Possibilities for

Future Burning Plasma Physics Experiments

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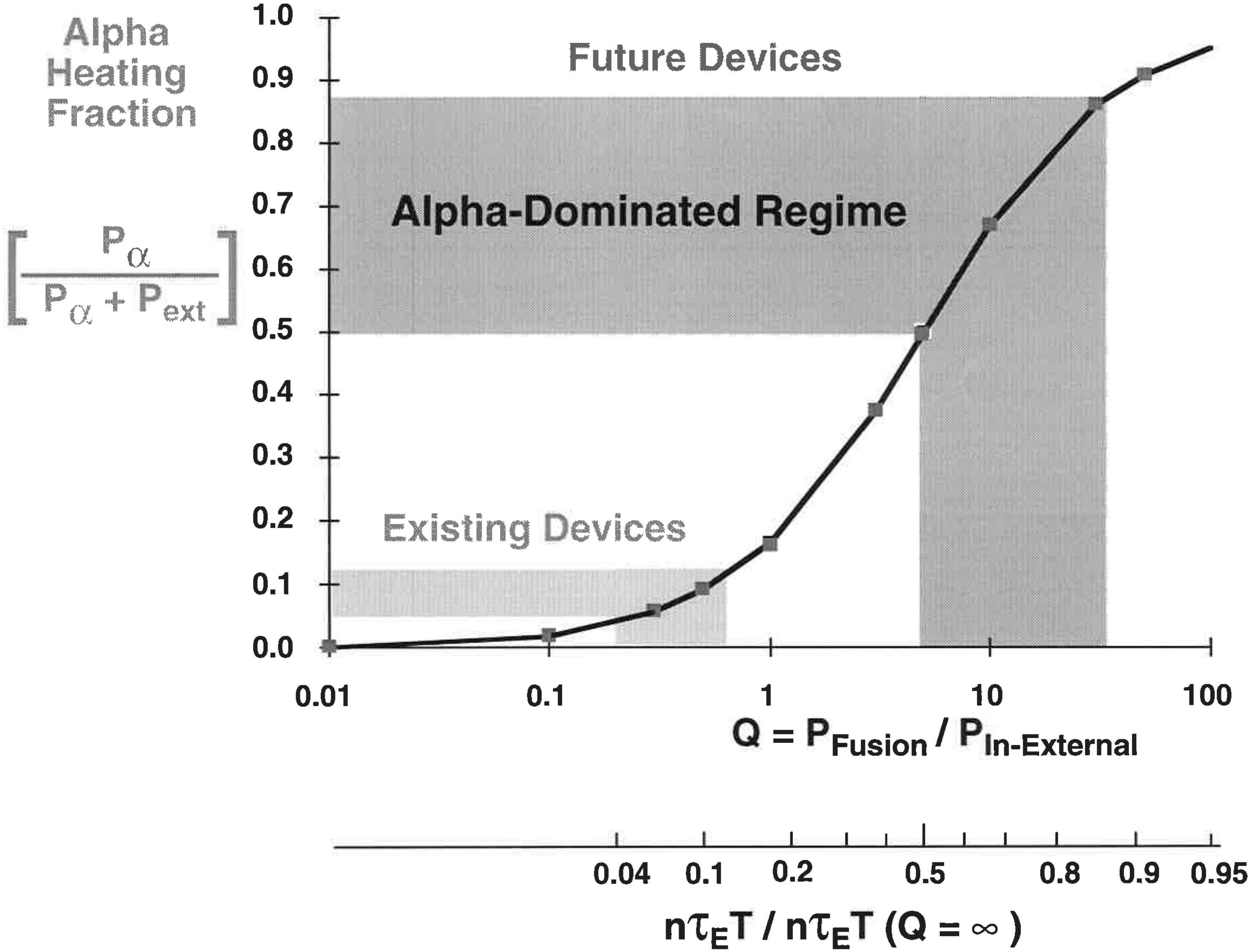
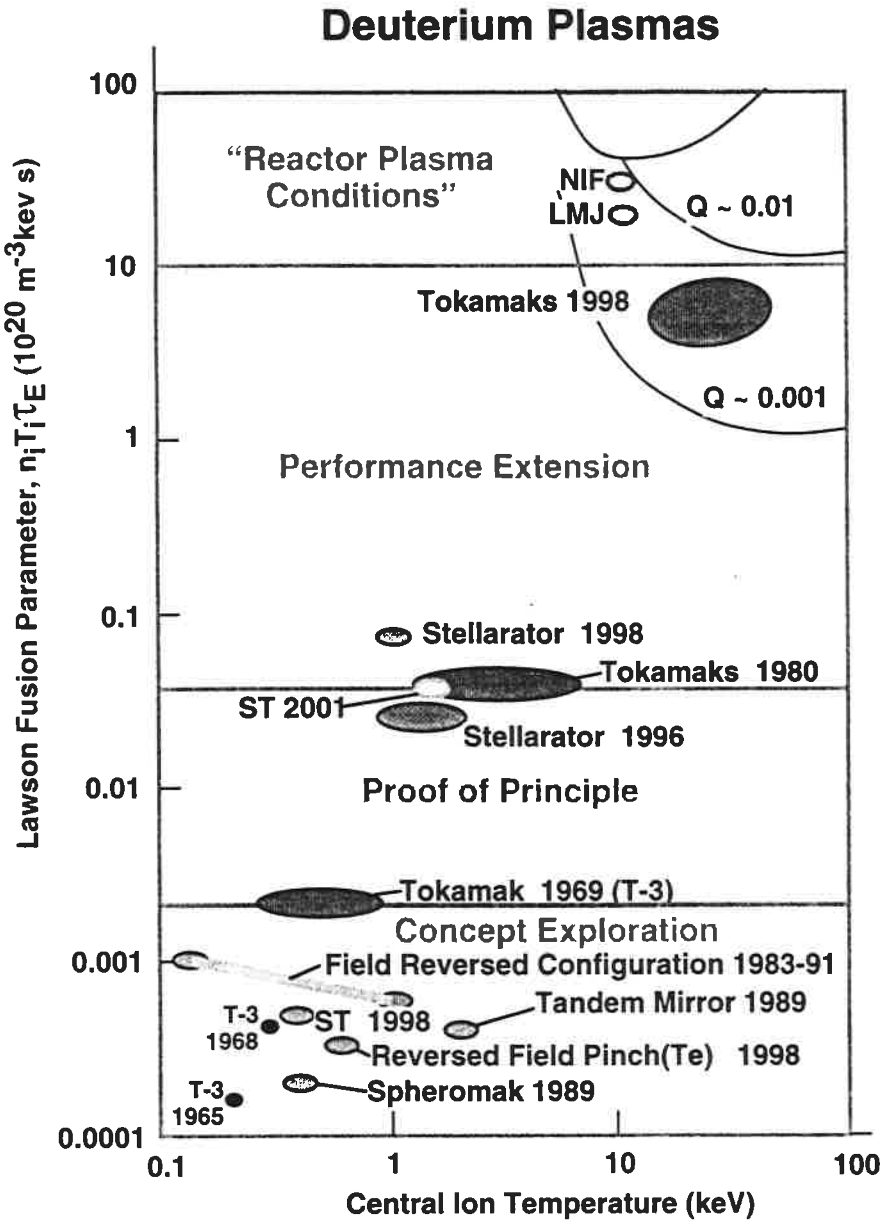
Physics Objectives for an Fusion Ignition Research Experiment

