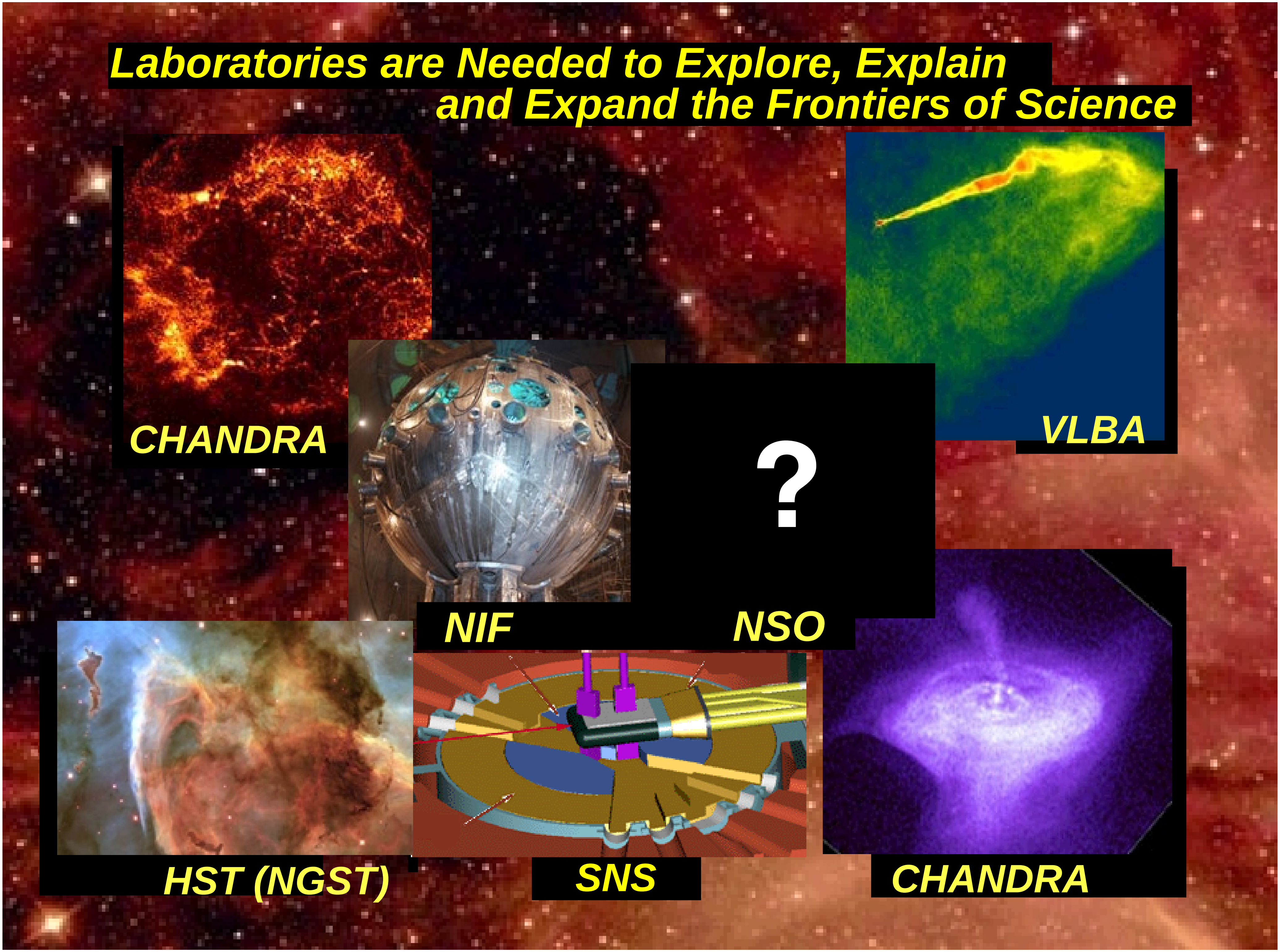

Laboratories are Needed to Explore, Explain
and Expand the Frontiers of Science
CHANDRA
VLBA
?
NIF
NSO
HST (NGST)
SNS
CHANDRA

FIRE

A Next Step Option for Magnetic Fusion

Dale M. Meade

for the FIRE Team

Presented at
5 th Large Tokamak Seminar
JAERI, Naka, Japan

September 7, 2001

http://fire.pppl.gov

Recent Events in the U. S.

- Fusion R&D recommended in National Energy Policy
- Energy Authorization Bill (HR 4) passed by the House on August 1, 2001 directs DOE to submit a plan for a U.S. Burning Plasma Experiment to Congress by July 2004.
- FESAC Endorses Recommendations of Burning Plasma Panel on August 2, 2001.
- National Research Council is preparing a proposal to review burning plasma physics as required by HR 4 and recommended by FESAC.
- Preparations are beginning for a Snowmass Summer Study July 8-19, 2002 that will emphasize burning plasmas.

Need to be ready if a “Window of Opportunity” opens.

Outline

- **Objectives for a Next Step Experiment in Magnetic Fusion**
- **Compact High Field Approach - General Parameters**
- **Burning Plasma Performance Considerations**
- **Advanced Tokamak Longer Pulse Possibilities**
- **Physics Issues, Cost and Timing**
- **Summary**

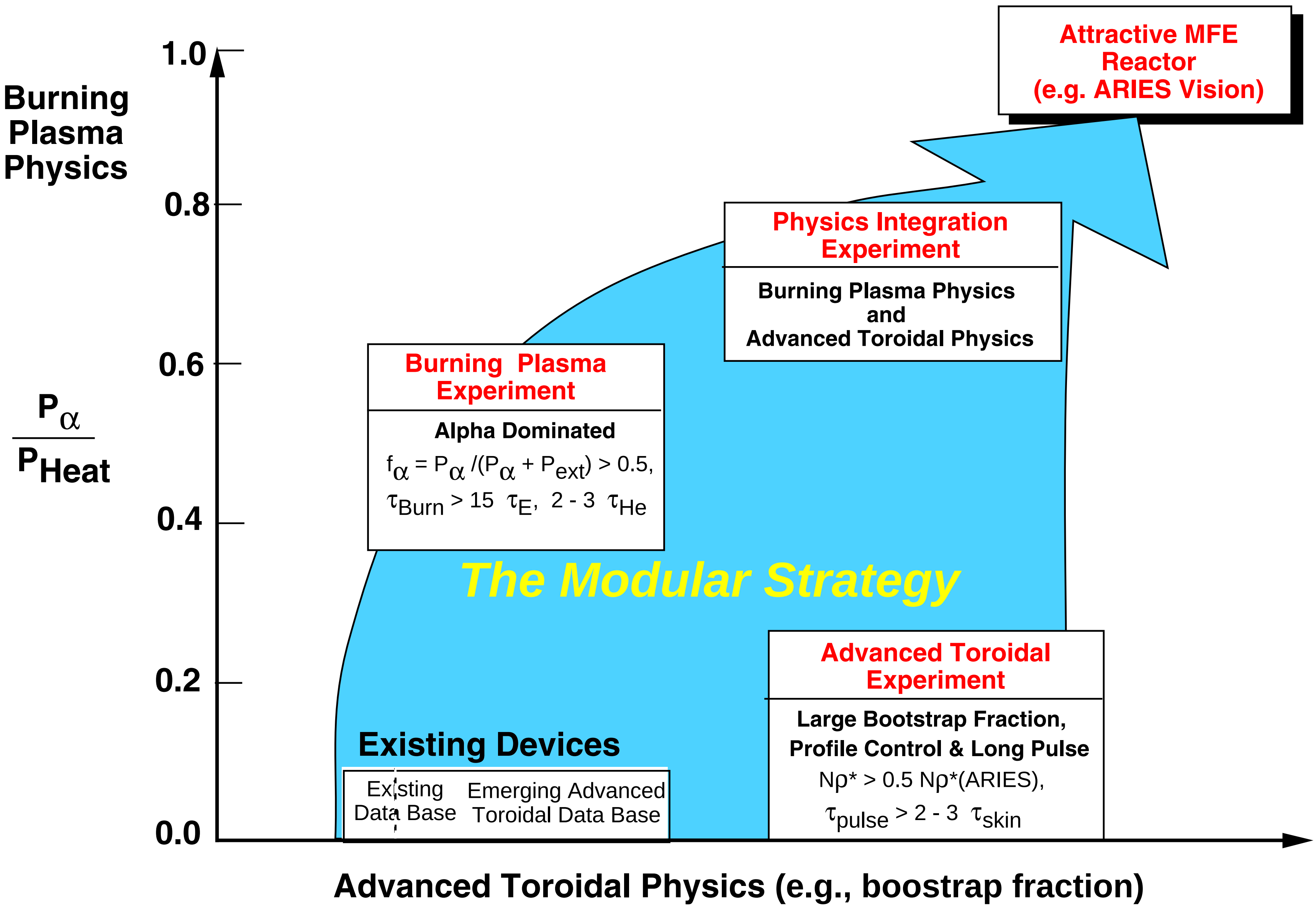
Fusion Science Objectives for a Major Next Step Magnetic Fusion Experiment

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



Get to a burning plasma with confidence using “todays” physics, but allow the flexibility to exploit tomorrow’s advanced physics.

Advanced Burning Plasma Exp't Requirements

Burning Plasma Physics

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

Advanced Toroidal Physics

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

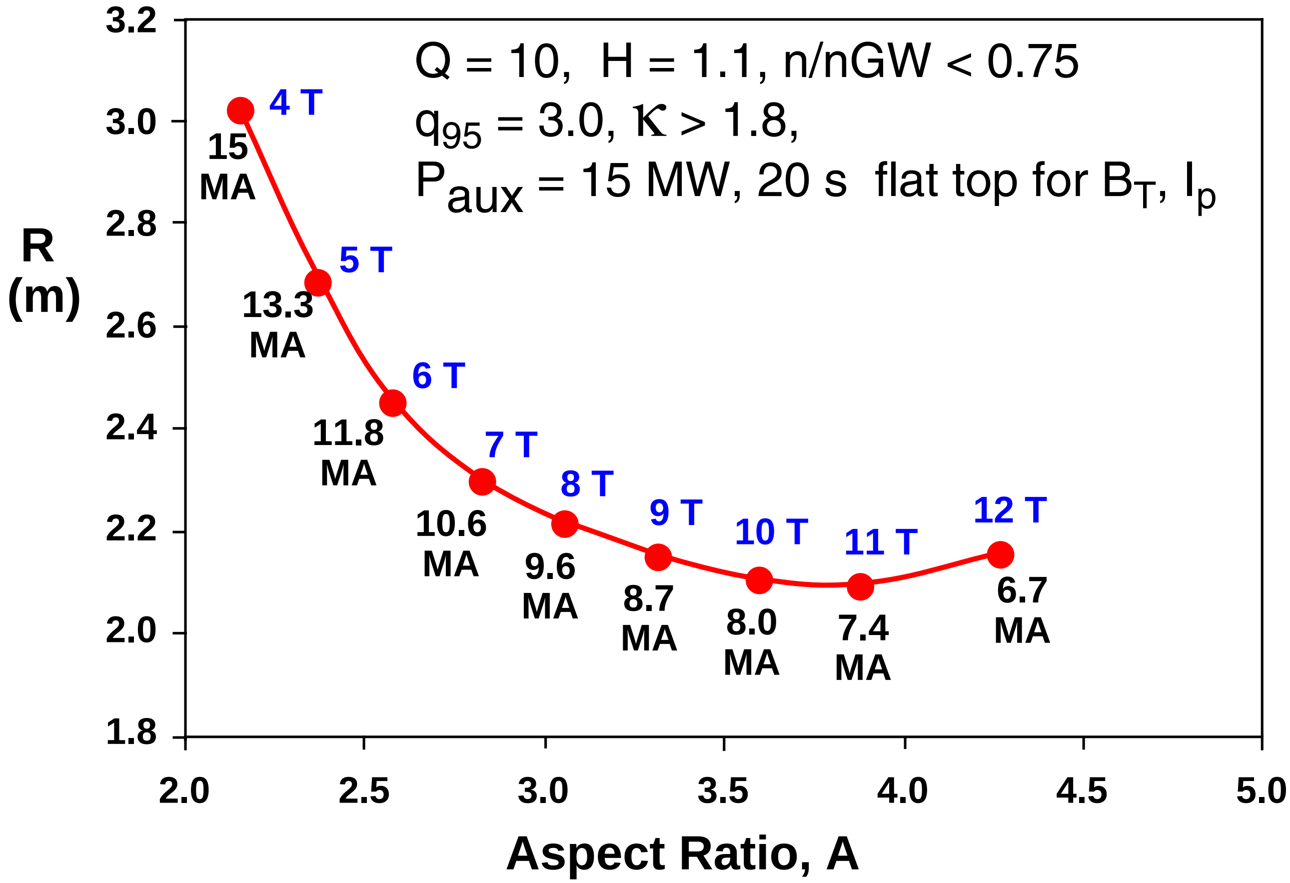
Quasi-stationary

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 $\tau_{divertor}$, $\tau_{first\ wall}$

Optimization of a Burning Plasma Experiment

- Consider an inductively driven tokamak with copper alloy TF and PF coils precooled to LN temperature that warm up adiabatically during the pulse.

