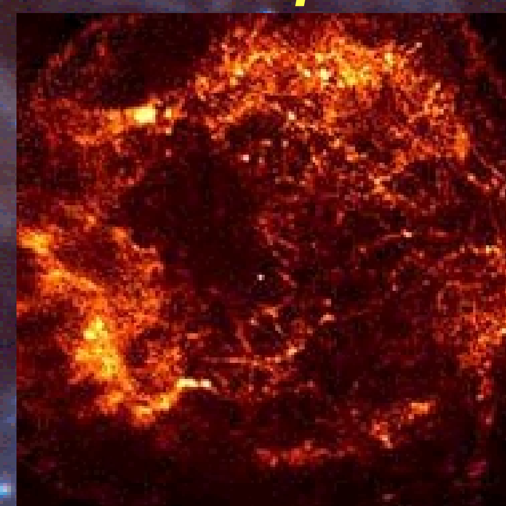
Fusion and Plasma Physics are at the Core of Nature's Most Intriguing Self-Driven Systems

Eagle Nebula

HST

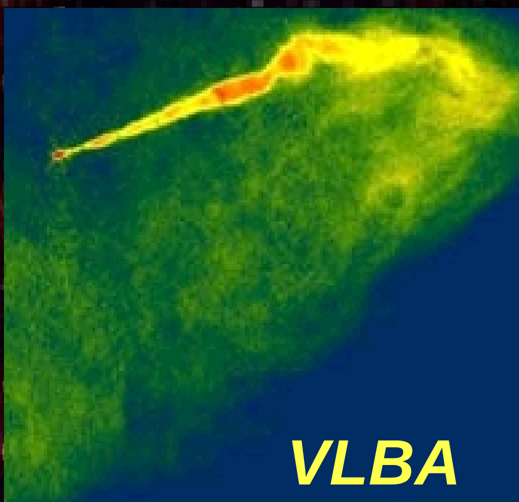
Cassiopia A

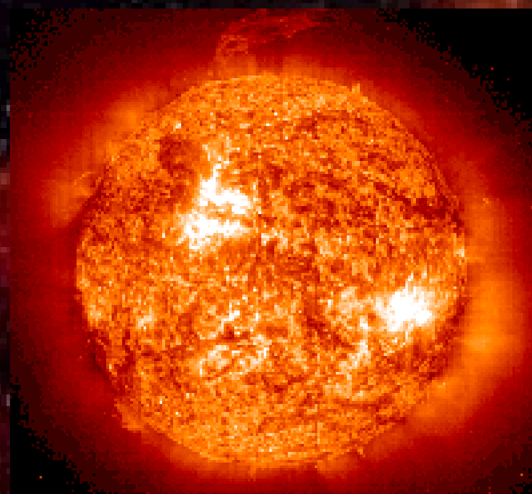


CHANDRA

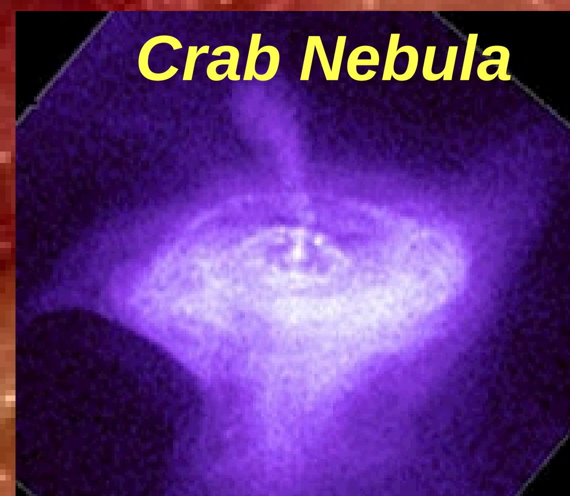
Can we Solve the Mystery of Producing a Stationary Self-Sustained Fusion Fire??

Galactic Jet - M87





SOHO



CHANDRA

Fusion: Power of the Cosmos Brought to Earth

Confining a Fusion Fire

A Grand Challenge for Science and Technology

Dale Meade

Princeton University

Presented at

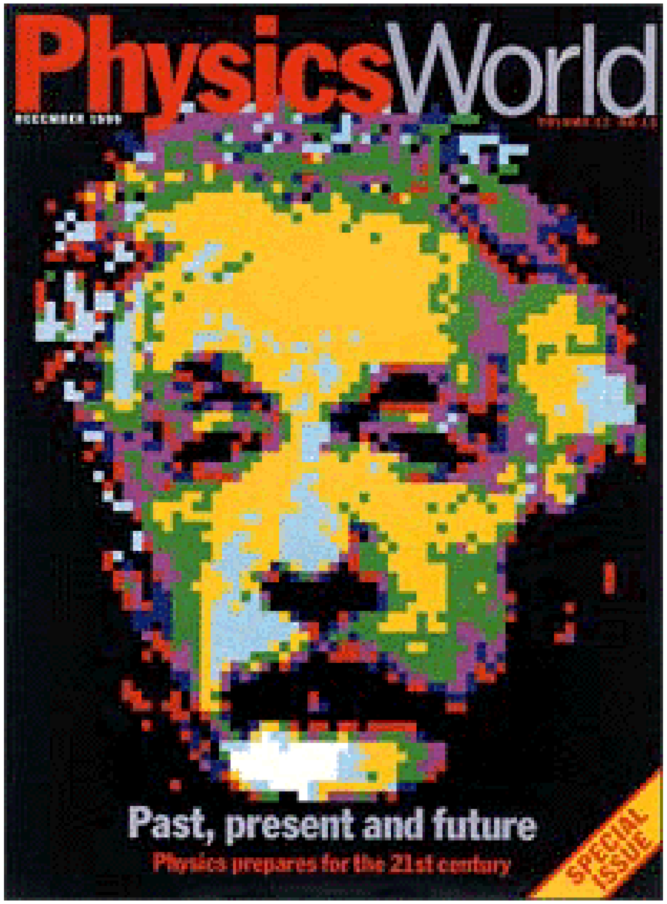
Columbia University Plasma Physics Colloquium

in the City of New York

http://fire.pppl.gov **January 26, 2001** **http://www.cpepweb.org**

Fusion is an Outstanding Physics Challenge and is Connected to Other Outstanding Challenges

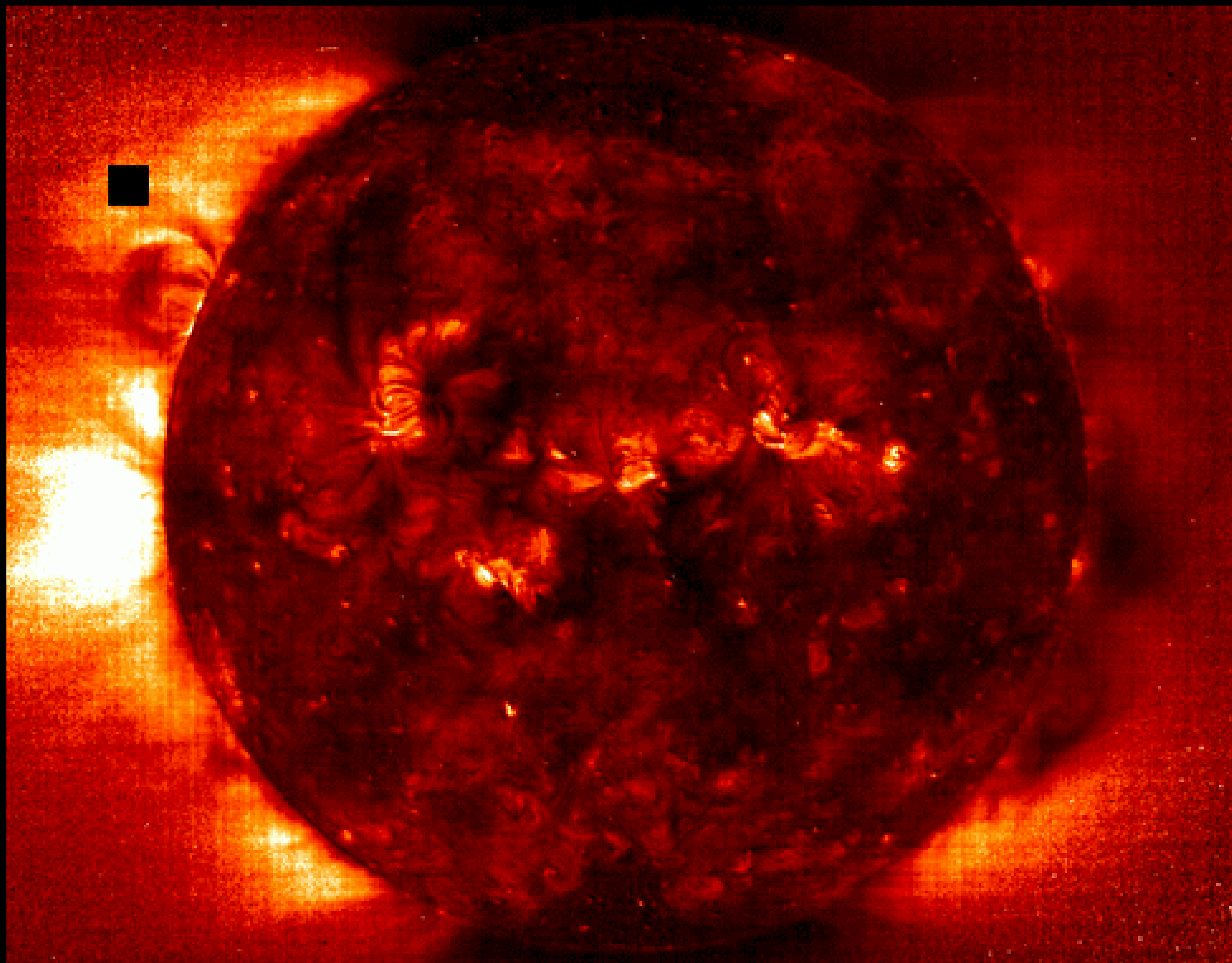
December 1999



Ten Outstanding Physics Challenges

- Quantum gravity presents the ultimate challenge to theorists
- Explaining high-T_c superconductors
- Unstable nuclei reveal the need for a complete theory of the nucleus
- Realizing the potential of fusion energy
- Climate prediction is heavy weather
- Turbulence nears a final answer
- Glass physics: still not transparent
- Solar magnetic field poses problems
- Complexity, catastrophe and physics
- Consciousness: the physicists view

Fusion Does Work at Large Size



Why is it so difficult in the lab?

SOHO

Relevant Reactions for Fusion in the Laboratory

$D^{+} + D^{+}$ --> $^{3}He^{++}$ (0.82 Mev) + n^{0} (2.5 MeV)

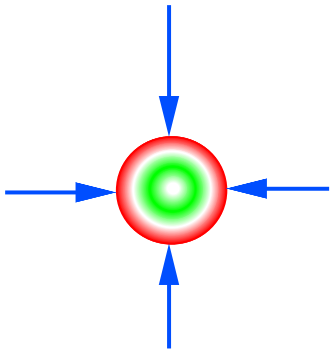
--> T^{+} (1 MeV) + p^{+} (3 MeV)

$D^{+} + {}^{3}He^{++}$ --> $^{4}He^{++}$ (3.6 MeV) + p^{+} (14.7 MeV)

$D^{+} + T^{+}$ --> $^{4}He^{++}$ (3.5 MeV) + n^{0} (14.1 MeV)

$Li^{6} + n$ --> ^{4}He (2.1 MeV) + T (2.7 Mev)

There are Three Principal Fusion Concepts



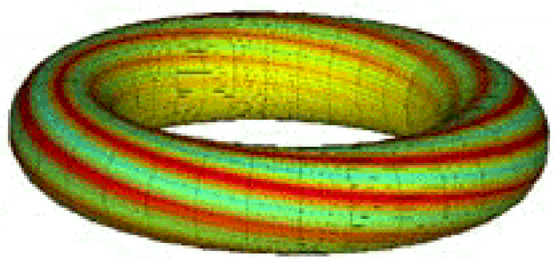
Spherical Inertial

gravitational

transient compression

- drive (laser-D/I, beam)
- radial profile
- time profile

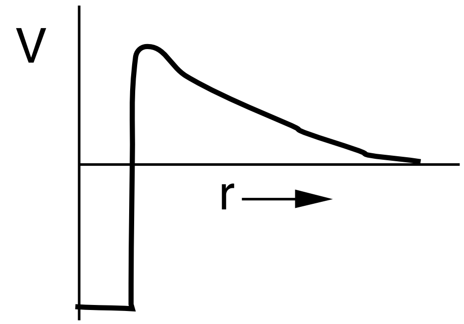
electrostatic



Toroidal Magnetic

surface of helical B lines

- twist of helix
- twist profile
- plasma profile
- toroidal symmetry



Reactivity Enhancement

muon catalysis

polarized nuclei

others?

