Exploring the Frontiers of Burning Science

Dale Meade and the FIRE Team

ITC-12 / APFA ’01 Meeting
December 14, 2001

Toki, Japan

http://fire.pppl.gov

Is an Opportunity Emerging for Fusion in the U. S.?

Secretary of Energy – Abraham - DOE Mission and Priorities – Oct. 24, 2001 (to DOE Lab Directors and DOE)

"I would add to this list two priorities that deserve special mention. The first involves the unique technological contribution we can make to our energy and national security by finding new sources of energy. Whether it is fusion or a hydrogen economy, or ideas that we have not yet explored, I believe we need to leapfrog the status quo and prepare for a future that, under any scenario, requires a revolution in how we find, produce and deliver energy."

"I intend, therefore, that this Department take a leadership role in exploring how we can identify and use potentially abundant new sources of energy with dramatic environmental benefits."

By end of January conduct a strategic missions review to: ...identify new sources of energy......

Federal Reserve Chairman Greenspan - On Energy Supply – Nov. 13, 2001 (Rice University)

"In the more distant future remains the potential of fusion power. A significant breakthrough in this area has been sought for years but seems discouragingly beyond reach. But success could provide a major contribution to our nation's future power needs. The input costs of fusion power would be minor, and it produces negligible nuclear waste or pollutants."

What should we do to be ready?

Activities in the U. S. to Assess Next Steps in MFE

- House of Representatives passed the Energy Authorization Bill (HR 4) on August 1, 2001. The U. S. Senate has prepared a similar bill regarding fusion.

  1. Calls for strengthening the base fusion sciences program

  2. Directs DOE to submit a plan for construction of 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, if it's construction is highly likely and cost effective for the U. S. relative to a domestic experiment.

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

- 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.

Full text on http://fire.pppl.gov

Fusion Frontiers to be Explored by the Next Stage of Fusion Research

- **Burning Plasma Physics**
  - strong nonlinear coupling inherent in a fusion dominated plasma
  - access, explore and understand fusion dominated plasmas

- **Advanced Toroidal Physics**
  - develop and test physics needed for an attractive MFE reactor
  - couple with burning plasma physics

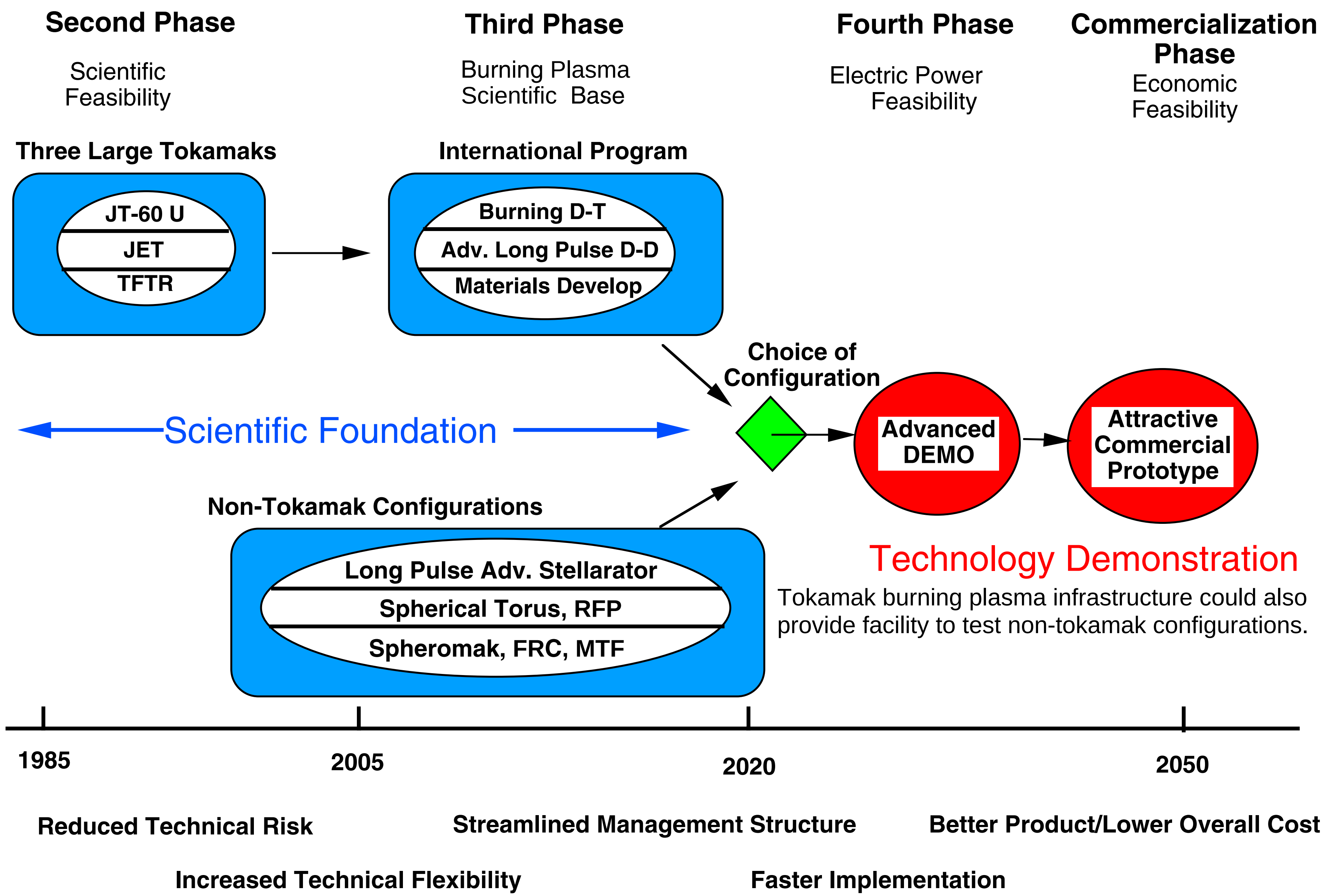
- **Boundary Physics and Plasma Technology** (coupled with above)
  - high particle and heat flux
  - couple core and divertor
  - fusion plasma - tritium inventory and helium pumping

- **Neutron Resistant Materials** (separate facility)
  - high fluence testing using " point" neutron source

- Superconducting Coil Technology does not have to be coupled to physics experiments - only if needed for physics objectives

- Nuclear Component Testing should wait for the correct reactor materials

The Multi-Machine Strategy for Magnetic Fusion



(The overall Multi-Machine Strategy includes IFE)

Outline

- Objectives for a Next Step Experiment in Magnetic Fusion
- Burning Plasma Performance Considerations
- Compact High Field Approach - General Parameters
- Advanced Tokamak Longer Pulse Possibilities
- 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
  November 29-30, 2001 at LLNL, Livermore, CA

- **Charge for First 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?
  Preparation for Snowmass Assessment

- 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 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

Fusion Science Objectives for a Major Next Step Burning Plasma 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 (Elmy H-Mode)

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 (Reversed Shear ITB)

