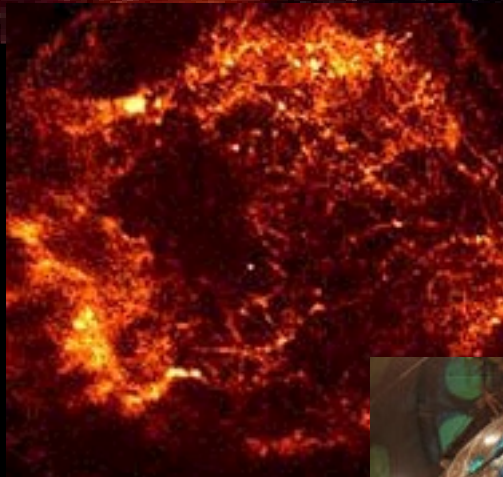
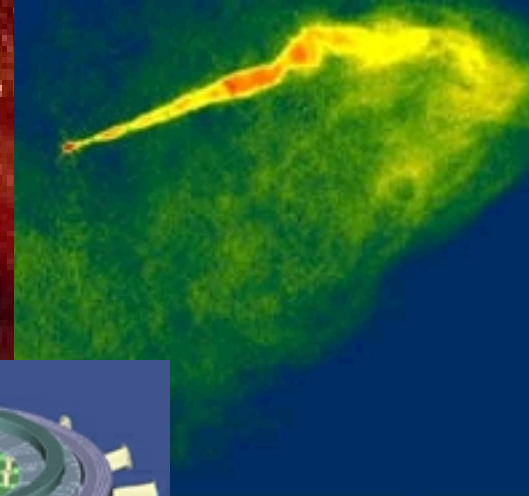


Laboratories to Explore the Frontiers of Plasma Science



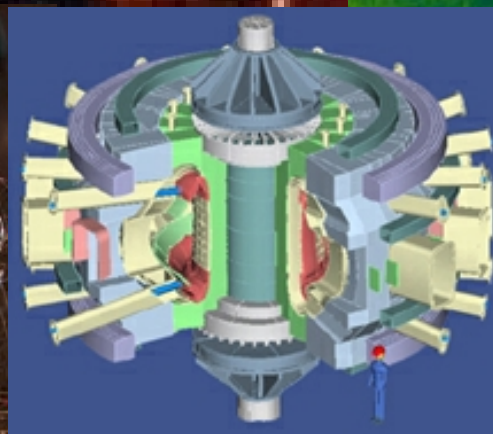
CHANDRA



VLBA



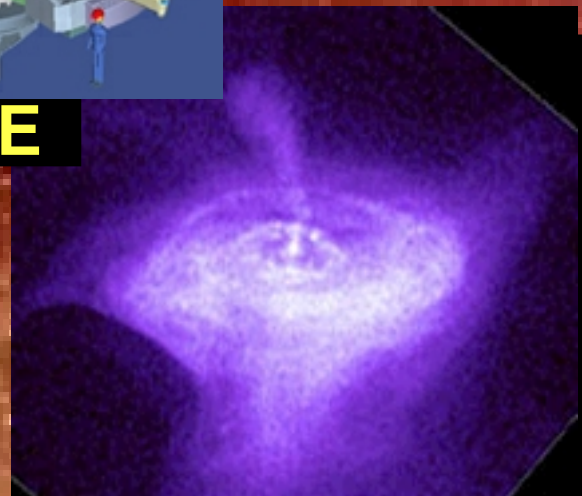
NIF



FIRE



HST



CHANDRA

Fusion Ignition Research Experiment (FIRE)

A Next Step Option for Magnetic Fusion Research

Dale M. Meade
National FIRE Design Study Team

Office of Fusion Energy Science, DOE
Germantown, MD

December 9, 1999

<http://fire.pppl.gov>

FIRE

Fusion Ignition Research Experiment



Contributors to the FIRE Design Study

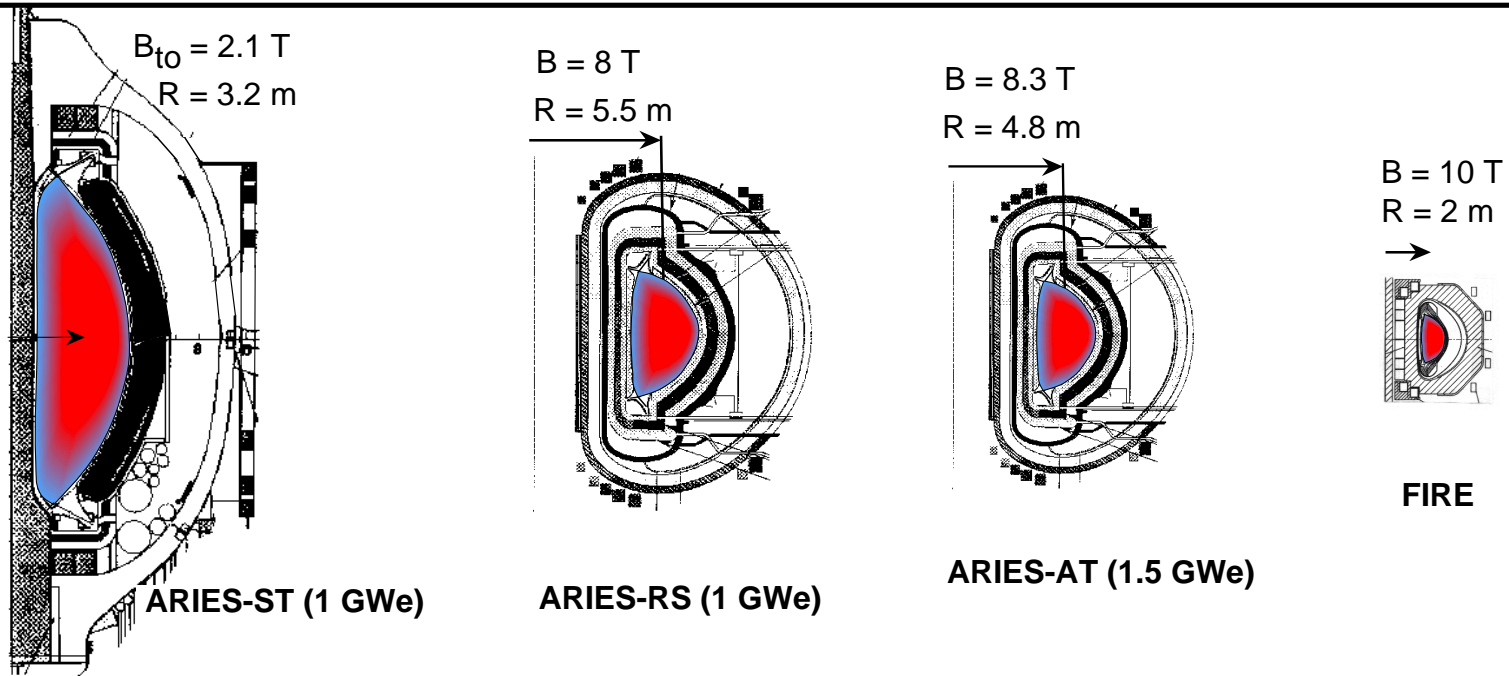
FIRE is a design study for a major Next Step Option in magnetic fusion and is carried out through the Virtual Laboratory for Technology. FIRE has benefited from the prior design and R&D activities on BPX, TPX and ITER.

**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**

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.”

