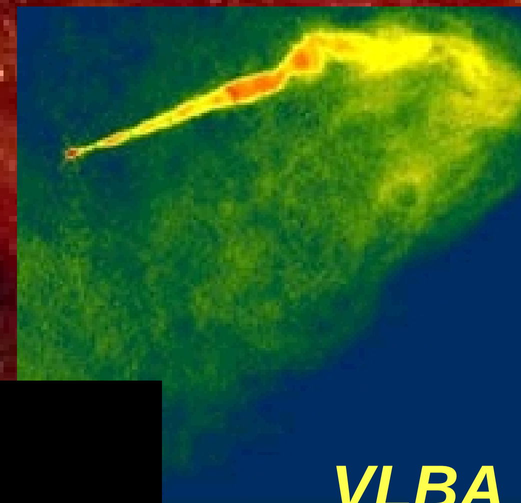
Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science

CHANDRA

NIF

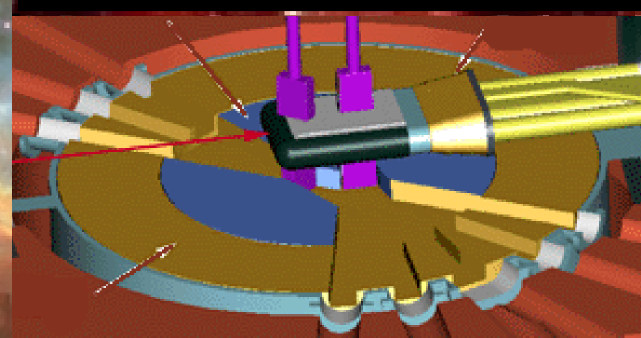
?

NSO

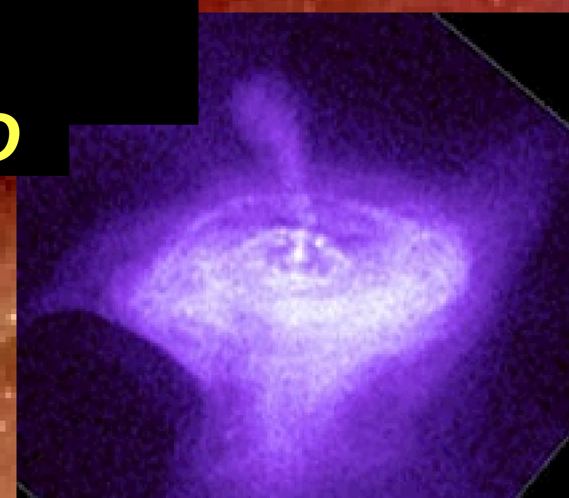


VLBA

HST (NGST)



SNS



CHANDRA

Fusion Ignition Research Experiment (FIRE)

A Next Step Option for Magnetic Fusion Research

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National FIRE Design Study Team

42nd APS-DPP and 10th ICPP
Quebec City, Canada

October 25, 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
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

NSO/FIRE Community Discussions

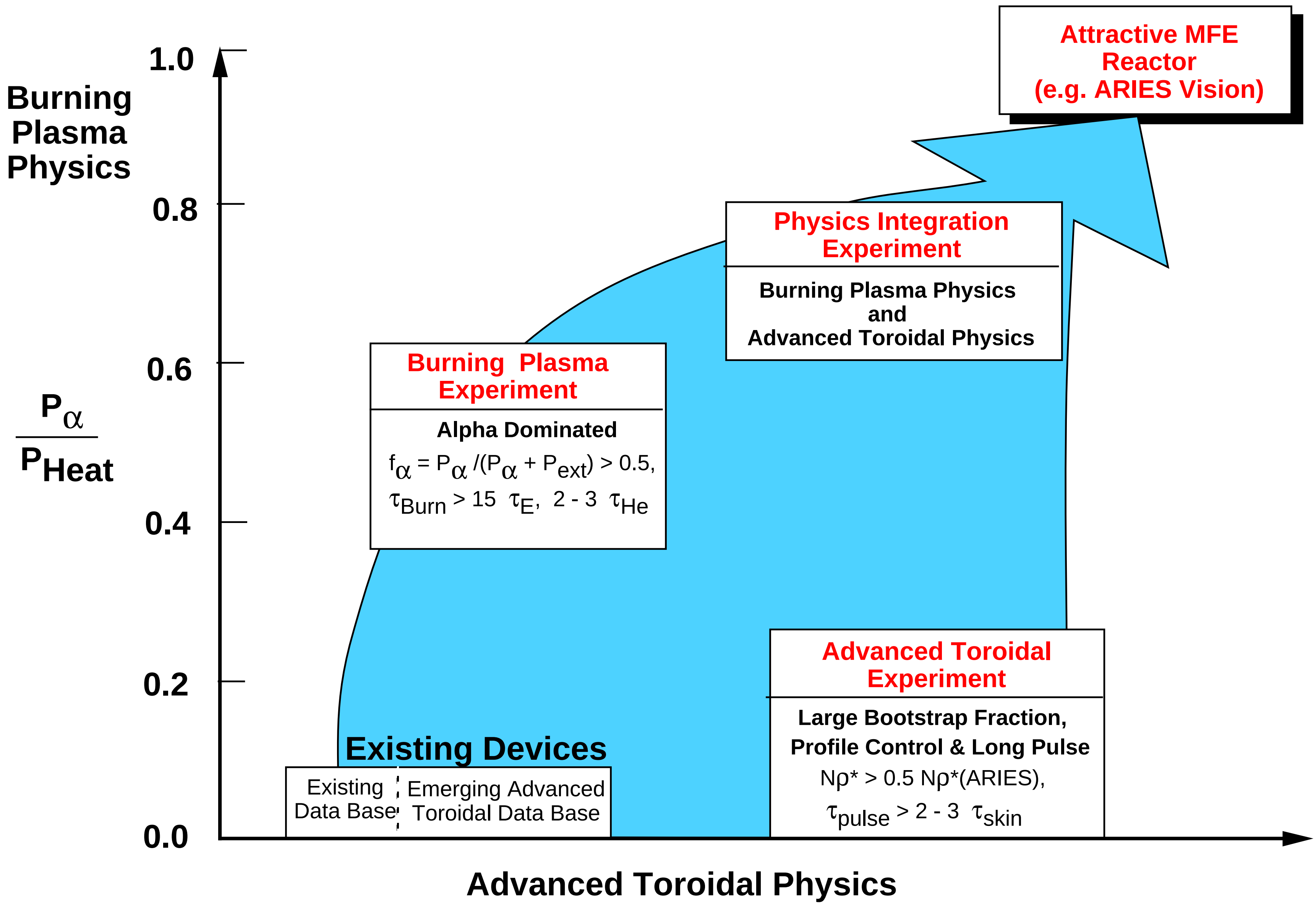
A Proactive NSO/FIRE Outreach Program has been undertaken to solicit comments and suggestions from the community on the next step in magnetic fusion.

- Presentations have been made and <u>comments received</u> from:

SOFT/France	**Sep 98**	**IAEA/Japan**	**Oct 98**	**APS-DPP**	**Nov 98**
FPA	**Jan 99**	**APEX/UCLA**	**Feb 99**	**APS Cent**	**Mar 99**
IGNITOR Wkshp	**May 99**	**NRC/NAS**	**May 99**	**GAT**	**May 99**
LLNL	**May 99**	**VLT-PAC**	**Jun 99**	**MIT PSFC**	**Jul 99**
Snowmass	**Jul 99**	**PPPL/SFG**	**Aug 99**	**VLT-PAC**	**Jun 99**
VLT-PAC	**Jun 99**	**MIT PSFC**	**Jul 99**	**U. Rochester**	**Aug 99**
NYU	**Oct 99**	**PPPL/SFG**	**Aug 99**	**U. Wis**	**Oct 99**
FPA	**Oct 99**	**SOFE**	**Oct 99**	**APS-DPP**	**Nov 99**
U. Maryland	**Dec 99**	**DOE/OFES**	**Dec 99**	**VLT PAC**	**Dec 99**
Dartmouth	**Jan 00**	**Harvey Mudd**	**Jan 00**	**FESAC**	**Feb 00**
ORNL	**Feb 00**	**Northwest'n**	**Feb 00**	**U. Hawaii**	**Feb 00**
Geo Tech	**Mar 00**	**U. Georgia**	**Mar 00**	**PPPL**	**Mar 00**
Naval Postgrad S	**Mar 00**	**U. Wis**	**Mar 00/Apr00**	**EPS/Budapest**	**Jun 00**
IPP/Garching	**Jun 00**	**CEA/Cadarache**	**Jun 00**	**JET-EFDA**	**Jun 00**
NSO-PAC	**Jul 00**	**SOFT/Spain**	**Sep 00**	**IAEA/Italy**	**Oct 00**
Int'l DB/Frascati	**Oct 00**	**CRPP/Lausanne**	**Oct 00**	**ANS/TOFE**	**Oct 00**
APS/DPP-ICPP	**Oct 00**	**TBD**	**Nov 00**	**TBD**	**Nov 00**
UFA BP Wkshp	**Dec 00**	**FESAC BP Review**	**00**		

- **The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. Over 10,000 visitors from around the world have logged on to the FIRE web site since the site was initiated in July, 1999.**

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



The "Old Paradigm" required three separate devices, the "New Paradigm" could utilize one facility operating in three modes or phases.

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

- Grunder Panel(98) and Madison Forum endorsed Burning Plasmas as next step.
- NRC Interim Report(99) identified “integrated physics of a self-heated plasma” as one of the critical unresolved fusion science issues.
- The Snowmass Fusion Summer Study(99) 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 (99) 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 Airaghi Report(00) also endorses Burning Plasma objectives, ITER construction and recommends the study of a Cu coil Tokamak as a backup to ITER.

Fusion Science Objectives for a Major Next Step Experiment (e.g., FIRE)

- Explore and understand the physics of alpha-dominated fusion plasmas:
    - Energy and particle transport (extend confinement predictability)
    - Macroscopic stability (β-limit, wall stabilization, NTMs)
    - Wave-particle interactions (fast alpha driven effects)
    - Plasma boundary (density limit, power and particle flow)
    - Strong coupling of previous issues due to self-heating(self-organization?)
- Test techniques to control and optimize alpha-dominated plasmas.
- Sustain alpha-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 some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.

We must Burn to Learn!!

