Physics Regimes

in the

Fusion Ignition Research Experiment (FIRE)

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for the FIRE Team

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Funchal, Madeira, Portugal

June 19, 2001

http://fire.pppl.gov

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

Outline

- **Objectives for a Next Step Experiment in Magnetic Fusion**
- **Compact High Field Approach - General Parameters**
- **Burning Plasma Performance Considerations**
- **Advanced Tokamak Possibilities**
- **Other Considerations** (Cost, timing, etc)
- **Summary**

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 10-11, 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?

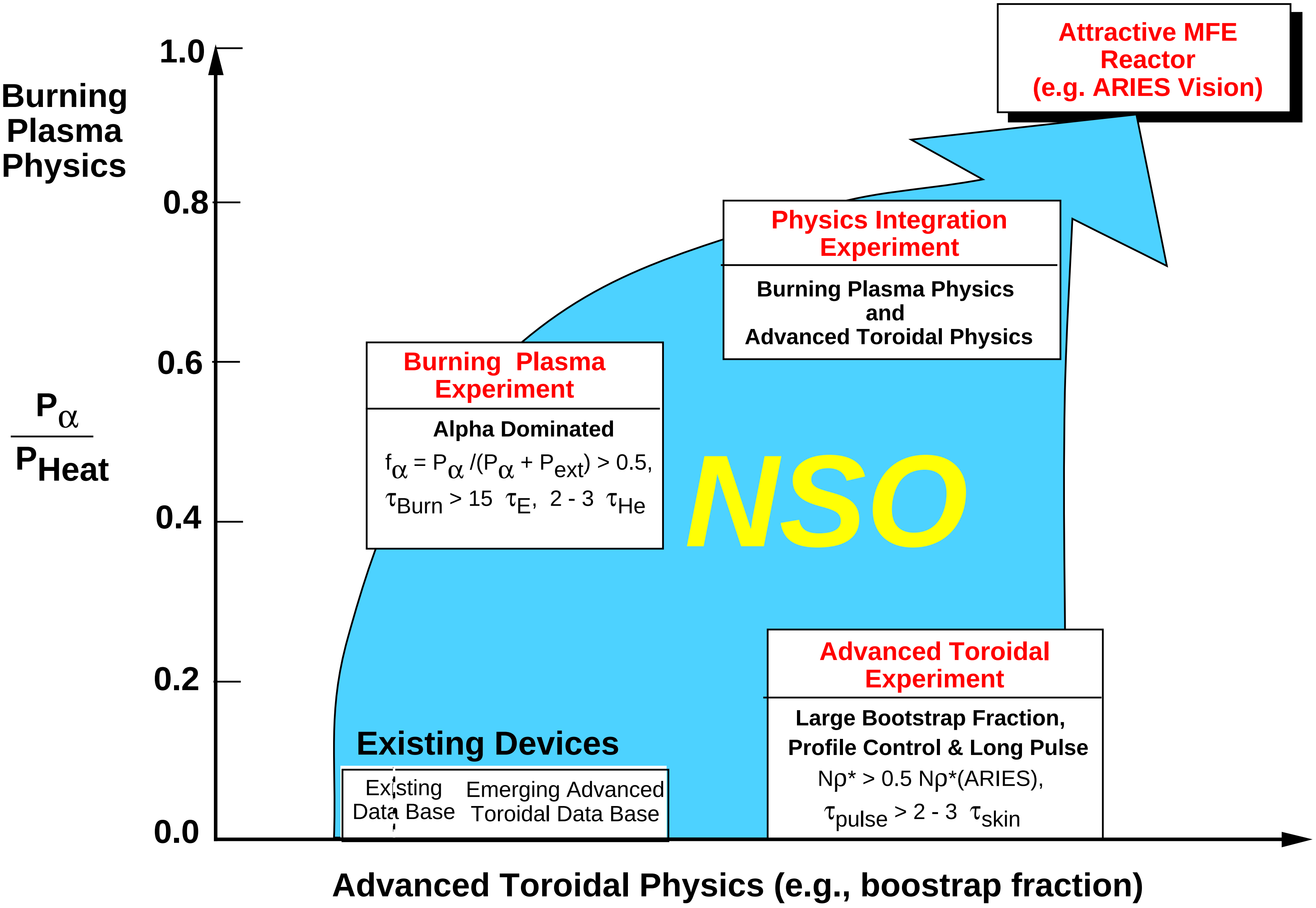
- Extensive PAC Reports provide detailed recommendations for the FIRE activity to address. NSO-PAC reports are on FIRE (http://fire.pppl.gov), will discuss in more detail under FY 2001-03 Plans.

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



Attractive MFE Reactor
(e.g. ARIES Vision)

Physics Integration Experiment

Burning Plasma Physics
and
Advanced Toroidal Physics

Burning Plasma Experiment

Alpha Dominated

$f_\alpha = P_\alpha / (P_\alpha + P_{ext}) > 0.5$,

$\tau_{Burn} > 15\ \tau_E$, $2 - 3\ \tau_{He}$

Existing Devices

Existing Data Base

Emerging Advanced Toroidal Data Base

Advanced Toroidal Experiment

Large Bootstrap Fraction,
Profile Control & Long Pulse

$N\rho^* > 0.5\ N\rho^*(\text{ARIES})$,

$\tau_{pulse} > 2 - 3\ \tau_{skin}$

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

Advanced Burning Plasma Exp't Requirements

Burning Plasma Physics

Q	≥ 5	ignition not precluded
$f_\alpha = P_\alpha/P_{heat}$	$\geq 50\%$	up to 83% at $Q = 25$
TAE/EPM	stable/unstable	

Advanced Toroidal Physics

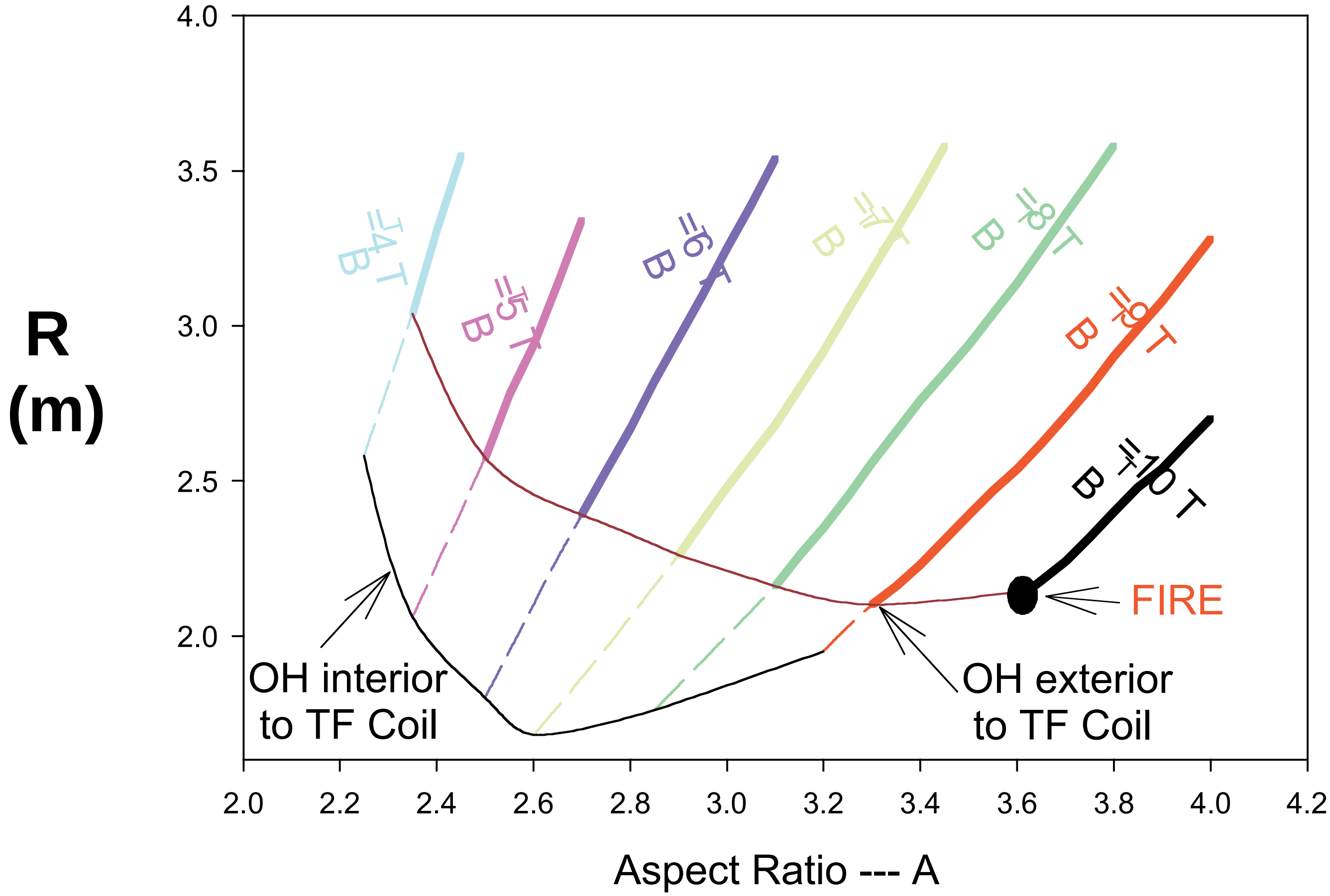
$f_{bs} = I_{bs}/I_p$	$\geq 50\%$	up to 75%
β_N	~ 2.5, no wall	~ 3.6, $n = 1$ wall stabilized

Quasi-stationary

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

Optimization of Burning Plasma Performance (Elmy H-Mode)

$\beta_N = 1.5$, $q_e = 3.13$, $Q=10$, $\kappa=1.8$, $H_{y,2}=1.0$, $\tau_{flat} = 20$ s

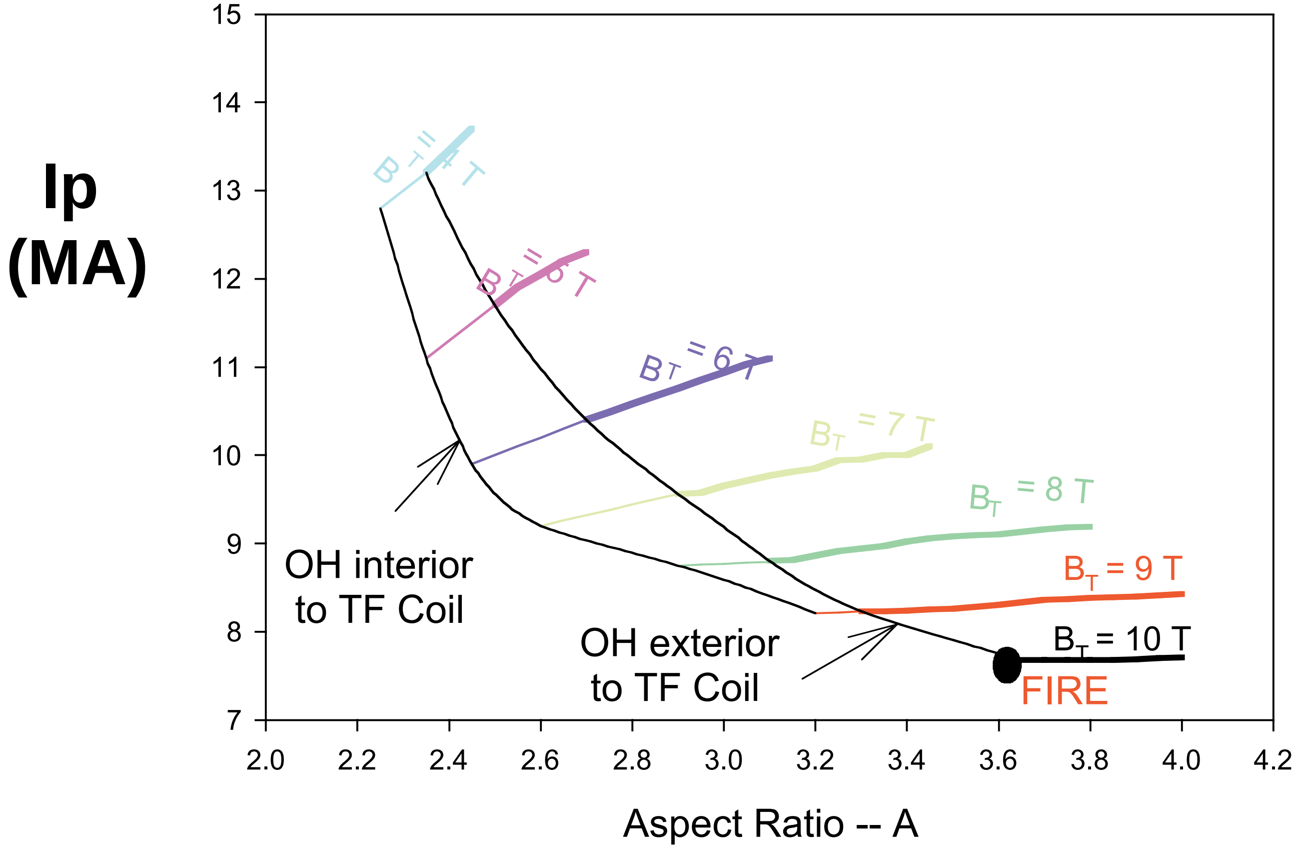


Jardin/Kessel

Similar to Reiersen 1991 and Schultz 2001

Optimization of Burning Plasma Performance (Elmy H-Mode)