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

- Grunder Panel (98) and Madison Forum endorsed Burning Plasmas as next step.
- NRC Interim Report (99) identified “integrated physics of a self-heated plasma” as one of the critical unresolved fusion science issues.
- The Snowmass Fusion Summer Study (99) endorsed the burning plasma physics objective, and that the tokamak was technically ready for high-gain experiment. A burning plasma experiment should also have advanced tokamak capability.
- SEAB (99) 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 as machine should proceed now so as to allow the prompt pursuit of this option.”
- NRC/FuSAC (00) - “The US scientific community needs to take the lead in articulating the goals of an achievable, cost-effective scientific burning plasma experiment, and to develop flexible strategies to achieve it, including international collaboration.”

Fusion Science Objectives for a Major Next Step Magnetic Fusion Experiment

Explore and understand the strong non-linear coupling that is fundamental to fusion-dominated plasma behavior (self-organization)

- Energy and particle transport (extend confinement predictability)
- Macroscopic stability (β-limit, wall stabilization, NTMs)
- Wave-particle interactions (fast alpha particle driven effects)
- Plasma boundary (density limit, power and particle flow)

- Test/Develop techniques to control and optimize fusion-dominated plasmas.
- Sustain fusion-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 various advanced operating modes and configurations in fusion-dominated plasmas to provide generic knowledge for fusion and non-fusion plasma science, and to provide a foundation for attractive fusion applications.

Plasma Requirements for a Fusion-Dominated Plasma

Power Balance

$$P_{aux\text{-}heat} + n^2 \langle\sigma v\rangle U_\alpha V_p/4 - C_B T^{1/2} n_e^2 V_p = 3nkTV_p/\tau_E + d(3nkTV_p)/dt$$

where: $n_D = n_T = n_e/2 = n/2$, $n^2 \langle\sigma v\rangle U_\alpha V_p/4 = P_\alpha$ is the alpha heating power, $C_B T^{1/2} n_e^2 V_p$ is the radiation loss, $W_p = 3nkTV_p$ and $\tau_E = W_p/(P_{aux\text{-}heat} - dW_p/dt)$ is the energy confinement time.

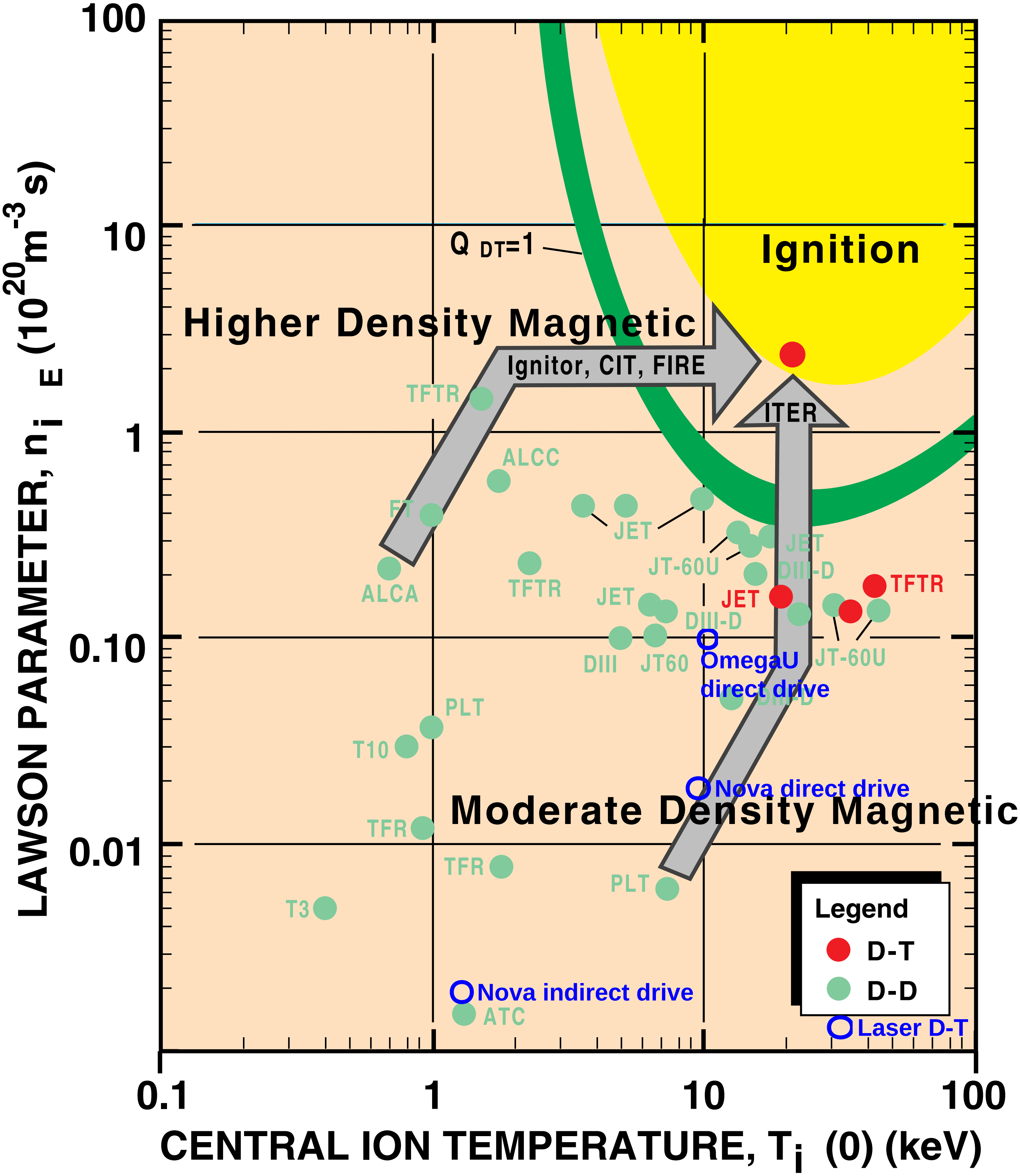
In Steady-state:

$$n\tau_E = \frac{3kT}{\langle\sigma v\rangle U_\alpha (Q+5)/4Q - C_B T^{1/2}}$$

where $Q = P_{fusion}/P_{aux\text{-}heat}$ Palpha/(Palpha + Paux-heat) = Q / (Q + 5)

Q = 1 is Plasma Breakeven, $Q = \infty$ is Plasma Ignition

Status of Laboratory Fusion Experiments



#97GR041.ntau-98 FIRE

International Thermonuclear Experimental Reactor (ITER)

<u>Parties</u>

US (left in 1998)

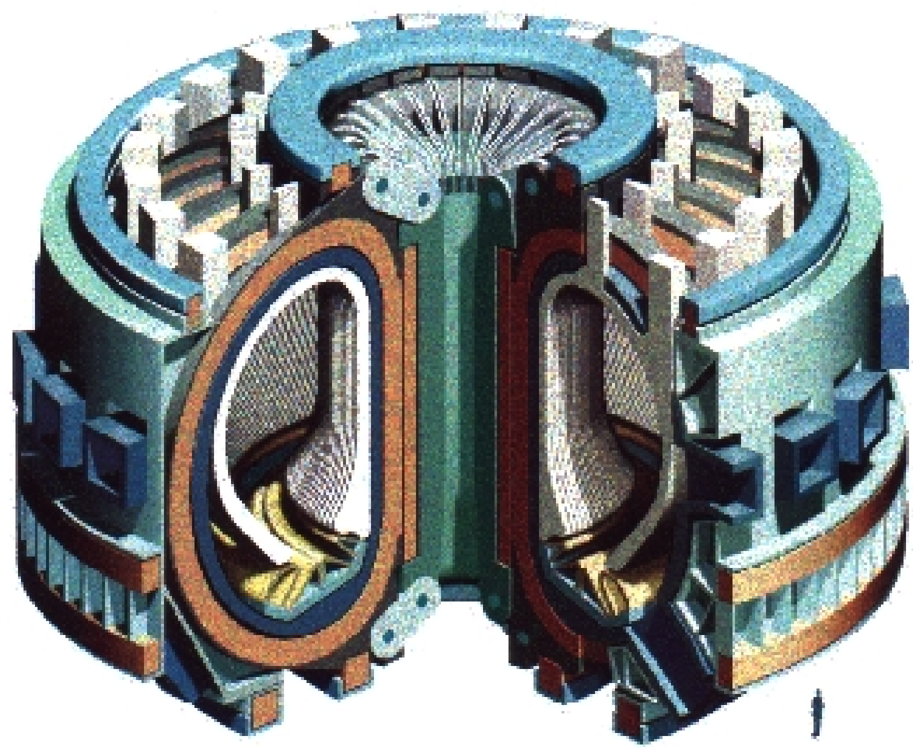
Japan

Europe

Russia

P_{fusion} ~ 1,500 MW for 1,000 seconds

Cost ~ $10 B



Japan, Europe and Russia are continuing to work on a reduced size version with a goal of reducing the cost to ~$5B.

Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.

NSO/FIRE Community Discussions

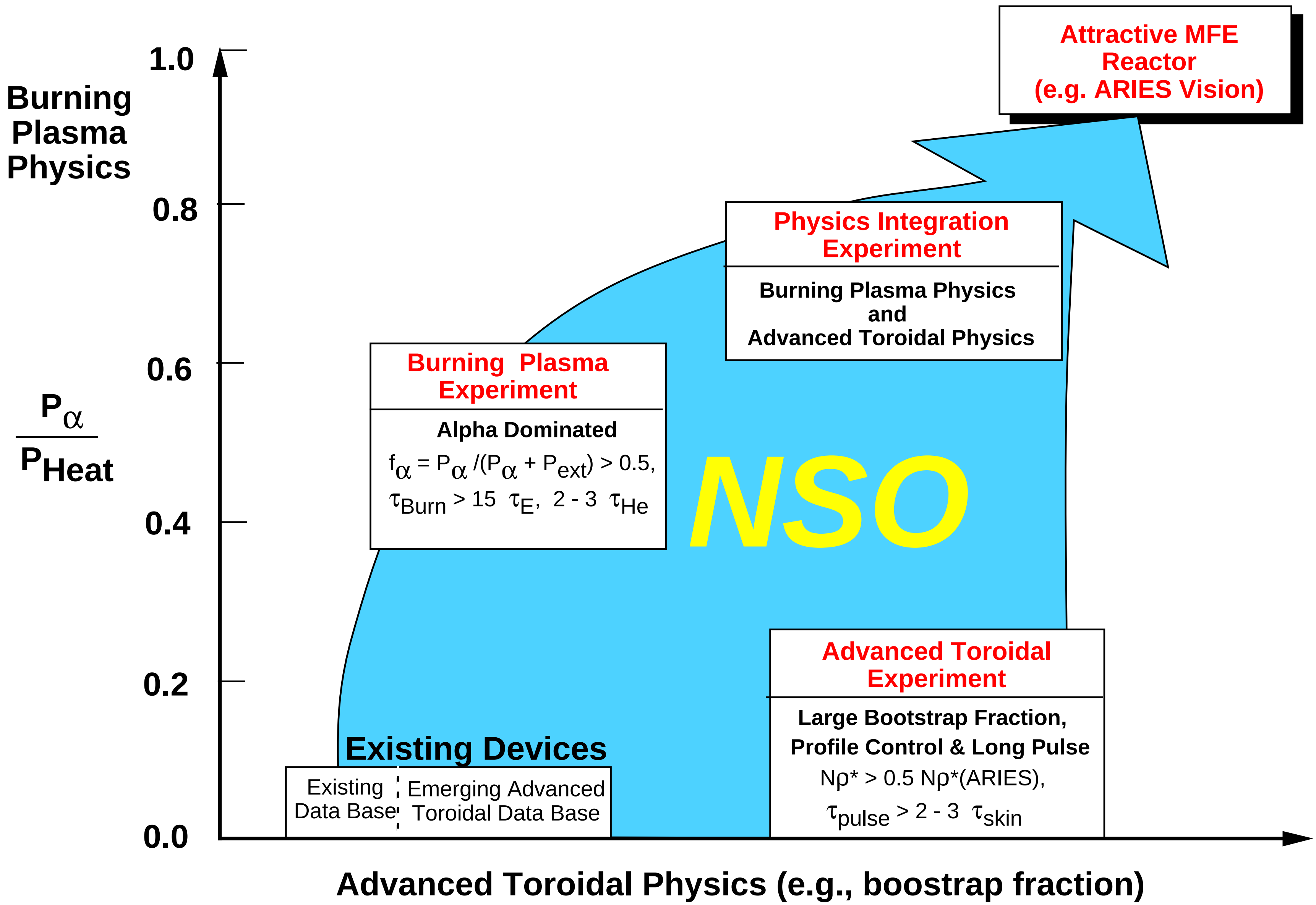
A Proactive NSO/FIRE Outreach Program has been undertaken to solicit comments and suggestions from the community on the next step in magnetic fusion.

