FIRE

The Burning Plasma Physics Element of the Modular Strategy

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for the FIRE Team

Presented to
PPPL Reseach Council

July 20, 2001

http://fire.pppl.gov

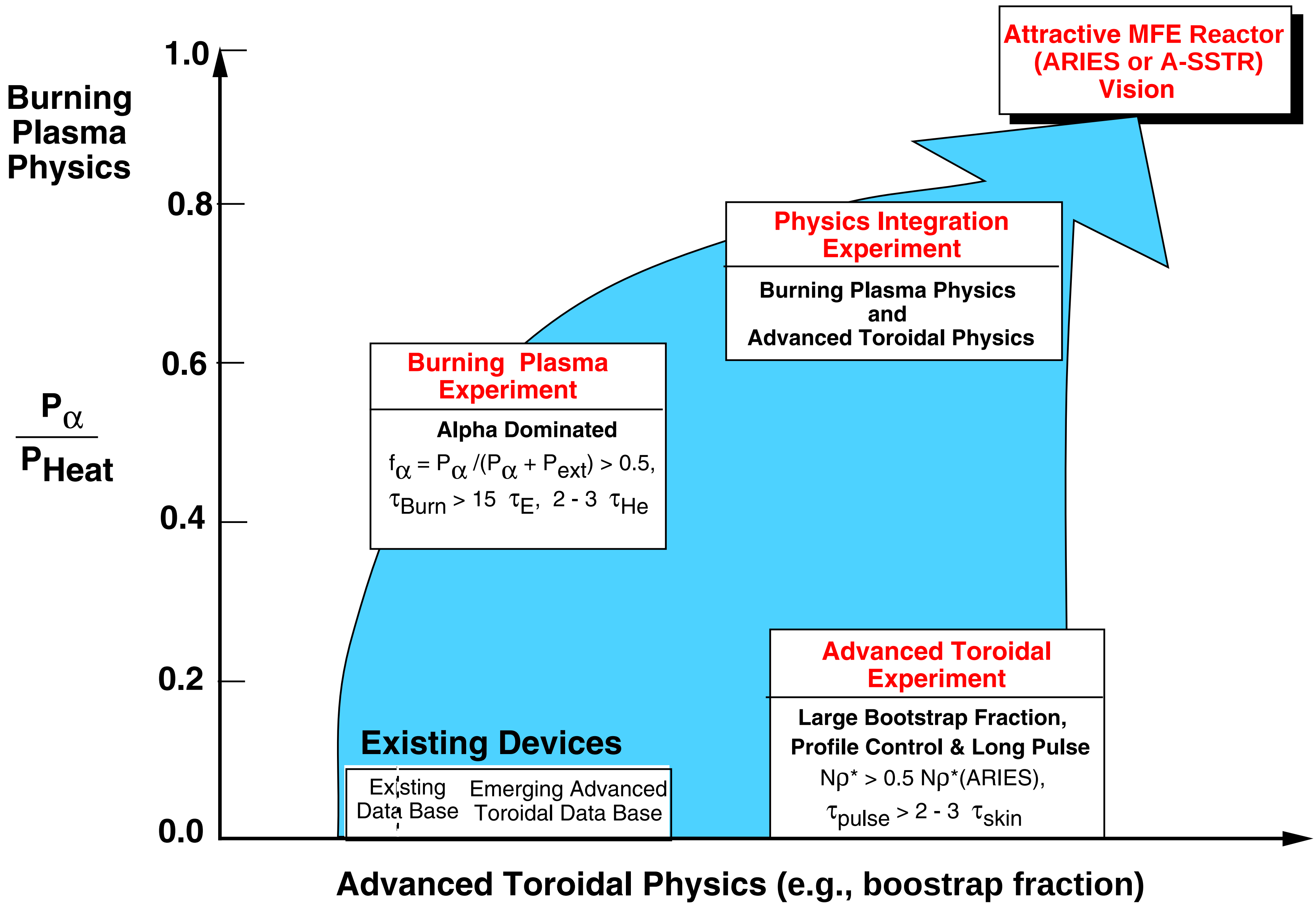
Fusion Science Objectives for a
Major Next Step Magnetic Fusion Science Experiment

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 Modular or Multi-Machine Strategy.

Advanced Burning Plasma Exp't Requirements

Burning Plasma Physics

Q	≥ 5, ~ 10 as target,	ignition not precluded
$f_\alpha = P_\alpha/P_{heat}$	≥ 50%, ~ 66% as target, up to 83% at Q = 25	
TAE/EPM	stable at nominal point, able to access unstable	

Advanced Toroidal Physics

$f_{bs} = I_{bs}/I_p$	≥ 50%	up to 75%
β_N	~ 2.5, no wall	~ 3.6, n = 1 wall stabilized