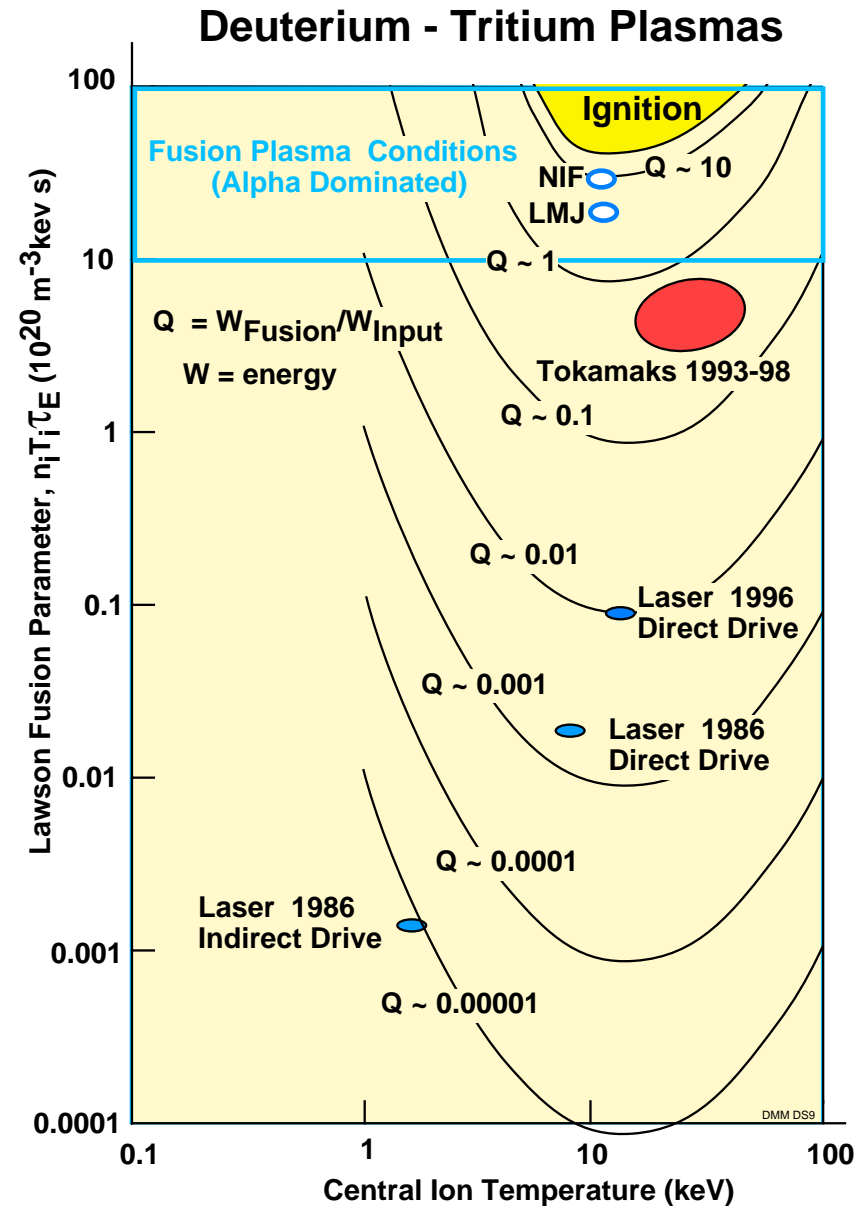
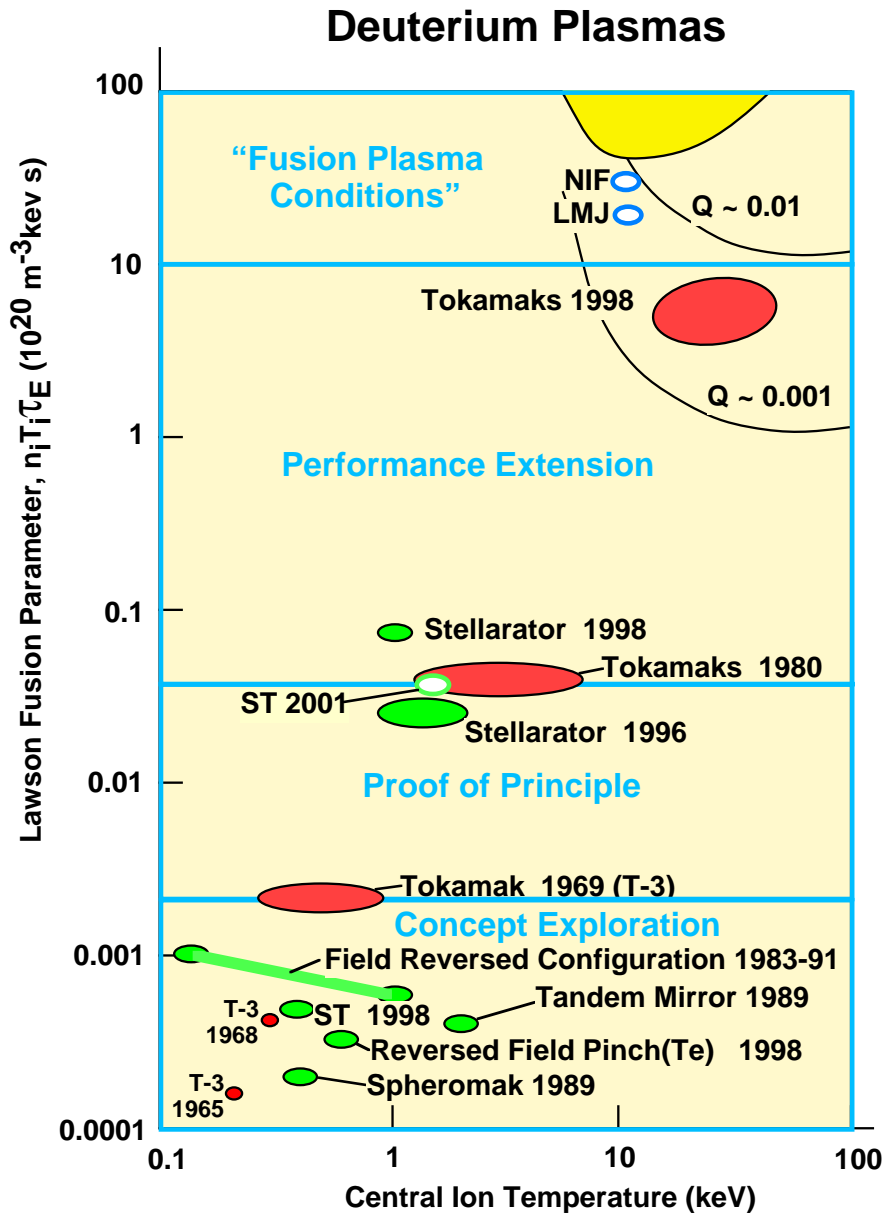
The Tokamak is the Most Advanced Magnetic Configuration, and has the Potential to be an Attractive Fusion Reactor



Fusion Metrics	ARIES-ST	ARIES-RS	ARIES-AT*	FIRE
Plasma Volume (m ³)	810	350	220	18
Plasma Surface (m ²)	580	440	320	60
Plasma Current (MA)	30	11	13	6.5
Fusion Power (MW)	3000	2200	2600	200
Fusion Power Density(MW/m ³)	3.7	6.2	12	12
Neutron Wall Load (MW/m ²)	4	4	6.4	3
COE Projected (mils/kWh)	81	76	≈50	

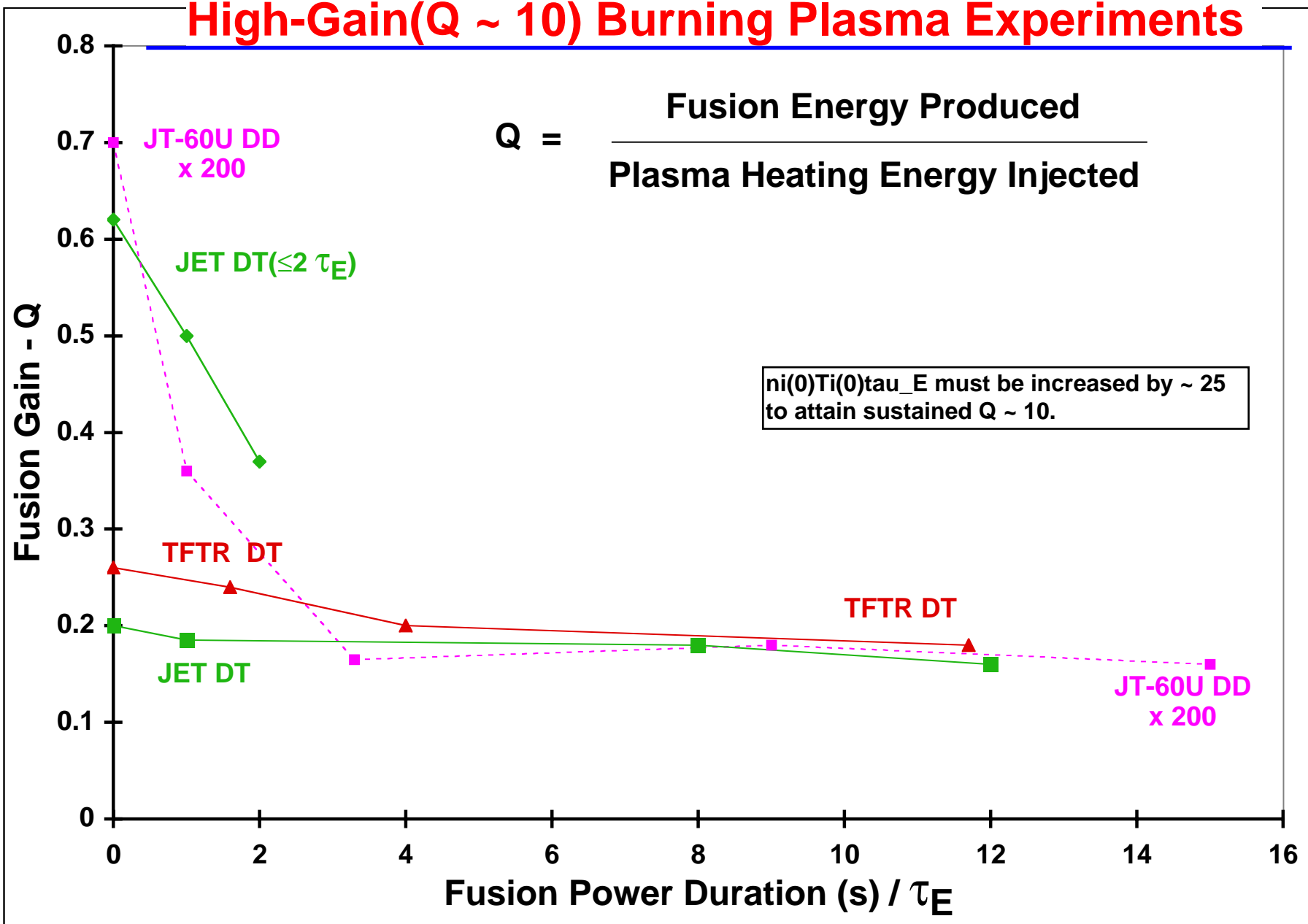
* preliminary result

Only the Tokamak is Technically Ready for a High-Gain Test.



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 fusion plasma and self-heating issues for magnetic fusion.

