\geq 50\%$, ~ 66% as target, up to 83% at $Q = 25$ |
| TAE/EPM | stable at nominal point, able to access unstable |

## Advanced Toroidal Physics

| | | |
|---|---|---|
| $f_{bs} = I_{bs}/I_p$ | $\geq 50\%$ | up to 75% |
| $\beta_N$ | ~ 2.5, no wall | ~ 3.6, $n = 1$ wall stabilized |

## Quasi-stationary Burn Duration

| | |
|---|---|
| Pressure profile evolution and burn control | $> 10\ \tau_E$ |
| Alpha ash accumulation/pumping | $>$ several $\tau_{He}$ |
| Plasma current profile evolution | 1 to 3 $\tau_{skin}$ |
| Divertor pumping and heat removal | several $\tau_{divertor}$ |

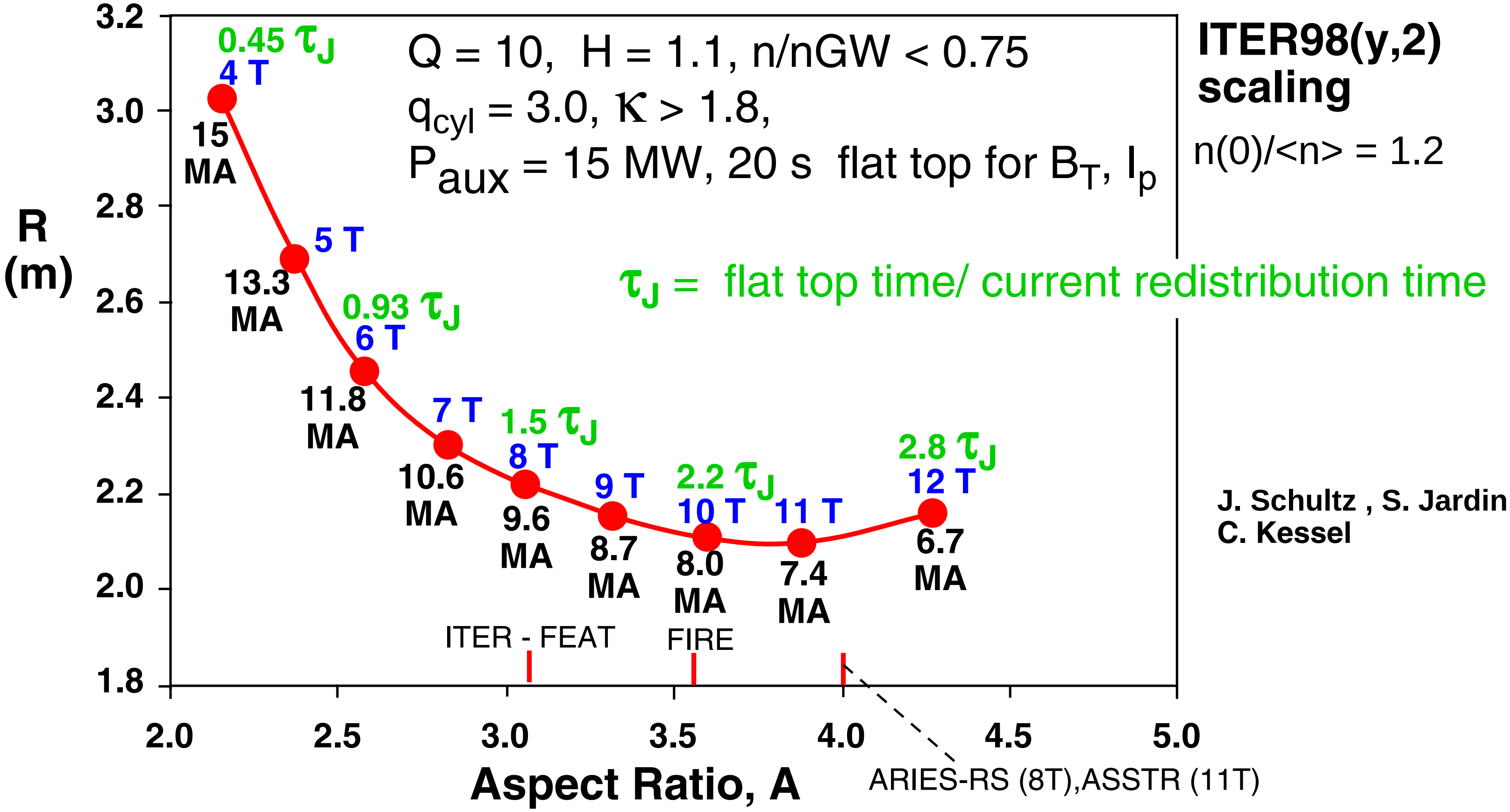
# FIRE has Adopted the Advanced Tokamak Features Identified by ARIES Studies

- High toroidal field
- Double null
- Strong shaping
  - $\kappa = 2.0$, $\delta = 0.7$
- Internal vertical position control coils
- Cu wall stabilizers for vertical and kink instabilities
- Very low ripple (0.3%)
- ICRF/FW on-axis CD
- LH off-axis CD
- LHCD stabilization of NTMs
- Tungsten divertor targets
- Feedback coil stabilization for Resistive Wall Modes (RWM)
- Burn times exceeding current diffusion times
- Pumped divertor/pellet fueling/impurity control to optimize plasma edge

# Optimization of a Burning Plasma Experiment

- Consider an inductively driven tokamak with copper alloy TF and PF coils precooled to LN temperature that warm up adiabatically during the pulse.

- Seek minimum R while varying A and space allocation for TF/PF coils for a specified plasma performance - Q and pulse length with physics and eng. limits.



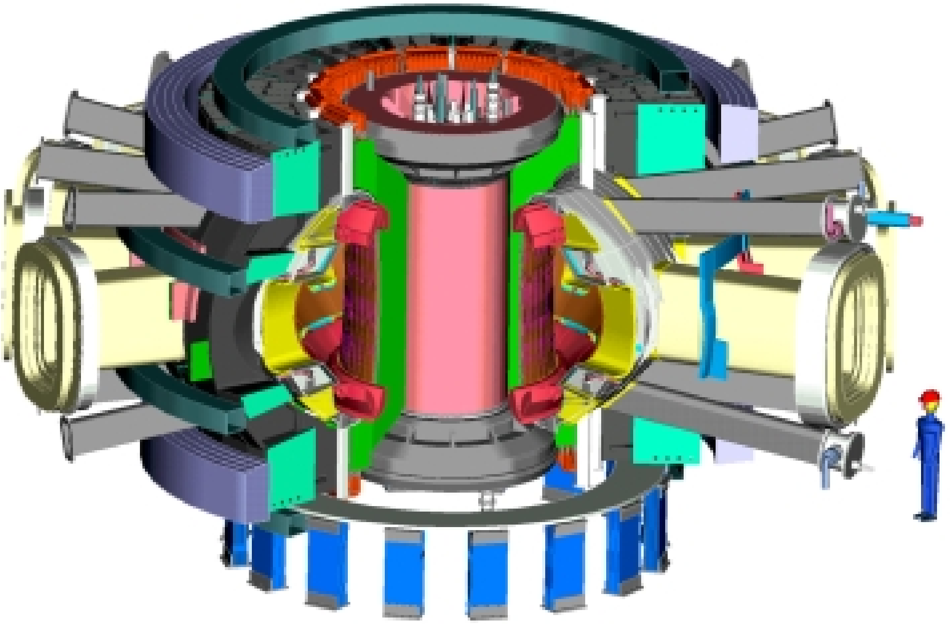
J. Schultz , S. Jardin
C. Kessel

**What is the optimum for advanced steady-state modes?**

# Fusion Ignition Research Experiment

# (FIRE)

http://fire.pppl.gov



1,400 tonne

## 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
- $Q \approx 10$, $P_{fusion} \sim 150$ MW
- Burn Time $\approx$ 20 s ( 2 tau_cr)
- Tokamak Cost $\approx$ \$351M (FY02)
- Total Project Cost $\approx$ \$1.2B(FY02) at Green Field site.

**Mission: Attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas.**

**CIT + TPX = FIRE leading to ARIES**

# Basic Parameters and Features of FIRE

| | |
|---|---|
| R, major radius | 2.14 m |
| a, minor radius | 0.595 m |
| $\kappa$x, $\kappa$95 | 2.0, 1.77 |
| $\delta$x, $\delta$95 | 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, ~6 -8 MW m-3 in plasma |
| Neutron wall loading | ~ 2.3 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 |

# Plasma Heating and Current Drive Systems

Note: Edge Barriers optimize at ~ 10T, while AT optimizes at ~ 6.6T

ICRF Heating: 20 MW, 80 – 120 MHz

| | **H** | **He 4** | **D** | **D-T** |
|---|---|---|---|---|
| **5 T** | • Direct Electron @120 MHz | •$H_{min}$@ 80 MHz<br>• Direct Electron @120 MHz | • $H_{min}$@ 80 MHz<br>• Direct Electron @120 MHz | • $H_{min}$@ 80 MHz<br>• Direct Electron @120 MHz |
| **6.6T** | • Direct Electron @120 MHz | • $H_{min}$@ 100 MHz<br>• Direct Electron @120MHz | • $H_{min}$@ 100 MHz<br>• Direct Electron @120 MHz | • $H_{min}$@ 100 MHz<br>• 2ΩD @100 MHz<br>• Direct Electron @120 MHz |
| **10 T** | • $He^3_{min}$ @100 MHz<br>• Direct Electron @120 MHz | • $He^3_{min}$ @100 MHz<br>• Direct Electron @120 MHz | • $He^3_{min}$ @100 MHz<br>• Direct Electron @120 MHz | • $He^3_{min}$ @100 MHz<br>• 2ΩT @100 MHz<br>• Direct Electron @120 MHz |

**Upgrades under Consideration**

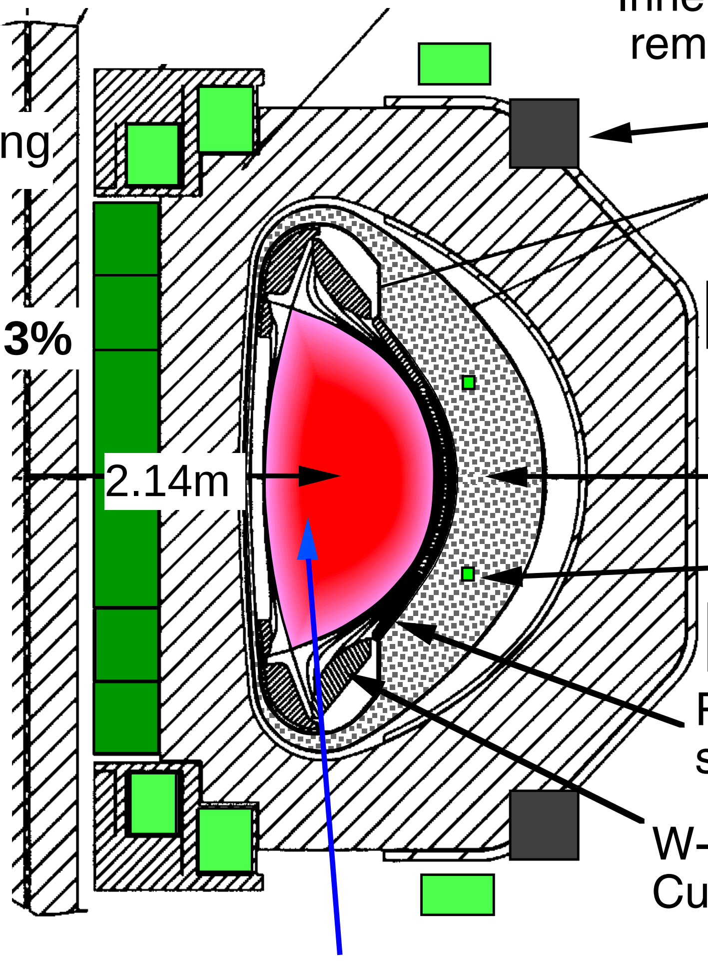
Lower Hybrid Current Drive: 20 - 30 MW, 4.6 - 5.6 GHz, n = 1.8- 2.2

Electron Cyclotron Current Drive 170 GHz @ r/a ≈ 0.33 for Adv Tok at 6.6T.

