FIRE Response to NSO-PAC3

and

Issues and Plans for Snowmass

Dale M. Meade

for the FIRE Team

Presented at
NSO-PAC 4 Meeting
Lawrence Livermore National Laboratory

November 29, 2001

http://fire.pppl.gov

Outline

Activities since last PAC and Progress on NSO PAC 3 Action Plan Meade

FIRE Physics /AT Progress Kessel

FIRE Activities in preparation for Snowmass Meade

(Ulrickson, Jardin, Nelson, Heitzenroeder on call)

FIRE/Burning Plasma Activities Since Last PAC

- HR 4 Passed by House, calls for increase in base budget and directs DOE to submit a plan for US construction of a burning plasma experiment. DOE may also submit a plan for participation in an international BP.

- FESAC Burning Plasma Panel Report endorsed by FESAC on Aug 2, final version released.

- FIRE Participated in
  - ITPA Confinement Data Base and Modeling (Sep 10-13)
  - FPA Meeting (Sep 24)
  - APS-DPP (five posters)
  - ITPA Diagnostic Meeting St Petersburg, Nov 14 - 16)

- Visits and discussions were held at SRS(2), Lehigh, JAERI-Naka, Univ. of Wisc., ORNL, Univ. of Wash (2).

- Follow up on
  - FIRE External Engineering Review Recommendations and Chits
  - NSO PAC Recommendations
  - Preparation for Snowmass

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."

By end of January conduct a strategic missions review to: ...identify new sources of energy......

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?

FUSAC Kennel Report (1999)

Recommendations on Chapter 3 – Plasma Confinement Configurations

The confinement configuration program should be specified in terms of scientific questions.

A roadmap for the fusion program should be drawn up that shows the path to answering the major scientific questions, as well as the progress so far in the development of fusion concepts.
The development of a roadmap for a fusion-based energy source is essential to aid in the long-term planning of the fusion program. The roadmap should show the important scientific questions, the evolution of confinement configurations, the relation between these two features, and their relation to the fusion energy goal.

Solid support should be developed within the broad scientific community for U.S. investment in a fusion burning experiment.

There should be continuing broad assessments of the outlook for fusion energy and periodic external reviews of fusion energy science.

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

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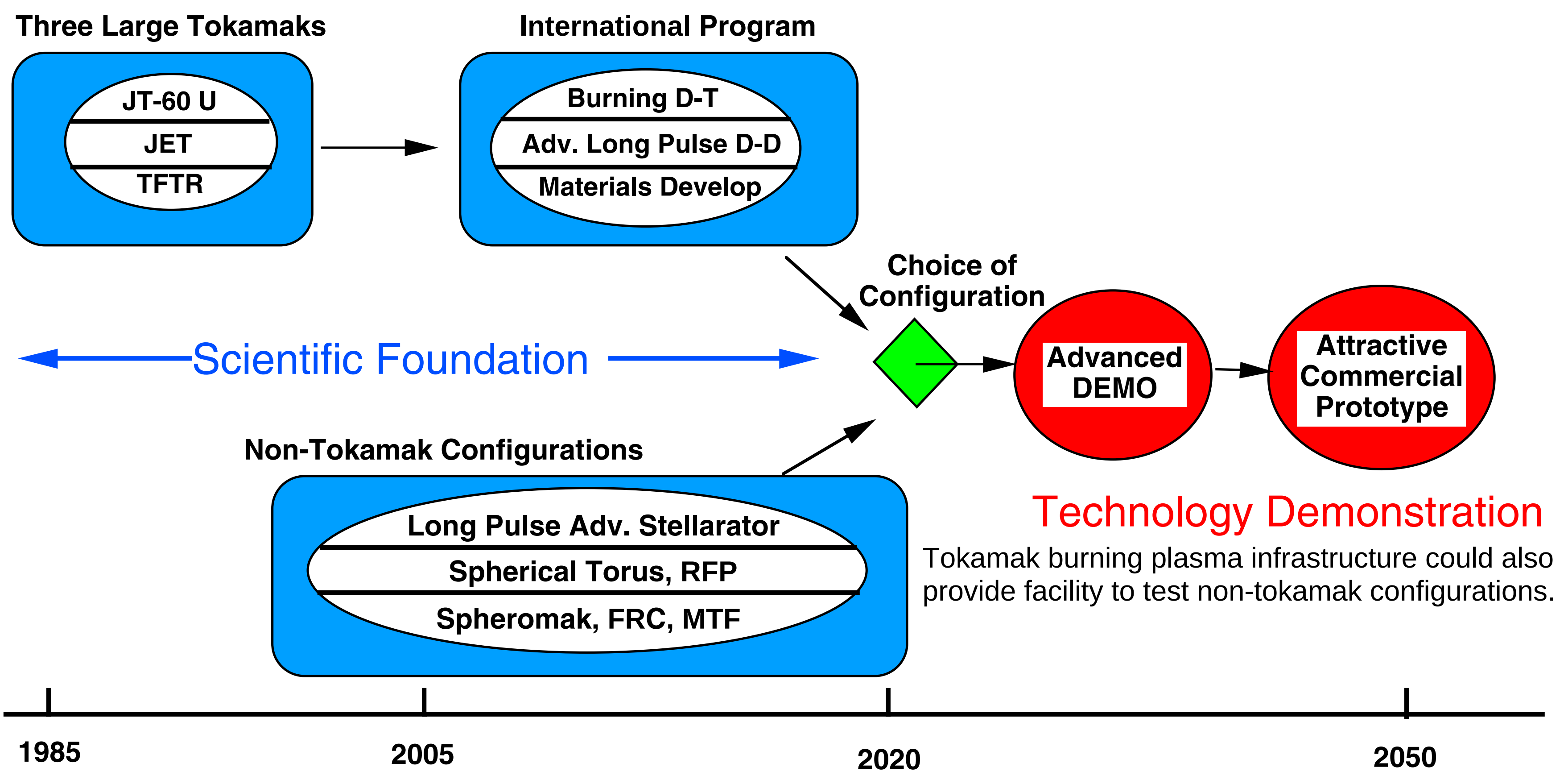
- Superconducting Coil Technology does not have to be coupled to physics experiments - only if needed for physics objectives

- Nuclear Component Testing should wait for the correct reactor materials

The Modular Strategy for MFE



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

Non-Tokamak Configurations

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

Choice of Configuration

Advanced DEMO

Attractive Commercial Prototype

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 Modular Strategy includes IFE)

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.

Need to develop an integrated burning plasma simulation with good visualization output - useful for design phase, experimental phase and to provide the transfer to other configurations and “DEMO”.

Advanced Burning Plasma Exp't Requirements

Burning Plasma Physics

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

Advanced Toroidal Physics

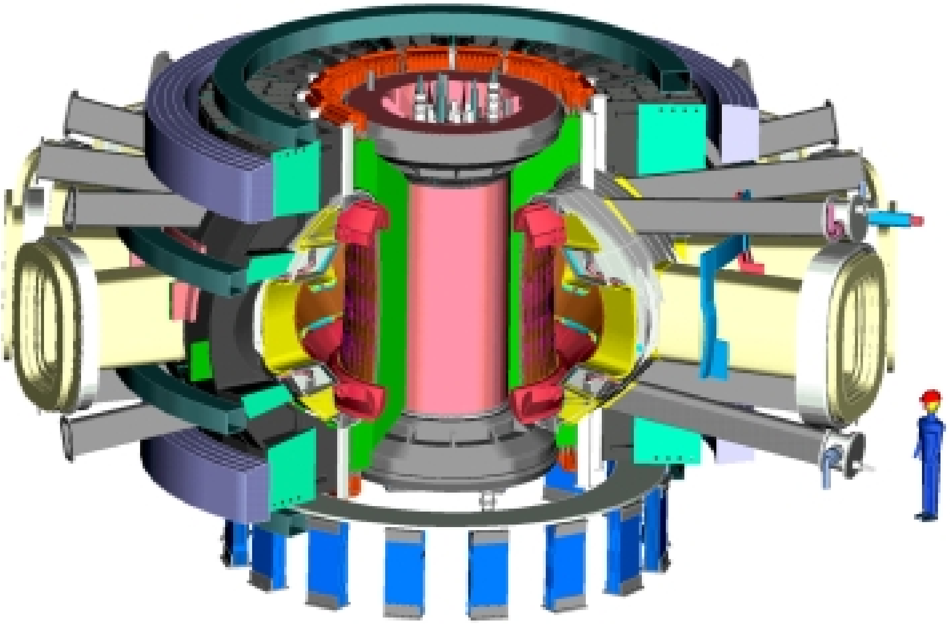
$f_{bs} = I_{bs}/I_{p}$	(~ 25 % in H-Mode) ≥ 50% as target AT up to 75% allowed
β_{N}	~ 2.5, no wall ~ 3.6, n = 1 wall stabilized

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 $\tau_{divertor}$, $\tau_{first\ wall}$

Fusion Ignition Research Experiment (FIRE)

http://fire.pppl.gov

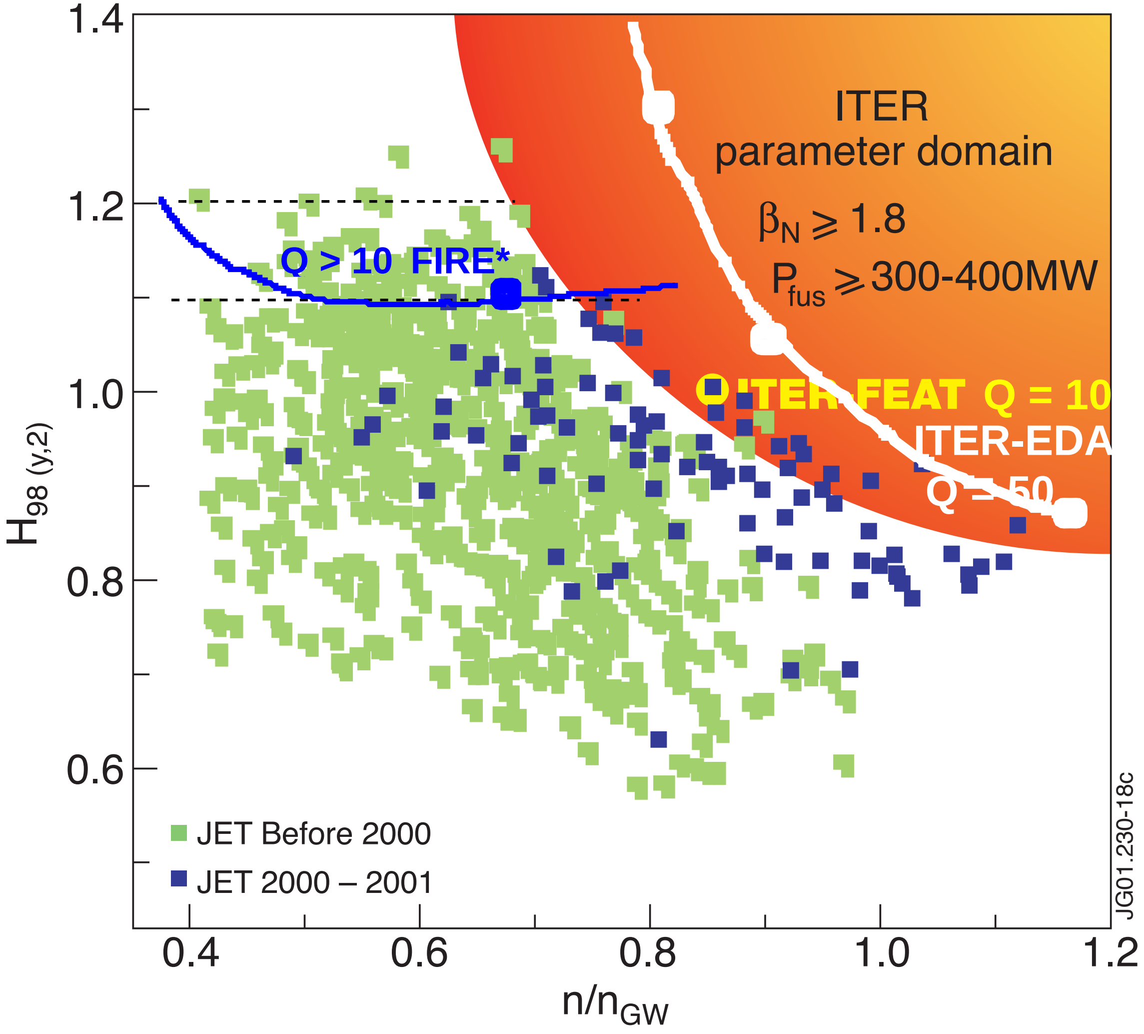


Design Features

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

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

Comparison Operating Ranges of ITER-EDA, ITER-FEAT and FIRE with JET H-Mode Data



- Extension of JET parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \geqslant 1.8$ using different approaches and