Quasi-stationary

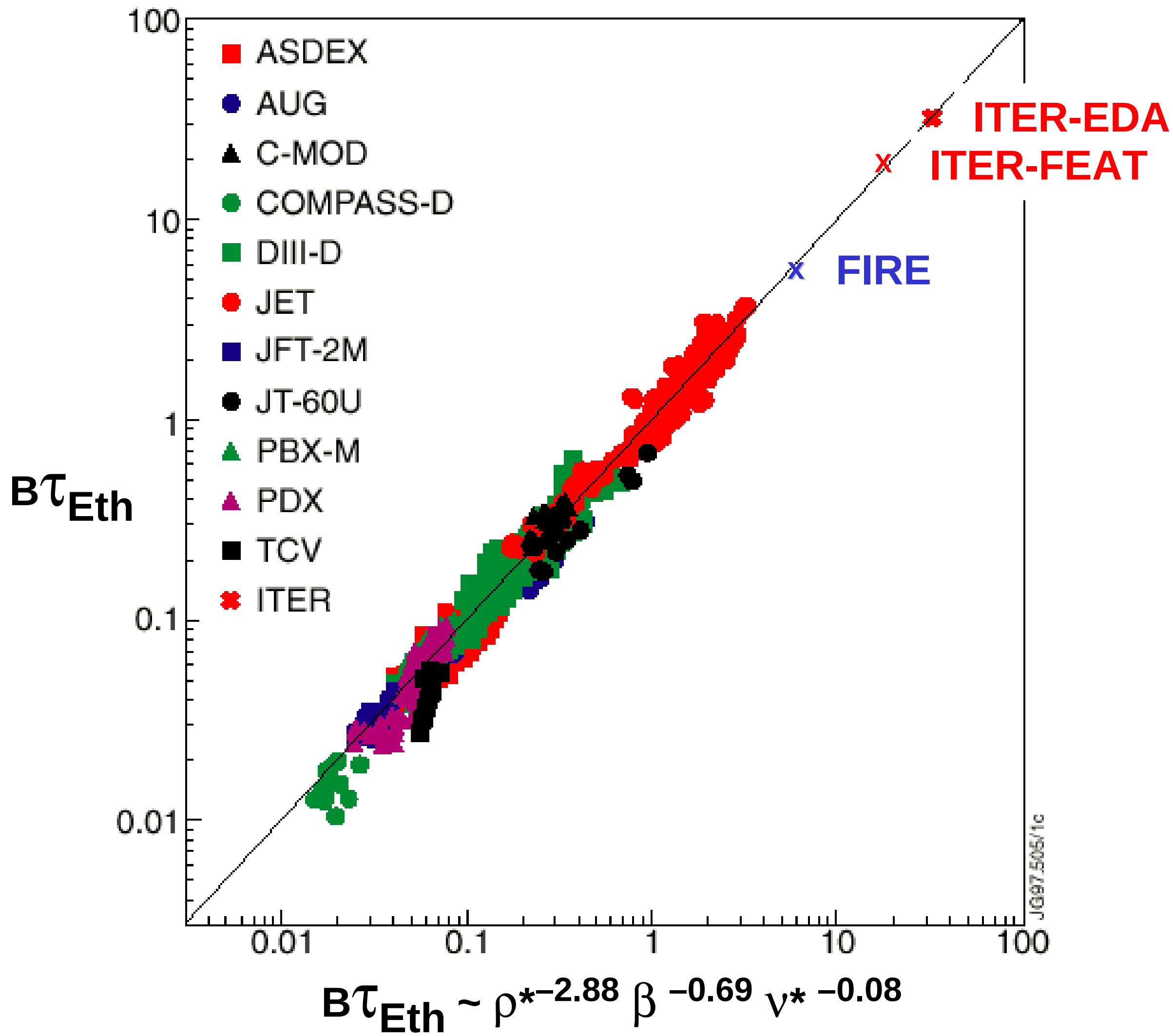
Pressure profile evolution and burn control	> 10 τ_E
Alpha ash accumulation/pumping	> several τ_{He}
Plasma current profile evolution	1 to 3 τ_{skin}
Divertor pumping and heat removal	several τ_{pump}, $\tau_{heat\ transfer}$

FIRE is a Modest Extrapolation in Plasma Confinement

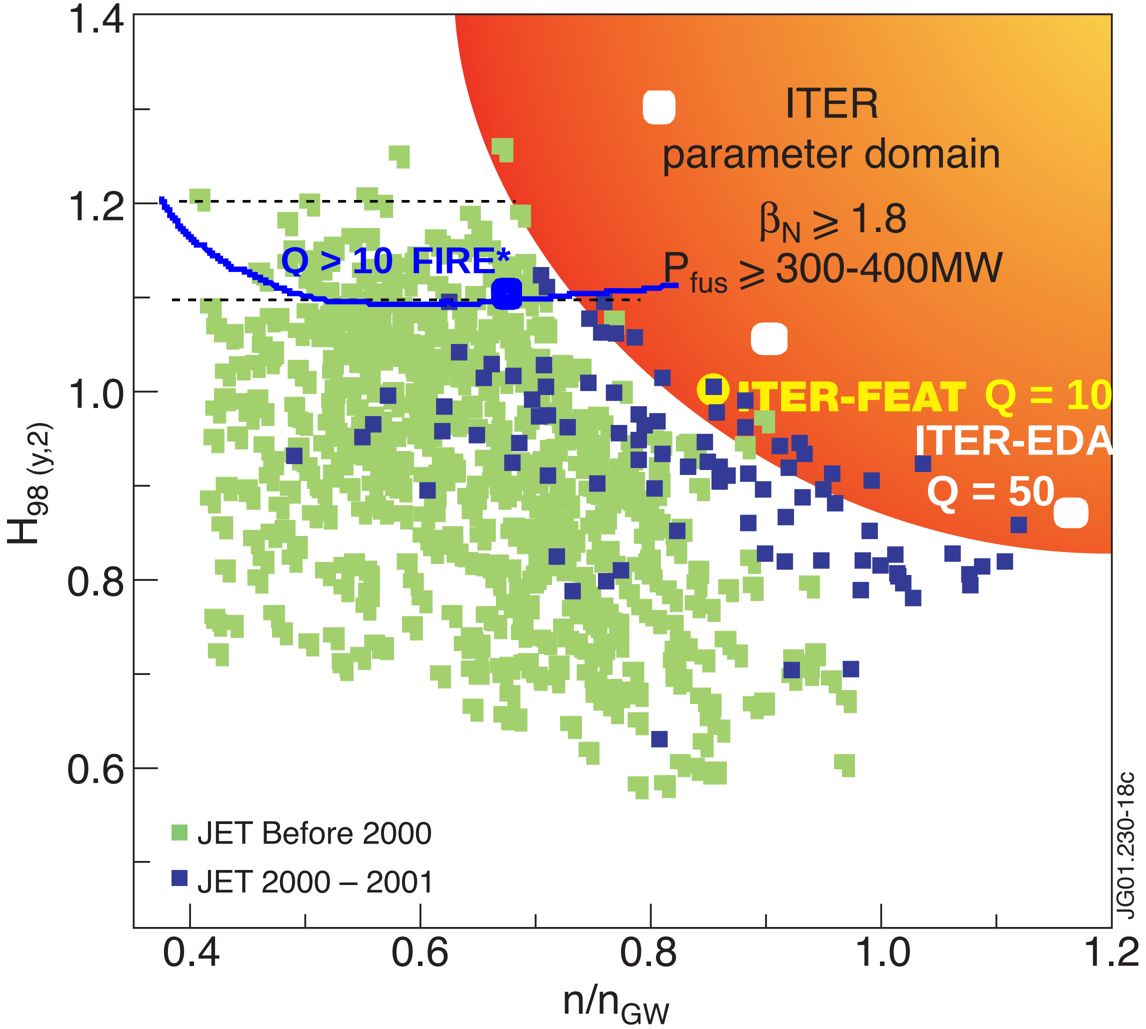
Dimensionless Parameters
$\omega_c\tau$
$\rho^* = \rho/\mathbf{a}$
$\nu^* = \nu_c/\nu_b$
β

