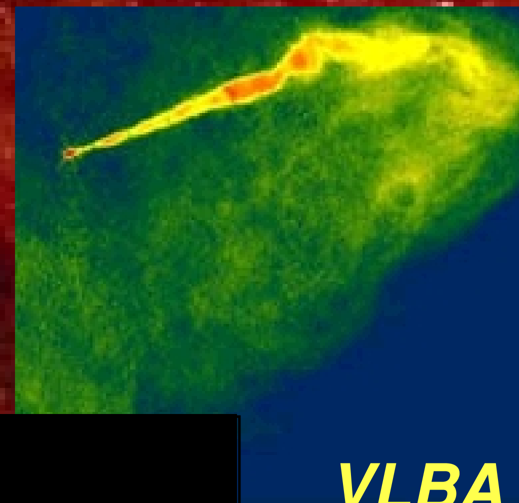
Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science

CHANDRA



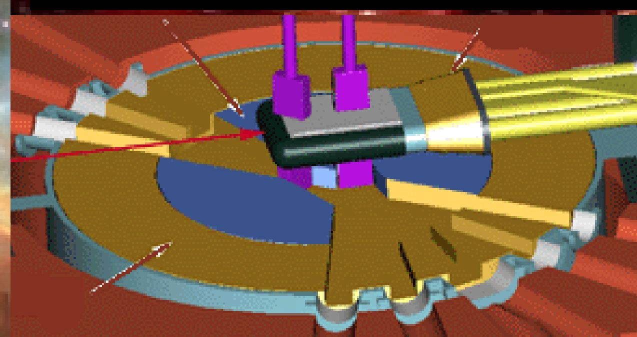
VLBA

NIF

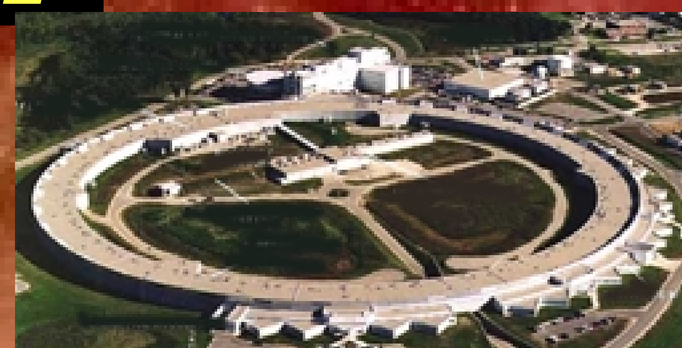
?

MFE

HST (NGST)



SNS



APS

FIRE, A Next Step Option for Magnetic Fusion

Status, Issues and Opportunities

Dale M. Meade

for the FIRE Team

Presented at
FIRE Drill Seminar at General Atomics
La Jolla, CA

April 9, 2002

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
- Burning Plasma Performance Considerations
- Compact High Field Approach - General Parameters
- Advanced Tokamak Longer Pulse Possibilities
- Summary

Recent Activities Impacting a Next Step in MFE

- Energy Authorization Bill (HR 4) passed by the House on August 1, 2001

  1. Calls for strengthening the base fusion sciences program

  2. 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, if it is highly likely to be constructed and cost-effective

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

- National Academy of Science 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

Critical Issues to be Addressed in 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

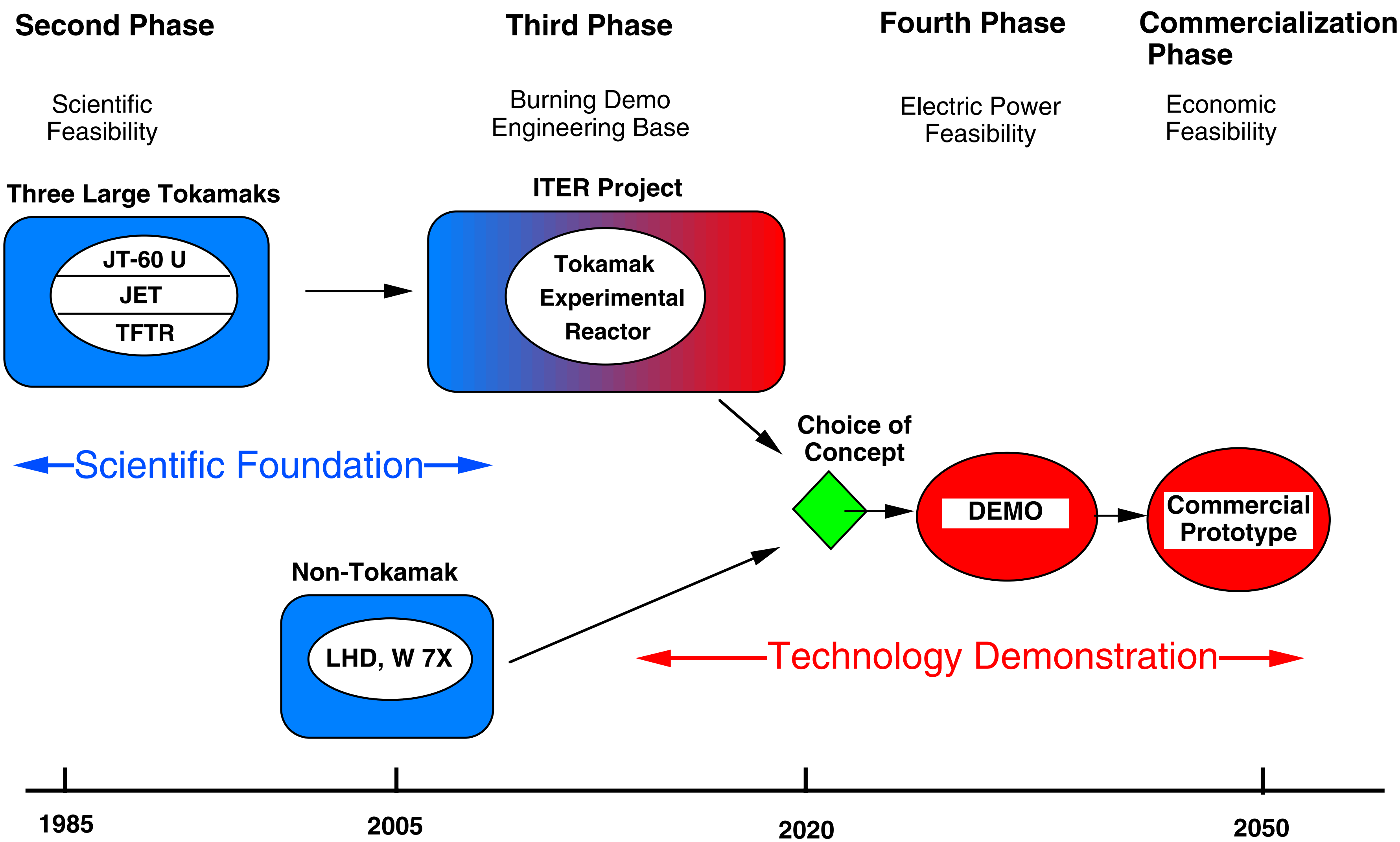
- **Boundary Physics and Plasma Technology** (coupled with above)
  - high particle and heat flux
  - couple core and divertor
  - fusion plasma - tritium inventory and helium pumping

- **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

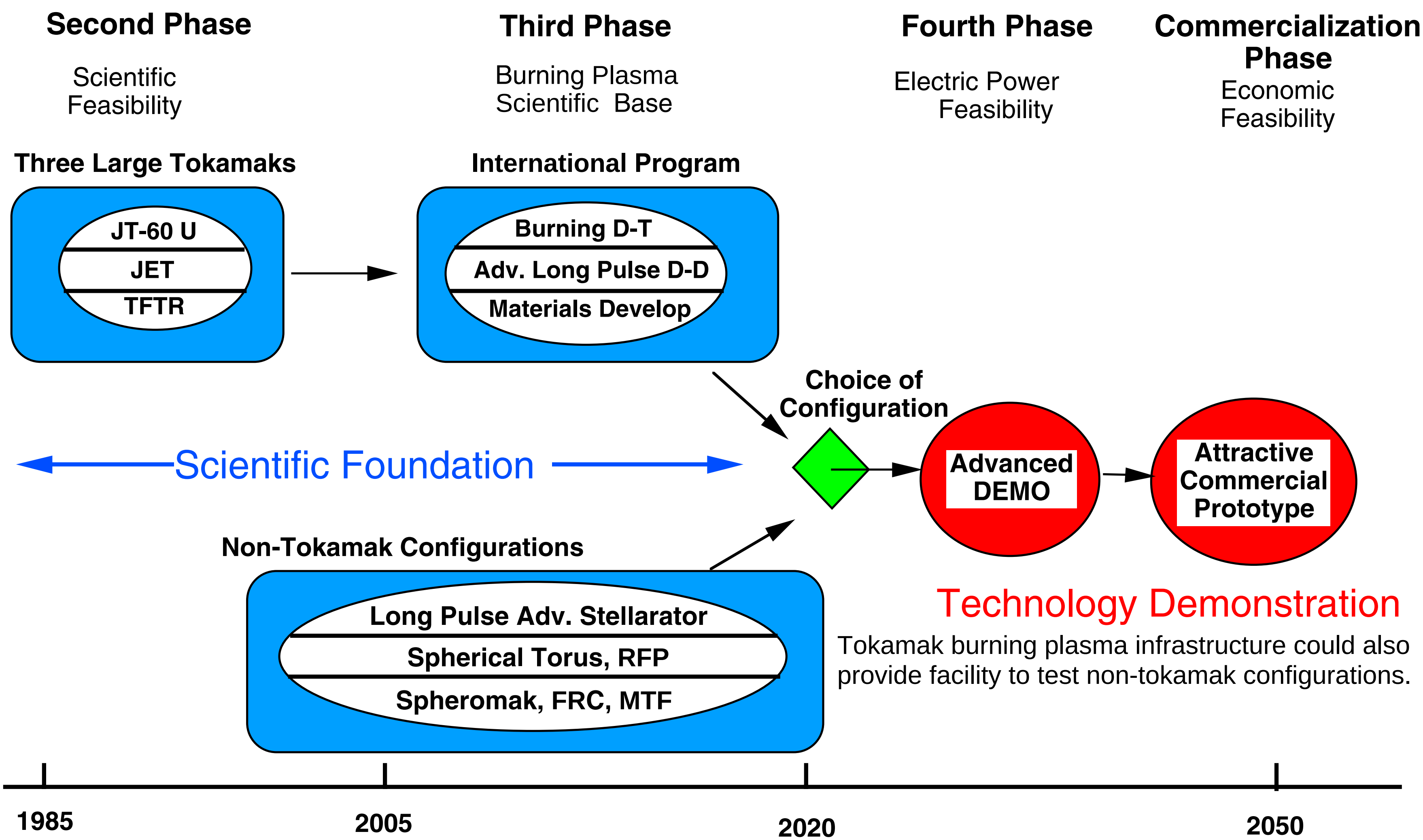
One Step to Two DEMOs [1, 2]



