Laboratories to Explore, Explain and Expand the Frontiers of Science

Fusion Ignition Research Experiment (FIRE)

A Next Step Option for Magnetic Fusion Research

Dale M. Meade
National FIRE Design Study Team

FIRE Physics Workshop
Princeton Plasma Physics Laboratory

May 1, 2000

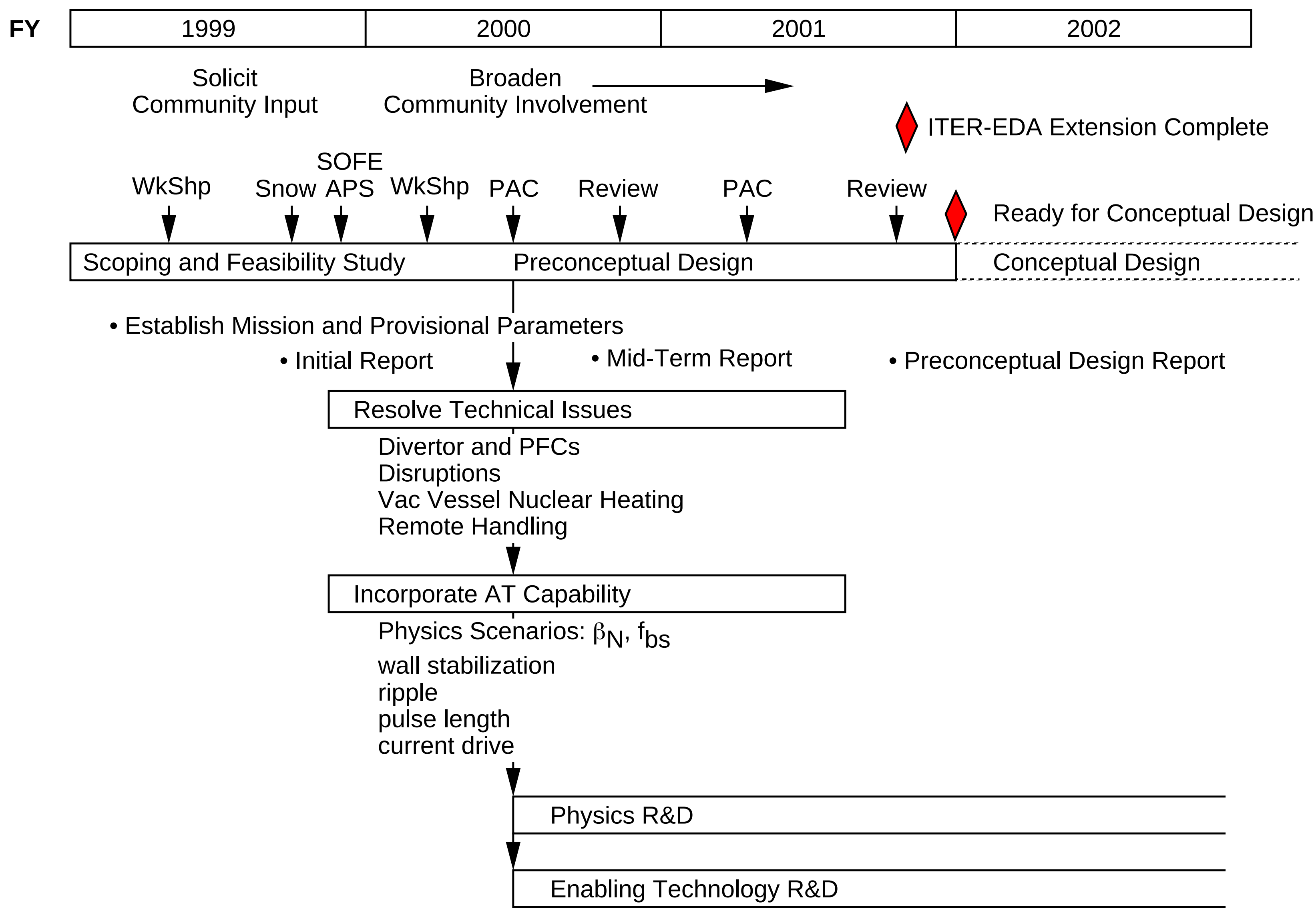
http://fire.pppl.gov

Contributors to the FIRE 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
Bechtel Technology and Consulting
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

Near Term Plan for an Advanced Tokamak Next Step (FIRE)



FIRE Physics Workshop 2000

- Welcome to the Workshop, we will be experimenting with some new methods of remote participation to improve future workshops. Remote particpants, please send email to fire@pppl.gov for access code.

- The goal of the workshop is:

to understand, assess and develop a plan
to address physics issues driving the FIRE design.

- Please fill out chits and submit them to discussion leader or me. We will use these to help develop a Physics R&D Plan for FIRE. We will post and respond to all chits.

- Focus on identifying high-leverage items for the “Discussion of Critical Issues, Opportunities and Needed Actions” on Wednesday.

Burning Plasma Physics is Widely Accepted as the Primary Objective for a Next Step in Fusion Research

- Grunder Panel and Madison Forum endorsed Burning Plasmas as next step.
- NRC Interim Report identified “integrated physics of a self-heated plasma” as one of the critical unresolved fusion science issues.
- The Snowmass Fusion Summer Study endorsed the burning plasma physics objective, and that the tokamak was technically ready for high-gain experiment.
- R. Pellat, Chair of the CCE-FU has stated that “the demonstration of a sustained burning plasma is the next goal” for the European Fusion Program.
- SEAB noted that “There is general agreement that the next large machine should, at least, be one that allows the scientific exploration of burning plasmas” and if Japan and Europe do not proceed with ITER “the U. S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost.” “In any event the preliminary planning for such a machine should proceed now so as to allow the prompt pursuit of this option.”

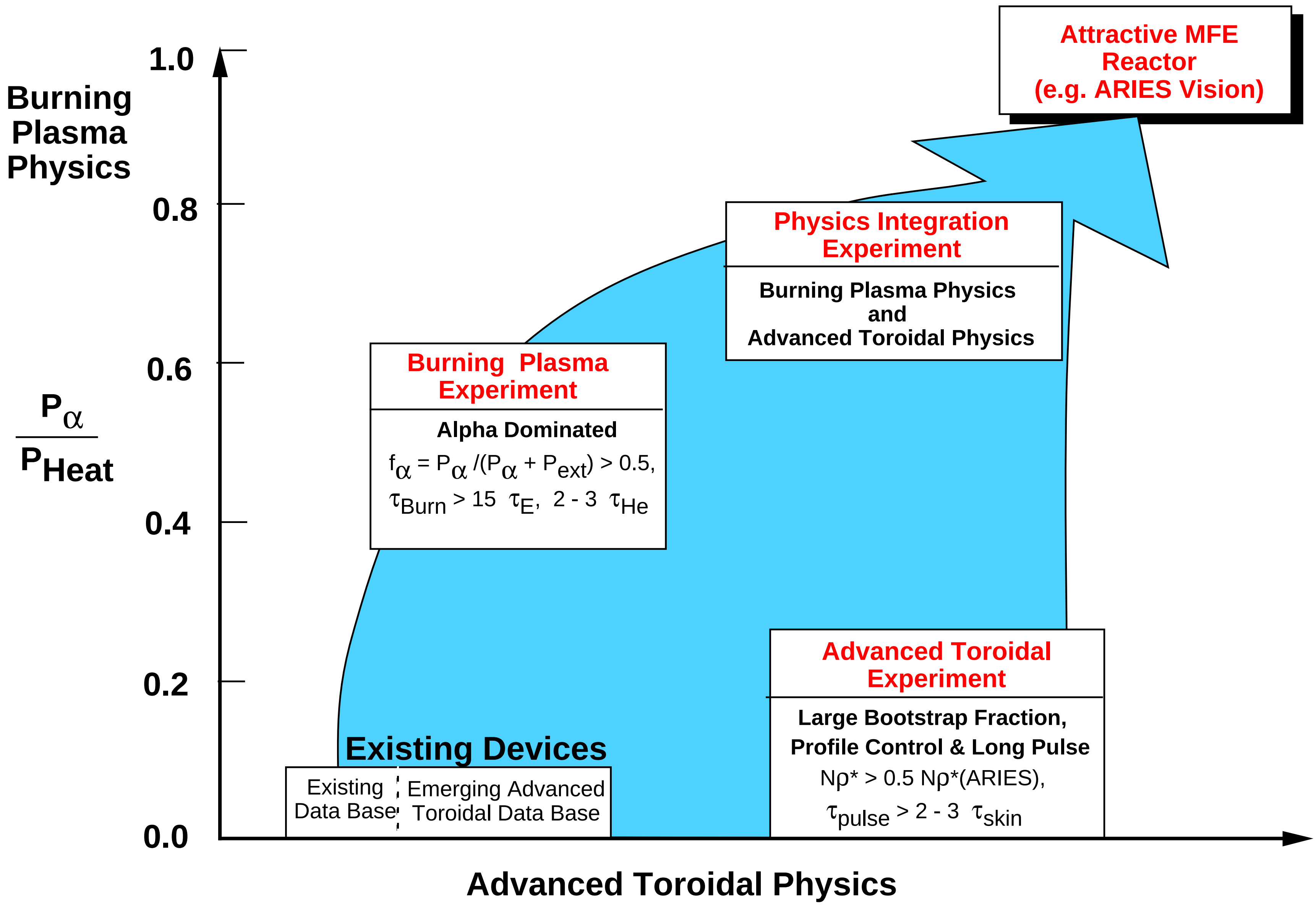
The Rosetta Stone for Fusion

	Fusion Energy	Fusion Science
plasma physics	$n\tau_E T$	ρ^*, ν^*, β $(BR^{5/4})$
burning physics	$Q = P_{fus}/P_{aux\text{-}heat}$	$f_\alpha = P_\alpha/(P_{aux\text{-}heat} + P_\alpha)$
time	s, min, hr	τ_E, τ_{skin}, etc
flexibility	low	high
availability	high	low
technology	nuclear	enabling

Fusion Science and Fusion Energy

have different languages, metrics, and missions.

