Status of Next Step Option Study on Fusion Ignition Research Experiment

The National FIRE Design Study

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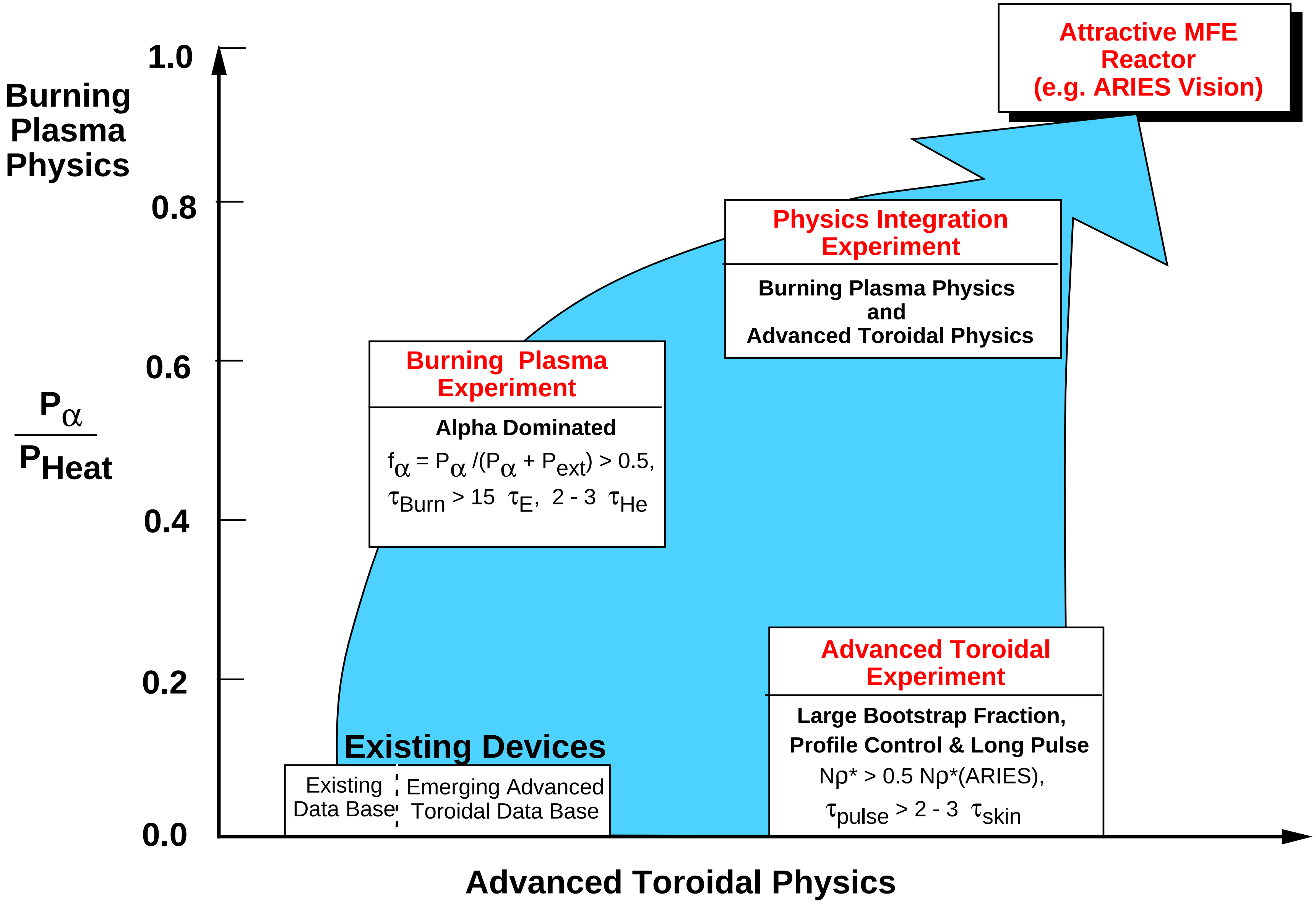
Presented at the Snowmass Summer Study

July 15, 1999

Stepping Stones for Developing the Physics Basis for an Attractive MFE Reactor



Attractive MFE Reactor (e.g. ARIES Vision)

Physics Integration Experiment

Burning Plasma Physics and Advanced Toroidal Physics

Burning Plasma Experiment

Alpha Dominated

$f_\alpha = P_\alpha / (P_\alpha + P_{ext}) > 0.5$,

$\tau_{Burn} > 15\ \tau_E$, 2 - 3 τ_{He}

Advanced Toroidal Experiment

Large Bootstrap Fraction, Profile Control & Long Pulse

Nρ* > 0.5 Nρ*(ARIES),

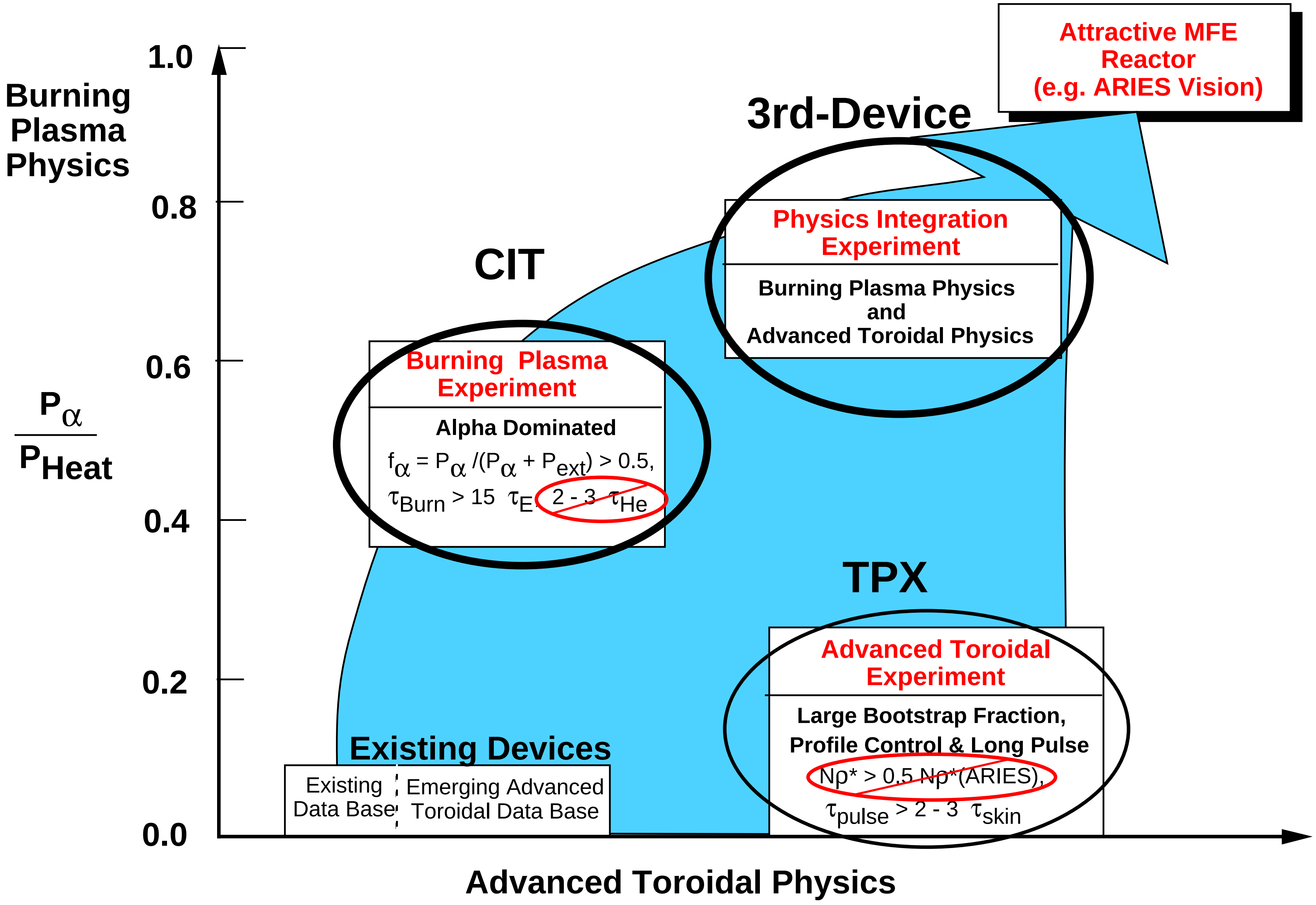
$\tau_{pulse} > 2 - 3\ \tau_{skin}$

Existing Devices

Existing Data Base

Emerging Advanced Toroidal Data Base

The "Old" Paradigm Required Three Devices.