1. Technical Feasibility of Fusion Energy, SubCom of (Japan) Fusion Council for Fusion Development Strategy, May 2000

2. European Plan Airaghi Report, May 2000

The Multi-Machine Strategy for Magnetic Fusion



Reduced Technical Risk

Streamlined Management Structure

Better Product/Lower Overall Cost

Increased Technical Flexibility

Faster Implementation

(The overall Multi-Machine Strategy includes IFE)

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

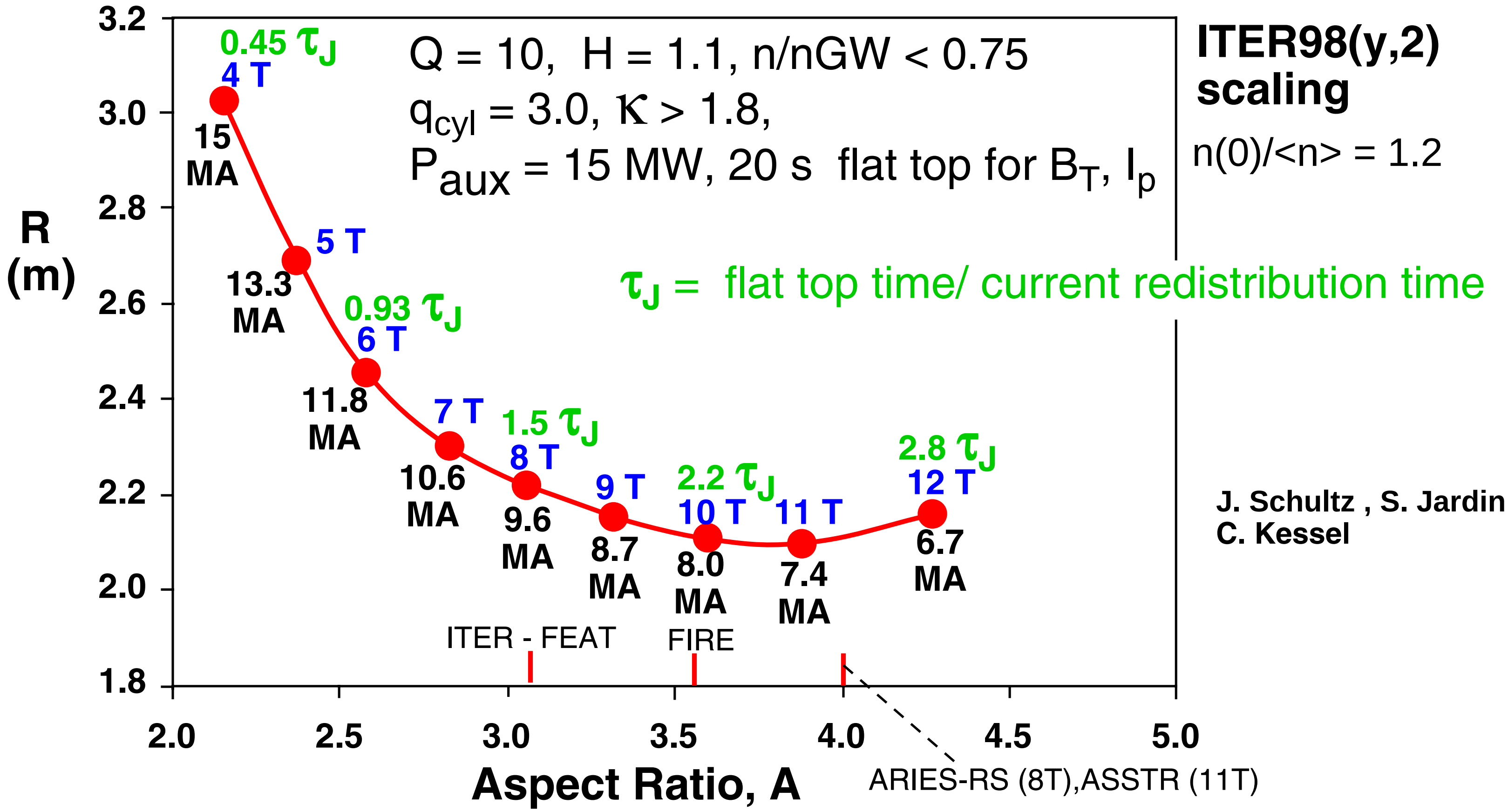
Quasi-stationary

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.

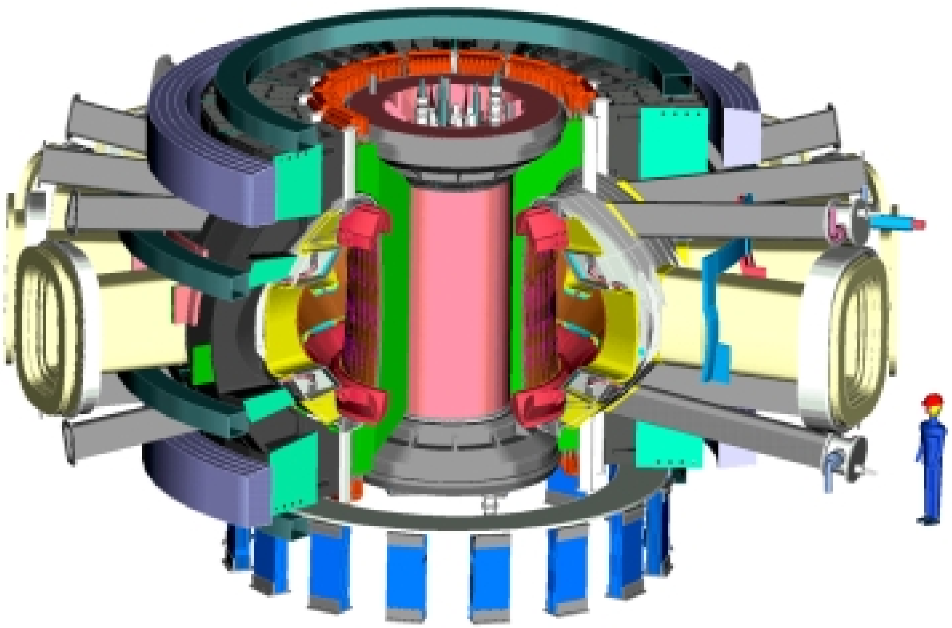
• Seek minimum R while varying A and space allocation for TF/PF coils for a specified plasma performance - Q and pulse length with physics and eng. limits.



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 fusion-dominated plasmas.

