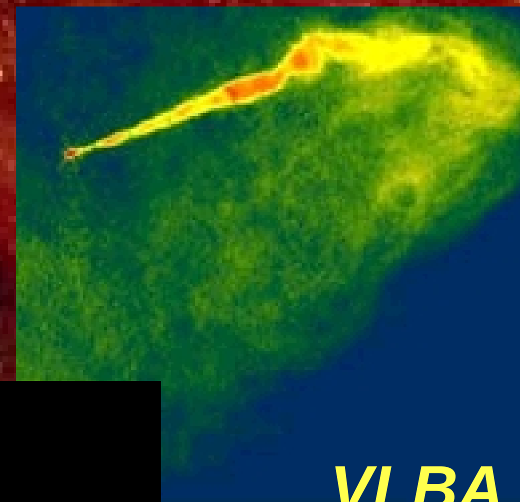
Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science


CHANDRA

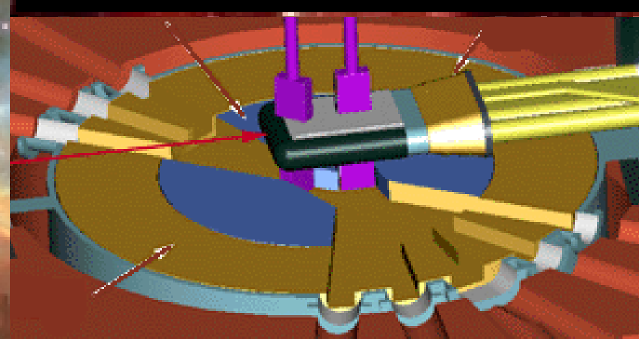

VLBA

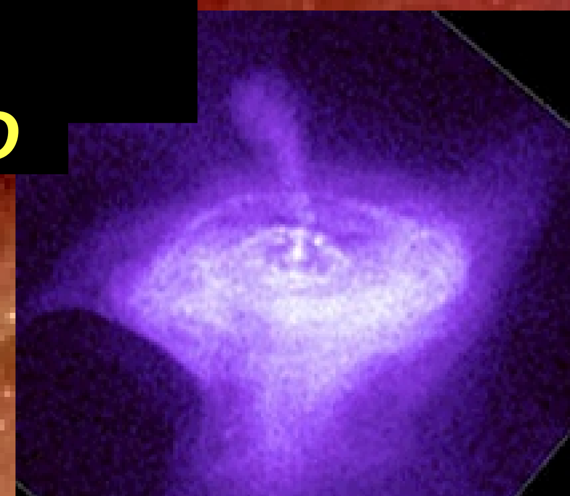

NIF

?

NSO


HST (NGST)


SNS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Fusion Ignition Research Experiment (FIRE)

A Next Step Option for Magnetic Fusion Research

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Ecole Polytechnique Fédérale de Lausanne

October 16, 2000

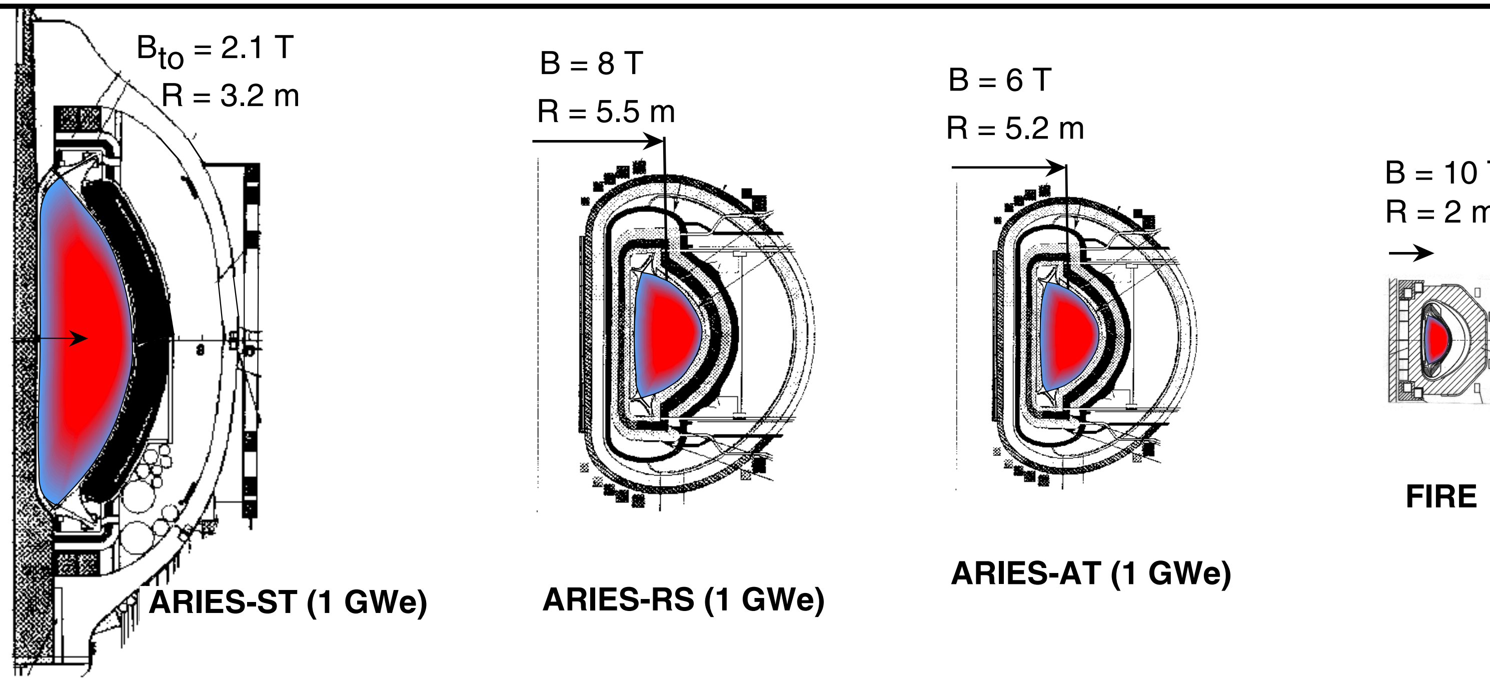
http://fire.pppl.gov

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

The Tokamak has the Potential to be an Attractive Fusion Reactor.



Fusion Metrics	ARIES-ST	ARIES-RS	ARIES-AT*	FIRE
Plasma Volume (m^3)	810	350	330	18
Plasma Surface (m^2)	580	440	426	60
Plasma Current (MA)	30	11	13	6.5
Fusion Power (MW)	3000	2200	1755	200
Fusion Power Density(MW/m^3)	3.7	6.2	5.3	12
Neutron Wall Load (MW/m^2)	4	4	3.5	3
COE Projected (mils/kWh)	81	76	≈55	

* 6/14/2000

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.

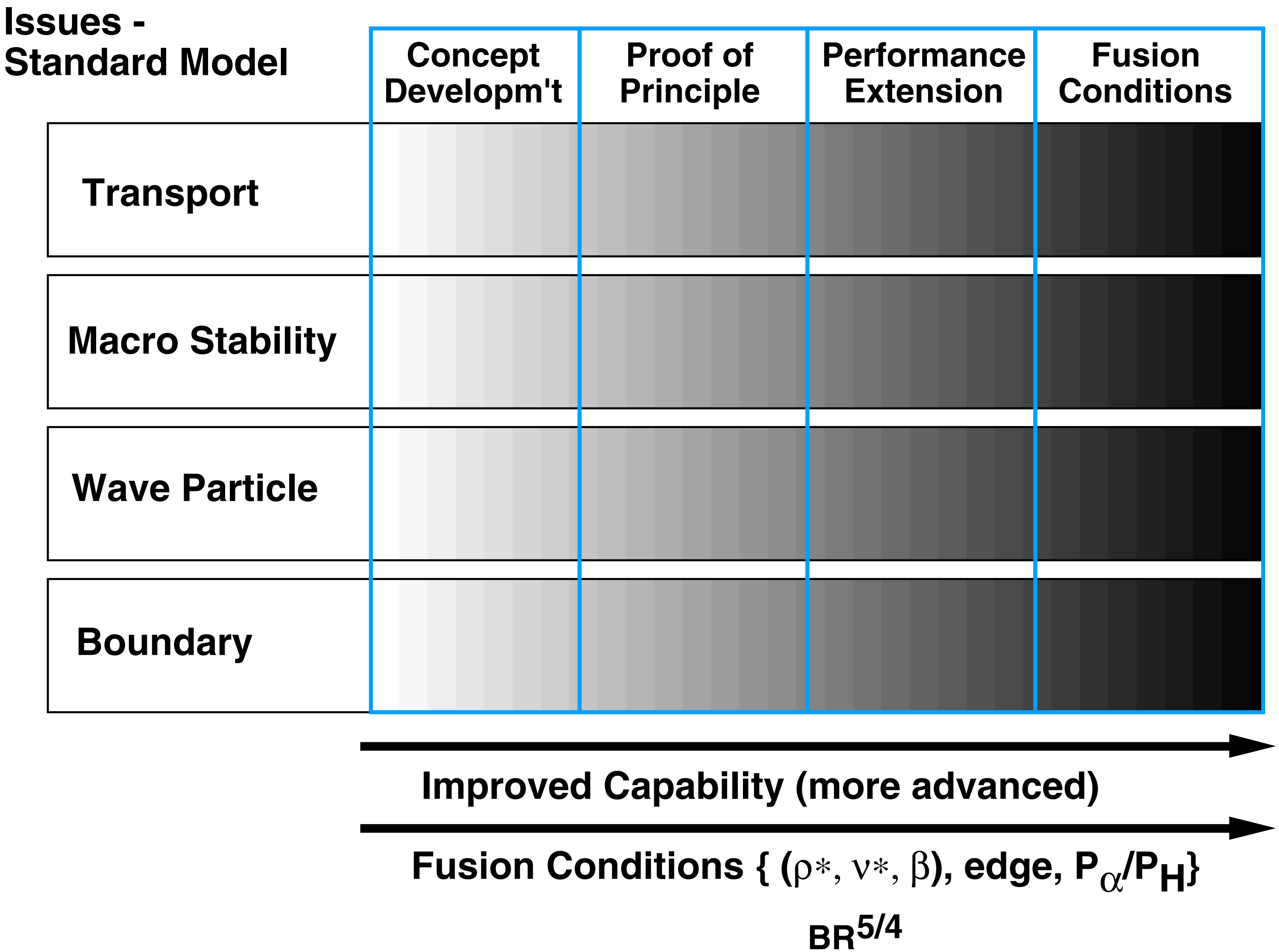
- Presentations have been made and comments received from:

SOFT/Fr	**Sep 98**	**IAEA/Ja**	**Oct 98**
APS-DPP	**Nov 98**	**FPA**	**Jan 99**
APEX/UCLA	**Feb 99**	**APS Cent**	**Mar 99**
IGNITOR	**May 99**	**NRC**	**May 99**
GA	**May 99**	**LLNL**	**May 99**
VLT-PAC	**Jun 99**	**MIT PSFC**	**Jul 99**
Snowmass	**Jul 99**	**PPPL/SFG**	**Aug 99**
U. Rochester	**Aug 99**	**NYU**	**Oct 99**
U. Wis	**Oct 99**	**FPA**	**Oct 99**
SOFE	**Oct 99**	**APS-DPP**	**Nov 99**
U. MD	**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**	**Feb00**
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**

- **The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. A steady stream of about 150 visitors per week log on to the FIRE web site since the site was initiated in early July, 1999.**

Magnetic Fusion Science

Part I



Requirements for Fusion Plasma Science

Study Physics of Fusion Plasmas (transport, pressure limits, etc.)

- Same plasma physics if $\rho^* = \rho/a$, $\nu_* = \nu_c / \nu_b$ and β are equal

  Requires $BR^{5/4}$ to be equal to that of a fusion plasma

Study Physics of Burning Plasmas (alpha confinement, self heating, etc)

- Alpha particle confinement requires $Ip(R/a) \geq 9$, $Ip(R/a) \sim BR(R/a)$
- Alpha heating dominant, $f_\alpha = P_\alpha/P_{heat} = Q/(Q+5) > 0.5$

  $f_\alpha = n\tau_E T \,/\, (n\tau_E T)_{Ignition}$ for $P_\alpha \gg P_{brem}$

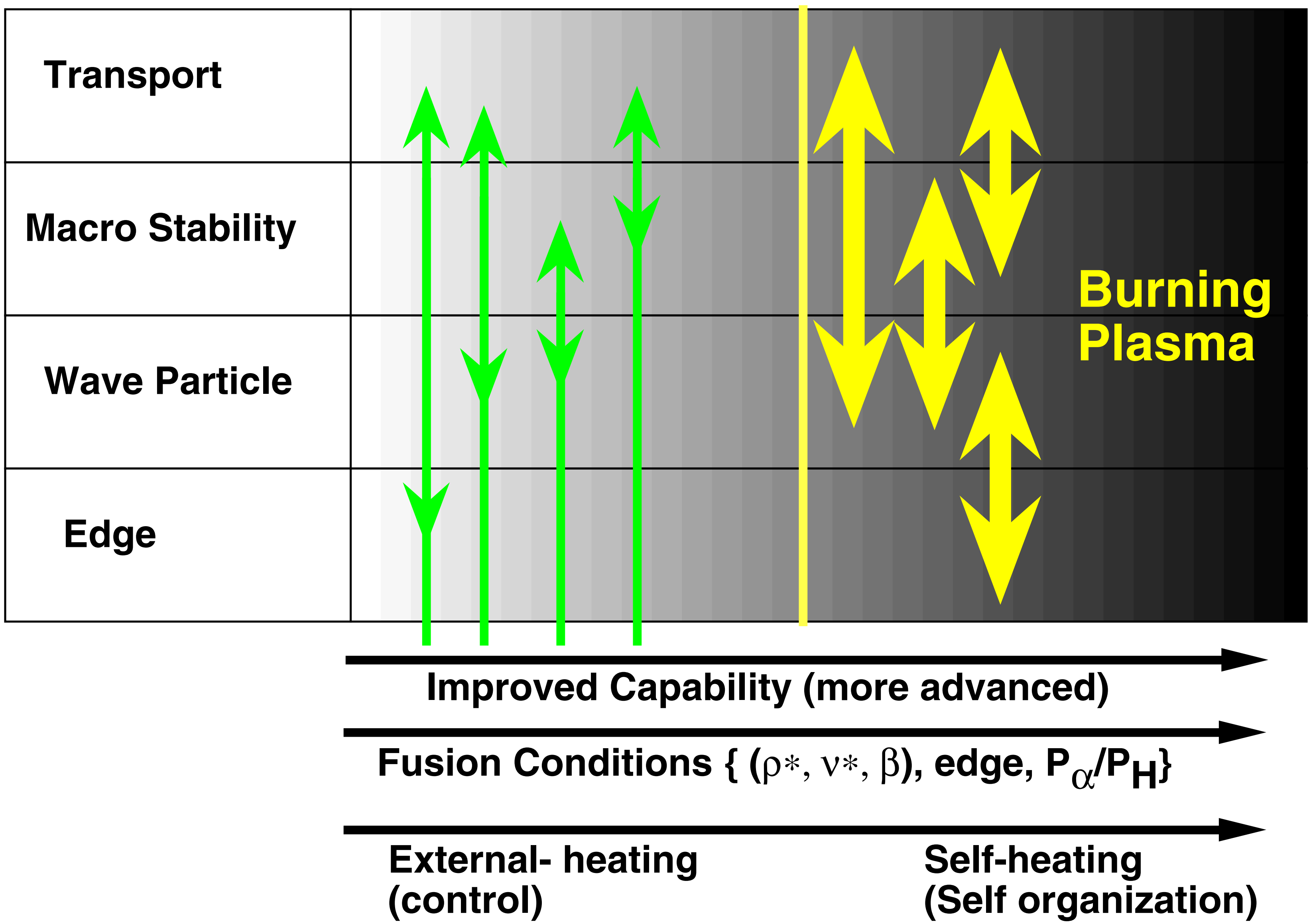
  $n\tau_E T = B \times \text{function}(\rho^*, \nu_*, \beta)$ in general