- Presentations have been made and comments received from:

SOFT/France	**Sep 98**	**IAEA/Japan**	**Oct 98**	**APS-DPP**	**Nov 98**
FPA	**Jan 99**	**APEX/UCLA**	**Feb 99**	**APS Cent**	**Mar 99**
IGNITOR Wkshp	**May 99**	**NRC/NAS**	**May 99**	**GAT**	**May 99**
LLNL	**May 99**	**VLT-PAC**	**Jun 99**	**MIT PSFC**	**Jul 99**
Snowmass	**Jul 99**	**PPPL/SFG**	**Aug 99**	**VLT-PAC**	**Jun 99**
VLT-PAC	**Jun 99**	**MIT PSFC**	**Jul 99**	**U. Rochester**	**Aug 99**
NYU	**Oct 99**	**PPPL/SFG**	**Aug 99**	**U. Wis**	**Oct 99**
FPA	**Oct 99**	**SOFE**	**Oct 99**	**APS-DPP**	**Nov 99**
U. Maryland	**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**	**Feb 00**	**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**
NSO-PAC	**Jul 00**	**SOFT/Spain**	**Sep 00**	**IAEA/Italy**	**Oct 00**
Int'l DB/Frascati	**Oct 00**	**CRPP/Lausanne**	**Oct 00**	**ANS/TOFE**	**Oct 00**
APS/DPP-ICPP	**Oct 00**	**VLT-PAC**	**Dec 00**	**UFA BP Wkp**	**Dec 00**
NSO-PAC2	**Jan 01**	**MIT IAP**	**Jan 01**	**Columbia U.**	**Jan 01**

- **The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. Over 14,000 visitors from around the world have logged on to the FIRE web site since the site was initiated in July, 1999.**

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.

Dimensionless Parameters Required for Fusion Plasma Physics Experiment

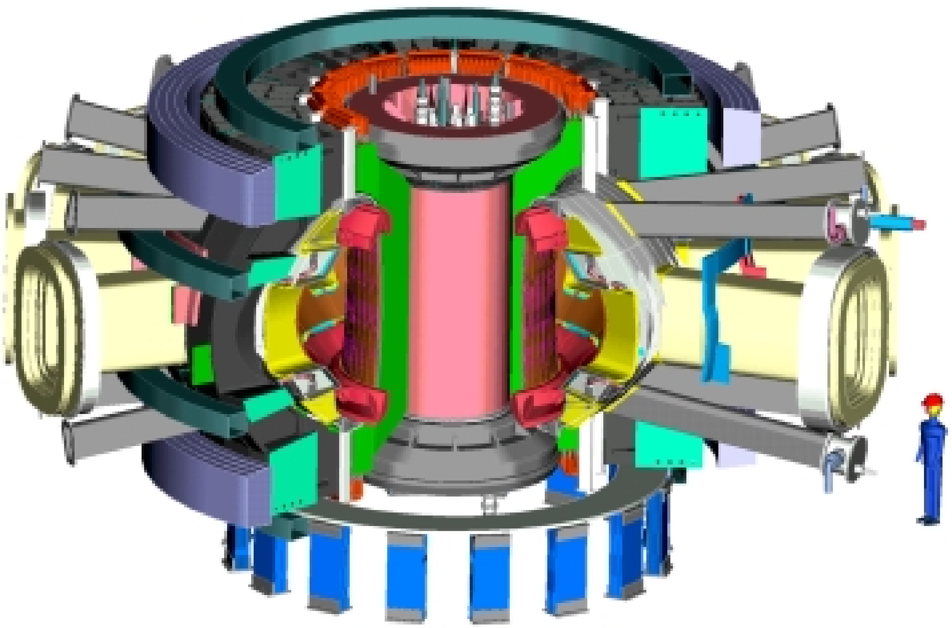
	Core*	Edge	Alpha	Duration			
	$BR^{5/4}$	?	P_α/P_{heat}	$\tau/\tau_{\alpha s}$	τ/τ_E	τ/τ_{He}	τ/τ_{CR}
<u>Explore and Understand Fusion Plasmas</u>	>0.5		>0.5	>3	>5	>3	>3
Energy and Particle Transport							
Macroscopic Stability							
Wave Particle (alpha heating, fast alpha)			β_α ~ ARIES				
Plasma Boundary		?					
<u>Test Control and Optimization Techniques</u>	>0.5		0.4 to 0.6		10	>3	1
<u>Sustain Fusion-Dominated Plasmas</u>	>0.5				10		
Exhaust of power, particles and ash			0.4 to 0.6			3 to 5	
Profile evolution impact on τE, MHD			0.5 to 0.8				1.5 to 3
<u>Explore and Understand Some AT Modes</u>			0.5 to 0.8		>10	5	1.5 to 3
ARIES-AT	**1**		**0.9**	**>10**	**> 10**	**>10**	**> 10**
FIRE Goals	**0.6**		**0.5 to 0.8**	**>10**	**>10**	**>5**	**1.5 to 3**
JET/TFTR D-T Experiments	**0.3**		**0.04**	**~3**	**10**	**~2**	**<0.2**

* Core parameters are normalized to ARIES-AT $BR^{5/4}$

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 ≈18.5s (≈12s)*
- 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.

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
DAD Associates
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

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.
Also enhanced performance option B = 10T, Ip = 7.7 MA with 20 s burn with R = 2.14m

FIRE would have Access for Diagnostics and Heating

FIRE Status

Physics - NSO PAC review with Action Plan to follow up on Recommendations

- Mission endorsed (recommend even more excitement)
- Evaluate FIRE performance on the basis of recent scalings e.g., ITER98(y,2) and recent results with enhanced regimes e.g., pellet fueling
- Enhanced performance design point being developed with I_p ~ 7.7 MA to increase confidence of high gain while maintaining pulse length (~ 1.5 τ_{cr})
- Potential for advanced tokamak modes is being developed

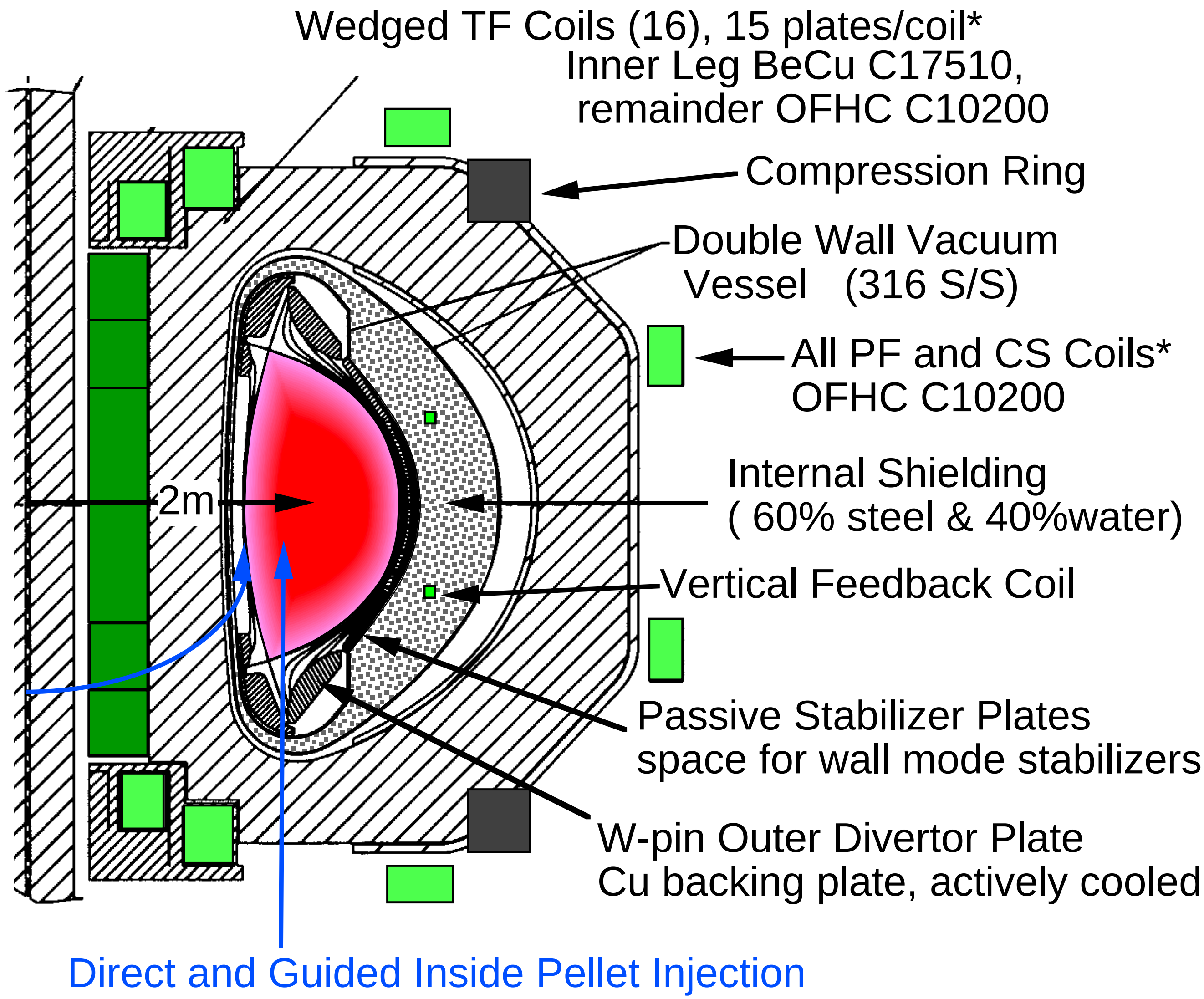
Engineering

- Pre-Conceptual Design Activity has addressed all subsystems. Engineering Report 2000 completed, see http://fire.pppl.gov. CD is available on request
- Baseline design of 10 T /20 s flat top and 12 T/12 s flat top exceeds original design goals of 10 T/10 s flat top.
- Actively cooled W outer divertor and baffle with conduction cooled inner W divertor, and Be first wall on Cu substrate satisfy cooling requirements.
- Cost Estimate of Baseline design gives $1.2B(FY-99$) for Green Field site with good possibility of < $1B(FY-99) at an existing site.

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.

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.

FIRE Confinement Projection Activities

Design Guidelines

- Similar to ITER-FEAT
  - Campbell APS paper on FIRE, ITER-FEAT presentation to TAC 7/00
  - Uckan, Wesley ANS paper
  - Meade, IAEA, ANS papers

Confinement Database Meeting (DB4)

- Collection of random vs library of repeatable (eg Barabaschi EPS paper)

FIRE Specific Assumptions

- JET H-mode data base of FIRE-like shots (55)

  $\kappa \geq 1.7$, $\beta_N > 1.7$, $2.7 < q_{95} < 3.5$, $Z_{eff} < 2$, $0.3 < n/n_{GW} < 0.8$

  - $<H(y,2> = 1.1$, $<n(0)/<n>_v> = 1.2$

- density peaking ≈ 1.2 consistent with 1-D modeling (e.g., Houlberg-ANS)

- Impurity assumption needs more analysis. Not taking credit for reduction at high density, but must make sure hi-Z ions do not get into core plasma.

Starting interactions with first principles modeling groups.