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



What is the optimal position for the Stepping Stones to obtain the required information while minimizing cost and time?

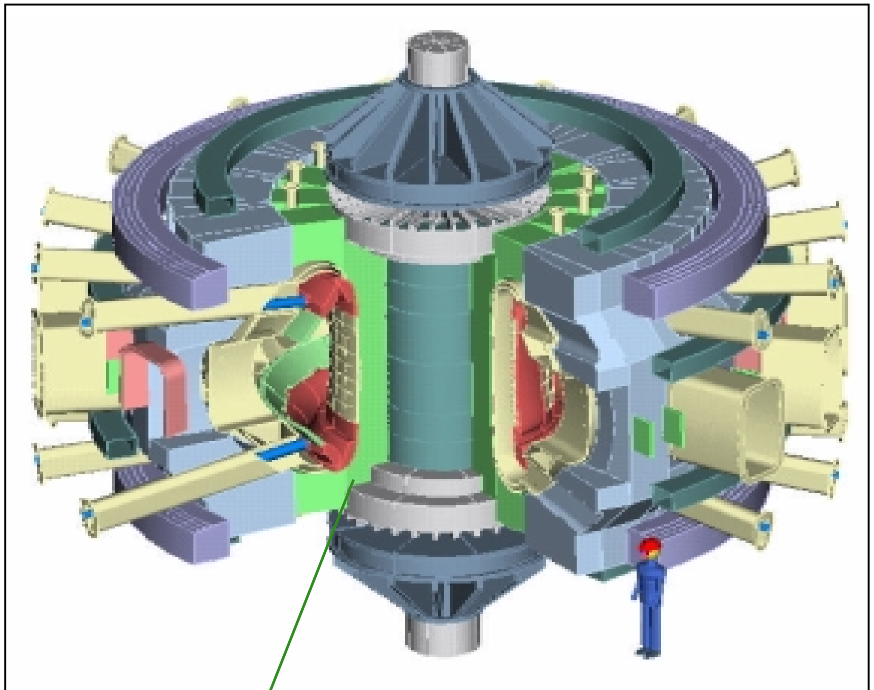
Burning Plasma Physics Objectives for a Fusion Ignition Research Experiment (FIRE)

- Explore and understand the physics of alpha-dominated fusion plasmas:
    - Energy confinement physics with alpha-dominated heating
    - β-limit physics with alpha- dominated heating **(self-organized)** [1]
    - Density limit physics with alpha- dominated heating
- Control alpha- dominated plasmas (e.g., modification of plasma profiles)

- Sustain alpha- dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effect of alpha-heating on the evolution of bootstrap current profile. **(self-organized)** [2]
- Exploration of alpha- dominated burning plasma physics in some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.
- Understand the effects of fast alpha particles on plasma stability.

Attain, explore, understand and optimize dominantly self-organized plasmas to provide knowledge for the design of attractive Magnetic Fusion systems.

Fusion **I**gnition **R**esearch **E**xperiment
(FIRE)



LN BeCu ("HTS")

Design Goals

- **R = 2.0 m, a = 0.525 m**
- **B = 10 T, (12T)***
- **W_{mag}= 3.8 GJ, (5.5 GJ)***
- **I_p = 6.5 MA, (7.7 MA)***
- **$P_{alpha} > P_{aux}$, P_{fusion} ~ 220 MW**
- **Q ~ 10, τ_E ~ 0.55s**
- **Burn Time ~ 20s (12s)***
- **Tokamak Cost ≤ \$0.3B**

  Base Project Cost ≤ \$1B

* Higher Field Upgrade

Attain, explore, understand and optimize dominantly self-organized plasmas to provide knowledge for the design of attractive MFE systems.

Basic Parameters and Features of FIRE Reference Baseline

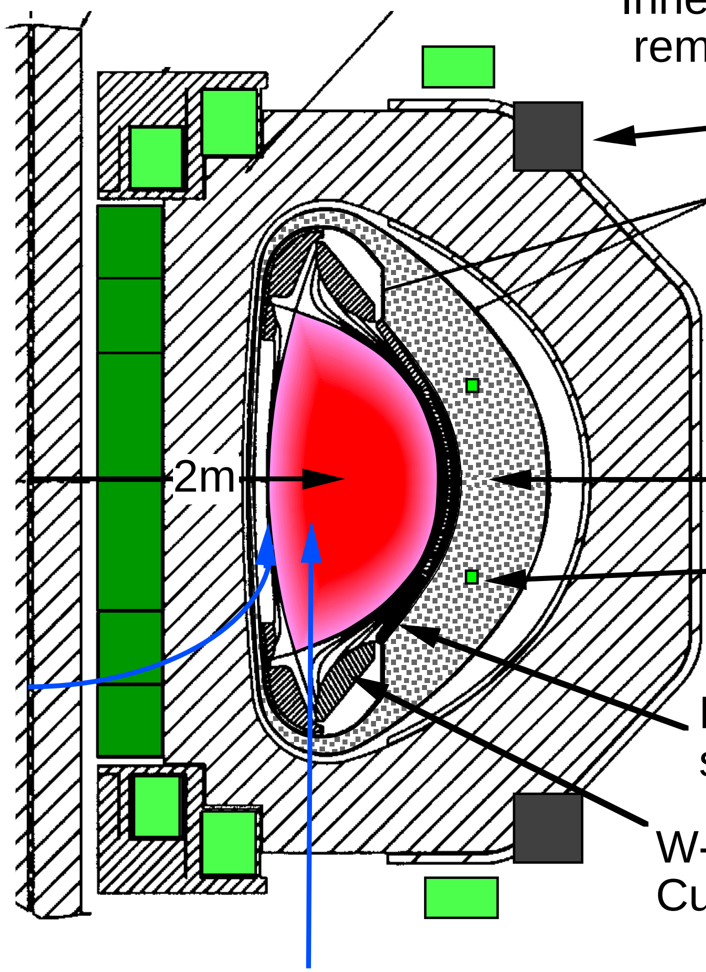
R, major radius	2.0 m
a, minor radius	0.525 m
κ95, elongation at 95% flux surface	~1.8
δ95, triangularity at 95% flux surface	~0.4
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, < 0.5% ripple @ Outer MP
Toroidal magnet energy	3.7 GJ
Ip, plasma current	~6.5 MA (7.7 MA at 12 T)
Magnetic field flat top, burn time	21 s at 10 T, P_{fusion} ~ 200 MW)
Pulse repetition time	2 hr @ full field
ICRF heating power, maximum	30 MW, 100MHz for $2\Omega_T$, 4 mid-plane ports
Neutral beam heating	None, may have diagnostic neutral beam
Lower Hybrid Current Drive	None in baseline, upgrade for AT phase
Plasma fueling	Pellet injection (≥2.5km/s vertical launch inside mag axis, possible guided slower speed pellets)
First wall materials	Be tiles, no carbon
First wall cooling	Inertial between pulses
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-inertial, outer plate active - water
Fusion Power/ Fusion Power Density	~200 MW, ~10 MW m-3 in plasma
Neutron wall loading	~ 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

Design Upgrade at B = 12T and Ip = 7.7MA with a 12 second flat top has been identified.

