FIRE

An Update and Response to NSO-PAC 2 Report

D. Meade

for the FIRE Team

Presented to
NSO-PAC 3 Meeting
UW-MSN, Madison, WI

July 10, 2001

http://fire.pppl.gov

Recent Events of Interest to NSO/FIRE

Community Discussions (since NSO-PAC 2 , Jan 22, 2001)

- talks/discussion- MIT, Columbia, OFES, LANL, Sandia, ANL, APS-Spring, UFA-BPS2, EPS, US-Japan

Physics Meetings

- APS Spring Meeting in Washington (April 30, 2001)
  - FIRE poster, low attendance at posters, made some good contacts
  - Interest by National Academy (Plasma Science) in an early BPS review
- UFA Burning Plasma Science Workshop (May 1-3, 2001 at GA)
  - 9 FIRE Related talks and contributions -FIRE UFA-BPS Website
  - followup - chit list
- EPS Controlled Fusion and Plasma Physics (June 18-22, 2001)
  - Fire paper/poster - lots of discussion
  - several papers with results relevant to FIRE (on FIRE web)
  - contacts made for future collaboration
  - Fusion Debate:
    - Reduced EURATOM budget includes ITER construction
    - and - one tokamak, one non-tokamak, technology for ITER

Recent Events of Interest to NSO/FIRE (2)

APS-DPP Annual Meeting, October 29, 2001 Long Beach, CA
- Session on Burning Plasma Science
  - Tutorial: (50 min) G. Navratil, Intro. to Burning Plasma Physics
  - Invited: W. Heidbrink, Energetic Particle Physics in Burn’g Plasmas
  - (Invited: Transport and Turbulence in Burning Plasmas)-imbedded

External Review of FIRE Engineering (June 5-7, 2001)
- Members: Bushnell, Parker, Pizutto, Puhn, Irby, Majumdar,Mioduszewski
- Excellent progress so far, detail impressive given the resources
- Identified ~ 6 Critical design and R&D issues. Thome to address

Fusion Bill (Fusion Energy Sciences Act 2001) -see FIRE web site
- Introduced in House May 9, Lofgren (D, CA), Cunningham (R, CA)
- Introduced in the Senate June 20, Feinstein (D, CA), Craig (R, ID)
- Calls for: DOE to submit a plan to Congress, by July 2004, for constructing a US Burning Plasma Experiment.
  - (we would have to hustle to make this, needs CD in FY2003)

National Energy Policy recommends development of next-generation technology- including hydrogen and fusion.

Summary of FIRE Response to NSO-PAC 2

2.0 Mission Statement

General science mission and objectives endorsed - need to jazz up

2.1: Mission Group (J. Perkins-LLNL, M.Campbell-GA, P. Colestock-LANL, D. Correll-LLNL, S. Cowley-UCLA/Imp.College, D. Gates, J. Drake, F. Dylla-JLAB, R. Fonck surveyed. (Next: HEP Snowmass, Science Edu, Science Writers and Reporters, Cong. Staff,)-Keys: frontier, exploration, discovery, knowledge gained,

Vision Statements

- Star Power in the Laboratory for solving Earth's energy future (DC)
- FIRE, Lighting the Way to Fusion (DM)
- Fusion: Power of the Cosmos brought to Earth (GN)
- Learning to Harness the Power of the Stars(DG)
- Burning Plasma Science, a Journey of Exploration and Discovery (TT)

Mission Statements (must have science emphasis)

- Attain, explore, understand and optimize fusion-dominated plasmas to provide knowledge for attractive magnetic fusion systems
- Burning Plasmas (self-heating from fusion reactions) within controlled laboratory experiments is the agreed upon next step in the road map for demonstrating fusion energy power plants. (DC)

2.0 Mission Statement (continued)

Recommendation 2.2*:* In the list of scientific objectives, put more emphasis on the strong nonlinear coupling of physics phenomena (e.g., bootstrap current, MHD stability, confinement, alpha effects, boundary behavior, etc.) that will occur in a burning plasma.

Scientific Objectives VG Updated here - needs logo/figure

Minimum Performance objectives (VG)

Recommendation 2.3: Open up the list of scientific objectives to the possibility of including non-fusion research.

Burn wave propogation?   Lower priority for now.

Fusion Science Objectives for a Major Next Step Magnetic Fusion Science 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	ignition not precluded
$f_\alpha = P_\alpha / P_{heat}$	$\geq 50\%$	up to 83% at Q = 25
TAE/EPM	stable/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 τ_{pump}, $\tau_{heat\ transfer}$

3.0 Plasma Dimensionless Parameters

Recommendation 3.1: The team may want to consider adding another dimensionless parameter (e.g., maximum R β_{α} , magnetic shear) that might better characterize the machine's ability to address alpha physics. **done, see attached**

Recommendation 3.2: We recommend that the project work to communicate this information better as these studies come to fruition. A table showing the range of key dimensionless parameters would be helpful. **done, see Figures and tables attached**

Recommendation 3.3: The FIRE team should develop extensive tables (at constant beta and collisionality) to show clearly where the device is positioned between existing experiments and other future devices, in order to show how big a step it represents.
Done Figure attached, could be improved

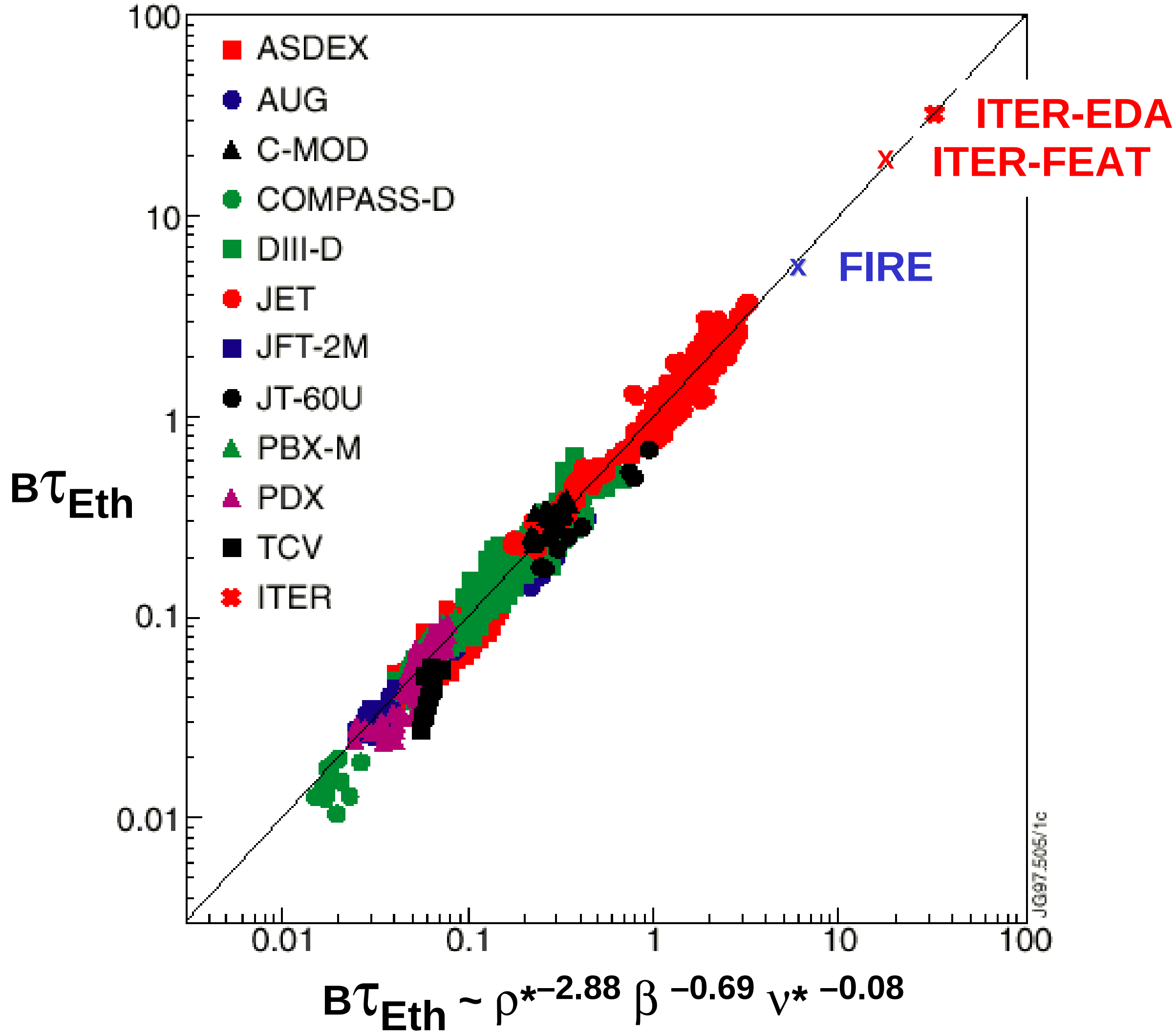
- Bτ_E VG
- table FIRE/IGNITOR/ITER add JET
- four panel VG r*, n*, Burn Time/τ_{CR} versus n/nGW
- fusion power waveforms vs time ($\tau_{CR} = \tau_{skin}$)

