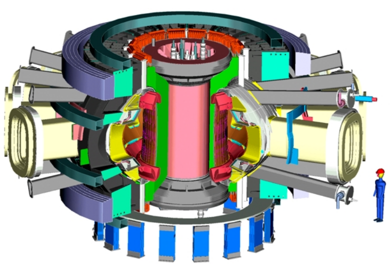
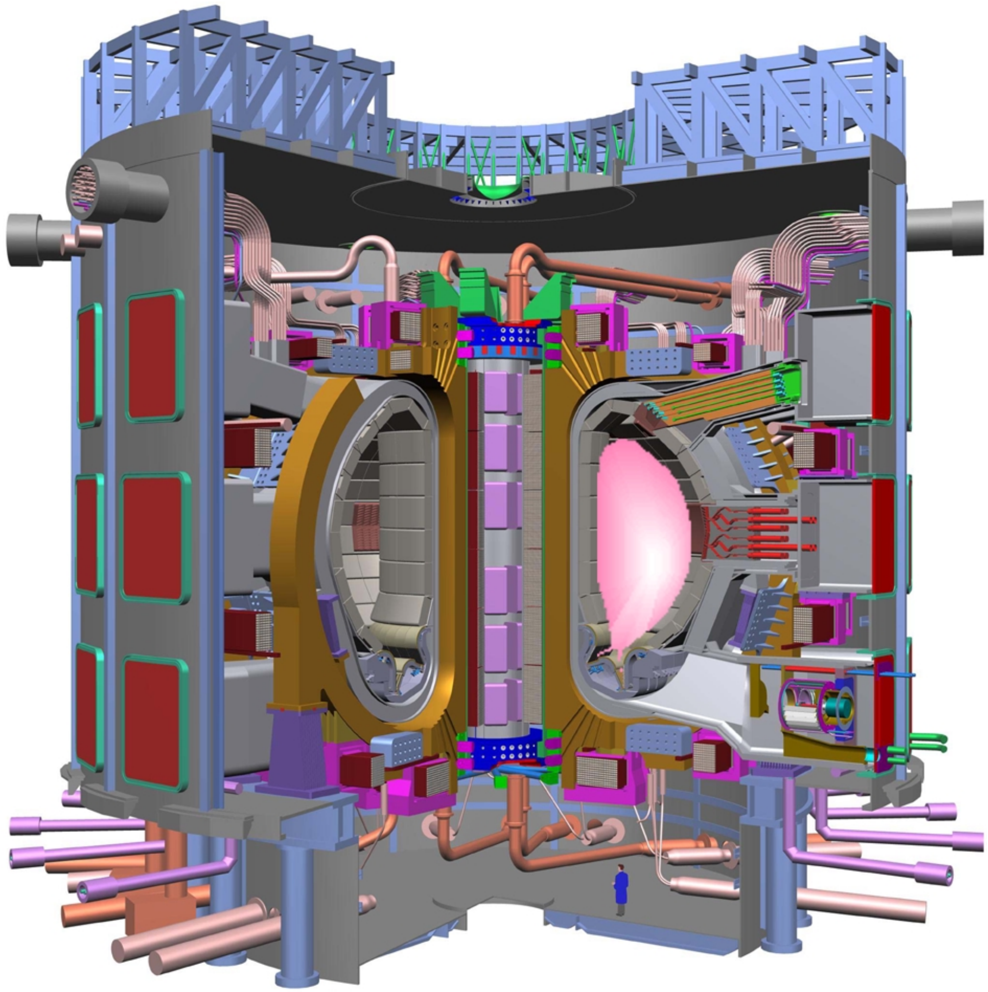
Burning Plasma Physics - The Next Frontier

Three Options
(same scale)



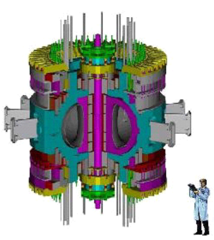
FIRE

US Based
International Modular Strategy



ITER-FEAT

JA, EU or CA Based
International Partnership



IGNITOR

Italian Based
International Collaboration

FIRE

A Next Step Option for Magnetic Fusion

Dale M. Meade

for the FIRE Team

Presented at
6th International Symposium on Fusion Nuclear Technology
San Diego, CA

April 10, 2002

http://fire.pppl.gov

Outline

- Objectives for a Next Step Experiment in Magnetic Fusion
- Burning Plasma Performance Considerations
- Compact High Field Approach - General Parameters
- Advanced Tokamak Longer Pulse Possibilities
- Summary

Recent Activities Impacting a Next Step in MFE

- Energy Authorization Bill (HR 4) passed by the House on August 1, 2001

  1. Calls for strengthening the base fusion sciences program

  2. Directs DOE to submit a plan for a U.S. Burning Plasma Experiment to Congress by July 2004. In addition, DOE may also develop a plan for United States participation in an international burning plasma experiment for the same purpose, if it is highly likely to be constructed and cost-effective

- Fusion Energy Sciences Advisory Committee (FESAC) endorses recommendations of FESAC Burning Plasma Panel for Proactive BP Program.

- National Academy of Science 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. International participation is encouraged.

Full text on http://fire.pppl.gov

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

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

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

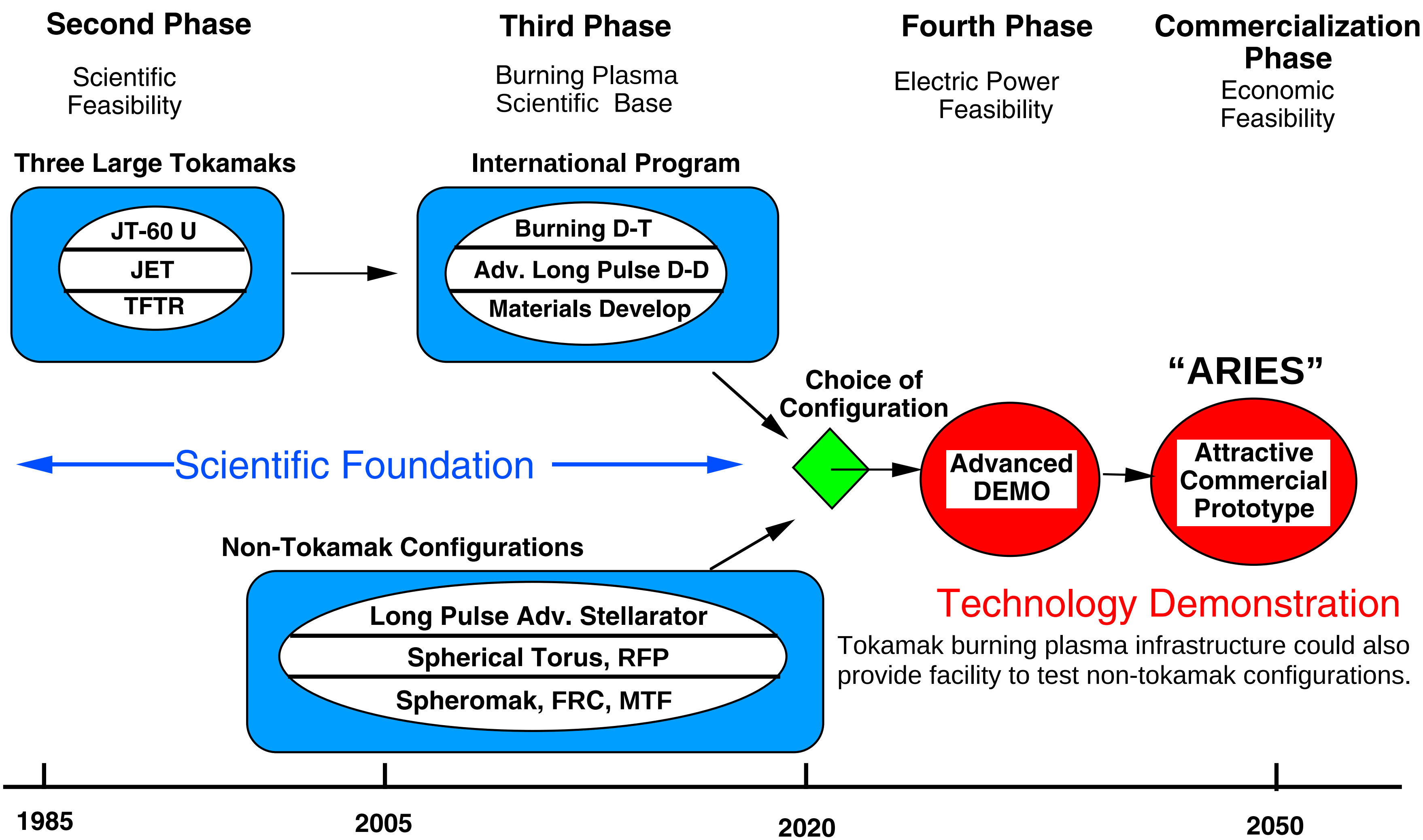
- **Boundary Physics and Plasma Technology** (coupled with above)
  - high particle and heat flux
  - couple core and divertor
  - fusion plasma - tritium inventory and helium pumping

- **Neutron Resistant Materials** (separate facility)
  - high fluence testing using “point”neutron source

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

- Nuclear Component Testing should wait for the correct reactor materials

The Multi-Machine Strategy for Magnetic Fusion



Reduced Technical Risk | **Streamlined Management Structure** | **Better Product/Lower Overall Cost**

Increased Technical Flexibility | **Faster Implementation**

(The overall Multi-Machine Strategy includes IFE)

Next Step Option (FIRE) Program 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

- **Meetings**
  July 20-21, 2000 at General Atomics, San Diego, CA.
  January 17-18, 2001 at MIT, Cambridge, MA
  July 10-11, 2001 at Univ. Wisc, Madison, WI
  November 29-30 at LLNL, Livermore, CA
- **Charge for First and Second meetings**
  Scientific value of a Burning Plasma experiment
  Scientific readiness to proceed with such an experiment
  Is the FIRE mission scientifically appropriate?
  Is the initial FIRE design point optimal?