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

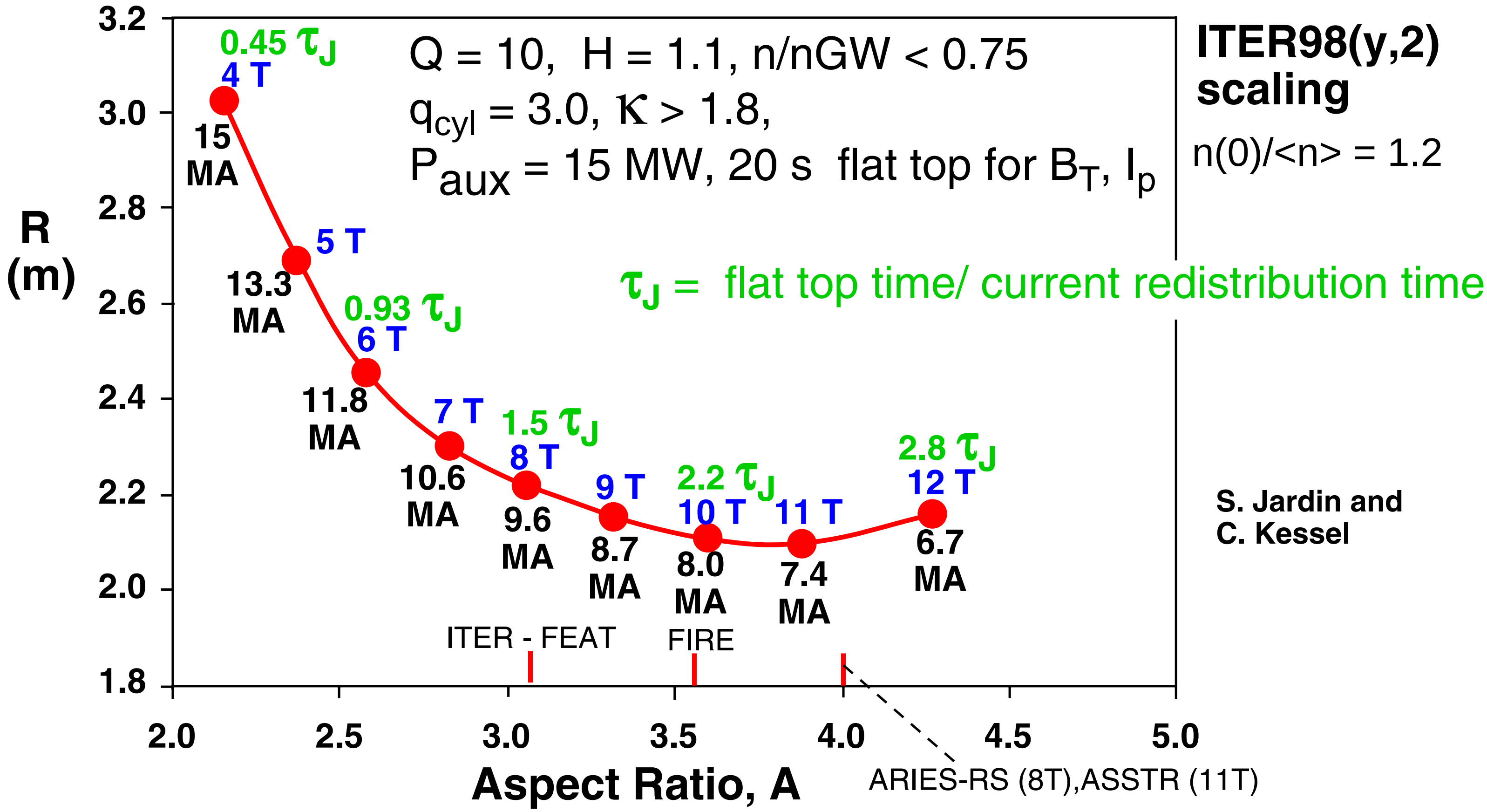
Quasi-stationary

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.

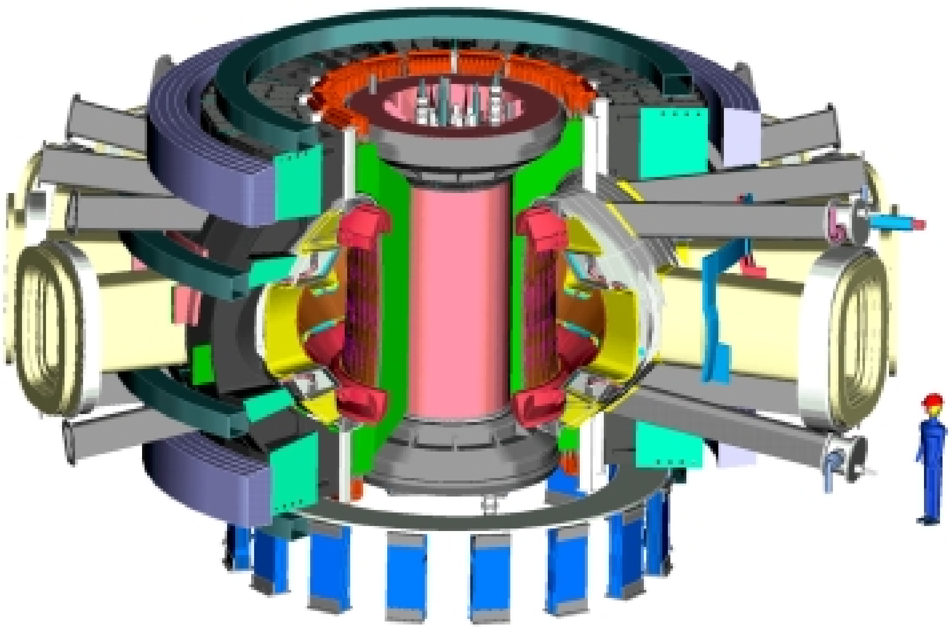


What is the optimum for advanced steady-state modes?

Fusion Ignition Research Experiment

(FIRE)

http://fire.pppl.gov



Design Features

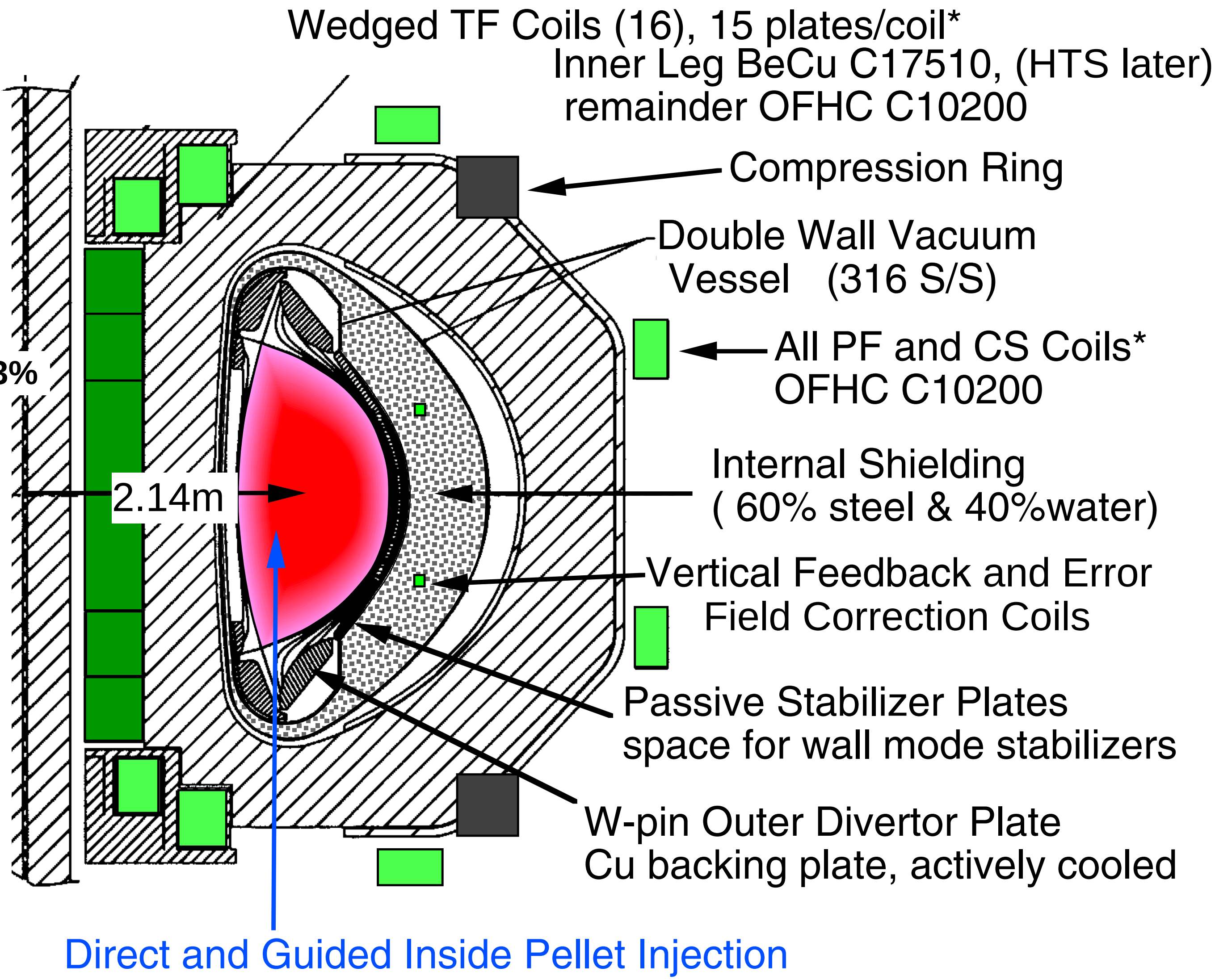
- R = 2.14 m, a = 0.595 m
- B = 10 T
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA
- $P_{aux} \leq$ 20 MW
- Q ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s
- Tokamak Cost ≈ $375M (FY99)
- Total Project Cost ≈ $1.2B at Green Field site.

Mission:
Attain, explore, understand and optimize magnetically confined fusion-dominated plasmas.

