Fusion Ignition Research Experiment (FIRE)

Dale M. Meade
National FIRE Design Study Team

American Physical Society, Division of Plasma Physics
Seattle, WA

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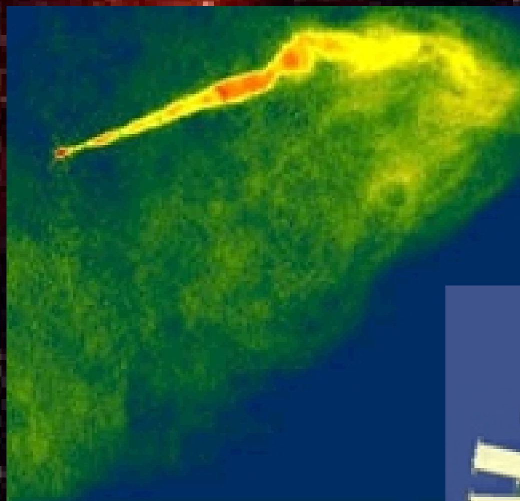
http://fire.pppl.gov

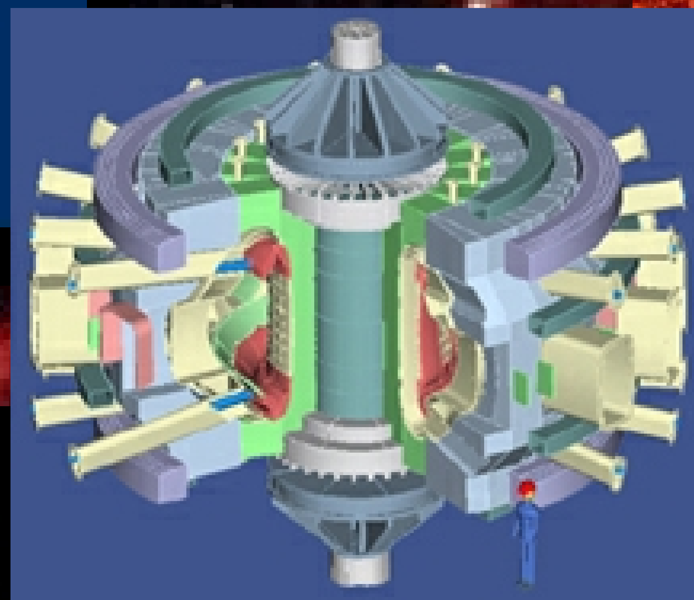
FIRE Fusion Ignition Research Experiment

Laboratories to Explore the Frontiers of Science



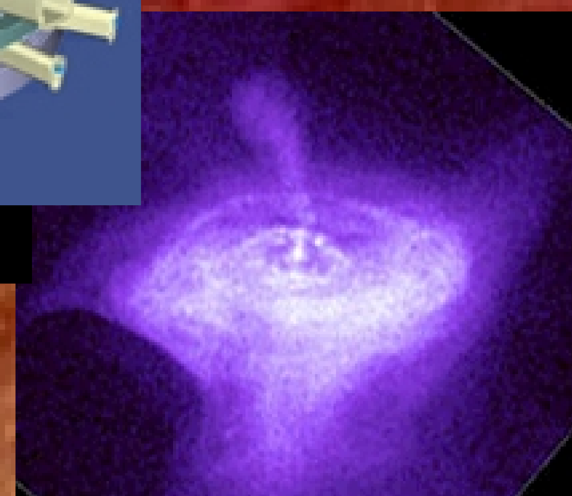
VLBA

CHANDRA



FIRE

HST



CHANDRA

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

Critical Magnetic Fusion Science Issues Must be Resolved

- Significant progress has been made in addressing the key issues of fusion, but critical issues remain to be resolved. The National Research Council Fusion Science Assessment Committee Interim Report has identified several critical unresolved fusion science issues:
  - Turbulence and transport
  - Energy density limits
  - Integrated physics of self-heated plasmas
- In addition, there are numerous critical technology issues such as:
  - Materials and technology for high heat and neutron flux
  - Maintainable and reliable systems
  - Economic and environmental attractiveness
- **How can we resolve the critical issues of magnetic fusion?**

(The NRC Interim Report and the SEAB Report on fusion are at http://fire.pppl.gov)

An Affordable Next Step Magnetic Fusion Experiment is Needed.

……A necessary next major scientific step is the exploration of the physics of a burning plasma. At the present time, only the tokamak is sufficiently advanced as to assure the necessary confinement in such an experiment. But some estimates indicate that such a device would cost in excess of $1 billion. Given the cost, it is not practical to construct a variety of large-scale machines using different concepts to explore this scientific frontier. Thus, the program confronts a management and technical challenge in undertaking the study of burning plasmas – which necessarily involves a major investment in one particular confinement approach (probably a tokamak) – while not prematurely foreclosing less mature confinement approaches that may ultimately offer a better path to a practical fusion energy source……

…..There is general agreement that the next large machine should, at the least, be one that allows the scientific exploration of burning plasmas. Given the anticipated cost of such a venture, the case for international collaboration in its construction is strong. Thus, although the difficulties in siting a multi-billion dollar project are substantial, avenues for international long-range planning for instruments of this scale must be explored…….

…..If they [Japan and Europe] decide to go forward [with ITER-RC], the U.S. should seek to participate in some fashion. If they do not, the U.S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost. The U.S. might seek international collaborators on such a project from the outset, or, if the funding and political circumstances allow, the U.S. might launch the project and invite international collaboration (the LHC model). In any event, however, preliminary planning for such a machine should proceed now so as to allow the prompt pursuit of this option. In order to participate in a burning-plasma experiment while preserving the breadth of the restructured program, the Department and the community should engage the Congress at an early stage………

From the 1999 SEAB Report on Fusion, full report at http://fire.pppl.gov

Burning Plasma Experiments Strongly Endorsed at 1999 Snowmass Fusion Summer Study

1. Burning plasma experiments are essential for the development of fusion.

2. The tokamak is technically ready for a high-gain burning plasma experiment.

3. The US should actively seek* opportunities to explore burning plasma physics by:

   Pursuing burning plasma physics through collaboration on potential international facilities (e.g., JET Upgrade, IGNITOR, and ITER-RC).

   Seeking a partnership position, should ITER construction proceed.

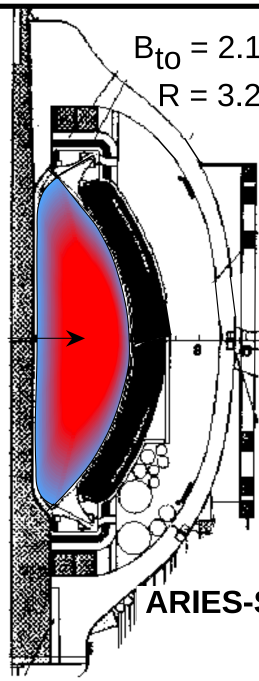
   Continued design studies of moderate cost Burning Plasma (BP) Experiments (e.g., FIRE) capable of exploring advanced regimes.

   Exploiting the capability of existing and upgraded tokamaks to explore and develop advanced operating regimes suitable for BP experiments.

   * one group in MFE endorsed “has exciting..” rather than “actively seek..”.