- Extensive PAC Reports provide detailed recommendations for the FIRE activity to address. NSO-PAC reports are on FIRE (http://fire.pppl.gov), will discuss in more detail under FY 2001-03 Plans.

FIRE Study is a Pre-Conceptual design, integrated costs (1998-2002) <$12M.

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	≥ 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%
β_N	~ 2.5, no wall	~ 3.6, n = 1 wall stabilized

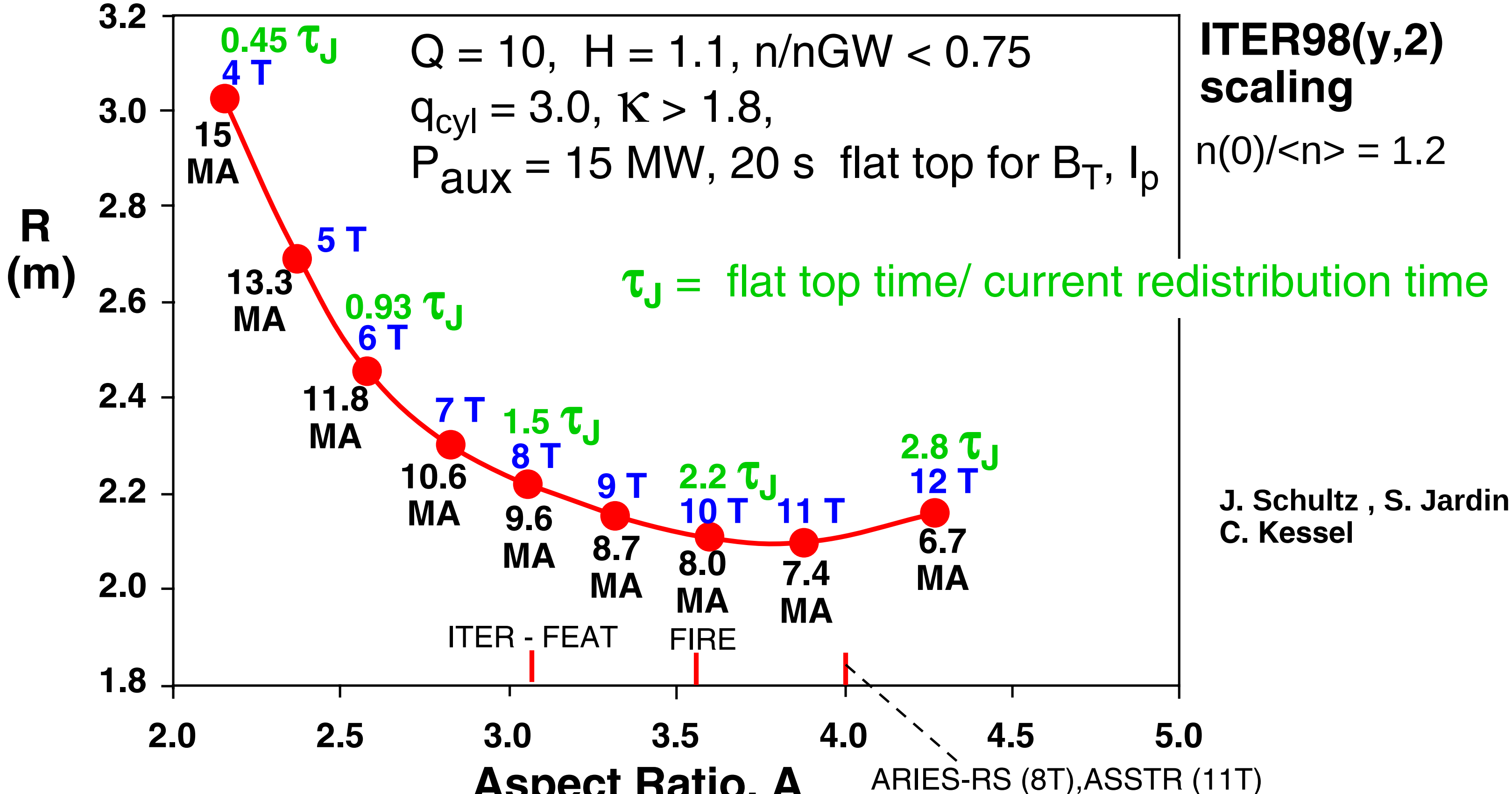
Quasi-stationary

Pressure profile evolution and burn control	> 10 τ_E
Alpha ash accumulation/pumping	> several τ_{He}
Plasma current profile evolution	1 to 3 τ_{skin}
Divertor pumping and heat removal	several $\tau_{divertor}$, $\tau_{first\ wall}$

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.

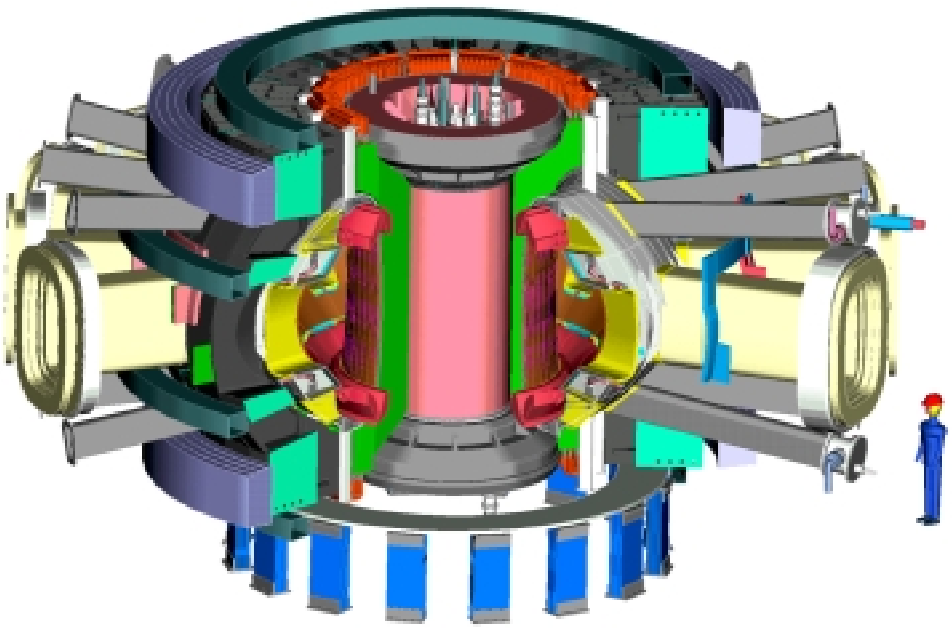
- Seek minimum R while varying A and space allocation for TF/PF coils for a specified plasma performance - Q and pulse length with physics and eng. limits.



What is the optimum for advanced steady-state modes?

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 ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s
- Tokamak Cost ≈ $375M (FY99)
- Total Project Cost ≈ $1.2B at Green Field site.

