The Modular Strategy for Fusion

and

The Status of FIRE

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for the FIRE Team

Presented at
Frontiers in Fusion Research
FPA Annual Meeting, Washington, DC

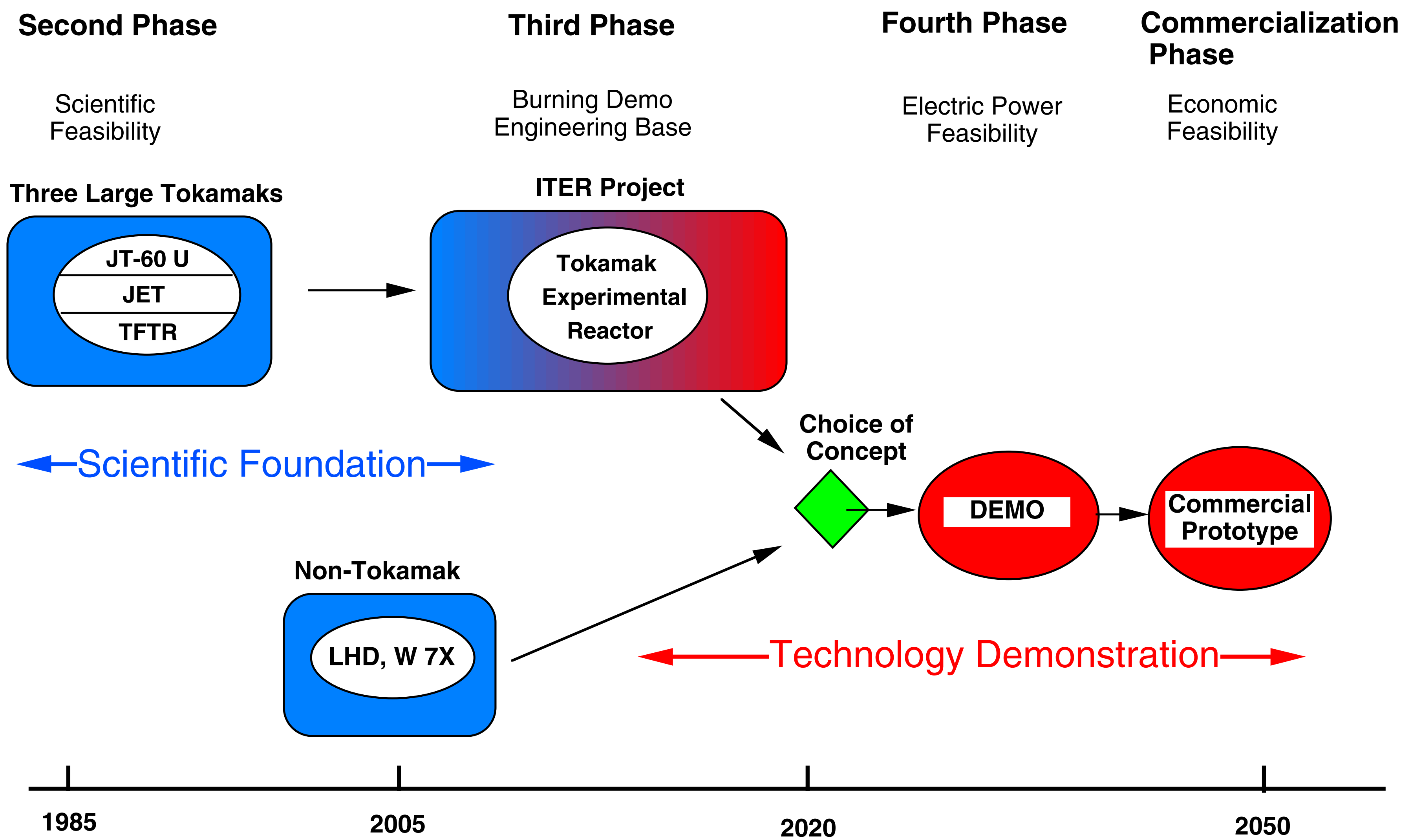
September 25, 2001

http://fire.pppl.gov

Outline

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

One Step to DEMO [1, 2]



1. Technical Feasibility of Fusion Energy, SubCom of (Japan) Fusion Council for Fusion Development Strategy, May 2000
2. European Plan Airaghi Report, May 2000

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

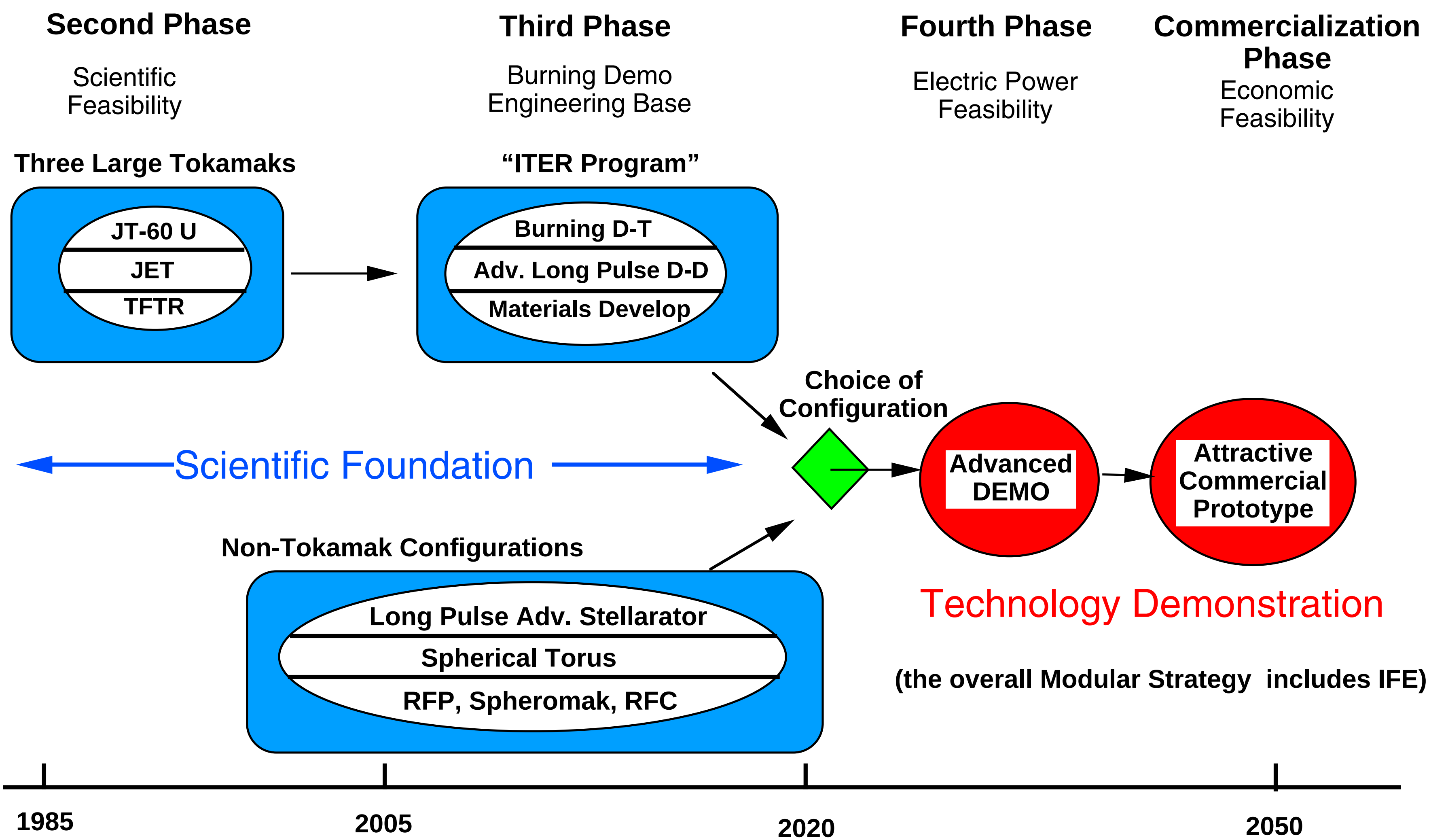
- **Boundary Physics and Plasma Technology** (coupled with above)
  - high particle and heat flux
  - couple core and divertor
  - fusion plasma - tritium inventory and helium pumping

- **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 reactor materials

The Modular Strategy for MFE



Reduced Technical Risk

Streamlined Management Structure

Better Product/Lower Overall Cost

Increased Technical Flexibility

Faster Implementation

Next Step Option Program Advisory Committee

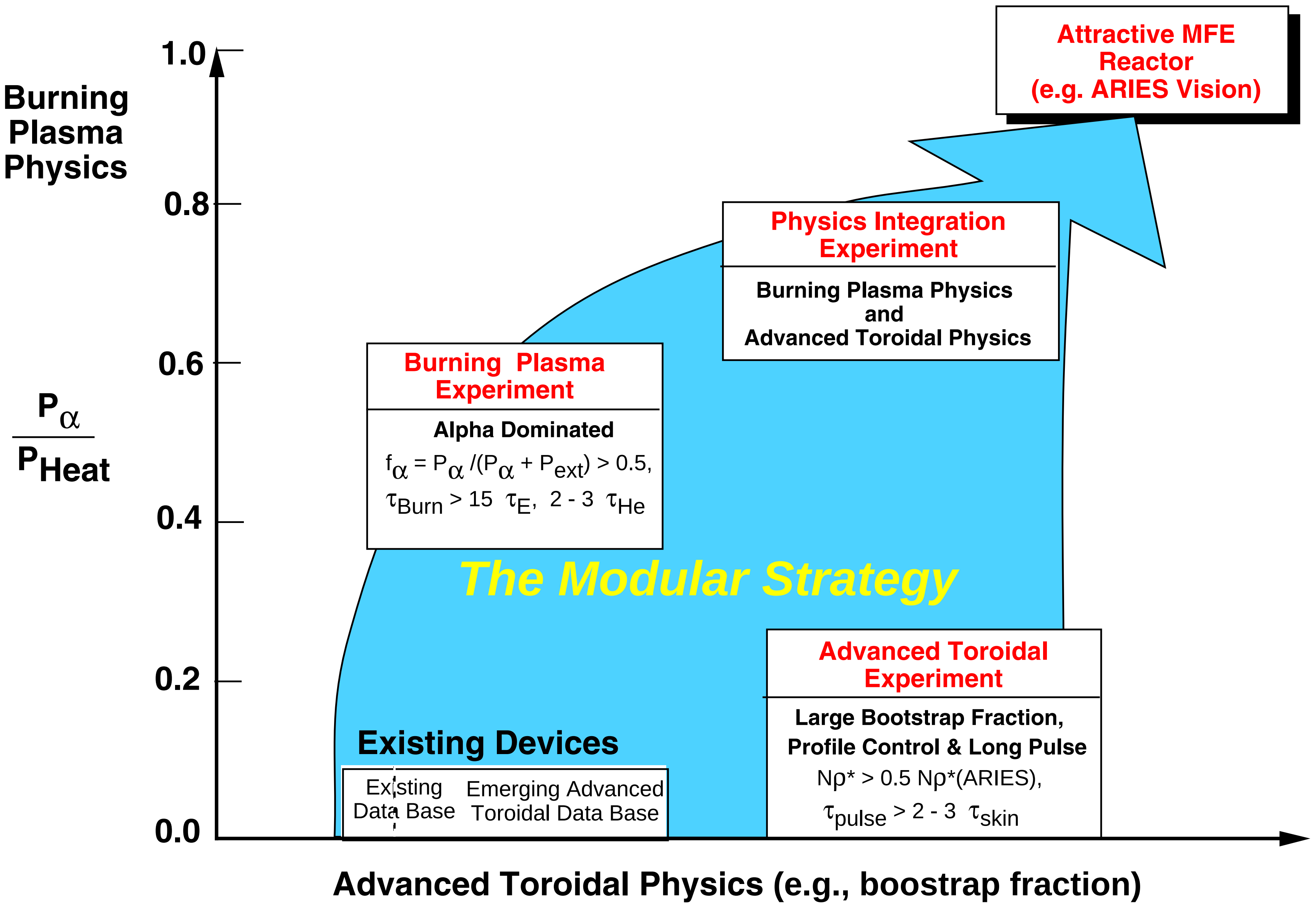
- **Members:** Tony Taylor (Chair), Gerald Navratil, Ray Fonck, David Gates, Dave Hill, Wayne Houlberg, Tom Jarboe, Mitsuro Kikuchi, Earl Marmar, Raffi Nazikian, Craig Petty, Rene Raffray, Paul Thomas, James VanDam

- **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

- **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.

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



Get to a burning plasma with confidence using “todays” physics, but allow the flexibility to exploit tomorrow’s advanced physics.

