Transport Issues and Needs

for the

Fusion Ignition Research Experiment (FIRE)

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for the FIRE Team

Presented at
ITPA Meeting on Burning Plasma Transport
NIFS, Toki, Japan

September 10, 2001

http://fire.pppl.gov

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.

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

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
- FIRE Issues and Needs
- 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.

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

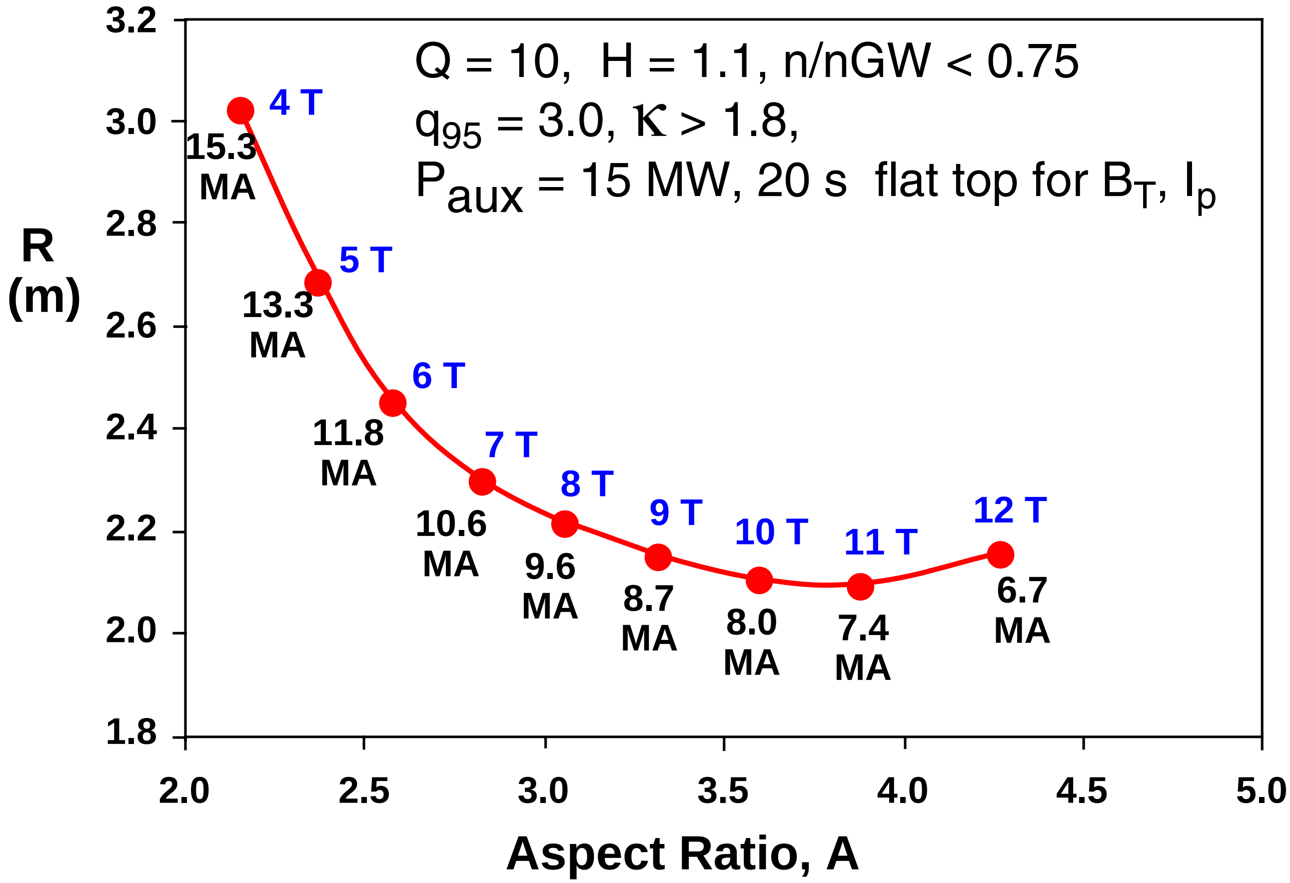
Quasi-stationary

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)

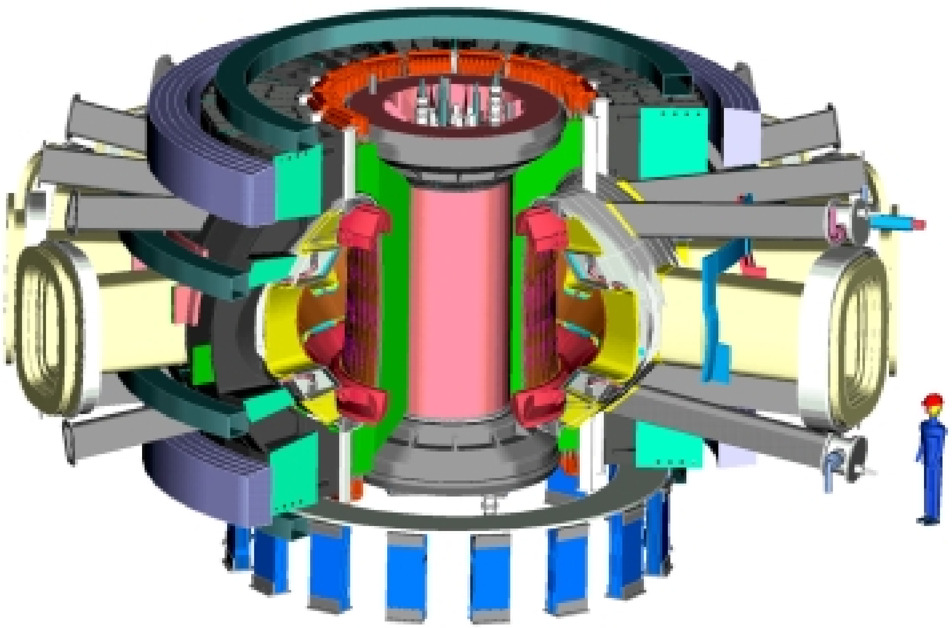
TF and PF coils unlinked

S. Jardin and
C. Kessel

What is the optimum for ITBs or AT modes?

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.

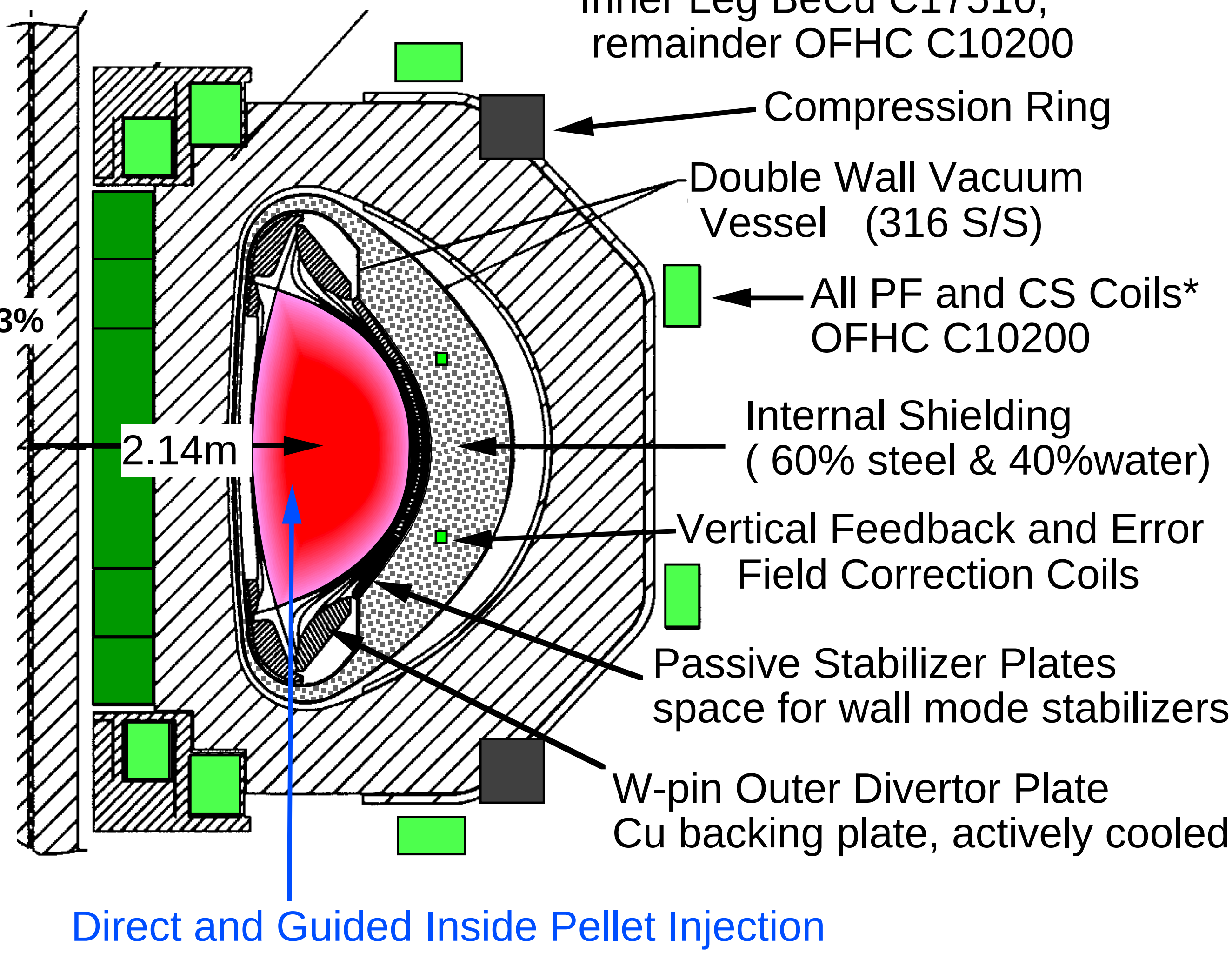
Mission:

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

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.