- Seek minimum R while varying A and space allocation for TF/PF coils for a specified plasma performance - Q and pulse length with physics and eng. limits.

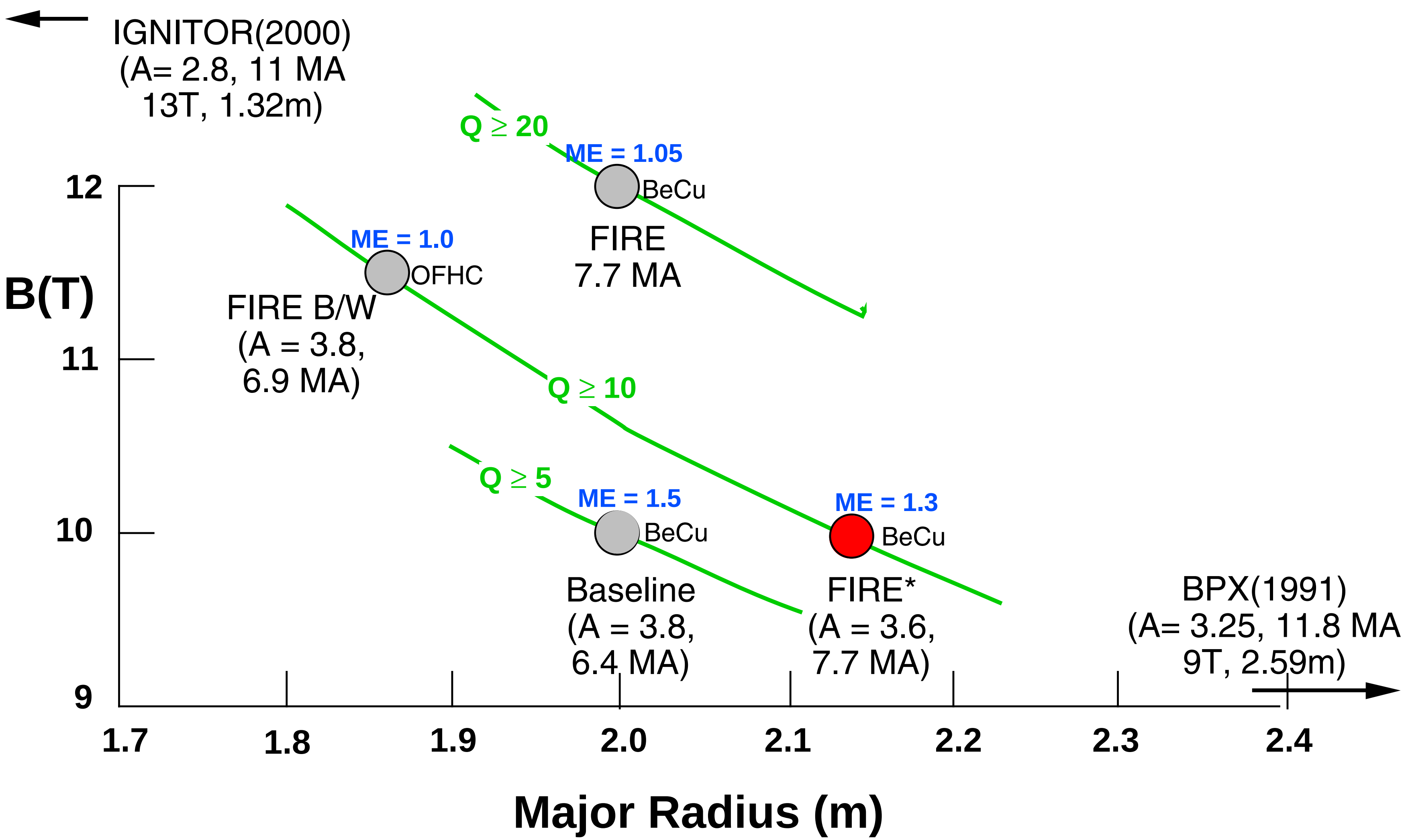


Elmy H-Mode
ITER 98 (y,2)

S. Jardin and
C. Kessel

What is the optimum for ITBs or AT modes?

FIRE Options that have been Considered

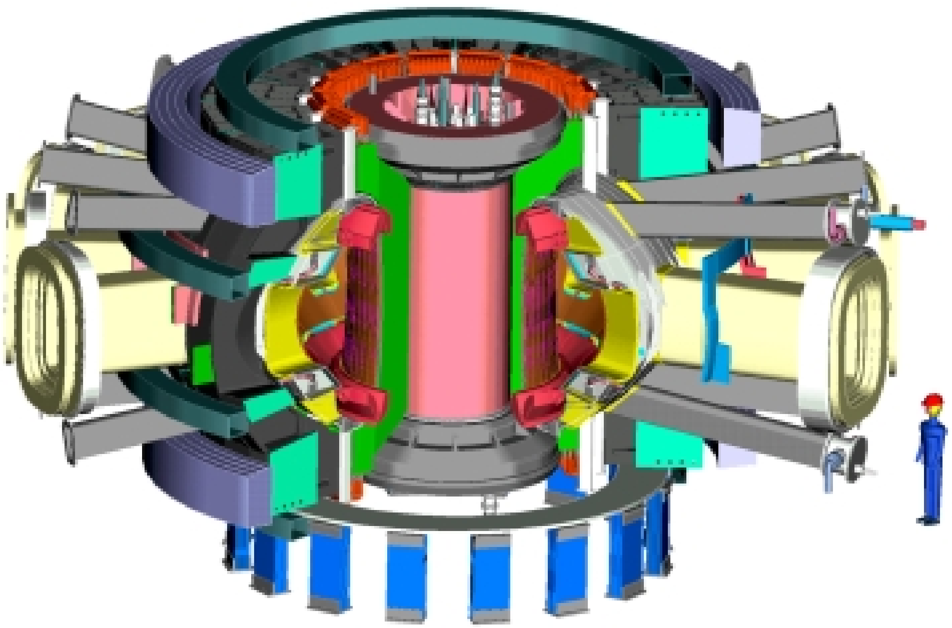


ME = Allowable Stress / TF Stress

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
- $Q \approx 10$, $P_{fusion} \sim 150$ MW
- Burn Time $\approx$ 20 s
- Tokamak Cost $\approx$ \$375M (FY99)
- Total Project Cost $\approx$ \$1.2B at Green Field site.

Mission:

Attain, explore, understand and optimize fusion-dominated plasmas.

Contributors to the FIRE Engineering 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*

R, major radius	2.14 m
a, minor radius	0.595 m
κx, $\kappa 95$	2.0, 1.77
δx, $\delta 95$	0.7, 0.55(AT) - 0.4(OH)
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	5.8 GJ
Ip, plasma current	7.7 MA
Magnetic field flat top, burn time	28 s at 10 T in dd, 20s @ Pdt ~ 150 MW)
Pulse repetition time	~3hr @ full field and full pulse length
ICRF heating power, maximum	20 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 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, ~6 -8 MW m-3 in plasma
Neutron wall loading	~ 2.3 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

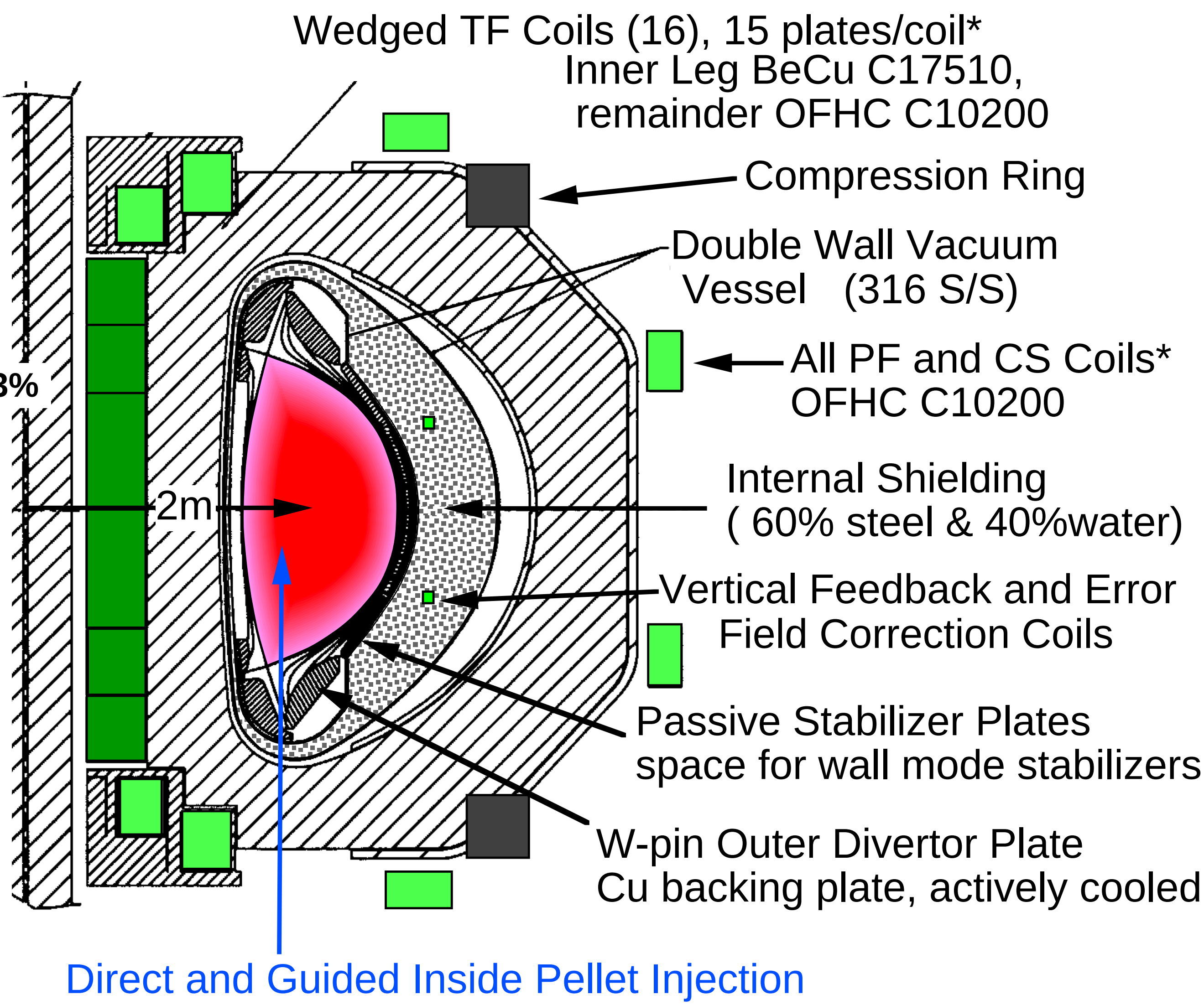
FIRE would have Access for Diagnostics and Heating

~ 25% of first wall for ports

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



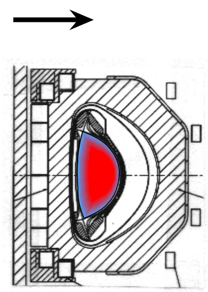
*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