Guidelines for Estimating Plasma Performance

Confinement (Elmy H-mode) - ITER98(y,2) based on today's data base

$$\tau_E = 0.144\, I^{0.93}\, R^{1.39} a^{0.58}\, n_{20}^{0.41} B^{0.15} A_i^{0.19} \kappa^{0.78}\, P_{heat}^{-0.69}\;\; H(y,2)$$

Density Limit - Base on today's tokamak data base

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

Beta Limit - theory and tokamak data base

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

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

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

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

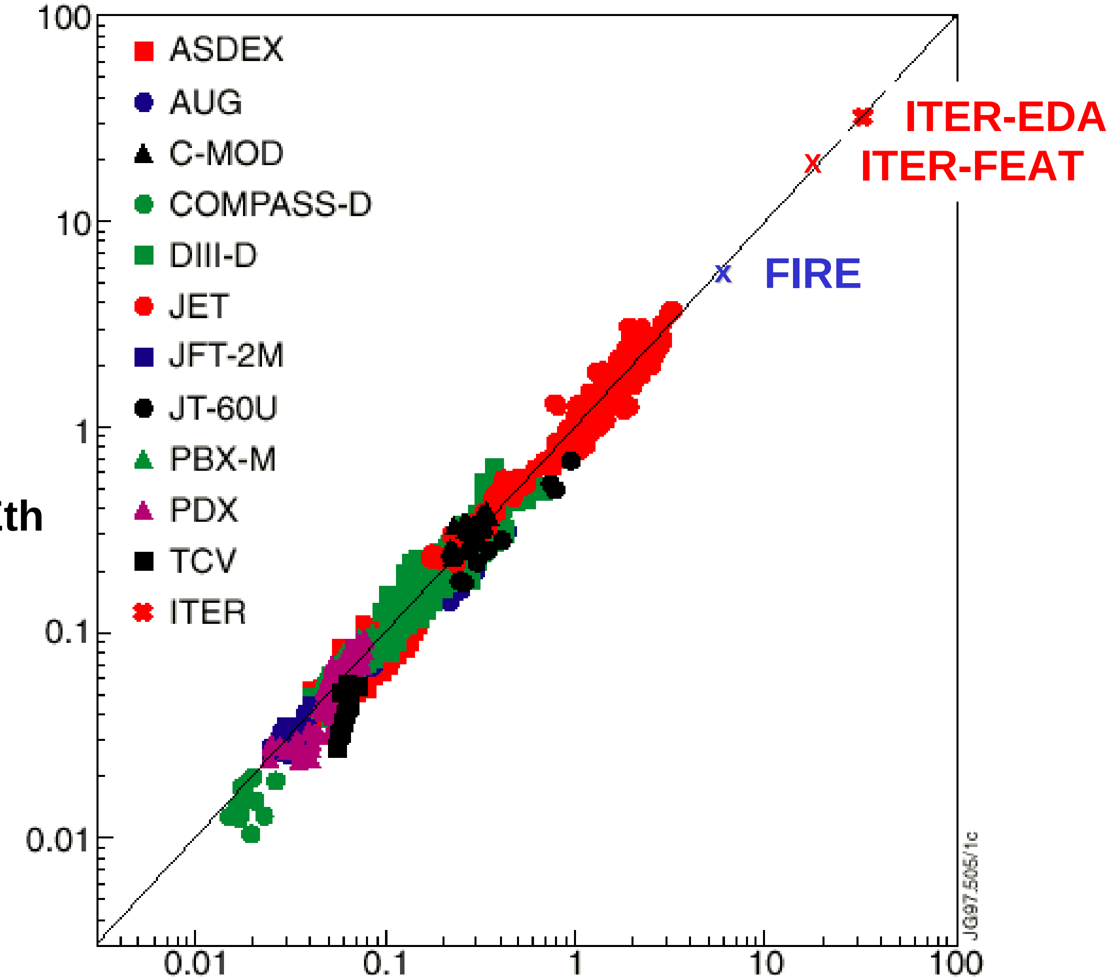
Understanding is mainly empirical. Better understanding is needed from existing experiments with improved simulations, and a benchmark in fusion-dominated plasmas is needed to confirm and extend the science basis.

FIRE is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters
$\omega_c \tau$ $\rho^* = \rho/\mathbf{a}$ $\nu^* = \nu_c/\nu_b$ β

Similarity Parameter
$\mathbf{B\ R^{5/4}}$

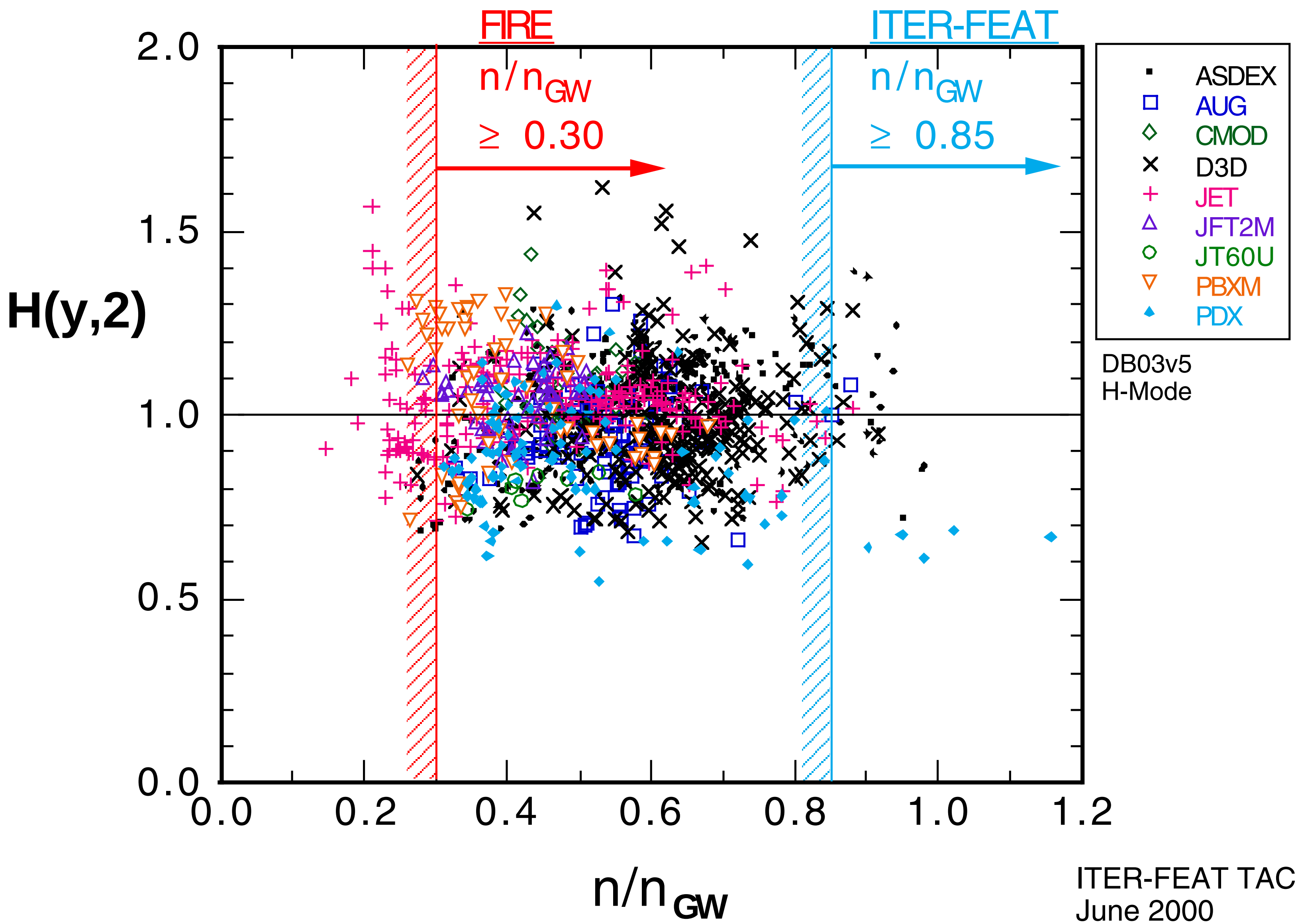
Kadomtsev, 1975



$B\tau_{Eth}$

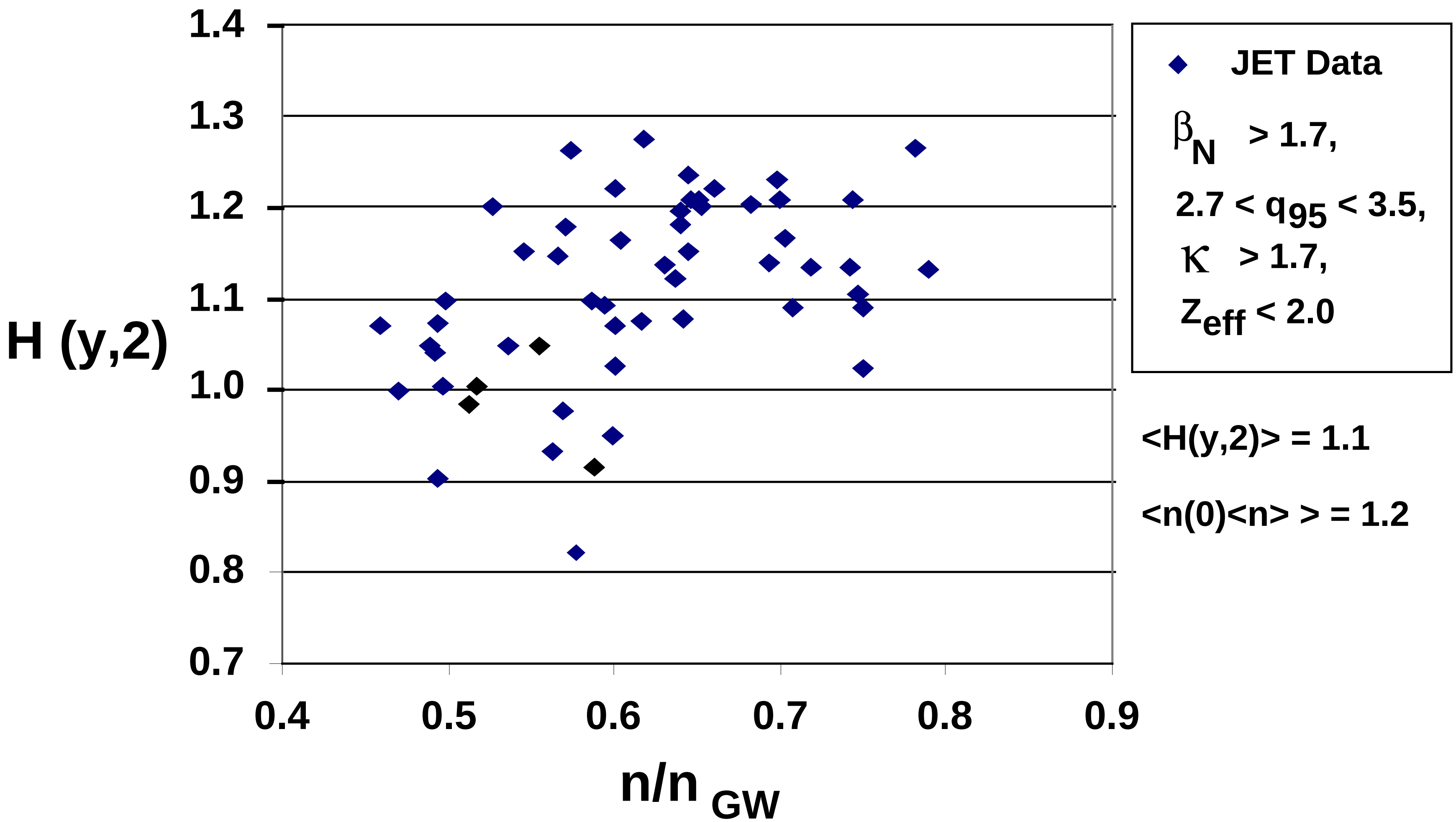
$B\tau_{Eth} \sim \rho^{*-2.88}\ \beta^{-0.69}\ \nu^{*-0.08}$