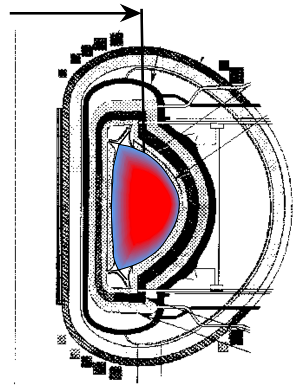
The Tokamak is the Most Advanced Magnetic Configuration, and has the Potential to be an Attractive Fusion Reactor

B_{to} = 2.1 T
R = 3.2 m



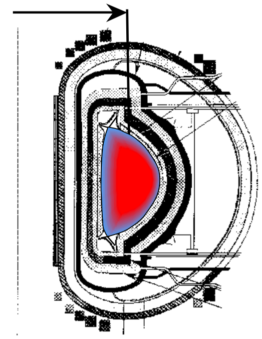
ARIES-ST (1 GWe)

B = 8 T
R = 5.5 m



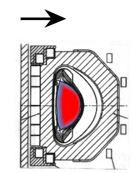
ARIES-RS (1 GWe)

B = 8.3 T
R = 4.8 m



ARIES-AT (1.5 GWe)

B = 10 T
R = 2 m

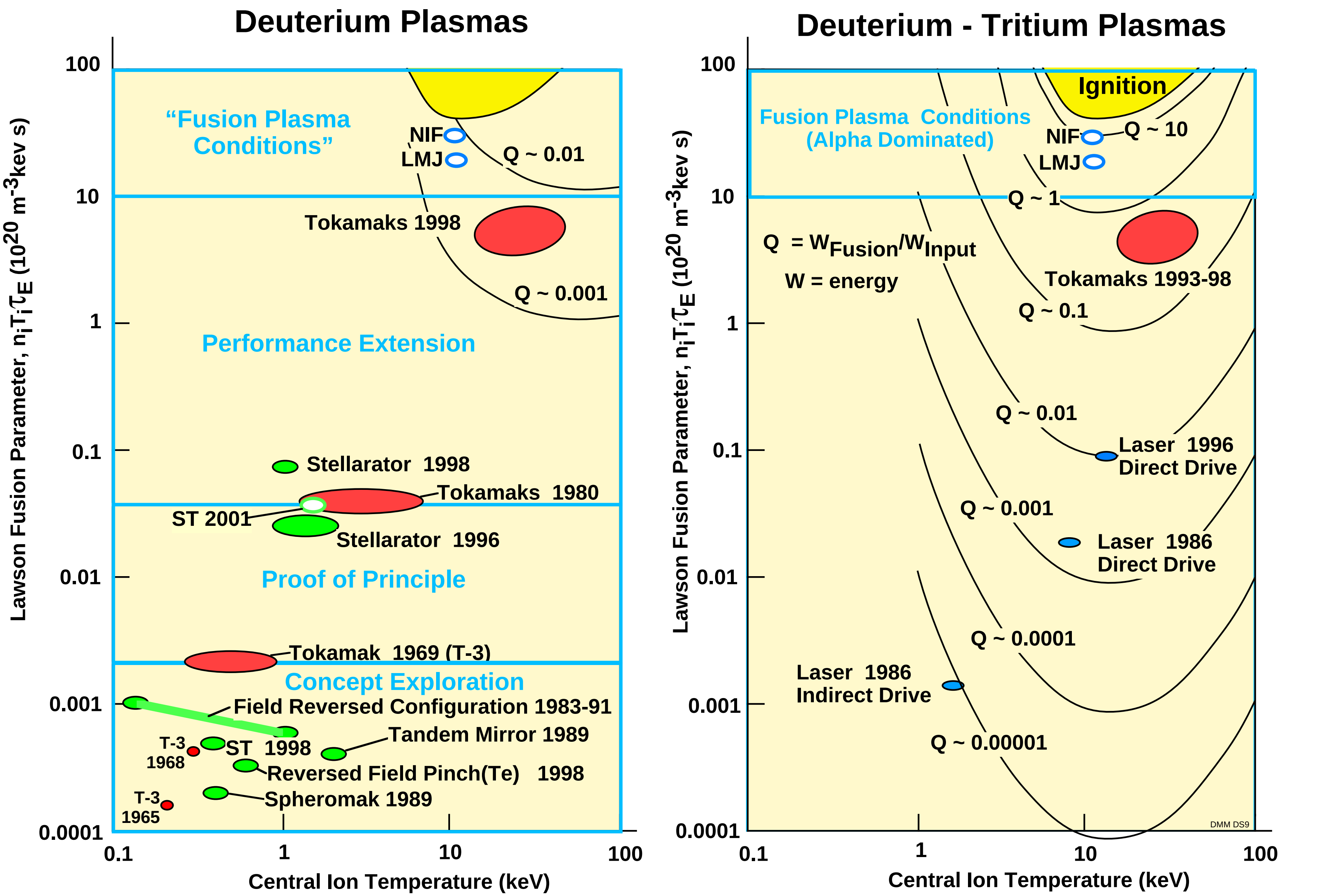


FIRE

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

The Tokamak is Poised to Resolve the Physics Issues for MFE.



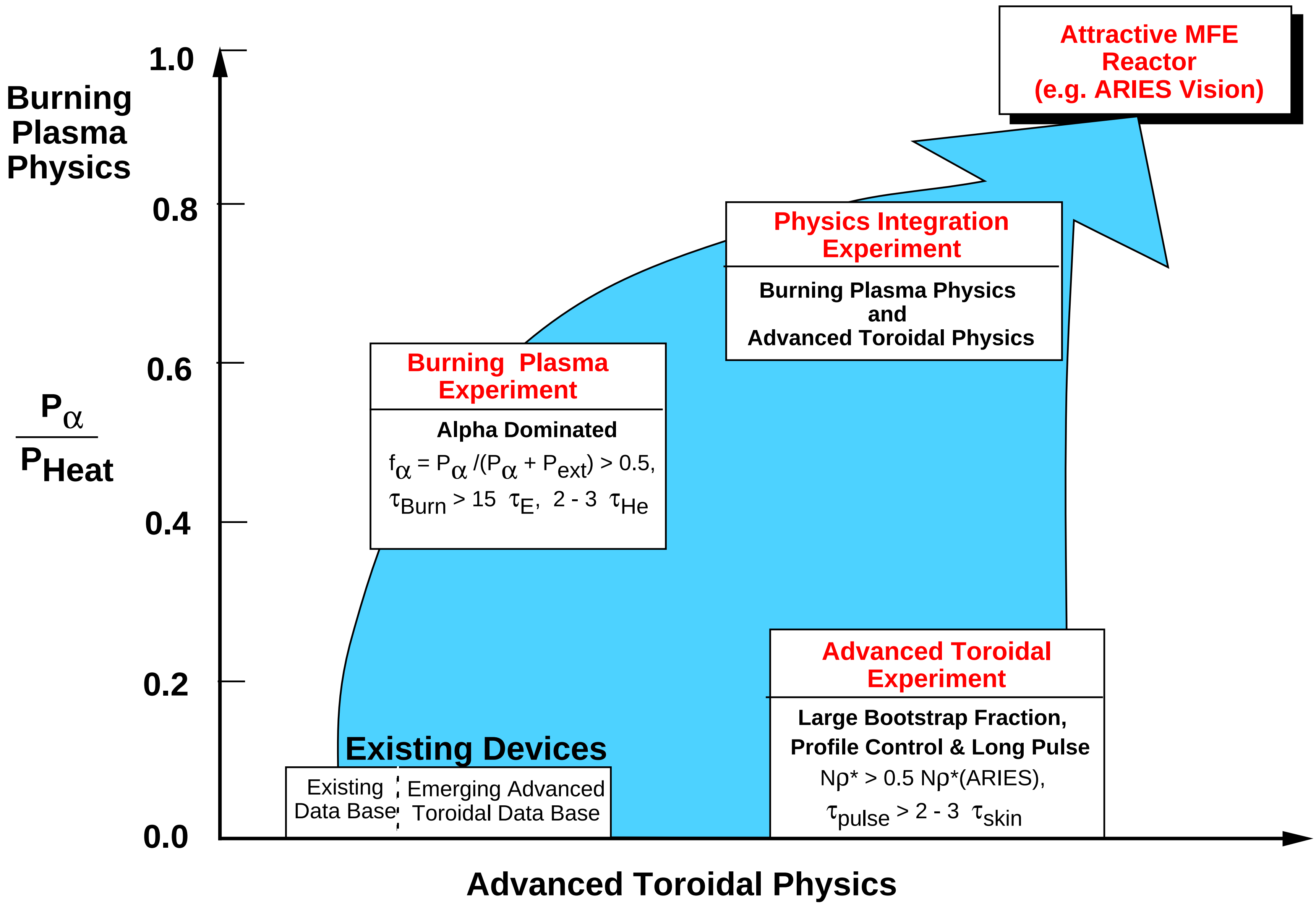
Only the tokamak is sufficiently advanced to permit the design, construction and initiation of a next step burning plasma experiment within the next decade that could address the fusion plasma and self-heating issues for magnetic fusion.