FIRE is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters
$\omega_c \tau$ $\rho^* = \rho/\mathbf{a}$ $\nu^* = \nu_c/\nu_b$ β

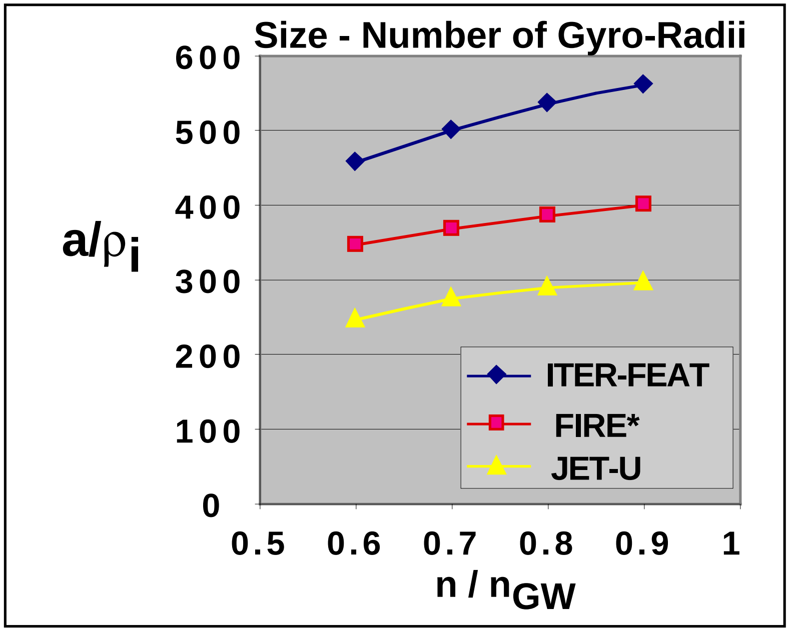
Similarity Parameter
$B\,R^{5/4}$

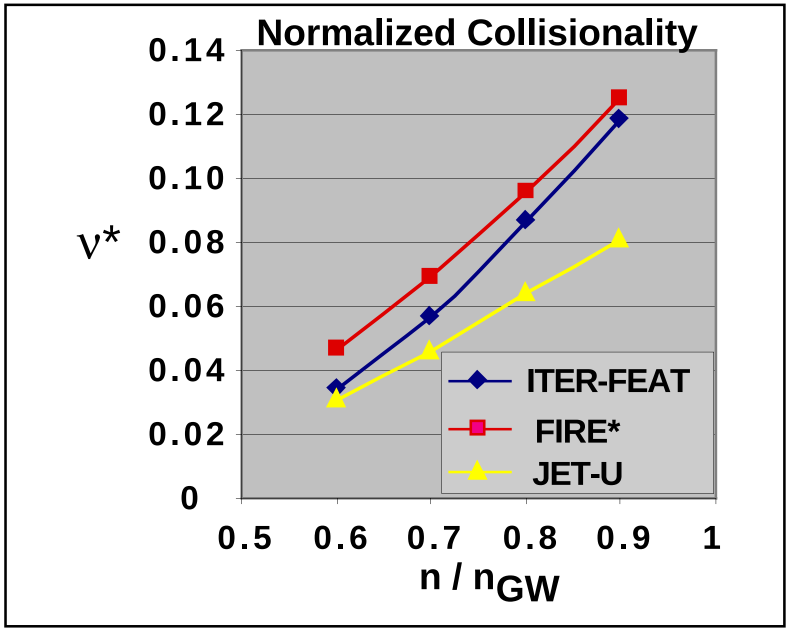
Kadomtsev, 1975

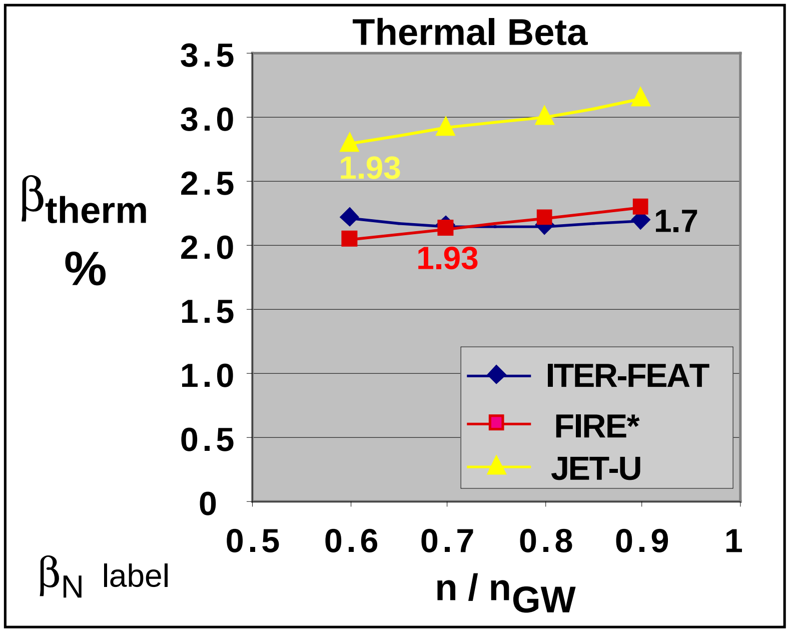


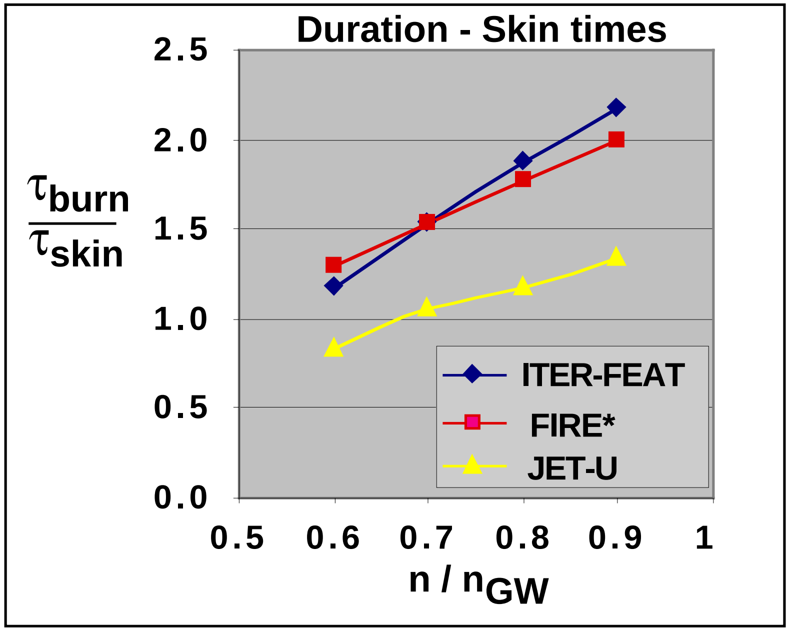
Parameters for H-Modes in Potential Next Step D-T Plasmas