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

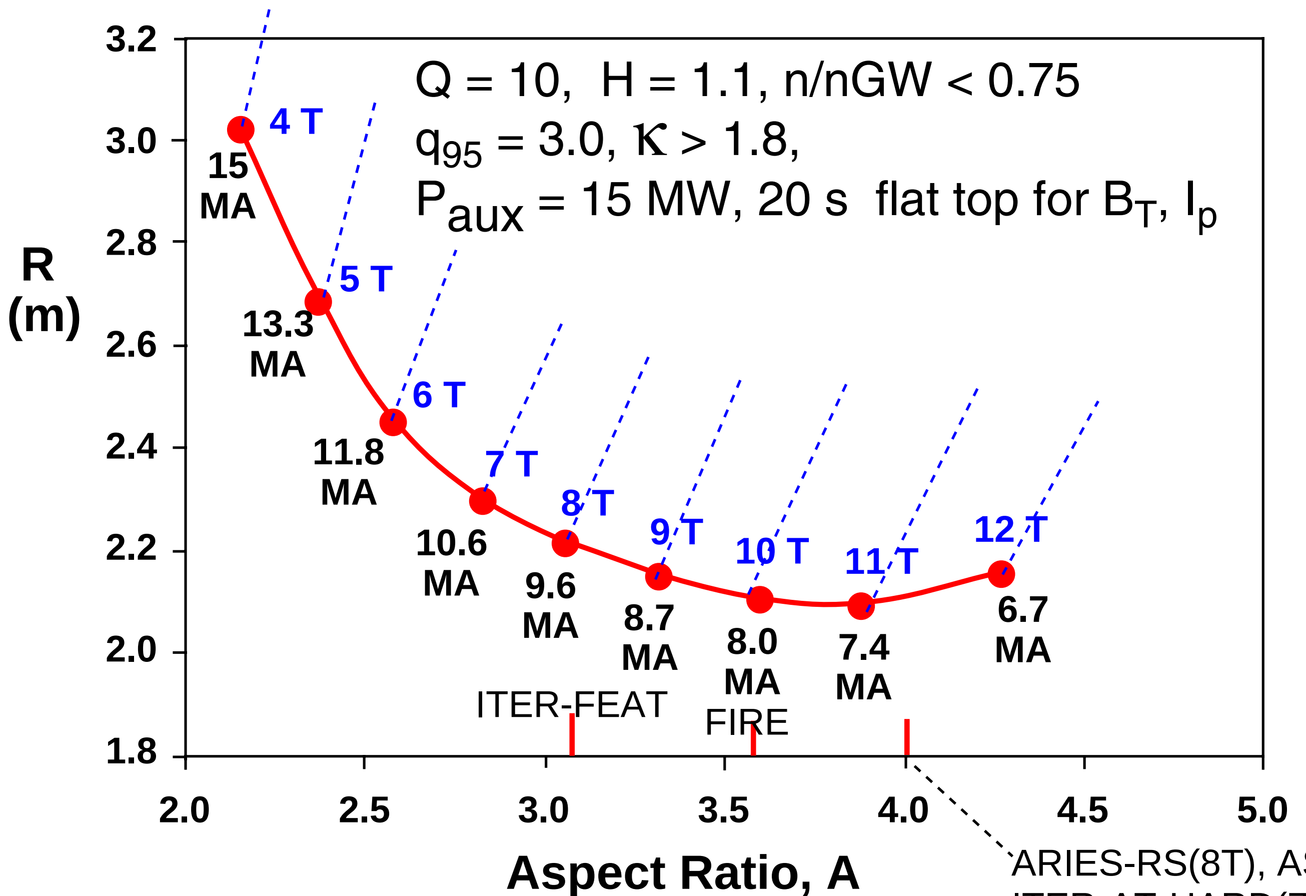
Quasi-stationary

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.



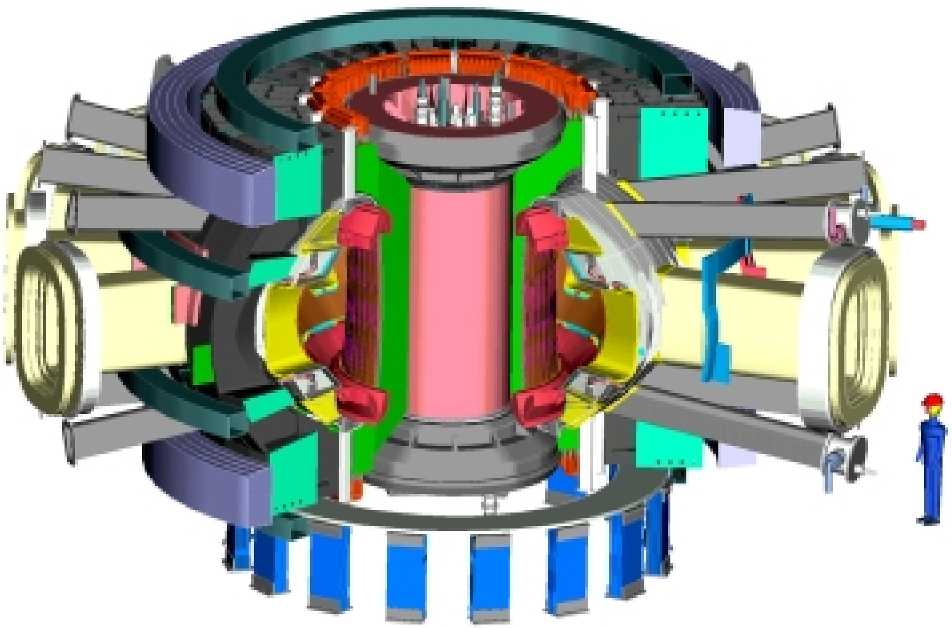
Elmy H-Mode
ITER 98 (y,2)

S. Jardin and
C. Kessel

What is the optimum for ITBs or AT 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.

Contributors to the FIRE Engineering Design Study

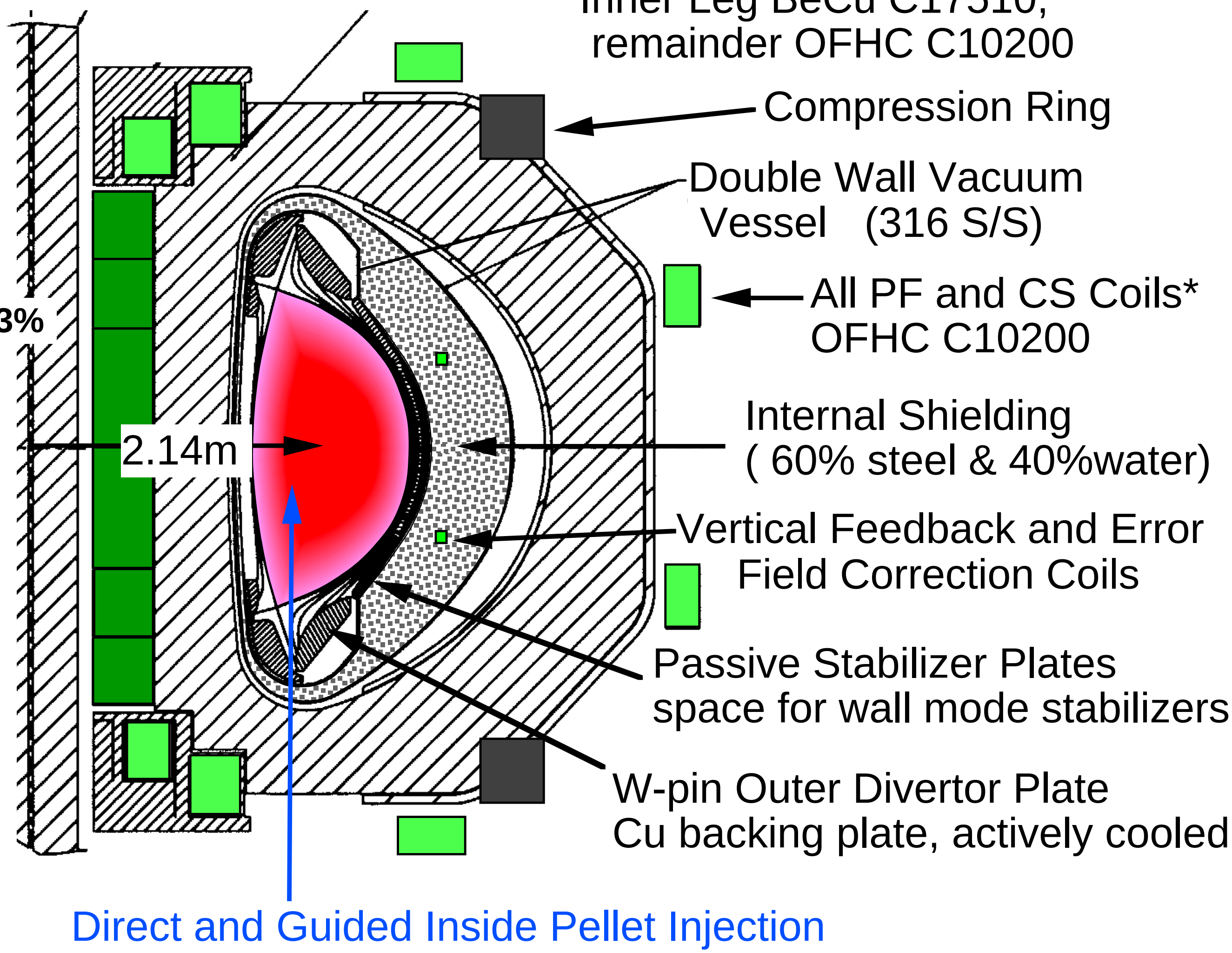
FIRE is a design study for a major Next Step Option in magnetic fusion and is carried out through the Virtual Laboratory for Technology. FIRE has benefited from the prior design and R&D activities on BPX, TPX and ITER.

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



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

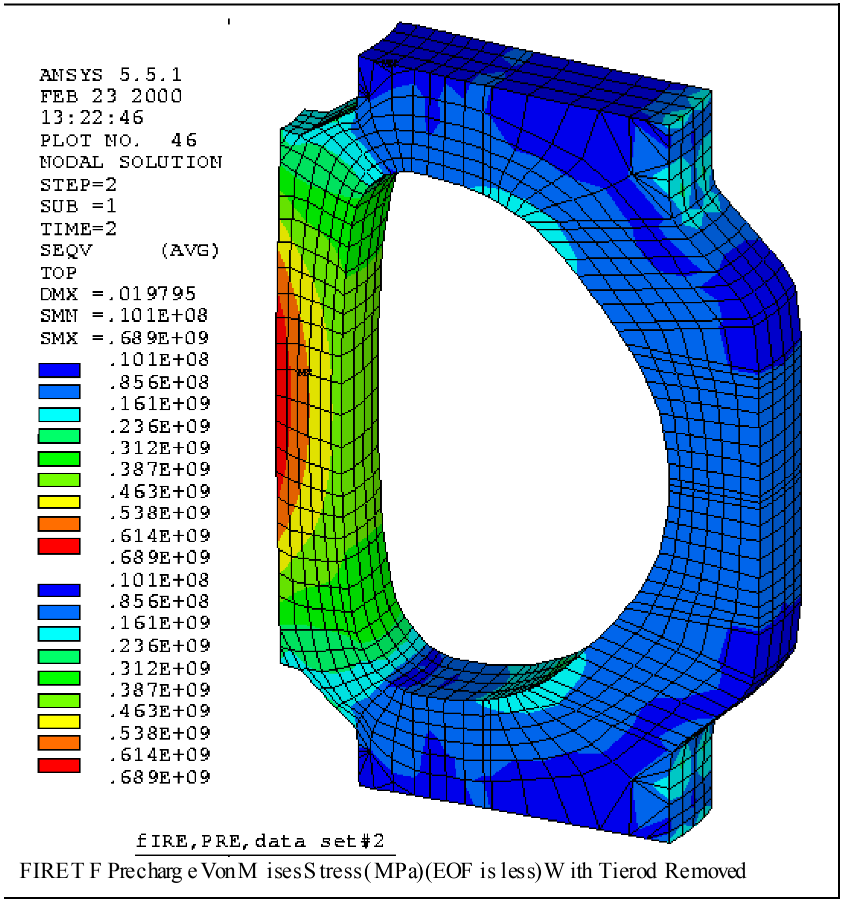
TF coils are being Designed with Added Margin.

- **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

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 2ΩT, 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

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

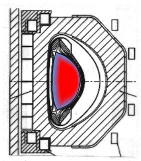
Solutions to these issues would be a major output from a next step experiment.