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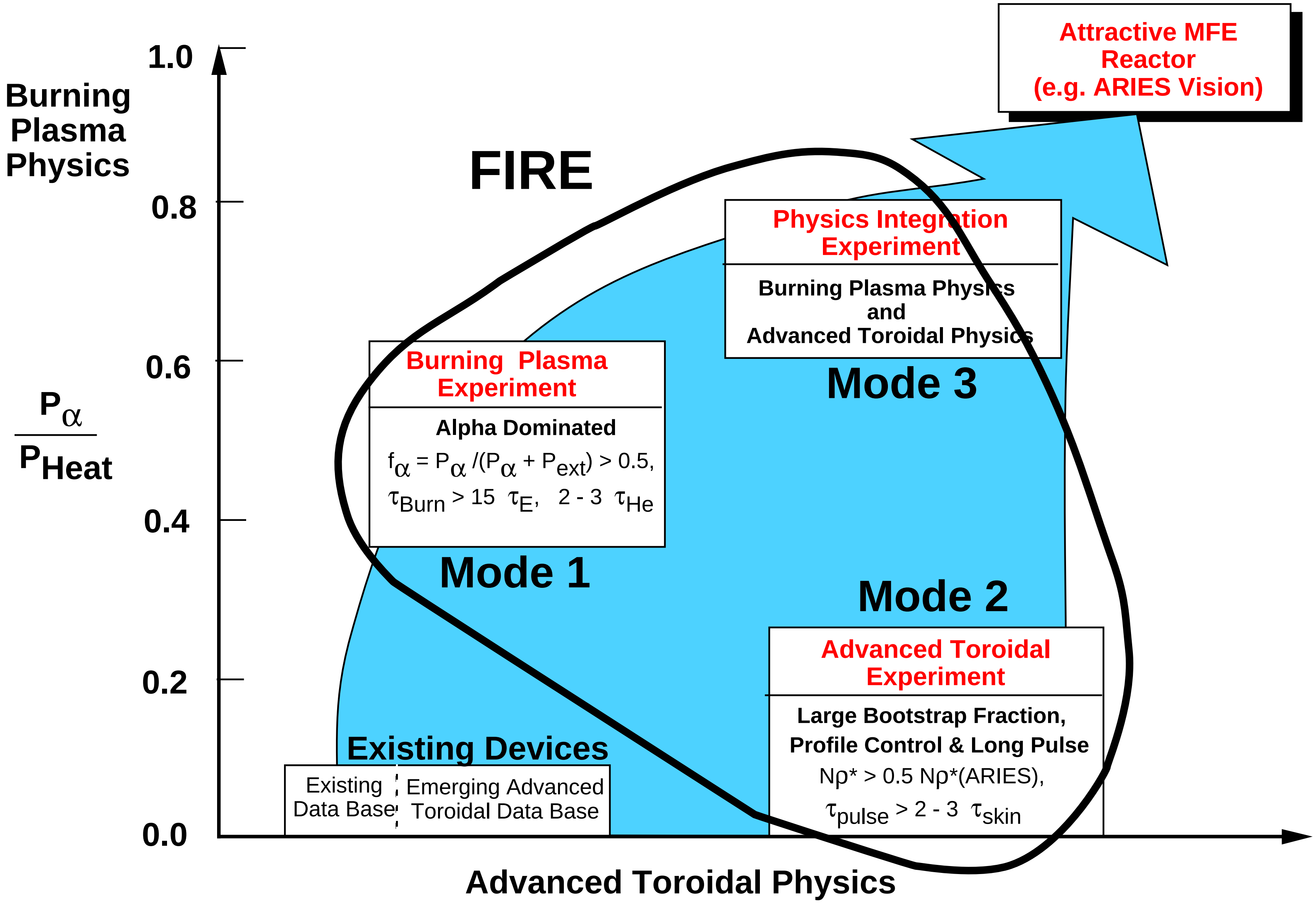
Existing Data Base

Emerging Advanced Toroidal Data Base

The “New” Paradigm - One Device with Three Modes.



Attractive MFE Reactor (e.g. ARIES Vision)

