FIRE

A Potential Next Step for Magnetic Fusion

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for the FIRE Team

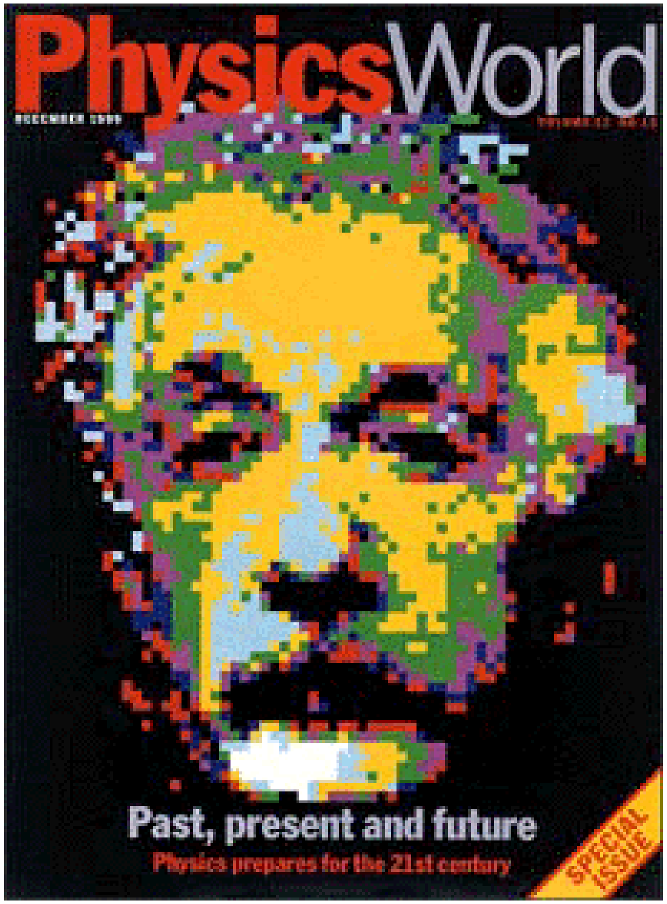
Presented at
Los Alamos National Laboratory
Los Alamos, NM

April 3, 2001

http://fire.pppl.gov

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

Outline and Main Points

Rational, Mission, Requirements and Readiness for Burning Plasma Experiment

- a compelling case must be made that has broad support
- UFA Wkp, NSO-PAC and FESAC will help define mission and requirements

FIRE Scientific Basis and Performance Projections

- evolving in response to community input
- Q ~ 10 for ≥ 1.5 skin times is goal (requires 7.7 MA @ 10T if ITER98H(y,2))
- add advanced tokamak (RS) capability

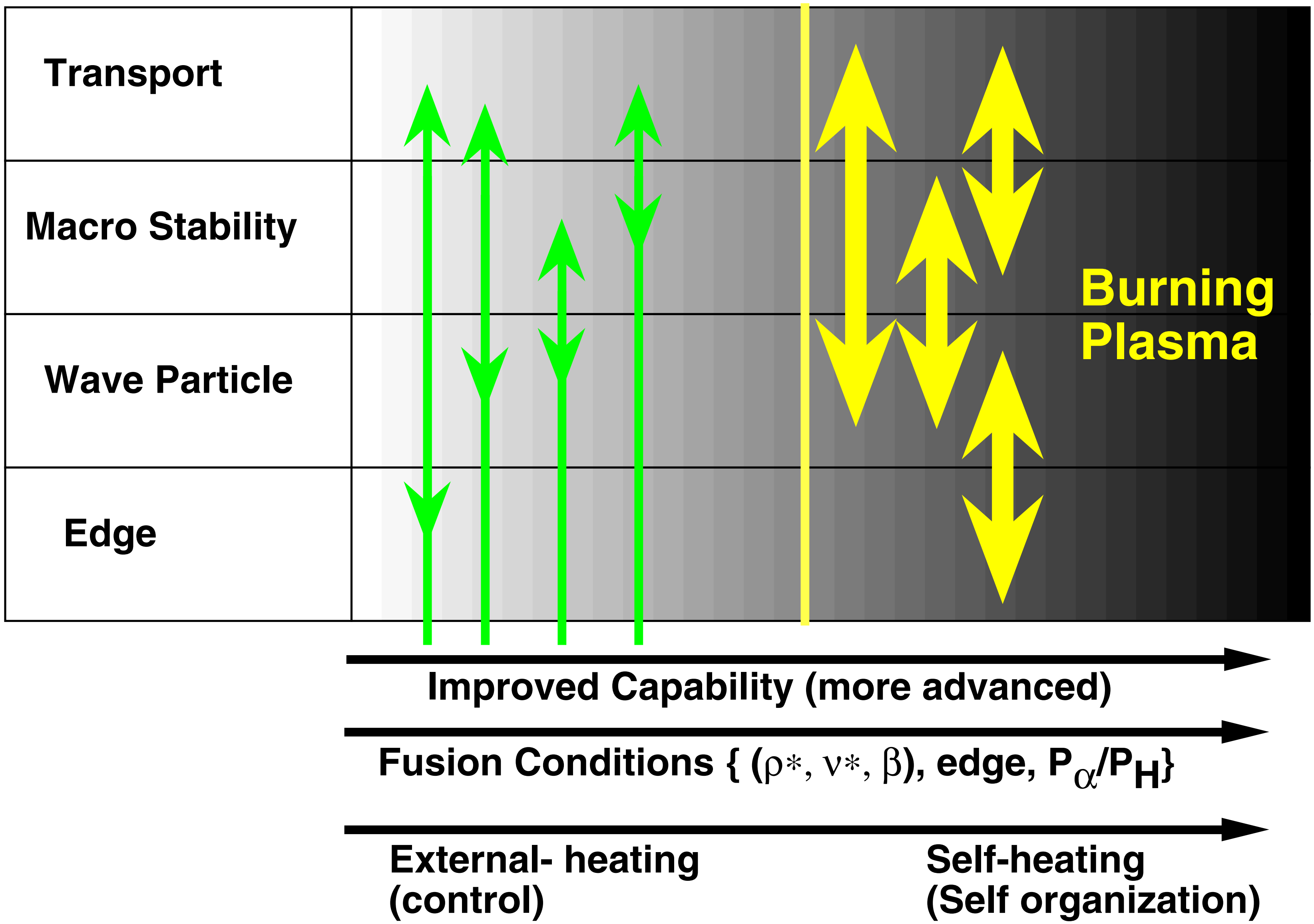
FIRE Engineering Basis

- Baseline wedged BeCu design meets new goals
- Looking for improvements - e.g., bucked and wedged TF

Plans

Magnetic Fusion Science

Issues - Strongly Coupled in a Fusion (Burning) Plasma



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

- 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.”

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
DOE OFES	Feb 01	LANL	Apr 01	SANL PP/FE	Apr 01

- **The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. Over 18,000 visitors from around the world have logged on to the FIRE web site since the site was initiated in July, 1999.**

UFA Workshop on Burning Plasma Science

First Workshop - 90 participants- December 11-13, 2000 University of Texas

- Extension of Madison Forum, Snowmass discussions on burning plasmas.
- Focused on Sciences Issues for/by burning plasmas
- Five Science Issue Breakout groups were established:
    1. Energetic Alpha Particles Issues for a Burning Plasma
    2. Confinement, Transport and Self-heating in Burning Plasma
    3. Macrostability in a Burning Plasma
    4. Boundary Plasma Science
    5. Relationship of Burning Plasma Science to Other Fields
- Strong nonlinear coupling that will occur in a strongly burning plasma was an overall theme. Action Item - need to develop a more compelling case.
- Some sentiment that a BP might be boring, that is, extrapolation too small from existing parameters. Others, expressed concern that strongly burning plasmas in an AT configuration with high bootstrap would be uncontrollable. Several areas identified where tokamak BP would shed light on understanding science issues for other configurations.

Second Workshop May 1-3, 2001 at General Atomics, **http://lithos.gat.com/bps2/**

Next Step Option Program Advisory Committee

- **Members:** Tony Taylor (Chair), Gerald Navratil, Ray Fonck, David Gates, Dave Hill, Wayne Houlberg, Tom Jarboe, Mitsuro Kikuchi, Earl Marmar, Raffi Nazikian, Craig Petty, Rene Raffray, Paul Thomas, James VanDam

- **Meetings**
  July 20-21, 2000 at General Atomics, San Diego, CA.
  January 17-18, 2001 at MIT, Cambridge, MA
  July 11-12, 2001 at Univ. Wisc, Madison, WI

- **Charge for First and Second meetings**
  Scientific value of a Burning Plasma experiment
  Scientific readiness to proceed with such an experiment
  Is the FIRE mission scientifically appropriate?
  Is the initial FIRE design point optimal?

- Extensive PAC Reports provide detailed recommendations for the FIRE activity to address. NSO-PAC reports are on FIRE (http://fire.pppl.gov), will discuss in more detail under FY 2001-03 Plans.

Common Themes Emerging from NSO-PAC, UFA Workshop and Community Discussions

Scientific Basis

an experiment with flexibility, affordable first step with capability for later upgrades .

able to access fusion dominated (P_{α} /P_{heat} ≥50%) — **increased Ip 6.44 MA to 7.7 MA**

reduced aspect ratio to 3.6

plasma sustained at least 1 -2 skin times — **increased size R = 2.0m to 2.14m**

address issues central to fusion science — **developing AT scenario for FIRE**

Technical Basis and Status

LN Cu coil tokamak can satisfy the scientific requirements. **What is the optimum config.?**

Baseline Wedged (BeCu) design meets requirem‘ts, will start peer review critical systems.

Beginning design of a Bucked and Wedged (Cu) Configuration.

Internal hardware and PFCs are a common challenge for tokamaks and other MF configs.

Community Involvement

Must develop a **more exciting and compelling case** for a next step magnetic fusion exp‘t.

Presently an outreach emphasis, **must transition to greater community involvement**.

UFA workshops, Science Initiatives for NSO, etc are opportunities for progress.

Vision and Mission for a Major Next Step in Magnetic Fusion

FIRE Vision Statement (some suggestions)

- **Lighting the Fusion Fire**
- Lighting the Way to the Future
- Exploring, Explaining and Expanding the frontiers of plasma science

FIRE Mission Statement

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

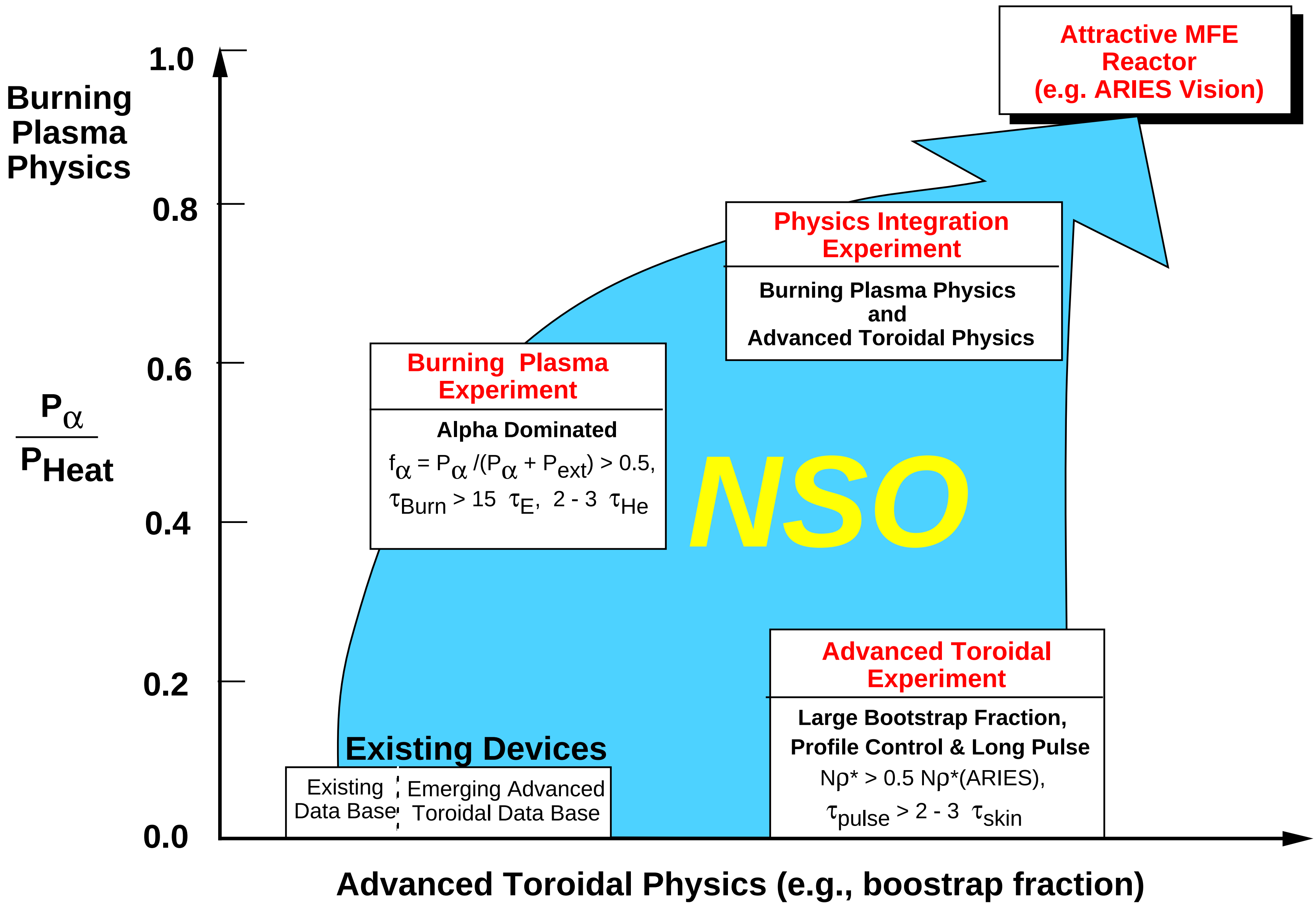
Fusion Science Objectives for a Major Next Step Magnetic Fusion Experiment

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.

