FIRE, A Potential Next Step Option for Magnetic Fusion

Dale M. Meade

for the FIRE Study Team

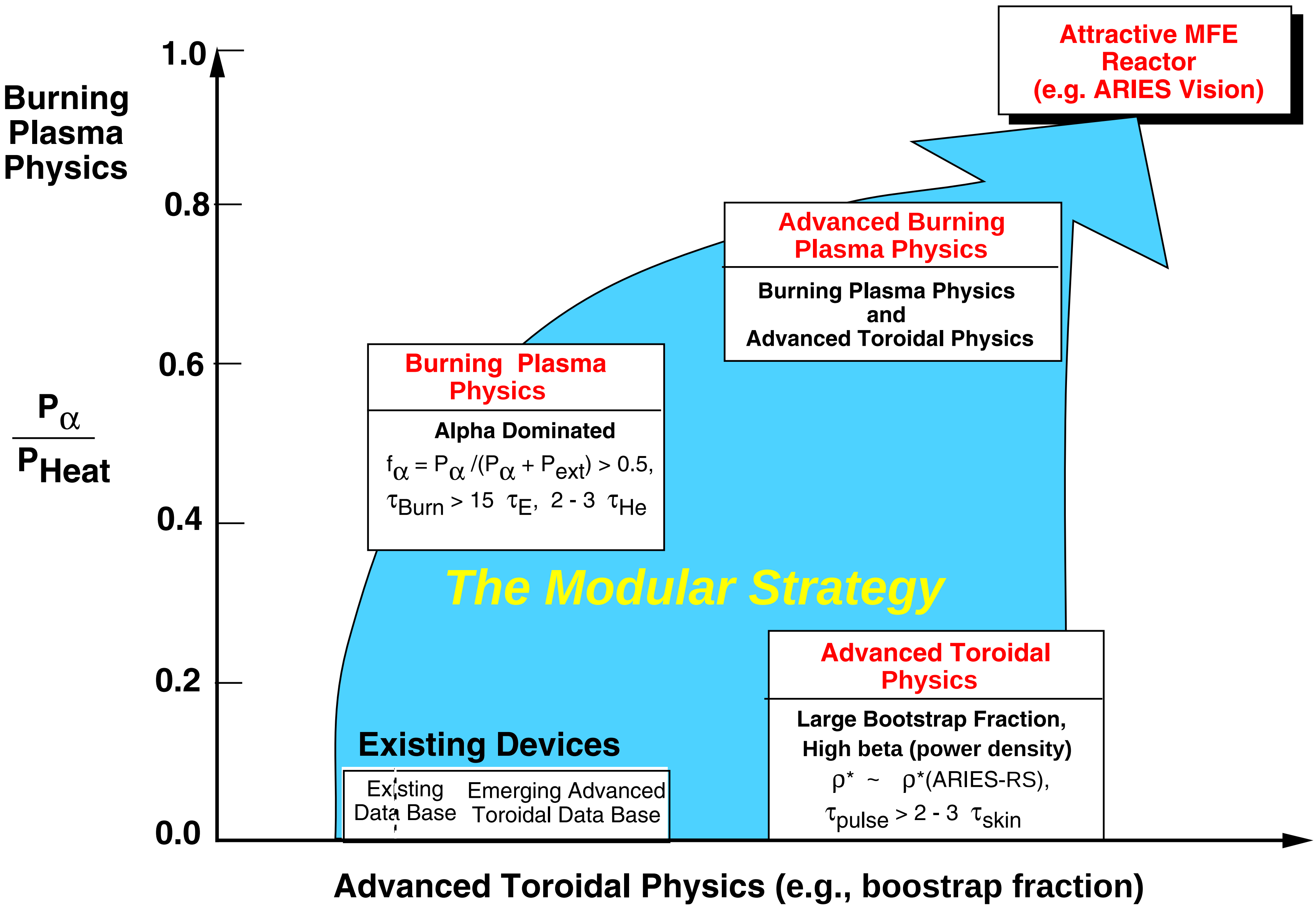
Presented at
Sherwood Snowmass Discussion
Rochester, NY

April 23, 2002

http://fire.pppl.gov

FIRE *Lighting the Way to Fusion*

FIRE's Goal is to Address the Critical Burning Plasma Science Issues for an Attractive MFE Reactor



Attain a burning plasma with confidence using "todays" physics, but allow the flexibility to explore tomorrow's advanced physics.

Next Step Option (FIRE) 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 at LLNL, Livermore, CA
- **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.

FIRE Study is a Pre-Conceptual design, integrated costs (1998-2002) <$12M.

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

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 Burn Duration

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

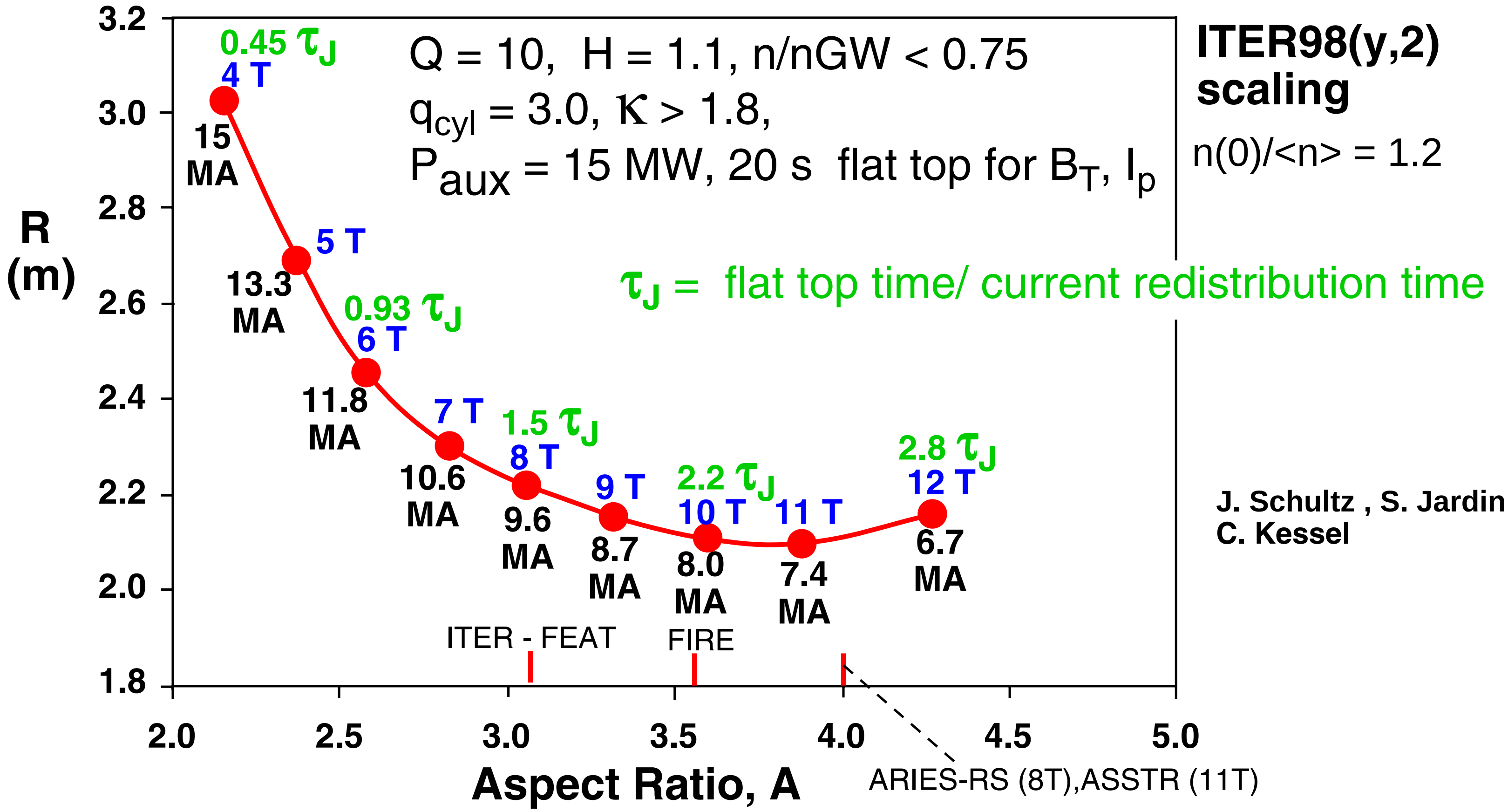
FIRE Has Adopted the AT Features Identified by ARIES Studies

- High toroidal field
- Double null
- Strong shaping
  - $\kappa = 2.0$, $\delta = 0.7$
- Internal vertical position control coils
- Cu wall stabilizers for vertical and kink instabilities
- Very low ripple (0.3%)
- ICRF/FW on-axis CD
- LH off-axis CD
- LHCD stabilization of NTMs
- Tungsten divertor targets
- Feedback coil stabilization of RWMs
- Burn times exceeding current diffusion times
- Pumped divertor/pellet fueling/impurity control to optimize plasma edge

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.

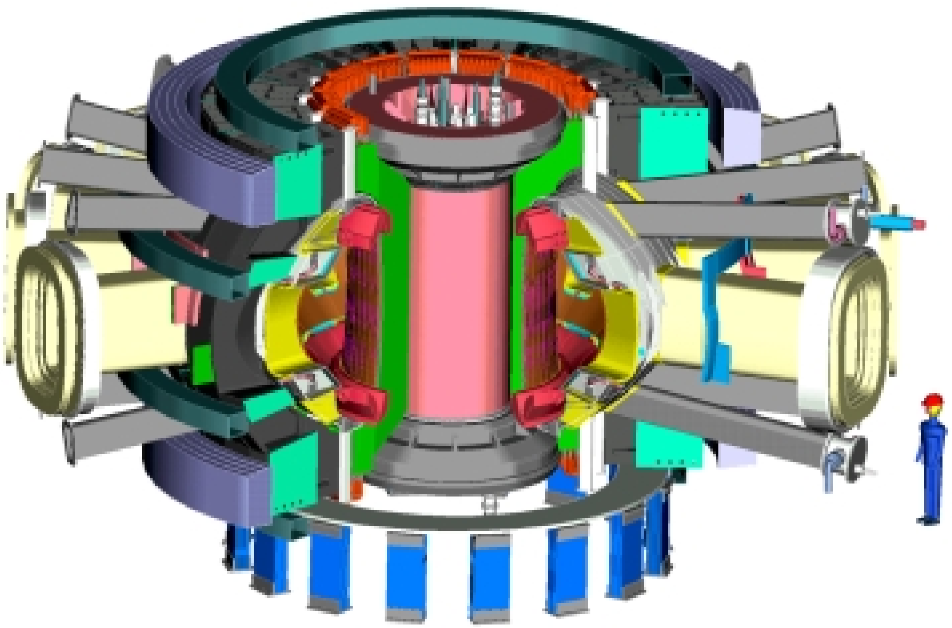


What is the optimum for advanced steady-state modes?