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

Science Steps	Magnetic Fusion	Inertial Fusion
Energy Development	(DEMO) (ITER-RC)	(DEMO) (ETF)
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



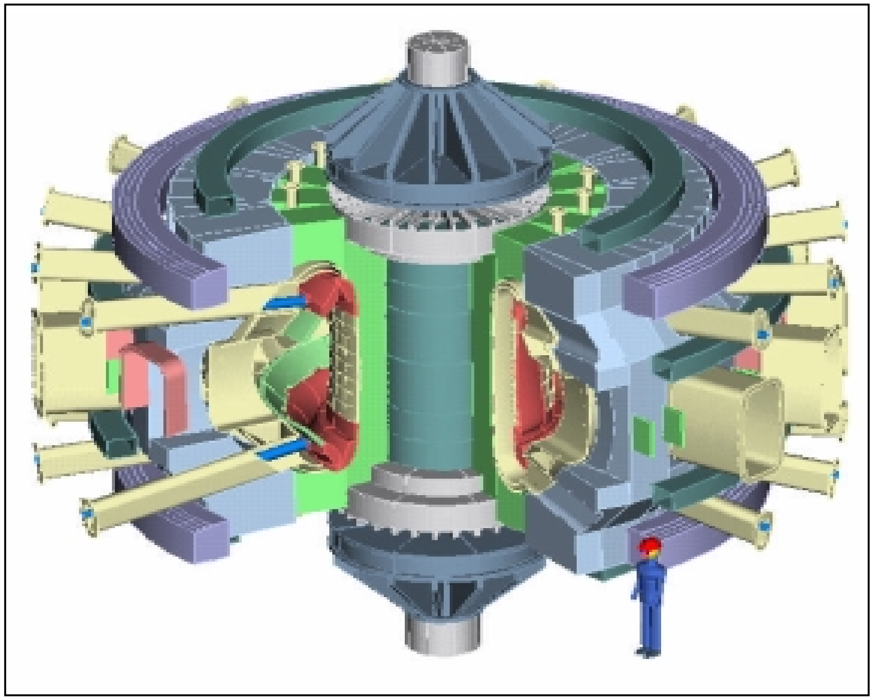
The "Old Paradigm" required three separate devices, the "New Paradigm" utilizes one facility operating in three modes or phases.

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)



Design Goals

- R = 2.0 m, a = 0.525 m
- B = 10 T, (12T)*
- W_{mag}= 3.8 GJ, (5.5 GJ)*
- I_p = 6.5 MA, (7.7 MA)*
- P_{fusion} ~ 220 MW
- Q ~ 10, τ_E ~ 0.55s
- Burn Time $\approx$ 21s (12s)*
- Tokamak Cost ≤ \$0.3B

  Base Project Cost ≤ \$1B

* 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
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	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

Design Option at B = 12T and Ip = 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.

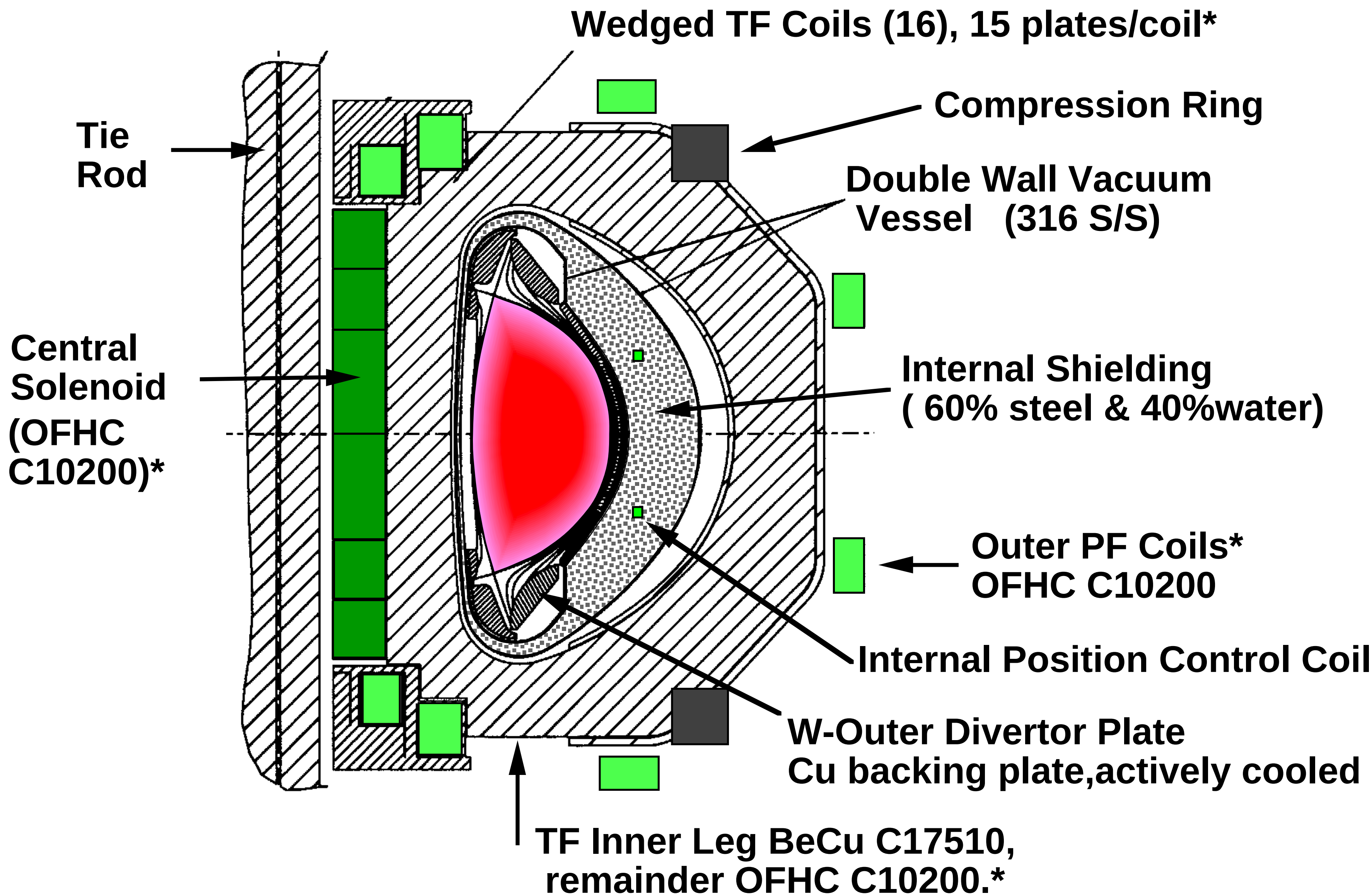
- FIRE has very many large access ports for diagnostics and heating systems, and the capability to add new systems as they are developed. A comprehensive diagnostic complement has been identified and initial port assignments have been made.

- 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 Engineering Features



*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

- Improved coil and plasma facing component materials, improved 3-D engineering computer models and 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