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

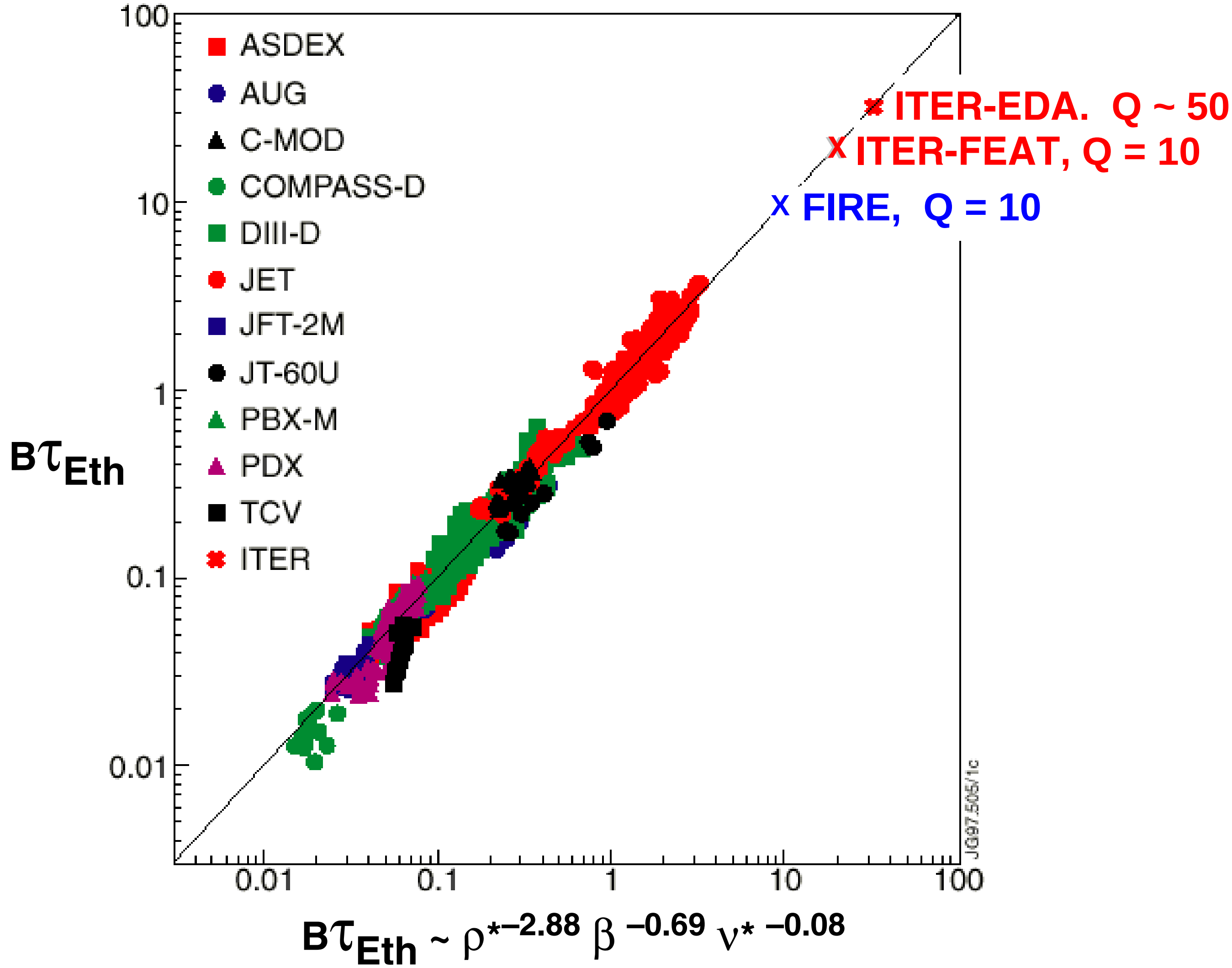
CIT + TPX = FIRE leading to ARIES

FIRE is a Modest Extrapolation in Plasma Confinement

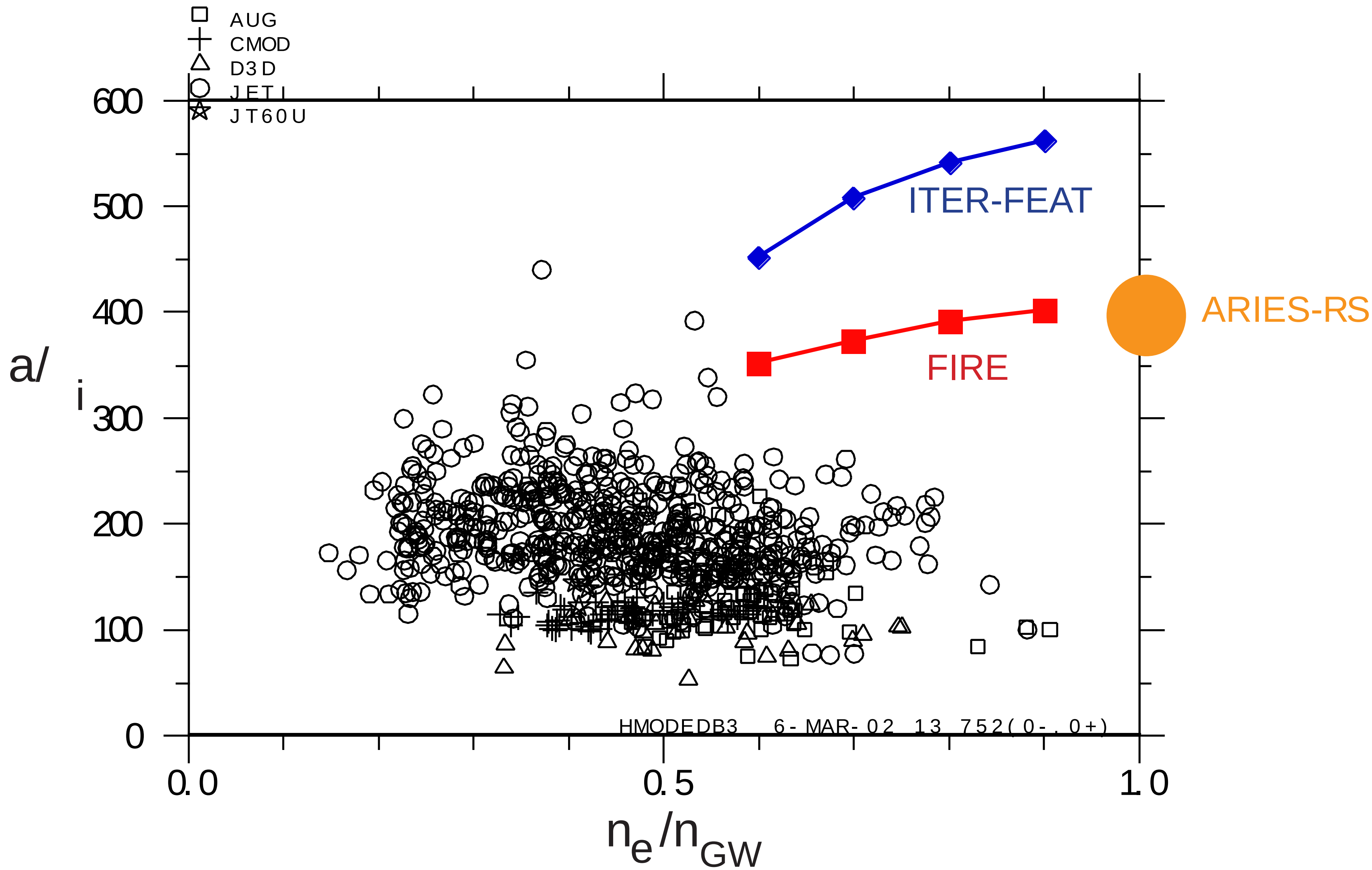
Dimensionless Parameters
$\omega_c \tau = B\,\tau$ $\rho^* = \rho/a$ $\nu^* = \nu_c/\nu_b$ β

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

Kadomtsev, 1975



FIRE would Extend the Transport Understanding Toward ARIES



FIRE and ITER-FEAT calculated for Q =10,

a/ρ_i evaluated at plasma center

Guidelines for Estimating Plasma Performance

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

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

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

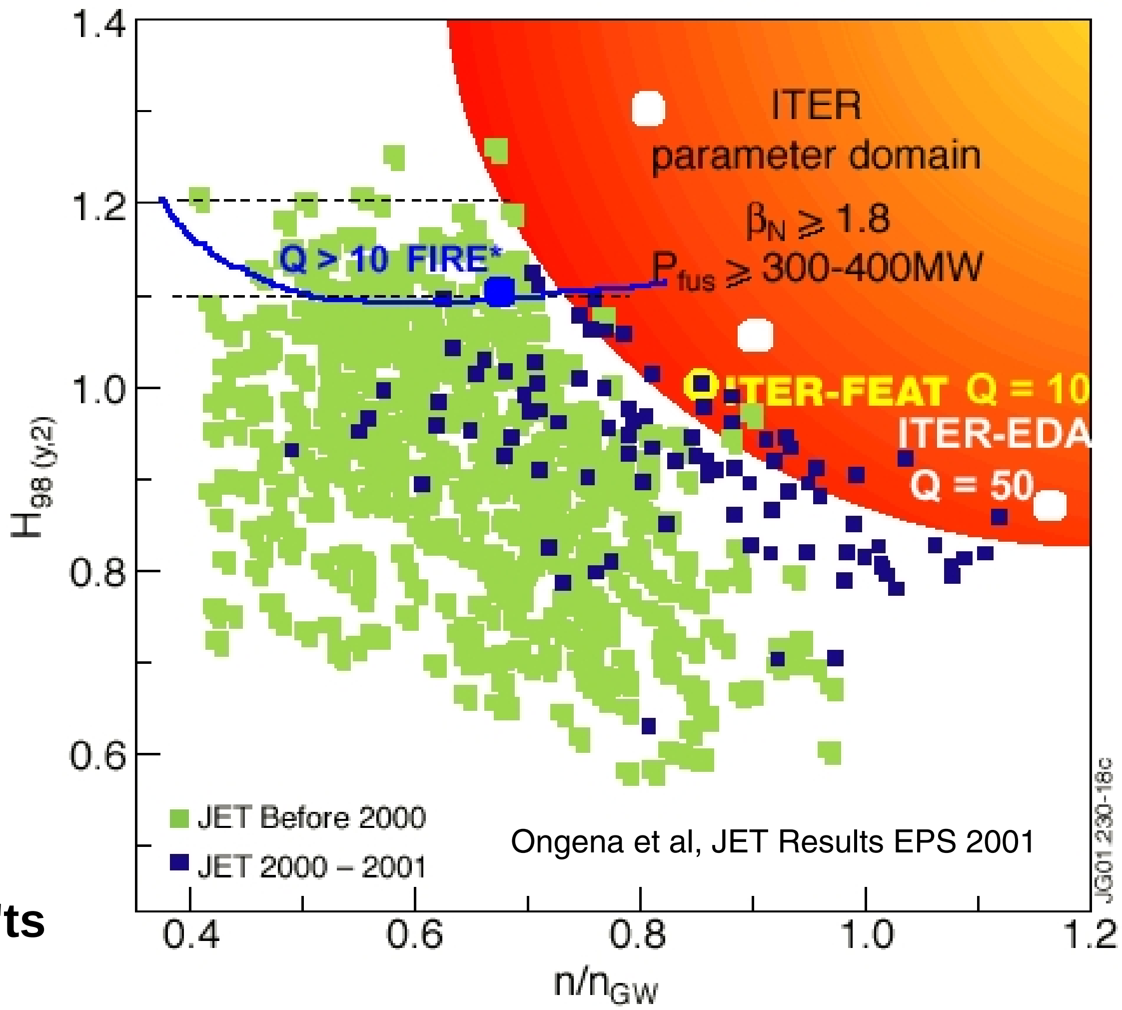
$$Pth \;\geq\; (2.84/Ai)\, n_{20}^{0.58}\, B^{0.82}\, Ra^{0.81} \quad , \text{ same as ITER-FEAT}$$

Helium Ash Confinement $\tau_{He} = 5\, \tau_E$, impurities = 3% Be, 0% W

Understanding is mainly empirical. Better understanding is needed from existing experiments with improved simulations, and a benchmark in alpha-dominated fusion plasmas is needed to confirm and extend the science basis.