# FIRE Incorporates Advanced Tokamak Features (ala ARIES)

**AT Features**

- DN divertor pumping
- strong shaping
- very low ripple **< 0.3%**
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



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

Compression Ring

Double Wall Vacuum
Vessel (316 S/S)

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.

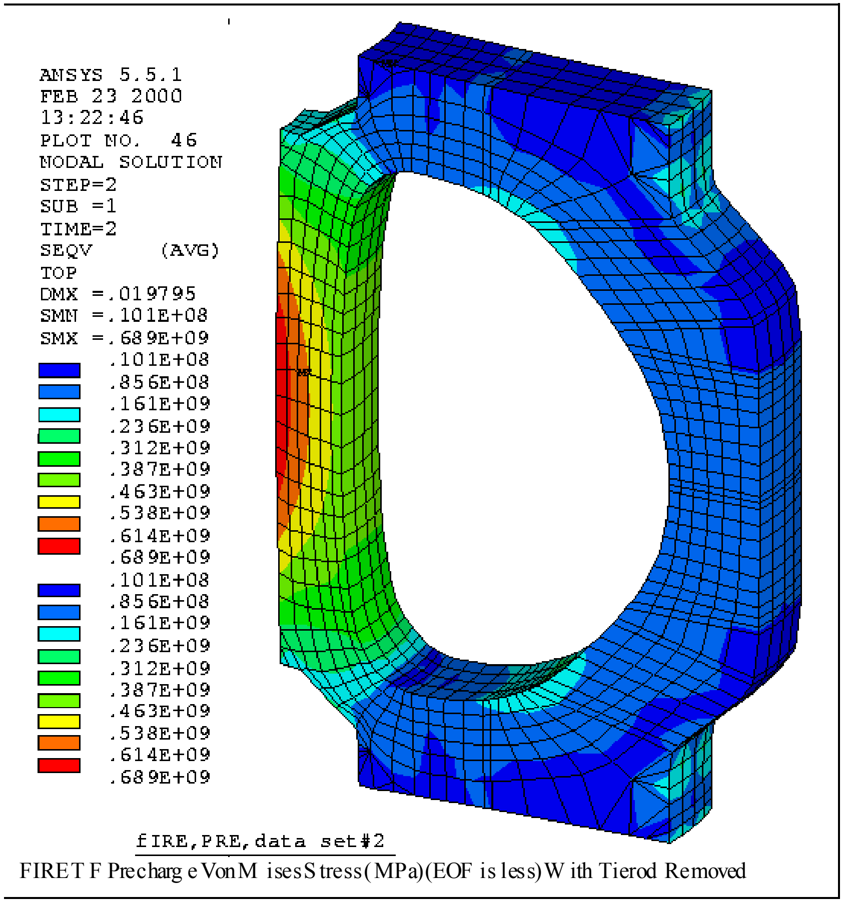
# TF coils are being Designed with Added Margin.

- **FIRE* Baseline**
  **R = 2.14 m, a = 0.595 m**
  **B = 10 T, Ip = 7.7 MA,**
  **20 s flat top, Pfus = 150 MW**

- **Wedged TF/compression ring**
  **BeCu (C17510) inner leg**

- **The peak conductor VM Stress of 529 MPa for 10 T (7.7 MA) is within the static allowable stress of 724 MPa**

  **(Allowable/Calculated = 1.3)**



**TF Coil Von Mises Stress Contours at 12 T**

# TF Conductor Material for FIRE is “Essentially” Available

- BeCu alloy C 17510 - 68% IACS is now a commercial product for Brush Wellman.
- A relatively small R&D program is needed to assure that the plates will be available in the properties and sizes required.

The plate on the right was manufactured for BPX

# Edge Physics and PFC Technology: Critical Issue for Fusion

Plasma Power and particle Handling under relevant conditions
  Normal Operation / Off Normal events

Tritium Inventory Control
  must maintain low T inventory in the vessel ⇒ all metal PFCs

Efficient particle Fueling
  pellet injection needed for deep and tritium efficient fueling

Helium Ash Removal
  need close coupled He pumping

Non-linear Coupling with Core plasma Performance
  nearly every advancement in confinement can be traced to the edge
  Edge Pedestal models first introduced in ~ 1992 first step in understanding
  Core plasma (low $n_{edge}$) and divertor (high $n_{edge}$) requirements conflict

Solutions to these issues would be a major output from a next step experiment.

# Tritium Considerations for FIRE and BP Experiments

- The tritium injected per shot in FIRE would be same as TFTR ≈ 0.2 g
- Retention fractions as high as JET and TFTR (~15%) would adversely impact operations.
- Tritium retention < 0.2% was measured (Wampler, Sandia) in the all metal system of C- Mod after DD operation.
    - **Carbon divertor targets are ruled out for FIRE, and W was chosen as a reactor relevant solution.**
- The Site Inventory Requirement for FIRE would be similar to TFTR (5g-T) which was Classified as DOE Category III, Low Hazard Facility (< 30g-T).

Site Limit of < 30g-T presently proposed with

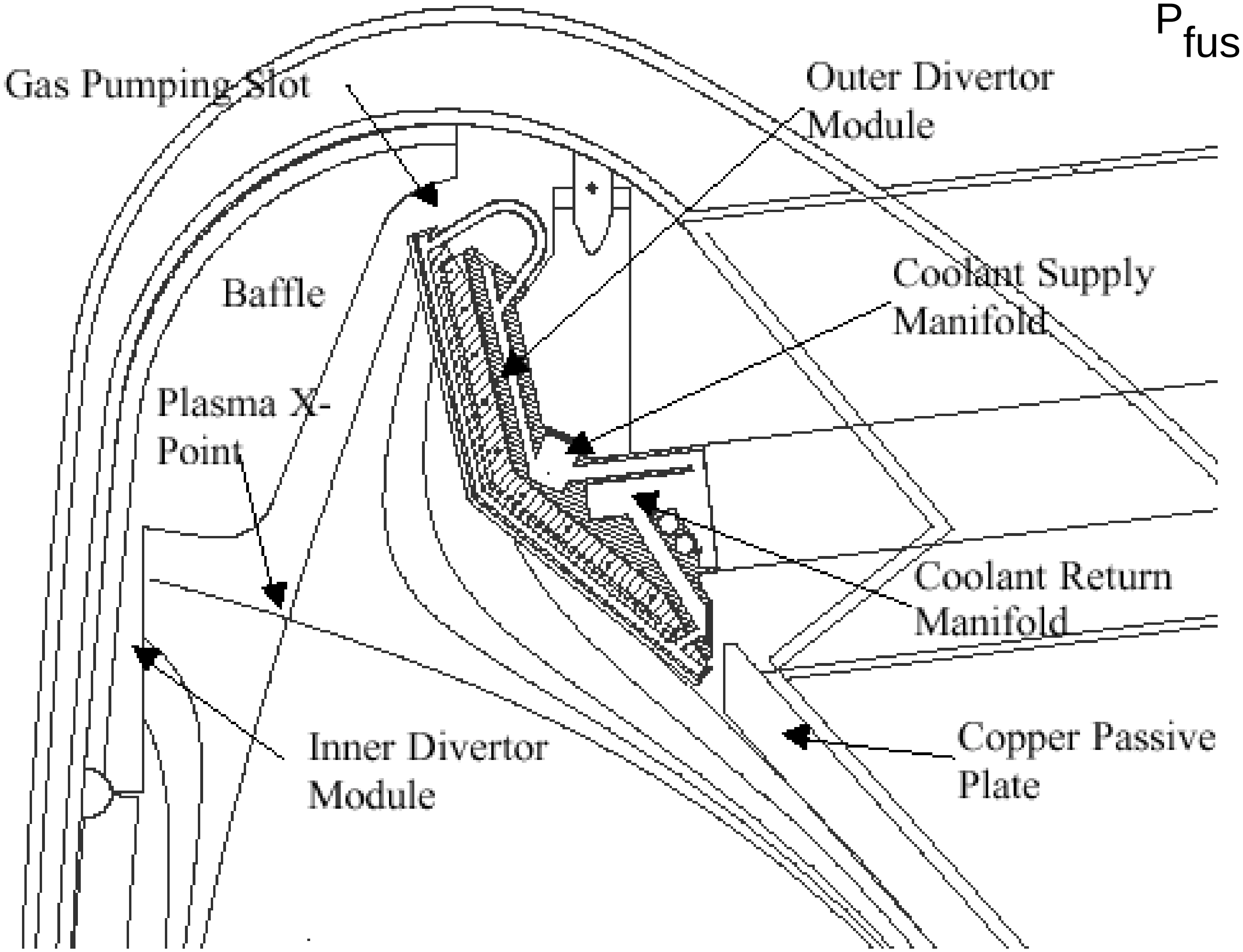
≤ 10 g-T in a single system

- Annual burn up of ~ few g-T, only small shipments of fuel and waste required.