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

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

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

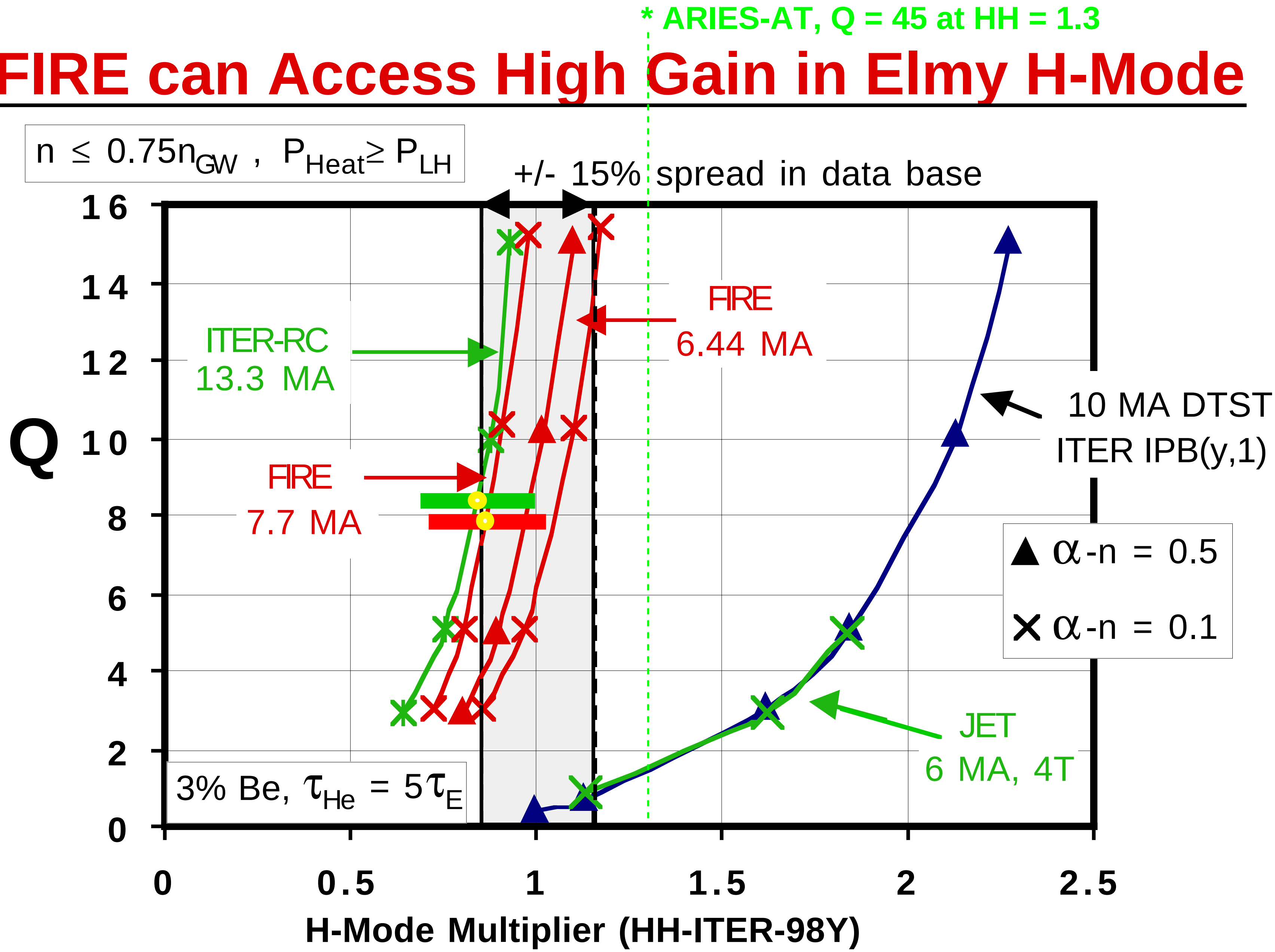
Helium Ash Confinement $\tau_{He} = 5\, \tau_E$, impurities = 3% Be

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

Nominal FIRE Plasma Parameters from 0-D Simulations

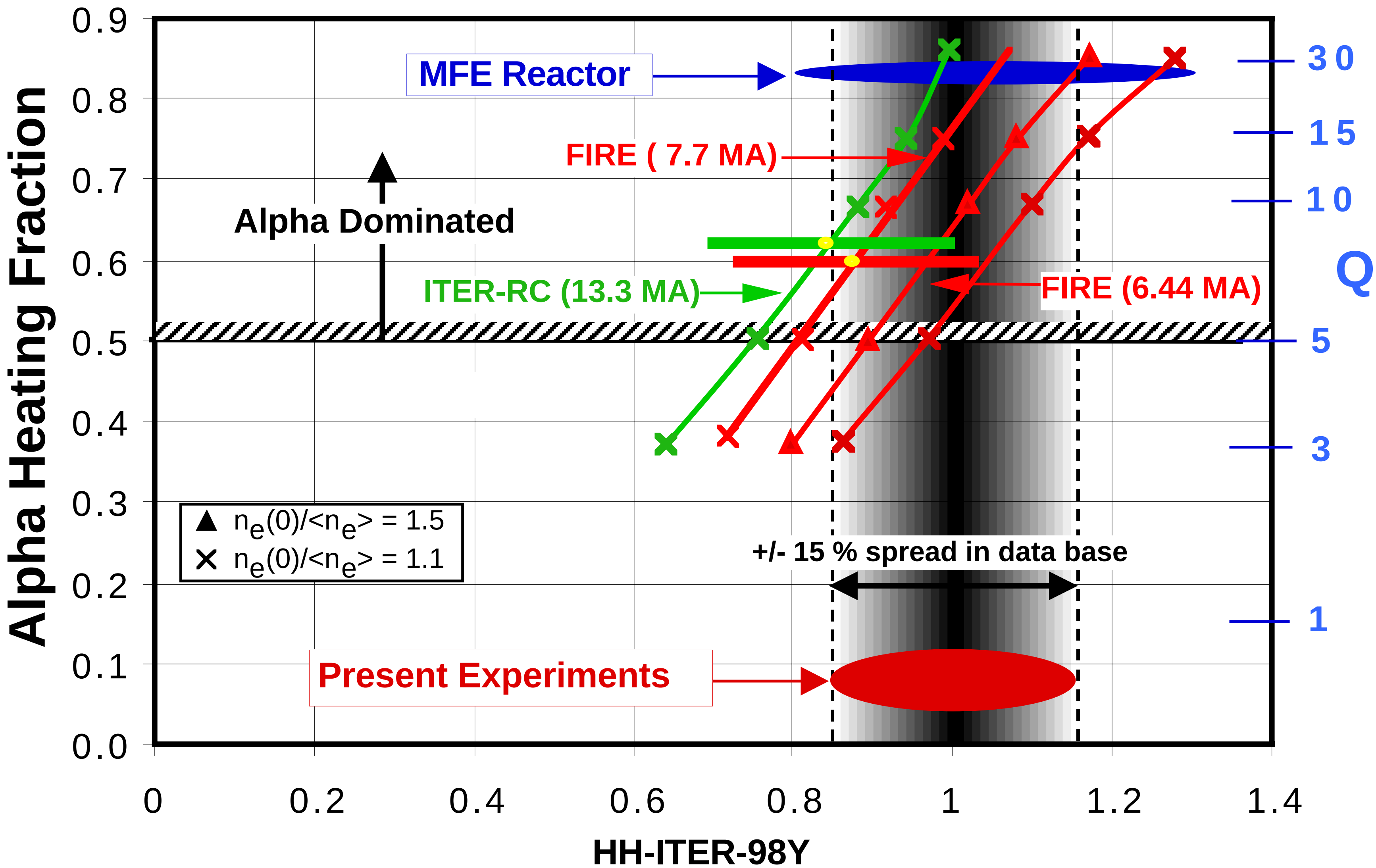
R, plasma major radius, m	2.0
A, plasma minor radius, m	0.525
R/a , aspect ratio	3.8
κ_95, plasma elongation at 95% flux	1.77
δ_95, plasma triangularity at 95% flux	0.4
q_95	3.02
B_t, toroidal magnetic field, T	10
I_p, plasma current, MA	6.44
l_i(3), internal plasma inductance	0.8
Fraction of bootstrap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

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. Modest improvement in confinement would allow access to the ARIES-AT regime.