Physics Integration Experiment

Burning Plasma Physics and Advanced Toroidal Physics

Mode 3

Burning Plasma Experiment

Alpha Dominated

$f_\alpha = P_\alpha/(P_\alpha + P_{ext}) > 0.5$,

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Mode 1

Mode 2

Advanced Toroidal Experiment

Large Bootstrap Fraction, Profile Control & Long Pulse

$N\rho^* > 0.5\ N\rho^*(\text{ARIES})$,

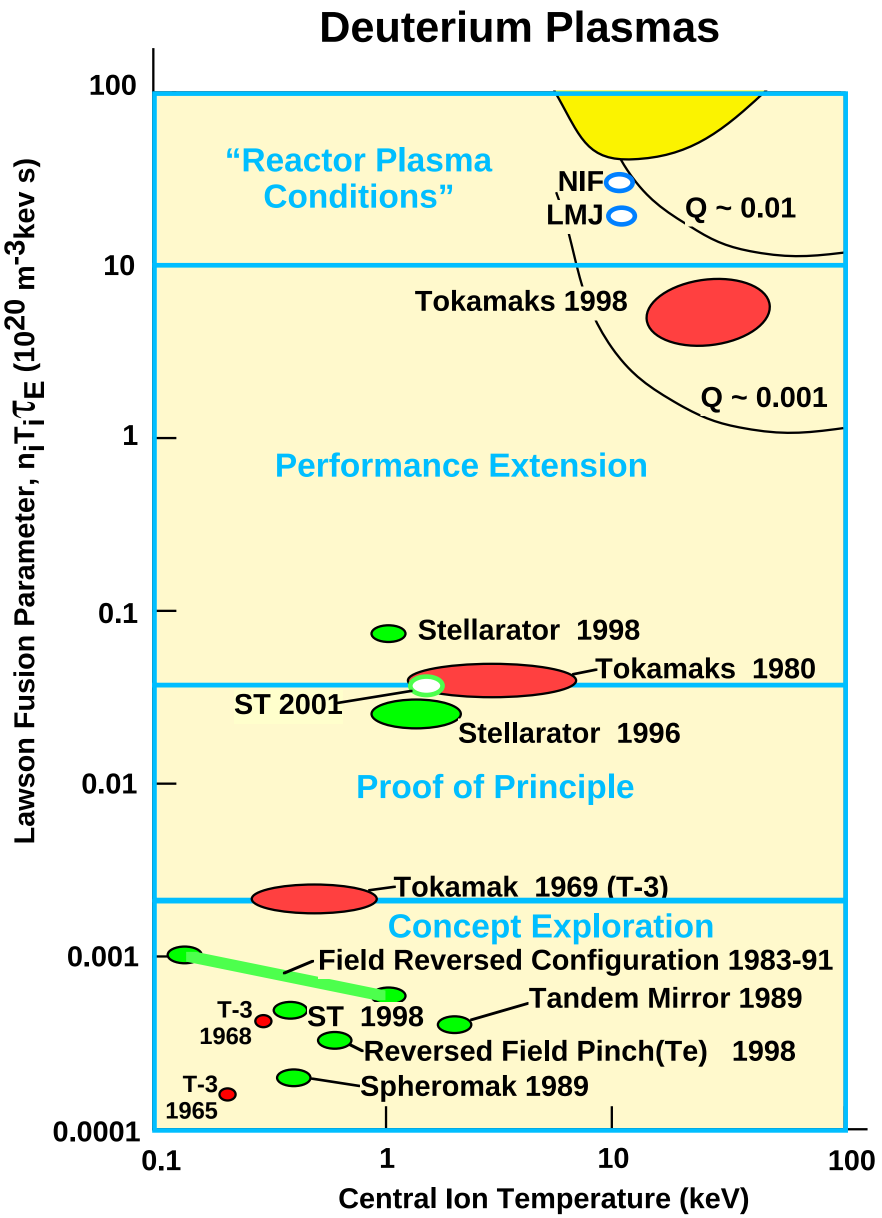
$\tau_{pulse} > 2 - 3\ \tau_{skin}$

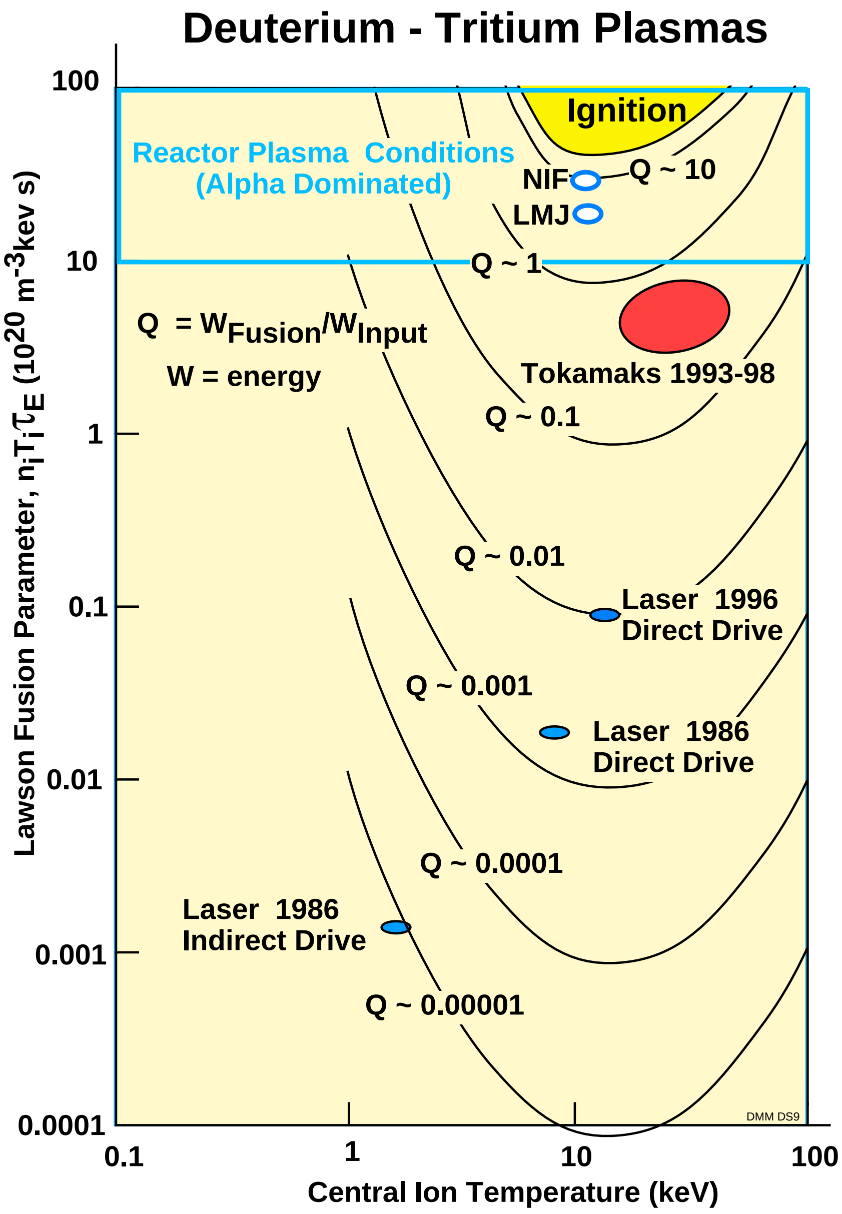
Existing Devices

Existing Data Base

Emerging Advanced Toroidal Data Base

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





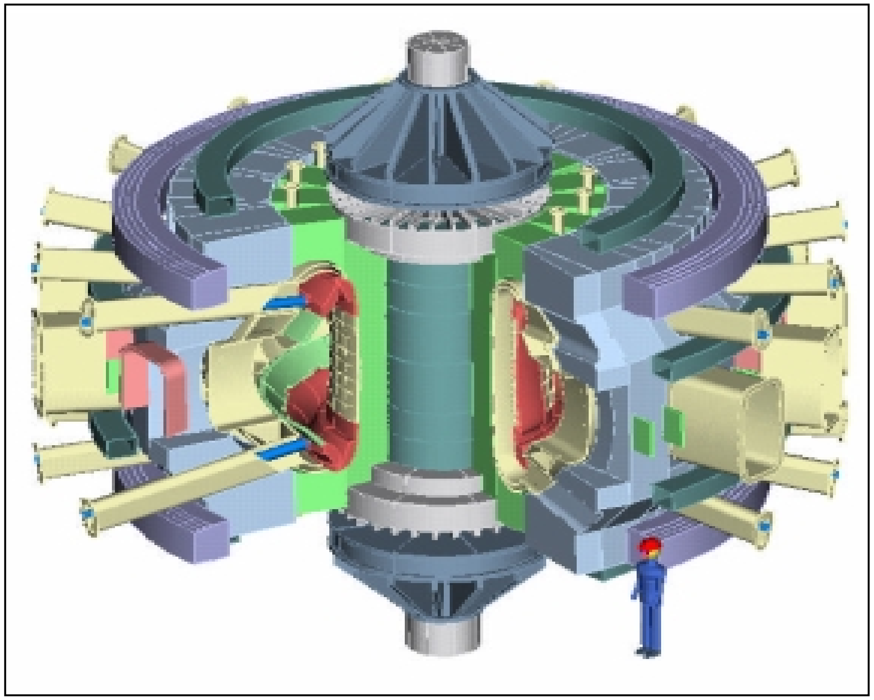
Only the tokamak is sufficiently advanced to permit the design, construction and initiation of a next step burning plasma experiment within the next decade that could address the alpha-dominated burning-plasma physics issues of magnetic fusion.

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

- Determine the conditions required to achieve alpha- dominated plasmas:
  - Energy confinement scaling with alpha- dominated heating
  - β-limits with alpha- dominated heating
  - Density limit scaling with alpha- dominated heating
- Control alpha- dominated plasmas (e.g., modification of plasma profiles)
- Sustainment of 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.
- Exploration of alpha- dominated 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.

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

Fusion Ignition Research Experiment (FIRE)



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_{fusion} ~ 220 MW
- Q ~ 10, τ_E ~ 0.55s
- Burn Time $\geq$ 18s (12s)
- Tokamak Cost $\leq$ \$0.3B

  Base Project Cost $\leq$ \$1B

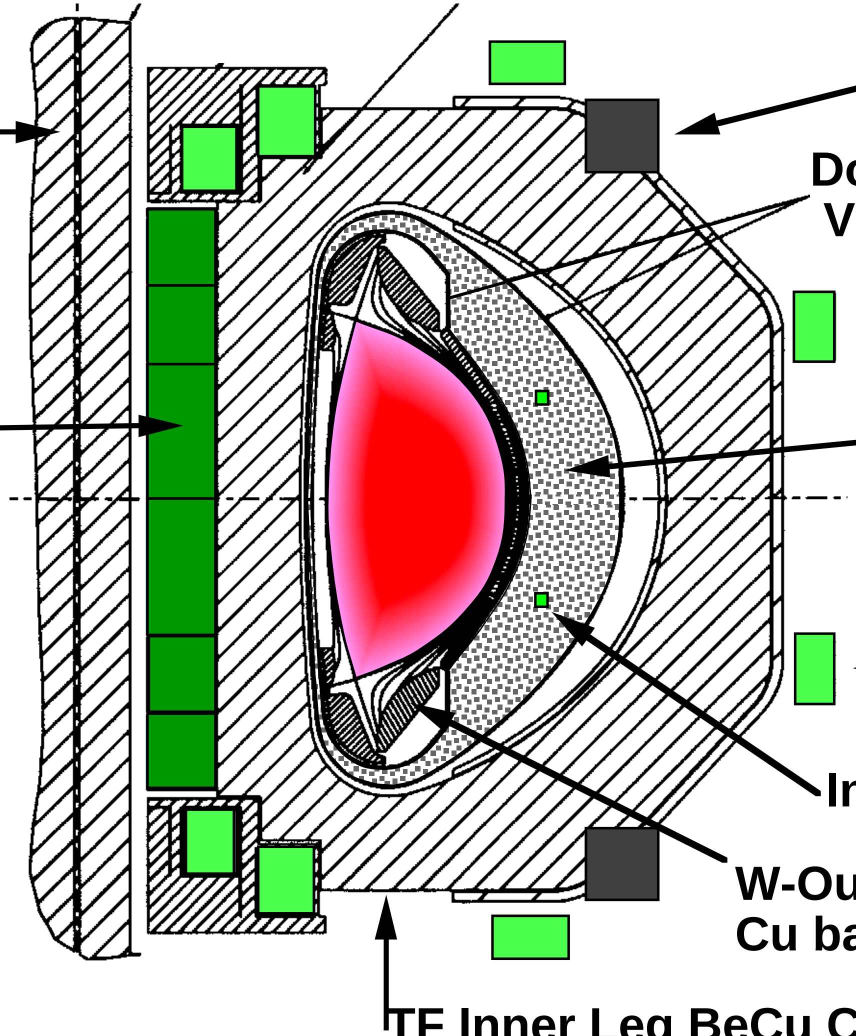
Attain, explore, understand and optimize alpha-dominated plasmas to provide knowledge for the design of attractive MFE systems.

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	≥ 10s (= 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 Facility

Possibility of an upgrade to B = 12T and Ip = 7.7MA with a 12 second flat top has been identified and will be a potential upgrade.