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

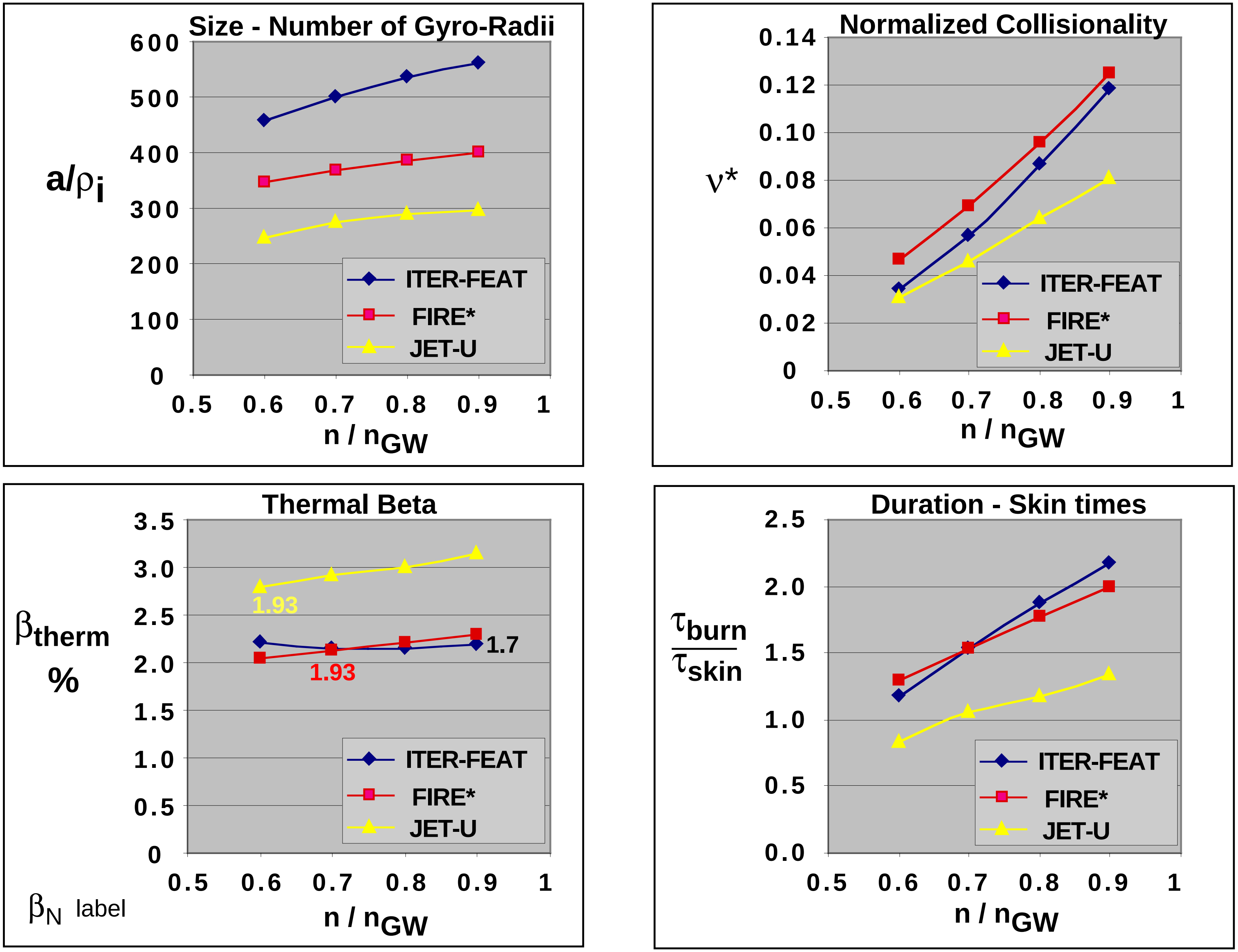
	Core*	Edge	Alpha	Duration			
	$BR^{5/4}$	?	P_α/P_{heat}	$\tau/\tau_{\alpha s}$	τ/τ_E	τ/τ_{He}	τ/τ_{CR}
<u>Explore and Understand Fusion Plasmas</u>	>0.5		>0.5	>3	>5	>3	>3
Energy and Particle Transport							
Macroscopic Stability							
Wave Particle (alpha heating, fast alpha)			β_α ~ ARIES				
Plasma 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 $BR^{5/4}$

$$P_\alpha /Pheat = Q /(Q + 5)$$

Dimensionless Parameters for Potential Next Step D-T Plasmas

ITER-FEAT (15 MA): Q = 10, H = 0.95, FIRE*(7.7 MA): Q = 10, H = 1.03, JET-U (6 MA): Q = 0.64, H = 1.1



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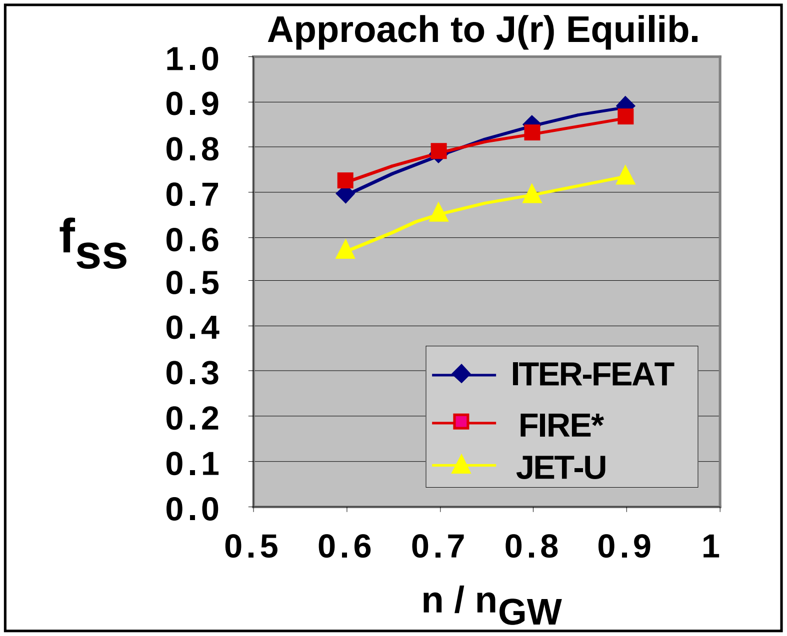
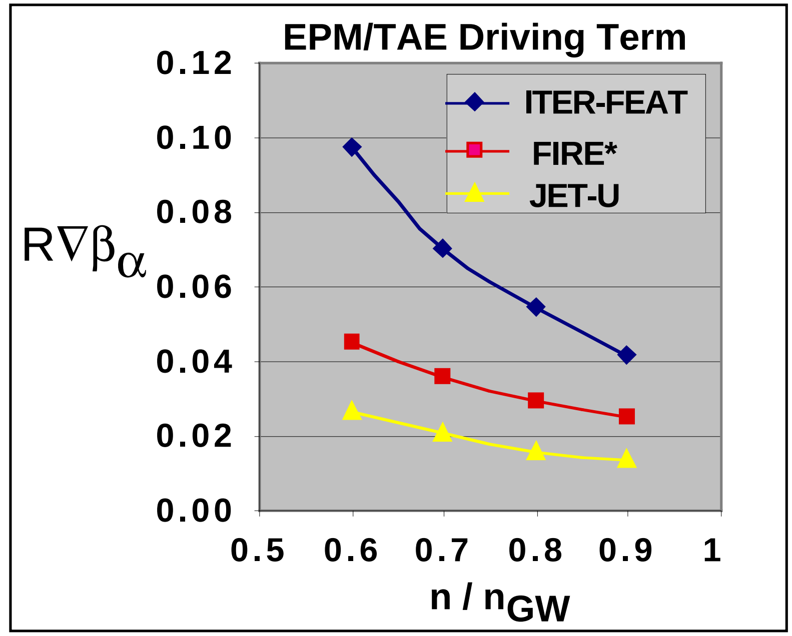
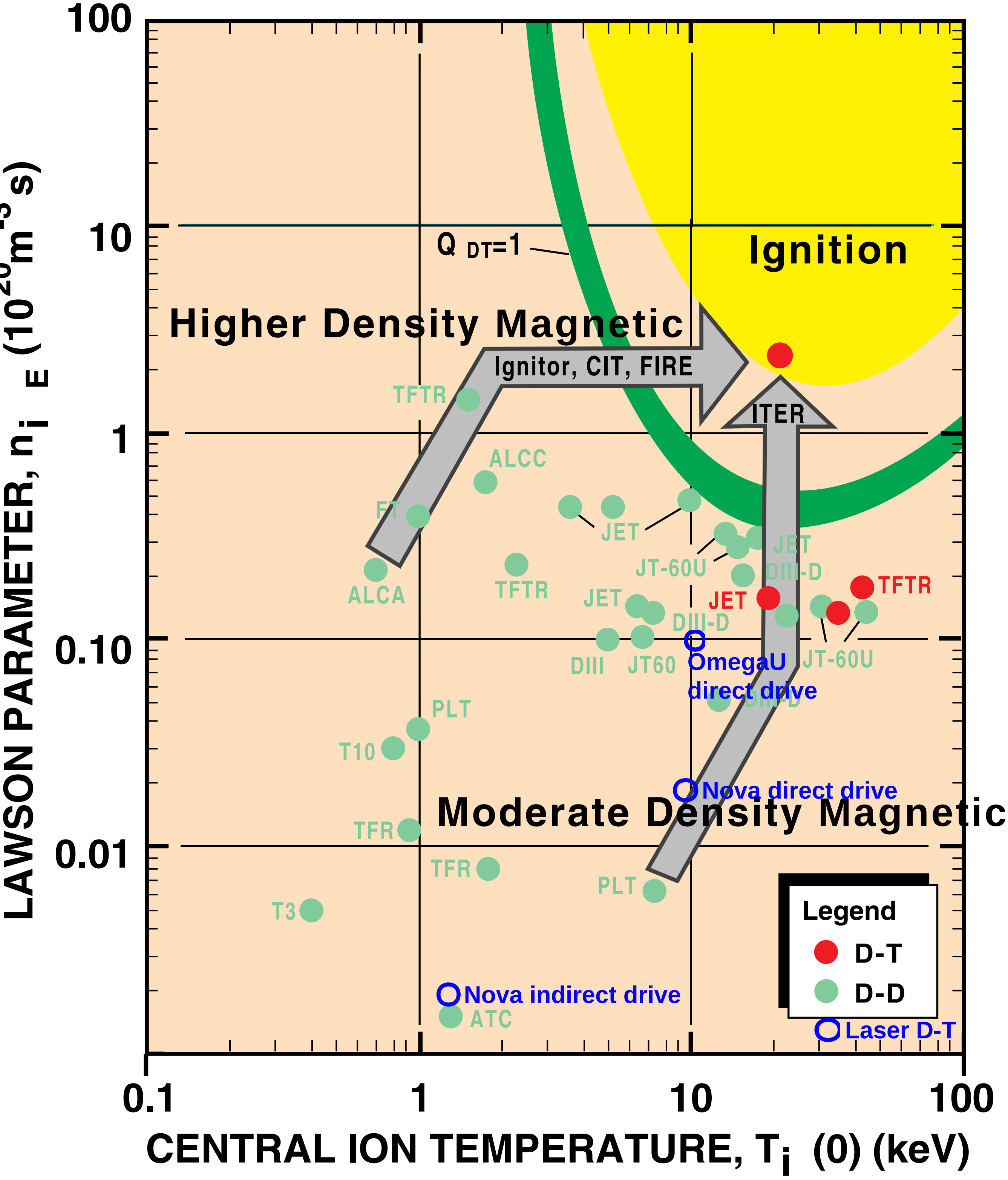




Summary Points on Dimensionless Parameters

- FIRE is a modest extrapolation in ρ^* and $R\nabla\beta_\alpha$, is this good or bad?
- Other FIRE and ITER-FEAT dimensionless parmaeters are quite close.
- JET-U (4T, 6 MA) parameters are substantially less, esp Q or $f_\alpha = P_\alpha$/Pheat. Large population of RF or NB ions will damp EPM/TAE modes.