  $n\tau_E T = B \times (BR^{5/4})^{4/3}$, if τ_E scales as Bohm

  $= B \times (BR^{5/4})^2$, if τ_E scales as gyroBohm

Magnetic Fusion Science

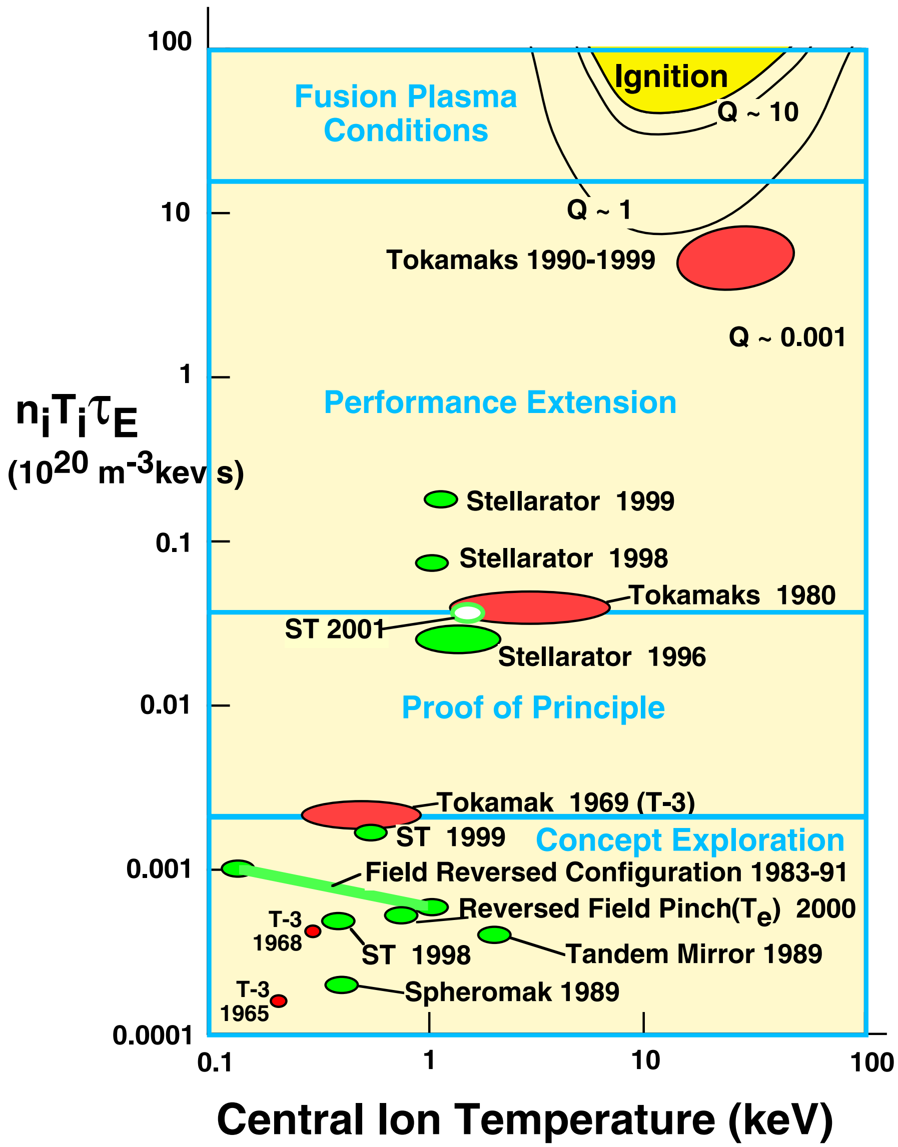
Issues - Strongly Coupled in a Fusion (Burning) Plasma

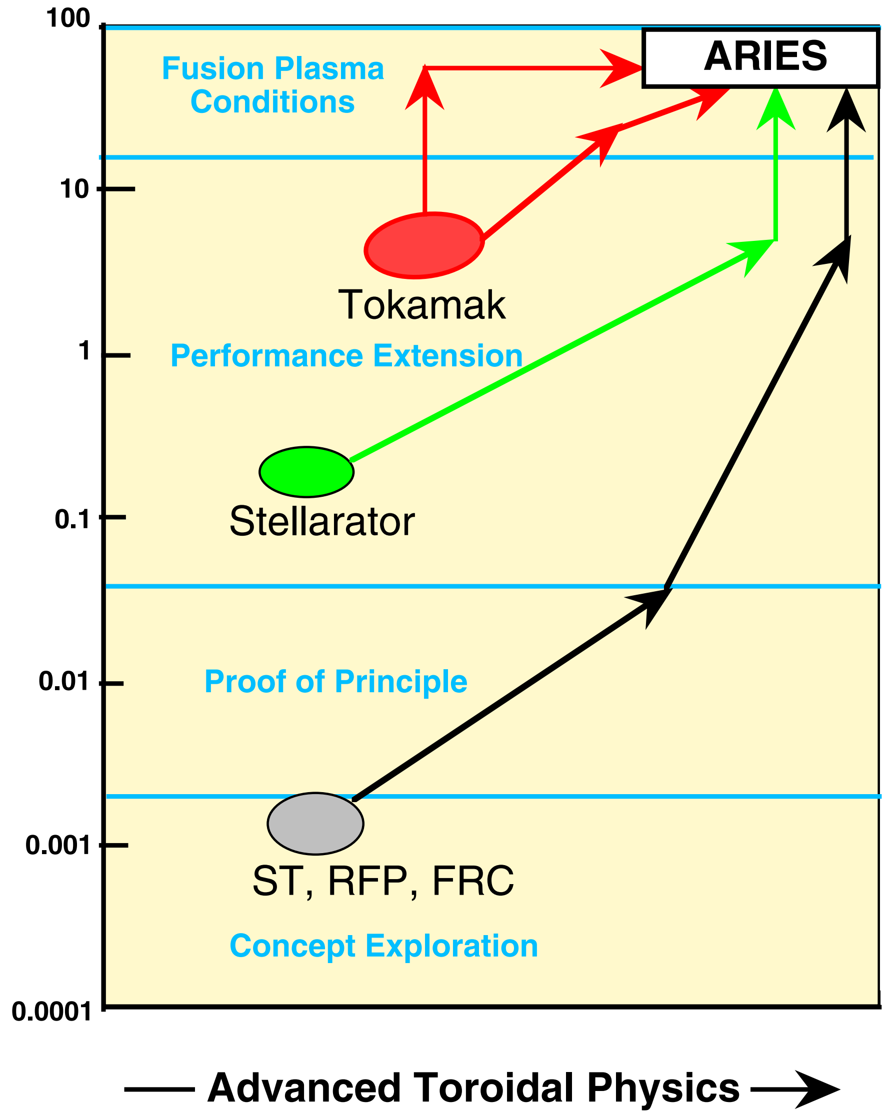


Burning Plasma Physics is Widely Accepted as the Primary Objective for a Next Step in Fusion Research

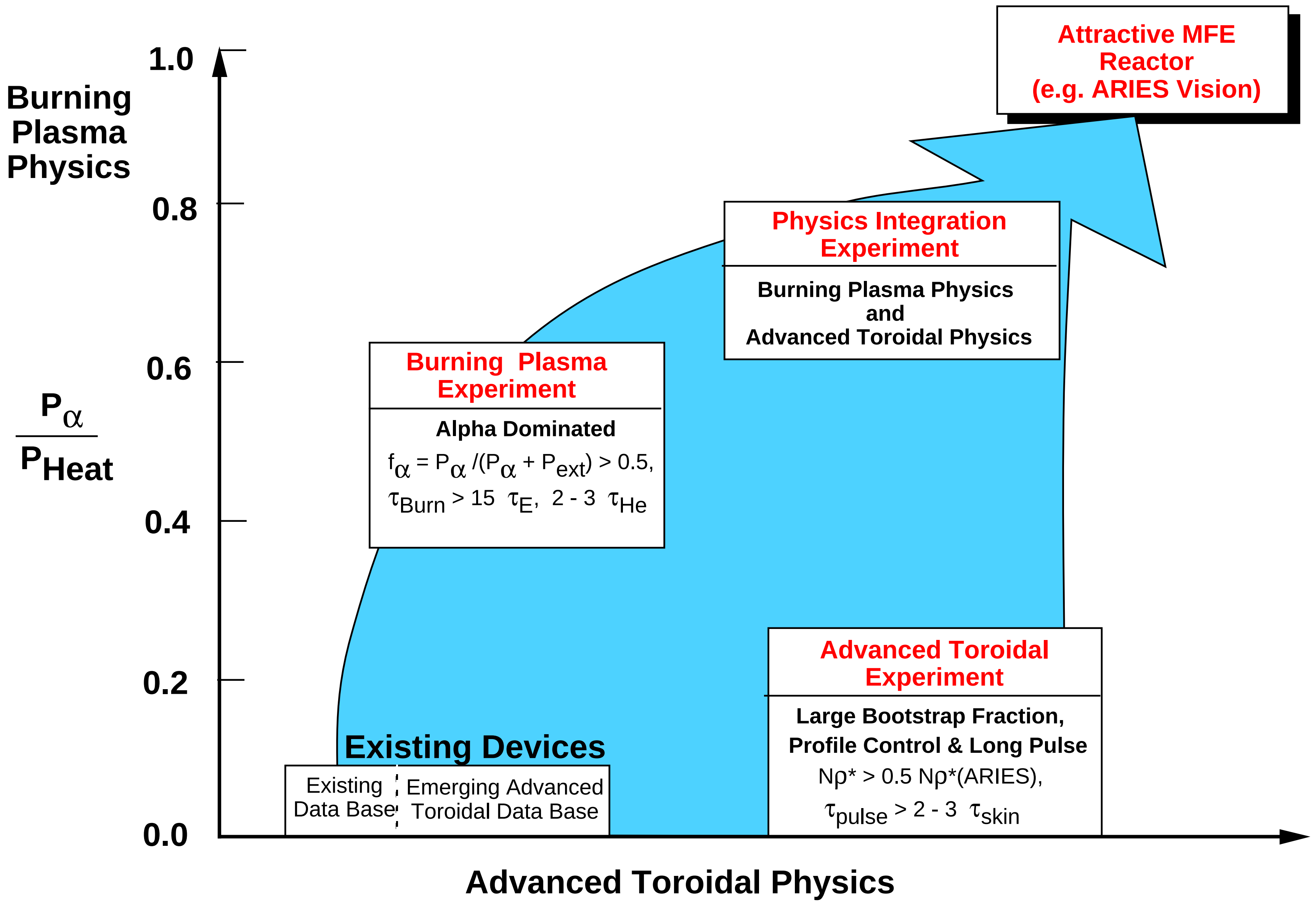
- Grunder Panel and Madison Forum endorsed Burning Plasmas as next step.
- NRC Interim Report identified “integrated physics of a self-heated plasma” as one of the critical unresolved fusion science issues.
- The Snowmass Fusion Summer Study endorsed the burning plasma physics objective, and that the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

Is the Tokamak Ready to Explore the Science of Fusion Plasmas?





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.

Purpose of the Next Step

Status - physics understanding and predictive capability is improving but uncertainties will always remain that must be tested in a “real” fusion plasma.

The purpose of NSO is to extend both physics understanding and performance

it is not to demonstrate that present understanding is correct.

Size of the extrapolation (risk) must be chosen to maximize the information in the critical areas for a fusion reactor.

At the same time, the cost constraints will force one toward a minimum size step.

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

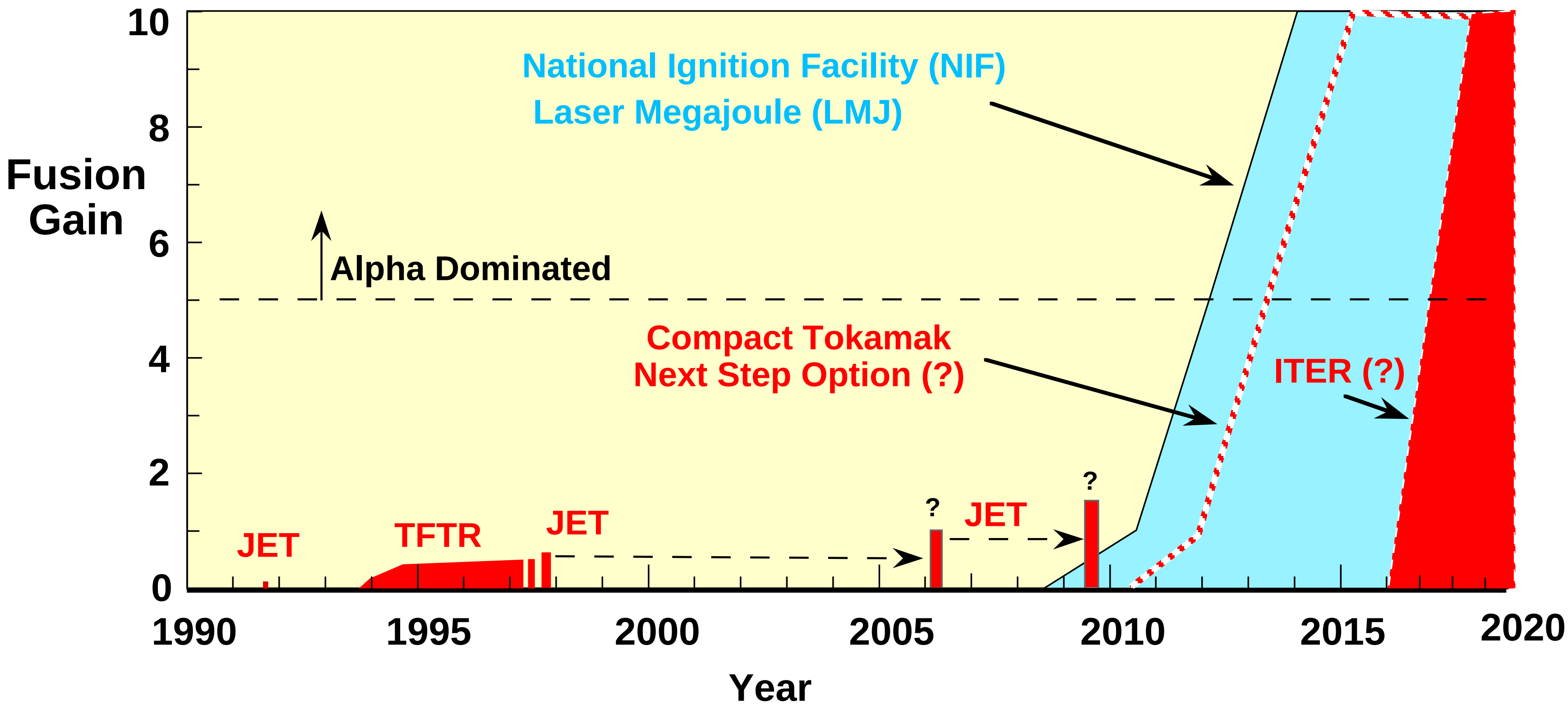
- Explore and understand the physics of alpha-dominated fusion plasmas:
    - Energy and particle transport (extend confinement predictability)
    - Macroscopic stability (β-limit, wall stabilization, NTMs)
    - Wave-particle interactions (fast alpha driven effects)
    - Plasma boundary (density limit, 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.

see also ITER Physics Basis Report Nuclear Fusion

Optimizing a Tokamak Next Step Experiment

- Utilize existing experimental, modeling and theoretical activities to extend the understanding of present plasma regimes with enhanced performance
    - revitalize the science issue expert groups, participate in the international effort, develop the physics basis for incorporating some AT features or flexibility into a Next Step experiment.
- Take advantage of the growing resources becoming available in various computer simulation initiatives to extend the capability of existing magnetic fusion simulation codes.
- Exploit this improved capability to refine/improve/optimize the design of a Next Step experiment to that it is able to test the essential physics issues and extend the physics understanding to fusion plasma conditions.
- Use a similar philosophy on the engineering issues to optimize the design.

Timetable for Burning Plasma Experiments



- Even with ITER, the magnetic fusion 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 a magnetic fusion burning plasma experiment(s) for the next decade.

