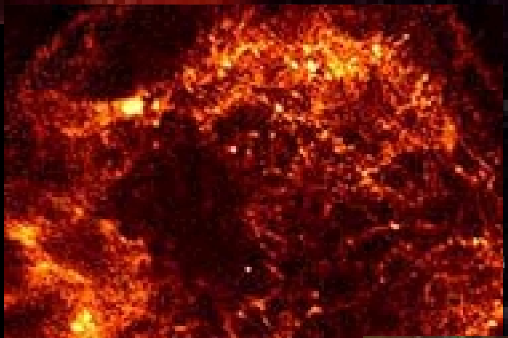
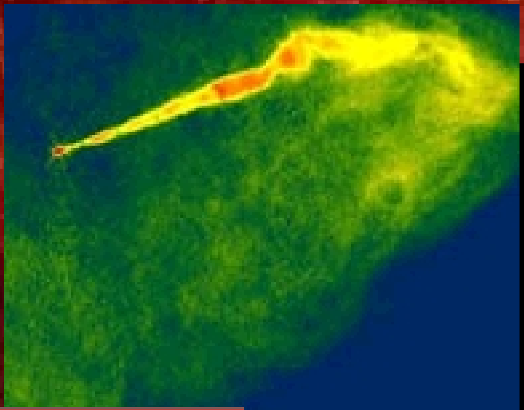
Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science



CHANDRA

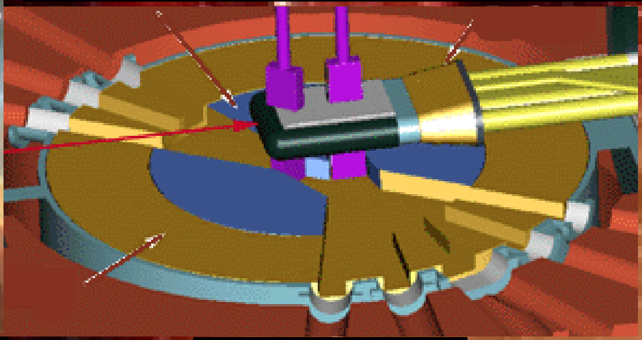


VLBA

NIF

NSO

HST (NGST)



SNS

APS

Exploring the Frontiers

of

Burning Plasma Science

Dale M. Meade

for the FIRE Team

Presented at
19th IEEE/NPSS Symposium on Fusion Engineering (SOFE)
Atlantic City, NJ

January 22, 2001

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

Is an Opportunity Emerging for Fusion?

Secretary of Energy – Abraham - DOE Mission and Priorities – Oct. 24, 2001 (to DOE Lab Directors and DOE)

“I would add to this list two priorities that deserve special mention. The first involves the unique technological contribution we can make to our energy and national security by finding new sources of energy. Whether it is fusion or a hydrogen economy, or ideas that we have not yet explored, I believe we need to leapfrog the status quo and prepare for a future that, under any scenario, requires a revolution in how we find, produce and deliver energy.”

“I intend, therefore, that this Department take a leadership role in exploring how we can identify and use potentially abundant new sources of energy with dramatic environmental benefits.”

Federal Reserve Chairman Greenspan - On Energy Supply – Nov. 13, 2001 (Rice University)

“In the more distant future remains the potential of fusion power. A significant breakthrough in this area has been sought for years but seems discouragingly beyond reach. But success could provide a major contribution to our nation's future power needs. The input costs of fusion power would be minor, and it produces negligible nuclear waste or pollutants.”

What should we do to be ready?

Activities to Assess Next Steps 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

Is Fusion a Possible Energy Source?

- Fusion would be an ideal long term energy source – the natural energy source

- “Fusion, energy of the future, always has been, always will be.”

- How much will it cost to find out?

  Spent ~$10B on MFE in the U.S. during the past 50 years.

- What must be done to make a convincing case?

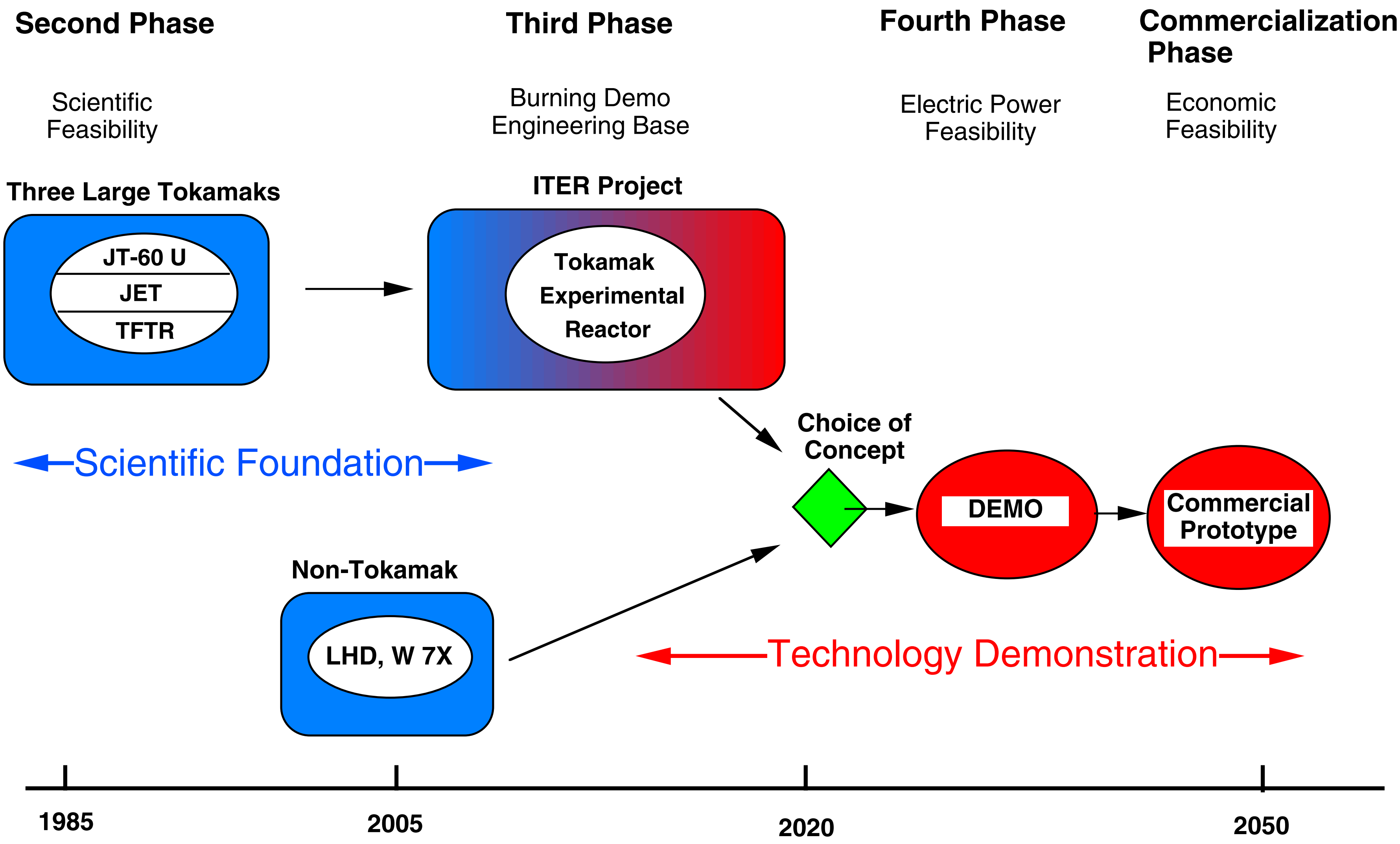
  Address the critics

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

One Step to Two DEMOs[1, 2]



Second Phase

Scientific Feasibility

Third Phase

Burning Demo
Engineering Base

Fourth Phase

Electric Power Feasibility

Commercialization Phase

Economic Feasibility

Three Large Tokamaks

JT-60 U
JET
TFTR

ITER Project

Tokamak Experimental Reactor

Non-Tokamak

LHD, W 7X

Choice of Concept

DEMO

Commercial Prototype

Scientific Foundation

Technology Demonstration

[1] Technical Feasibility of Fusion Energy, SubCom of (Japan) Fusion Council for Fusion Development Strategy, May 2000

[2] European Plan Airaghi Report, May 2000

Even the first Director of ITER recommended against this strategy.