FIRE Baseline for Snowmass Assessment

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

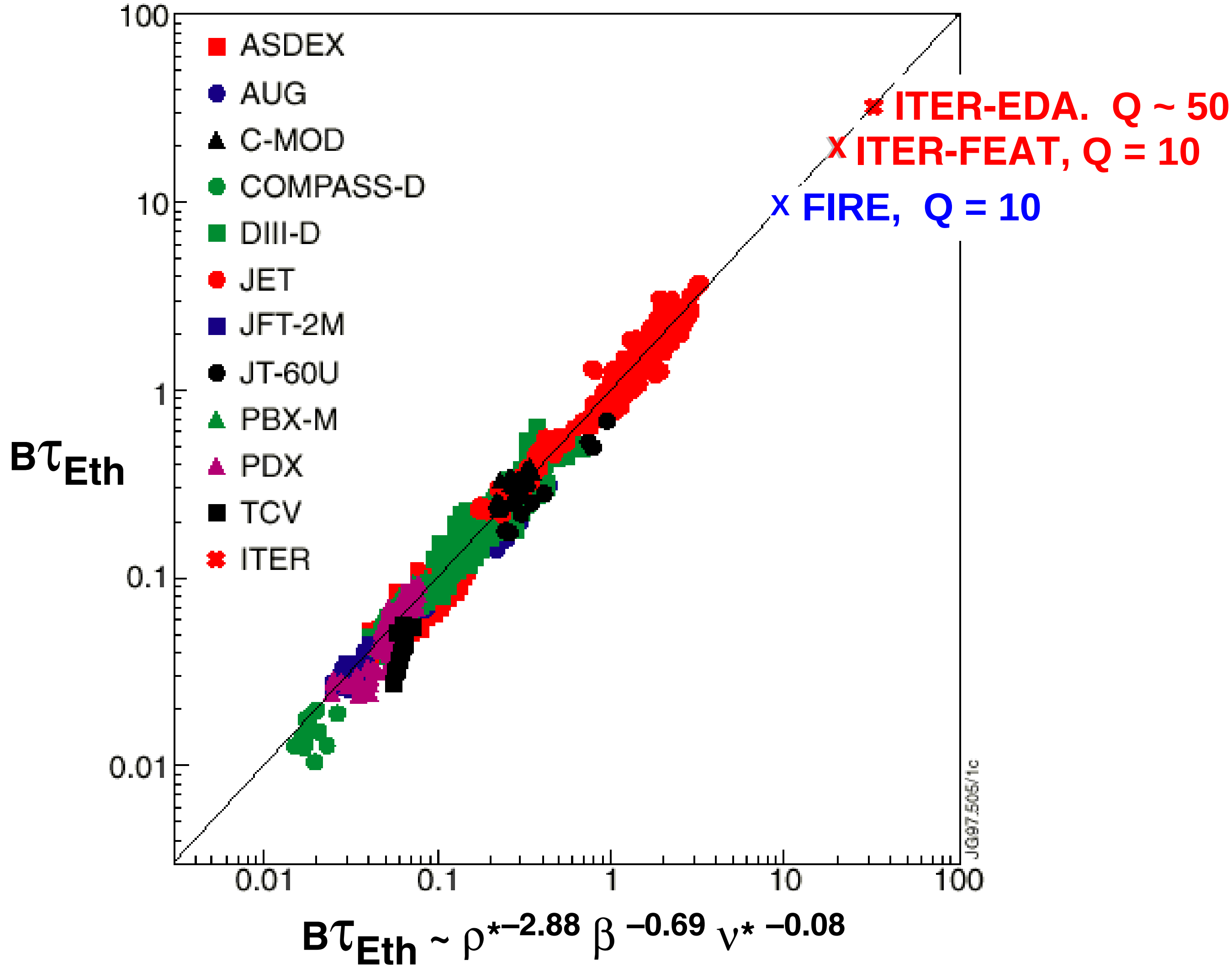
R, major radius	2.14 m
a, minor radius	0.595 m
κx, κ95	2.0, 1.77
δx, δ95	0.7, 0.55(AT) - 0.4(OH)
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.3% ripple @ Outer MP
Toroidal magnet energy	5.8 GJ
Ip, plasma current	7.7 MA
Magnetic field flat top, burn time	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	None planned, (NI-NBI backup to be evaluated)
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 Limits pulse length in some AT modes
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 5 - 15 g, (< 30 g, Low Hazard Nuclear Facility)

FIRE is a Modest Extrapolation in Plasma Confinement

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

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

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. Physics 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?

Empirical Guidelines for Estimating Confinement

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

$$n_{20} \leq 0.8\, n_{GW} = 0.8\, I_p/\pi a^2, \qquad n(0)/\langle n \rangle = 1.2$$

Beta Limit - theory and tokamak data base

$$\beta \leq \beta_N (I_p/aB), \quad \beta_N < 2.0 \text{ conventional}, \;\; \beta_N \sim 3.5 \text{ advanced mode}$$

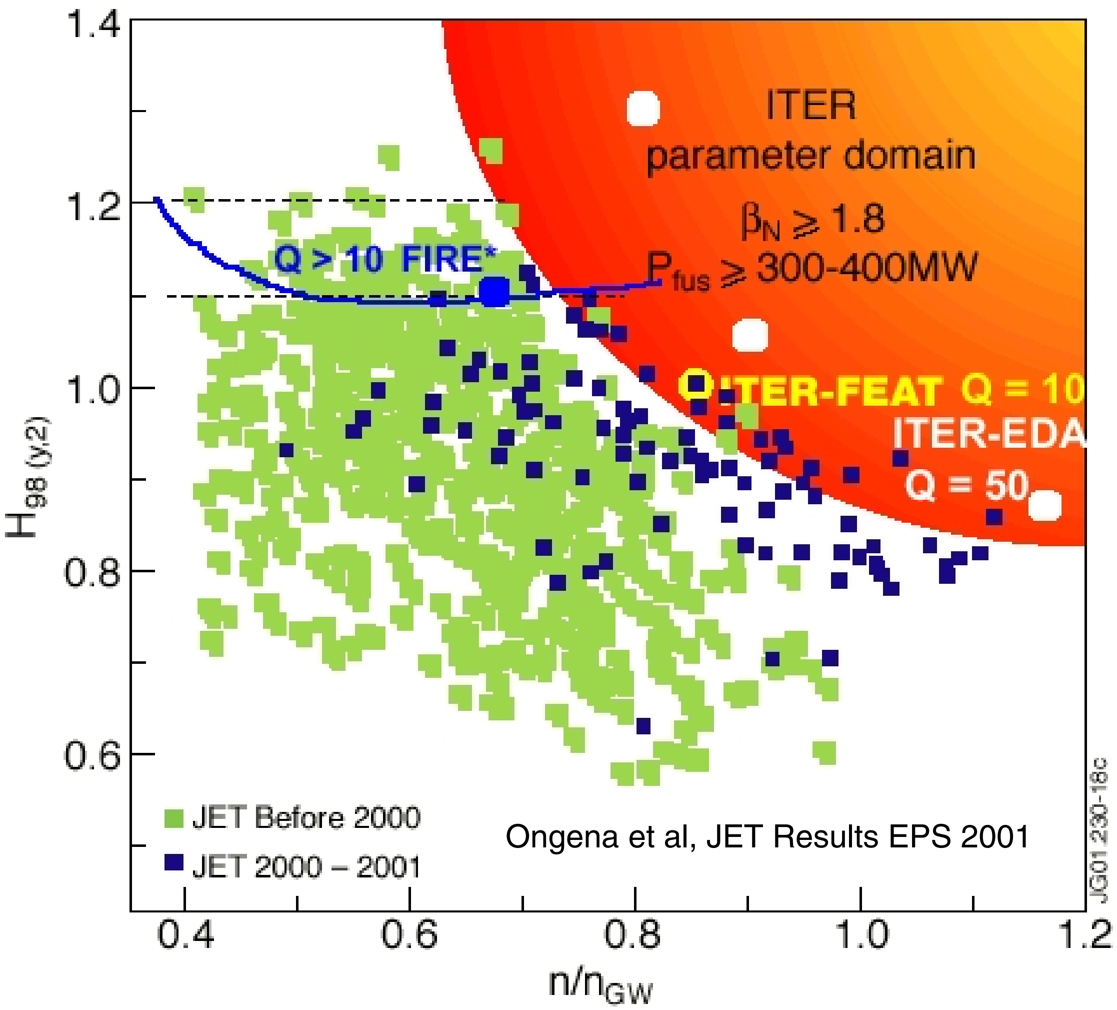
H-Mode Power Threshold - Based on today's tokamak data base

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

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

FIRE's Operating Density and Triangularity are Near the Optimum for the Elmy H-Mode

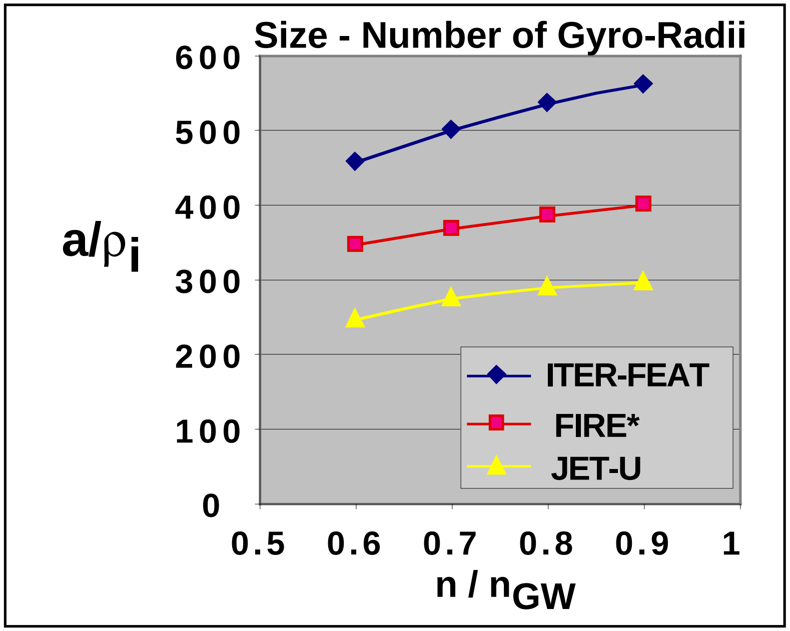
- **The optimum density for the H-Mode is $n/n_{GW} \approx 0.6 - 0.7$**
- **H-mode confinement increases with δ**
  - **$\delta \approx 0.7$ FIRE**
  - **$\delta \approx 0.5$ ITER-FEAT**
- **Elm size is reduced for $\delta > 0.5$**
- **Z_{eff} decreases with density (Mathews/ITER scaling)**
- **DN versus SN ?**