PC-2-14 Mike Ulrickson

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

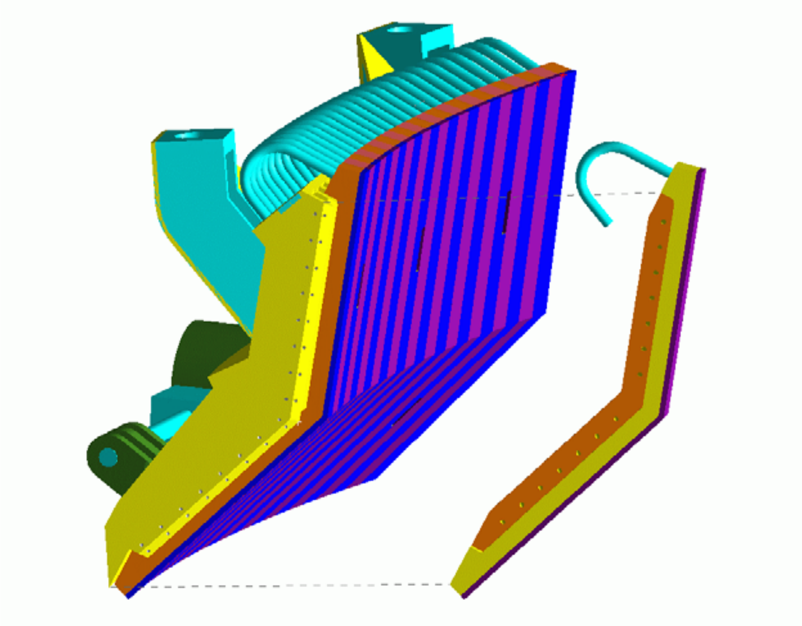
$P_{fusion}$ < 200 MW



**Reference Design is semi-detached operation with <15 MW / m2.**

# Divertor Module Components for FIRE

*Sandia*

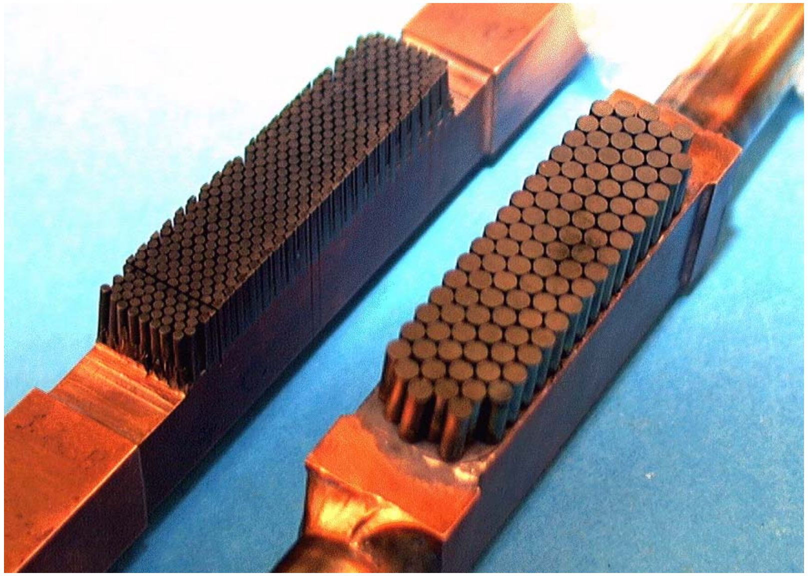


**Finger Plate for**

**Outer Divertor Module**

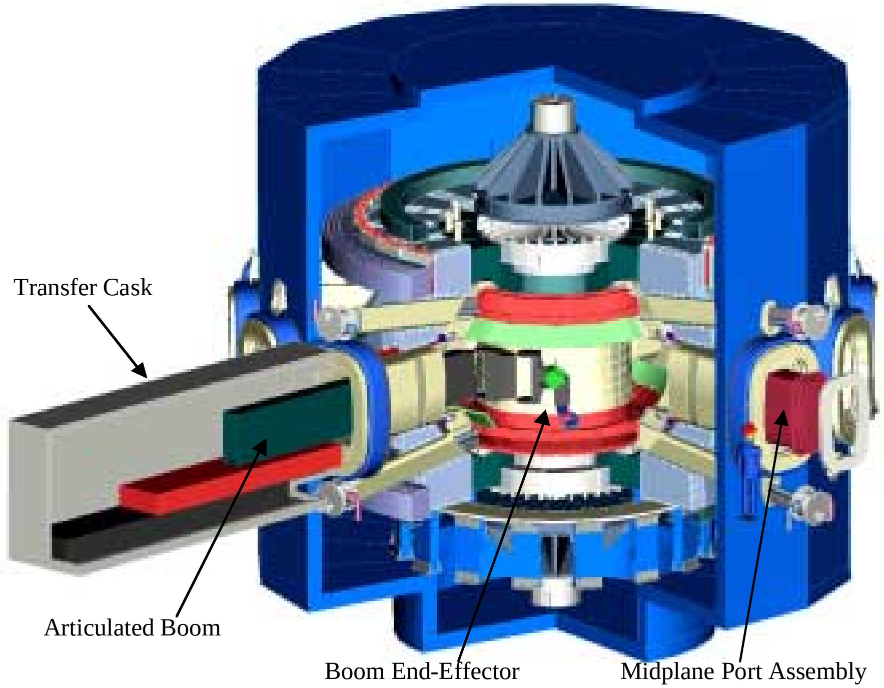
**Two W Brush Armor Configurations**

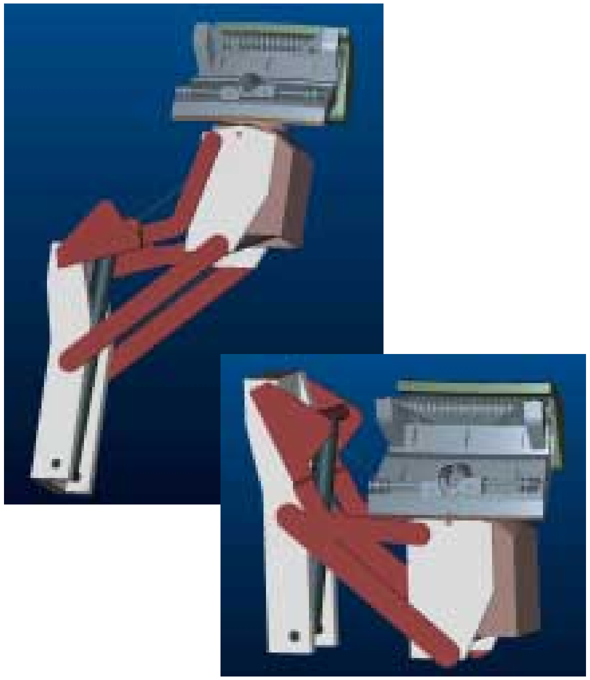
**Tested at 25 MW/m$^2$**



**Carbon targets used in most experiments today are not compatible with tritium inventory requirements of fusion reactors.**

# FIRE In-Vessel Remote Handling System





## In-vessel transporter

- Articulated boom deployed from sealed cask
- Complete in-vessel coverage from 4 midplane ports
- Fitted with different end-effector depending on component to be handled
- First wall module end-effector shown

## Divertor end-effector

- High capacity (module wt. ~ 800 kg)
- Four positioning degrees of freedom
- Positioning accuracy of millimeters required

# FIRE Plasma Regimes

**Edge Barrier** (H-Mode)

Fusion dominated: $f_\alpha > 50\%$, $\approx 67\%$(target), alpha heating tests, TAEs

| | | |
|---|---|---|
| Heating | ICRF | 20 MW, 80 – 120 MHz, baseline |
| NTM | LHD | 20- 30 MW, 4.6 - 5.6 GHz, upgrade |

**Internal Transport Barrier and Advanced Tokamak (RS, RF-ITBs)**

Toward ARIES: high beta $\beta_N \approx 5$, high bootstrap $f_{bs} \approx 90\%$, $f_\alpha > 80\%$

- Double Barrier (Off Axis ICRF)
- Inductive Optimized Shear (NCS, RS,…)
- Non-Inductive Optimized Shear ($\beta_N \sim 4$, $f_{bs} \sim 80\%$ and $f_\alpha > 50\%$)

| | |
|---|---|
| Heating | ICRF |
| Current Drive | LHCD |
| NTM | ECCD (170 GHz, resonant @ $r/a \approx 0.3$ for $B = 6.6T$) |
| RWM | Feedback Stabilization Coils in FW (~ 10 port plugs) |

# Physics Basis for FIRE is Similar to ITER's

**Confinement (Elmy H-mode) - ITER98(y,2) based on today's data base**

$$\tau_E = 0.144\, I^{0.93}\, R^{1.39} a^{0.58}\, n_{20}^{0.41} B^{0.15} A_i^{0.19} \kappa^{0.78}\, P_{heat}^{-0.69}\ \ H(y,2)$$

**Density Limit - Based on today's tokamak data base**

$$n_{20} \leq 0.8\, n_{GW} = 0.8\, I_p/\pi a^2,$$

**Beta Limit - theory and tokamak data base**

$$\beta \leq \beta_N(I_p/aB), \quad \beta_N < 2.5 \text{ conventional}, \ \beta_N \sim 4 \text{ advanced}$$

**H-Mode Power Threshold - Based on today's tokamak data base**

$$Pth \geq (2.84/Ai)\, n_{20}^{0.58} B^{0.82} Ra^{0.81}$$ , same as ITER-FEAT

**Helium Ash Confinement $\tau_{He} = 5\ \tau_E$, Impurities = 3% -1.5%Be, 0% W**

But FIRE has high triangularity and double null
- both favorable for confinement and attaining small ELMs