Basic Parameters and Features of FIRE

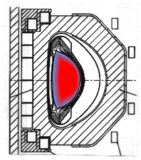
R, major radius	2.14 m
a, minor radius	0.595 m
κx, κ95	2.0, 1.77
δx, δ95	0.7, 0.55(AT) - 0.4(OH)
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.3% ripple @ Outer MP
Toroidal magnet energy	5.8 GJ
Ip, plasma current	7.7 MA
Magnetic field flat top, burn time	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 is being Designed to Test the Physics and In-Vessel Technologies for ARIES-RS

Pfusion
= ~ 150 MW

Volume
= 27 m^3

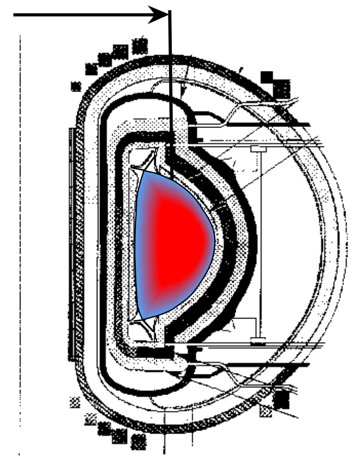
B = 10 T
R = 2.14 m
→



FIRE

~ 3X

B = 8 T
R = 5.5 m



ARIES-RS The “Goal”

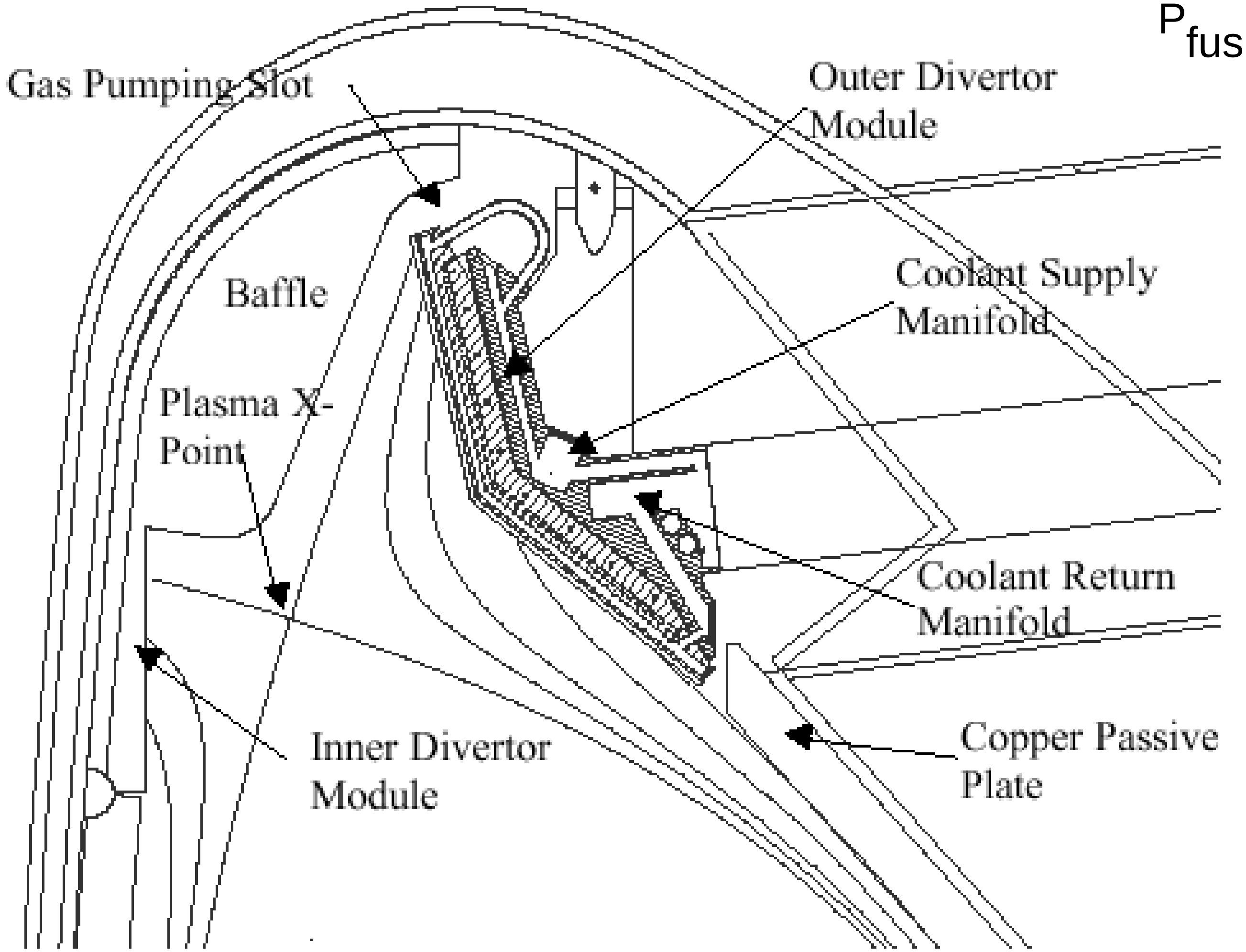
Pfusion
= 2170 MW

Volume
= 350 m^3

	JET	FIRE	ARIES-RS
Fusion Power Density (MW/m^3)	0.2	5.5	6
Neutron Wall Loading (MW/m^2)	0.2	2.3	4
Divertor Challenge (Pheat/NR)	~5	~10	~35
Power Density on Div Plate (MW/m^2)	3	~15-19 → 6	~5
Burn Duration (s)	4	20	steady

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

P_{fusion} < 200 MW



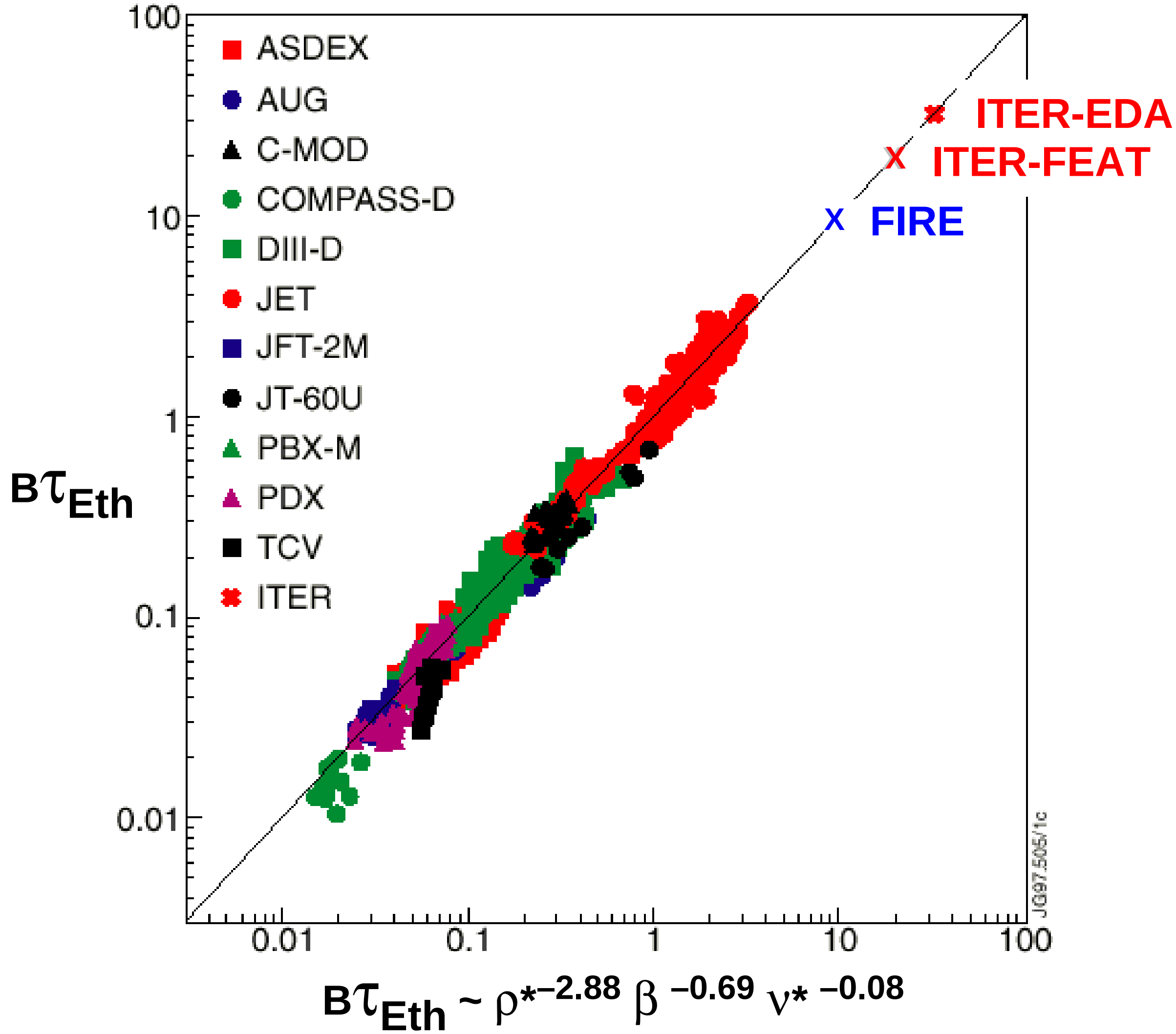
Reference Design is semi-detached operation with <15 MW / m2.