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

R = 2.14 m B = 10 T

P_{fusion} = ~ 150 MW

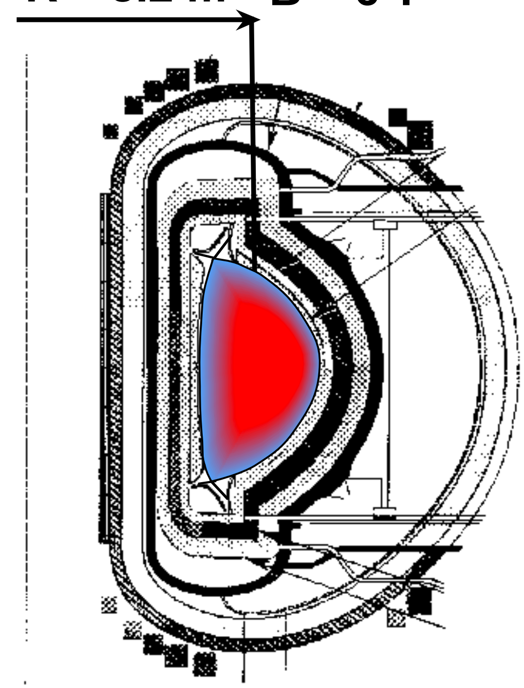
Volume = 27 m^3



FIRE

~ 3X

R = 5.2 m B = 6 T



P_{fusion} = 1755 MW

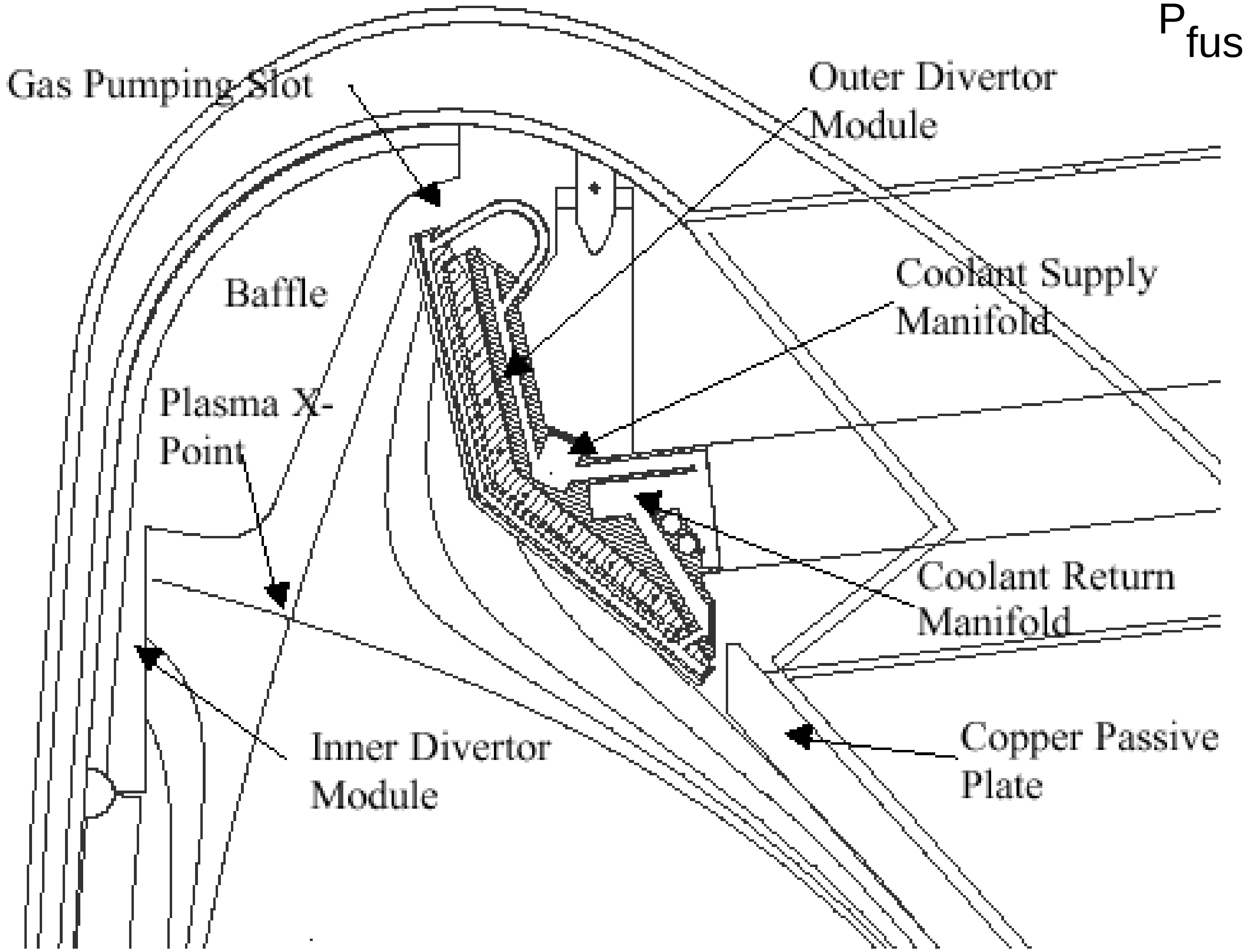
Volume = 330 m^3

ARIES-AT The “Goal”

	FIRE	ARIES-AT
Fusion Power Density (MW/m^3)	5.5	5.3
Neutron Wall Loading (MW/m^2)	2.3	3.5
Divertor Challenge (Pheat/NR)	~10	~35
Power Density on Div Plate (MW/m^2)	~15 - 19 $\rightarrow$ 6	~5
Burn Duration (s)	~20	steady

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

P_{fusion} < 200 MW



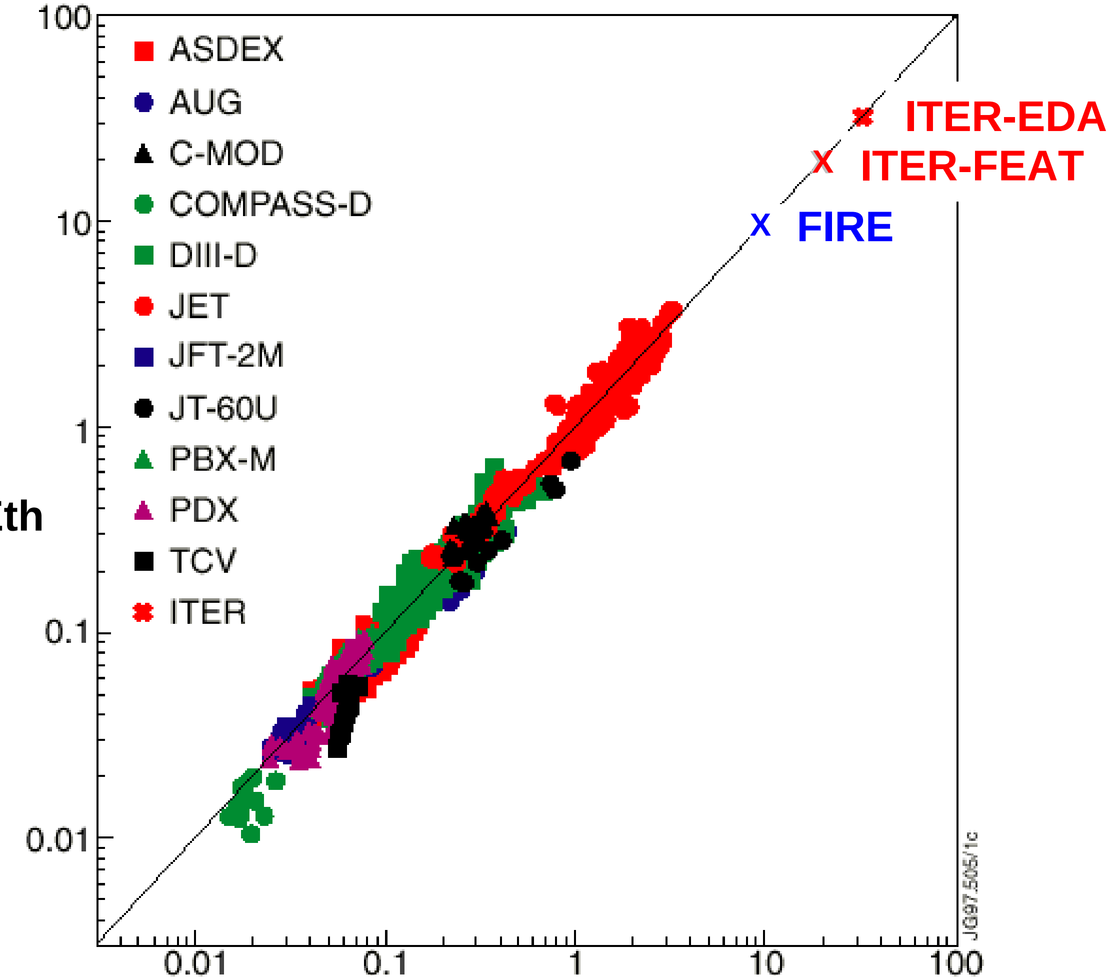
Reference Design is semi-detached operation with <15 MW / m2.

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

$\mathbf{B}\tau_{\mathbf{Eth}}$



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

Kadomtsev, 1975

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 - Based on today's tokamak data base

$$n_{20} \leq 0.8\ n_{GW} = 0.8\ I_p/\pi a^2,$$

Beta Limit - theory and tokamak data base

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

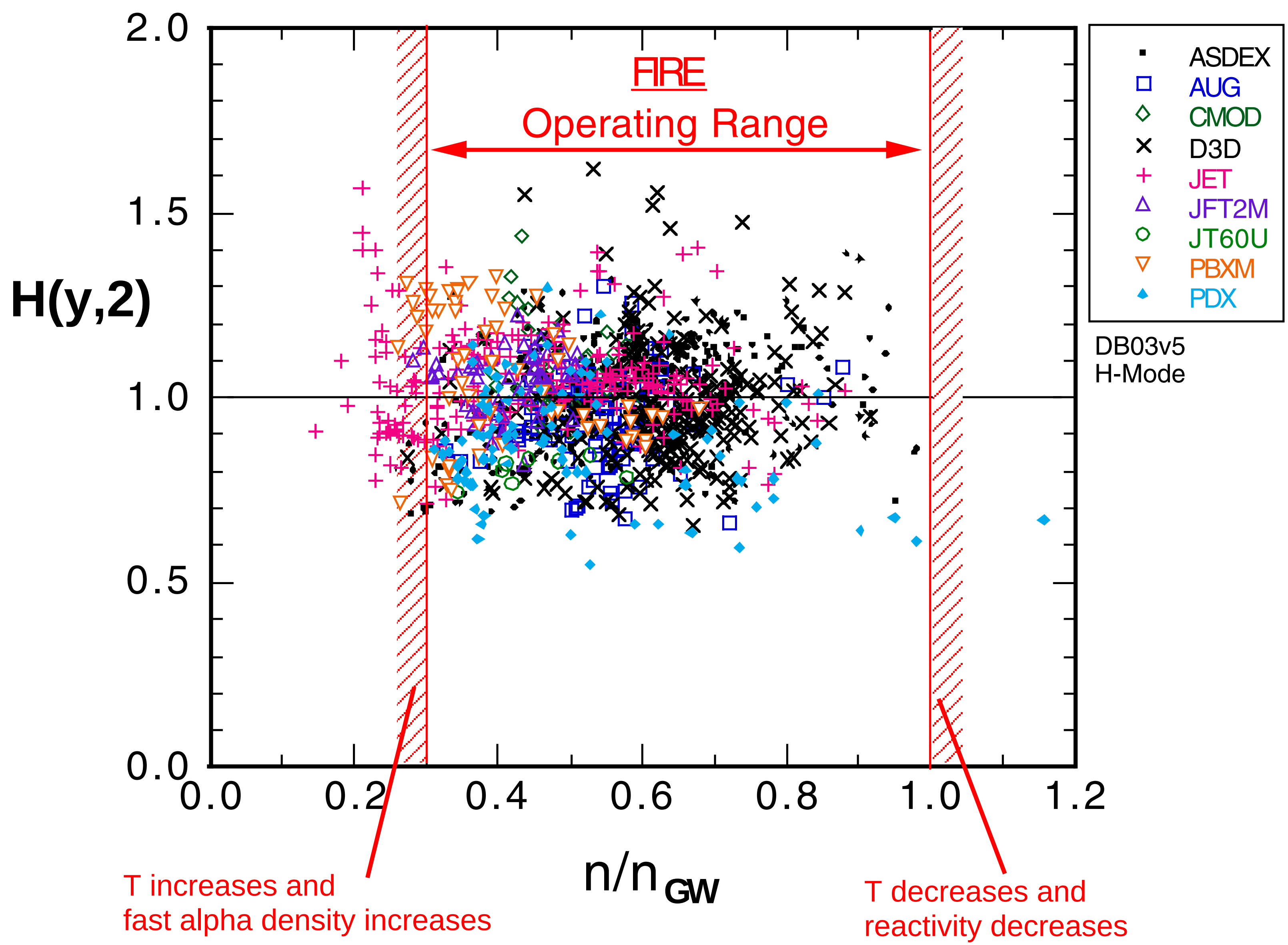
H-Mode Power Threshold - Based on today's tokamak data base