FIRE Engineering Features



Wedged TF Coils (16), 15 plates/coil*

Tie Rod

Compression Ring

Double Wall Vacuum Vessel (316 S/S)

Central Solenoid (Be Cu C17510)*

Internal Shielding (60% steel & 40%water)

Outer PF Coils* OFHC C102

Internal Position Control Coil

W-Outer Divertor Plate Cu backing plate,actively cooled

TF Inner Leg BeCu C17510, remainder OFHC C102.*

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

Fusion Power Density and Neutron Wall Loading are Key Metrics for Economic Fusion

	TFTR	FIRE	ITER-RC	ARIES-RS	ARIES-ST
Power Density (MWm^{-3})	0.28	12.2	0.54	6.2	3.6
Neutron Wall Loading (MWm^{-2})	0.12	3	0.53	4	4
Neutron Fluence (MWy m^{-2})	$<10^{-7}$	<0.01	<1	120	120
Duration (s)	0.5	10	400	steady	steady

- ARIES-RS (tokamak) has two times higher power density than the ARIES-ST (spherical torus).

- FIRE, the compact high field tokamak, exceeds ARIES-RS power densities and approaches ARIES-RS wall loading for 20 second pulses.

- ITER-RC is about a factor of 10 lower in power density and wall loading than ARIES-RS.

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

Tokamak experiments (1989-1999) have developed improved 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

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.

Engineering Innovations

- Improved materials and 3-D design analysis

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

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

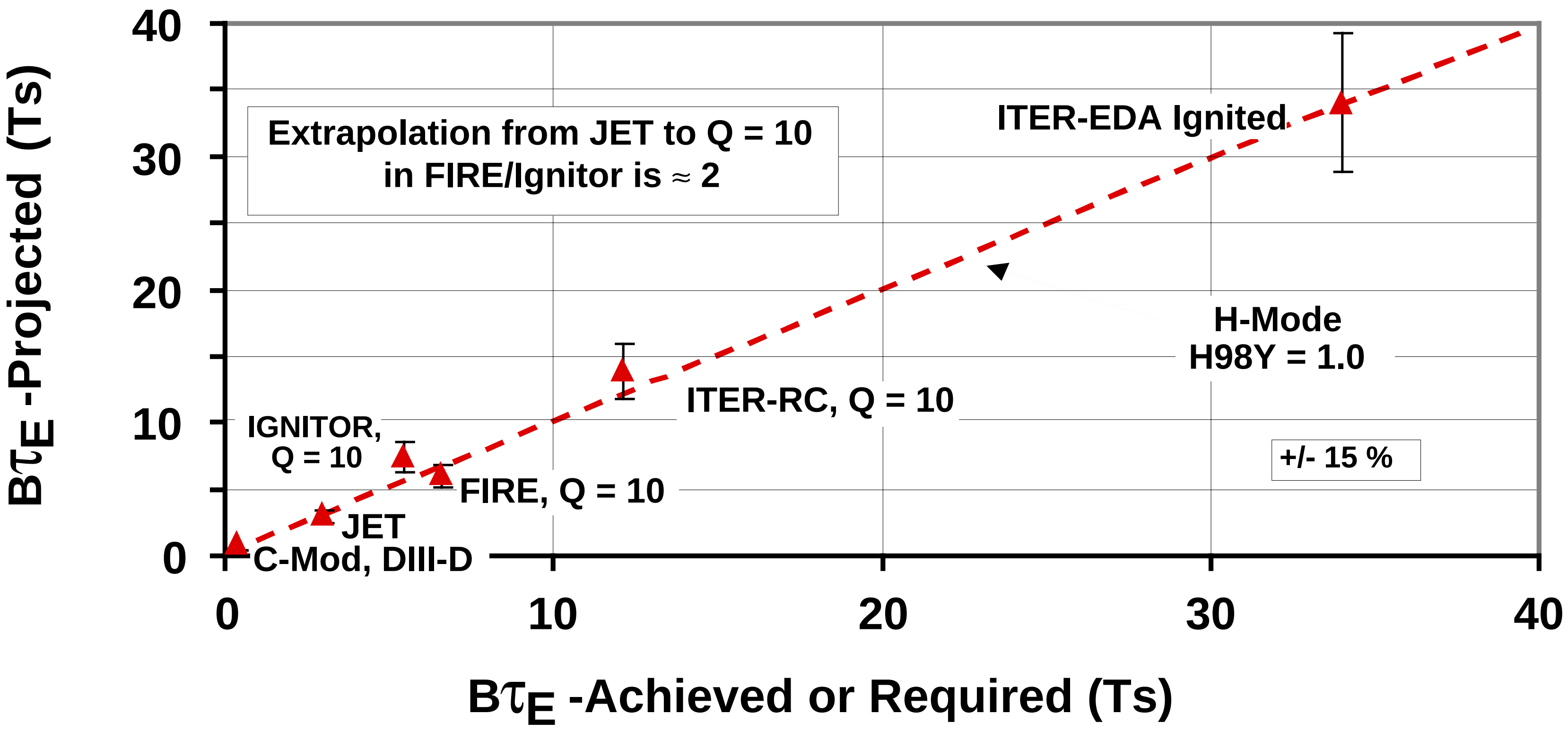
Helium Ash Confinement $\tau_{He} = 5\, \tau_E$, impurities = 3% Be

Understanding is mainly empirical. Better understanding is needed from existing experiments with improved simulations, and a benchmark in alpha-dominated plasmas is needed before energy demonstration projects are constructed.

Nominal FIRE Plasma Parameters from 0-D Simulations

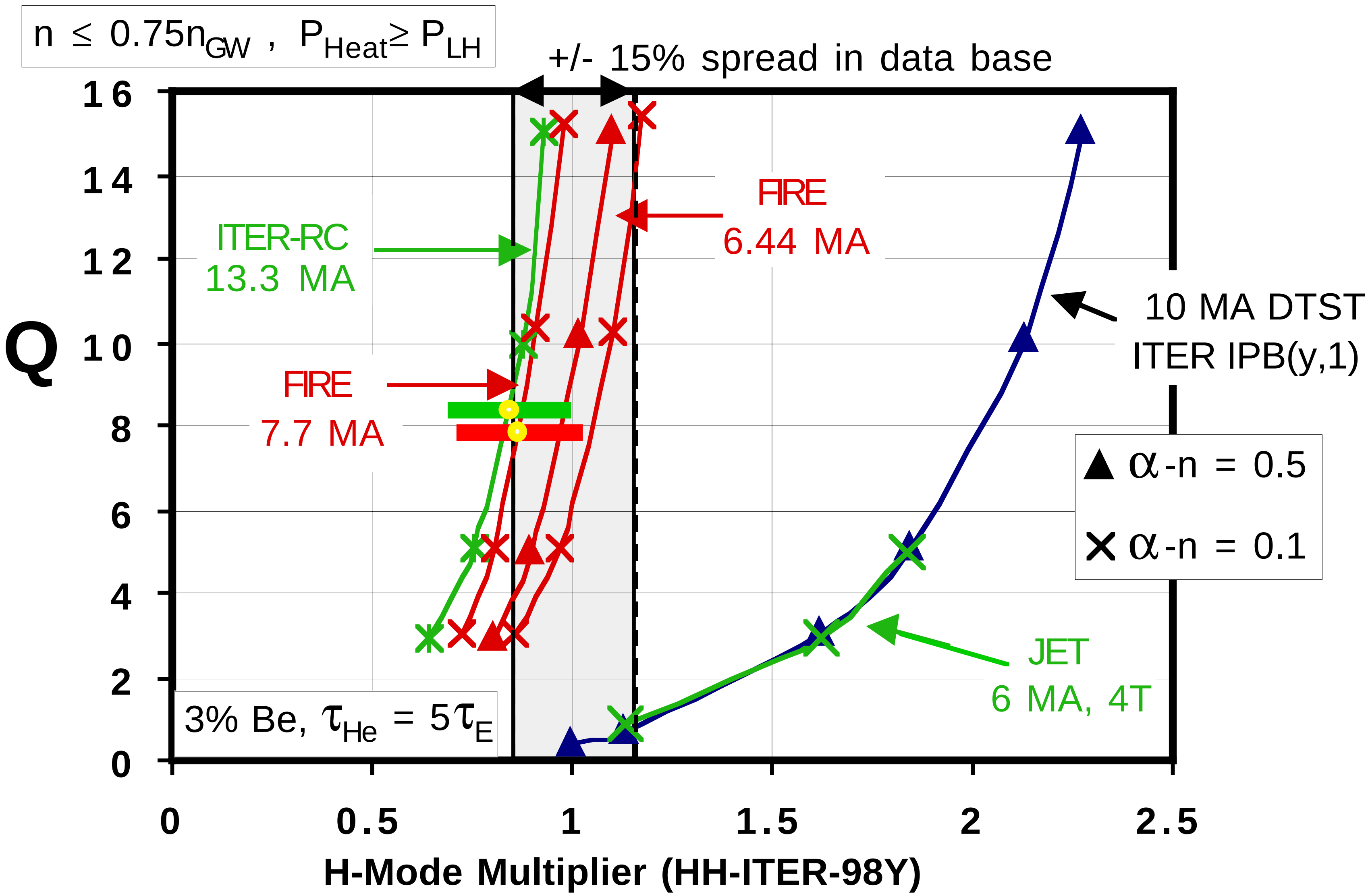
R, plasma major radius, m	2.0
A, plasma minor radius, m	0.525
R/a , aspect ratio	3.8
κ_95, plasma elongation at 95% flux	1.77
δ_95, plasma triangularity at 95% flux	0.4
q_95	3.02
B_t, toroidal magnetic field, T	10
I_p, plasma current, MA	6.44
l_i(3), internal plasma inductance	0.8
Fraction of bootstrap 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