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



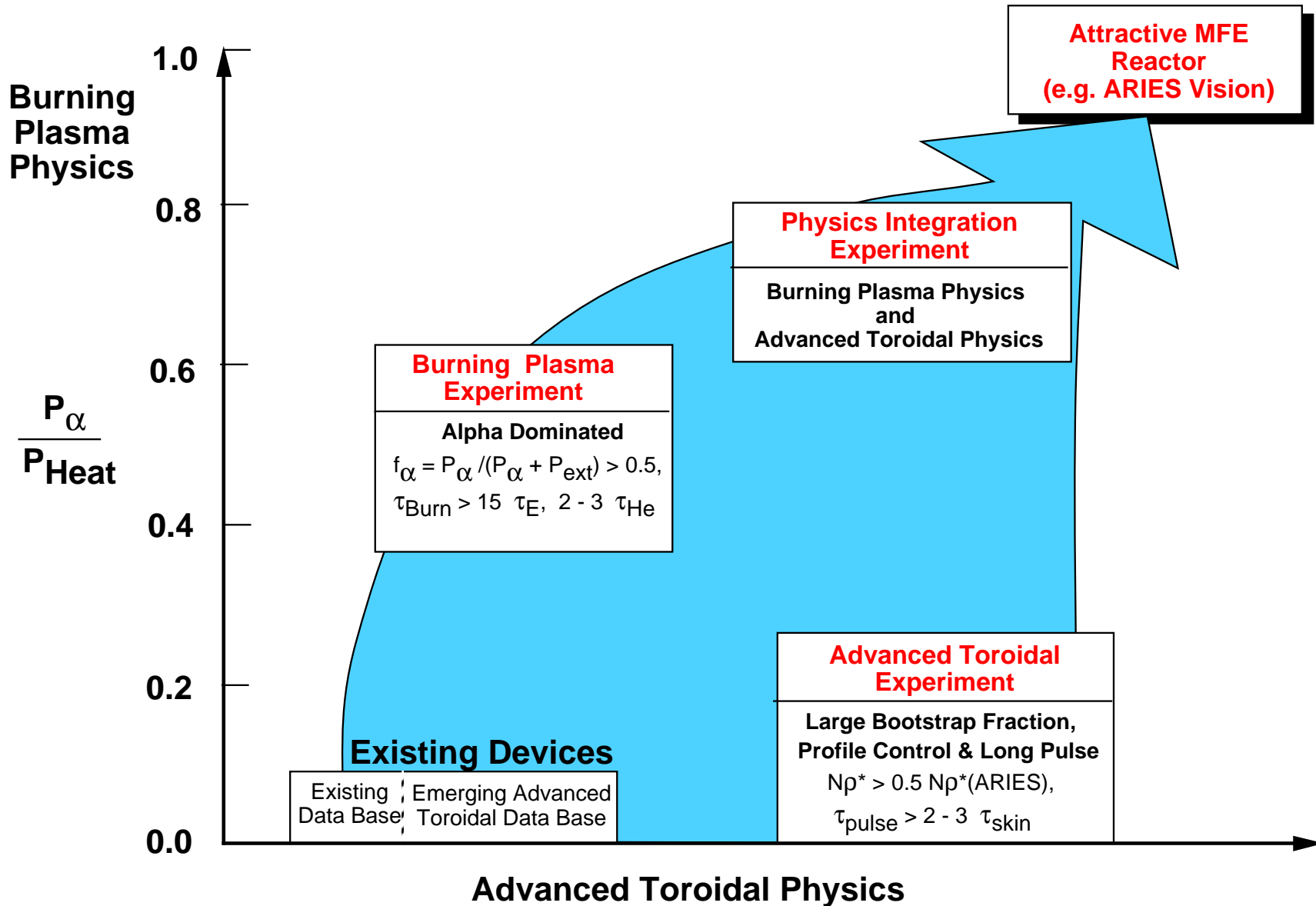
MFE Experimental Facilities are Needed to Investigate Plasma Science at Fusion Conditions

		Magnetic Fusion	Inertial Fusion
↑		(DEMO) (ITER-RC)	(DEMO) (ETF)
Science Steps	Fusion Plasma Conditions	(FIRE, IGNITOR)	NIF*, LMJ* (X-1)
	Performance Extension	JET, TFTR, JT-60U, DIII-D, C-Mod, AUG, LHD, W-7X*	Omega-U, NOVA, GEKKO 12, Vulcan, Russian Z
	Proof of Principle	PLT, DIII, PBX, TFR, Asdex, 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

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



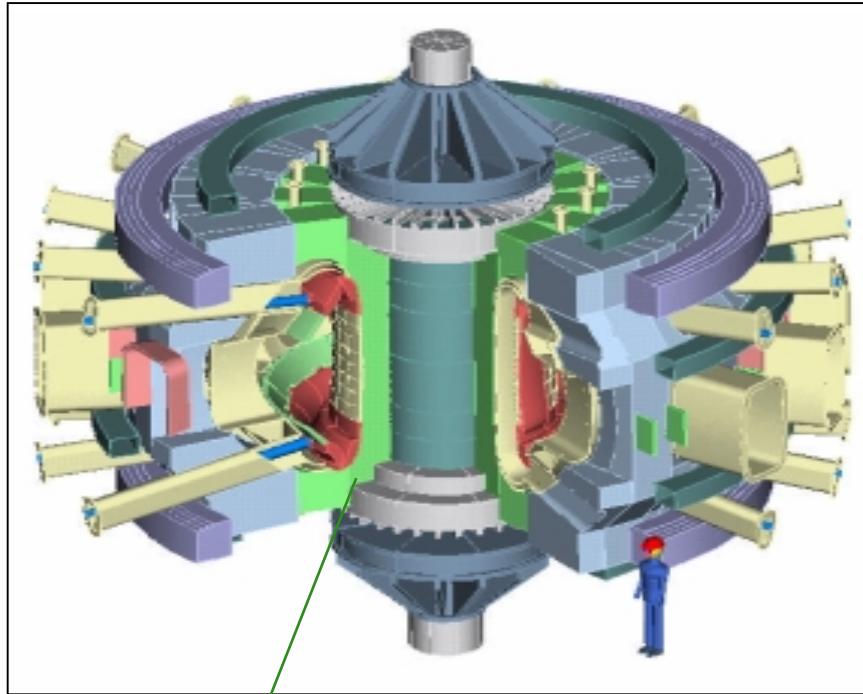
The “Old Paradigm” required three separate devices, the “New Paradigm” utilizes one facility operating in three modes or phases.

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)



LN BeCu ("HTS")

Design Goals

- $R = 2.0 \text{ m}$, $a = 0.525 \text{ m}$
- $B = 10 \text{ T}$, (12T)*
- $W_{\text{mag}} = 3.8 \text{ GJ}$, (5.5 GJ)*
- $I_p = 6.5 \text{ MA}$, (7.7 MA)*
- $P_{\text{fusion}} \sim 220 \text{ MW}$
- $Q \sim 10$, $\tau_E \sim 0.55\text{s}$
- Burn Time = 21s (12s)*
- Tokamak Cost $\leq \$0.3\text{B}$
Base Project Cost $\leq \$1\text{B}$

* Higher Field Option

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
κ_{95} , elongation at 95% flux surface	~1.8
δ_{95} , triangularity at 95% flux surface	~0.4
q_{95} , 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
I_p , plasma current	~6.5 MA (7.7 MA at 12 T)
Magnetic field flat top, burn time	21 s at 10 T, $P_{\text{fusion}} \sim 200$ 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 (≥ 2.5 km/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 I_p
Tritium site inventory	Goal < 30 g, Category 3, Low Hazard Nuclear Facility

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

Flexibility is Critical for the Next Step Facility

- The exploration, understanding and optimization of burning plasma and “long pulse” advanced tokamak physics requires a flexible facility.
- Long-pulse reactor-scale deuterium plasma experiments require remote handling which is also needed for burning plasma experiments.
- FIRE has very many large access ports for diagnostics and heating systems, and the capability to add new systems as they are developed. A comprehensive diagnostic complement has been identified and initial port assignments have been made.
- The scale of FIRE provides adequate performance while the small size will facilitate modification as the experimental program proceeds.