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









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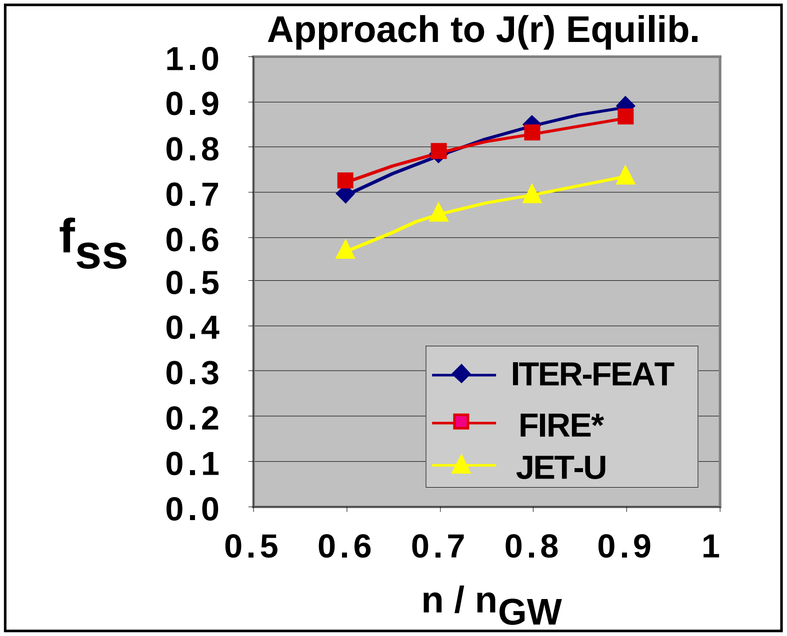
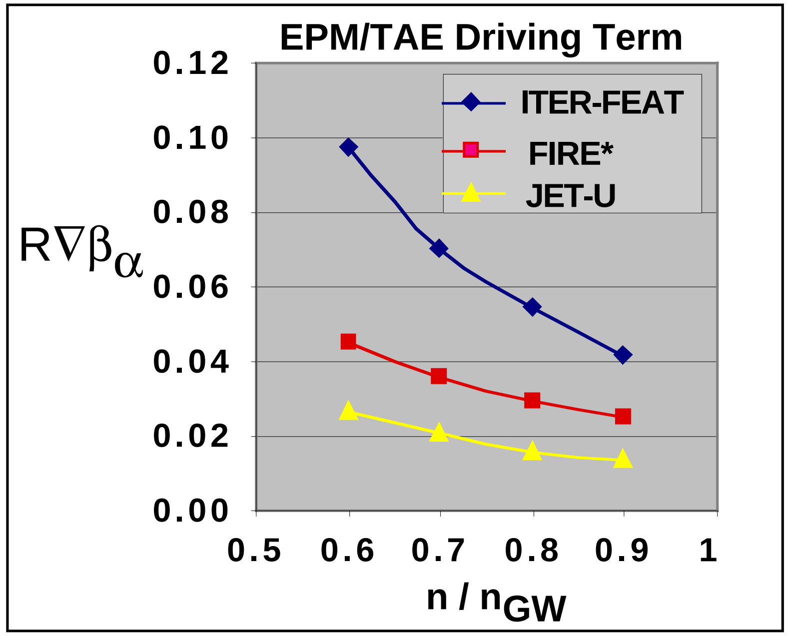




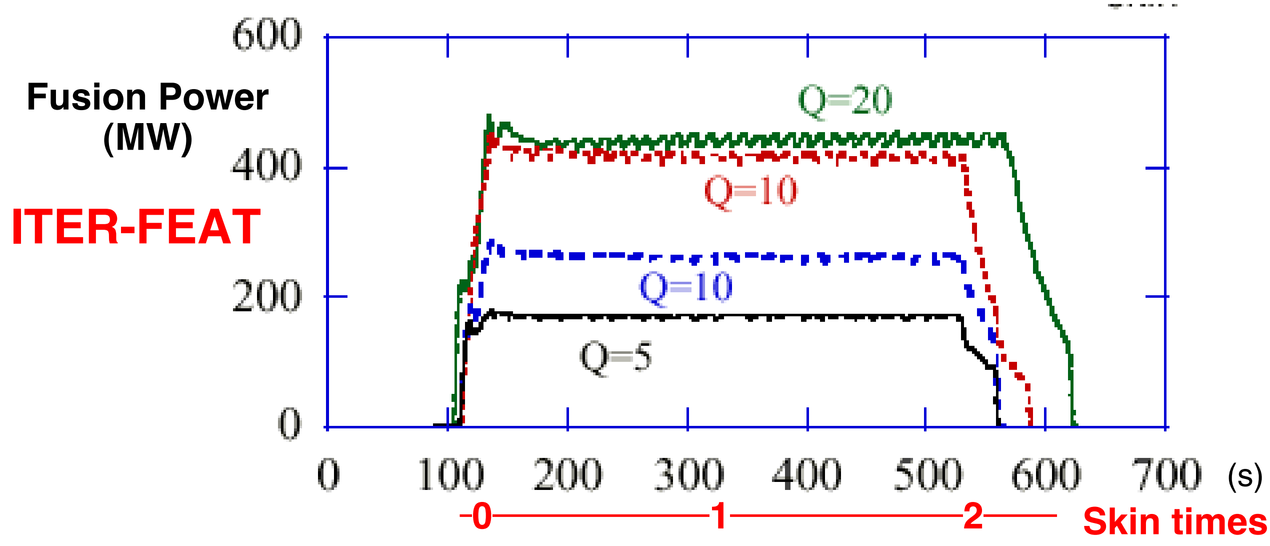
Summary Points on Dimensionless Parameters

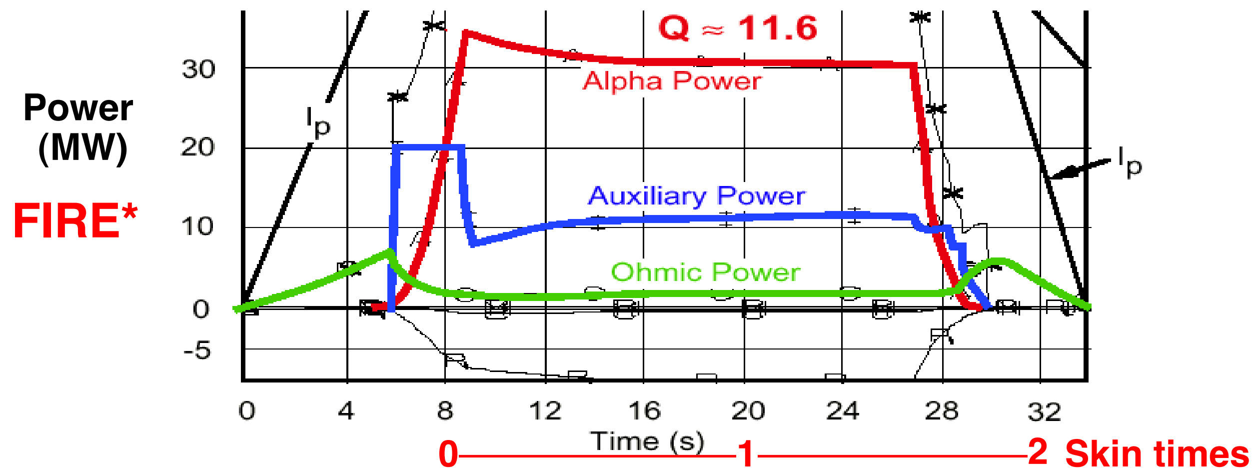
- FIRE is a modest extrapolation in ρ^* and $R\nabla\beta_{\alpha}$, is this good or bad?
- Other FIRE and ITER-FEAT dimensionless parmaeters are quite close.
- Achieving Q > 1 in JET-U would imply very high Q for similar modes in ITER-FEAT and FIRE.