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

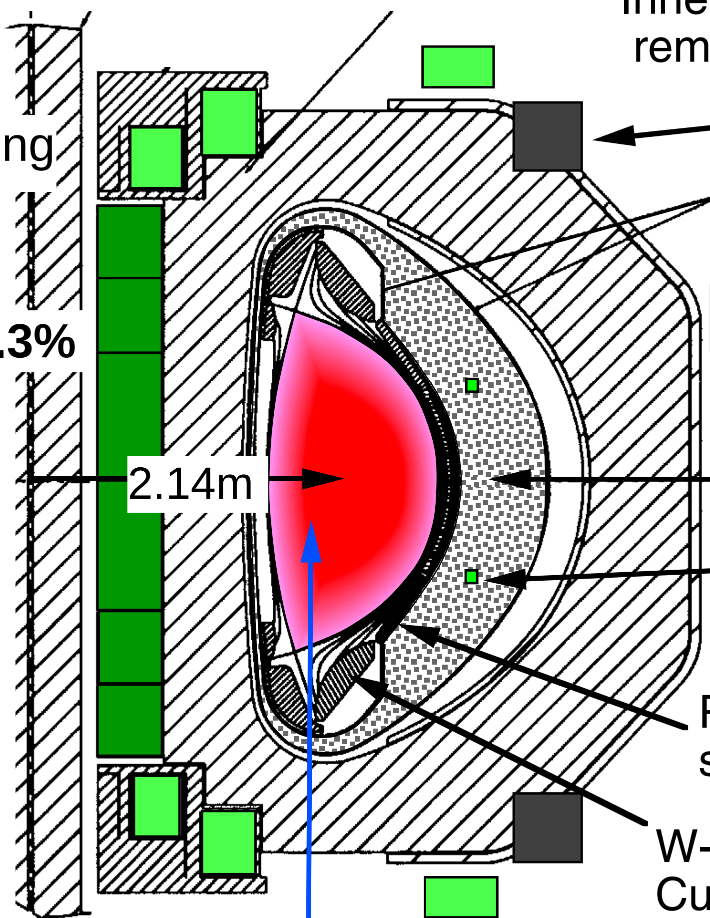
Mission: Attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas.

CIT + TPX = FIRE leading to ARIES

FIRE Incorporates Advanced Tokamak Features

AT Features

- DN divertor pumping
- 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, $\kappa 95$	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

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

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

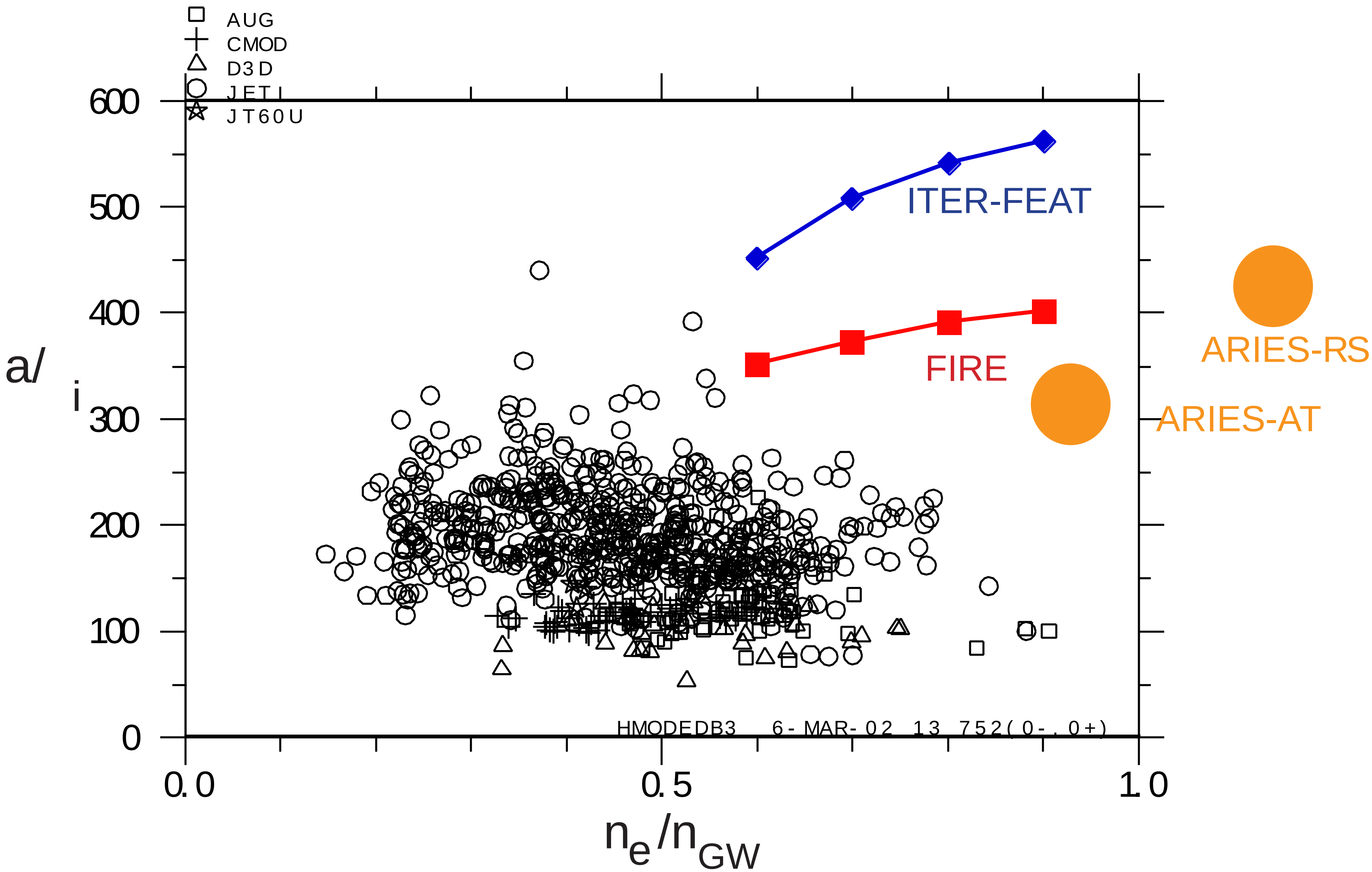
H-Mode Power Threshold - Based on today's tokamak data base

$$Pth \geq (2.84/Ai)\, n_{20}^{0.58}\, B^{0.82}\, Ra^{0.81}$$, 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.