Dimensionless Parameters Required for Fusion Plasma Physics Experiment

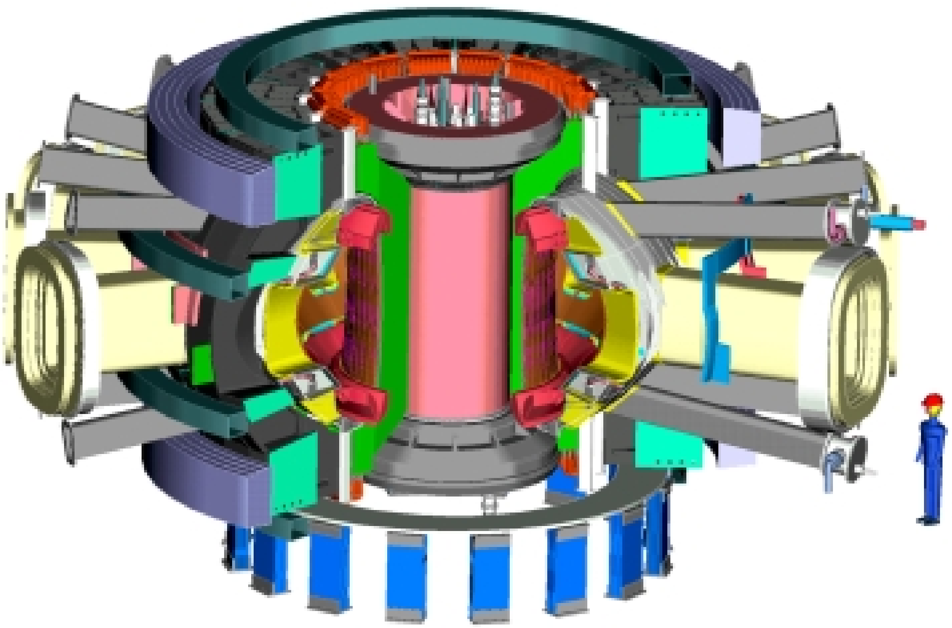
	Core*	Edge	Alpha	Duration			
	$BR^{5/4}$	?	P_{α}/P_{heat}	$\tau/\tau_{\alpha s}$	τ/τ_E	τ/τ_{He}	τ/τ_{CR}
Explore and Understand Fusion Plasmas	>0.5		>0.5	>3	>5	>3	>3
Energy and Particle Transport							
Macroscopic Stability							
Wave Particle (alpha heating, fast alpha)			β_{α} ~ ARIES				
Plasma Boundary		?					
Test Control and Optimization Techniques	>0.5		0.4 to 0.6		10	>3	1
Sustain Alpha Dominated Plasmas	>0.5				10		
Exhaust of power, particles and ash			0.4 to 0.6			3 to 5	
Profile evolution impact on τE, MHD			0.5 to 0.8				1.5 to 3
Explore and Understand Some AT Modes			0.5 to 0.8		>10	5	1.5 to 3
ARIES-AT	**1**		**0.9**	**>10**	**> 10**	**>10**	**> 10**
FIRE Goals	**0.6**		**0.5 to 0.8**	**>10**	**>10**	**>5**	**1.5 to 3**
JET/TFTR D-T Experiments	**0.3**		**0.04**	**~3**	**10**	**~2**	**<0.2**

* Core parameters are normalized to ARIES-AT $BR^{5/4}$

Fusion Ignition Research Experiment

(FIRE)

http://fire.pppl.gov



Design Goals

- R = 2.0 m, a = 0.525 m
- B = 10 T, (12T)*
- W_{mag}= 3.8 GJ, (5.5T)*
- I_p = 6.5 MA, (7.7 MA)*
- $P_{alpha} > P_{aux}$, $P_{fusion} < 200$ MW
- Burn Time ≈18.5s (≈12s)*
- Tokamak Cost ≤ $0.3B

  Base Project Cost ≤ $1B

* Higher Field Mode

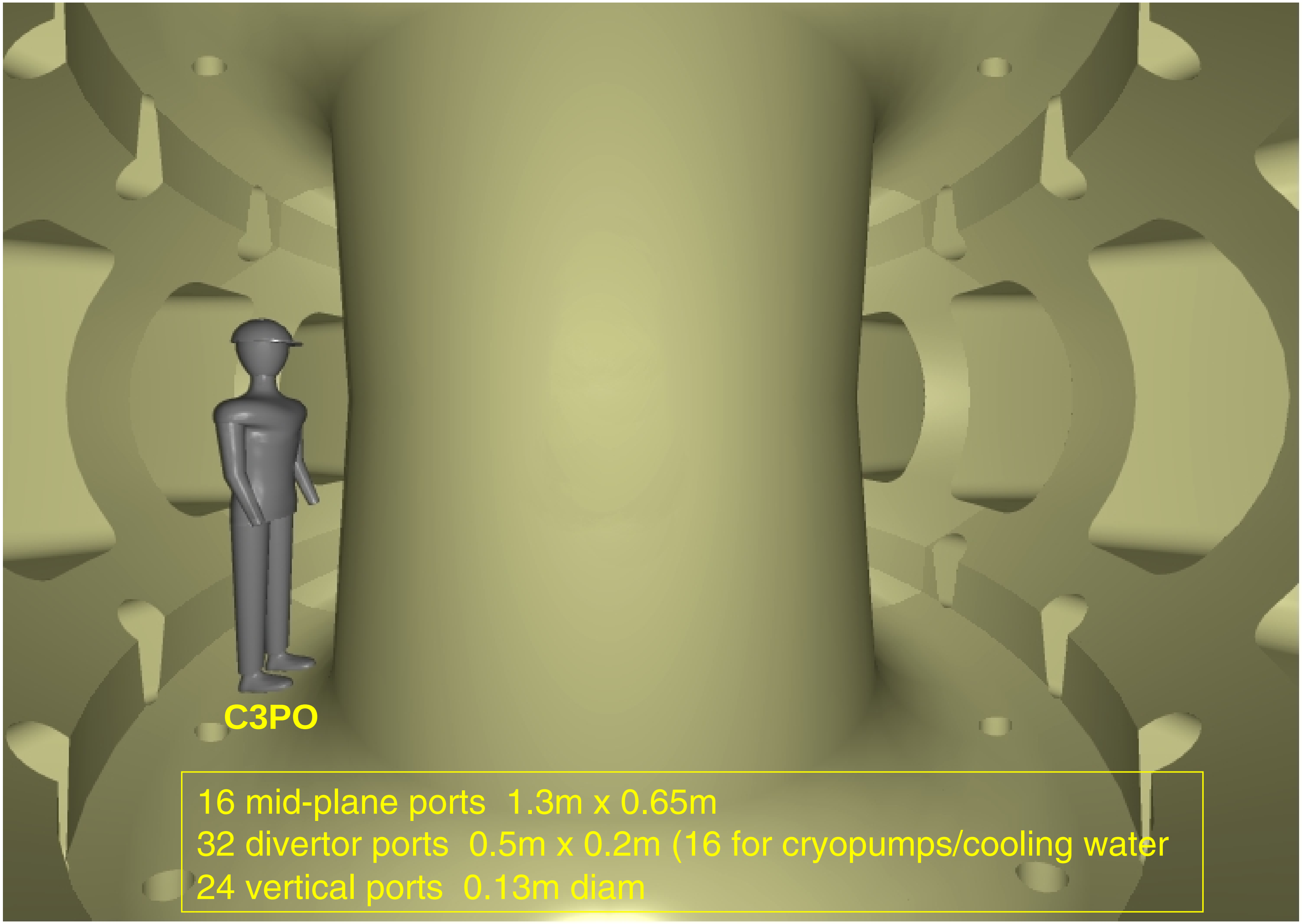
Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.

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, 0.34% 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	26 s at 10 T in dd, 18.5s @ Pdt ~ 200 MW)
Pulse repetition time	~3hr @ full field and full pulse length
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	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	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

Higher Field Mode B = 12T and Ip = 7.7MA with a 12 second flat top has been identified.

FIRE would have Access for Diagnostics and Heating



FIRE Status

Physics - NSO PAC review with Action Plan to follow up on Recommendations

- Mission endorsed (recommend even more excitement)
- Evaluate FIRE performance on the basis of recent scalings e.g., ITER98(y,2) and recent results with enhanced regimes e.g., pellet fueling
- Enhanced performance design point being developed with I_p ~ 7.7 MA to increase confidence of high gain while maintaining pulse length (~ 1.5 τ_{cr})
- Potential for advanced tokamak modes is being developed

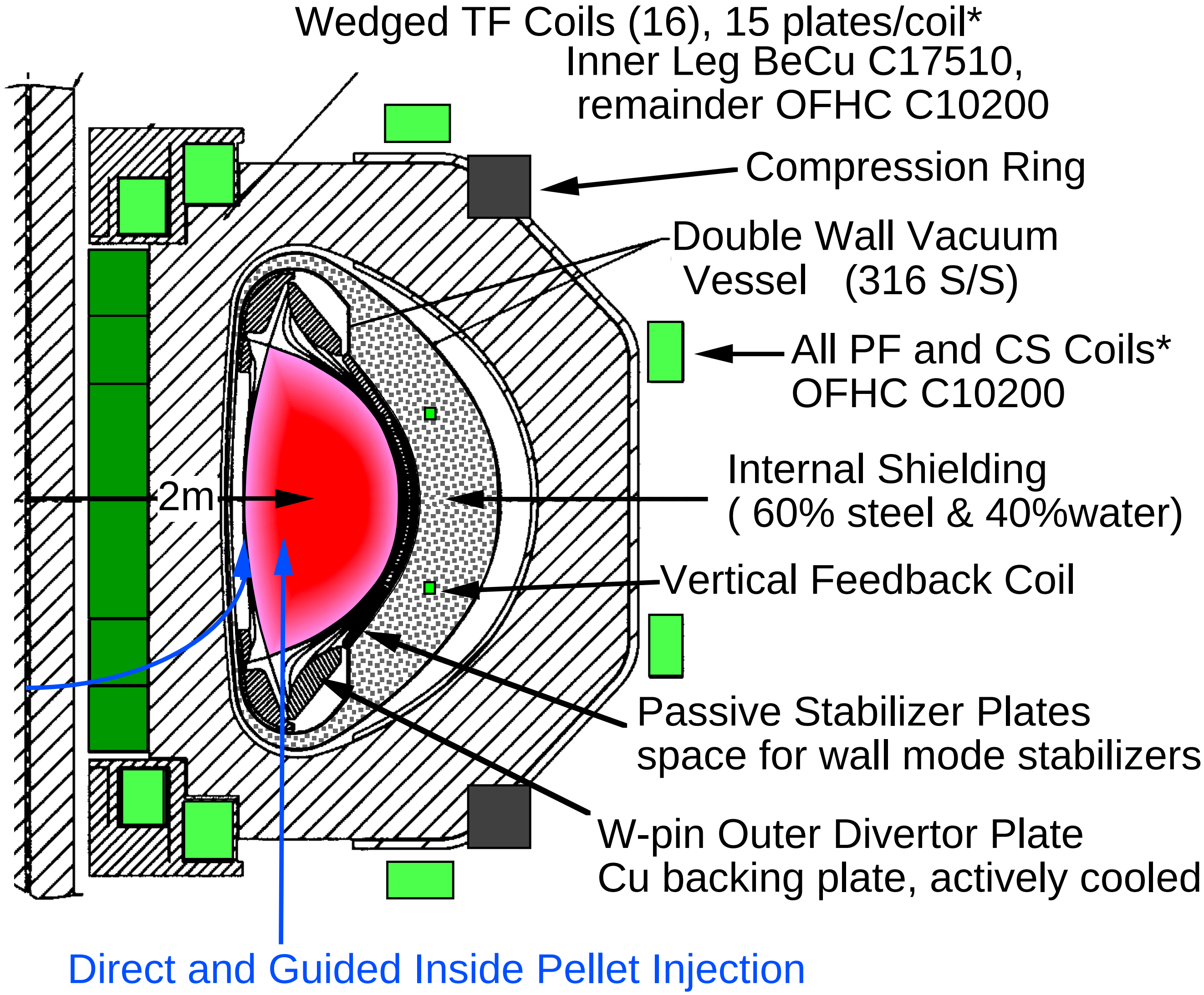
Engineering

- Pre-Conceptual Design Activity has addressed all subsystems. Engineering Report 2000 completed, see http://fire.pppl.gov. CD is available on request
- Baseline design of 10 T /20 s flat top and 12 T/12 s flat top exceeds original design goals of 10 T/10 s flat top.
- Actively cooled W outer divertor and baffle with conduction cooled inner W divertor, and Be first wall on Cu substrate satisfy cooling requirements.
- Cost Estimate of Baseline design gives $1.2B(FY-99$) for Green Field site with good possibility of < $1B(FY-99) at an existing site.