FIRE Incorporates Advanced Tokamak Innovations

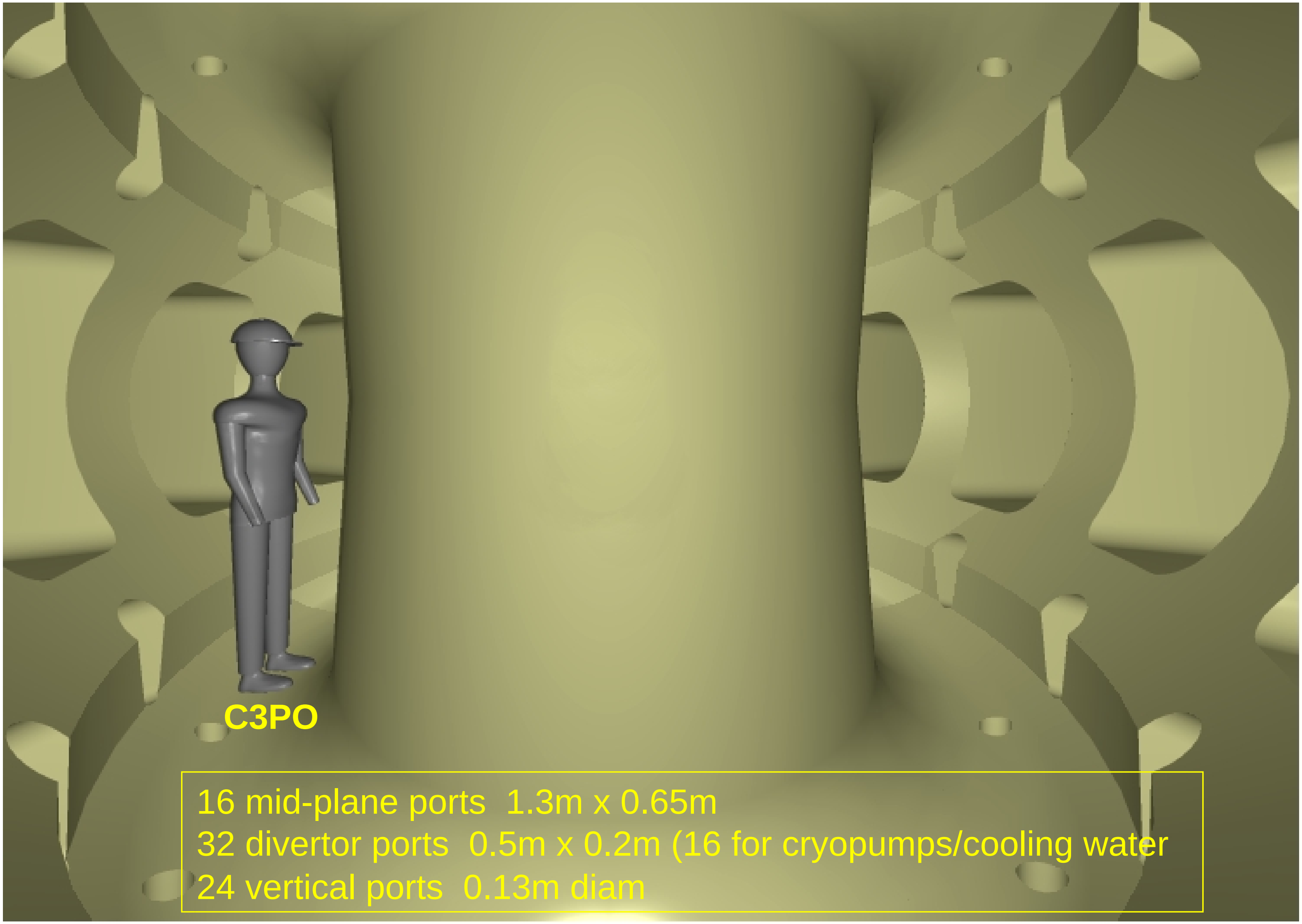
AT Features

- DN divertor
- strong shaping
- very low ripple
- 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.

FIRE would have Access for Diagnostics and Heating



Guidelines for Estimating Plasma Performance

Confinement (Elmy H-mode) - Based on today's tokamak data base

$$\tau_E = 0.094\, I^{0.97}\, R^{1.7}\, a^{0.23}\, n_{20}^{0.41}\, B^{0.08} A_i^{0.2}\, \kappa^{0.67}\, P_{heat}^{-0.63}$$

Density Limit - Base on today's tokamak data base

$n_{20} \leq 0.75\, n_{GW} = 0.75\, I_p/\pi a^2$, H98 $\approx$ 1 up to 0.75 n_{GW} (JET, 1998)

Beta Limit - theory and tokamak data base

$\beta \leq \beta_N(I_p/aB)$, β_N ~2.5 conventional, β_N ~ 4 advanced

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

$Pth \geq (0.9/Ai)\, n^{0.75}\, B\, R^2$, nominal L to H, with H to L being ~ half when well below the density limit.

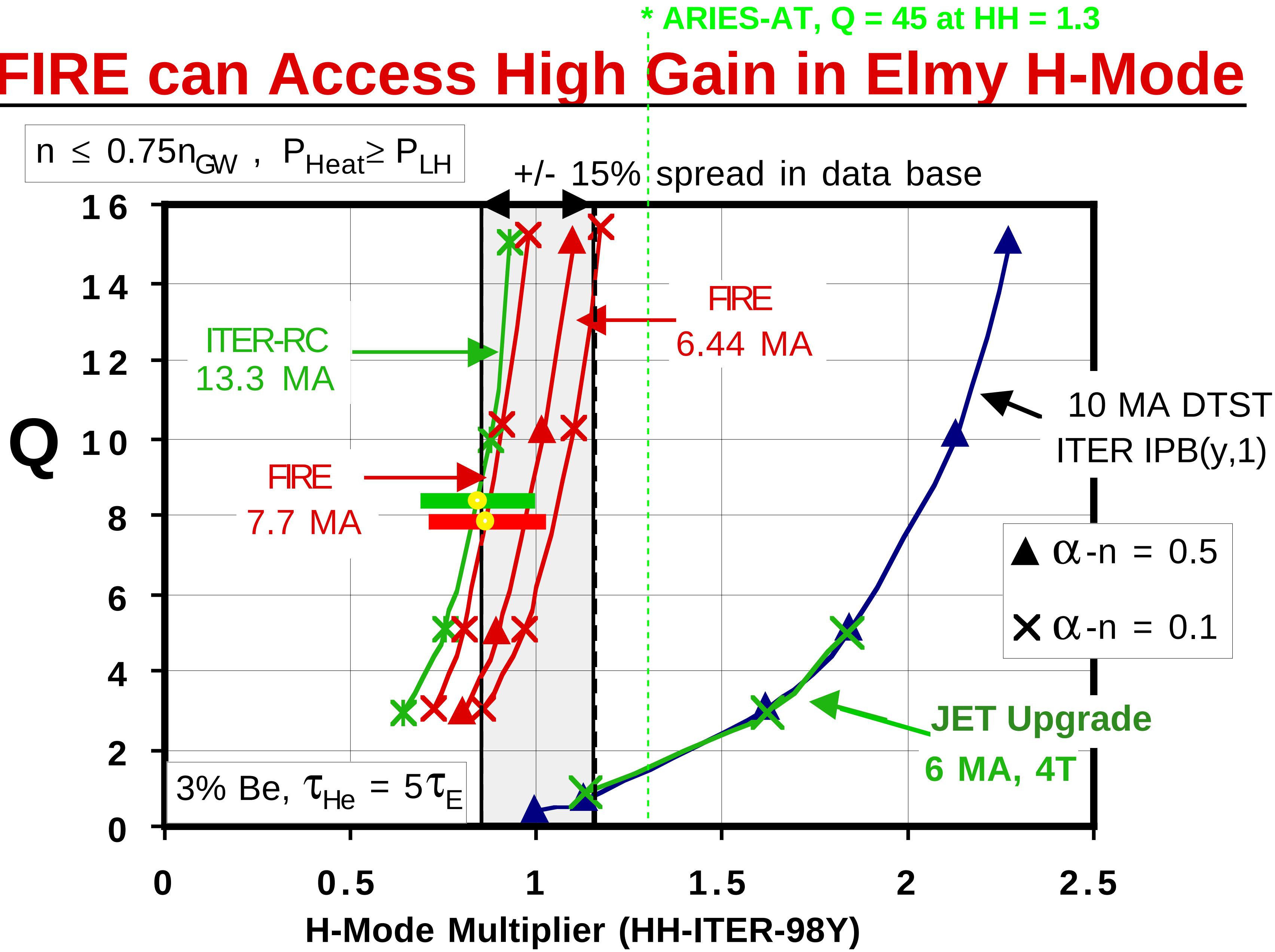
Helium Ash Confinement $\tau_{He} = 5\, \tau_E$, impurities = 3% Be

Workshop Action Item: What changes should be made to these guidelines?

Nominal FIRE Plasma Parameters from 0-D Simulations

R, plasma major radius, m	2.0
A, plasma minor radius, m	0.525
R/a , aspect ratio	3.8
κ_95, plasma elongation at 95% flux	1.77
δ_95, plasma triangularity at 95% flux	0.4
q_95	3.02
B_t, toroidal magnetic field, T	10
I_p, plasma current, MA	6.44
l_i(3), internal plasma inductance	0.8
Fraction of bootstrap current	0.25
Ion Mass, 50/50 D/T	2.5
<ne>, 10^20 /m^3, volume average	4.5
α_n, density profile peaking = 1 + α_n	0.5
<n>l/Greenwald Density Limit, ≤ 0.75	**0.70**
<T>n, density averaged temperature, keV	8.2
T(0), central temperature, keV	13.1
α_T, temperature profile peaking = 1 + α_T	1
Impurities, Be:high Z, %	3 : 0
Alpha ash accumulation, n_α/n_e, %	2.6
Zeff	1.41
ν*, collisionality at q = 1.5	0.043
P_ext , MW	22
P_fusion, MW	223
P_heat , MW	56.5
tau_p*(He)/tau_E	5.00
tau_E, energy confinement time s	0.57
ITER98H-multiplier, ≤1	**1.04**
ITER89P - Multiplier	2.41
$n_d(0)T(0)\tau_E$, 10^20 m^-3keVs	41.69
Q_DT	10.16
IA, MA	24.5
Plasma current redistribution time, s	13.9
Pheat/P(L->H), ≥ 1	**1.149**
W_p, plasma thermal energy, MJ	32.18
β_total, thermal plasma + alphas, %	3.11
β_N, ≤ 2.5	**2.54**
Core Plasma Pressure, atmospheres	~ 20