- In addition Plasma purity as required for ITER: Zeff ~ 1.5

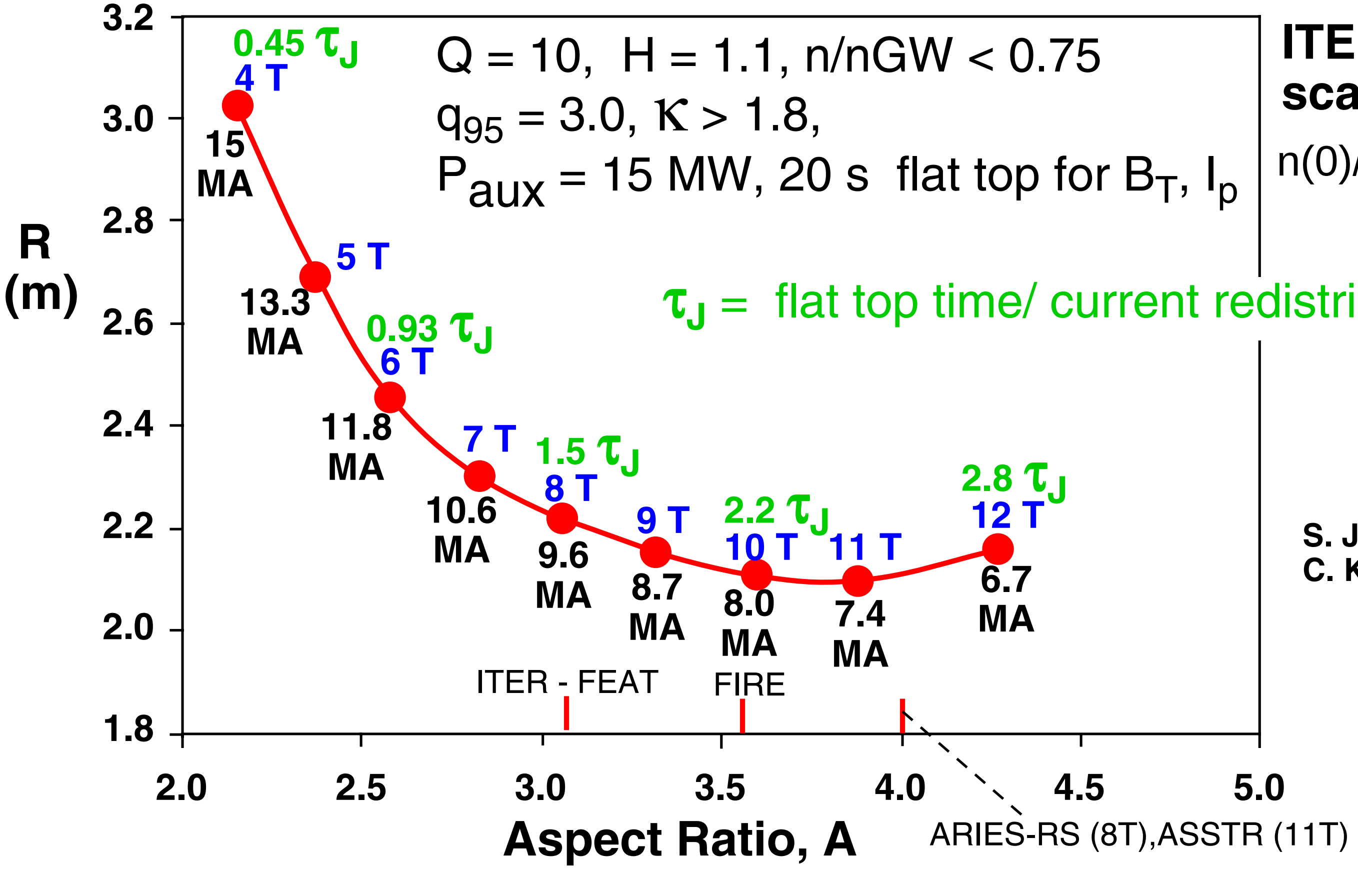
- For quasi-stationary phases of several seconds

- **A more extensive study of the operating range with the latest public data base DB3v10 will be done for Snowmass. Also Cordey EPS paper showing H(n/nGW, δ , n(0)/<n>, etc**

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.



$Q = 10$, $H = 1.1$, $n/n_{GW} < 0.75$

$q_{95} = 3.0$, $\kappa > 1.8$,

$P_{aux} = 15$ MW, 20 s flat top for B_T, I_p

ITER98(y,2) scaling

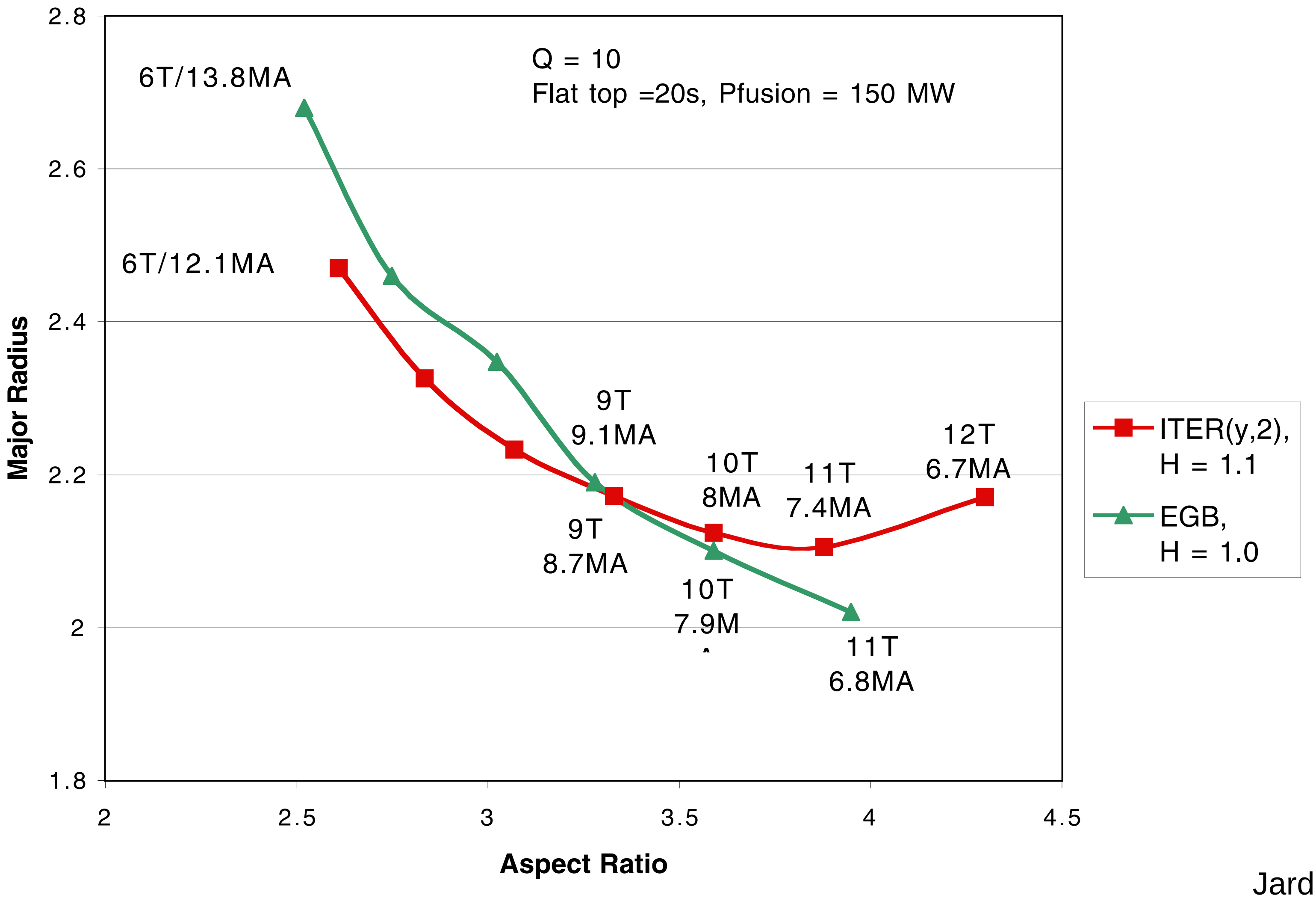
$n(0)/\langle n \rangle = 1.2$

$\tau_J =$ flat top time/ current redistribution time

S. Jardin and C. Kessel

What is the optimum for advanced steady-state modes?