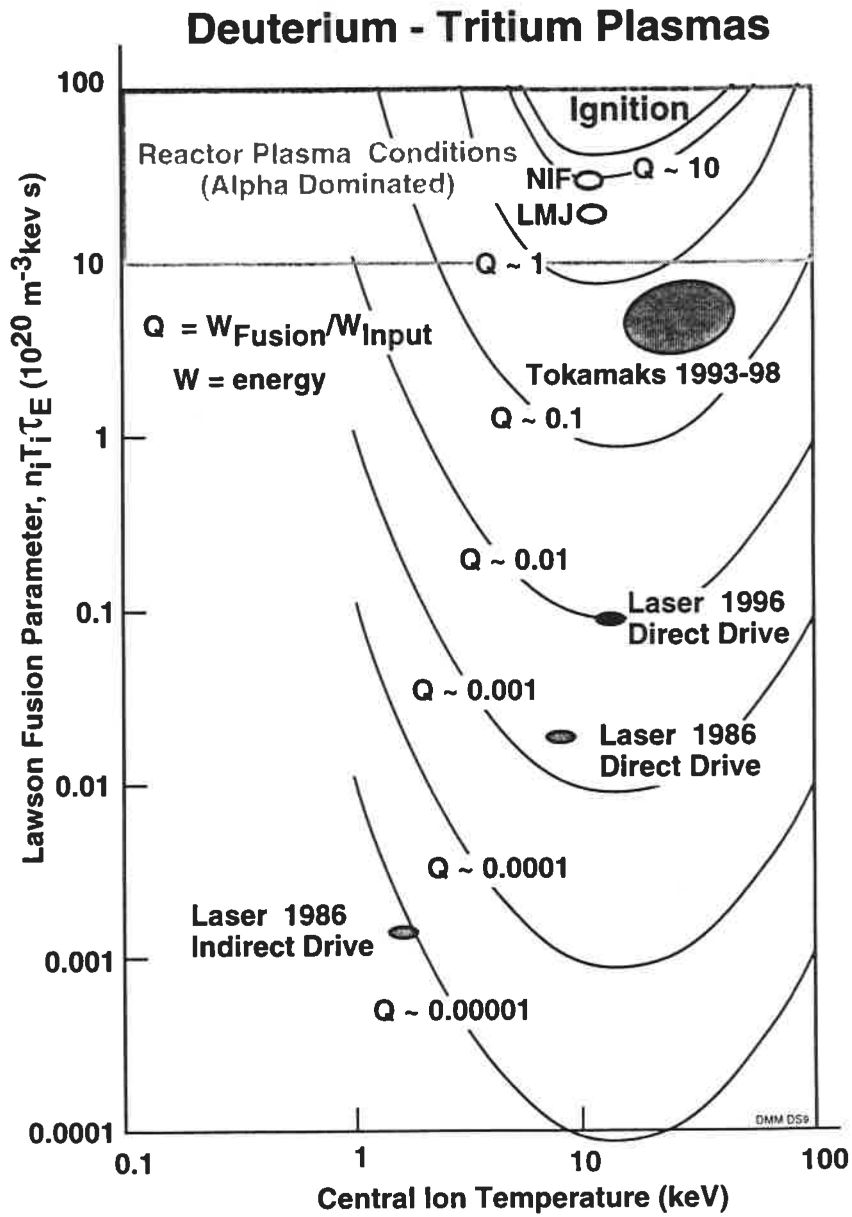
- Determination of the conditions required to achieve high Q plasmas:
  - energy confinement scaling with dominant alpha heating
  - β-limits with dominant alpha heating
  - density limit scaling with dominant alpha heating
- Control of high Q plasmas (e.g., modification of plasma profiles)
- Sustainment of high Q plasma - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effect of alpha heating on the evolution of bootstrap current profiles.
- Exploration of high Q burning plasma physics in some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.
- Determination of the effects of fast alpha particles on plasma stability.