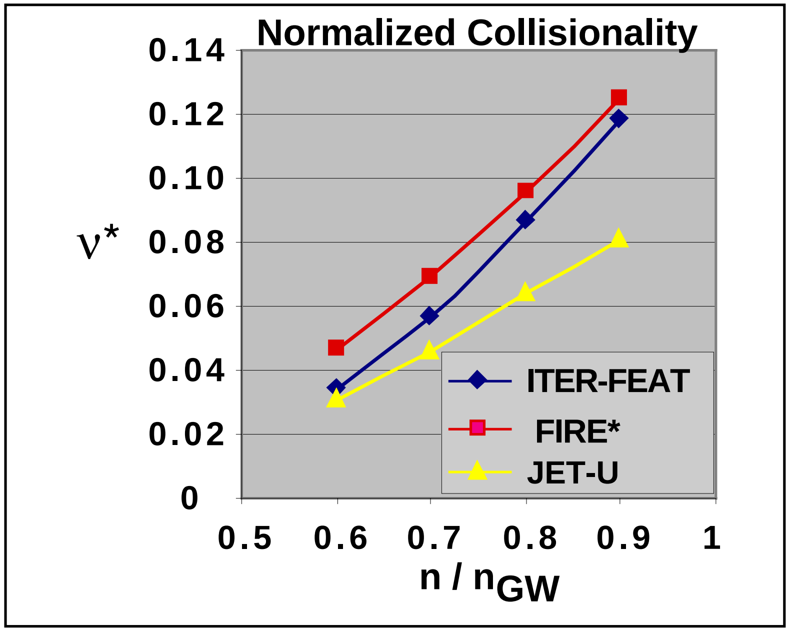


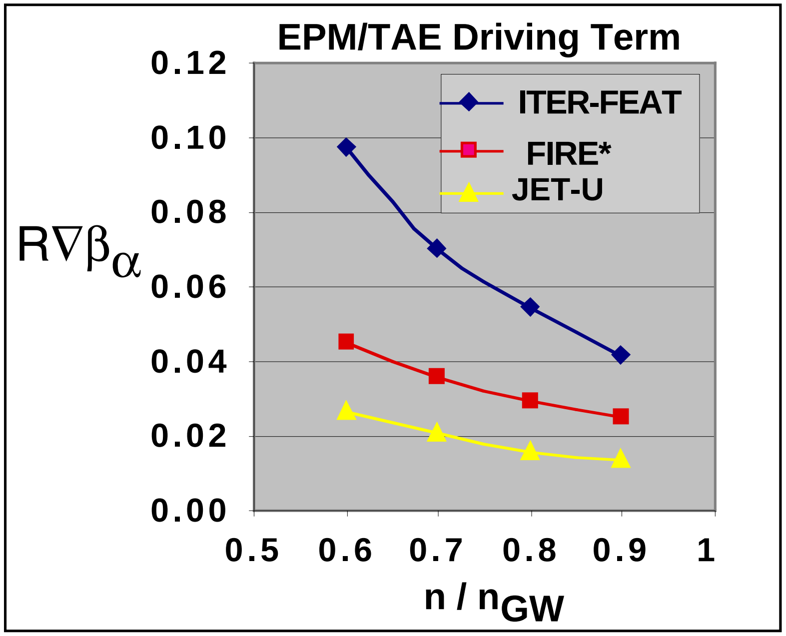
Cordey et al, H = function (δ, n/n_{GW}, n(0)/<n>) EPS 2001

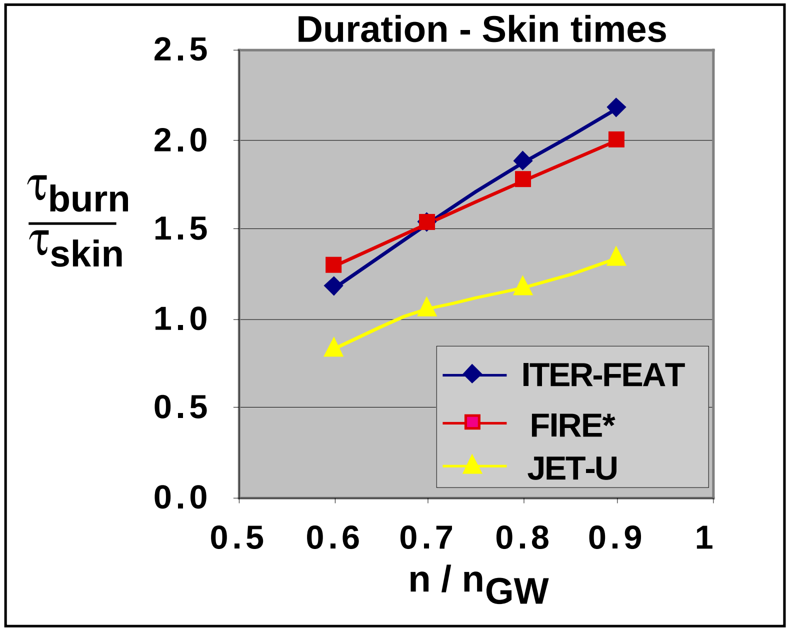
Parameters for H-Modes in Potential Next Step D-T Plasmas