Status of Laboratory Fusion Experiments

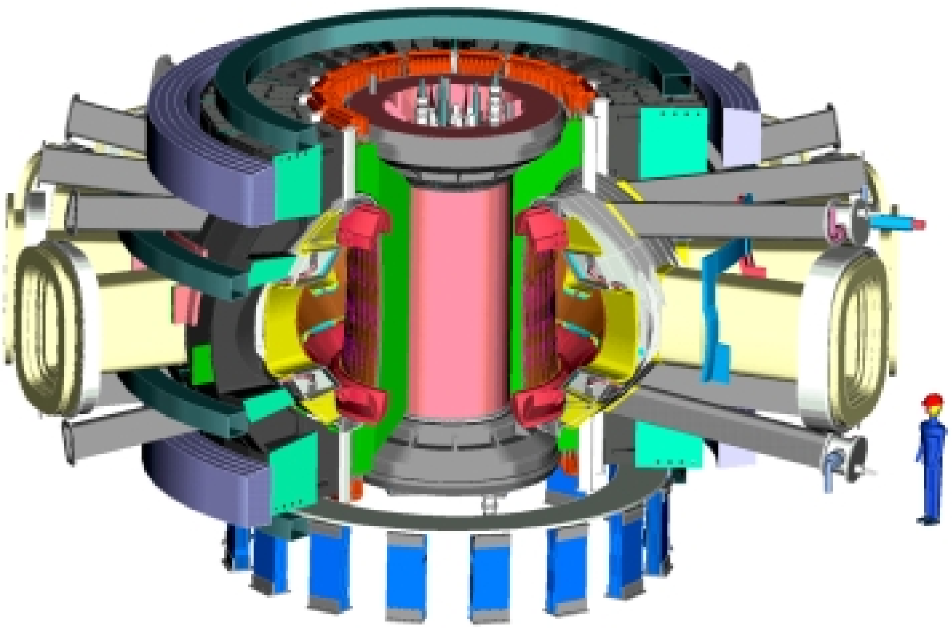


#97GR041.ntau-98 FIRE

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

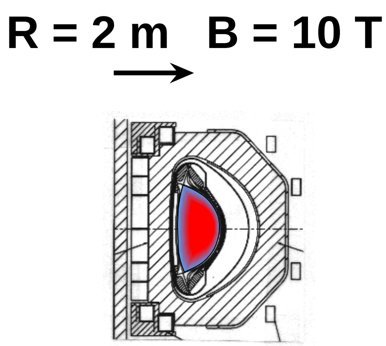
Higher Field Mode B = 12T and Ip = 7.7MA with a 12 second flat top has been identified.
Also enhanced performance option B = 10T, Ip = 7.7 MA with 20 s burn with R = 2.14m

FIRE would have Access for Diagnostics and Heating

FIRE is being Designed to Test the Physics and In-Vessel Technologies for ARIES-AT

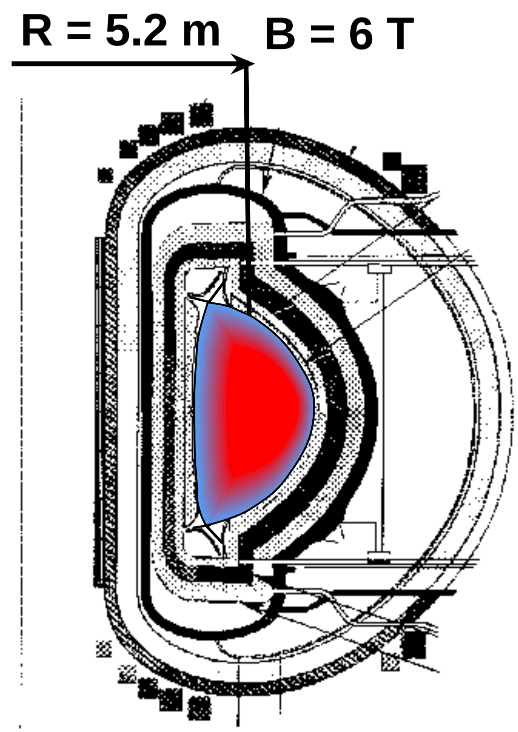
P_{fusion} = ~ 200 MW

Volume = 18 m^3



FIRE

~ 3X



ARIES-AT The "Goal"

P_{fusion} = 1755 MW

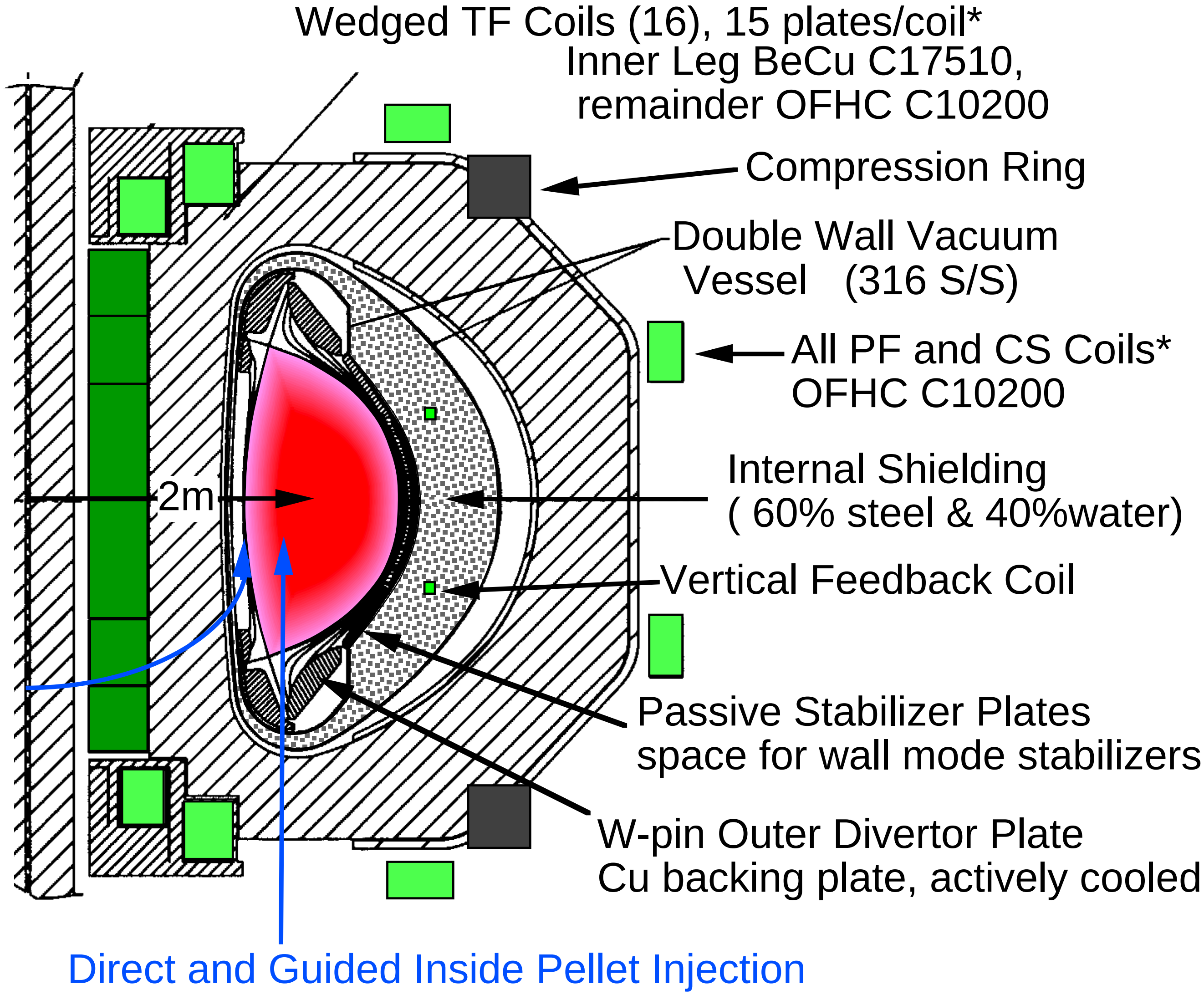
Volume = 330 m^3

	FIRE	ARIES-AT
Fusion Power Density (MW/m^3)	12	5.3
Neutron Wall Loading (MW/m^2)	3	3.5
Divertor Challenge (Pheat/R)	25	~70
Power Density on Div Plate (MW/m^2)	~25 $\rightarrow$ 5	~5
Burn Duration (s)	~20	steady