# FIRE is a Modest Extrapolation in Plasma Confinement

**Dimensionless Parameters**

$\omega_c \tau = B\ \tau$

$\rho^* = \rho/a$

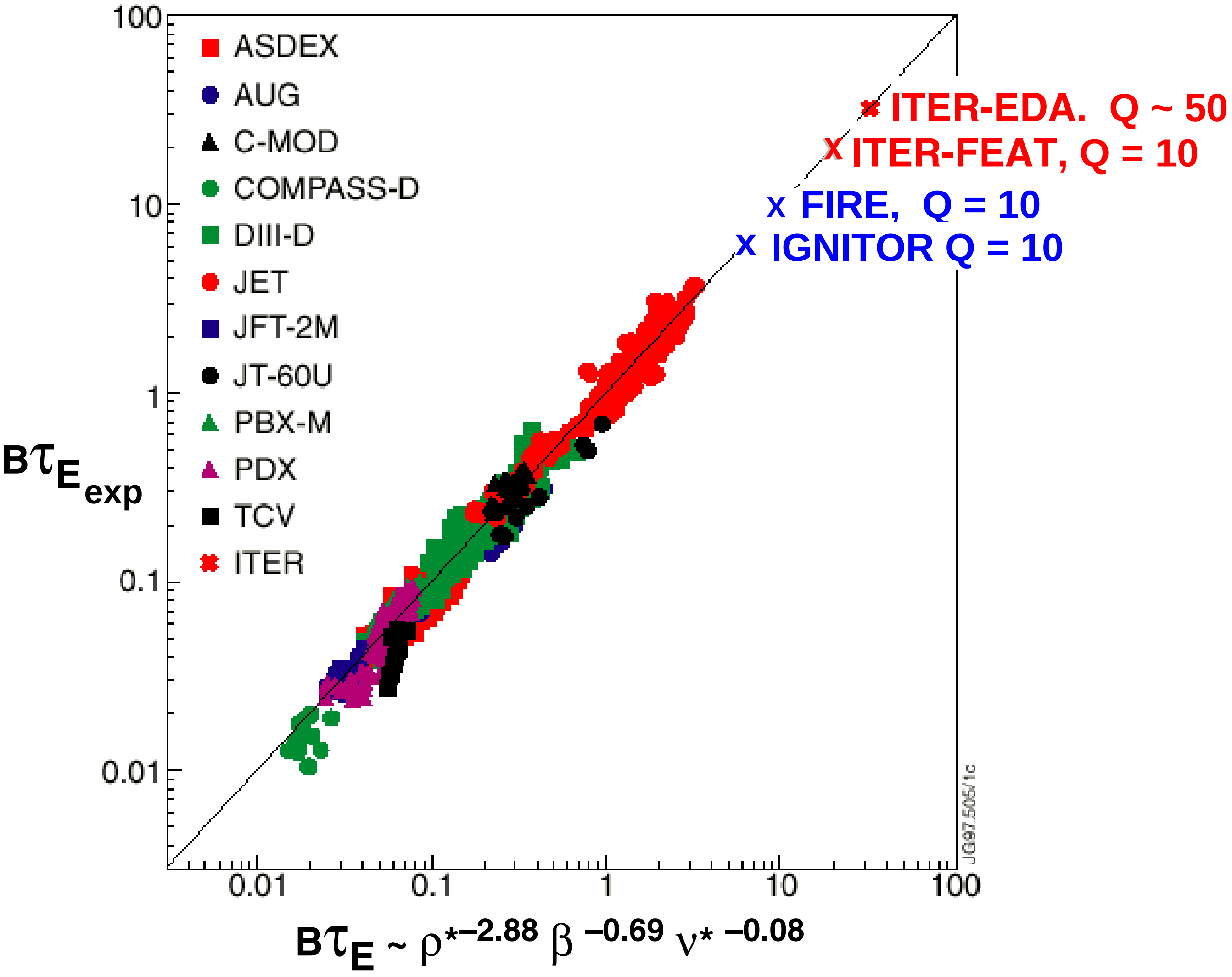
$\nu^* = \nu_c/\nu_b$

$\beta$

**Similarity Parameter**

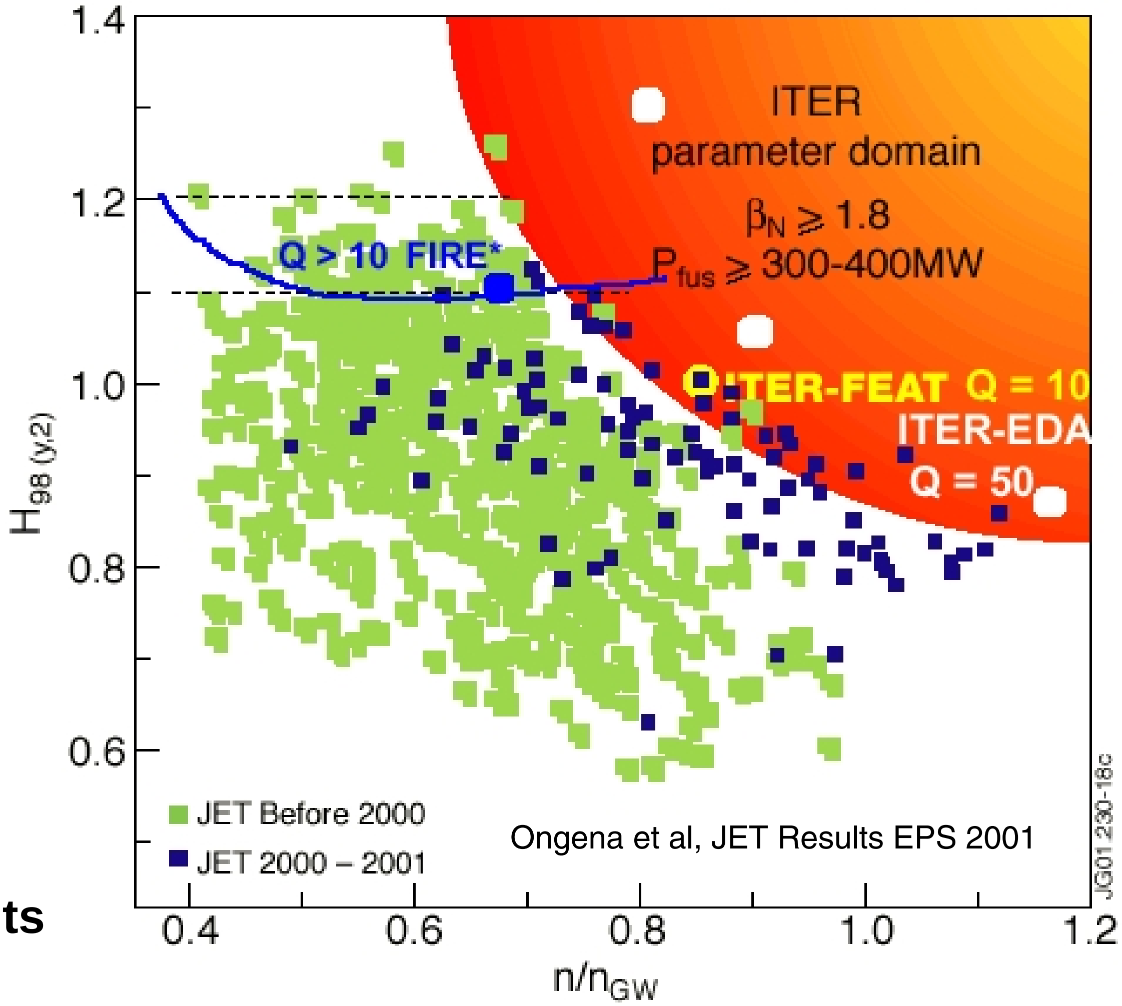
$B\ R^{5/4}$

Kadomtsev, 1975



# FIRE's Operating Density and Triangularity are Near the Optimum for the Elmy H-Mode

- **The optimum density for the H-Mode is $n/n_{GW} \approx 0.6 - 0.7$**
- **H-mode confinement increases with $\delta$**
    - **$\delta \approx 0.7$ FIRE**
    - **$\delta \approx 0.5$ ITER-FEAT**
- **Elm size is reduced for $\delta > 0.5$**
- **$Z_{eff}$ decreases with density (Mathews/ITER scaling)**
- **DN versus SN ? C- Mod Exp'ts**

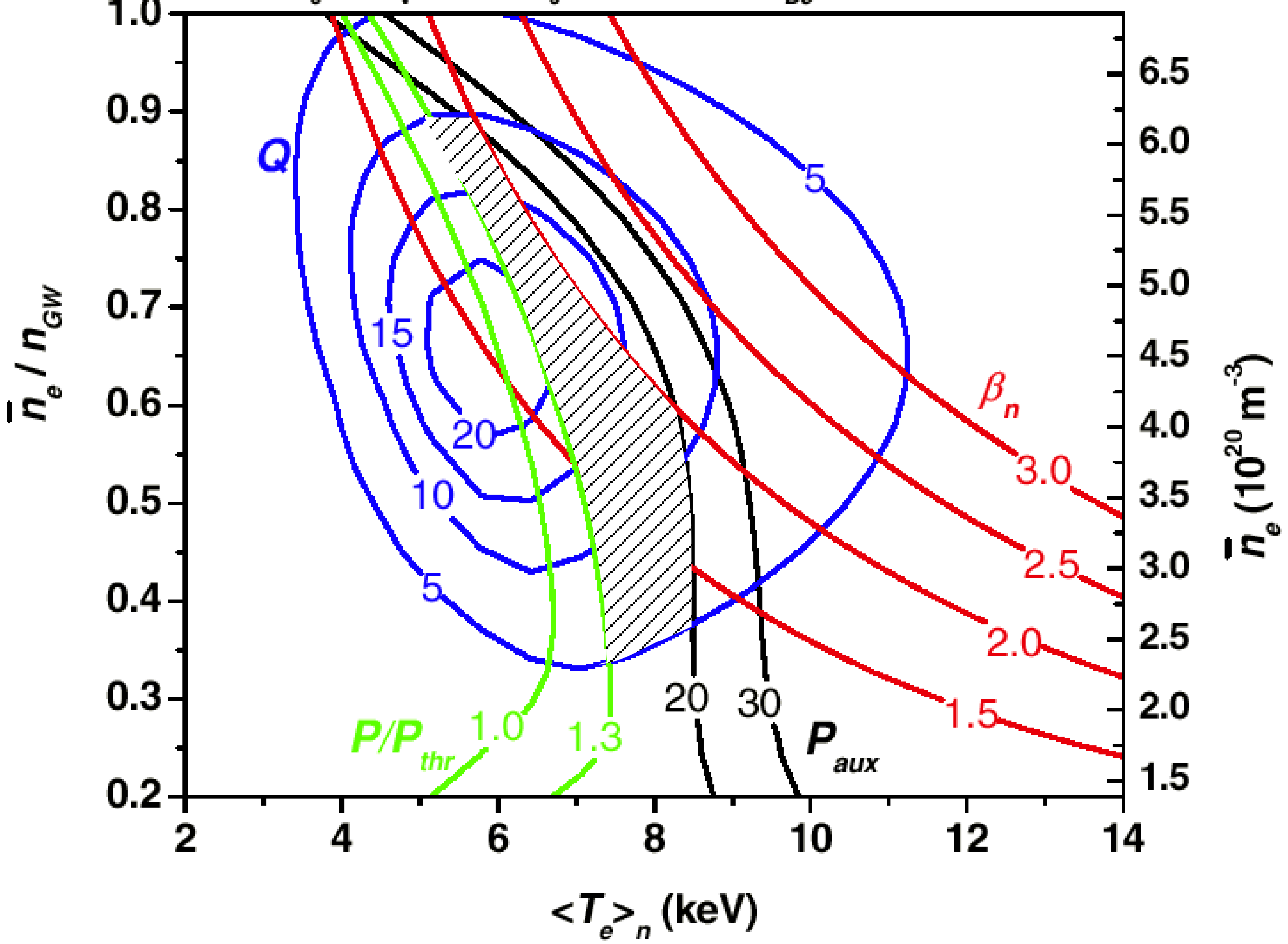


Ongena et al, JET Results EPS 2001

**Cordey et al, H = function ( $\delta$, $n/n_{GW}$, $n(0)/\langle n \rangle$) EPS 2001**

# FIRE Operating Space for H-Mode

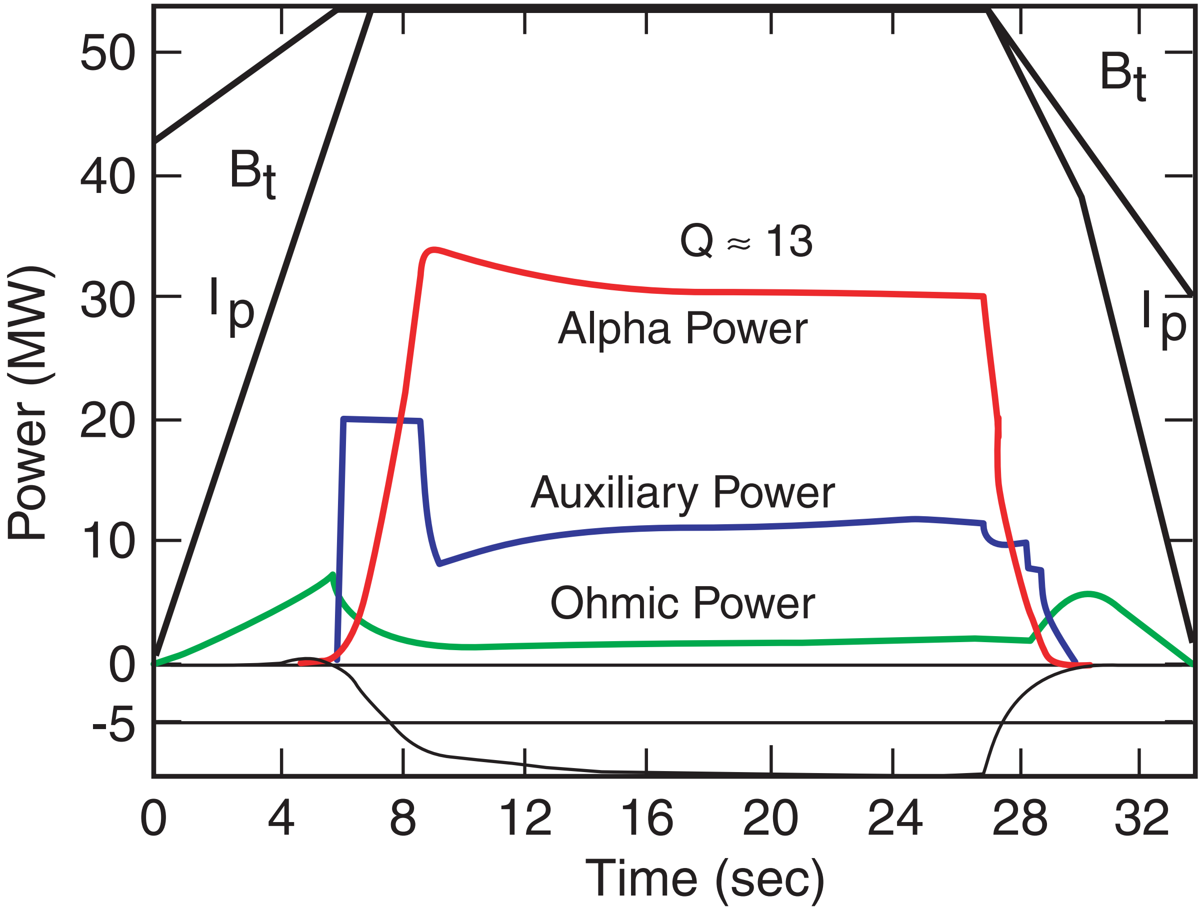
$T_0/\langle T\rangle_v = 2.5$, $n_0/\langle n\rangle = 1.25$, $f_{Be} = 1.5\%$



H(y,2) with Cordey Extension (EPS-2001)