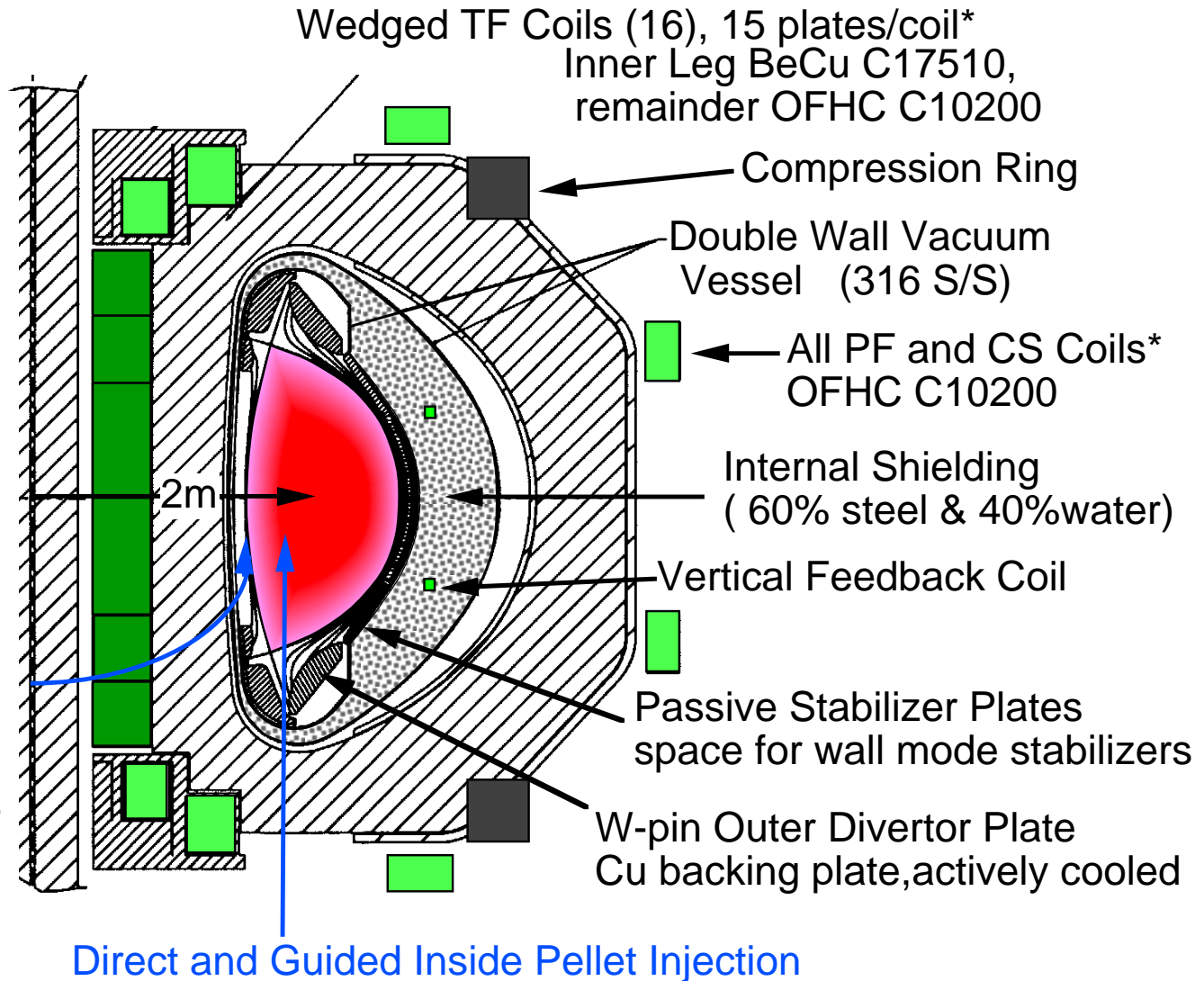
In reality, FIRE also stands for

Flexible Ignition Research Experiment

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.

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>

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

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) - Based on today's tokamak data base

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

Density Limit - Base on today's tokamak data base

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

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

$$P_{\text{th}} \geq (0.9/A_i) n^{0.75} B R^2, \quad \text{nominal L to H, with H to L being } \sim \text{half} \\ \text{when well below the density limit.}$$

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

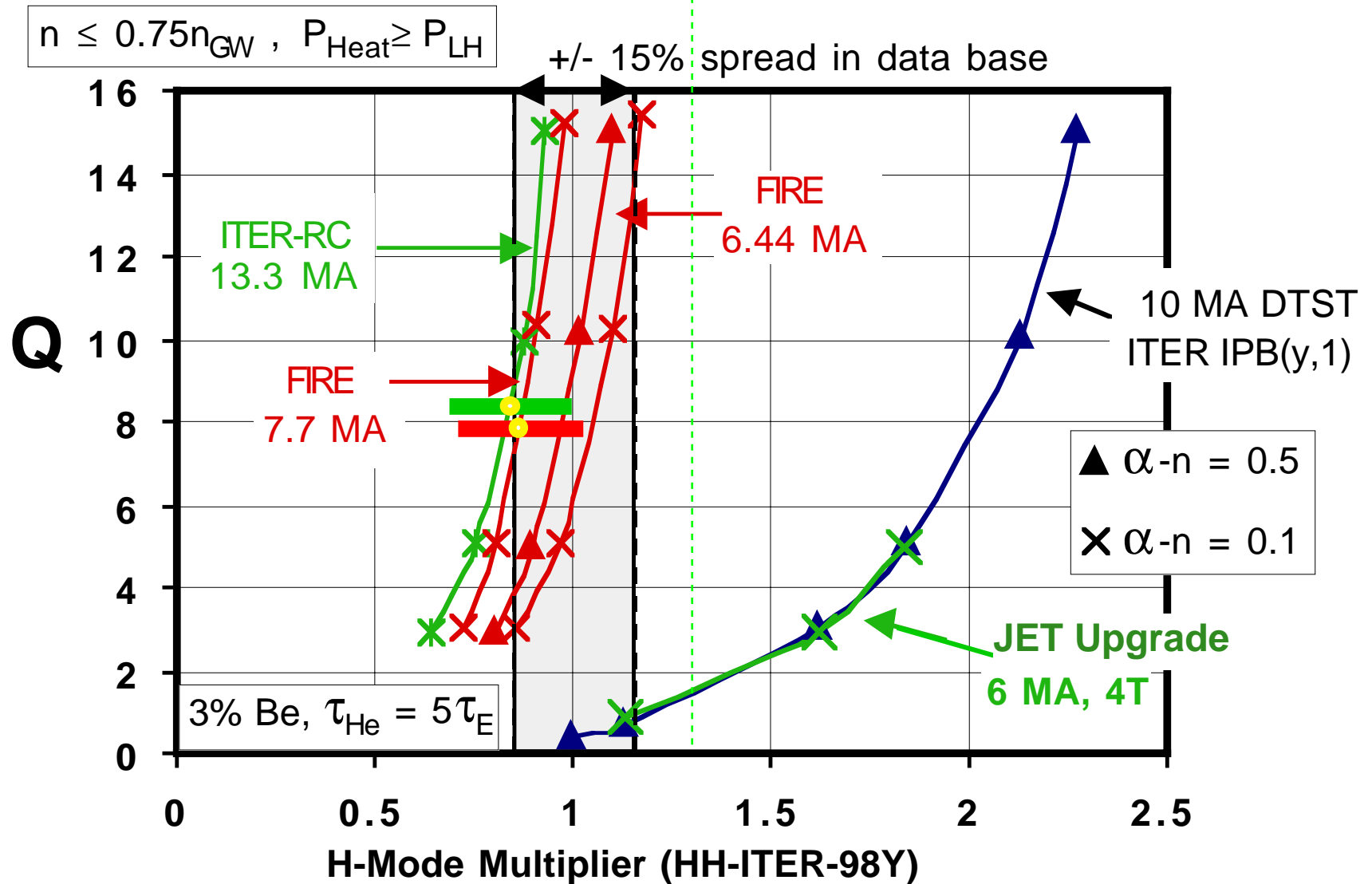
Understanding is mainly empirical. Better understanding is needed from existing experiments with improved simulations, and a benchmark in alpha-dominated fusion plasmas is needed before Fusion Energy Demonstration projects can be constructed.

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
$\langle n_e \rangle$, 10 ²⁰ /m ³ , volume average	4.5
α_n , density profile peaking = 1 + α_n	0.5
$\langle n \rangle / \text{Greenwald Density Limit}, \leq 0.75$	0.70
$\langle T \rangle_n$, 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
Z _{eff}	1.41
v*, 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)τ _E , 10 ²⁰ m ⁻³ keVs	41.69
Q _{DT}	10.16
IA, MA	24.5
Plasma current redistribution time, s	13.9
P_{heat}/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

* ARIES-AT, Q = 45 at HH = 1.3

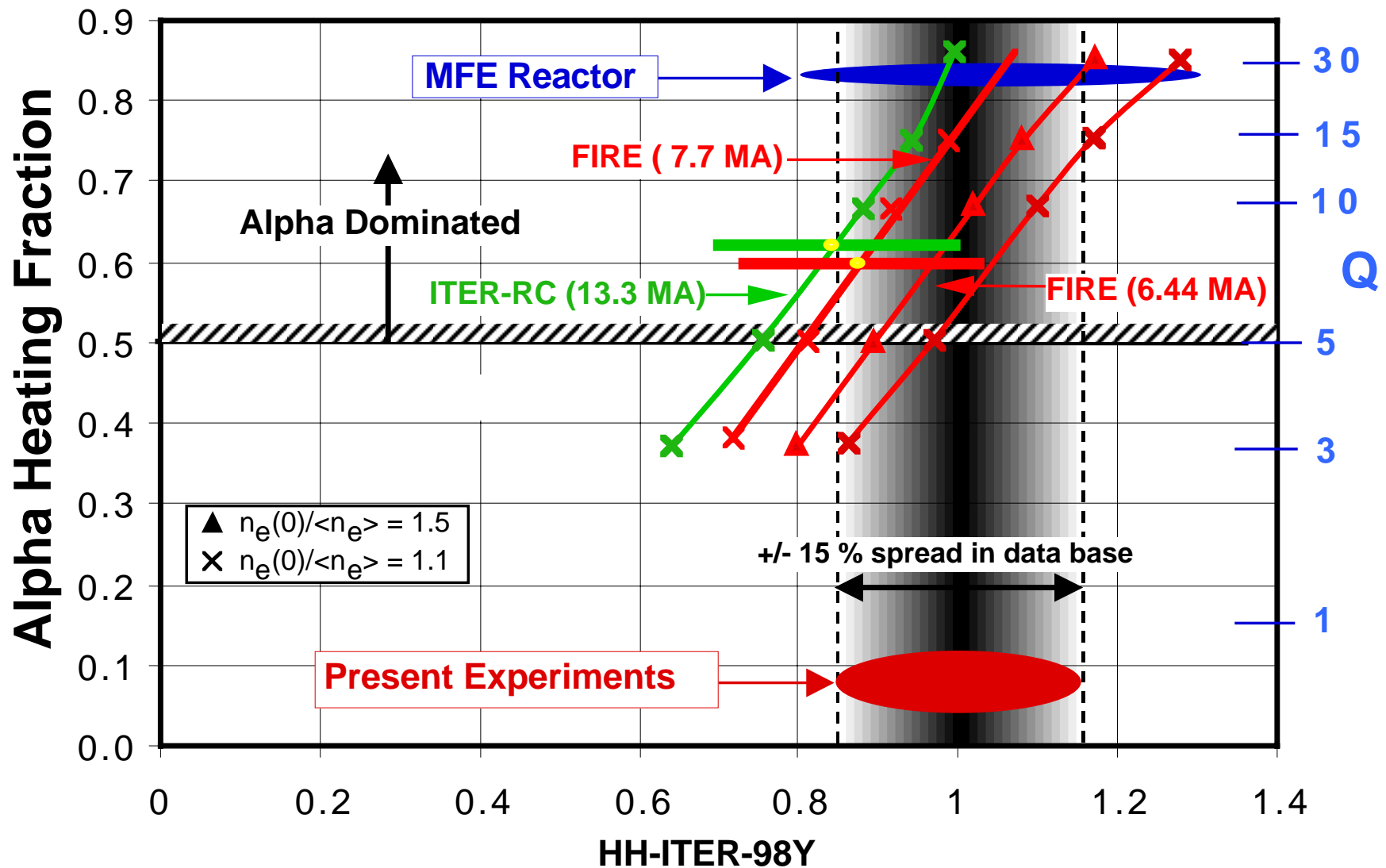
FIRE can Access High Gain in Elmy H-Mode