CIT + TPX = FIRE

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

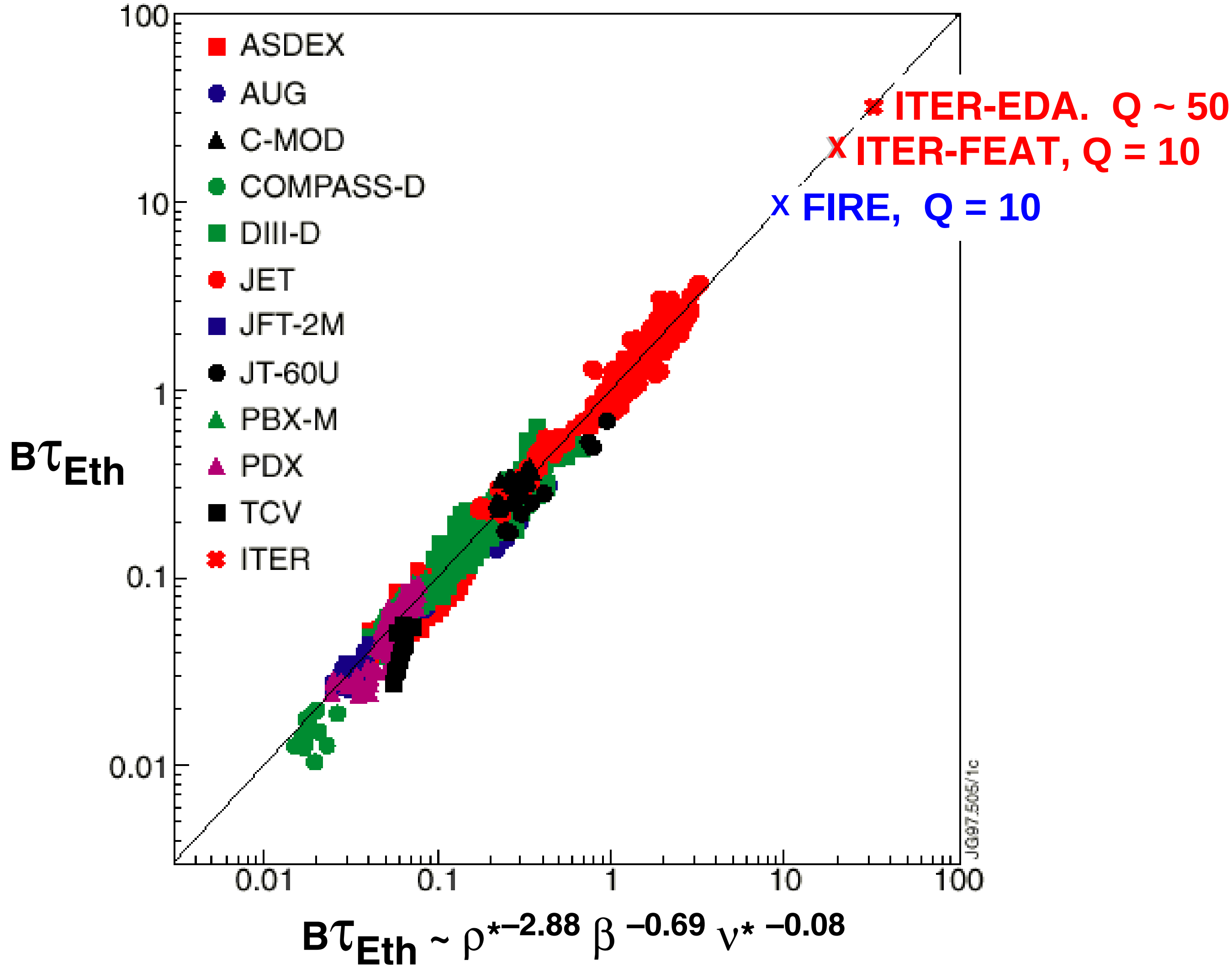
  3. Physics based core transport models
     - gyrokinetic/gyrofluid (PPPL-IFS, GLF 23)
     - multi-mode model
  4. Edge Pedestal and density limit models
- What experimental capabilities or features in a next step experiment are needed to better resolve and understand transport issues?

FIRE is a Modest Extrapolation in Plasma Confinement

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

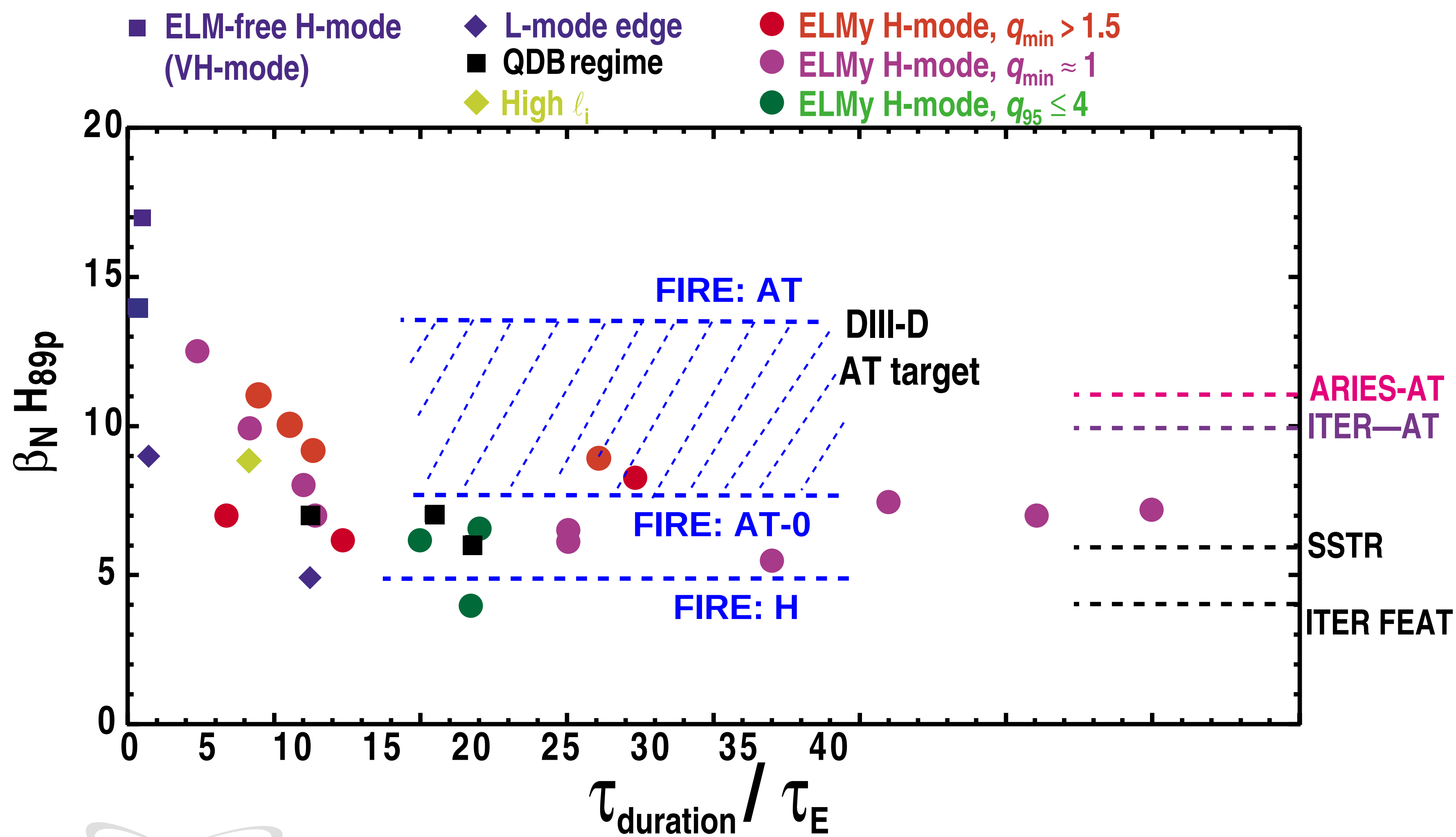
Similarity Parameter
$B\,R^{5/4}$

Kadomtsev, 1975



Potential Operating Modes for Burning Plasma Experiments

- Advanced performance found in many operating regimes



079—02/TST/wj

From Taylor et al

Guidelines for Estimating Elmy H-Mode 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

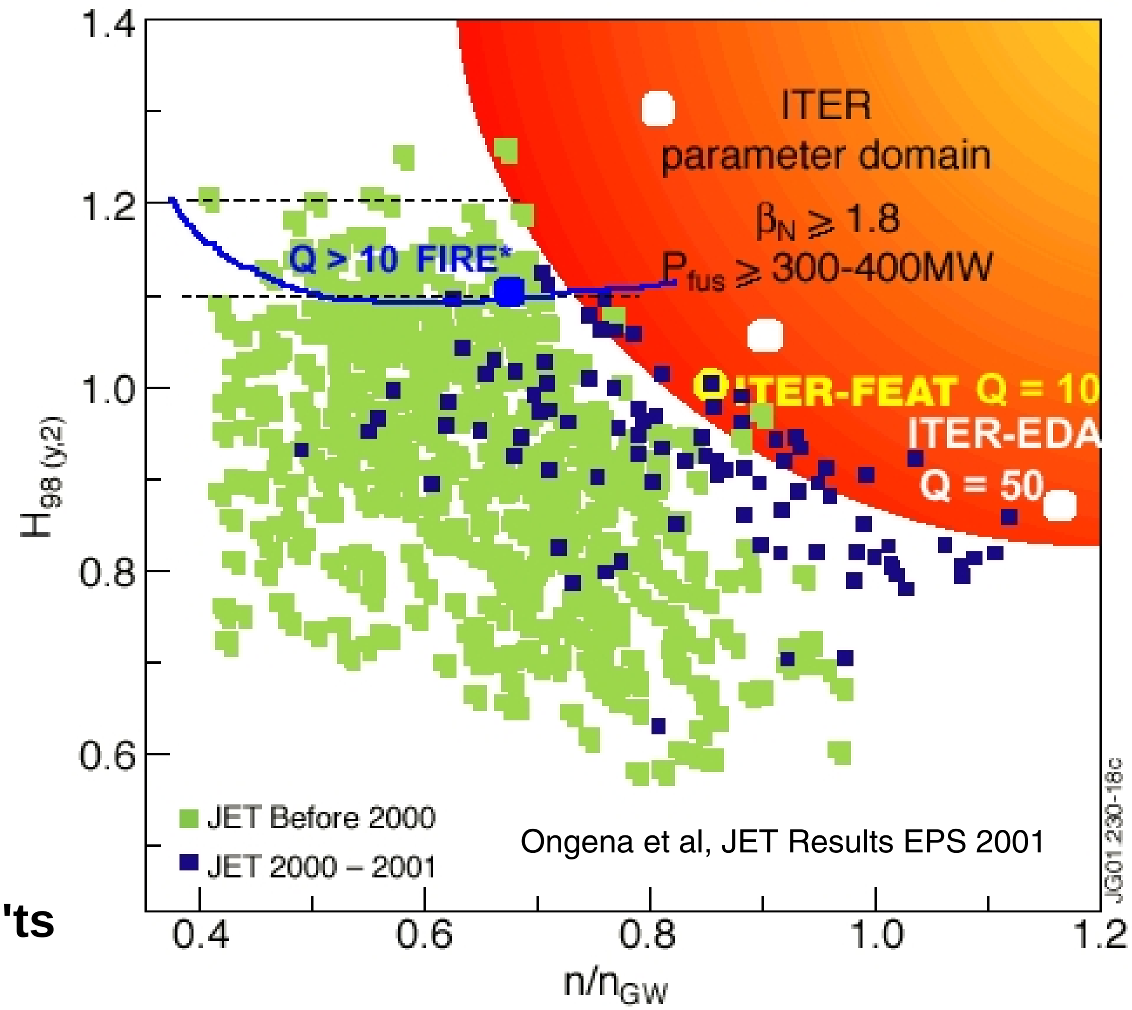
$$Pth \geq (2.84/Ai)\ n_{20}^{0.58}\ B^{0.82}\ Ra^{0.81}$$, same as ITER-FEAT