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

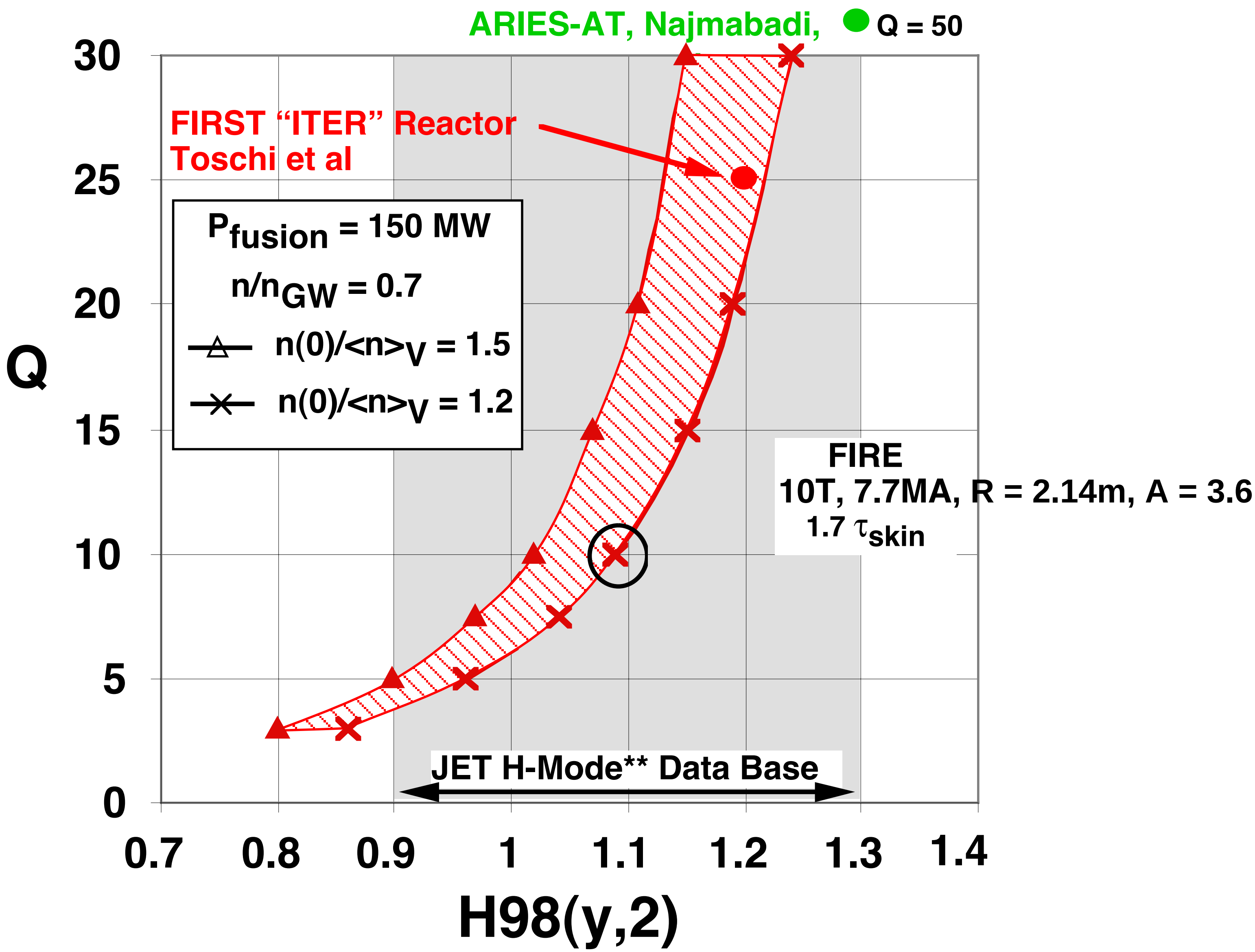








Projections to FIRE Compared to Envisioned Reactors



Physics Based Model GLF23
Pedestal Temperature Requirements for Q=10

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

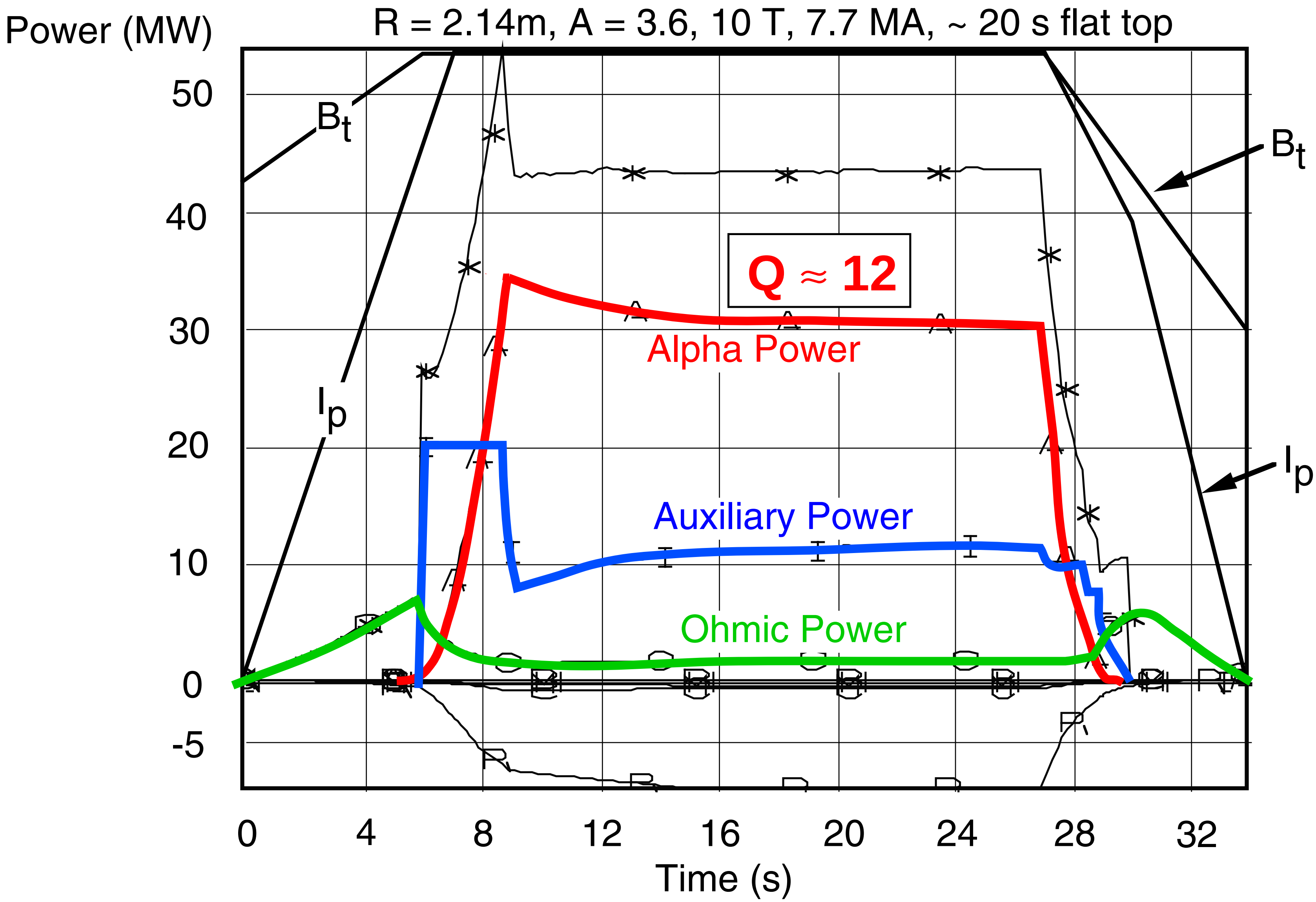
Need a model for the pedestal temperature, FIRE has the advantage of highest triangularity and low density $n/n_{GW} = 0.6 - 0.7$

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

J. Kinsey and R. Waltz

LEHIGH University

1 1/2-D Simulation of Elmy H-Mode in FIRE (TSC)



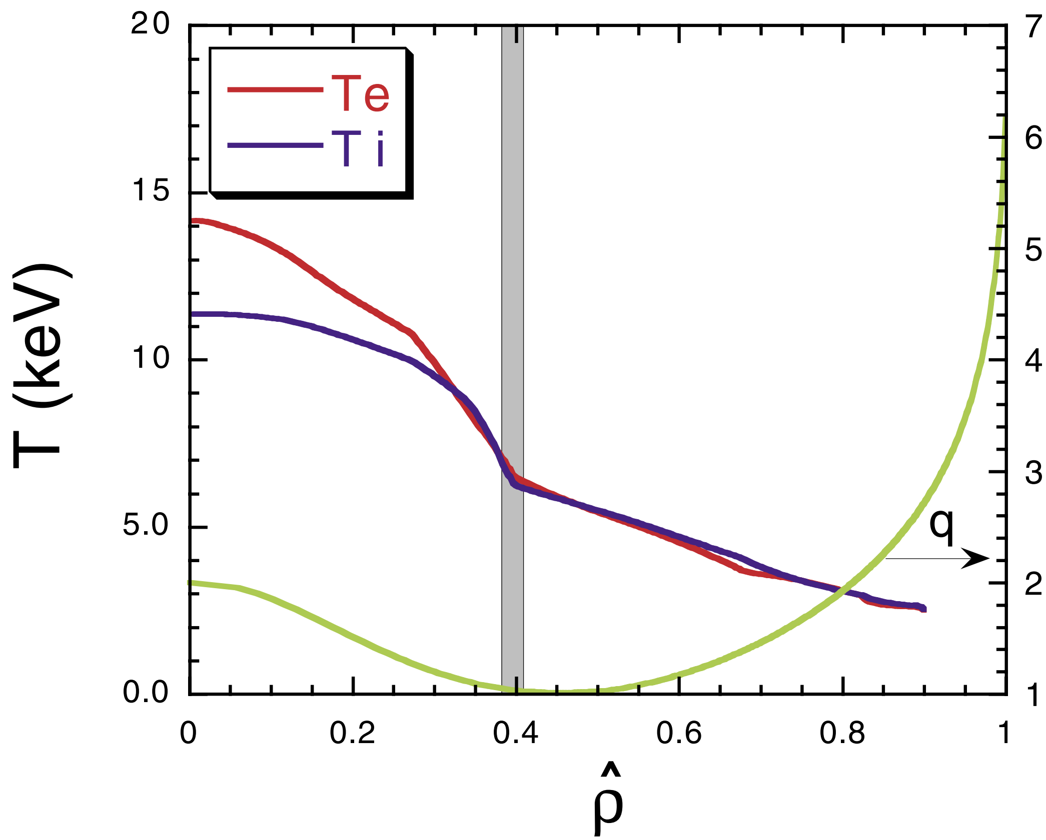
- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and n/n_{GW} = 0.67
- Burn Time ≈ 20 s ≈ 21 τ_E ≈ 4 τ_{He} ≈ 2 τ_{skin}

Q = Pfusion/(Paux + Poh)

GLF23 Predicts an Internal Transport Barrier in FIRE as a Result of Shafranov-Shift Stabilization of the ITG Mode

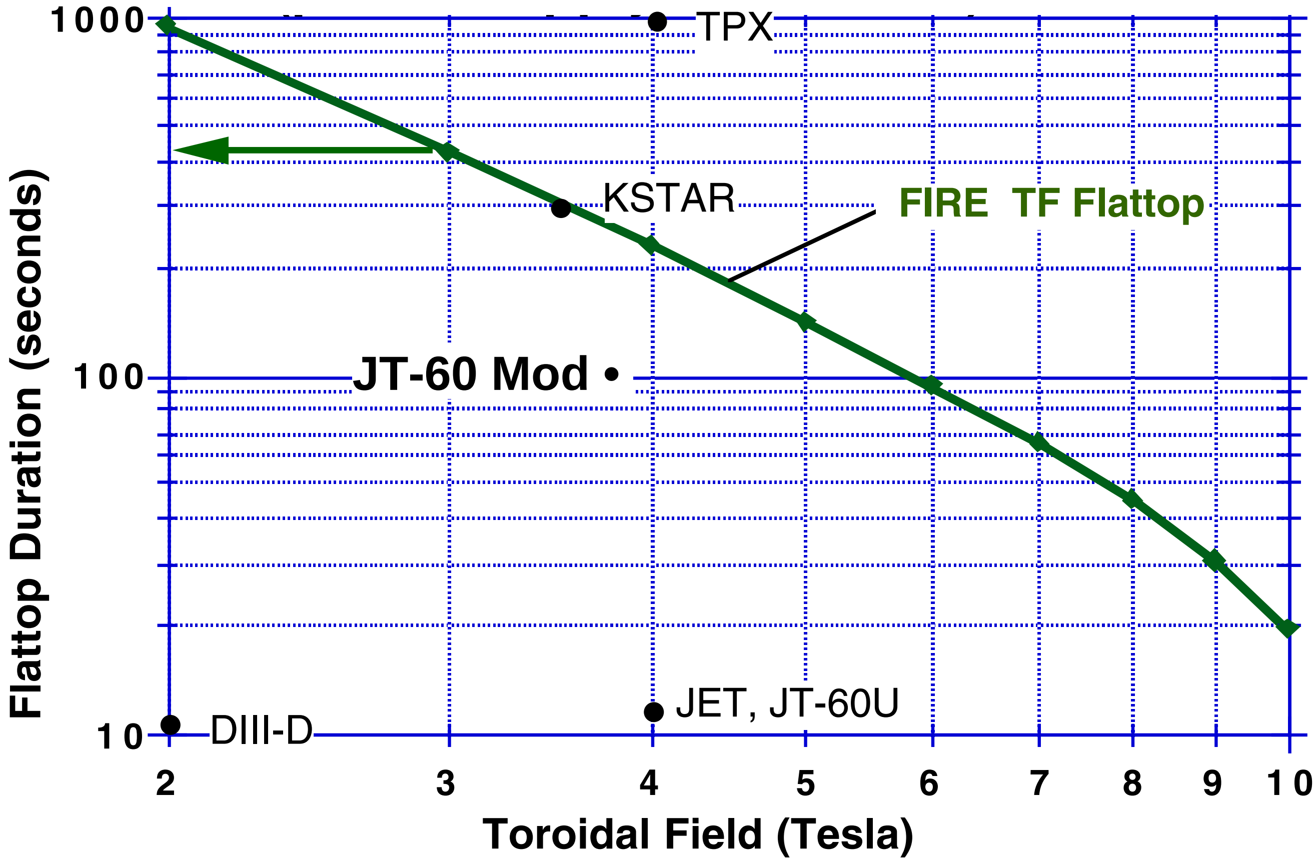
- ***Barrier only forms if some density peaking is present.***
- ***Diamagnetic component of ExB shear helps after ITB is formed.***