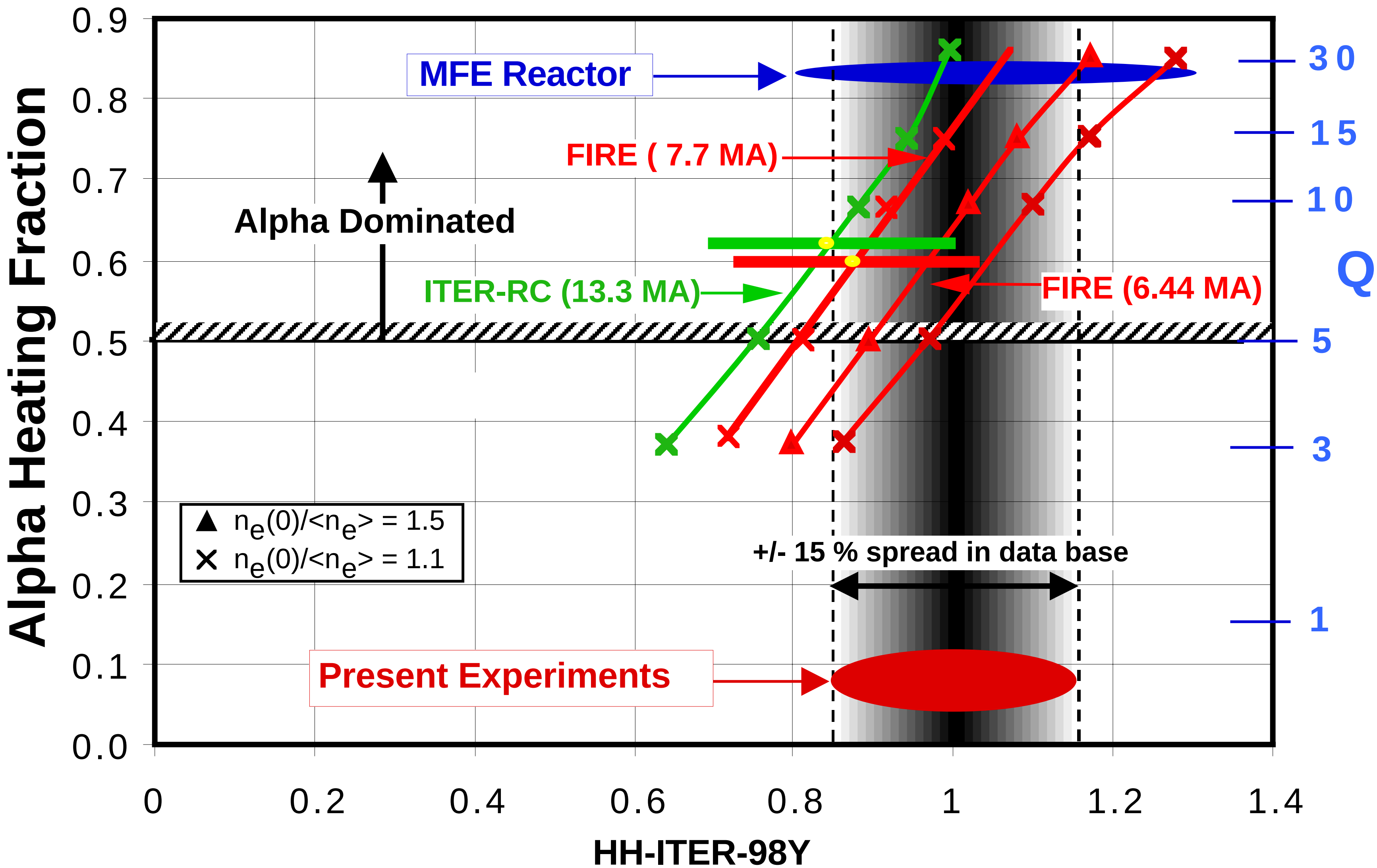
FIRE can Access High Gain in Elmy H-Mode



The baseline FIRE (6.44 MA) can access the alpha-dominated regime (Q > 5) for HH = 1.

The Energy Mission is vulnerable to uncertainties in confinement.

FIRE can Access Alpha-Dominated Plasmas in H-Mode

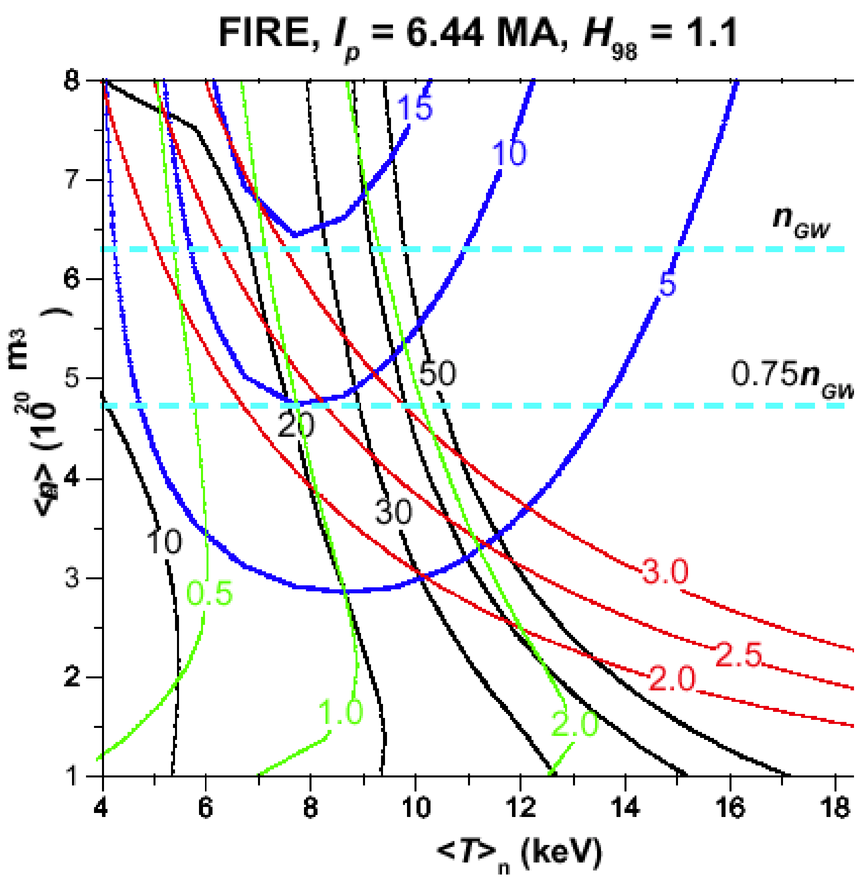


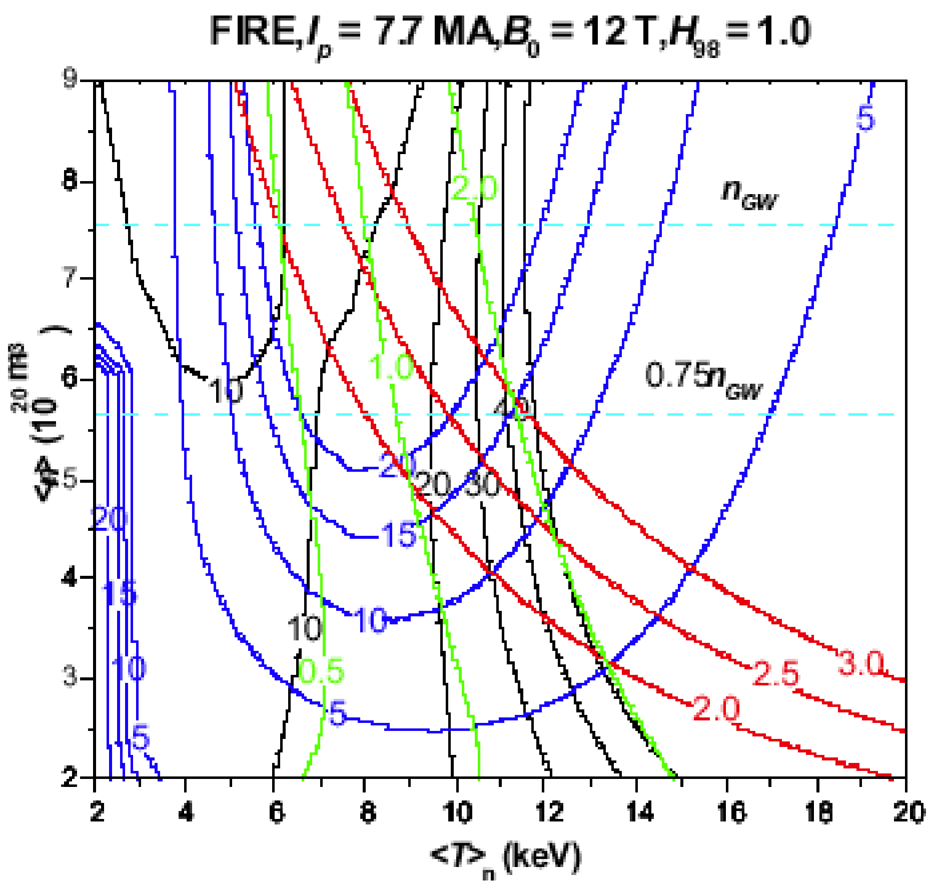
The Science Mission is robust to uncertainties in confinement.

falpha vs HH98-7/APS Cent

Baseline Operating Point can Access Q ~ 10
with Significant Operating Space for Q > 5