FIRE can Access Most of the H-Mode Database



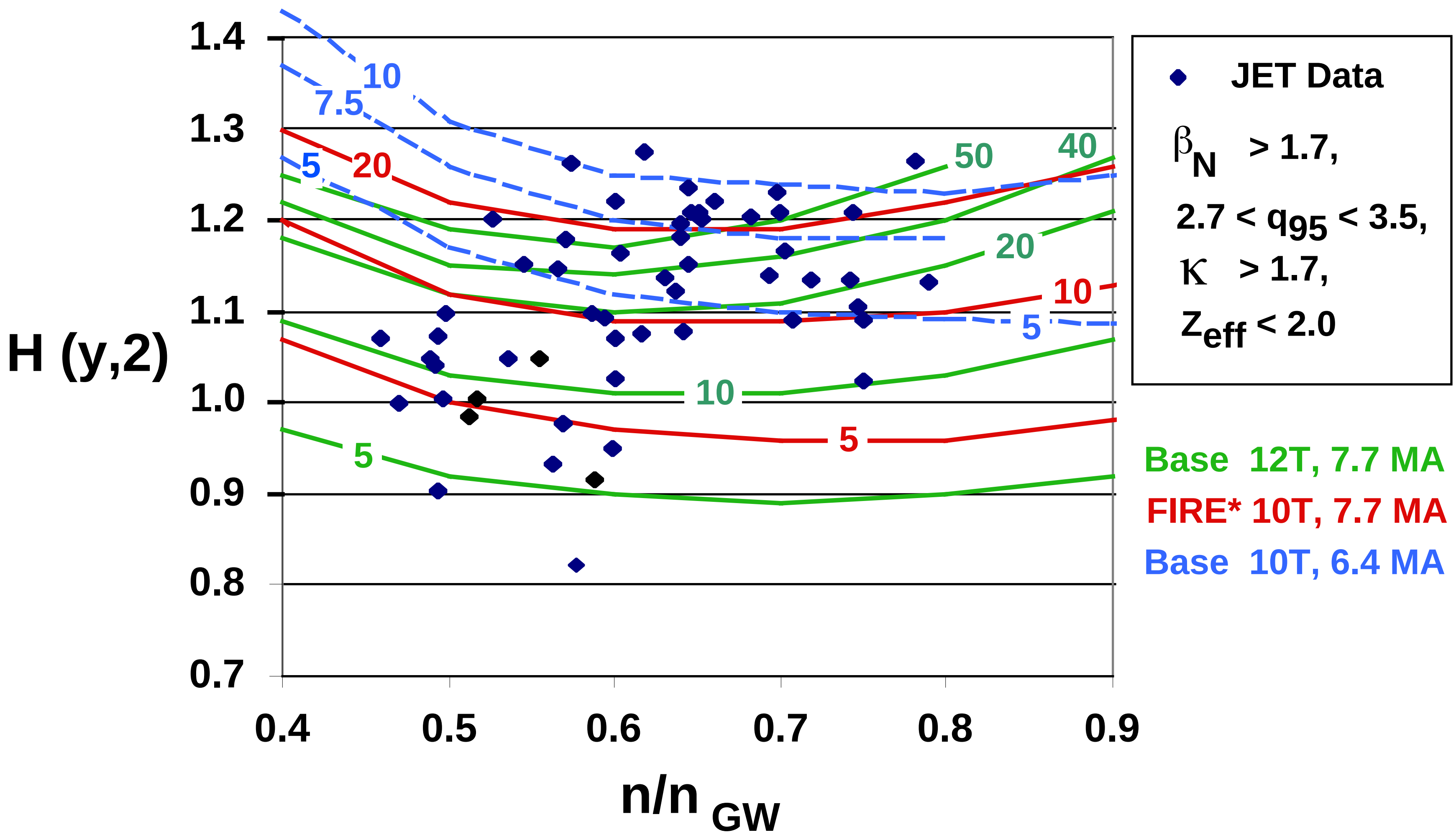
ITER-FEAT TAC Meeting
June 2000

JET H-Mode Data Selected for FIRE-like Parameters

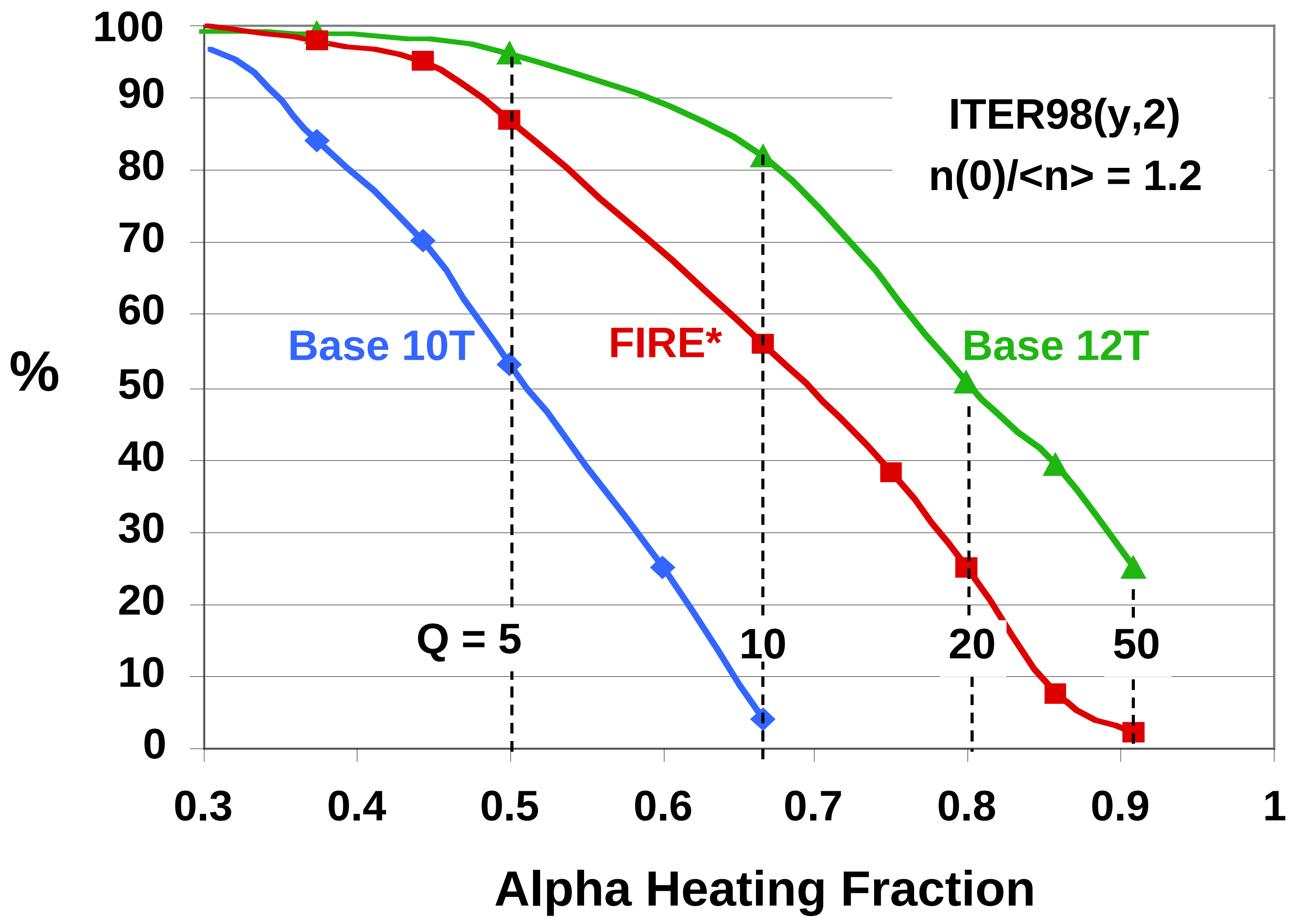


This approach discussed at IAEA(Sorrento) and at the International Confinement Database meeting (Frascati).

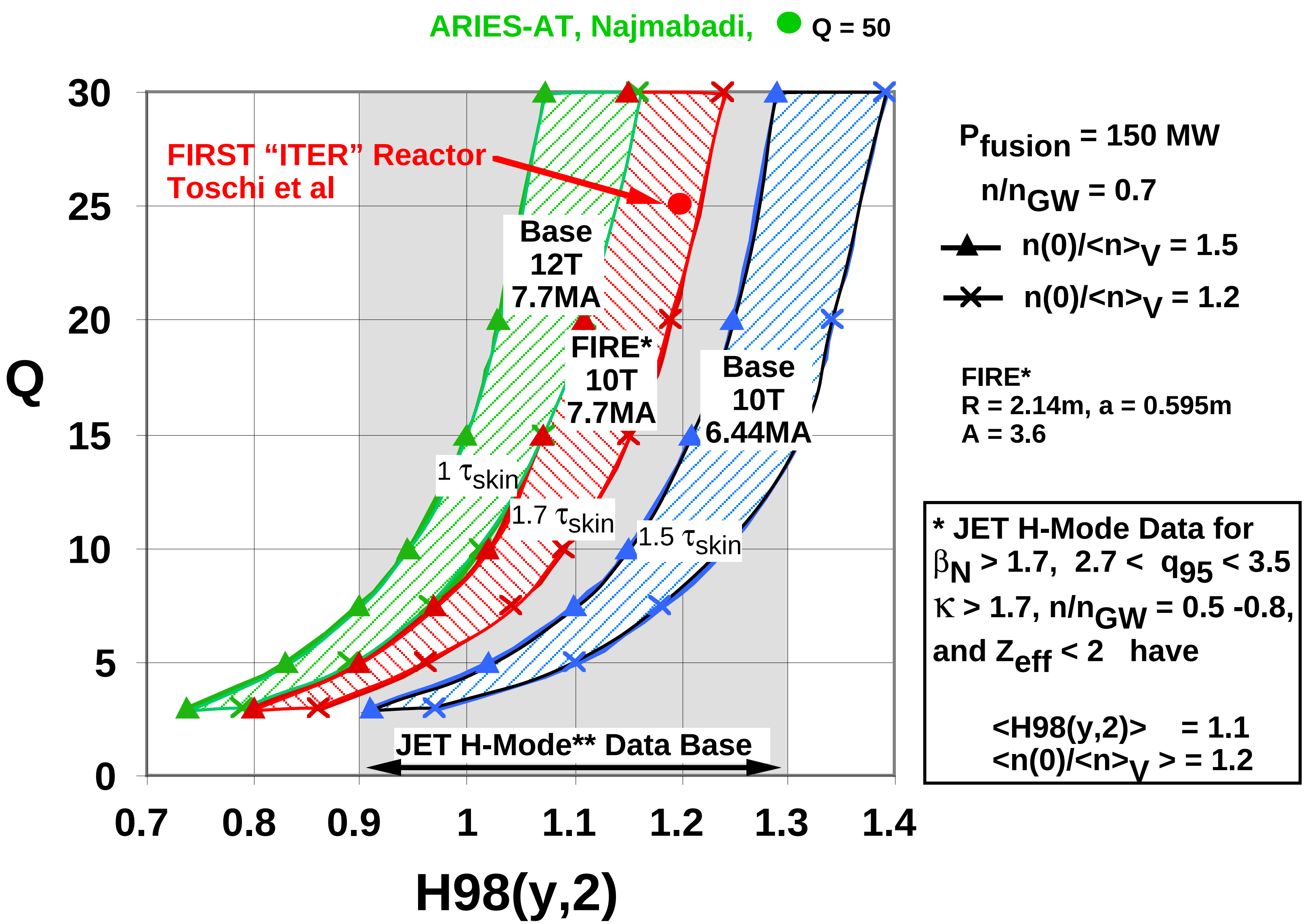
Confinement Enhancement Required to Access Various Q-values Compared with JET H-Mode Data



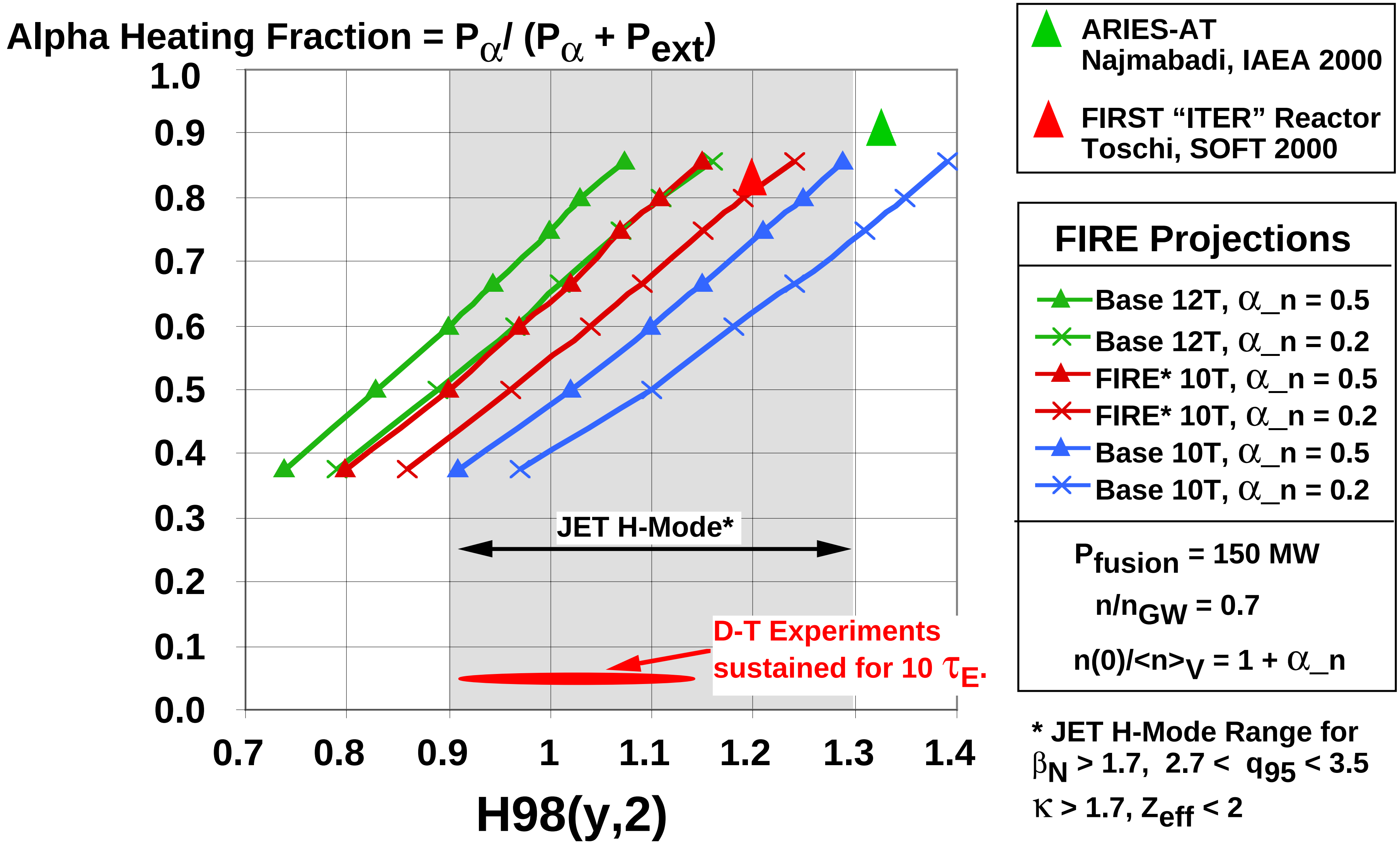
Percentage of JET FIRE-like Data Points that Project to a Specific Alpha Heating Fraction (Q)