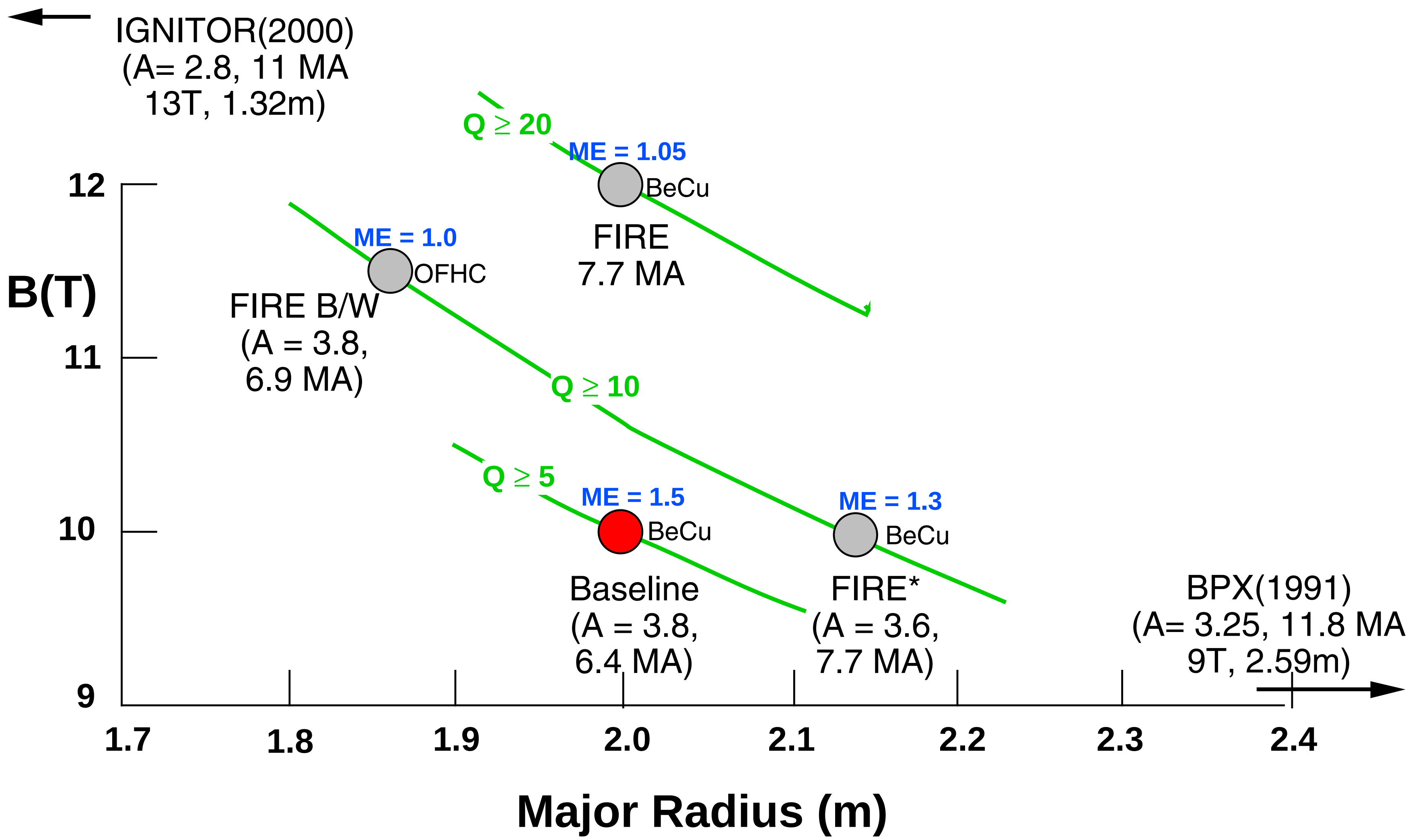
β_N = 1.5, q_e = 3.13, Q=10, κ=1.8, $H_{y,2}$=1, τ_{flat} = 20 s



Jardin/Kessel

What is the optimum aspect ratio for advanced modes?

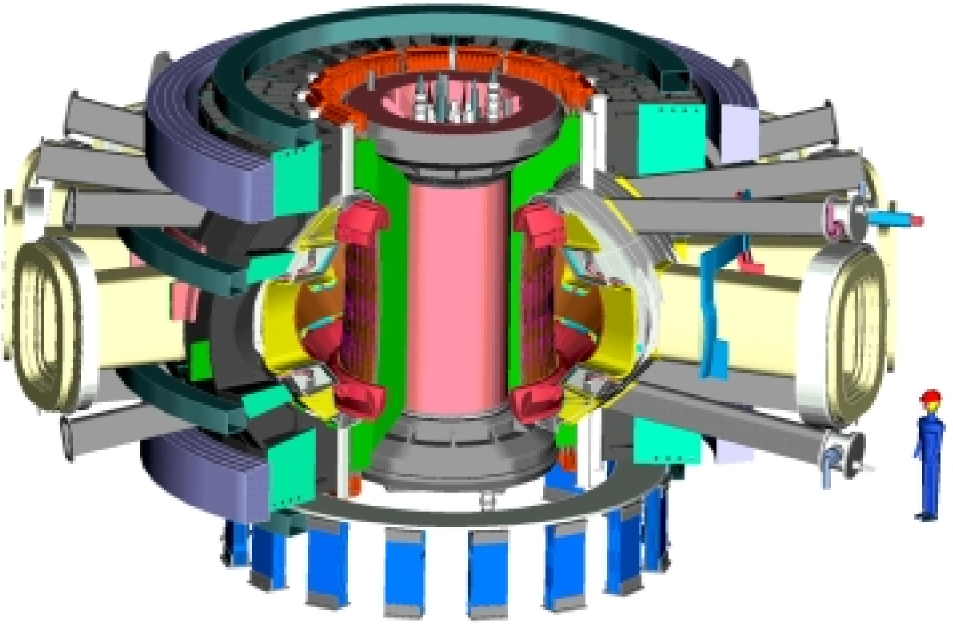
FIRE Options that have been Considered



ME = Allowable Stress / TF Stress

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, (5.5 GJ)*
- 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 Option

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

Opportunities for Optimizing FIRE

Goal : Q ≈ 10, pulse length ≈ 2 skin times, ≈ $1B

Physics

Base Operation - H-Mode-recent advances give important improvements

Advanced Operation - be able to incorporate, but do not rely on AT

Engineering

Plasma Shape: aspect ratio, elongation/triangularity

Magnetic field: wedged , bucked and wedged

Plasma current: volt-sec, disruptions

Materials: TF conductor, TF Insulator, Plasma facing components,

Manufacturing: new processes,

Basic Parameters and Features of FIRE Reference Baseline

R, major radius	2.0 m
a, minor radius	0.525 m
κx, κ95	2.0, 1.77
δx, δ95,	0.7, 0.4
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.3% 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	Upgrade for edge rotation, CD - 120 keV PNBI?
Lower Hybrid Current Drive	Upgrade for AT-CD phase, 20 - 30 MW, 5.6 GHz
Plasma fueling	Pellet injection (≥2.5km/s vertical launch inside mag axis, 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	150 - 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 Option B = 12T and Ip = 7.7MA with a 12 second flat top has been

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

(and Advanced Tokamak Stabilization Systems)

16 mid-plane ports 1.3m x 0.65m
32 divertor ports 0.5m x 0.2m (16 for cryopumps/cooling water
24 vertical ports 0.13m diam

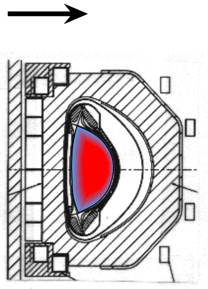
~ 25% of first wall for ports

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

P_{fusion} = ~ 200 MW

Volume = 18 m^3

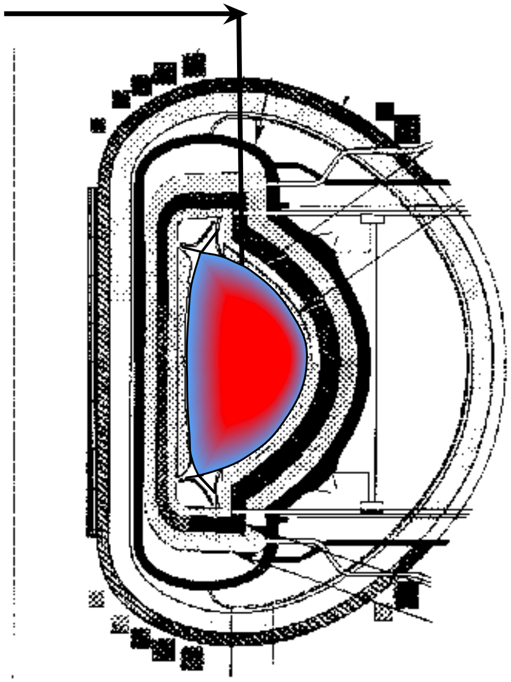
R = 2 m B = 10 T



FIRE

~ 3X

R = 5.2 m B = 6 T



ARIES-AT The “Goal”

P_{fusion} = 1755 MW

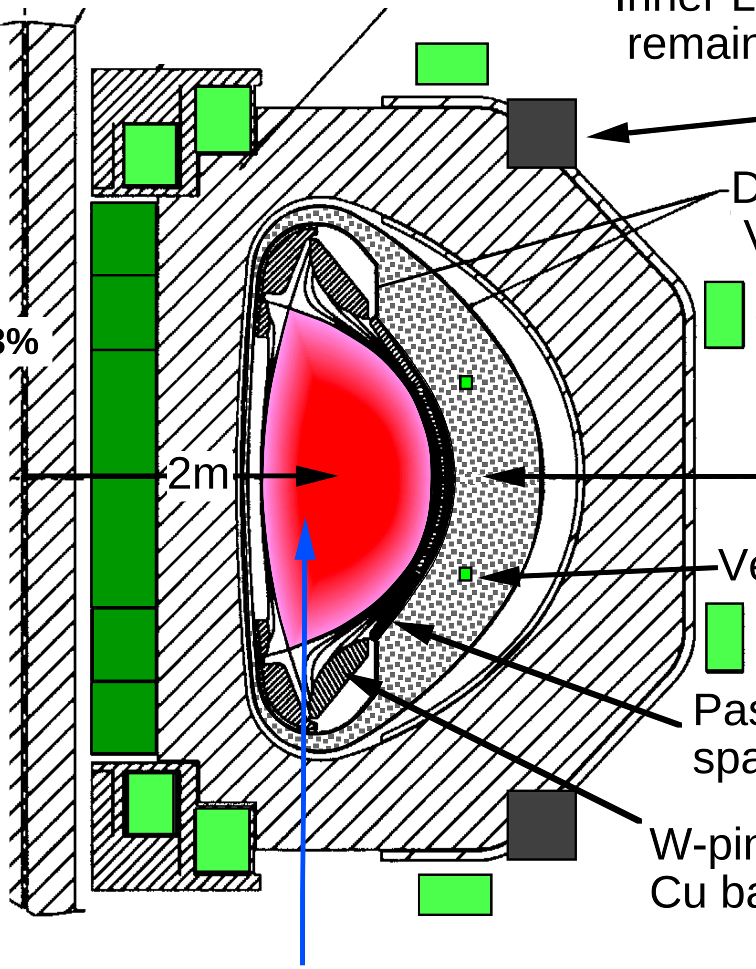
Volume = 330 m^3

	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 → 5	~5
Burn Duration (s)	~20	steady

FIRE Incorporates Advanced Tokamak Innovations

AT Features

- DN divertor
- strong shaping
- very low ripple **< 0.3%**
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