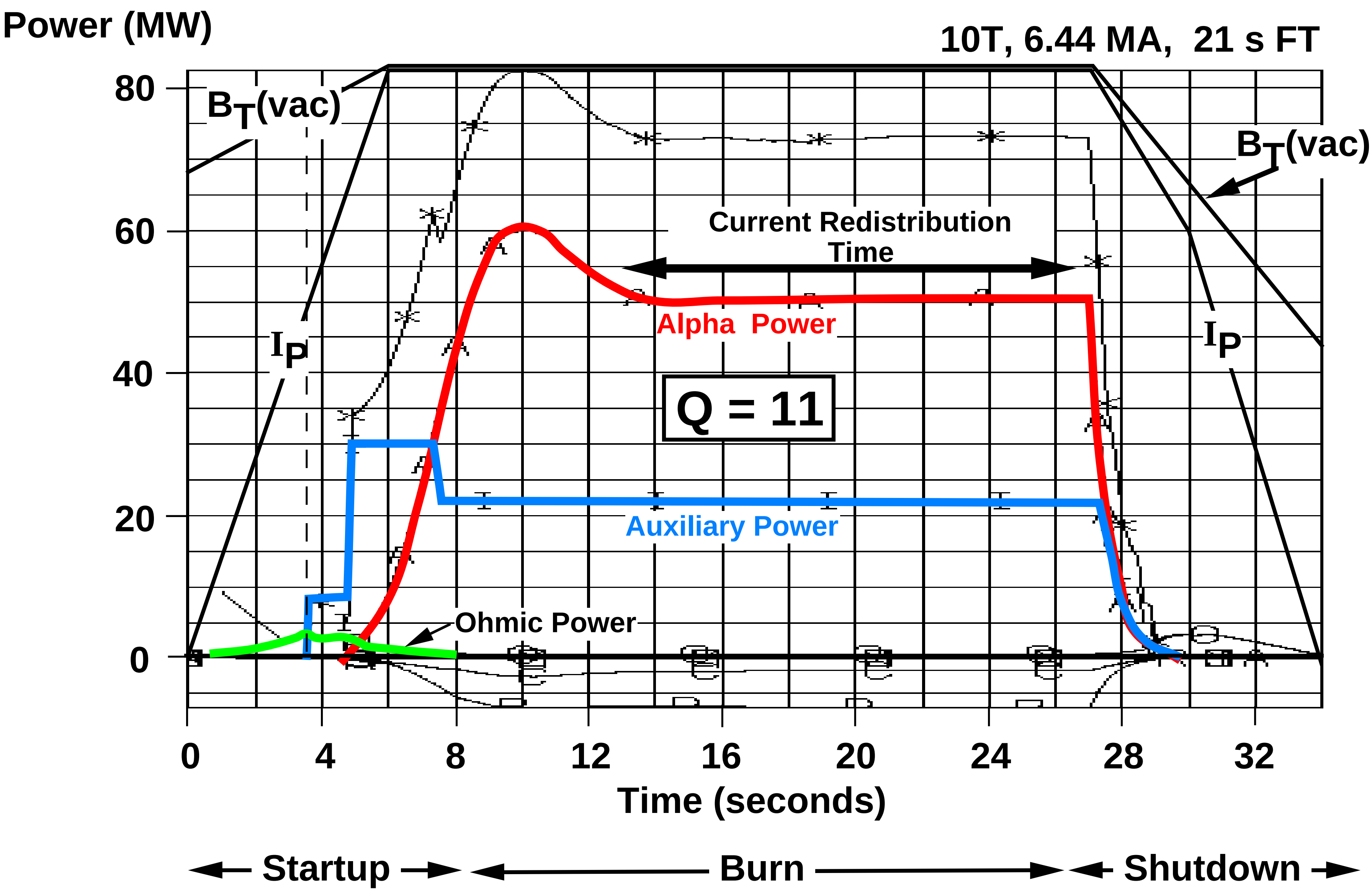
Confinement Required for Alpha-Dominated Plasmas