*John Mandrekas, 07/02/02*

# Simulation of Burning Plasma in FIRE



B = 10 T

$I_p$ = 7.7 MA

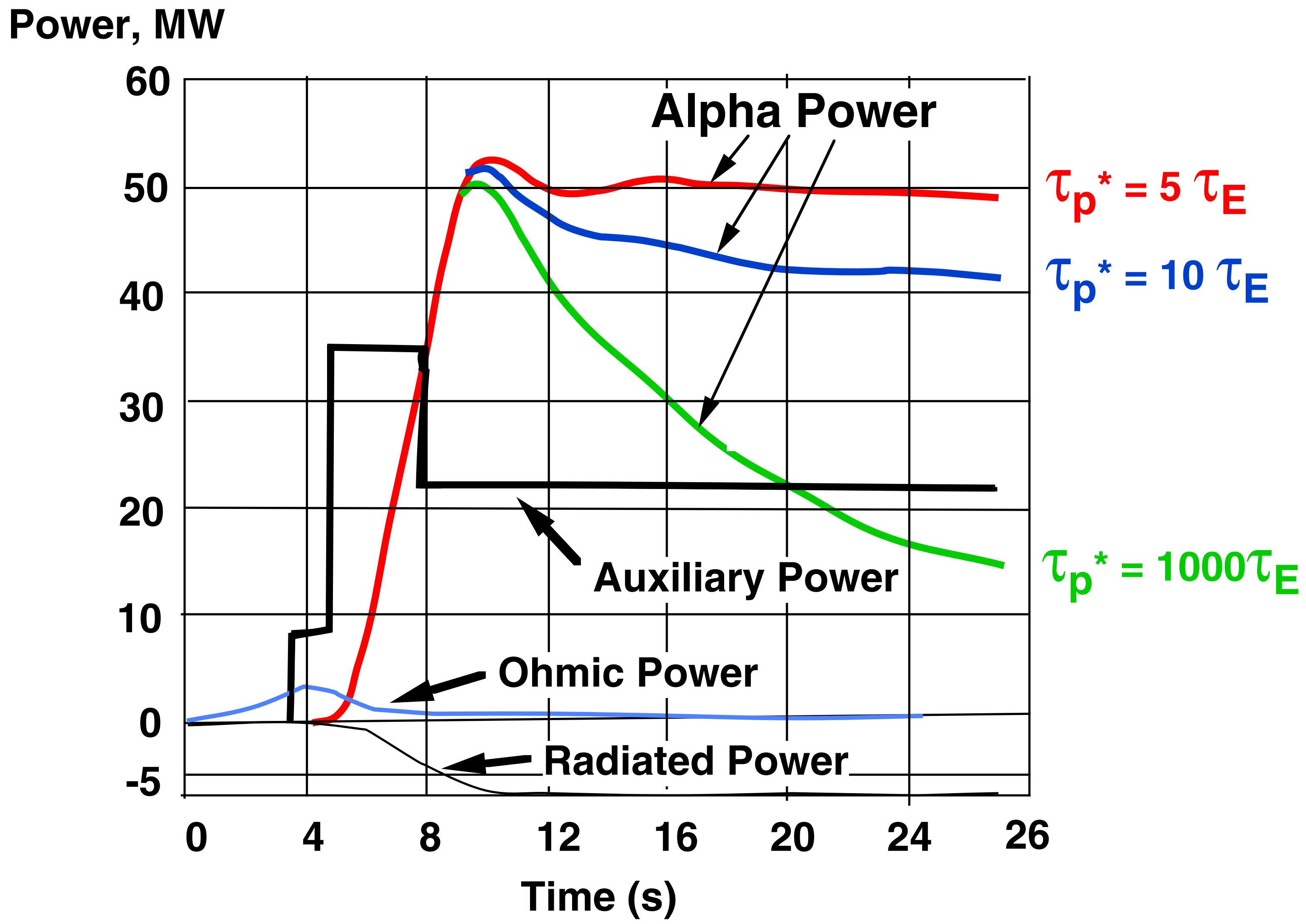
R = 2.14 m

A = 3.6

- ITER98(y, 2) with H(y, 2) = 1.1, $n(0)/\langle n \rangle = 1.2$, and $n/\ n_{GW} = 0.67$
- Burn Time ≈ 20 s ≈ $21\tau_E \approx 4\tau_{He} \approx 2\tau_{CR}$

Q = Pfusion/( Paux + Poh)

# Helium Ash Removal Techniques Required for a Reactor can be Studied on FIRE

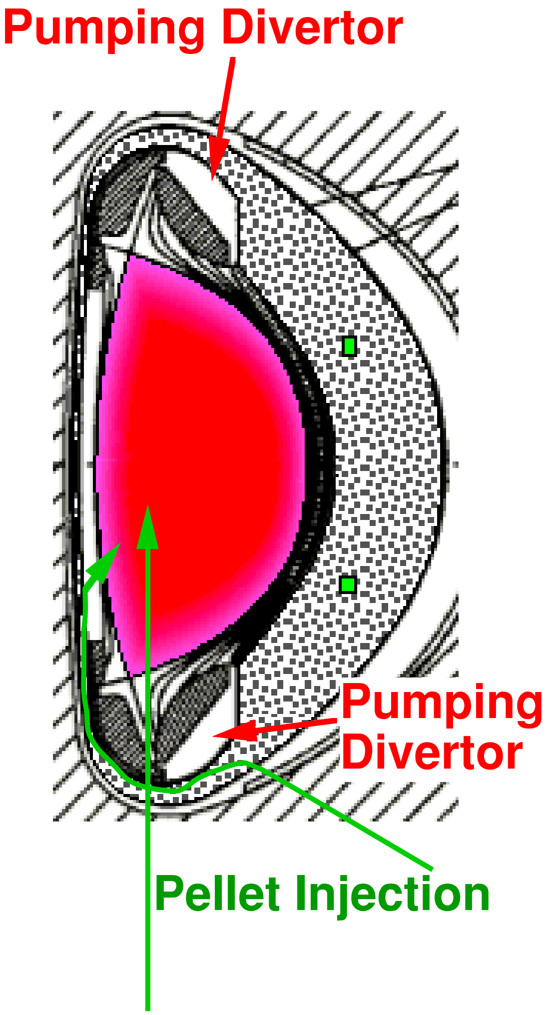


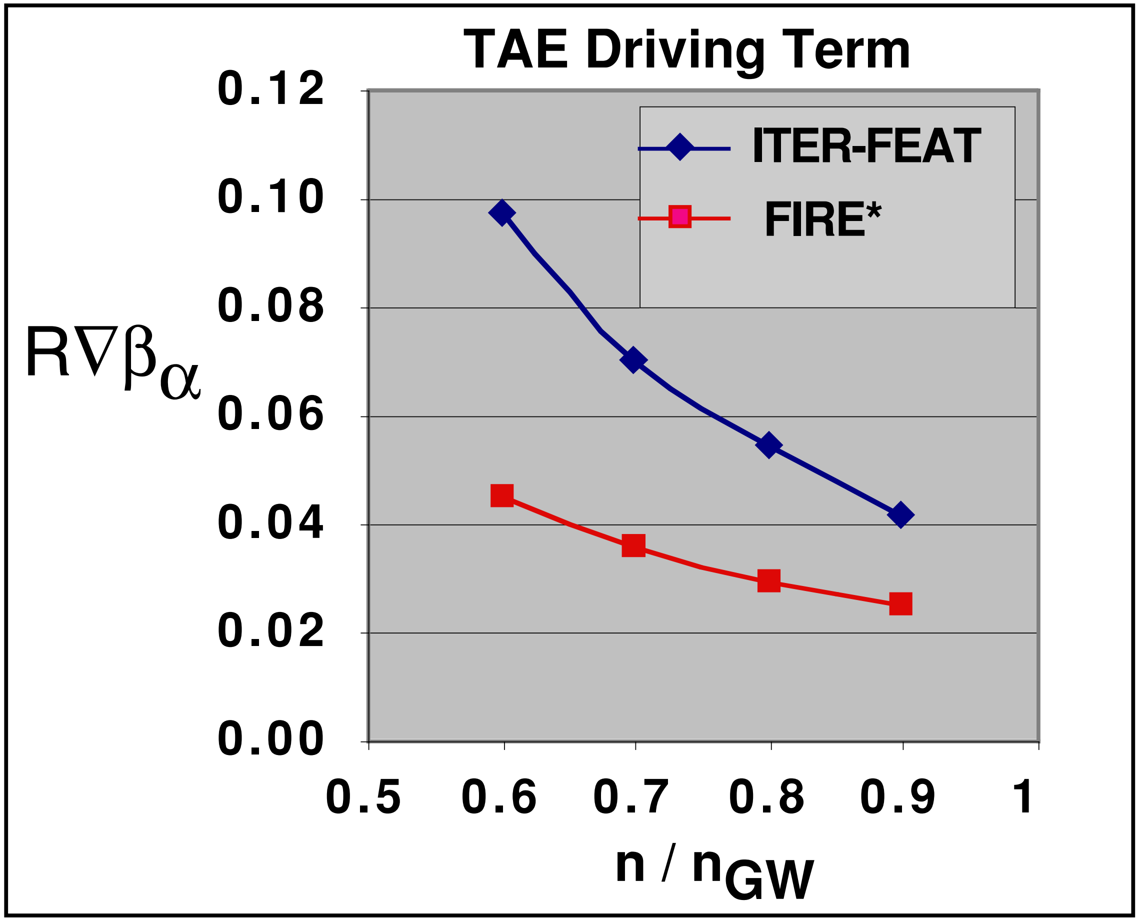
Fusion power can not be sustained without helium ash punping.

TSC/Kessel/21-q.ps

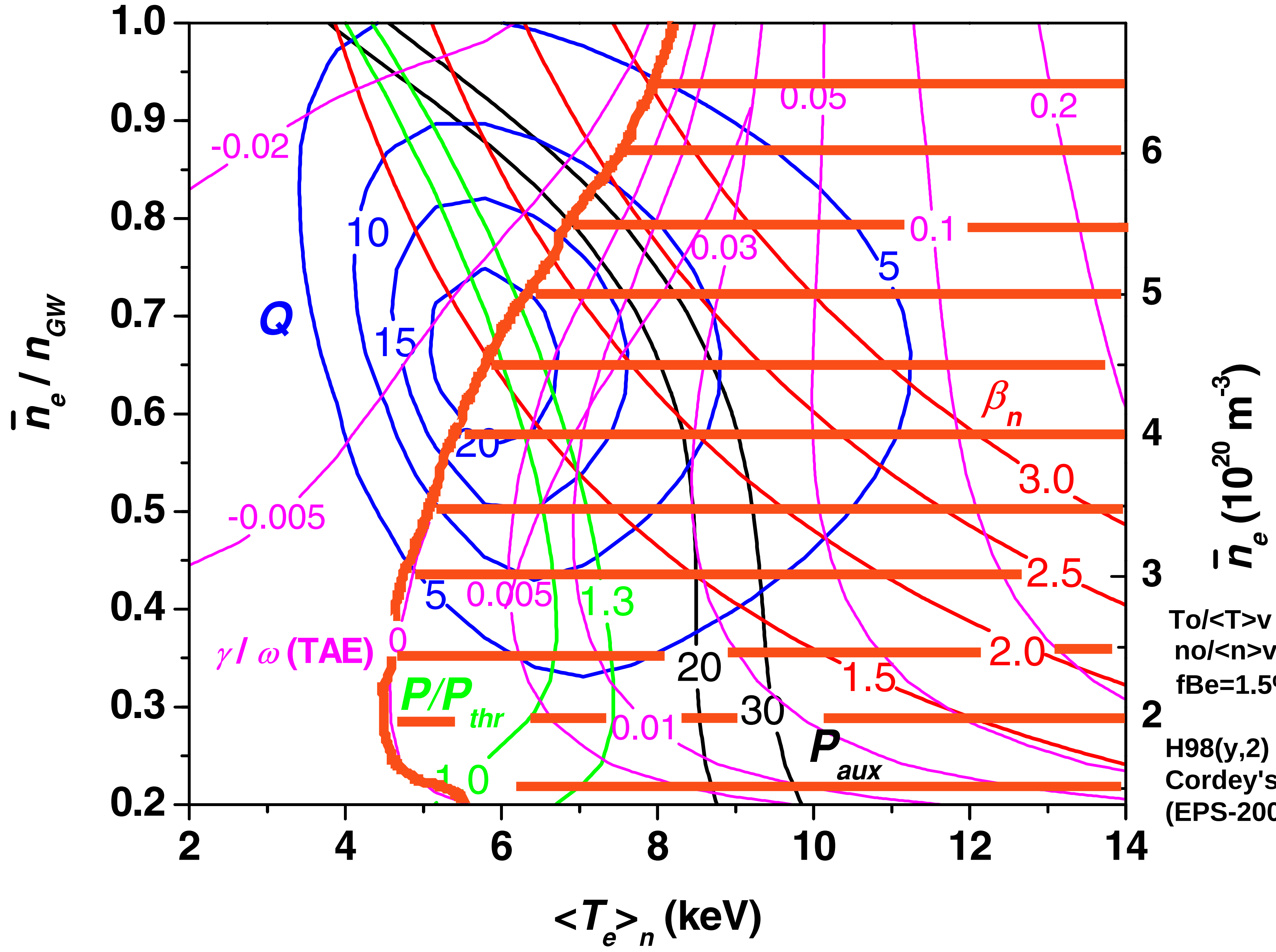
# Energetic Particle Drive can be Varied in FIRE Using Divertor Pumping and Pellet Injection