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.

Recent Innovations have Markedly Improved the Technical Basis for a Compact High Field Tokamak Burning Plasma Exp't.

Tokamak experiments (1989-1999) have developed enhanced confinement modes that scale (e.g.,ITER-98H) 1.3 times higher than the 1989 CIT design assumption.

Alcator C-Mod - the prototype for Compact High Field tokamaks has shown:

- Confinement in excess of 1.4 times the 1989 design guidelines for CIT and ~1.15 times the recent ITER-98H design guidelines.
- Successful ICRF heating at high density in shaped diverted plasmas.
- Successful detached divertor operation at high power density.

VDEs and halo currents have made internal hardware design more difficult.

D-T experiments on TFTR and JET have shown:

- Tritium can be handled safely in a laboratory fusion experiment!!!
- D-T plasmas behaved roughly as predicted with slight improvements in confinement in plasmas with weak alpha-heating.

Engineering Innovations to increase capability and reduce cost

- Improved coil and plasma facing component materials, improved 3-D engineering computer models and design analysis, advanced manufacturing.

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 - Base on today's tokamak data base

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

Beta Limit - theory and tokamak data base

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

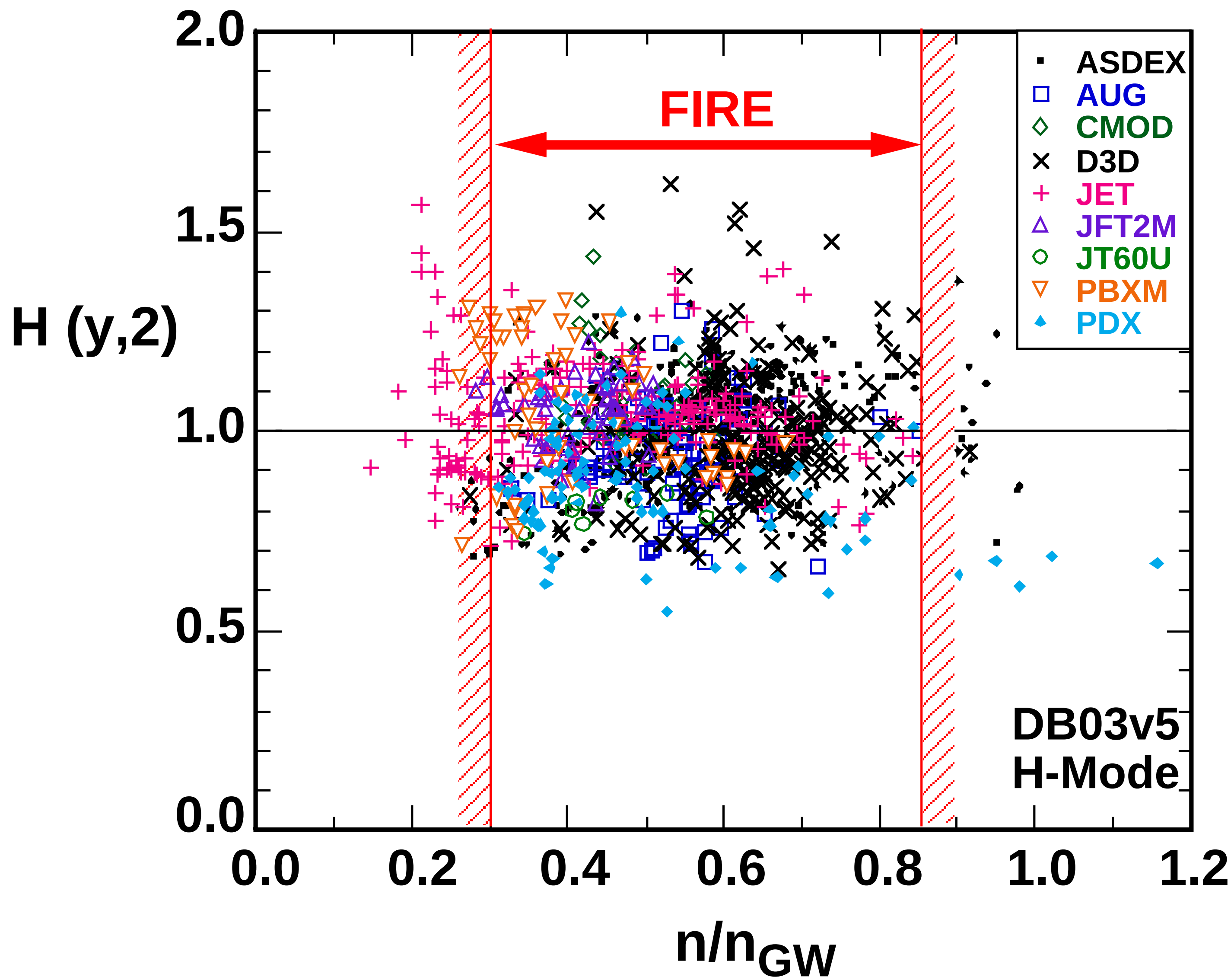
H-Mode Power Threshold - Based on today's tokamak data base

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

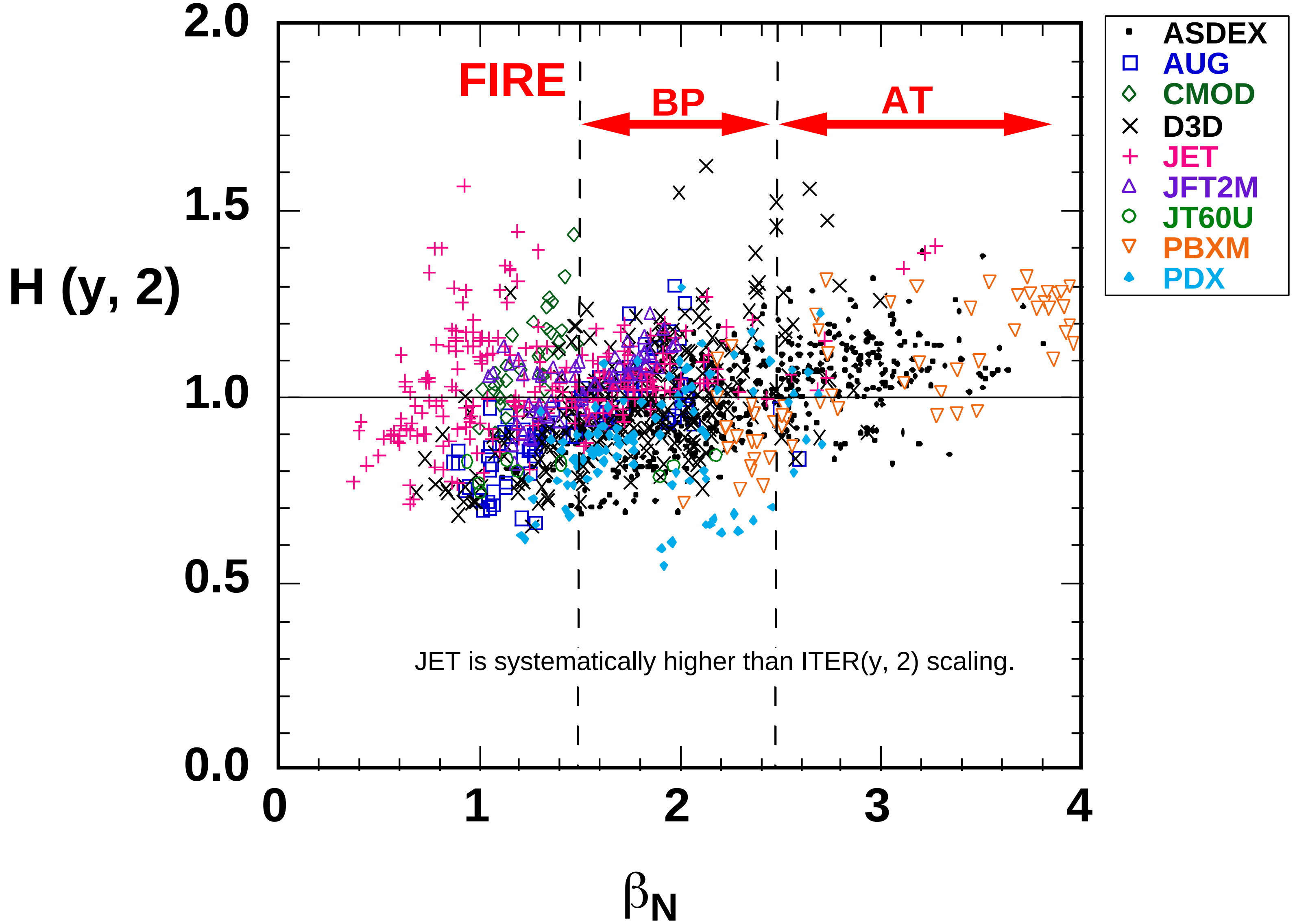
Helium Ash Confinement $\tau_{He} = 5\ \tau_E$, impurities = 3% Be

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 can Access Most of the H-Mode Database



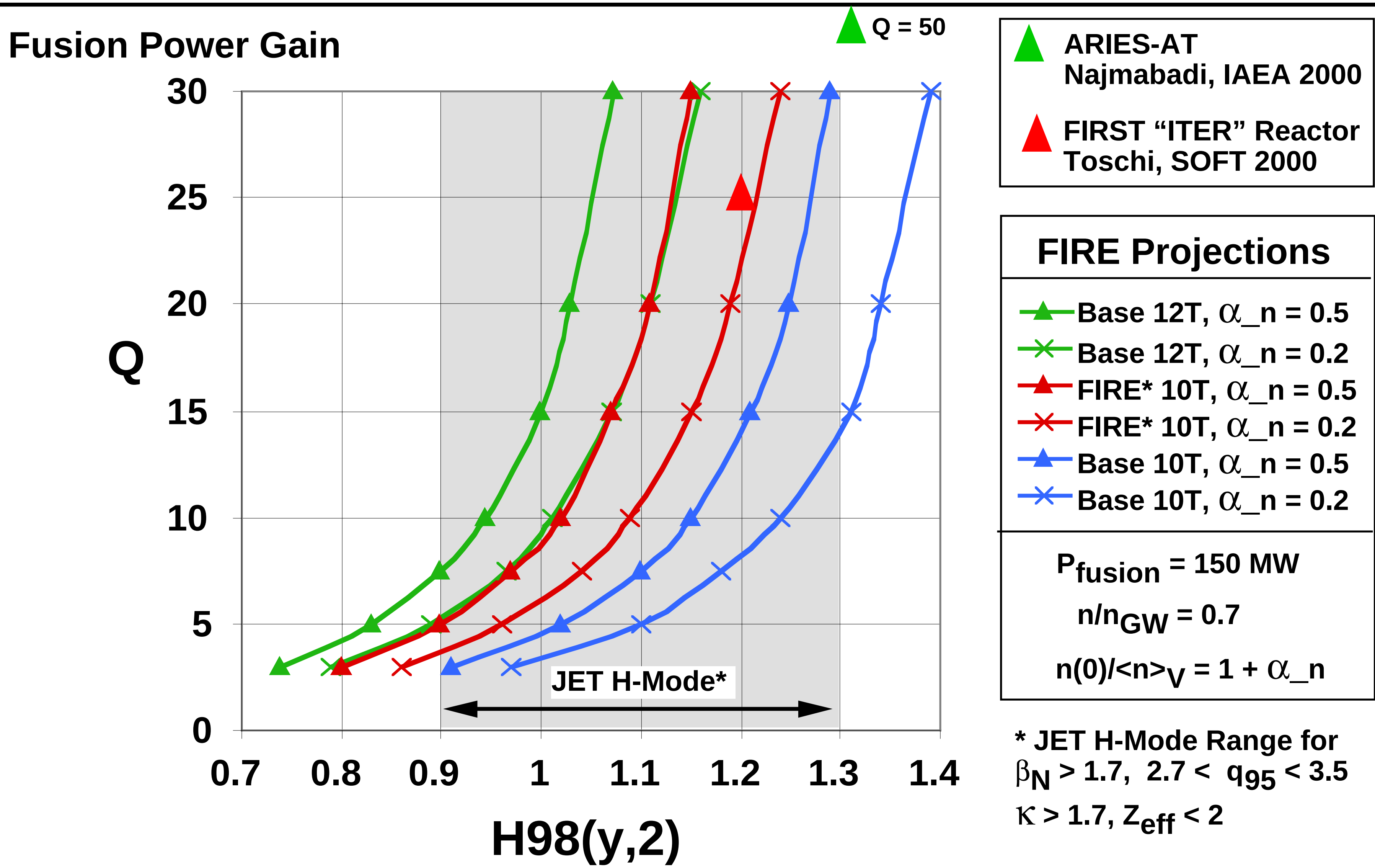
ITER(y,2) Scaling Underestimates Confinement at High β_N