Wedged TF Coils (16), 15 plates/coil*
Inner Leg BeCu C17510,
remainder OFHC C10200

Compression Ring

Double Wall Vacuum
Vessel (316 S/S)

All PF and CS Coils*
OFHC C10200

Internal Shielding
(60% steel & 40%water)

Vertical Feedback and Error
Field Correction Coils

Passive Stabilizer Plates
space for wall mode stabilizers

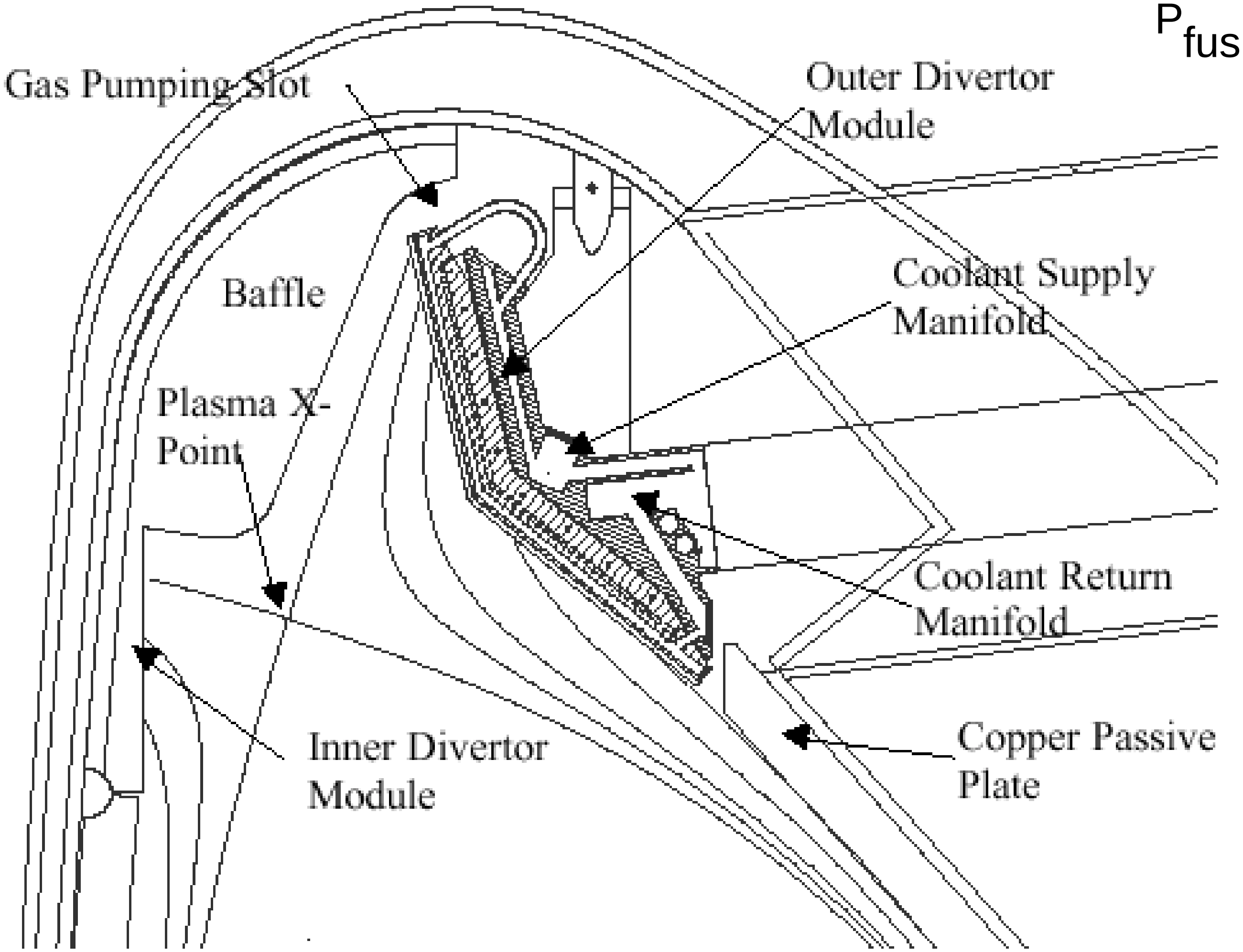
W-pin Outer Divertor Plate
Cu backing plate, actively cooled

Direct and Guided Inside Pellet Injection

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

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

P_{fusion} < 200 MW



Reference Design is semi-detached operation with <15 MW / m2.

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 is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters

$\omega_c \tau$

$\rho^* = \rho / \mathbf{a}$

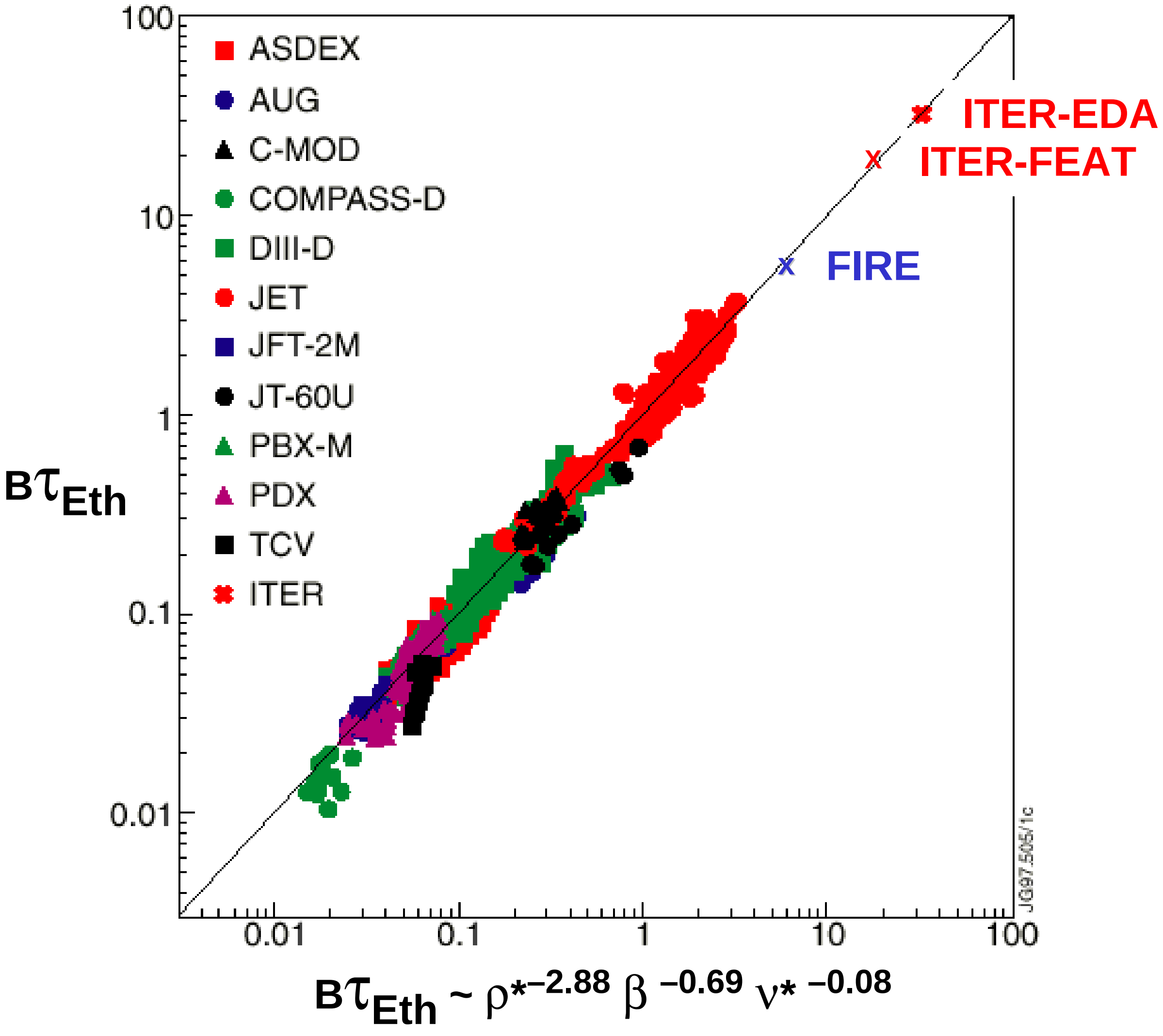
$\nu^* = \nu_c / \nu_b$

β

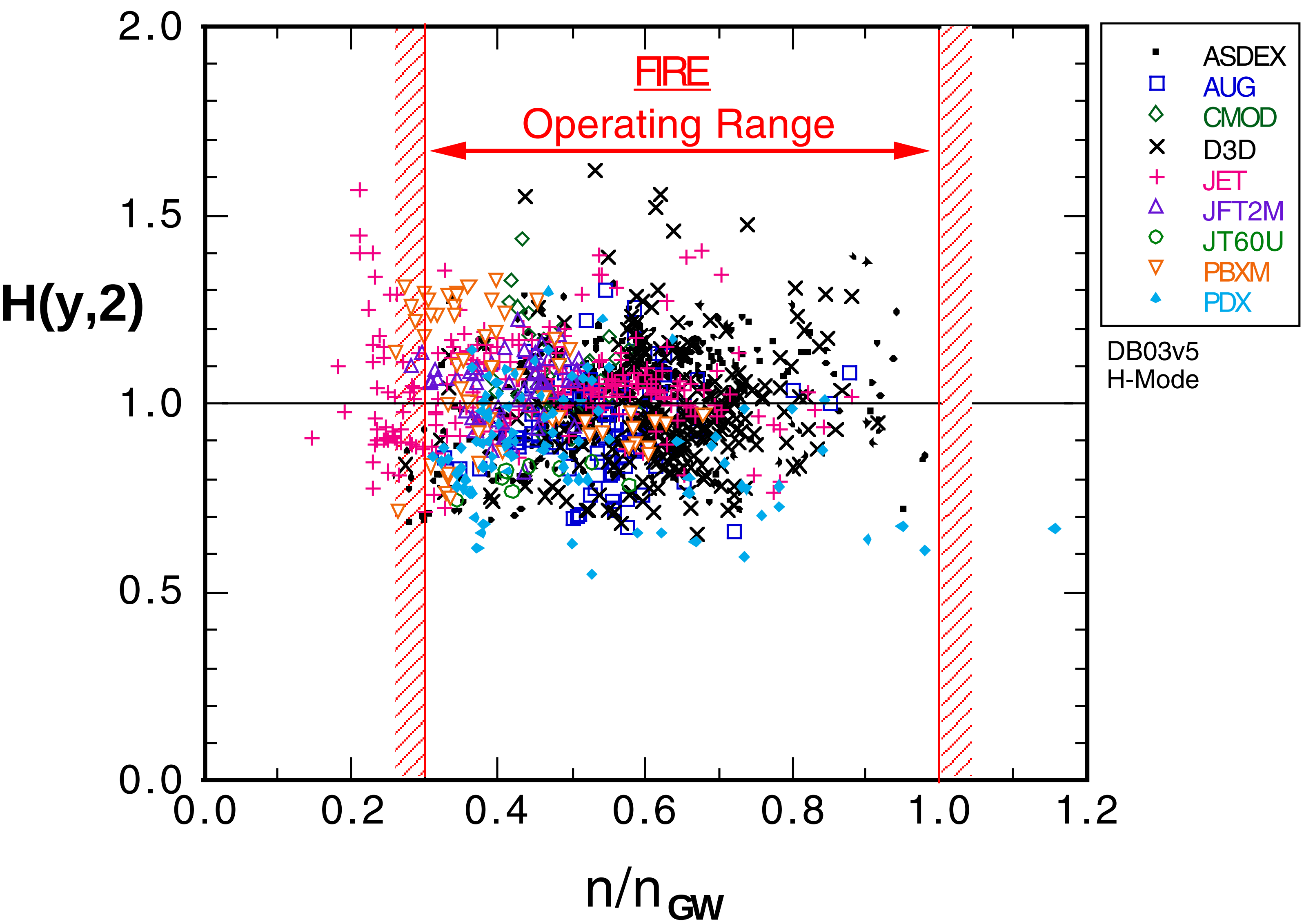
Similarity Parameter

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

Kadomtsev, 1975

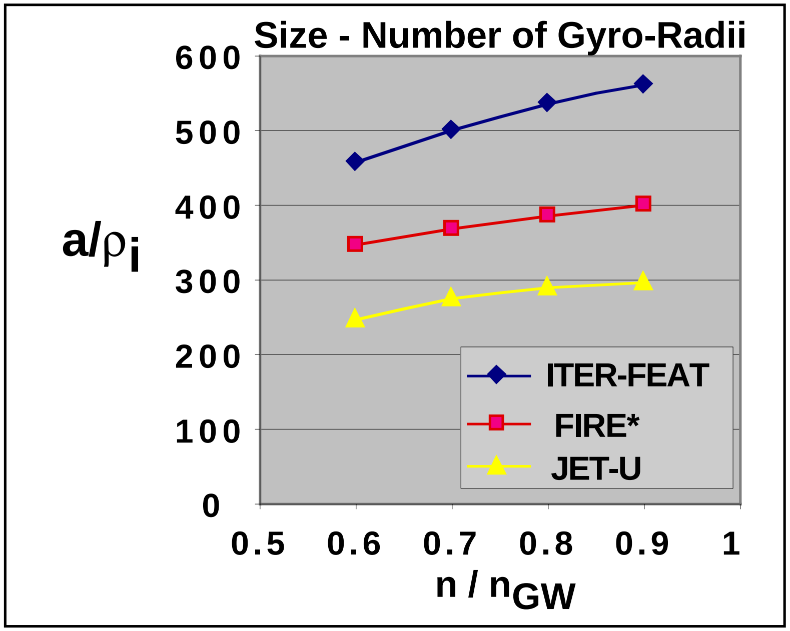


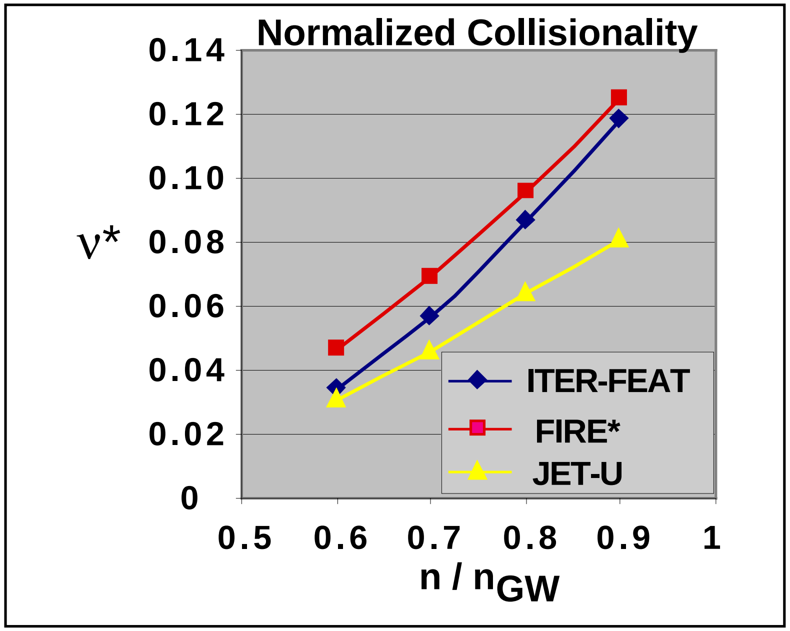
FIRE can Access Most of the H-Mode Database

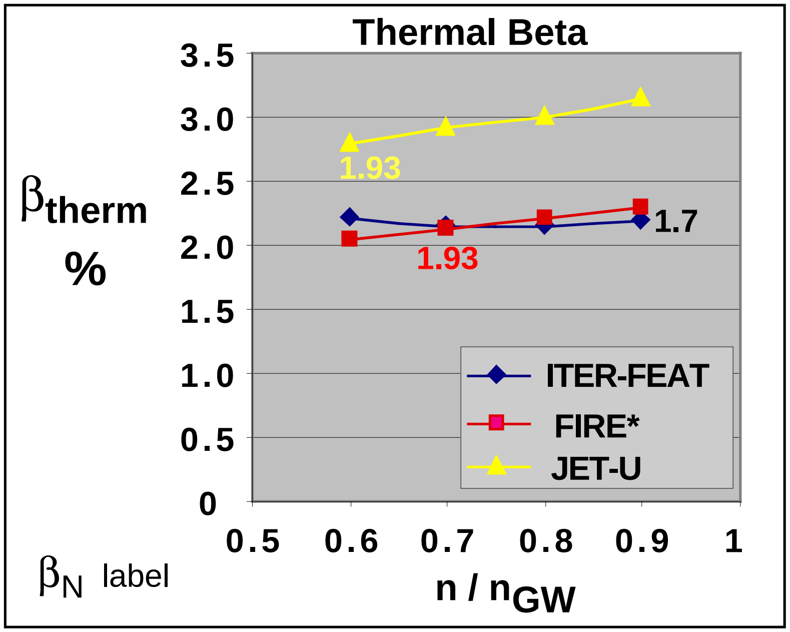


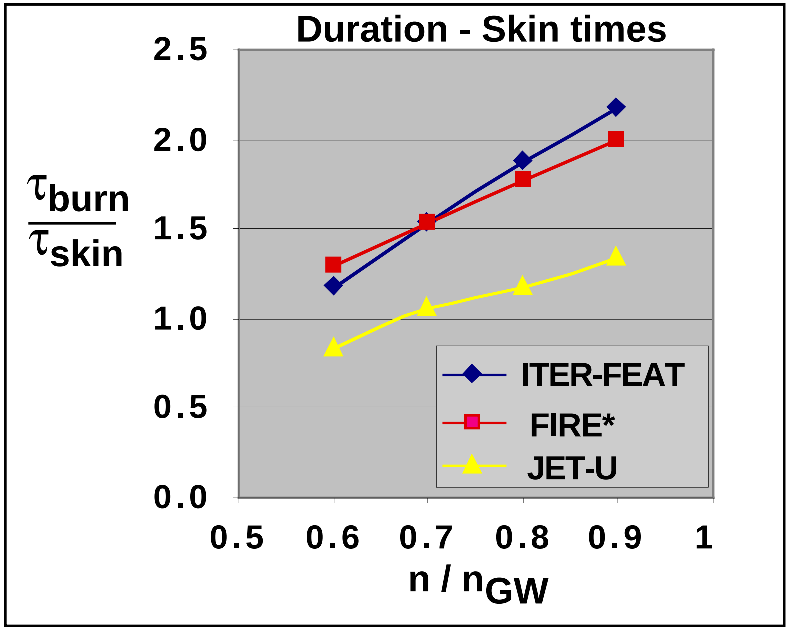
Parameters for H-Modes in Potential Next Step D-T Plasmas

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


Size - Number of Gyro-Radii

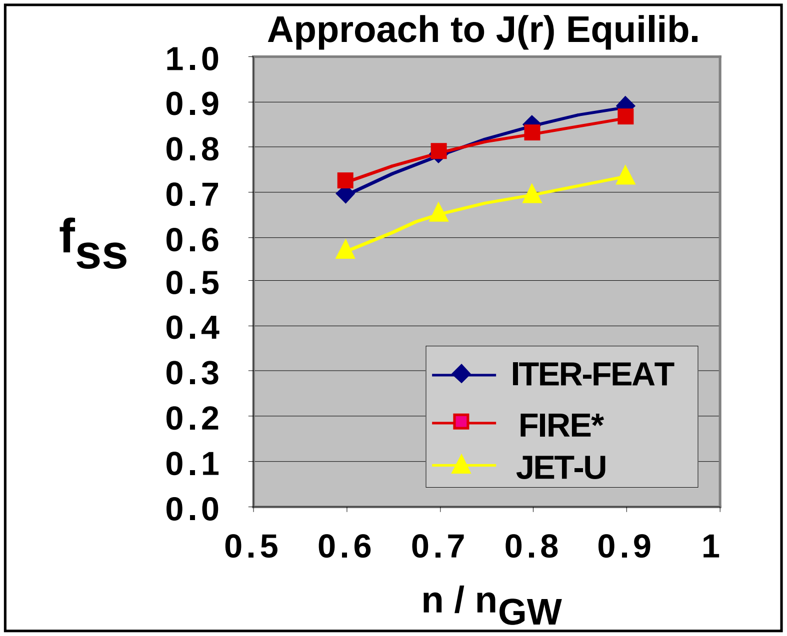

Normalized Collisionality

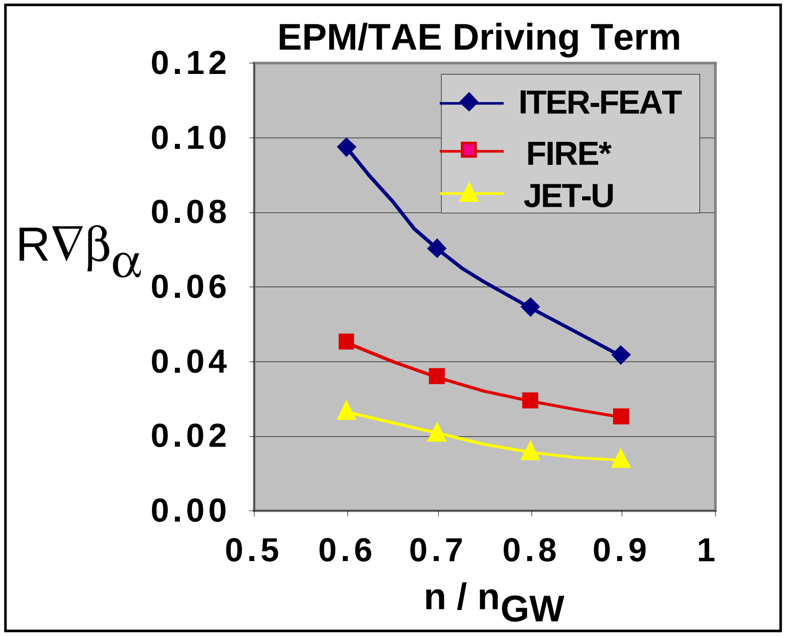

Thermal Beta


Duration - Skin times

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

ITER-FEAT: Q = 10 H = 0.95, FIRE*: Q = 10 , H = 1.03, JET-U: Q = 0.64, H = 1.1

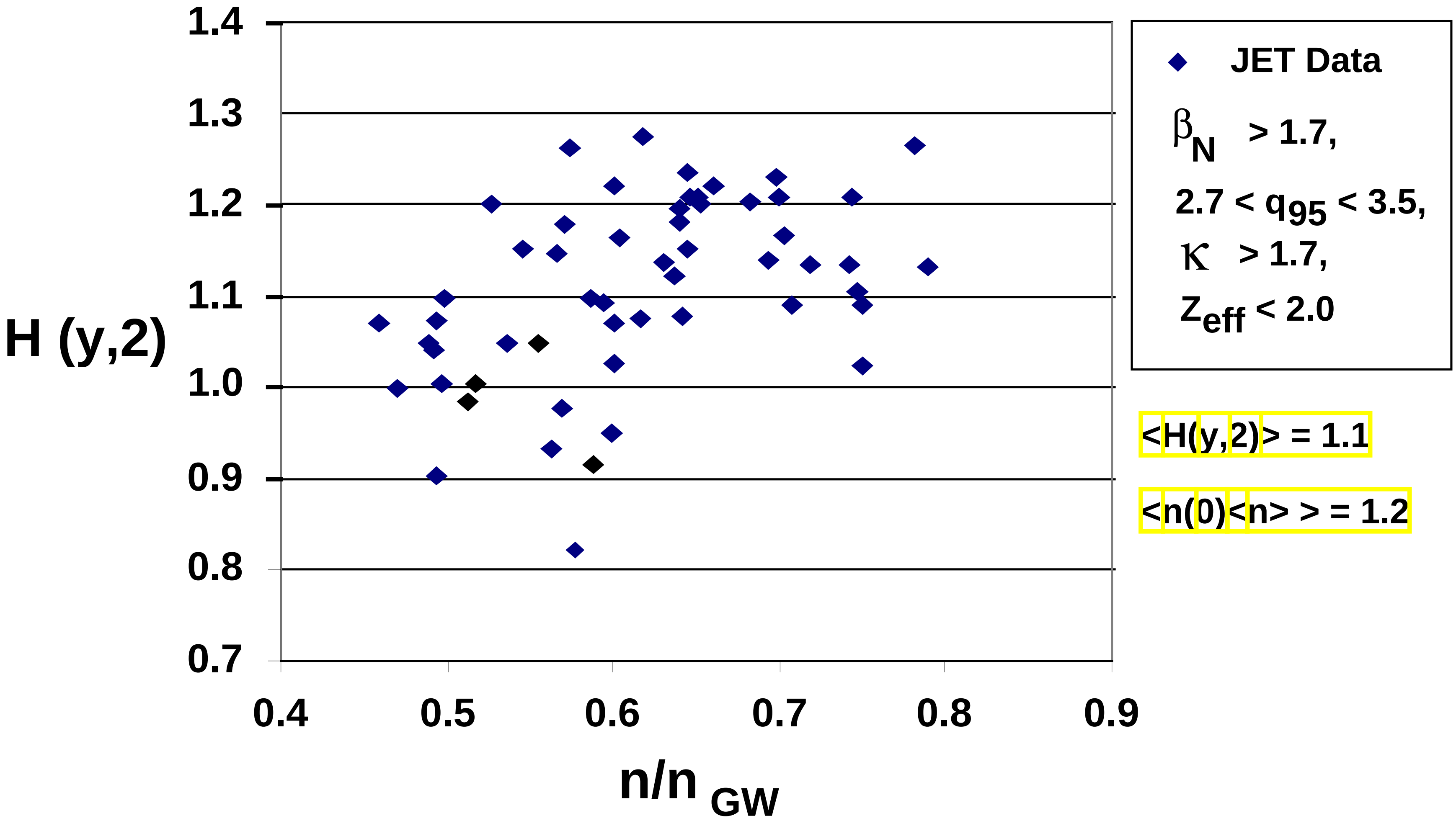




Summary Points on Dimensionless Parameters

- 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.
- Achieving Q > 1 in JET-U would imply very high Q for similar modes in ITER-FEAT and FIRE.