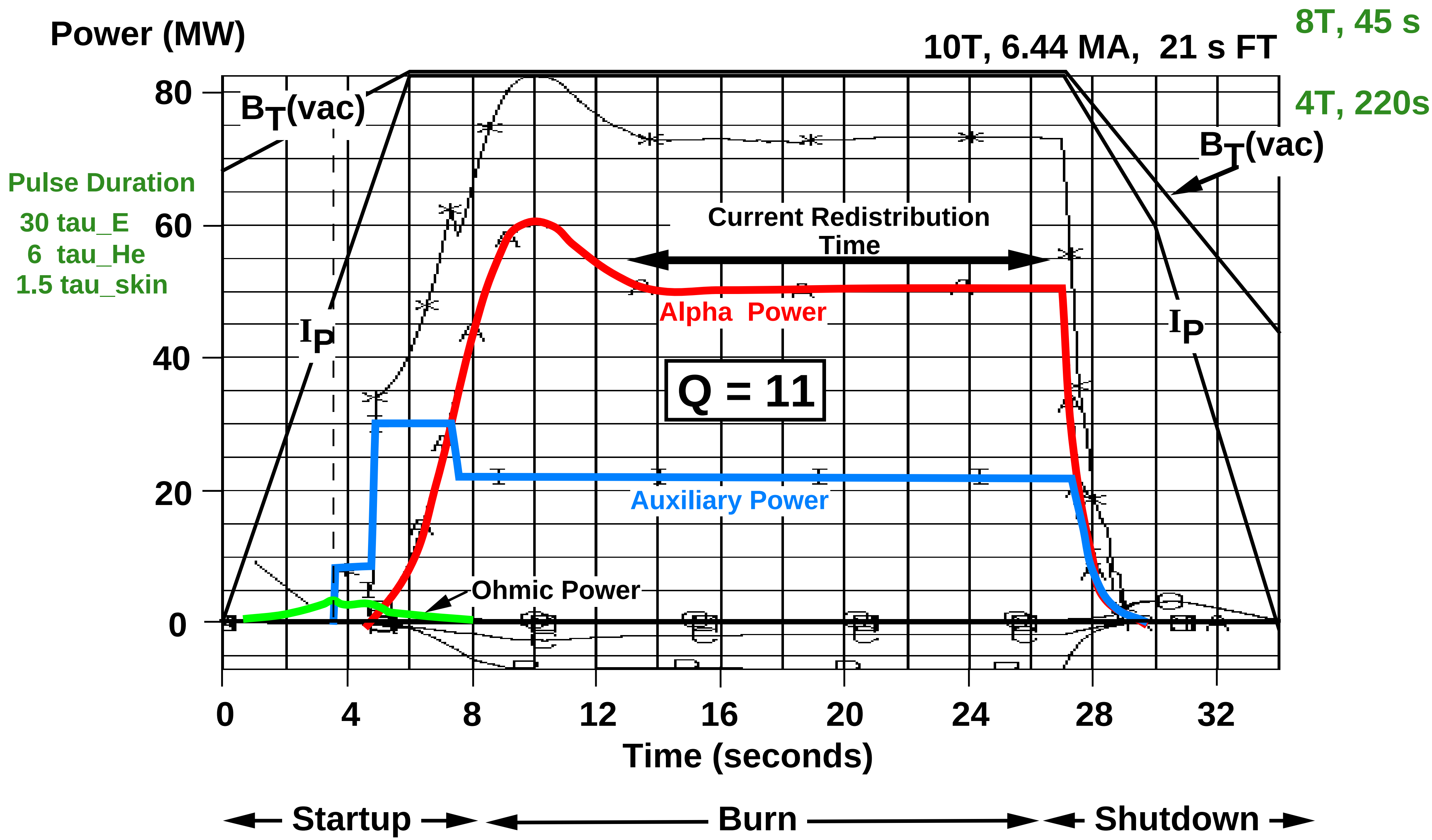
12 T Upgrade can Access Q > 25
with Significant Operating Space for Q > 10





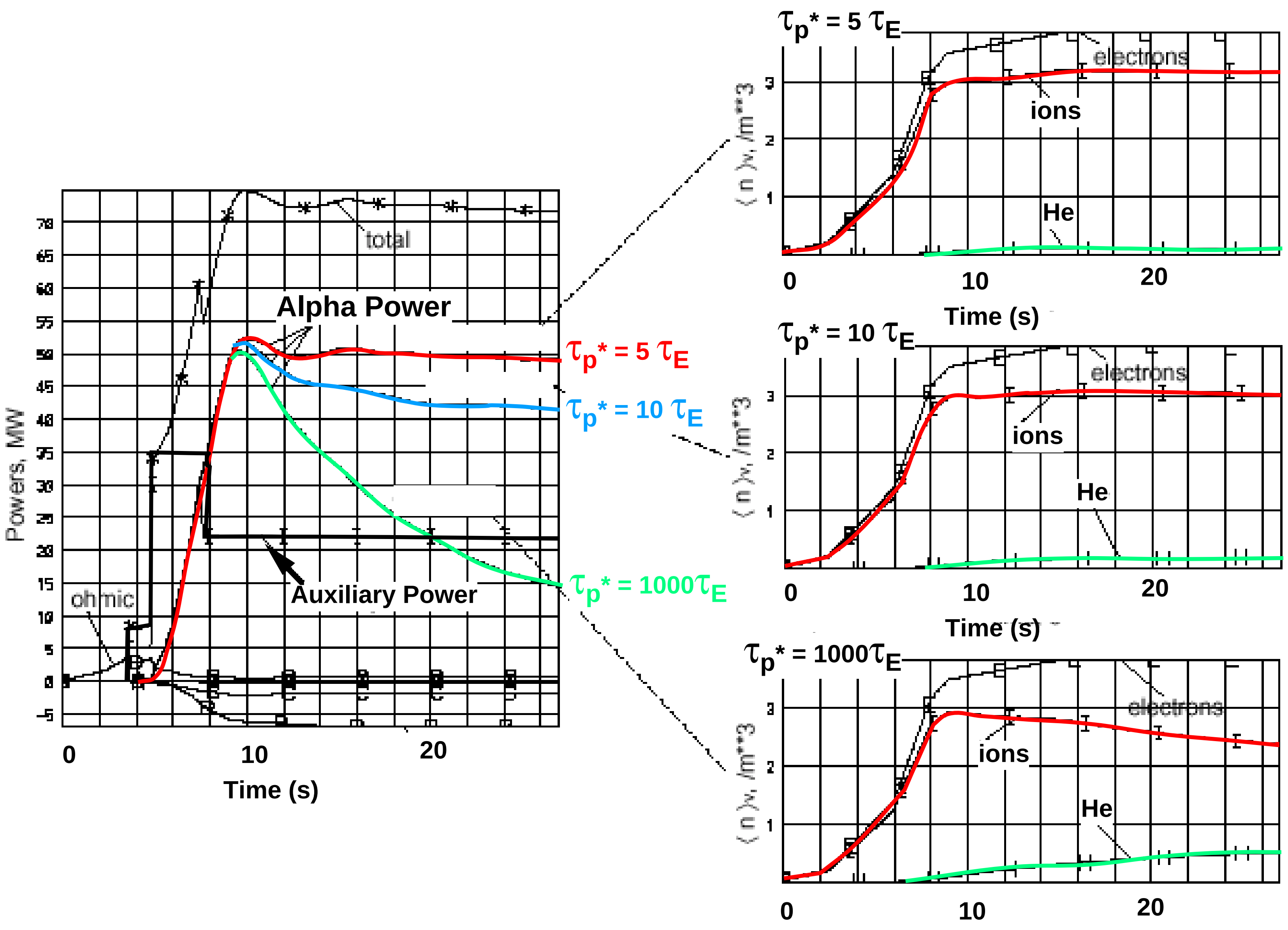
John Mandrekas

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



* The Tokamak Simulation Code (TSC) is one of several plasma simulation codes. Click here http://w3.pppl.gov/topdac/

Helium Ash Accumulation can be Explored on FIRE



Adjust divertor pumping to control helium ash

TSC/Kessel/21-q.ps

FIRE could Access High-Gain Advanced Tokamak Regimes for Long Durations

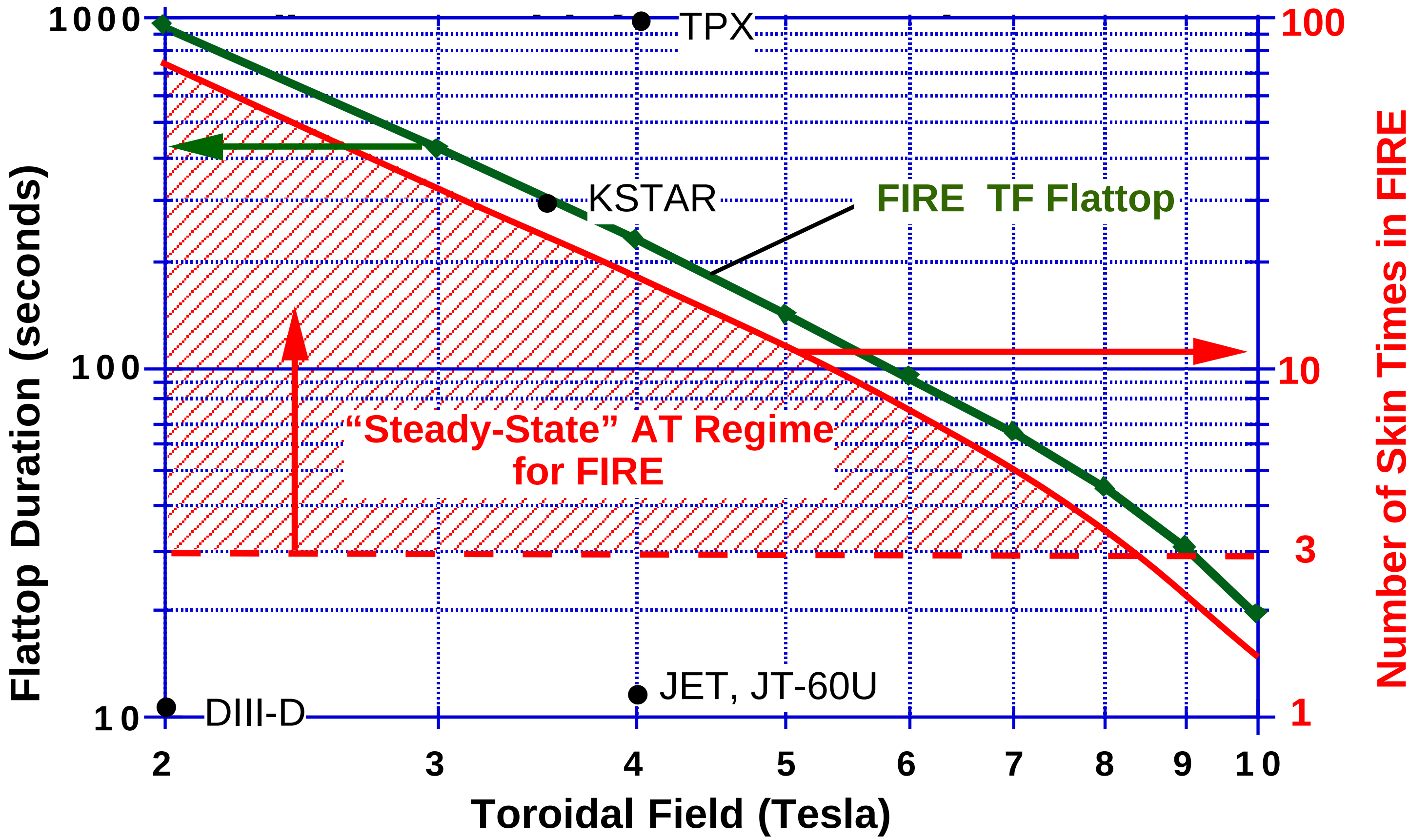
- The coupling of advanced tokamak modes with strongly burning plasmas is a generic issue for all advanced “toroidal” systems. The VLT PAC, Snowmass Burning Plasma and Energy Subgroup B recommended that a burning plasma experiment should have AT capability.