Parameters Required to Study Burning Plasma Physics



The Tokamak is Technically Ready for a High-Gain Experiment.





Physics Requirements for Next Step Experiments

Study Physics of Fusion Plasmas

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 heating dominant, $f\alpha = P\alpha/Pheat = Q/(Q+5)$

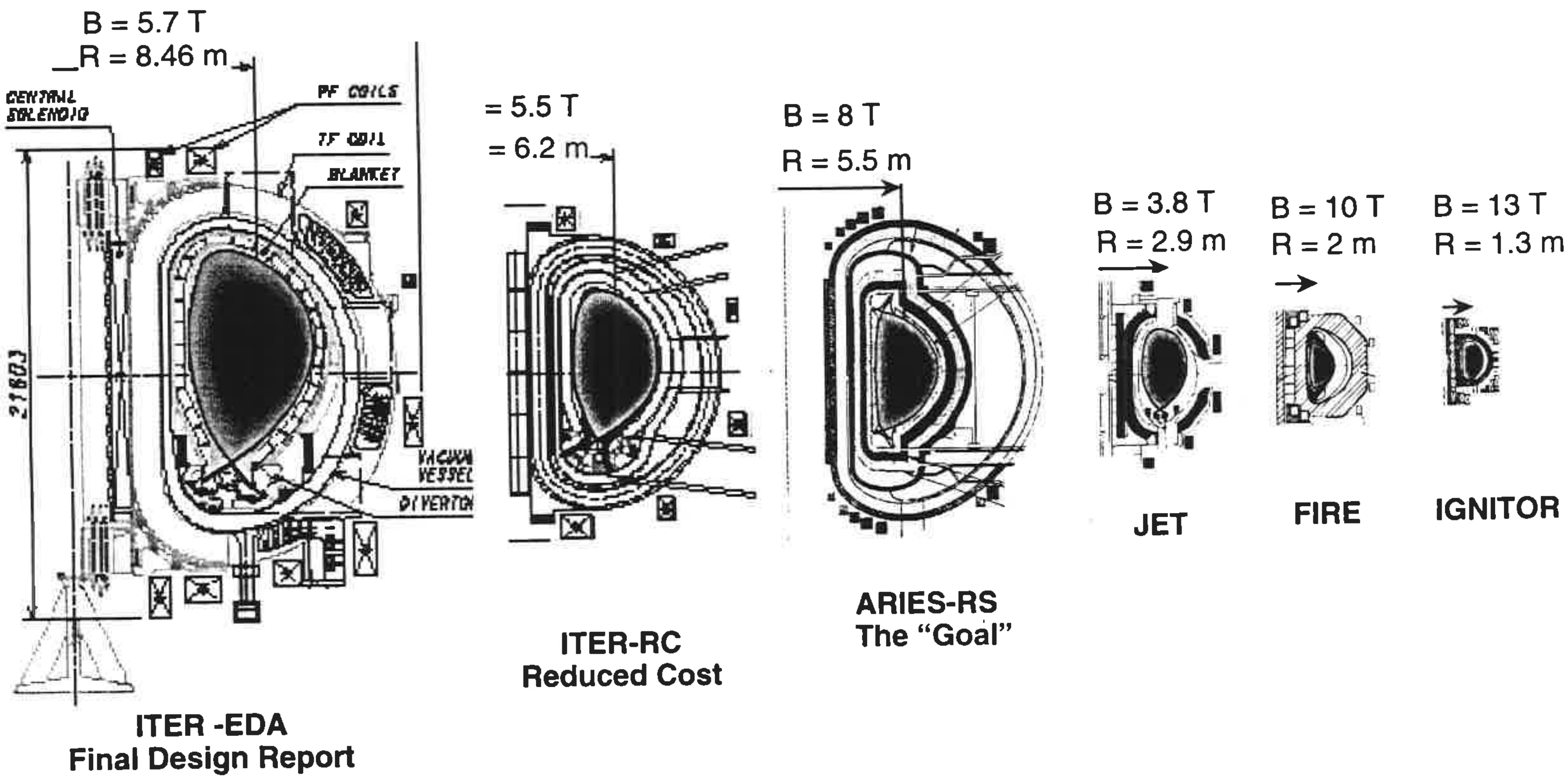
Q = function of $n\tau_E T$, e.g., Lawson diagram

$n\tau_E T = B \times (BR^{5/4})$, if τ_E is given by ITER98H empirical scaling at fixed beta

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

Alpha particle confinement requires $Ip(R/a) \geq 9$, $Ip(R/a) \sim BR(R/a)$

IGNITOR and FIRE Offer the Possibility of an Affordable Near-Term Step in MFE.



Cost Drivers	EDA	ITER-RC	ARIES-RS	JET	FIRE	IGNITOR
Plasma Volume (m^3)	2000	740	350	95	18	11
Plasma Surface (m^2)	1200	640	420	150	60	36
TF Magnet Energy (GJ)	100	41	75	1.6	4	4
Fusion Power (MW)	1500	400	2170	16	200	200
Burn Duration (s)	1000	400	steady	1	10	5

Technical Basis for a Compact High Field Tokamak Burning Plasma Experiment has Increased Markedly since 1989-1991.

Tokamak experiments (1989-1999) have developed improved confinement modes that scale(e.g.,ITER-98H) 1.25 times higher than the 1989 CIT 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

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 but alpha heating effects were weak.