MFE Experimental Facilities are Needed to Investigate Plasma Science at Fusion Conditions

Science Steps	Magnetic Fusion	Inertial Fusion
Energy Development	(DEMO) (ITER-FEAT)	(DEMO) (ETF)
Fusion Plasma Conditions	(FIRE, IGNITOR)	NIF*, LMJ* (X-1)
Performance Extension	JET, TFTR, JT-60U, DIII-D. C-Mod. AUG. Tore Supra, FTU LHD, W-7X*	Omega-U, NOVA, GEKKO 12, PHEBUS Vulcan, Russian Z
Proof of Principle	PLT,DIII,PBX, TFR, Asdex, TCV, JFT-2M W-7AS, JIPPT-2 NSTX,MAST MST	Shiva, OMEGA Nike,Super Ashura NOVETTE GEKKO IV (IREs)
Concept Exploration	T-3, Many tokamaks Many stellarators Several STs Many Pinches Many Mirrors	AURORA Argus Cyclops JANUS PFBA

> 500 MF exp'ts since 1957 ~100 IF exp'ts since 1970

* Under Construction, ( ) Design Study

The Rosetta Stone for Fusion

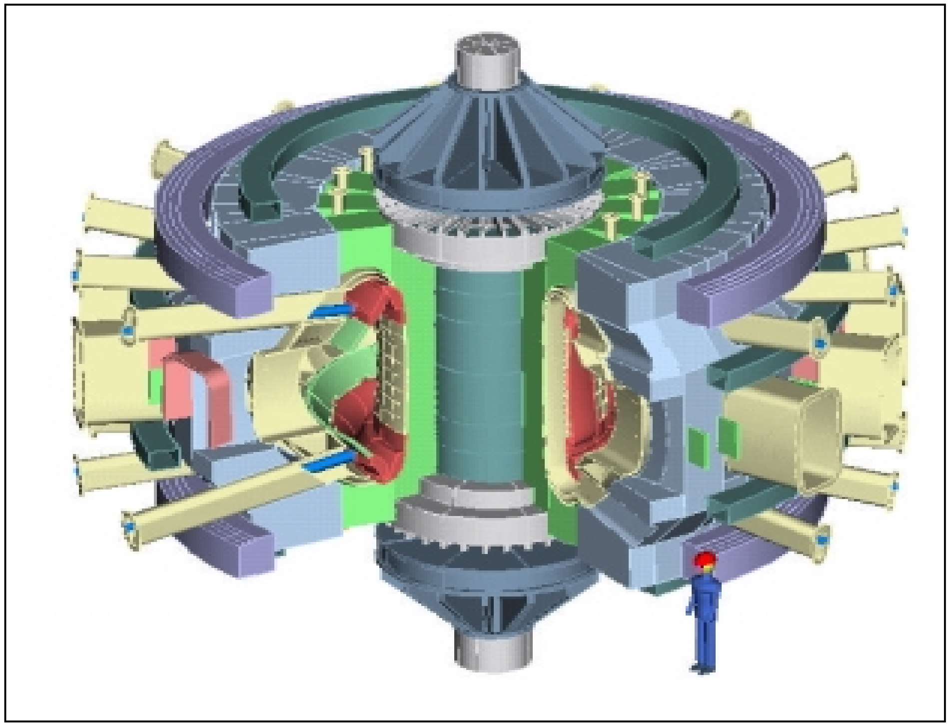
	Fusion Energy	Fusion Science
plasma physics	$n\tau_E T$	ρ^*, ν^*, β $(BR^{5/4})$
burning physics	$Q = P_{fus}/P_{aux\text{-}heat}$	$f_\alpha = P_\alpha/(P_{aux\text{-}heat} + P_\alpha)$
time	s, min, hr	τ_E, τ_{skin}, etc
flexibility	low	high
availability	high	low
technology	nuclear	enabling

Fusion Science and Fusion Energy have different languages, metrics, and missions.

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 ≥10s (~18s)
- 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.

A Robust and Flexible Design for FIRE has been Achieved

- Toroidal and poloidal coil structures are independent allowing operational flexibility
    - The toroidal field coils are wedged with static compression rings to increase capability to withstand overturning moments and to ease manufacturing.

- 16 coil TF system with large bore provides
    - Large access ports (1.3m high by 0.7m wide) for maintenance and diagnostics.
    - Low TF ripple (0.3% at plasma edge) provides flexibility for lower current AT modes without large alpha losses due to ripple.

- Double-null divertor configuration for H-mode and AT modes with helium pumping that is maintainable/replaceable/upgradeable remotely

- Double wall vacuum vessel with integral shielding (ITER-like) to reduce neutron dose to TF and PF coils, and machine structure.

- Cooling to LN2 allows full field (10T) flattop for 20s or 4T (TPX-like) flattop for 250s.

The FIRE Engineering Report and 16 FIRE papers presented at the IEEE Symposium on Fusion Engineering are available on the web at http://fire.pppl.gov

Basic Parameters and Features of FIRE Reference Baseline

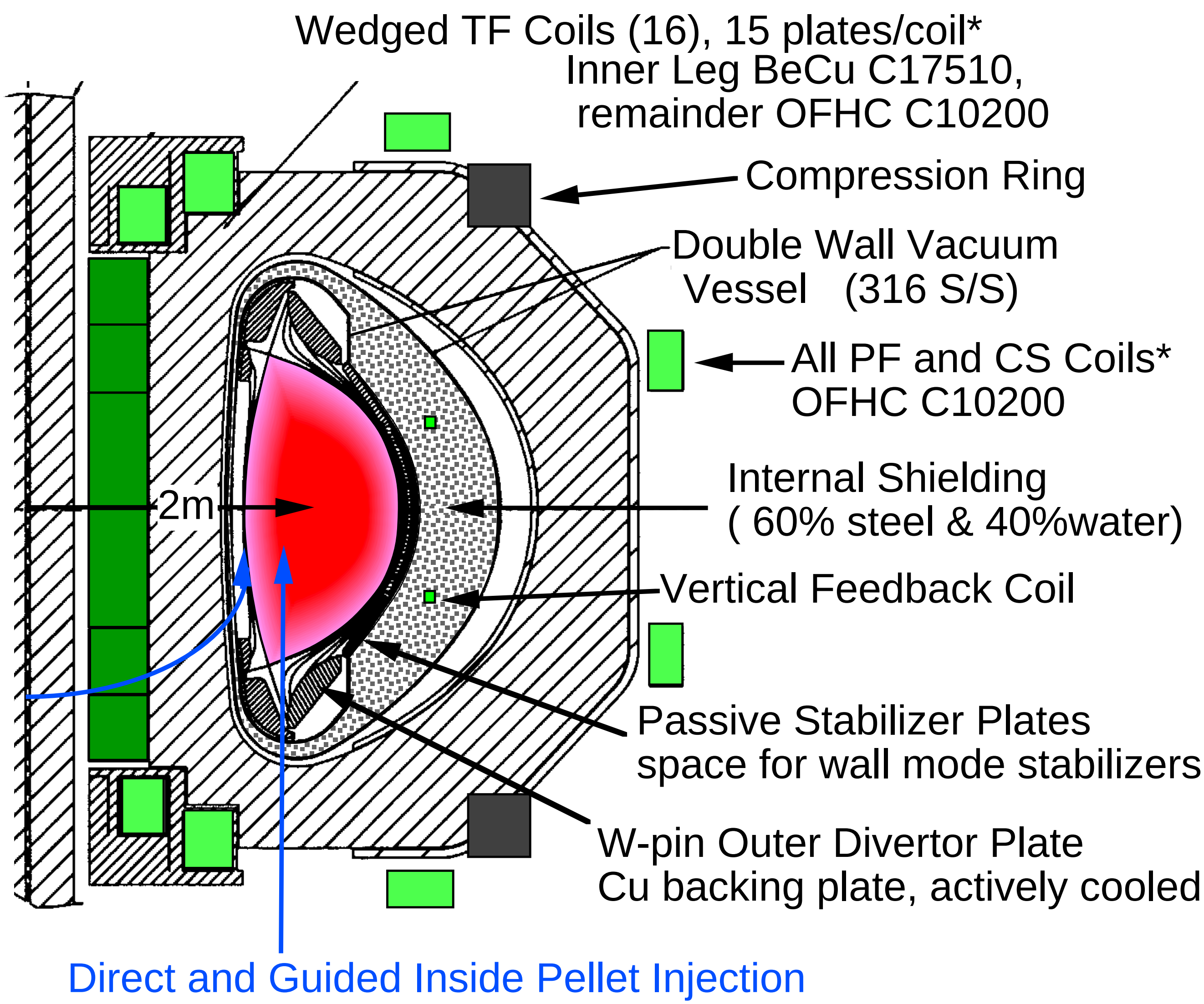
R, major radius	2.0 m
a, minor radius	0.525 m
κ95, elongation at 95% flux surface	~1.8
δ95, triangularity at 95% flux surface	~0.4
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.34% ripple @ Outer MP
Toroidal magnet energy	3.7 GJ
Ip, plasma current	~6.5 MA (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 Incorporates Advanced Tokamak Innovations

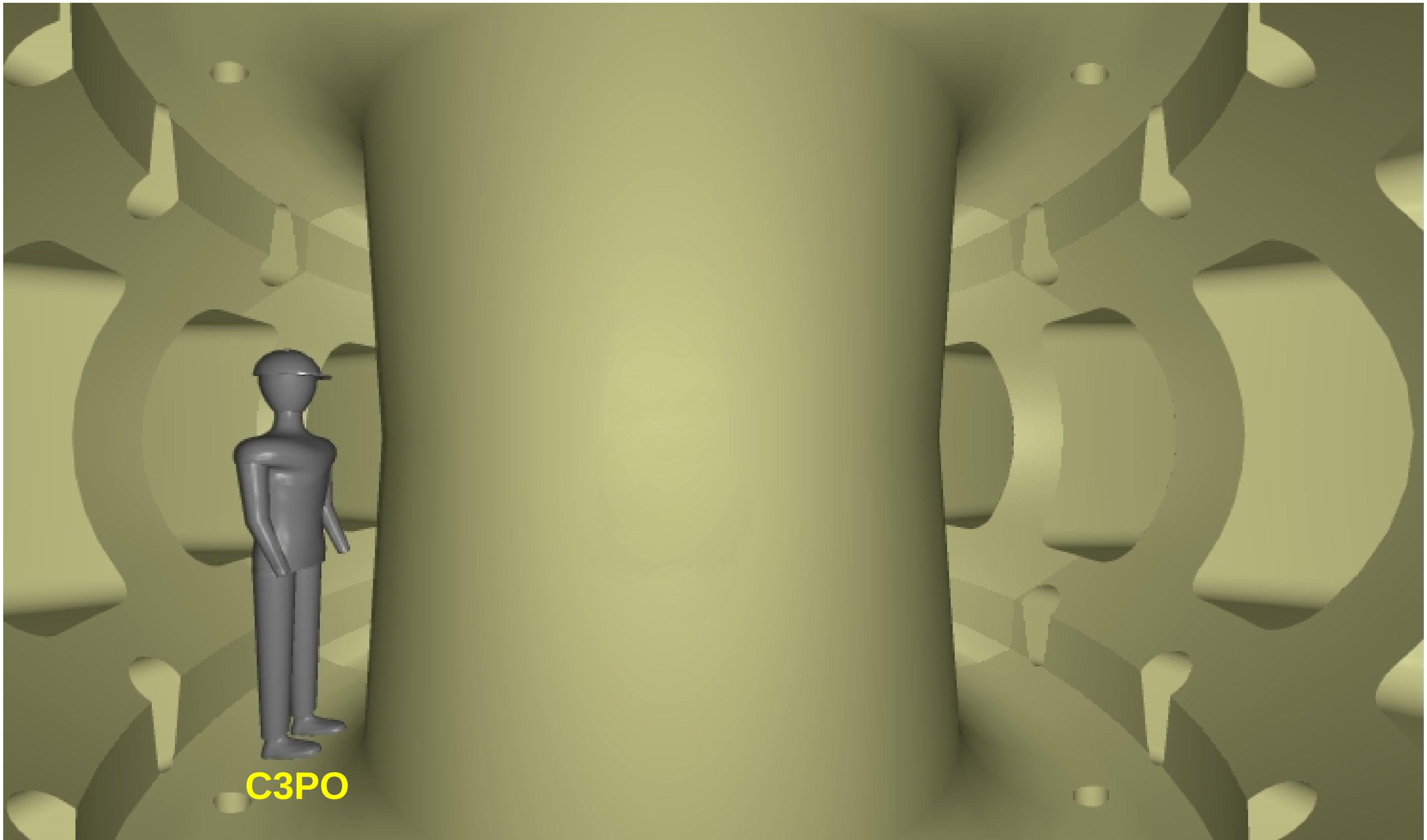
AT Features

- DN divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



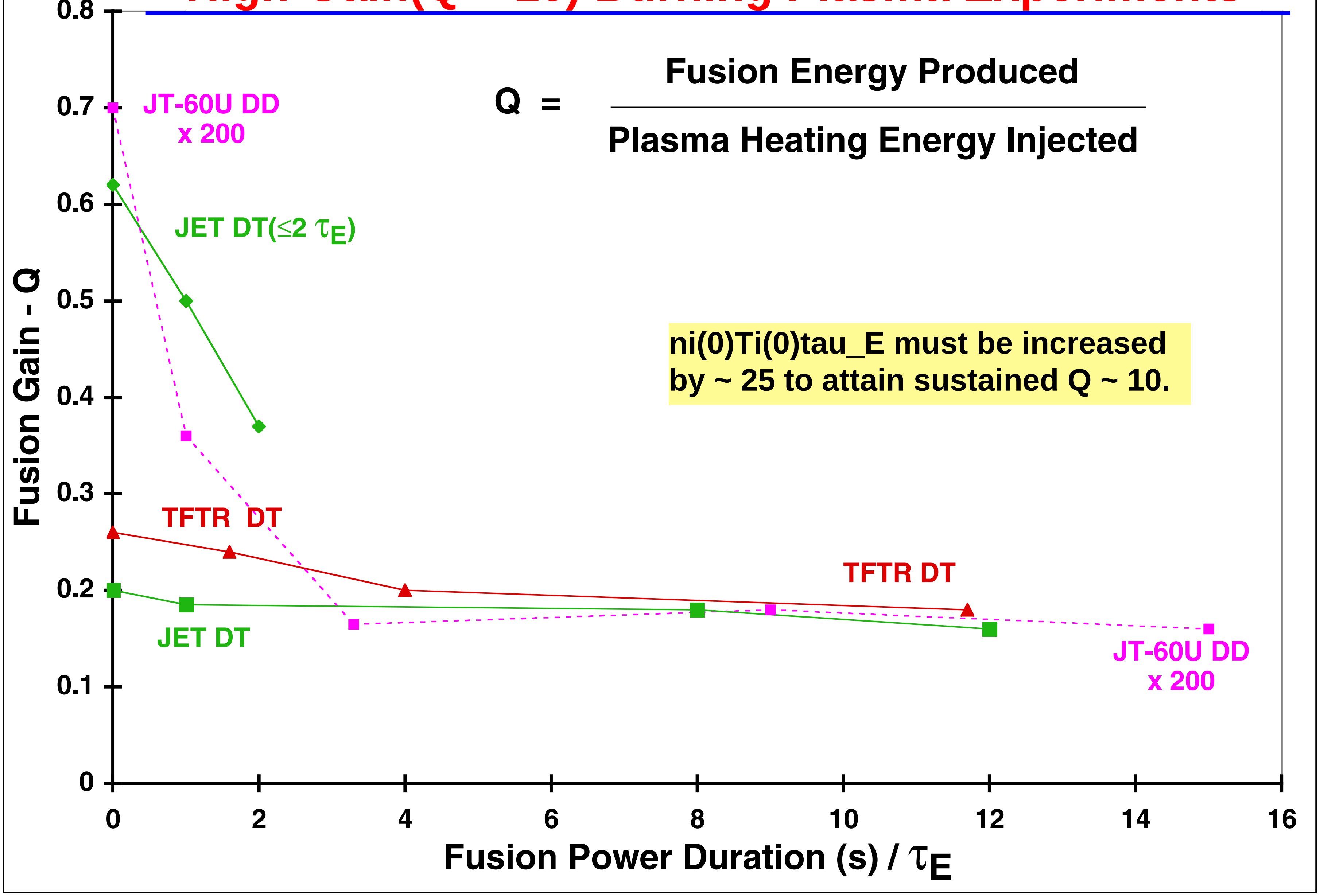
*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

FIRE would have Access for Diagnostics and Heating



16 mid-plane ports 1.3m x 0.65m
32 divertor ports 0.5m x 0.2m (16 for cryopumps/cooling water
24 vertical ports 0.13m diam

Q Must be Increased by ~50 for Sustained High-Gain(Q ~ 10) Burning Plasma Experiments