The Multi-Machine Strategy for Magnetic Fusion

Second Phase

Scientific
Feasibility

Third Phase

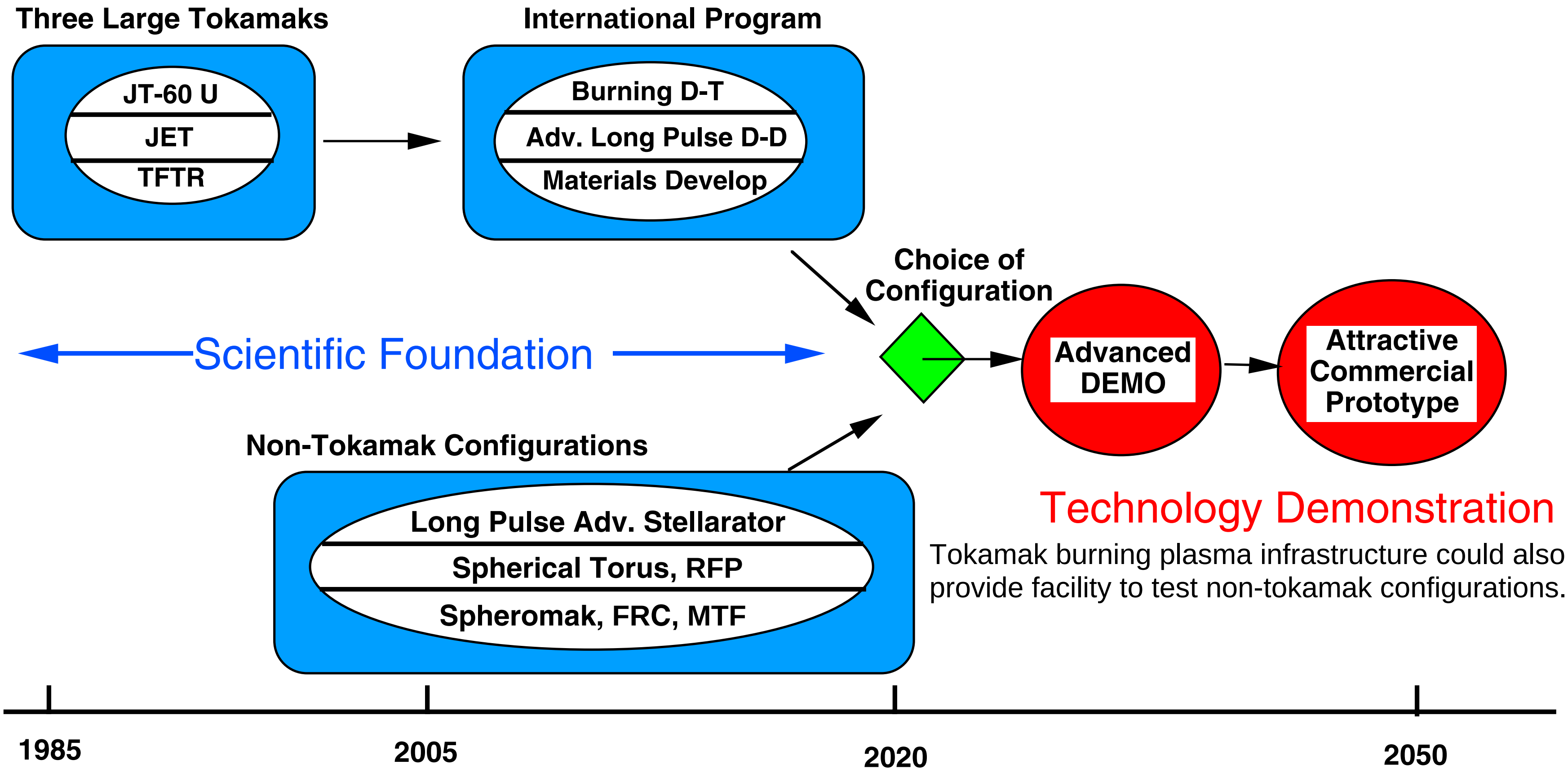
Burning Plasma
Scientific Base

Fourth Phase

Electric Power
Feasibility

Commercialization Phase

Economic
Feasibility



Three Large Tokamaks

JT-60 U
JET
TFTR

International Program

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

Scientific Foundation

Choice of Configuration

Advanced DEMO

Attractive Commercial Prototype

Non-Tokamak Configurations

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

Technology Demonstration

Tokamak burning plasma infrastructure could also provide facility to test non-tokamak configurations.

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

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

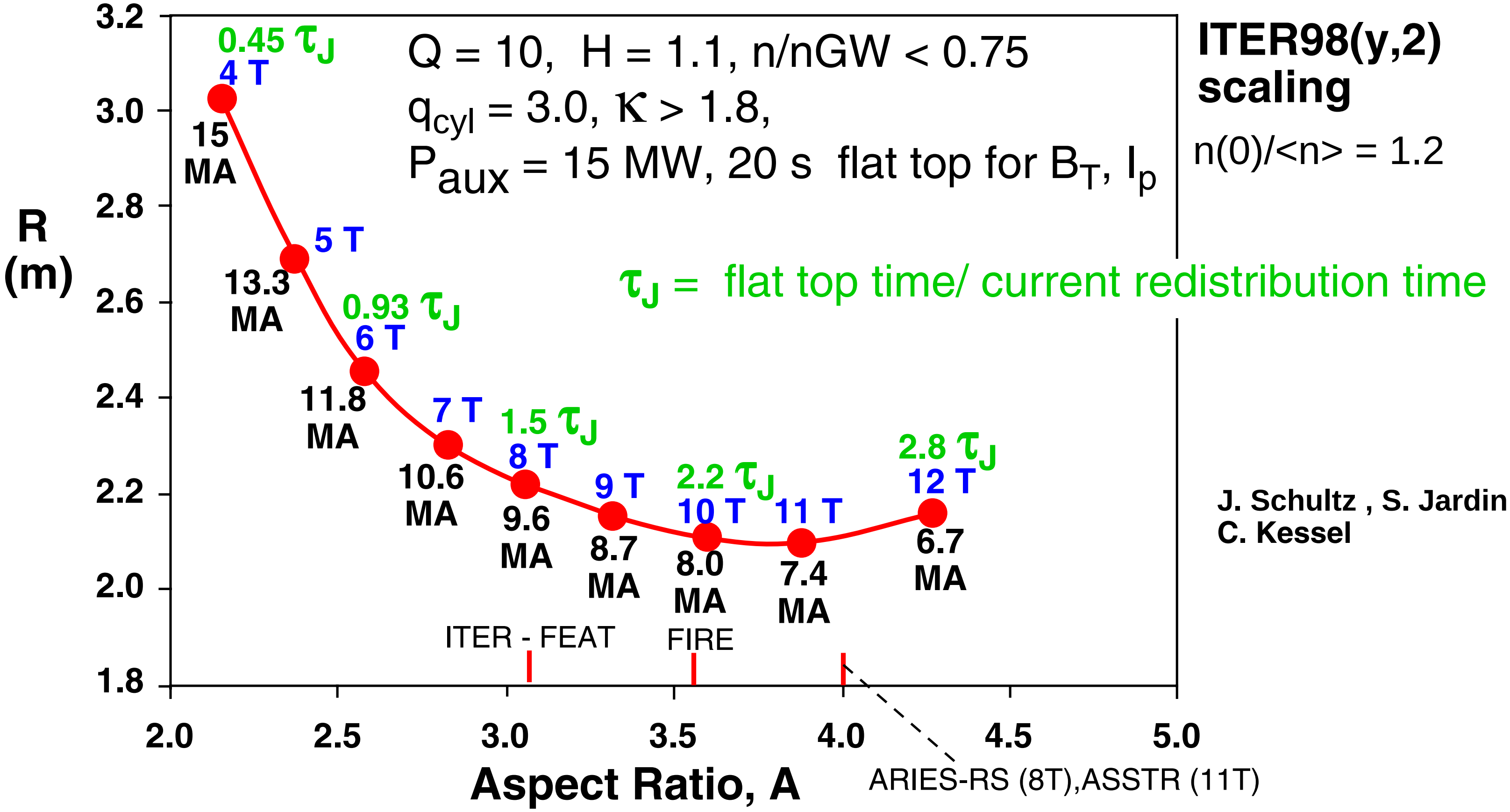
Quasi-stationary

Pressure profile evolution and burn control	$> 10\ \tau_E$
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.



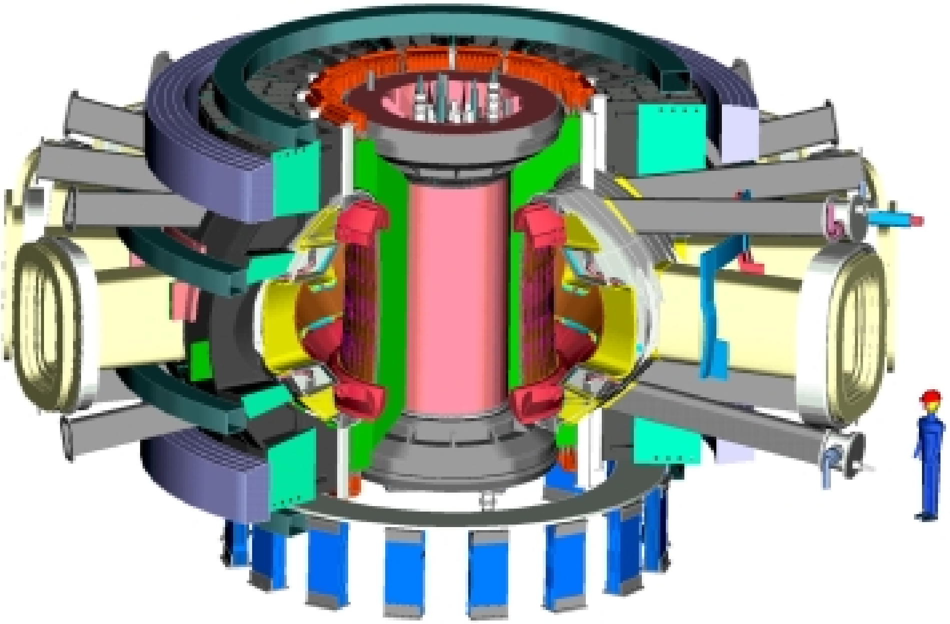
J. Schultz , S. Jardin
C. Kessel

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 fusion-dominated plasmas.