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.

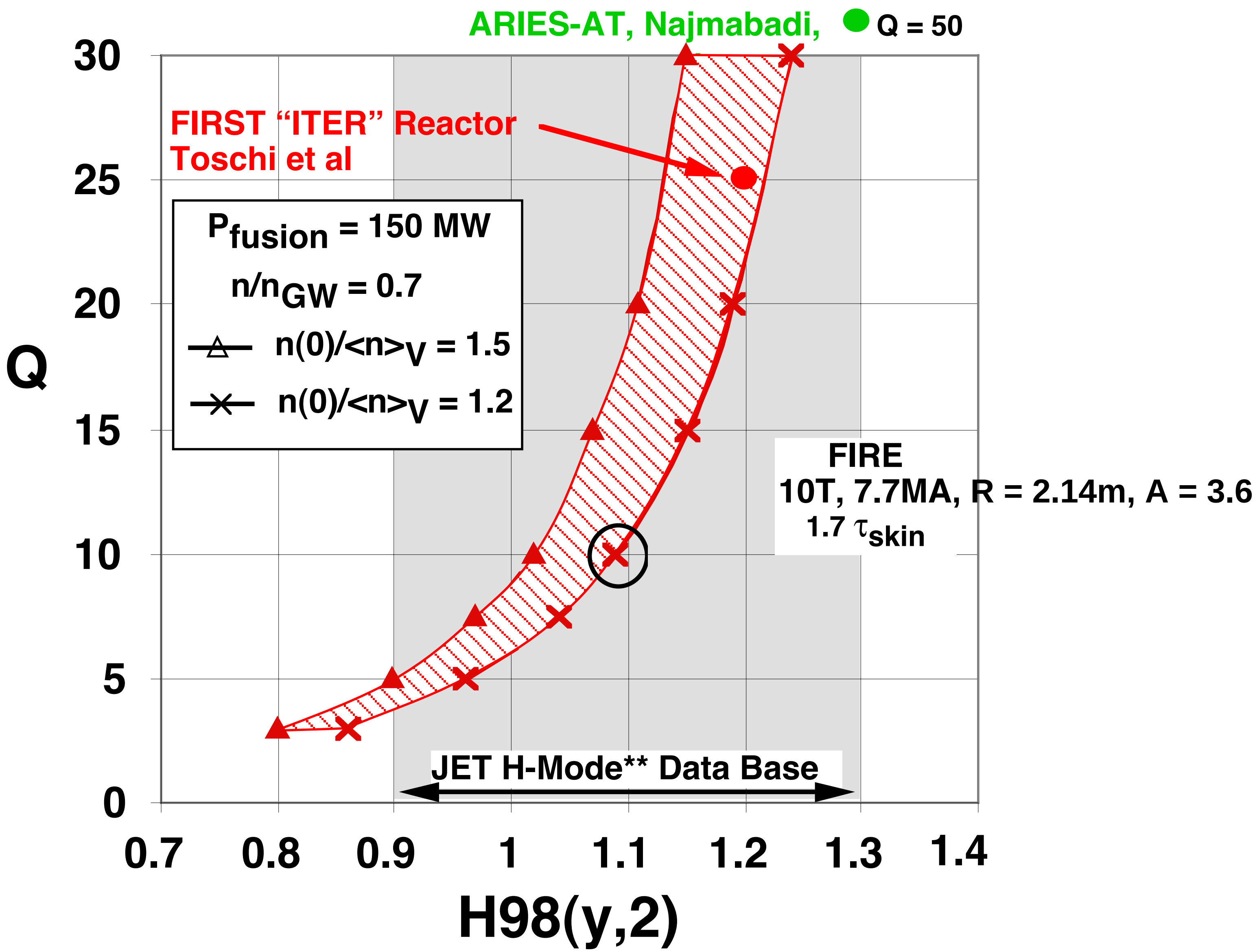
FIRE's Operating Density and Triangularity are Near the Optimum for the Elmy H-Mode