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

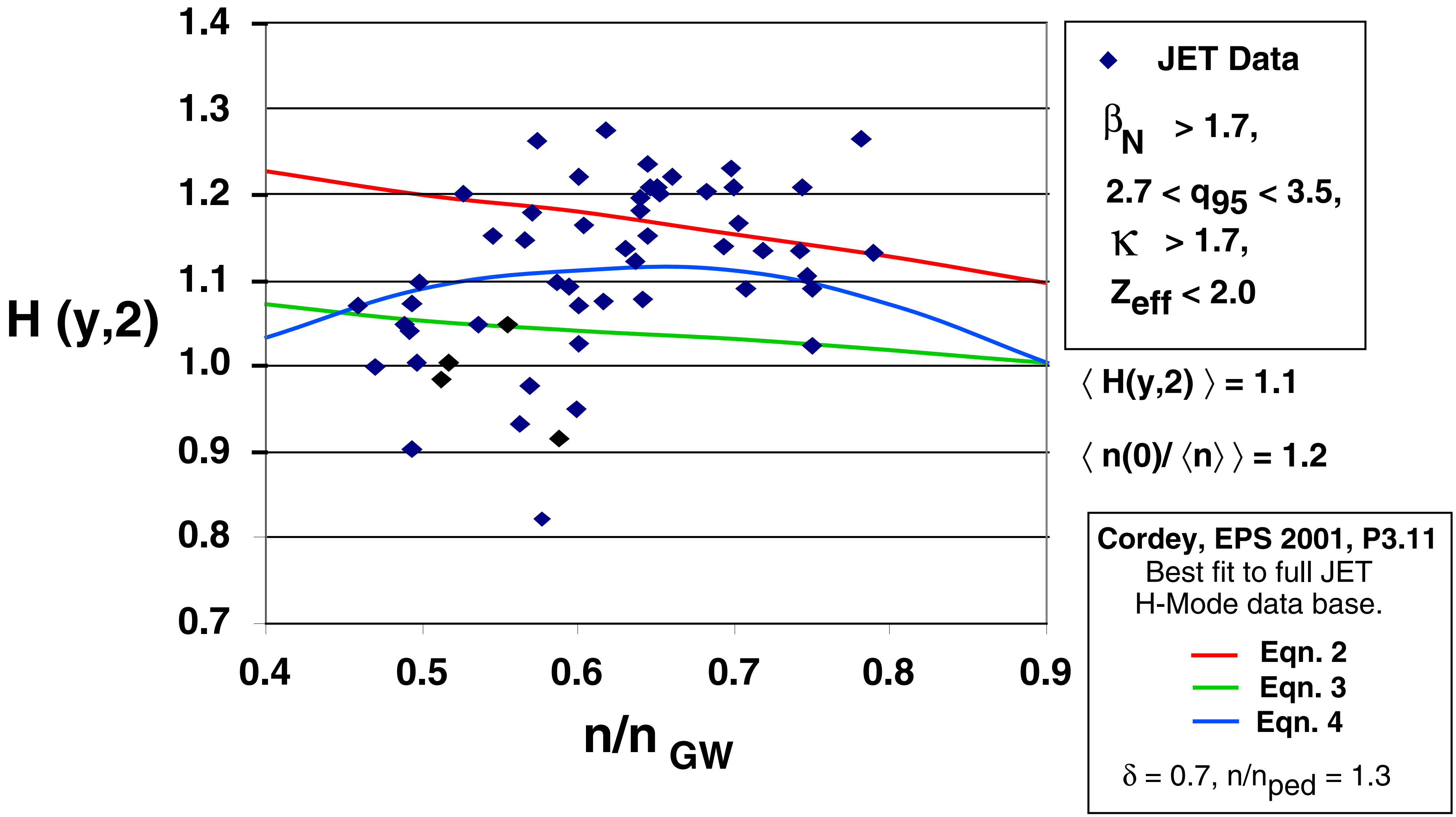
Helium Ash Confinement $\tau_{He} = 5\ \tau_E$, impurities = 3% Be

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

FIRE can Access Most of the H-Mode Database

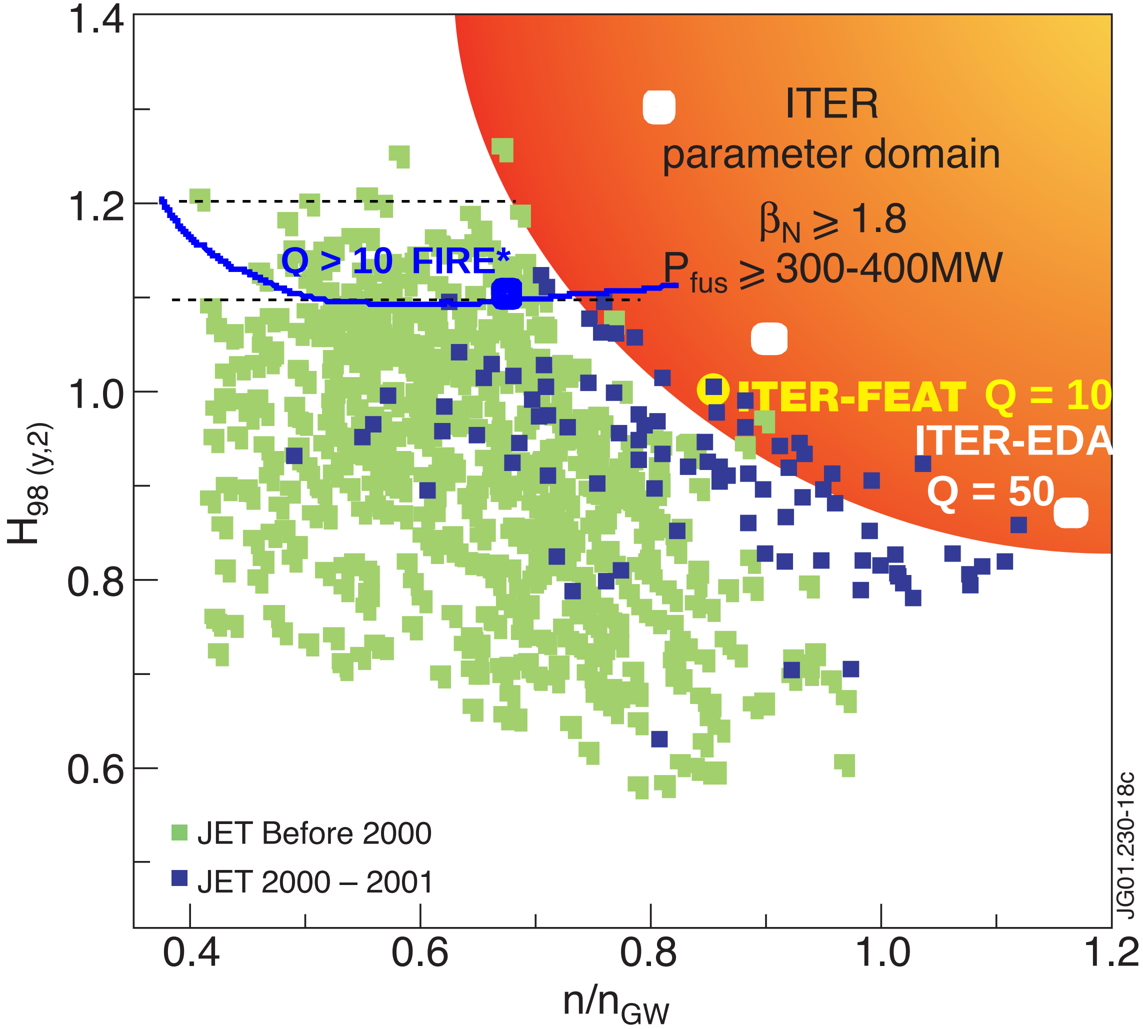


JET H-Mode Data Selected for FIRE-like Parameters



This needs to be extended to include JT-60U data, especially enhanced H-mode and reversed shear.

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 $\beta_N \gtrsim 1.8$ using different approaches and

- In addition Plasma purity as required for ITER: Zeff ~ 1.5

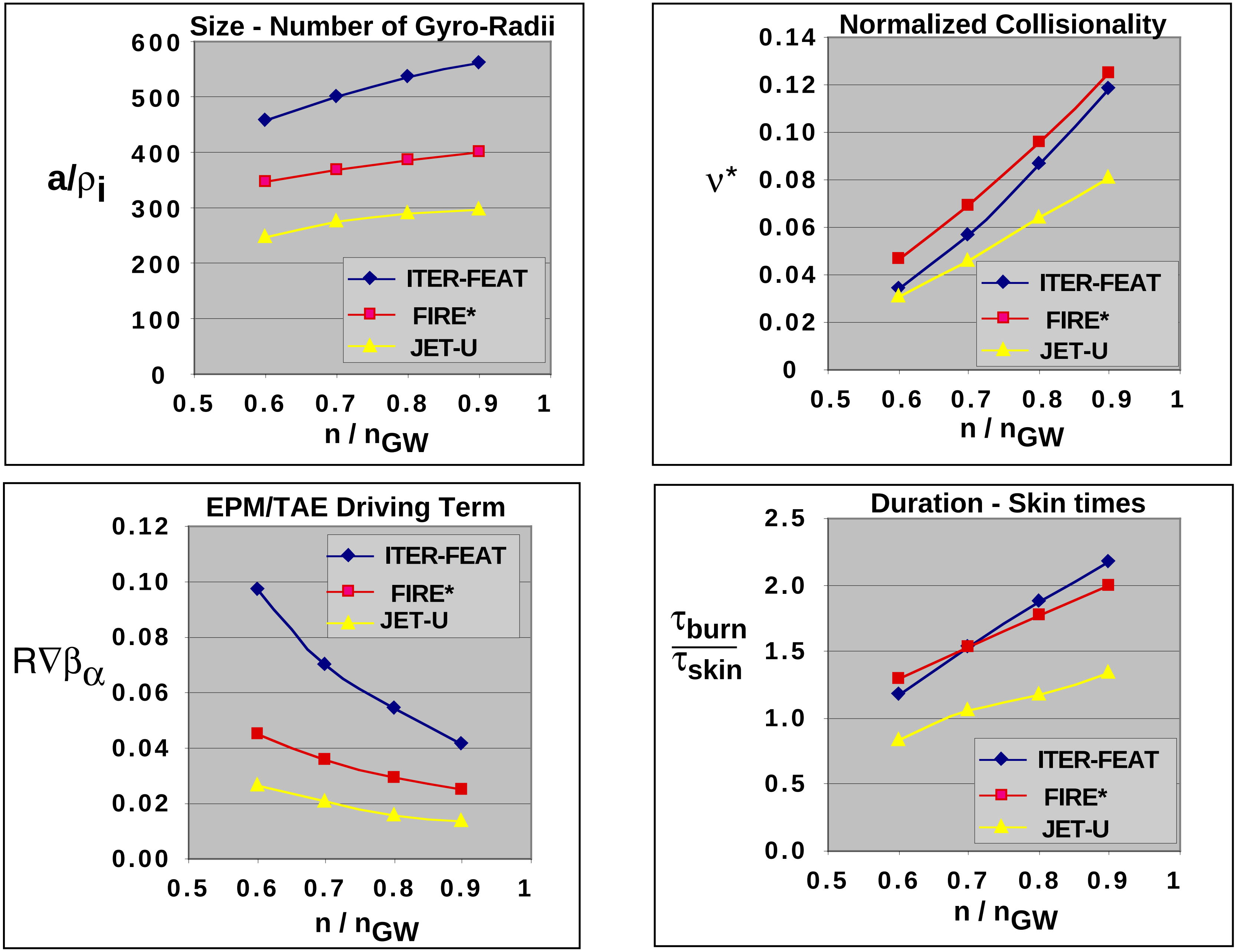
- For quasi-stationary phases of several seconds

- **Consolidation of ITER Q = 10 Reference scenario**

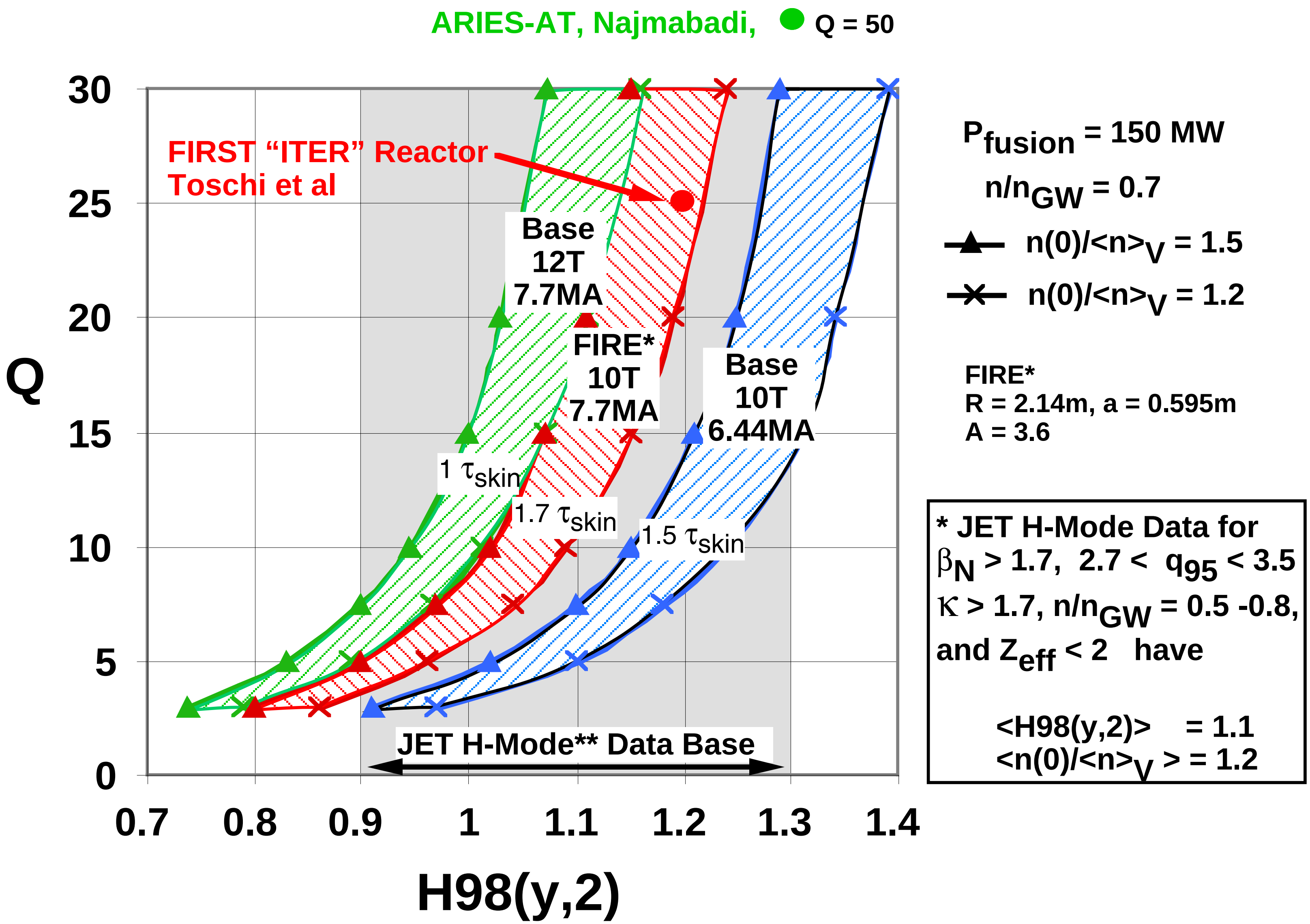
- **FIRE and ITER exploit different parts of the data base. Note added - DMM**