Extrapolation of Normalized-Confinement to Q = 10 Plasmas is Small (≈2) for FIRE and IGNITOR



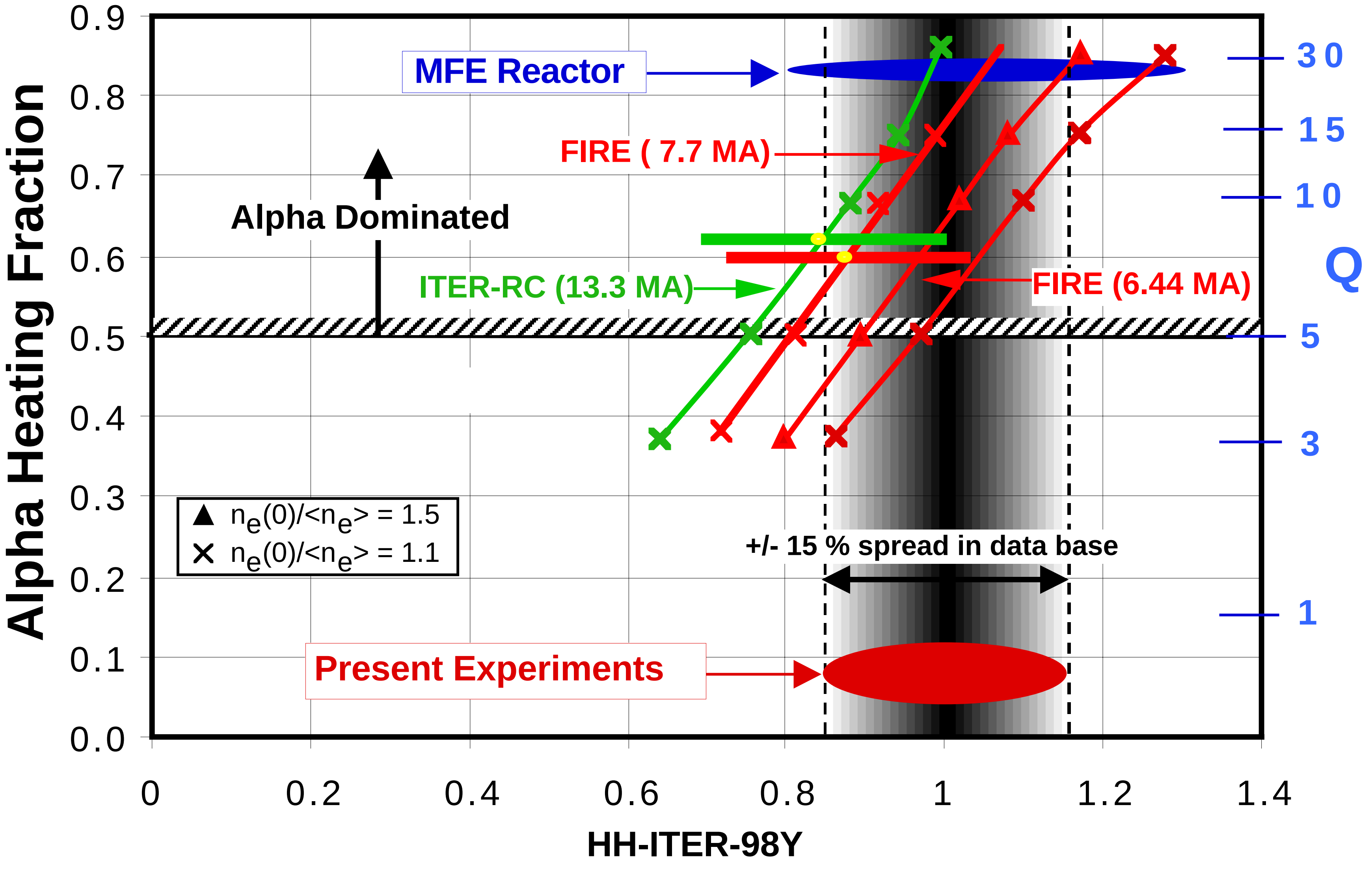
High magnetic field allows FIRE and IGNITOR to operate at high density, thereby reducing the required extrapolation in confinement, the most uncertain quantity.

Confinement for High Gain in Elmy H-Mode



The baseline FIRE(6.44 MA) can access the alpha-dominated regime (Q > 5).
FIRE could be extended to 7.7 MA to provide increased margin equal to ITER-RC.

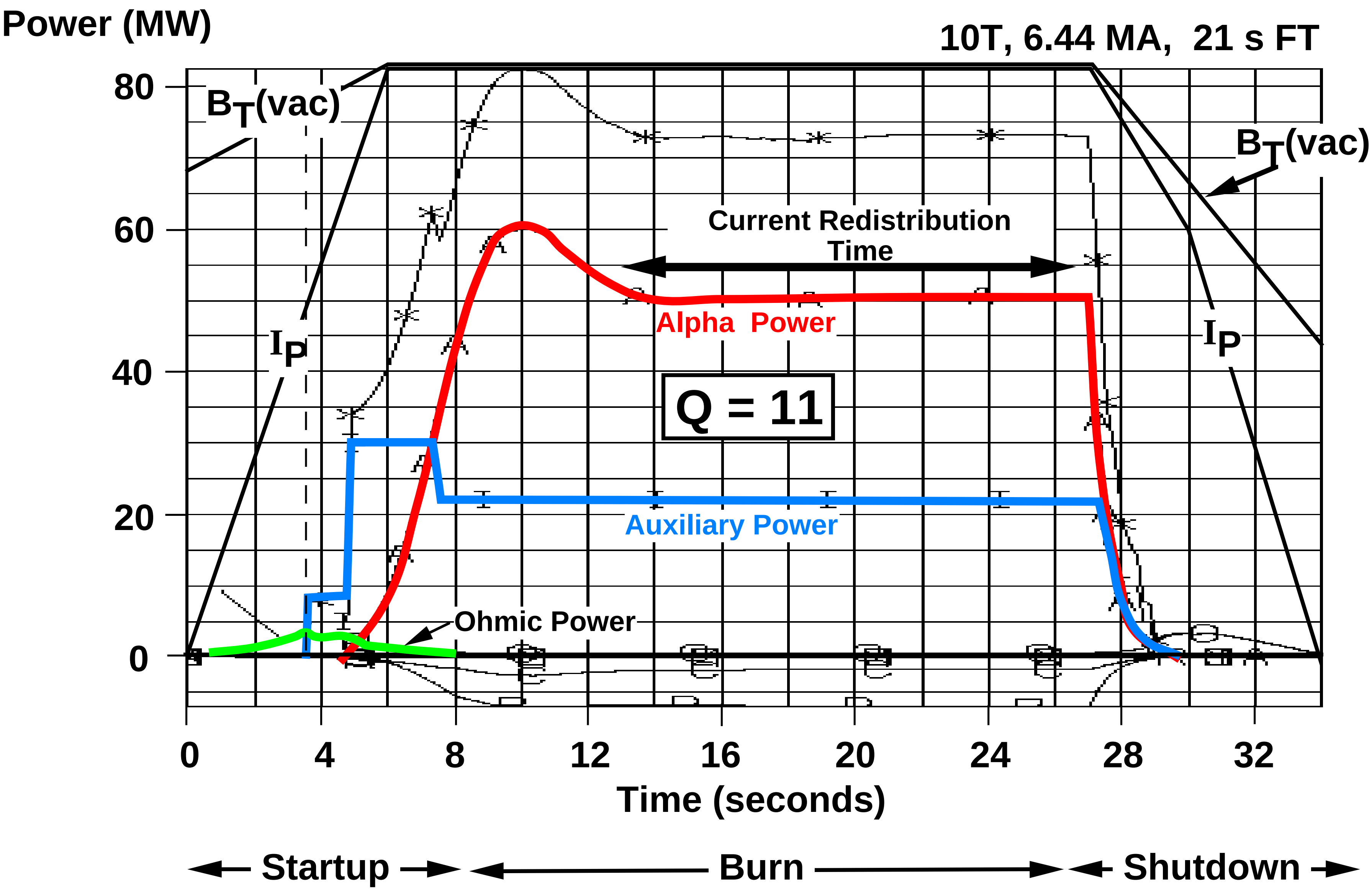
Confinement Required for Alpha-Dominated Plasmas



The dynamics of a burning plasma is determined by the alpha heating fraction which is not subject to a sharp threshold versus confinement.