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

Kadomtsev, 1975

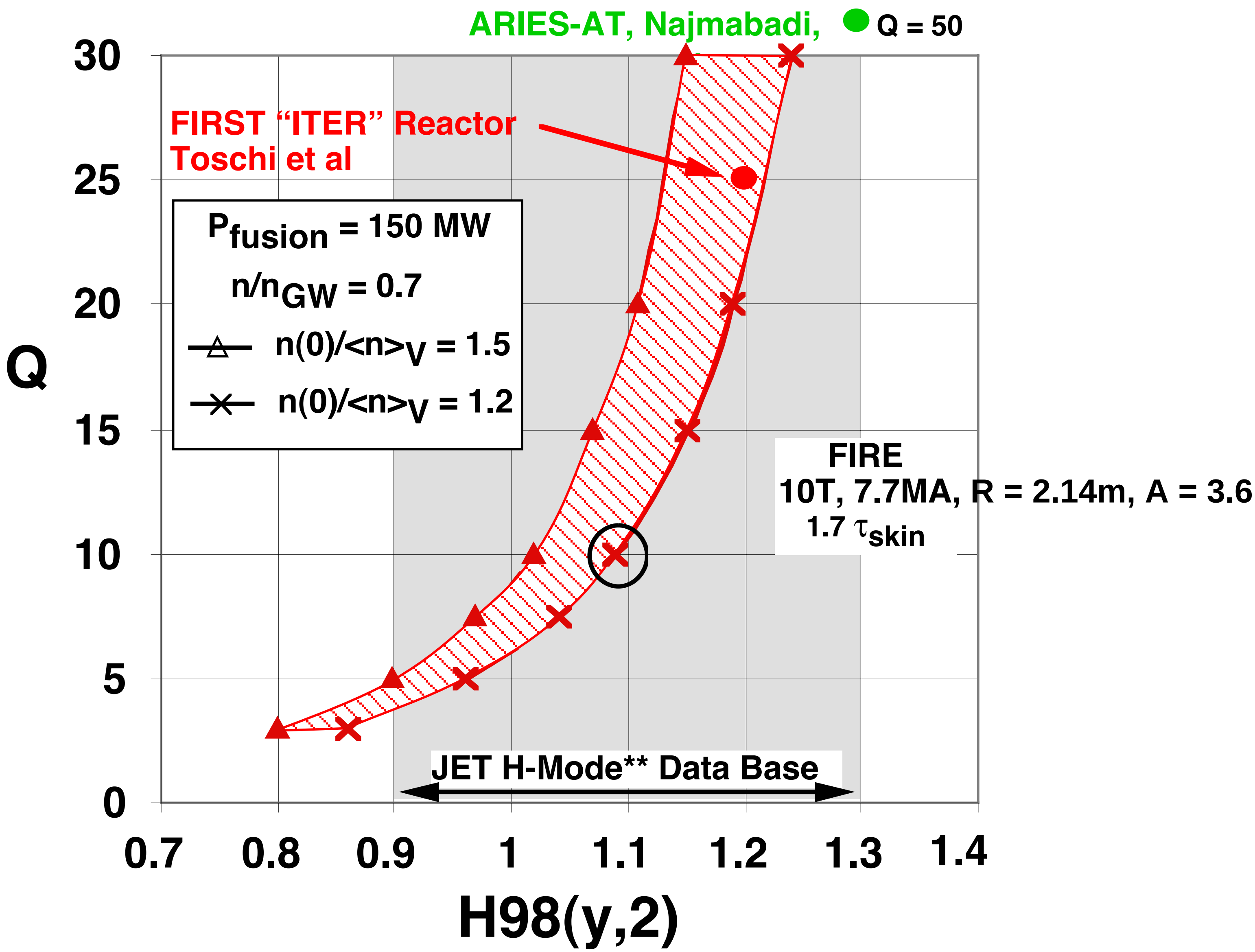


Comparison Operating Ranges of ITER-EDA, ITER-FEAT and FIRE with JET H-Mode Data



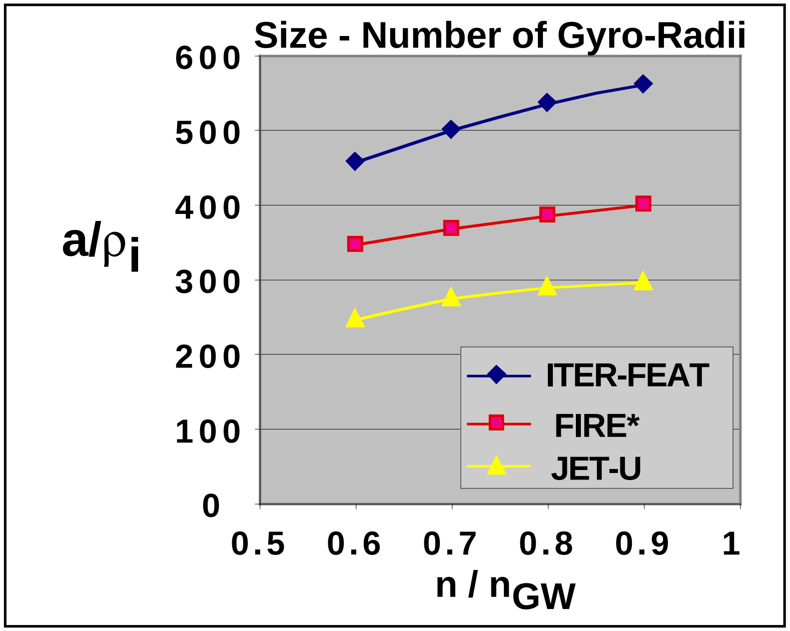
- Extension of JET parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \geqslant 1.8$ using different approaches and
- In addition Plasma purity as required for ITER: Zeff ~ 1.5
- For quasi-stationary phases of several seconds
- **Consolidation of ITER Q = 10 Reference scenario**
- **Data Base for FIRE* Q > 10 is as strong as ITER. Note and ITER-EDA added - DMM**