FIRE would Extend the Transport Understanding Toward ARIES

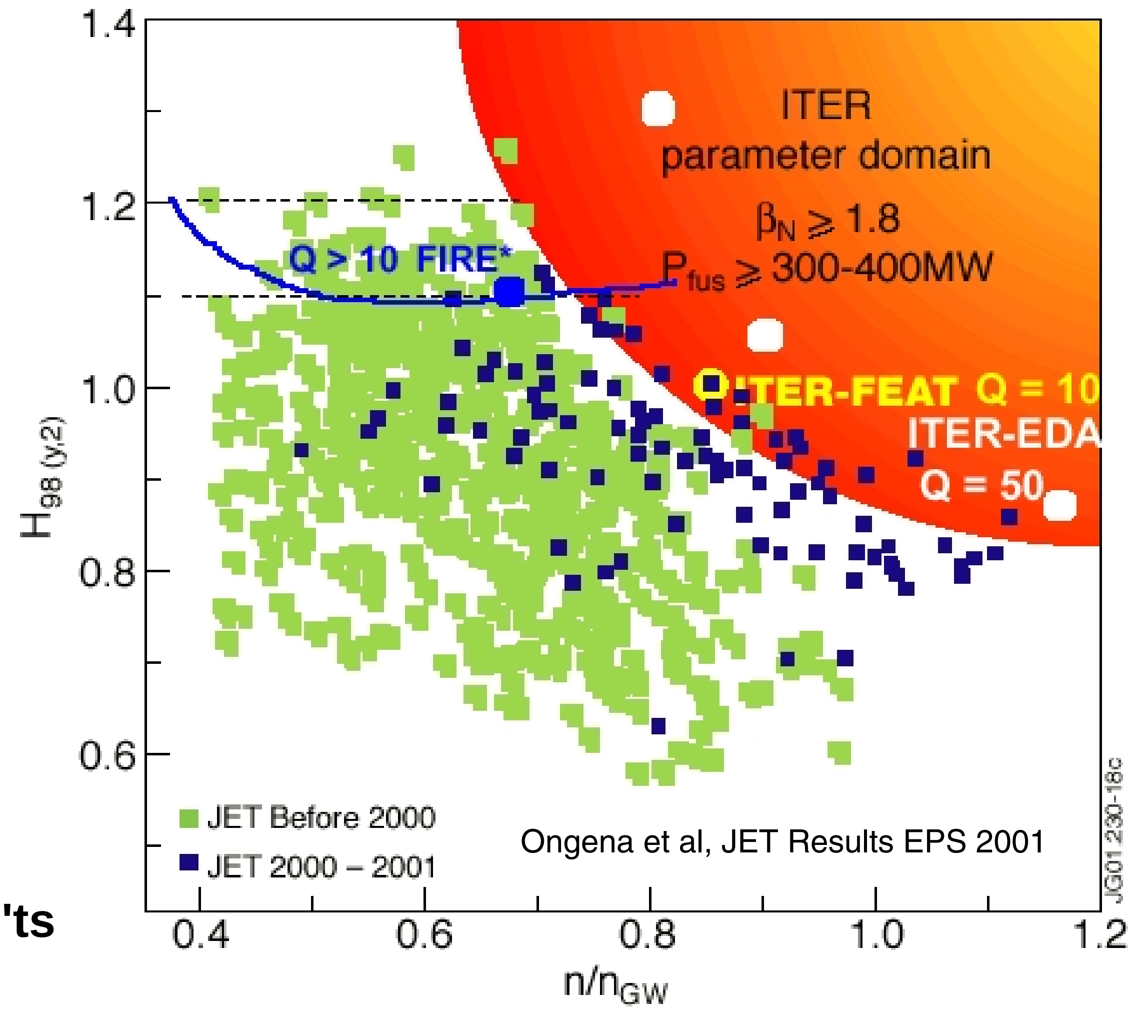


FIRE and ITER-FEAT calculated for Q =10,

a/ρ_i evaluated at plasma ~ 0.5a

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 ? C- Mod Exp'ts



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

Increasing Triangularity Enhances H-Mode Confinement

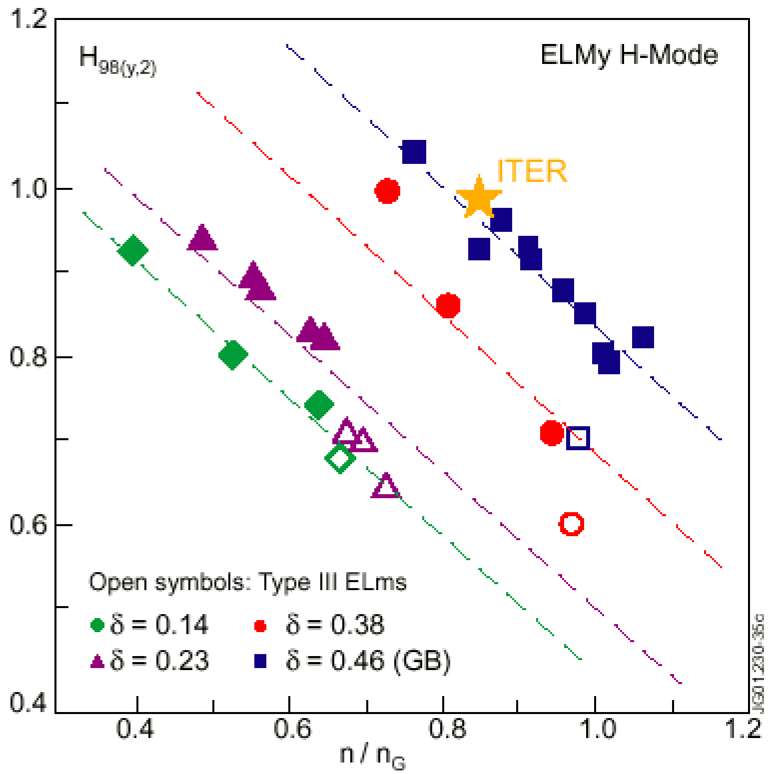


Figure 2.2-2 Confinement Enhancement Factor Relative to the ITERH-98(y,2) Scaling as a Function of n/n_G in JET[5]

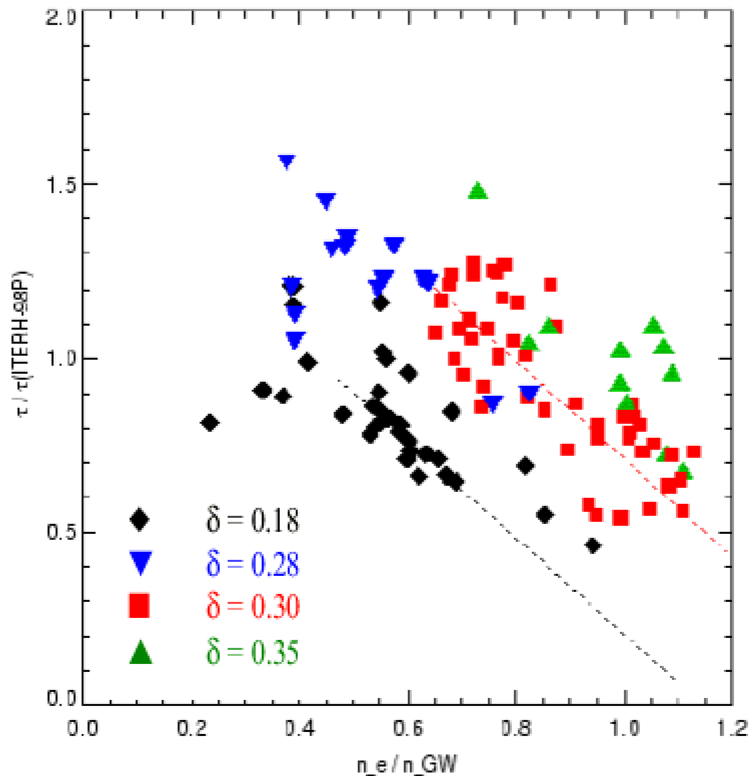


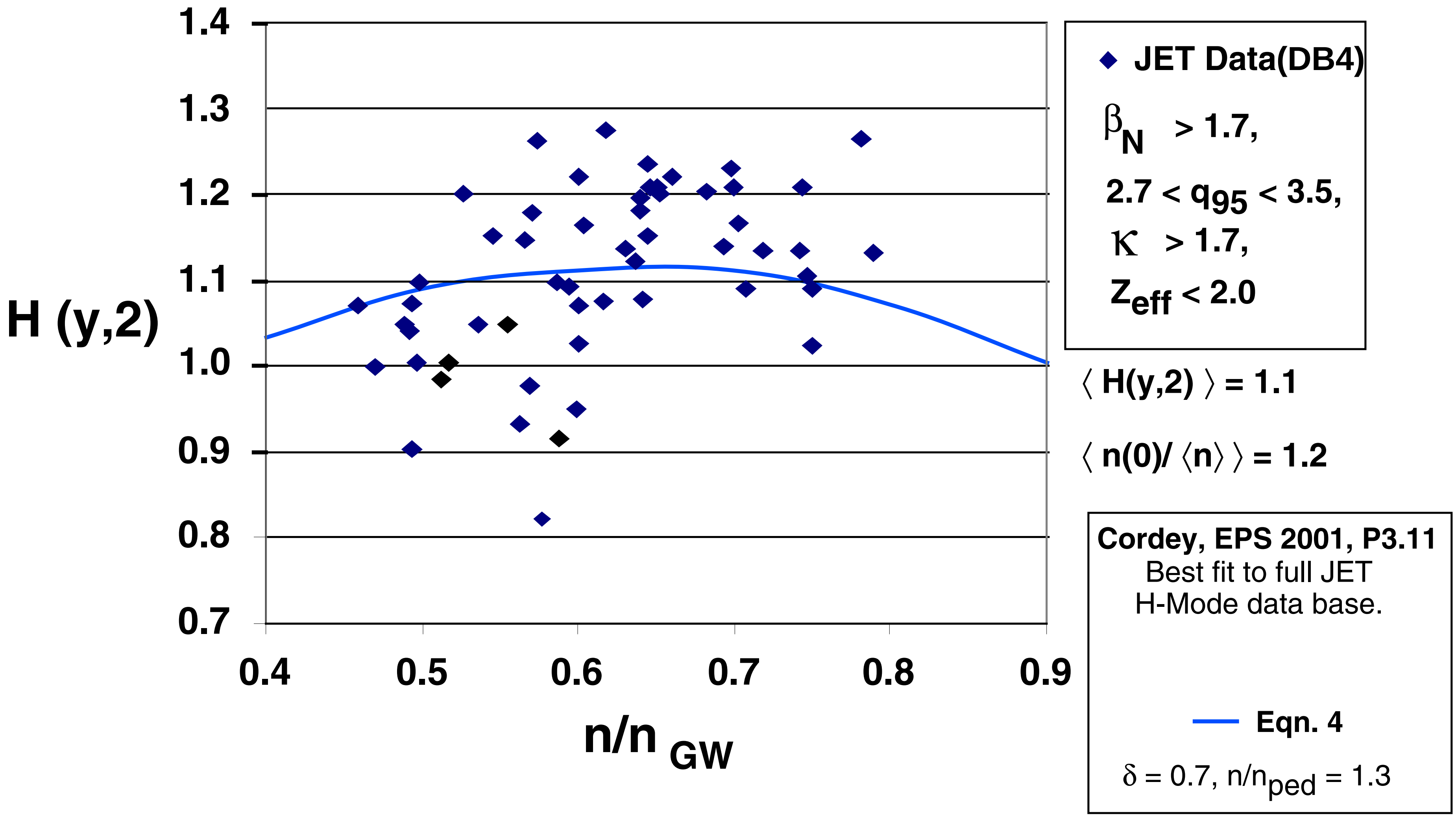
Figure 2.2-3 Confinement Enhancement Factor Relative to the ITERH-98P(y) Scaling as a Function of n/n_G in ASDEX Upgrade[6]

- Trade-off between triangularity and heating power: lower δ discharges need higher P_{in}/P_{L-H}