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

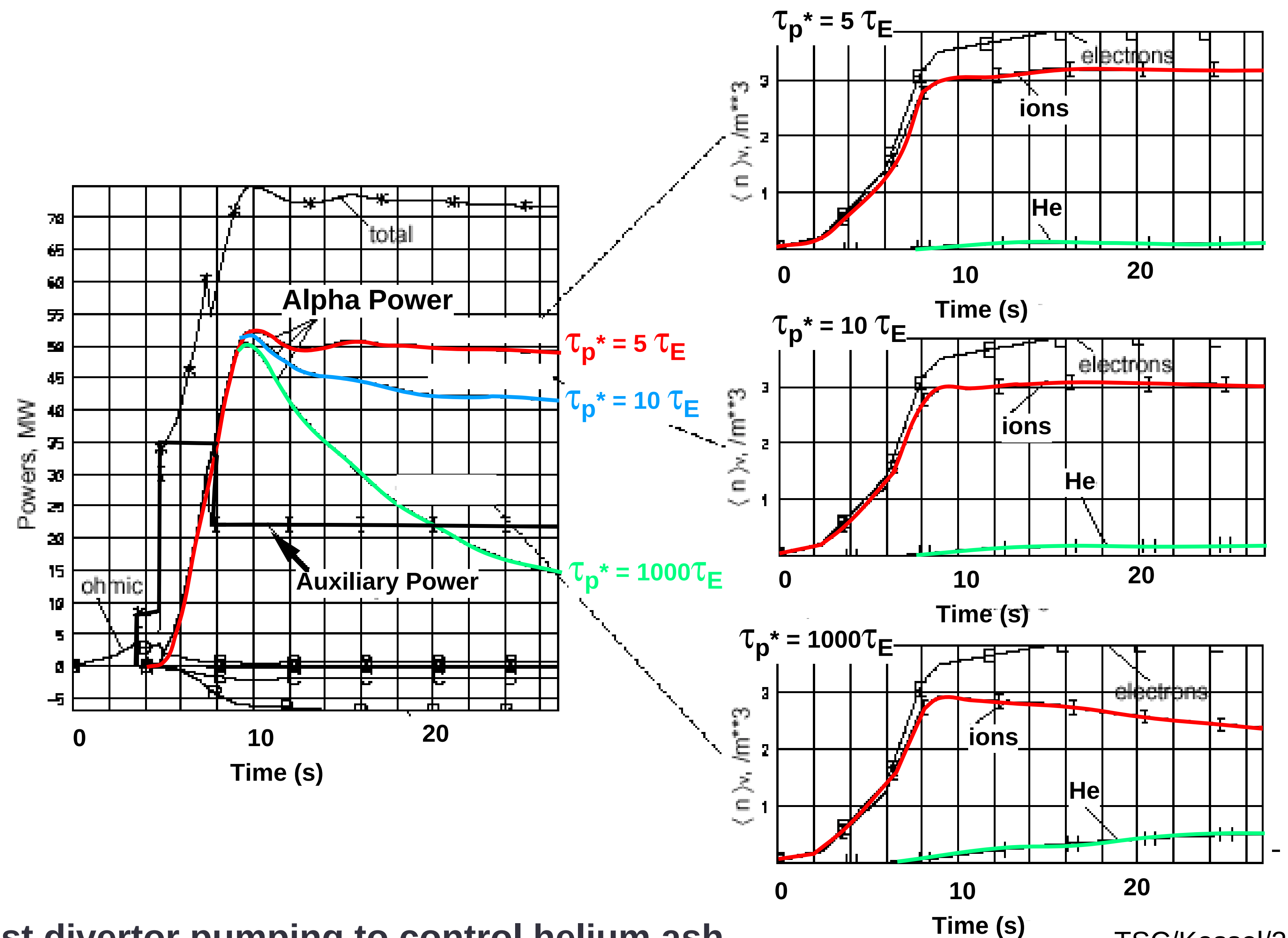
falpha vs HH98-7/APS Cent

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/**

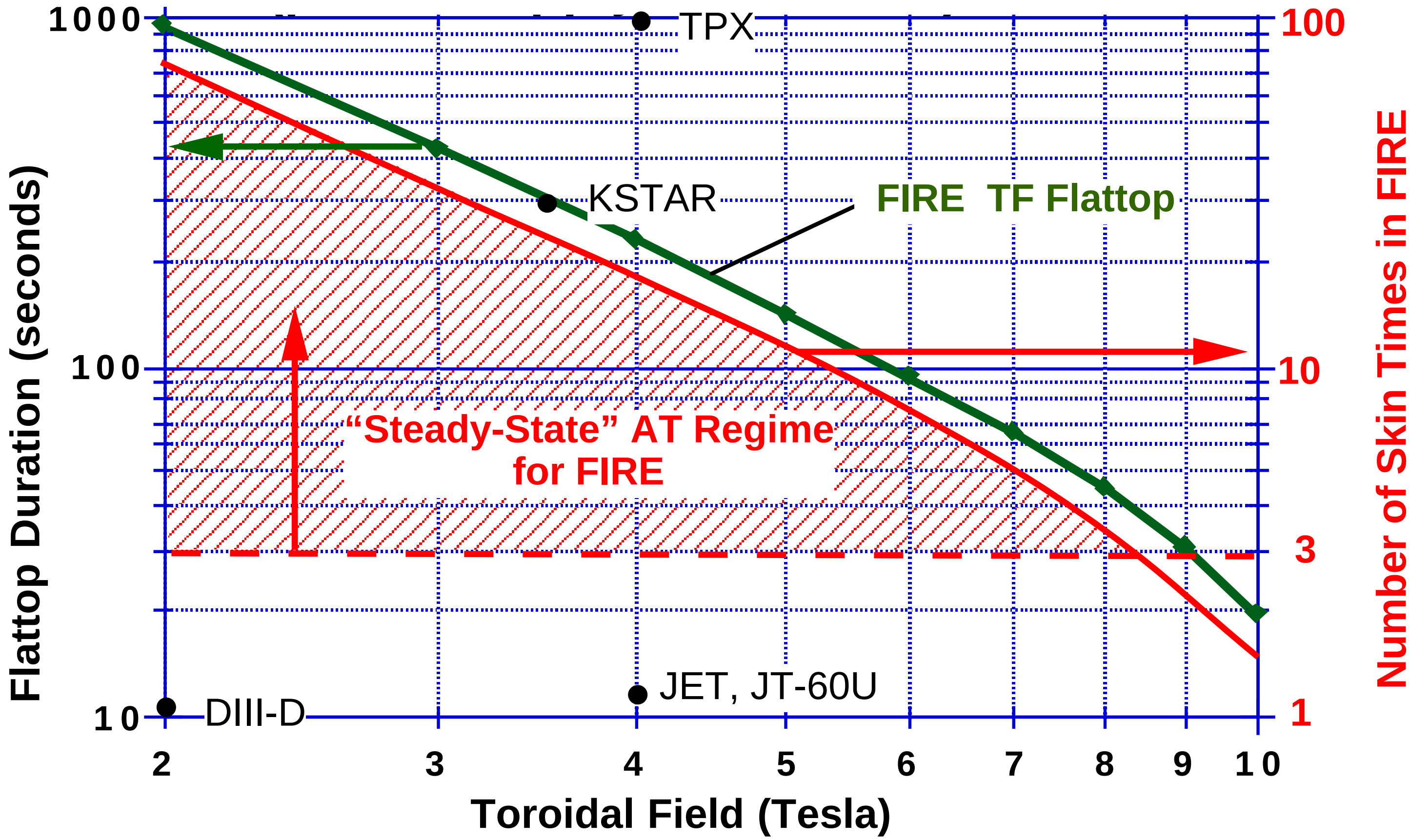
Helium Ash Accumulation can be Explored on FIRE



Adjust divertor pumping to control helium ash

TSC/Kessel/21-q.ps

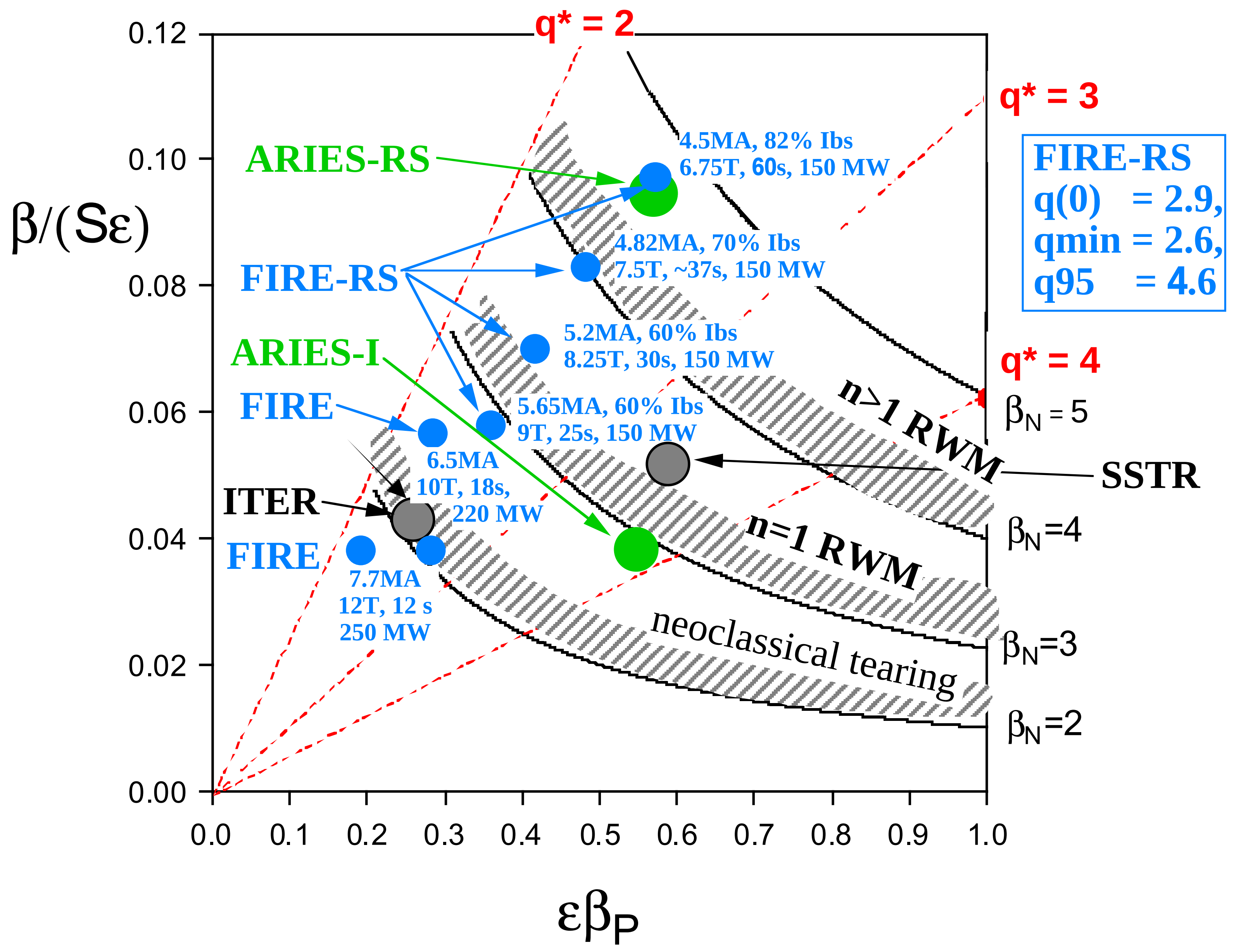
FIRE can Access "Long Pulse" Advanced Tokamak Modes at Reduced Toroidal Field.



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



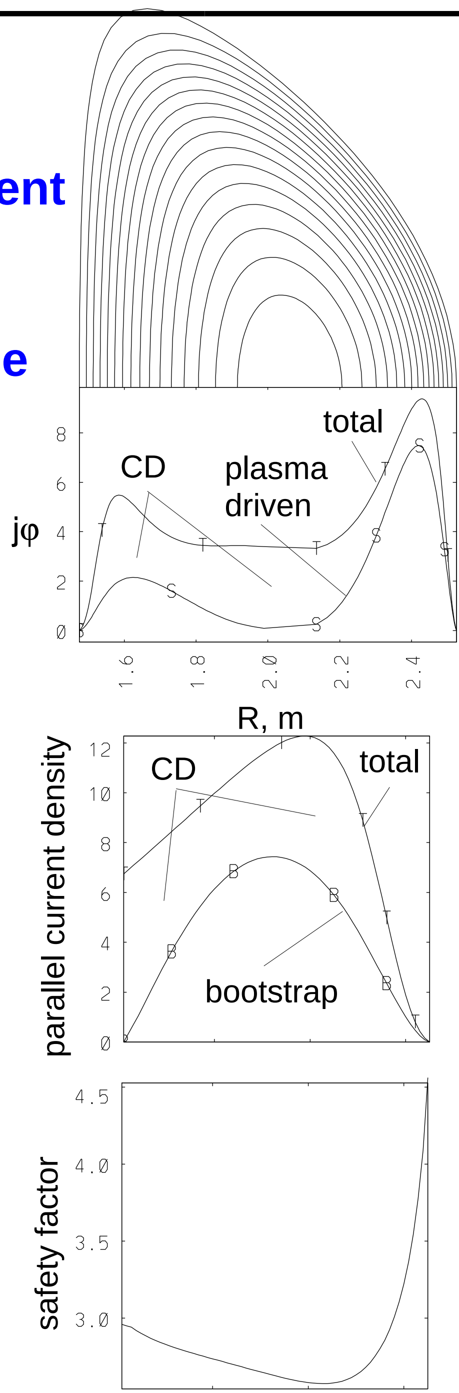
FIRE can Test Advanced Regimes of Relevance to ARIES-AT