ITER-FEAT: Q = 10 H = 0.95, FIRE*: Q = 10 , H = 1.03,





# Exploration of TAE Mode Stability in FIRE

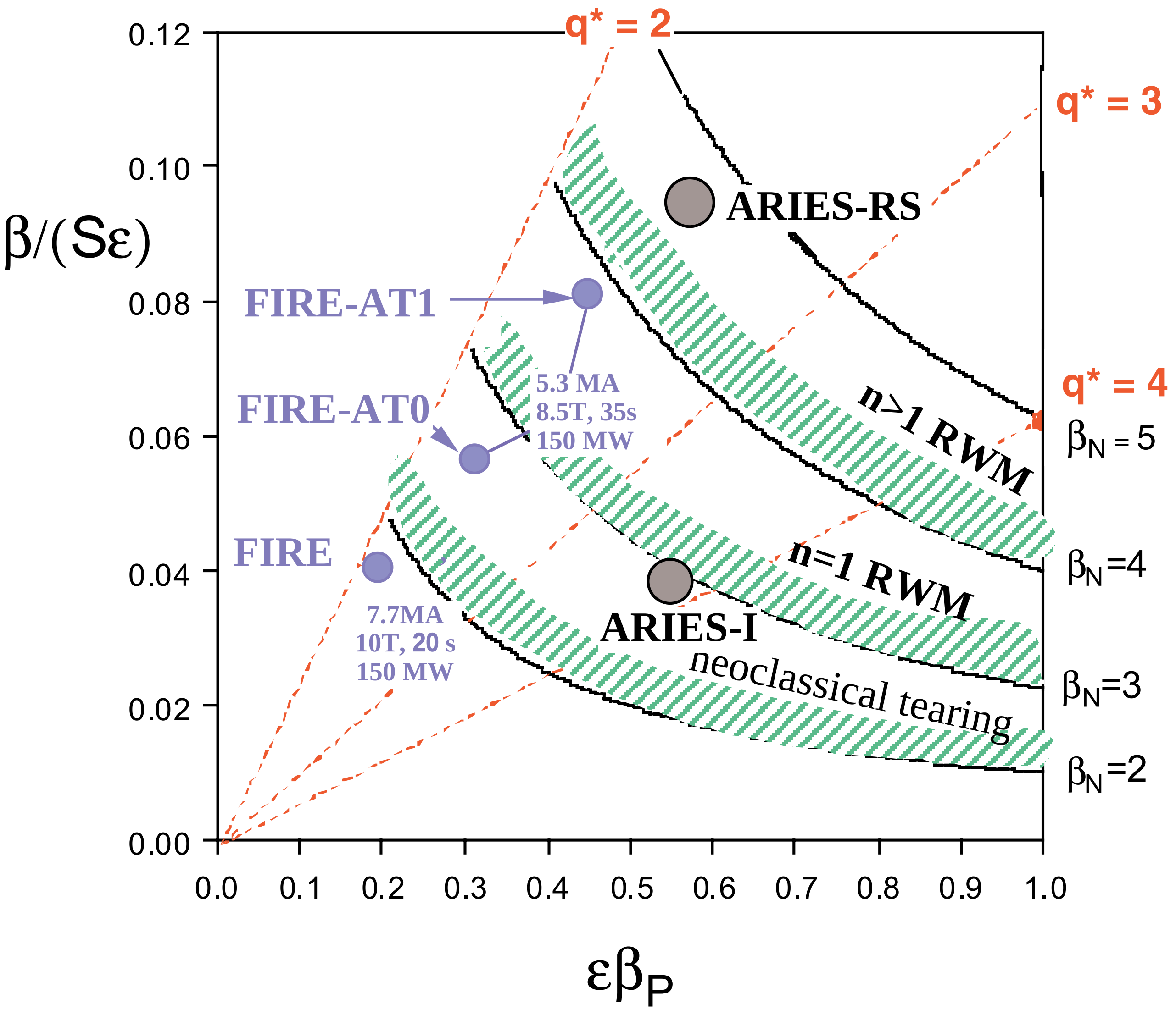


To/<T>v = 2.5
no/<n>v = 1.25
fBe=1.5%

H98(y,2) with
Cordey's Extension
(EPS-2001)

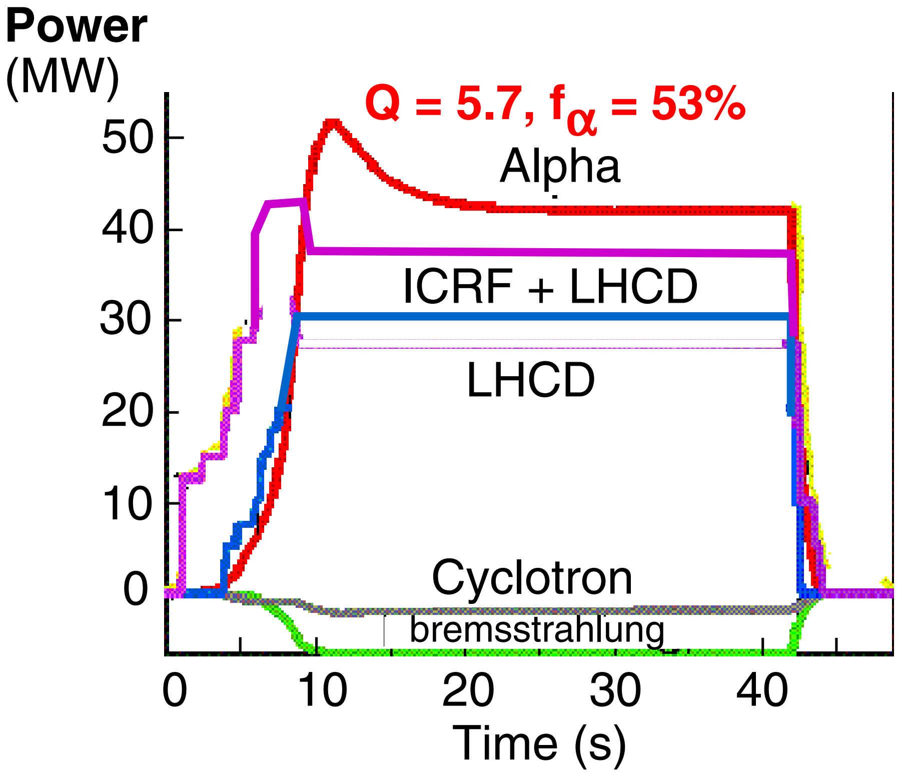
*John Mandrekas, 07/02/02*

# FIRE would Test a Sequence of AT Modes



# Advanced Burning Plasma Physics could be Explored in FIRE

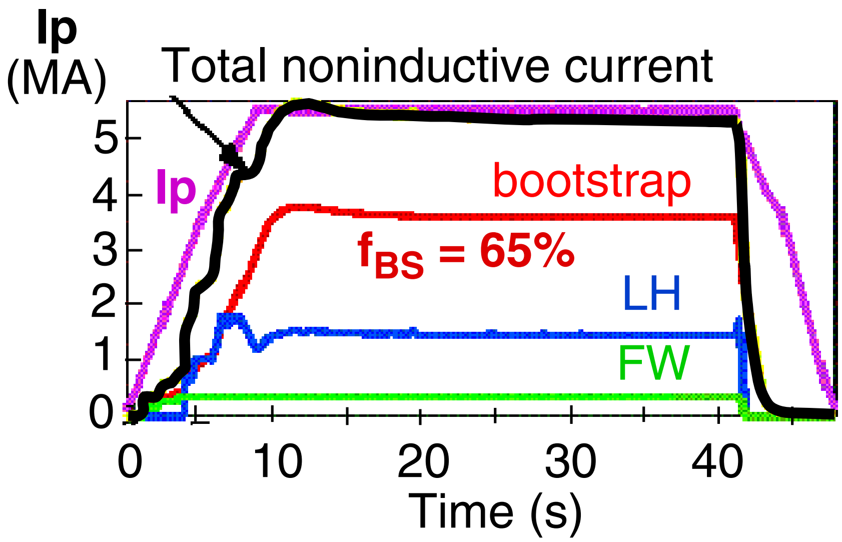
**Self-Heating Dominant**



**Self-Current Drive Dominant**

**Fully Non-Inductive for > 1 $\tau_{CR}$**

**8.5 T, 5.4 MA, t(flattop) = 32 s**



Tokamak simulation code results for H(y, 2) = 1.4, $\beta_N$ = 3.5 , would require RW mode stabilization. q(0) = 2.9, $q_{min}$ = 2.2 @ r/a = 0.8, 8.5 T, 5.5 MA

# Burning Plasma Simulation Initiative

- A more comprehensive simulation capability is needed to address the strong non-linear coupling inherent in a burning plasma.