CIT + TPX = FIRE

FIRE is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters

$\omega_c\tau = B\ \tau$

$\rho^* = \rho/a$

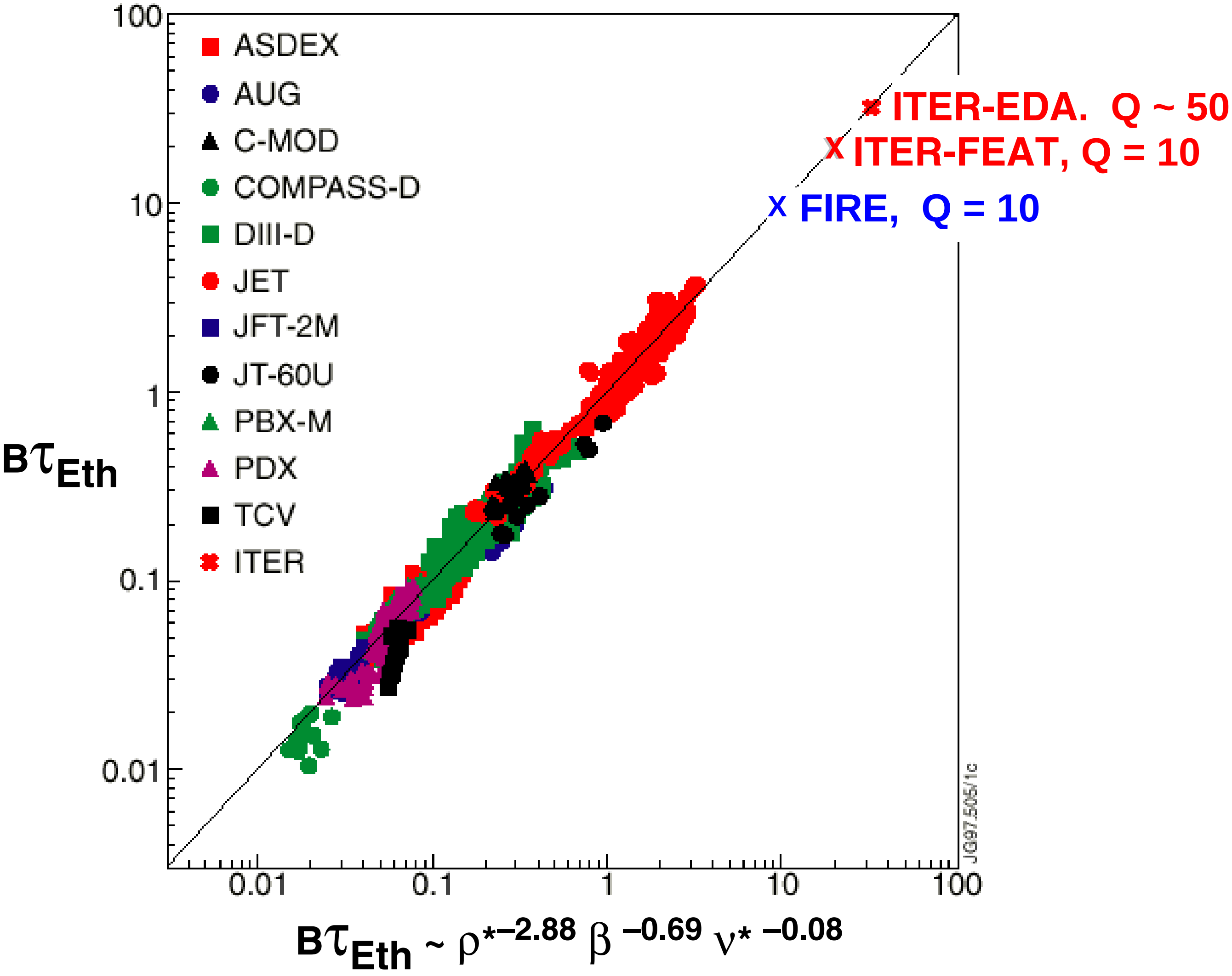
$\nu^* = \nu_c/\nu_b$

β

Similarity Parameter

$B\ R^{5/4}$

Kadomtsev, 1975



ITER-EDA. Q ~ 50

ITER-FEAT, Q = 10

FIRE, Q = 10

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

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

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

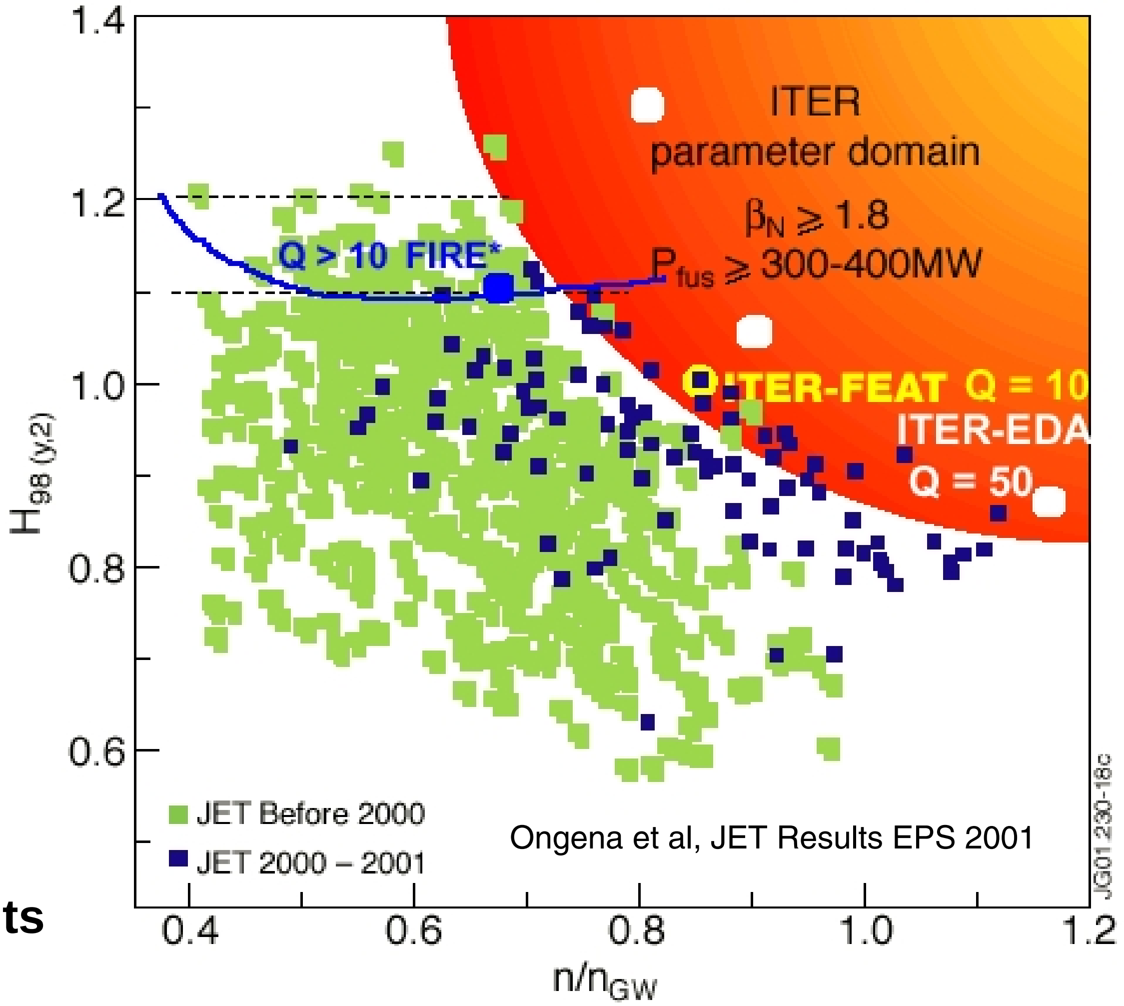
$Pth \geq (2.84/Ai)\, n_{20}^{0.58} B^{0.82} Ra^{0.81}$, same as ITER-FEAT

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

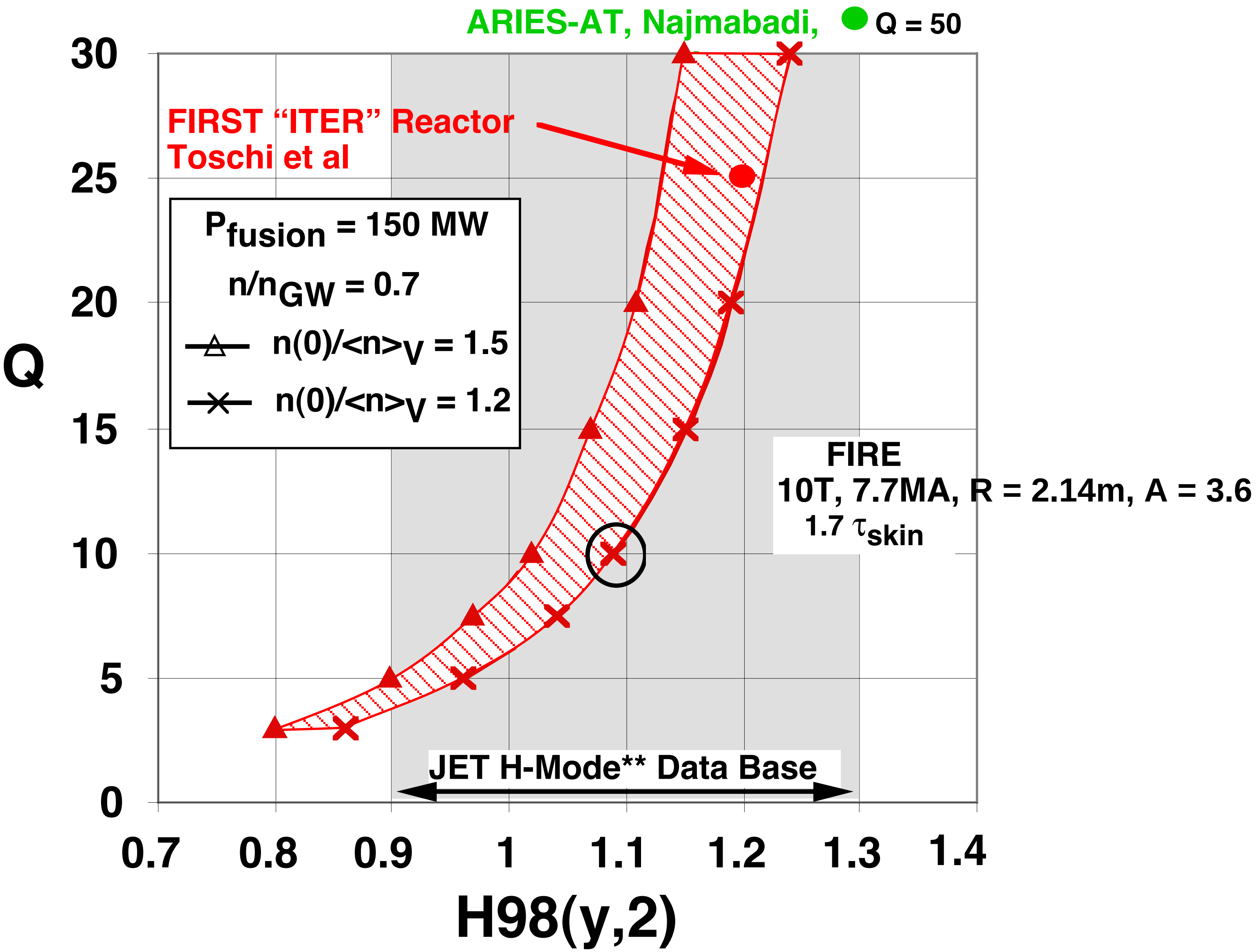
- **The optimum density for the H-Mode is $n/n_{GW} \approx 0.6 - 0.7$**
- **H-mode confinement increases with δ**
  - **$\delta \approx 0.7$ FIRE**
  - **$\delta \approx 0.5$ ITER-FEAT**
- **Elm size is reduced for $\delta > 0.5$**
- **Z_{eff} decreases with density (Mathews/ITER scaling)**
- **DN versus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