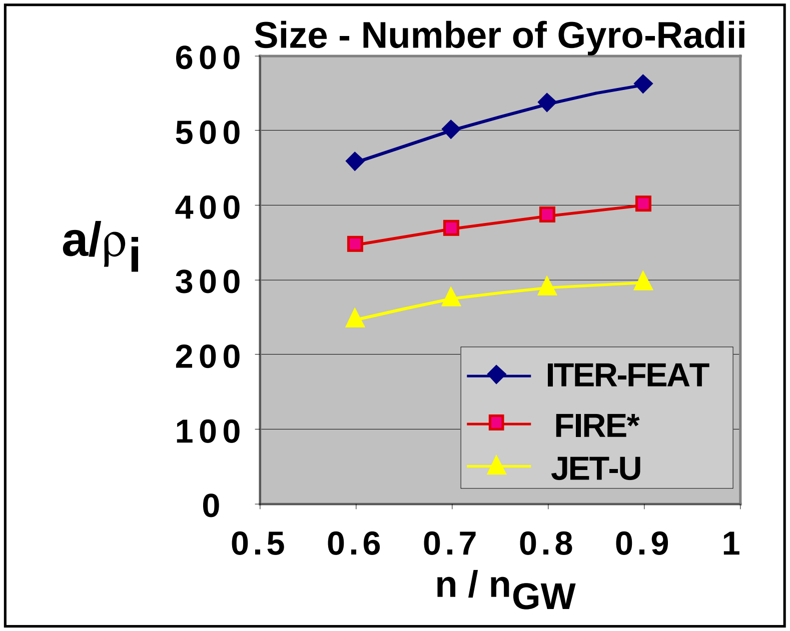
Comparison of ITER98(y,2) and Electrostatic GyroBohm Scaling

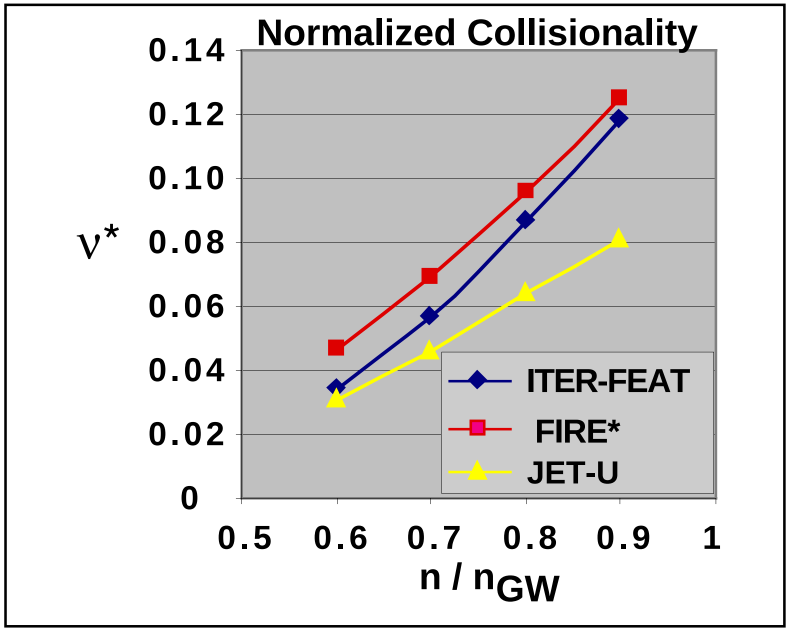


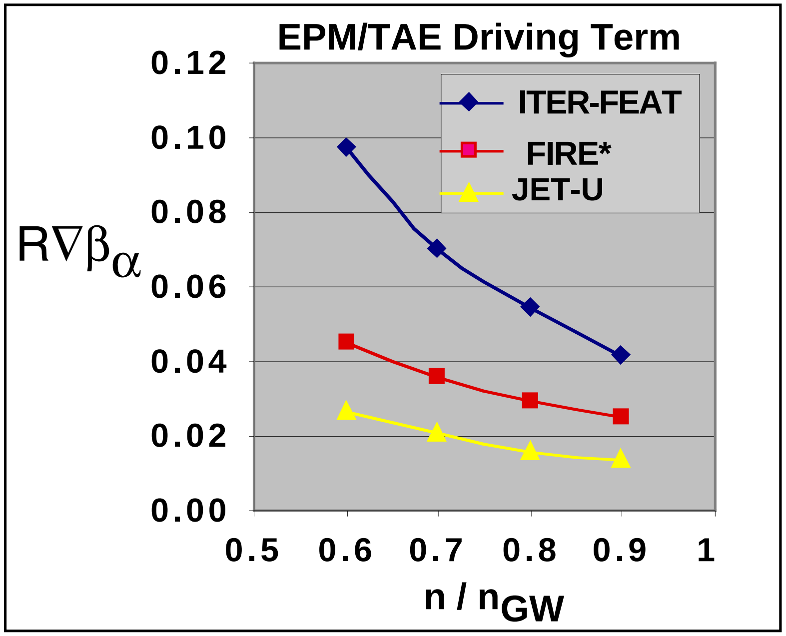
Jardin, Kessel

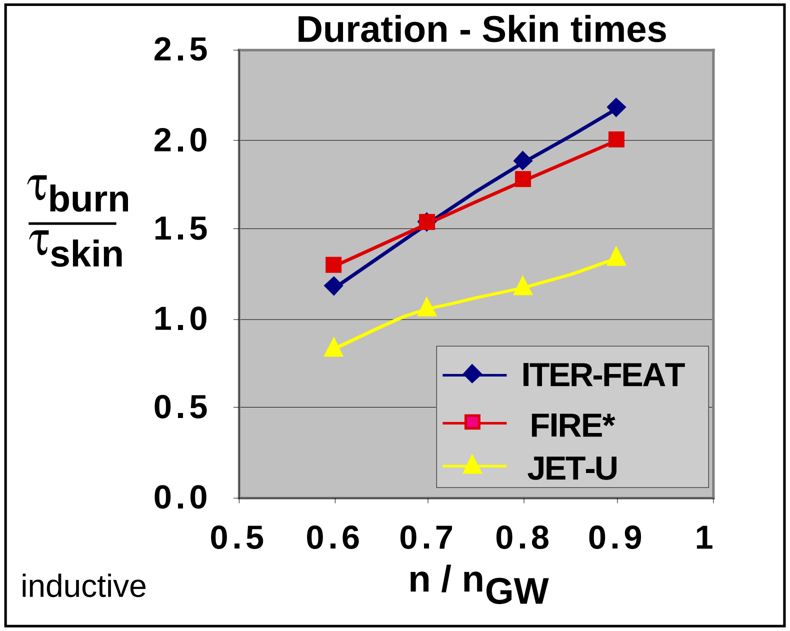
Parameters for H-Modes in Potential Next Step D-T Plasmas