FIRE Incorporates Advanced Tokamak Innovations

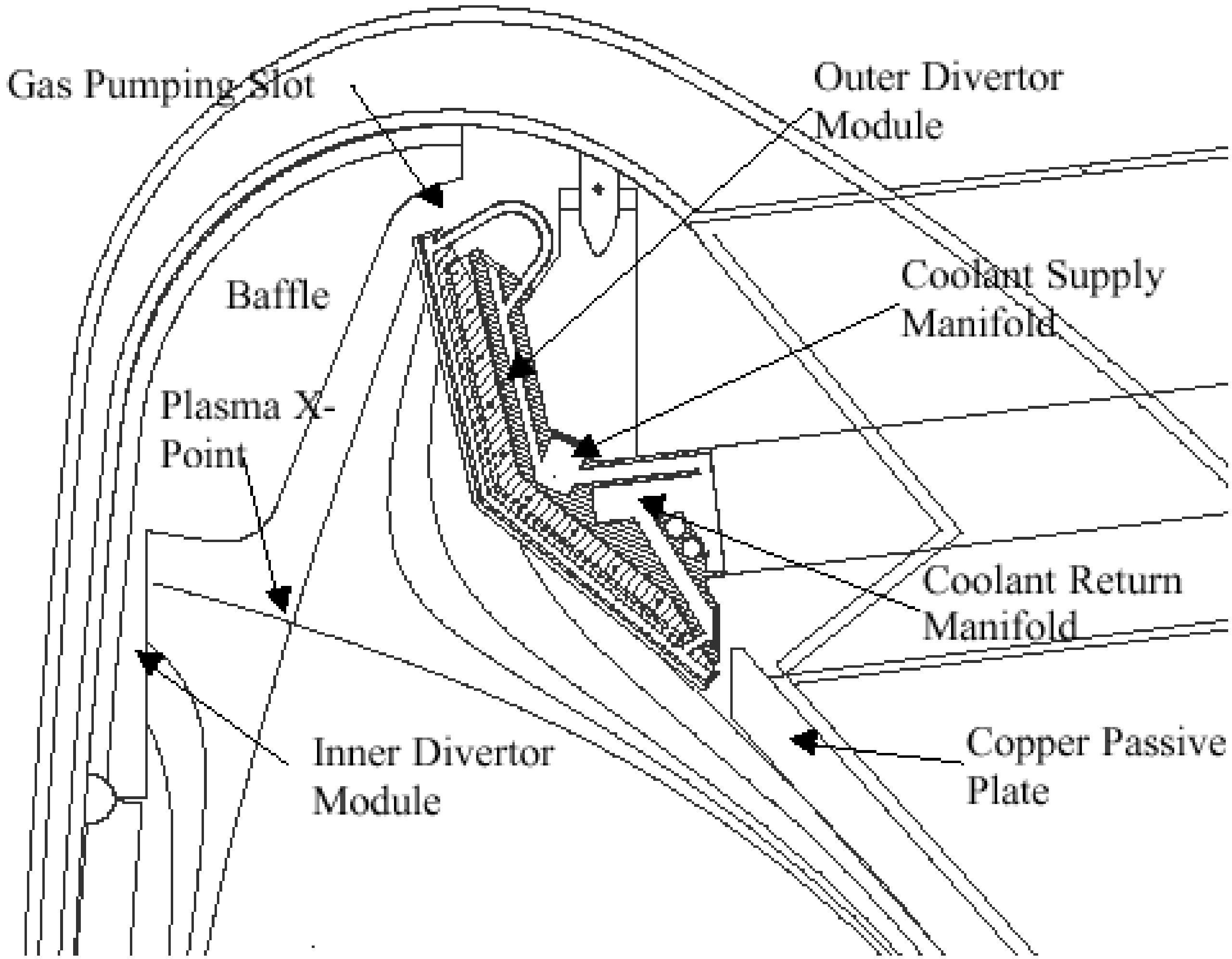
AT Features

- DN divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



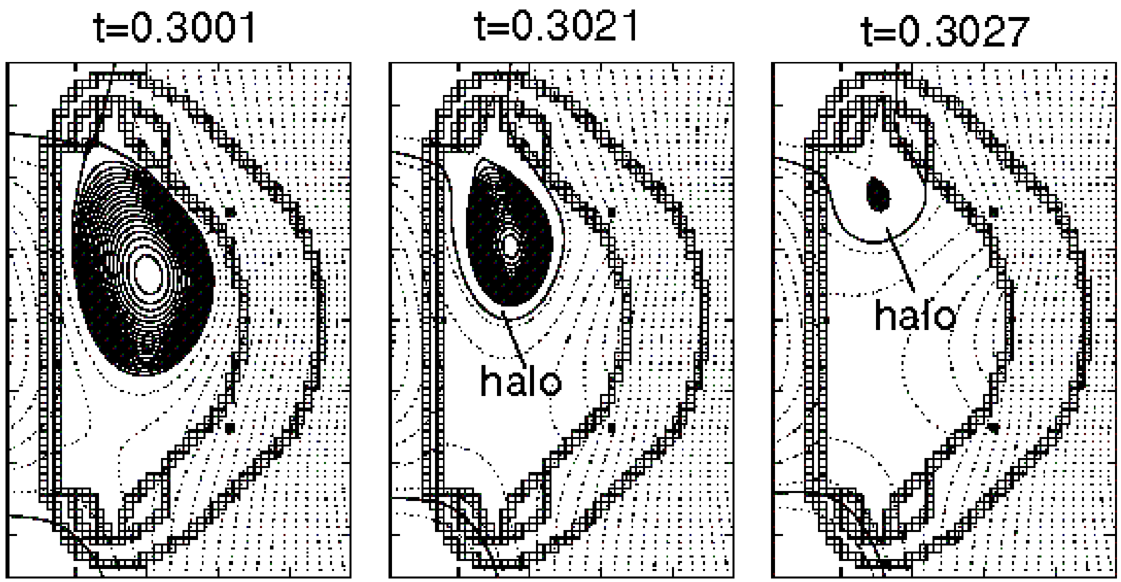
*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

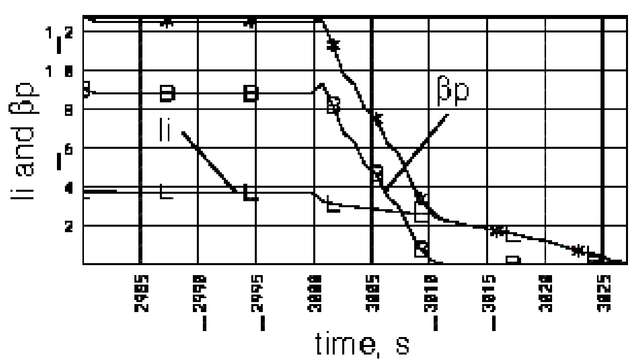
FIRE's Divertor Must Handle Attached(25 MW/m2) and Detached(5 MW/m2) Operation

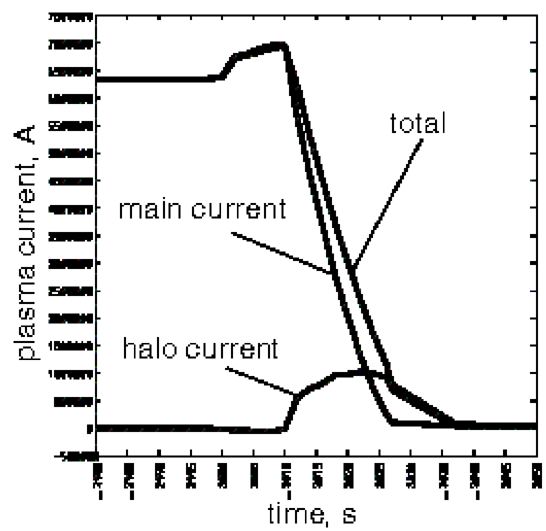


FIRE Must Handle Disruptions

VDE Simulation with 3 MA/ms Current Quench







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)

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

  - $\langle H(y,2\rangle = 1.1$, $\langle n(0)/\langle n\rangle_v\rangle = 1.2$

- 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

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

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

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

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

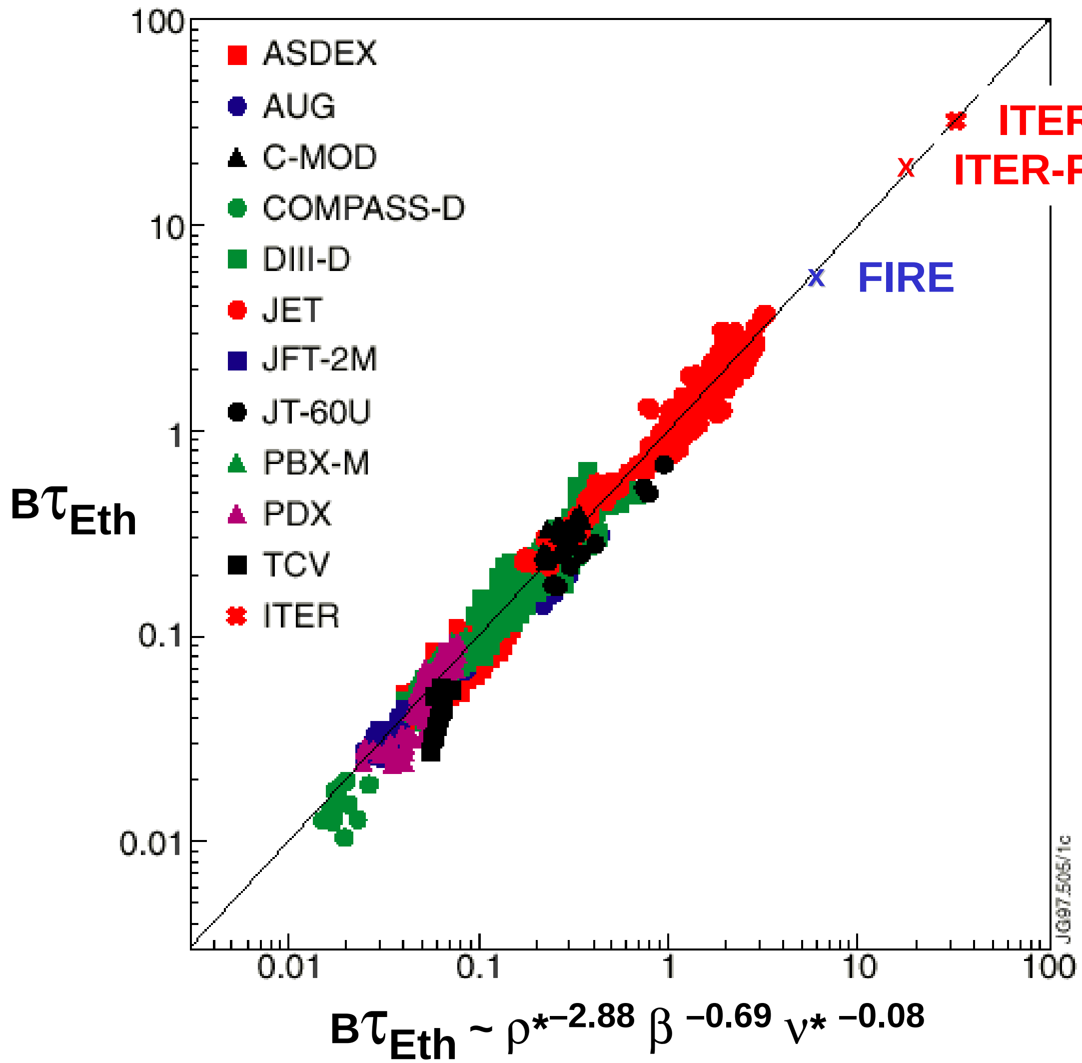
Understanding is mainly empirical. Better understanding is needed from existing experiments with improved simulations, and a benchmark in fusion-dominated plasmas is needed to confirm and extend the science basis.

FIRE is a Modest Extrapolation in Plasma Confinement

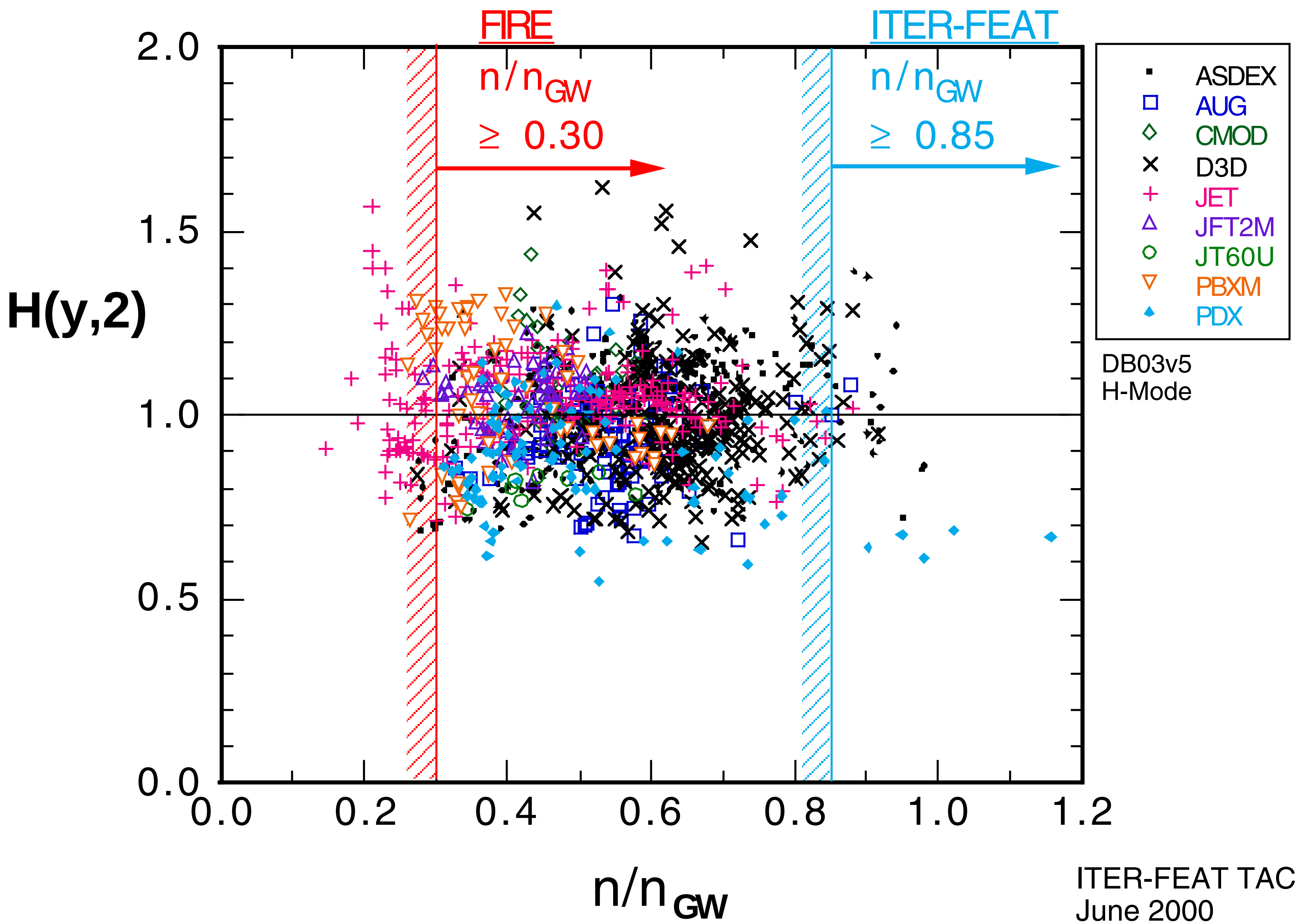
Dimensionless Parameters
$\omega_c\tau$
$\rho^* = \rho/a$
$\nu^* = \nu_c/\nu_b$
β