JET H-Mode Data Selected for FIRE-like Parameters



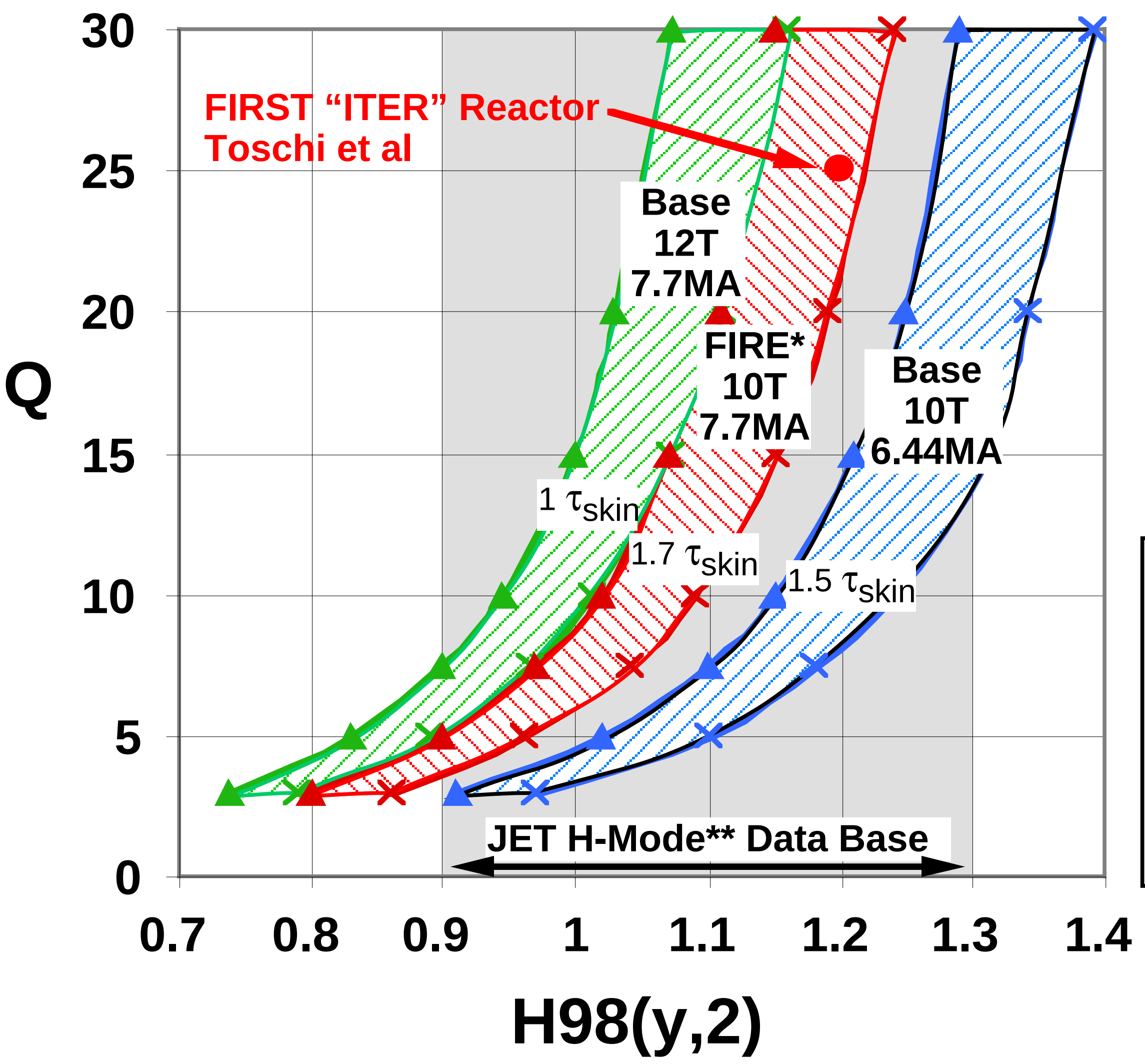
<H(y,2)> = 1.1

<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

ARIES-AT, Najmabadi, ● Q = 50



P_{fusion} = 150 MW

n/n_{GW} = 0.7

▲ $n(0)/<n>_V$ = 1.5

× $n(0)/<n>_V$ = 1.2

FIRE*
R = 2.14m, a = 0.595m
A = 3.6

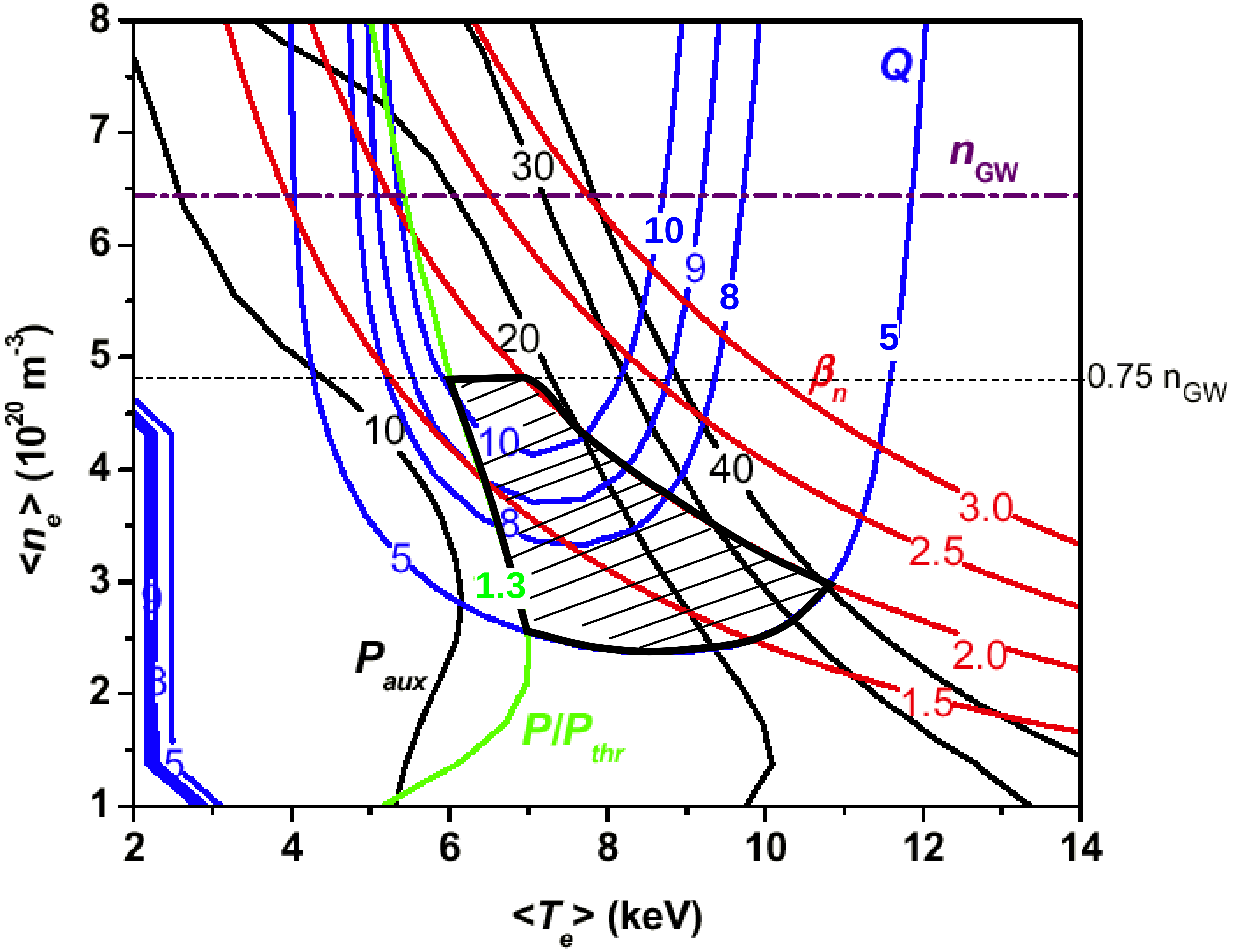
* JET H-Mode Data for β_N > 1.7, 2.7 < q_{95} < 3.5 κ > 1.7, n/n_{GW} = 0.5 -0.8, and Z_{eff} < 2 have

<H98(y,2)> = 1.1
$<n(0)/<n>_V>$ = 1.2

FIRE* Parameters

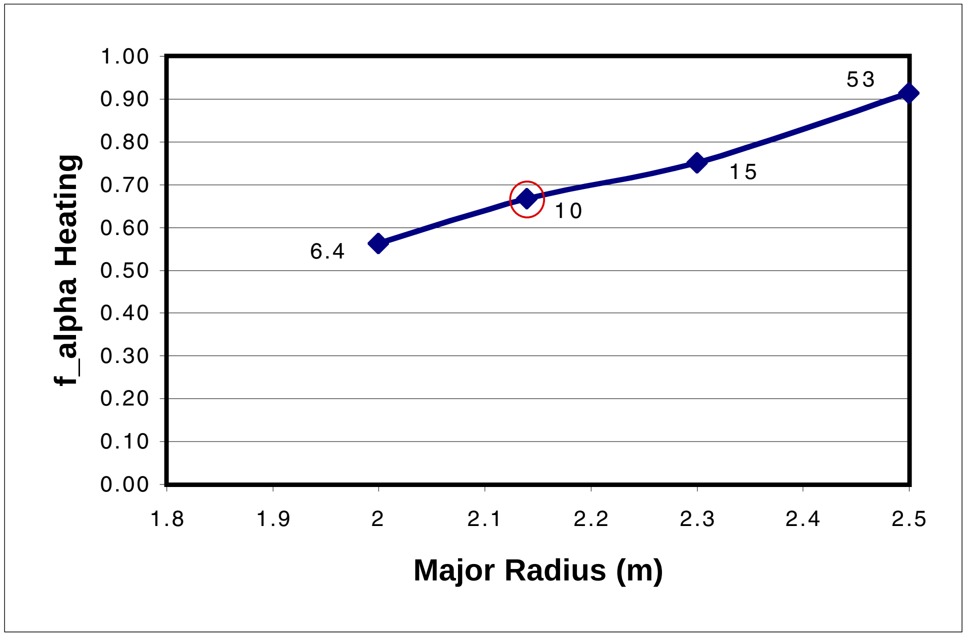
R_plasma/ a_plasma	2.14 / 0.595
A	3.6
κa	1.81
δ95	0.4
<ne>, 10^20 /m^3	4.55
Paux (MW)	14.5
Pheat (MW) = Ploss	34
Bt(T) / Ip(MA)	10 / 7.7
Ion Mass	2.5
H(y,2)-ITER98	1.11
H-ITER 89P	2.61
alpha_n / alpha_T	0.2 / 1.0
li(3)	0.8
τaup*(He)/τauE	5
Cbs	0.7
f_bs	0.27
ν*	0.058
1/ρ*(uses To)	352
β (thermal only), %	2.24
q95	3.05
<n>l/greenwald	0.70
P_fusion (MW)	150.7
Pheat/P(L->H)	1.29
Q_DT*= Pfusion/Paux	10.39
Q_DT =Pf/(Pext + Poh)	10.01
fraction_alpha heating	0.67
τauE	1.04
ni(0)τ_ETi(0)	52.27
skin time	12.23
W(MJ), thermal / W alpha (MJ)	35.3 / 2.3
beta_alpha, %	0.15
Rgradbeta_alpha	0.04
v_alpha/v_alfven	2.01
beta_total, %	2.38
beta_N	1.84
eps*betap	0.20
<T>n / To	6.47 / 11.04
Zeff	1.41
Be concentration,%	3.00
Ar concentration, %	0.00
He concentration, %	2.30
Ploss/2πRx/ndiv (MW/m)	1.48