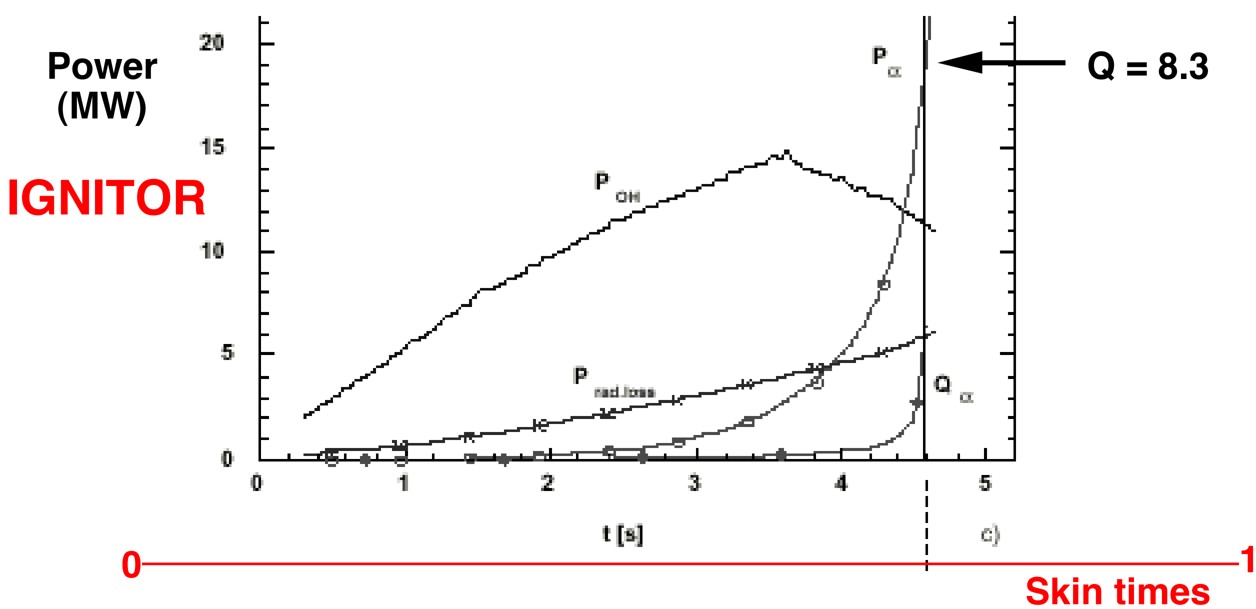
Dimensionless Parameters Describing Physics Performance in Burning Plasmas

Parameters	Symbol	Unit	IGNITOR	FIRE	ITER
Base Burning Plasma Mode					
Normalized collisionality ν^* @ a/2			0.043	0.058	0.045
Normalized size (a/ρ_i)	$1/\rho^*$		390	352	483
Normalized pressure (beta toroidal)	β_{tor}	%	1.5	2.4	2.6
Normalized pressure (beta poloidal)	β_{pol}		0.26	0.72	0.62
Normalized beta $\beta_{tor}/(I/aB)$	β_N		0.9	1.84	1.81
Normalized density	n_l/n_{GW}		0.4	0.7	0.85
Confinement relative to L-Mode	H89-P		1.7	2.6	2.0
Confinement relative to H-Mode	H(y,2)-IPB98			1.1	0.99
Loss Power / H-mode Threshold	P_{L-H}			1.3	2.4
Alpha Ash (He) Confinement	τ_{He} / τ_E		> 6	5	5
Impurity Content	Z_{eff}		1.2	1.41	1.7
(Alpha /Total) plasma heating	f_α		0.67	0.67	0.67
Normalized size $a/\rho_{f\alpha}$	$1/\rho^*_\alpha$		7	7	12
Alpha beta	β_α	%	0.1	0.15	0.34
Alpha instability Driving Term	$R \nabla \beta_\alpha$		0.02	0.039	0.077
Norm. Alpha particle velocity	$v_\alpha/v_{Alfvén}$		1.6	2	1.6

Normalized Burn Time (Plasma Skin Time)