Optimizing The FIRE Design Point

	Base	Base	Higher B	Shaping	Size
R_o, plasma major radius, m	**2.00**	**2.00**	**2.00**	**2.00**	**2.14**
a, plasma minor radius, m	**0.525**	**0.525**	**0.525**	**0.556**	**0.595**
R_o/a, aspect ratio	**3.81**	**3.81**	**3.81**	**3.60**	**3.60**
κ_{95}, plasma elongation at 95% flux	1.77	1.77	1.77	1.77	1.77
δ_{95}, plasma triangularity at 95 % flux	**0.40**	**0.40**	**0.40**	**0.50**	**0.5**
q95	3.03	3.03	3.03	3.05	3.05
Bt, toroidal magnetic field at R_o, T	**10**	**10**	**12**	**10**	**10**
Ip, plasma current, MA	**6.44**	**6.44**	**7.71**	**7.71**	**8.25**
li(3), internal plasma inductance	0.80	0.80	0.80	0.80	0.8
Bootstrap current fraction, approx.	0.31	0.31	0.24	0.26	0.24
<ne>, 10^20 /m^3, volume average	4.22	4.22	5.40	4.83	4.55
α_n, densiy profile peaking = 1 + α_n	**0.5**	**0.5**	**0.2**	**0.2**	**0.2**
<n>l/Greenwald	**0.65**	**0.65**	**0.65**	**0.65**	**0.65**
<T>n, density weighted average temperature, keV	7.3	7.4	6.4	6.7	6.45
T(0), central temperature, keV	11.6	11.7	10.9	11.4	11
α_T, temperature profile peaking = 1+ α_T	1	1	1	1	1
Impurities, Be; Hi Z, %	3;0	3;0	3;0	3;0	3;0
taup*(He)/tauE	5	5	5	5	5
Alpha ash concentration, %	1.69	2.40	2.25	2.28	2.3
Zeff	1.39	1.41	1.41	1.41	1.41
ν*, collisionality at q = 1.5	0.051	0.049	0.06	0.048	0.058
Pext (MW)	30	15	15	15	15
P_fusion (MW)	150.6	151.5	149.2	150.6	150
Pheat = Pext + Palpha - Prad(core), (MW)	52.0	37.0	34.2	35.3	34.5
Pheat/P_{th}(L->H)	**2.33**	**1.66**	**1.20**	**1.46**	**1.31**
tauE	0.52	0.73	0.88	0.89	1.02
ITER98H(y,2)-Multiplier	**1.03**	**1.16**	**1.01**	**1.09**	**1.03**
ITER89P-Multiplier	2.10	2.52	2.37	2.52	2.44
nd(0)T(0)tau_E, 10^20m^-3 kev s	31.9	45.3	51.9	49.3	51.28
Q_{DT}	**5.0**	**10.1**	**9.9**	**10.0**	**10.0**
Plasma current redistribution time, s	11.7	11.8	9.6	11.2	12.2
W(MJ), plasma kinetic energy	26.8	27.1	30.1	31.6	35.2
Fast alpha energy/Plasma W, %	7.8	7.9	6.1		6
Beta_total, %	2.5	2.56	1.94	2.62	2.37
Beta_N	**2.1**	**2.1**	**1.58**	**1.89**	**1.71**

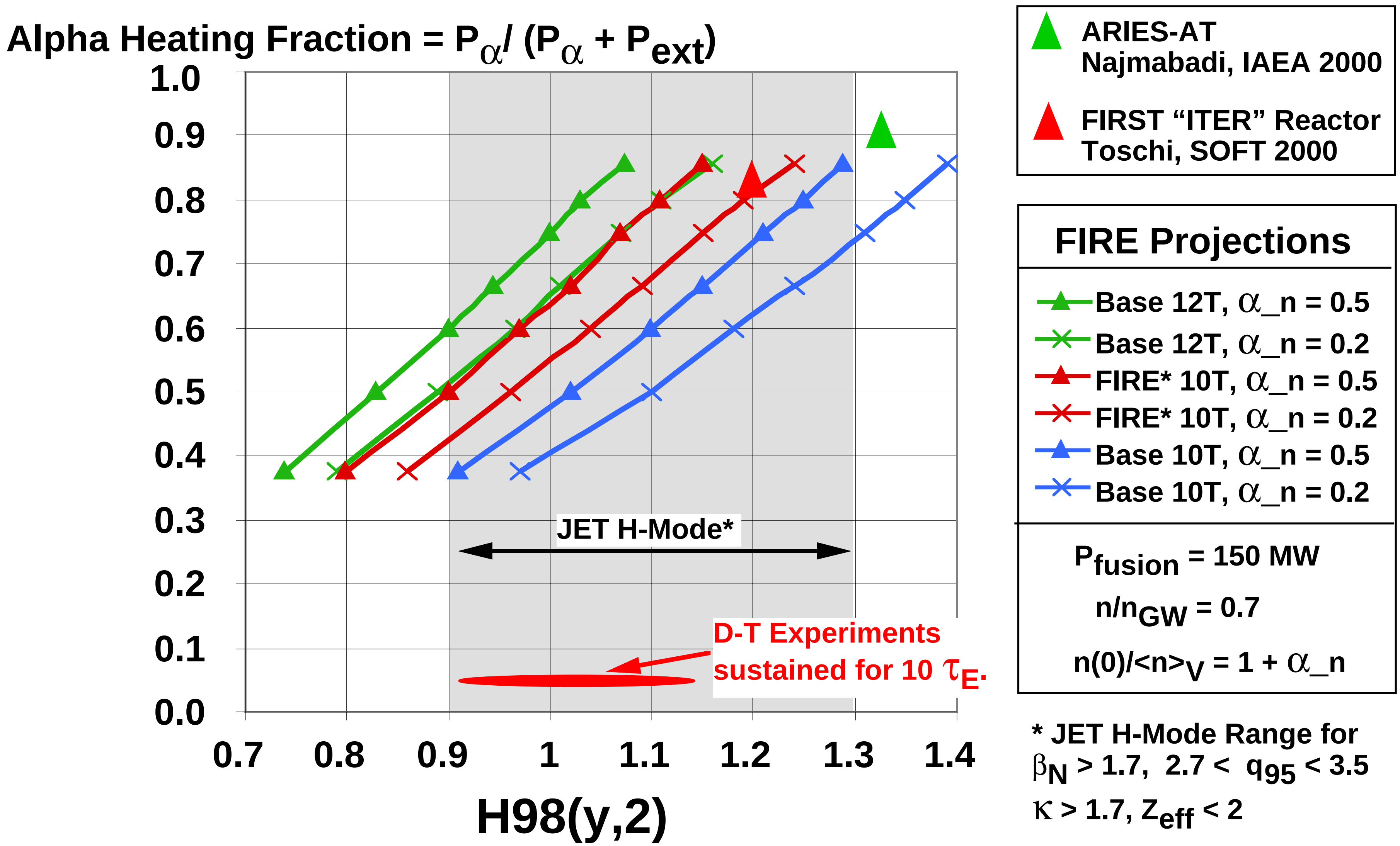
Projections of FIRE Performance as Confinement is Enhanced Toward that Required for Attractive Reactors



* JET H-Mode Range for $\beta_N > 1.7$, $2.7 < q_{95} < 3.5$
$\kappa > 1.7$, $Z_{eff} < 2$

Fusion power gain, the energy goal, is very sensitive to confinement uncertainty at high gain.

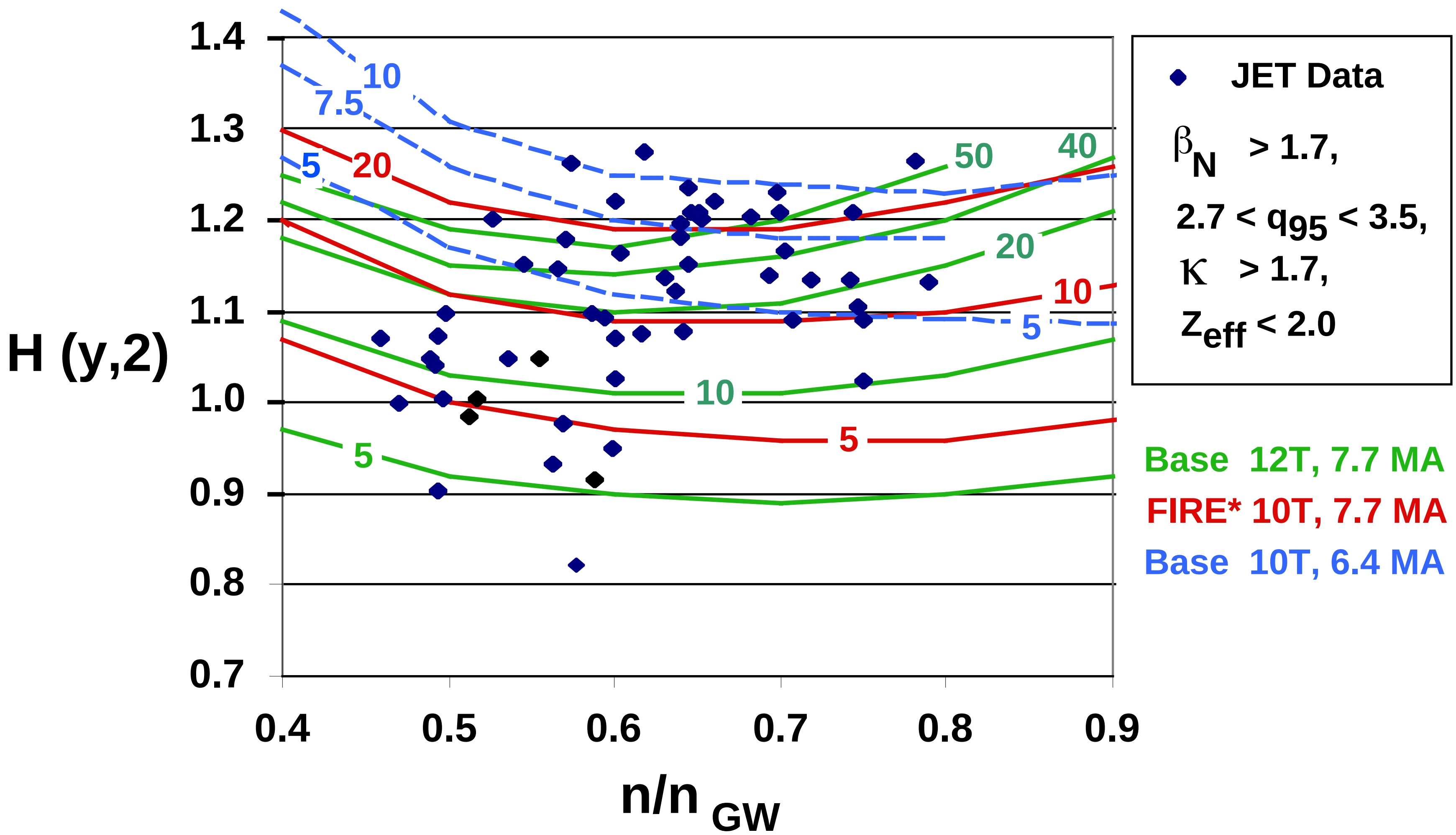
Projections of FIRE Performance as Confinement is Enhanced Toward that Required for Attractive Reactors