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



Projections of FIRE Compared to Envisioned Reactors

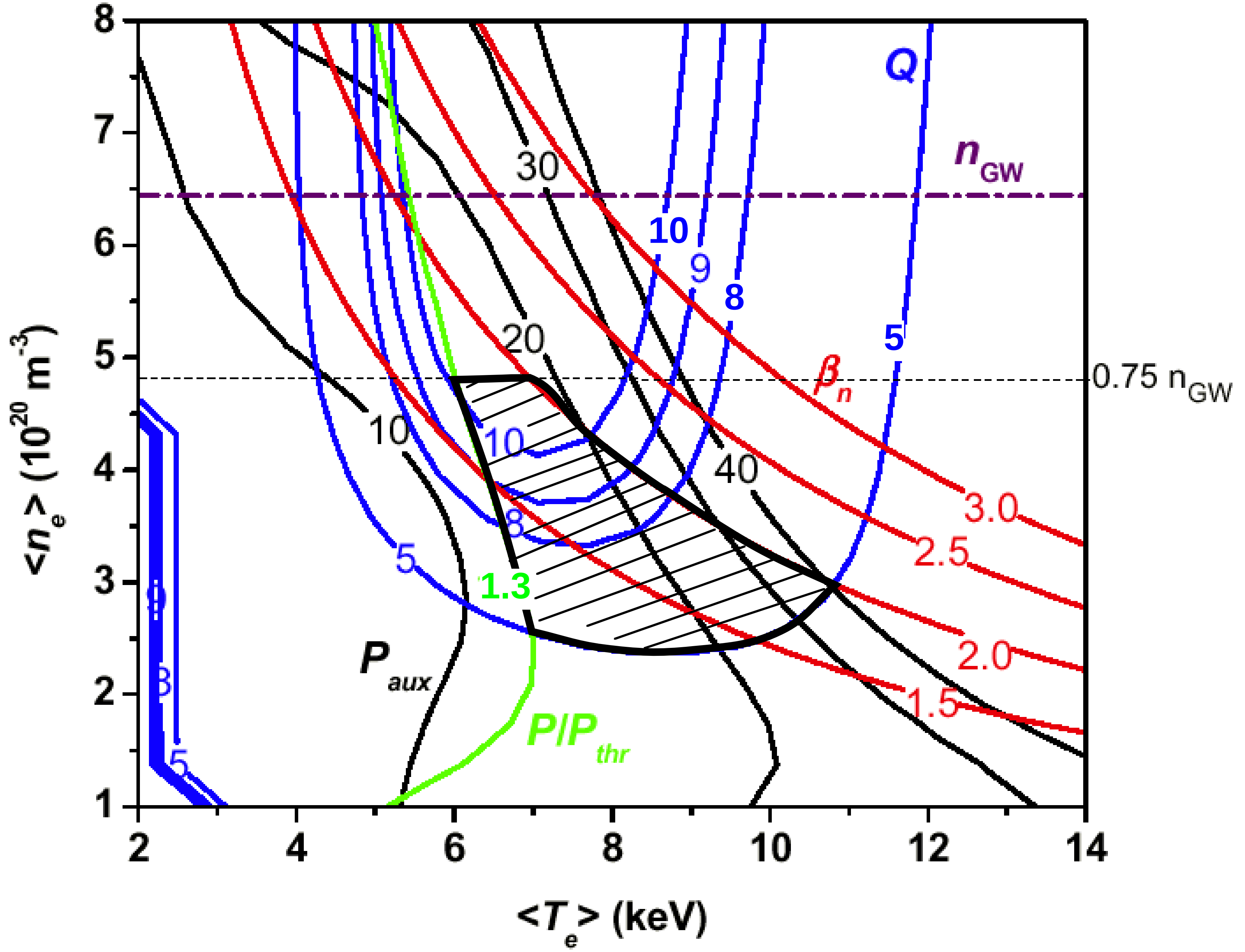


Need JT-60U data on modestly enhanced modes

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

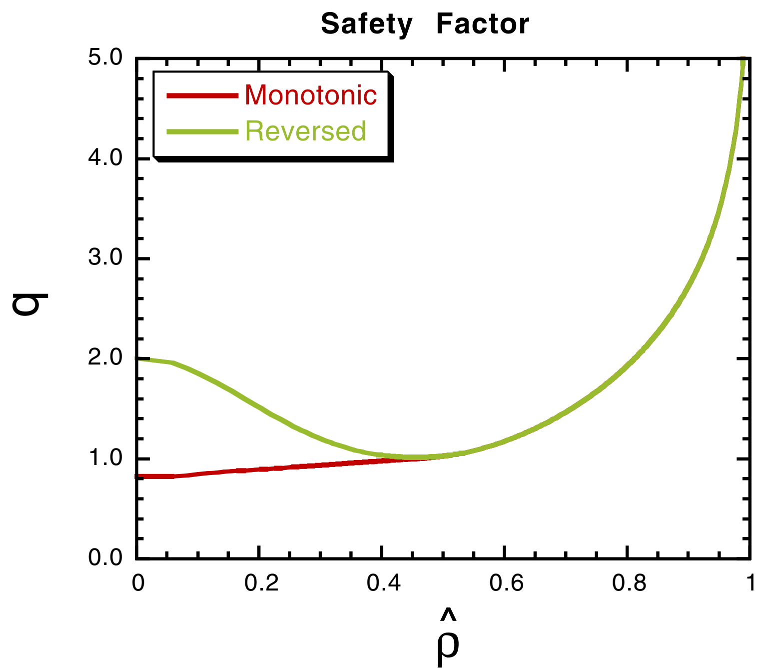
FIRE* 10T, 2.14m, 7.7 MA, H(y,2) = 1.14, α_n = 0.2

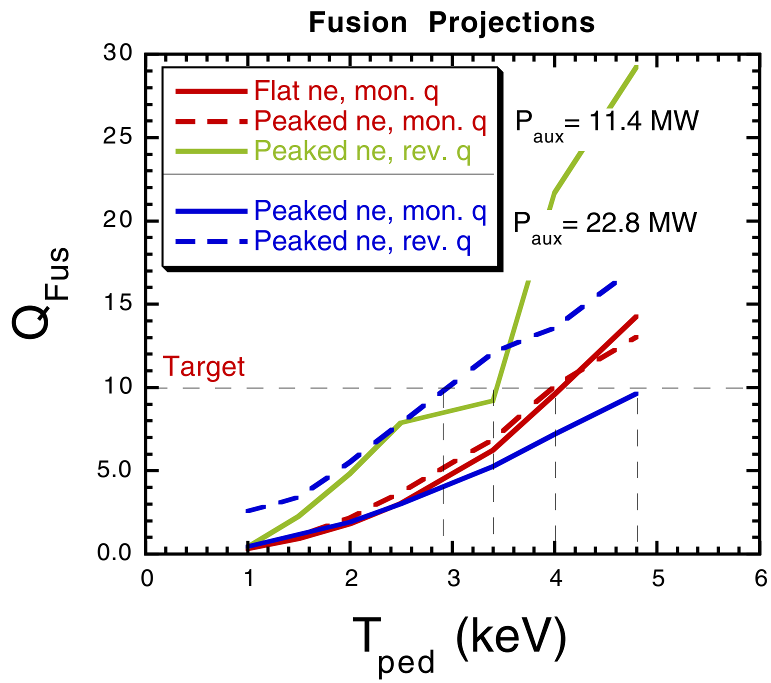


Fusion Projections for FIRE Using GLF 23

J. E. Kinsey, R. E. Waltz and G. M. Staebler

- ***Temperature profiles predicted for monotonic and reversed q-profiles while computing the effects of ExB shear and alpha-stabilization***
  - $n_{ped} = 3.6\mathrm{x}10^{20}\ m^{-3}$, $n_{e0}/n_{ped} = 1.5$
  - ***ExB shear effects small since no toroidal rotation except for peaked density, reversed shear case where ITB develops***
  - ***Alpha heating computed using TRANSP reaction rates***