Waveforms from talks presented at UFA BPS Workshop 2

4.0 Confinement Scaling

Endorsed ITER IPB98(y,2) choice

4.1(a) Dimensionless scaling projections ITER98 (y,2) (ρ , ν , β) **Future**

4.1(b) Robustness to various scalings - ITER(y,2) is lowest of empirical

4.2 document choice of H(y,2) ≈ 1.1, n(0)/ n = 1.2, $n/n_{GW} \approx 0.65$

Cordey, EPS 2001 paper JET H-Mode data H(y, 2) ≈ 1.1 for FIRE

Ongena JET overview paper at EPS VG attached

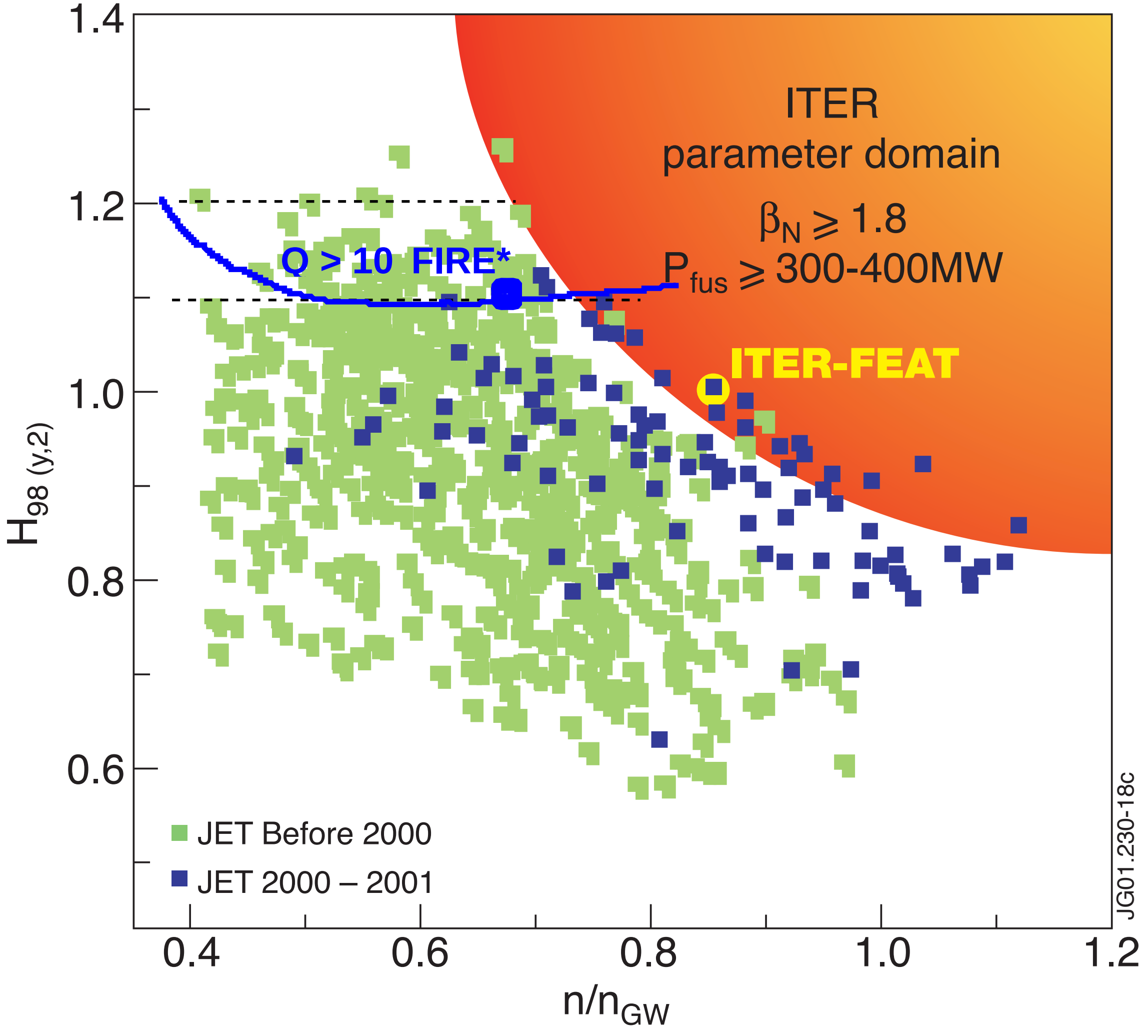
FIRE documented at ANS, UFA Workshop, EPS

4.3 Utilize Physics Based Models

Kinsey/Waltz GLF 23 VGs 2

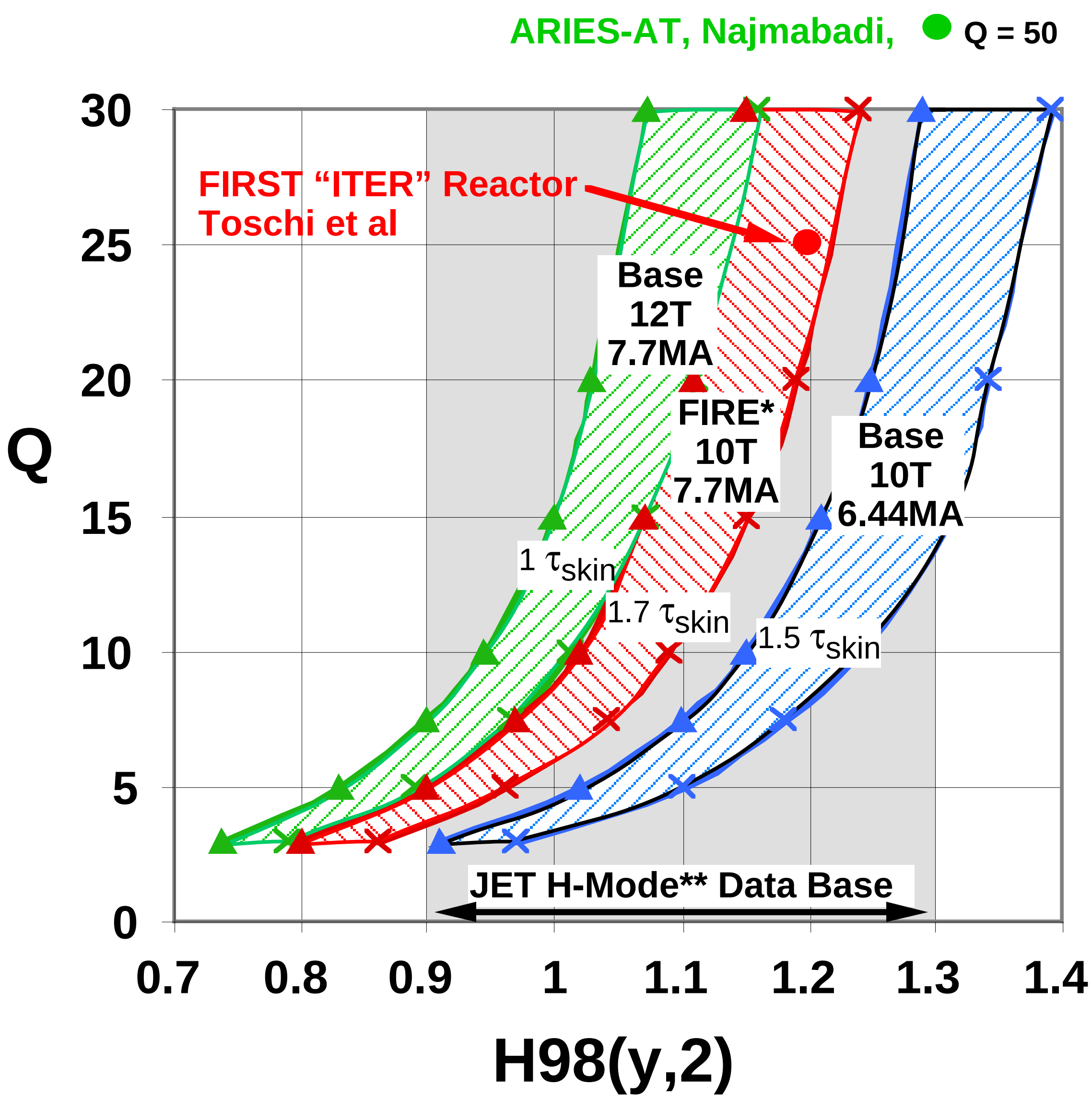
Hammett Pedestal VG

Three Methods Used to Obtain $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ for ITER



- Extension of parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \geqslant 1.8$ 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**
- **Data Base for FIRE* Q > 10 is as strong as ITER-FEAT. Note added - DMM**