Ongena et al, JET Results EPS 2001

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

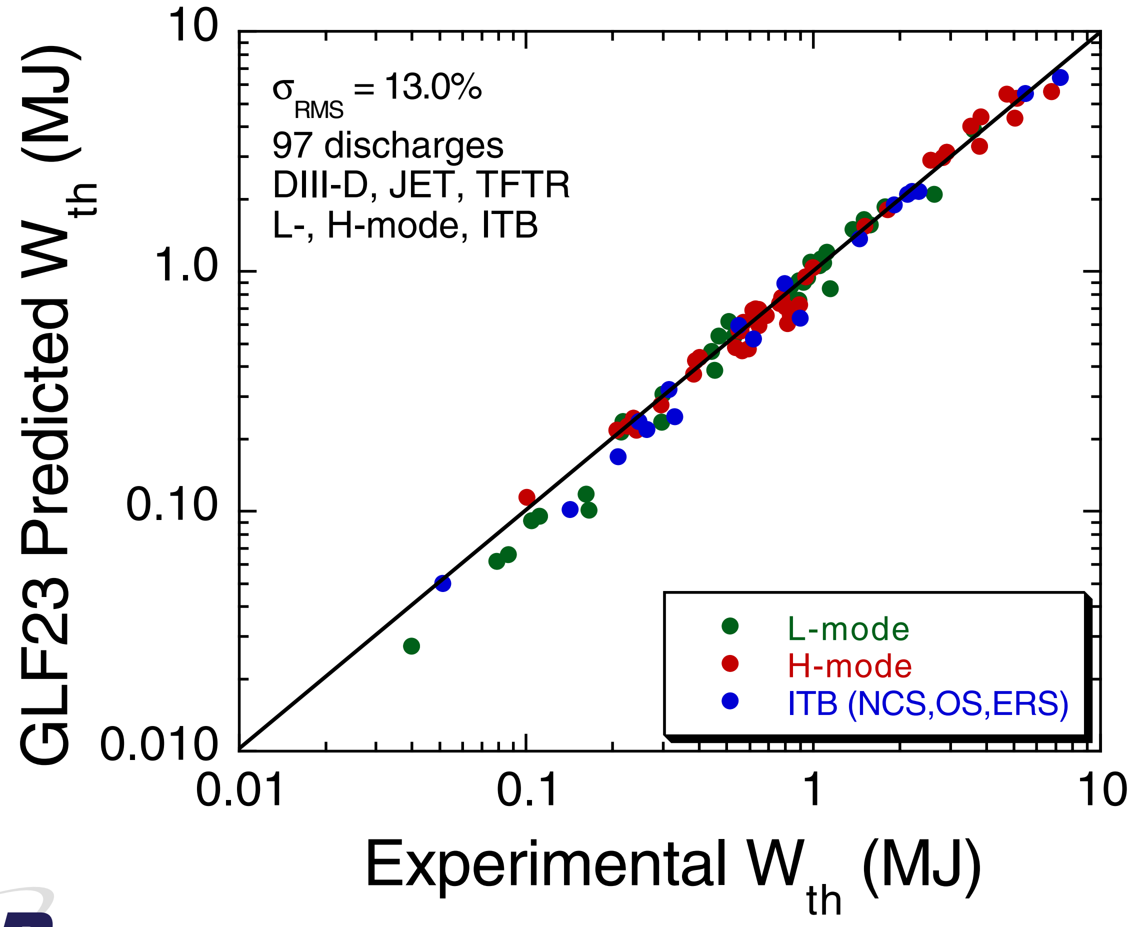
Projections to FIRE Compared to Envisioned Reactors



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

Pedestal Temperature Requirements for Q=10

Device	Flat ne◆	Peaked ne*	Peaked ne w/ reversed q
IGNITOR❖	5.1	5.0	5.1
FIRE	4.1	4.0	3.4
ITER-FEAT✦	5.8	5.6	5.4

◆ flat density cases have monotonic safety factor profile

* $n_{eo} / n_{ped} = 1.5$ with n_{ped} held fixed from flat density case

❖ 10 MW auxiliary heating

11.4 MW auxiliary heating

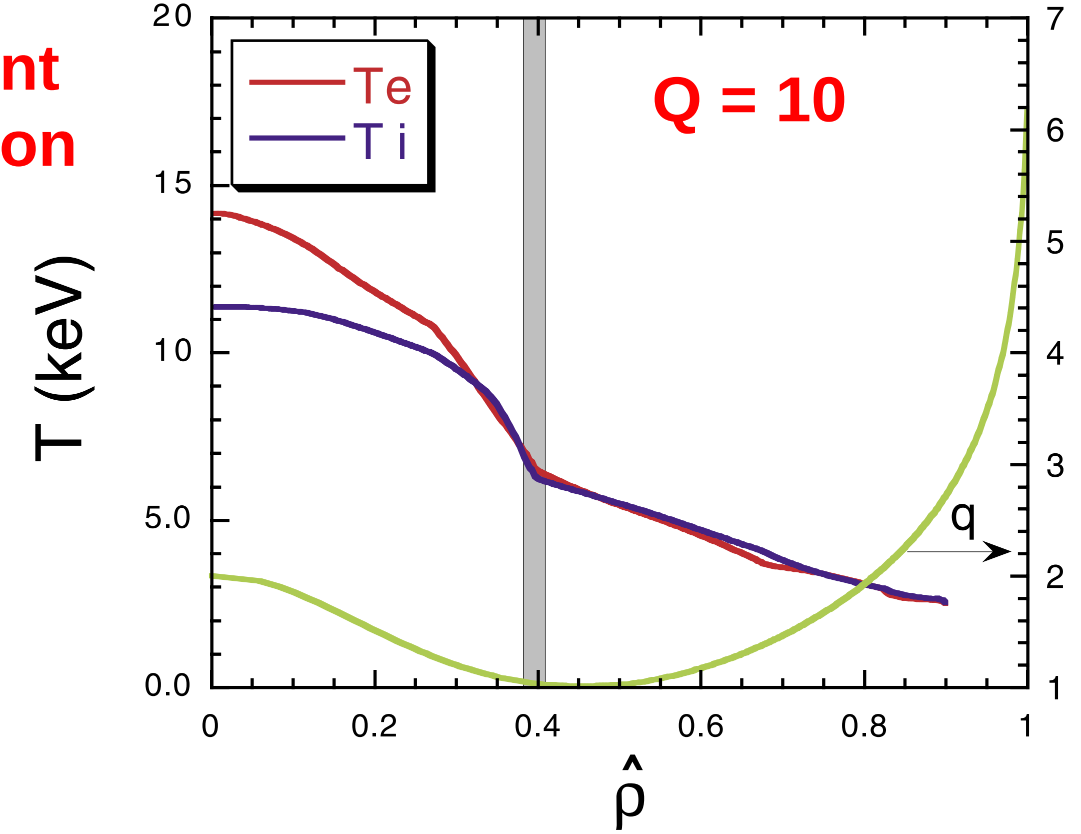
✦ 50 MW auxiliary heating

Need a model for the pedestal temperature, FIRE has the advantage of highest triangularity and low density $n/n_{GW} = 0.6 - 0.7$

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

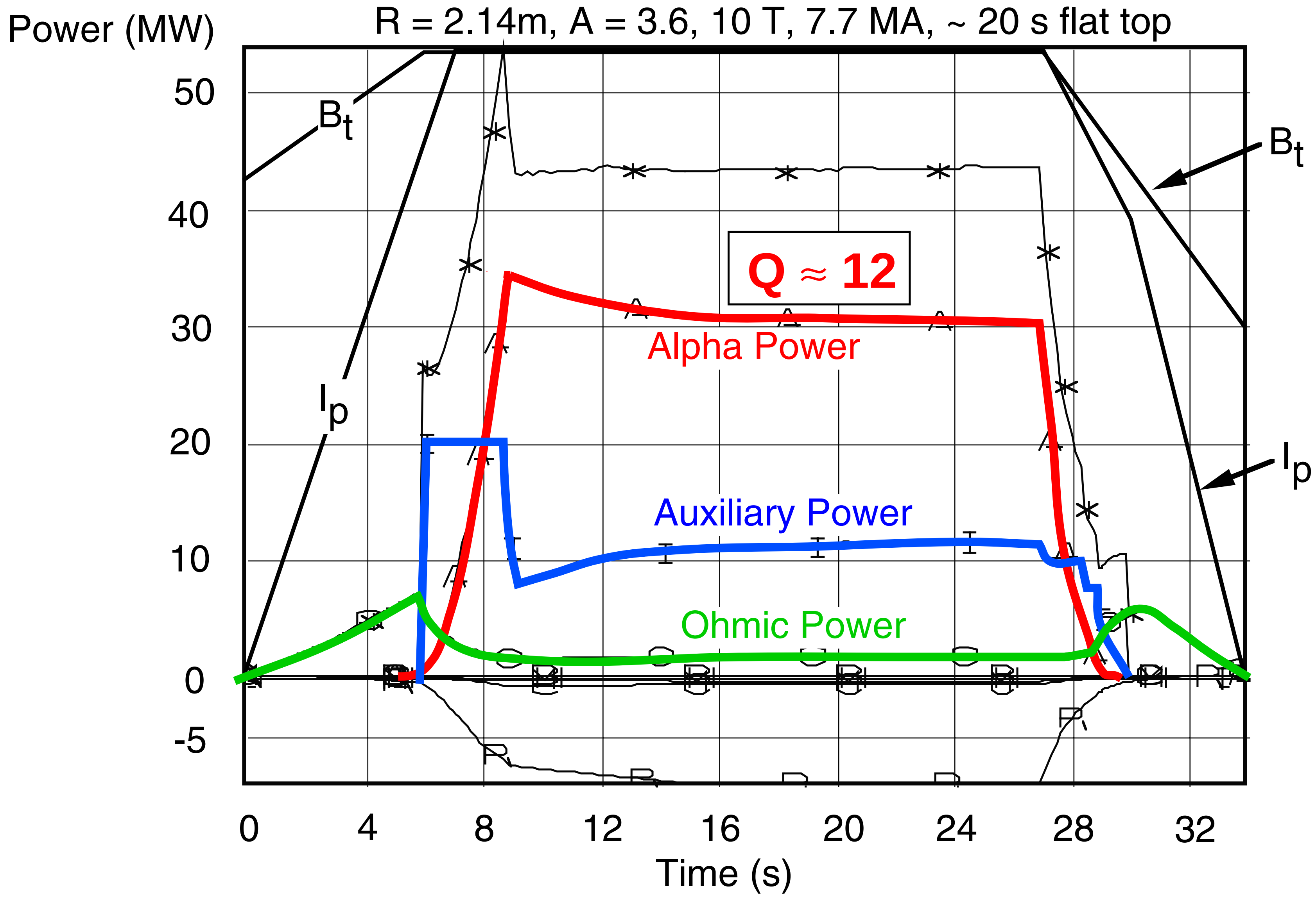
- ***Barrier only forms if some density peaking is present.***
- ***Diamagnetic component of ExB shear helps after ITB is formed.***