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

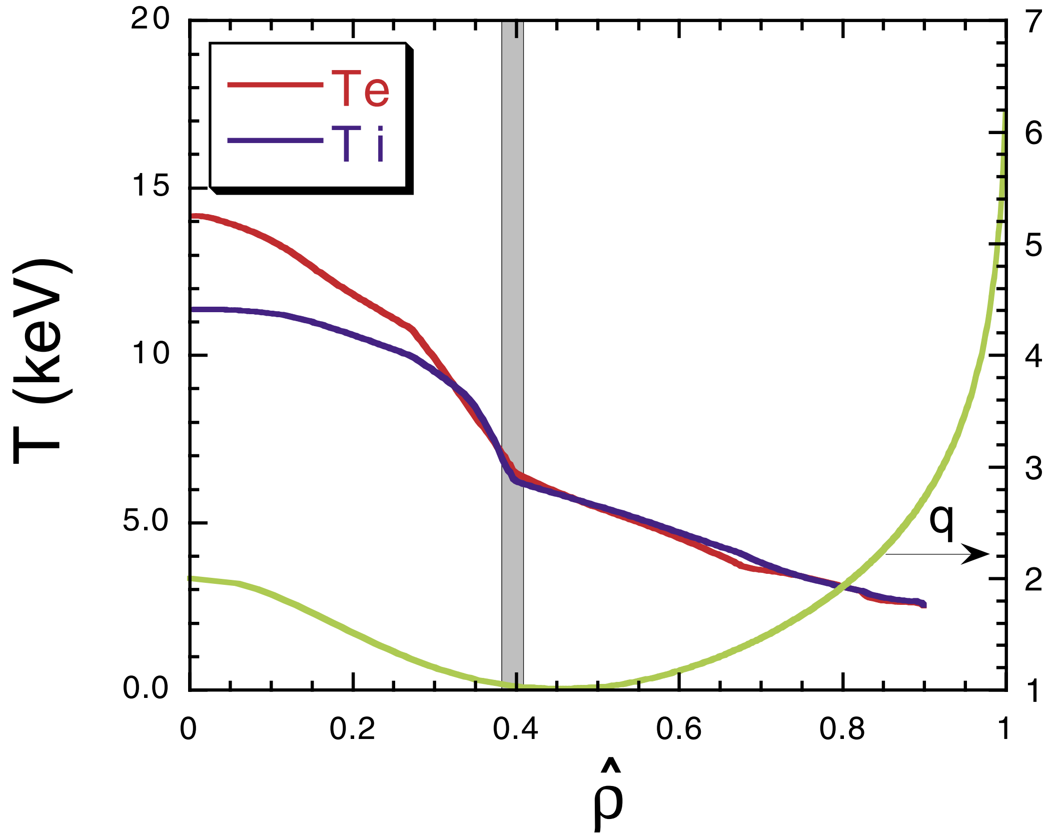
11.4 MW auxiliary heating

✦ 50 MW auxiliary heating

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

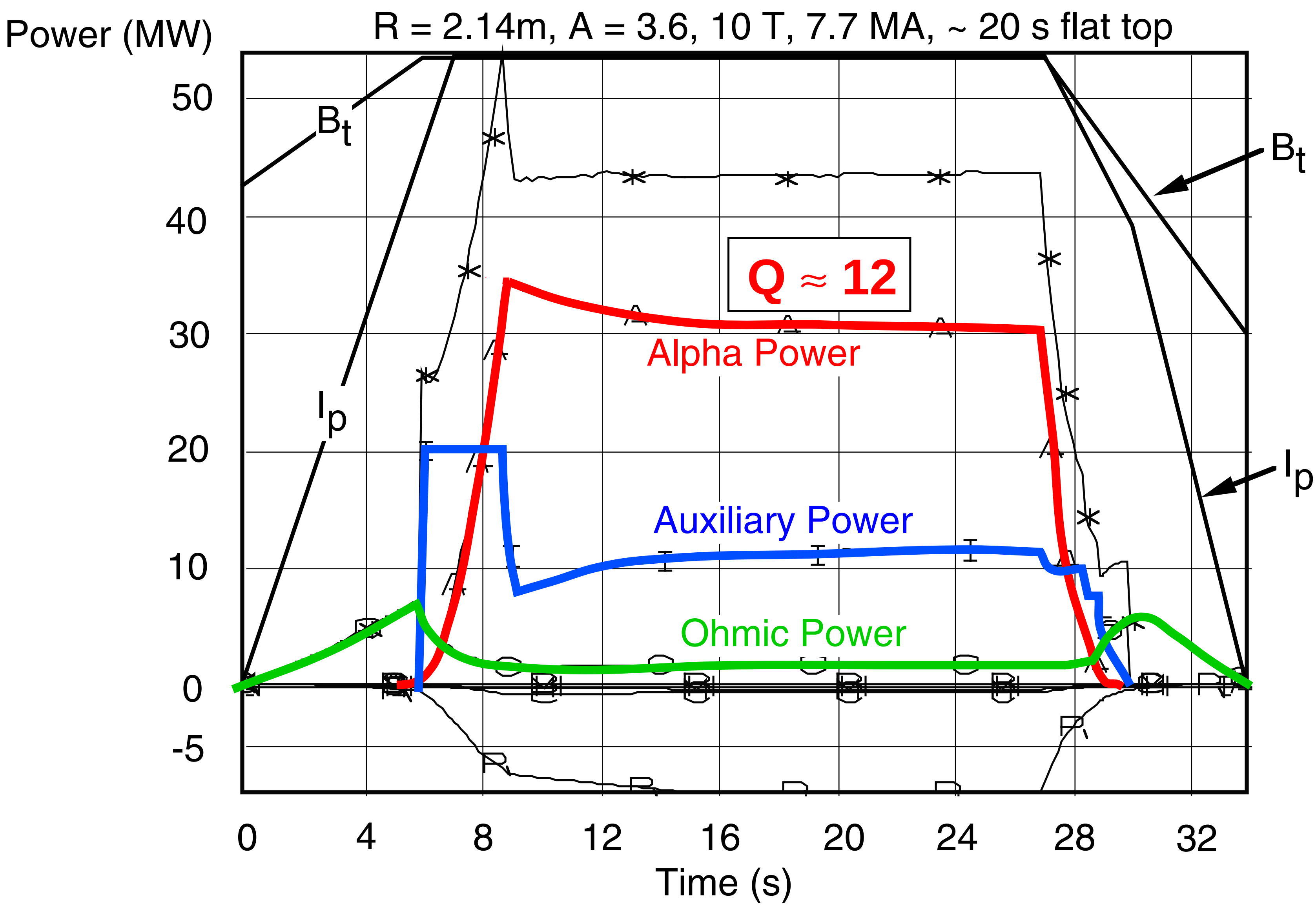
GLF23 Predicts an ITB In FIRE as a Result of Alpha-stabilization of the ITG Mode

- 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

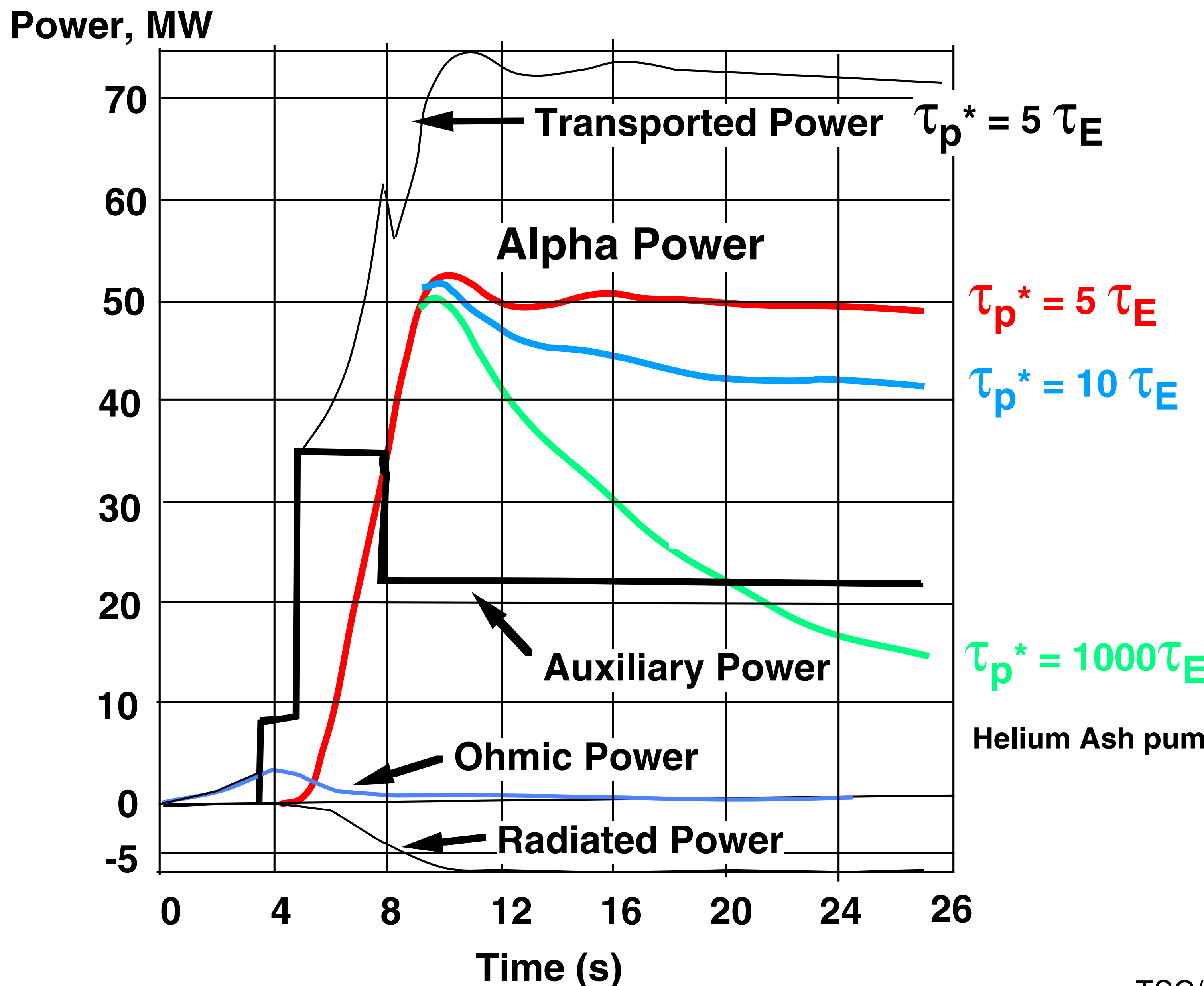
1 1/2-D Simulation of Burn Control in FIRE* (TSC)



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

Q = Pfusion/(Paux + Poh)

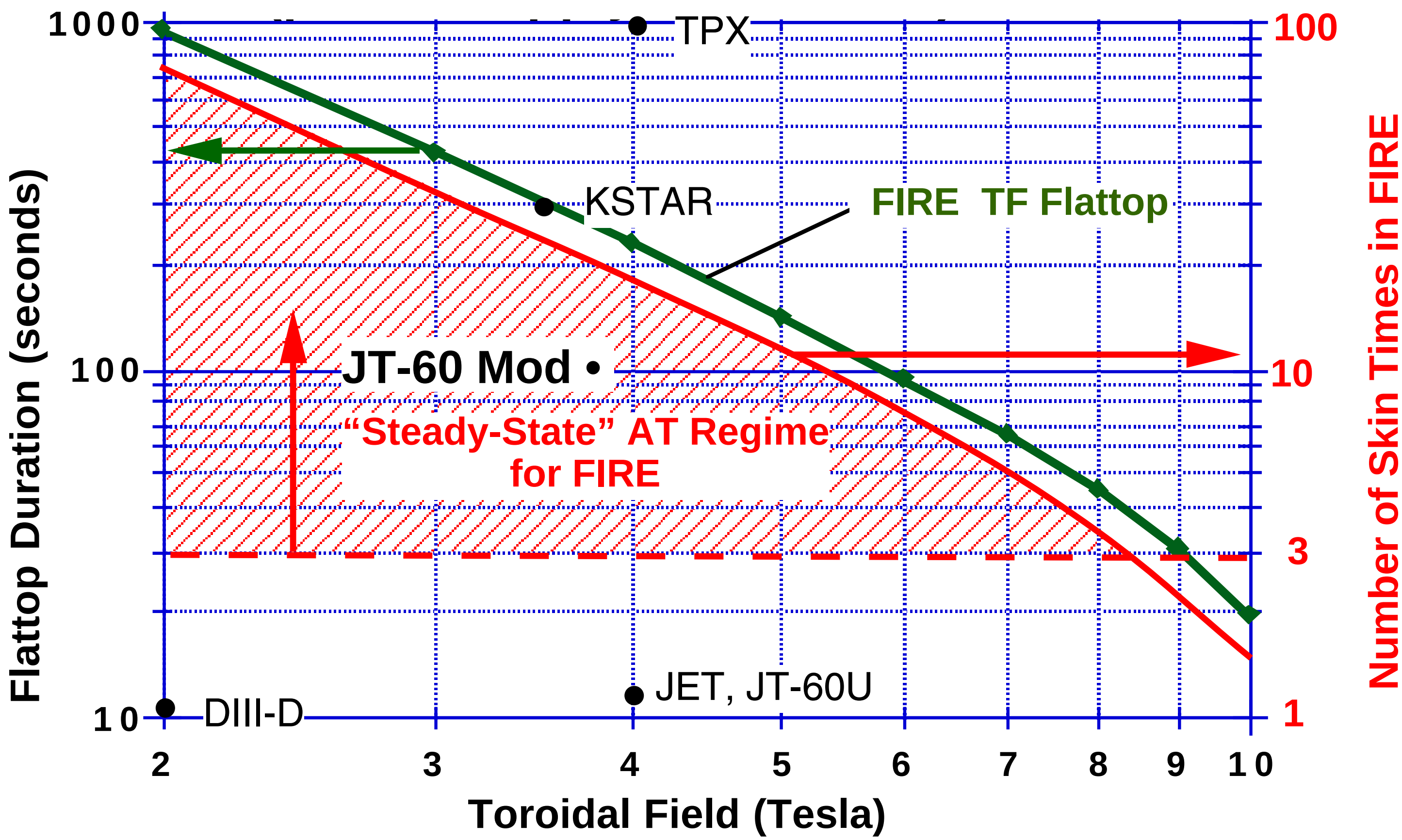
Helium Ash Removal can be Explored on FIRE



Helium Ash pumping is needed.