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


Size - Number of Gyro-Radii

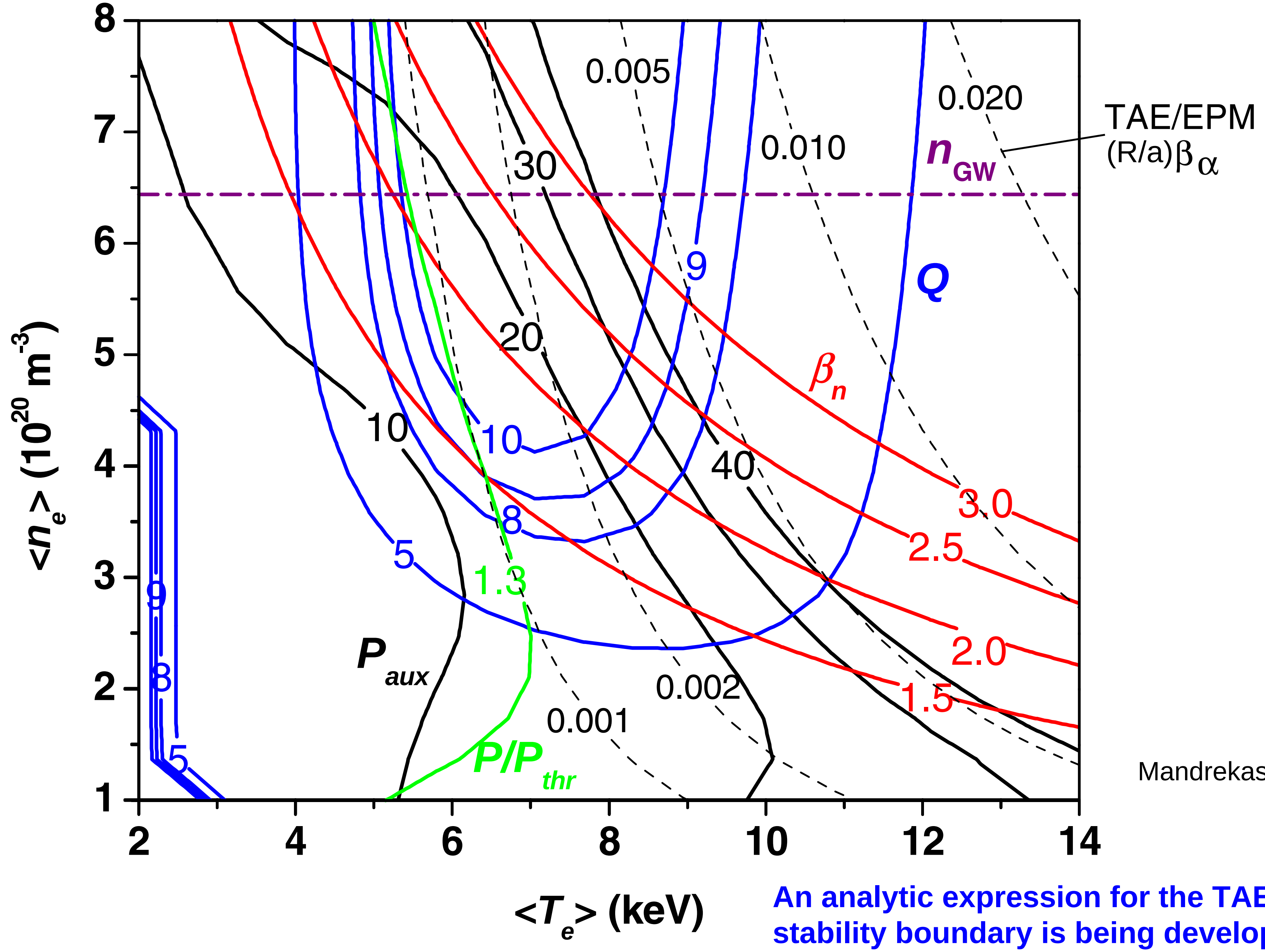

Normalized Collisionality


EPM/TAE Driving Term


Duration - Skin times

inductive

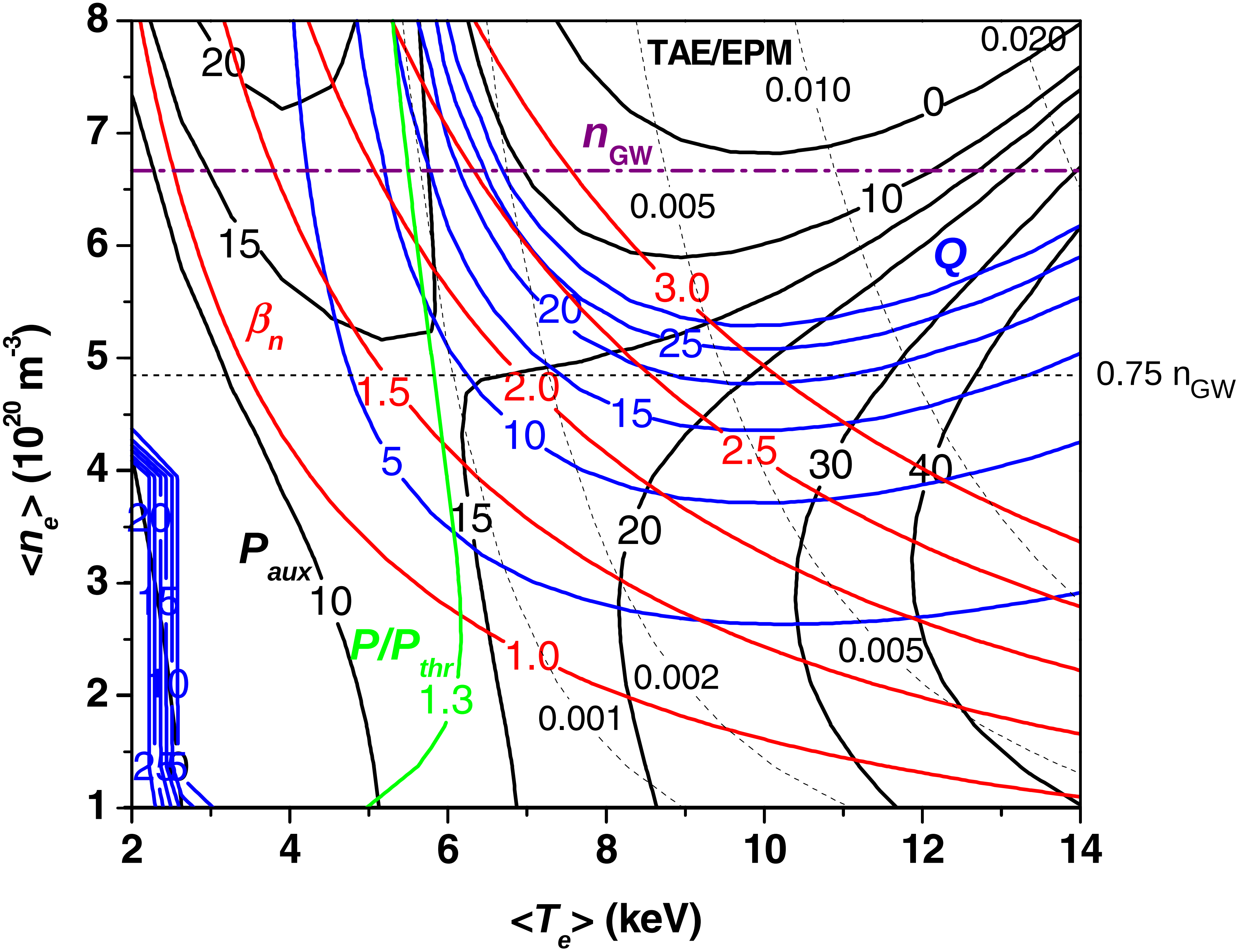
FIRE 10T, 7.7 MA, H(y,2) = 1.14, α_n = 0.2



Mandrekas

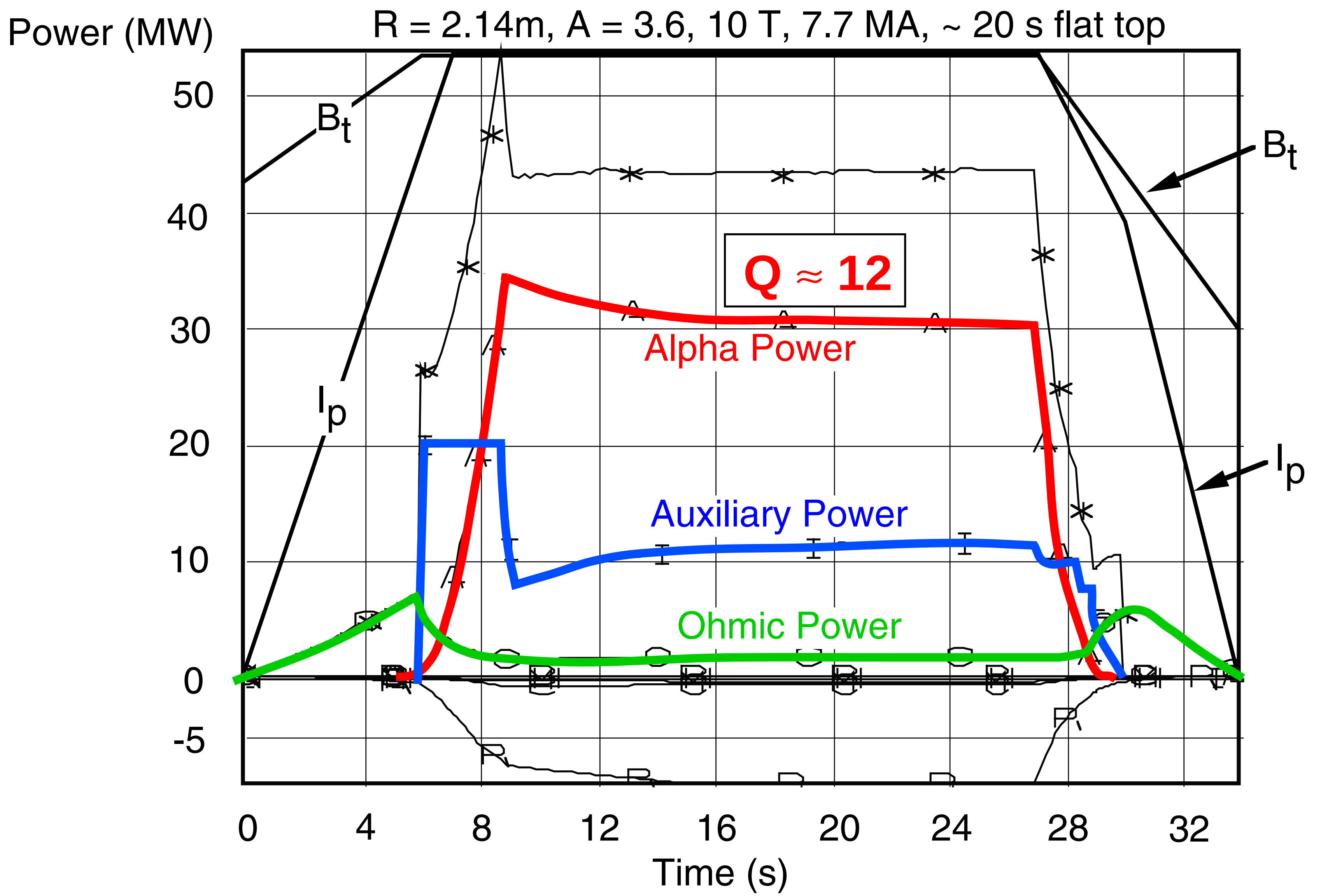
An analytic expression for the TAE/EPM stability boundary is being developed.

FIRE 10T, 7.7 MA, H_{EGB} = 1.0, α_n = 0.2



Mandrekas

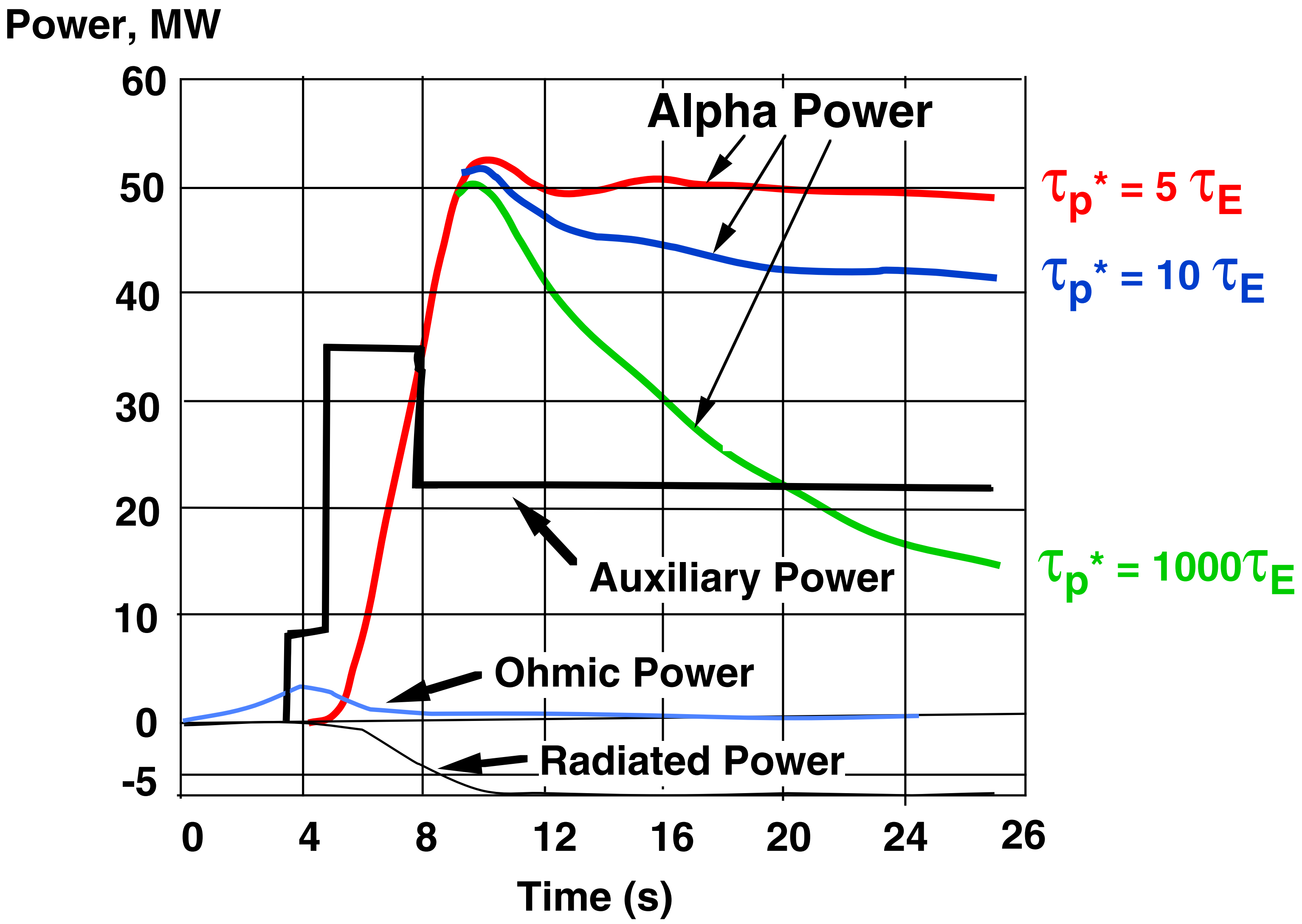
1 1/2-D Simulation of Burn Control in FIRE (TSC)



- 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)

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
Early case - 1999

switch to C. Kessel , FIRE Physics /AT Progress

FIRE Physics Issues and Needs

- Most are the same as for ITER-FEAT!
- Differences arise due to:
  - Double null divertor - higher δ, shorter path to divertor, neutral stability point
    no asymmetric alpha ripple loss region, ($\delta B/B = 0.3\%$)
  - Lower density relative to n_{GW}, higher density relative to NBI, RF, neutrals
  - All metal PFCs, esp. W divertor targets, • No neutral beam heating
- Specific Interests (requests)
  - Core Confinement (H-Mode and close relatives)
    - Understand requirements for enhanced H-modes at $n/n_{GW} \approx 0.6 - 0.7$
    - Compare SN $\Rightarrow$ DN or nearly DN ; maybe more than triangularity
    - Extend global studies/analysis $H = H(\delta, n/n_{GW}, n(0)/<n>)$
    - H-mode power threshold for DN, hysteresis, $H = f(P - P_{th})$
    - Pedestal height/width as SN $\Rightarrow$ DN; elms as SN $\Rightarrow$ DN
    - Rotation as SN $\Rightarrow$ DN
    - Expand H-Mode data base for ICRF only plasmas
    - Demonstration discharges and similarity studies
    - Density Profile Peaking - expectations/requirements?