- **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**

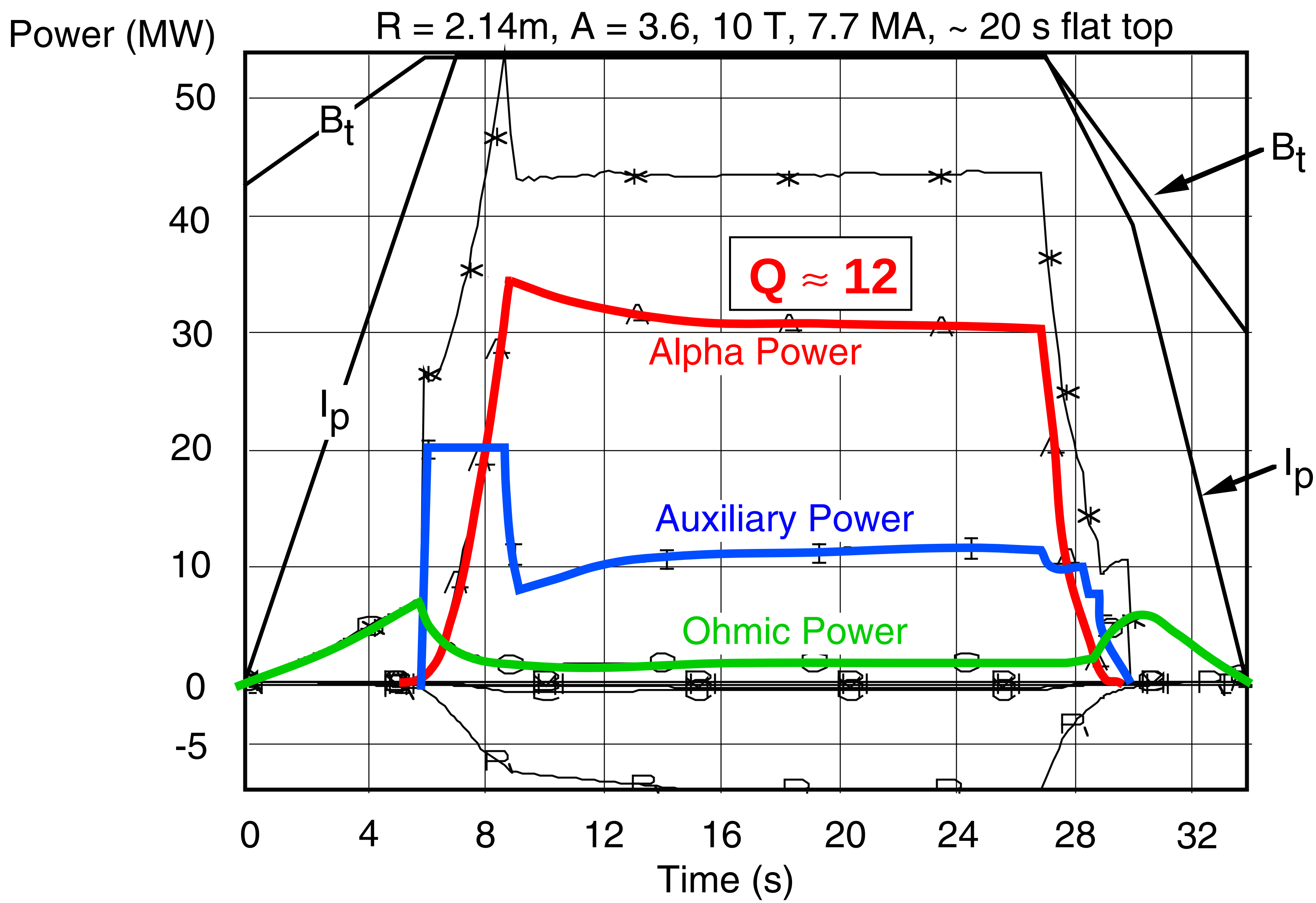


Cordey et al, H = function (δ, n/n_{GW}, n(0)/<n>) EPS 2001

Projections to FIRE Compared to Envisioned Reactors



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

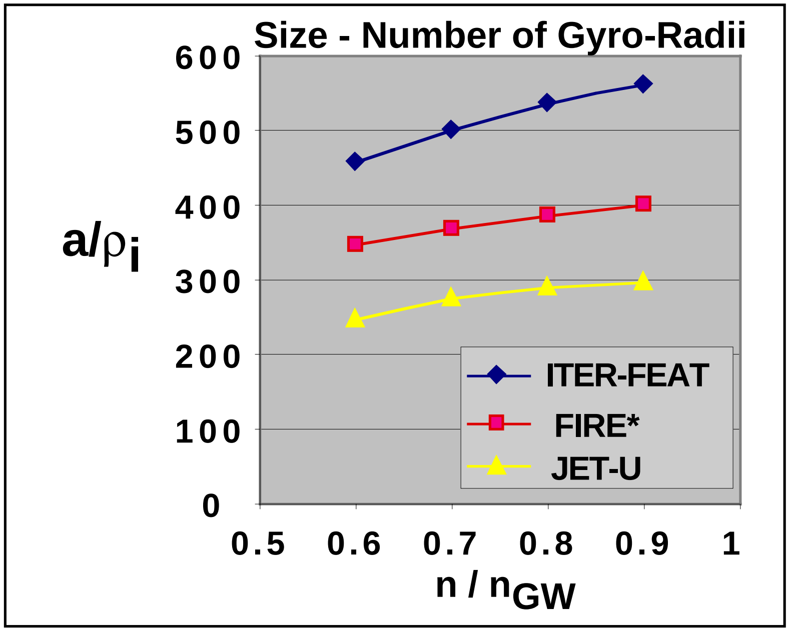


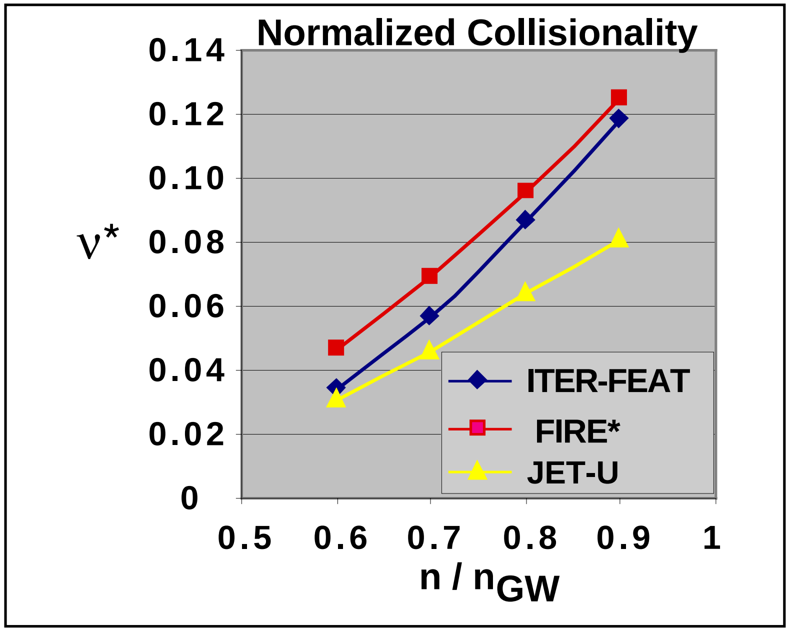
- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and $n/n_{GW} = 0.67$
- Burn Time ≈ 20 s ≈ 21 $\tau_E \approx 4\ \tau_{He} \approx 2\ \tau_{skin}$

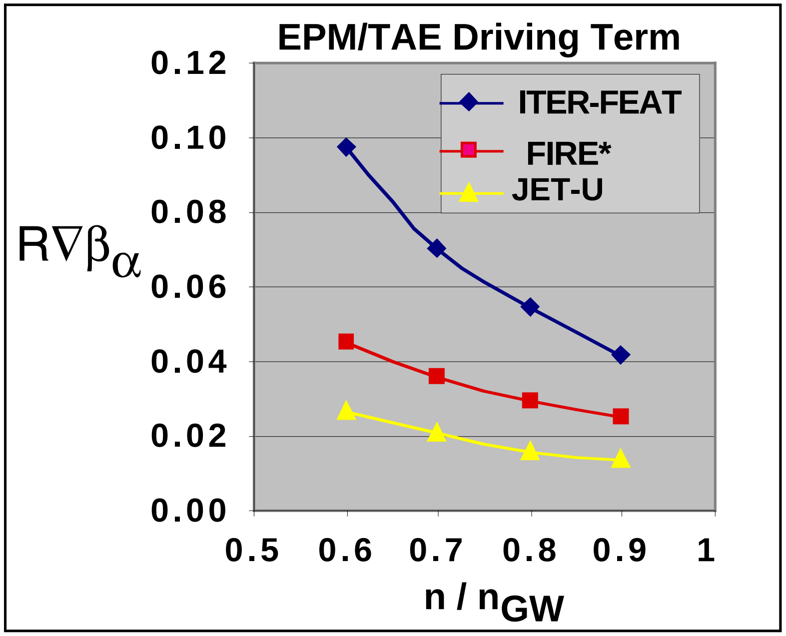
Q = Pfusion/(Paux + Poh)

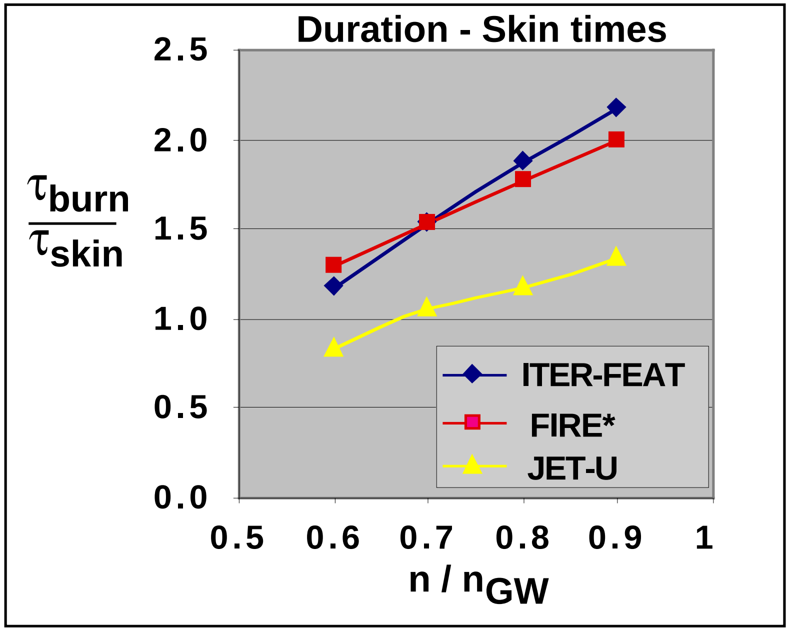
Parameters for H-Modes in Potential Next Step D-T Plasmas

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









Improved Performance Projections Using the GLF23 Transport Model for Proposed Burning Plasma Experiments

J.E. Kinsey[1], G.M. Staebler[2], and R.E. Waltz[2]