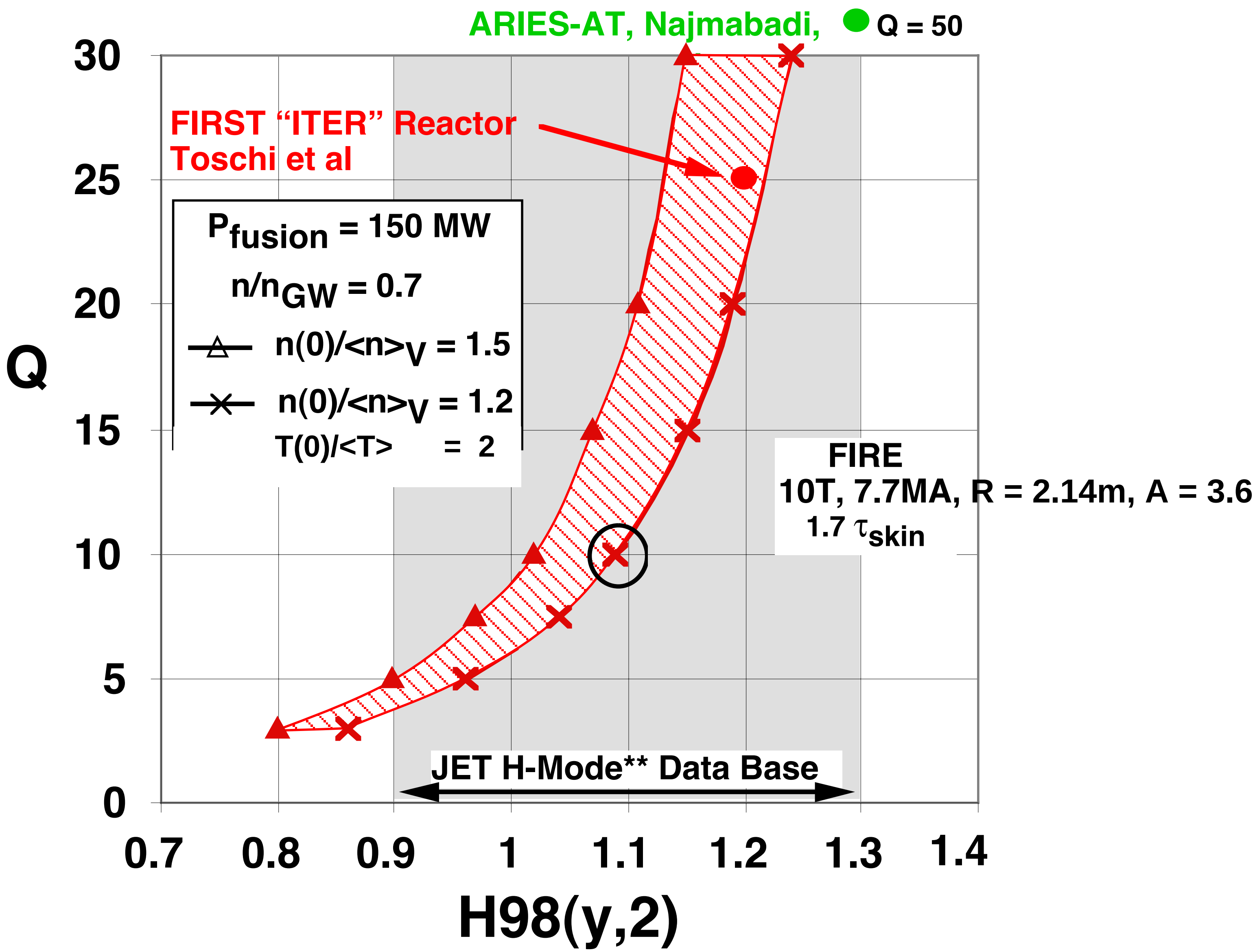
Note: triangularity is determined at the separatrix

Extracted from the ITER-FEAT Physics Basis 2001, page 11

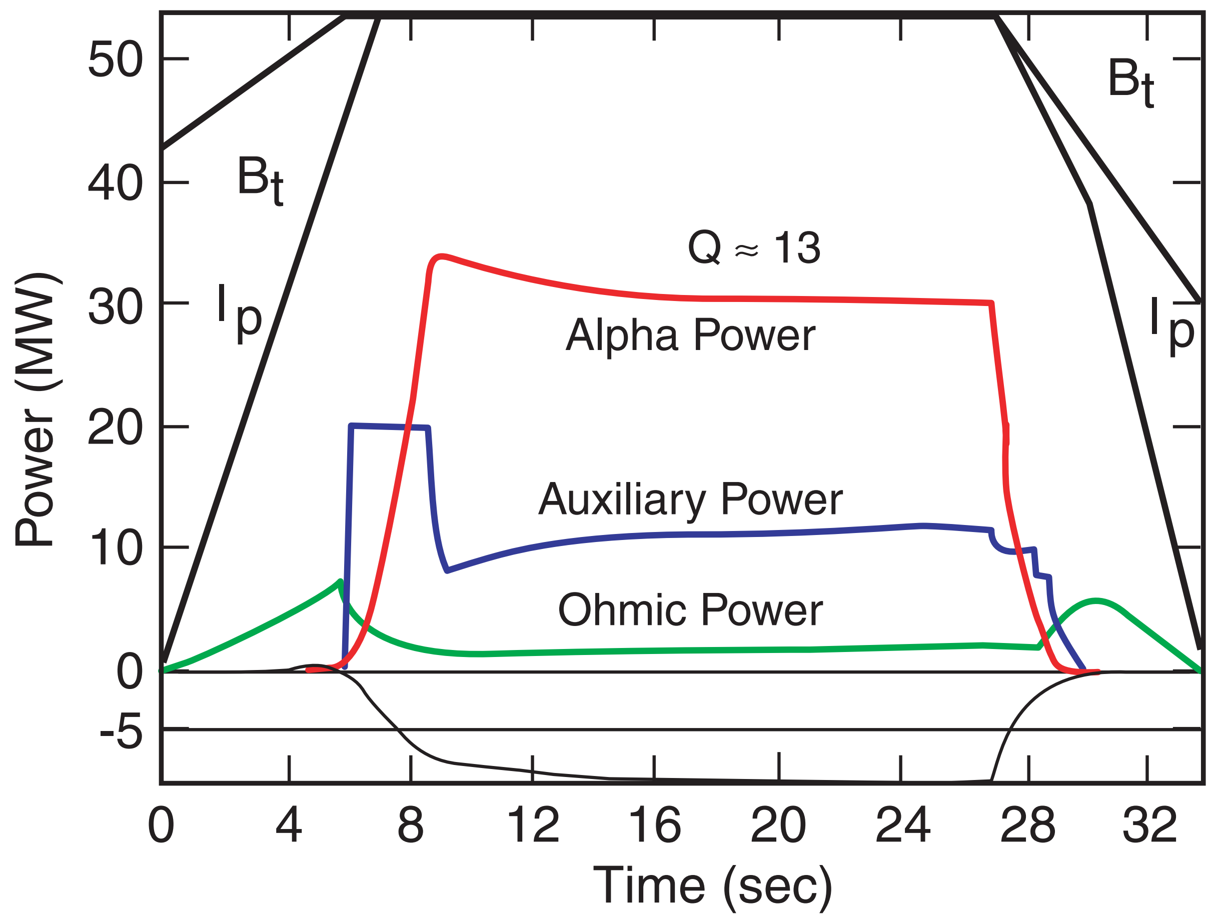
JET H-Mode Data Selected for FIRE-like Parameters