FIRE Physics Issues and Needs (p.2)

- Internal Transport Barriers (AT Modes)
  - Access to ATs with: RF heated, q_{95} ~ 3.5 - 4, $T_i/T_e \approx 1$,
  - density peaking needed for efficient LHCD
  - n = 1stabilization by feedback

- SOL and Divertor - Impurities
  - Justification for using $n_z \Downarrow$ as $n_e \Uparrow$?
  - ASDEX Upgrade and C-Mod Hi Z impurity in core and "tritium"retention
  - Consistency of partially detached divertor with good τ_E and He removal
  - Models and improved designs for extending lifetime (Elms/disruptions)

- Plasma Termination and Halo Currents
  - Does DN neutral zone reduce force or frequency of disruptions?
  - Develop early warning, mitigation and recovery techniques

- Finite-β effects
  - stabilization of NTMs using LHCD (Δ' modification)
  - elms for enhanced confinement modes
  - TAE, EPM studies in DD with beams and RF

- Diagnostic development -

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

June 7, 2001

To: Charles Baker

From Charles Bushnell
Jim Irby
Saurin Majumdar
Peter Mioduszewski
Ron Parker
Aldo Pizzuto
Fred Puhn

Subject: External Review of FIRE

The above Committee has concluded 3 days of listening to presentations and detail discussions with the Engineering Team of FIRE. While many design details, concerns, comments and recommendations are attached to this letter, we feel ***very strongly*** that the following four points should be made up front for your consideration:

1. The Pre-Conceptual design team has done an outstanding job of looking across the Physics requirements, and investigating a through range of devices that could be considered. The team has created concepts for new machines that can explore most of the critical physics issues in burning plasmas in a facility of modest cost.

2. These Pre-Conceptual investigations have been carried out in amazing detail, considering our observations that the team is less than the required "critical mass" for the proper confrontation of this effort. This has limited their ability to fully address a number of critical engineering problems in detail.

3. It is ***CRITICAL*** that immediate **resources** be provided to raise the team to the required "critical mass" so that it can properly conclude the Pre-Conceptual Design phase in an expeditious and efficient manner.

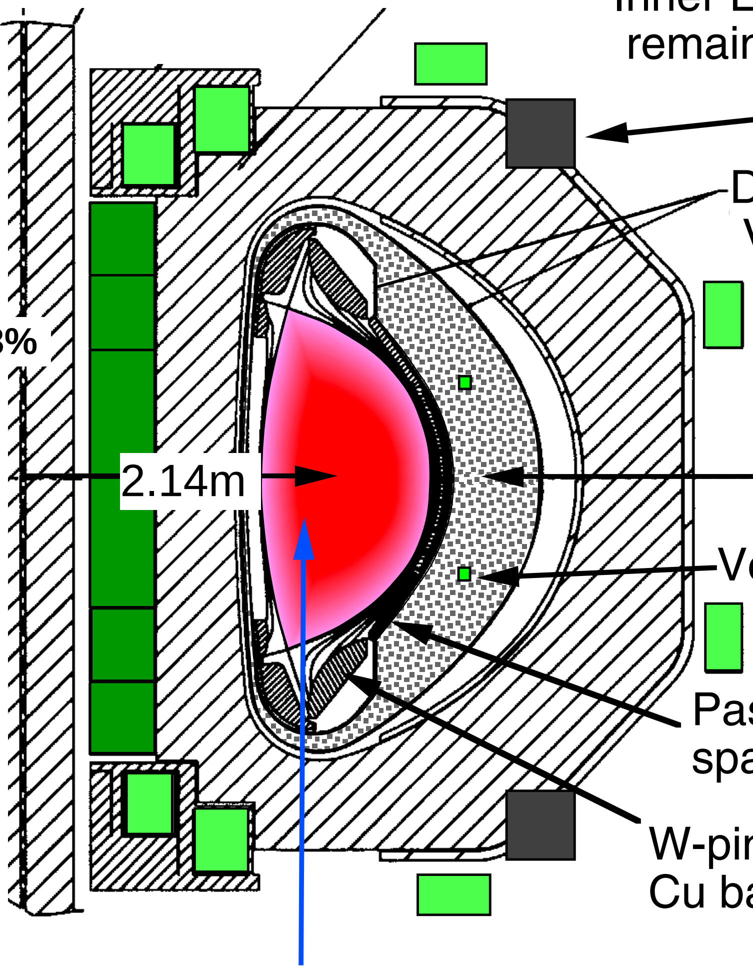
4. It is also ***CRITICAL*** that immediate **resources** be provided to expeditiously engage in the R&D necessary to support the above design effort.

Attachments: 1.0 Magnet System Summary with summary [associated "chits" at PPPL]
2.0 Vacuum system, PFCs, IRH, Fueling and Pumping Summary with summary [associated "chits" at PPPL]

FIRE Baseline for Snowmass Assessment

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

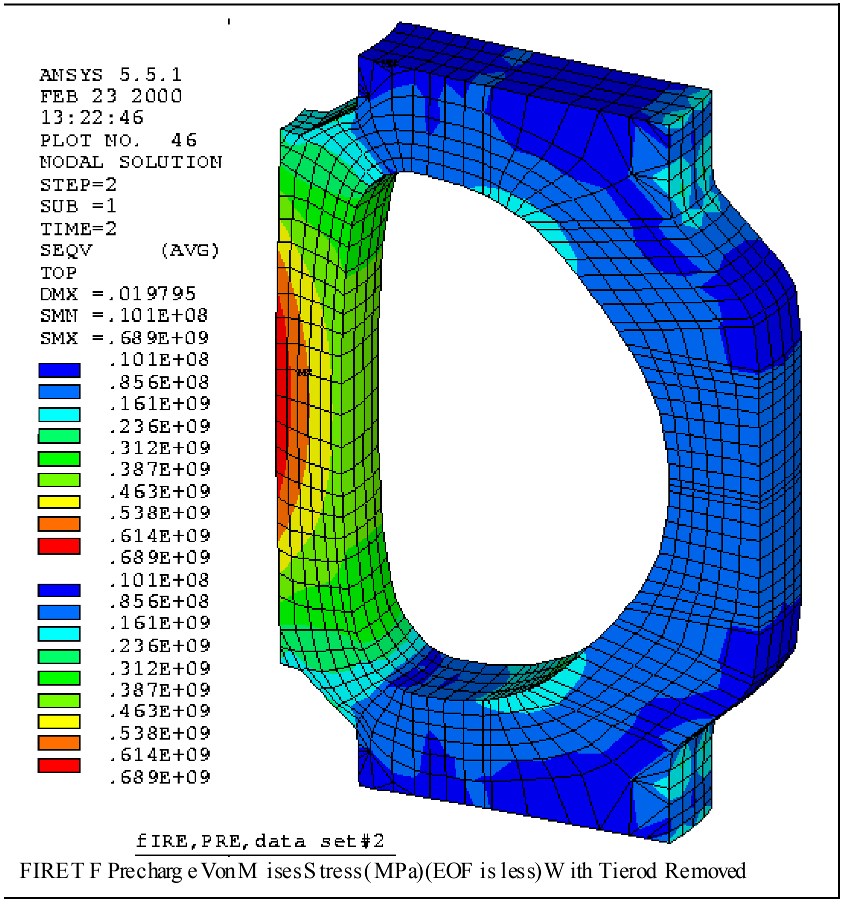
Direct and Guided Inside Pellet Injection

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

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.
- Recent discussions with Brush Wellman are very encouraging. May be able to provide slightly higher conductivity 72% IACS

The plate on the right was manufactured for BPX

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 Limits pulse length in many AT modes
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

Diagnostics proposed for FIRE (1)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Magnetic Measurements			
Plasma current	√	Rogowski Coils	All magnetics inside vacuum vessel
Plasma shape and position	√	Flux/voltage loops	Very high radiation environment and high
Shape, position & MHD	√	Saddle coils (inc. locked-mode)	temperature apply for all magnetics
	√	Discrete Br, Bz coils	Very little space behind first wall/divertor
Plasma pressure	√	Diamagnetic loops	
Disruption-induced currents	√	Halo current sensors	
Current Density Profiles			
Current density for most of profile	√	Motional Stark effect	Requires neutral beam. Two views may give Er
		FIR polarimetry	Most sightlines radial; poor coverage in radial plane
Current density in edge		Li-beam polarimetry	Requires Lithium beam; integration issue
Electron Density			
Core electron density profile	√	Thomson scattering	Tangential laser, imaging view required by small plasma size
		FIR multichannel interferometer/polarimeter	Most sightlines radial; poor coverage in radial plane; tangential polarimeter
X-point/divertor density profiles		Thomson scattering	Design integration into side ports with divertor/first wall
Edge, transp. boundary profile		mm-wave reflectometer	
Edge density profile		Fast-moving probe	
Divertor density variation along separatrix		Multichannel interferometer	Complex integration with divertor/baffle; Dynamic range may make this impossible
Divertor plate density		Fixed probes	RIED may affect probe insulation

Diagnostics proposed for FIRE (2)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Electron Temperature			
Core electron temperature profile	√	Thomson scattering	Tangential laser, imaging view required by small plasma size
		ECE heterodyne radiometer	
		ECE Michelson interferometer	Provides best calibration for ECE diagnostice
X-point/divertor temperature profiles		Thomson scattering	Design integration into side portswith divertor/first wall
Edge temperature profile		Fast-moving probe	
Divertor plate electron temp.		Fixed probes	RIED may affect probe insulation
Ion Temperature			
Core ion temperature profile	√	Charge exchange spectroscopy	Requires neutral beam
		Imaging x-ray crystal spect.	Full radial coverage would require close-in curved crystal; detector noise issue?
		Neutron camera spectroscopy	Full coverage difficult; spatial res. Poor
Divertor ion temperature		UV spectroscopy	
Plasma Rotation			
Core rotation profile	√	Charge exchange spectroscopy	Requires neutral beam: balanced views for vθ needed
		Imaging x-ray crystal spect.	Full radial coverage would require close-in curved crystal; detector noise issue?
Relative Isotope Concentration			
Density of D and T concentrations in core	√	Charge-exchange spectroscopy	Requires neutral beam
		Neutron spectroscopy	Can DD neutrons be discriminated from DT and TT neutrons?