Projections of FIRE Compared to Envisioned Reactors



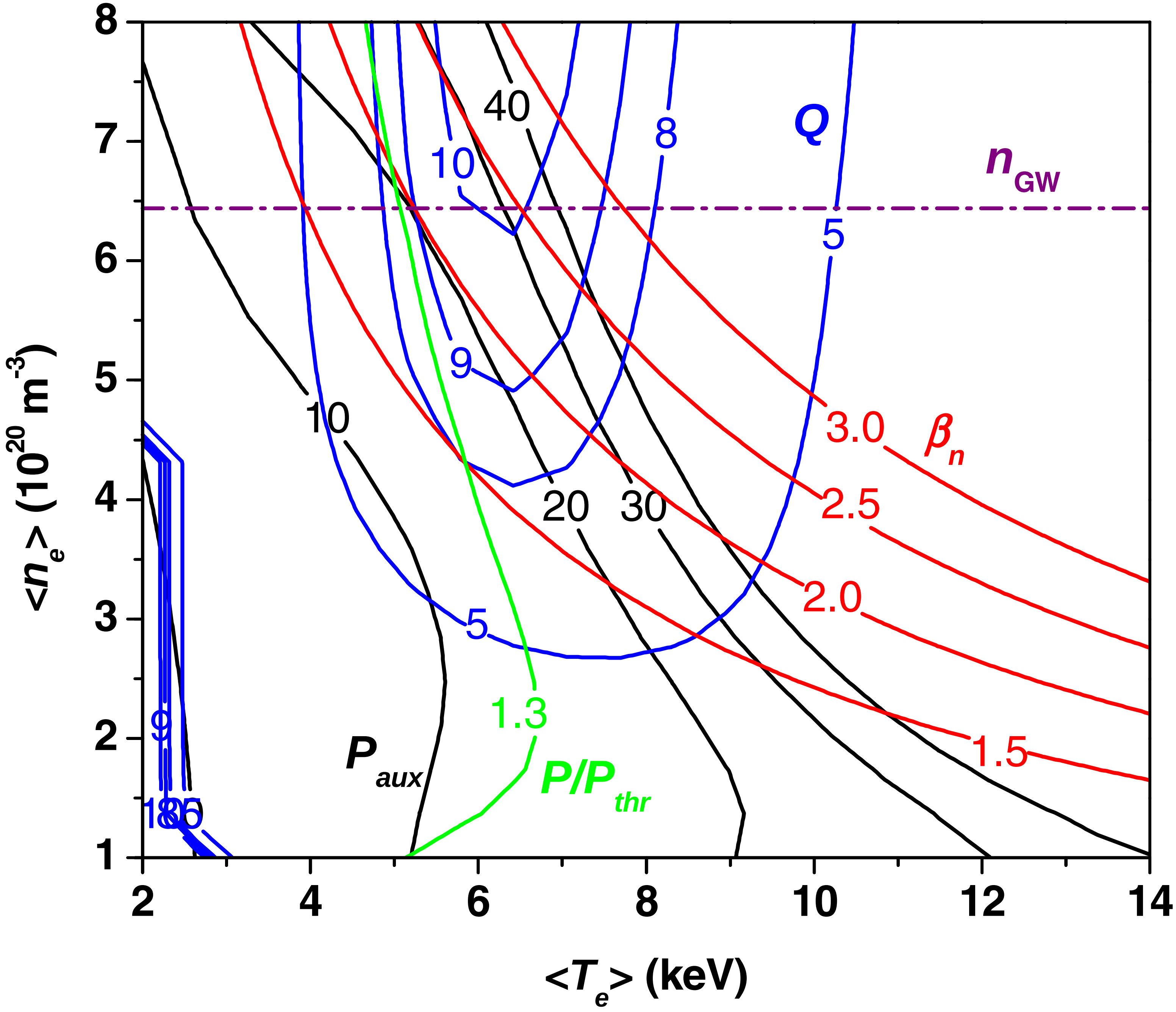
Projections of FIRE Performance as Confinement is Enhanced Toward that Required for Attractive Reactors



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

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

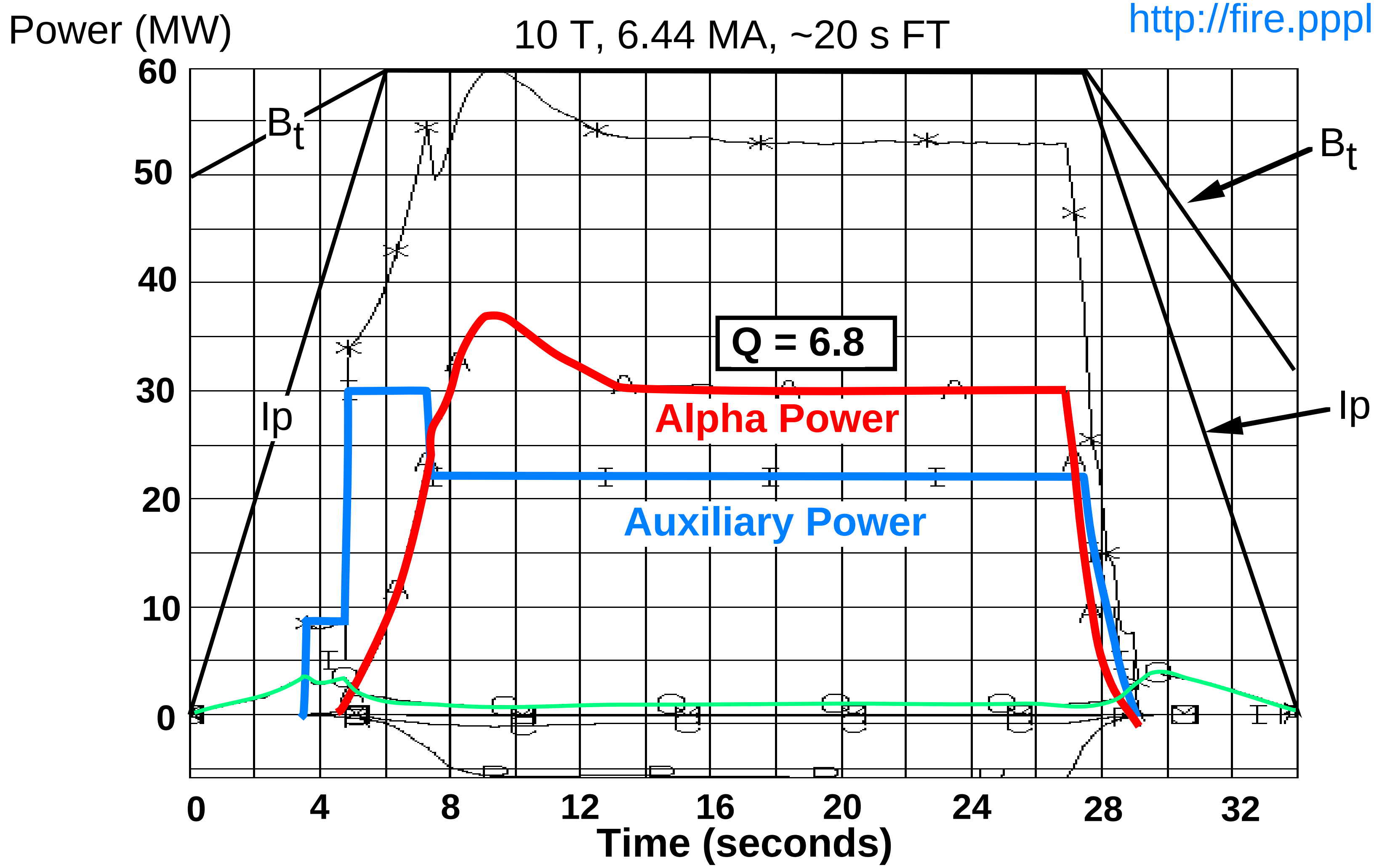
FIRE* 10T, R=2.14m, 7.7 MA, H(y,2) = 1.1, α_n = 0.2



pop*H1p1an02.pdf

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}

FIRE could Access High-Gain Advanced Tokamak Regimes for Long Durations

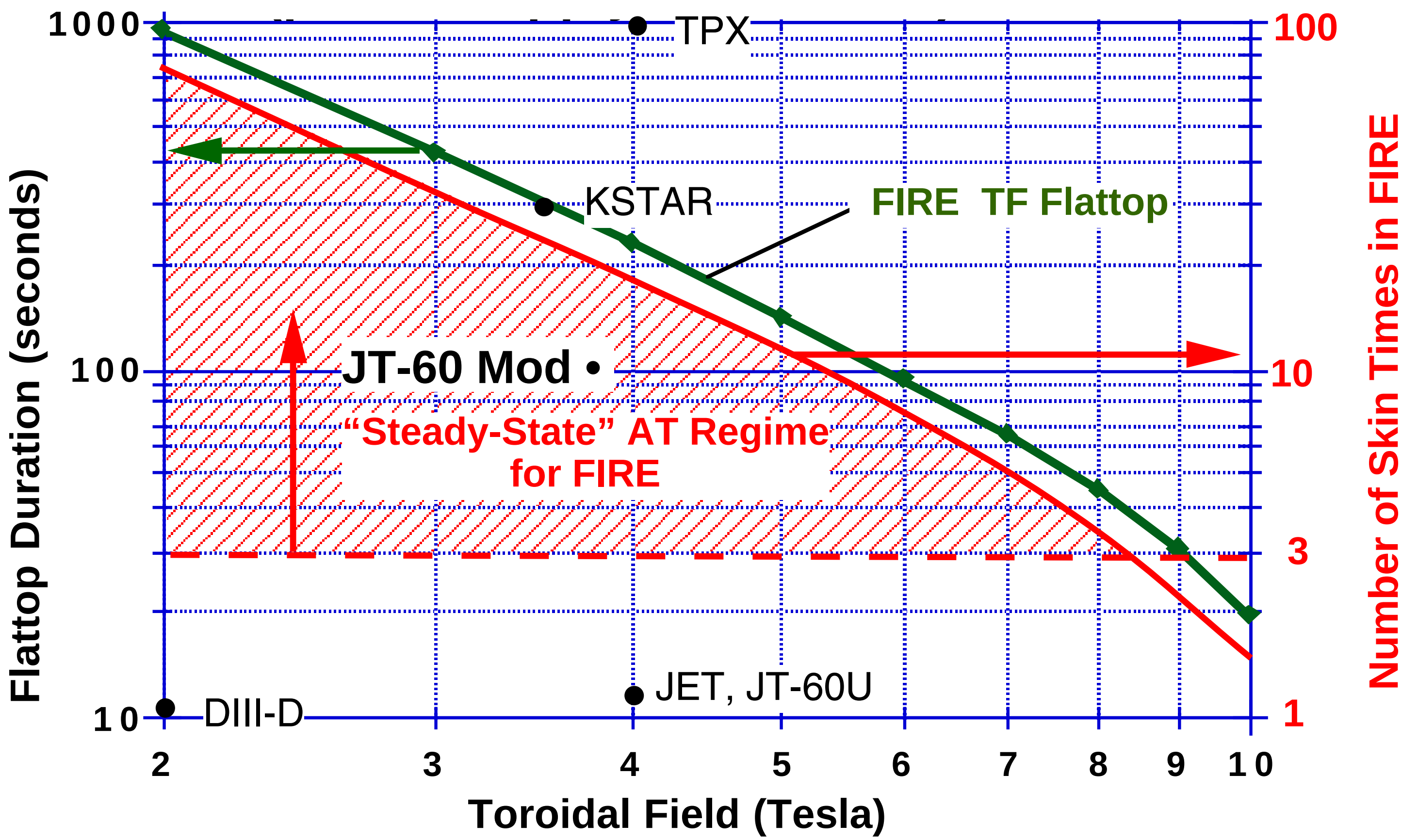
- The coupling of advanced tokamak modes with strongly burning plasmas is a generic issue for all advanced “toroidal” systems. The VLT PAC, Snowmass Burning Plasma and Energy Subgroup B recommended that a burning plasma experiment should have AT capability.