- H-Mode Pedestal Requirements

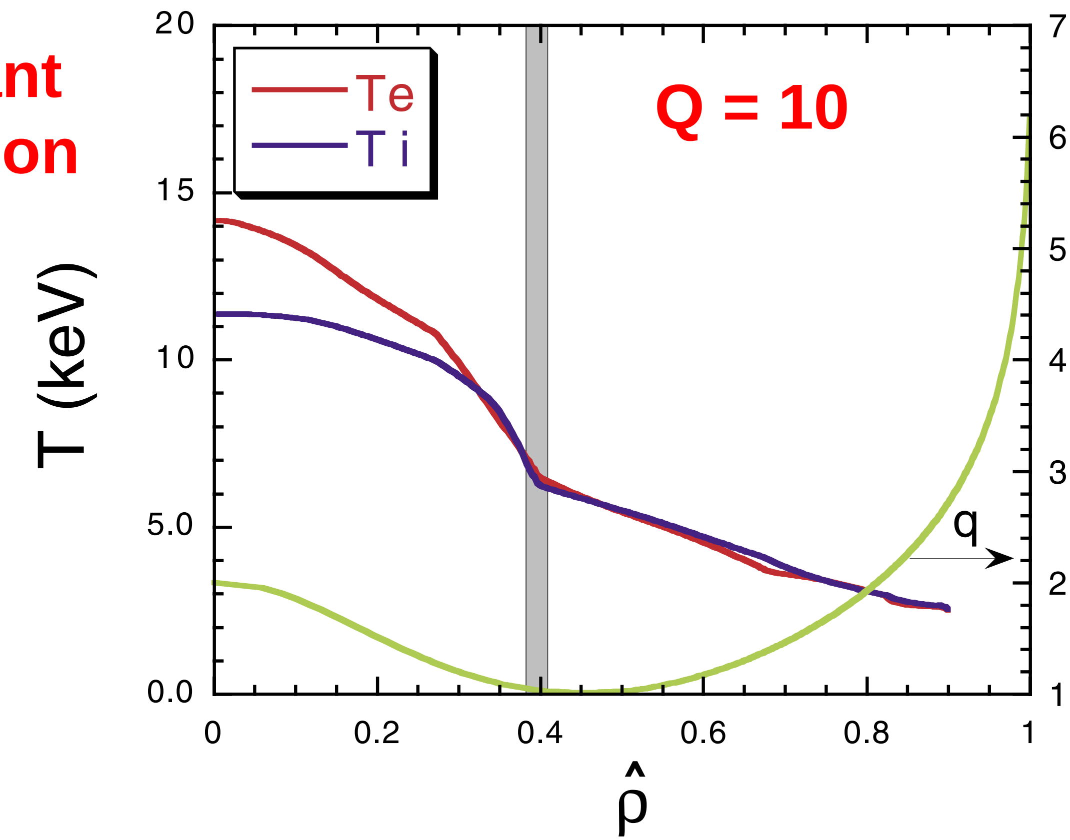
Device	n/n_G	P_{aux} (MW)	T_{ped} (Q=10)	T_{ped} (Q=10, n/n_G=0.85)
IGNITOR	0.50	10.0	2.8	2.0
FIRE	0.65	11.4	3.1	2.5
ITER-FEAT	0.85	40.0	4.5	4.5

- The prediction of pedestal temperatures is critical issue for all BP experiments.

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.***

Reactor relevant no beam rotation



Kinsey, Waltz and Staebler
UFA BPS Workshop 2

Advanced Tokamak Scenarios for the Fusion Ignition Research Experiment

C. Kessel

Princeton Plasma Physics Laboratory

General Atomics, April 9, 2002

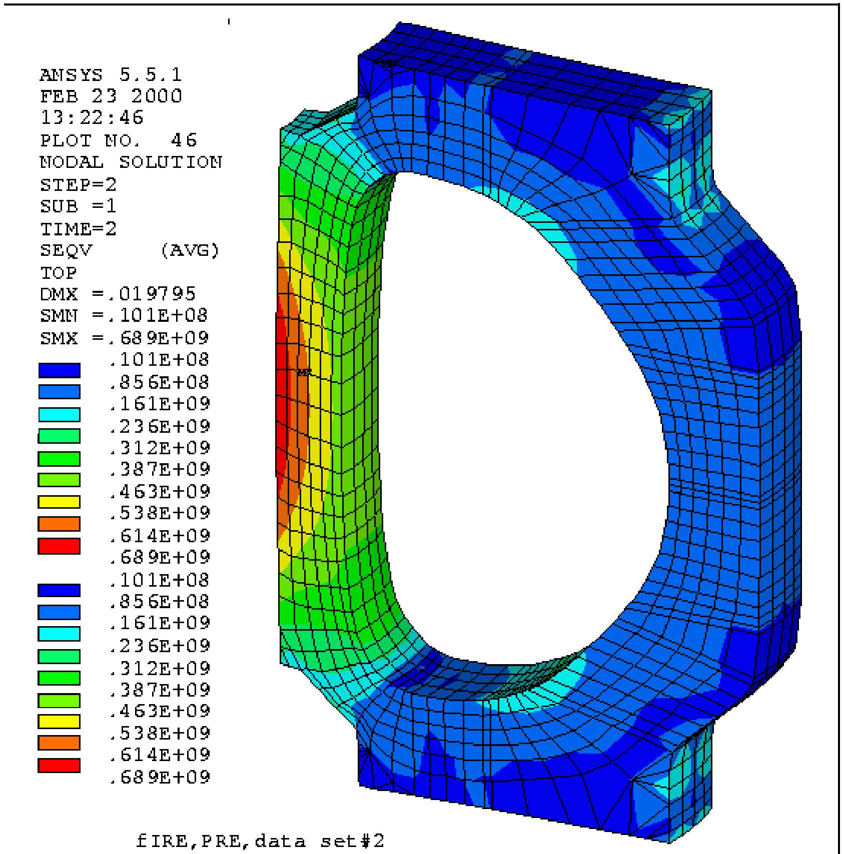
Basic Parameters and Features of FIRE

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, 4.6 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

TF coils are being Designed with Added Margin.

- **FIRE Baseline R = 2.14 m, a = 0.595 m B = 10 T, Ip = 7.7 MA, 20 s flat top, Pfus = 150 MW**
- **Wedged TF/compression ring BeCu (C17510) inner leg**
- **The peak conductor VM Stress of 529 MPa for 10 T (7.7 MA) is within the static allowable stress of 724 MPa**

  (Allowable/Calculated = 1.3)



FIRE TF Precharge Von Mises Stress (MPa) (EOF is less) With Tierod Removed

TF Coil Von Mises Stress Contours at 12 T

TF Conductor Material for FIRE is “Essentially” Available

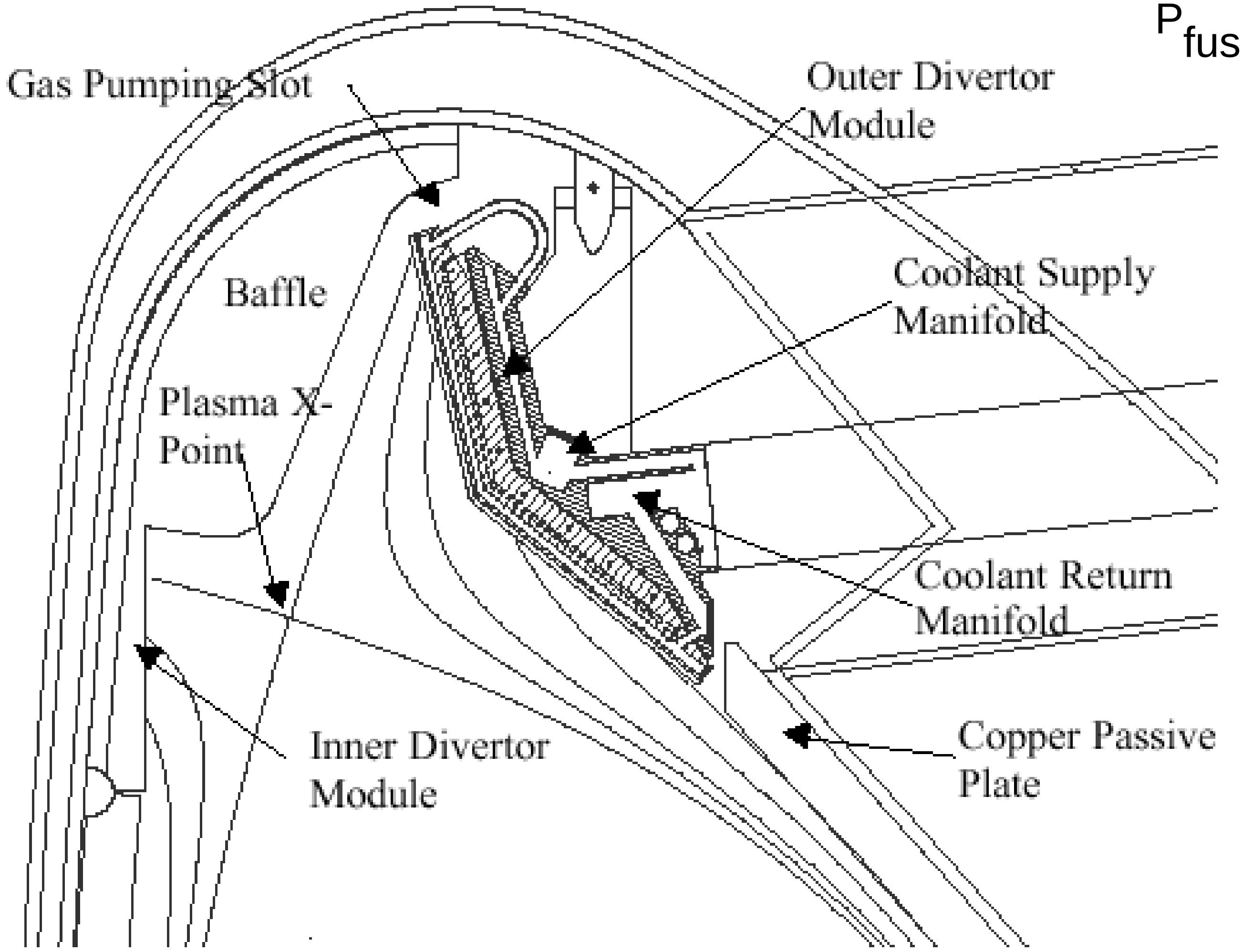
- BeCu alloy C 17510 - 68% IACS is now a commercial product for Brush Wellman.

- A relatively small R&D program is needed to assure that the plates will be available in the properties and sizes required.