- FIRE, with strong plasma shaping, flexible double null poloidal divertor, low TF ripple, dual inside launch pellet injectors, and space reserved for the addition of current drive (LHCD) and/or a smart conducting wall, has the capabilities needed to investigate advanced tokamak regimes in a high gain burning plasma.

- The LN inertially cooled TF coil has a pulse length capability ~250 s at 4T for DD plasmas. This long pulse - AT capability rivals that of any existing divertor tokamak or any under construction. **The coils are not the limit.**

- Recent AT regimes on DIII-D (Shot 98977) sustained for ~ 16 τ_E serve as demonstration discharges for initial AT experiments on FIRE. Need to develop self-consistent scenarios with profile control on FIRE with durations ~ 3 τ_{skin} .

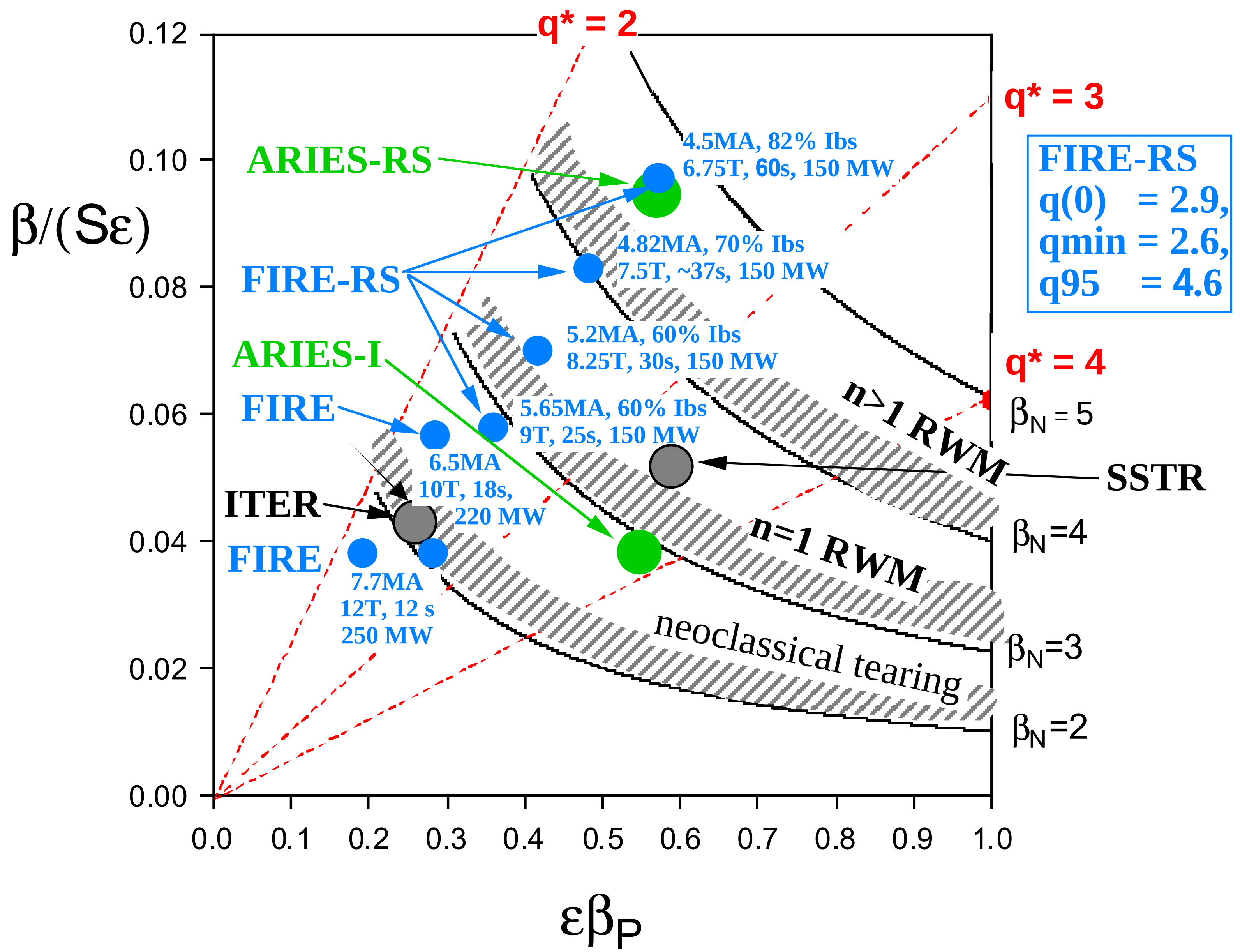
FIRE can Access "Long Pulse" Advanced Tokamak Modes at Reduced Toroidal Field.



Note: FIRE is ≈ the same size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-RC .

The combination of KSTAR and FIRE could cover the range from steady-state non-burning advanced-tokamak modes to "quasi-equilibrium" burning plasmas in advanced tokamak modes.

FIRE can Access MHD Regimes of Interest from Today's Data Base to those Envisioned for ARIES-RS



FIRE can Test Advanced Regimes of Relevance to ARIES-AT

Confinement Required to access this regime

Q = 10, HH = 1.2

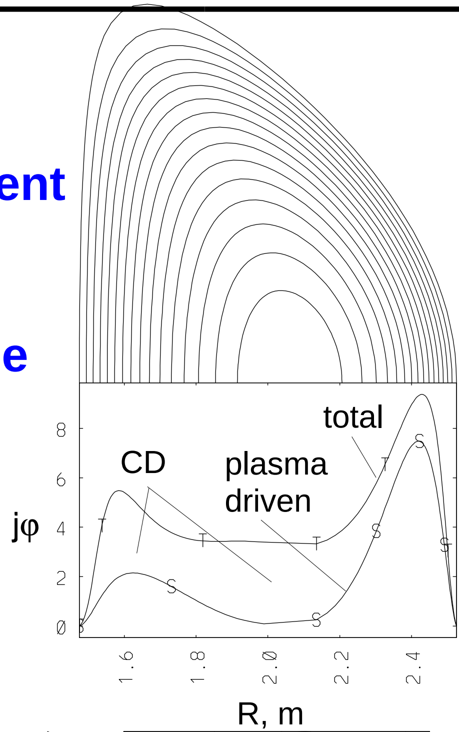
or

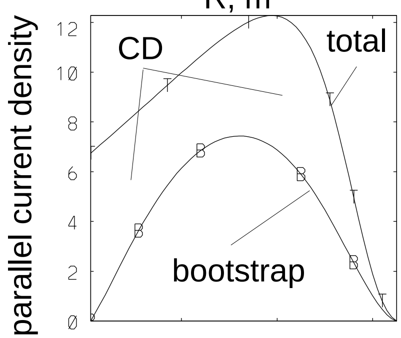
Q = 5, HH = 1.06

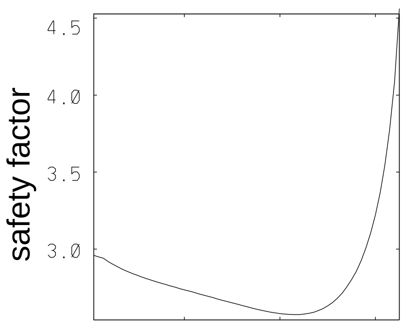
Needs self-consistent current drive power