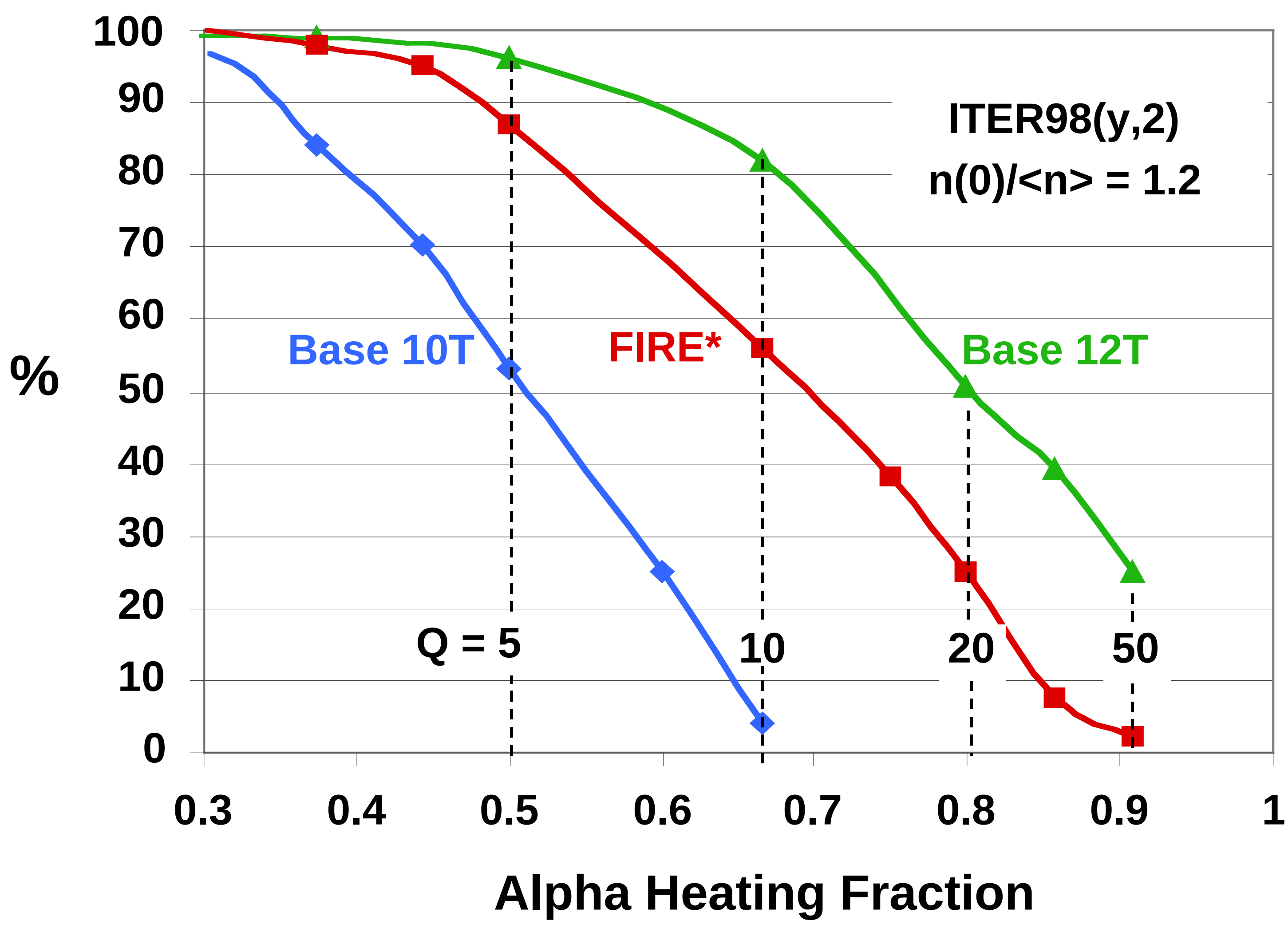
* JET H-Mode Range for $\beta_N > 1.7$, $2.7 < q_{95} < 3.5$, $\kappa > 1.7$, $Z_{eff} < 2$

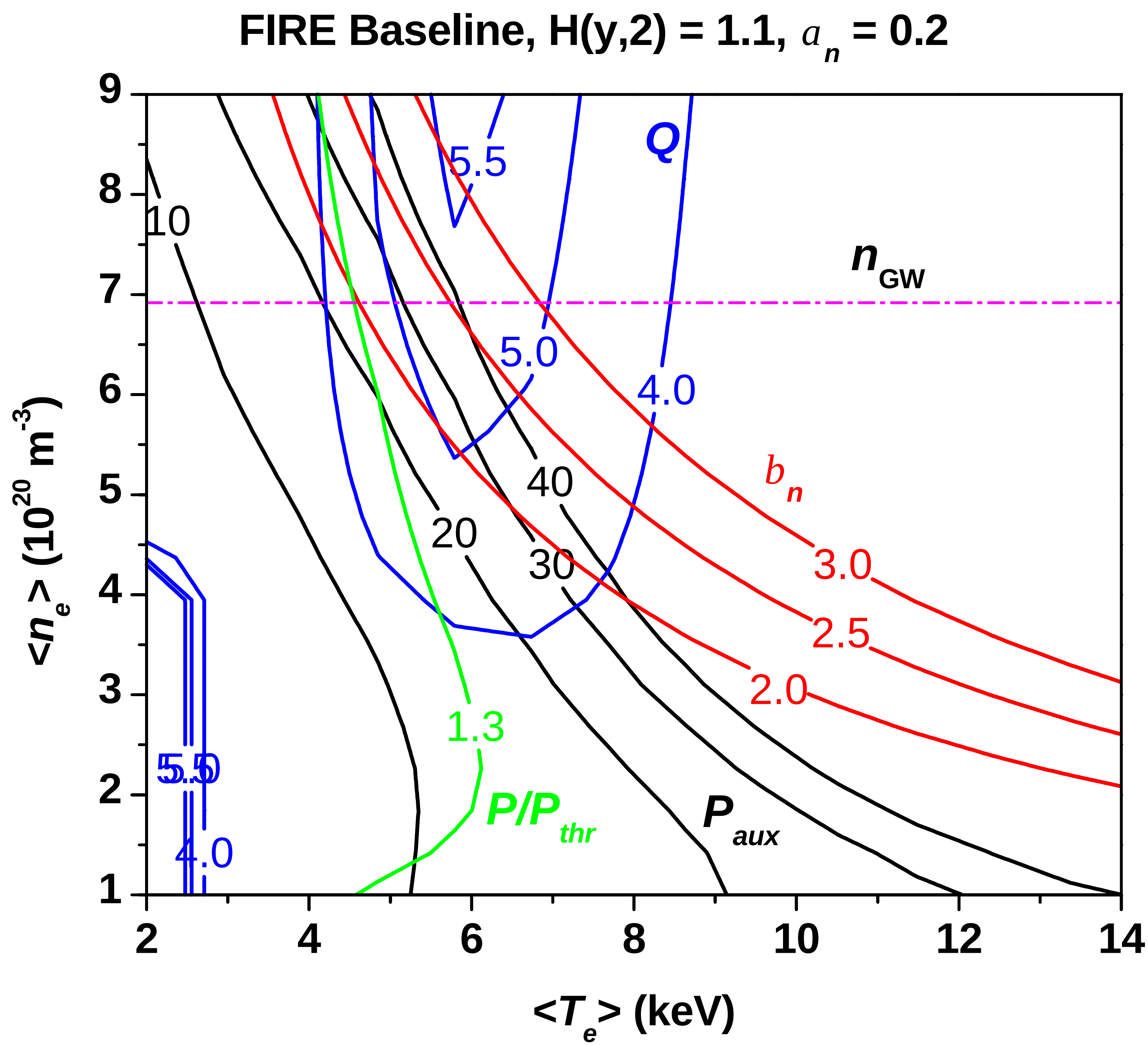
Alpha heating fraction, the science goal, is less sensitive to confinement uncertainty.