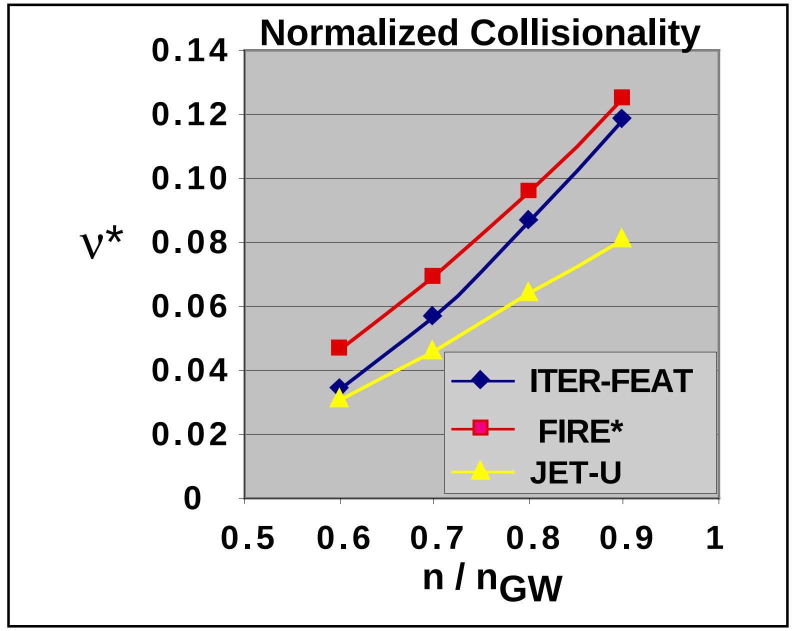
Projections to FIRE Compared to Envisioned Reactors

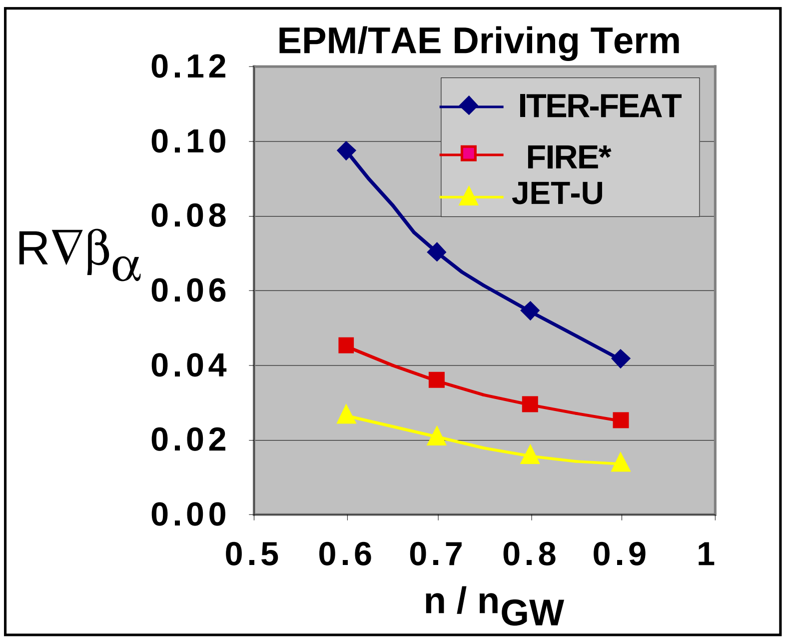


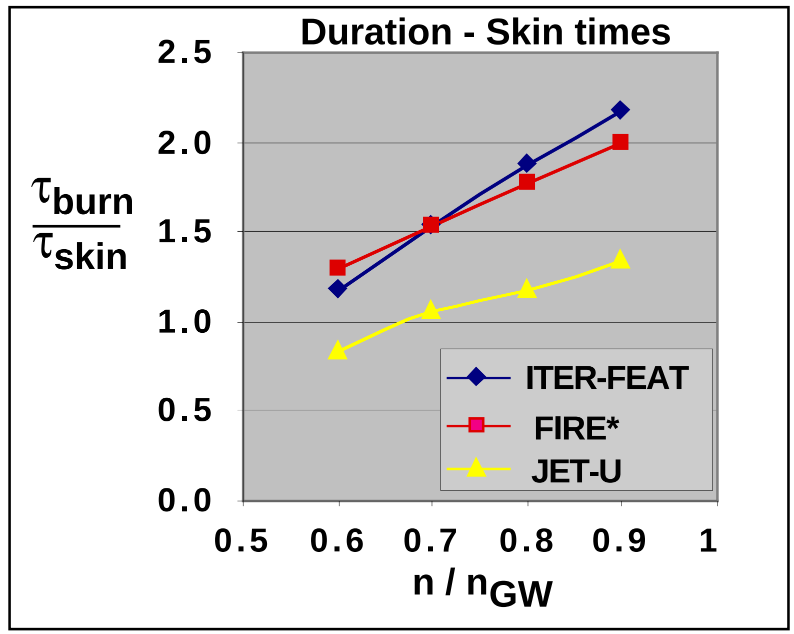
Parameters for H-Modes in Potential Next Step D-T Plasmas