Confinement Required to access this regime

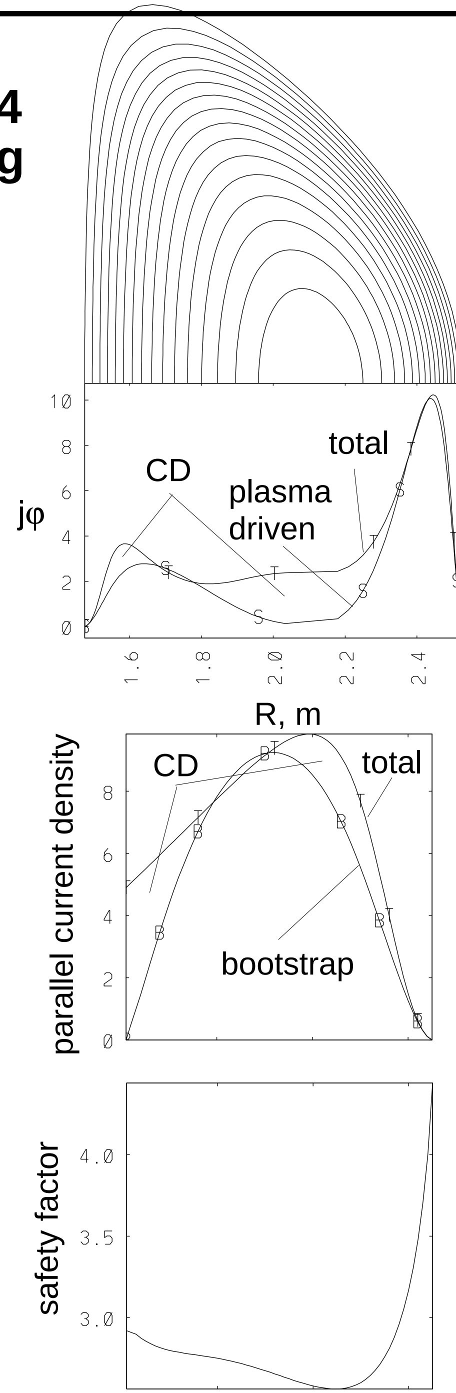
Q = 10, HH = 1.2

or

Q = 5, HH = 1.06



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

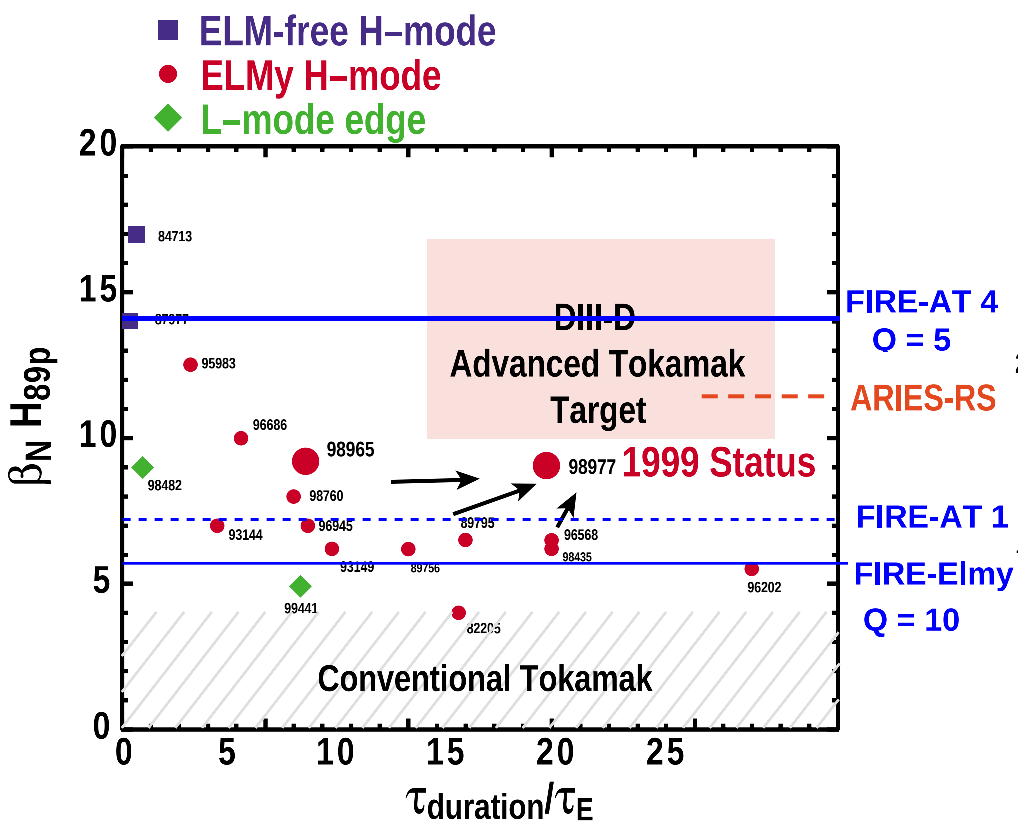
Q = 10, HH = 1.56

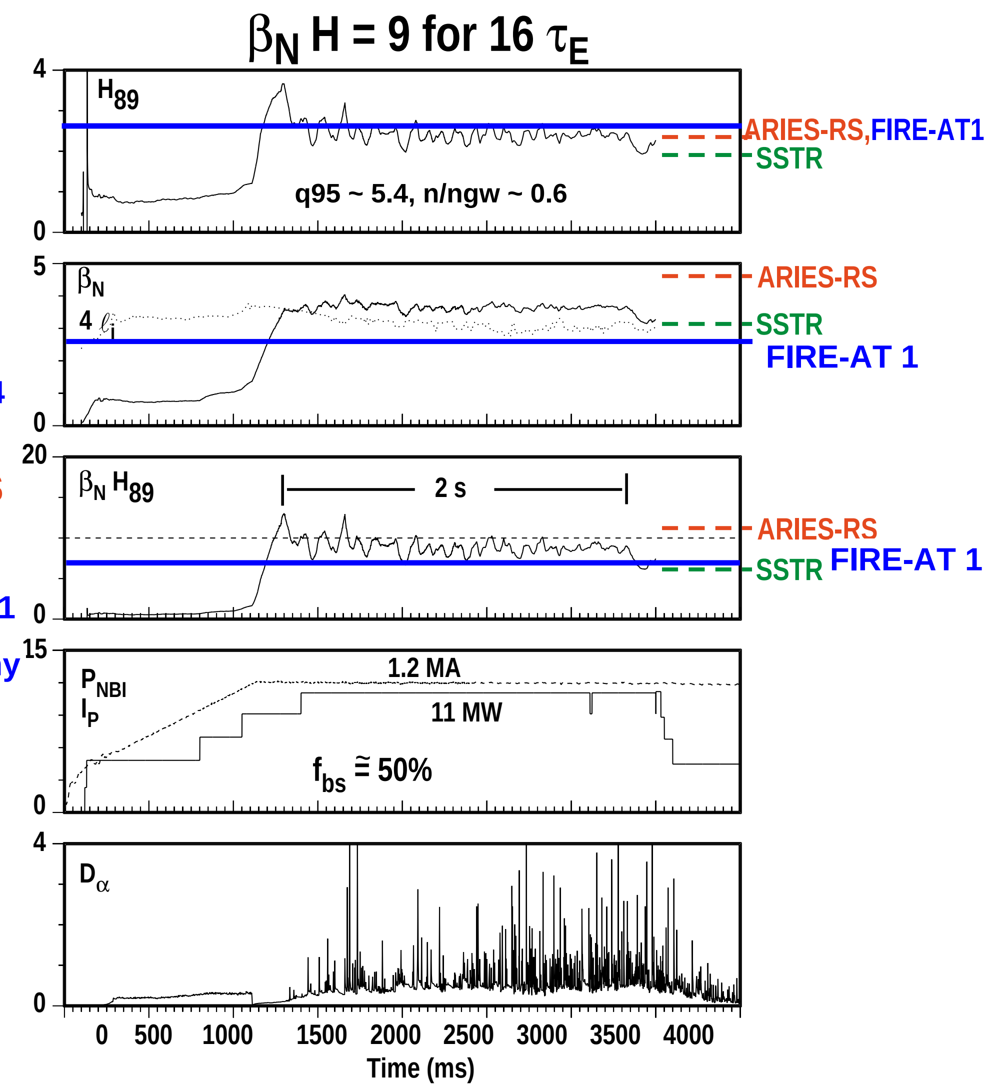
or

Q = 5, HH = 1.36

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
SAN DIEGO

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.