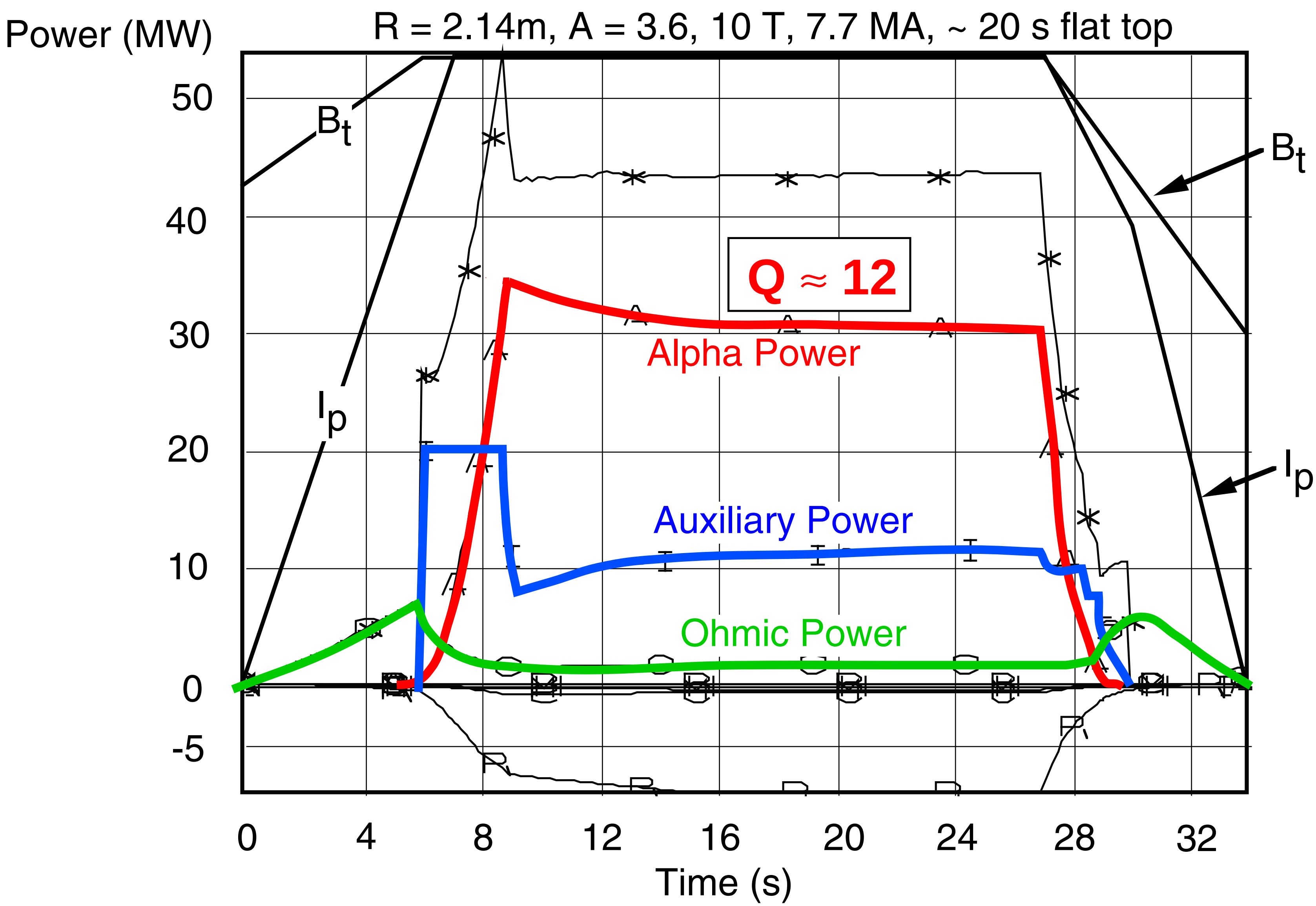
FIRE's Operating Density and Triangularity are Near the Optimum for the Elmy H-Mode

- **The optimum density for the H-Mode is $n/n_{GW} \approx 0.6$ - 0.7**
- **H-mode confinement increases with δ**
  - **$\delta \approx 0.7$ 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**



Cordey et al, H = function (δ, n/n_{GW}, $n(0)/<n>$) EPS 2001

1 1/2-D Simulation of Elmy H-Mode in FIRE (TSC)



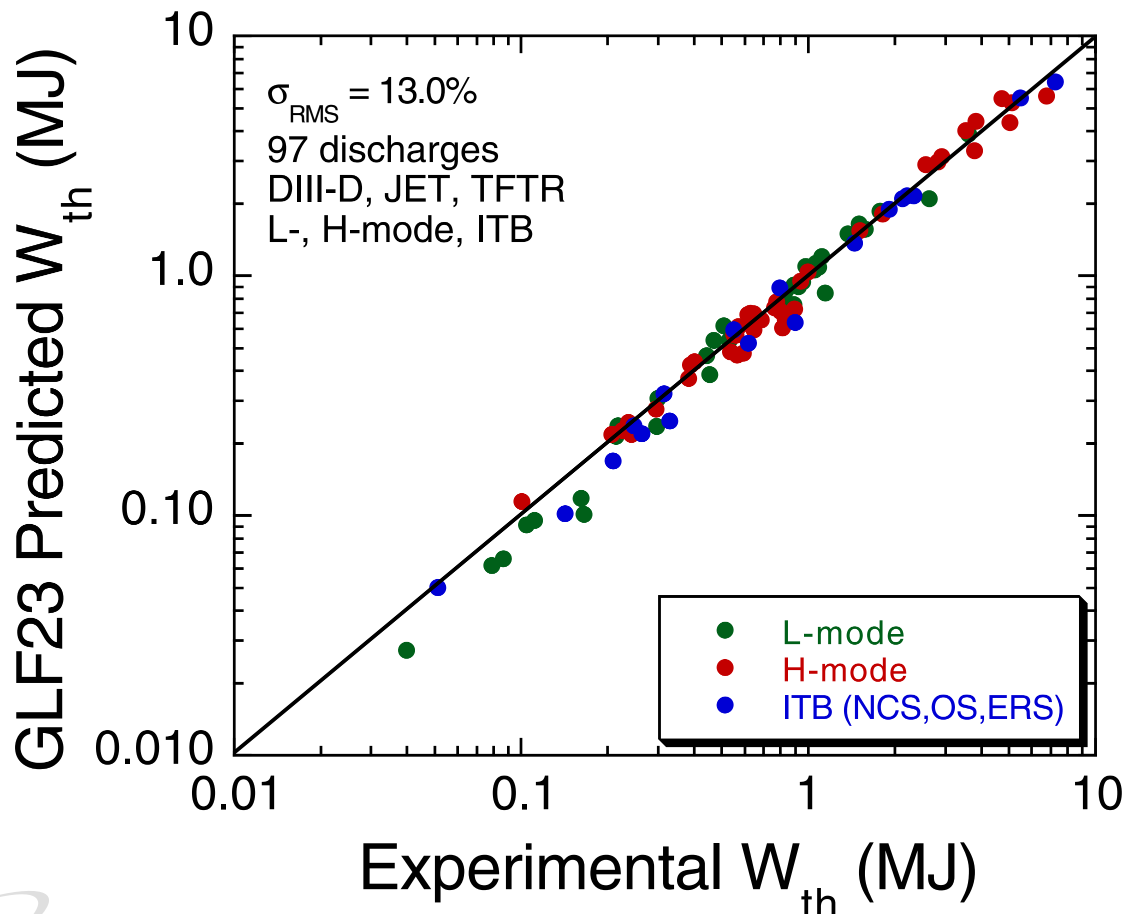
- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and n/n_{GW} = 0.67
- Burn Time ≈ 20 s ≈ 21 τ_E ≈ 4 τ_{He} ≈ 2 τ_{skin}

Q = Pfusion/(Paux + Poh)

Physics Based Transport Model

GLF23 Transport Model With Real Geometry ExB Shear Shows Improved Agreement With L- and H-mode and ITB Profile Database

- ***Statistics computed incremental stored energy (subtracting pedestal region) using exactly same model used for ITB simulations***