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

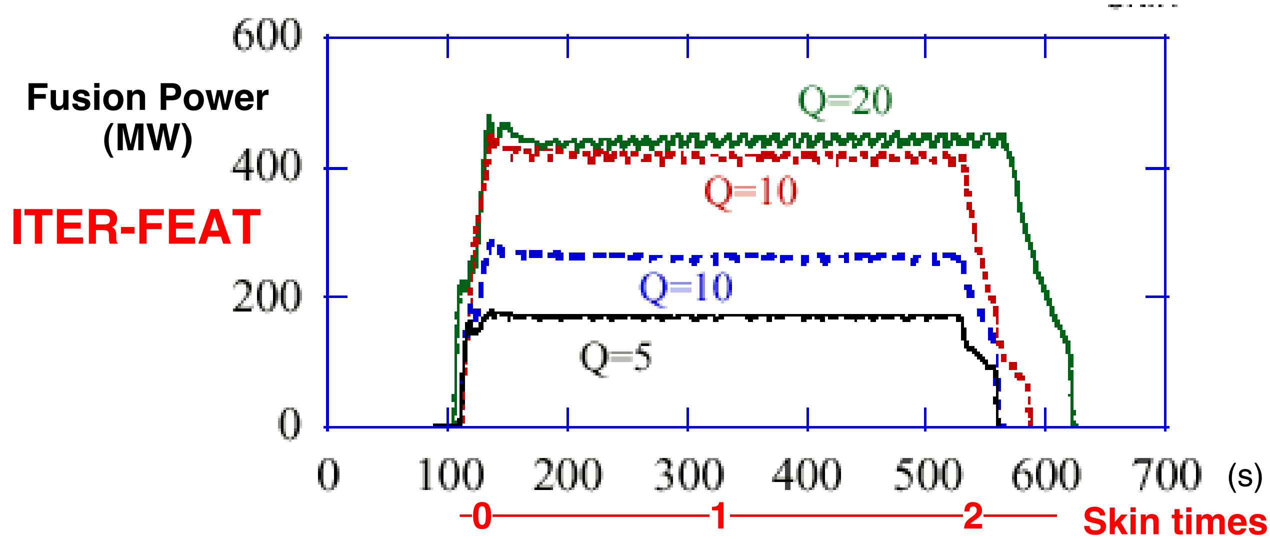


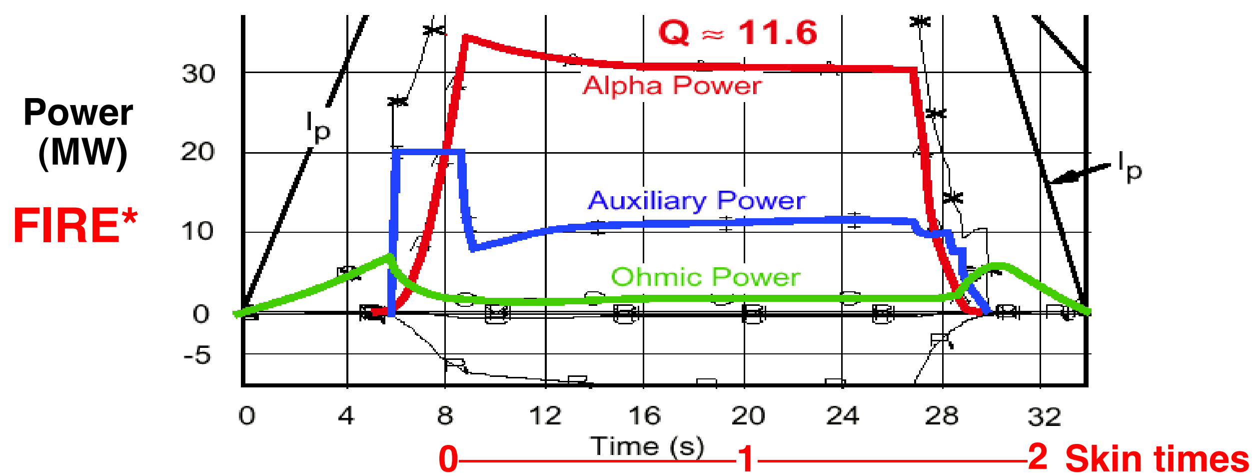


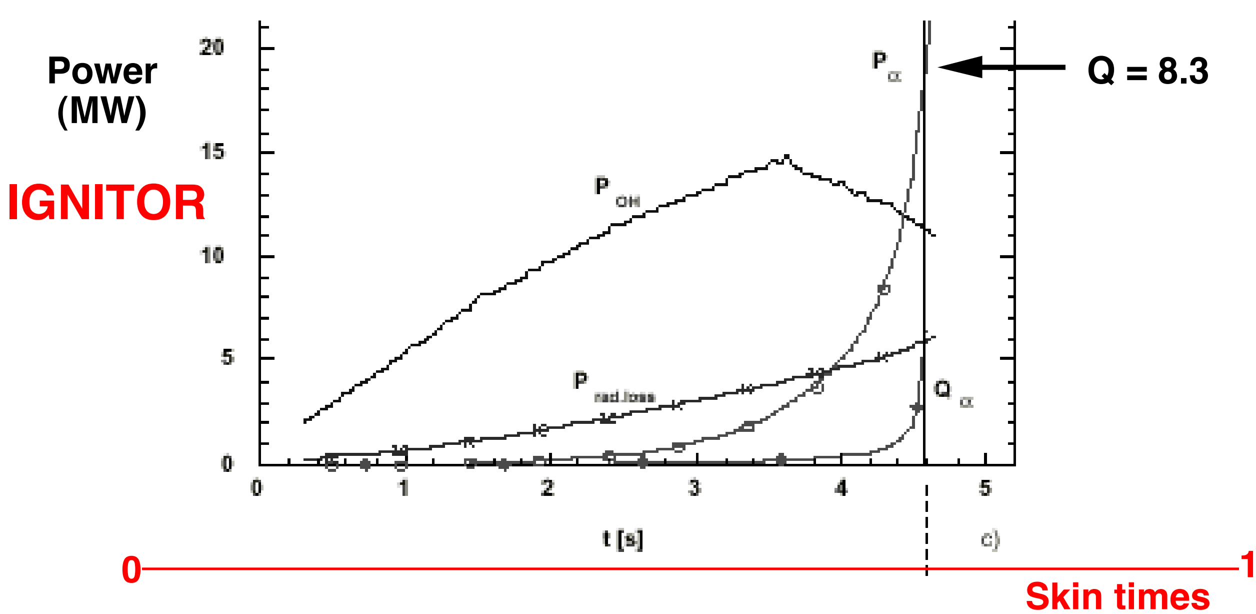




Normalized Burn Time (Plasma Skin Time)







Waveforms from talks presented at UFA BPS Workshop 2

Pedestal Temperature Requirements for Q=10

GLF 23 Studies by Kinsey, Waltz and Staebler

Device	Flat ne◆	Peaked ne*	Peaked ne w/ reversed q
IGNITOR❖	5.1	5.0	5.1
FIRE	4.1	4.0	3.4
ITER-FEAT✦	5.8	5.6	5.4

◆ flat density cases have monotonic safety factor profile

* $n_{eo} / n_{ped} = 1.5$ with n_{ped} held fixed from flat density case

❖ 10 MW auxiliary heating

11.4 MW auxiliary heating

✦ 50 MW auxiliary heating

FIRE has the strongest shaping and low n/nGW which projects to high pedestal temperature.