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

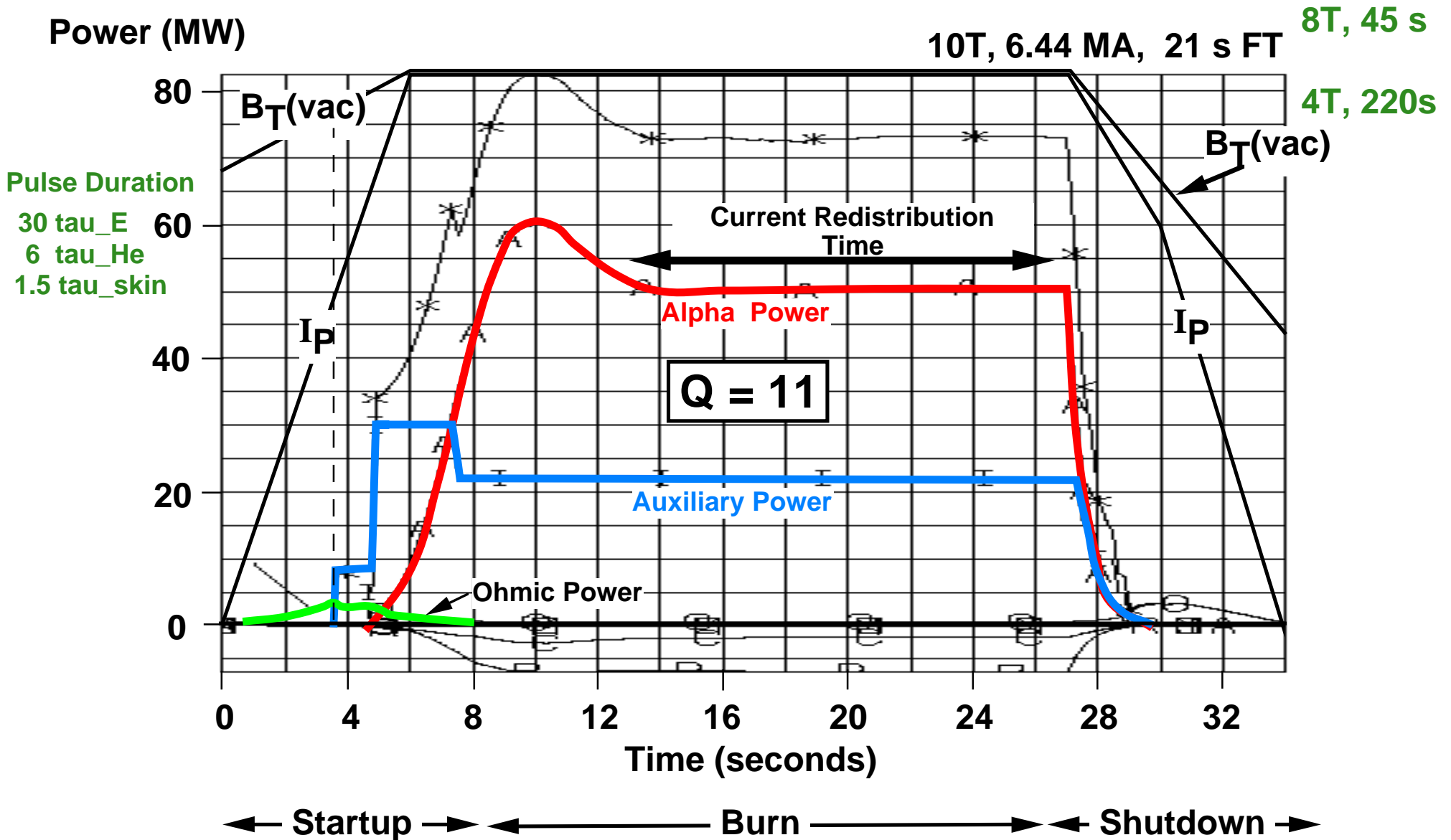
The Energy Mission is vulnerable to uncertainties in confinement.

Confinement Required to Access Alpha-Dominated Plasmas



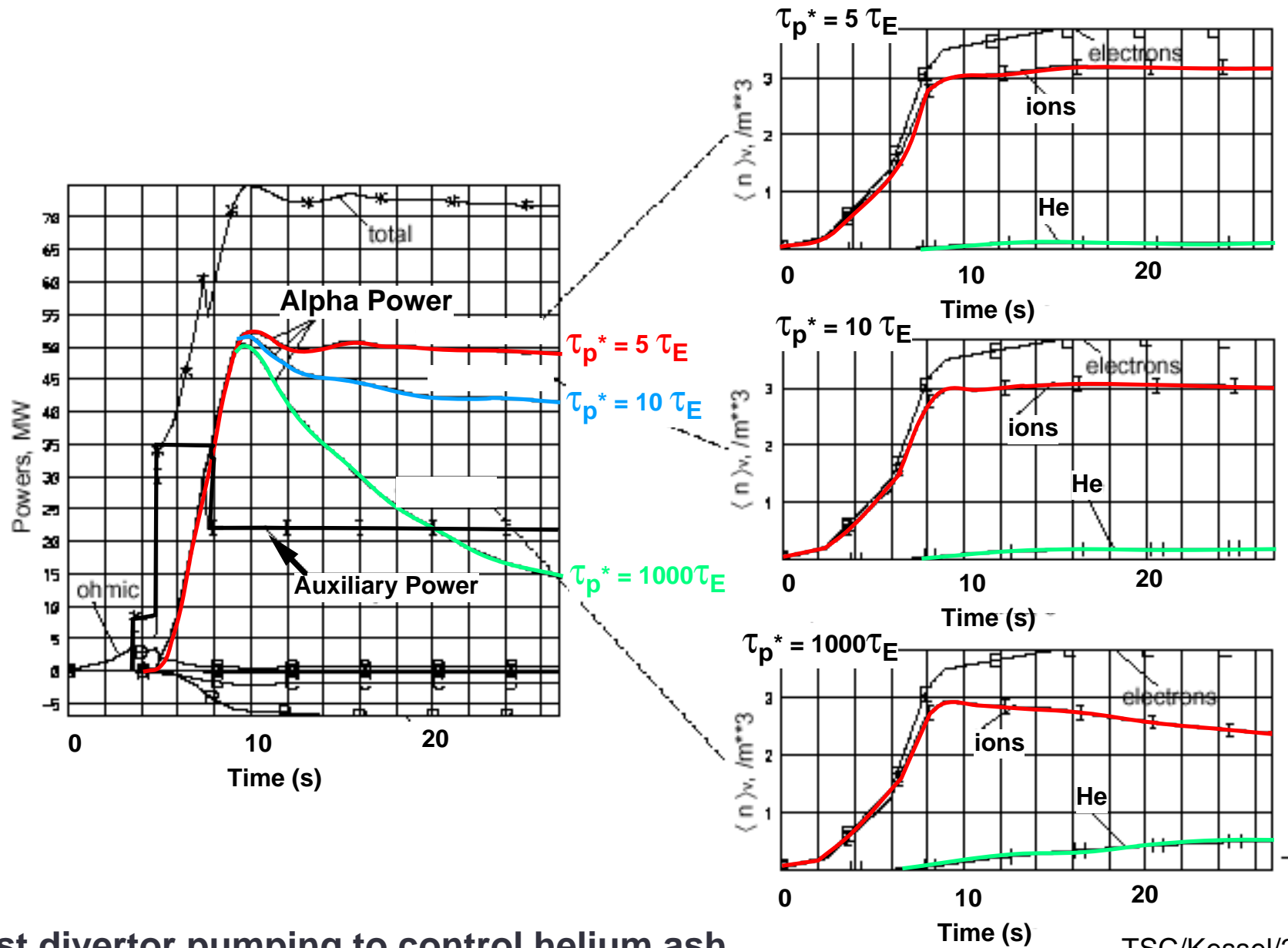
The Science Mission is not vulnerable to uncertainties in confinement.