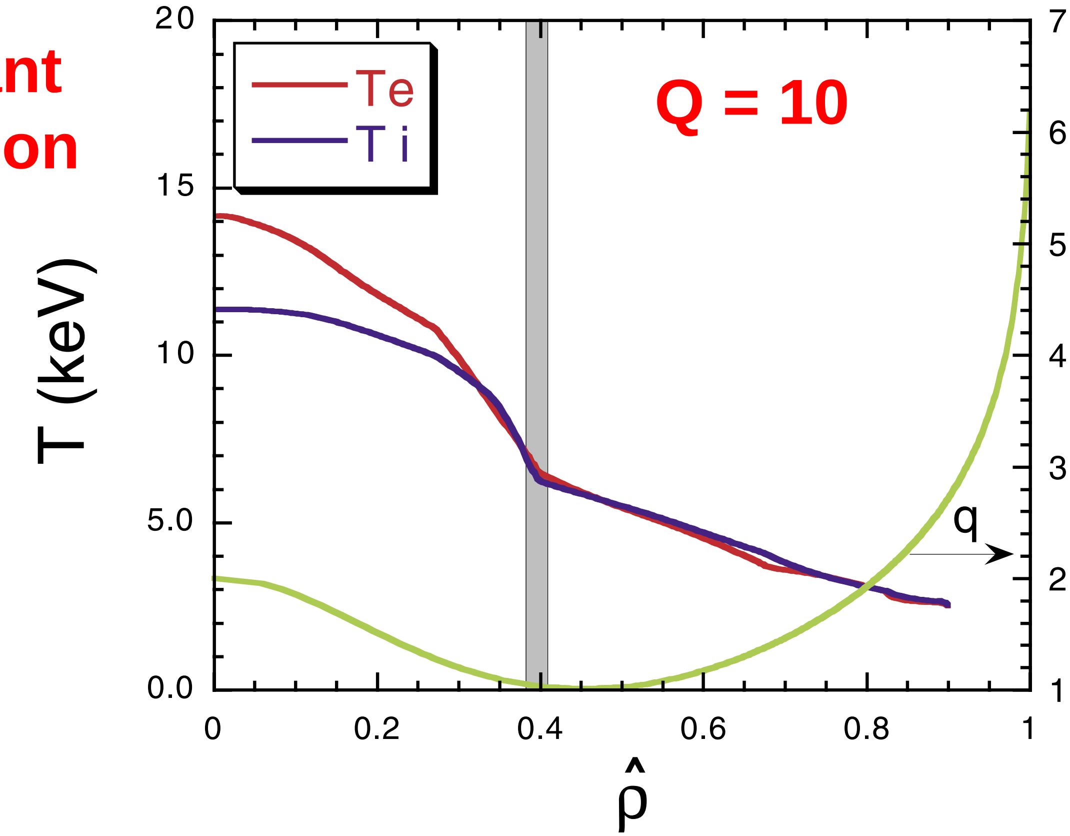


* T_e , T_i , v_ϕ predicted for ITBs

GLF23 Predicts an Internal Transport Barrier in FIRE as a Result of Shafranov-Shift Stabilization of the ITG Mode

- ***Barrier only forms if some density peaking is present.***
- ***Diamagnetic component of ExB shear helps after ITB is formed.***