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Diagnostics proposed for FIRE (3)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Radiation			
Zeff,visible bremsstrahlung	√	Visible bremsstrahlung array	
Core hydrogen isotopes, low-Z impurities		Visible filterscopes	
Divertor isotopes and low-Z impurities	√	Divertor filterscopes	
Core low-Z impurities		Visible survey spectrometer	
		UV survey spectrometer	
Divertor low-Z impurities and detachment	√	Multichord visible spectrometer	Very little space to develop sightlines
High-Z impurities		X-ray pulse height analysis	Single sightline, detector noise
Divertor impurities		UV spectrometer	Access issue into divertors
Total radiation profile		Bolometer arrays	Mounting and radiation-hardness of bolometers are challenges
Total light image		Visible TV imaging	
MHD and Fluctuations			
Low-frequency MHD	√	Discrete Br, Bz coils	Very little space behind first wall/divertor
		Saddle coil for locked-mode	
		Neutron fluctuation dets.	
High-frequency MHD, TAE, etc.	√	High-frequency Mirnov coils	HF-coils behind tile-gaps, little space
Core density fluctuations		Mm-wave reflectometers	
		Beam emission spectroscopy	Requires neutral beam
Core electron temp. fluctuations		ECE grating polychromators	
Neutron Measurements			
Calibrated neutron flux	√	Epithermal neutron detectors	Calibration difficult with significant shielding
Neutron energy spectra		Multichannel neutron camera	Difficult to get wide spatial coverage

Diagnostics proposed for FIRE (4)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Alpha-particle Measurements			
Escaping alpha-particles/fast-ions		Faraday cups/scintillators at first wall	Much development needed to handle heat loads and signal transmission
		IR TV imaging	Only gives information about total loss location
Confined thermalizing alphas/spatial distribution		α-CHERS	Requires neutral beam, very high throughput optics
Confined alpha-particles' energy distribution		Collective scattering	Need development to optimize wavelength/ spatial resolution; assume mm-wave
Spatial redistribution of alphas		Li-Pellet charge exchange	Needs high-energy repetitive impurity pellet; very difficult access
Volume-average alpha-particle energy spectrum		Knock-on bubble-chamber neutron detectors	Development of detectors required
		Neutron spectrometer	Evaluates knock-on tail above 14 MeV
Runaway electrons			
Start-up runaways	√	Hard x-ray detectors	Inside vacuum vessel; survival with necessary sightlines is issue
Disruption potential runaways	√	Synchrotron rad. detection	Far-forward light cone must be detected
Divertor Pumping Performance			
Pressure in divertor gas-box		ASDEX-type pressure gauges	Concern about RIED affecting operation
Helium removed to divertor		Penning spectroscopy	

Diagnostics proposed for FIRE (5)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Machine Operation Support			
Vacuum base pressure	√	Torus ion gauges	On main pumping duct
Vacuum quality		Residual gas analyzer	On main pumping duct
Vacuum vessel illumination		Insertable lamps	To enable initial level of internal inspection
Surface Temperature			
First-wall/RF antenna temp.	√	IR TV imaging	
Divertor plate temperatures and detachment	√	IR TV imaging	
		Thermocouples	
Neutral particle sources for diagnostics			
Neutral particle source for core spectroscopy	indirect	Diagnostic neutral beam	Pulsed high power beam required for penetration at ~ 150 keV/amu
Lithium source for polarimetry		High current lithium beam	In development for DIII-D (JET?)
Lithium pellet target for confined alpha spatial dist.		High velocity lithium pellet injector	> 5 km/s, ~10 Hz development needed

Edge Physics and PFC Technology: Critical Issue

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

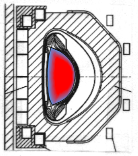
Solutions to these issues would be a major output from a next step experiment.

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

Pfusion
= ~ 150 MW

Volume
= $27\ m^3$

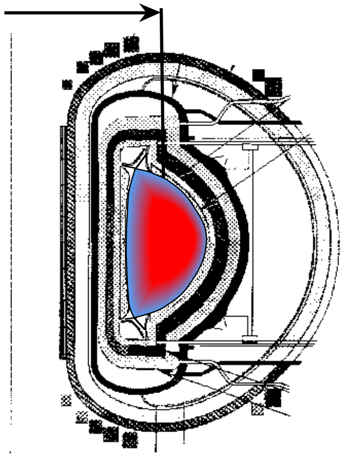
B = 10 T
R = 2.14 m
→



FIRE

~ 3X

B = 8 T
R = 5.5 m



ARIES-RS The "Goal"