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

$$\tau_E = 0.144\, I^{0.93}\, R^{1.39} a^{0.58}\, n_{20}^{0.41} B^{0.15} A_i^{0.19} \kappa^{0.78}\, P_{heat}^{-0.69}$$

Density Limit - Base on today's tokamak data base

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

Beta Limit - theory and tokamak data base

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

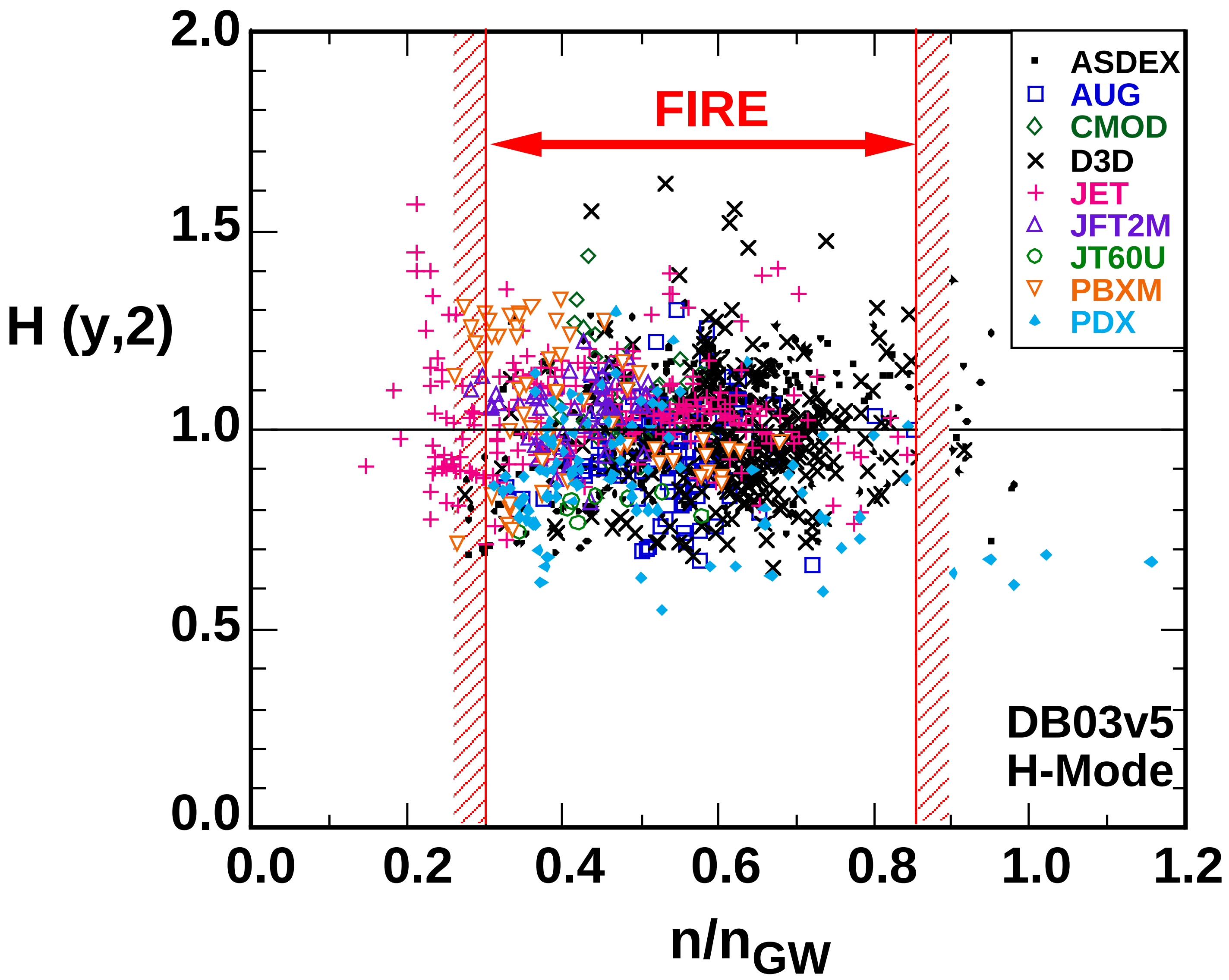
H-Mode Power Threshold - Based on today's tokamak data base

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

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 the science basis.

FIRE can Access Most of the H-Mode Database



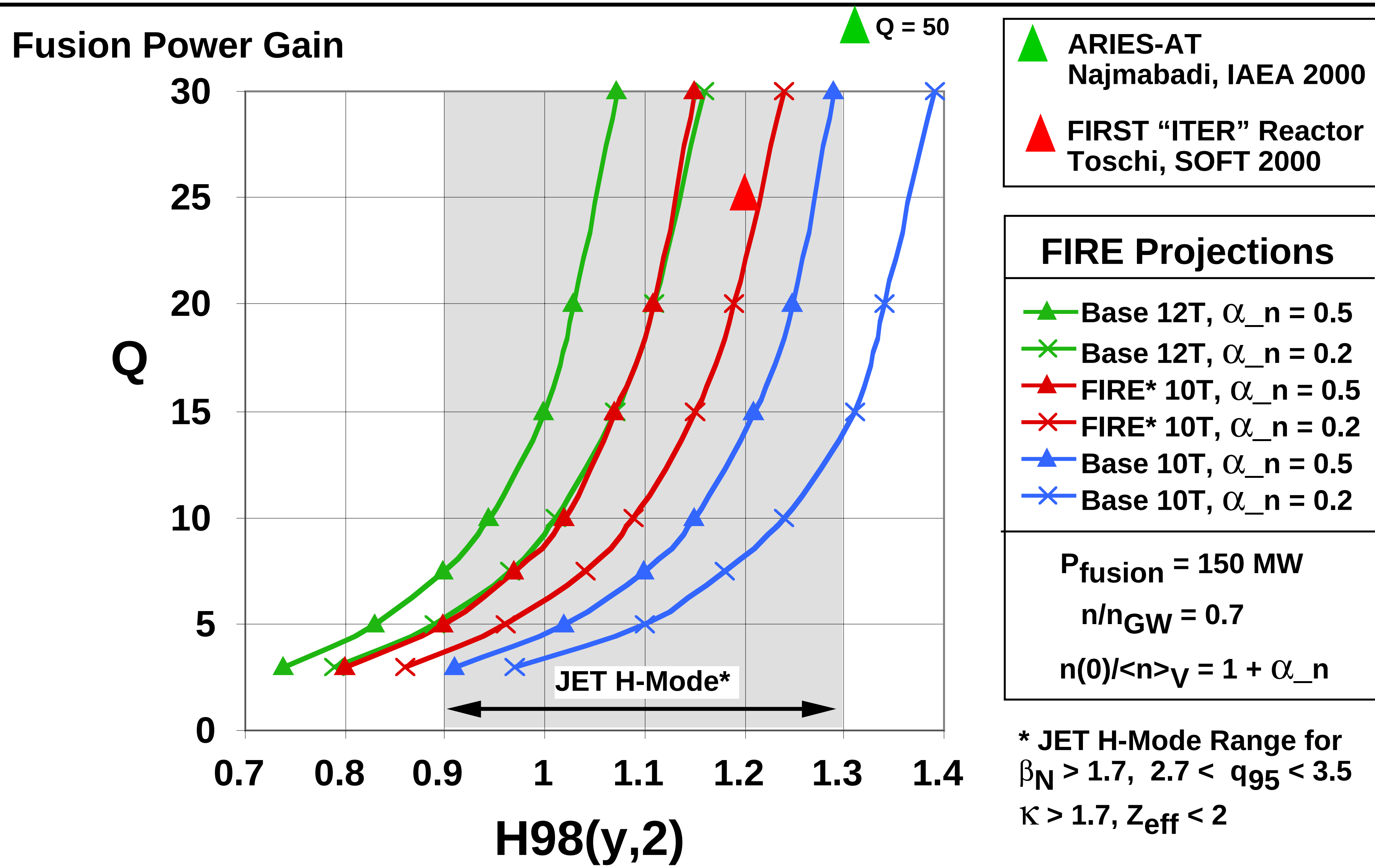
Nominal FIRE(10T) Plasma Parameters from 0-D Model

R_o, plasma major radius, m	**2.00**
a, plasma minor radius, m	**0.525**
R_o/a, aspect ratio	3.81
$\kappa95$, plasma elongation at 95% flux	1.77
$\delta95$, plasma triangularity at 95 % flux	**0.40**
q95	3.03
Bt, toroidal magnetic field at R_o, T	**10**
Ip, plasma current, MA	**6.44**
li(3), internal plasma inductance	0.80
Bootstrap current fraction, approx.	0.31
Ion Mass	2.5
<n_e>, 10^20 /m^3, volume average	4.22
α_n, densiy profile peaking = 1 + α_n	**0.5**
<n>l/Greenwald	**0.65**
<T>n, density weighted average temperature, keV	7.3
T(0), central temperature, keV	11.6
α_T, temperature profile peaking = 1+ α_T	1
Impurities, Be; Hi Z, %	3;0
taup*(He)/tauE	5
Alpha ash concentration, %	1.69
Zeff	1.39
ν*, collisionality at q = 1.5	0.051
Pext (MW)	15
P_fusion (MW)	150.6
Pheat = Pext + Palpha - Prad(core), (MW)	52.0
Pheat/P_{th}(L->H)	**2.33**
IA	24.50
tauE	0.52
ITER98H(y,2)-Multiplier	**1.03**
ITER89P-Multiplier	2.10
nd(0)T(0)tau_E, 10^20m^-3 kev s	31.9
Q_DT	**5.0**
Plasma current redistribution time, s	11.7
W(MJ), plasma kinetic energy	26.8
Fast alpha energy/Plasma W, %	7.8
Beta_total, %	2.5
Beta_N	**2.1**
tritium Mass (g)	0.016

Nominal FIRE(12T) Plasma Parameters from 0-D Model

R_o, plasma major radius, m	**2.00**
a, plasma minor radius, m	**0.525**
R_o/a, aspect ratio	3.81
κ_{95}, plasma elongation at 95% flux	1.77
δ_{95}, plasma triangularity at 95 % flux	**0.40**
q95	3.03
Bt, toroidal magnetic field at R_o, T	**12**
Ip, plasma current, MA	**7.71**
li(3), internal plasma inductance	0.80
Bootstrap current fraction, approx.	0.24
Ion Mass	2.5
<ne>, 10^20 /m^3, volume average	5.40
α_n, densiy profile peaking = 1 + α_n	**0.2**
<n>l/Greenwald	**0.65**
<T>n, density weighted average temperature, keV	6.4
T(0), central temperature, keV	10.9
α_T, temperature profile peaking = 1+ α_T	1
Impurities, Be; Hi Z, %	3;0
taup*(He)/tauE	5
Alpha ash concentration, %	2.25
Zeff	1.41
ν^*, collisionality at q = 1.5	0.06
Pext (MW)	15
P_fusion (MW)	149.2
Pheat = Pext + Palpha - Prad(core), (MW)	34.2
Pheat/P_{th}(L->H)	**1.20**
IA	29.37
tauE	0.88
ITER98H(y,2)-Multiplier	**1.01**
ITER89P-Multiplier	2.37
nd(0)T(0)tau_E, 10^20m^-3 kev s	51.9
Q_{DT}	**9.9**
Plasma current redistribution time, s	9.6
W(MJ), plasma kinetic energy	30.1
Fast alpha energy/Plasma W, %	6.1
Beta_total, %	1.94
Beta_N	**1.58**

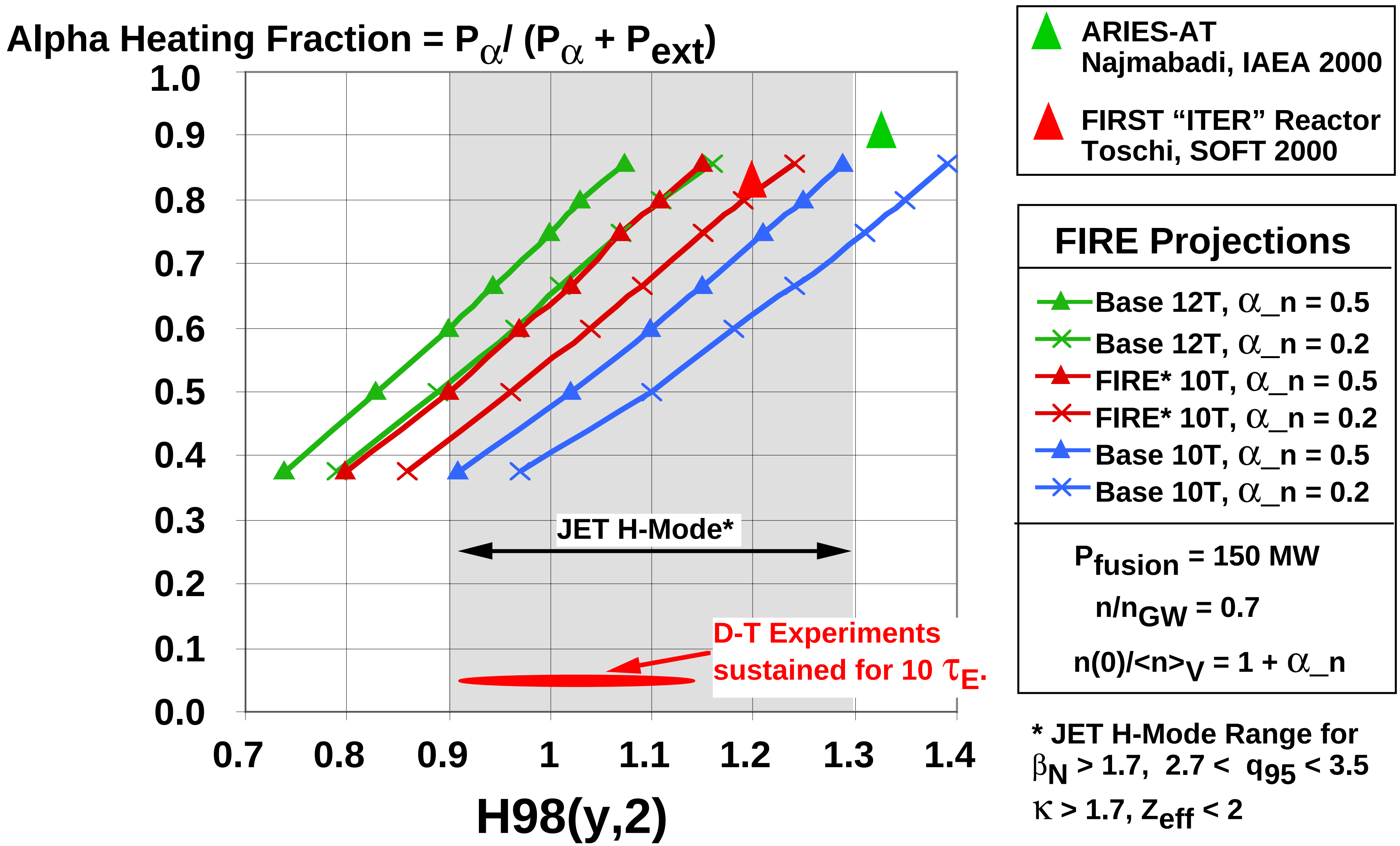
Projections of FIRE Performance as Confinement is Enhanced Toward that Required for Attractive Reactors