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

Kadomtsev, 1975



Transport Issues/Benefits from a Major Next Step Tokamak Experiment

- Predicting confinement and performance is a central issue for a next step experiment that challenges our understanding and predictive capability.

- Methods Available

  1. 0-D Statistical based models (eg ITER scalings for H-Mode)
     dimensionless variables ala wind tunnel
     projections from individual points(Barabaschi) or similar points(DM)

  2. 1 1/2-D (WHIST, TSC, Baldur, ASTRA)
     profiles and time evolution

  3. "First Principles" based core transport models
     - gyrokinetic/gyrofluid (PPPL-IFS, GLF 23)
     - multi-mode model
  4. Edge Pedestal and density limit models
- What experimental capabilities or features in a next step experiment are needed to better resolve and understand transport issues?

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

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

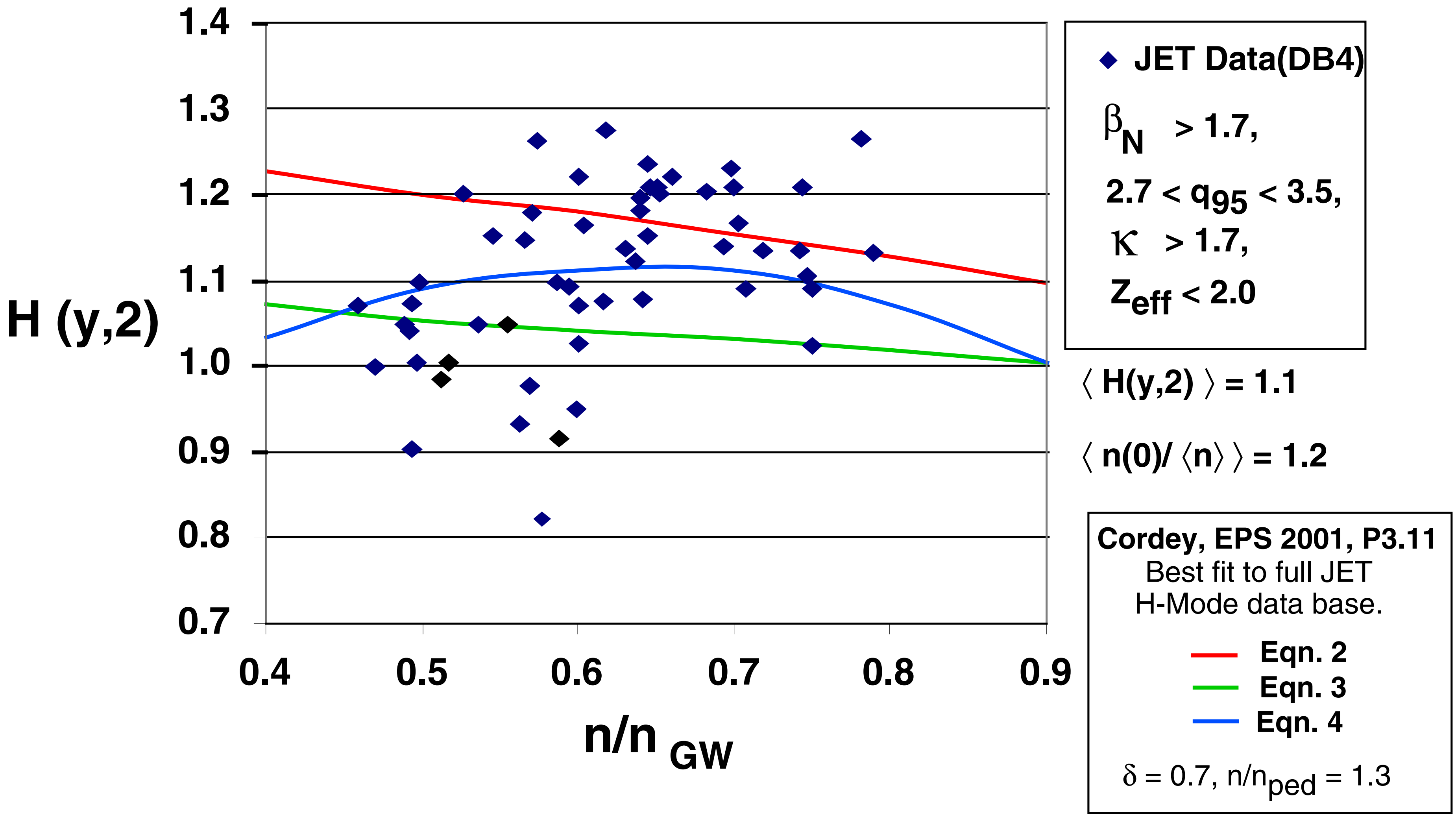
H-Mode Power Threshold - Based on today's tokamak data base

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

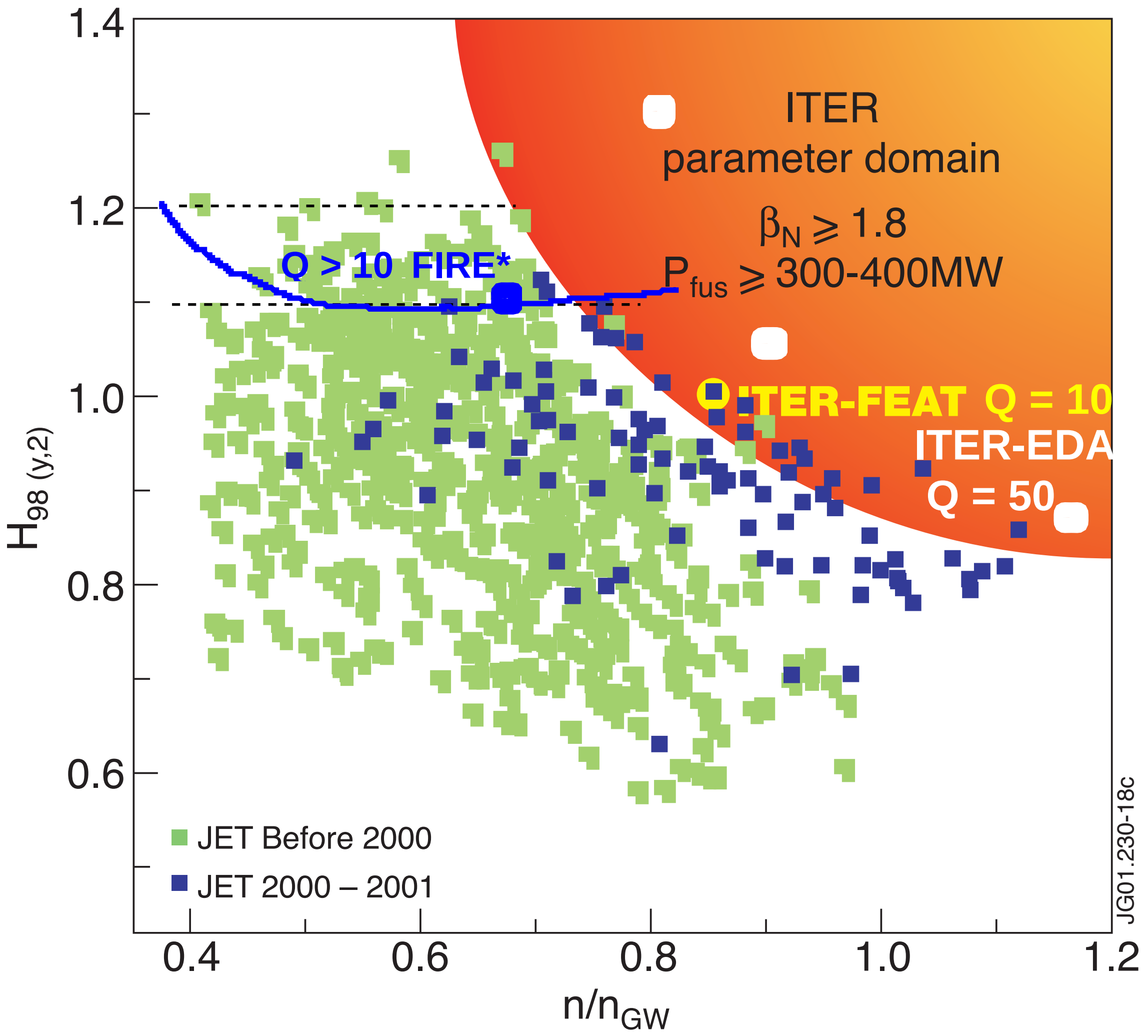
Helium Ash Confinement $\tau_{He} = 5\, \tau_E$, impurities = 3% Be, 0% W