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

Kadomtsev, 1975

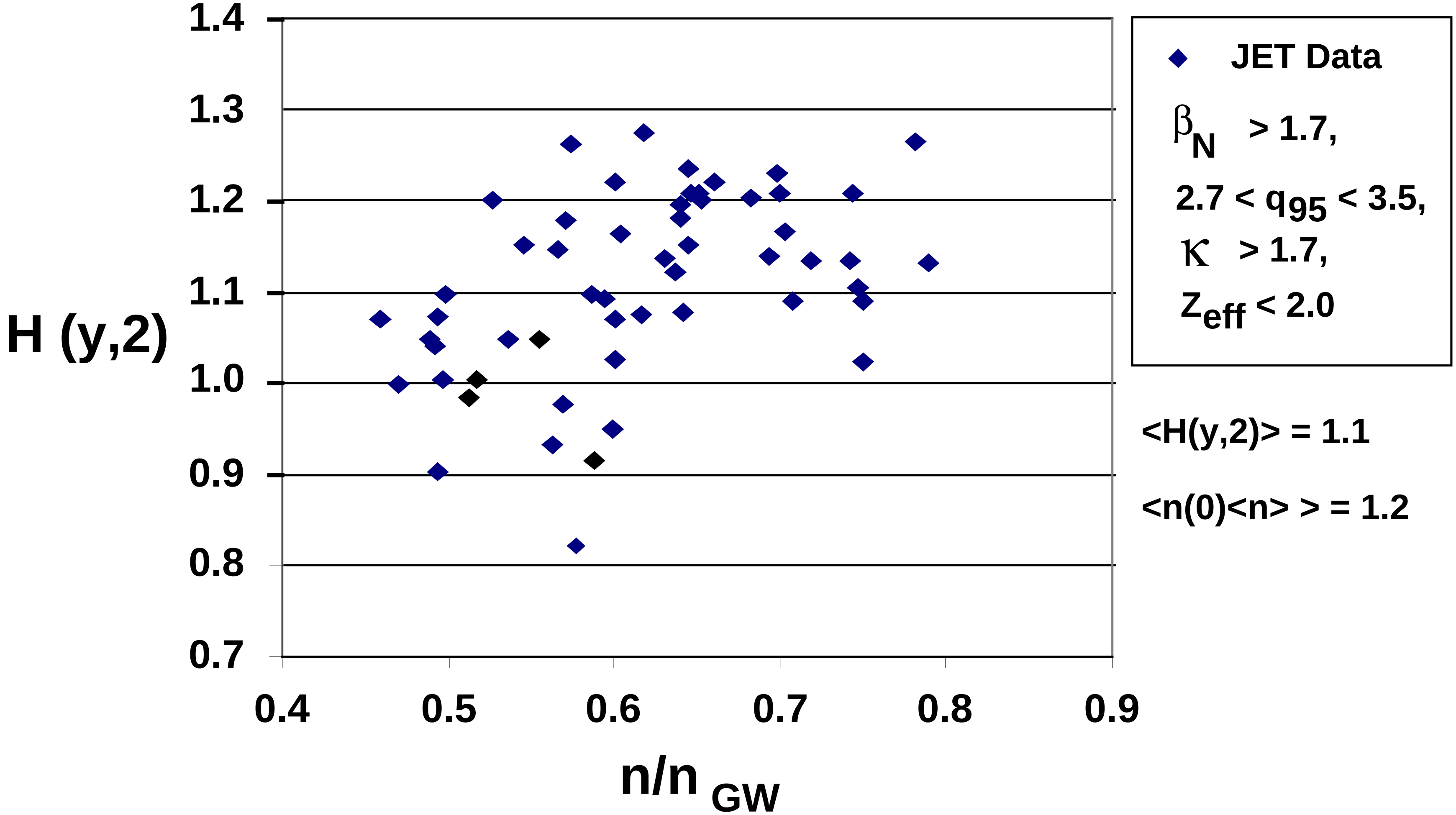


FIRE can Access Most of the H-Mode Database



ITER-FEAT TAC Meeting
June 2000

JET H-Mode Data Selected for FIRE-like Parameters

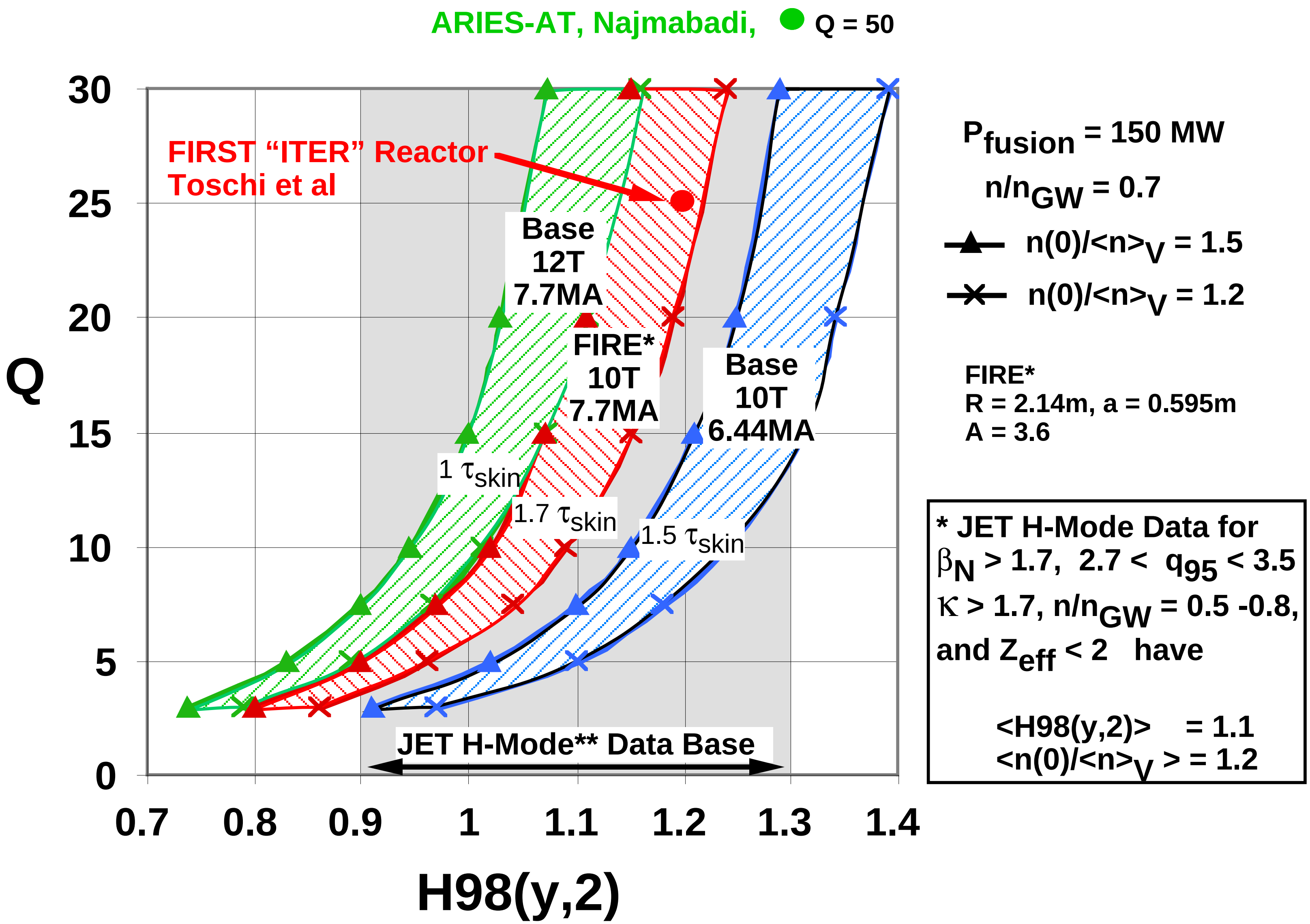


<H(y,2)> = 1.1

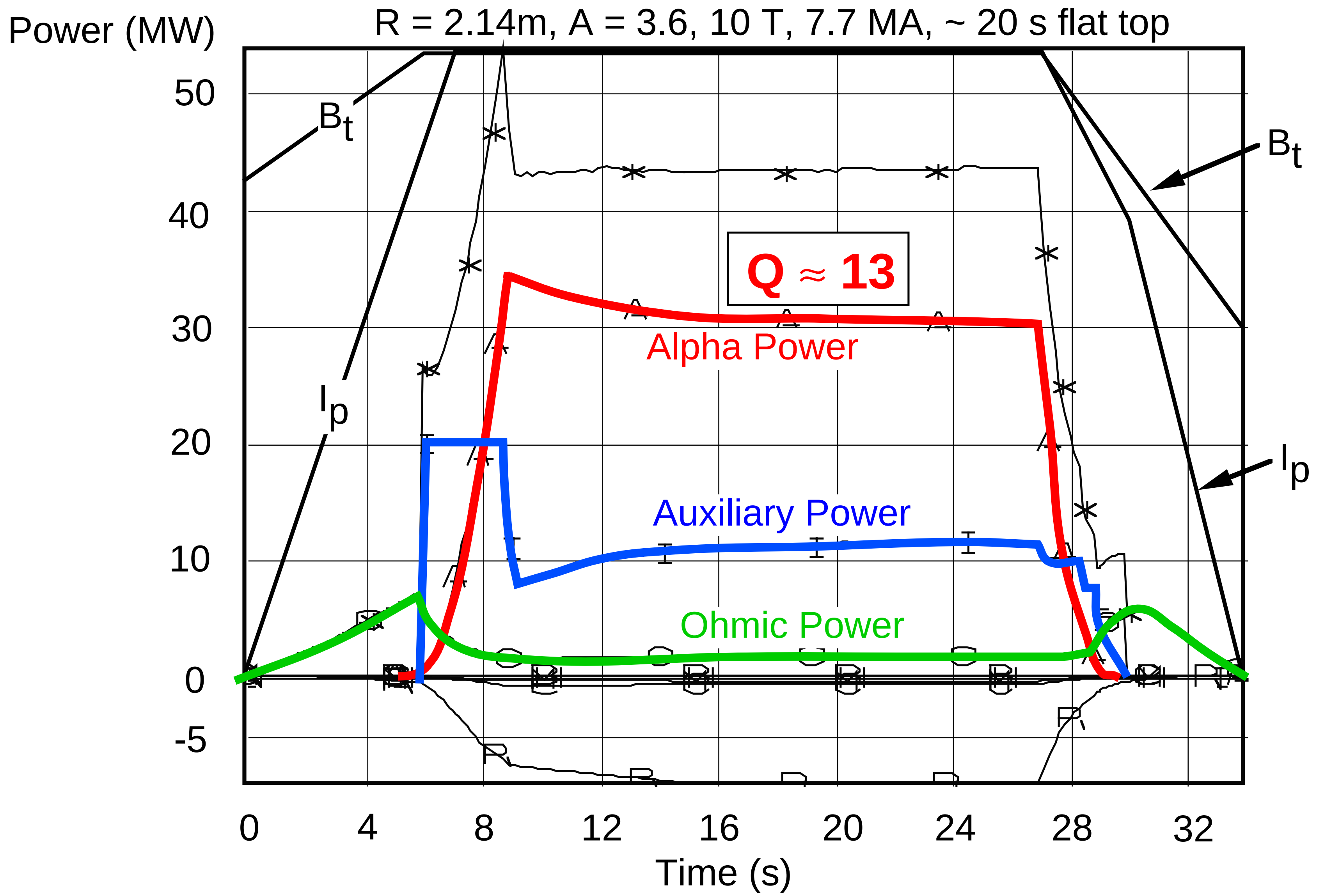
<n(0)<n> > = 1.2

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

Projections of FIRE Compared to Envisioned Reactors

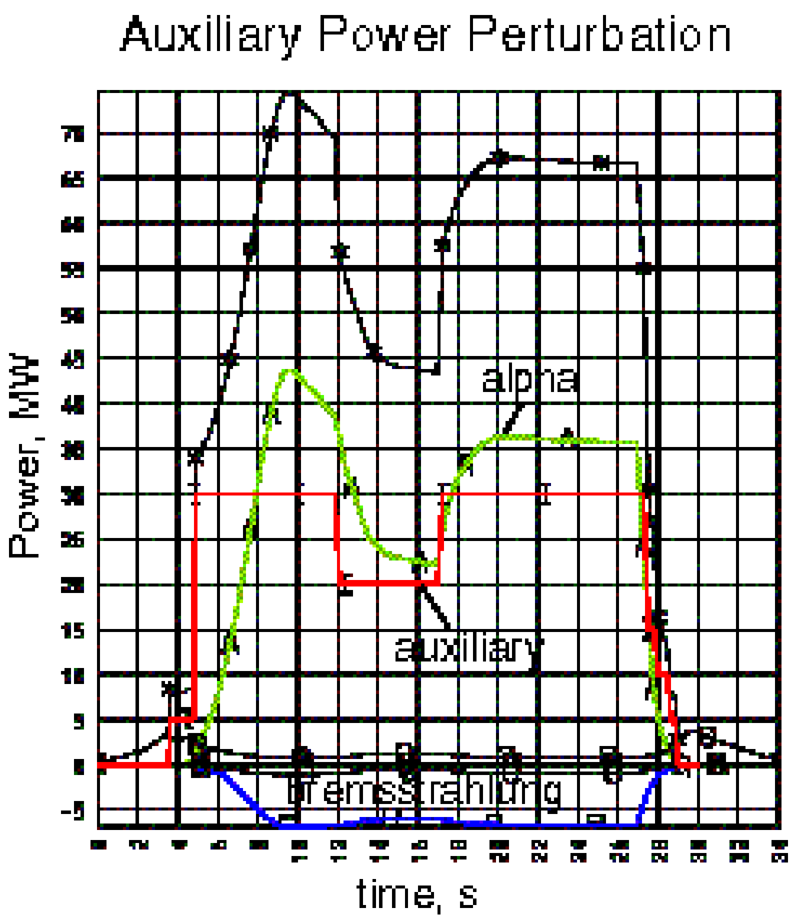


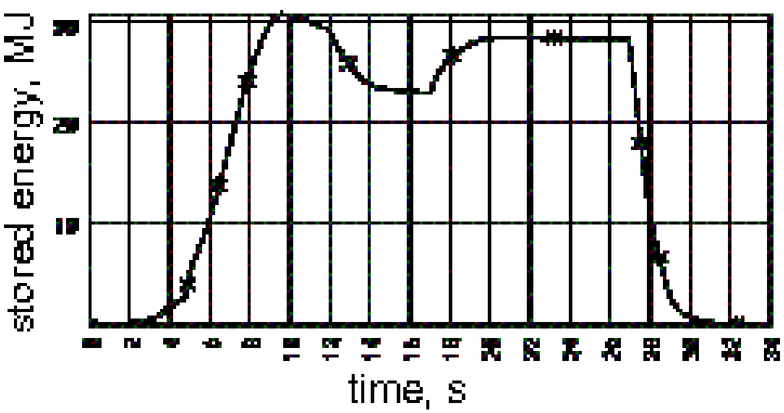
1 1/2-D Simulation of Burn Control in FIRE* (TSC)