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

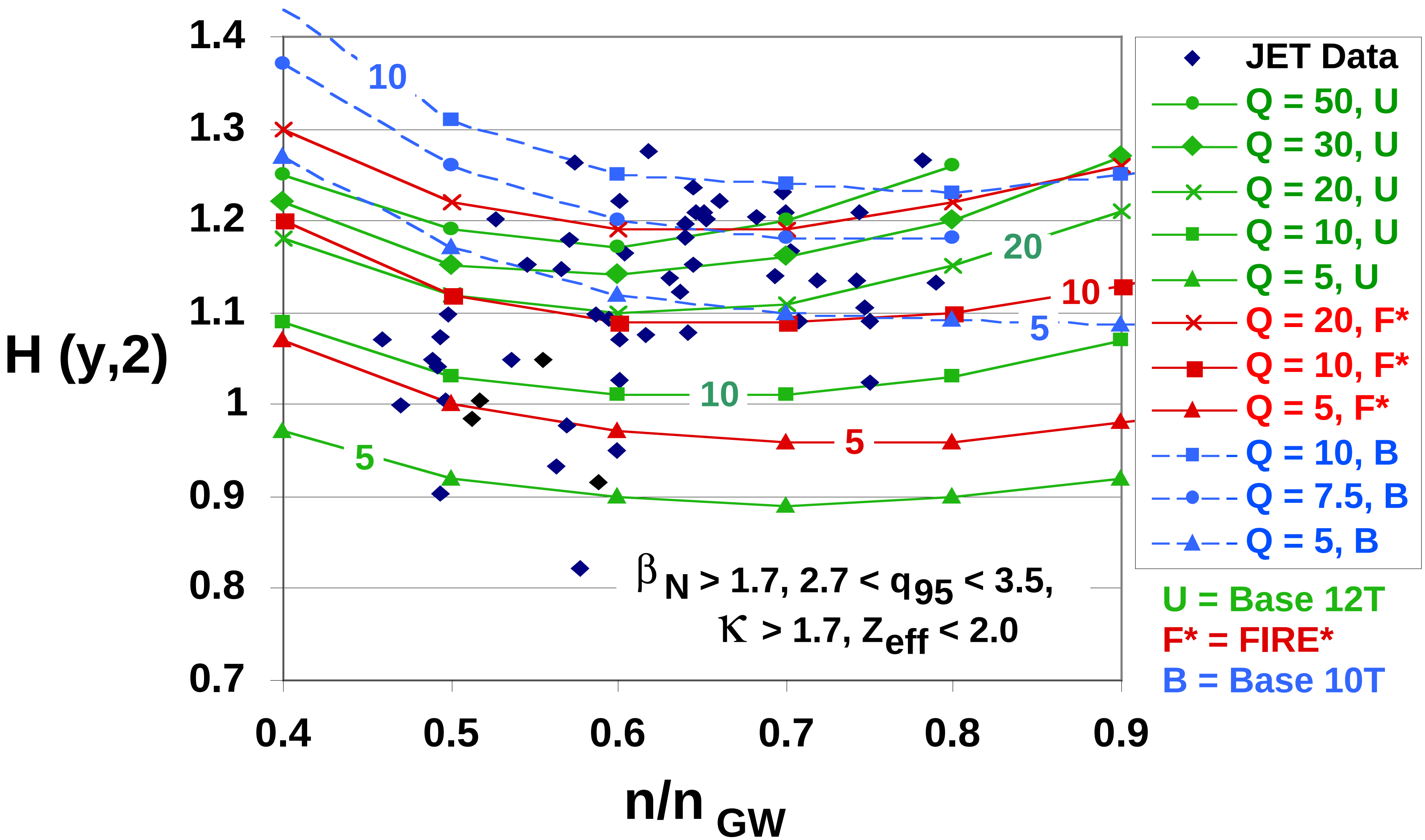
Fusion power gain, the energy goal, is very sensitive to confinement uncertainty at high gain.

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

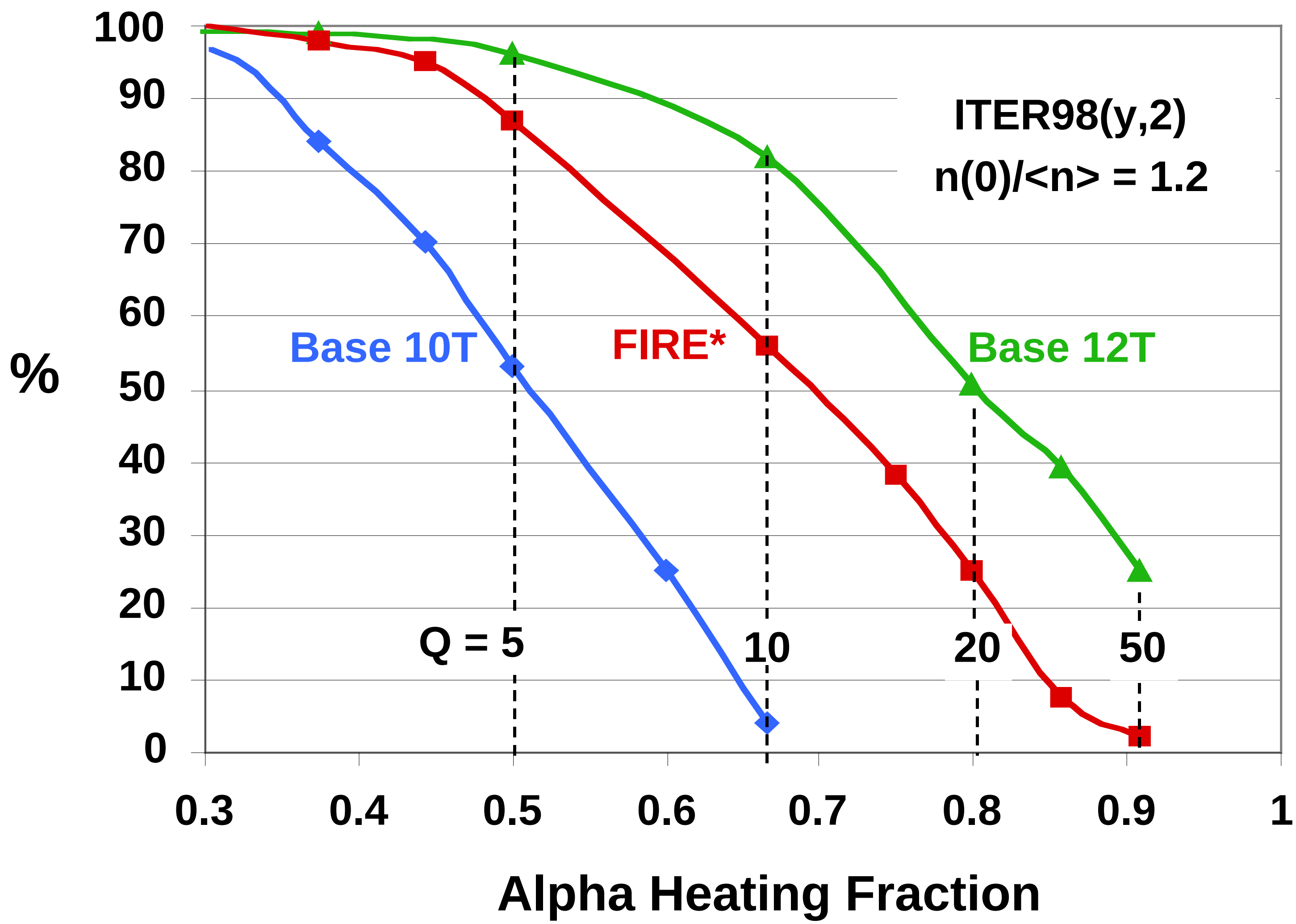


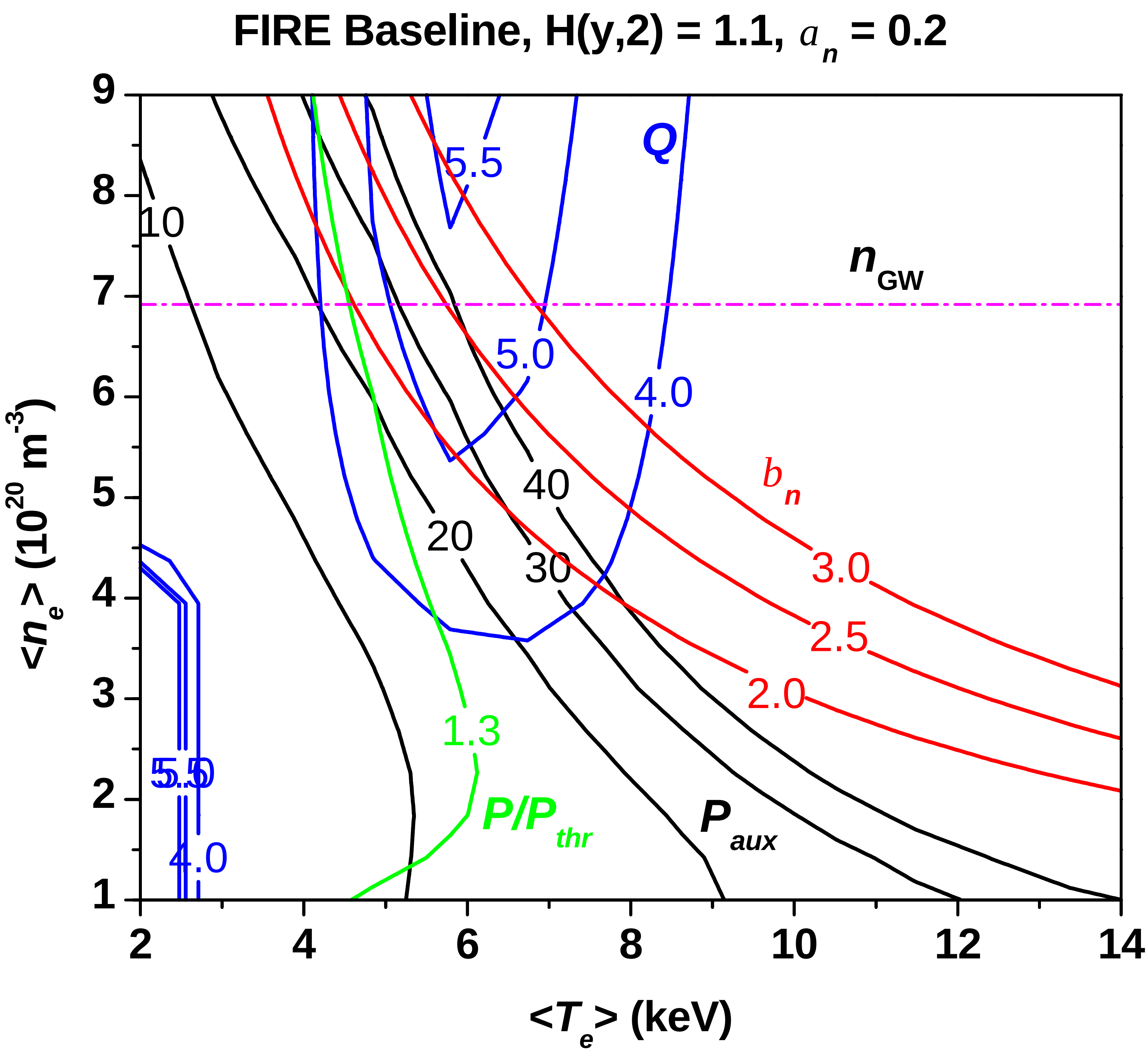
Alpha heating fraction, the science goal, is less sensitive to confinement uncertainty.

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



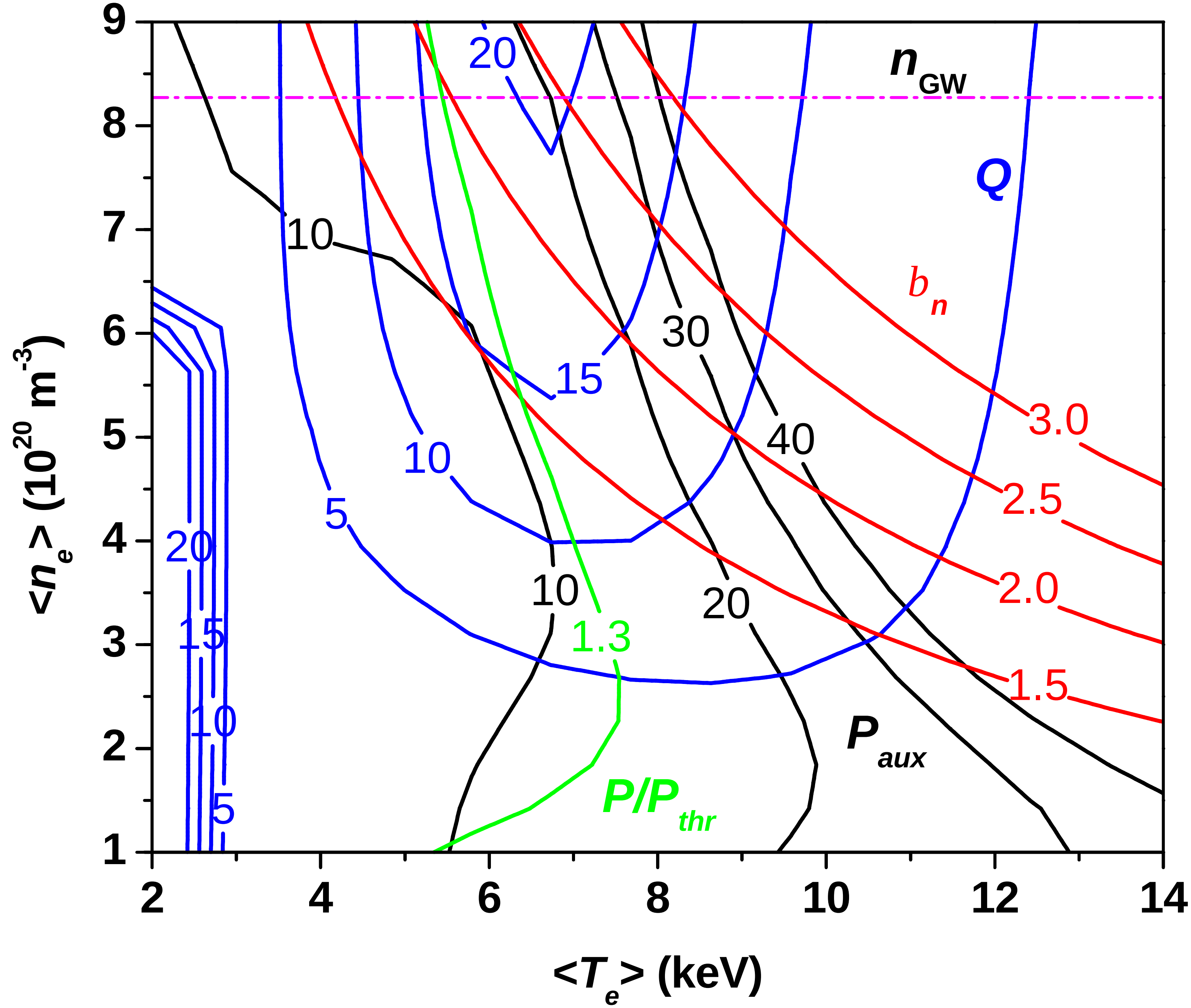
Percentage of JET FIRE-like Data Points that Project to a Specific Alpha Heating Fraction (Q)