- 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} .

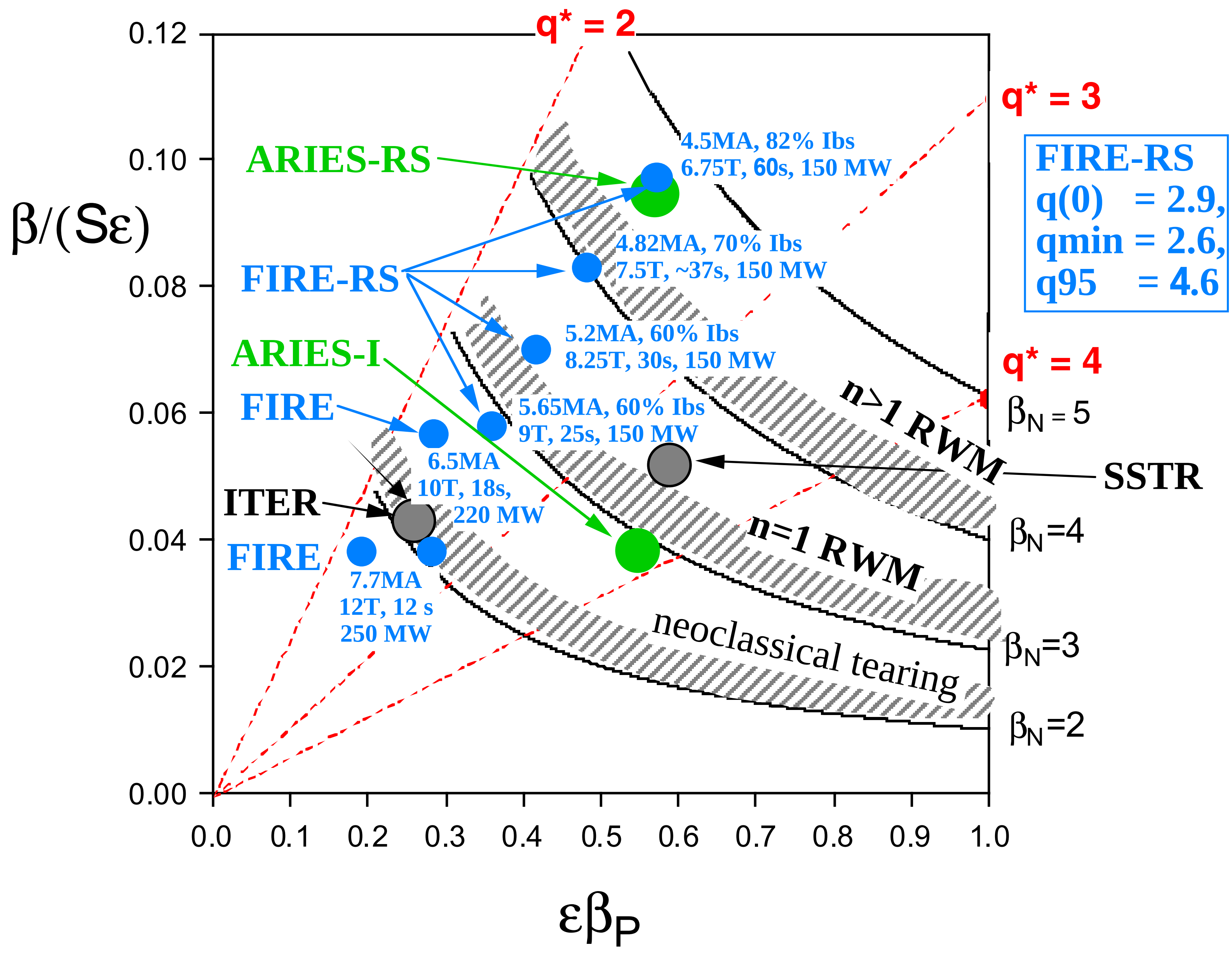
FIRE could Access "Long Pulse" Advanced Tokamak Mode Studies at Reduced Toroidal Field.



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 .

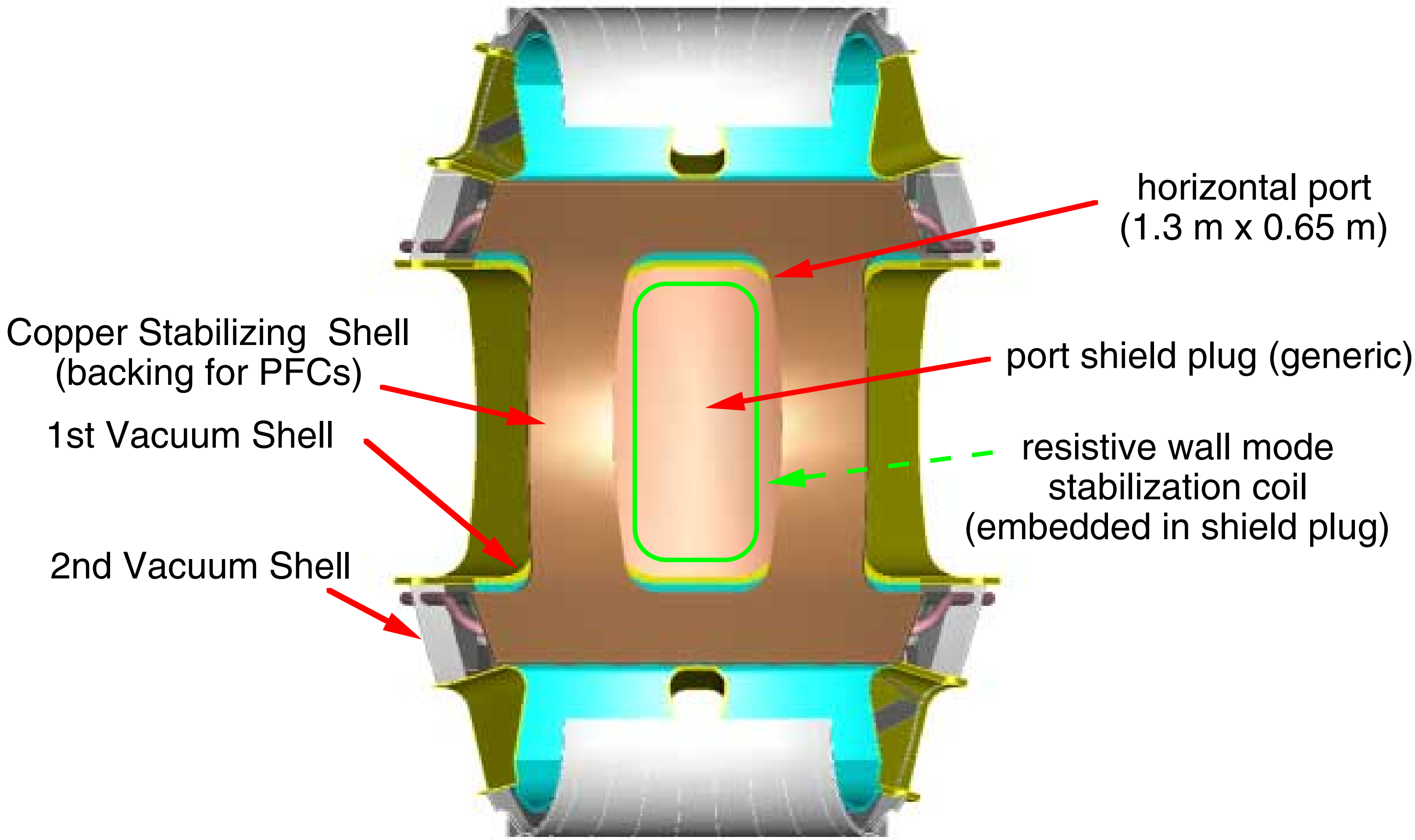
The combination of JET-U, JT-60 Mod, KSTAR and FIRE could cover the range fromsteady-state non-burning advanced-tokamak modes to "quasi-equilibrium" burning plasmas in advanced tokamak modes.

FIRE can Access MHD Regimes of Interest from Today's Data Base to those Envisioned for ARIES-RS



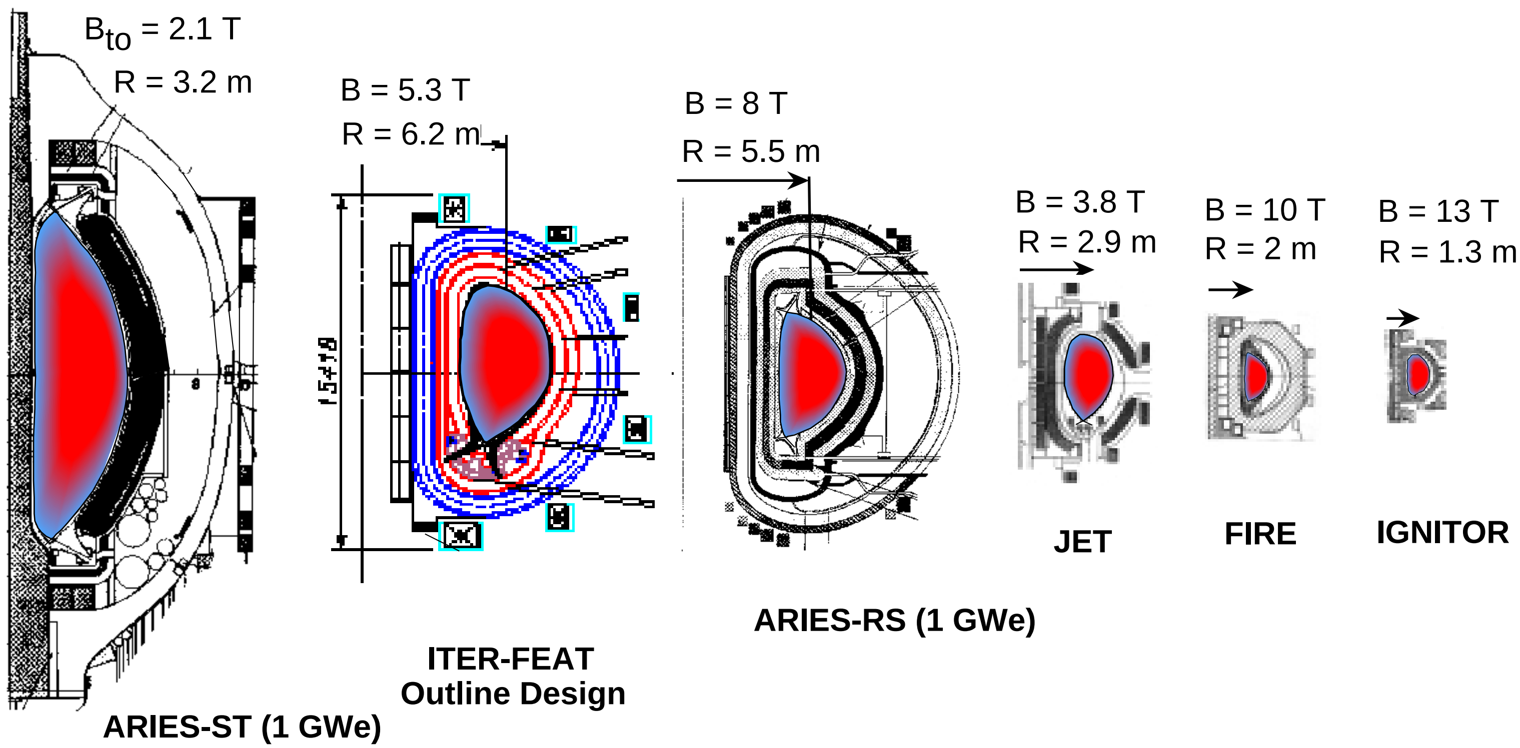
Potential for Resistive Wall Mode Stabilization System

view of hoizontal port front looking from plasma side



Concept under development by J. Bialek, G. Navratil, C.Kessel et al

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

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

Preliminary FIRE Cost Estimate (FY99 US$M)