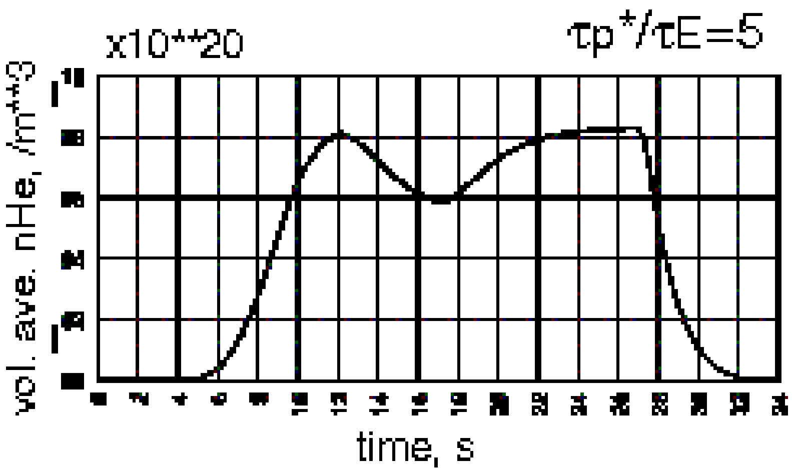


- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and n/n_{GW} = 0.67
- Burn Time ≈ 18 s ≈ 21 τ_E ≈ 4 τ_{He} ≈ 2 τ_{skin}