Reactor relevant no beam rotation



Kinsey, Waltz and Staebler
UFA BPS Workshop 2

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

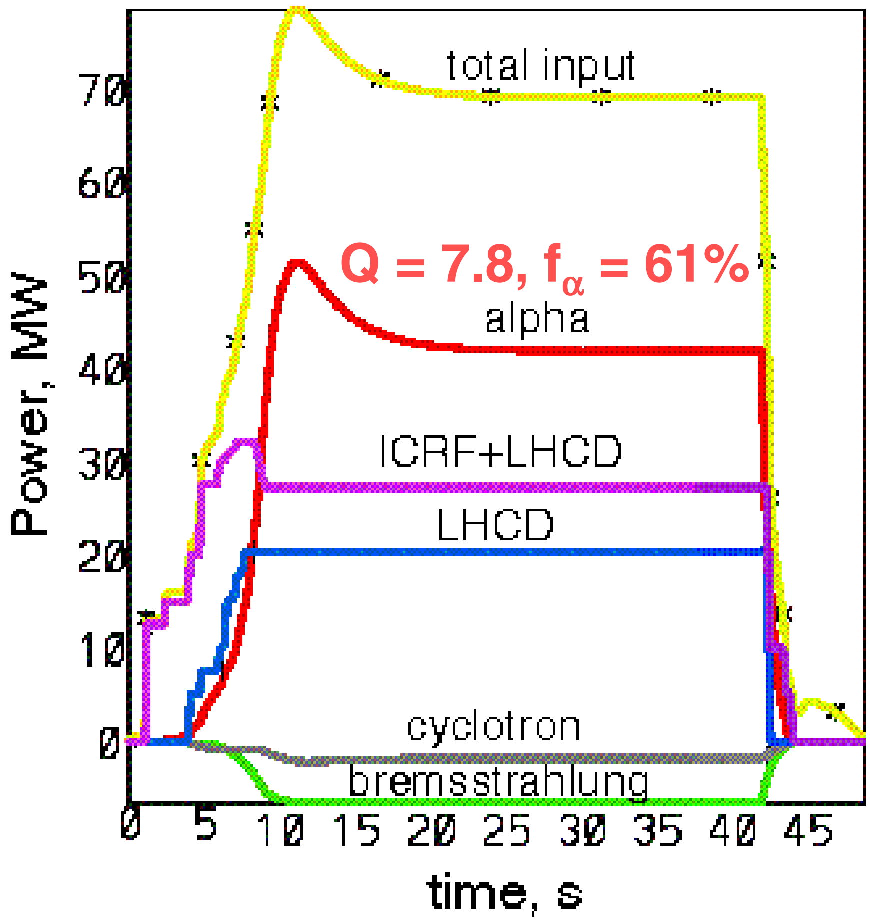


- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and $n/n_{GW} = 0.67$
- Burn Time ≈ 20 s ≈ 21 $\tau_E \approx 4\ \tau_{He} \approx 2\ \tau_{skin}$

Q = Pfusion/(Paux + Poh)

TSC Simulation of a “Fusion Dominated” Plasma

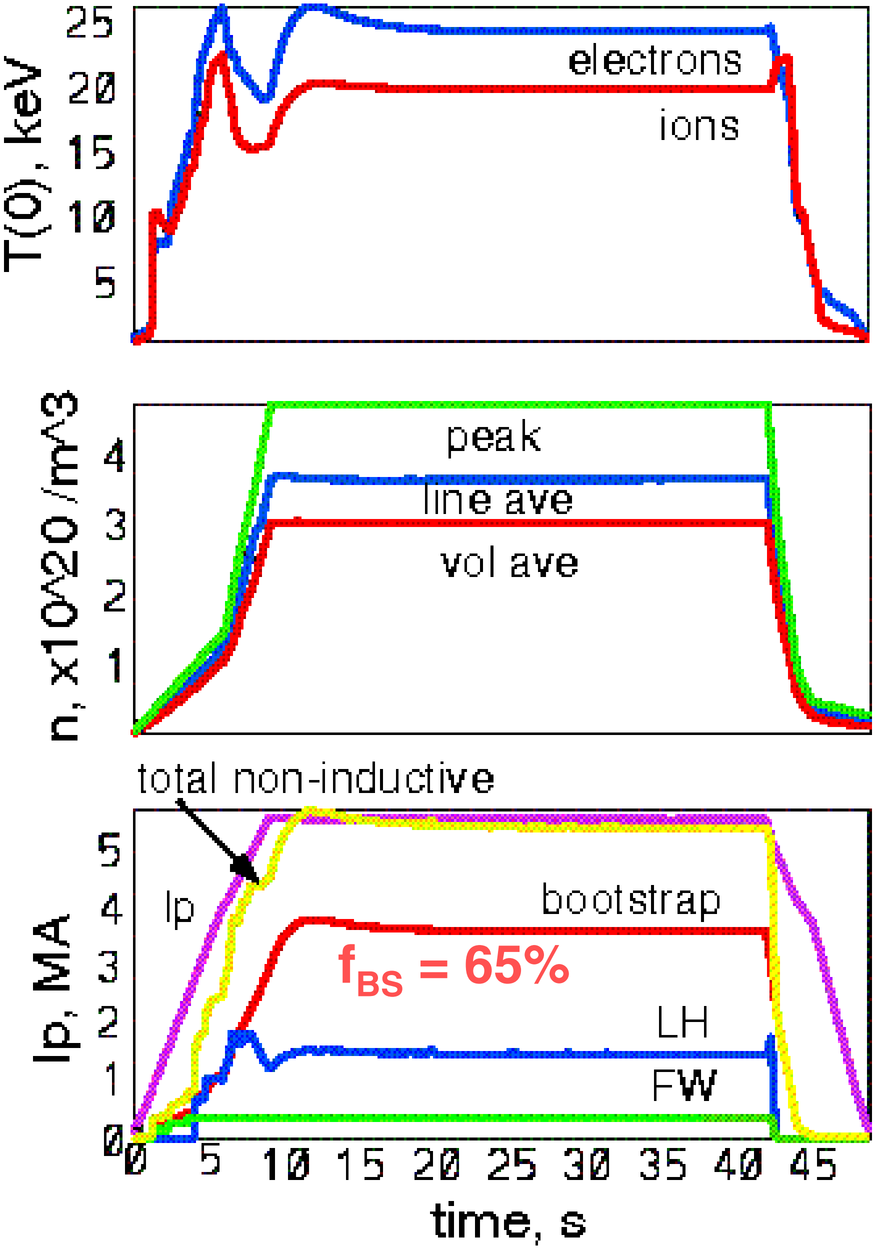
8.5 T, 5.4 MA, t(flattop) = 32 s



Q = 7.8, f_{α} = 61%

H(y,2) = 1.6,

β_N = 3.5, n(0)/<n> = 1.5



f_{BS} = 65%

Contributors to the FIRE Engineering Design Study

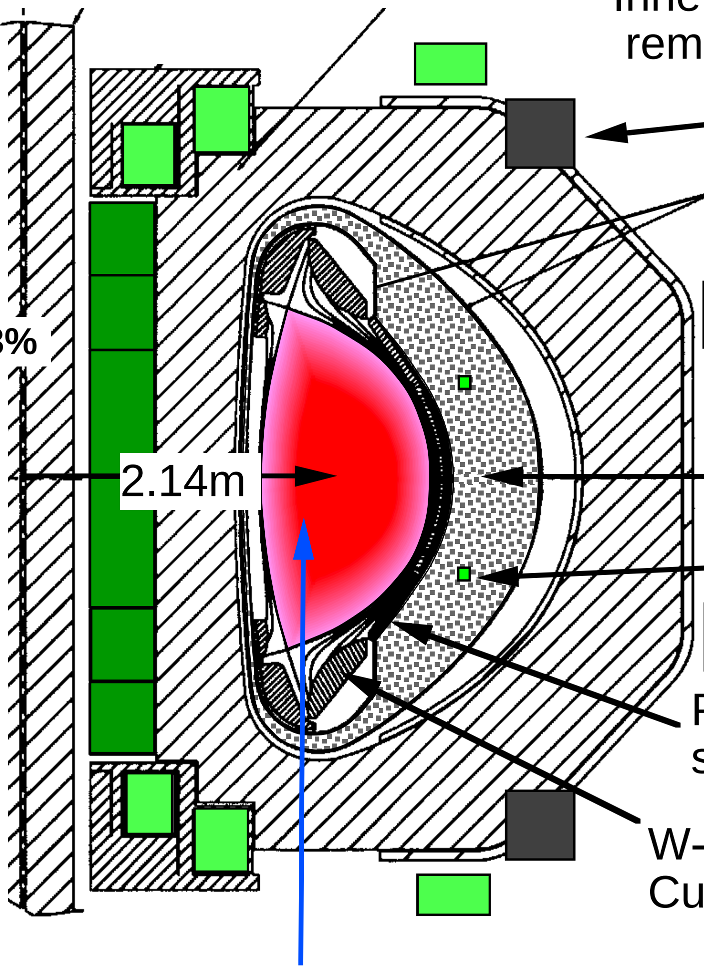
FIRE is a design study for a major Next Step Option in magnetic fusion and is carried out through the Virtual Laboratory for Technology. FIRE has benefited from the prior design and R&D activities on BPX, TPX and ITER.