Projections to FIRE Compared to Envisioned Reactors



Simulation of Burning Plasma in FIRE



B = 10 T

I_p = 7.7 MA

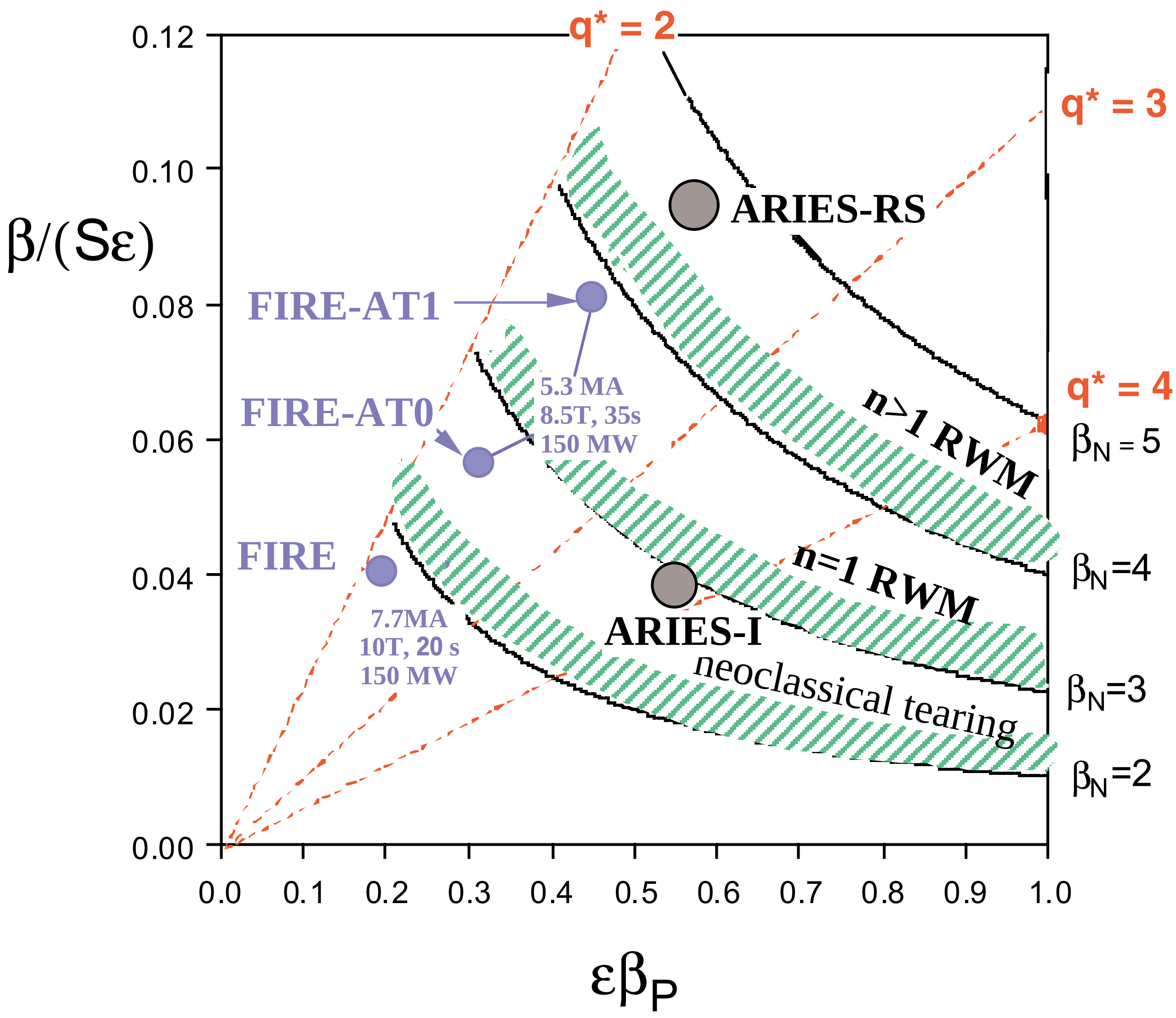
R = 2.14 m

A = 3.6

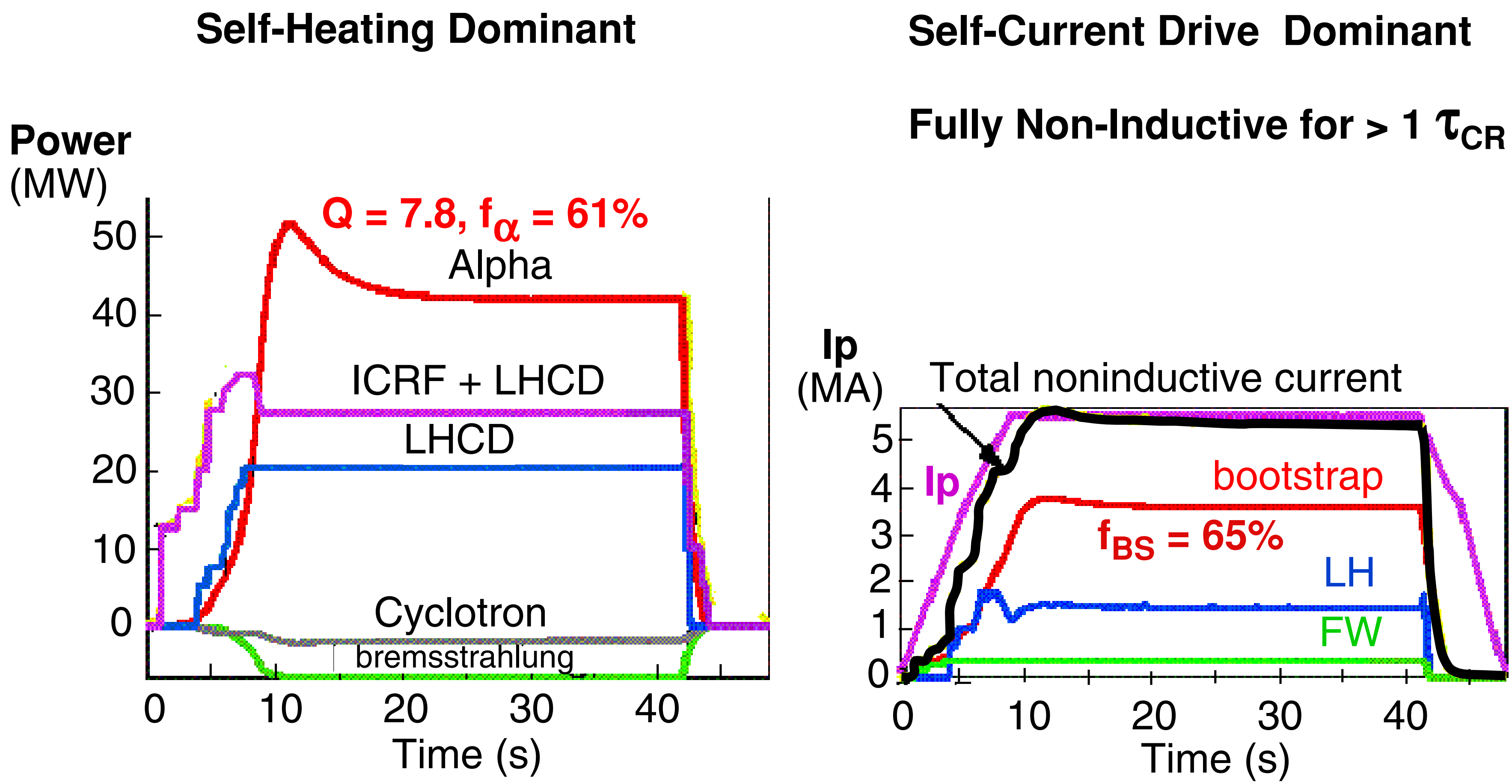
- ITER98(y, 2) with H(y, 2) = 1.1, n(0)/⟨n⟩ = 1.2, and n/ n_{GW} = 0.67
- Burn Time ≈ 20 s ≈ $21\tau_E \approx 4\tau_{He} \approx 2\tau_{CR}$

Q = Pfusion/(Paux + Poh)

FIRE would Test a Sequence of AT Modes



Advanced Burning Plasma Physics could be Explored in FIRE



Tokamak simulation code results for H(y, 2) = 1.6, β_N = 3.5 , would require RW mode stabilization. q(0) = 2.9, q_{min} = 2.2 @ r/a = 0.8, 8.5 T, 5.5 MA

Edge Physics and PFC Technology: Critical Issue for Fusion

Plasma Power and particle Handling under relevant conditions
Normal Operation / Off Normal events

Tritium Inventory Control
must maintain low T inventory in the vessel ⇒ all metal PFCs

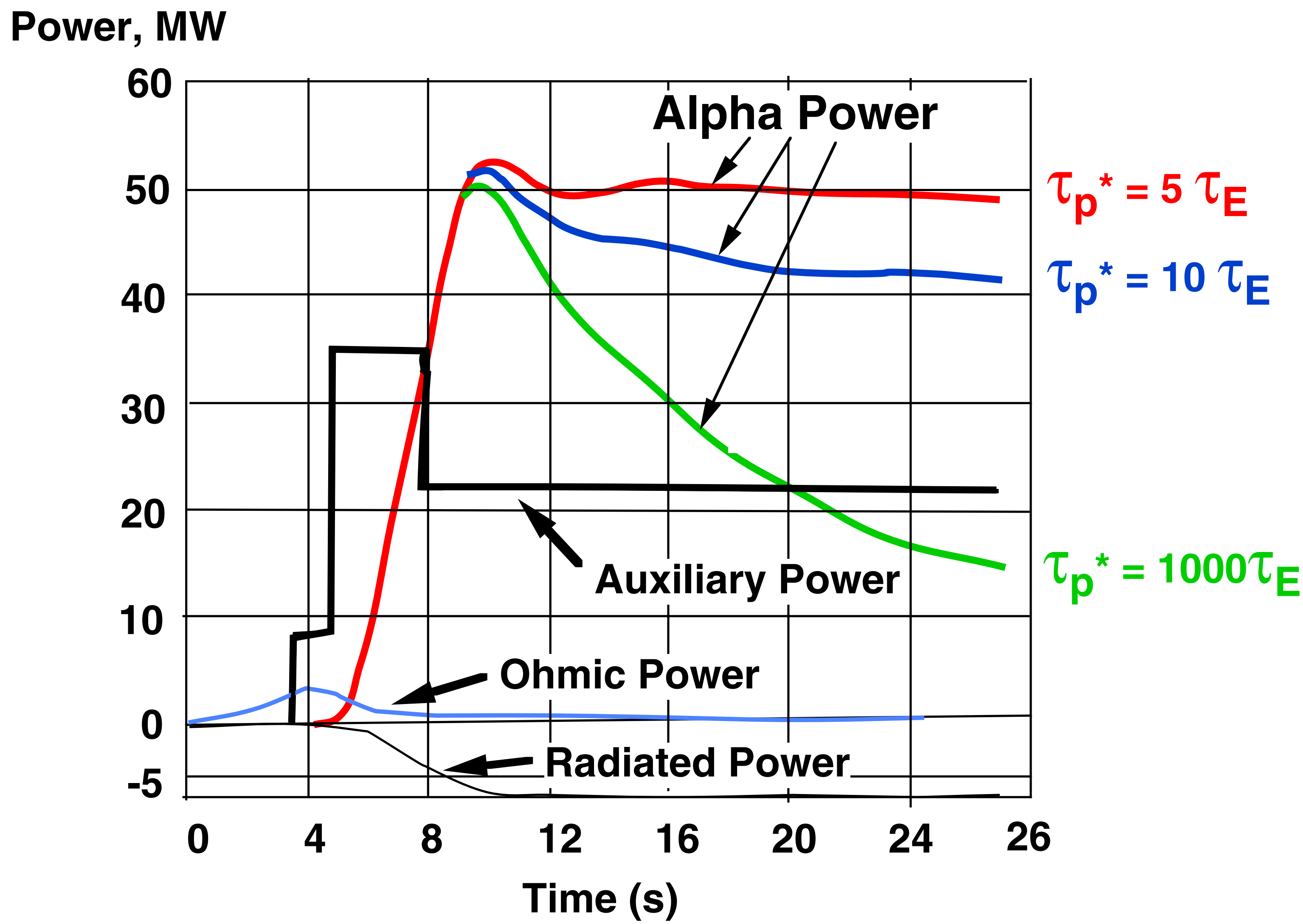
Efficient particle Fueling
pellet injection needed for deep and tritium efficient fueling

Helium Ash Removal
need close coupled He pumping

Non-linear Coupling with Core plasma Performance
nearly every advancement in confinement can be traced to the edge
Edge Pedestal models first introduced in ~ 1992 first step in understanding
Core plasma (low n_{edge}) and divertor (high n_{edge}) requirements conflict

Solutions to these issues would be a major output from a next step experiment.