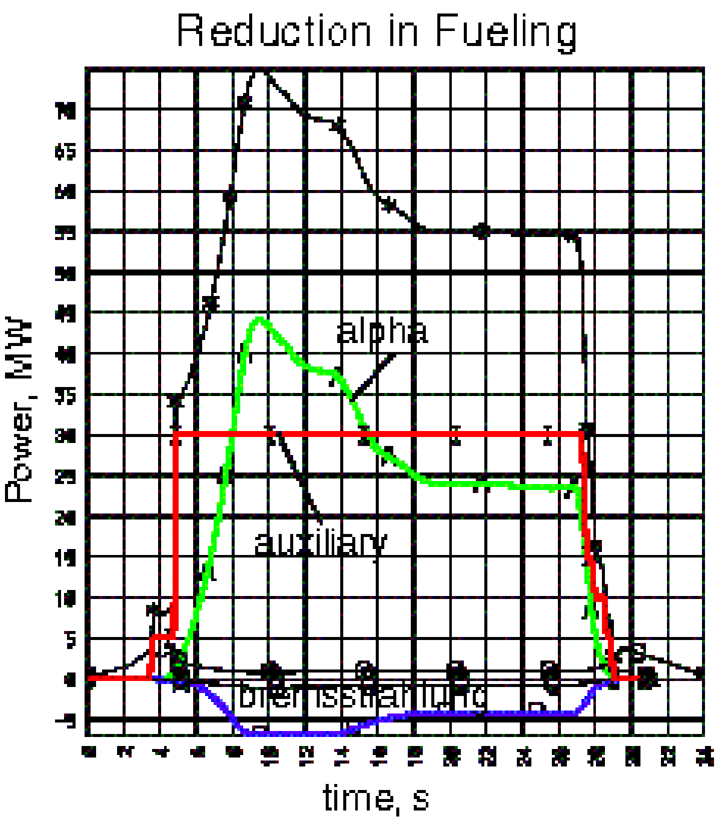
Plasma Response to P_{aux} Modulation

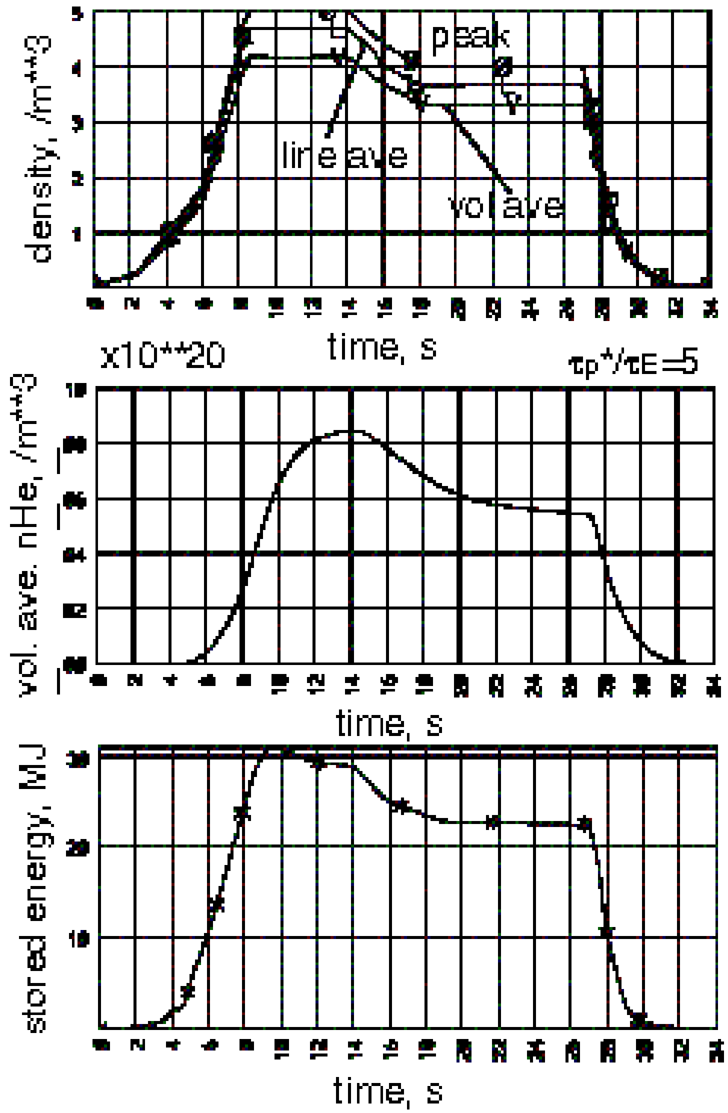




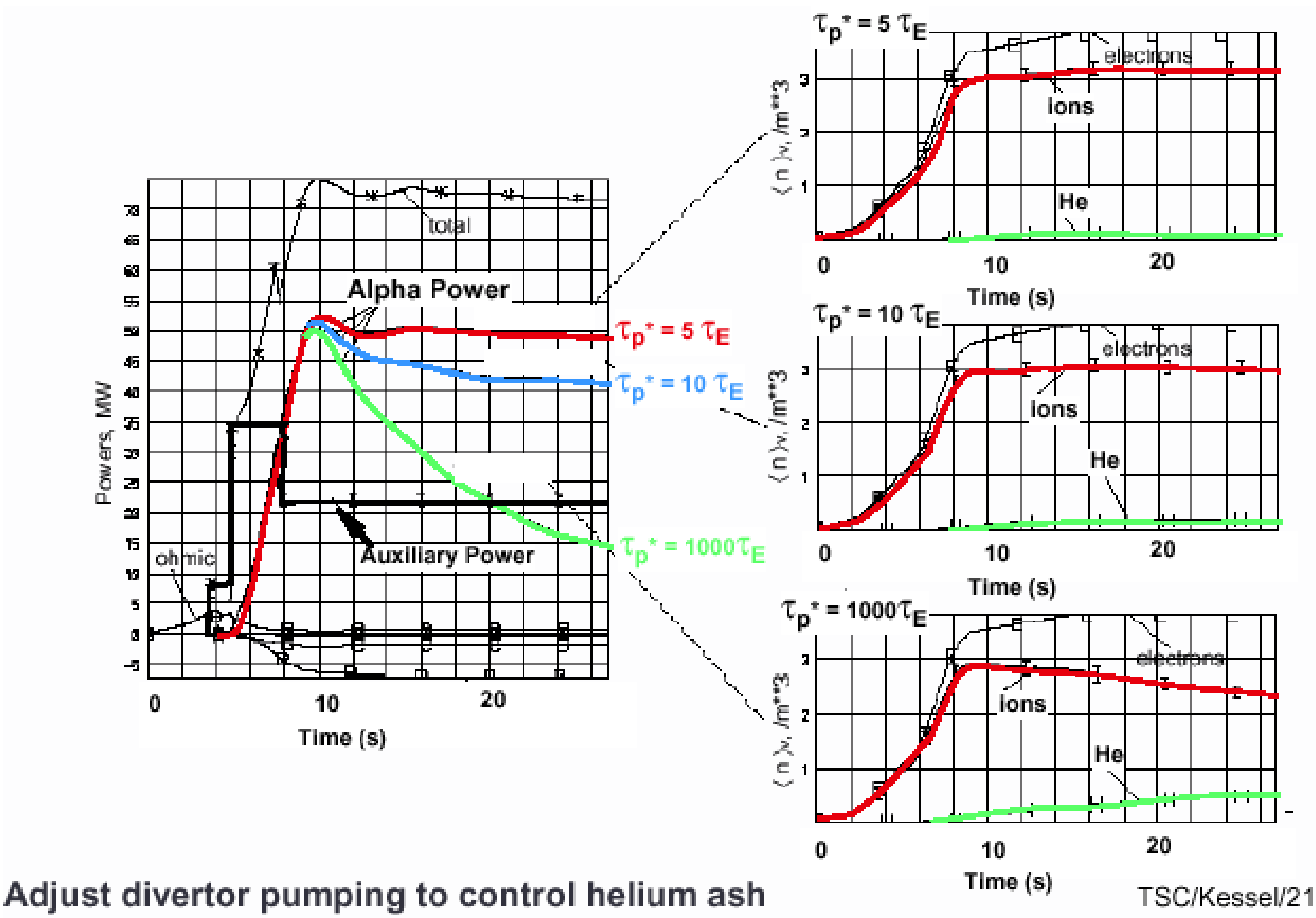


Plasma Response to Fueling Modulation





Divertor Pumping Needed for Plasma Burn



Adjust divertor pumping to control helium ash

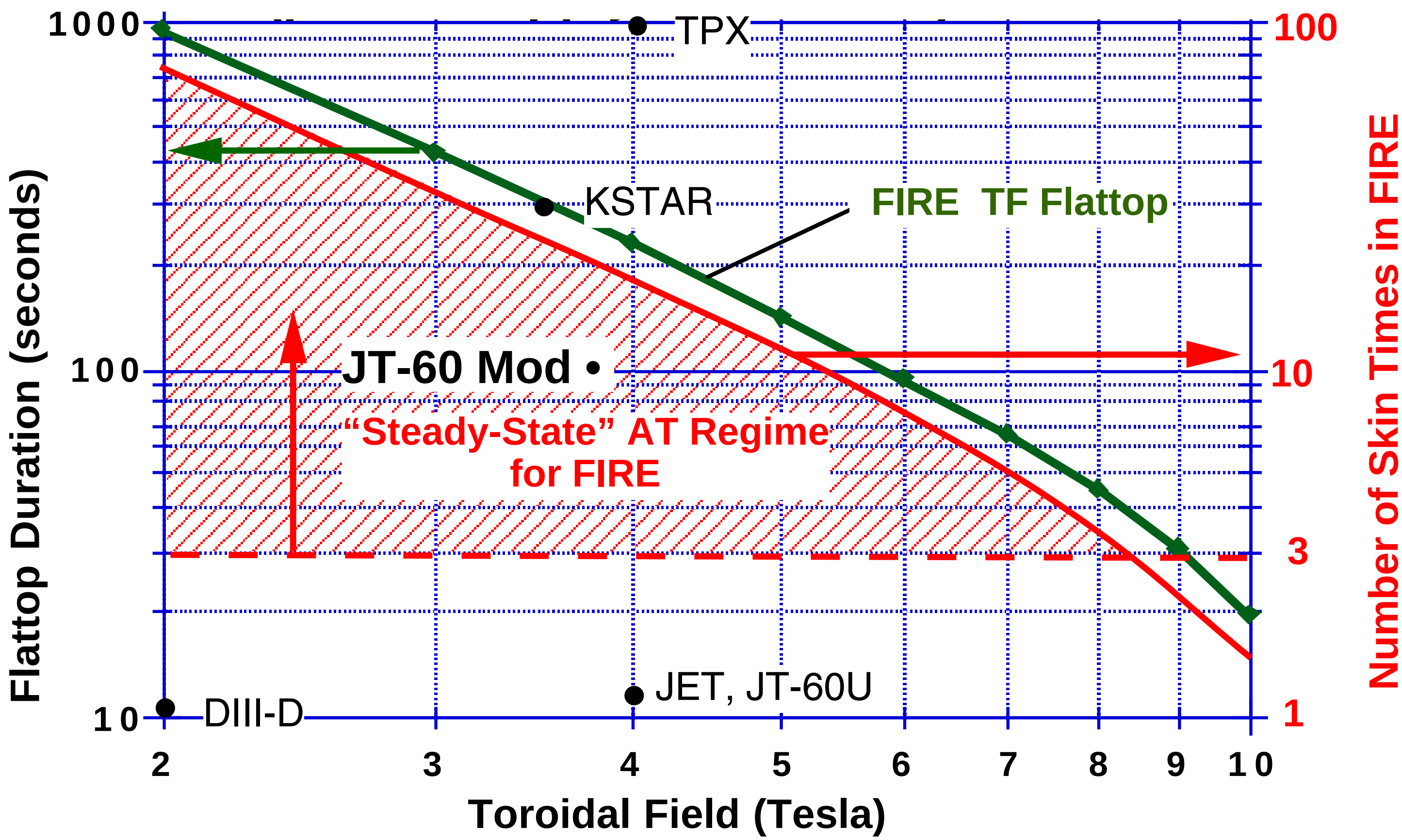
TSC/Kessel/21-q.ps

FIRE Has Several Operating Modes Based on Present Day Physics

- Reference: ELMing H-mode
  - B=10 T, Ip=6.5 MA, Q=5, t(pulse)=18.5 s
- High Field: ELMing H-mode
  - B=12 T, Ip=7.7 MA, Q=10, t(pulse)=12 s
- AT Mode: Reverse Shear with fbs>50%
  - B=8.5 T, Ip=5.0 MA, Q=5, t(pulse)=35 s
- Long Pulse DD: AT Mode and H-mode
  - B=4 T, Ip=2.0 MA, Q=0, t(pulse)>200 s

FIRE can study both burning AND long pulse plasma physics in the same device

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.

A Series of Advanced Tokamak Regimes Aimed at the Ultimate ARIES-AT can be studied with Alpha Heating.