If CIT had been built, it would be working now.

Guidelines for Estimating Plasma Performance

Beta Limit - theory and tokamak data base, neoclassical tearing developing

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

Confinement (Elmy Hmode) Based on today's tokamak data base

$$\tau_E = 0.94\, I^{0.97}\, R^{1.7}\, a^{0.23}\, n_{20}^{0.41}\, B^{0.08} A_i^{0.2}\, \kappa^{0.67}\, P_{heat}^{-0.63}$$

Density Limit - today's tokamak data base

$$n_{20} \leq 0.75\, n_{GW} = I_p/\pi a^2$$

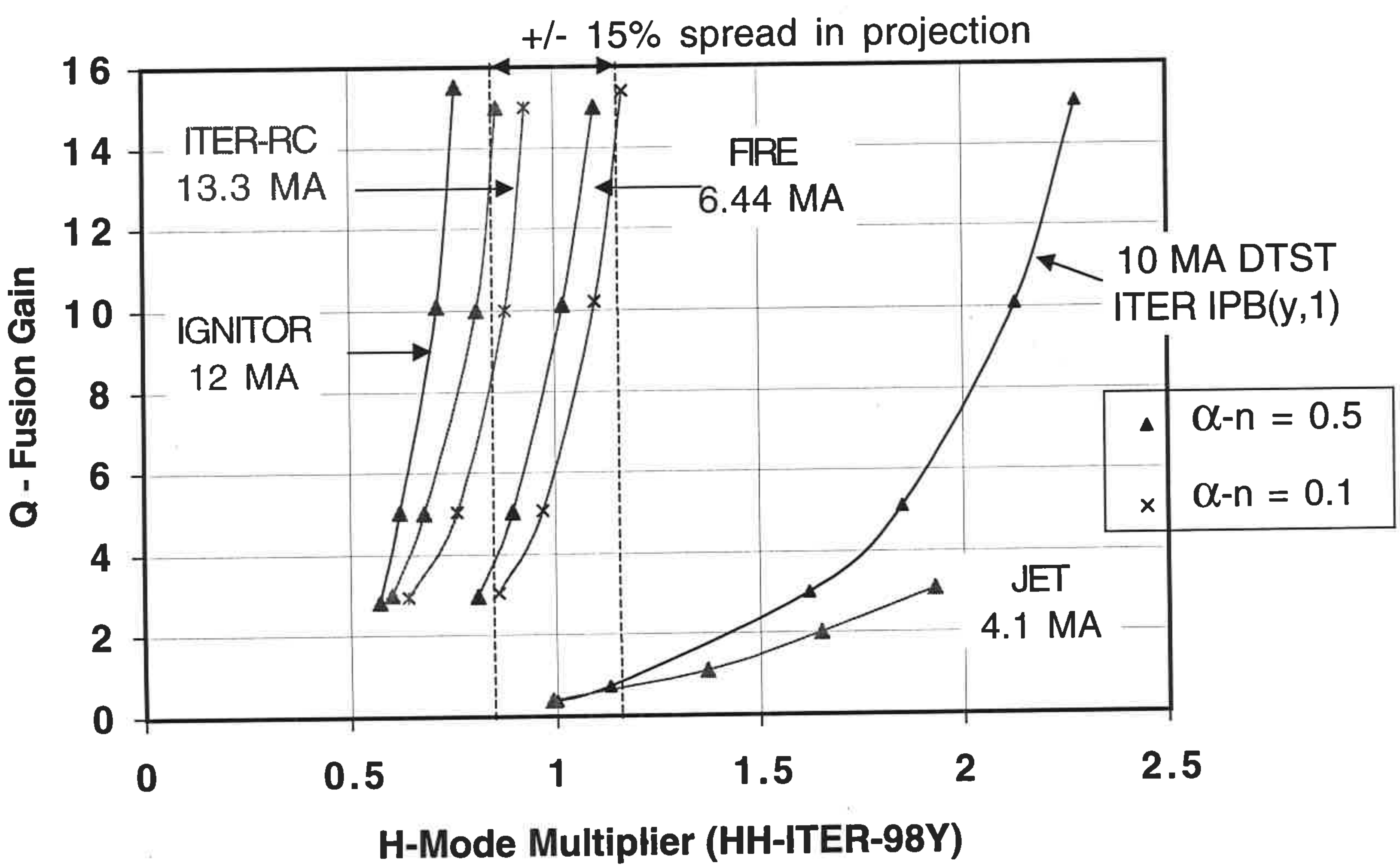
H-Mode Power Threshold - today's tokamak data base