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 Incorporates Advanced Tokamak Innovations

AT Features

- DN divertor
- 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.

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

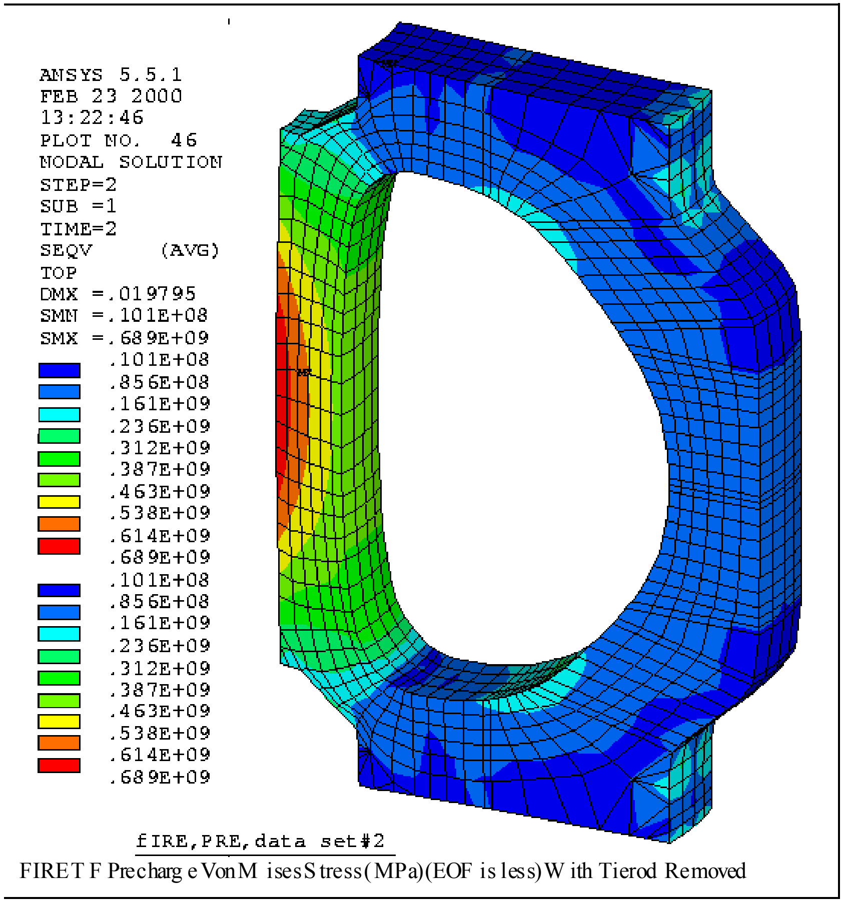
TF coils are being Designed with Added Margin.

- **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

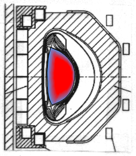
Solutions to these issues would be a major output from a next step experiment.

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

Pfusion
= ~ 150 MW

Volume
= 27 m^3

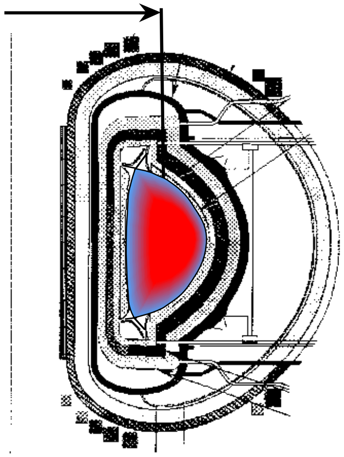
B = 10 T
R = 2.14 m
→



FIRE

~ 3X

B = 8 T
R = 5.5 m



Pfusion
= 2170 MW

Volume
= 350 m^3

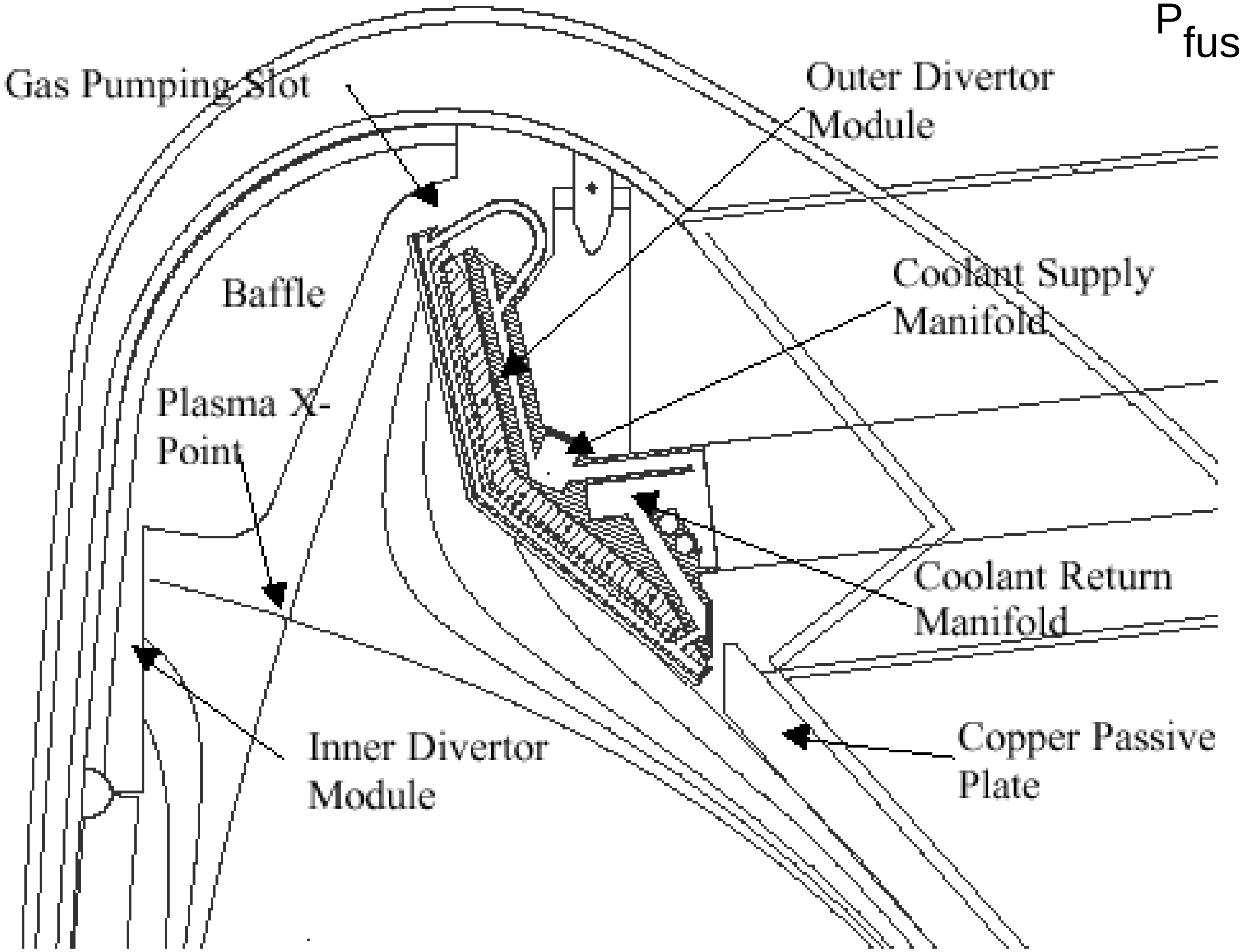
ARIES-RS The "Goal"