Steps to ARIES-AT

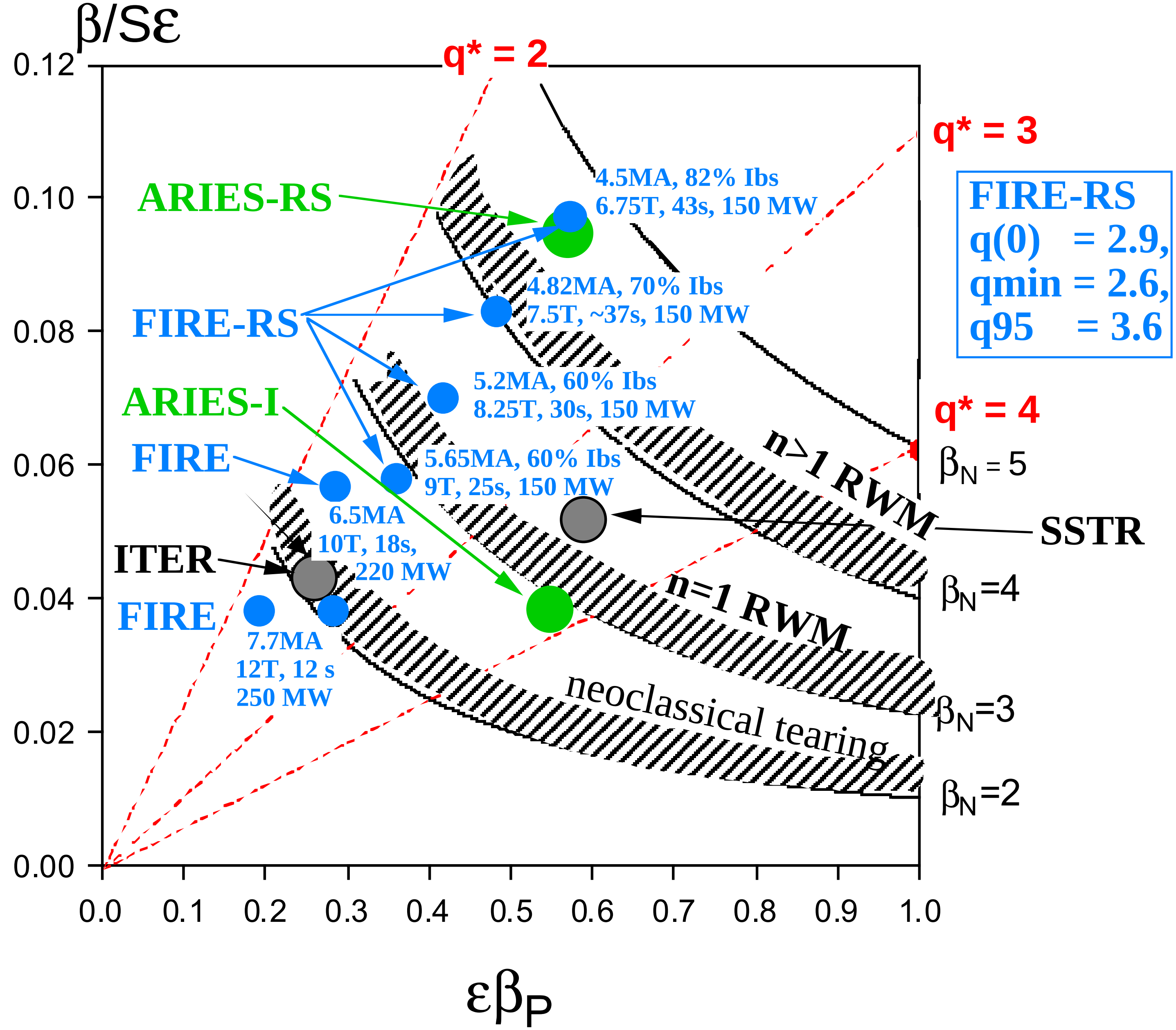
1) stabilize NTM's

2) stabilize n=1 RWM

3) stabilize n>1 RWMs

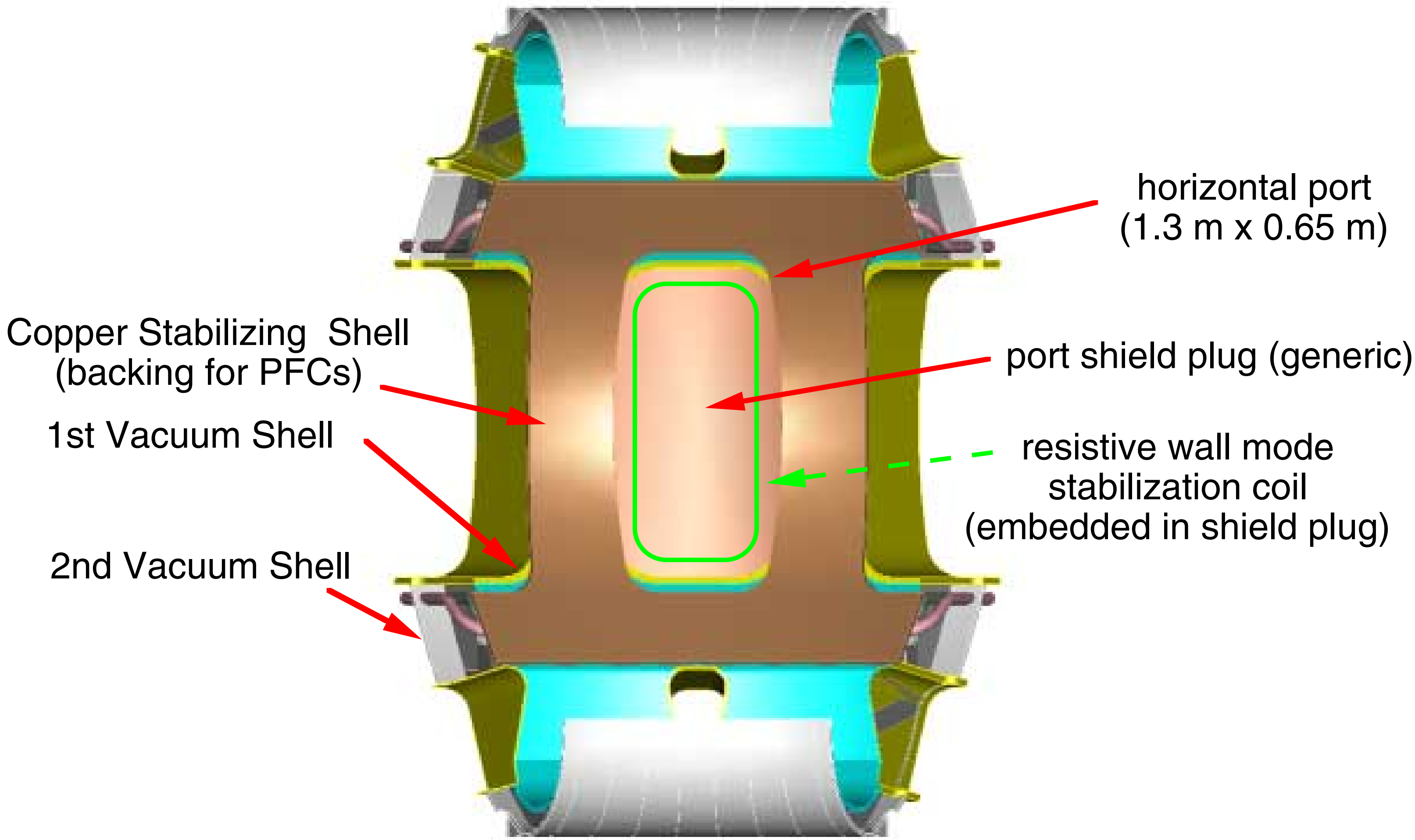
*each step with higher f_{bs}

**each step with more profile control



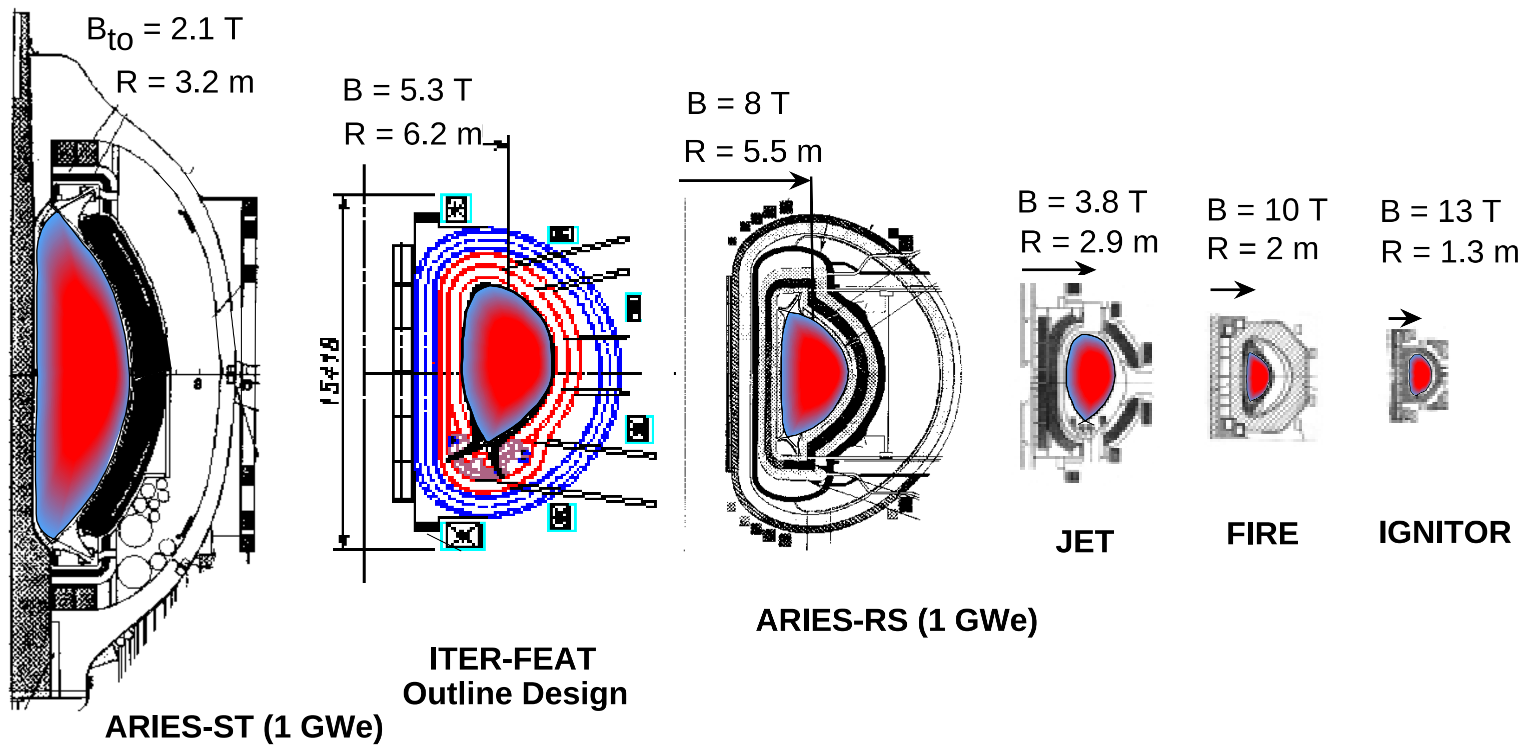
FIRE is Evaluating Methods to Stabilize Resistive Wall Modes

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)

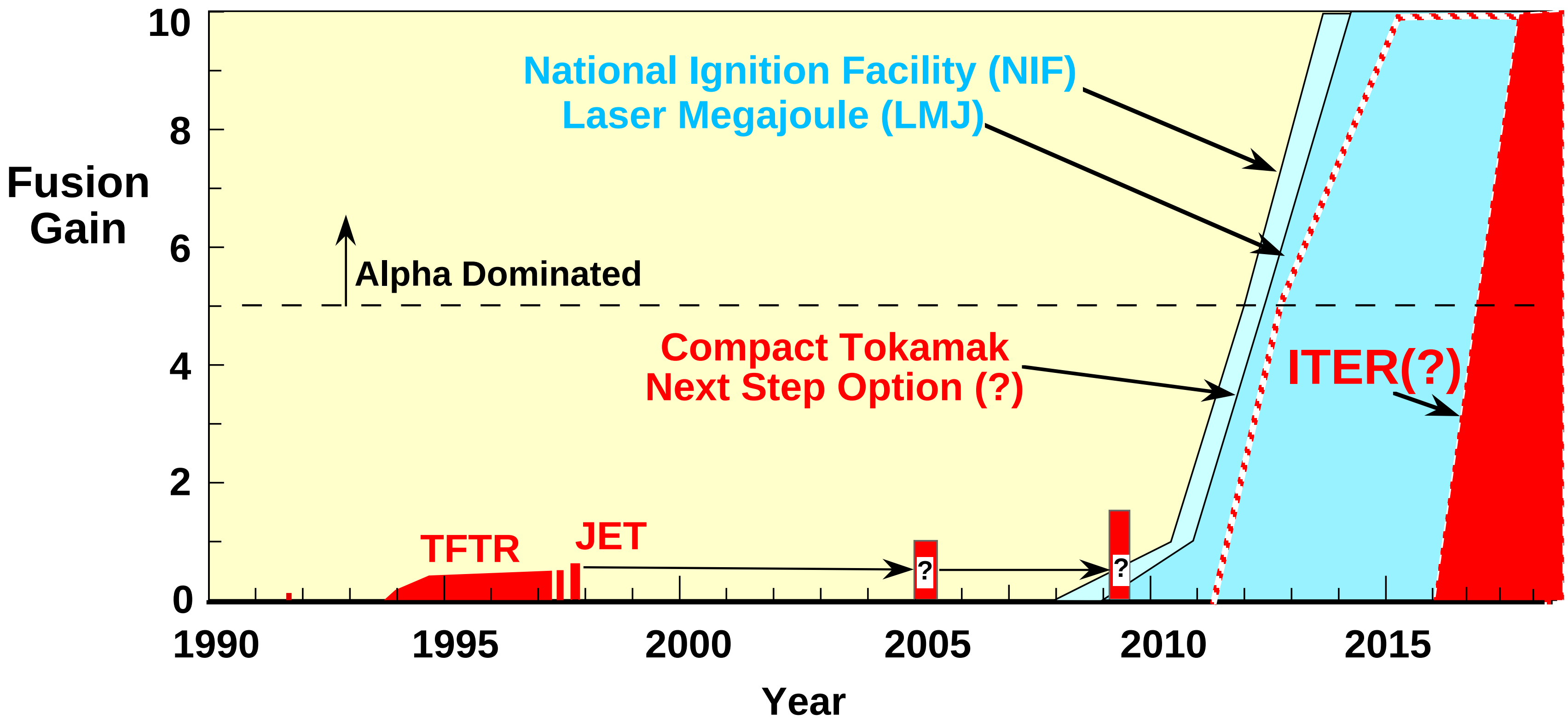
	Estimated Cost	Contingency	Total with Contingency
1.0 Tokamak Core	252.2	75.2	323.0
1.1 Plasma Facing Components	65.0	17.0	
1.2 Vacuum Vessel/In-Vessel Structures	35.2	9.7	
1.3 TF Magnets /Structure	113.8	37.2	
1.4 PF Magnets/Structure	28.4	8.5	
1.5 Cryostat	1.8	0.5	
1.6 Support Structure	7.5	2.2	
2.0 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



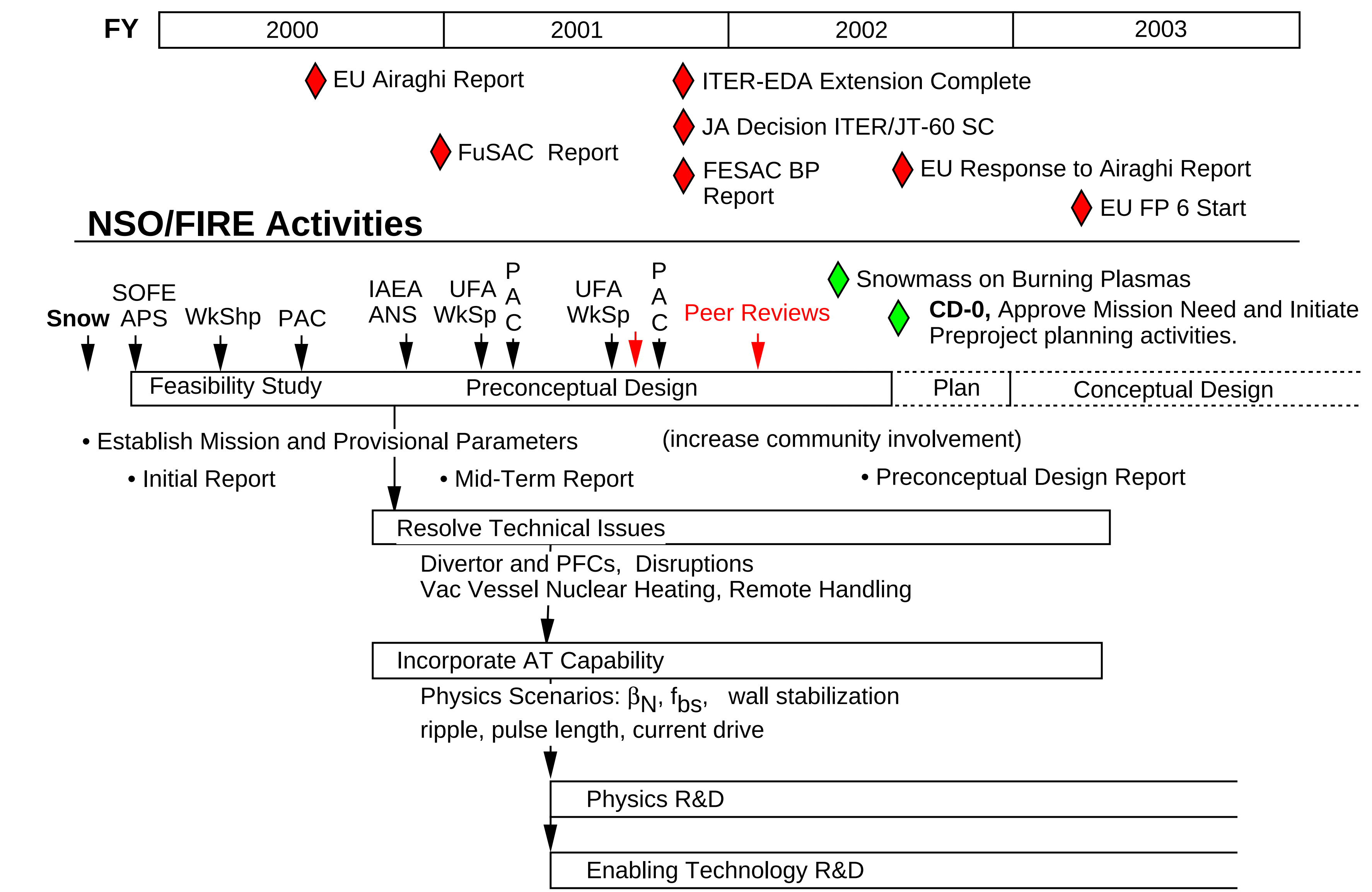
- Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for ≥ 15 years.

- 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.

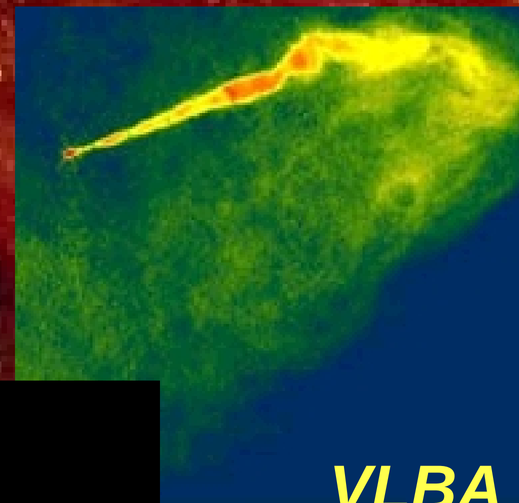
- The FIRE design point has been chosen to be a “stepping stone” between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.

- 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



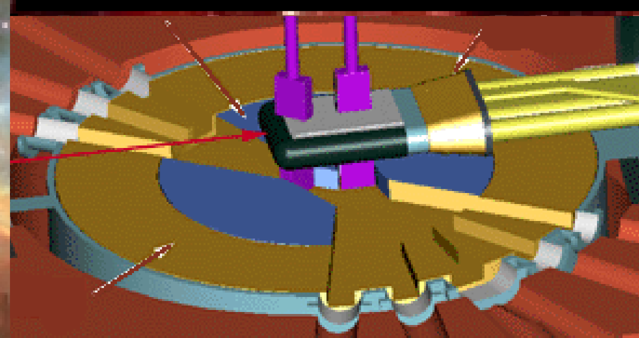
VLBA

NIF

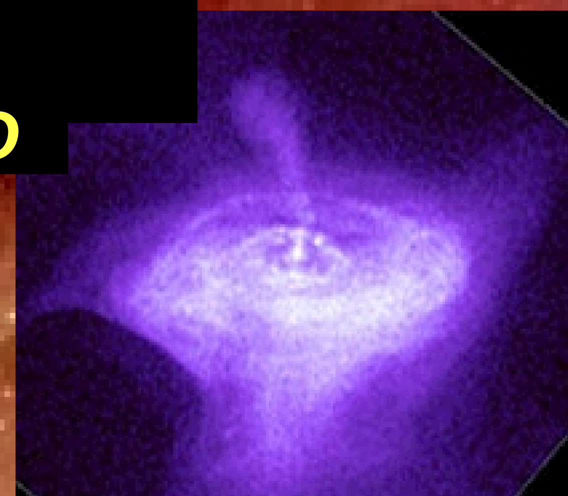
?

NSO

HST (NGST)



SNS



CHANDRA