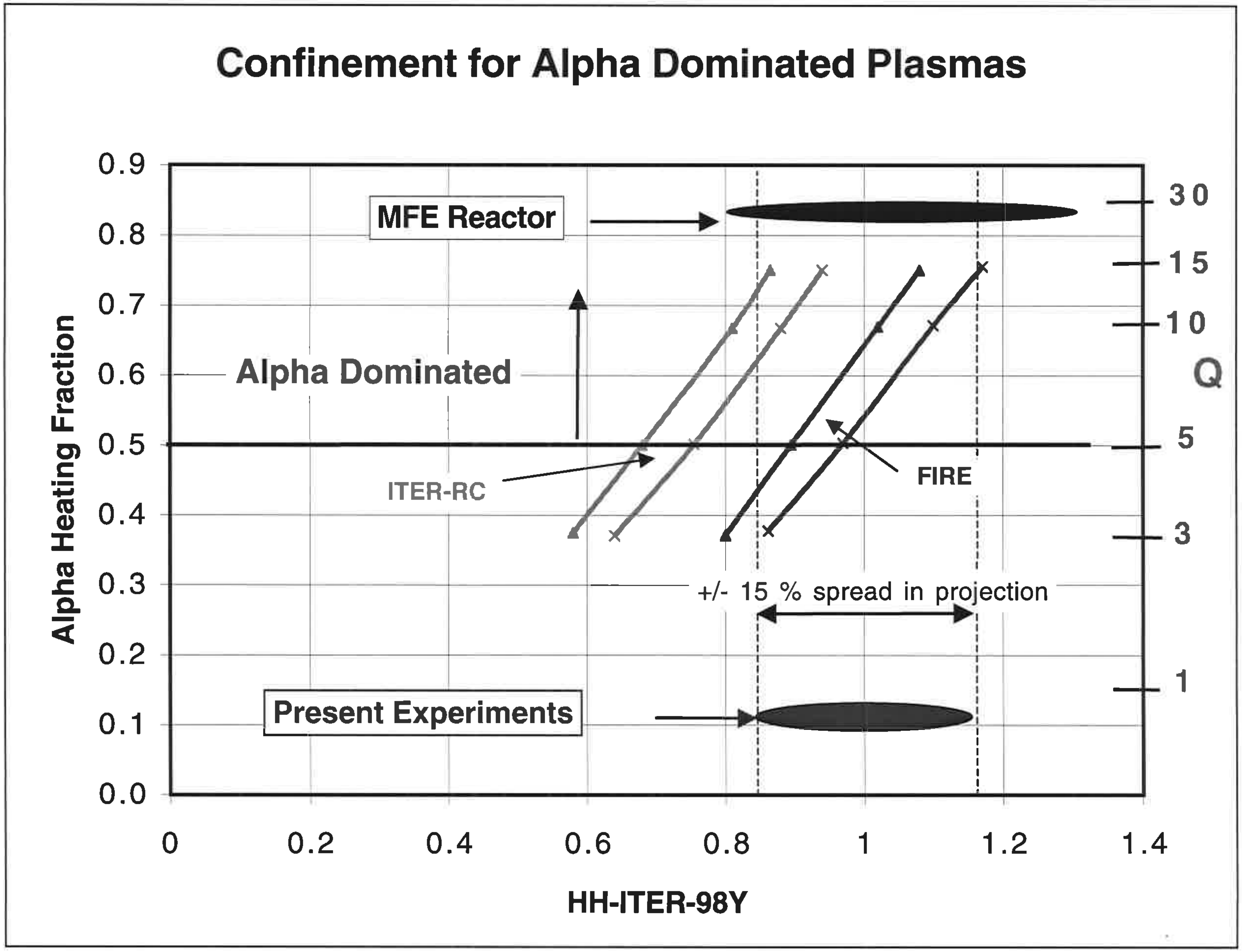
$Pth \geq (0.9/Ai)\, n^{0.75}\, B\, R^2$, nominal L to H, with H to L being ~ half when well below the density limit

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

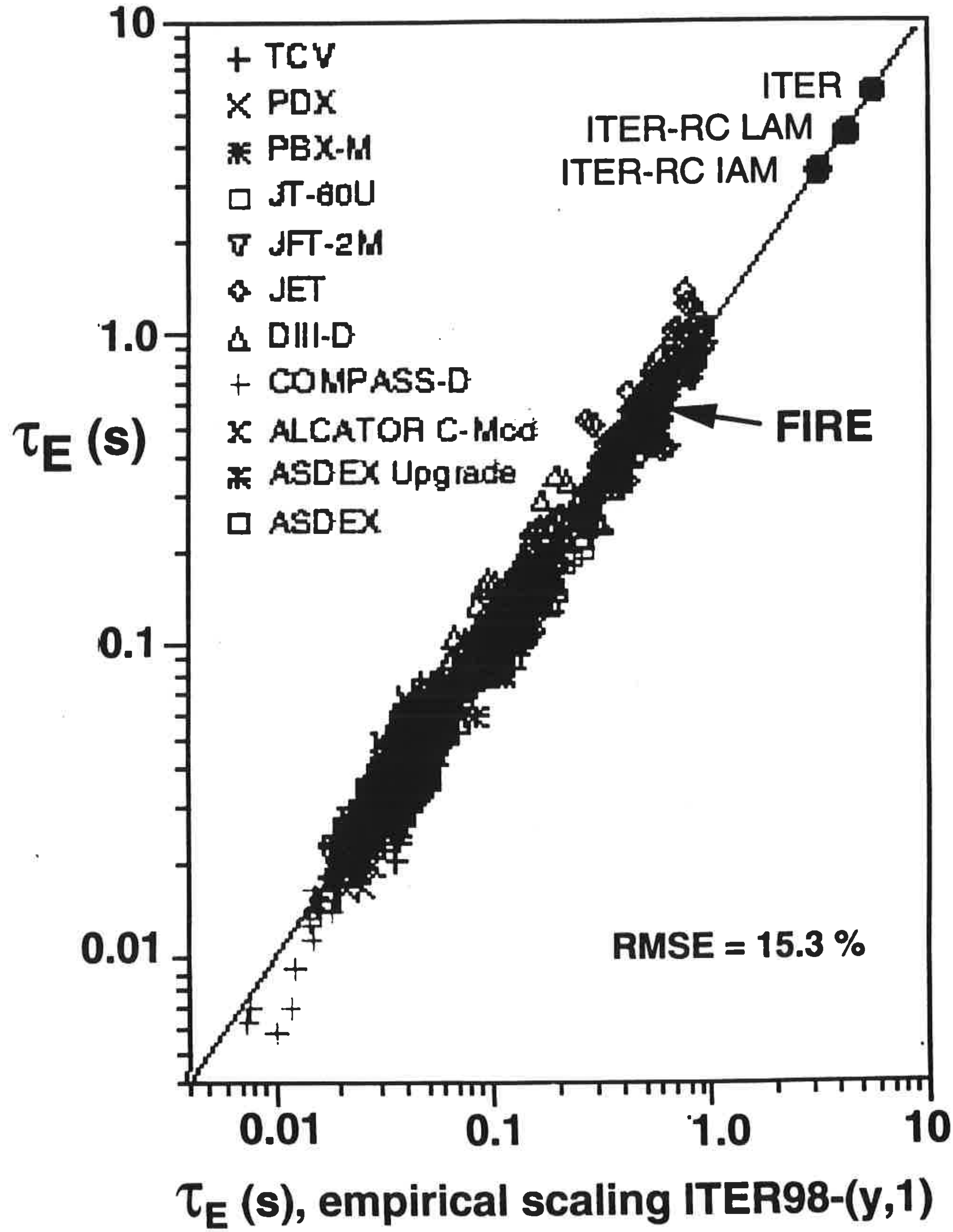
Guidelines are mainly empirical, need to benchmark in an alpha dominated plasma.