	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

PC-2-14 Mike Ulrickson

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

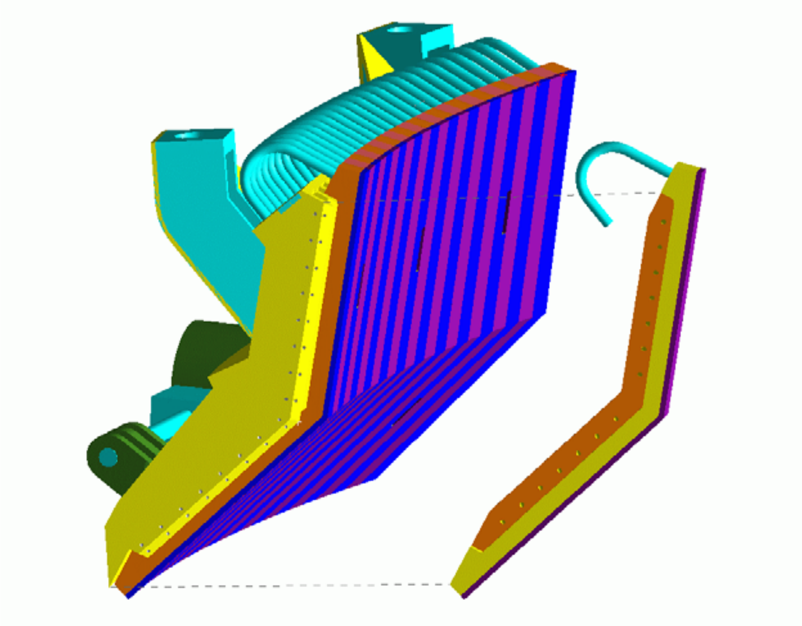
P_{fusion} < 200 MW



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

Divertor Module Components for FIRE

Sandia

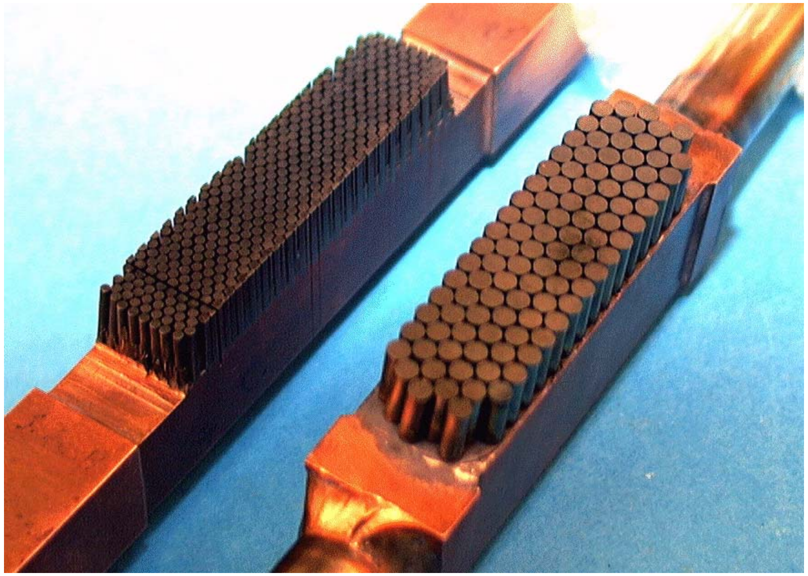


Finger Plate for

Outer Divertor Module

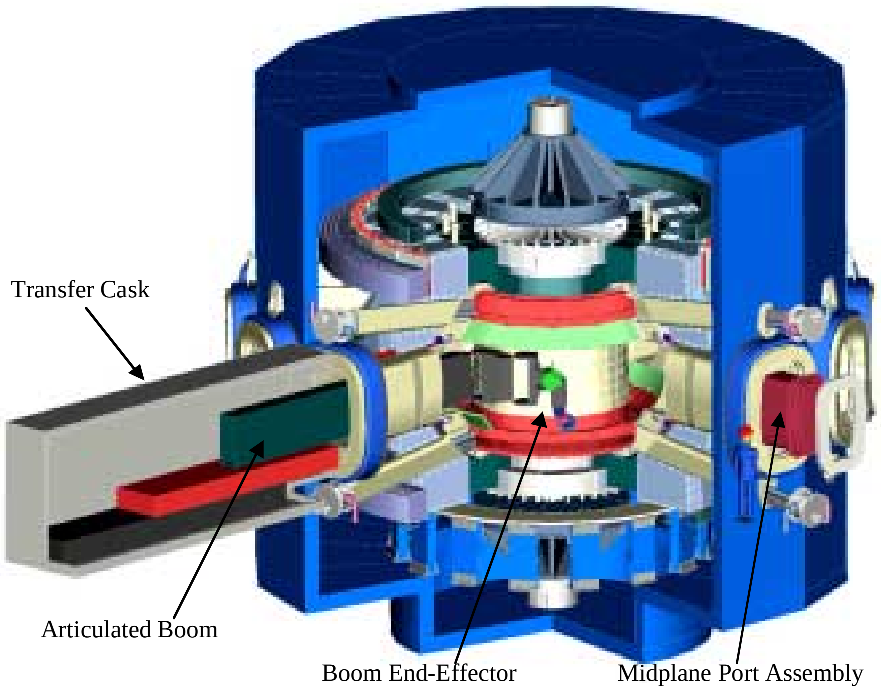
Two W Brush Armor Configurations

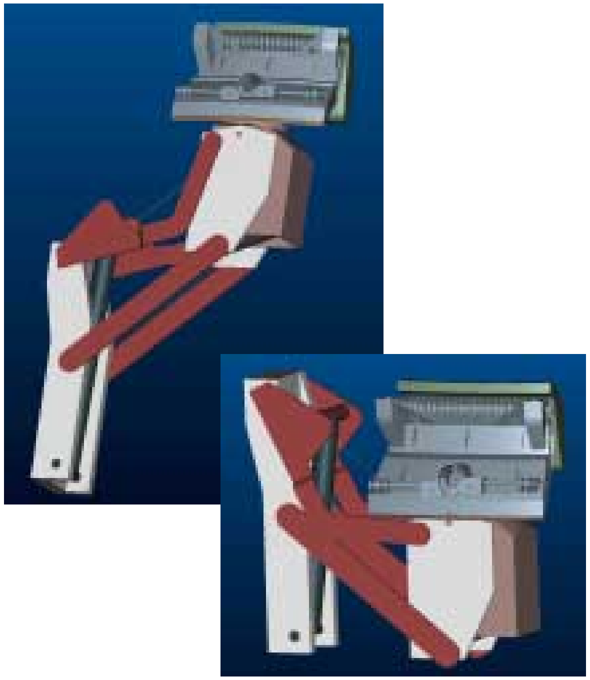
Tested at 25 MW/m^2



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

FIRE In-Vessel Remote Handling System





In-vessel transporter

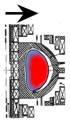
- Articulated boom deployed from sealed cask
- Complete in-vessel coverage from 4 midplane ports
- Fitted with different end-effector depending on component to be handled
- First wall module end-effector shown

Divertor end-effector

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

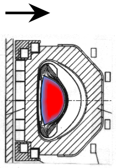
Potential Next Step Burning Plasma Experiments

B = 13 T
R = 1.3 m



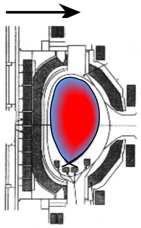
IGNITOR

B = 10 T
R = 2.14 m



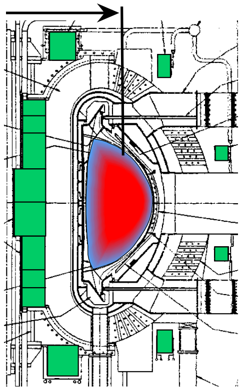
FIRE

B = 3.8 T
R = 2.9 m



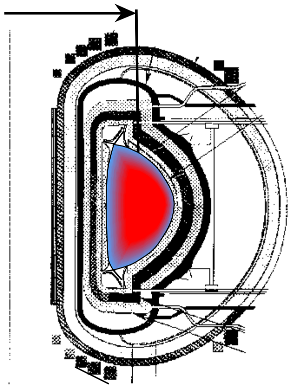
JET U

B = 7 T
R = 5 m



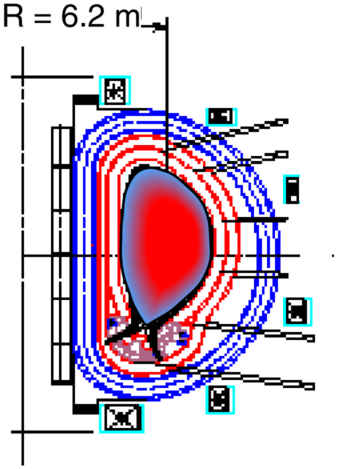
PCAST 5

B = 8 T
R = 5.5 m



ARIES-RS (1 GWe)