Confinement Enhancement Required to Access Various Q-values Compared with JET H-Mode Data

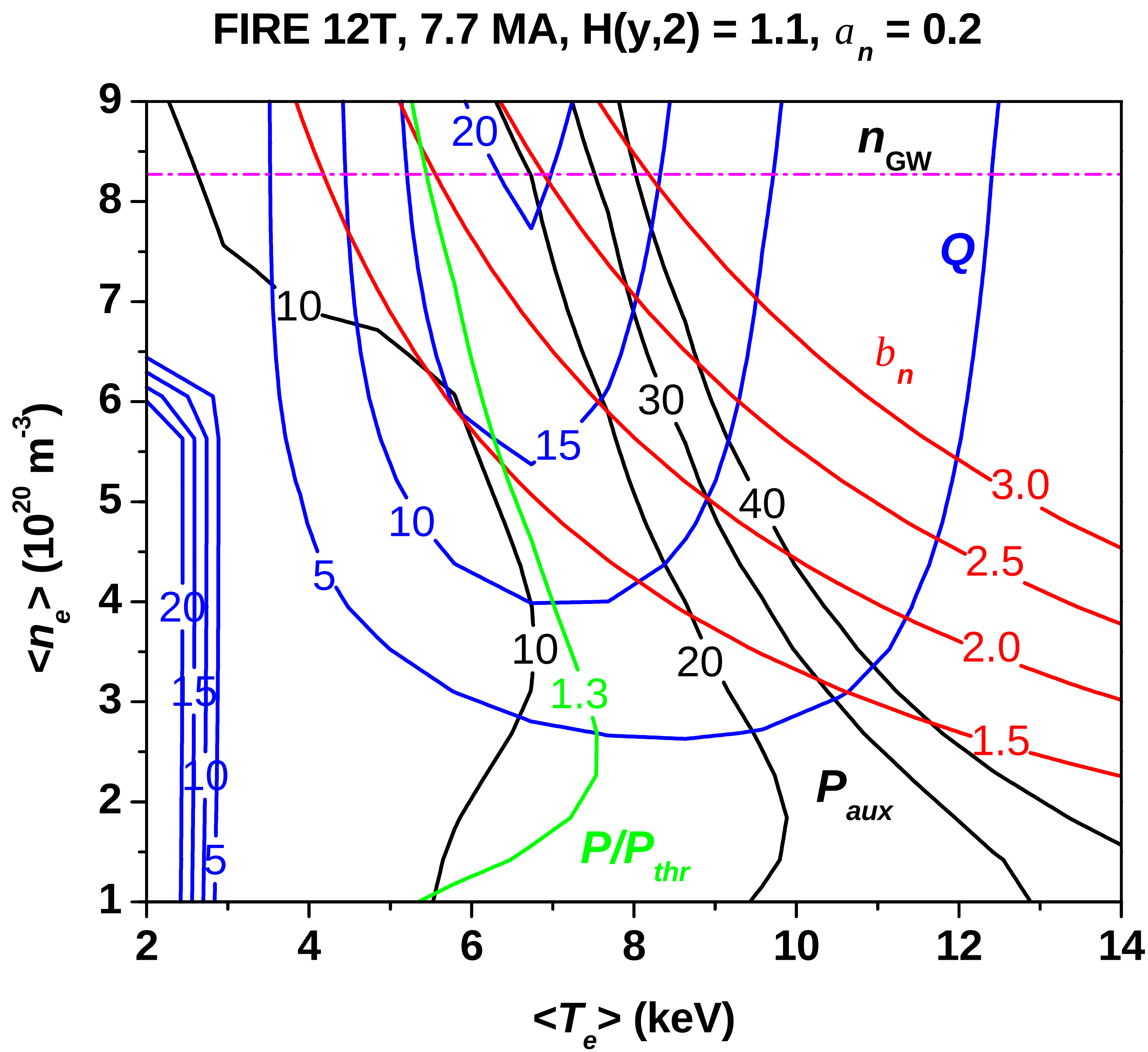


Percentage of JET FIRE-like Data Points that Project to a Specific Alpha Heating Fraction (Q)





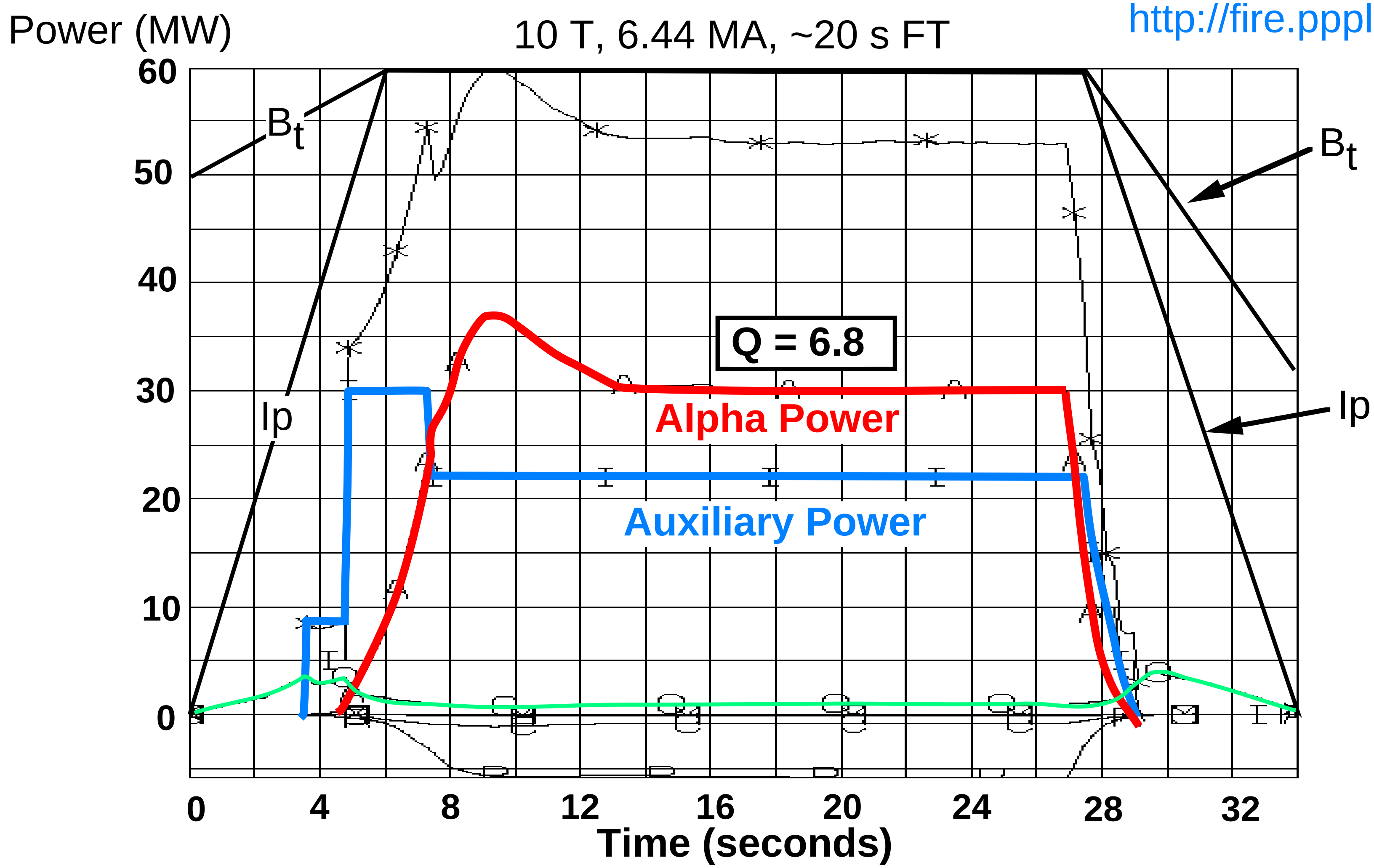
FIRE Baseline, H(y,2) = 1.1, a_n = 0.2
9
8
7
6
5
4
3
2
1
2
4
6
8
10
12
14
$\langle T_e \rangle$ (keV)
$\langle n_e \rangle$ (10^{20} m^{-3})
10
20
30
40
5.5
5.0
4.0
Q
n_{GW}
b_n
3.0
2.5
2.0
1.3
P/P_{thr}
P_{aux}
5.5
5.0
4.0



FIRE 12T, 7.7 MA, H(y,2) = 1.1, a_n = 0.2
n_{GW}
Q
b_n
3.0
2.5
2.0
1.5
10
30
40
20
10
20
15
10
5
20
15
10
5
1.3
P/P_{thr}
P_{aux}
9
8
7
6
5
4
3
2
1
2
4
6
8
10
12
14
$<n_e>$ (10^{20} m^{-3})
$<T_e>$ (keV)

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

http://fire.pppl.gov



- ITER98(y, 2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.25 and n/n_{GW} = 0.59
  - Pulse Duration ≈ 30 τ_E, 6 τ_{He} and ~1.5 τ_{skin}

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

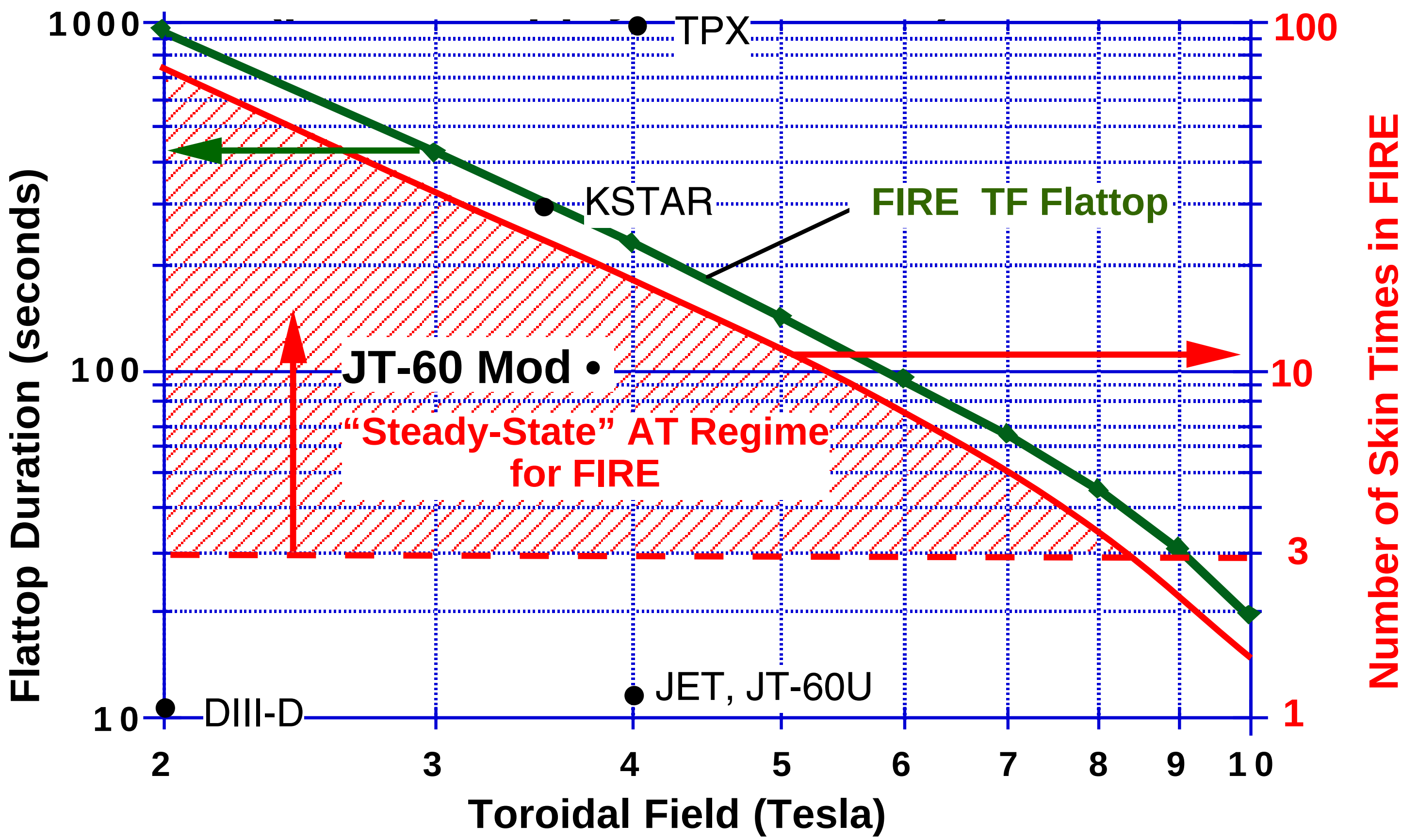
- The coupling of advanced tokamak modes with strongly burning plasmas is a generic issue for all advanced “toroidal” systems. The VLT PAC, Snowmass Burning Plasma and Energy Subgroup B recommended that a burning plasma experiment should have AT capability.

- 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} .