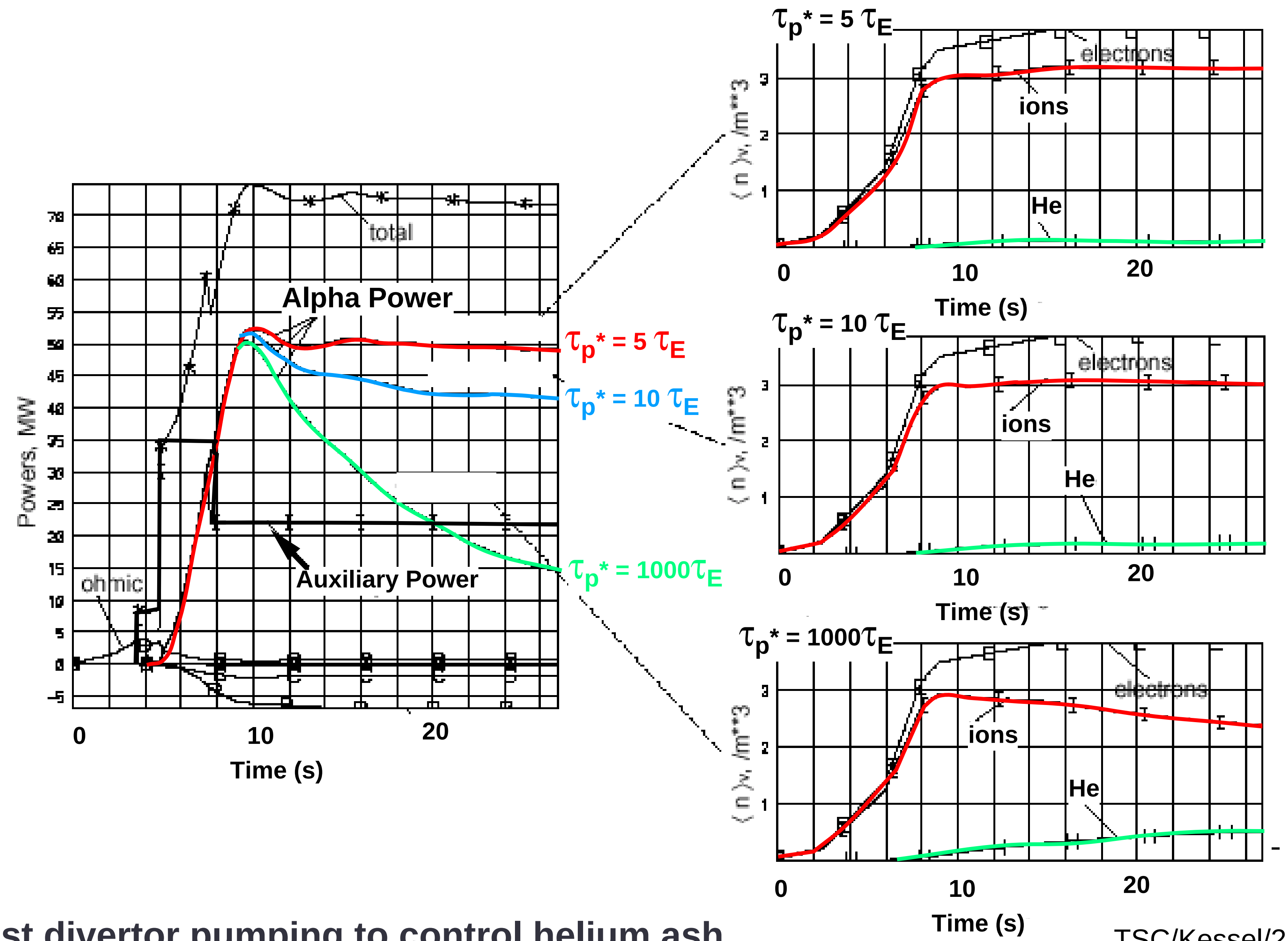
falpha vs HH98-7/APS Cent

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/**

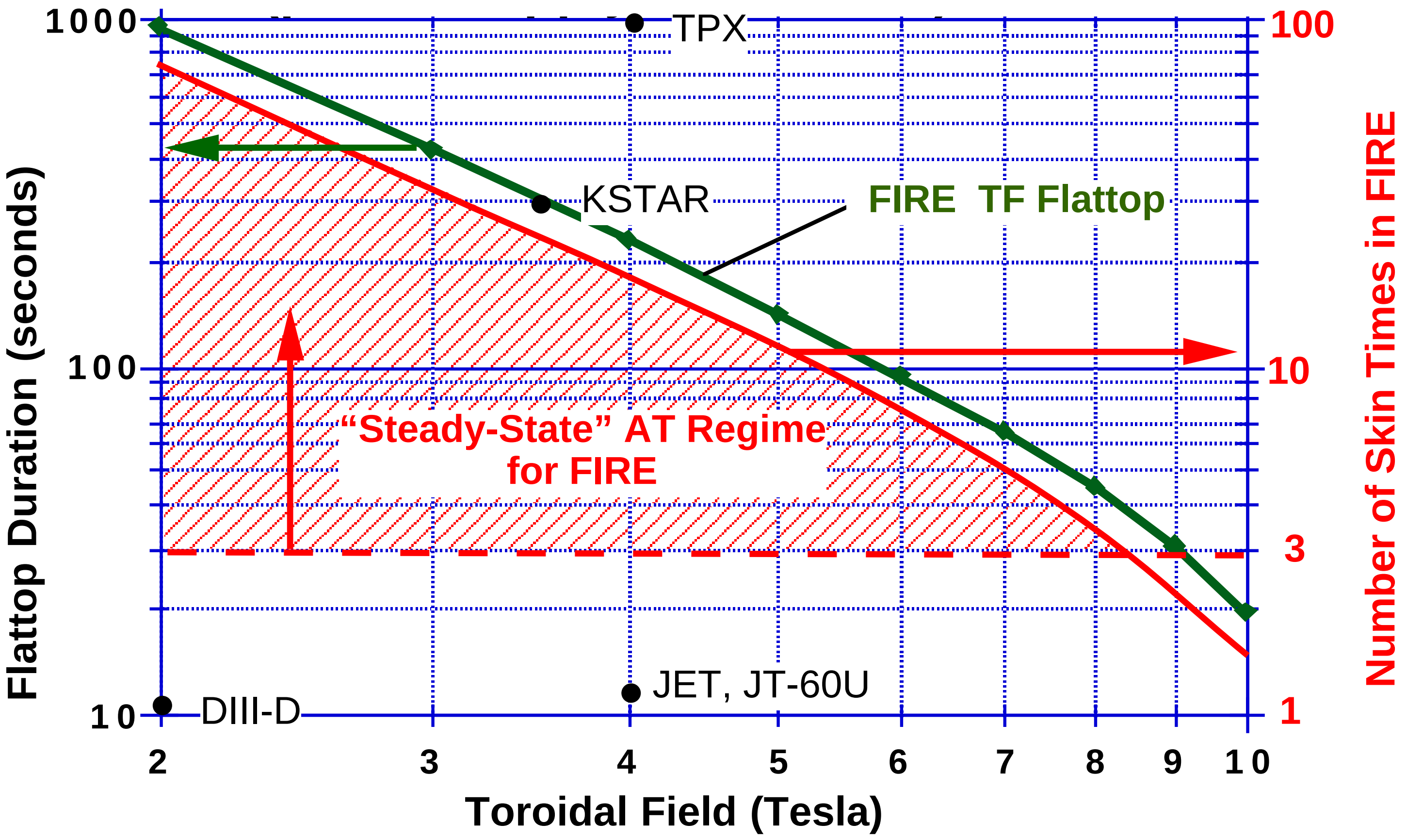
Helium Ash Accumulation can be Explored on FIRE