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/](http://w3.pppl.gov/topdac/)

Helium Ash Accumulation can be Explored on FIRE

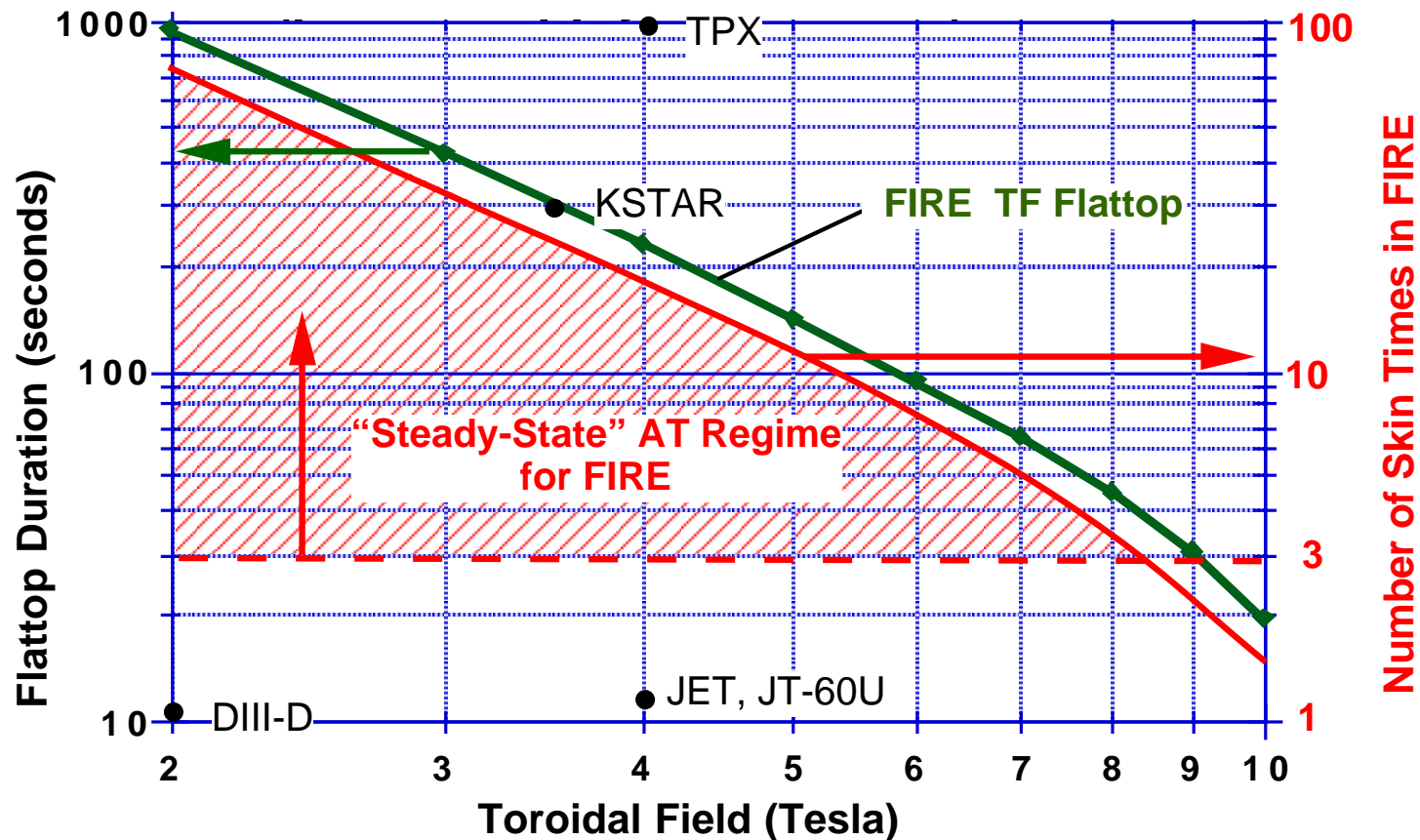


Adjust divertor pumping to control helium ash

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 $\sim 16 \tau_E$ serve as demonstration discharges for initial AT experiments on FIRE. Need to develop self-consistent scenarios with profile control on FIRE with durations $\sim 3 \tau_{\text{skin}}$.

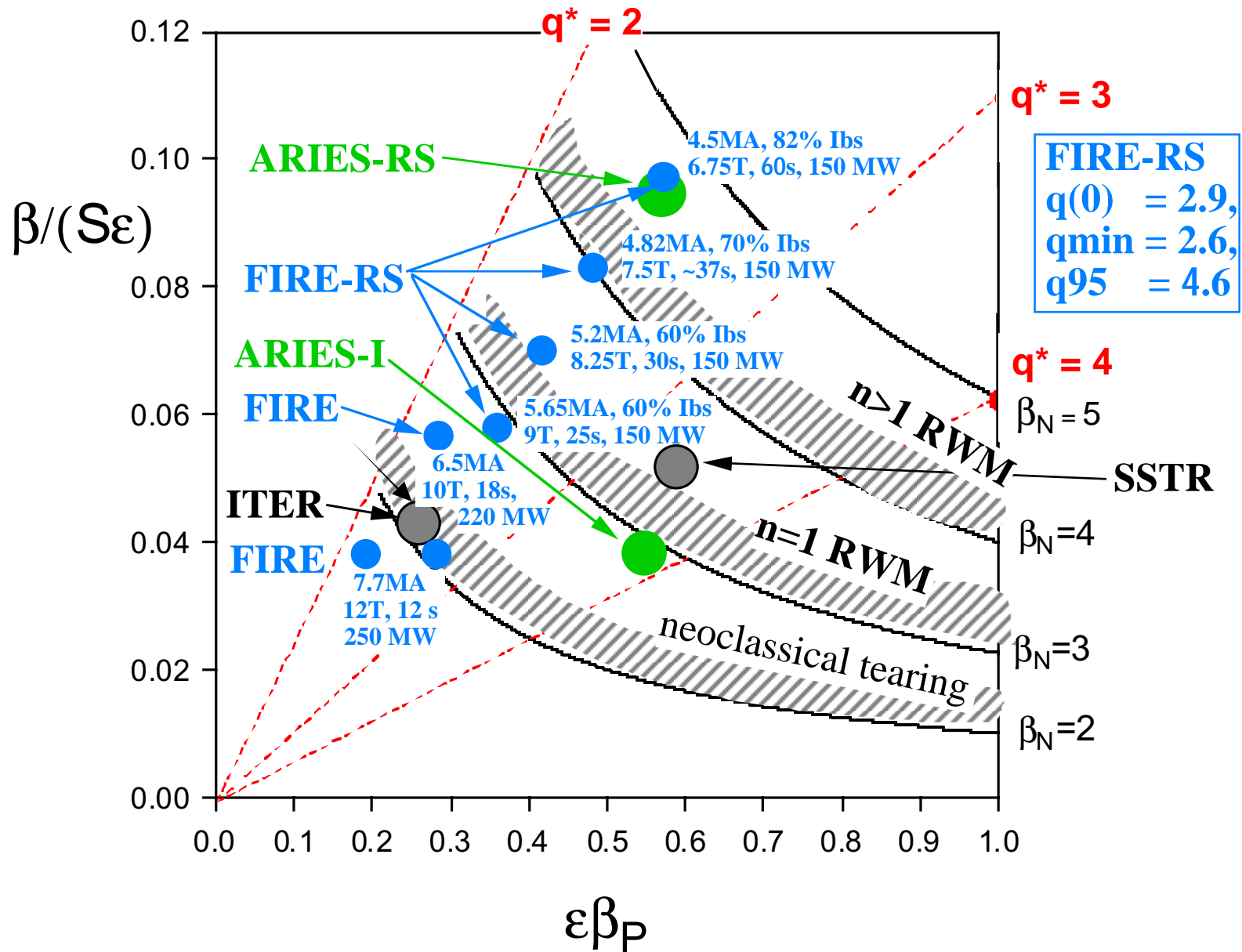
FIRE can Access “Long Pulse” Advanced Tokamak Modes at Reduced Toroidal Field.