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

Pfusion
= ~ 150 MW

Volume
= 27 m^3

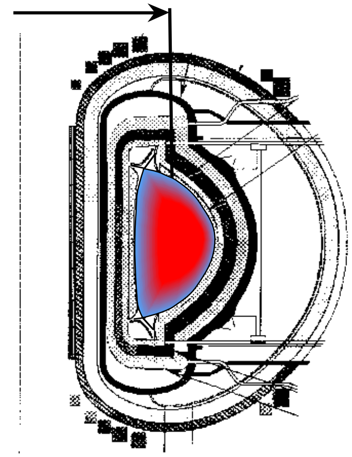
B = 10 T
R = 2.14 m
→



FIRE

~ 3X

B = 8 T
R = 5.5 m



ARIES-RS The “Goal”

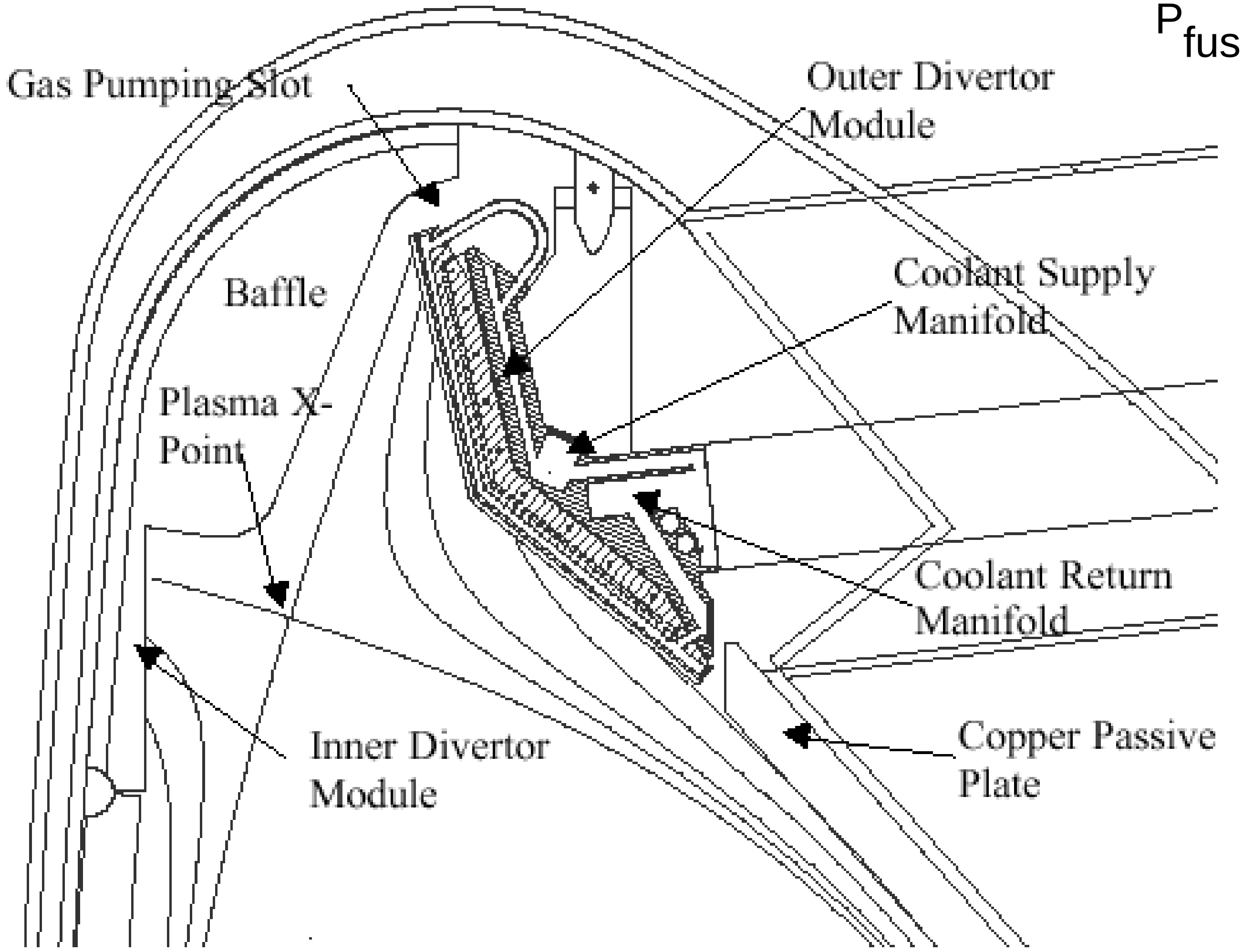
Pfusion
= 2170 MW

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

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

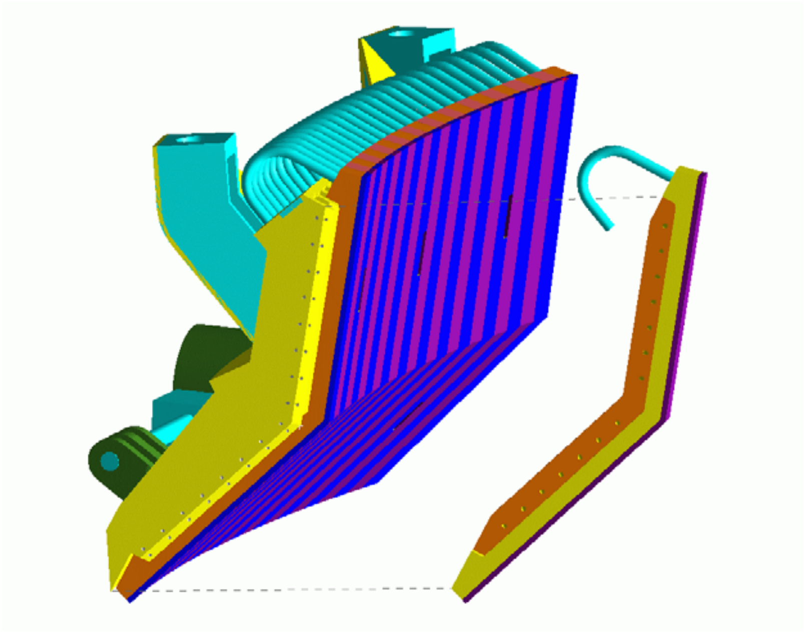
P_{fusion} < 200 MW



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

Divertor Module Components for FIRE

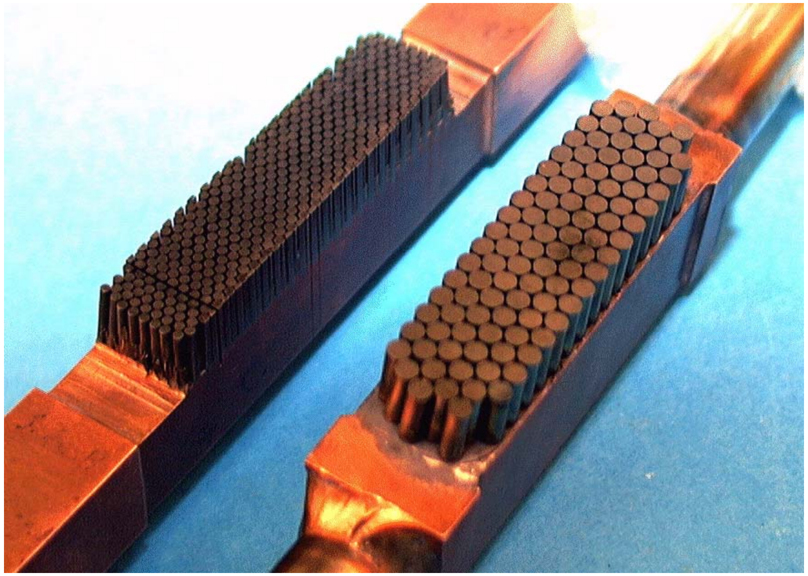
Sandia



Finger Plate for

Outer Divertor Module

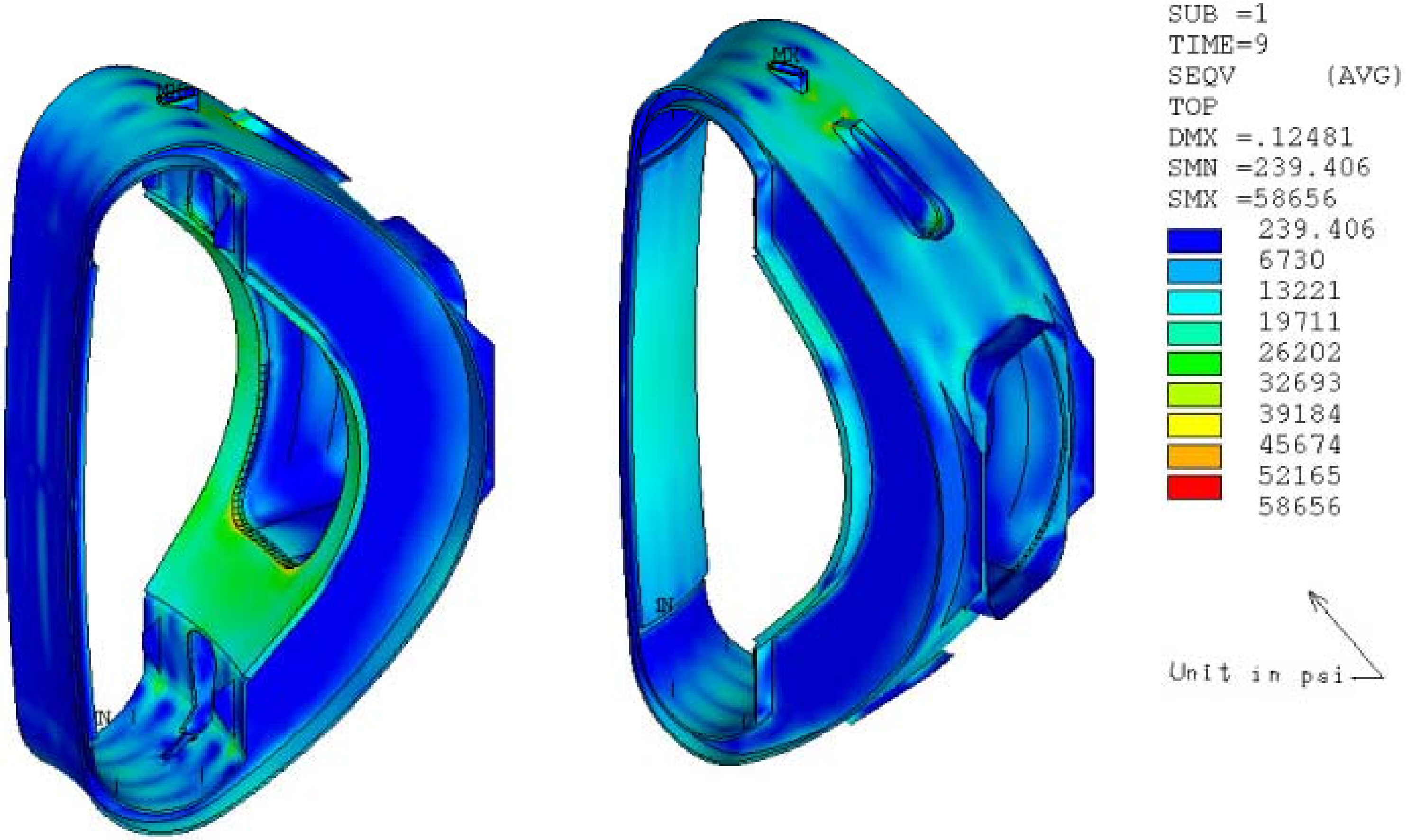
Two W Brush Armor Configurations Tested at 25 MW/m²



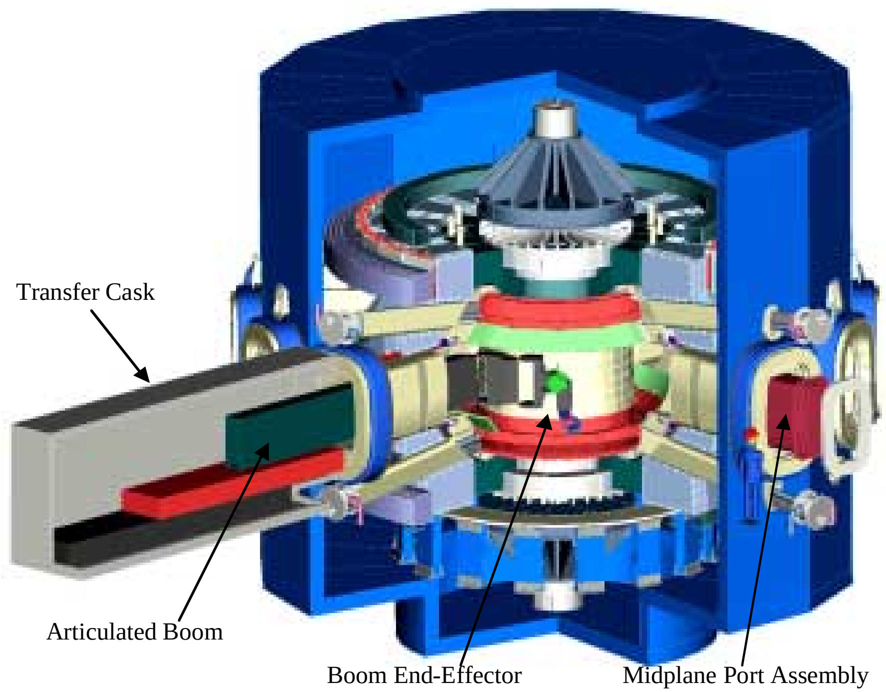
Carbon targets used in most experiments today are not compatible with tritiun inventory requirements of fusion reactors.