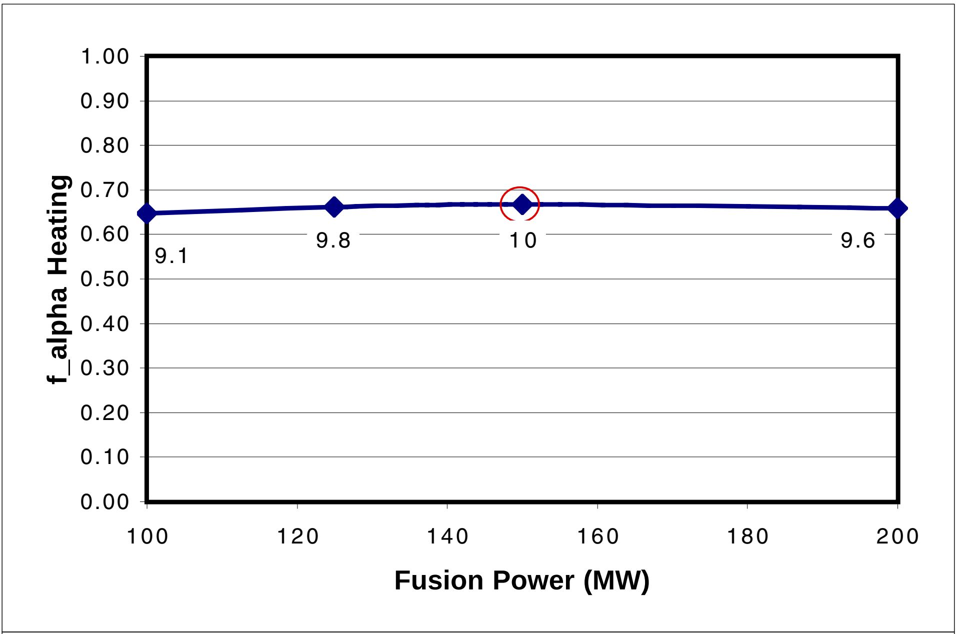
FIRE* 10T, 2.14m, 7.7 MA, H(y,2) = 1.14, α_n = 0.2

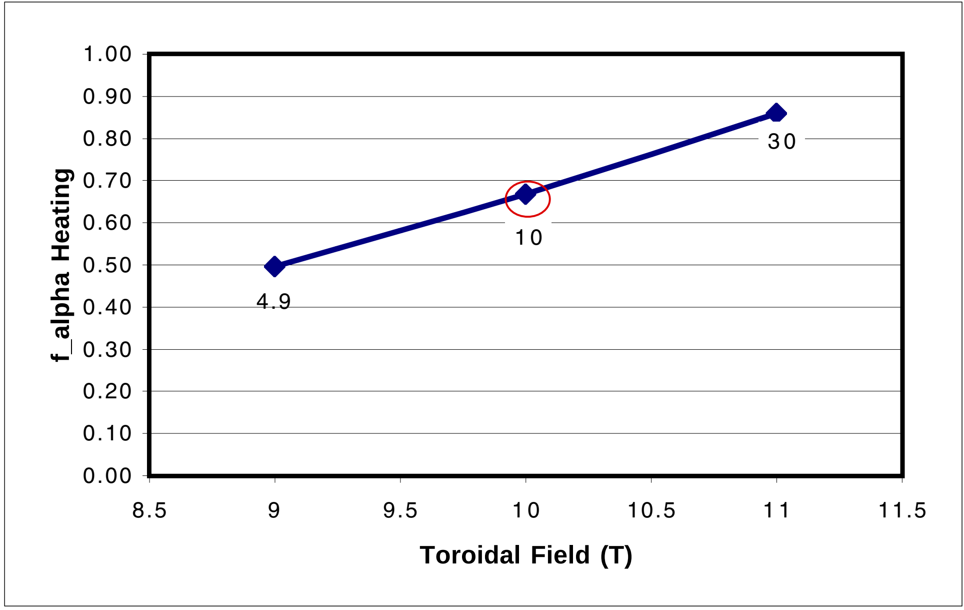


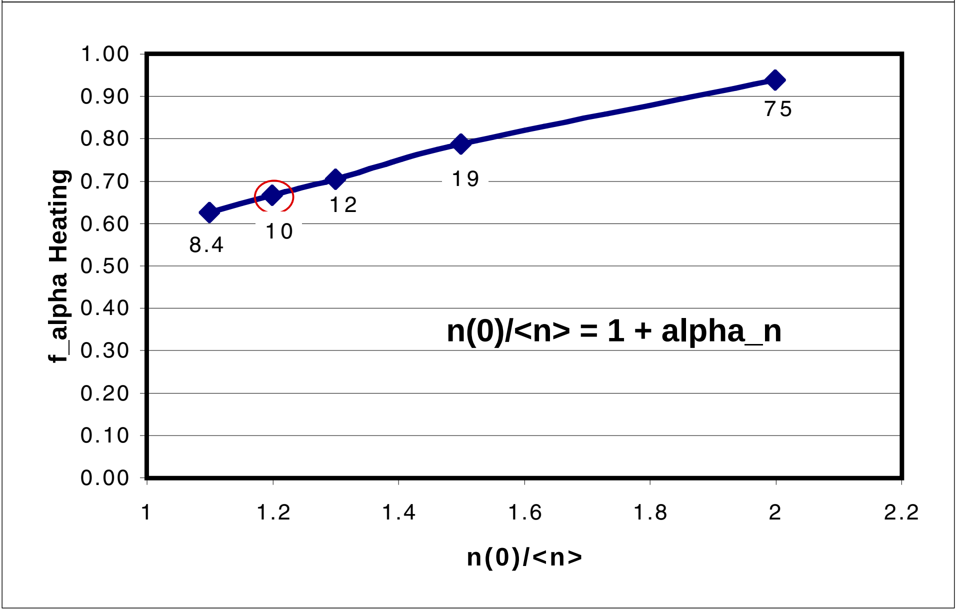
Sensitivity Scans on FIRE*

(A = 3.60, κ95 = 1.77, δ95 = 0.4, ITER98(y,2), H = 1.027, n/nGW = 0.7, nBe = 0.4%)





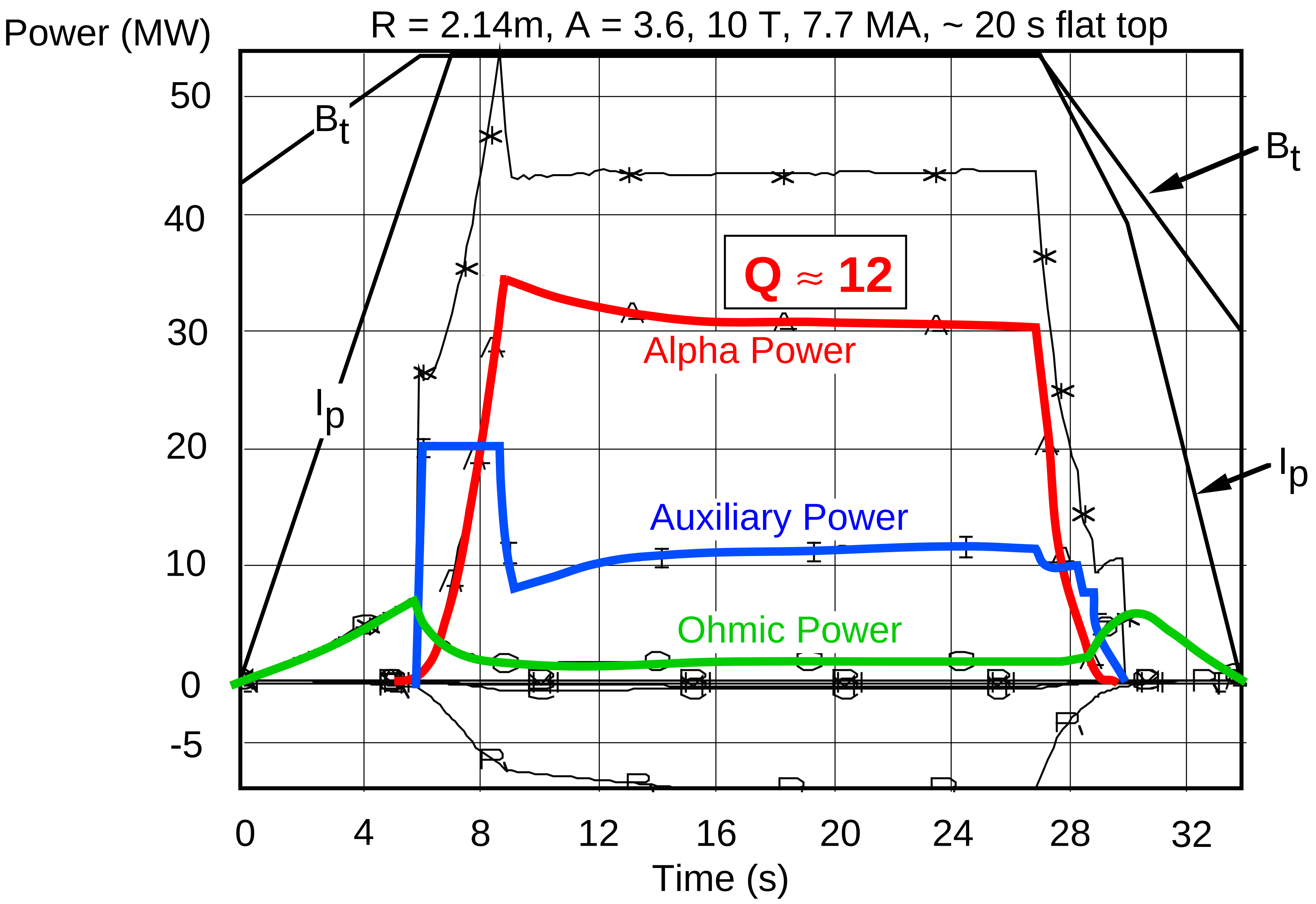




Note: kappa area would make H = 1.01

FIRE* Scans Compare

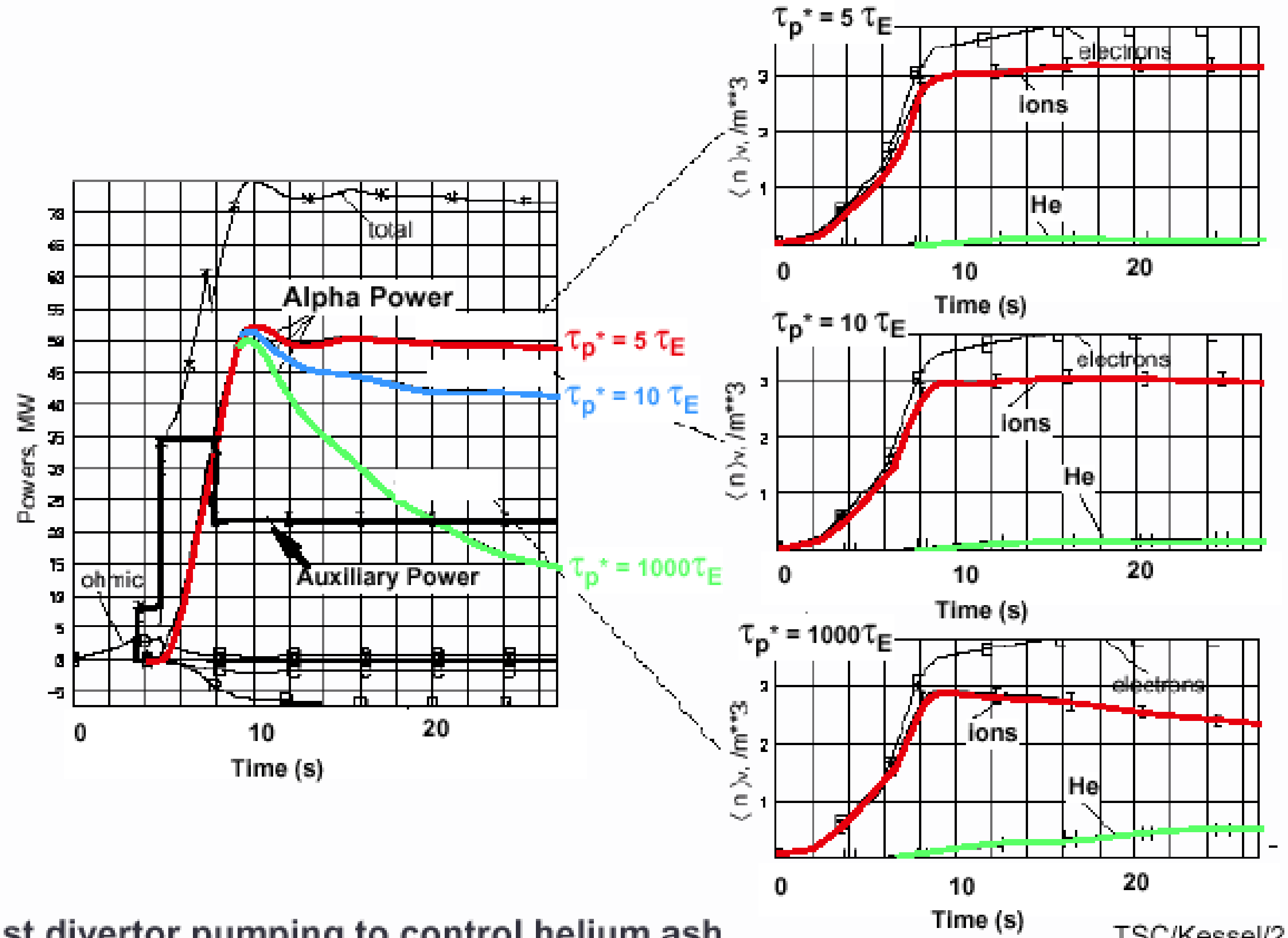
1 1/2-D Simulation of Burn Control in FIRE* (TSC)