Helium Ash Removal Techniques Required for a Reactor can be Studied on FIRE

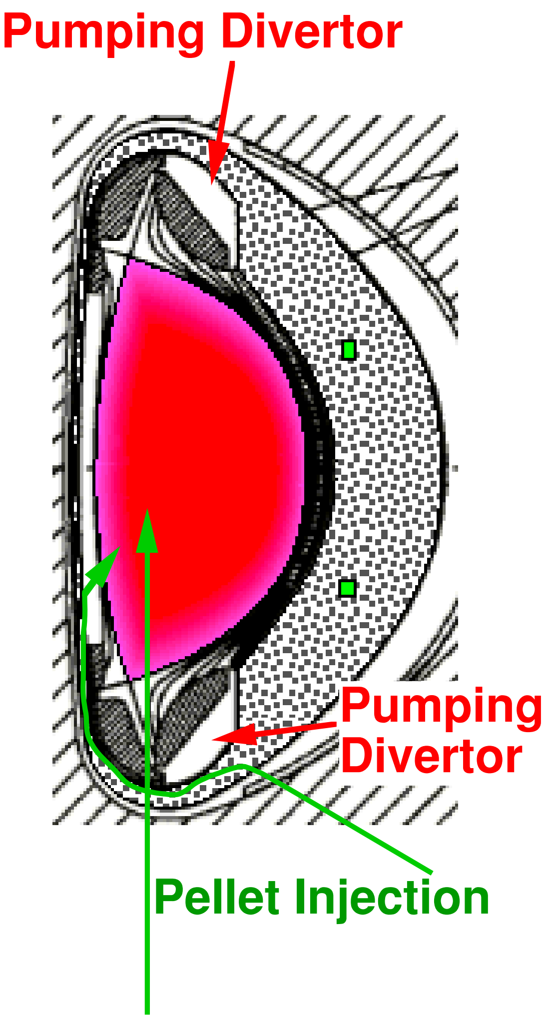


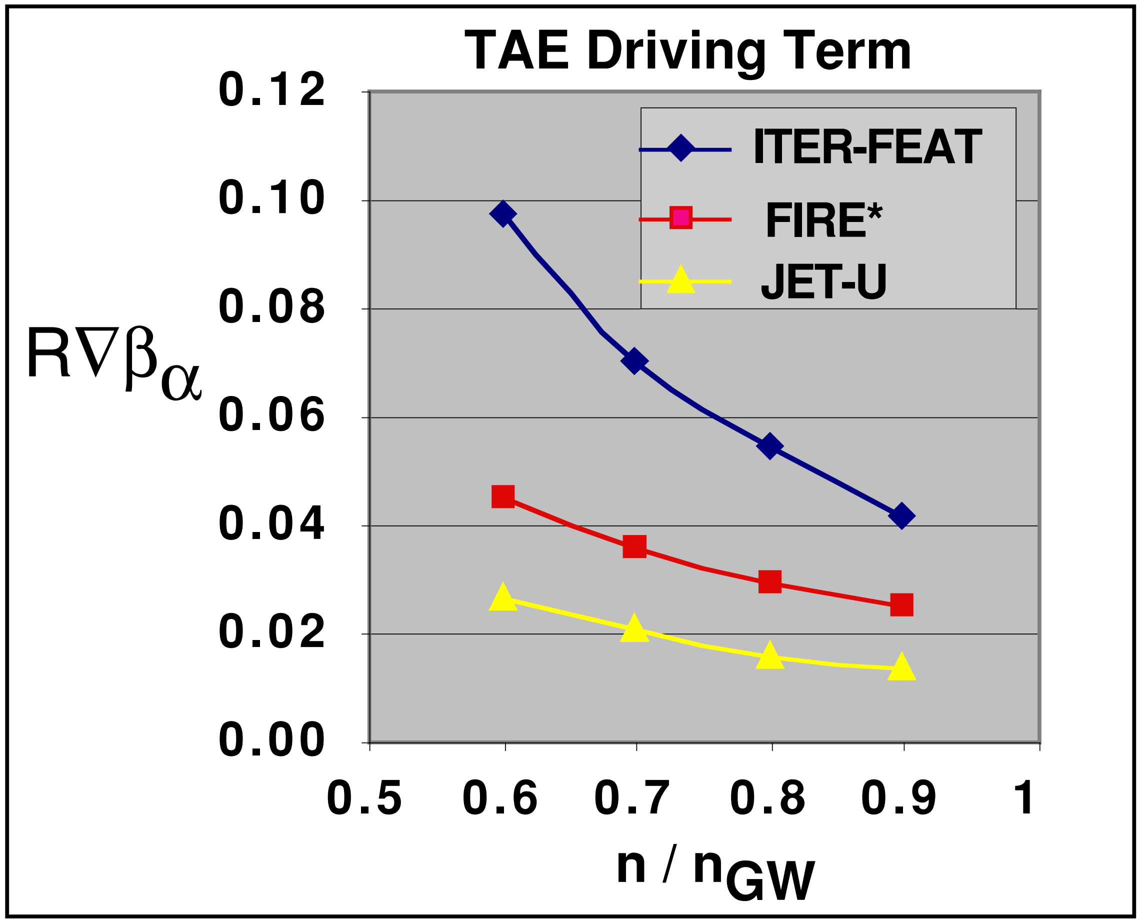
Fusion power can not be sustained without helium ash punping.

TSC/Kessel/21-q.ps

Energetic Particle Drive can be Varied in FIRE Using Divertor Pumping and Pellet Injection

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



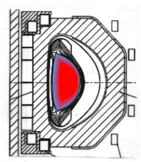


FIRE would Test the High Power Density In-Vessel Technologies Needed for ARIES-RS

Pfusion = ~ 150 MW

Volume = 27 m^3

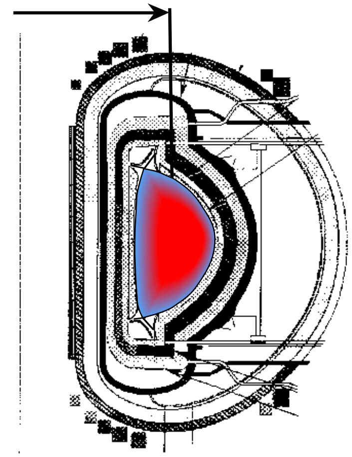
B = 10 T
R = 2.14 m →



FIRE

~ 3X

B = 8 T
R = 5.5 m



ARIES-RS The “Goal”