Combined stresses, 20 s pulse

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

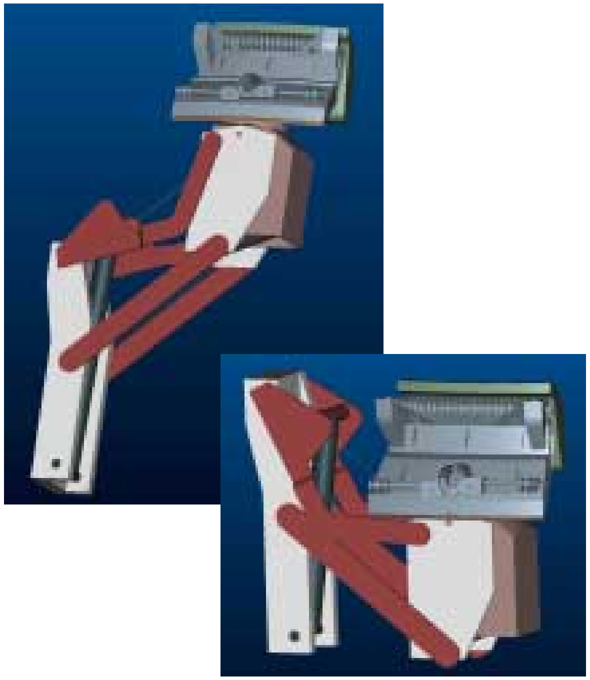


FIRE In-Vessel Remote Handling System



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

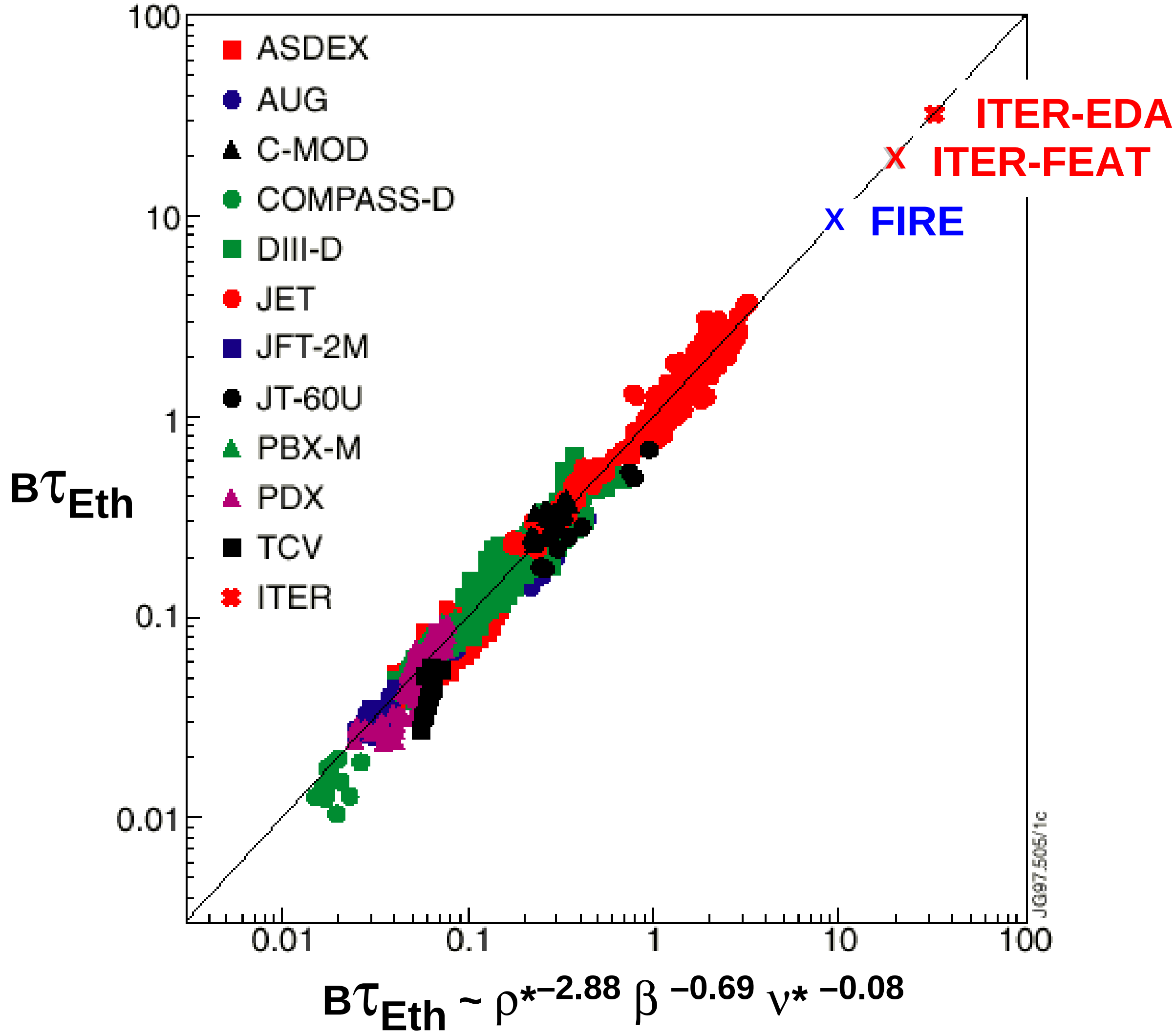
- High capacity (module wt. ~ 800 kg)
- Four positioning degrees of freedom
- Positioning accuracy of millimeters required

FIRE is a Modest Extrapolation in Plasma Confinement

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

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

Kadomtsev, 1975



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

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

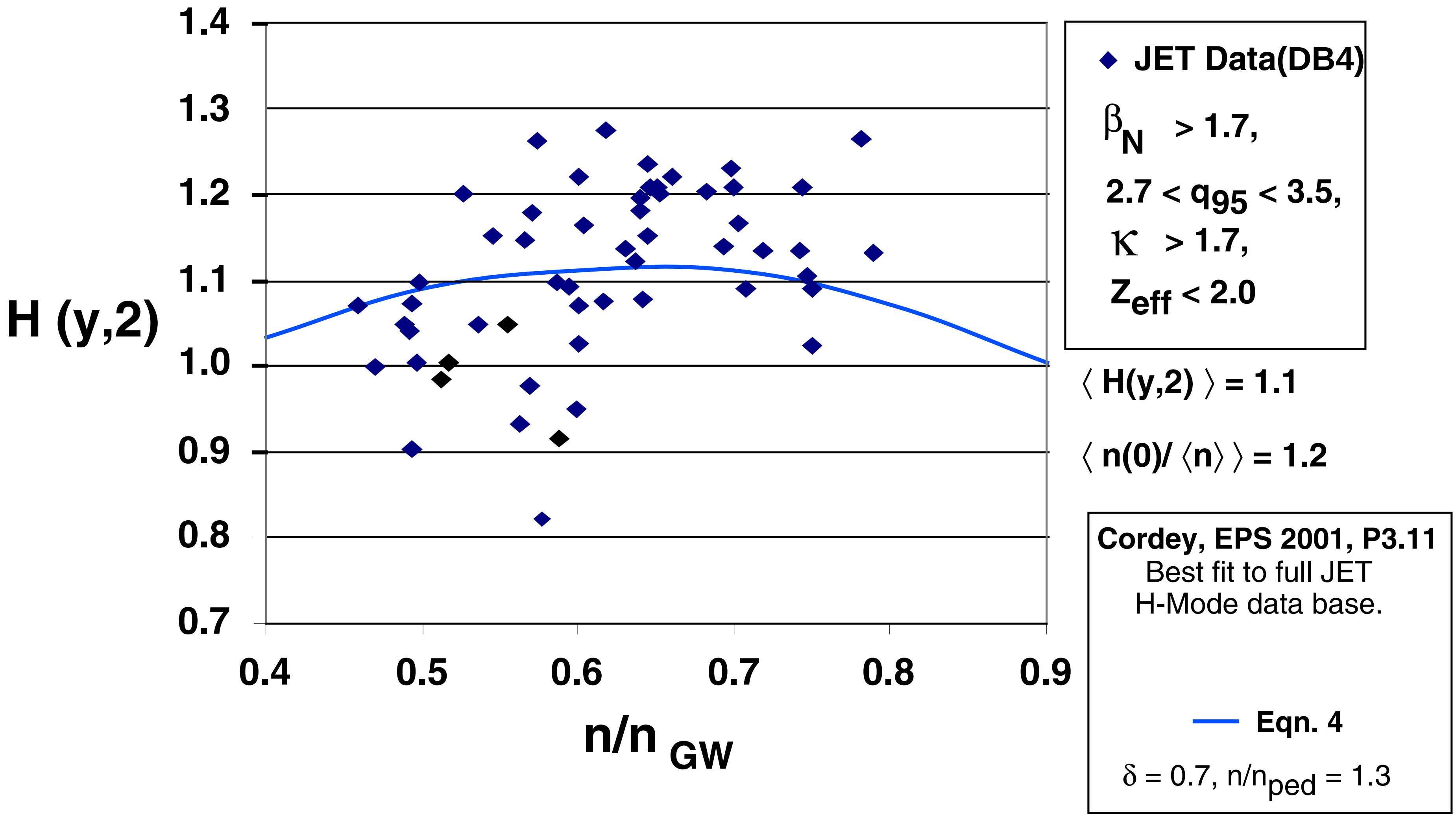
H-Mode Power Threshold - Based on today's tokamak data base

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

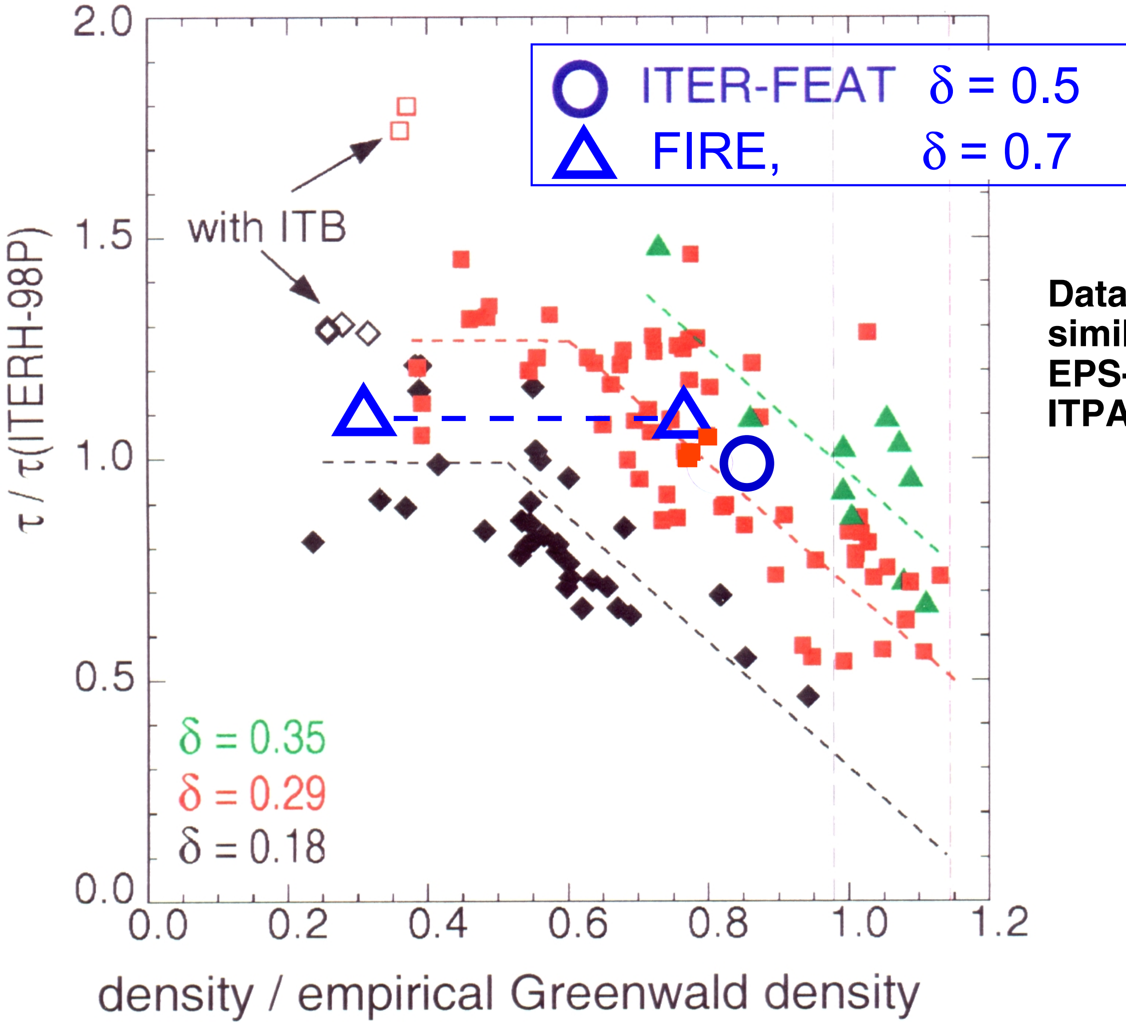
Helium Ash Confinement $\tau_{He} = 5\, \tau_E$, impurities = 3% Be, 0% W

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.