Adjust divertor pumping to control helium ash

TSC/Kessel/21-q.ps

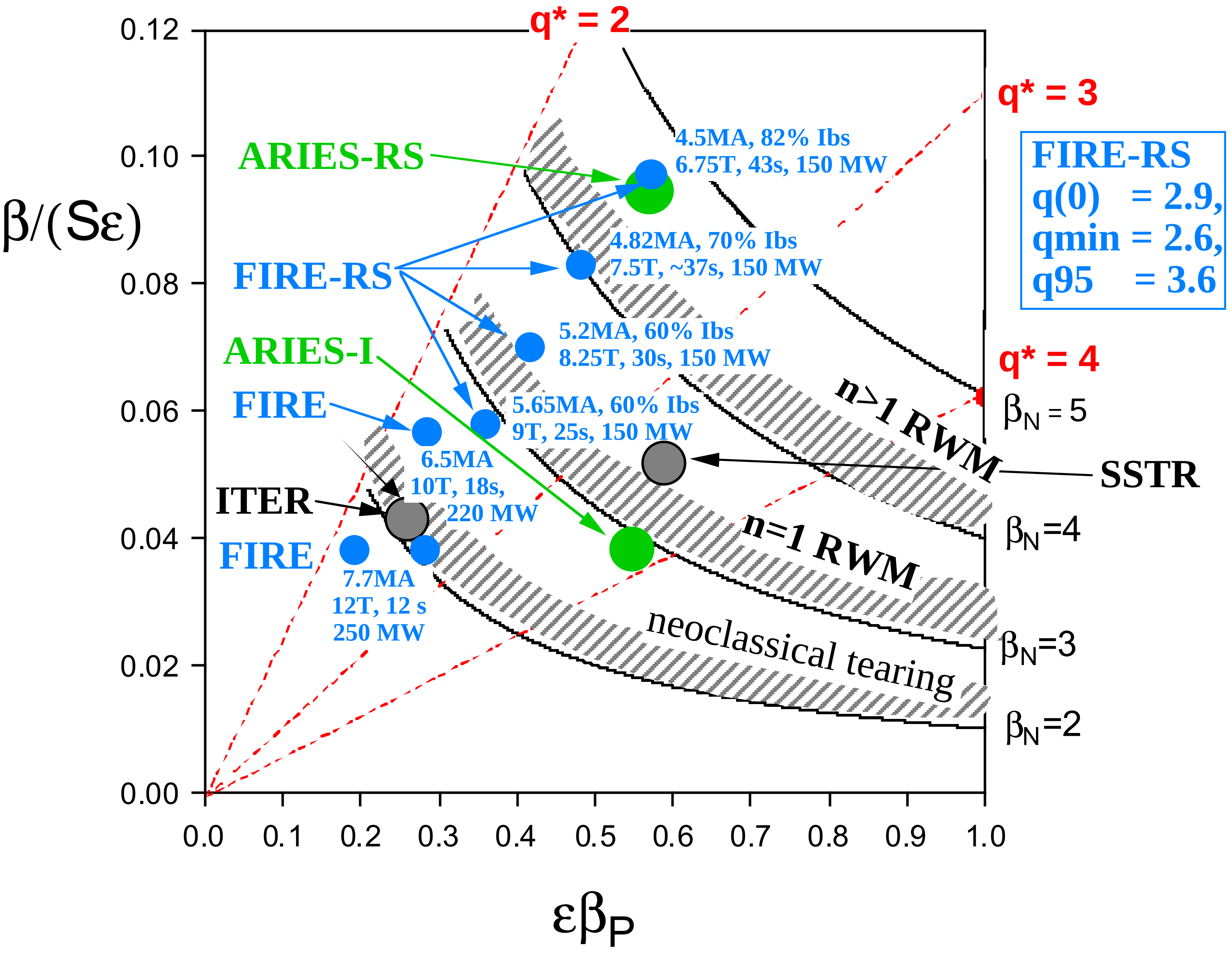
FIRE can Access "Long Pulse" Advanced Tokamak Modes at Reduced Toroidal Field.



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



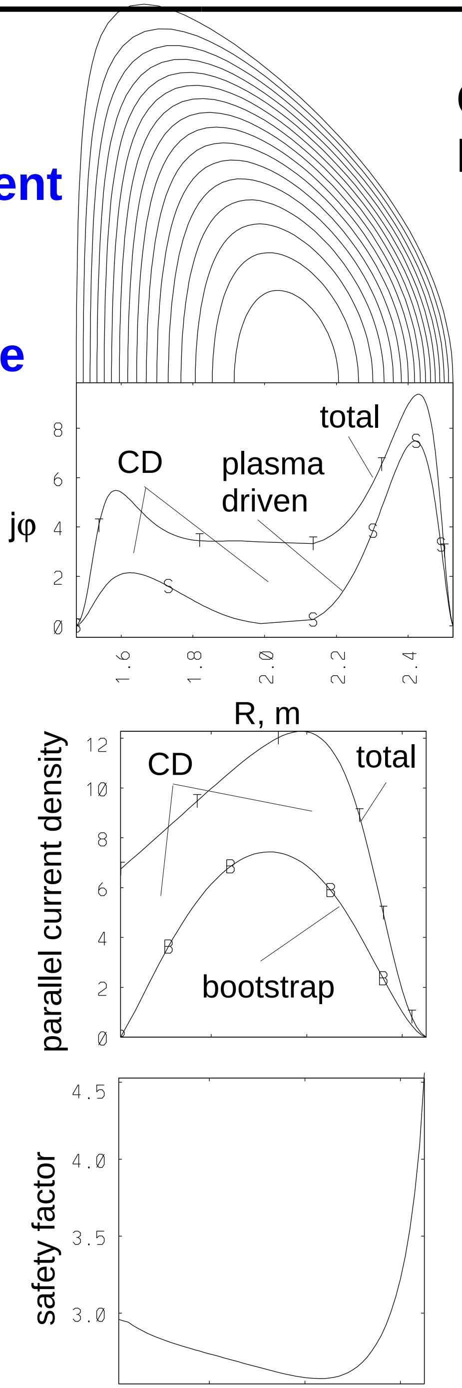
FIRE Alpha-Dominated Advanced Tokamak Configurations

Confinement Required to access this regime

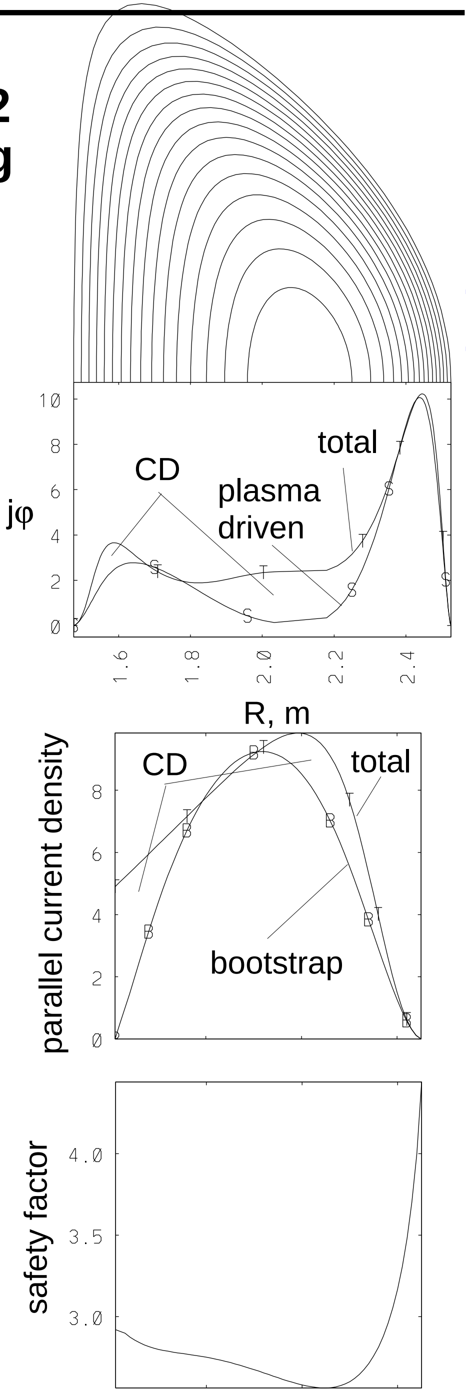
Q = 10, HH = 1.2

or

Q = 5, HH = 1.06



Case 1 Modest AT		**Case 2 Strong AT**
30	**Flat top(s)**	**60**
5.65	I_p(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

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

Cost Background for FIRE

- Three tokamaks physically larger but with lower field energy than FIRE have been built.