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.

JET H-Mode Data Selected for FIRE-like Parameters



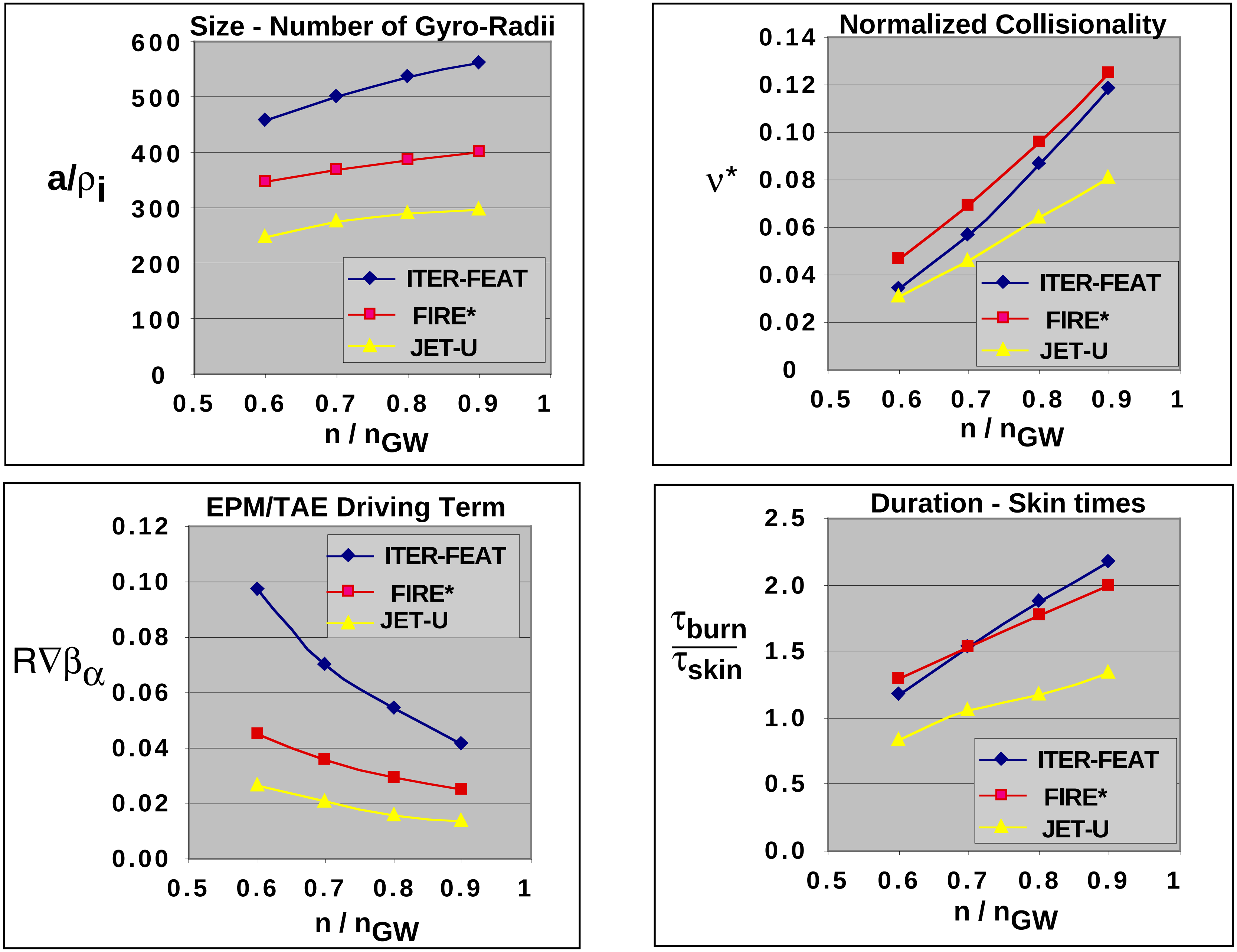
Comparison Operating Ranges of ITER-EDA, ITER-FEAT and FIRE with JET H-Mode Data



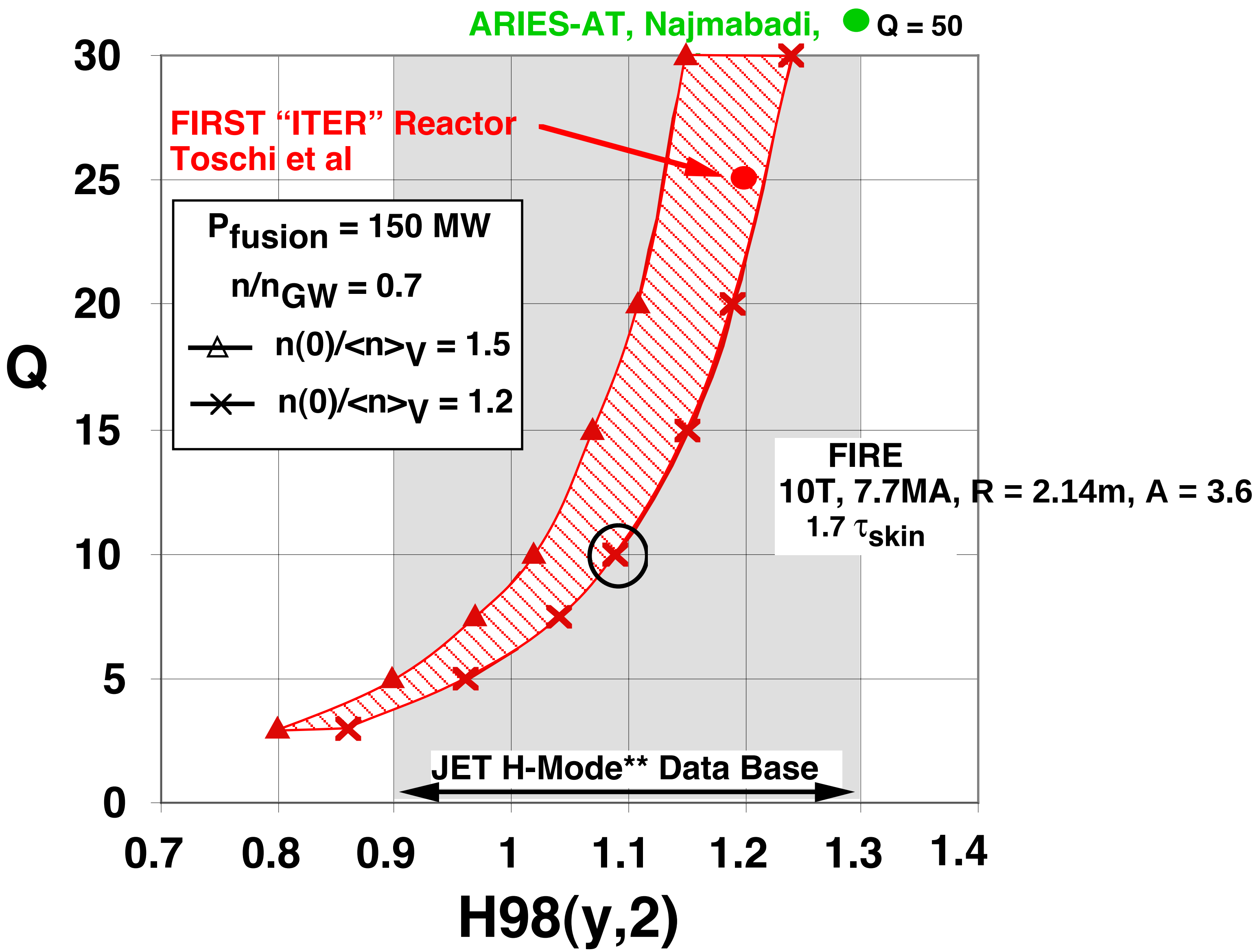
- Extension of JET parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \gtrsim 1.8$ using different approaches and
- In addition Plasma purity as required for ITER: Zeff ~ 1.5
- For quasi-stationary phases of several seconds
- **Consolidation of ITER 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