Pfusion
= 2170 MW

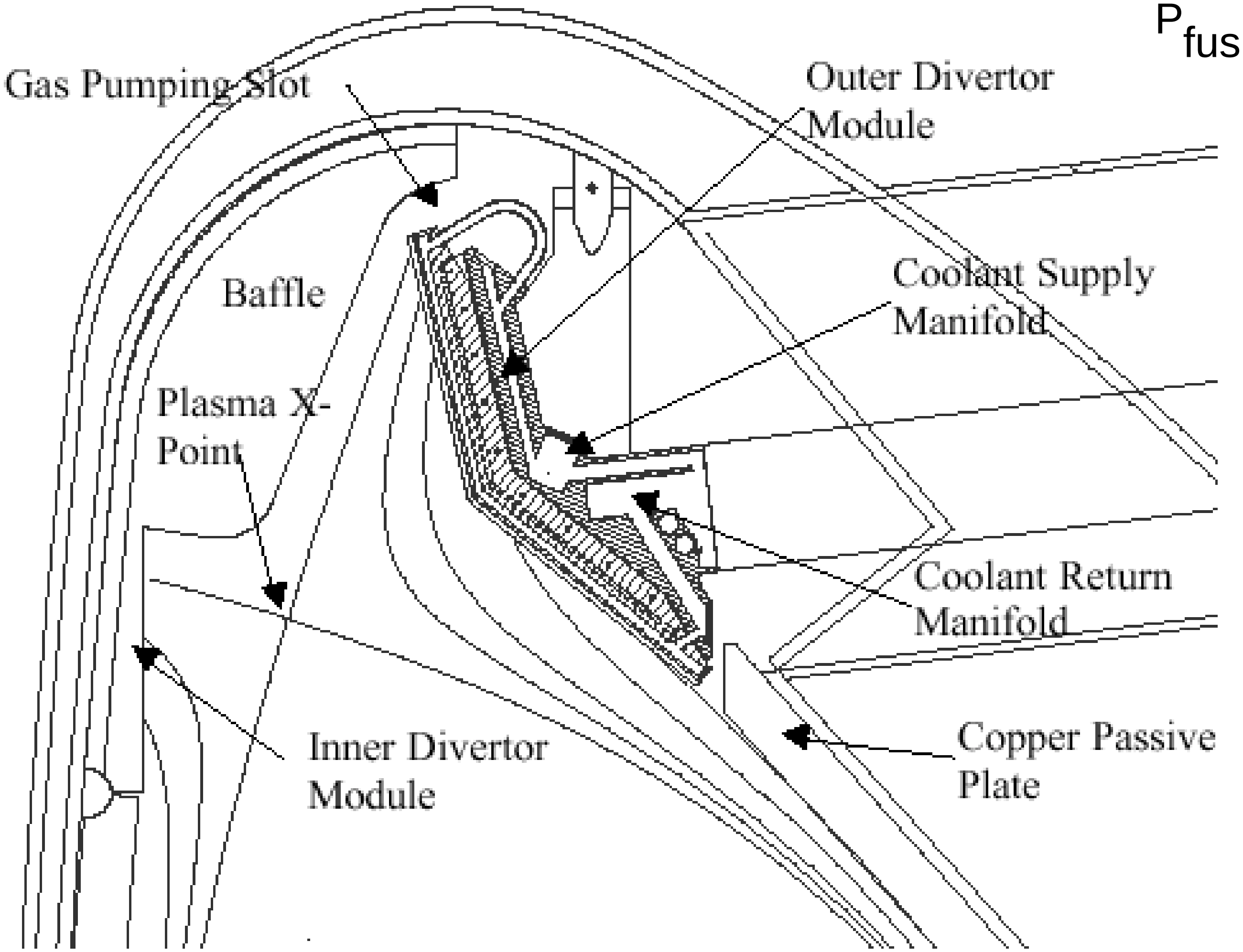
Volume
= $350\ m^3$

	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

* Note: FIRE outer divertor plate is in steady-state

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

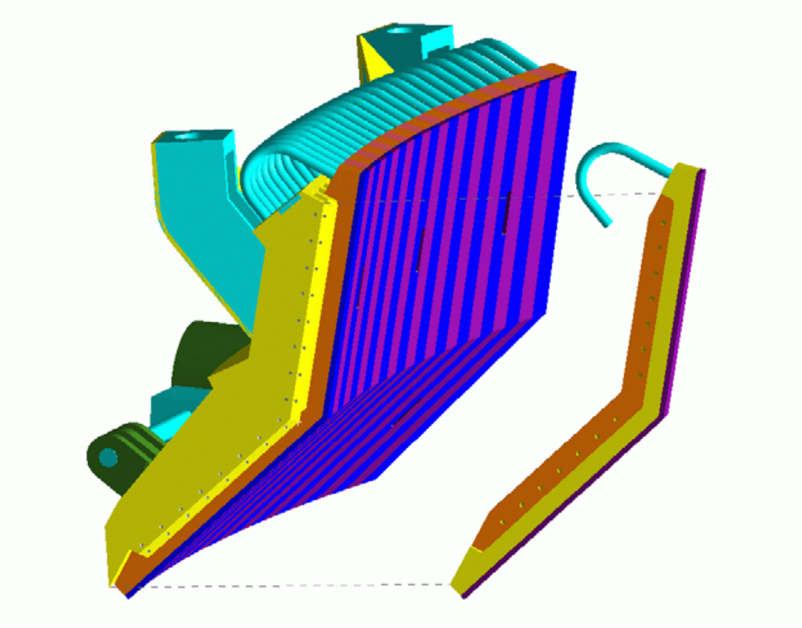
$P_{fusion} < 200$ MW



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

Divertor Module Components for FIRE

Sandia

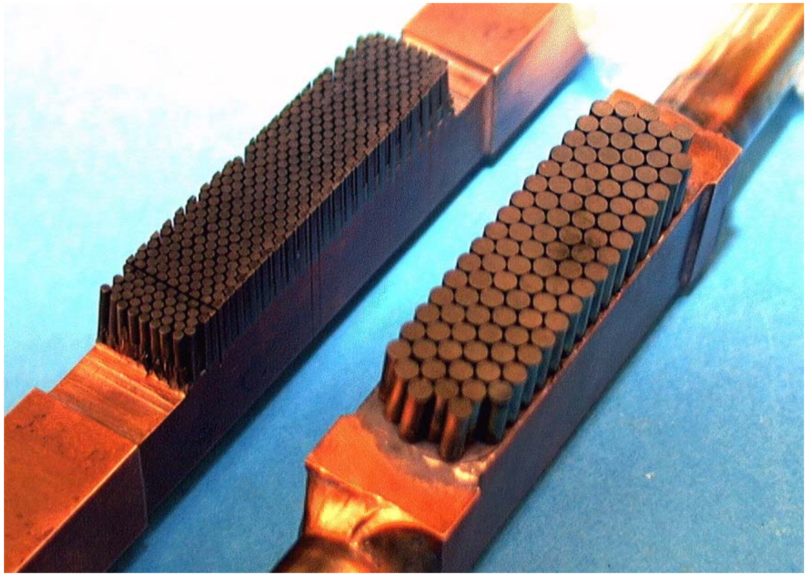


Finger Plate for

Outer Divertor Module

Two W Brush Armor Configurations

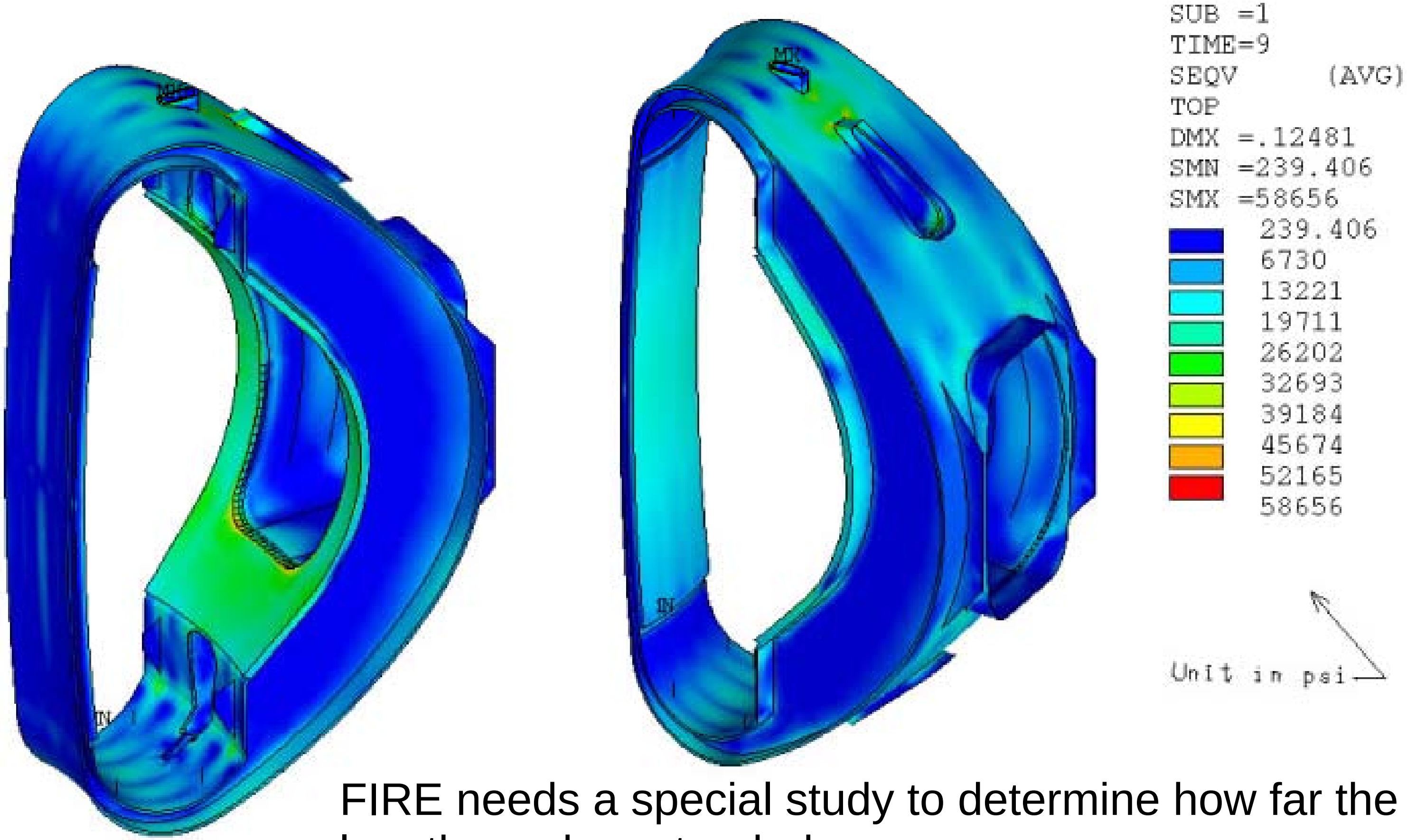
Tested at 25 MW/m^2



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

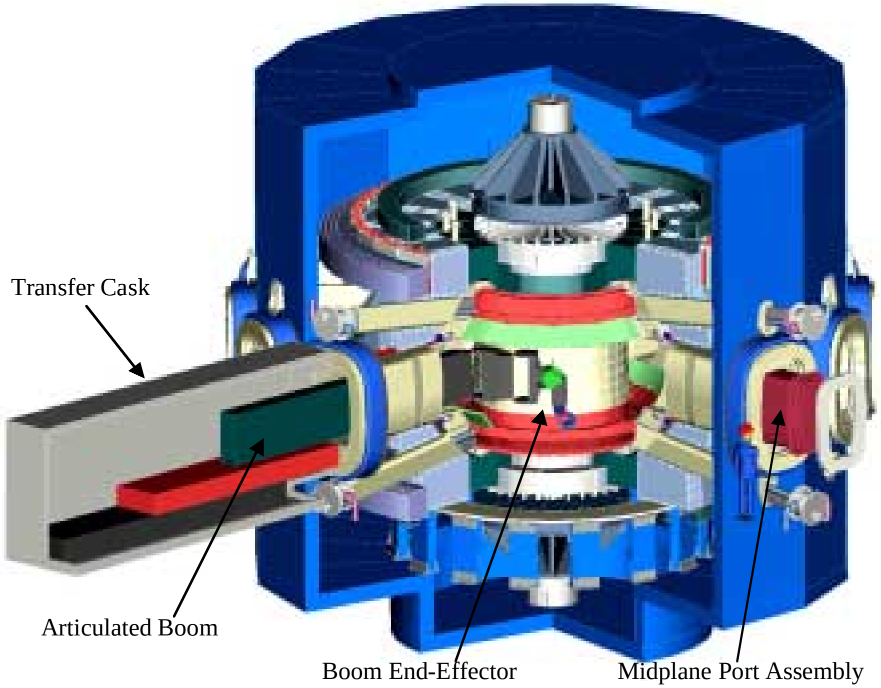
Combined stresses, 20 s pulse

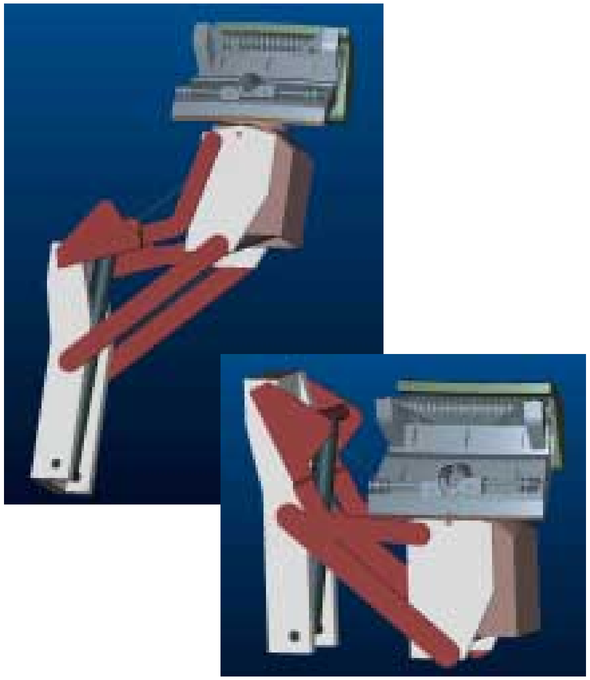
- **Nuclear heating, gravity, coolant pressure, vacuum**



FIRE needs a special study to determine how far the pulse length can be extended.