Duration

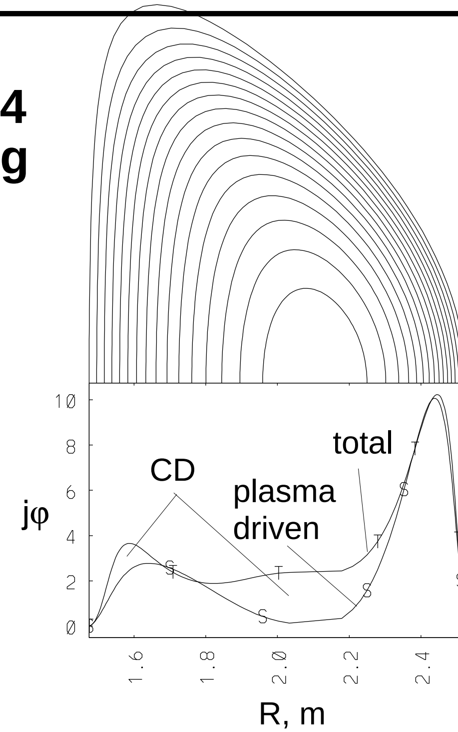
~2 tau_skin

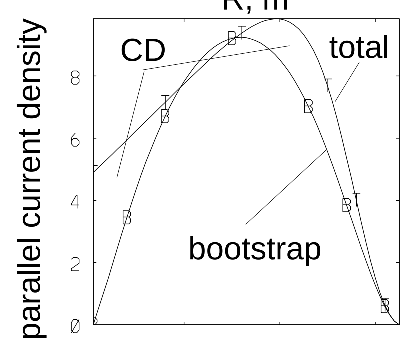


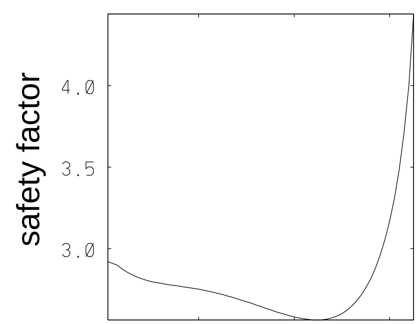




Case 1 Modest AT		Case 4 Strong AT
30	Flat top(s)	60
5.65	Ip(MA)	4.50
9.00	B_T(T)	6.75
2.90	q_o	2.90
2.60	q_{min}	2.60
1.31	β_p	2.11
2.60	β_N	4.50
3.10	β(%)	5.70
0.42	li	0.39
0.50	f_{bs}	0.82
165	P_{fus}(MW)	170
29.4	W_{th}(MJ)	30.1
0.65	n_e/n_{Gr}	0.81
2.40	α-loss(%)	9.40







Confinement Required to access this regime

Q = 10, HH = 1.56

or

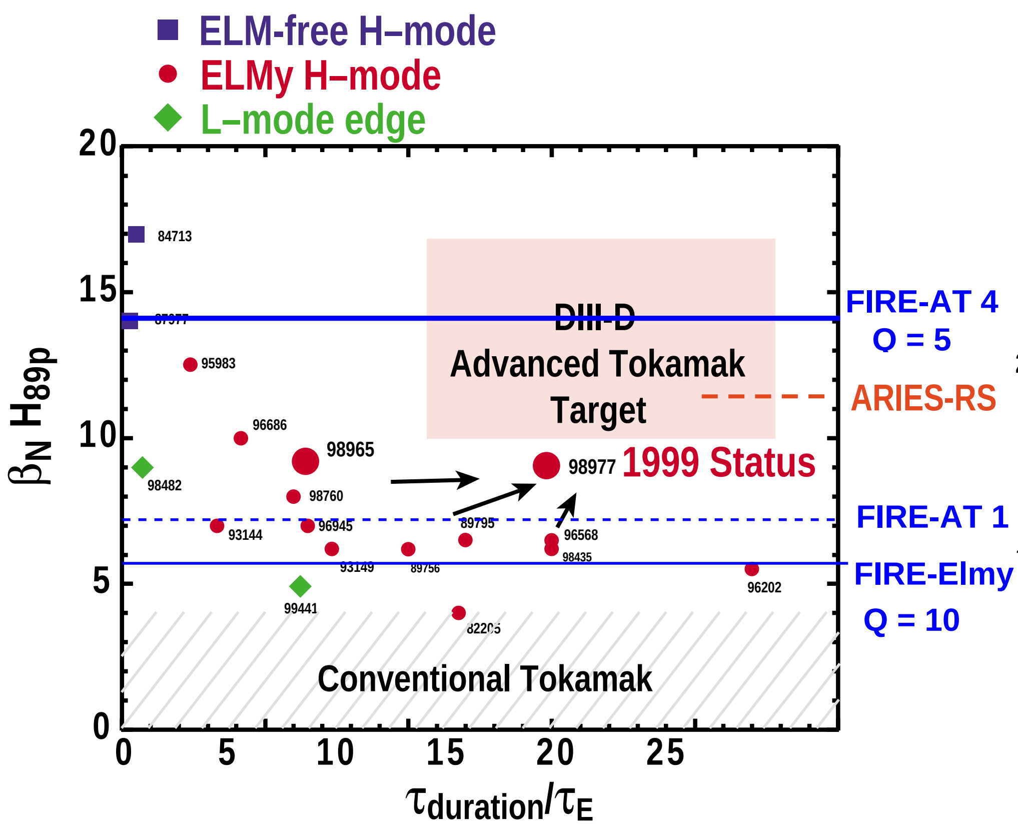
Q = 5, HH = 1.36

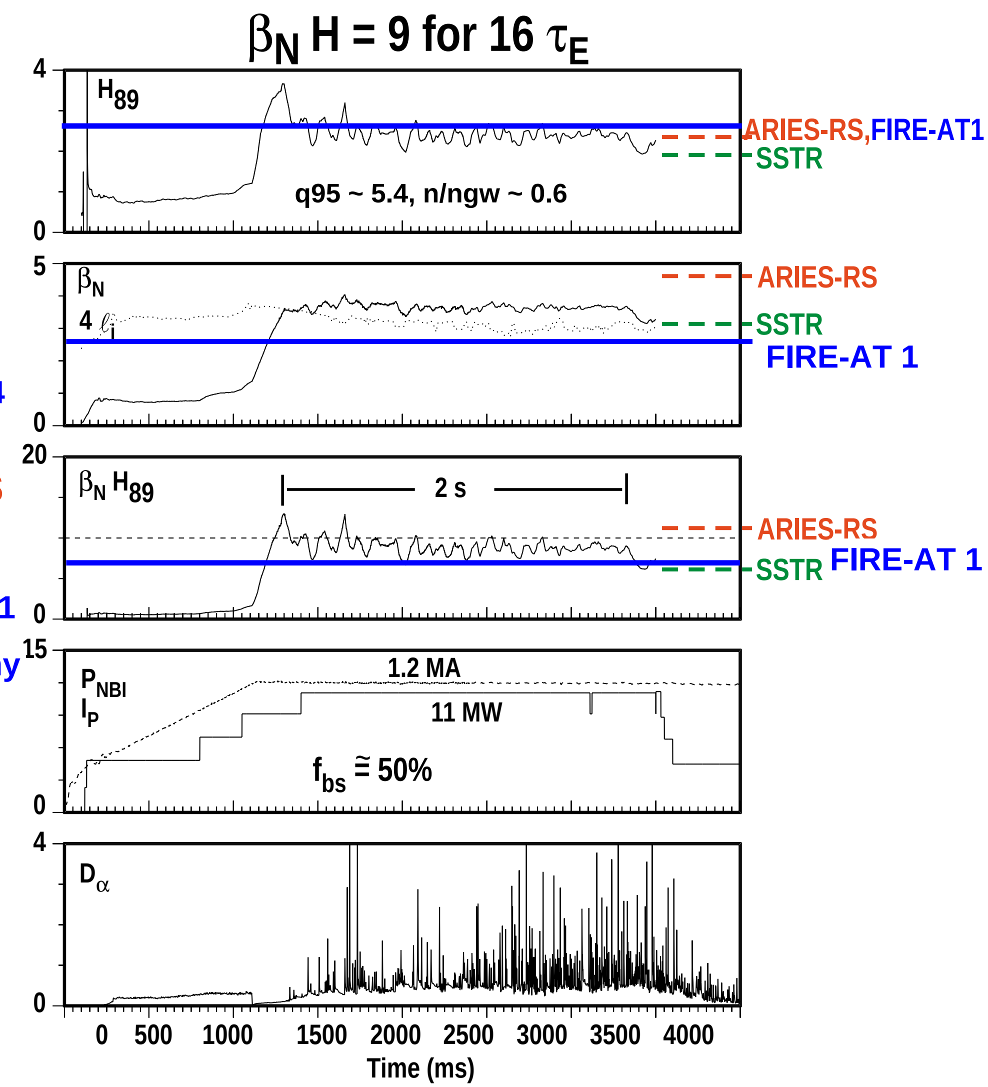
Duration

~ 4 tau_skin

The transport calculations assumed 150 MW of fusion power and n(0)/<n> = 1.5.