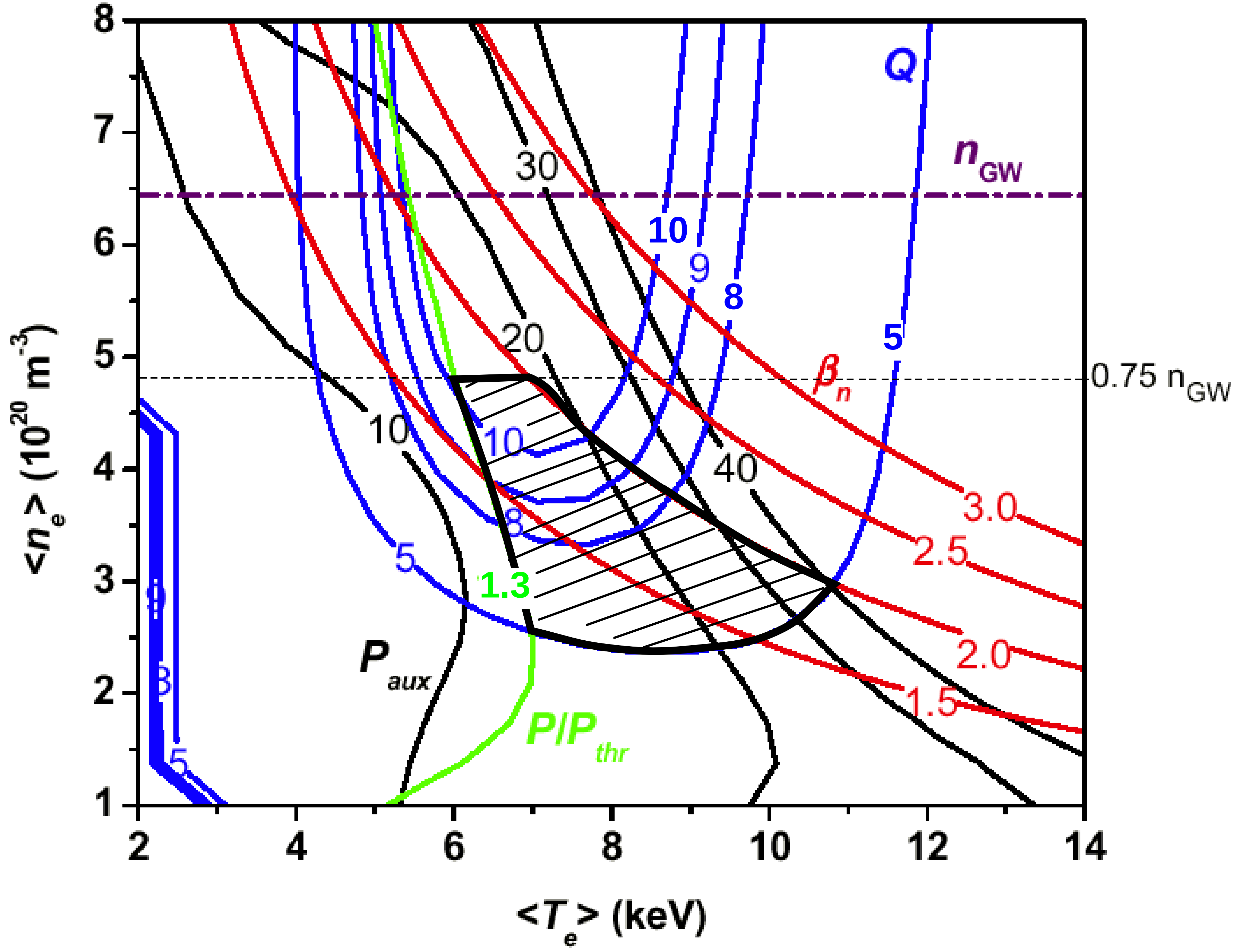
ITER-FEAT (15 MA): Q = 10, H = 0.95, FIRE*(7.7 MA): Q = 10, H = 1.03, JET-U (6 MA): Q = 0.64, H = 1.1



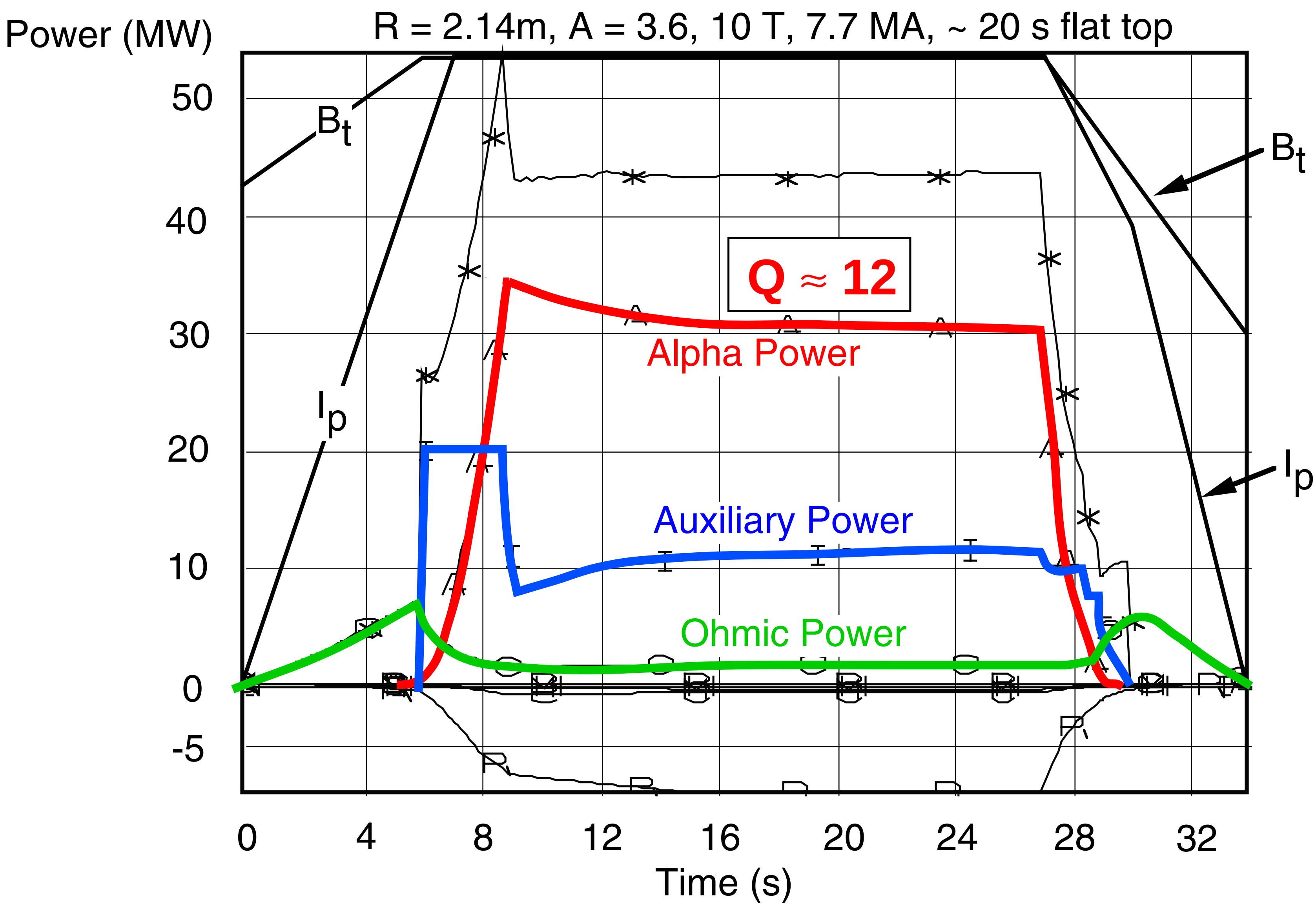
Projections to FIRE Compared to Envisioned Reactors