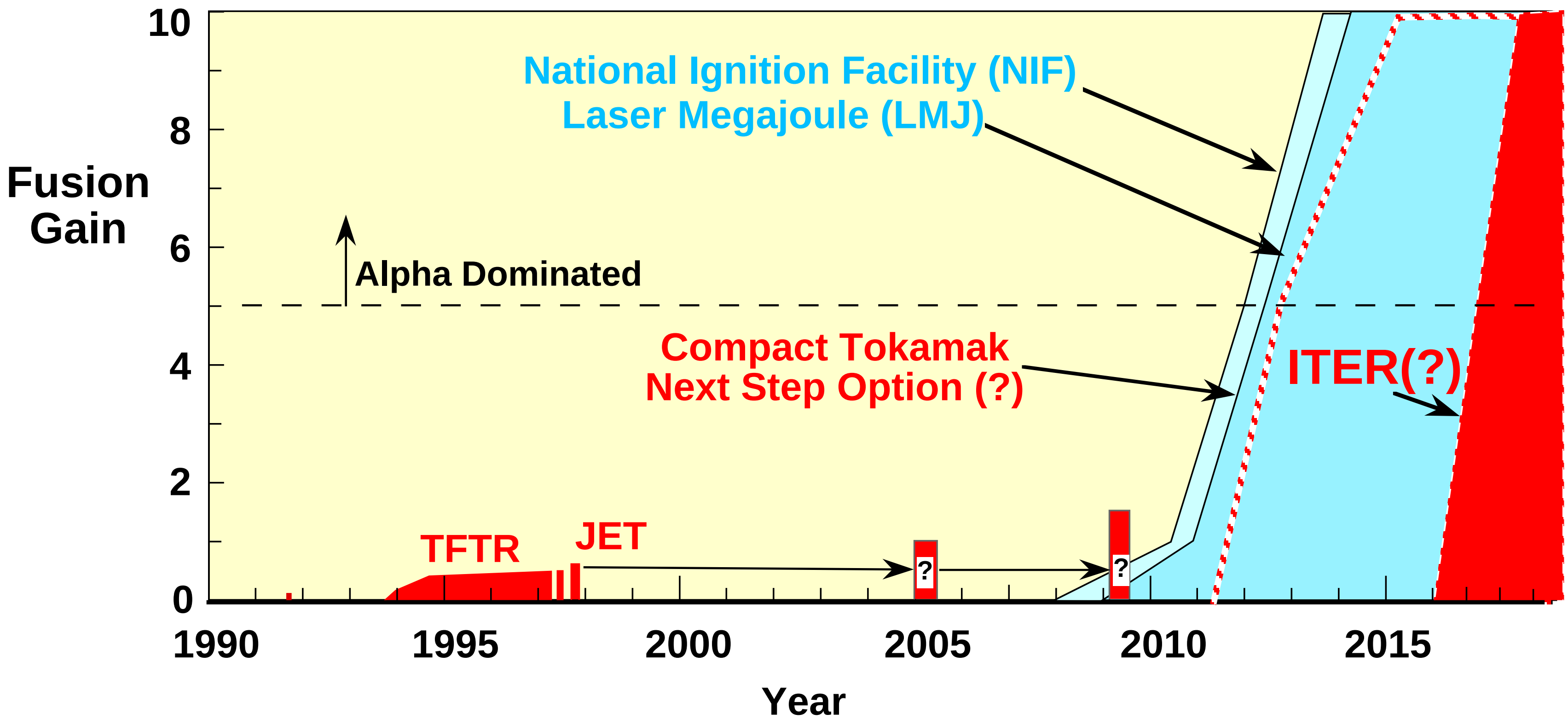
	Estimated Cost	Contingency	Total with Contingency
1.0 Tokamak Core	252.2	75.2	323.0
1.1 Plasma Facing Components	65.0	17.0	
1.2 Vacuum Vessel/In-Vessel Structures	35.2	9.7	
1.3 TF Magnets /Structure	113.8	37.2	
1.4 PF Magnets/Structure	28.4	8.5	
1.5 Cryostat	1.8	0.5	
1.6 Support Structure	7.5	2.2	
2.0 Auxiliary Systems	134.6	39.3	173.9
2.1 Gas and Pellet Injection	7.1	1.4	
2.2 Vacuum Pumping System	13.0	2.0	
2.3 Fuel Recovery/Processing	7.0	1.0	
2.4 ICRF Heating	107.4	34.9	
3.0 Diagnostics (Startup)	22.0	4.9	26.9
4.0 Power Systems	177.3	42.0	219.3
5.0 Instrumentation and Controls	18.9	2.5	21.4
6.0 Site and Facilities	151.4	33.8	185.2
7.0 Machine Assembly and Remote Maintenance	88.3	21.8	110.1
8.0 Project Support and Oversight	100.1	15.0	115.1
9.0 Preparation for Operations/Spares	16.2	2.4	18.6
Preconceptual Cost Estimate (FY99 US$M)	**960.9**	**236.9**	**1193.5**

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

This estimate is work in progress and will be reviewed in the winter 2000.

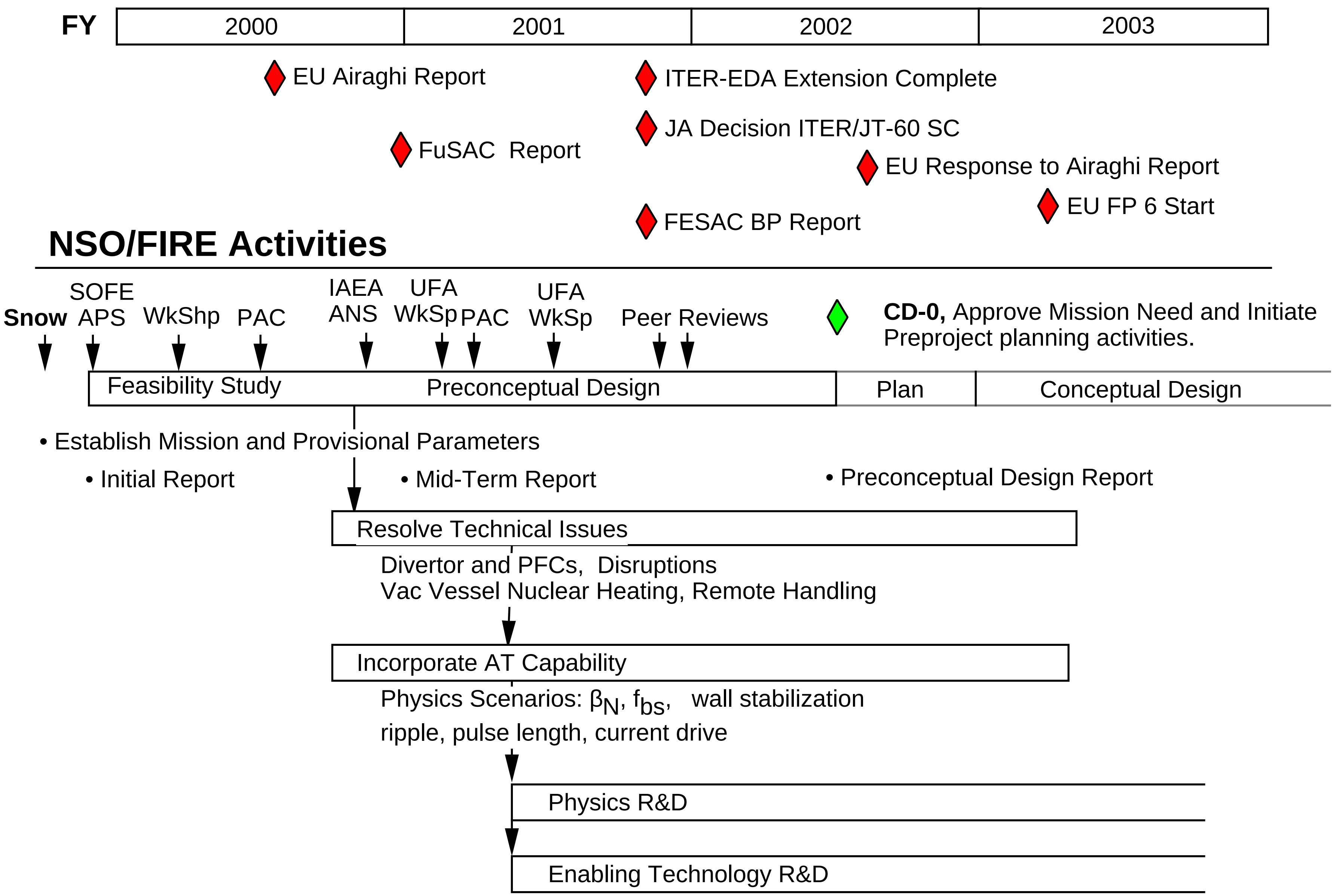
October 13, 2000

Timetable for "Burn to Learn" Phase of Fusion



- 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.

Timetable for a Major Next Step in MFE



Major Conclusions of the FIRE Design Study

- Exploration, understanding and optimization of fusion-dominated (high-gain) burning plasmas are critical issues for all approaches to fusion.

- The tokamak is a cost-effective vehicle to investigate fusion-dominated 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 fusion-dominated plasma issues, many of the long pulse advanced tokamak issues and begin the coupling of fusion-dominated plasmas with advanced toroidal physics in a $1B class facility.

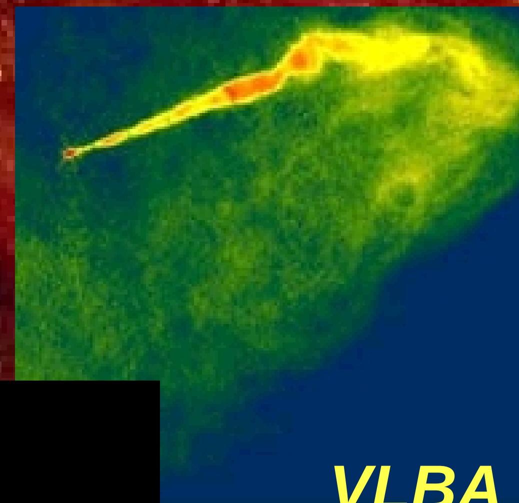
- The FIRE design point has been chosen to be a “stepping stone” between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.

- A plan is being developed for an Advanced Tokamak Next Step that will address physics, engineering and cost issues in FY 2000-2 with the goal of being ready to begin a Conceptual Design in 2003.

http://fire.pppl.gov

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

CHANDRA



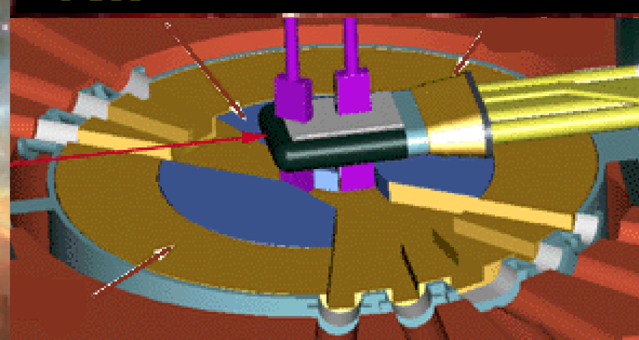
VLBA

NIF

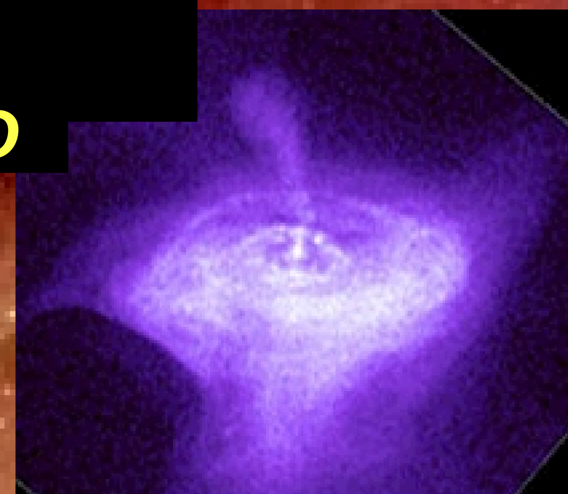
?

NSO

HST (NGST)



SNS



CHANDRA