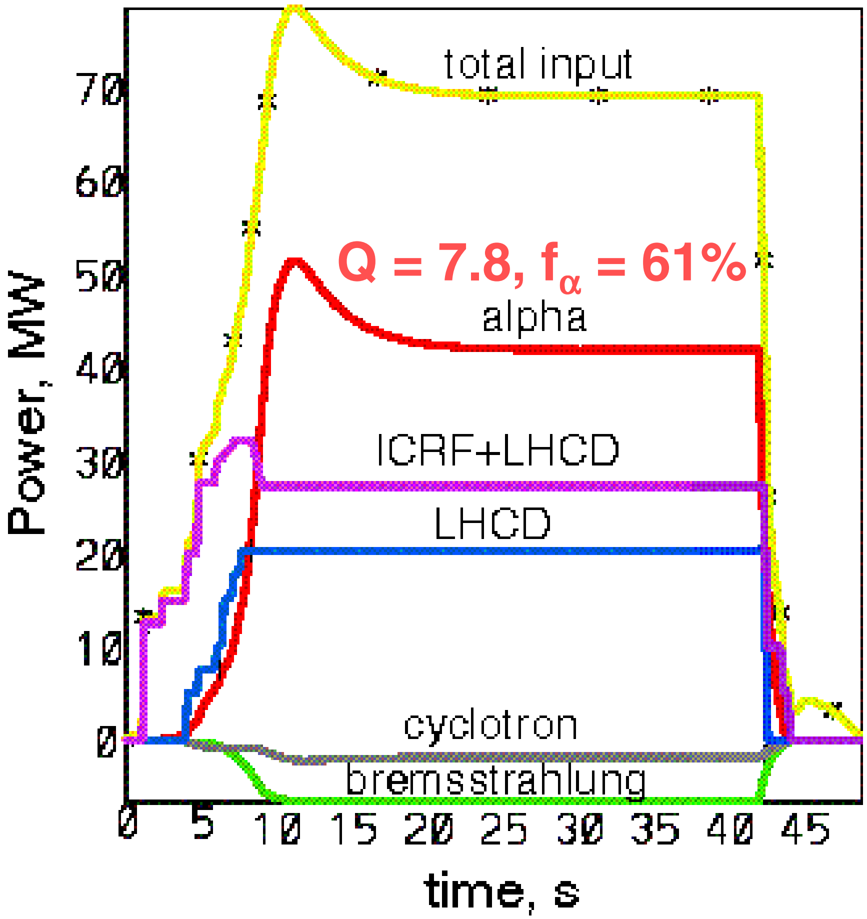
Reactor relevant no beam rotation

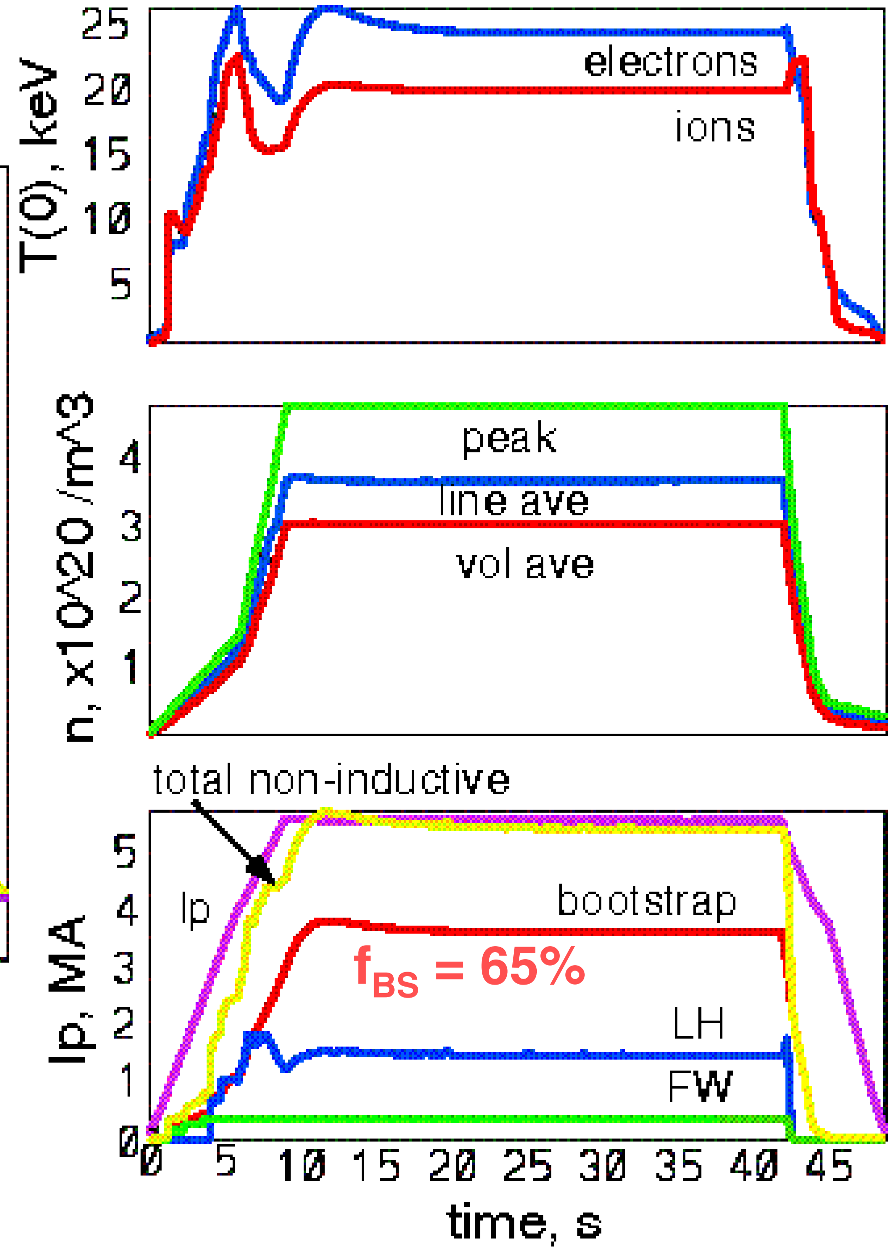


Kinsey, Waltz and Staebler
UFA BPS Workshop 2

Simulation of Advanced Tokamak Regime in FIRE

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





H(y,2) = 1.6,

β_N = 3.5, n(0)/<n> = 1.5

Fusion Dominated Plasma

Contributors to 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

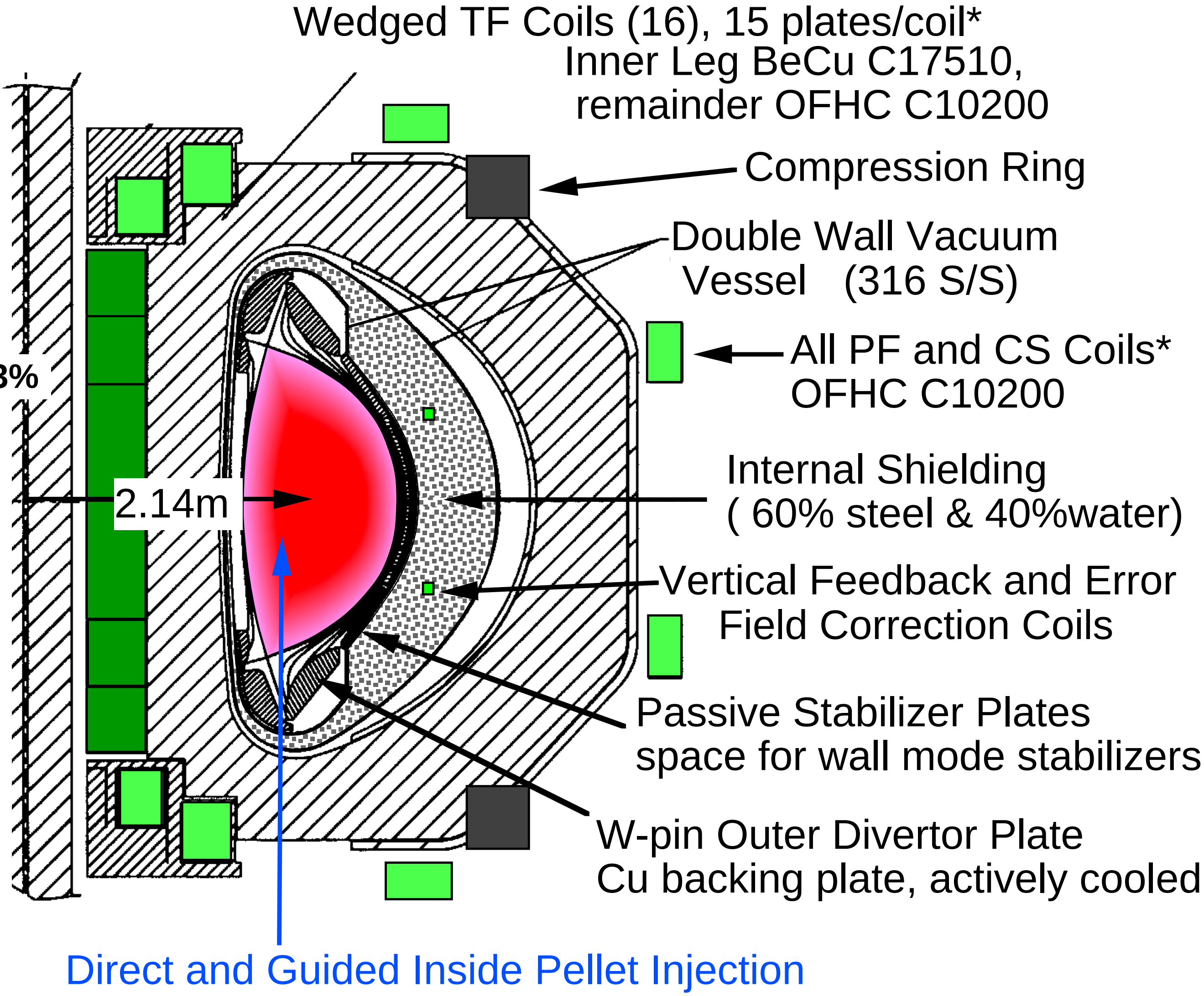
FIRE at ISFNT-6

FIRE Vacuum Vessel Design and Configuration	Brad Nelson	P-1.VAC-2
FIRE, A Next Step Option for Magnetic Fusion	Dale Meade	I- 3.BPC-3
Plasma Heating and Current Drive Systems for the Fusion Ignition Research Experiment (FIRE)	David Swain	P-3.BPC-1
Nuclear Features of the Fusion Ignition Research Experiment (FIRE)	Mohamed Sawan	P-3.BPC-2
Physics Basis and Simulation of Burning Plasma Physics for the Fusion Ignition Research Experiment (FIRE)	Charles Kessel	P-3.BPC-3
Engineering Overview of the Fusion Ignition Research Experiment (FIRE)	Richard Thome	P-4.NSD-1
Design of the Fusion Ignition Research Experiment (FIRE) Plasma Facing Components	Dan Driemeyer	P-4.FWC-19
Magnet Structural Design for the Fusion Ignition Research Experiment (Fire)	Peter Titus	P-5.MAT-43

FIRE Incorporates Advanced Tokamak Features

AT Features

- DN divertor
- strong shaping
- very low ripple **< 0.3%**
- 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.

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, ~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

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

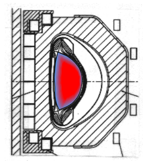
Solutions to these issues would be a major output from a next step experiment.

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

Pfusion
= ~ 150 MW

Volume
= 27 m^3

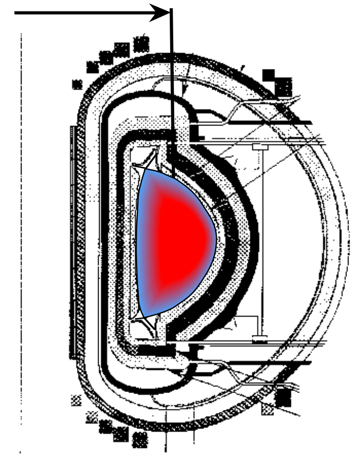
B = 10 T
R = 2.14 m →



FIRE

~ 3X

B = 8 T
R = 5.5 m



ARIES-RS The “Goal”

Pfusion
= 2170 MW

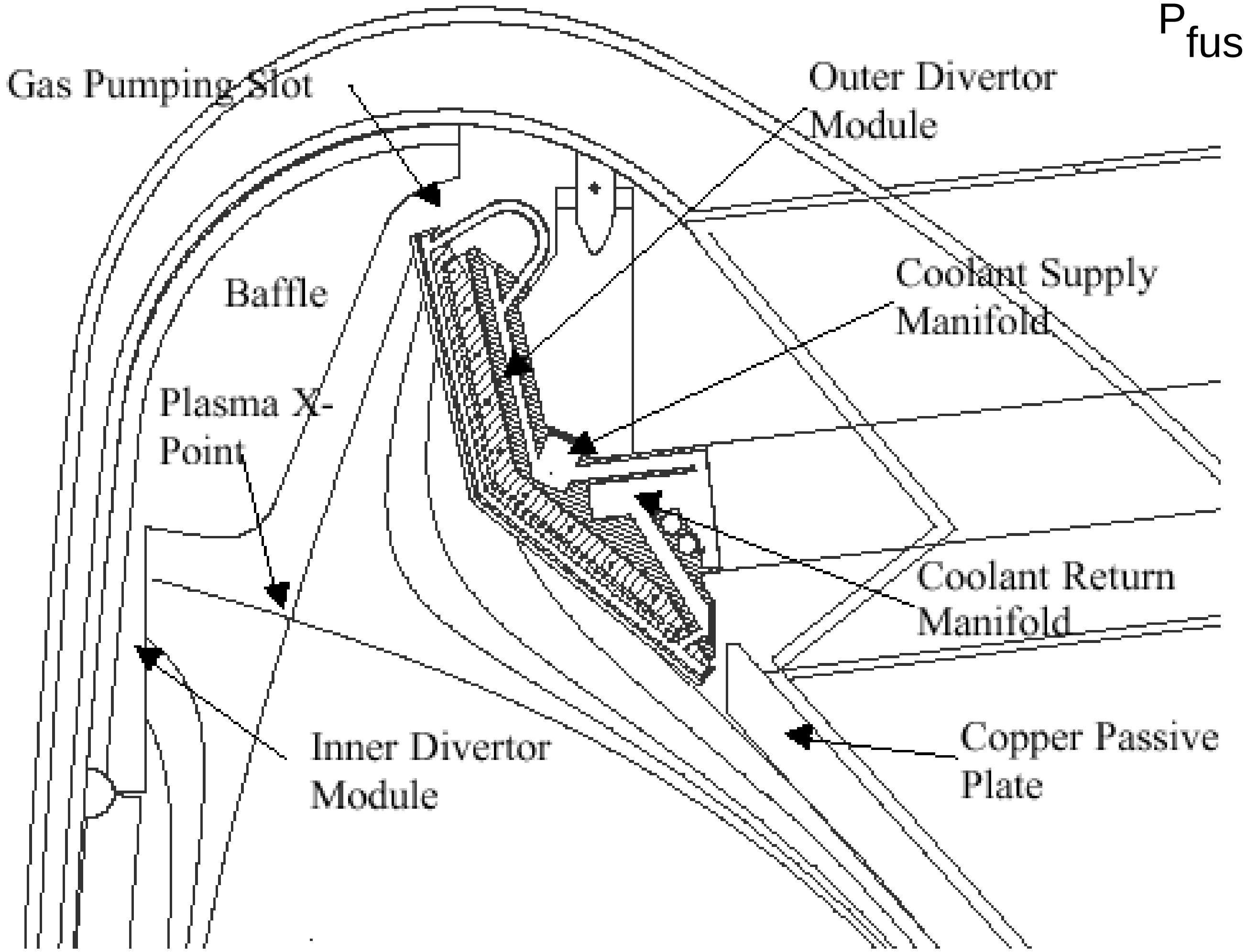
Volume
= 350 m^3

	JET	FIRE	ARIES-RS
Fusion Power Density (MW/m^3)	0.2	5.5	6
Neutron Wall Loading (MW/m^2)	0.2	2.3	4
Divertor Challenge (Pheat/NR)	~5	~10	~35
Power Density on Div Plate (MW/m^2)	3	~15-19 → 6	~5
Burn Duration (s)	4	20	steady