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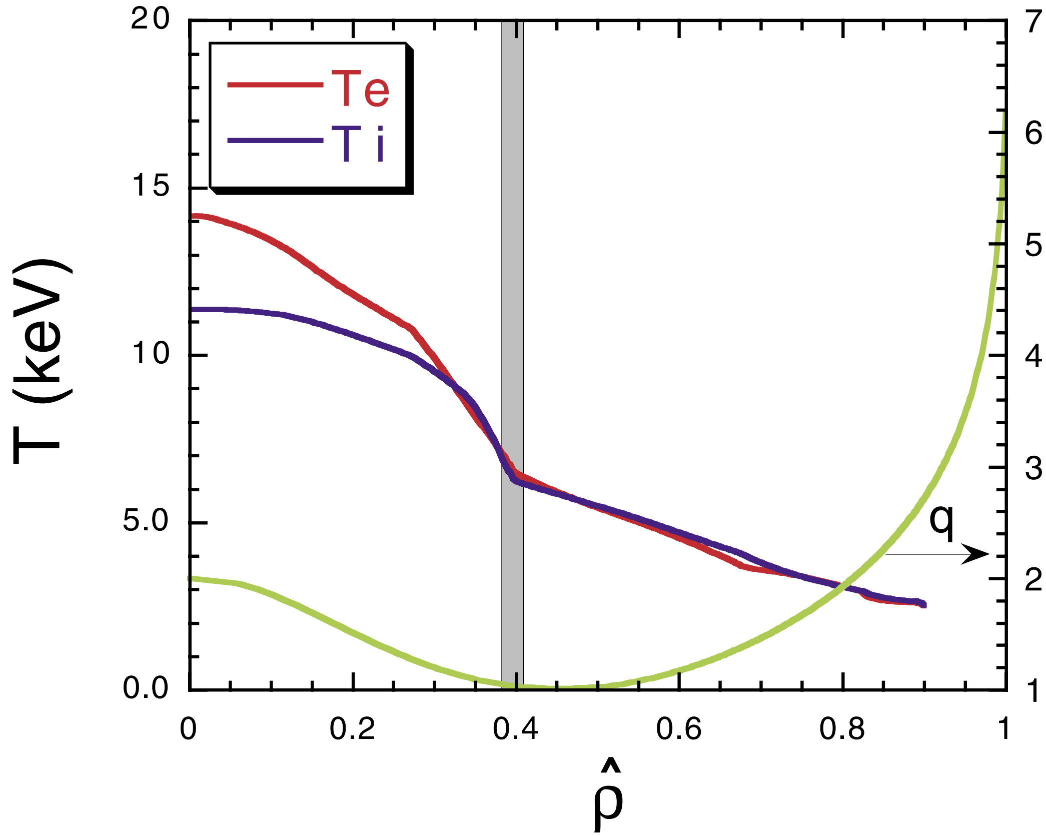
GLF23 Predicts an ITB In FIRE as a Result of Alpha-stabilization of the ITG Mode

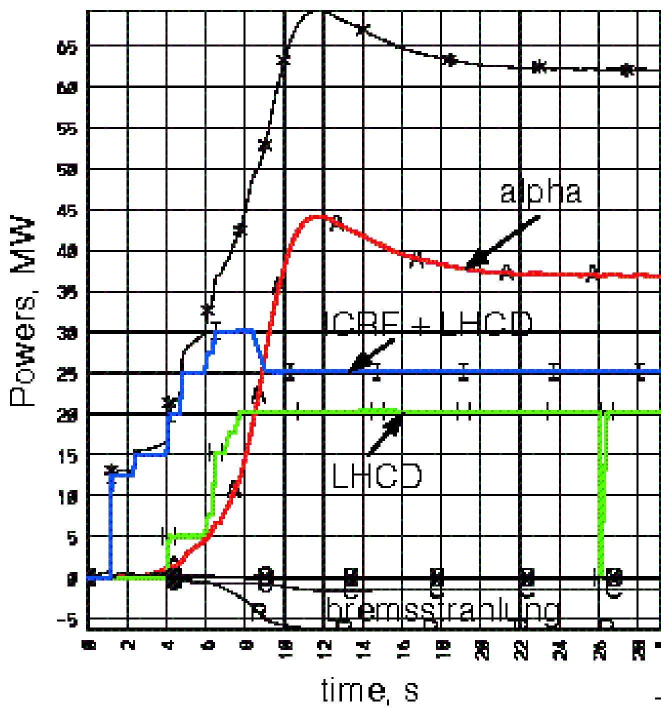
- Barrier only forms if some density peaking is present
- Diamagnetic component of ExB shear helps after ITB is formed

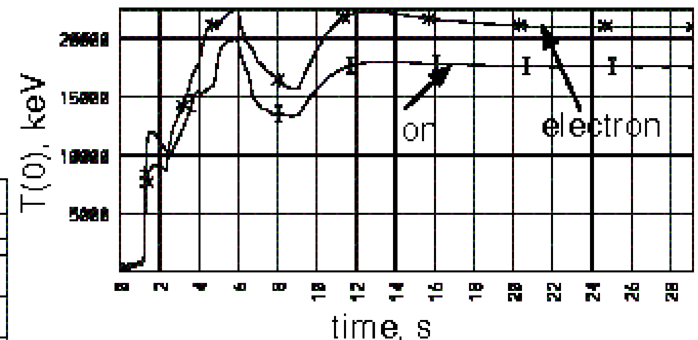


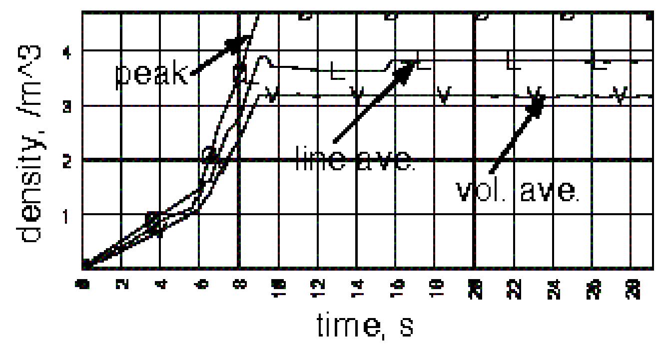
Kinsey, Waltz and Staebler
UFA BPS Workshop 2

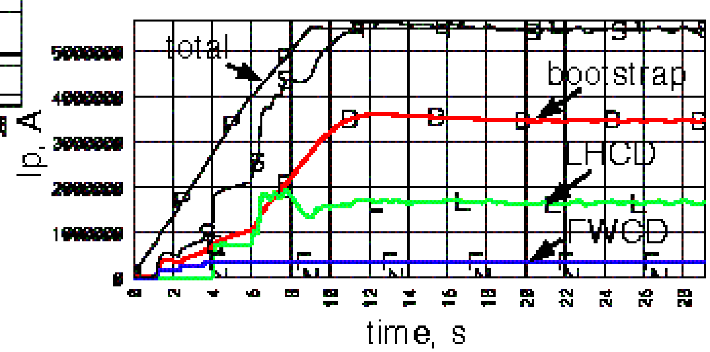
Dynamic Burning AT Simulations with TSC-LSC for FIRE