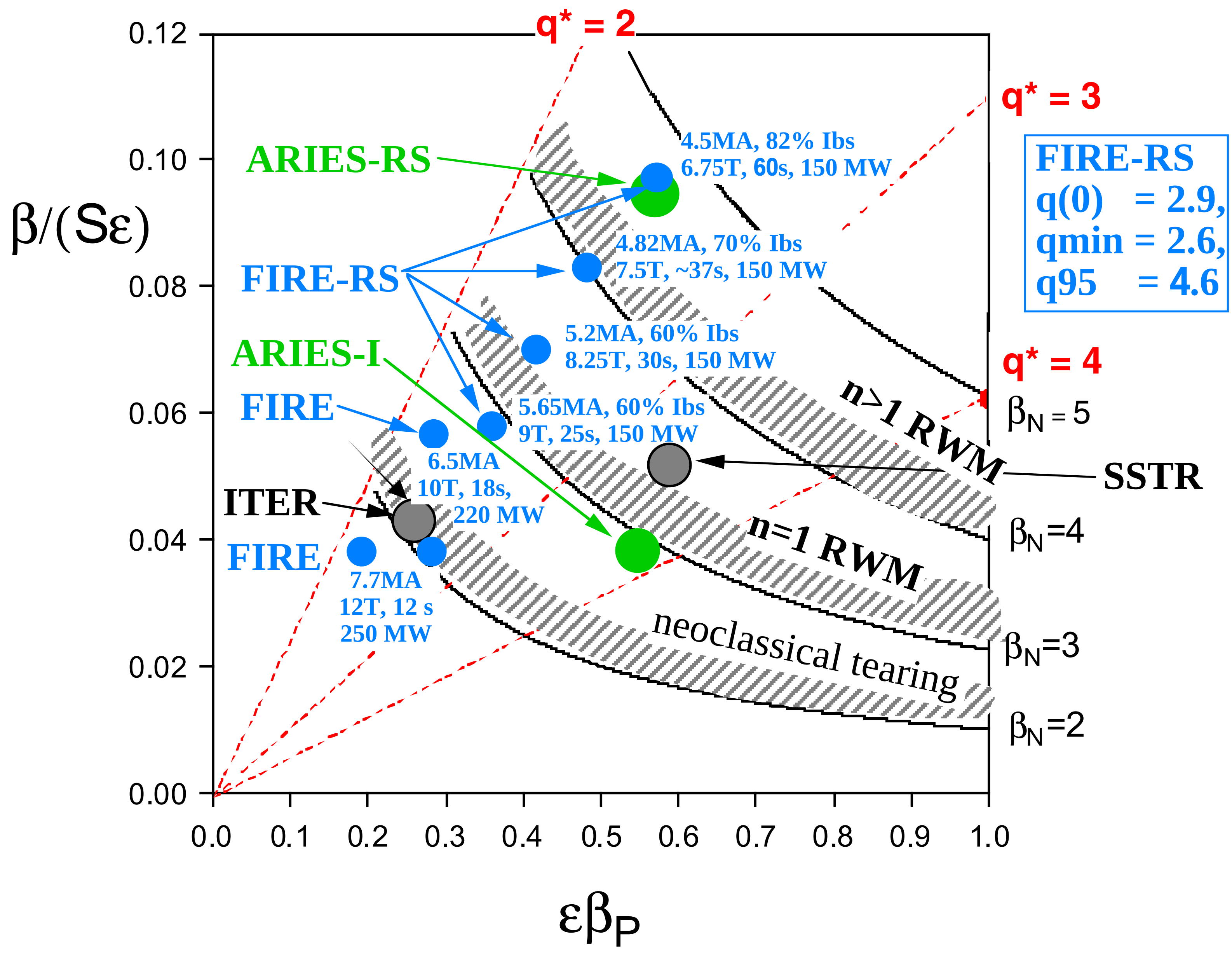
FIRE could Access "Long Pulse" Advanced Tokamak Mode Studies at Reduced Toroidal Field.



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

The combination of JET-U, JT-60 Mod, KSTAR and FIRE could cover the range fromsteady-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

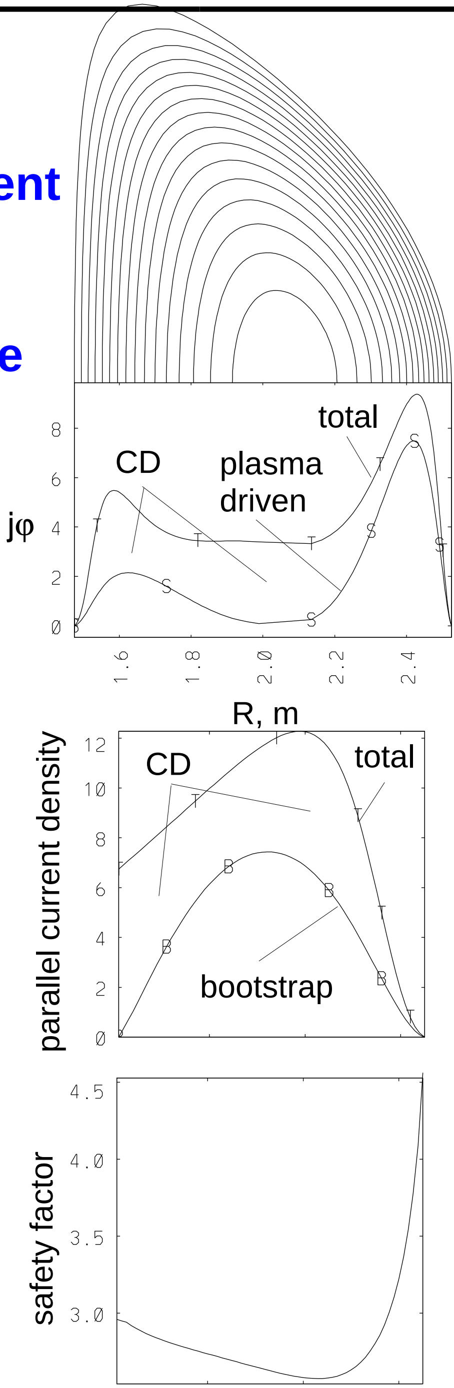
Q = 10, HH = 1.2

or

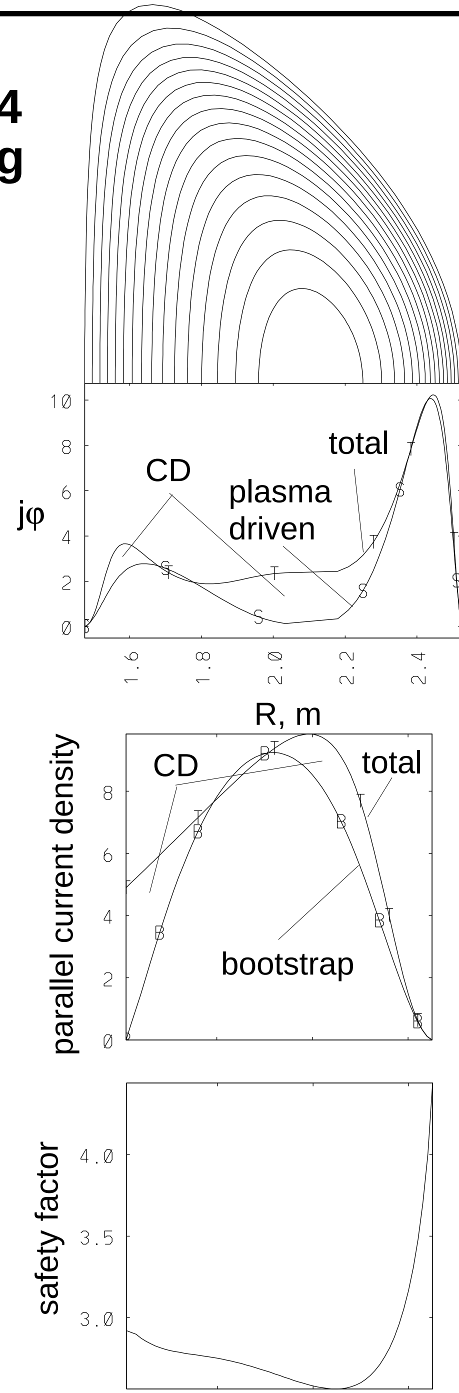
Q = 5, HH = 1.06

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

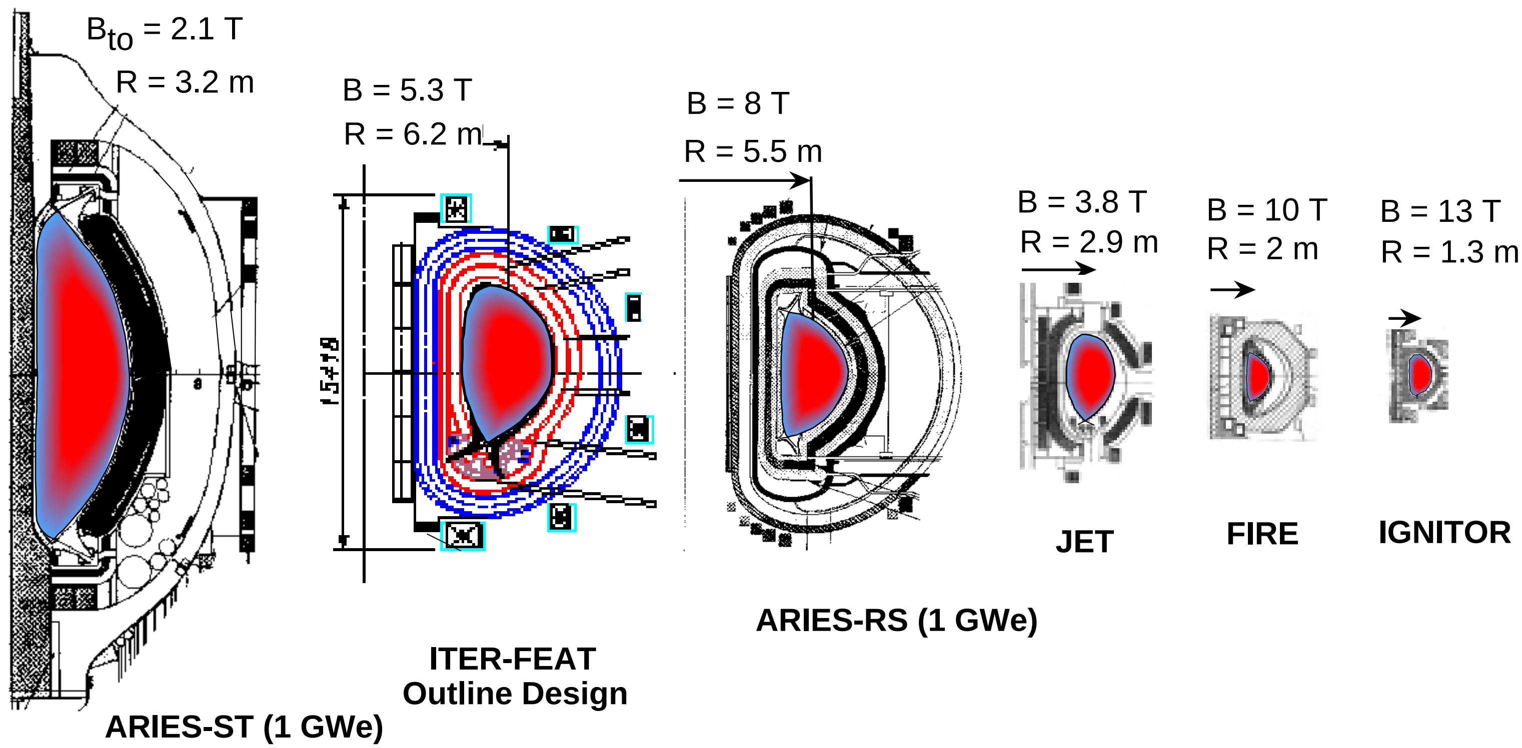
Q = 5, HH = 1.36

Duration

~ 4 tau_skin

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

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

FIRE Power Requirements for BeCu or CuTF Coils

	10T (20s flattop)		12T (12s flattop)	
BeCu	Peak Power (MW)	Peak Energy (GJ)	Peak Power (MW)	Peak Energy (GJ)
TF	490	11.5	815	11.5
PF	250	2.2	360	3.7
RF	60	1	60	0.6
$\sum$	800	14.7	1235	15.8
Grid	550 (TF&RF)	12.5	600 (TFbase)	10.9
MG	250 (PF)	2.2	635 (TFsupp&PF&RF)	4.9