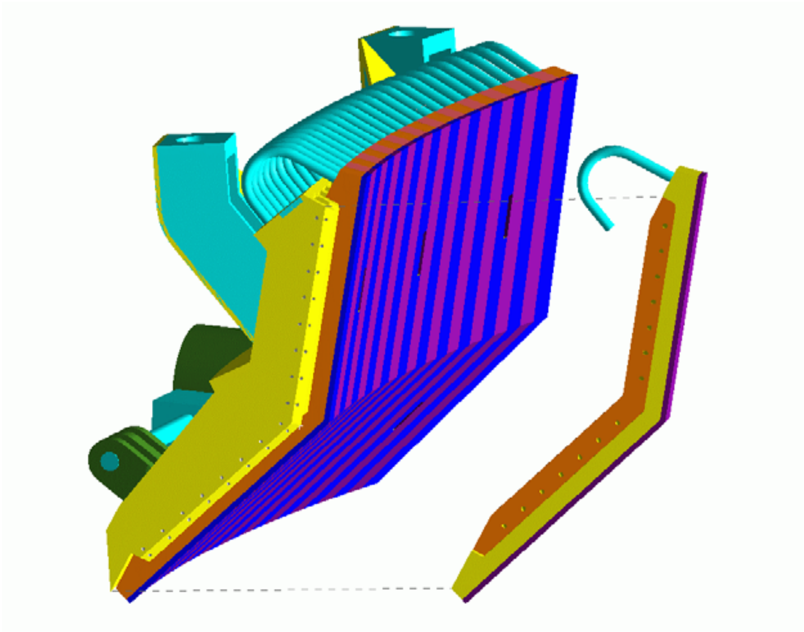
Pfusion = 2170 MW

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

Divertor Module Components for FIRE

Sandia

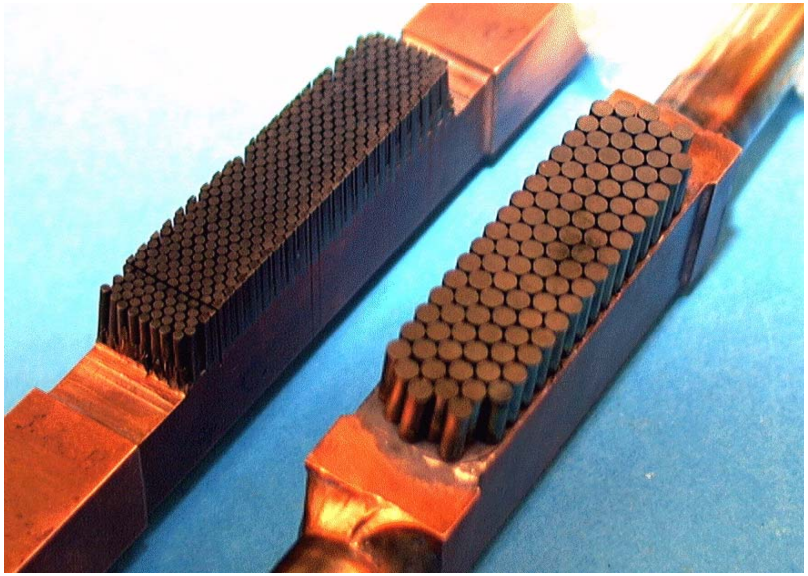


Finger Plate for

Outer Divertor Module

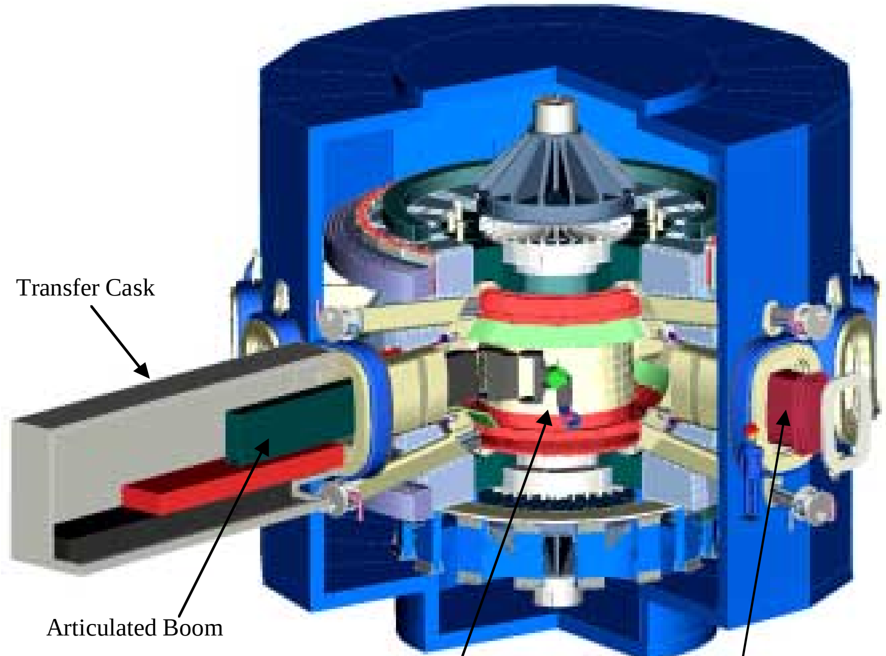
Two W Brush Armor Configurations

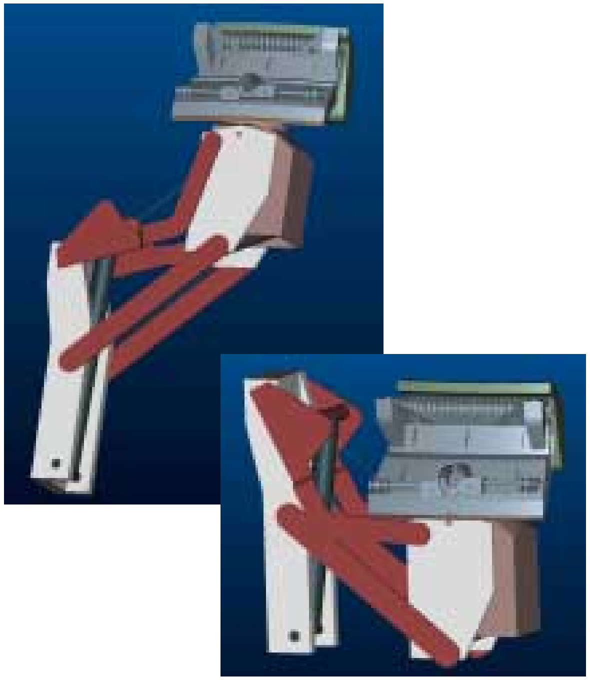
Tested at 25 MW/m^2



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

FIRE In-Vessel Remote Handling System





In-vessel transporter

- Articulated boom deployed from sealed cask
- Complete in-vessel coverage from 4 midplane ports
- Fitted with different end-effector depending on component to be handled
- First wall module end-effector shown

Divertor end-effector

- High capacity (module wt. ~ 800 kg)
- Four positioning degrees of freedom
- Positioning accuracy of millimeters required

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.

- FIRE with a construction cost ~ $1B, has the potential to :

  - address the important burning plasma issues, performance ~ ITER
  - 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 in the U. S.

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

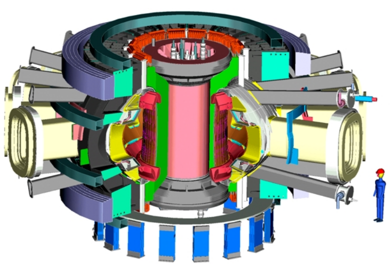
  - Apply recent enhanced confinement and advanced modes to FIRE
  - Understand conditions for enhanced confinement regimes-triangularity
  - Compare DN relative to SN - confinement, stability, divertor, etc
  - Complete disruption analysis, develop better disruption control/mitigation.

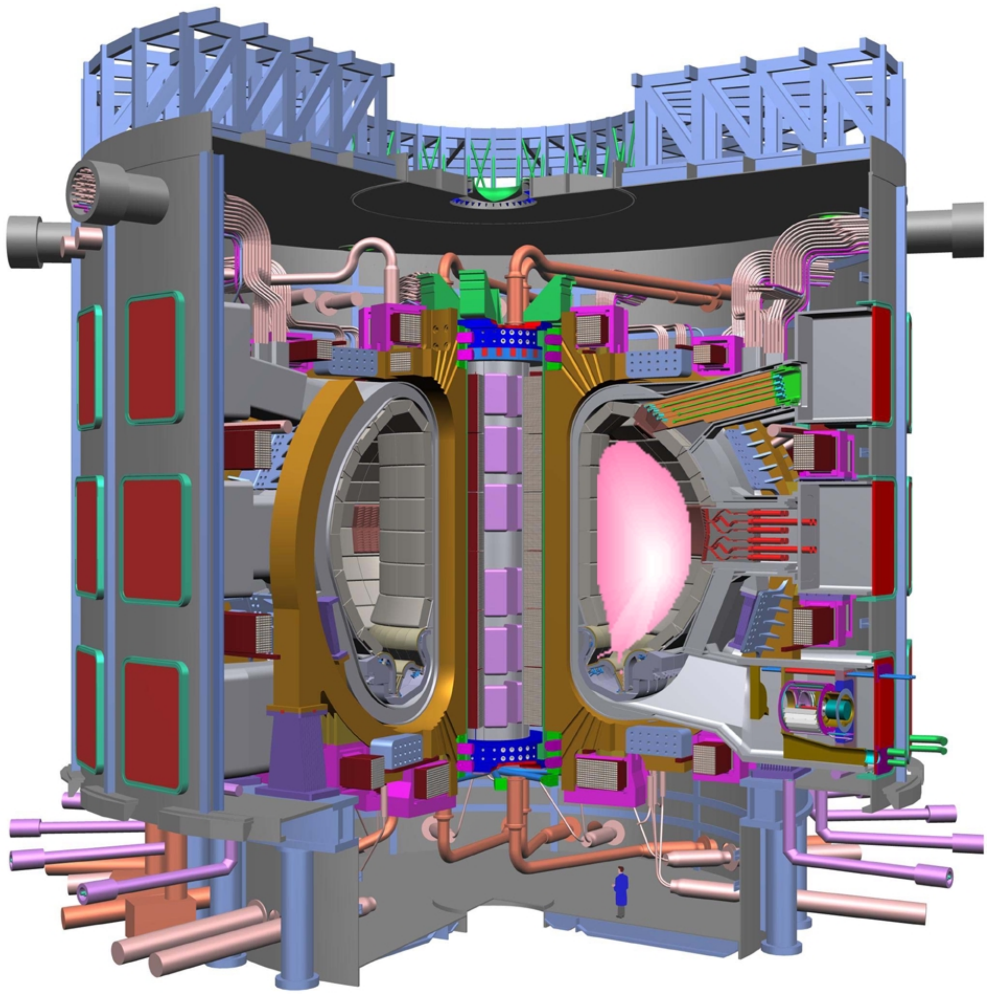
- If a postive decision is made in this year, FIRE is ready to begin Conceptual Design in FY2003 with target of first plasmas ~ 2010.

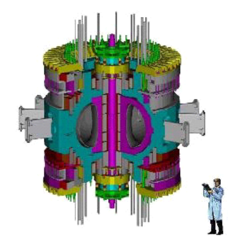
http://fire.pppl.gov

Burning Plasma Physics - The Next Frontier

Three Options
(same scale)







FIRE

US Based
International Modular Strategy

ITER-FEAT

JA, EU or CA Based
International Partnership

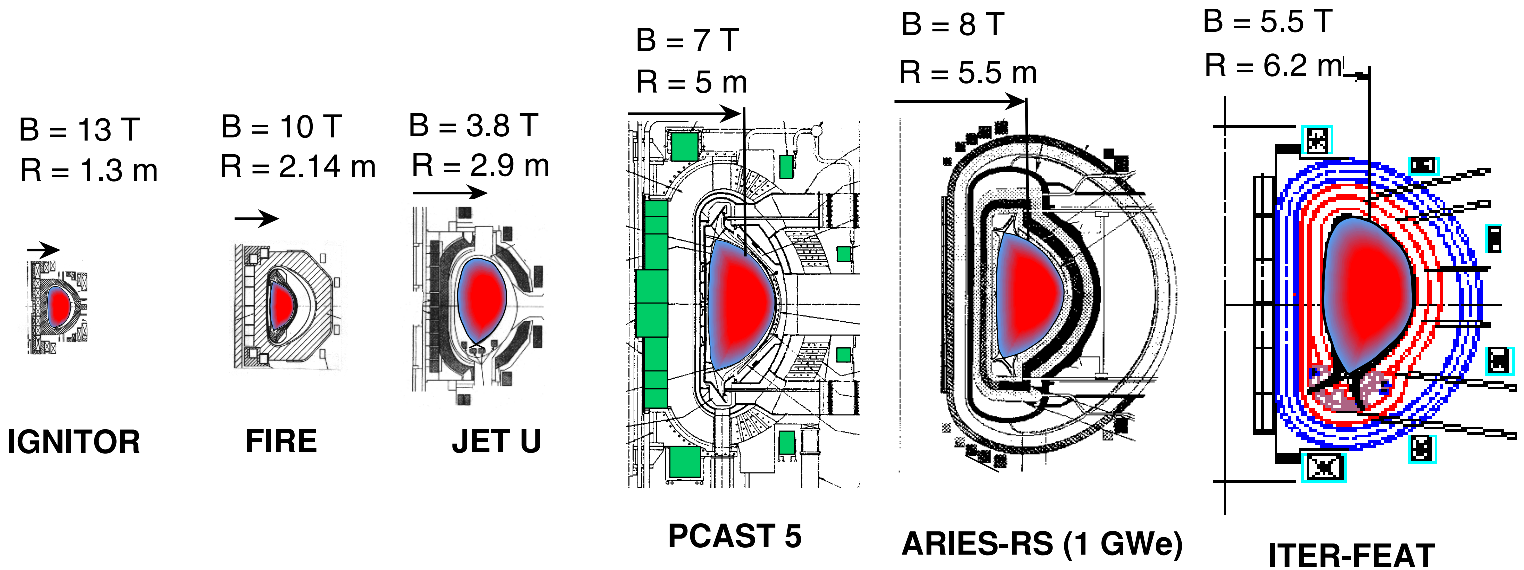
IGNITOR

Italian Based
International Collaboration

FIRE Parameters and Design Goals

	FIRE	ITER-FEAT	ARIES-RS
κ_x/κ_{95}	2.0/1.77	1.85/1.7	2/1.7
δ_x/δ_{95}	0.7/0.4-0.55	0.49/0.33	0.7/0.5
Divertor	DN	SN	DN
R (m)	2.14	6.2	5.5
A = R/a	3.6	3.1	4.0
B (T)	10	5.3	8
I_p (MA)	7.7	15	11.3
$Q = P_{fus}/(P_{oh} + P_{aux})$	10	10	27
Burn Time (inductive) (s)	20	400	steady
Current Redistributions	~2	~2	infinite
P_{fusion}(MW)	150	400	2170
P_{fusion}/Vol (MW/m^3)	5.6	0.5	6.2
Neutron Wall loading (MW/m^2)	2.3	0.5	4
First Wall Thermal Equilib.	no	yes	yes
Divertor Target material	W	C(W?)	W
$P_{fusion} - P_{bremm} /N2\pi R_x$ (MW/m)	1.5	1.4(0.7)	8.1
Div. Target Thermal Equilib.	yes	yes	yes