Projections of FIRE Compared to Envisioned Reactors



P_{fusion} = 150 MW

n/n_{GW} = 0.7

▲ $n(0)/<n>_V$ = 1.5

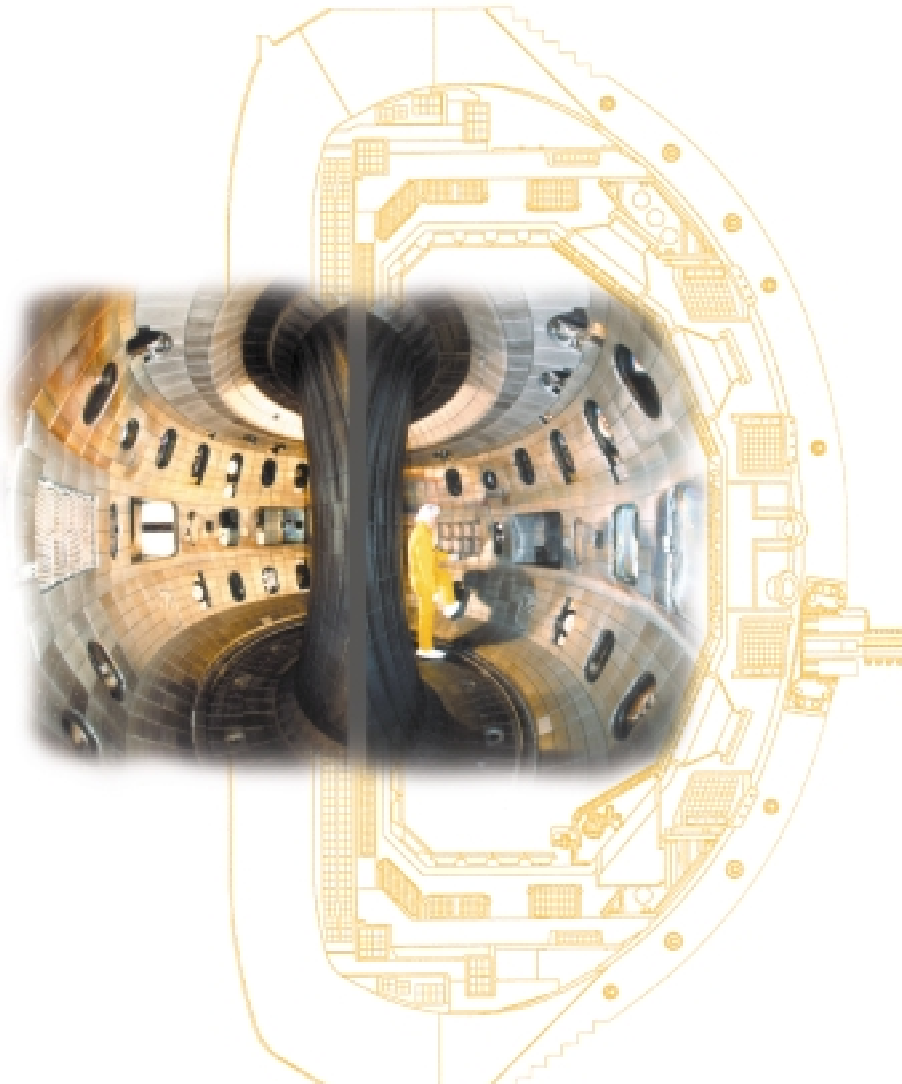
✕ $n(0)/<n>_V$ = 1.2

FIRE*
R = 2.14m, a = 0.595m
A = 3.6

* JET H-Mode Data for β_N > 1.7, 2.7 < q_{95} < 3.5 κ > 1.7, n/n_{GW} = 0.5 -0.8, and Z_{eff} < 2 have