	10T (45s flattop)		12T (25s flattop)	
Cu	Peak Power (MW)	Peak Energy (GJ)	Peak Power (MW)	Peak Energy (GJ)
TF	267	12.6	345	13.2
PF	250	5	360	4.6
RF	60	2.3	60	1.3
$\sum$	577	19.9	765	19.1
Grid	577 (All Systems)	19.9	404 (TF&RF)	14.5
MG	0	0	360 (PF)	4.6

Preliminary FIRE Cost Estimate (FY99 US$M)

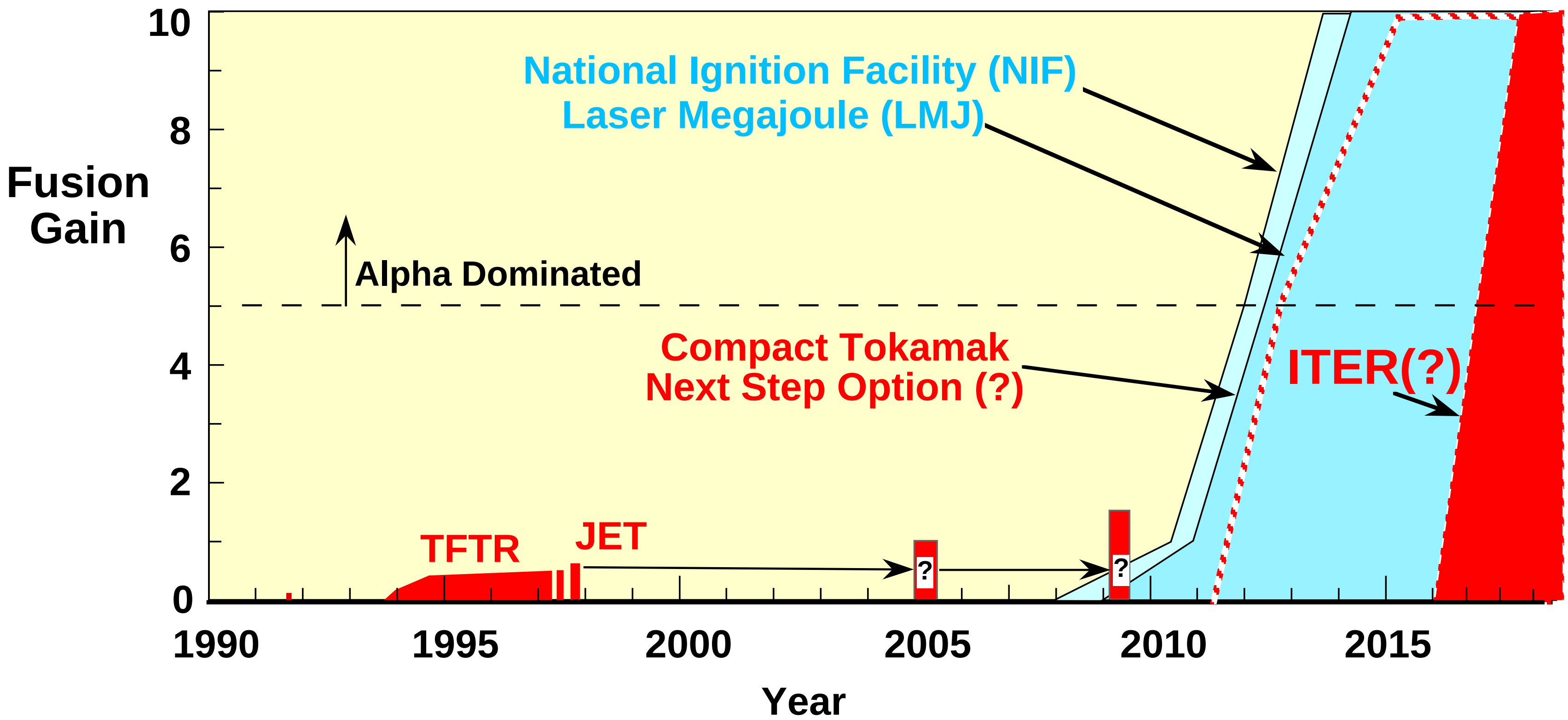
	Estimated Cost	Contingency	Total with Contingency
1.0 Tokamak Core	252.2	75.2	323.0
1.1 Plasma Facing Components	65.0	17.0	
1.2 Vacuum Vessel/In-Vessel Structures	35.2	9.7	
1.3 TF Magnets /Structure	113.8	37.2	
1.4 PF Magnets/Structure	28.4	8.5	
1.5 Cryostat	1.8	0.5	
1.6 Support Structure	7.5	2.2	
2.0 Auxiliary Systems	134.6	39.3	173.9
2.1 Gas and Pellet Injection	7.1	1.4	
2.2 Vacuum Pumping System	13.0	2.0	
2.3 Fuel Recovery/Processing	7.0	1.0	
2.4 ICRF Heating	107.4	34.9	
3.0 Diagnostics (Startup)	22.0	4.9	26.9
4.0 Power Systems	177.3	42.0	219.3
5.0 Instrumentation and Controls	18.9	2.5	21.4
6.0 Site and Facilities	151.4	33.8	185.2
7.0 Machine Assembly and Remote Maintenance	88.3	21.8	110.1
8.0 Project Support and Oversight	100.1	15.0	115.1
9.0 Preparation for Operations/Spares	16.2	2.4	18.6
Preconceptual Cost Estimate (FY99 US$M)	**960.9**	**236.9**	**1193.5**

Assumes a Green Field Site with **No** site credits or significant equipment reuse.

This estimate is work in progress and will be reviewed in the winter 2000.

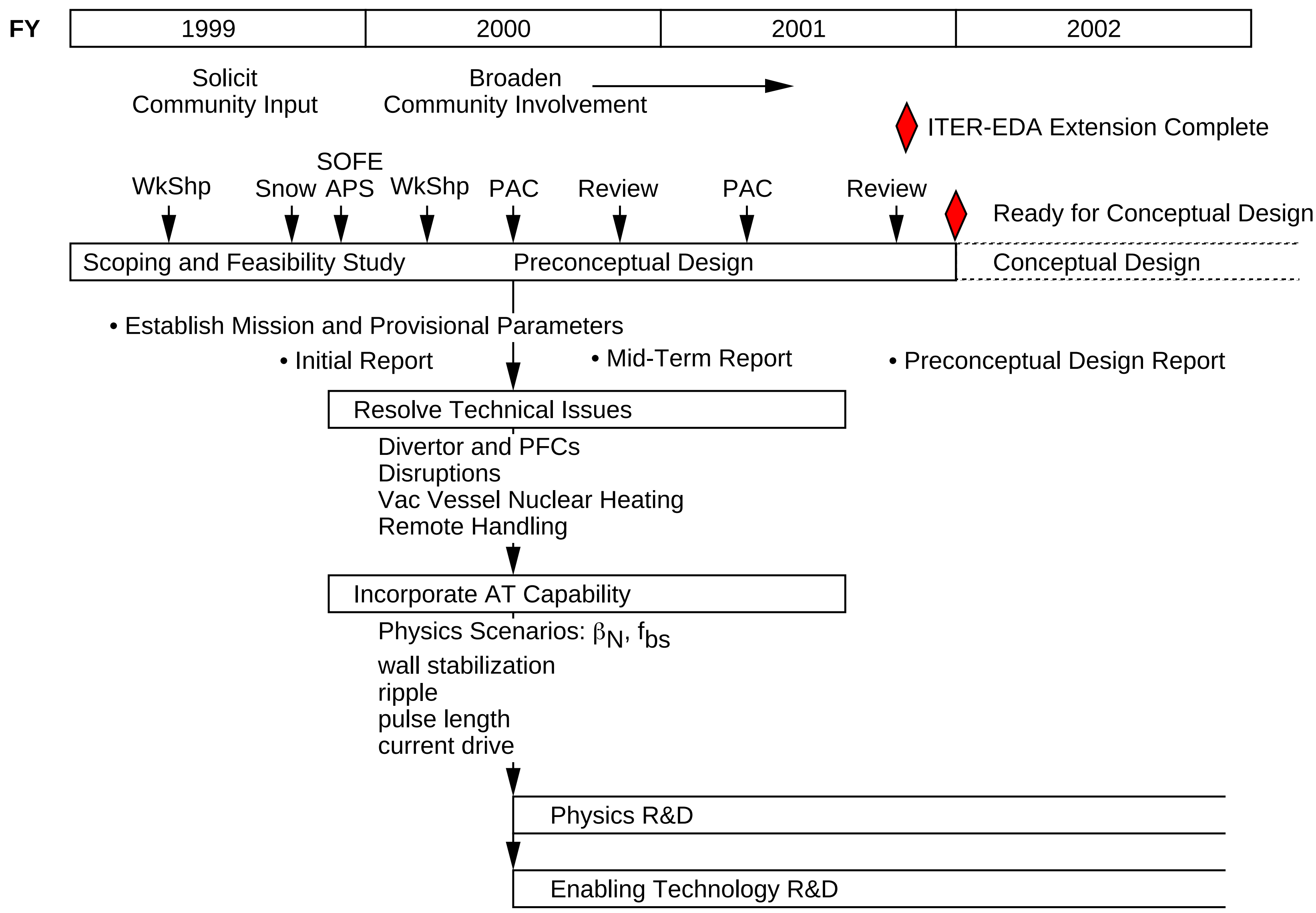
October 13, 2000

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.

Basic Strategy for an Advanced Tokamak Next Step (FIRE)



Future Work (More Innovation and Improvement)

- Understand and incorporate recent JET, ASDEX-U, JT-60U, DIII-D and C-Mod enhanced performance results to refine FIRE performance projections.
- Incorporate disruption scenarios into design, evaluate experimental data on VDEs in DN vs SN configurations. Evaluate mitigation techniques.
- Develop some specific AT modes including needs for auxiliary systems for profile control and feedback stabilization.
- Peer reviews of engineering and cost of Baseline design
- Evaluate engineering features of enhanced performance design point (7.7 MA)
  - improved shaping (lower aspect ratio, higher triangularity)
  - all OFHC bucked and wedged design (11.5 T @25 s with 50% elect. power)
- Identify critical R&D items.

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.

http://fire.pppl.gov