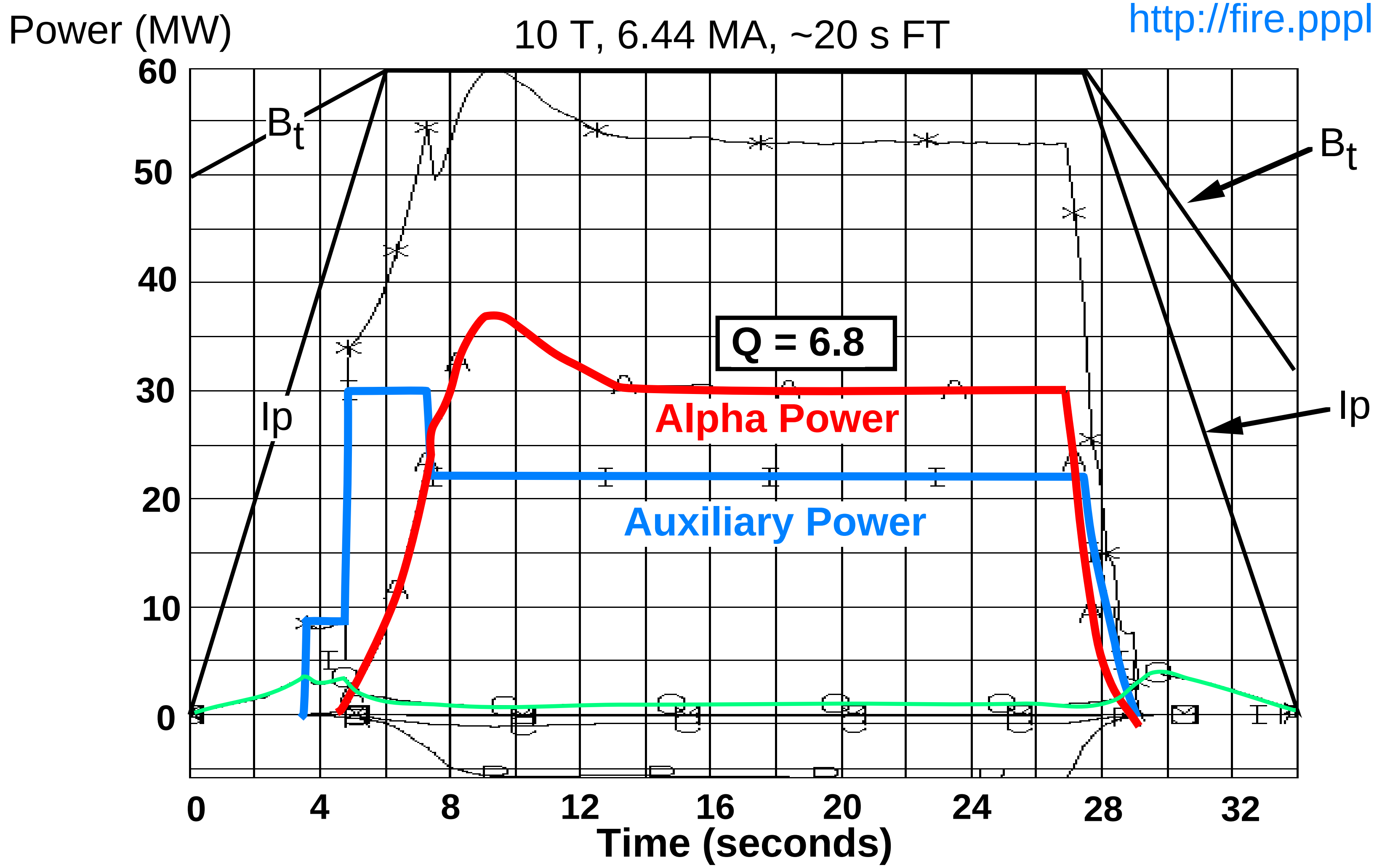
FIRE Baseline, H(y,2) = 1.1, α_n = 0.2
9
8
7
6
5
4
3
2
1
2
4
6
8
10
12
14
$\langle n_e \rangle$ (10^{20} m^{-3})
$\langle T_e \rangle$ (keV)
10
20
30
40
5.5
5.0
4.0
Q
n_{GW}
b_n
3.0
2.5
2.0
1.3
P/P_{thr}
P_{aux}
5.5
5.0
4.0

FIRE 12T, 7.7 MA, H(y,2) = 1.1, a_n = 0.2



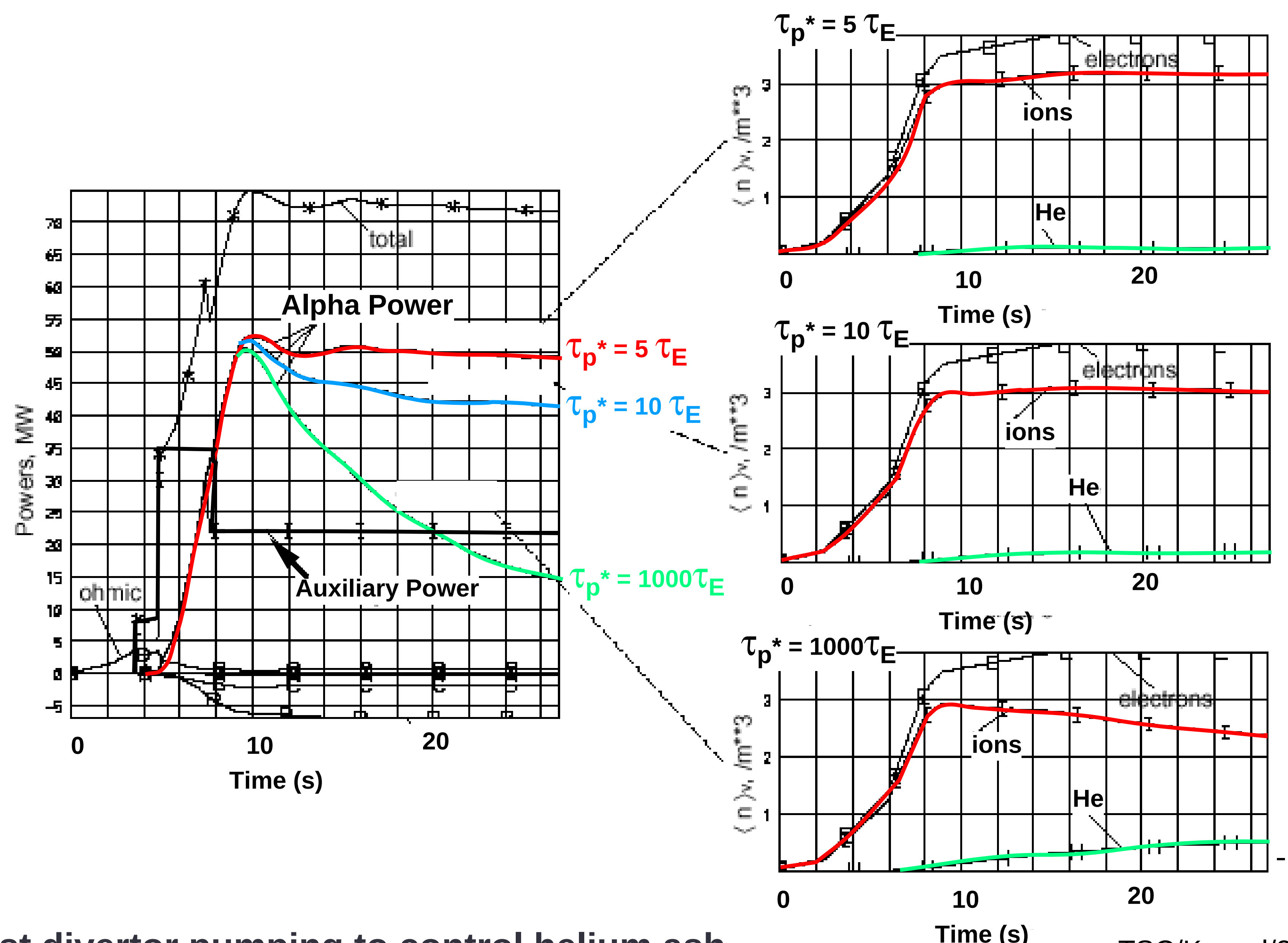
1 1/2-D Simulation of Burn Control in FIRE

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}

Helium Ash Accumulation could 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

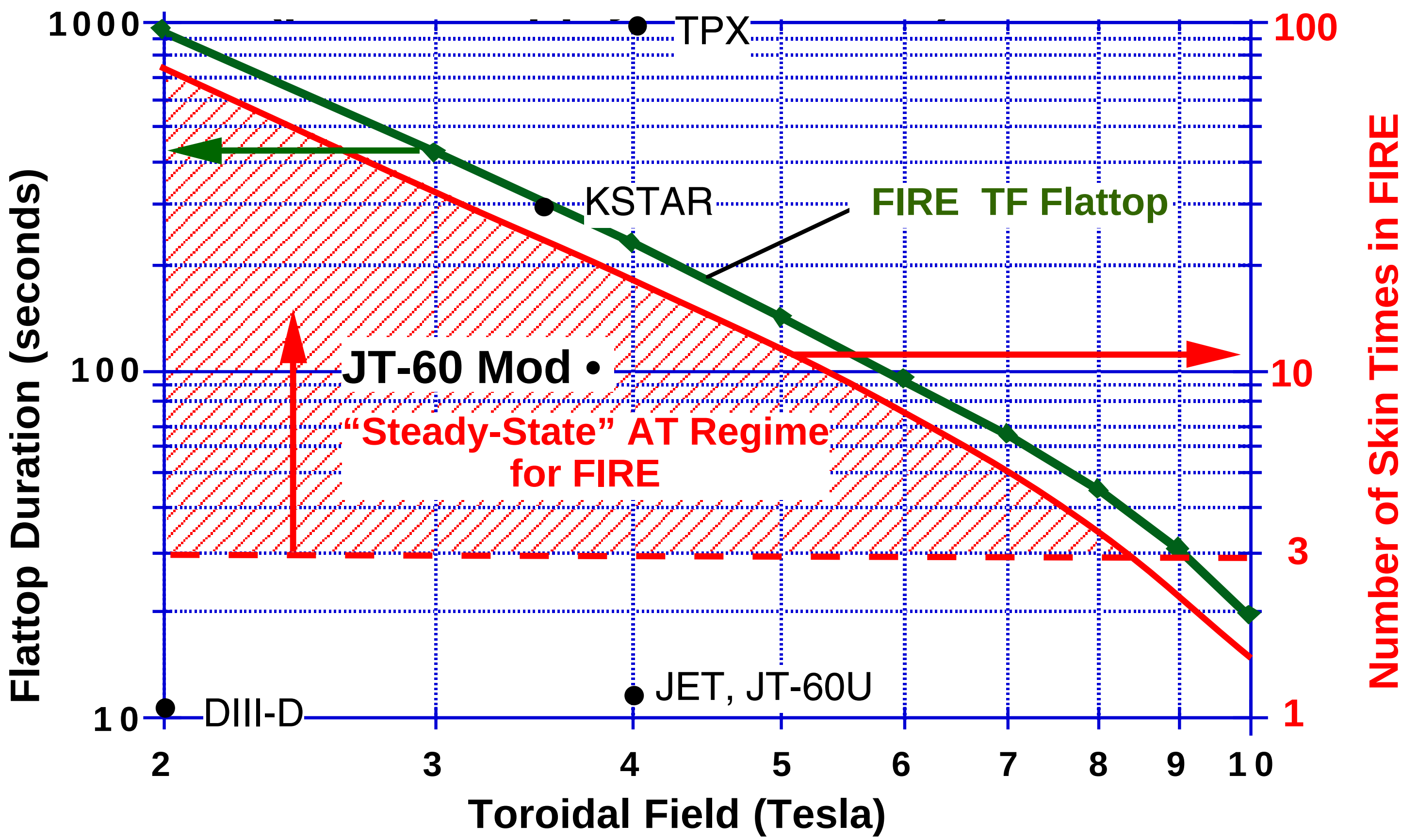
- The coupling of advanced tokamak modes with strongly burning plasmas is a generic issue for all advanced “toroidal” systems. The VLT PAC, Snowmass Burning Plasma and Energy Subgroup B recommended that a burning plasma experiment should have AT capability.

- 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 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 .

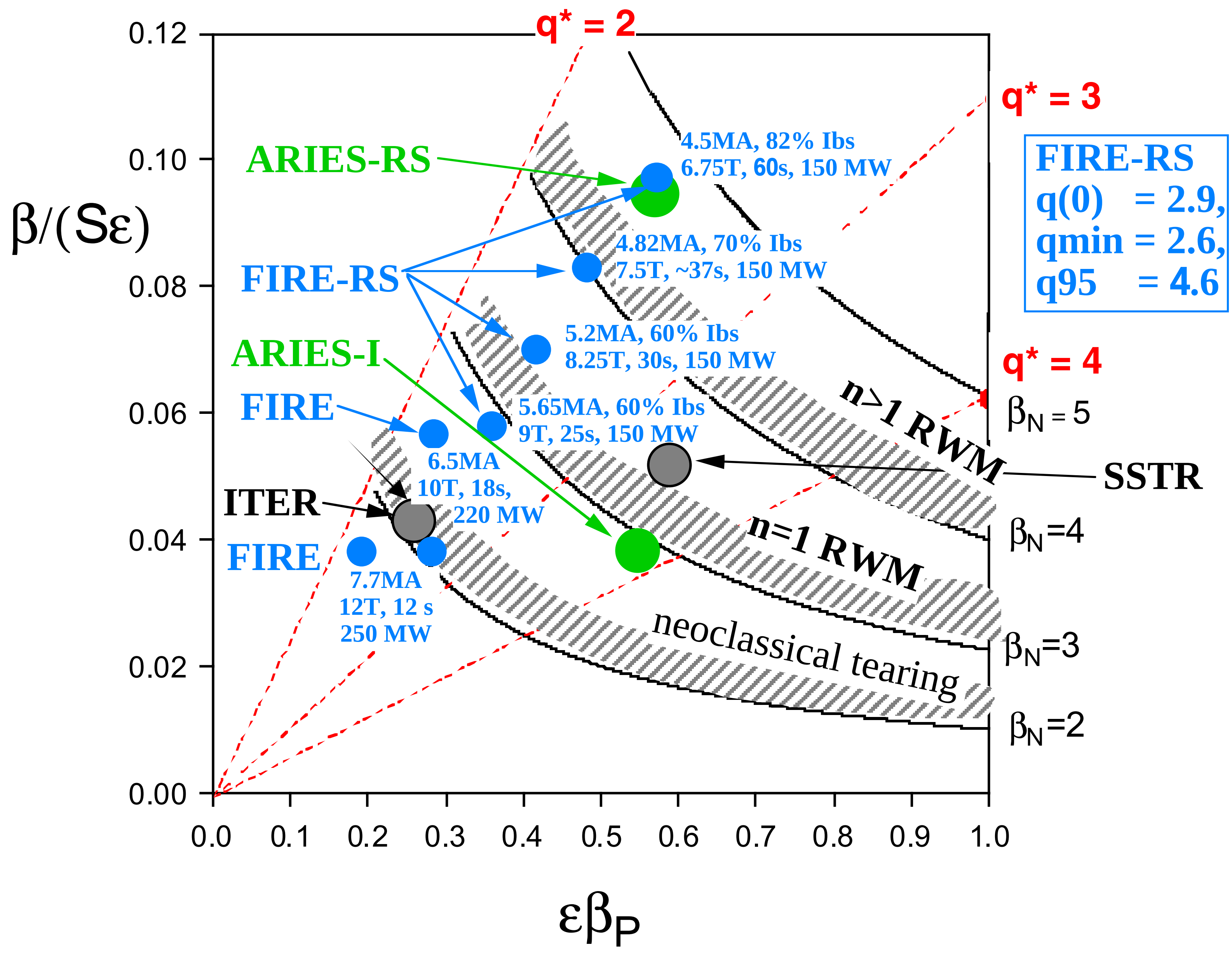
The combination of JET-U, JT-60 Mod, KSTAR and FIRE could cover the range fromsteady-state non-burning advanced-tokamak modes to "quasi-equilibrium" burning plasmas in advanced tokamak modes.