I_p=5.5 MA, B_t=8.5 T, Q=7.5,
β_N=3.0, β=4.4%, P_{LH}=20 MW,
I_{LH}=1.7 MA, I_{BS}=3.5 MA (64%),
I_{FW}=0.35 MA







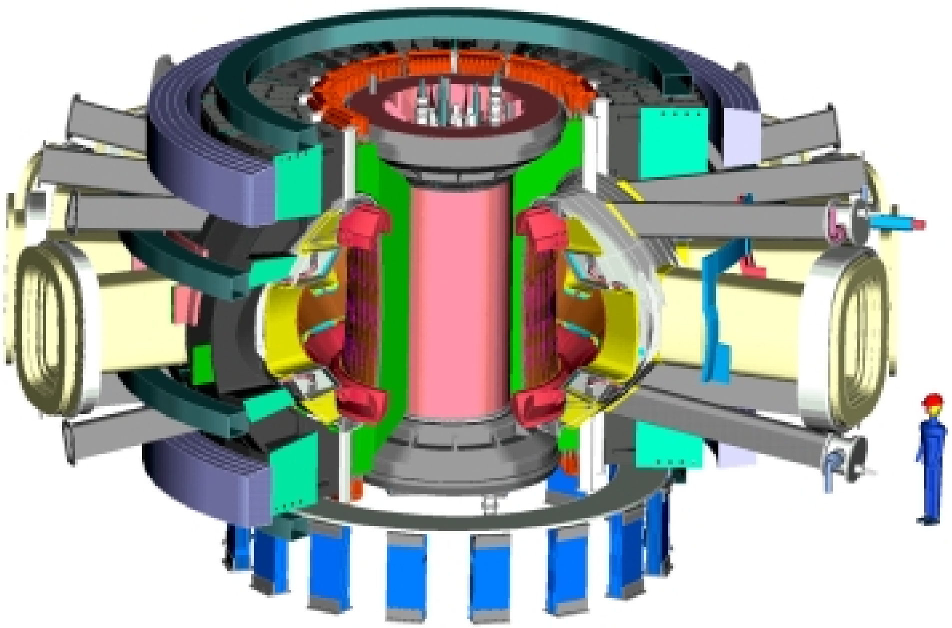


H(y,2)=1.6

Fusion Ignition Research Experiment

(FIRE*)

http://fire.pppl.gov

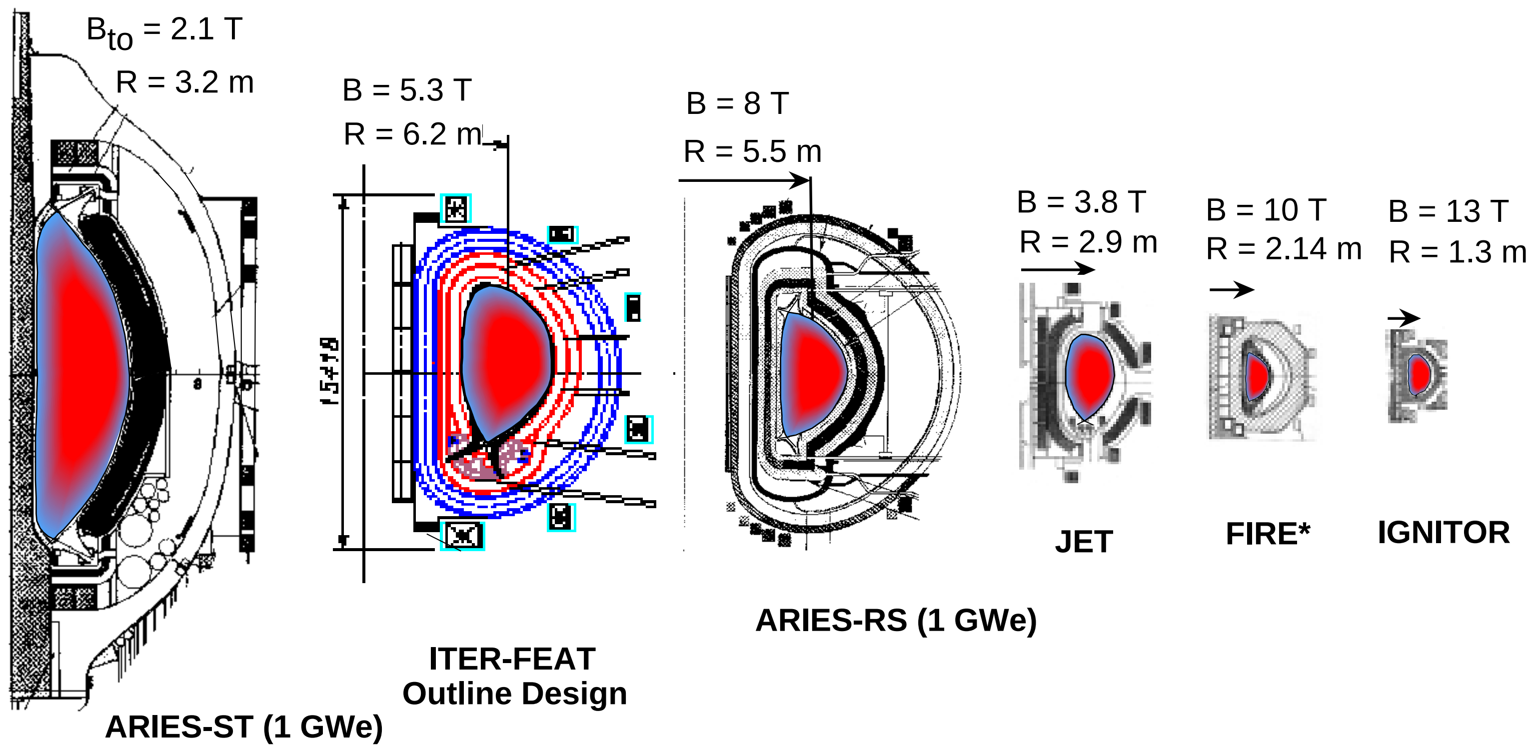


Design Features

- R = 2.14 m, a = 0.595 m
- B = 10 T
- W_{mag} = 5.2 GJ
- I_p = 7.7 MA
- $P_{aux} \leq$ 20 MW
- Q ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s
- Tokamak Cost ≈ $375M (FY99)
- Total Project Cost ≈ $1.2B at Green Field site.

Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.