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

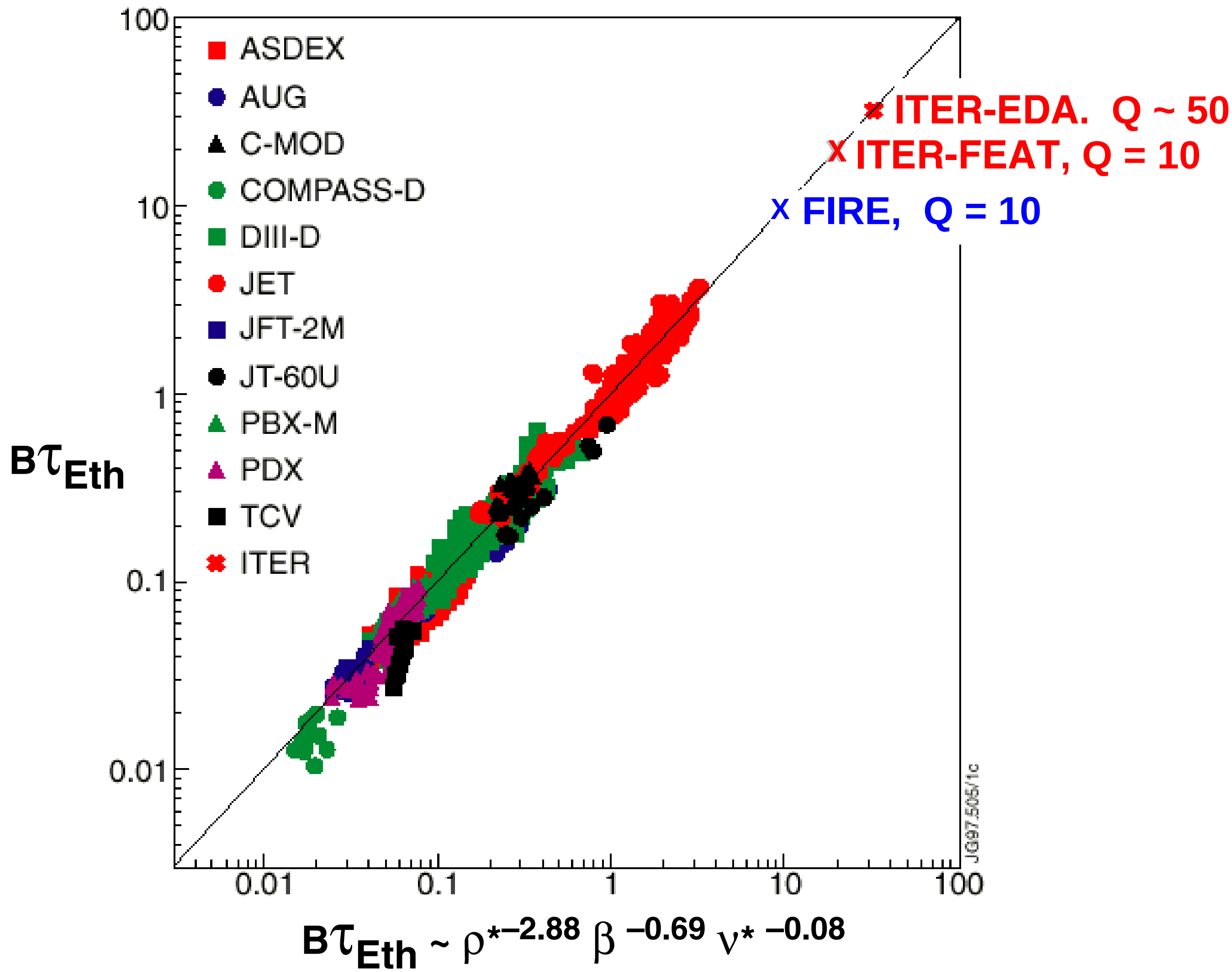
AR RS/ITERs/PCAST/FIRE/IGN

FIRE is a Modest Extrapolation in Plasma Confinement

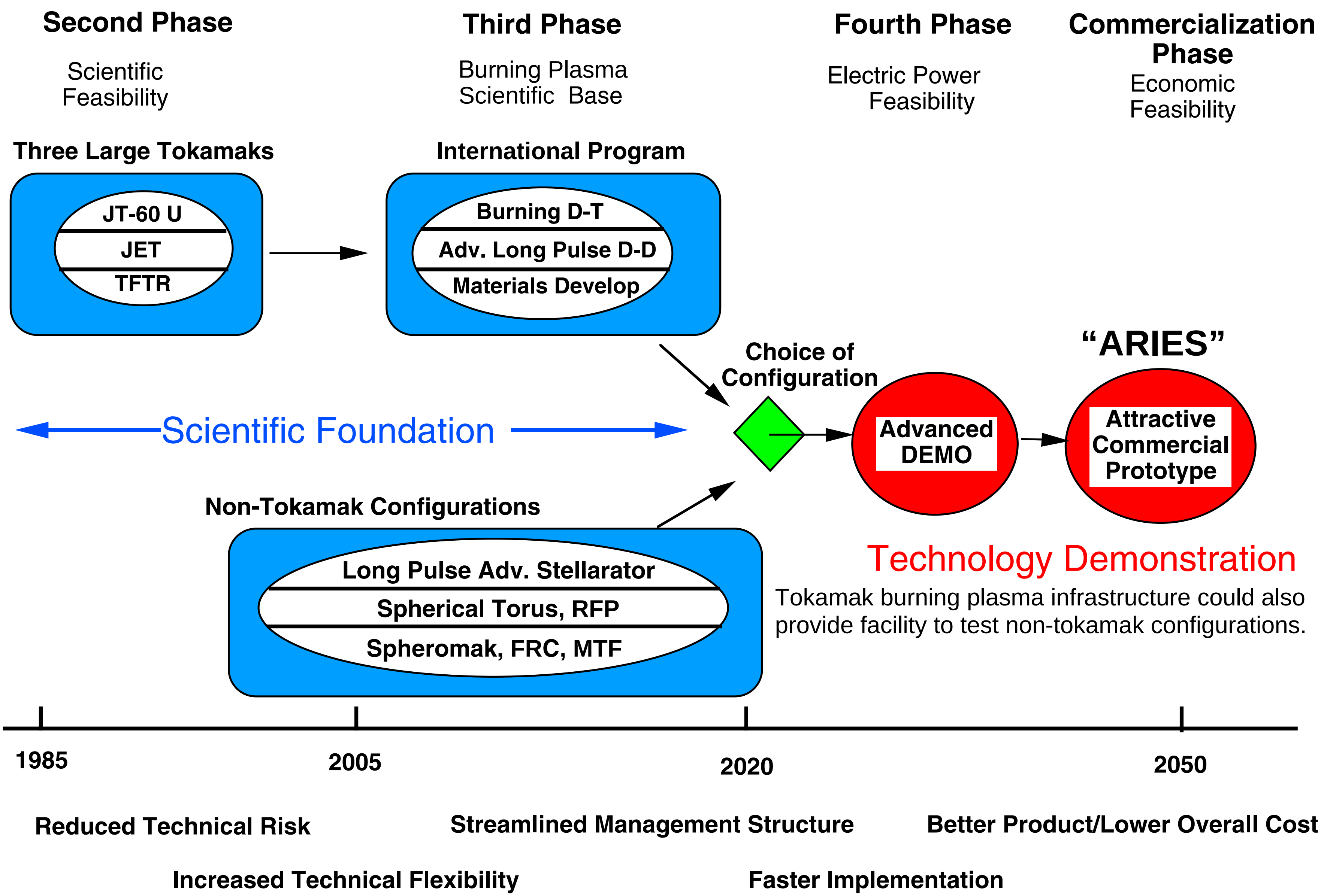
Dimensionless Parameters
$\omega_c\tau = B\,\tau$
$\rho^* = \rho/a$
$\nu^* = \nu_c/\nu_b$
β

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

Kadomtsev, 1975



The Multi-Machine Strategy for Magnetic Fusion



(The overall Multi-Machine Strategy includes IFE)

Timetable for a Major Next Step in Magnetic Fusion

USFY 2001	USFY 2002	USFY 2003	USFY 2004	USFY 2005

ITER Activities and Decisions

- ITER-EDA Complete
- Japan Site offer
- EU Site offer
- Preferred ITER Site Chosen
- Sixth European Framework Programme → Jan 1 2007
- ITER - Final Agreement Signed
- ITER Legal Entity
- ITER Construction Authorization

US Activities and Decisions

- FESAC BP Recommendations
- Snowmass Assessment
- FESAC BP Strategy Panel
- National Academy Review
- DOE Decison CD-0
- DOE Response to Congress per HR-4/S-1766

U.S. Burning Plasma Design Activity - FIRE

Preconceptual Design	Response to Snowmass	Plan	Conceptual Design	Prelim. Design

Plan	Conceptual Design	Prelim. Design

New Initiative in FY 2003?

Burning_Plasa_sched