FIRE 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

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

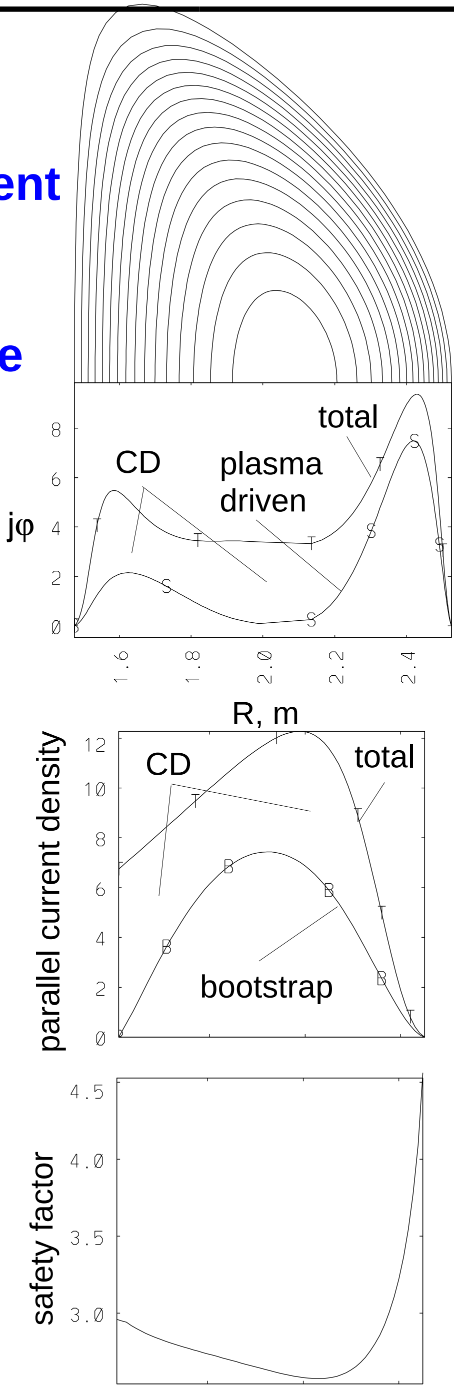
Q = 10, HH = 1.2

or

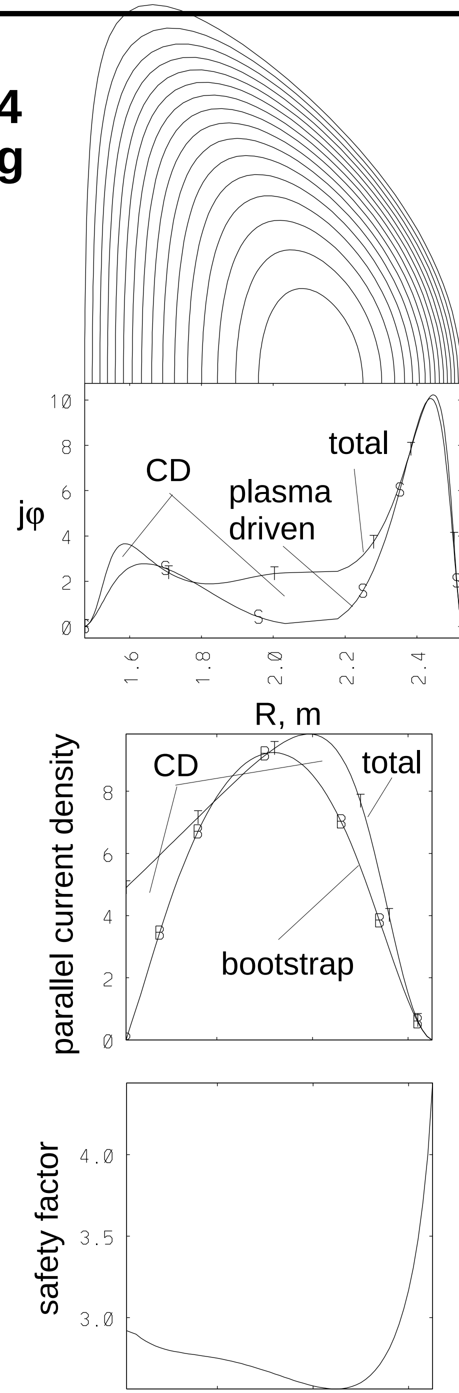
Q = 5, HH = 1.06

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

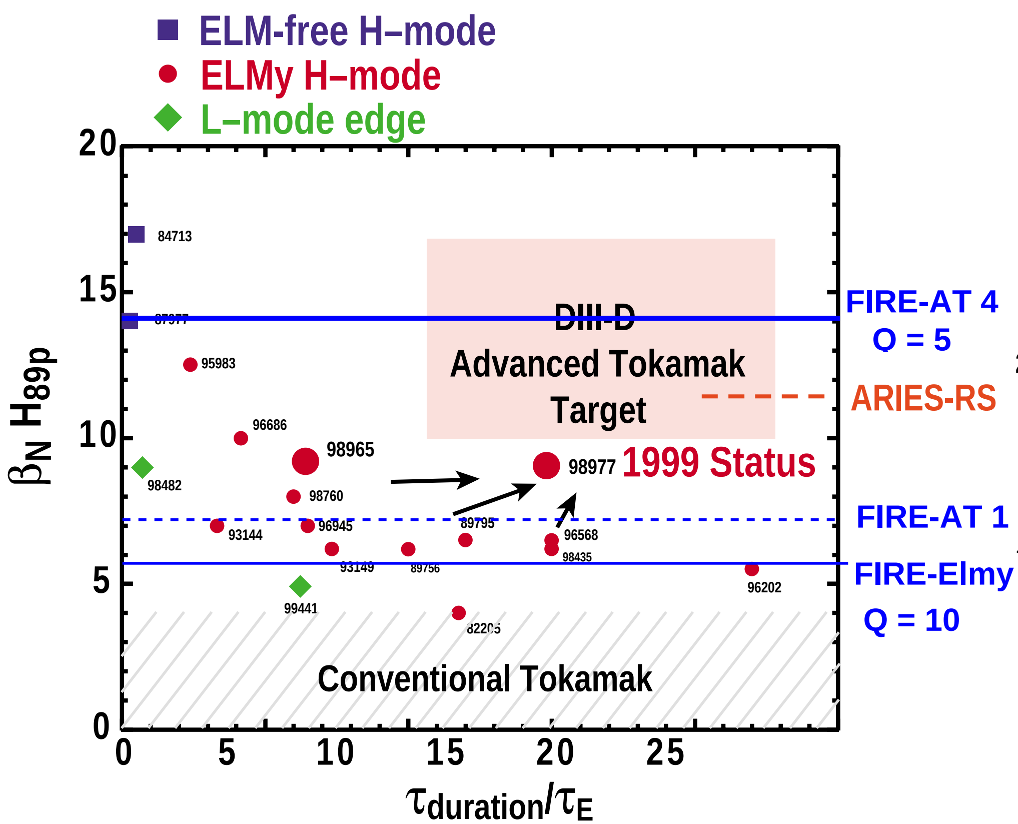
Q = 5, HH = 1.36

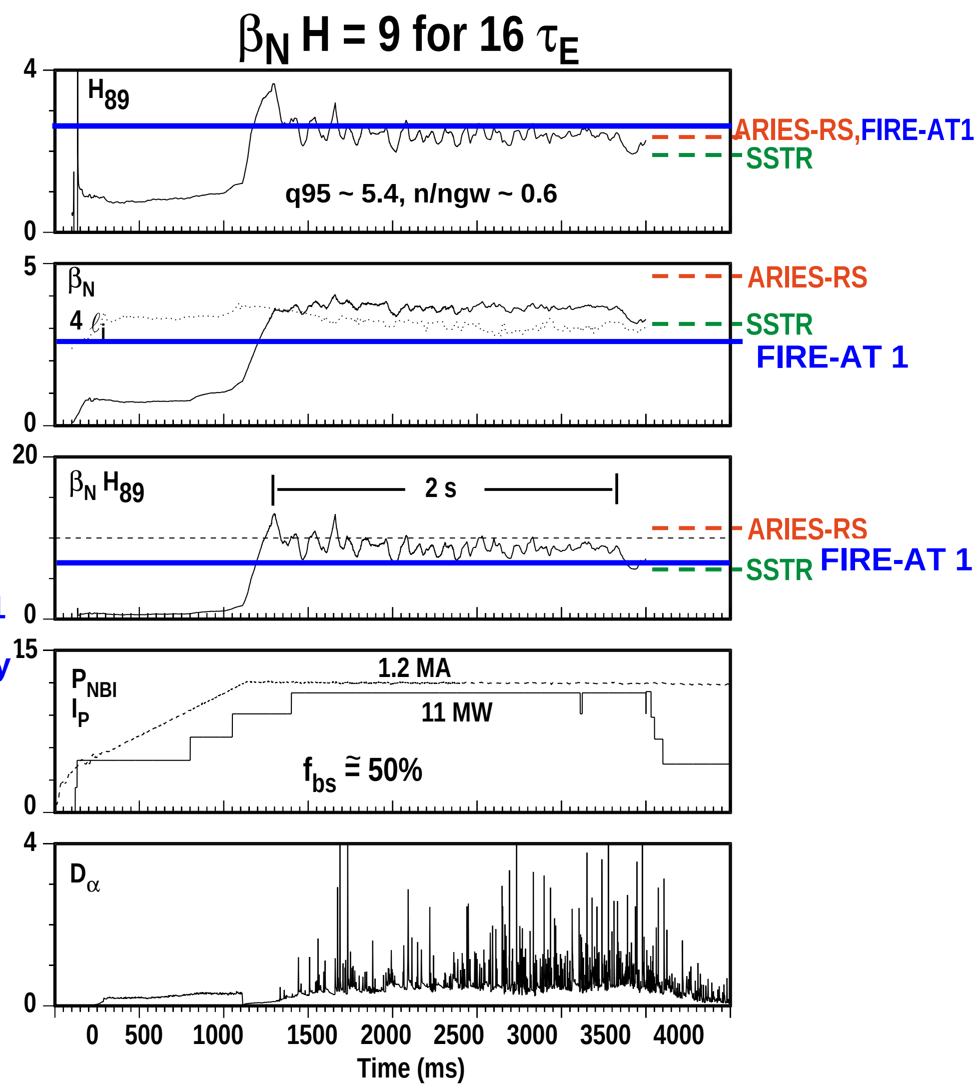
Duration

~ 4 tau_skin

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

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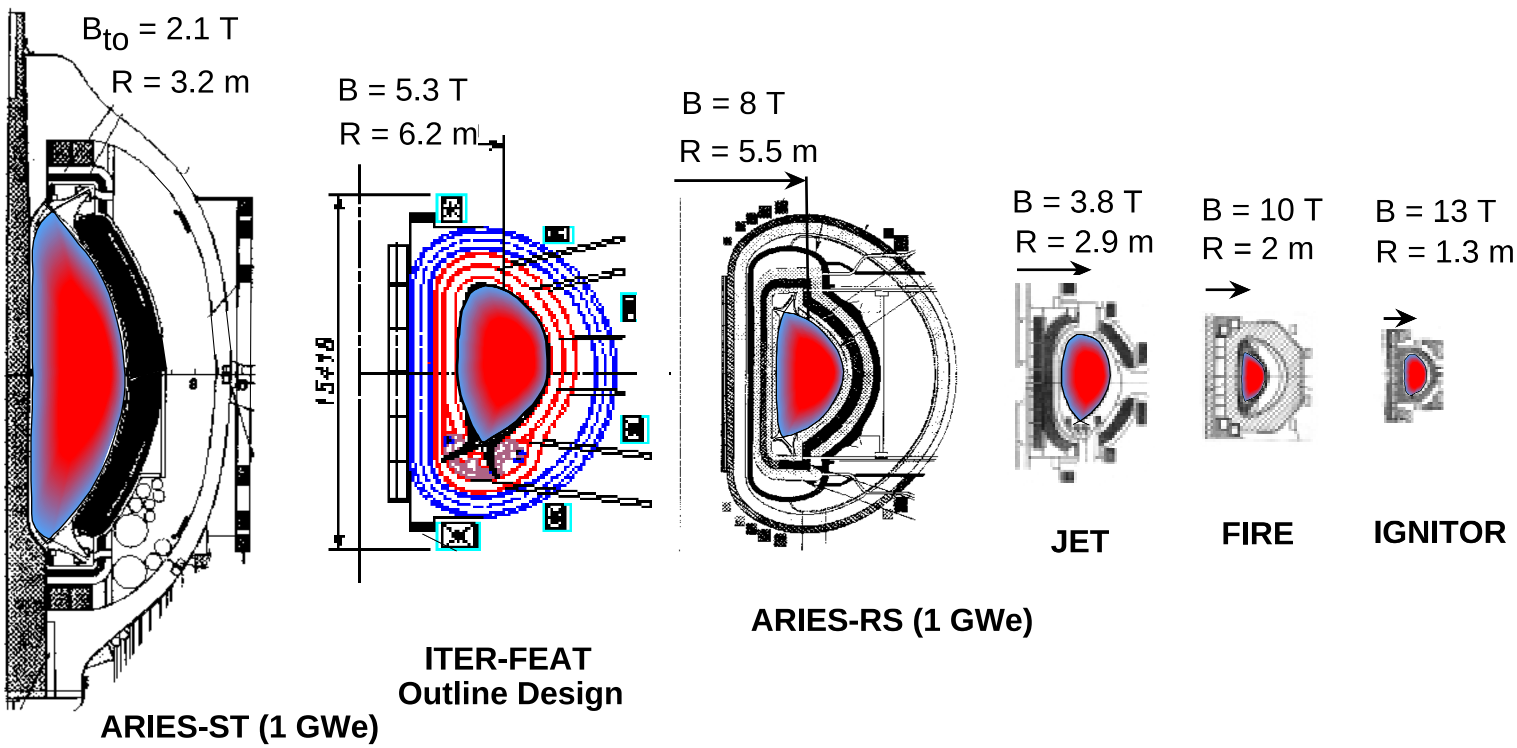
DIII-D shot 98977 is close to a Demonstration Discharge for FIRE-AT 1
FIRE-AT 1 requires q95 = 4.5, n/ngw = 0.65, β_N H89 = 7.1, and produces fbs = 50% and Q = 10 (Pfusion =150 MW, Pin = 15 MW). This mode would be useful for quasi-steady experiments ~ 2 skin times.

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

Preliminary FIRE Cost Estimate (FY99 US$M)

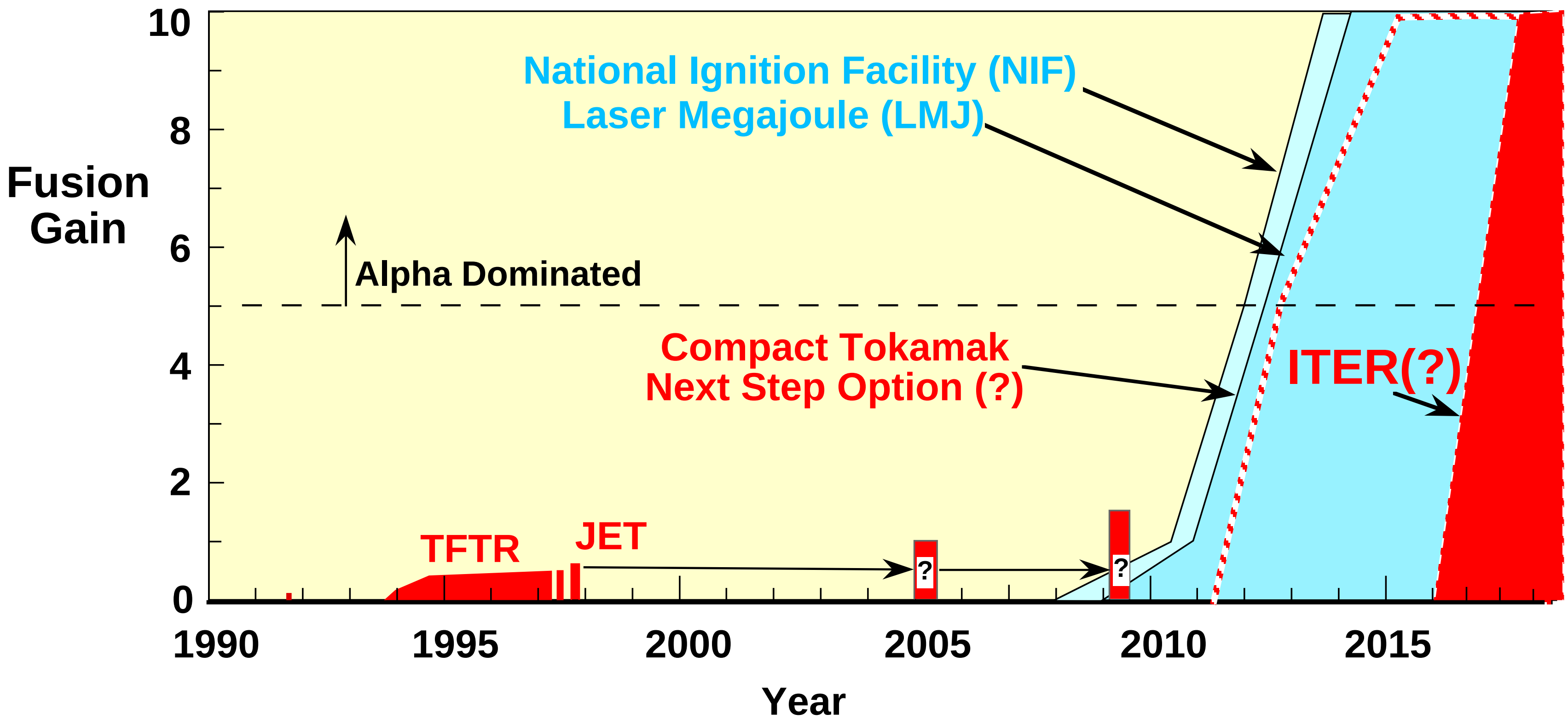
	Estimated Cost	Contingency	Total with Contingency
1.0 Tokamak Core	210.2	66.0	276.2
1.1 Plasma Facing Components	44.8	13.5	
1.2 Vacuum Vessel/In-Vessel Structures	34.6	10.9	
1.3 TF Magnets /Structure	103.7	34.8	
1.4 PF Magnets/Structure	13.0	2.6	
1.5 Cryostat	1.8	0.5	
1.6 Support Structure	12.3	3.7	
2.0 Auxiliary Systems	147.5	46.1	193.6
2.1 Gas and Pellet Injection	7.1	1.4	
2.2 Vacuum Pumping System	13.0	2.0	
2.3 Fuel Recovery/Processing(Rough Estimate)	20.0	10.0	
2.4 ICRF Heating	107.4	32.7	
3.0 Diagnostics (Startup)	18.4	12.2	30.6
4.0 Power Systems	149.4	37.4	186.8
5.0 Instrumentation and Controls	18.9	2.5	21.4
6.0 Site and Facilities	172.2	40.8	213.0
7.0 Machine Assembly and Remote Maintenance	70.7	18.0	88.7
8.0 Project Support and Oversight	107.6	16.2	123.8
9.0 Preparation for Operations/Spares	16.2	2.4	18.6
Preconceptual Cost Estimate (FY99 US$M)	**911.1**	**241.6**	**1152.7**

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

This estimate is work in progress and will be finalized in August 2000.