Q = 10



Kinsey, Waltz and Staebler
UFA BPS Workshop 2

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

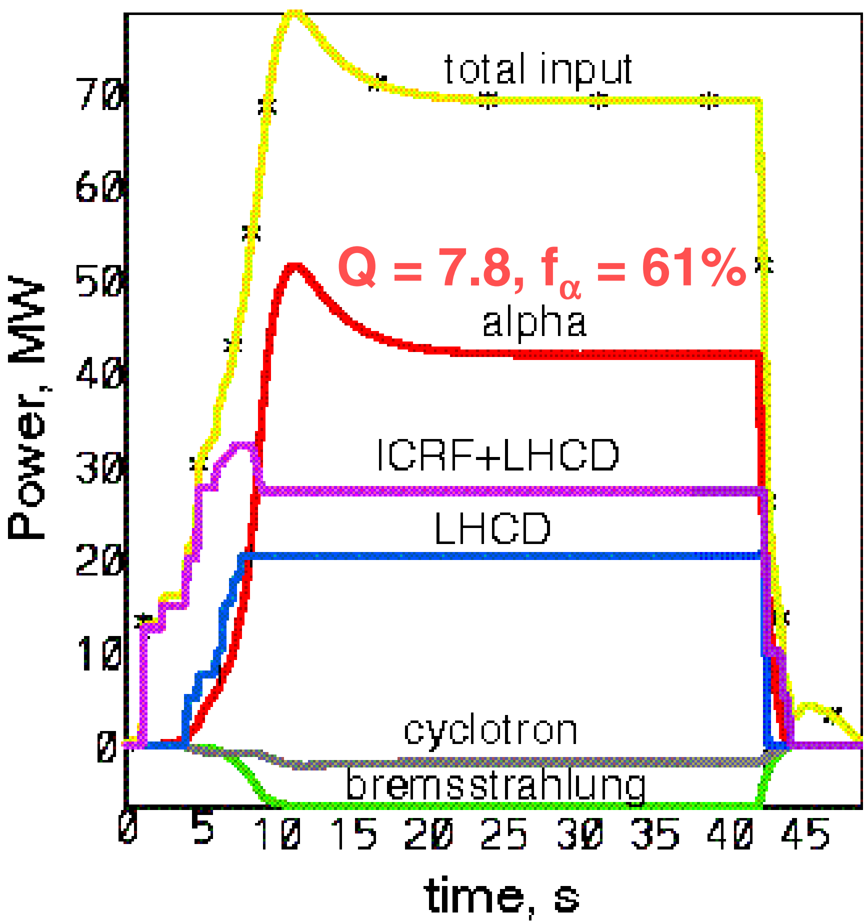


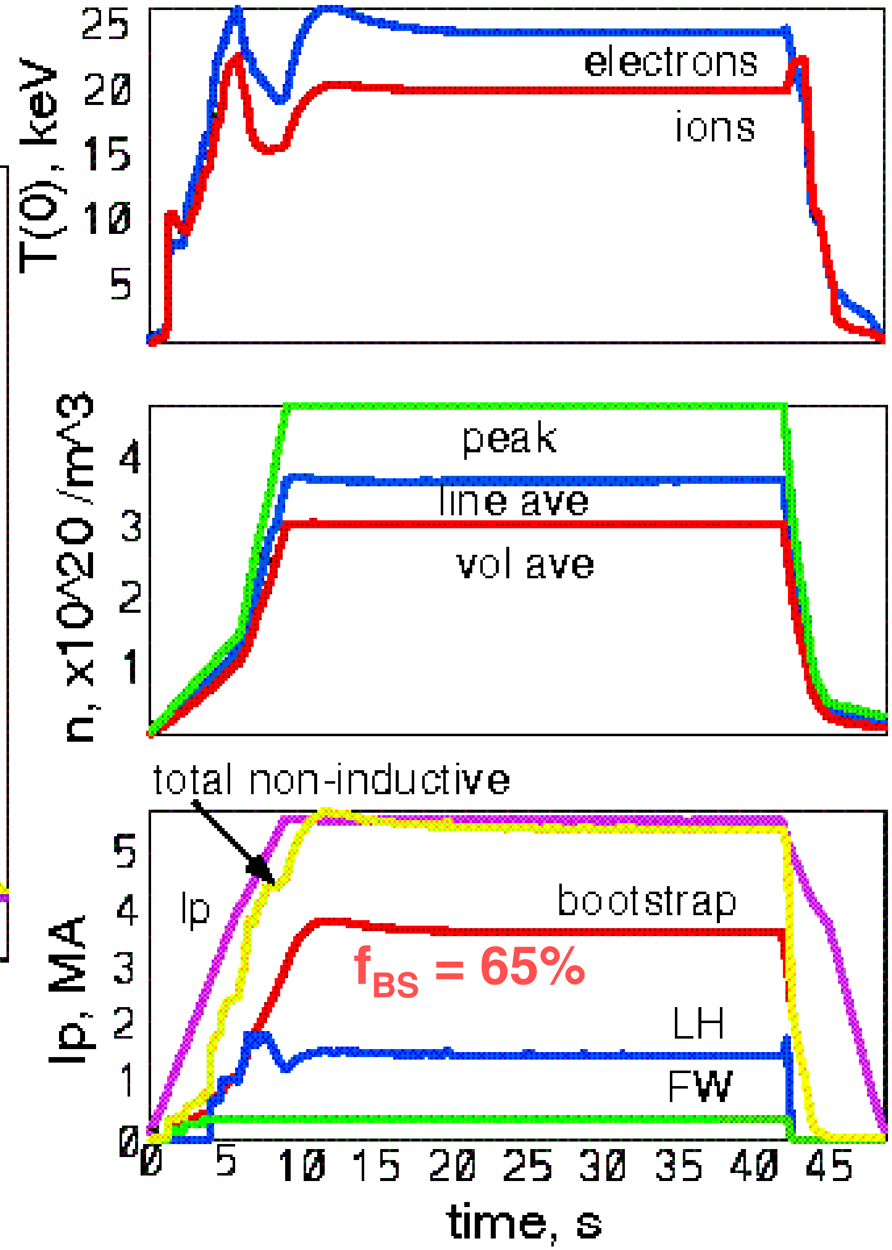
Note: FIRE is ≈ the same physical size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT .
The Number of Skin Times curve assumes a constant skin time of 13s.