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



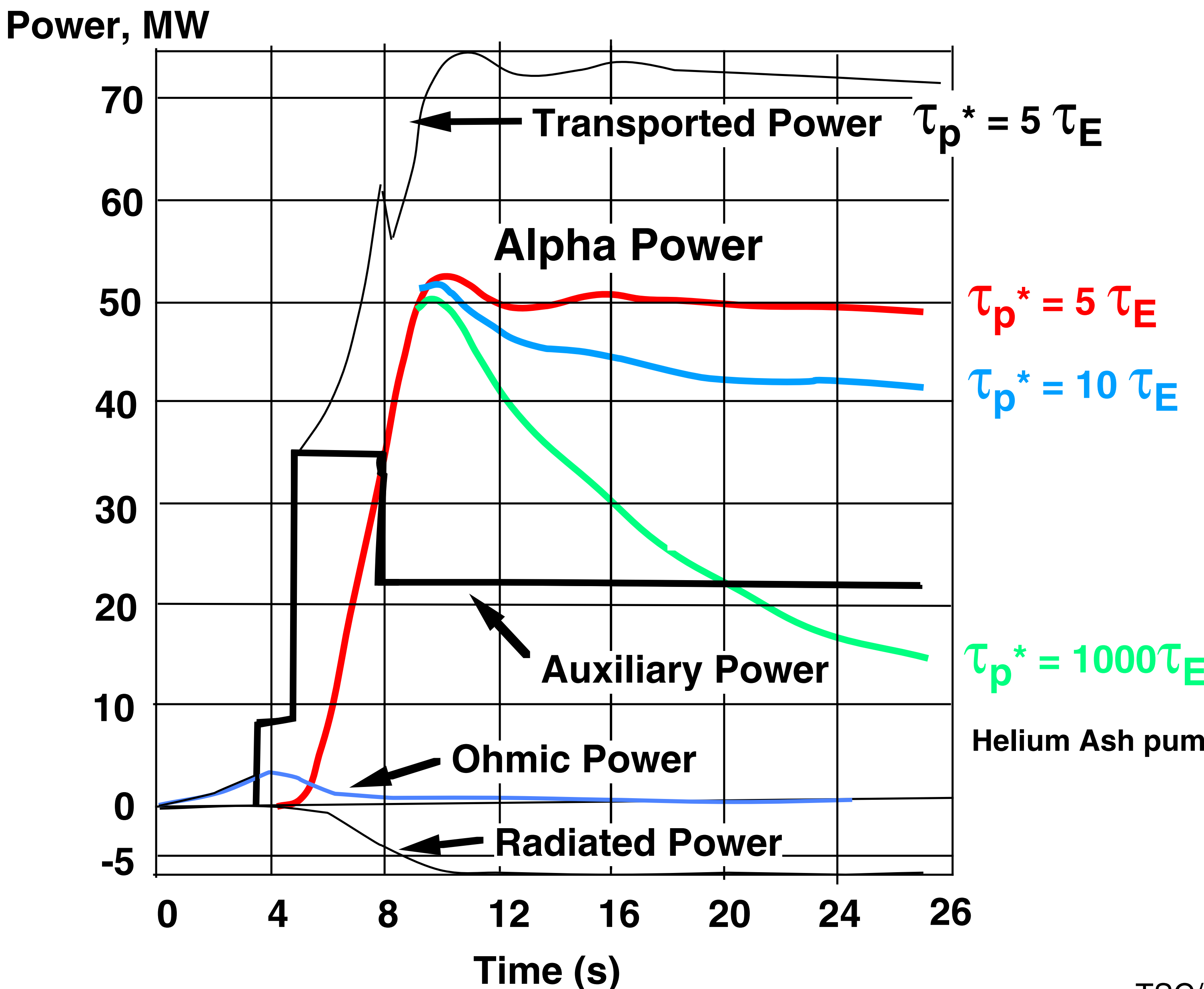
1 1/2-D Simulation of Burn Control in FIRE* (TSC)



- 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)

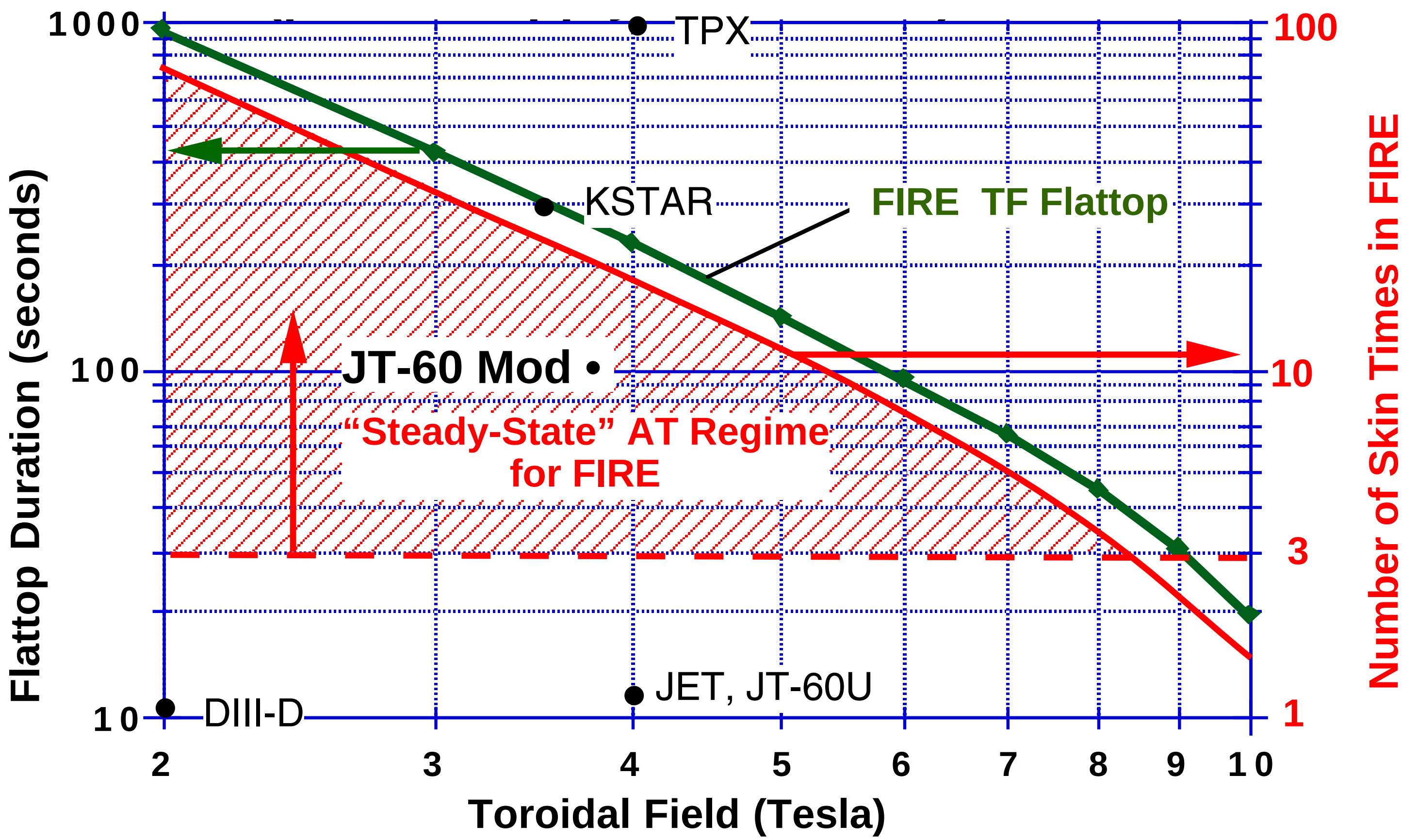
Helium Ash Removal can be Explored on FIRE



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.