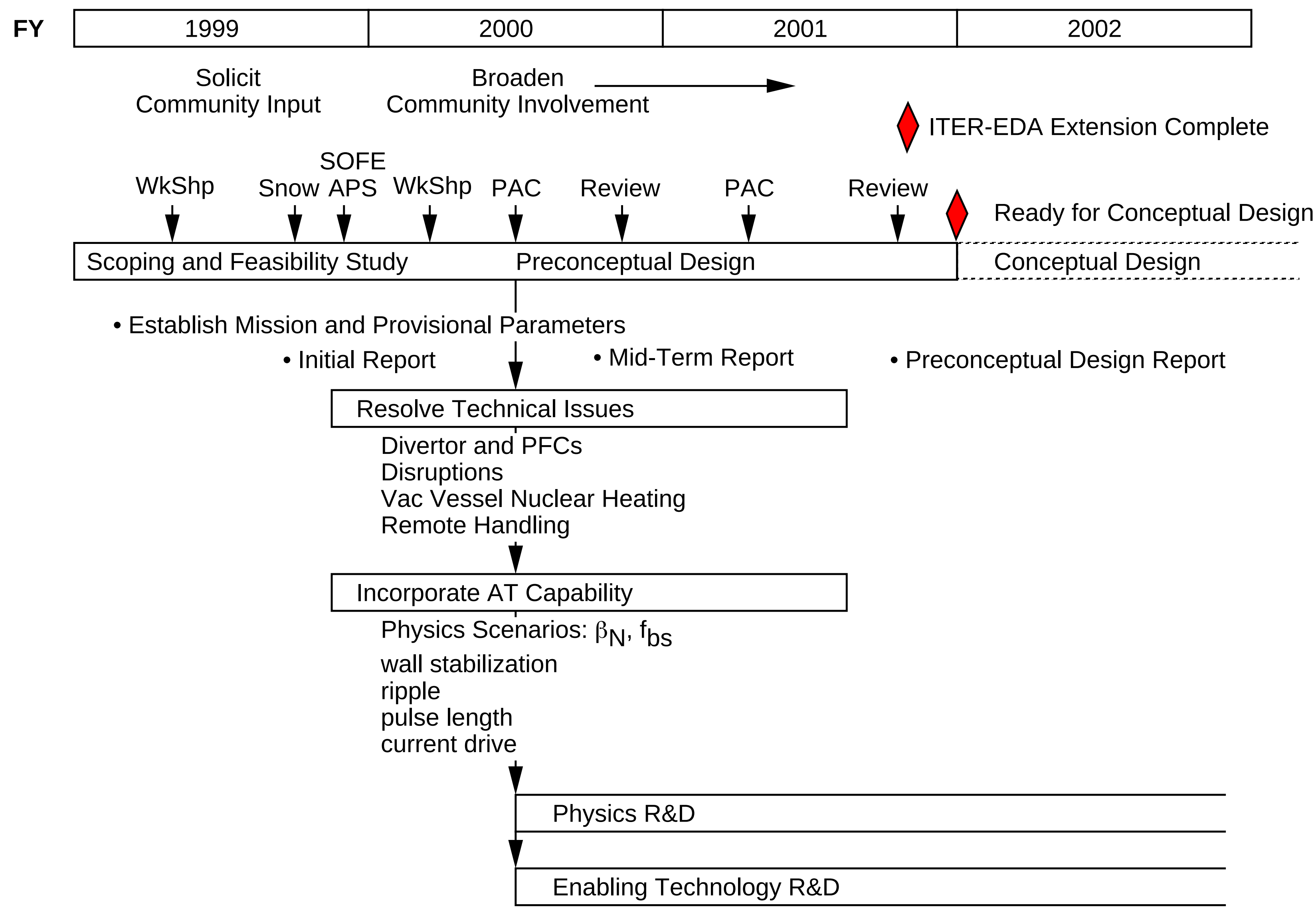
June 1, 2000

Timetable for Burning Plasma Experiments



- 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)



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 threshold, edge pedestal, enhanced H-mode, AT-modes
  - stability - NTMs, RWM, disruptions: conducting wall? feedback coils? VDE(DN)?
  - 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 scenarios, higher fluence TF insulator
  - 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.

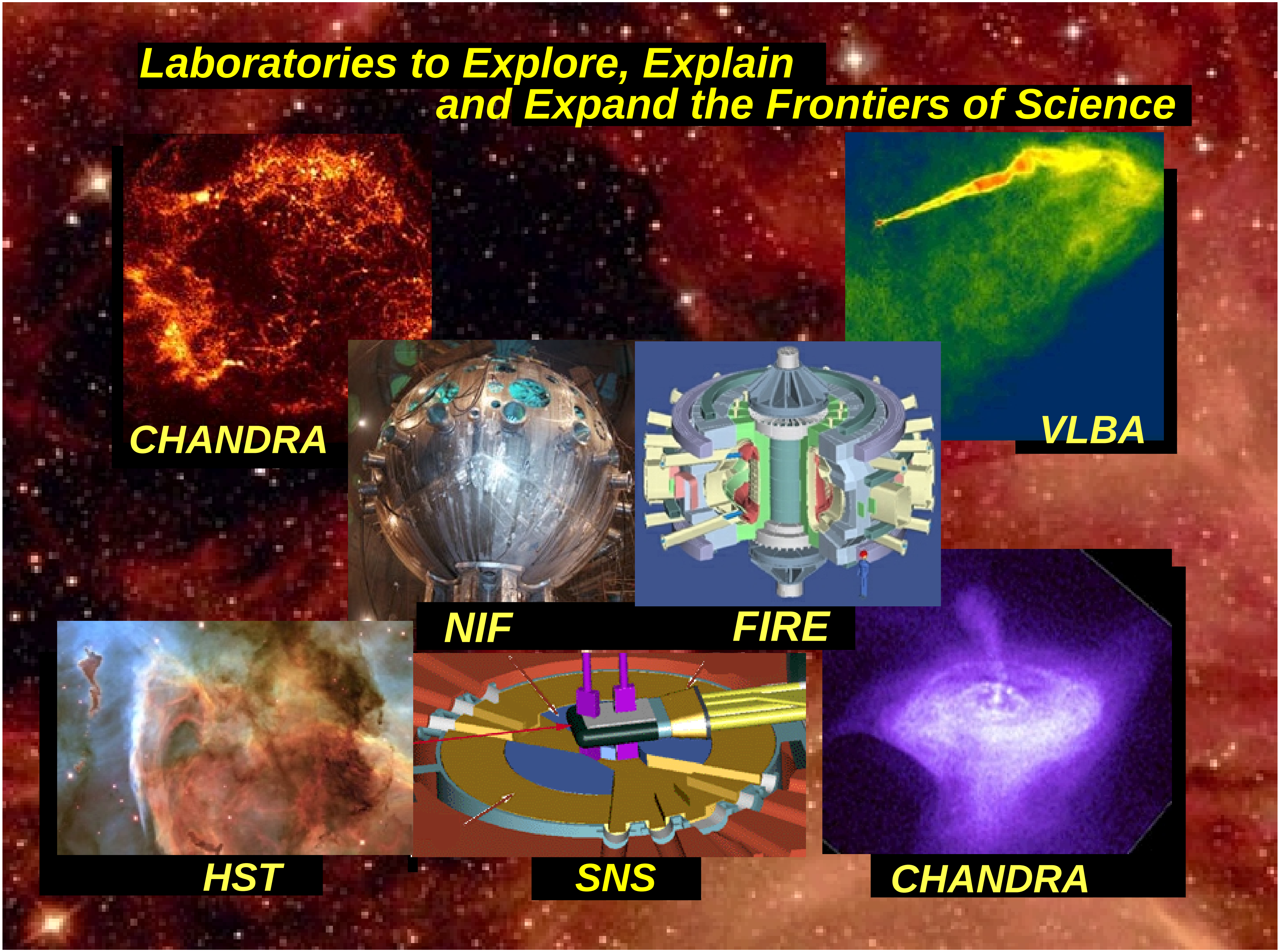
- The tokamak is a cost-effective vehicle to investigate alpha-dominated fusion plasma physics and its coupling to advanced toroidal physics for MFE. The tokamak is technically ready for a next step to explore fusion plasma physics.

- 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.

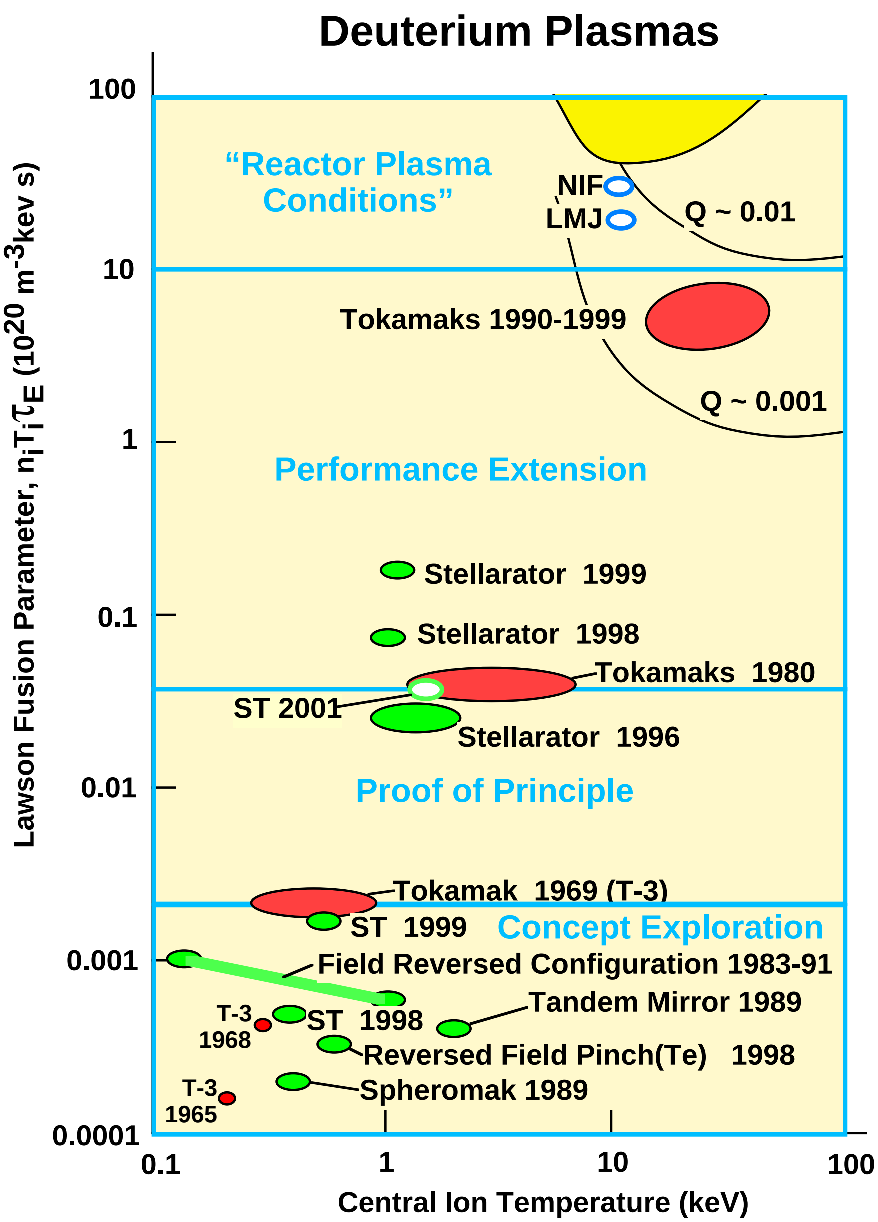
- The FIRE design point has been chosen to be a “stepping stone” between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.

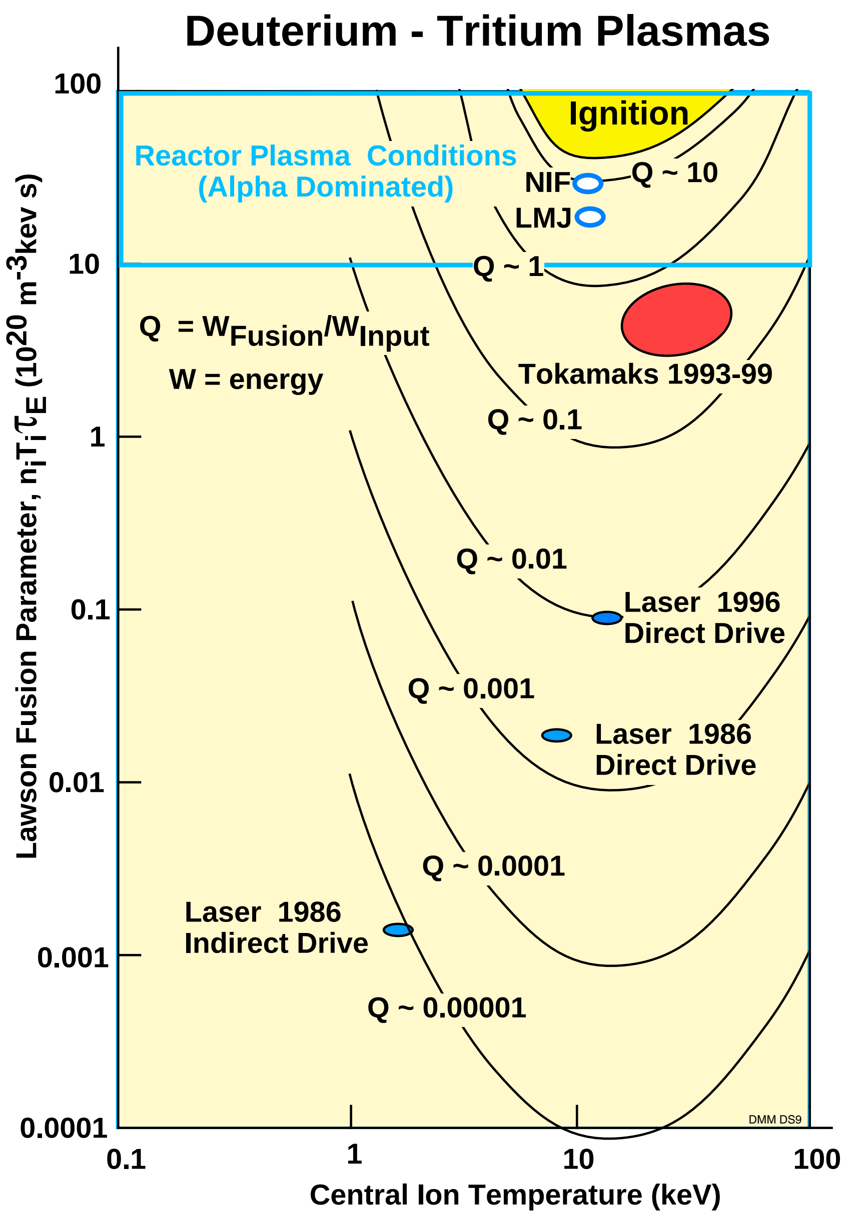
- A plan is being developed for an Advanced Tokamak Next Step that will address physics, engineering and cost issues in FY 2000-1 with the goal of being ready to begin a Conceptual Design in 2002.

http://fire.pppl.gov


Laboratories to Explore, Explain
and Expand the Frontiers of Science
CHANDRA
VLBA
NIF
FIRE
HST
SNS
CHANDRA

The Tokamak is Technically Ready for a Major Next Step Experiment





The tokamak is sufficiently advanced to permit the design, construction and initiation of a next step burning plasma experiment within the next decade that could address the fusion plasma and self-heating issues for magnetic fusion.