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

TSC Simulation of a “Fusion Dominated” Plasma

8.5 T, 5.4 MA, t(flattop) = 32 s





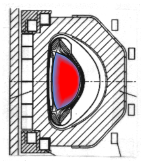
H(y,2) = 1.6,
β_N = 3.5, n(0)/<n> = 1.5

FIRE Would Explore the Edge Physics and In-Vessel Technology Frontier

Pfusion
= ~ 150 MW

Volume
= 27 m^3

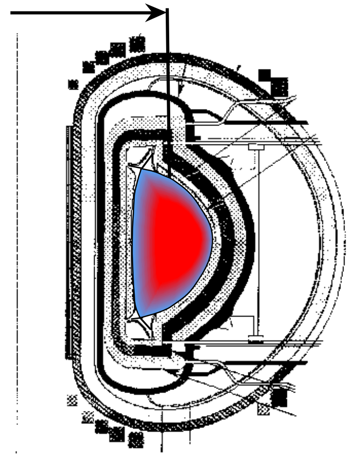
B = 10 T
R = 2.14 m
→



FIRE

~ 3X

B = 8 T
R = 5.5 m



Pfusion
= 2170 MW

Volume
= 350 m^3

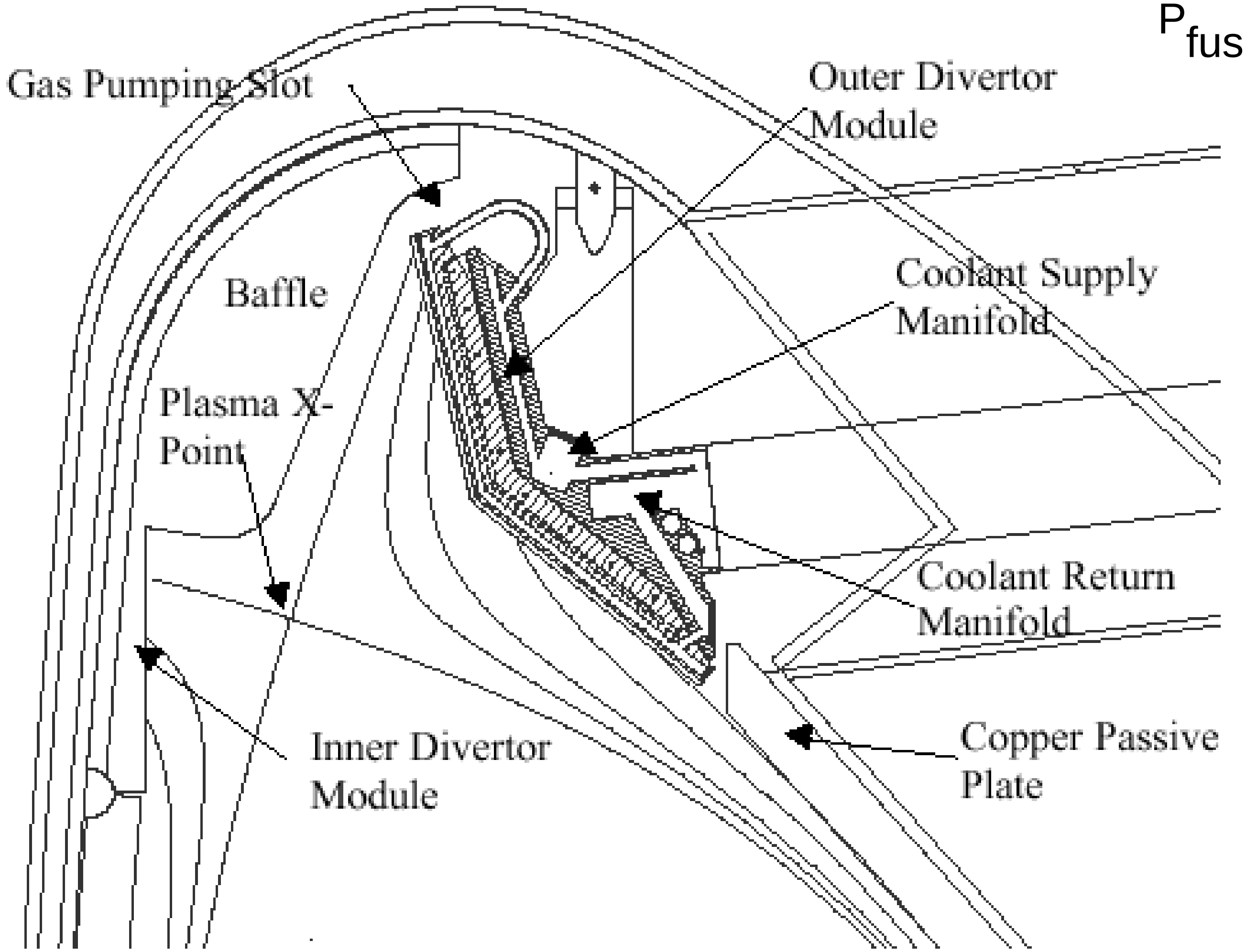
ARIES-RS The “Goal”

	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 (Ploss/NR)	~5	~10	~35
Power Density on Div Plate (MW/m^2)	3	~15-19 → 6	~5
Burn Duration (s)	4	20*	steady

* Note: FIRE outer divertor plate is in steady-state

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

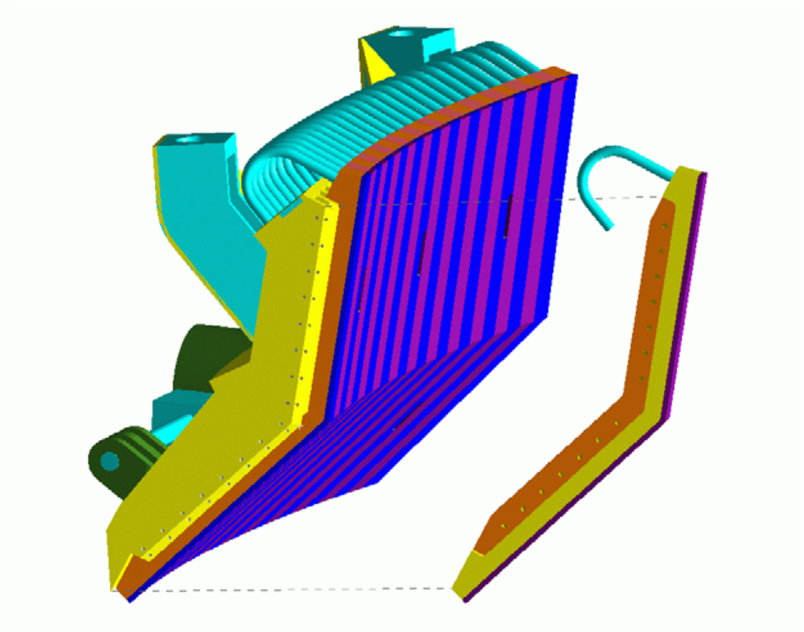
P_{fusion} < 200 MW



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

Divertor Module Components for FIRE

Sandia

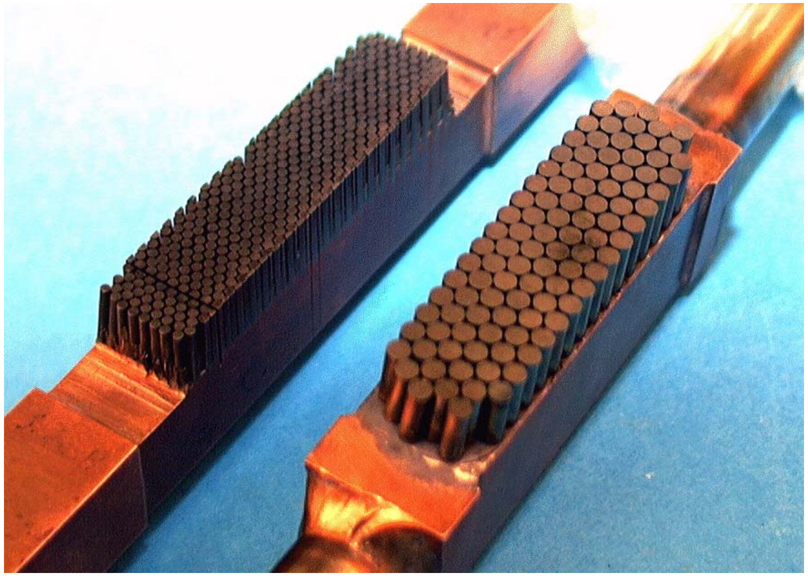


Finger Plate for

Outer Divertor Module

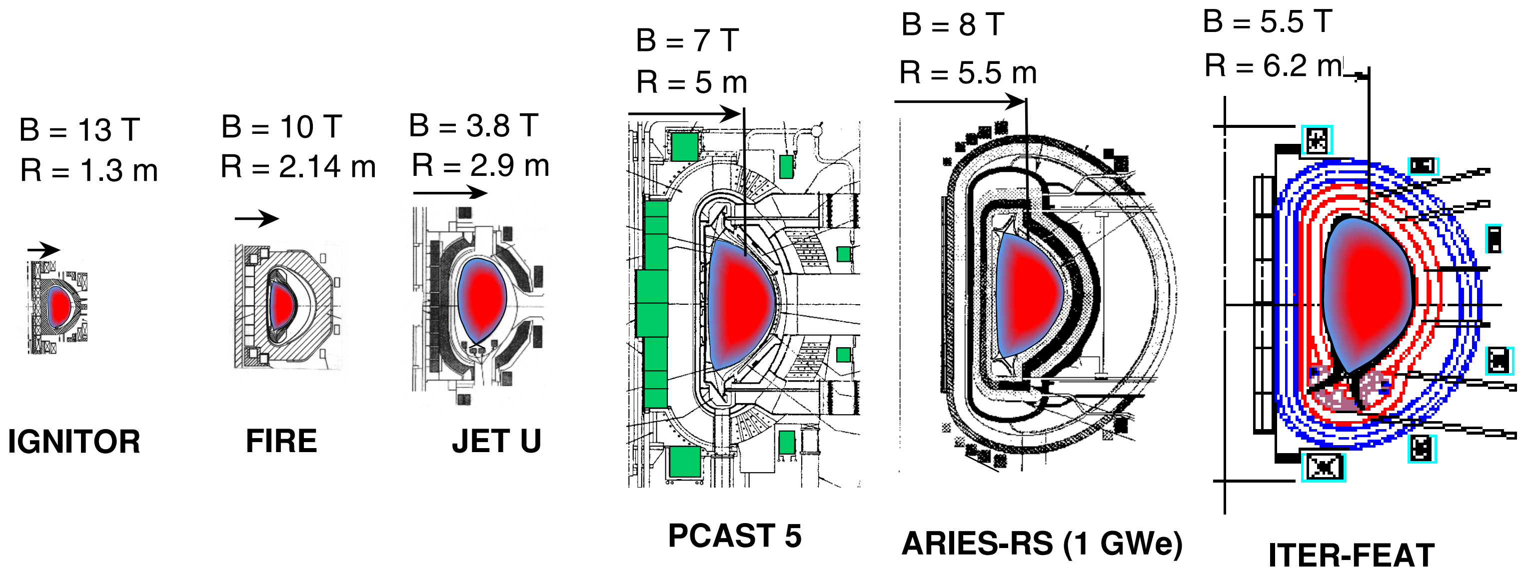
Two W Brush Armor Configurations

Tested at 25 MW/m^2



Carbon targets used in most experiments today are not compatible with tritiun inventory requirements of fusion reactors.