Note: FIRE is \approx 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

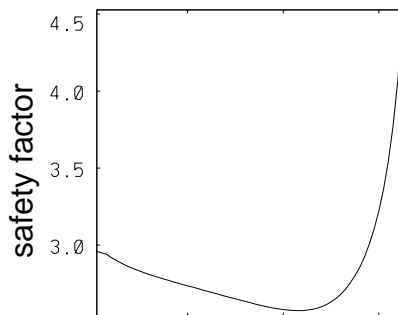
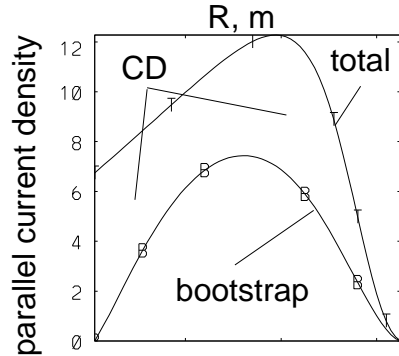
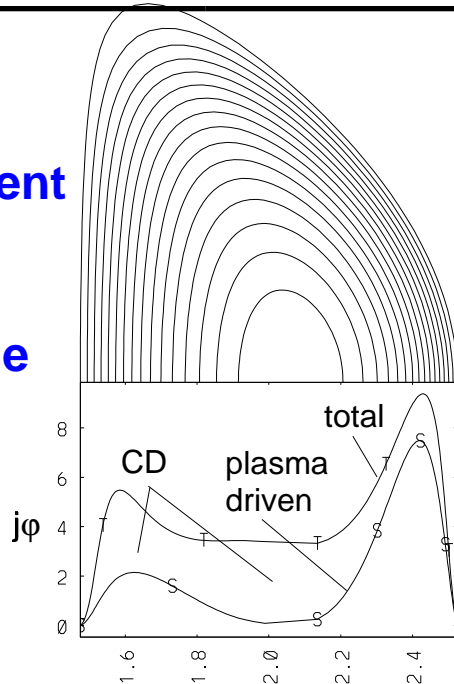
$Q = 10,$
 $HH = 1.2$

or

$Q = 5,$
 $HH = 1.06$

Duration

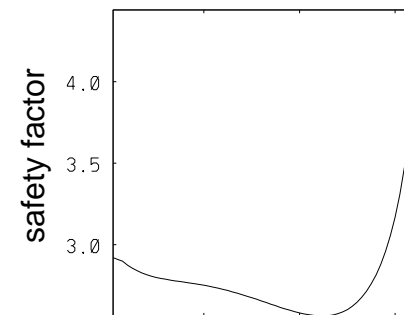
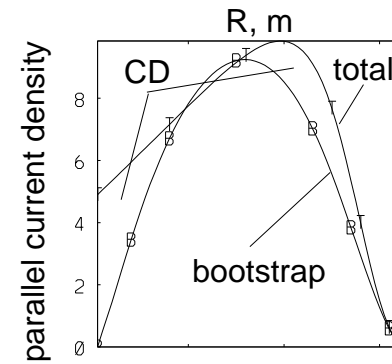
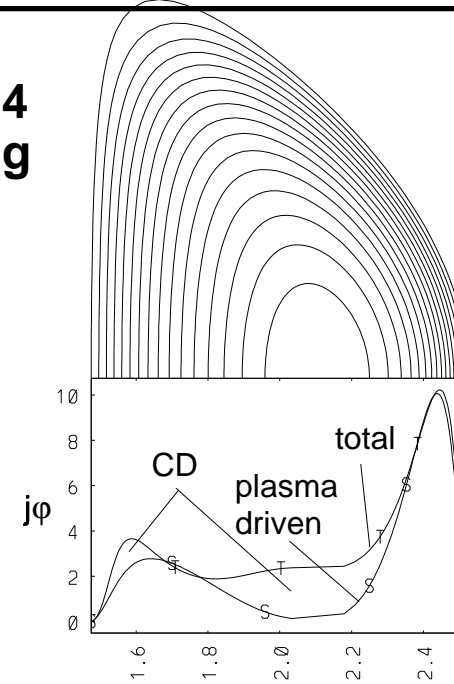
$\sim 2 \tau_{skin}$



Case 1
Modest
AT

30	Flat top(s)	60
5.65	I_p (MA)	4.50
9.00	B_T (T)	6.75
2.90	q_0	2.90
2.60	q_{min}	2.60
1.31	β_p	2.11
2.60	β_N	4.50
3.10	$\beta(\%)$	5.70
0.42	li	0.39
0.50	fbs	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

Case 4
Strong
AT



Confinement
Required
to access
this regime

$Q = 10,$
 $HH = 1.56$

or

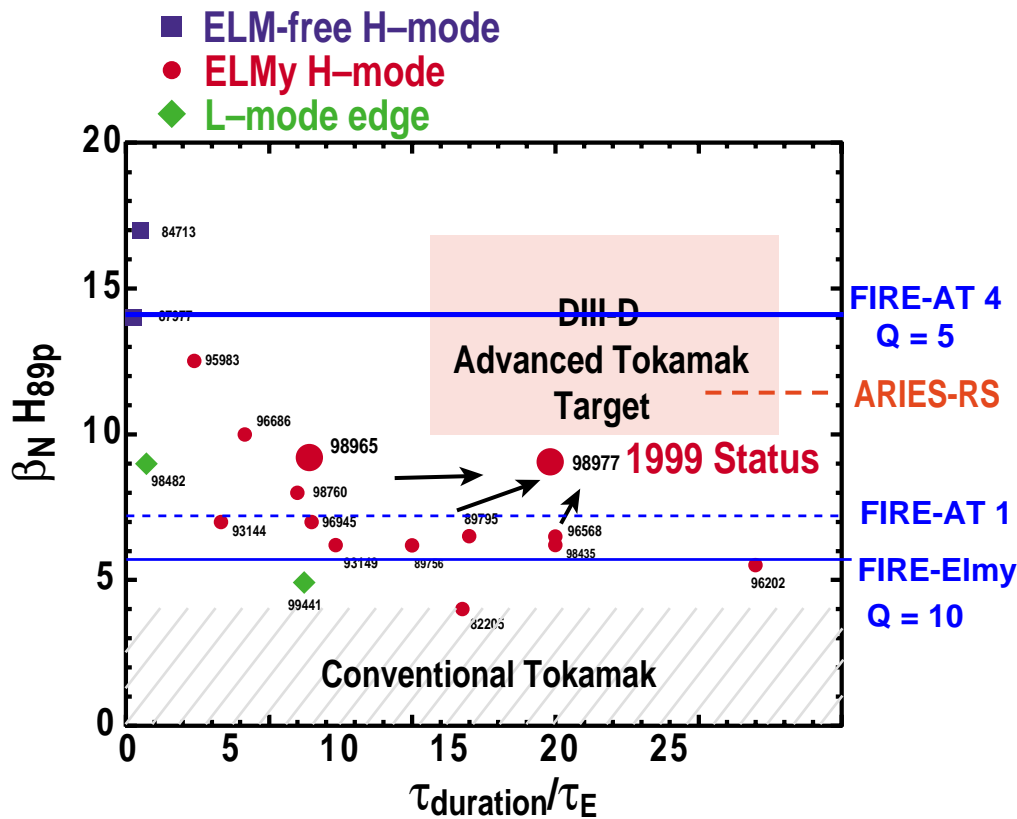
$Q = 5,$
 $HH = 1.36$

Duration

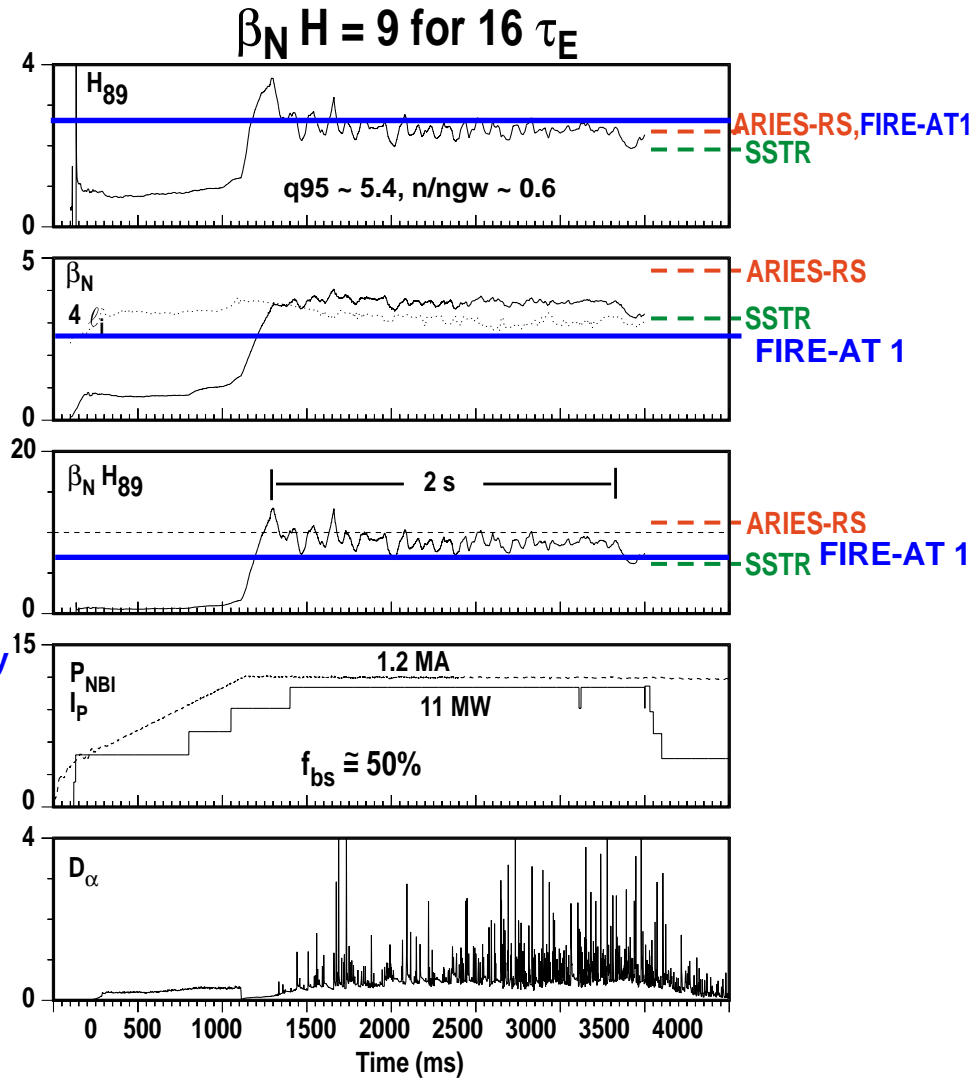
$\sim 4 \tau_{skin}$

The transport calculations assumed 150 MW of fusion power and $n(0)/\langle n \rangle = 1.5$.