The plate on the right was manufactured for BPX

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

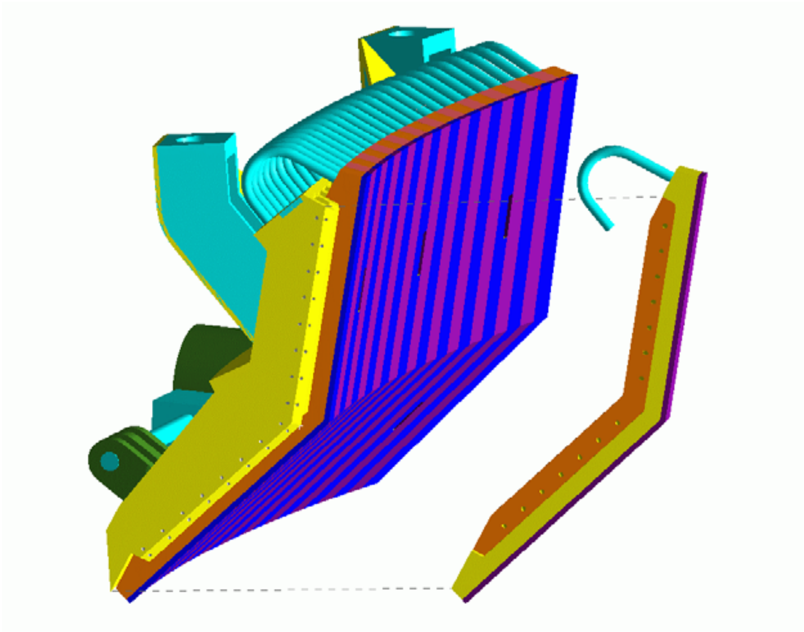
P_{fusion} < 200 MW



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

Divertor Module Components for FIRE

Sandia

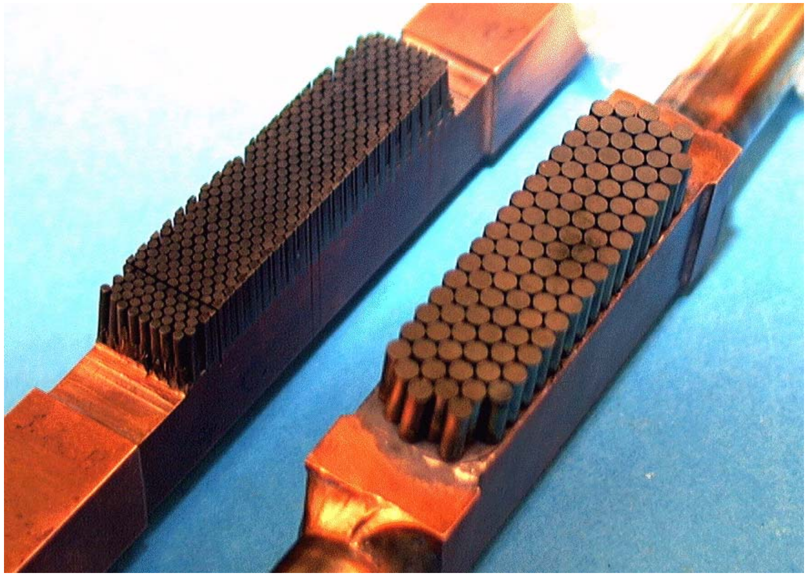


Finger Plate for

Outer Divertor Module

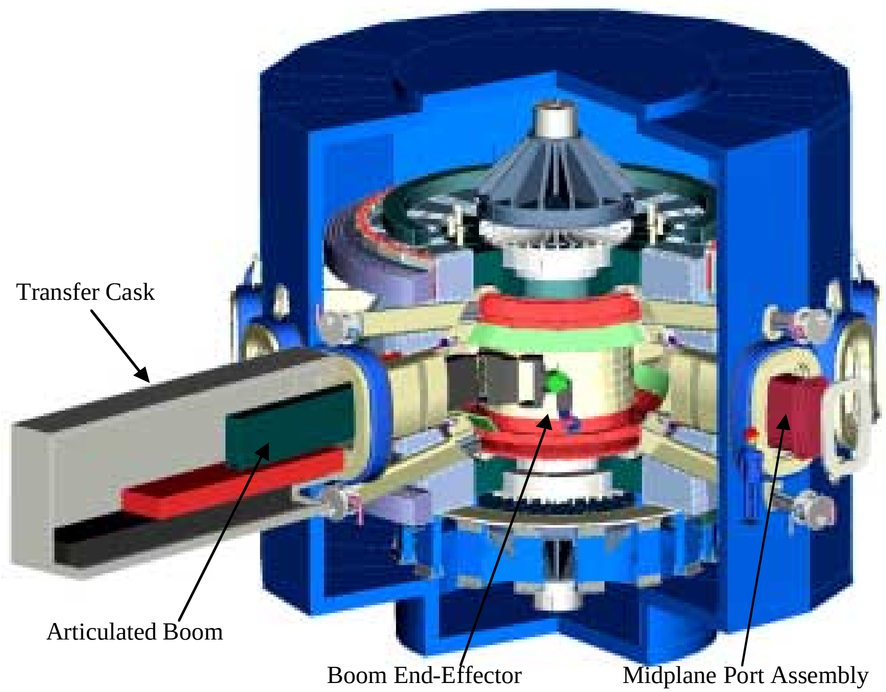
Two W Brush Armor Configurations

Tested at 25 MW/m^2



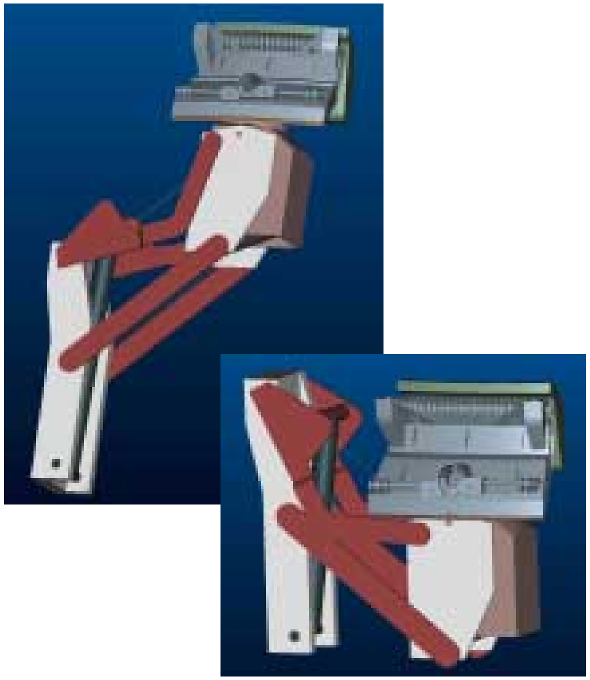
Carbon targets used in most experiments today are not compatible with tritiun inventory requirements of fusion reactors.

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

Diagnostics and Physics Operations

- Diagnostic – access, preliminary set and layout, issues
- Operating Regimes and Plasma Control-
- Remote Maintenance -
- Tritium Inventory –
- Pulsed Repetition Time -
- Operating Plan – similar to BPX plan

FIRE would have Access for Diagnostics and Heating

(and Advanced Tokamak Stabilization Systems)

~ 25% of first wall for ports

An Update on FIRE Diagnostics

- Reminder of proposed FIRE parameters
- Recent Considerations of Diagnostic Integration
- Assessment Grid for Diagnostics:
  - Diagnostics Integration
  - Physics/Diagnostics

………………………………………………………………….

- Proposed Measurement Specifications for FIRE Physics Studies
- Proposed FIRE Diagnostics (table shown at 1st ITPA Meeting)
- Draft Diagnostic Port Assignments

Diagnostics proposed for FIRE (1)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Magnetic Measurements			
Plasma current	√	Rogowski Coils	All magnetics inside vacuum vessel
Plasma shape and position	√	Flux/voltage loops	Very high radiation environment and high
Shape, position & MHD	√	Saddle coils (inc. locked-mode)	temperature apply for all magnetics
	√	Discrete Br, Bz coils	Very little space behind first wall/divertor
Plasma pressure	√	Diamagnetic loops	
Disruption-induced currents	√	Halo current sensors	
Current Density Profiles			
Current density for most of profile	√	Motional Stark effect	Requires neutral beam. Two views may give Er
		FIR polarimetry	Most sightlines radial; poor coverage in radial plane
Current density in edge		Li-beam polarimetry	Requires Lithium beam; integration issue
Electron Density			
Core electron density profile	√	Thomson scattering	Tangential laser, imaging view required by small plasma size
		FIR multichannel interferometer/polarimeter	Most sightlines radial; poor coverage in radial plane; tangential polarimeter
X-point/divertor density profiles		Thomson scattering	Design integration into side ports with divertor/first wall
Edge, transp. boundary profile		mm-wave reflectometer	
Edge density profile		Fast-moving probe	
Divertor density variation along separatrix		Multichannel interferometer	Complex integration with divertor/baffle; Dynamic range may make this impossible
Divertor plate density		Fixed probes	RIED may affect probe insulation

Diagnostics proposed for FIRE (2)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Electron Temperature			
Core electron temperature profile	√	Thomson scattering	Tangential laser, imaging view required by small plasma size
		ECE heterodyne radiometer	
		ECE Michelson interferometer	Provides best calibration for ECE diagnostice
X-point/divertor temperature profiles		Thomson scattering	Design integration into side portswith divertor/first wall
Edge temperature profile		Fast-moving probe	
Divertor plate electron temp.		Fixed probes	RIED may affect probe insulation
Ion Temperature			
Core ion temperature profile	√	Charge exchange spectroscopy	Requires neutral beam
		Imaging x-ray crystal spect.	Full radial coverage would require close-in curved crystal; detector noise issue?
		Neutron camera spectroscopy	Full coverage difficult; spatial res. Poor
Divertor ion temperature		UV spectroscopy	
Plasma Rotation			
Core rotation profile	√	Charge exchange spectroscopy	Requires neutral beam: balanced views for vθ needed
		Imaging x-ray crystal spect.	Full radial coverage would require close-in curved crystal; detector noise issue?
Relative Isotope Concentration			
Density of D and T concentrations in core	√	Charge-exchange spectroscopy	Requires neutral beam
		Neutron spectroscopy	Can DD neutrons be discriminated from DT and TT neutrons?