Confinement for High Gain in H-Mode

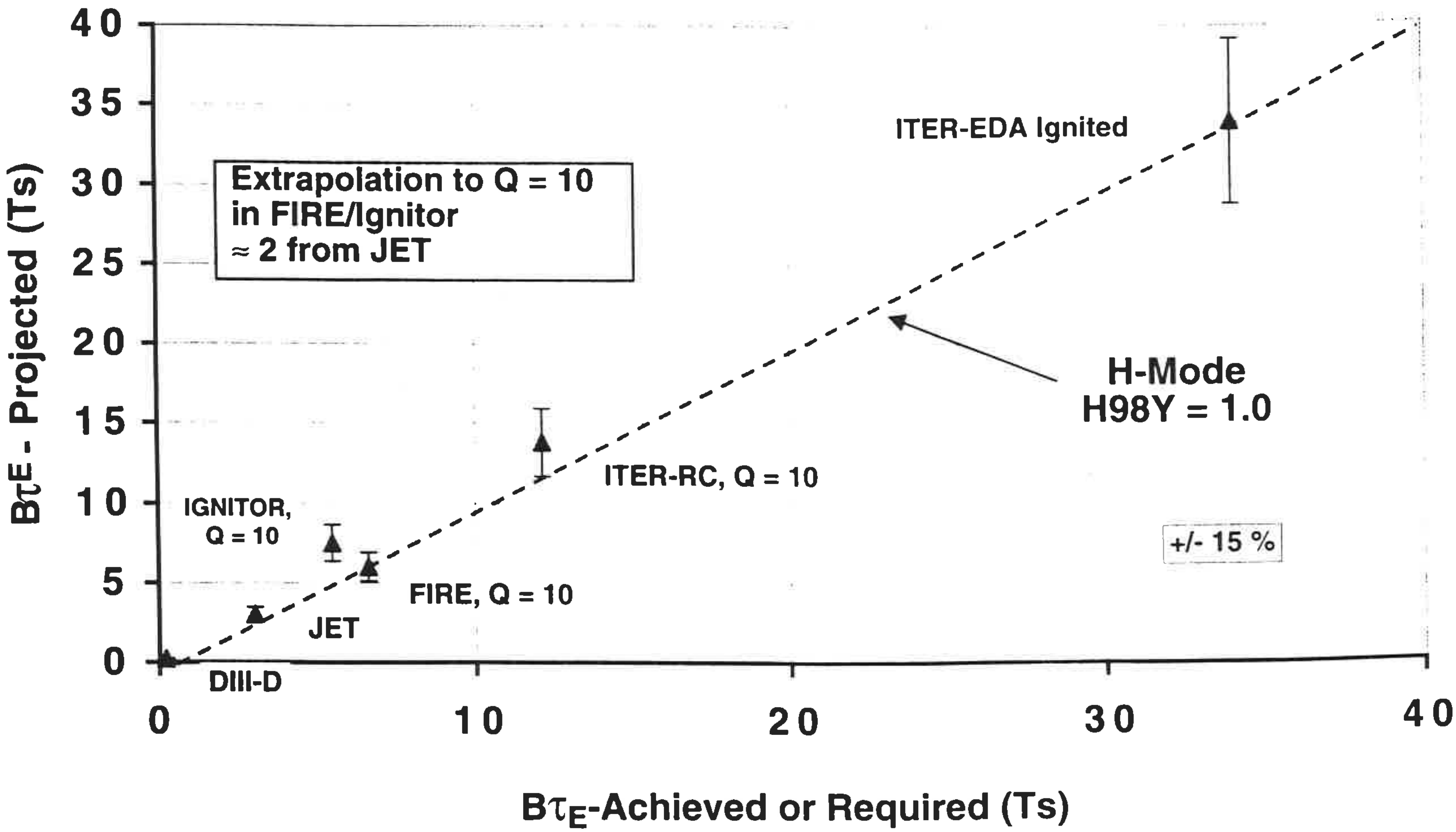



Confinement for Alpha Dominated Plasmas
MFE Reactor
Alpha Dominated
ITER-RC
FIRE
+/- 15 % spread in projection
Present Experiments
Alpha Heating Fraction
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
HH-ITER-98Y
Q
30
15
10
5
3
1