JET H-Mode Data Selected for FIRE-like Parameters



High Triangularity Enhances Confinement and Internal Transport Barrier (ITB) Formation

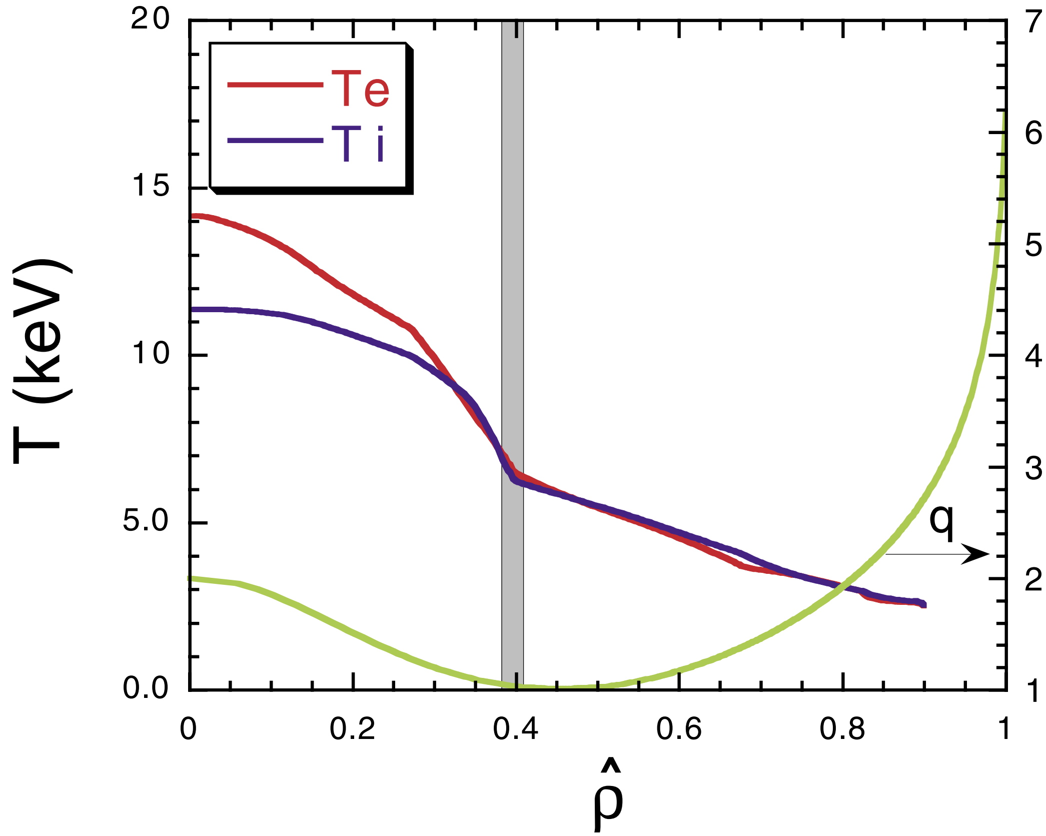


Data from ASDEX Upgrade similar results from others at EPS- June 2001 ITPA- September 2001 .

Similar conclusions from first principles physics modeling (GLF23)
- high triangularity and moderate n/n_{GW} facilitates ITB formation in FIRE.

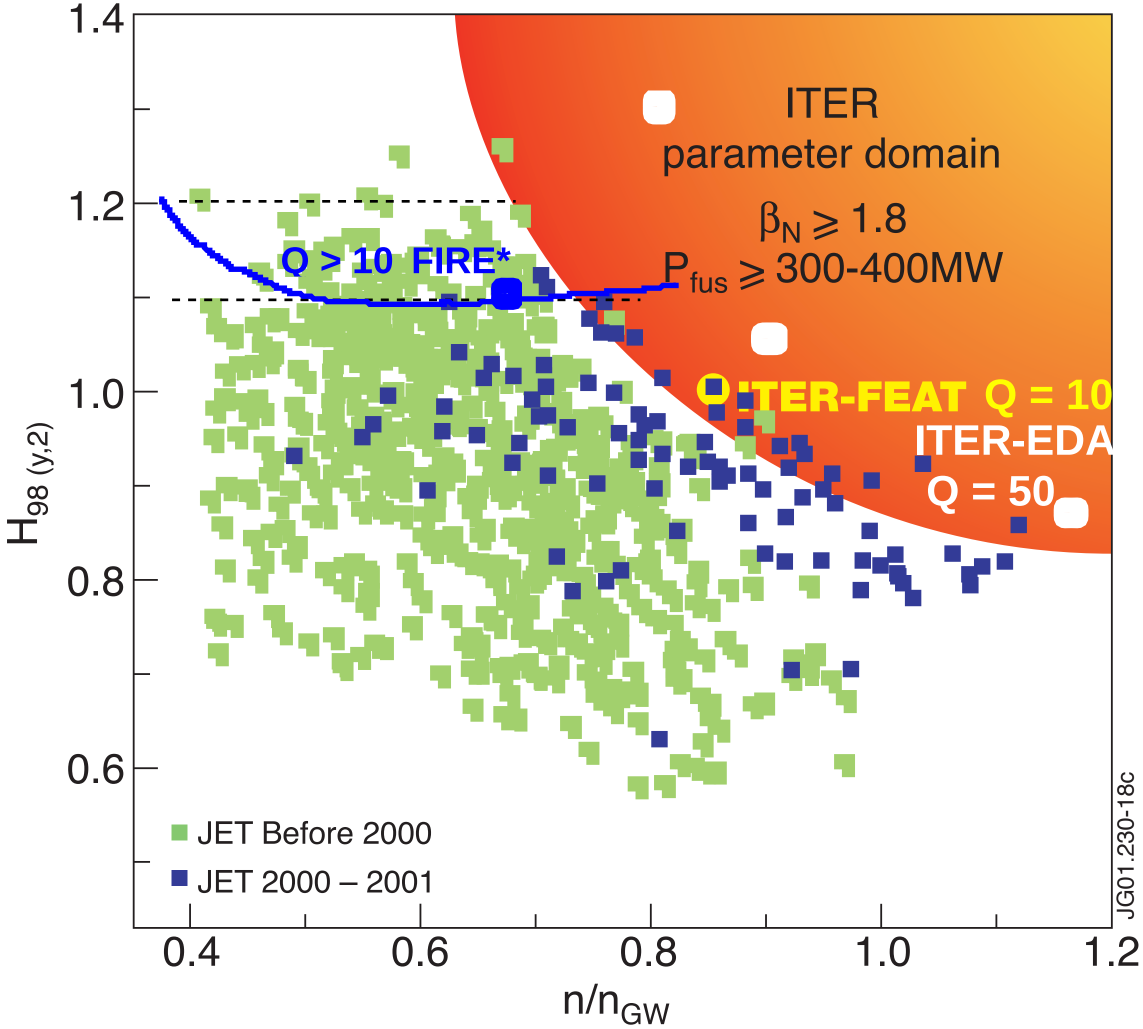
GLF23 Predicts an Internal Transport Barrier in FIRE as a Result of Shafranov-Shift Stabilization of the ITG Mode

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



Kinsey, Waltz and Staebler
UFA BPS Workshop 2

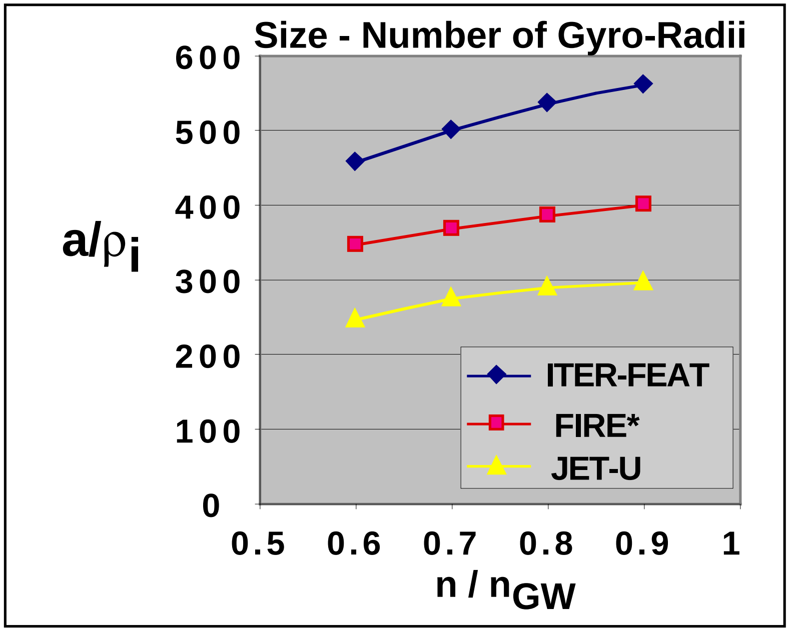
Comparison Operating Ranges of ITER-EDA, ITER-FEAT and FIRE with JET H-Mode Data

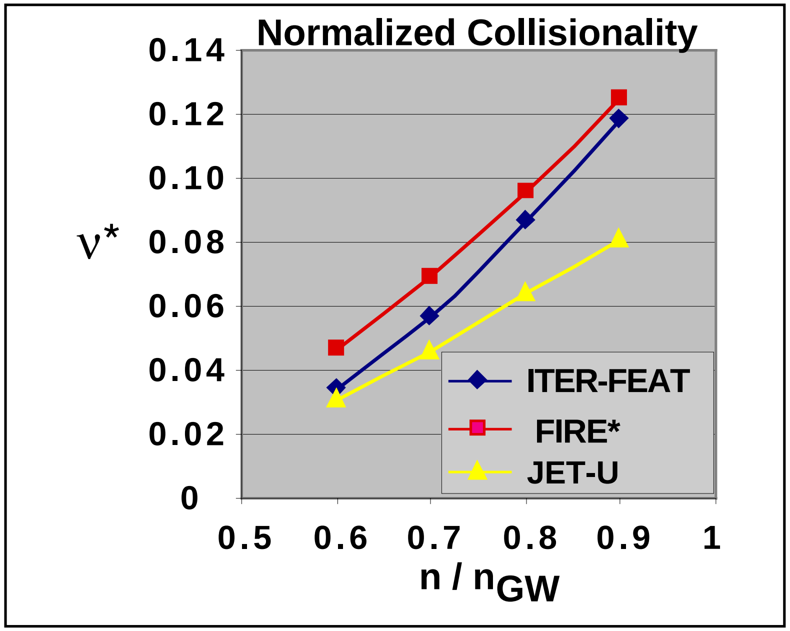


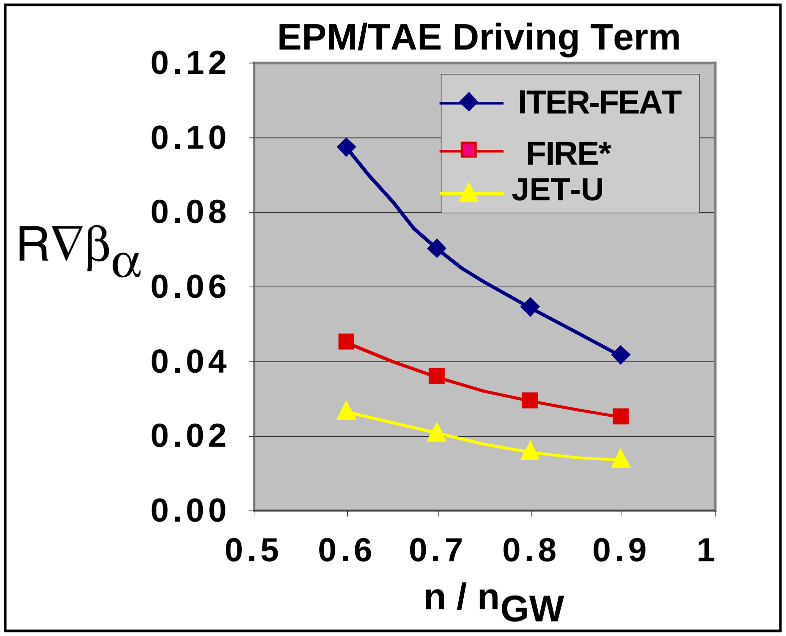
- Extension of JET parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \gtrsim 1.8$ using different approaches and
- In addition Plasma purity as required for ITER: Zeff ~ 1.5
- For quasi-stationary phases of several seconds
- **Consolidation of ITER Q = 10 Reference scenario**
- **FIRE and ITER exploit different parts of the data base. Note added - DMM**

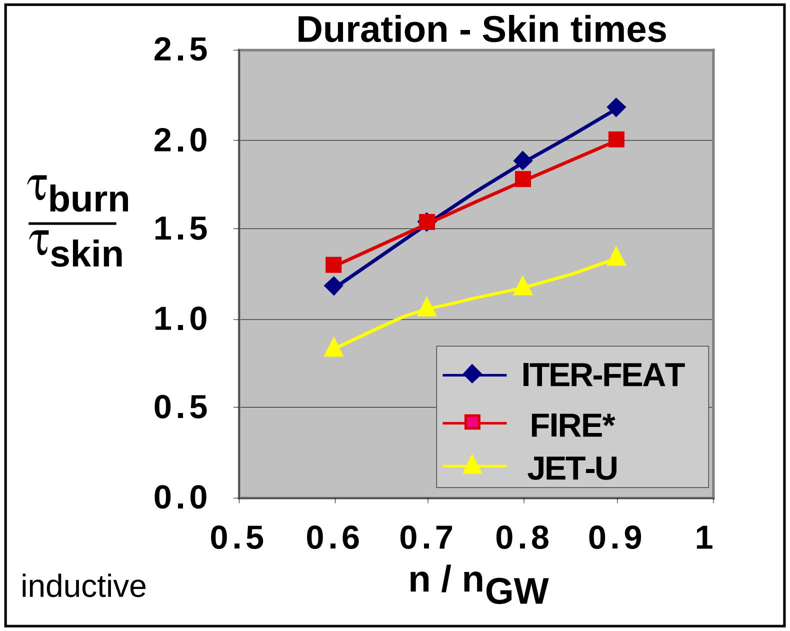
Parameters for H-Modes in Potential Next Step D-T Plasmas