Diagnostics proposed for FIRE (3)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Radiation			
Zeff,visible bremsstrahlung	√	Visible bremsstrahlung array	
Core hydrogen isotopes, low-Z impurities		Visible filterscopes	
Divertor isotopes and low-Z impurities	√	Divertor filterscopes	
Core low-Z impurities		Visible survey spectrometer	
		UV survey spectrometer	
Divertor low-Z impurities and detachment	√	Multichord visible spectrometer	Very little space to develop sightlines
High-Z impurities		X-ray pulse height analysis	Single sightline, detector noise
Divertor impurities		UV spectrometer	Access issue into divertors
Total radiation profile		Bolometer arrays	Mounting and radiation-hardness of bolometers are challenges
Total light image		Visible TV imaging	
MHD and Fluctuations			
Low-frequency MHD	√	Discrete Br, Bz coils	Very little space behind first wall/divertor
		Saddle coil for locked-mode	
		Neutron fluctuation dets.	
High-frequency MHD, TAE, etc.	√	High-frequency Mirnov coils	HF-coils behind tile-gaps, little space
Core density fluctuations		Mm-wave reflectometers	
		Beam emission spectroscopy	Requires neutral beam
Core electron temp. fluctuations		ECE grating polychromators	
Neutron Measurements			
Calibrated neutron flux	√	Epithermal neutron detectors	Calibration difficult with significant shielding
Neutron energy spectra		Multichannel neutron camera	Difficult to get wide spatial coverage

Diagnostics proposed for FIRE (4)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Alpha-particle Measurements			
Escaping alpha-particles/fast-ions		Faraday cups/scintillators at first wall	Much development needed to handle heat loads and signal transmission
		IR TV imaging	Only gives information about total loss location
Confined thermalizing alphas/spatial distribution		α-CHERS	Requires neutral beam, very high throughput optics
Confined alpha-particles' energy distribution		Collective scattering	Need development to optimize wavelength/ spatial resolution; assume mm-wave
Spatial redistribution of alphas		Li-Pellet charge exchange	Needs high-energy repetitive impurity pellet; very difficult access
Volume-average alpha-particle energy spectrum		Knock-on bubble-chamber neutron detectors	Development of detectors required
		Neutron spectrometer	Evaluates knock-on tail above 14 MeV
Runaway electrons			
Start-up runaways	√	Hard x-ray detectors	Inside vacuum vessel; survival with necessary sightlines is issue
Disruption potential runaways	√	Synchrotron rad. detection	Far-forward light cone must be detected
Divertor Pumping Performance			
Pressure in divertor gas-box		ASDEX-type pressure gauges	Concern about RIED affecting operation
Helium removed to divertor		Penning spectroscopy	

Diagnostics proposed for FIRE (5)

Physics Parameter	Control	Diagnostic Set	Issues and Comments
Machine Operation Support			
Vacuum base pressure	√	Torus ion gauges	On main pumping duct
Vacuum quality		Residual gas analyzer	On main pumping duct
Vacuum vessel illumination		Insertable lamps	To enable initial level of internal inspection
Surface Temperature			
First-wall/RF antenna temp.	√	IR TV imaging	
Divertor plate temperatures and detachment	√	IR TV imaging	
		Thermocouples	
Neutral particle sources for diagnostics			
Neutral particle source for core spectroscopy	indirect	Diagnostic neutral beam	Pulsed high power beam required for penetration at ~ 150 keV/amu
Lithium source for polarimetry		High current lithium beam	In development for DIII-D (JET?)
Lithium pellet target for confined alpha spatial dist.		High velocity lithium pellet injector	> 5 km/s, ~10 Hz development needed

Tritium Retention in TFTR and JET.

	TFTR	JET (DTE1)
Total tritium injected by NBI	3.1 g	0.6 g
Total tritium injected by gas puff	2.1 g	34.4 g
Total tritium retained during DT operations	2.6 g	11.5 g
Initial % retention during T puff fueling	≈ 90%	≈ 40%
(wall saturation + isotope exchange)		
Longer term % retention including D only	51%	17%
fueling (mostly co-deposition)		
Tritium remaining in torus	0.85 g (4/98)	4.2 g (7/98)
Long term retention	16% (4/98)	12% (7/98)
		6% (12/99)
Average deuterium retention (for comparison)	≈ 40%	≈ 10-15%

Table 1 from
Tritium Issues in Next Step Devices, C H Skinner and G Federici
Invited talk at the International Conference on Advanced Diagnostics for Magnetic and Inertial Fusion
Proceedings of the International Conference on Advanced Diagnostics for Magnetic and Inertial Fusion
Varenna, Italy Sept. 3-7th, 2001. PPPL report PPPL-3604, Preprint: September 2001, UC-70

Some General Comparisons of DT in TFTR/JET with FIRE,ITER and ARIES-AT

	TFTR	JET	FIRE	FIRE	ITER-FEAT	ITER-FEAT	ARIES-AT	
B, T	5.2	3.8	10	10	5.3	5.3	6	
R,m	2.55	2.96	2.14	2.14	6.2	6.2	5.2	
n, vol average, 10^20 m-3	0.5	0.3	4.55	4.55	1	1	2.1	
Q	0.3	0.6	10	10	10	10	30	
Pfusion	11	16	150	150	400	400	1719	
Tritium Considerations								
tritium plasma mass, mg			25	25	170	170	150	
energy confinement time, s			1	1	3	3	1.5	
particle confinement time,s			5	5	15	15	7.5	
pulse duration, s			20	20	400	3600	9.00E+04	one day for ARIES
fueling efficiency, %			50	50	50	50	50	
tritium used /pulse, g			0.2	0.2	9.1	81.6	3600	per day for ARIES
In vessel-Inventory Limit, g			15	15	350	350	500	
Divertor Target material			W	C	C	C	metal	
tritium retention, %	51	17	0.2	15	15	15	0.038	
Pulses allowed			37500	500	257	29	365	days for ARIES
rep rate, pulses/day			5	5	50	5		
days until change out			7500	100	5	6	365	

Conclusion:

the retention must be less than 0.038% in a reactor for one year of operation before intervention to reduce tritum inventory.

if FIRE has retention less than 0.2%, it will never have to stop for tritium intervention.

if ITER has a 15% retention with graphite, its operation is severely restricted. It would have to stop after one week if running full duty cycle.

if ITER has 0.2% retention, it must stop every year for an intervention

Divertor Power Handling Considerations	TFTR	JET	FIRE	FIRE	ITER-FEAT	ITER-FEAT	ARIES-AT
Power transported to edge, MW		22	34		97		313
P/2R, MW/m		4	8		8		30
P/2Rw, MW/m2, w~(L/B)^0.5, L ~ R		4	17		7		32

Conclusion: ITER and FIRE are a factor of two and four beyond JET, but a factor of four and two short of reactor conditions

Disruption Considerations	TFTR	JET	FIRE	FIRE	ITER-FEAT	ITER-FEAT	ARIES-AT
Plasma Energy, MJ		16	34		340		460
Wp/2R, MJ/m		3	8		27		44
Wp/2Rw, MJ/m2, w~(L/B)^0.5, L ~ R		3	17		25		48

Conclusion: FIRE and ITER are factors of three to nine beyond JET, but a factor of at least two short of reactor conditions

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} ~ 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

More Work Needed to Define Plasma Control Possibilities

- Density (core, edge)
  - pellet fueling/divertor pumping
    - density relative to nGW, fast alpha
- ITBs
  - ICRH ala C-Mod
    - control timing and strength of ITBs
- Current Profile Control
  - ramping, Lower Hybrid Current Drive
- Rotation Control
  - edge NBI injection being looked at
    - What are the rotation requirements?
- RWM Stabilization
  - feedback coils in port plugs near plasma
- Disruption
  - pellets, jets, neural net control systems

Burning Plasma Simulation Initiative*

- A more comprehensive simulation capability is needed to address the strong non-linear coupling inherent in a burning plasma.

- A comprehensive simulation could help:

    - better understand and communicate the important BP issues,

    - refine the design and expectations for BP experiments,

    - understand the experimental results and provide a tool for better utilization of the experimental run time, and

    - Carry the knowledge forward to the following tokamak step or to burning plasmas in other configurations.

- This is something we should be doing in any to support any of the future possibilities

***sometimes known as Virtual AT Simulator**

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
    - 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