B = 5.5 T
R = 6.2 m



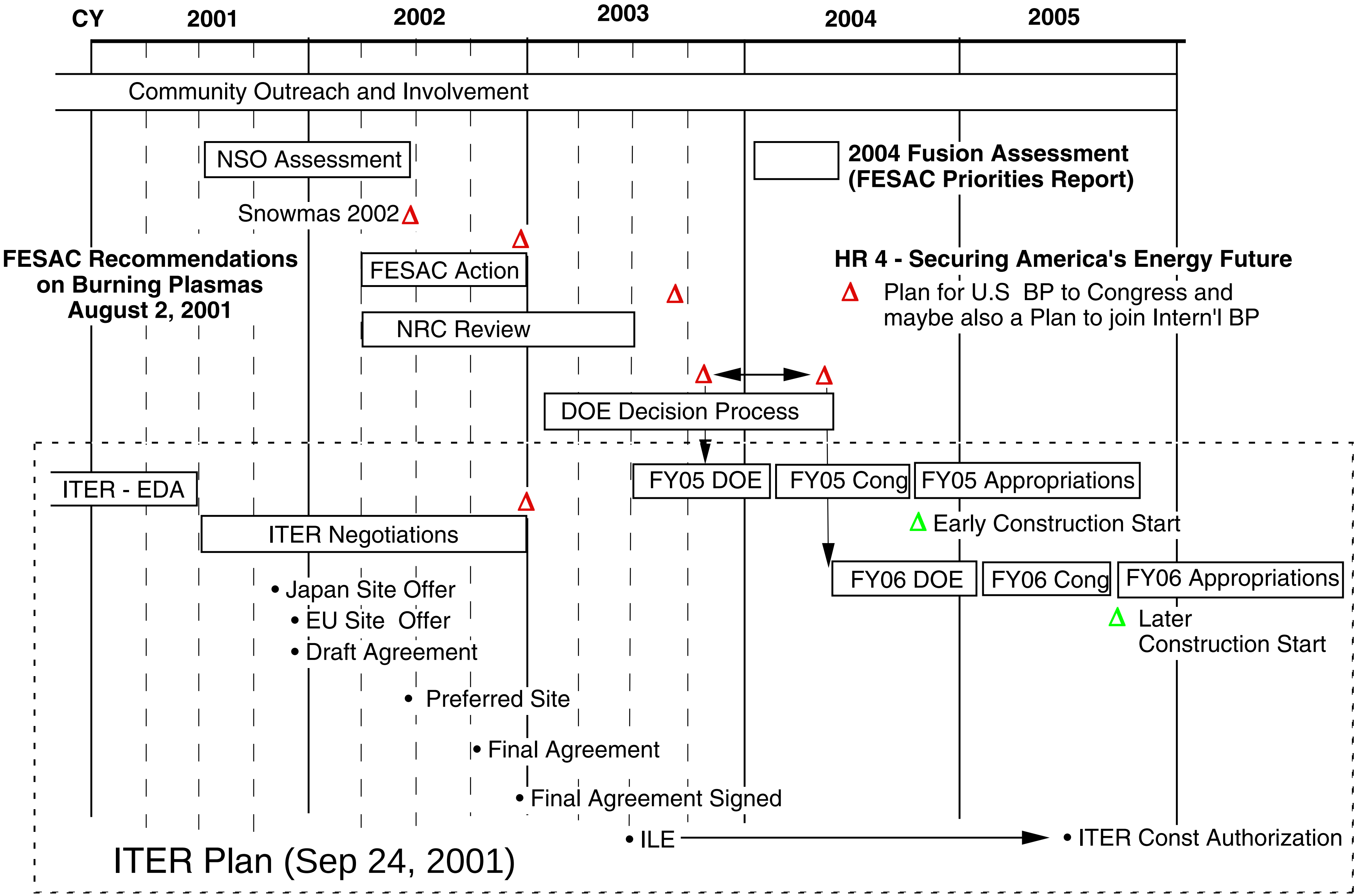
ITER-FEAT

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

FESAC Recommendation and ITER Plan for Burning Plasmas



CY 2001 2002 2003 2004 2005

Community Outreach and Involvement

NSO Assessment

Snowmas 2002 △

2004 Fusion Assessment (FESAC Priorities Report)

FESAC Recommendations on Burning Plasmas
August 2, 2001

FESAC Action

NRC Review

HR 4 - Securing America's Energy Future

△ Plan for U.S BP to Congress and maybe also a Plan to join Intern'l BP

DOE Decision Process

ITER - EDA

ITER Negotiations

FY05 DOE

FY05 Cong

FY05 Appropriations

△ Early Construction Start

FY06 DOE

FY06 Cong

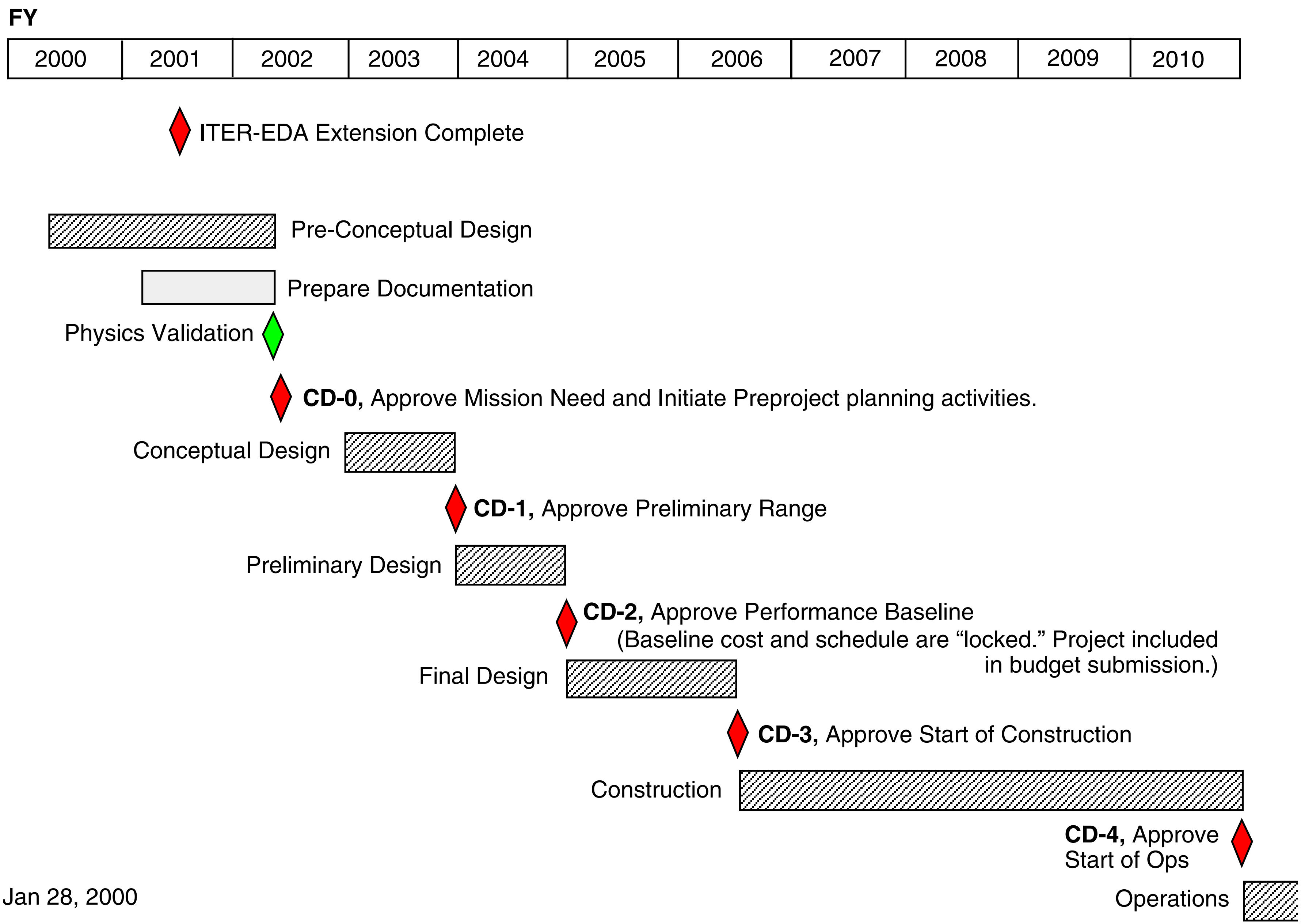
FY06 Appropriations

△ Later Construction Start

- Japan Site Offer
- EU Site Offer
- Draft Agreement
- Preferred Site
- Final Agreement
- Final Agreement Signed
- ILE
- ITER Const Authorization

ITER Plan (Sep 24, 2001)

Illustrative Schedule for U.S. Burning Plasma Experiment



FY

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

ITER-EDA Extension Complete

Pre-Conceptual Design

Prepare Documentation

Physics Validation

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

Conceptual Design

CD-1, Approve Preliminary Range

Preliminary Design

CD-2, Approve Performance Baseline
(Baseline cost and schedule are “locked.” Project included in budget submission.)

Final Design

CD-3, Approve Start of Construction

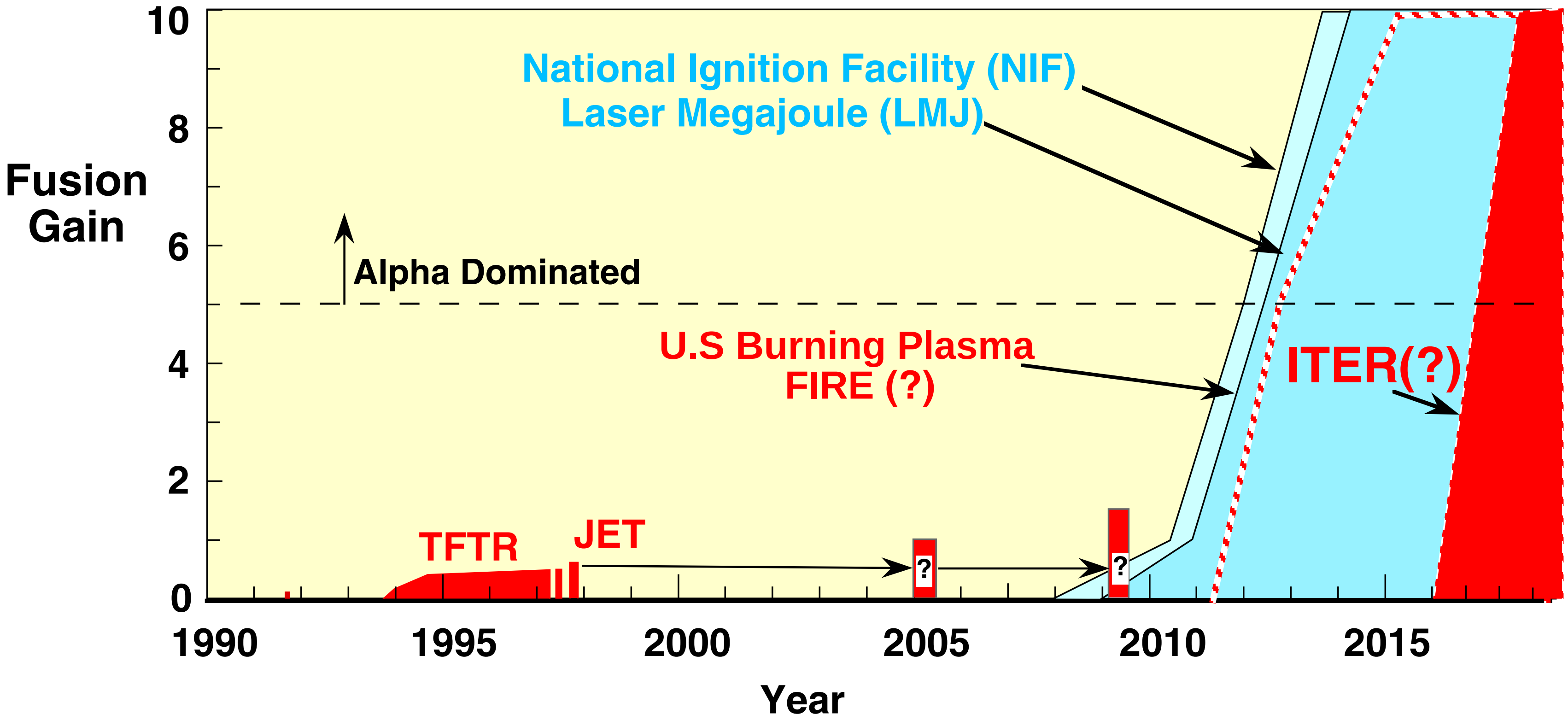
Construction

CD-4, Approve Start of Ops

Operations

Jan 28, 2000

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..**

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

Additional FIRE Papers

PC-2-11 Fusion Ignition Research Experiment Machine Configuration Update. T. Brown

PC-2-12 Challenges for Plasma Diagnostics in a Next Step device (FIRE). K. Young

PC-2-13 Nuclear Considerations for FIRE. M. Sawan

PC-2-14 Design of Fusion Ignition Research Experiment (FIRE) Plasma Facing Components. M. Ulrickson

PC-2-15 Alternative Structural Concepts for the Fusion Ignition research Experiment (FIRE). P. Titus

OC-5-3 Engineering Status and Plans for FIRE. P. Heitzenroeder

OC-5-4 Advanced Tokamak Scenarios for the FIRE Burning Plasma Experiment. C. Kessel