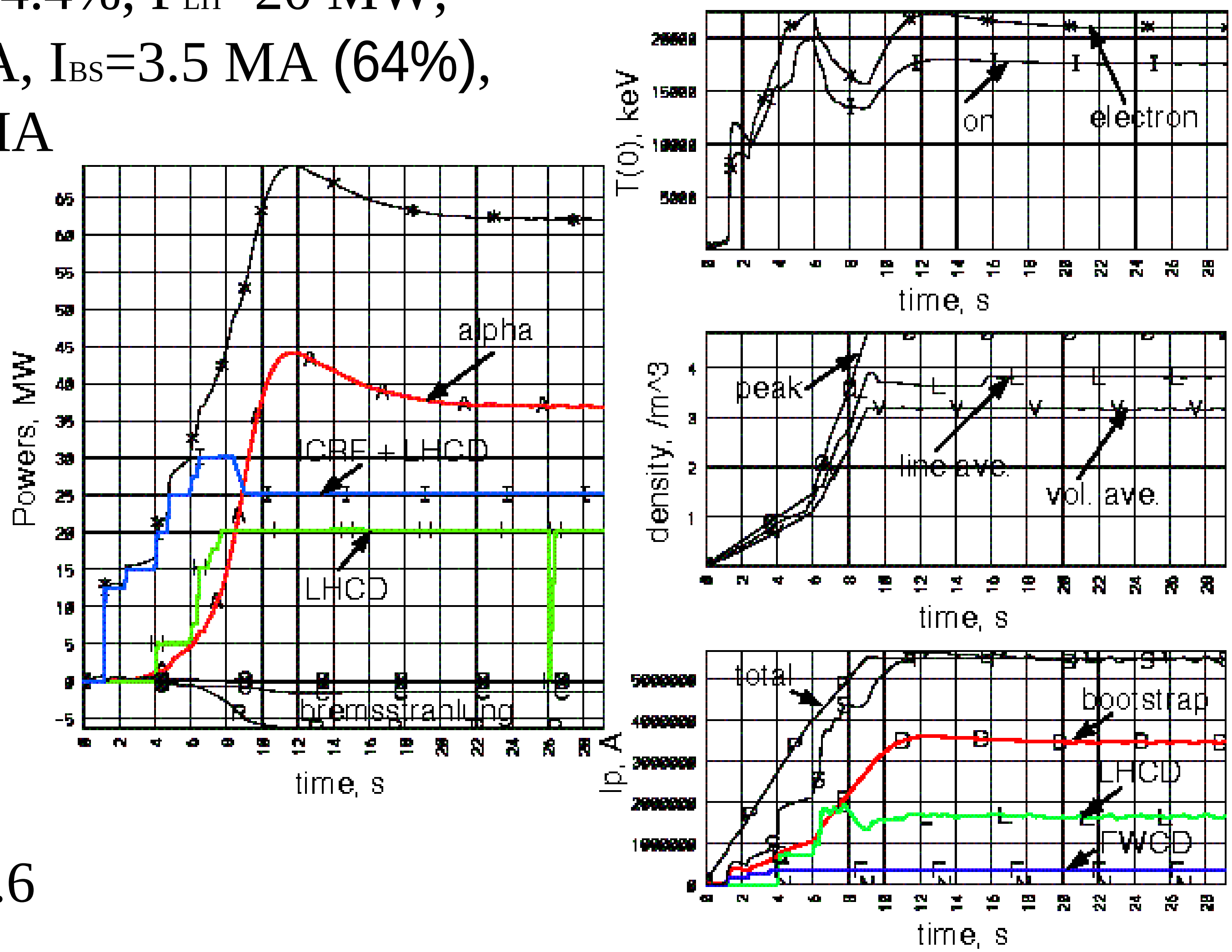


Note: FIRE is ≈ the same physical size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT .
The Number of Skin Times curve assumes a constant skin time of 13s.

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

Dynamic Burning AT Simulations with TSC-LSC for FIRE

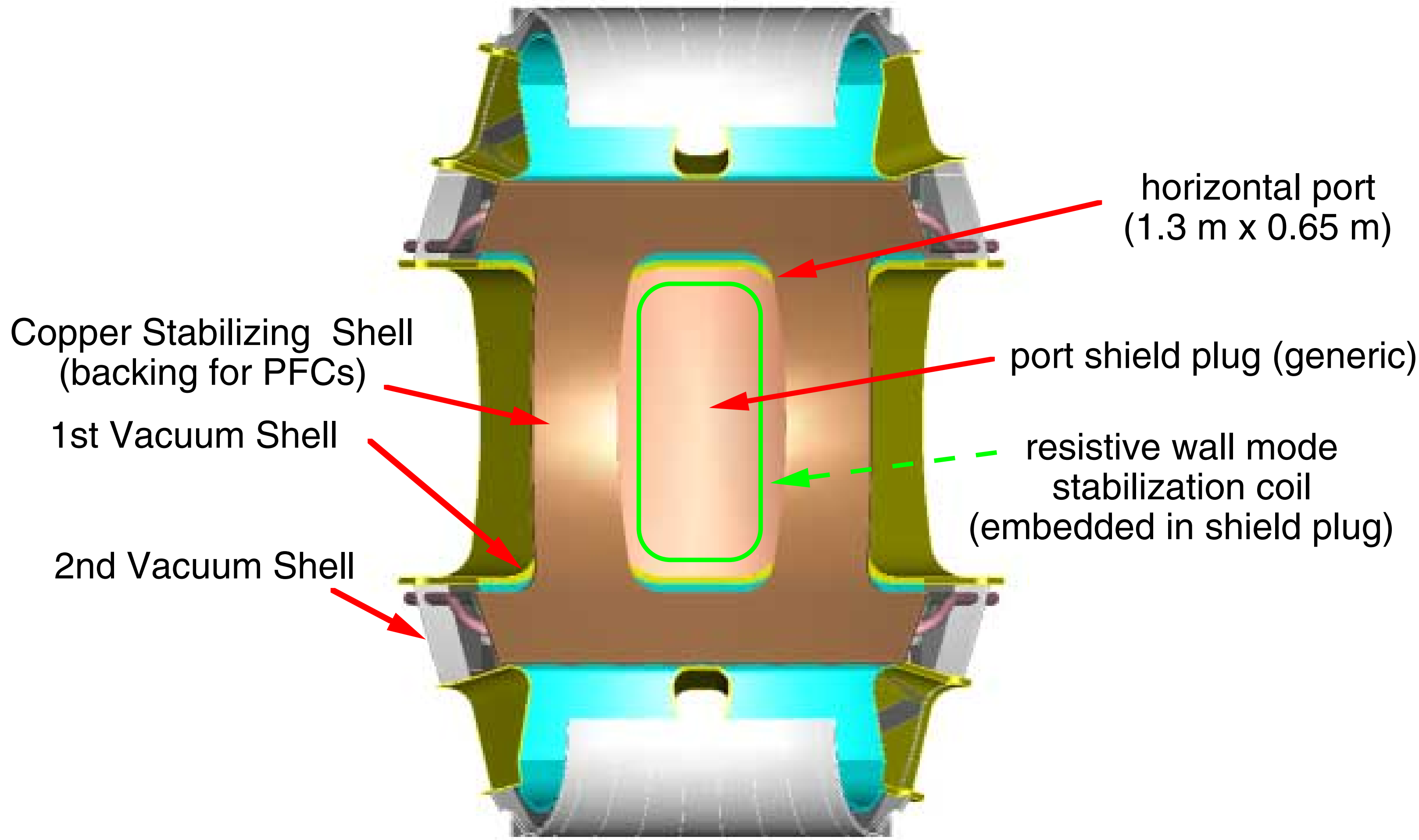
Ip=5.5 MA, Bt=8.5 T, Q=7.5,
β_N=3.0, β=4.4%, P_{LH}=20 MW,
I_{LH}=1.7 MA, I_{BS}=3.5 MA (64%),
I_{FW}=0.35 MA



H(y,2)=1.6

Potential for Resistive Wall Mode Stabilization System

view of hoizontal port front looking from plasma side



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, • No neutral beam heating
- 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, $q_{95} \sim 3.5 - 4$, $T_i/T_e \approx 1$,
  - 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