<H98(y,2)> = 1.1
$<n(0)/<n>_V>$ = 1.2

Burning Plasma Projections Using The GLF23 Transport Model



by
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* Lehigh University

Acknowledgements:
C. Kessel, D. Meade, G. Hammett

Presented at
Burning Plasma Workshop II

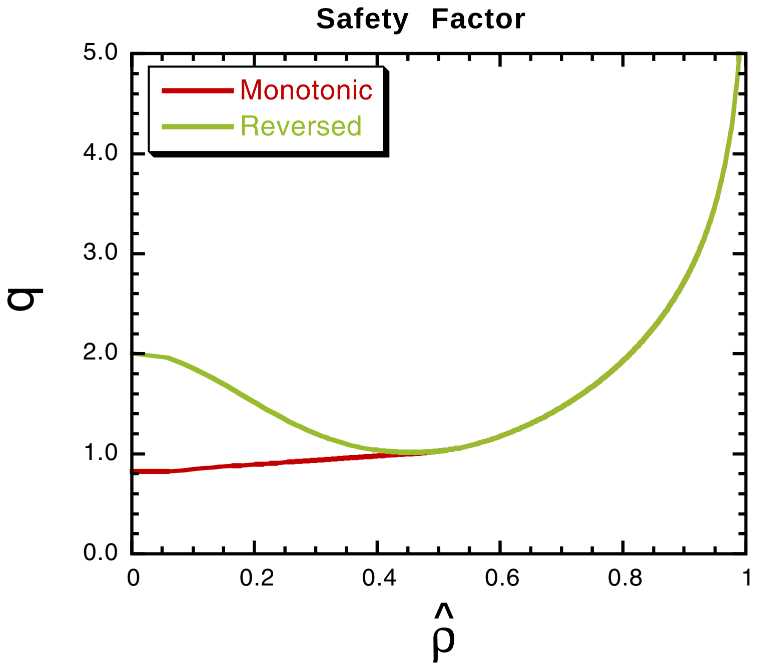
May 1, 2001

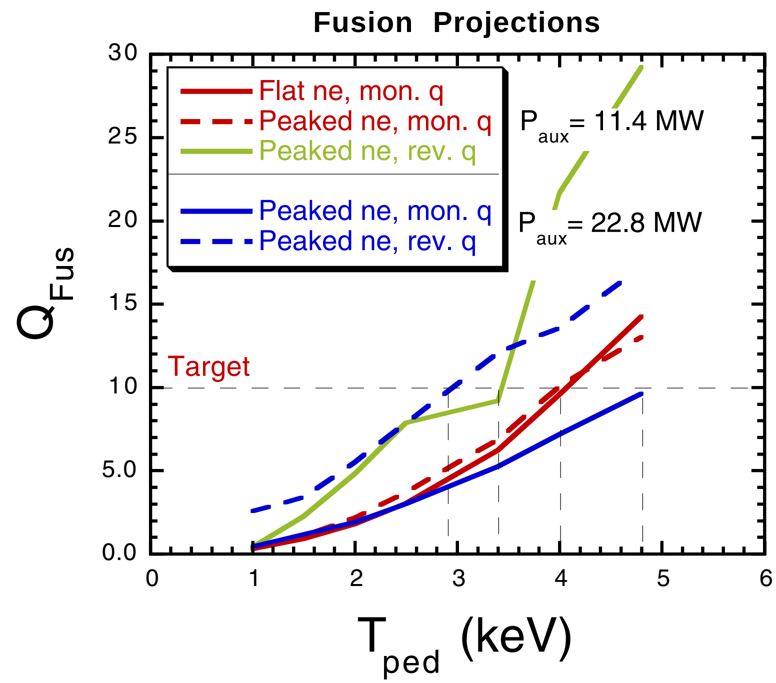
DIII-D
NATIONAL FUSION FACILITY

LEHIGH
University

Fusion Projections for FIRE

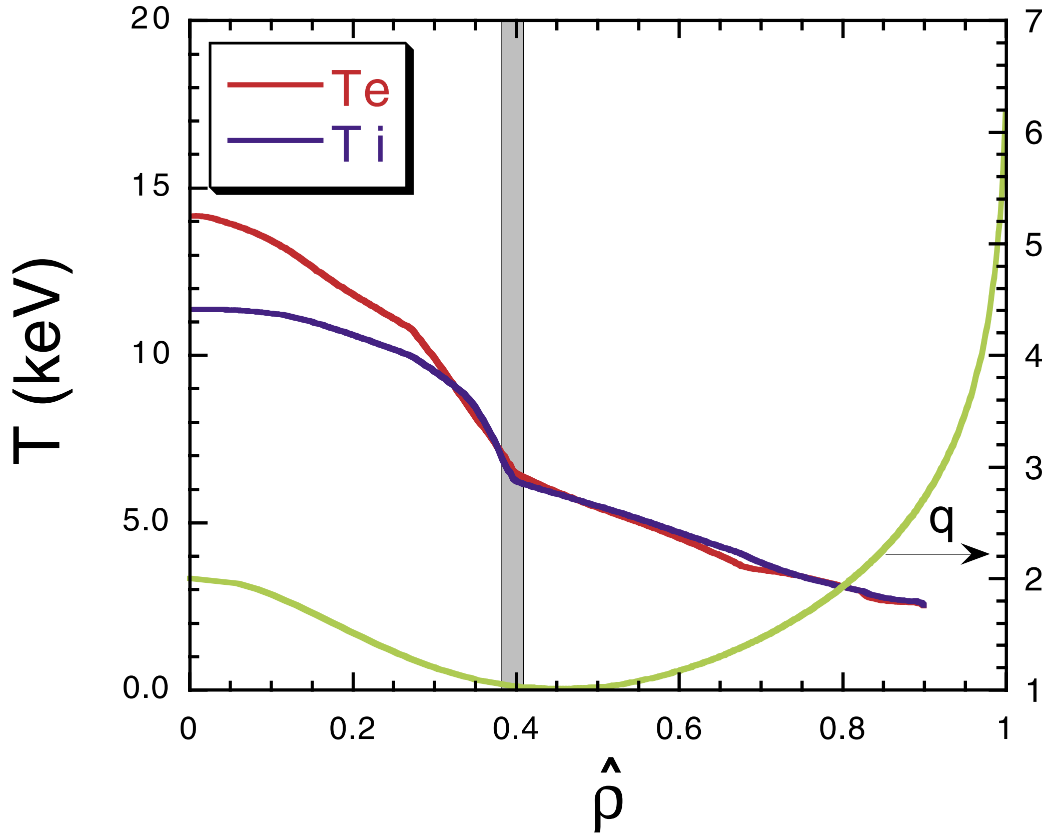
- ***Temperature profiles predicted for monotonic and reversed q-profiles while computing the effects of ExB shear and alpha-stabilization***
  - $n_{ped} = 3.6\times10^{20}\ m^{-3}$, $n_{e0}/n_{ped} = 1.5$
  - ***ExB shear effects small since no toroidal rotation except for peaked density, reversed shear case where ITB develops***
  - ***Alpha heating computed using TRANSP reaction rates***





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

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



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

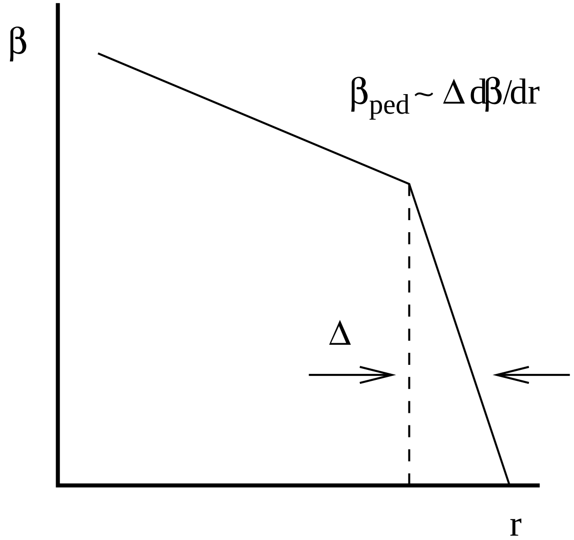
11.4 MW auxiliary heating

✦ 50 MW auxiliary heating

Edge pedestal scalings very uncertain, but most favor higher-field designs with stronger shaping...

- Wide range of theory & expt. evidence: $\Delta/R \propto \rho_{*\theta}$ **(JT-60U, JET)**, $\rho_{*\theta}^{2/3-1/2}$, $\beta_{pol}^{1/2}\rho_*^0$ **(very interesting DIII-D evidence of a second stable edge, which would have a more favorable scaling to reactors)**

Hammett, Dorland presented at UFA BPS - Workshop1



- **Making two assumptions (and use Uckan formula for** $q_{95}RI_p/(Ba^2)$**):**

  1. **Width** $\Delta \propto \sqrt{\epsilon}\rho_\theta \propto \rho q/(\kappa\sqrt{\epsilon})$ **(scaling preferred by two largest tokamaks)**
  2. **stability limit** $\partial\beta/\partial r \propto [1+\kappa^2(1+10\delta^2)]/Rq^2$ **(rough fit to JT-60U, Koide et.al., Phys. Plasmas 4, 1623 (1997), other expts.), get:**

$$T_{ped} = C_0 \left(\frac{n_{Gr}}{n_{ped}}\right)^2 \left[\frac{1+\kappa^2(1+10\delta^2)}{[1+\kappa^2(1+2\delta^2-1.2\delta^3)]} \frac{(1-(a/R)^2)^2}{(1.17-0.65a/R)}\right]^2 \frac{A_i R}{\kappa^2 a}$$

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

Sensitivity of Fusion Power to Some Assumptions

Baseline assumptions:

IFS-PPPL model for $\chi_{i,e}$ modified with $\Delta(R/L_{Tcrit}) = 2$ to roughly fit Dimits shift seen in gyrokinetic simulations.

$\langle n_e \rangle / n_{\text{Greenwald}} = 0.74$. **Modest density peaking,** $n_0/\langle n_e \rangle = 1.18$, $n_{ped}/\langle n_e \rangle = 0.65$. $n(r) = (n_0 - n_{ped})(1-(r/a)^2)^{0.5} + n_{ped}$.

P_{aux} **adjusted to keep** $P_{net} \geq 1.2 P_{99L \rightarrow H}$ **= 30 MW for baseline FIRE, =57 MW for baseline ITER-FEAT.**

	n_0 $10^{20}/m^3$	n_{ped} $10^{20}/m^3$	T_{ped} keV	P_{fusion} MW	Q	T_{i0} keV	P_{aux} MW
FIRE baseline case	6.75	3.6	4.8	264	620.0	18.6	0
$\downarrow T_{ped}$ 30%	6.75	3.6	3.4	142	9.7	15.3	14
flatten $n(r)$	3.60	3.6	4.8	117	22.0	21.7	5
original IFS-PPPL	6.75	3.6	4.8	155	13.0	12.9	11
original IFS-PPPL $\downarrow T_{ped}$ 30%	6.75	3.6	3.4	69	2.6	10.2	26
ITER-FEAT baseline case	1.09	0.58	2.9	192	5.8	18.3	32
$\downarrow T_{ped}$ 30%	1.09	0.58	2.0	111	2.4	15.5	45
ITER-FEAT with FIRE T_{ped}	1.09	0.58	4.8	381	816.0	23.5	0
ITER-FEAT with FIRE $T_{ped} \downarrow 30\%$	1.09	0.58	3.4	241	10.1	19.8	23

5.0 Design Point Studies

5.1(a) Describe Design Point Drivers

- Fusion Performance f_α or Q requires high B and/or large a, $\sim(IA)^2 \sim(Ba)^2$

- Plasma Duration of 1 to 3 skin times for evolution of plasma current profile

  $\tau_{skin} \sim \kappa a^2 T^{3/2}$, favors small a (large aspect ratio), high n

- Plasma Duration has several limits
  heating time for cryogenic TF and OH coils $t \sim (L/B)^2$
  heating time for divertor plate (OK for steady-state $P_{loss} \leq 60$ MW)
  heating time for 1st wall/Vac Ves (~20s for $P_f = 3 MWm^{-2} + P_{rad} = 60$ MW)
  volt-sec required to inductively drive current $(B_{OH}/B_T)(a_{OH}/a)^2$

  Plasma wall loading ≤ 3 MWm^{-2} is ≈ first wall non-active cooling limit

- Adv. tokamak favors higher A for larger f_{BS} and smaller current is req'd.

5.1(b) Extend system codes studies to aspect ratio = 3 with fixed mission

_ Done. see S. Jardin this meeting, also J. Schultz Ext Eng Review.

5.1(c) Look at incremental cost of meeting various objectives Q = 5,10 with duration of 1 or 2 skin times. Cost of AT tools.

Systems Studies Results (FIRESALE-J. Schultz)

1. System Code (FIRESALE) has a costing algorithm matched to SuperCode and calibrated with prior cost estimates for BP studies.