Confinement Required for Q ~ 10 in FIRE falls within the Range Achieved on Existing Tokamaks



Extrapolation of Normalized-Confinement to Q = 10 Plasmas is Small for FIRE and IGNITOR



IGNITOR and FIRE are Complementary Approaches

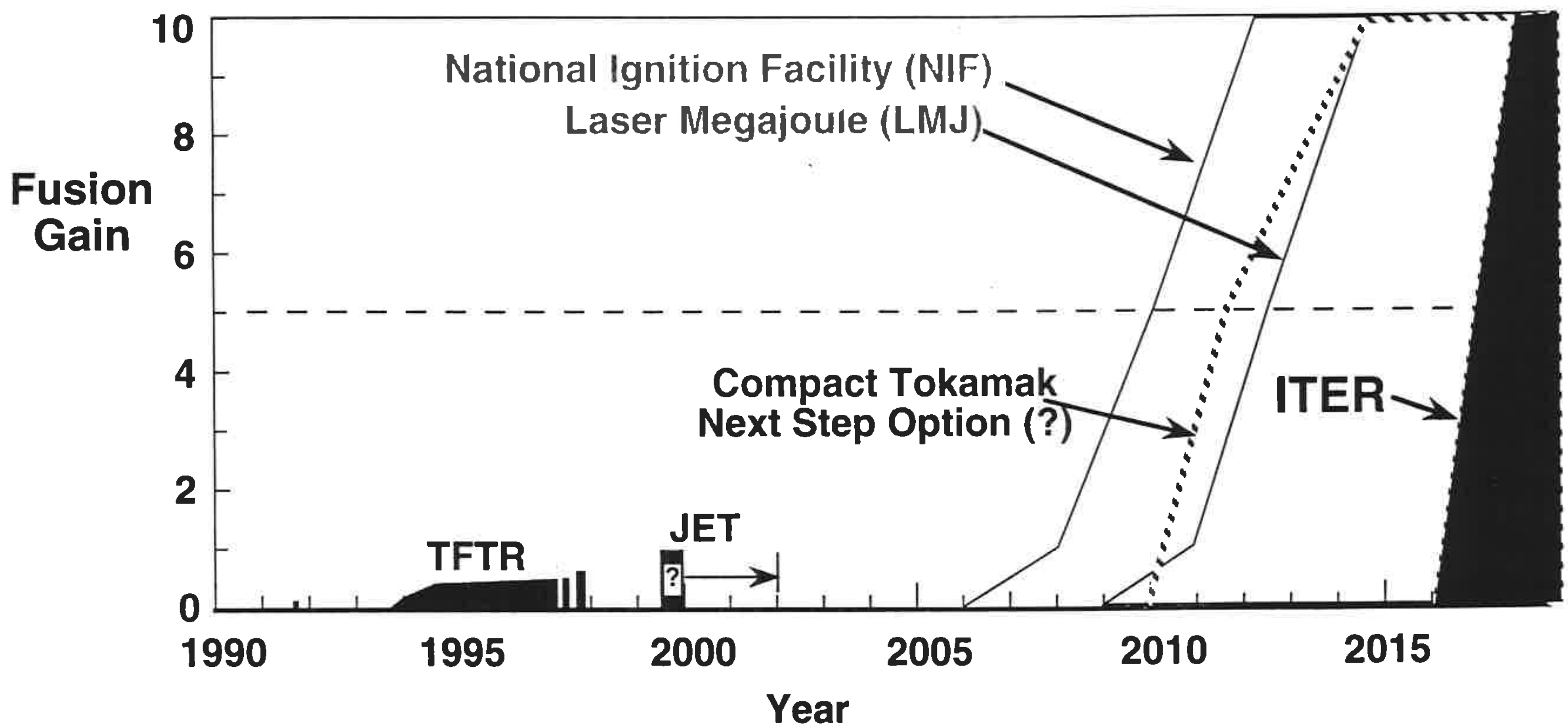
- The world magnetic fusion program should have multiple burning plasma experiments like inertial fusion (NIF and LMJ).

IGNITOR - roll forward using conservative physics
high field (13T) moderate pulse length(~5s)
significant ohmic heating
moderate shaping and wall limiter for power handling

FIRE - roll backward from ARIES with "advanced" physics
reduced field (10T to 8T), longer pulse lengths (12 to 33 s)
stronger shaping and divertor for helium exhaust
significant capability for "long pulse" adv. tok. experiments.