R = 2.14m, A = 3.6, 10 T, 7.7 MA, ~ 20 s flat top

- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and $n/n_{GW} = 0.67$
- Burn Time ≈ 20 s ≈ 21 $\tau_E \approx 4\ \tau_{He} \approx 2\ \tau_{skin}$

Q = Pfusion/(Paux + Poh)

Divertor Pumping Needed for Plasma Burn



Adjust divertor pumping to control helium ash

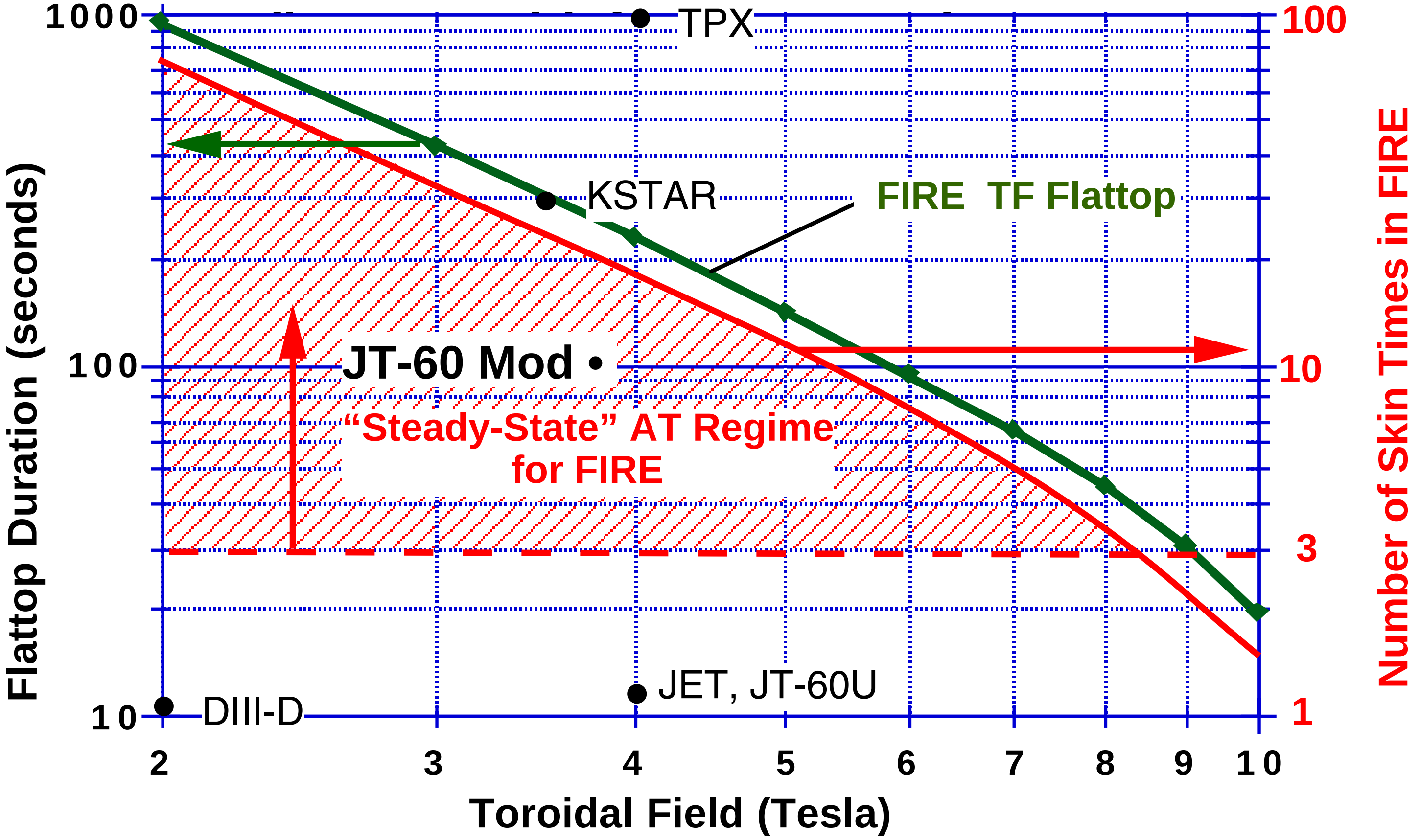
TSC/Kessel/21-q.ps

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

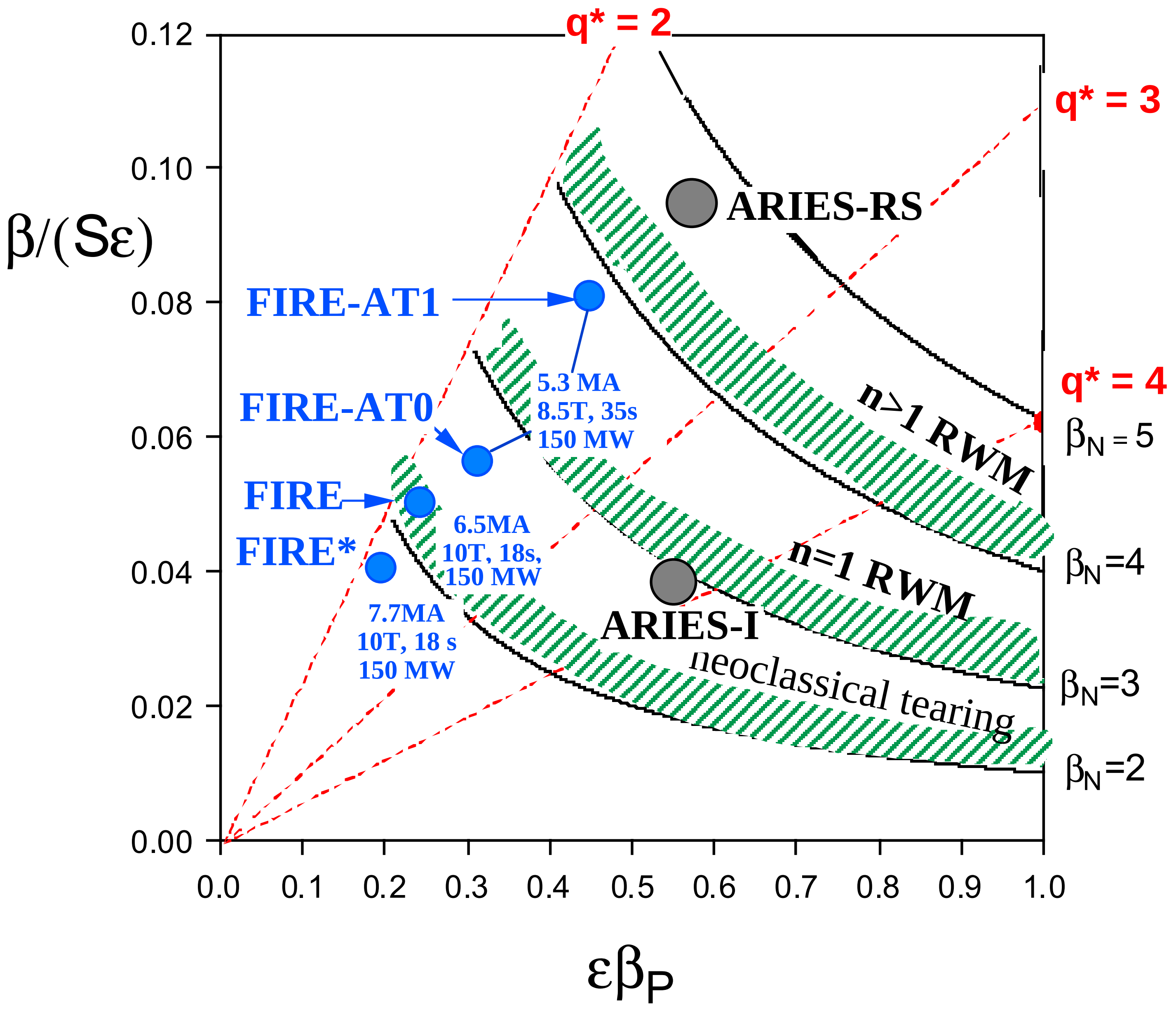
FIRE can study both burning AND long pulse plasma physics in the same device

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



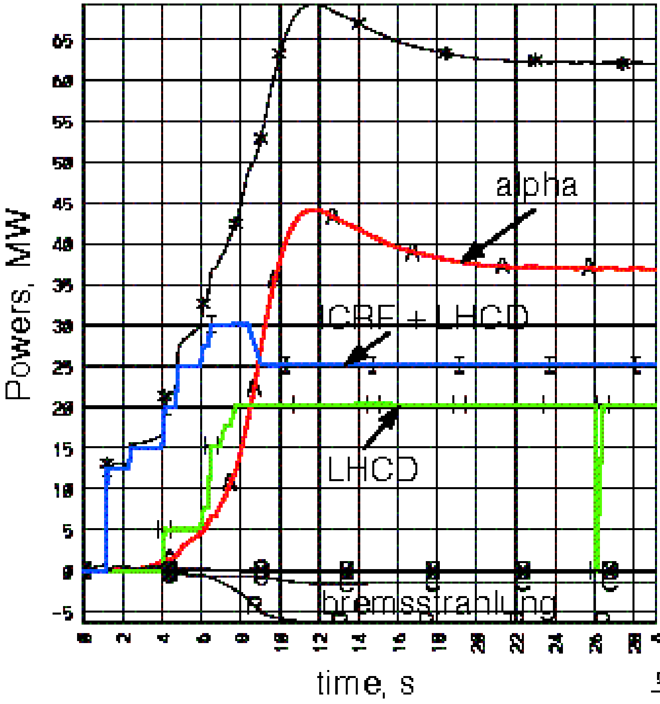
Note: FIRE is ≈ the same physical size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT .
The Number of Skin Times curve assumes a constant skin time of 13s.