- A comprehensive simulation could help:

  - better understand and communicate the important BP issues,

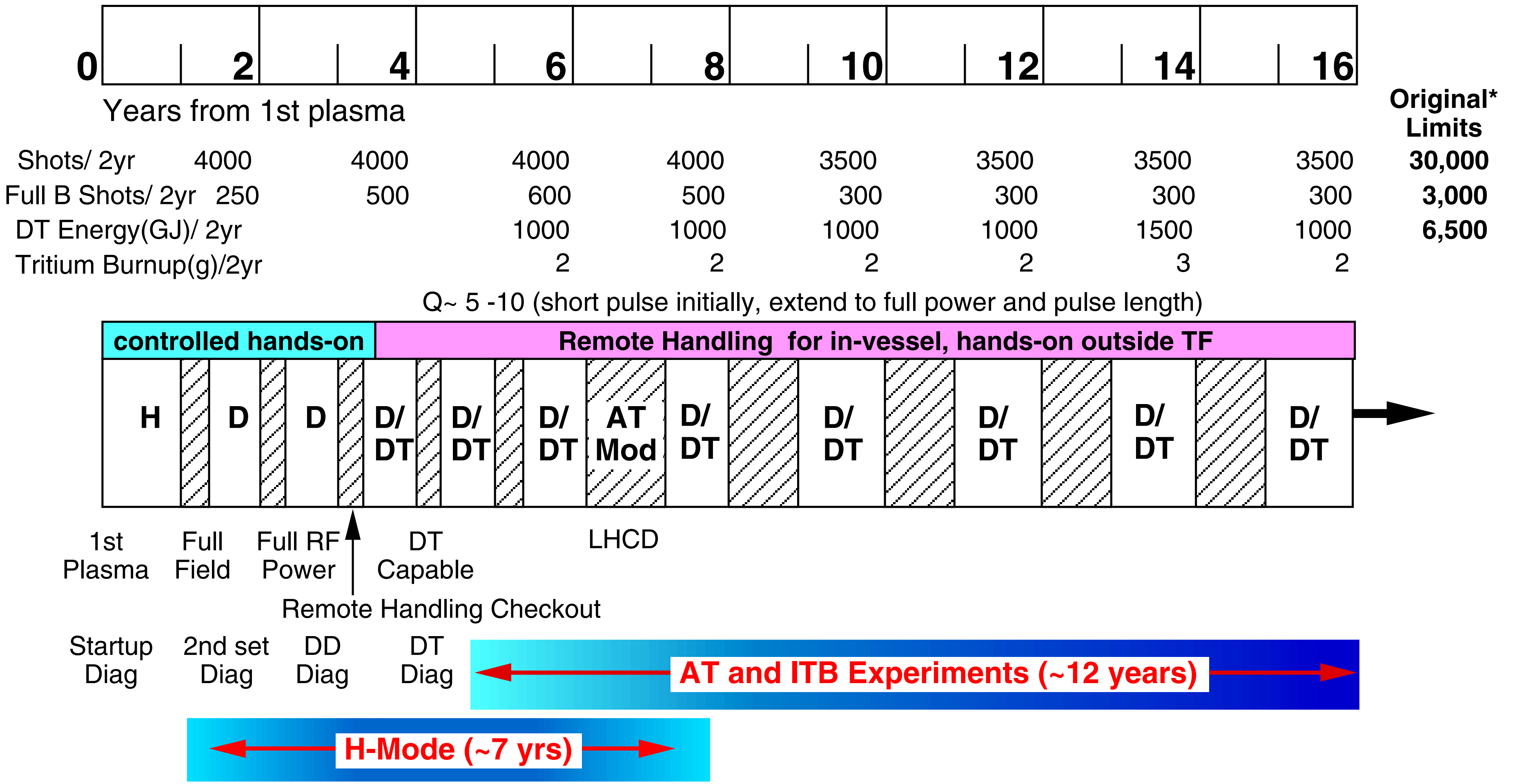
  - refine the design and expectations for BP experiments,

  - understand the experimental results and provide a tool for better utilization of the experimental run time, and

  - Carry the knowledge forward to the following tokamak step or to burning plasmas in other configurations.

- This is something we should be doing in any to support any of the future possibilities

# FIRE Experimental Plan



| Years from 1st plasma | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | Original* Limits |
|---|---|---|---|---|---|---|---|---|---|
| Shots/ 2yr | 4000 | 4000 | 4000 | 4000 | 3500 | 3500 | 3500 | 3500 | **30,000** |
| Full B Shots/ 2yr | 250 | 500 | 600 | 500 | 300 | 300 | 300 | 300 | **3,000** |
| DT Energy(GJ)/ 2yr | | | 1000 | 1000 | 1000 | 1000 | 1500 | 1000 | **6,500** |
| Tritium Burnup(g)/2yr | | | 2 | 2 | 2 | 2 | 3 | 2 | |

- Control
- Cleanup
- Fueling
- Diagnostics
- Operations
- RF tests

- InitialRF Heating
- Plasma Power Handling
- Initial Physics studies

- Alpha heating
- Energy transport
- Fast particle
- Particle and ash removal

- Global Burn control
- Transient Profile control
- Transient Adv Tok

- Optimization of AT modes
- Non Inductive Profile control
- Improve Divertor and FW power handling
- Extend pulse length

# Issues for FIRE and Burning Plasmas

**Transport**

Effects of high $\delta$, double null on confinement– exp’t, theory, modeling

ITBs w/o external momentum - Off Axis ICRF (C-Mod), Shafranov shift

**Power Handling (and indirectly Tritium Retention)**

Effects of high $\delta$, double null on ELMs (JET, AUG,DIII-D,JT-60U)

Effect of neutral stability point and disruption behavior/mitigation (C-Mod)

**AT Mode Development (B ≈ 6.6 T, > 1 $\tau_{CR}$ duration)**

Optimize Lower Hybrid Current drive

Improve Power Handling – a generic problem

ECCD (170 GHz) for NTM control

**When could we start counting on AT-like performance in designing a BP?**

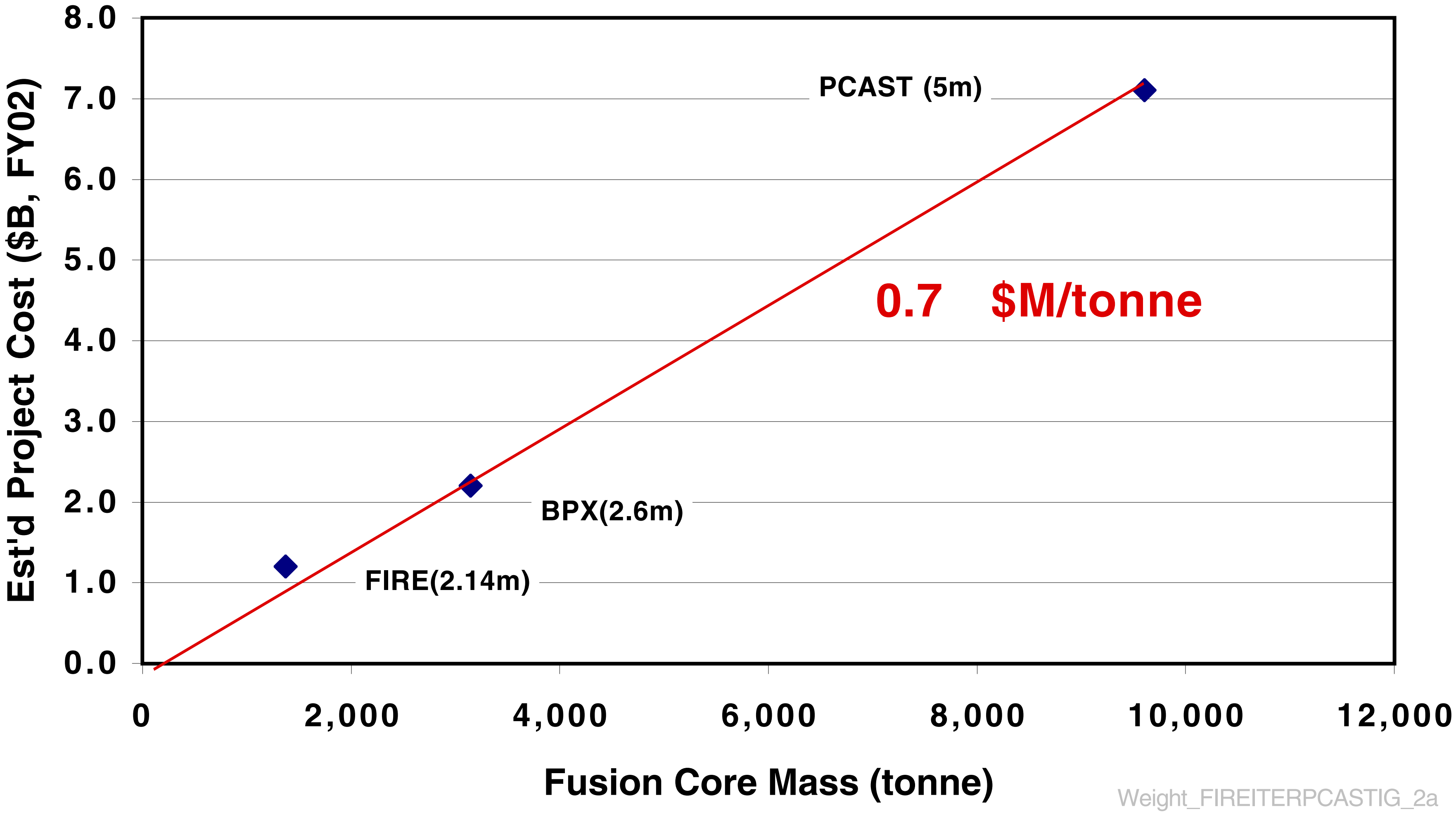
# Cost Estimate of FIRE Preconceptual Design (FY 2002$)

| Greenfield Site Cost Estimate | Estimated Cost | | Conting'y | Total with Conting'y |
|---|---|---|---|---|
| **1 - Fusion Core Systems** | | $279,524 | $71,279 | $350,803 |
| 1.1 Plasma Facing Components | $66,977 | | | |
| 1.2 Vacuum Vessel & In-Vessel Structures | $42,354 | | | |
| 1.3 Toroidal Field Magnets and Structures | $123,121 | | | |
| 1.4 Poloidal Field Magnets and Structures | $35,732 | | | |
| 1.5 Cryostat | $1,919 | | | |
| 1.6 Tokamak Support Structure | $9,420 | | | |
| **2 - Auxiliary Systems** | | $89,789 | $22,896 | $112,685 |
| 2.1 Gas & Pellet Injection Fueling Systems | $4,769 | | | |
| 2.2 Vacuum Pumping System | $12,645 | | | |
| 2.3 Fuel Recovery and Processing Systems | $4,089 | | | |
| 2.4 RF Heating/Current Drive Systems | $68,286 | | | |
| **3 - Diagnostic Systems** | | $21,455 | $5,471 | $26,926 |
| **4 - Power Systems** | | $153,504 | $39,144 | $192,648 |
| **5 - Central Instrumentation & Controls** | | $18,337 | $4,676 | $23,013 |
| **6 - Site and Facilities** | | $143,882 | $36,690 | $180,572 |
| **7 - Machine Assembly &Remote Maintenance** | | $80,375 | $20,496 | $100,871 |
| **8 - Project Support & Oversight** | | $118,378 | $30,186 | $148,564 |
| **9 - Preparations for Operations** | | $40,351 | $10,290 | $50,641 |
| **10 - R&D During Construction** | | $19,328 | $4,929 | $24,256 |
| **Cost Estimate of Preconceptual Design (FY 2002$)** | | $945,595 | $241,127 | $1,186,721 |