FIRE In-Vessel Remote Handling System





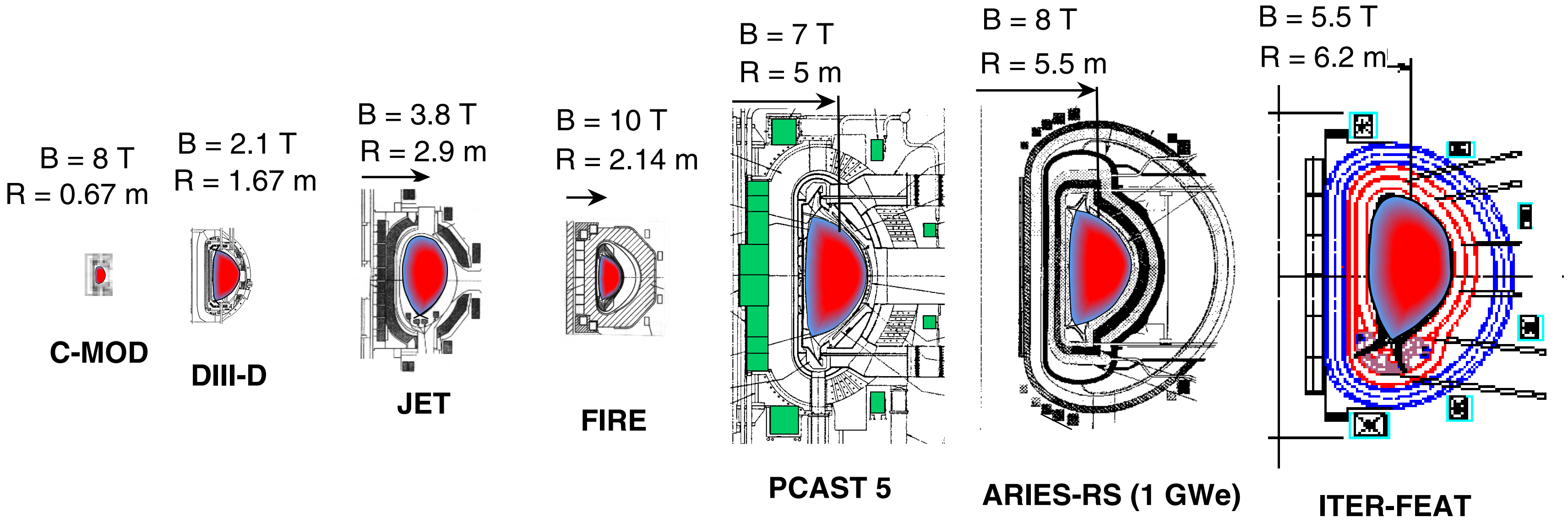
In-vessel transporter

- 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

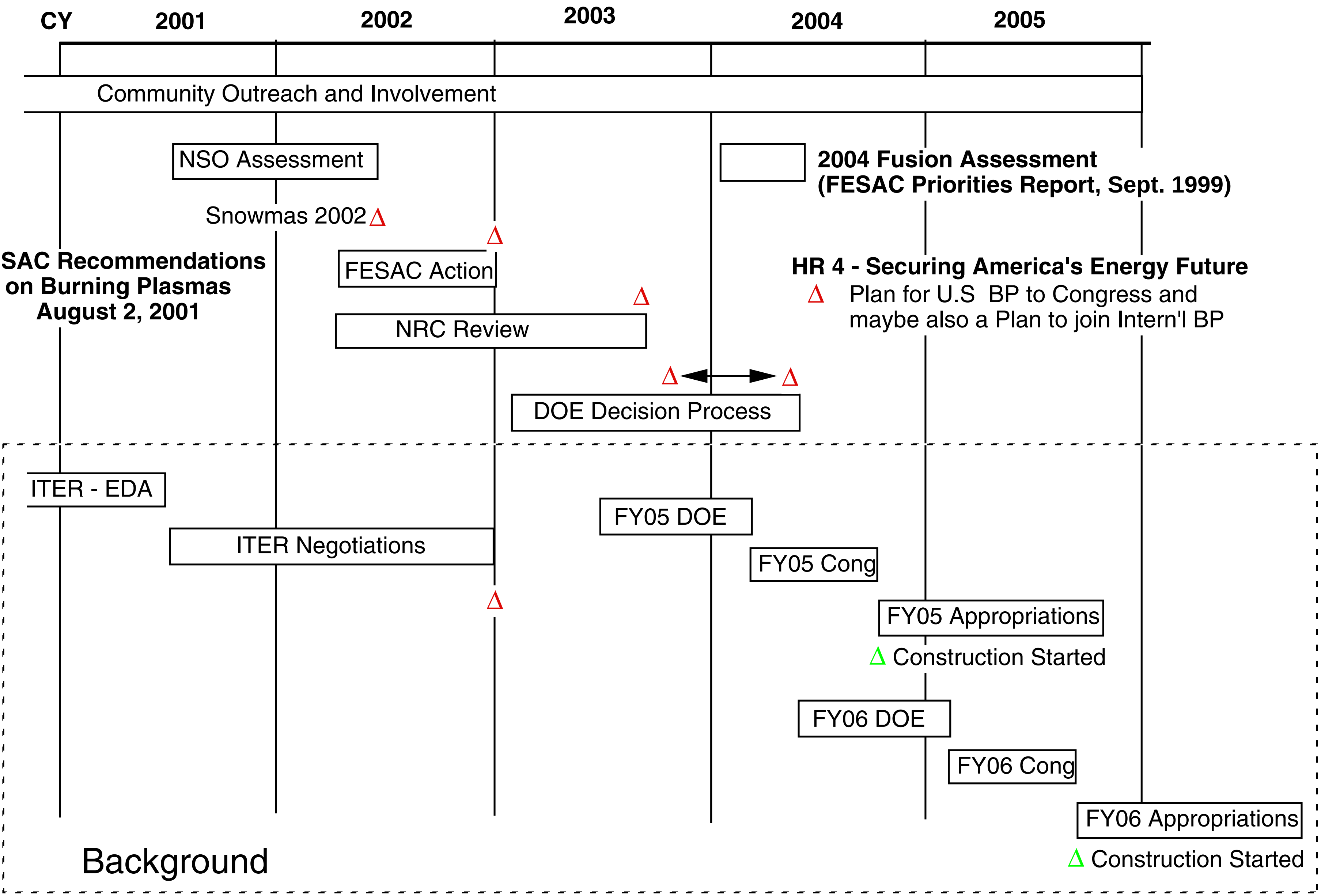
- High capacity (module wt. ~ 800 kg)
- Four positioning degrees of freedom
- Positioning accuracy of millimeters required

What are the Costs of Next Step Burning Plasma Experiments?



Cost Drivers	C-MOD	DIII-D	JET	FIRE	PCAST	ARIES-RS	ITER-FEAT
Plasma Volume (m^3)	1	18	95	27	390	350	828
Plasma Surface (m^2)	7	30	180	60	420	390	610
Plasma Current (MA)	2	2	4	7.7	15	11.3	15
Magnet Energy (GJ)			1.6	5	40	85	50
Fusion Power (MW)			16	150	400	2170	400
Burn Duration (s), inductive		1	1	20	120	steady	400
τ Burn/ τ CR	5	1	≤1	2	1	steady	2
Cost Estimate ($B-2000$)			~0.9	1.2	6.7	10.6/2	4.6

Recommended US Plan for Burning Plasmas



CY 2001 2002 2003 2004 2005

Community Outreach and Involvement

NSO Assessment

Snowmas 2002 Δ

Δ

FESAC Action

FESAC Recommendations on Burning Plasmas August 2, 2001

Δ

NRC Review

2004 Fusion Assessment (FESAC Priorities Report, Sept. 1999)

HR 4 - Securing America's Energy Future

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

Δ ◄——► Δ

DOE Decision Process

ITER - EDA

ITER Negotiations

Δ

FY05 DOE

FY05 Cong

FY05 Appropriations

Δ Construction Started

FY06 DOE

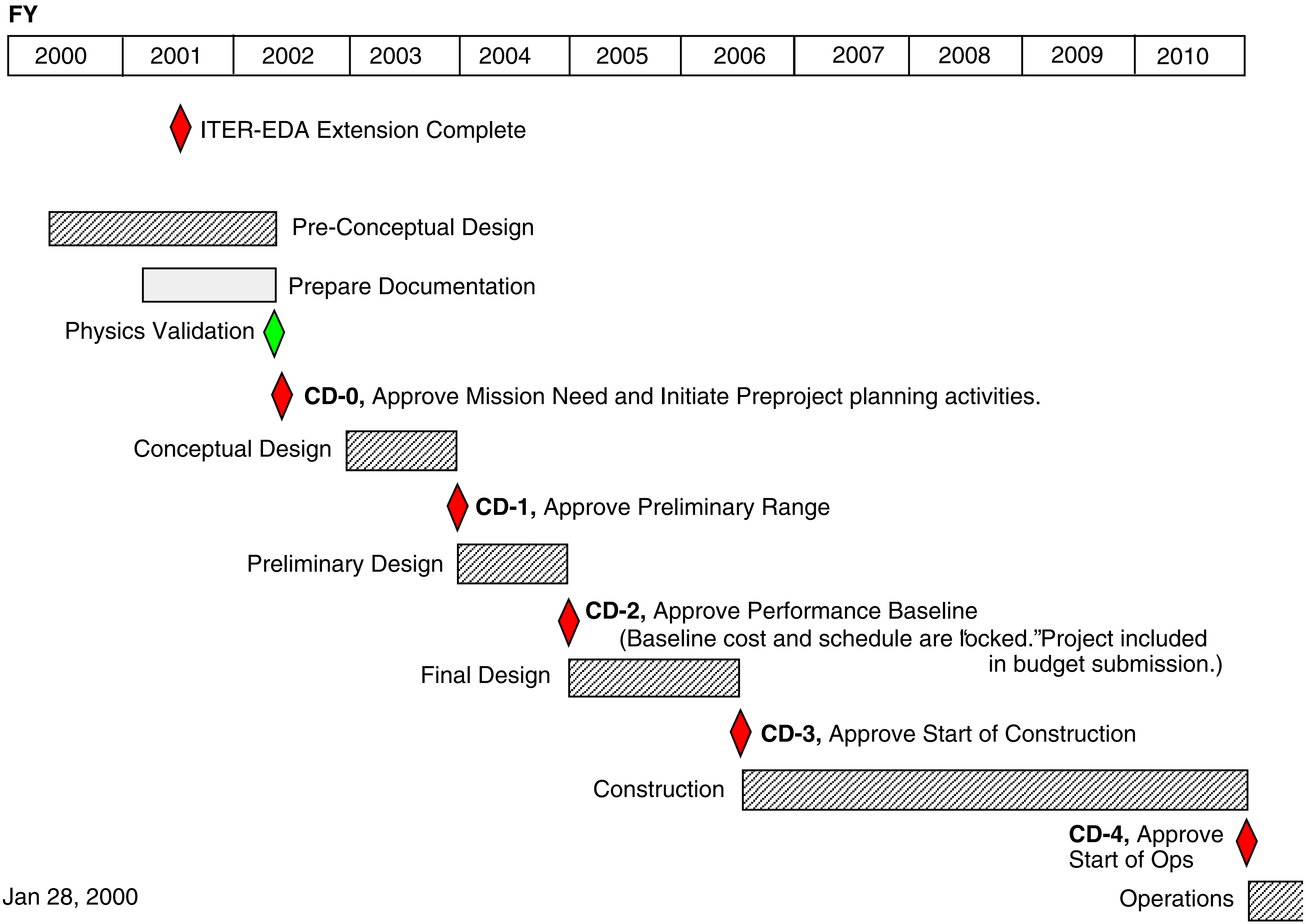
FY06 Cong

FY06 Appropriations

Δ Construction Started

Background

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

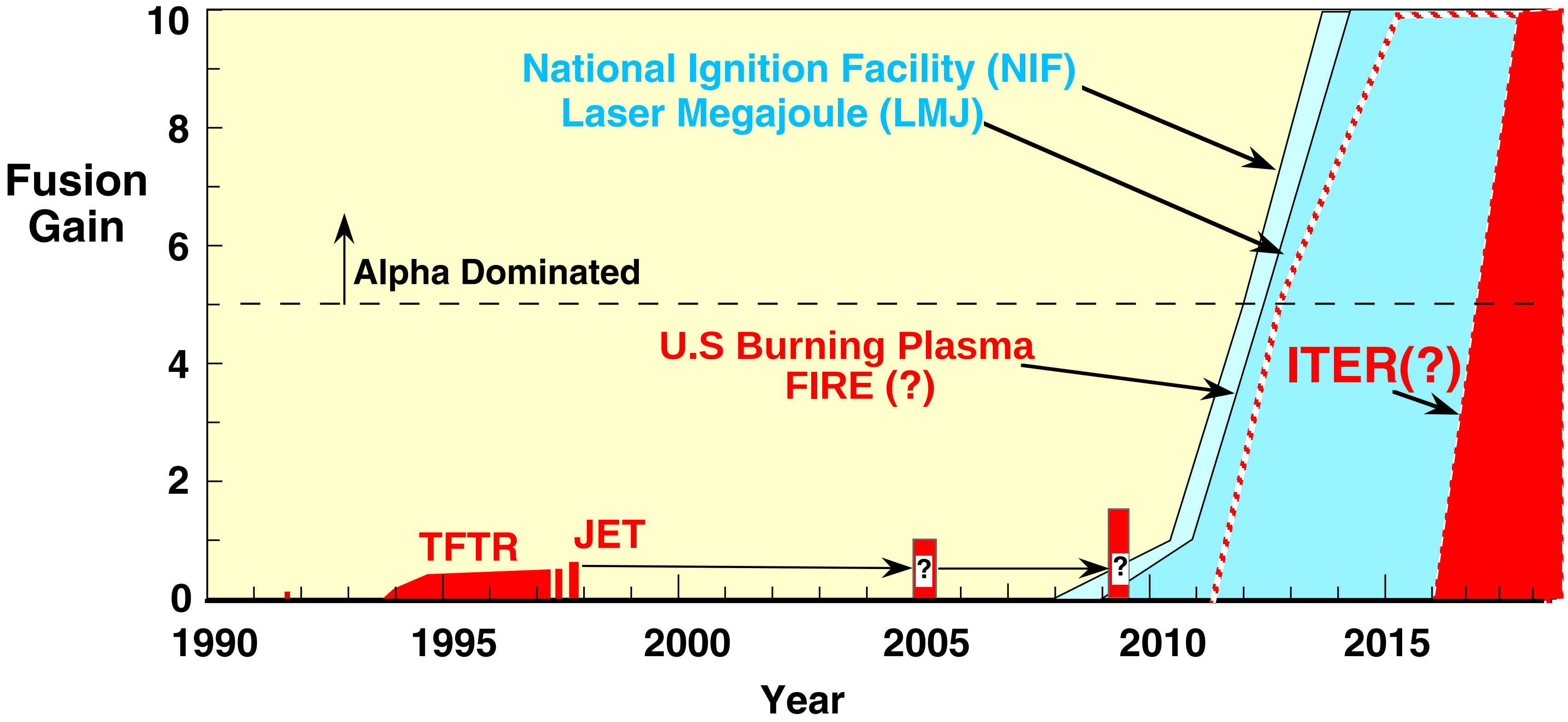
Construction

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.

- A compact high field tokamak, like FIRE, has the potential:
  - address the important burning plasma issues,
  - most of the advanced tokamak issues and,
  - begin to study the strong non-linear coupling between BP and AT in a tokamak with the goal of also providing generic BP science and possibly BP infrastructure for non-tokamak BP experiments.

- 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.
  - Respond to FIRE Engineering Review and NSO PAC on specific physics R&D and engineering design and R&D issues.

http://fire.pppl.gov