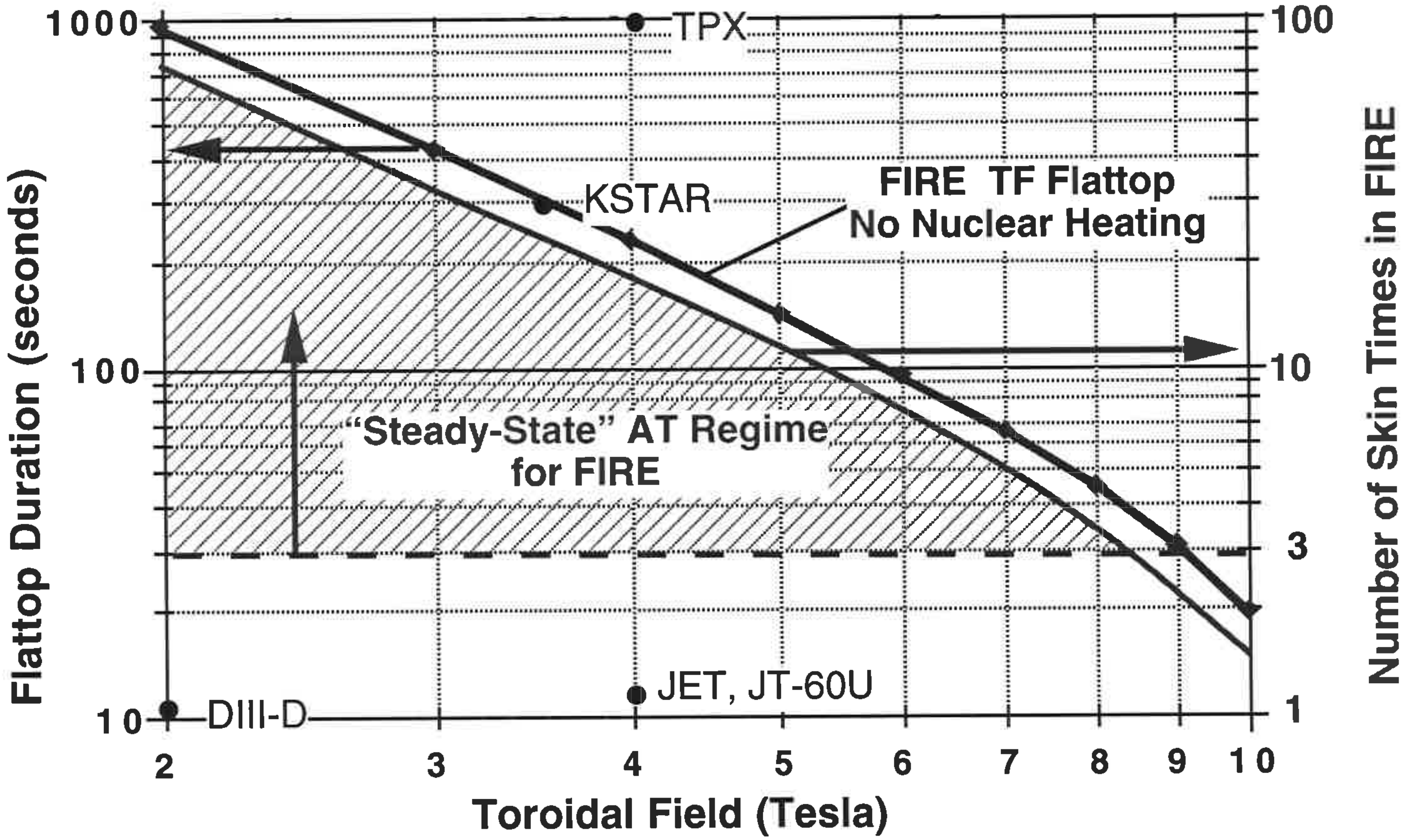
These compact high field tokamaks in collaboration with emerging activities in Europe and Japan on Next Step experiments could provide the basis for an International Modular (Multiple Machine) Strategy.

Timetable for Burning Plasma Experiments



- Even with ITER, the MFE program will be unable to address the 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 in ~ 2010.
- The information "exists now" to make a technical assessment, and decision on MFE burning plasma experiments for the next decade.

Fire can Access "Long Pulse" Advanced Tokamak Modes at Reduced Toroidal Field in D_2



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 .

FIRE can do essentially all of the TPX long pulse AT mission.

Next Step Opportunities
Burning Plasma Physics and the Physics of Fusion Plasmas

Burning Plasma Physics

Explore Alpha-Dominated Burning Plasmas

$P_\alpha / P_{heat} \geq 0.5$ (i.e., Q ~ 5 - 10)

Burn time > ~ 10 τ_E

Previous
Example: CIT ($600M FY89), BPX (1500M FY92)

Physics of Fusion Plasmas

Explore Long-Pulse Advanced-Tokamak Plasmas

Physics parameters ($\rho*$, $\nu*$ and β) beyond JET

Pulse duration > 3 - 10 $\tau_{current\ redistribution}$

Previous
Example: TPX $750 M(FY95), JT-60 SU(~$3B)

A New Paradigm for the Modular Strategy

- The Physics Modules for Burning Plasmas and Long-Pulse Advanced Tokamak **Experiments** can be done in a single facility.
- Recognize that :
  - LN cooled Cu alloys are surrogates for high temperature superconductors allowing high magnetic field at moderate pulse and long pulse at moderate field.
  - Long pulse high performance advanced tokamak experiments in deuterium will require remote handling of internal components.
- A single facility such as a ~$1B class Compact High Field Tokamak could address:
  - most of the long-pulse Advanced Tokamak issues operating in D-D
  - most of the Burning Plasma issues operating in D-T
  - many of the Burning Plasma Advanced Tokamak integration issues in D-T.

The Development of Innovations to Reduce the Cost of Fusion Devices is Essential

Physics operating space choices

Engineering technology choices

Materials choices

Engineering Innovations

- Modern design tools
- New manufacturing techniques, e.g., Lasform, spray casting, etc

The development of HiTc superconductors with high strength structural materials over the next 30 years leading to 15T magnetic fields could revolutionize MFE.

Summary

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 plasma physics, and its coupling to generic advanced toroidal physics for MFE.

The performance of a burning plasma depends sensitively on the details of confinement, β-limits, density limits, and edge plasma conditions. It is essential that we test our understanding at near fusion plasma conditions, especially under alpha -dominated conditions.

The compact high field tokamak offers the possibility of addressing the important alpha-dominated plasma issues, many of the long pulse advanced tokamak issues and beginning the integration of alpha-dominated plasmas with advanced toroidal physics in a \$1B class facility (≤ ~\$300M for core tokamak).