**TPC w/o contingency $946M**

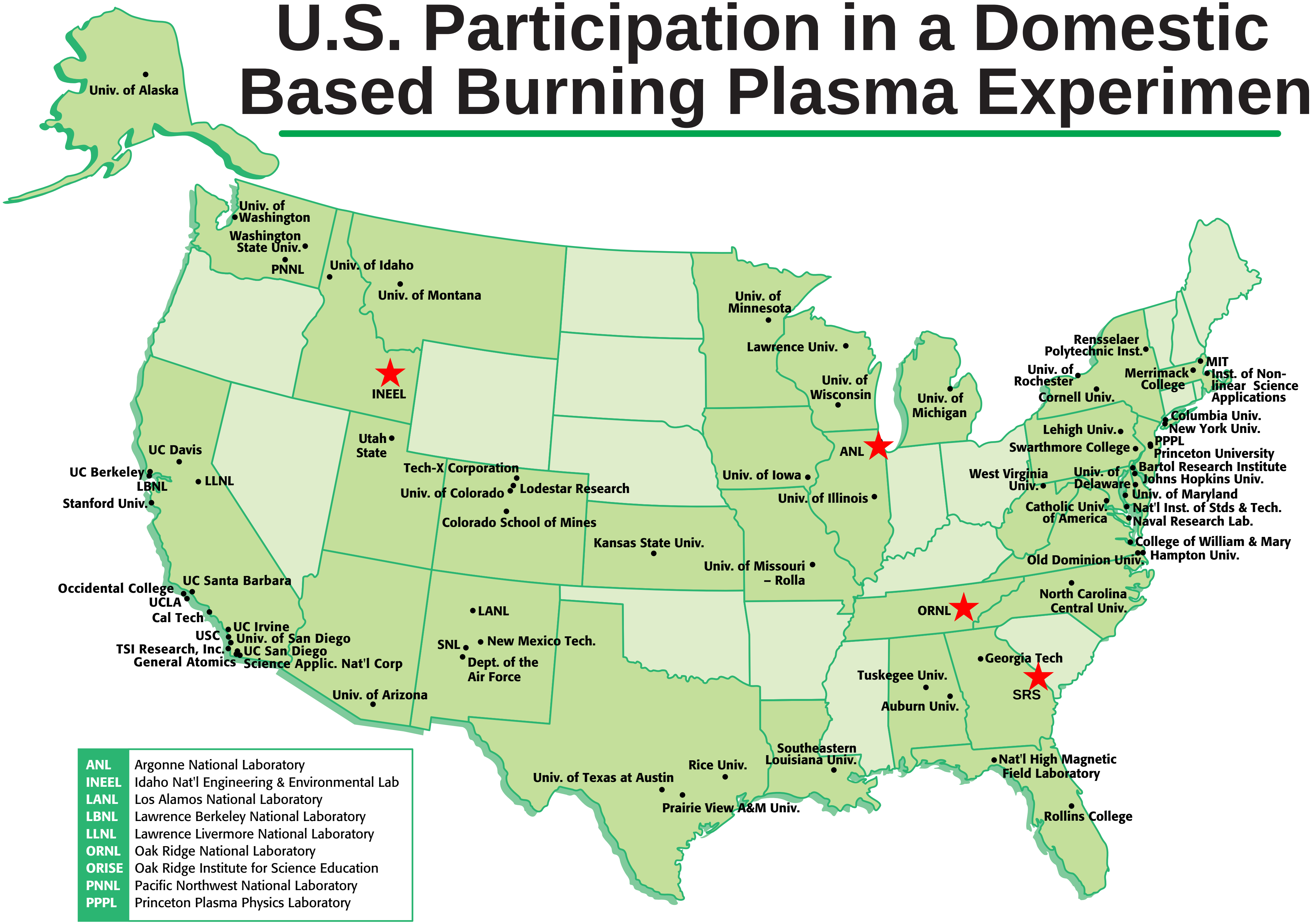
**TPC with contingency $1,200M**

# Correlation of Estimated Total Project Cost and Fusion Core Mass



Weight_FIREITERPCASTIG_2a

# U.S. Participation in a Domestic Based Burning Plasma Experiment

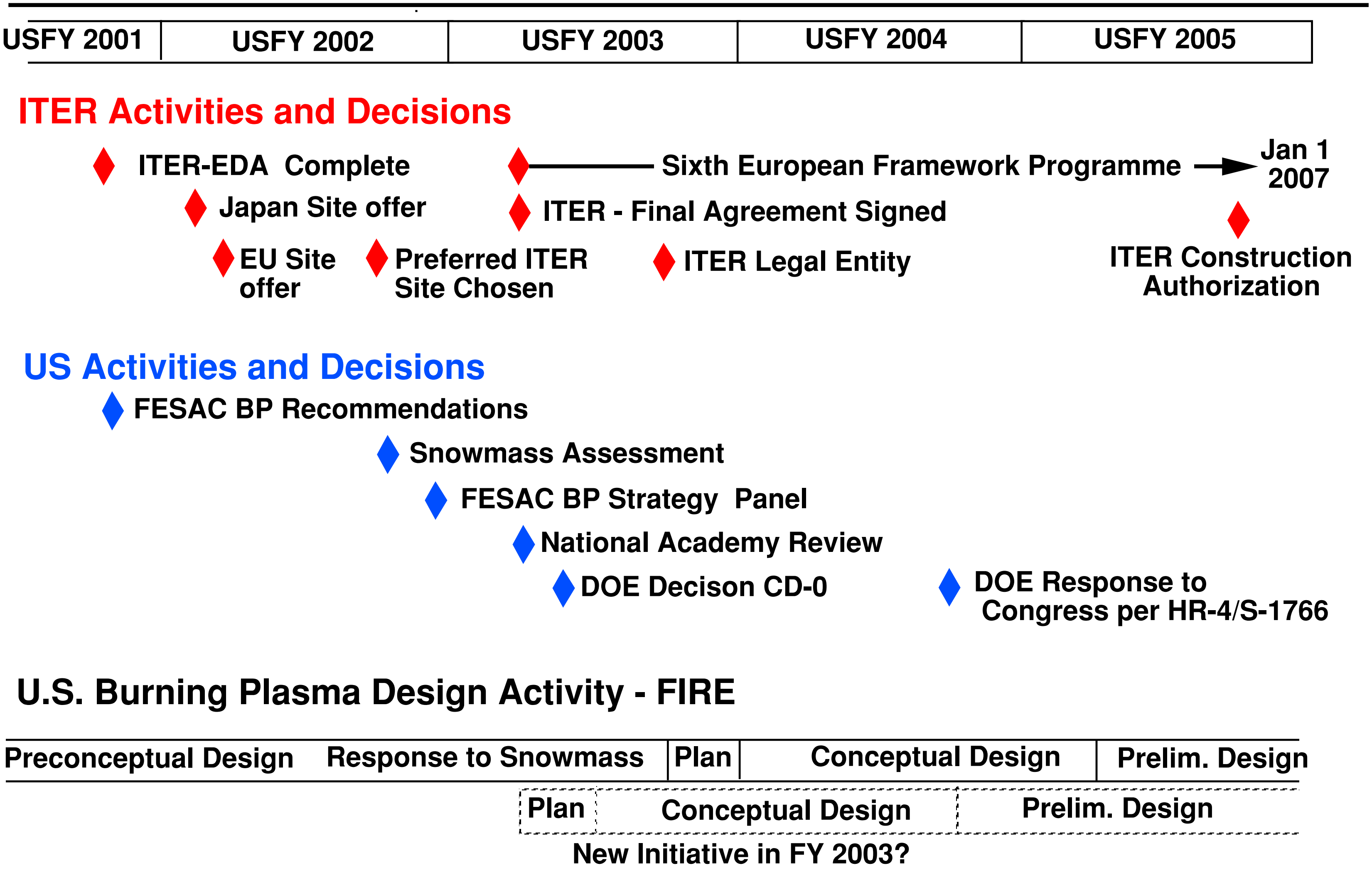


| | |
|---|---|
| **ANL** | Argonne National Laboratory |
| **INEEL** | Idaho Nat'l Engineering & Environmental Lab |
| **LANL** | Los Alamos National Laboratory |
| **LBNL** | Lawrence Berkeley National Laboratory |
| **LLNL** | Lawrence Livermore National Laboratory |
| **ORNL** | Oak Ridge National Laboratory |
| **ORISE** | Oak Ridge Institute for Science Education |
| **PNNL** | Pacific Northwest National Laboratory |
| **PPPL** | Princeton Plasma Physics Laboratory |

★ Potential sites for U.S. Based Burning Plasma Experiment

OCTOBER 2001

# Timetable for a Major Next Step in Magnetic Fusion



USFY 2001 | USFY 2002 | USFY 2003 | USFY 2004 | USFY 2005

## ITER Activities and Decisions

◆ ITER-EDA Complete

◆ Japan Site offer

◆ EU Site offer

◆ Preferred ITER Site Chosen

◆ Sixth European Framework Programme → Jan 1 2007

◆ ITER - Final Agreement Signed

◆ ITER Legal Entity

◆ ITER Construction Authorization

## US Activities and Decisions

◆ FESAC BP Recommendations

◆ Snowmass Assessment

◆ FESAC BP Strategy Panel

◆ National Academy Review

◆ DOE Decison CD-0

◆ DOE Response to Congress per HR-4/S-1766

## U.S. Burning Plasma Design Activity - FIRE

Preconceptual Design | Response to Snowmass | Plan | Conceptual Design | Prelim. Design

Plan | Conceptual Design | Prelim. Design

New Initiative in FY 2003?

Burning_Plasa_sched

# Next Steps for FIRE

- Listen and respond to critiques and suggestions for improvements.

- Update design goals and physics basis, review with Community, NSO PAC and DOE.

- Produce a Physics Description Document, and carry out a Physics Validation Review

- Initiate Project Activities (in 2003)

    Form National Project Structure

    Begin Conceptual Design

    Initiate R&D Activities

    Begin Site Evaluations

# Summary

- A Window of Opportunity may be opening for U.S. Energy R&D. We should be ready. The Diversified International Portfolio has advantages for addressing the science and technolgy issues of fusion.

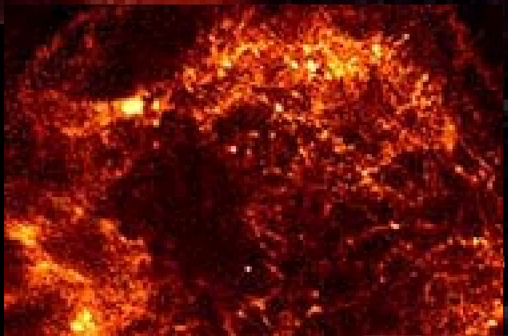
- FIRE with a construction cost ~ $1B, has the potential to :
  - address the important burning plasma issues, performance ~ ITER
  - investigate the strong non-linear coupling between BP and AT,
  - stimulate the development of reactor relevant PFC technology, and
  - provide generic BP science and possibly BP infrastructure for non-tokamak BP experiments in the U. S.

- Some areas that need additional work to realize this potential include:
  - Apply recent enhanced confinement and advanced modes to FIRE
  - Understand conditions for enhanced confinement regimes-triangularity
  - Compare DN relative to SN - confinement, stability, divertor, etc
  - Complete disruption analysis, develop better disruption control/mitigation.

- If a postive decision is made in this year, FIRE is ready to begin Conceptual Design in FY2003 with target of first plasmas ~ 2010.

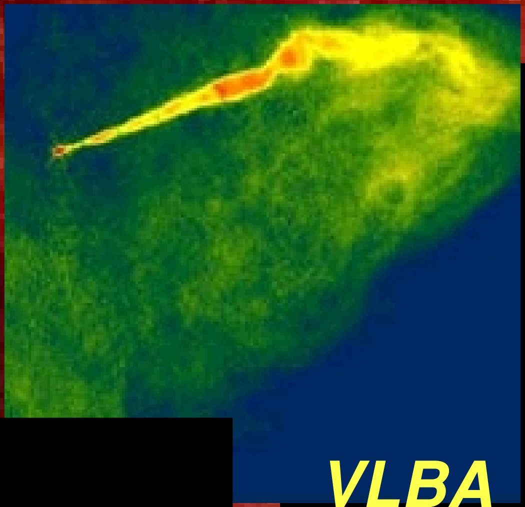
***http://fire.pppl.gov***

# The U.S. Builds ~1$B Facilities to Explore, Explain and Expand the Frontiers of Science



CHANDRA

NIF

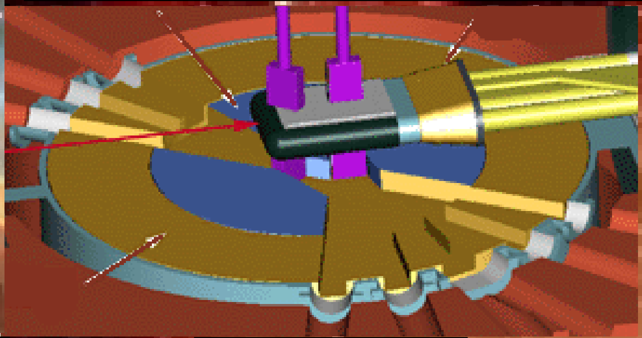


VLBA

?

MFES

HST (NGST)



SNS

APS