TSC/Kessel/21-q.ps
Early case - 1999

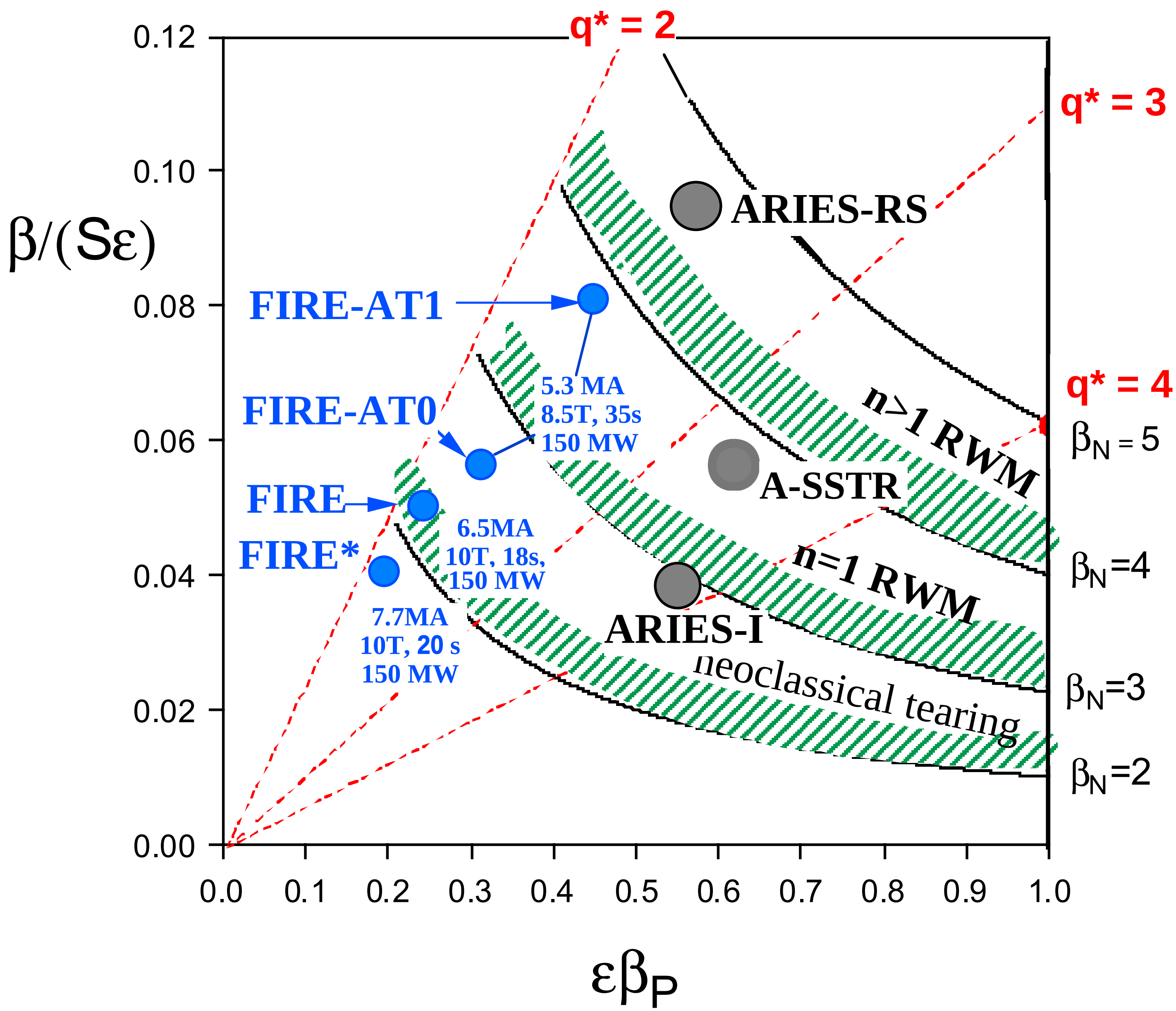
FIRE could Access "Long Pulse" Advanced Tokamak Mode Studies at Reduced Toroidal Field.



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.

The main limit to long pulses is the divertor and first wall - a generic problem for magnetic fusion.

Progress Toward Advanced Reactor Plasmas will Require a Sequence of Steps



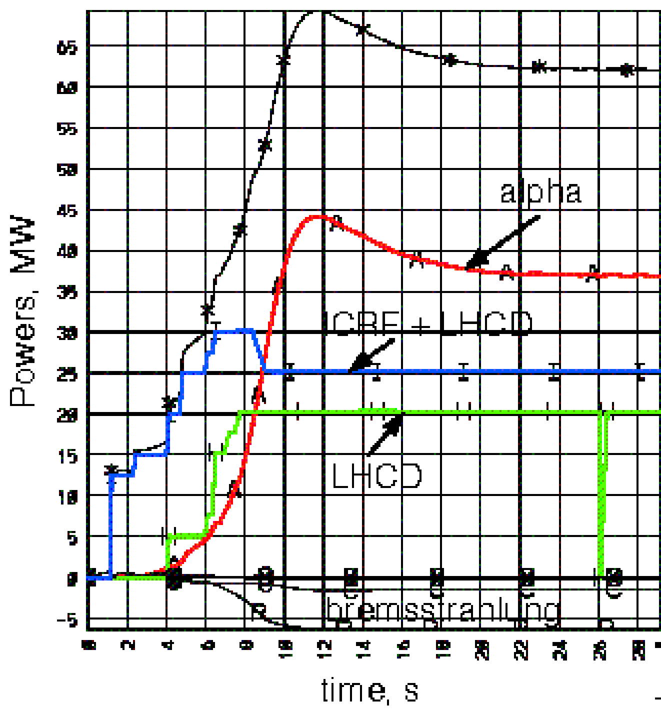
Dynamic Burning AT Simulations with TSC-LSC for FIRE