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

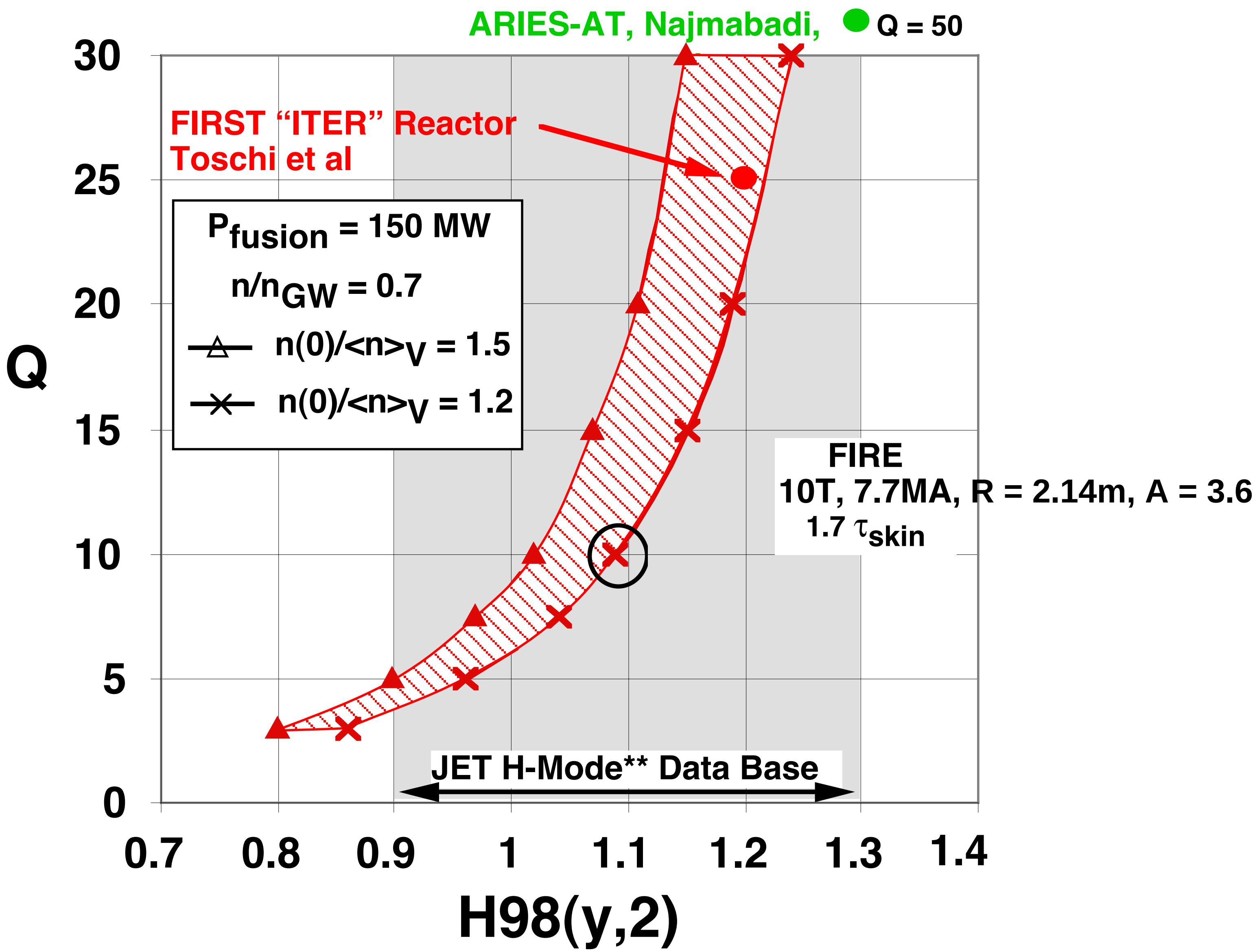




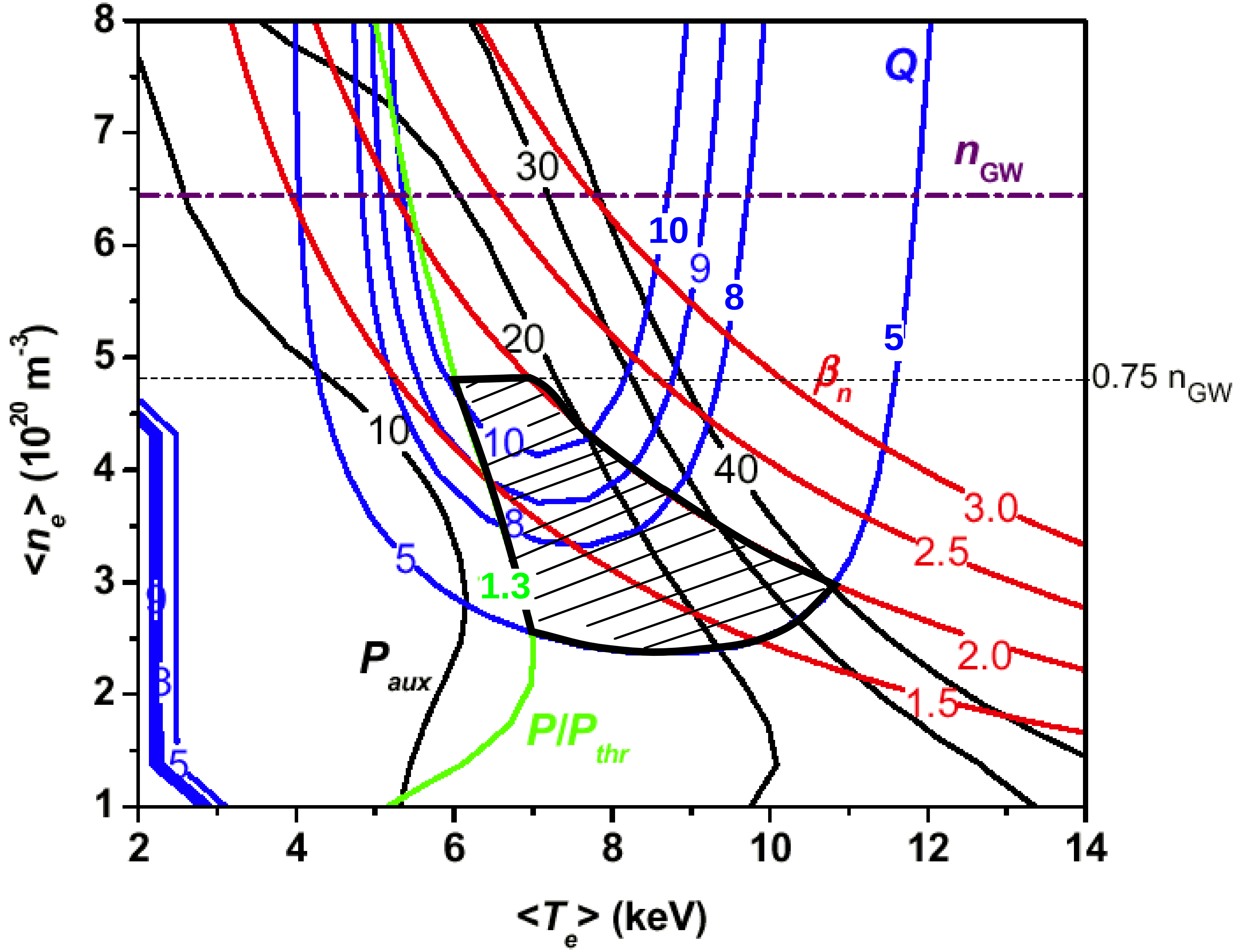




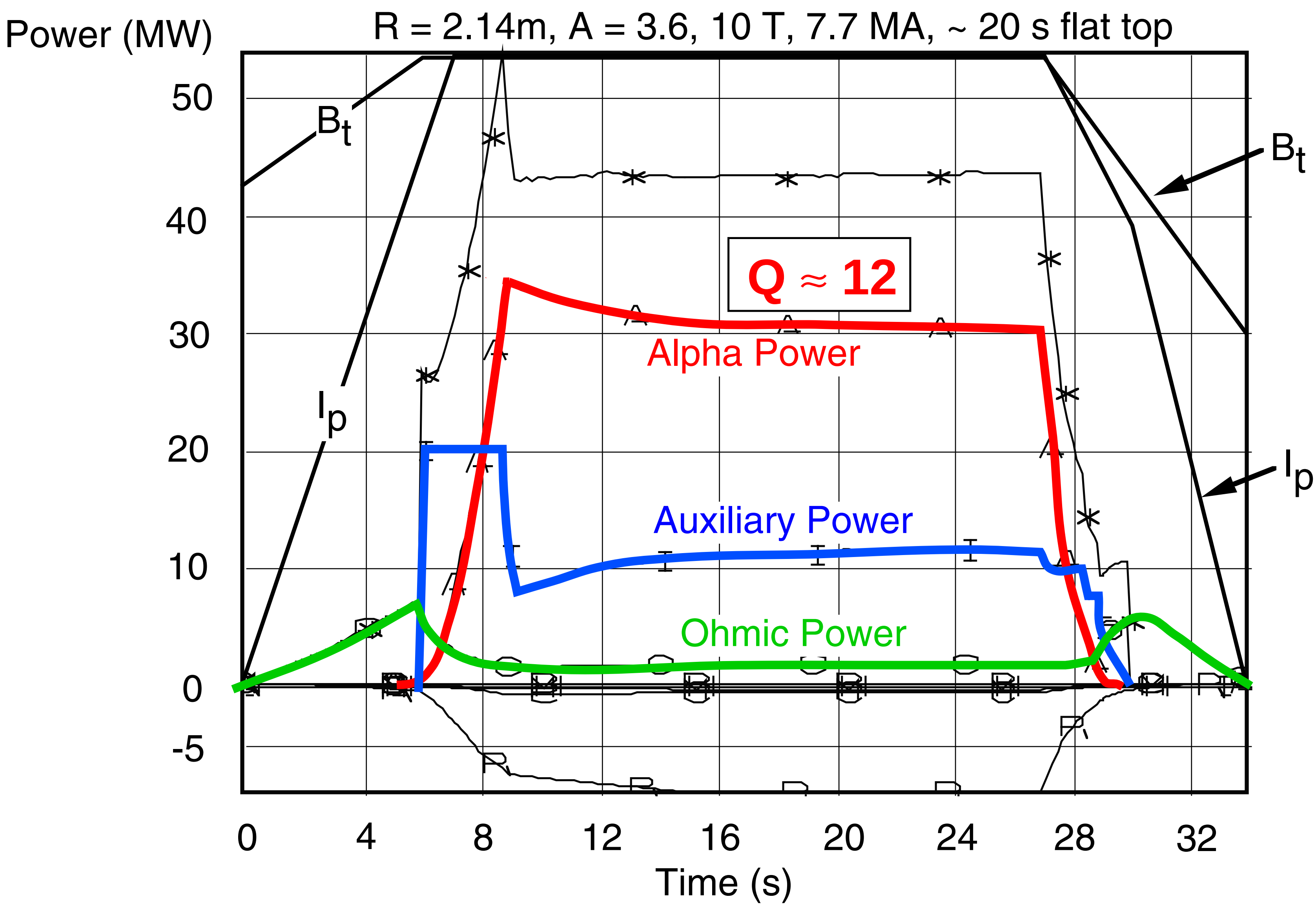
Projections to FIRE Compared to Envisioned Reactors