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

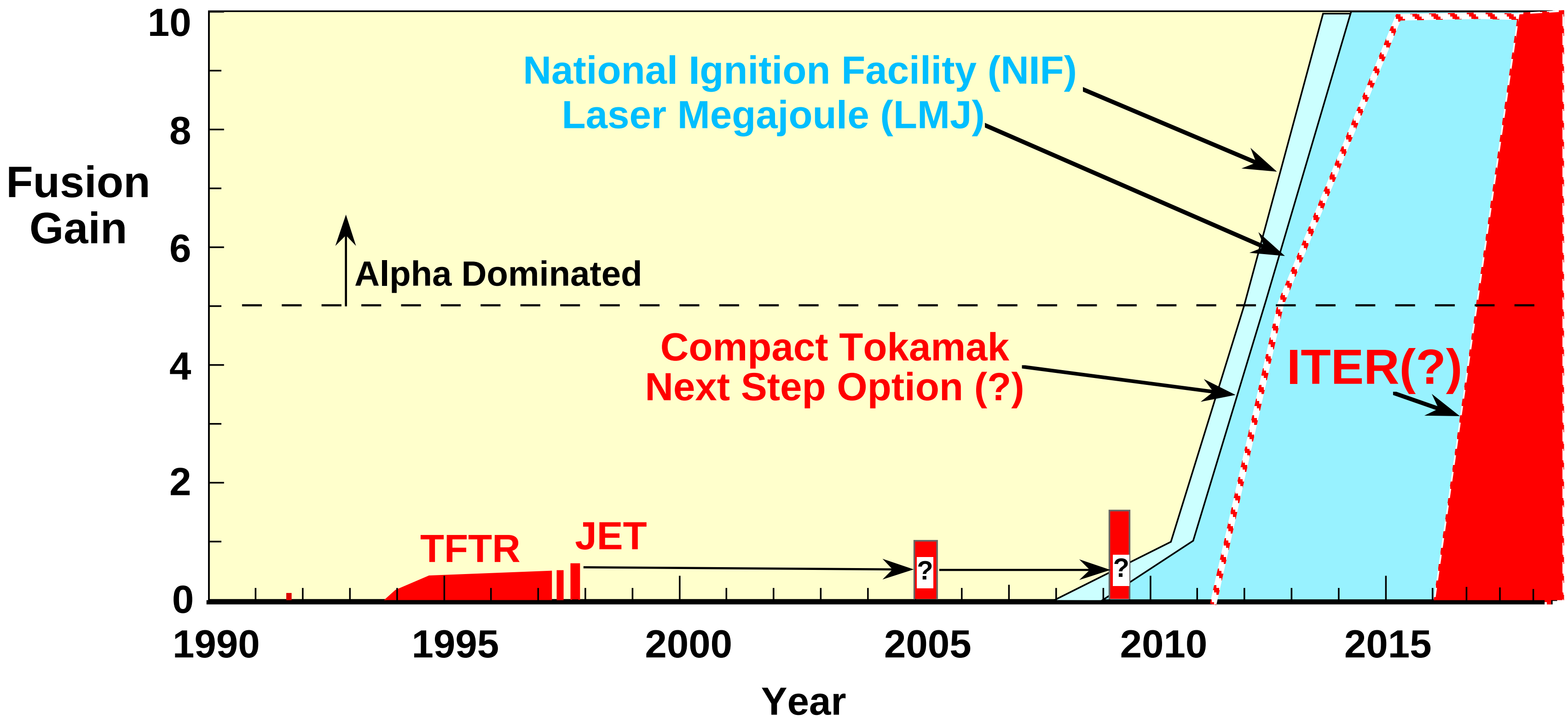
  under quasi-stationary conditions in a $1B class facility.

- Some areas that need additional work to realize this potential include:

    - Consider data base as a Library not just collection of statistical points
    - Understand physics behind enhanced confinement regimes
    - Compare DN relative to SN - confinement, stability, divertor, etc
    - Understand high density/low density aspects of FIRE, and to future
    - Develop better disruption control/mitigation techniques.
    - **Others from this workshop!!**

http://fire.pppl.gov

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.

Recent Events

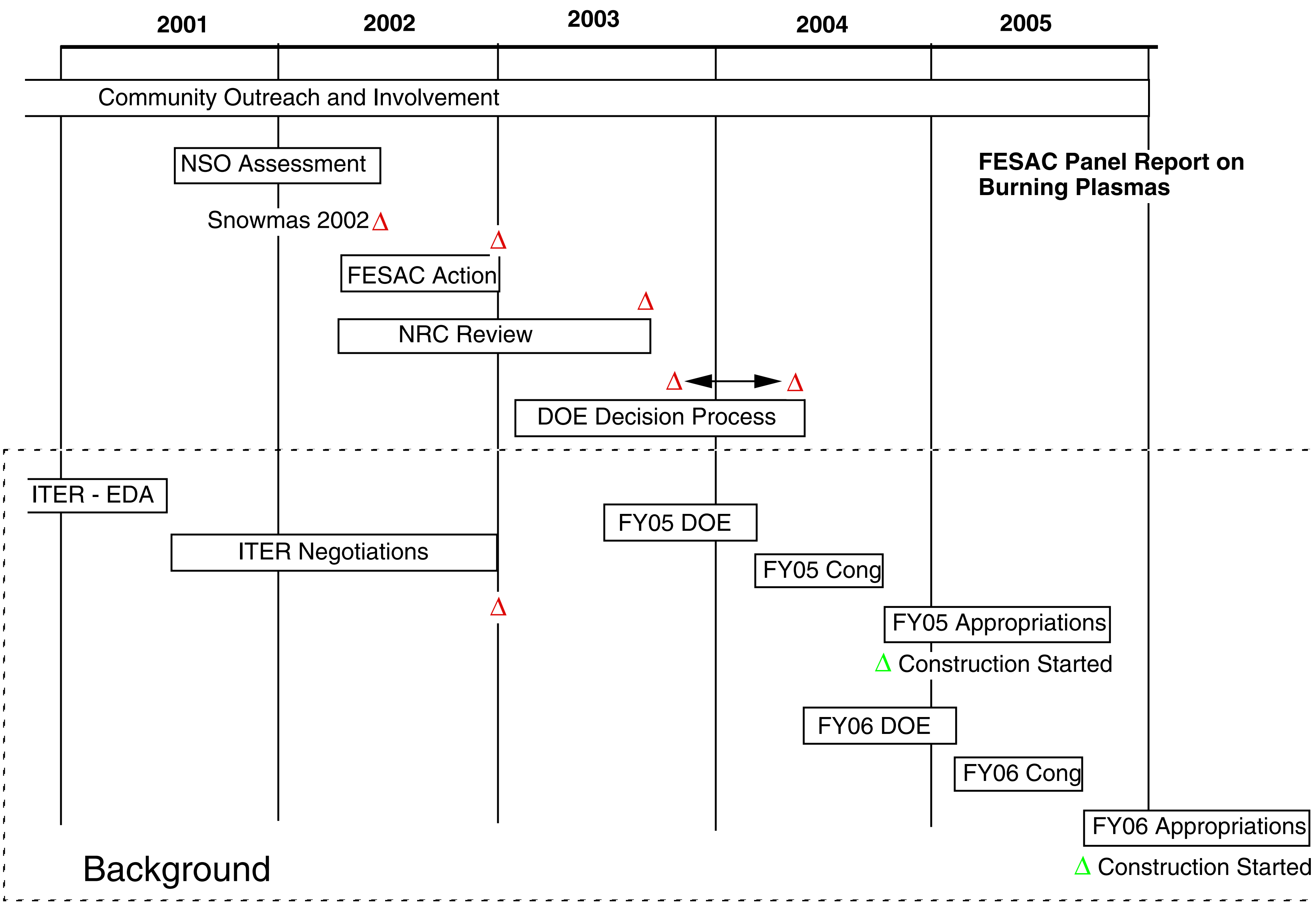
- Energy Authorization Bill (HR 4) passed by the House on August 1, 2001 directs DOE to submit a plan for a U.S. Burning Plasma Experiment to Congress by July 2004. In addition, DOE may also develop a plan for United States participation in an international burning plasma experiment for the same purpose,….

- Fusion Energy Sciences Advisory Committee (FESAC) endorses recommendations of FESAC Burning Plasma Panel on August 2.

- 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 2002 that will emphasize burning plasmas. International participation is encouraged.

Recommended US Plan for Burning Plasmas



2002 Fusion Energy Sciences Summer Study
8-19 July 2002

The 2002 Fusion Summer Study will be a forum for the critical assessment of major next-steps in the fusion energy sciences program, and will provide crucial community input to the long range planning activities undertaken by the DOE and the FESAC. It will be an ideal place for a broad community of scientists to examine goals and proposed initiatives in burning plasma science in magnetic fusion energy and integrated research experiments in inertial fusion energy.

This meeting is open to every member of the fusion energy science community and significant international participation is encouraged.

Program Committee Co-Chairs:

Roger Bangerter, *Lawrence Berkeley National Laboratory*
Gerald Navratil, *Columbia University*
Ned Sauthoff, *Princeton University*

Objectives of the Fusion Summer Study:

1) Review scientific issues in burning plasmas to establish the basis for following two objectives. Address the relation of burning plasma in tokamaks to innovative MFE confinement concepts and ignition in IFE to integrated research facilities.
2) Provide a forum for critical discussion and review of proposed MFE burning plasma experiments (e.g. IGNITOR, FIRE, and ITER) and assess the scientific and technological research opportunities and prospective benefits of these approaches to the study of burning plasmas.
3) Provide a forum for the IFE community to present plans for prospective integrated research facilities, assess present status of the technical base for each, and establish a timetable and technical progress necessary to proceed for each.

Background

The 2002 Summer Study will build on earlier planning activity at the 1999 Fusion Summer Study and the scientific assessments at the UFA sponsored Burning Plasma Science Workshops (Austin, Dec 2000; San Diego, May 2001). The scientific views of the participants developed during the Summer Study preparation activities and during the 2002 Summer Study itself, will provide critical fusion community input to the decision process of FESAC and DOE in 2002-2003, and to the review of burning plasma science by the National Academy of Sciences called for by FESAC and Energy Legislation which was passed by the House of Representatives [H. R. 4].

Output of the Fusion Summer Study:

An executive summary based on summary reports from each of the working groups will be prepared as well as a comprehensive proceedings of plenary and contributed presentations.