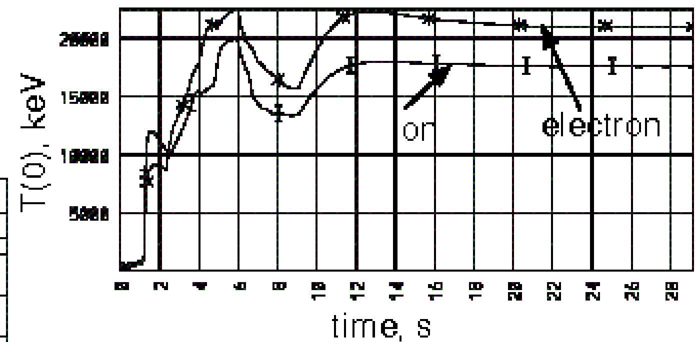
I_p=5.5 MA, B_t=8.5 T, Q=7.5,

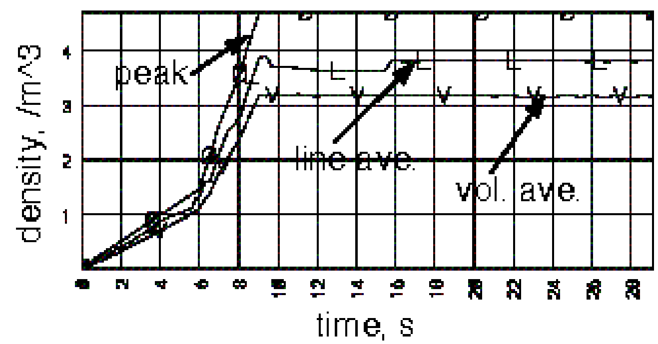
β_N=3.0, β=4.4%, P_{LH}=20 MW,

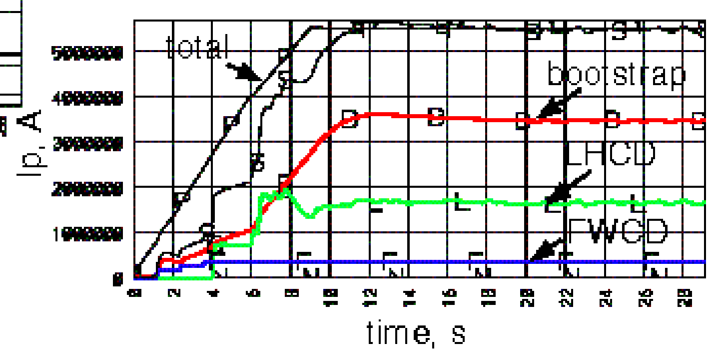
I_{LH}=1.7 MA, I_{BS}=3.5 MA (64%),

I_{FW}=0.35 MA





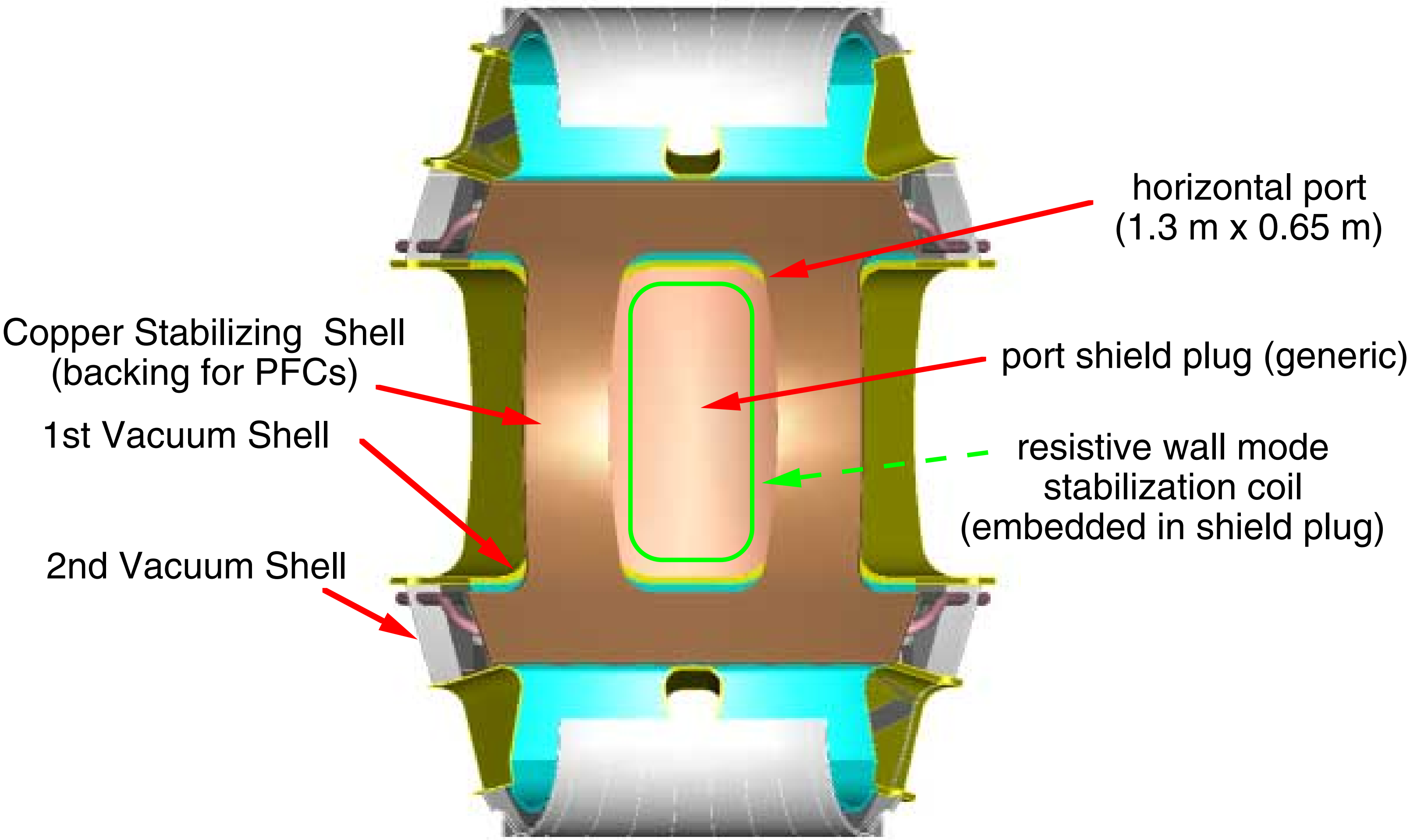




H(y,2)=1.6

Potential for Resistive Wall Mode Stabilization System

view of hoizontal port front looking from plasma side



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

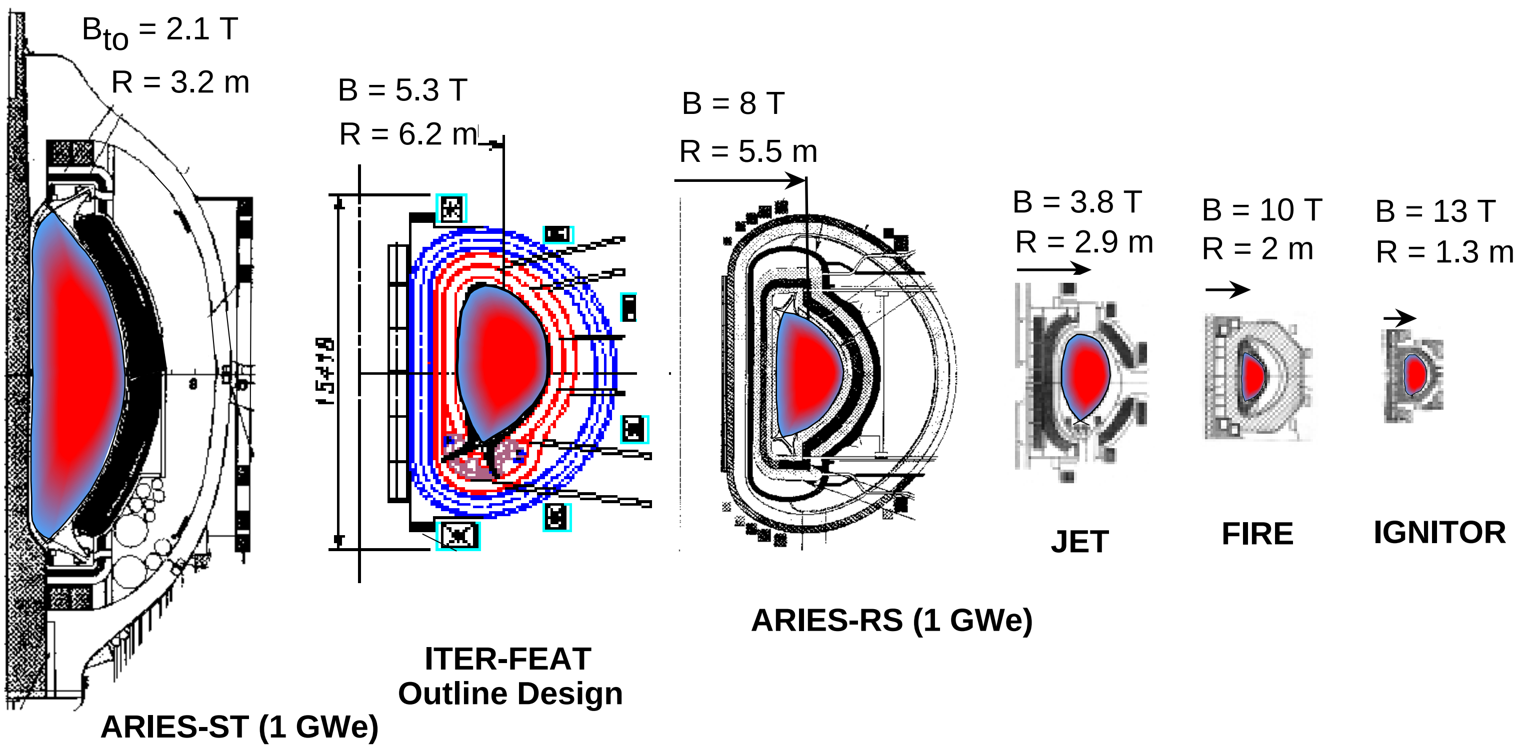
FIRE Issues and Needs

- Most are the same as for ITER-FEAT!
- Differences arise due to:
  - double null divertor - higher δ, shorter path to divertor, neutral stability point
    no asymmetric alpha ripple loss region, ($\delta B/B = 0.3\%$)
  - lower density relative to n_{GW}, higher density relative to NBI, RF, neutrals
  - all metal PFCs, esp. W divertor targets
- Specific Interests (requests)
  - Core Confinement (H-Mode and close relatives)
    - Understand requirements for enhanced H-modes at $n/n_{GW} \approx 0.6 - 0.7$
    - Compare SN $\Rightarrow$ DN or nearly DN ; maybe more than triangularity
    - Extend global studies/analysis $H = H(\delta, n/n_{GW}, n(0)/\langle n \rangle)$
    - H-mode power threshold for DN, hysteresis, $H = f(P - P_{th})$
    - Pedestal height/width as SN $\Rightarrow$ DN; elms as SN $\Rightarrow$ DN
    - Rotation as SN $\Rightarrow$ DN
    - Expand H-Mode data base for ICRF only plasmas
    - Demonstration discharges and similarity studies
    - Density Profile Peaking - expectations/requirements?

FIRE Issues and Needs (p.2)

- Internal Transport Barriers (AT Modes)
  - Access to ATs with: RF heated, q_{95} ~ 3.5 - 4, $T_i/T_e \approx 1$,
  - density peaking needed for efficient LHCD
  - n = 1stabilization by feedback
- SOL and Divertor - Impurities
  - Justification for using $n_z \Downarrow$ as $n_e \Uparrow$?
  - ASDEX Upgrade and C-Mod Hi Z impurity in core and "tritium" retention
  - Consistency of partially detached divertor with good τ_E and He removal
  - Models and improved designs for extending lifetime (Elms/disruptions)
- Plasma Termination and Halo Currents
  - Does DN neutral zone reduce force or frequency of disruptions?
  - Develop early warning, mitigation and recovery techniques
- Finite-β effects
  - stabilization of NTMs using LHCD (Δ' modification)
  - elms for enhanced confinement modes
  - TAE, EPM studies in DD with beams and RF
- Diagnostic development - high priority needs to added in a future meeting

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

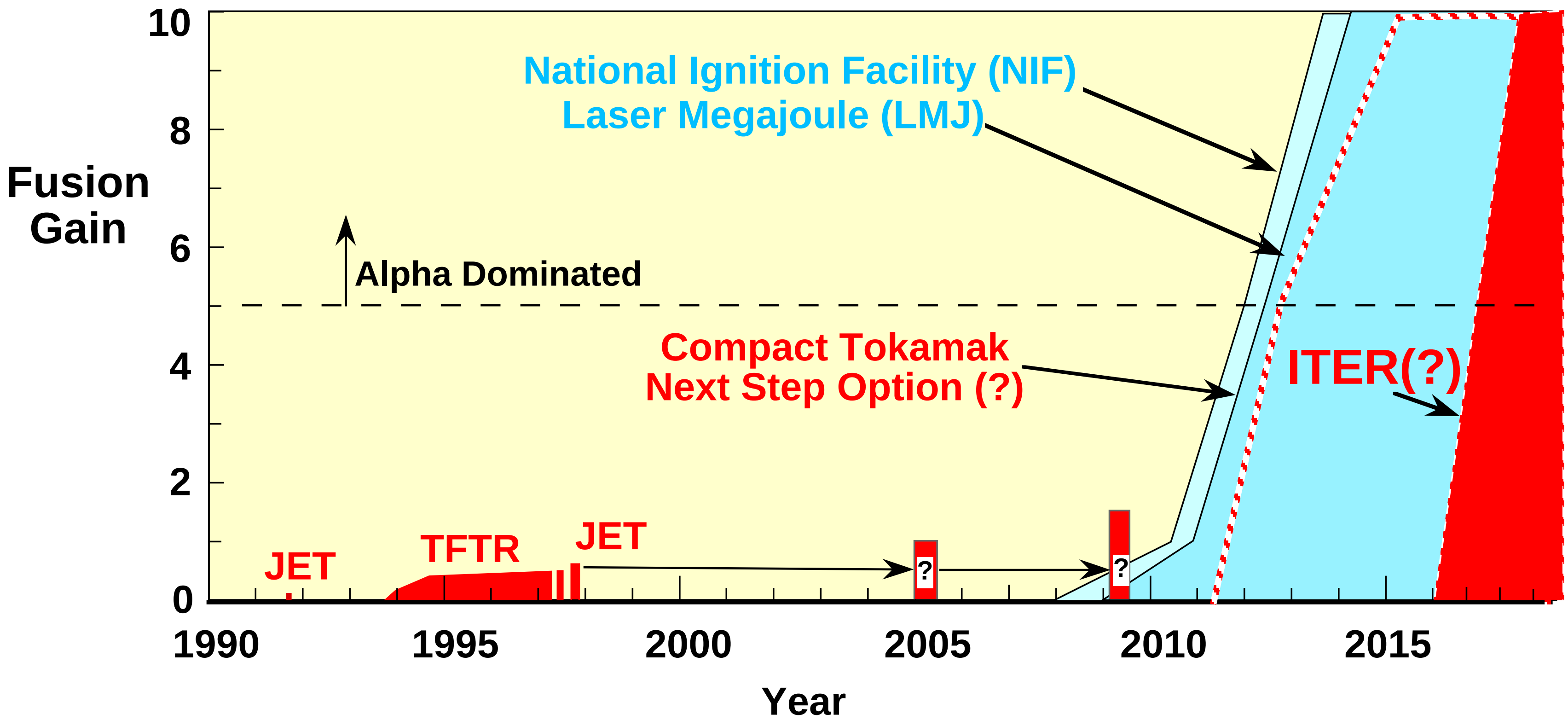
Preliminary FIRE Cost Estimate (FY99 US$M)

	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.

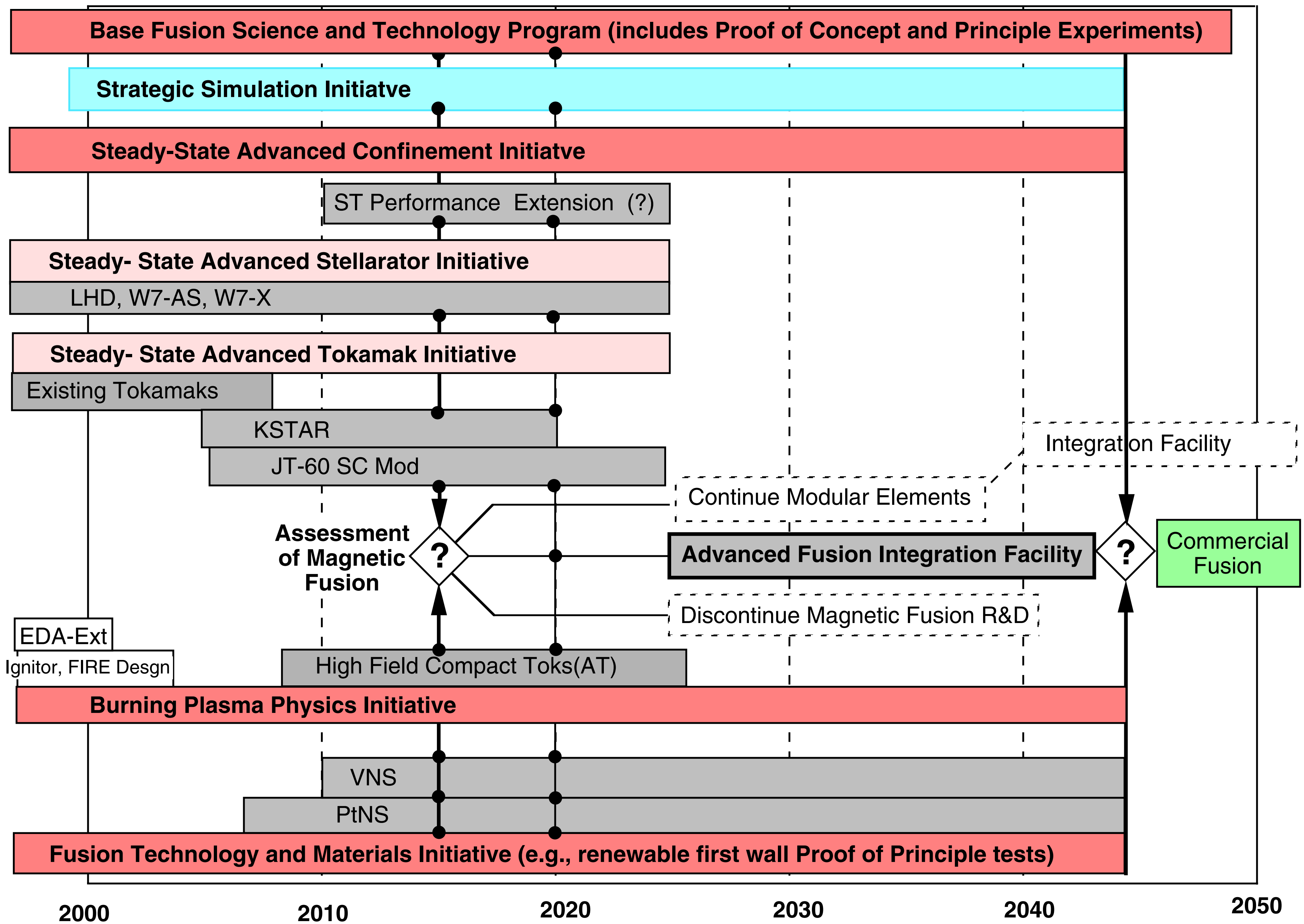
June 5, 2001

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.

A Modular Strategy for the Magnetic Fusion Program



Note: The grey bars correspond to operation.

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, has the potential:
  - 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.

- Some areas that need additional work to realize this potential include:
  - Apply JT-60U enhanced confinement and advanced modes to FIRE
  - Understand conditions for enhanced confinement regimes in JT-60
  - Compare DN relative to SN - confinement, stability, divertor, etc
  - Review JT-60U divertor results and apply to FIRE
  - Develop better disruption control/mitigation techniques.
  - Others from this discussion.

http://fire.pppl.gov

Panel Recommendation Fully Endorsed by FESAC August 2, 2001

3. *The US Fusion Energy Sciences Program should establish a proactive US plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment. If the opportunity for international collaboration occurs, the US should be ready to act and take advantage of it, but should not be dependent upon it. The US should implement a plan as follows to proceed towards construction of a burning plasma experiment:*

- Hold a "Snowmass" workshop in the summer, 2002 for the critical scientific and technological examination of proposed burning plasma experimental designs and to provide crucial community input and endorsement to the planning activities undertaken by FESAC. Specifically, the workshop should determine which of the specific burning plasma options are technically viable, but should not select among them. The workshop would further confirm that a critical mass of fusion scientists believe that *the time to proceed is now* and not some undefined time in the future.

- Carry out a uniform technical assessment led by the NSO program of each of the burning plasma experimental options for input into the Snowmass summer study.

- Request the Director of the Office of Energy Sciences to charge FESAC with the mission of forming an "action" panel in Spring, 2002 to select among the technically viable burning plasma experimental options. The selected option should be communicated to the Director of the Office of Science by January, 2003.

- Initiate a review by a National Research Council panel in Spring, 2002, with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by Fall, 2003. This is consistent with a submission of a report by DOE to congress no later than July, 2004.

- Initiate an outreach effort coordinated by FESAC (or an ad-hoc body) to establish an appreciation and support for a burning plasma experiment from science and energy policy makers, the broader scientific community, environmentalists and the general public. This effort should begin now.