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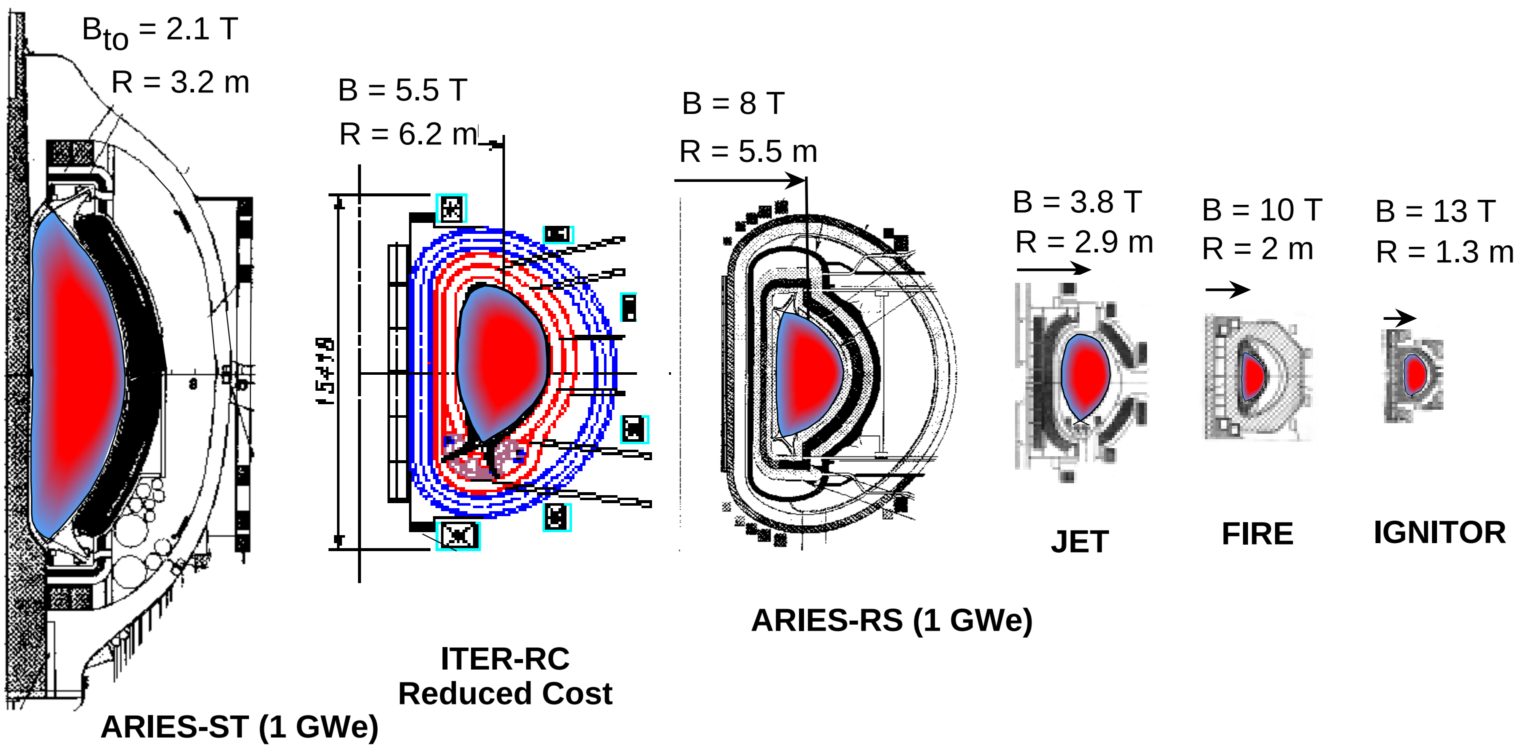
Potential Next Step Burning Plasma Experiments and Demonstrations in MFE



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 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)

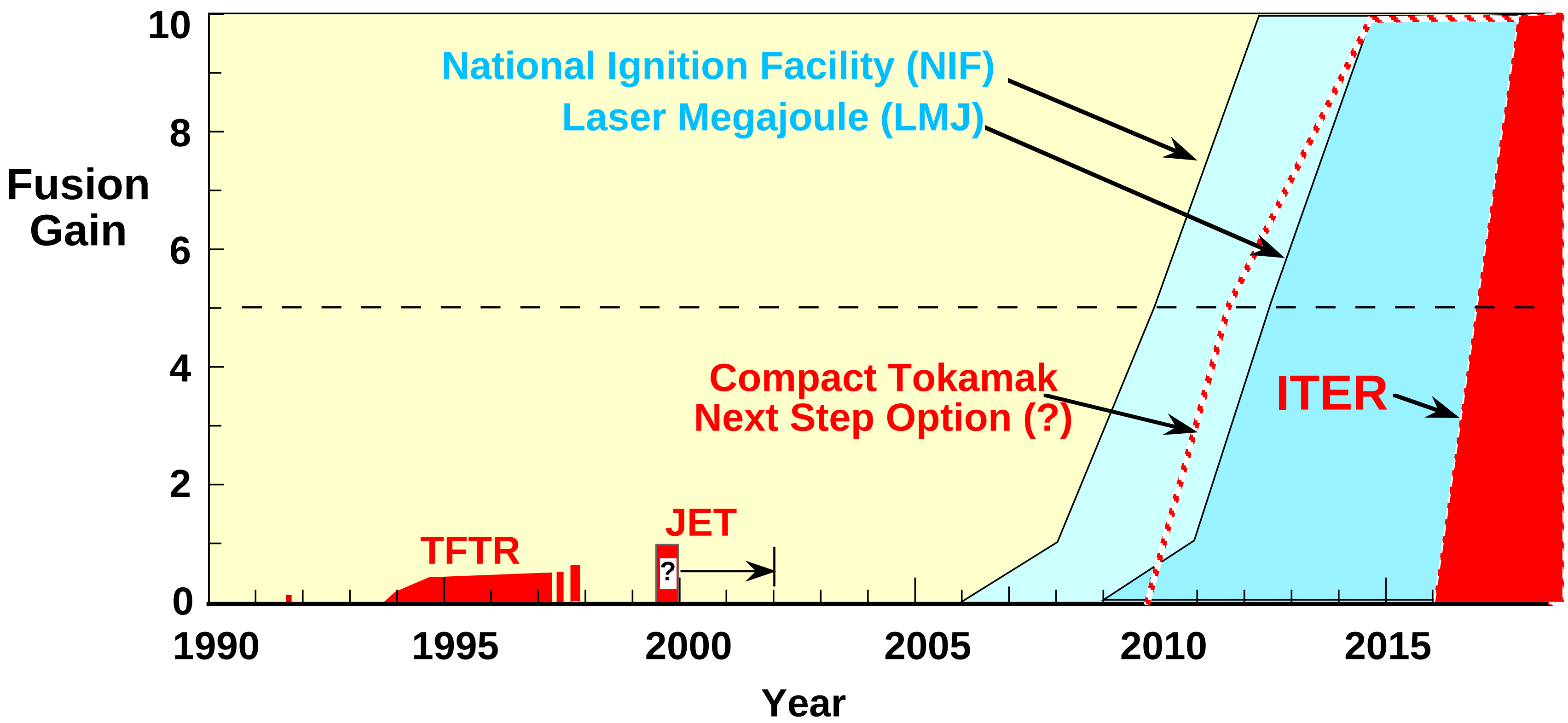
* FIRE would have liquid nitrogen cooled coils.

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)

Meade, April-1999

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 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 for 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.