Potential Next Step Burning Plasma Experiments

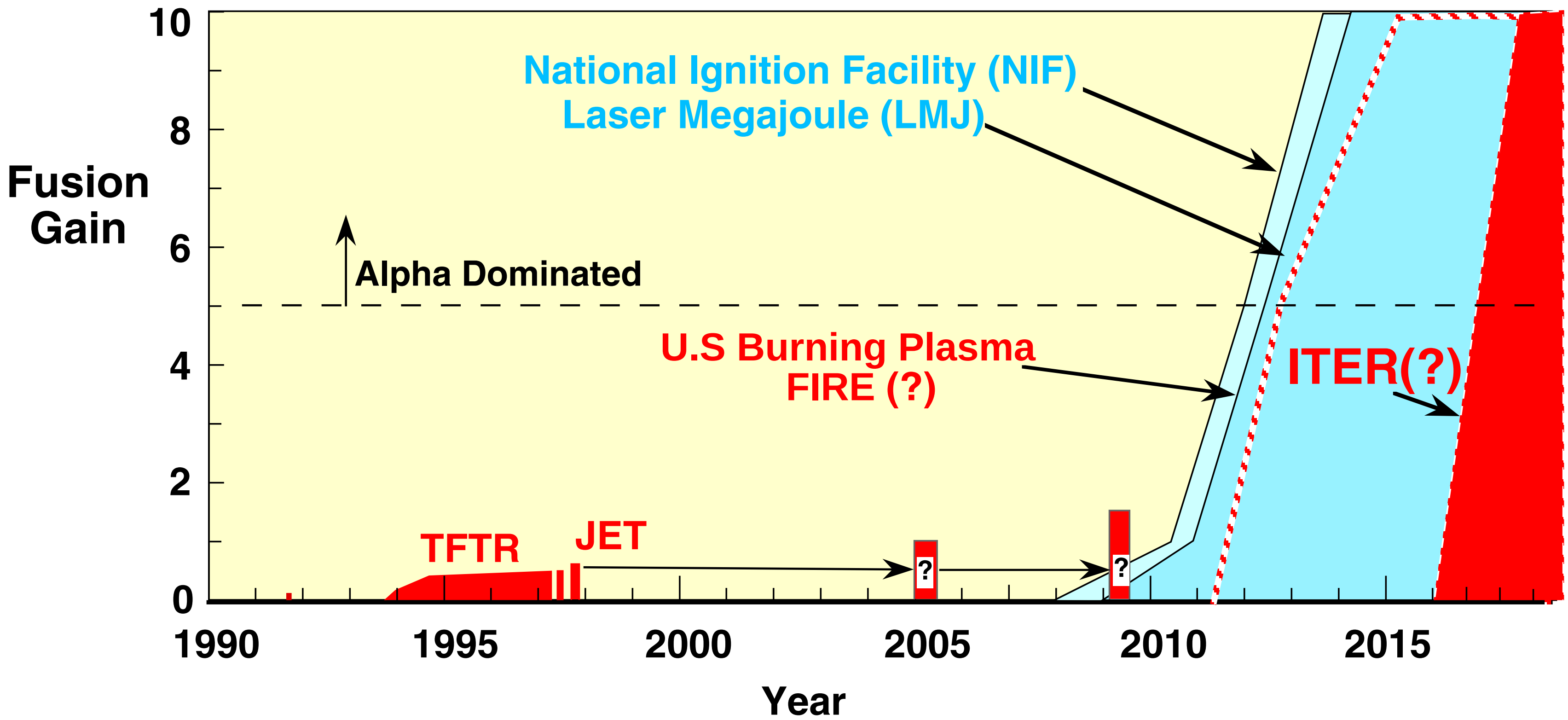


Cost Drivers	IGNITOR	FIRE	JET U	PCAST	ARIES-RS	ITER-FEAT
Plasma Volume (m^3)	11	27	108	390	350	828
Plasma Surface (m^2)	36	60	160	420	420	610
Plasma Current (MA)	12	7.7	6	15	11.3	15
Magnet Energy (GJ)	5	5	1.6	40	85	50
Fusion Power (MW)	100	150	30	400	2170	400
Burn Duration (s), inductive	~1	20	10	120	steady	400
τ Burn/ τ CR		~2	0.6	1	steady	2
Cost Estimate ($B-2000$)		1.2	~0.6	6.7	10.6*	4.6

* first , $5.3 B for 10th of a kind

AR RS/ITERs/PCAST/FIRE/IGN

Timetable for Exploring the Burning Plasma Frontier



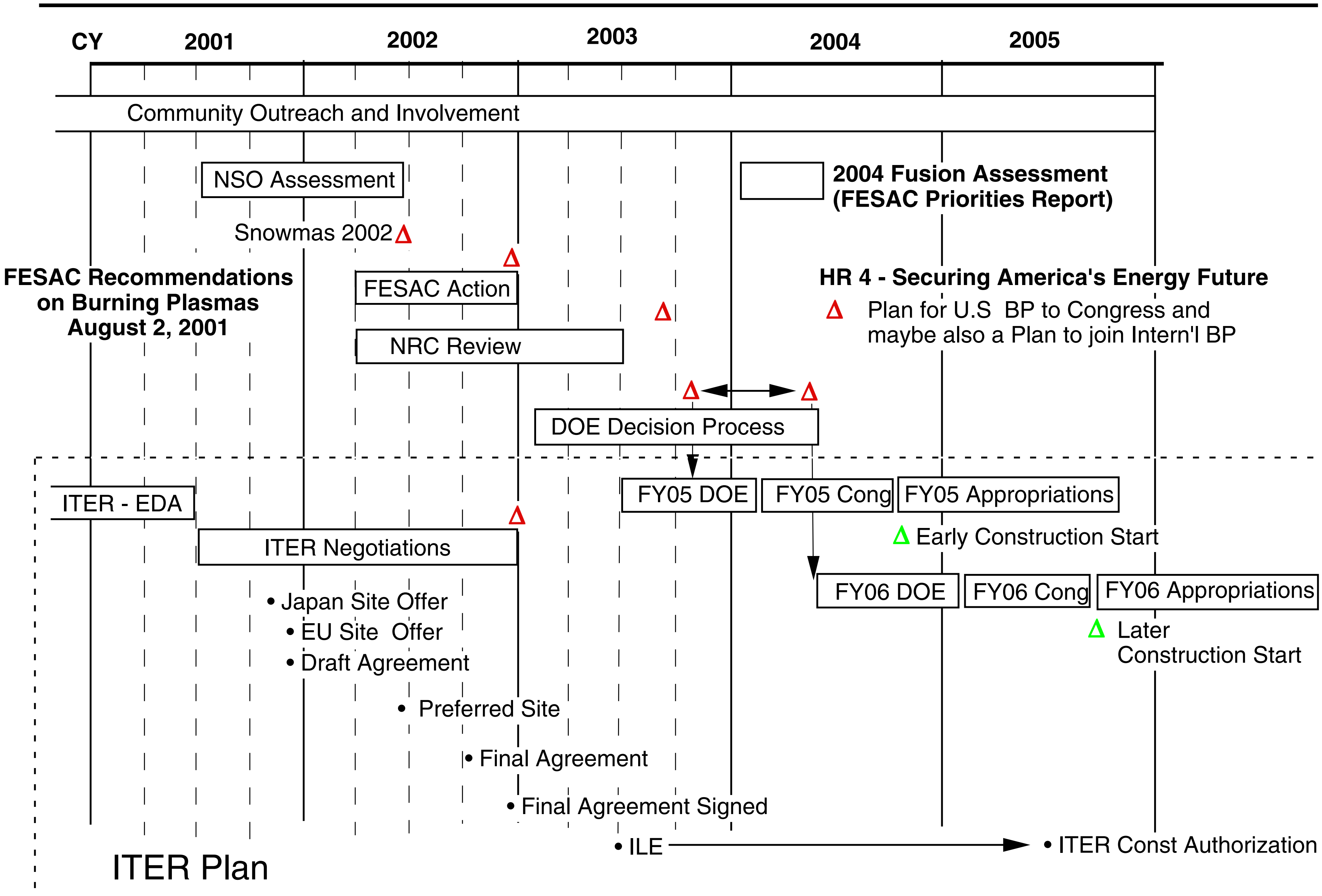
- Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for ≥ 15 years.

- 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 Snowmass 2002 Summer Study will provide a forum to assessing approaches. The NRC Review in 2002 will assess contributions to broader science issues..

FESAC Recommendation and ITER Plan for Burning Plasmas



Summary

- A Window of Opportunity may be opening for U.S. Energy R&D. We should be ready. The Modular or Multi-Machine Strategy has advantages for addressing the science and technolgy issues of fusion.

- A compact high field tokamak, like FIRE, has the potential:

  - address the important burning plasma issues,
  - investigate the strong non-linear coupling between BP and AT,
  - stimulate the development of reactor relevant PFC technology, and
  - provide generic BP science and possibly BP infrastructure for non-tokamak BP experiments.

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

  - Apply recent enhanced confinement and advanced modes to FIRE
  - Understand conditions for enhanced confinement regimes
  - Compare DN relative to SN - confinement, stability, divertor, etc
  - Complete disruption analysis, develop better disruption control/mitigation.
  - Respond to FIRE Engineering Review and NSO PAC on specific physics R&D and engineering design and R&D issues.

http://fire.pppl.gov