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

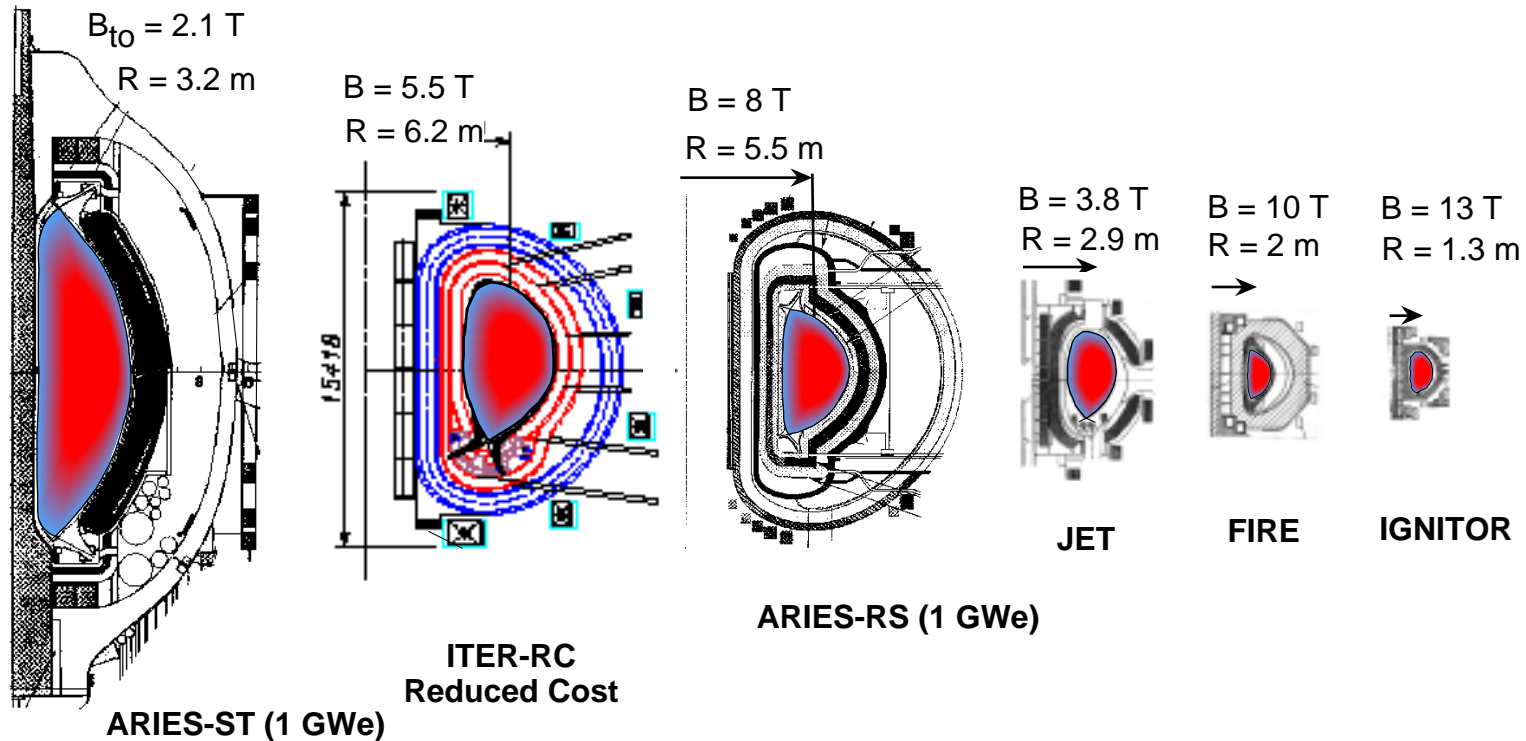


FIRE-Elmy is conventional Elmy H-Mode
 FIRE-AT 1 is modest AT with 50% fbs and $\beta_N = 2.6$
 FIRE-AT 4 is strong AT with 82% fbs and $\beta_N = 4.5$



DIII-D shot 98977 is close to a Demonstration Discharge for FIRE-AT 1
 FIRE-AT 1 requires $q_{95} = 4.5, n/ngw = 0.65, \beta_N H_{89} = 7.1$, and
 produces $f_{bs} = 50\%$ and $Q = 10$ ($P_{\text{fusion}} = 150 \text{ MW}, P_{\text{in}} = 15 \text{ MW}$). This
 mode would be useful for quasi-steady experiments ~ 2 skin times.

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)	810	740	350	95	18	11
Plasma Surface (m^2)	580	640	440	150	60	36
Plasma Current (MA)	28	13	11	4	6.5	12
Magnet Energy (GJ)	29	50	85	2	5	5
Fusion Power (MW)	3000	400	2200	16	200	100
Burn Duration (s)	steady	400	steady	1	20	5

A high-field tokamak with copper coils leads to a much smaller (i. e. cheaper) high-gain burning plasma experiment than one with superconducting coils.

Cost Background for FIRE

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

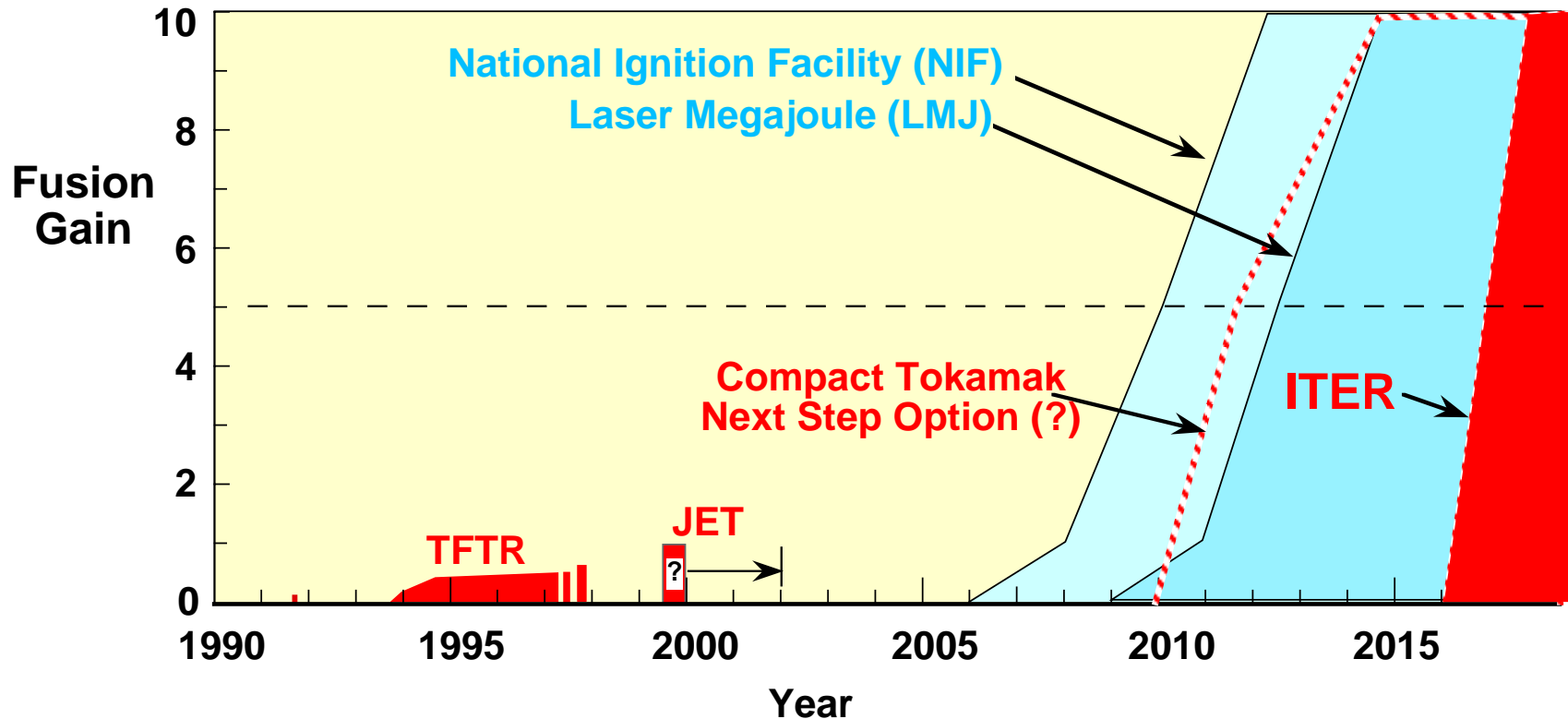
Water Cooled Coils	B(T)	R(m)	Coil Energy (GJ)	Const. Cost
TFTR (1983), US	5.2	2.5	1.5	\$498M
JET (1984), Europe	3.4	2.96	1.4	~\$600M
JT-60 (1984), Japan	4.4	3.2	2.9	~\$1000M
FIRE*, US	10	2.0	3.8	(< \$1000M)

* 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)

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

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?
 - 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 tokamaks and the physics required for the ARIES vision of magnetic fusion energy. FIRE is the “Goldilocks” approach.
- A dual track plan 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.