FIRE* 10T, 2.14m, 7.7 MA, H(y,2) = 1.14, α_n = 0.2



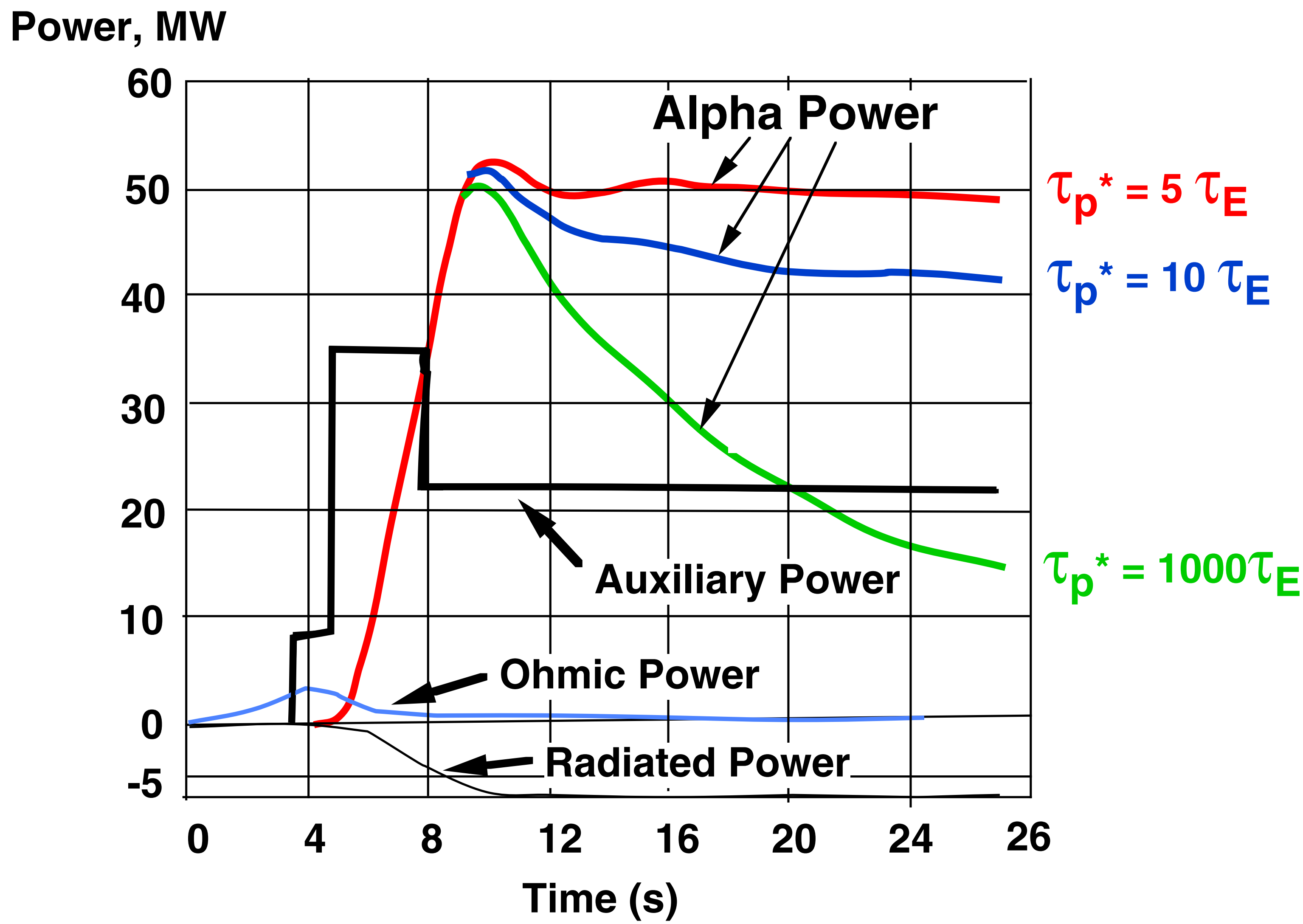
1 1/2-D Simulation of Burn Control in FIRE* (TSC)



- 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)

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

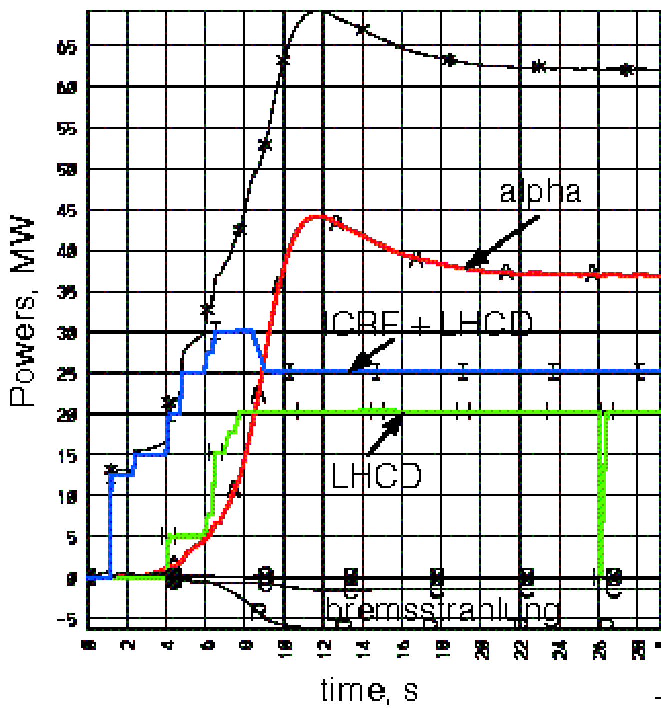


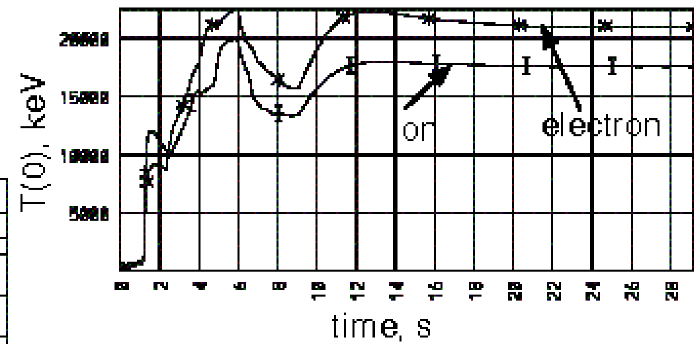
Fusion power can not be sustained without helium ash punping.

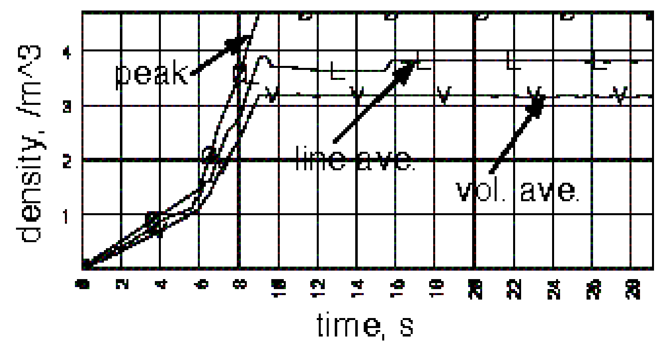
TSC/Kessel/21-q.ps
Early case - 1999

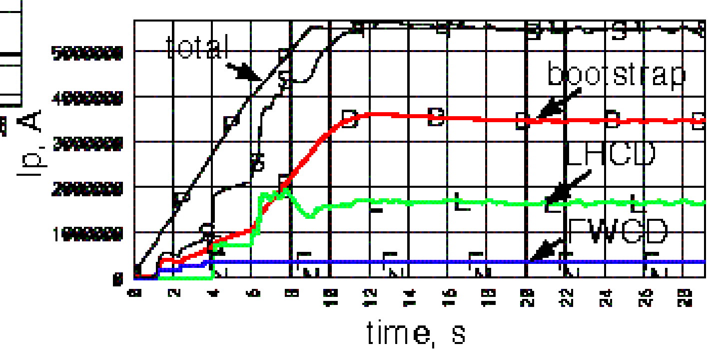
Dynamic Burning AT Simulations with TSC-LSC for FIRE

Ip=5.5 MA, Bt=8.5 T, Q=7.5,
β_N=3.0, β=4.4%, P_{LH}=20 MW,
I_{LH}=1.7 MA, I_{BS}=3.5 MA (64%),
I_{FW}=0.35 MA





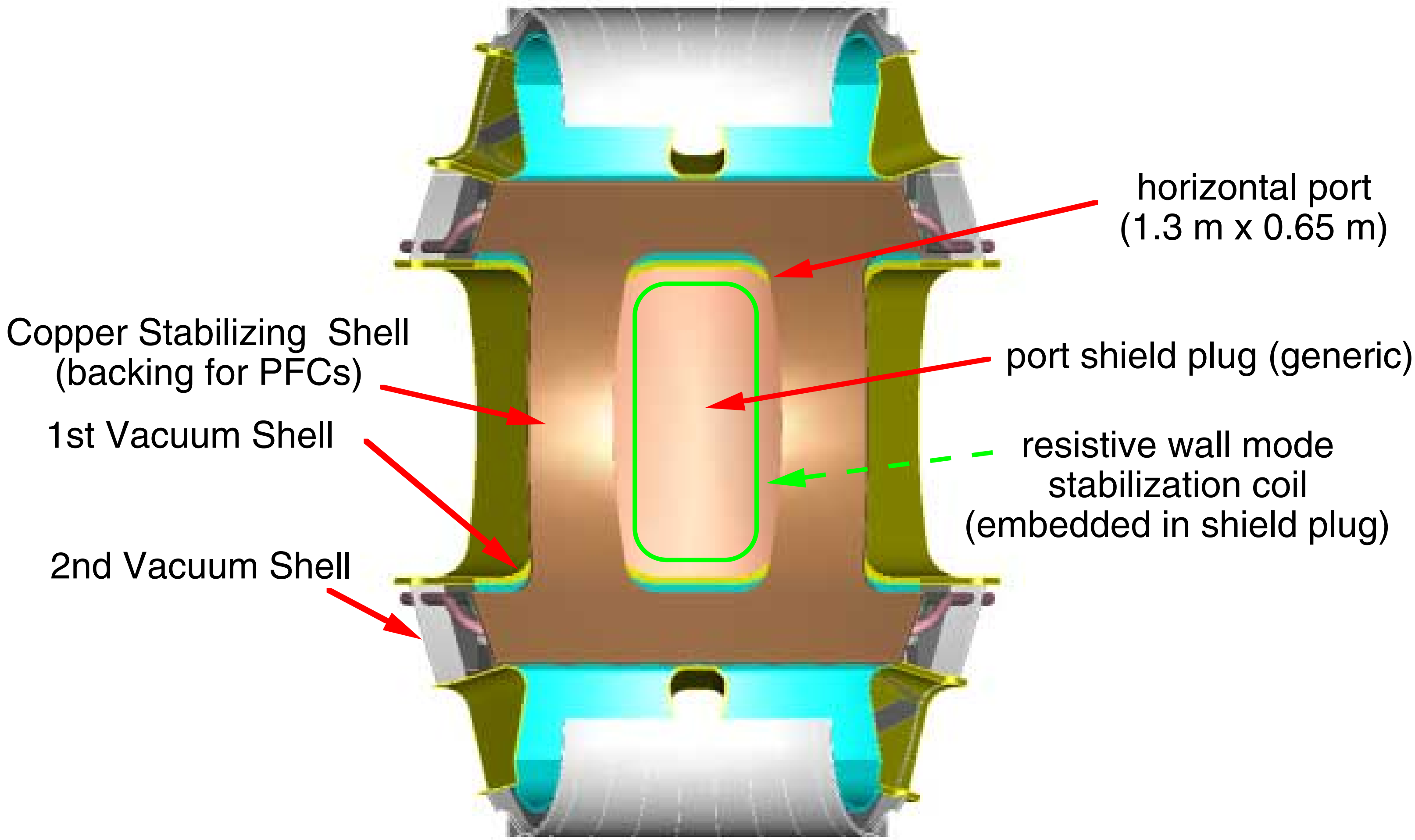




H(y,2)=1.6

Potential for Resistive Wall Mode Stabilization System

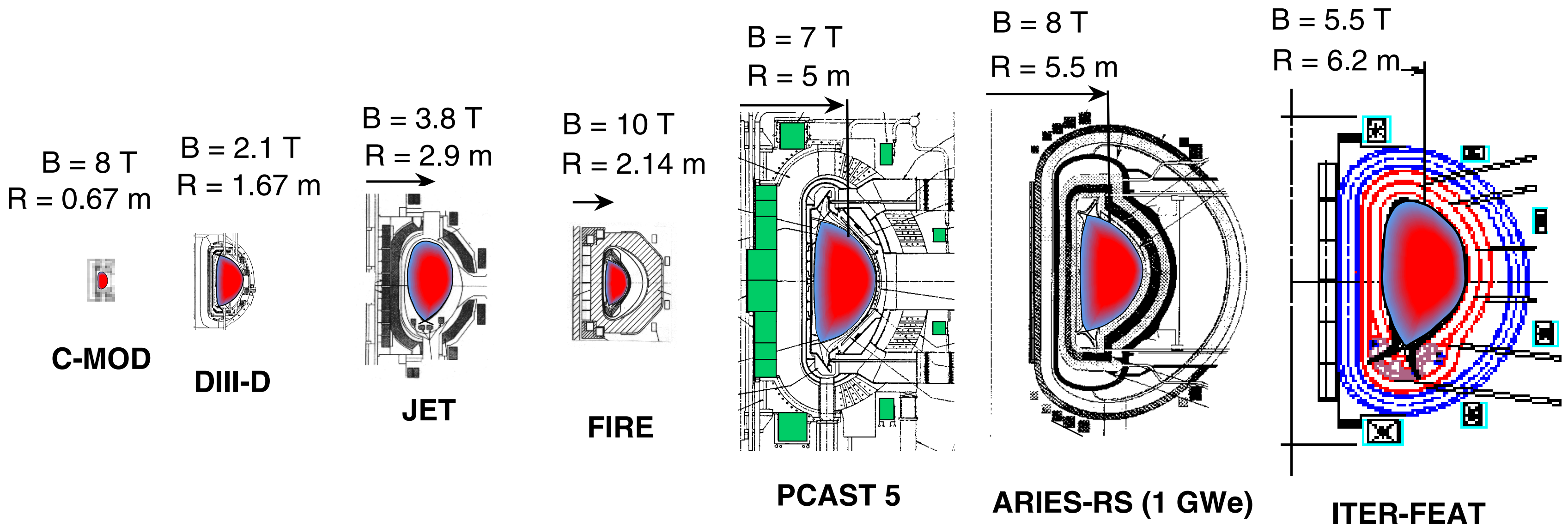
view of hoizontal port front looking from plasma side



Wall stabilization required to attain full Advanced Tokamak potential.