Long-Pulse Advanced Tokamak Performance Achieved in DIII-D Leads to Interesting High-Gain Advanced Burning Plasma Experiments





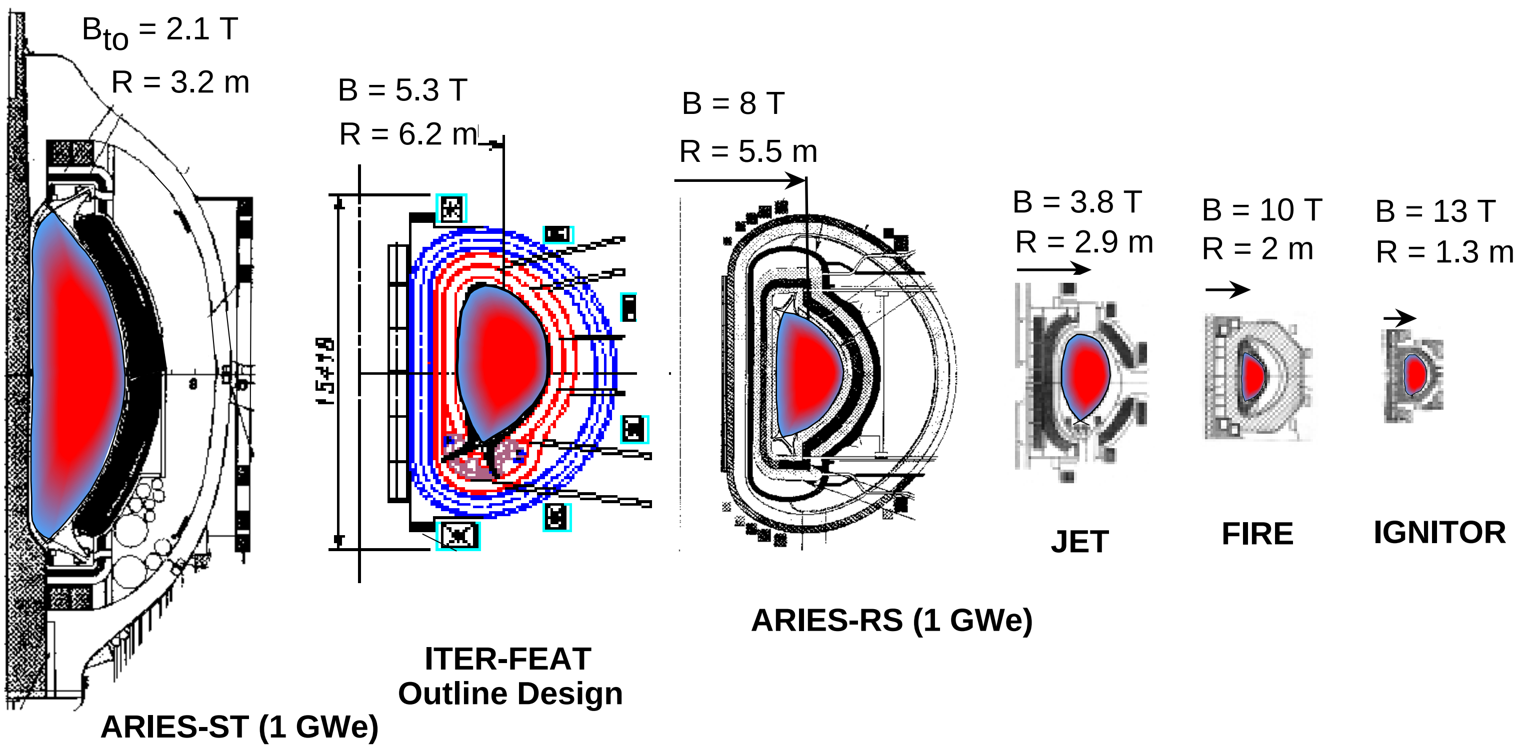
FIRE-Elmy is conventional Elmy H-Mode
FIRE-AT 1 is modest AT with 50% fbs and β_N = 2.6
FIRE-AT 4 is strong AT with 82% fbs and β_N = 4.5

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

DIII-D shot 98977 is close to a Demonstration Discharge for FIRE-AT 1 FIRE-AT 1 requires q95 = 4.5, n/ngw = 0.65, β_N H89 = 7.1, and produces fbs = 50% and Q = 10 (Pfusion =150 MW, Pin = 15 MW). This mode would be useful for quasi-steady experiments ~ 2 skin times.

264–99

Potential Next Step Burning Plasma Experiments and Demonstrations in MFE



Cost Drivers	ARIES-ST	ITER-FEAT	ARIES-RS	JET	FIRE	IGNITOR
Plasma Volume (m^3)	810	837	350	95	18	11
Plasma Surface (m^2)	580	678	440	150	60	36
Plasma Current (MA)	28	15	11	4	6.5	12
Magnet Energy (GJ)	29	50	85	2	5	5
Fusion Power (MW)	3000	500	2200	16	200	100
Burn Time (s), inductive	steady	300	steady*	1	20	5

* assumes non-inductive current drive

Status of FIRE Costing Activity (12/12/99)

- Preliminary input from subsystem engineers (k$)

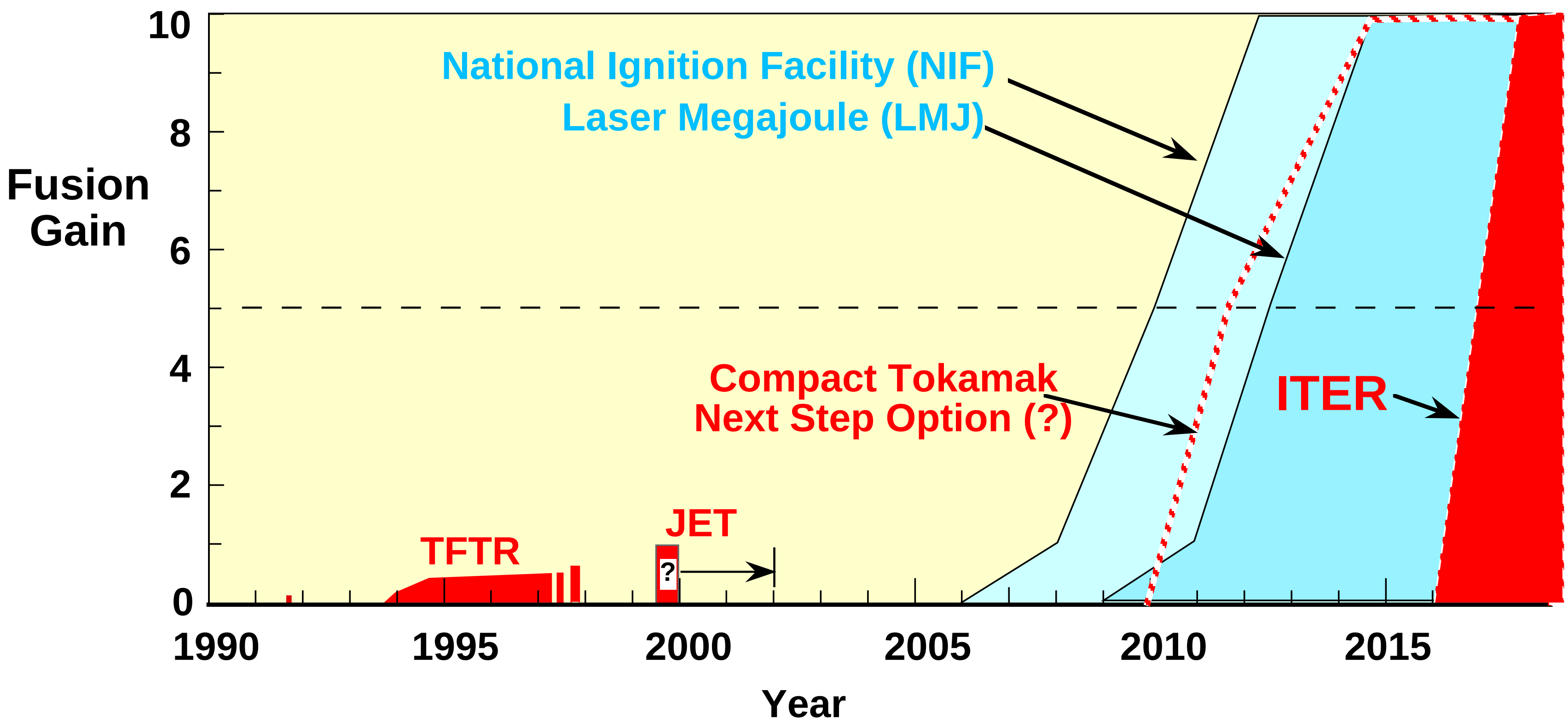
Tokamak	$284,500
Ancillary	$157,039
Power	$235,000
Facility	$206,035
Project Support	$180,412
Total	**$1,063,006* (k$)**

*FY2000$ without contingency

- The initial estimates are being reviewed to eliminate double counting and include missing cost elements.

- The cost estimate will be available for external review by mid-July.

Timetable for Burning Plasma Experiments



- Even with ITER, the MFE program would be unable to address the burning plasma issues in alpha-dominated ($Q > 5$) plasmas for $\geq$ 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 ~ 2010.

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

First Version
January 1998

Critical Issues for FIRE and Magnetic Fusion

The critical physics and engineering issues for FIRE are the same as those for fusion, the goal of FIRE is to help resolve these issues for magnetic fusion. The issues and questions listed below need to be addressed in the near future.

- Physics
    - confinement - H-mode power threshold, edge pedestal, AT modes,
    - stability - NTMs, RWM, disruptions: conducting wall? feedback coils? VDE?
    - heating and current drive - ICRF is baseline: NBI & LHCD as upgrades?
    - boundary - detached divertor operation, impurity levels, confinement
    - self-heating - fast alpha physics and profile effects of alpha heating

    Development of self-consistent self-heated AT modes with external controls

- Engineering
    - divertor and first wall power handling (normal operation and disruptions)
    - divertor, first wall and vacuum vessel for long pulse AT modes
    - evaluate low inventory tritium handling possibilities
    - complete many engineering details identified in FIRE Engineering Report
    - evaluate potential sites for Next Step MFE experiment
    - complete cost estimate for baseline, identify areas for cost reduction

Major Conclusions of the FIRE Design Study

- Exploration, understanding and optimization of alpha-dominated (high-gain) burning plasmas are critical issues for all approaches to fusion.

- The tokamak is a cost-effective vehicle to investigate alpha-dominated fusion plasma physics and its coupling to advanced toroidal physics for MFE. The tokamak is technically ready for a next step to explore fusion plasma physics.

- The FIRE compact high field tokamak can address the important alpha-dominated plasma issues, many of the long pulse advanced tokamak issues and begin the integration of alpha-dominated plasmas with advanced toroidal physics in a $1B class facility.

- The FIRE 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 plan is being developed for an Advanced Tokamak Next Step that will address physics, engineering and cost issues in FY 2000-1 with the goal of being ready to begin a Conceptual Design in 2002.