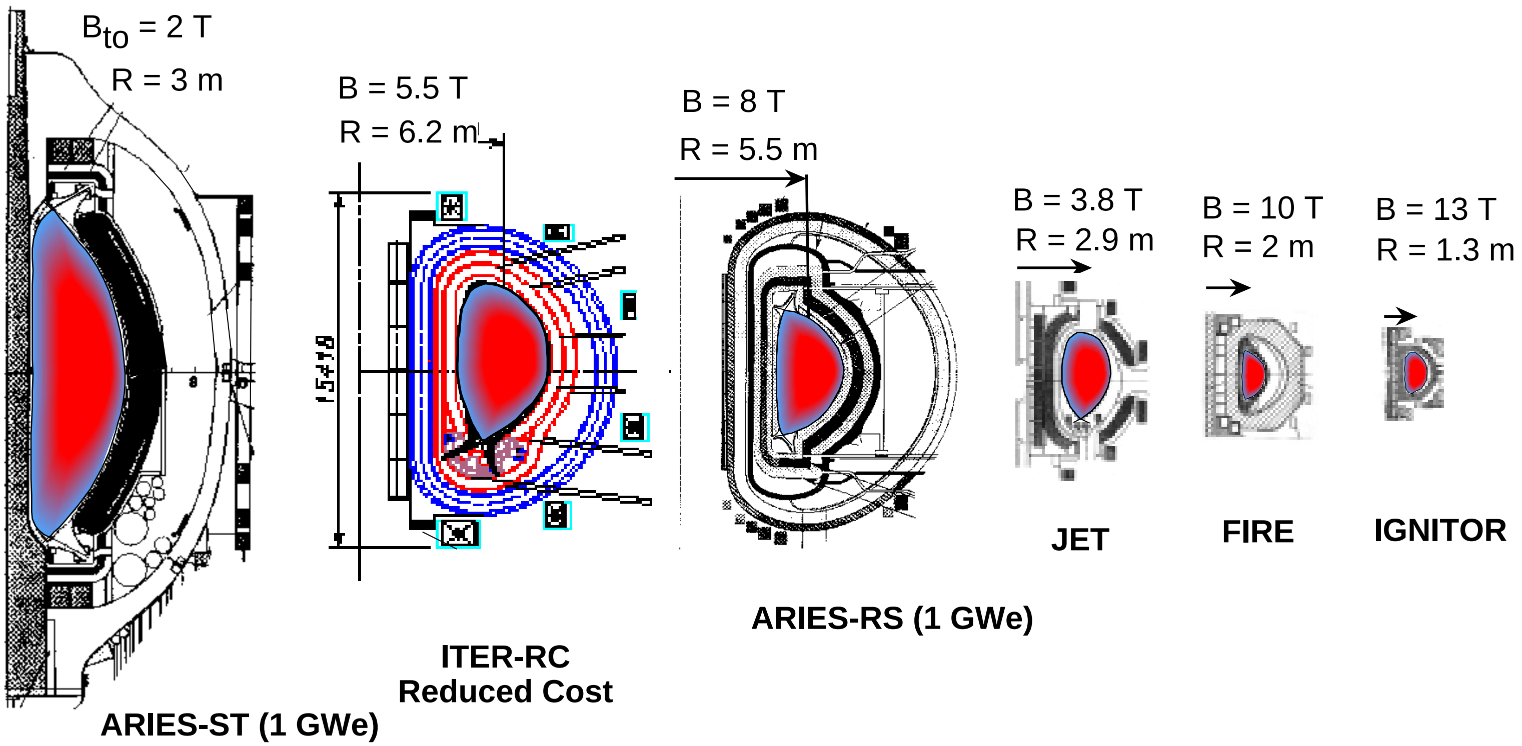
Water Cooled Coils	B(T)	R(m)	Coil Energy (GJ)	Const. Cost
TFTR (1983), US	5.2	2.5	1.5	$498M
JET (1984), Europe	3.4	2.96	1.4	~$600M
JT-60 (1984), Japan	4.4	3.2	2.9	~$1000M
FIRE*, US	10	2.0	3.8	(< $1000M)

* FIRE would have liquid nitrogen cooled coils.

Cost estimates from previous design studies with similar technology.

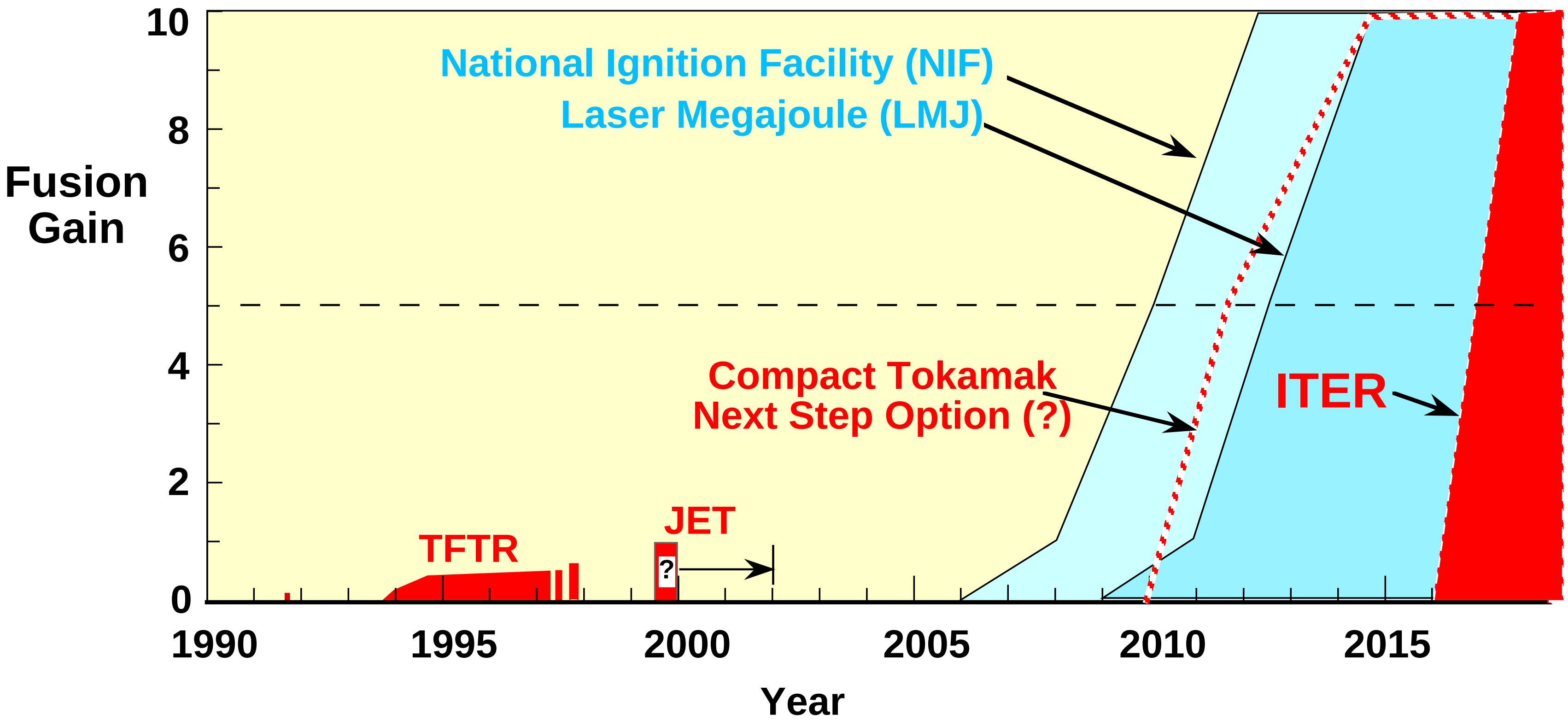
Liquid N, Cu coils	B(T)	R(m)	Coil Energy (GJ)	Const. Cost
CIT (1989),	11	2.14	5	$600M (FY-89)
BPX (1991)	9.1	2.59	8.4	$1,500M (FY-92)
BPX-AT(1992)	10	2.0	4.2	$642M (FY-92)
FIRE	10	2.0	3.8	(<$1000M FY-00)

Potential Next Step Burning Plasma Experiments and Demonstrations in MFE



Cost Drivers	ARIES-ST	ITER-RC	ARIES-RS	JET	FIRE	IGNITOR
Plasma Volume (m^3)	860	740	350	95	18	11
Plasma Surface (m^2)	630	640	420	150	60	36
Plasma Current (MA)	30	13	11	4	6.5	12
Magnet Energy (GJ)	29	50	85	2	5	5
Fusion Power (MW)	2861	400	2170	16	200	200
Burn Duration (s)	steady	400	steady	1	10	5

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 ≥ 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 technical assessment, and decision on MFE burning plasma experiments for the next decade.

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

- 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 tokamak facilities and the physics required in the ARIES vision for magnetic fusion energy.

- A dual track Modular Strategy for Magnetic and Inertial Fusion including strong base programs and near-term alpha-dominated burning plasma experiments would provide a strong science foundation for fusion while providing visible deliverables by ~ 2010.