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	26	11
Plasma Surface (m^2)	580	678	440	150	67	36
Plasma Current (MA)	28	15	11	4	7.7	12
Magnet Energy (GJ)	29	50	85	2	7	5
Fusion Power (MW)	3000	500	2200	16	150	100
Burn Time (s), inductive	steady	300	steady*	1	20	5

* assumes non-inductive current drive

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 Goal	10	2.0	3.8	(<$1,000M FY-99)
PCAST (120s)	7	5.0	30	~$4,000M (FY-95)

Preliminary FIRE Cost Estimate (FY99 US$M)

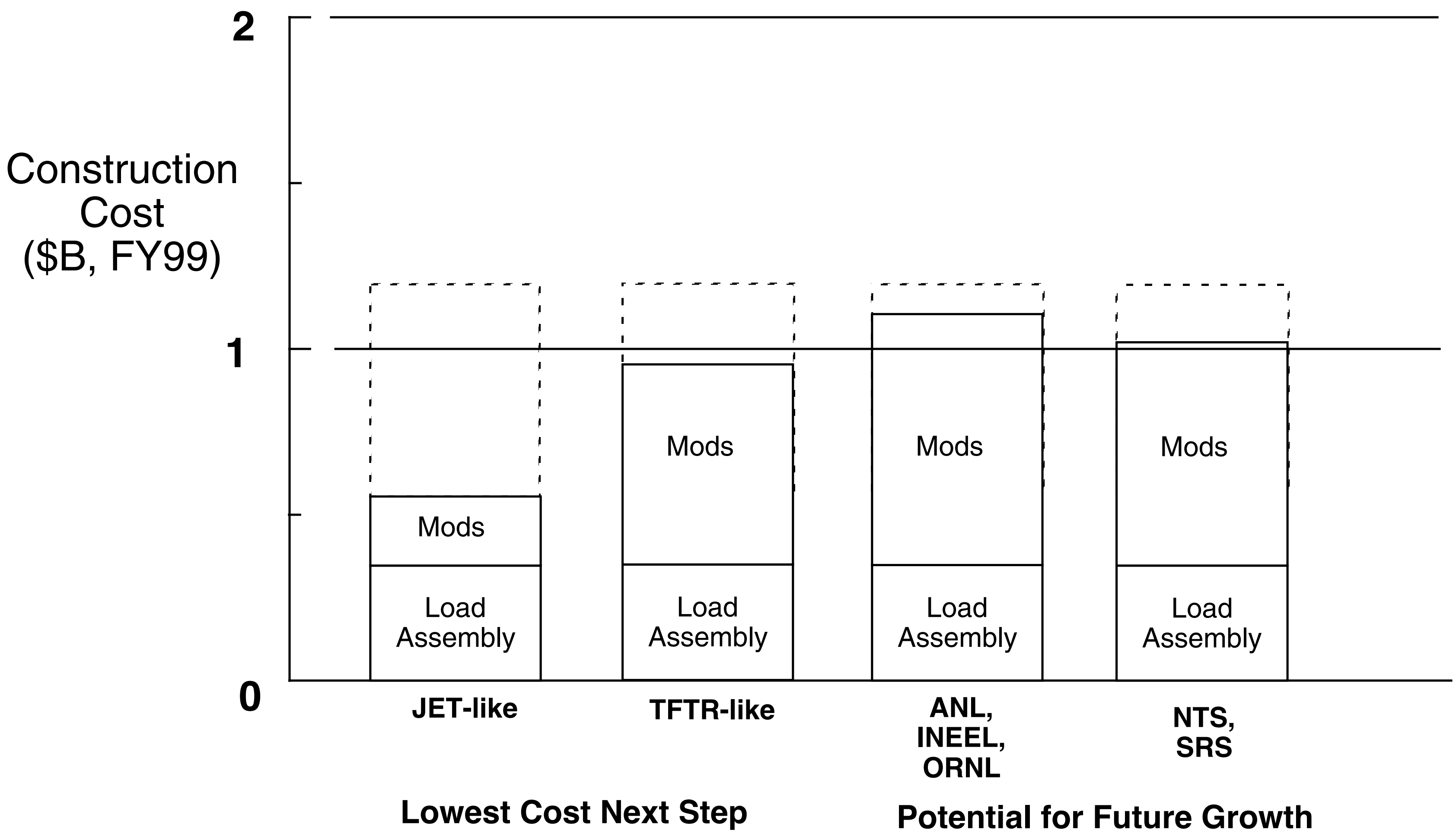
	Estimated Cost	Contingency	Total with Contingency
1.0 Tokamak Core	266.3	78.5	343.8
1.1 Plasma Facing Components	71.9	19.2	
1.2 Vacuum Vessel/In-Vessel Structures	35.4	11.6	
1.3 TF Magnets /Structure	117.9	38.0	
1.4 PF Magnets/Structure	29.2	7.2	
1.5 Cryostat	1.9	0.6	
1.6 Support Structure	9.0	1.8	
2.0 Auxiliary Systems	135.6	42.5	178.1
2.1 Gas and Pellet Injection	7.1	1.4	
2.2 Vacuum Pumping System	9.6	3.4	
2.3 Fuel Recovery/Processing	7.0	1.0	
2.4 ICRF Heating	111.9	36.6	
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	77.0	18.0	95.0
8.0 Project Support and Oversight	88.8	13.3	102.2
9.0 Preparation for Operations/Spares	16.2	2.4	18.6
Preconceptual Cost Estimate (FY99 US$M)	**953.6**	**237.8**	**1190.4**

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

Tokamak Core estimate is bottoms up estimate by industry.

June 5, 2001

Site Credits could be Significant and Need to be Evaluated



1. Could the TFTR site ever be used for tritium again? We need to determine this very soon.

2. Defense Program sites may be special opportunities.

Summary

- Most issues are being resolved, others are soluble and will take time and resources.
- The design point is in about the right place wrt to feasibility and BP mission. The AT mission and capability is very promising but need additional work.
- The cost needs to be thoroughly reviewed and scrubbed. The tokamak is ≈ $375M, with a total cost ≈ $1.2B. Need to begin assessing possible sites.
- Need a physics R&D List/Plan.
  - Many generic or ITER specific items are being worked.
  - Need work on FIRE specific items; e.g.,
    - double null effects on confinement, stability, power handling,
    - all metal PFCs, W divertor targets, Be first wall
    – optimized confinement at n~ 0.7 n_{GW}
    – AT mode development q_{min}≈ 2.2, q_{95} ~ 3.7
- Need to begin work on Engineering R&D items.
- Community interest is increasing, need stronger community involvement and organization of this effort will need resources to carry this forward.