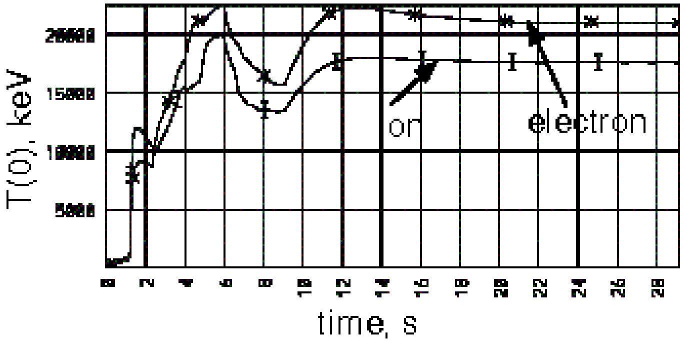
Progress Toward ARIES-like Plasmas will Require a Sequence of Steps

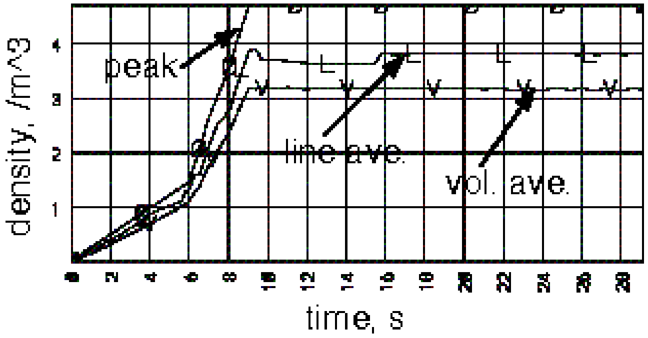


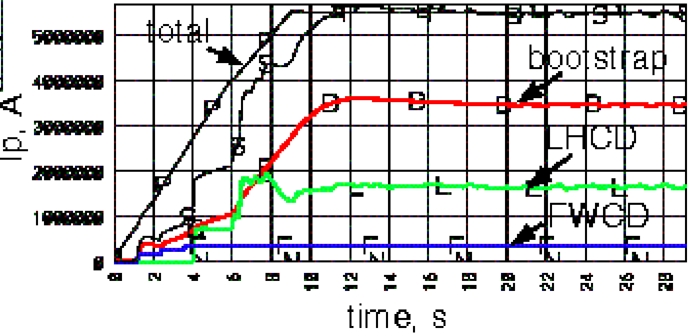
Dynamic Burning AT Simulations with TSC-LSC for FIRE

Ip=5.5 MA, Bt=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





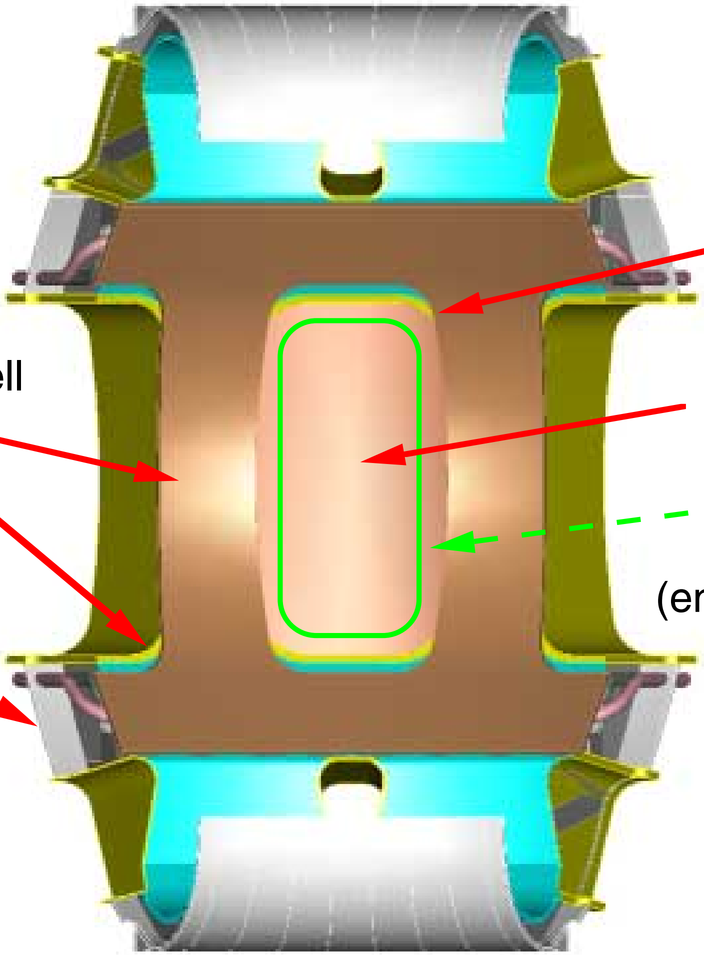




H(y,2)=1.6

Potential for Resistive Wall Mode Stabilization System

view of hoizontal port front looking from plasma side



horizontal port
(1.3 m x 0.65 m)

Copper Stabilizing Shell
(backing for PFCs)

port shield plug (generic)

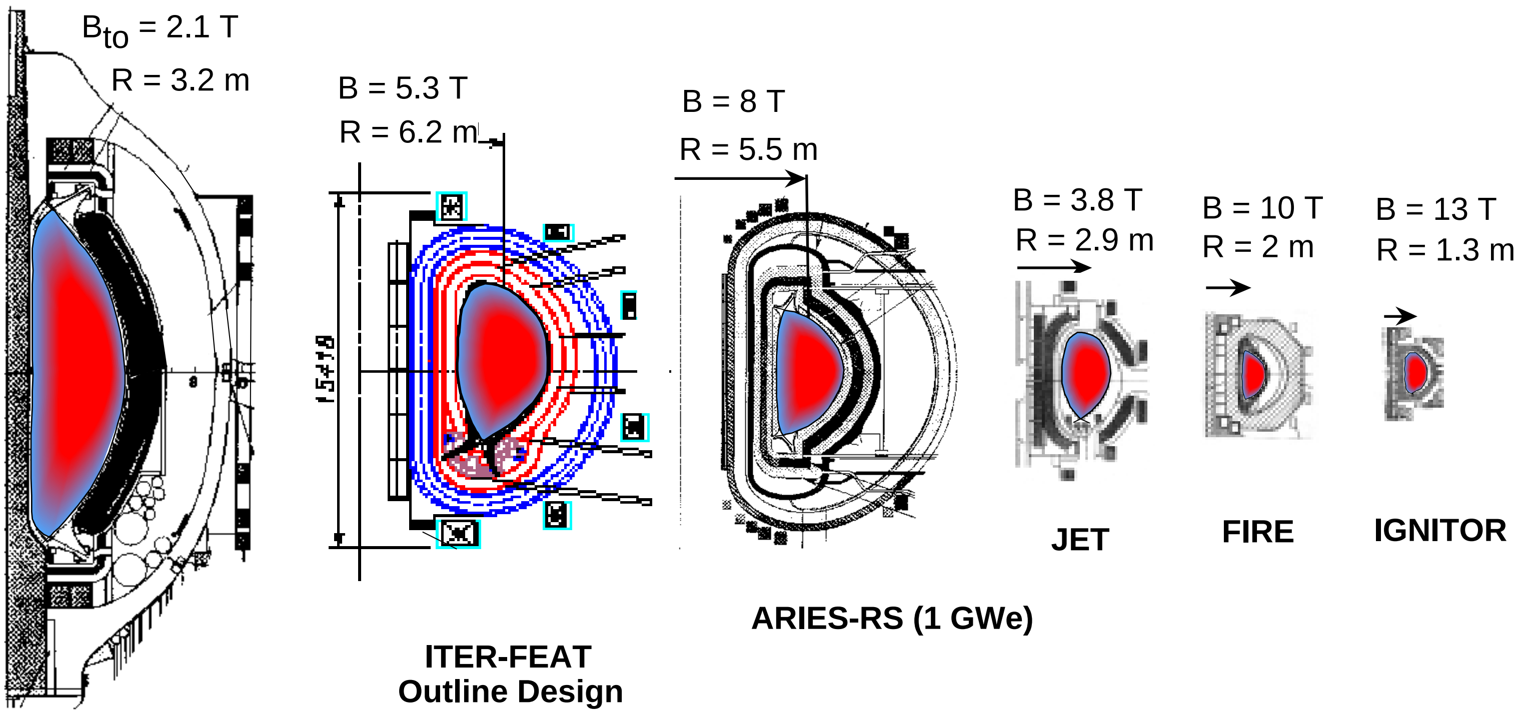
1st Vacuum Shell

resistive wall mode
stabilization coil
(embedded in shield plug)

2nd Vacuum Shell

Concept under development by Columbia Univ. J. Bialek, G. Navratil, C.Kessel(PPPL) et al

Potential Next Step Burning Plasma Experiments and Demonstrations in MFE



ARIES-RS (1 GWe)

ITER-FEAT
Outline Design

ARIES-ST (1 GWe)

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 (31s flattop)		12T (22s 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

Note: TF and PF power peaks will not be coincident as assumed above. The Cu TF configurations will require bucking and wedging.

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-00)
PCAST (120s)	7	5.0	30	~$4,000M (FY-95)

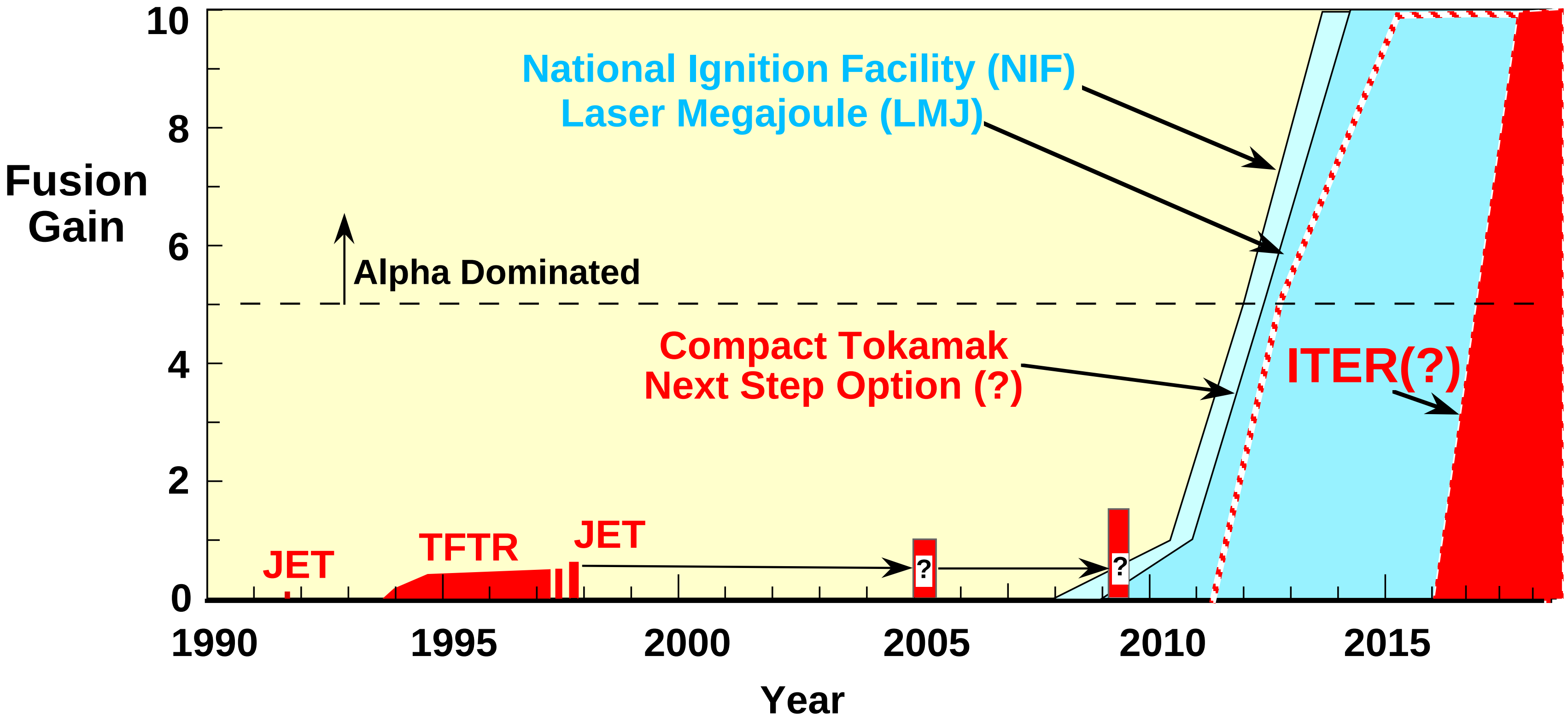
Preliminary FIRE Cost Estimate (FY99 US$M)

	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.

June 5, 2001

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.

Summary

- The FIRE "Pre-Conceptual" 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 compact high field tokamak, like FIRE, can:
  - address the important burning plasma issues,
  - most of the advanced tokamak issues and,
  - begin to study the strong non-linear coupling between BP and AT

  under quasi-stationary conditions in a $1B class facility.

- Many opportunities exist for improving/optimizing the FIRE design
  - optimimum aspect ratio for BP and AT with adequate pulse length
  - stronger shaping with more feedback
  - assume higher H factors, or base design on AT
  - Utilize bucking/wedging coil design to allow OFHC Cu longer pulse
  - Develop neutron damage resistant TF insulation - increase fluence
  - **others from this meeting**

http://fire.pppl.gov