Concept under development by Columbia Univ. J. Bialek, G. Navratil, C.Kessel(PPPL) et al

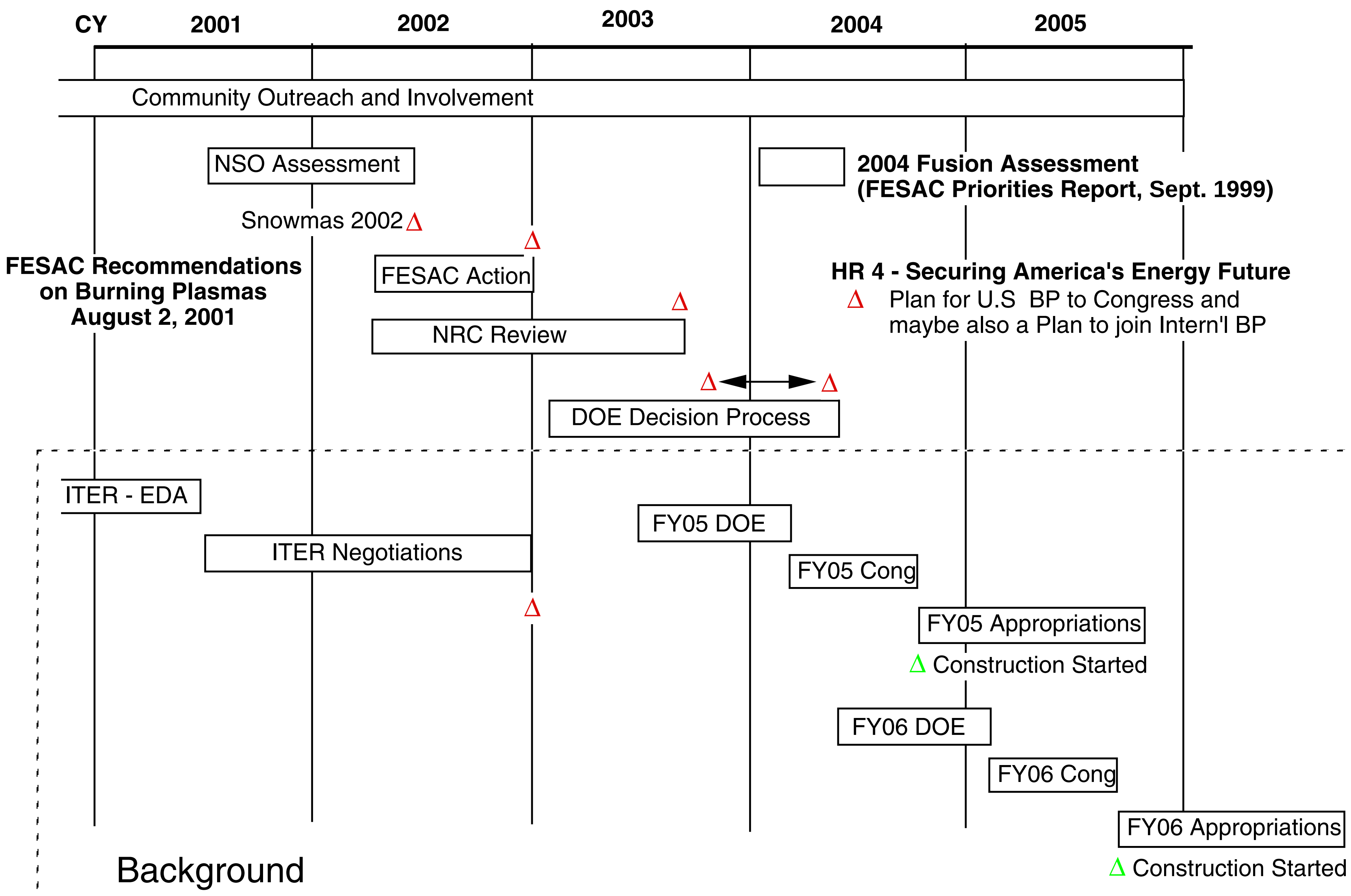
Advanced Tokamak Program Leading to an Attractive MFE Reactor



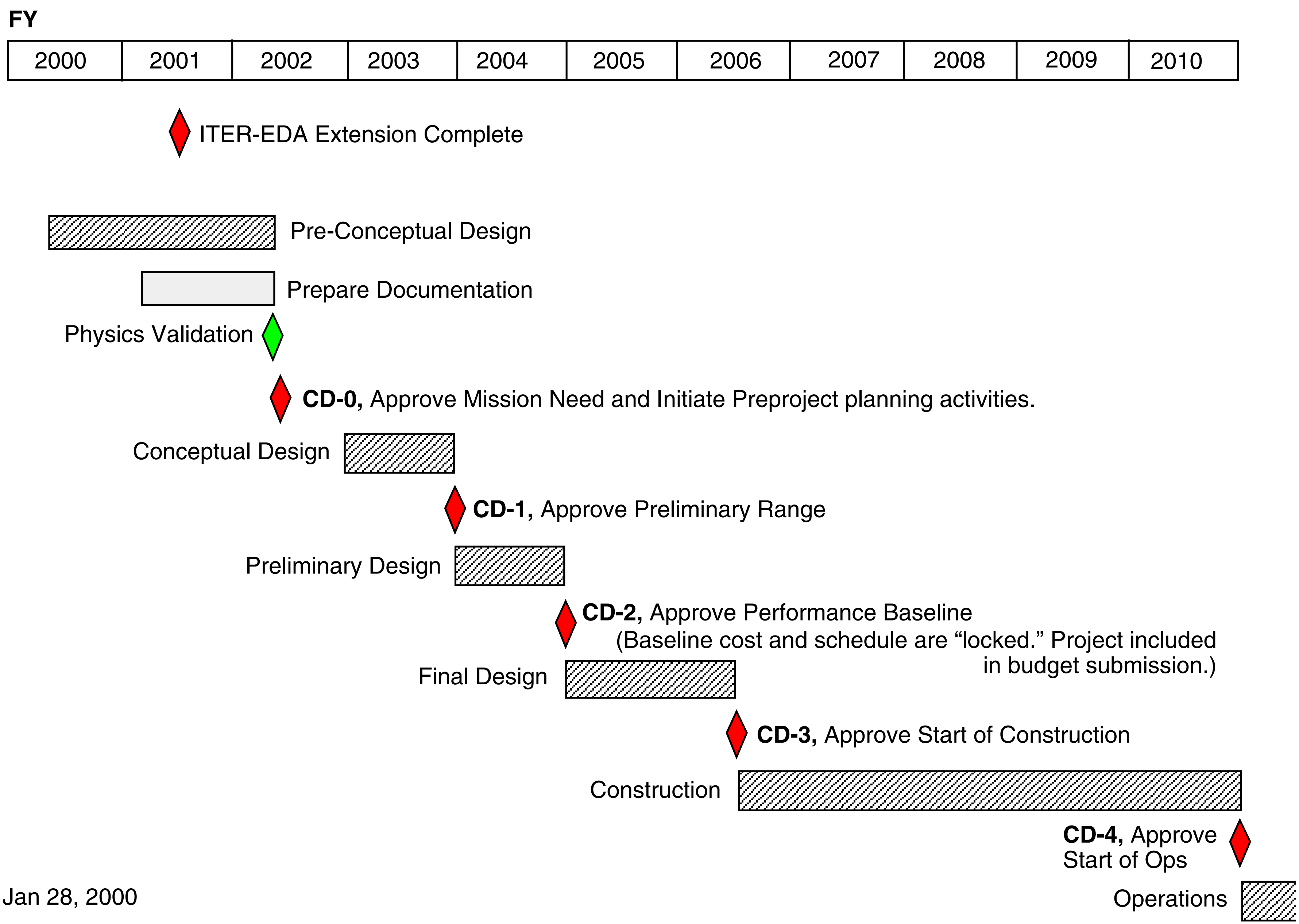
Cost Drivers	C-MOD	DIII-D	JET	FIRE	PCAST	ARIEs-RS	ITER-FEAT
Plasma Volume (m^3)	1	18	95	27	390	350	828
Plasma Surface (m^2)	2	30	180	60	420	390	610
Plasma Current (MA)	2	2	4	7.7	15	11.3	15
Magnet Energy (GJ)			1.6	5	40	85	50
Fusion Power (MW)			16	150	400	2170	400
Burn Duration (s), inductive		1	1	20	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

AR RS/ITERs/PCAST/FIRE-9a4

Recommended US Plan for Burning Plasmas

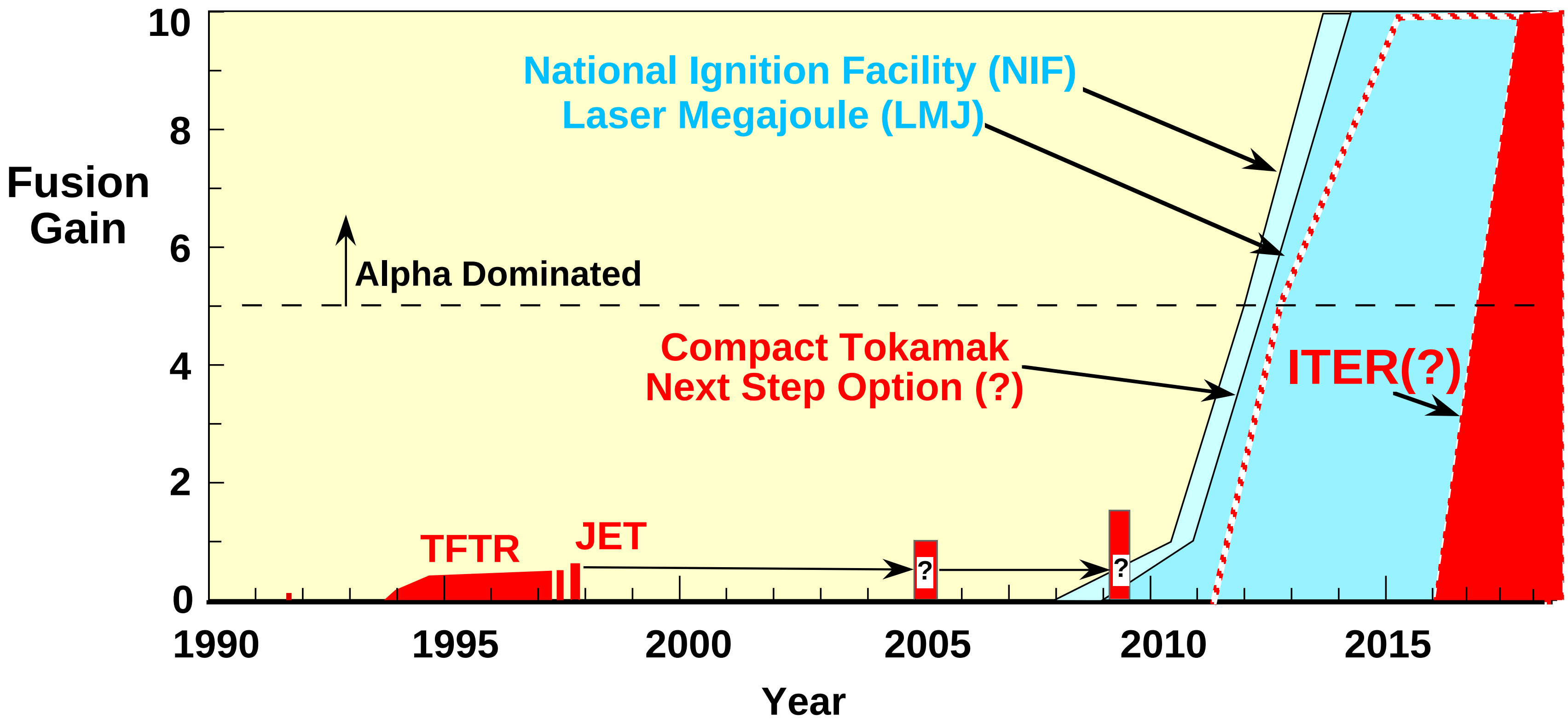


Illustrative Schedule for U.S. Burning Plasma Experiment



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 information "exists now" to make a technical assessment, and decision on MFE burning plasma experiments for the next decade.

Summary

- The FIRE "Pre-Conceptual" design point has been chosen to be a "stepping stone" between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.

- A 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

  under quasi-stationary conditions in a $1B class facility.

- 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