Poster Thursday AM
Ulrickson, Driemeyer

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

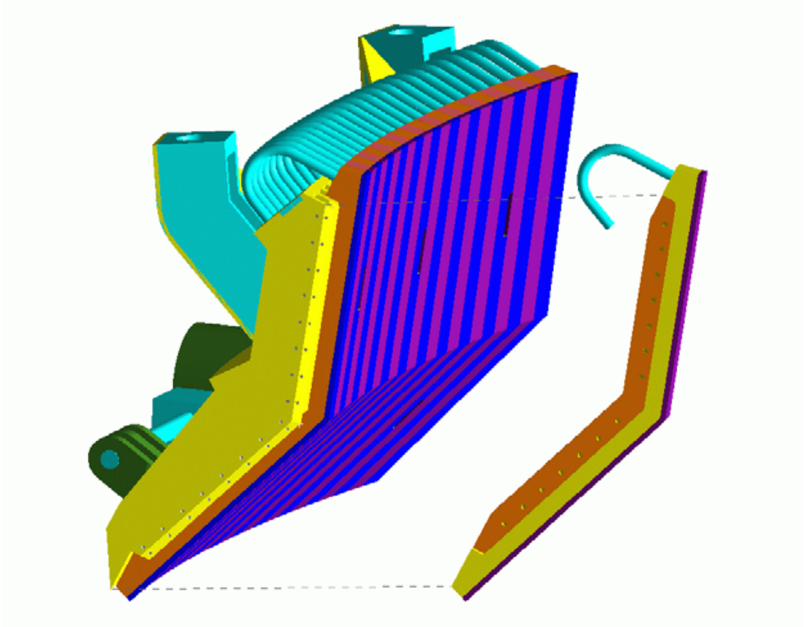
P_{fusion} < 200 MW



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

Divertor Module Components for FIRE

Sandia

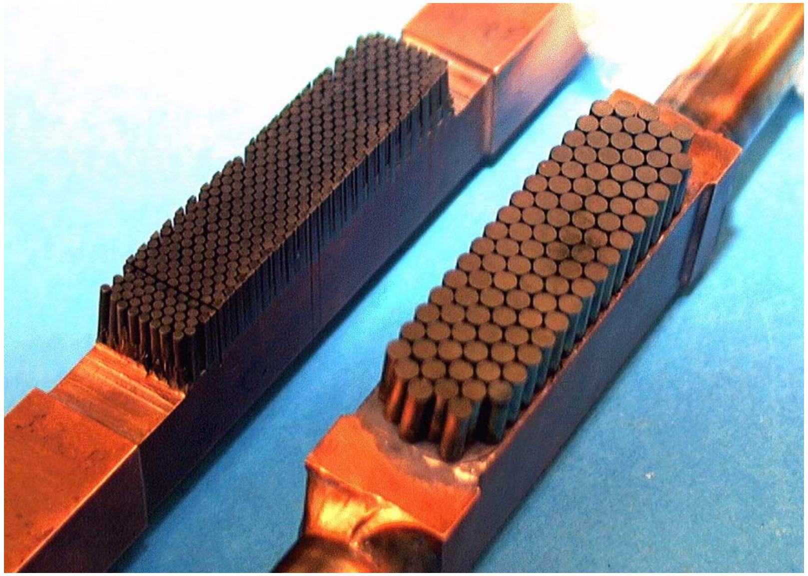


Finger Plate for

Outer Divertor Module

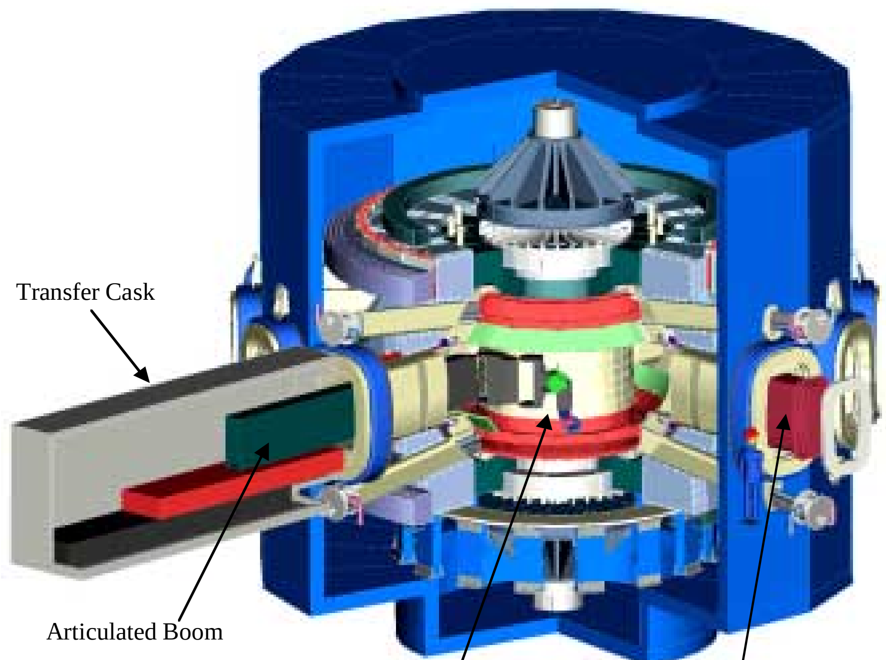
Two W Brush Armor Configurations

Tested at 25 MW/m²



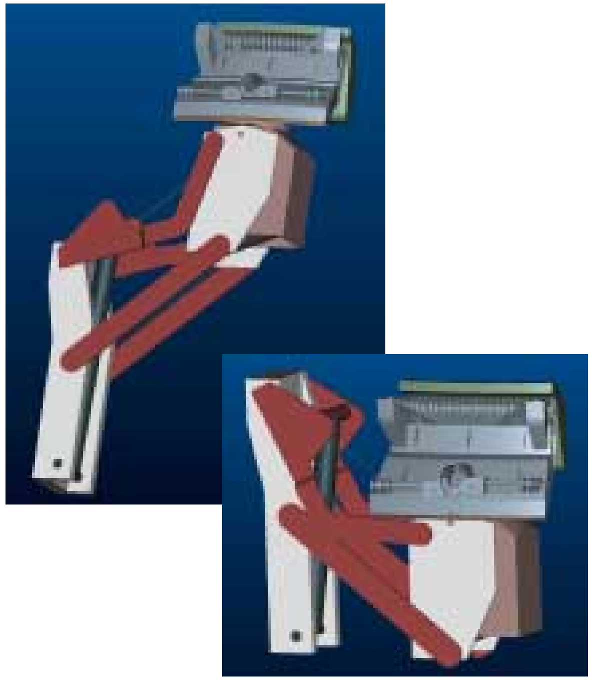
Carbon targets used in most experiments today are not compatible with tritiun inventory requirements of fusion reactors.

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

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

Sixth European Framework Programme → Jan 1 2007

Japan Site offer

ITER - Final Agreement Signed

EU Site offer

Preferred ITER Site Chosen

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

The 2002 Fusion Summer Study will be a forum for the critical assessment of major next-steps in the fusion energy sciences program, and will provide crucial community input to the long range planning activities undertaken by the DOE and the FESAC. It will be an ideal place for a broad community of scientists to examine goals and proposed initiatives in burning plasma science in magnetic fusion energy and integrated research experiments in inertial fusion energy.

This meeting is open to every member of the fusion energy science community and significant international participation is encouraged.

Objectives of the Fusion Summer Study:

- Review scientific issues in burning plasmas to establish the basis for the following two objectives. Address the relation of burning plasma in tokamaks to innovative MFE confinement concepts and of ignition in IFE to integrated research facilities.
- Provide a forum for critical discussion and review of proposed MFE burning plasma experiments (e.g. IGNITOR, FIRE, and ITER) and assess the scientific and technological research opportunities and prospective benefits of these approaches to the study of burning plasmas.
- Provide a forum for the IFE community to present plans for prospective integrated research facilities, assess present status of the technical base for each, and establish a timetable and technical progress necessary to proceed for each.

Background: The 2002 Summer Study will build on earlier planning activity at the 1999 Fusion Summer Study and the scientific assessments at the UFA sponsored Burning Plasma Science Workshops (Austin, Dec 2000; San Diego, May 2001). The scientific views of the participants developed during the 2002 Summer Study preparation activities and during the 2002 Summer Study itself, will provide critical fusion community input to the decision process of FESAC and DOE in 2002-2003, and to the review of burning plasma science by the National Academy of Sciences called for by FESAC and Energy Legislation which was passed by the House of Representatives [H. R. 4].

Output of the Fusion Summer Study: An executive summary based on summary reports from each of the working groups will be prepared as well as a comprehensive proceedings of plenary and contributed presentations.

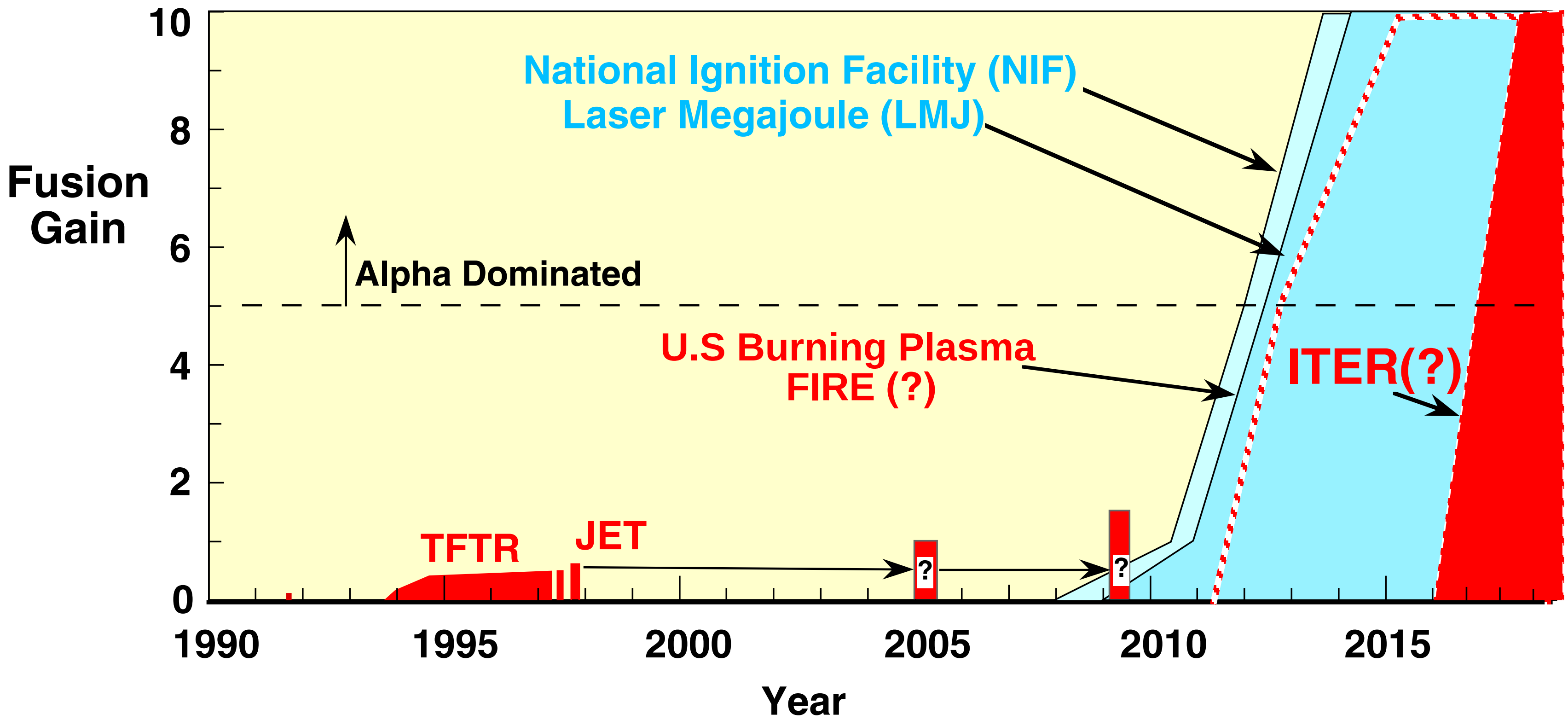
Program Committee Co-Chairs:

Roger Bangerter, *Lawrence Berkeley National Laboratory*
Gerald Navratil, *Columbia University*
Ned Sauthoff, *Princeton University*

For More Information: **http://web.gat.com/snowmass/**

http://fire.pppl.gov

Timetable for “Burn to Learn” Phase of Fusion



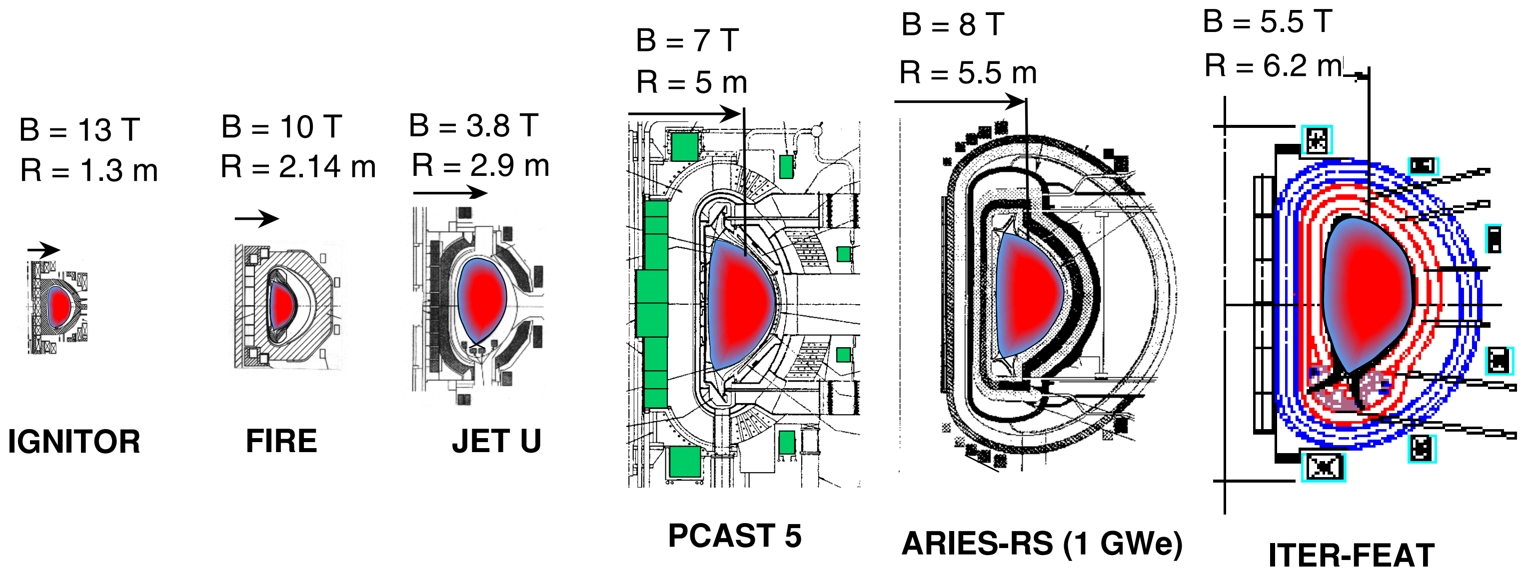
- Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for ≥ 15 years.

- 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 Snowmass 2002 Summer Study will provide a forum to assessing approaches. The NRC Review in 2002 will assess contributions to broader science issues..

Potential Next Step Burning Plasma Experiments



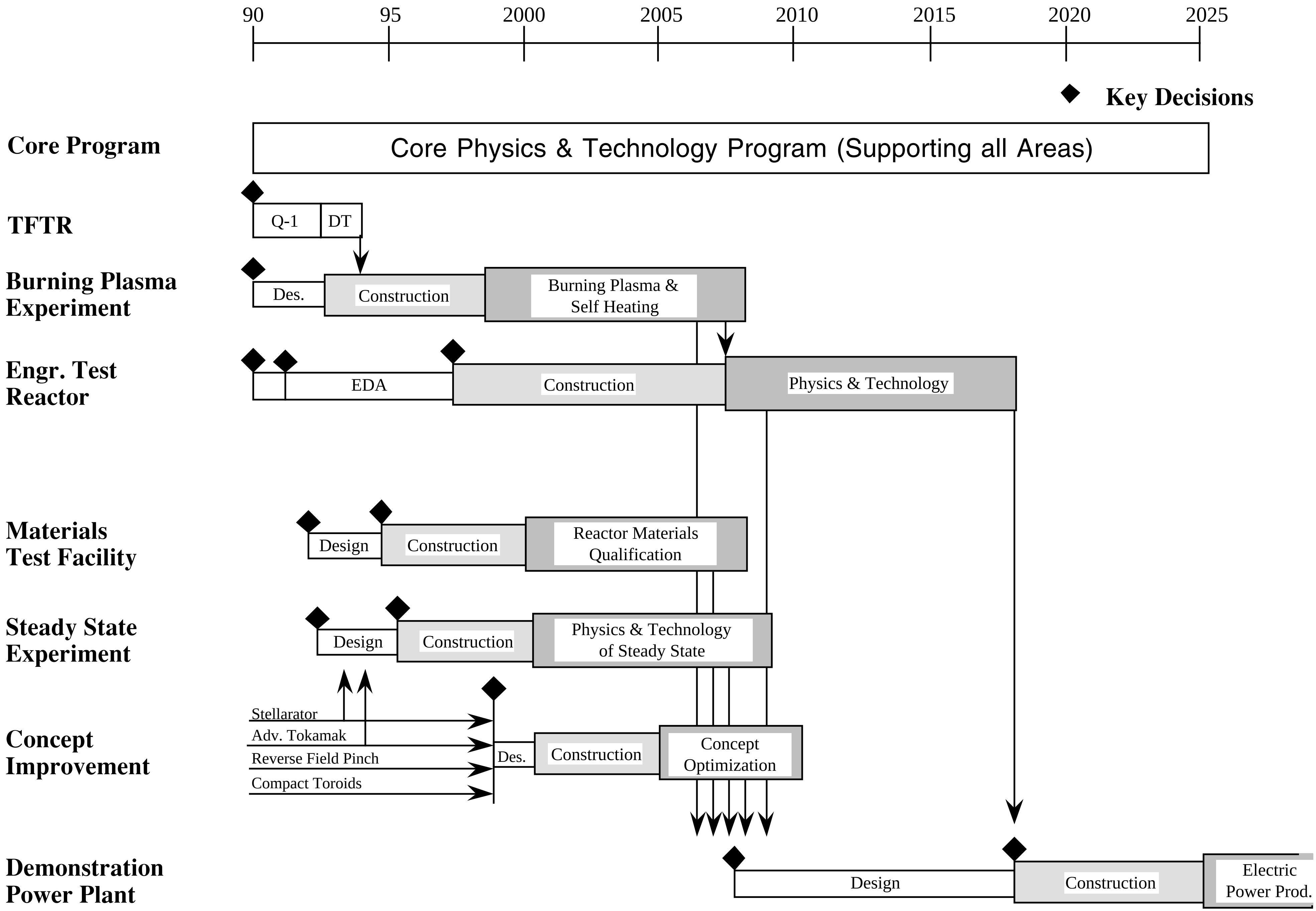
Cost Drivers	IGNITOR	FIRE	JET U	PCAST	ARIES-RS	ITER-FEAT
Plasma Volume (m^3)	11	27	108	390	350	828
Plasma Surface (m^2)	36	60	160	420	420	610
Plasma Current (MA)	12	7.7	6	15	11.3	15
Magnet Energy (GJ)	5	5	1.6	40	85	50
Fusion Power (MW)	100	150	30	400	2170	400
Burn Duration (s), inductive	~1	20	10	120	steady	400
τ Burn/ τ CR		~2	0.6	1	steady	2
Cost Estimate ($B-2000$)		1.2	~0.6	6.7	10.6*	4.6

* first , $5.3 B for 10th of a kind

AR RS/ITERs/PCAST/FIRE/IGN

FPAC 1990

MFE DEVELOPMENT PROGRAM



JM 8-9-90

Summary

- A Window of Opportunity may be opening for U.S. Energy R&D. We should be ready. The Modular or Multi-Machine Strategy 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
    - 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