   Total Cost ~$R^{1.01}$, Magnets(10%) ~ $R^{1.64}$, tokamak cost(25%) ~ $R^{1.25}$

   Note: actual FIRE cost estimate based on estimates by subsystem engineers with industry estimate (Boeing/AES) for the tokamak.

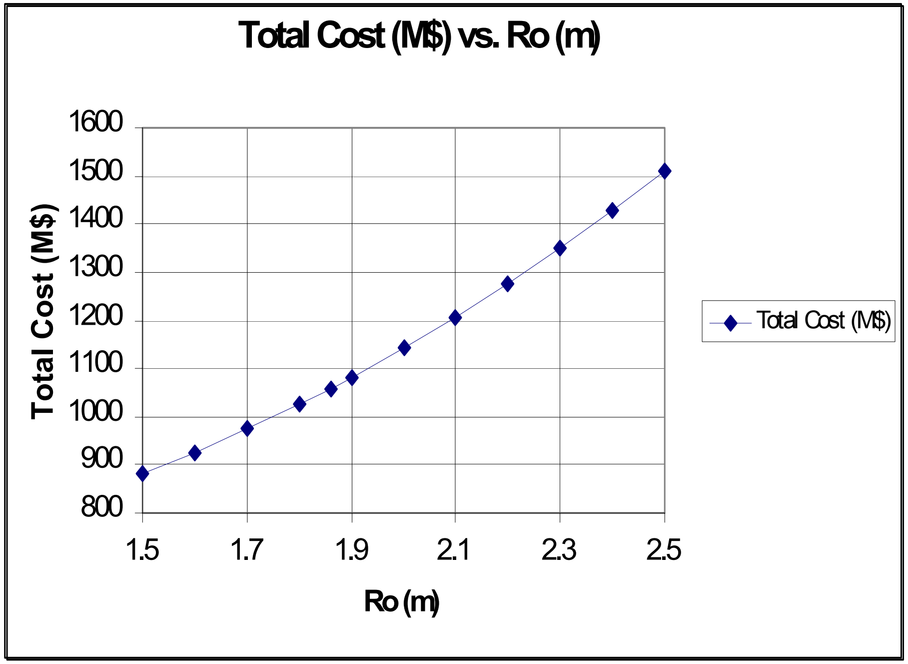
2. Sensitivity to Mission Study (A ≈ 3.8 is minimum size/cost for FIRE-like)

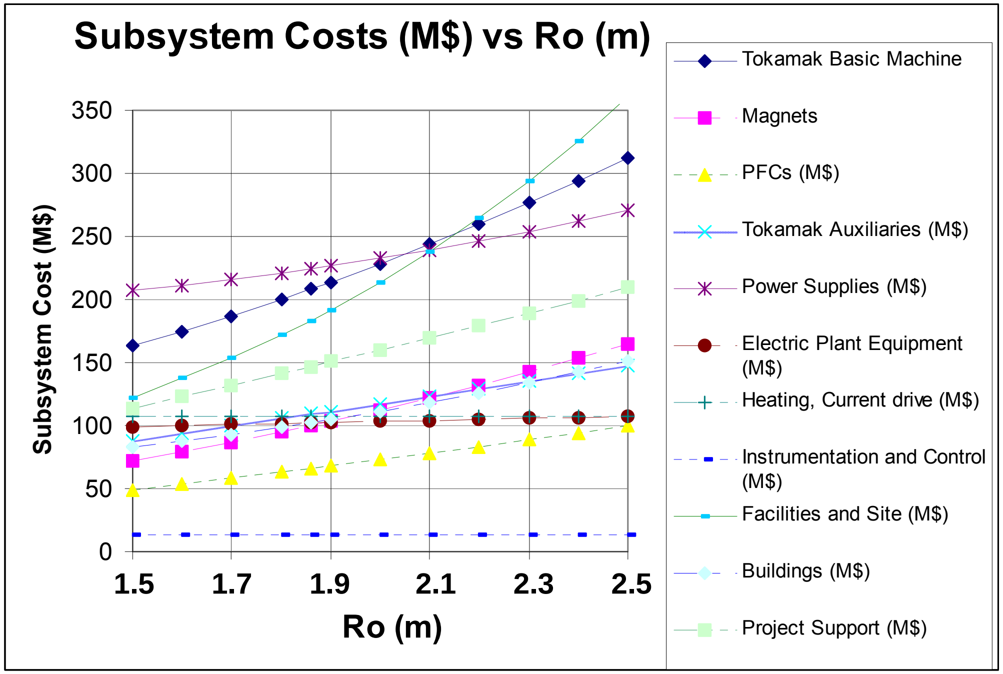
Bucked/Wedged	Q	Burn Time/τ_{CR}	R(m)	Cost ($B)
11.5 T	5	1	1.59	0.92
A = 3.8	5	2		
	10	1		
	10	2	1.86	1.06

3. Sensitivity to Mission (Wedged and Bucked/Wedged) $2\tau_{CR}$

Q	5	10	Ignition
Cost ($B) - B/W	0.97	1.06	1.29
Cost ($B) - Wedged	1.06	1.19	1.50
Relative Cost	1	~1.1	~1.4

Cost (M$) vs Ro; Subsystem Sensitivity





Vary R_o; B_t=11.5 T, A=3.8, q_L=3.1, not fixed mission

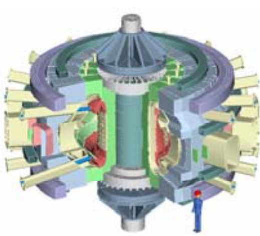
$/Ro Sensitivity = 1.01

$/Ro: Paux, I&C = 0

Magnets=1.64

Basic Machine=1.2510

Buildings=1.14



Burning Plasma Systems Code Study (Jardin/Kessel)

Wedged	Q = 5	Q = 10
Pulse Length 5s ≈ 0.5 τ_{CR}	A_{opt} = 3.73 R_{min} = 1.70 m I_P = 6.46 MA $ = 0.95	A_{opt} = 3.57 R_{min} = 1.85 m I_P = 7.77 MA $ = 1.03
Pulse Length 10s≈ 1 τ_{CR}	A_{opt} = 3.86 R_{min} = 1.79 m I_P = 6.32 MA $ = 1.0	A_{opt} = 3.67 R_{min} = 1.93 m I_P = 7.62 MA $ = 1.08
Pulse Length 20s≈ 2 τ_{CR}	A_{opt} = 4.08 R_{min} = 1.95 m I_P = 6.09 MA $ = 1.09	A_{opt} = 3.87 R_{min} = 2.09 m I_P = 7.37 MA $ = 1.17

H = 1.1, κ > 1.7, P_{aux} = 15 MW, Z_{eff} = 1.4   B ≈ 11T for all cases
$ assumed to scale as R based on Schultz FIRESALE systems code
Relative results for different missions same as FIRESALE

5.1(c) Cost of AT tools- Need to determine requirements first

- C. Greenfield Talk at UFA-BPS2 has Comprehensive List of AT tools

  Density Profile: High field side launch in baseline

  Current Profile: ICRF FWCD existing source - needs launcher
  LHCD identified upgrade needs ~ 20 MW, 5.6 GHz

  Feedback Stabilization: possibly in port plug faces - analysis underway

  Rotation: Is external momentum input required? reactor relevant concept?

  Upgrade of first wall cooling for longer pulses?

6.0 Design Point (Sensitivity)

a) What is the operational margin with respect to Q for operation at de-rated parameters?
Sensitivity to B, density peaking. figure attached.

b) Assess the reliability for operation near the maximum parameters of current and magnetic field
Deferred, depends on design details.

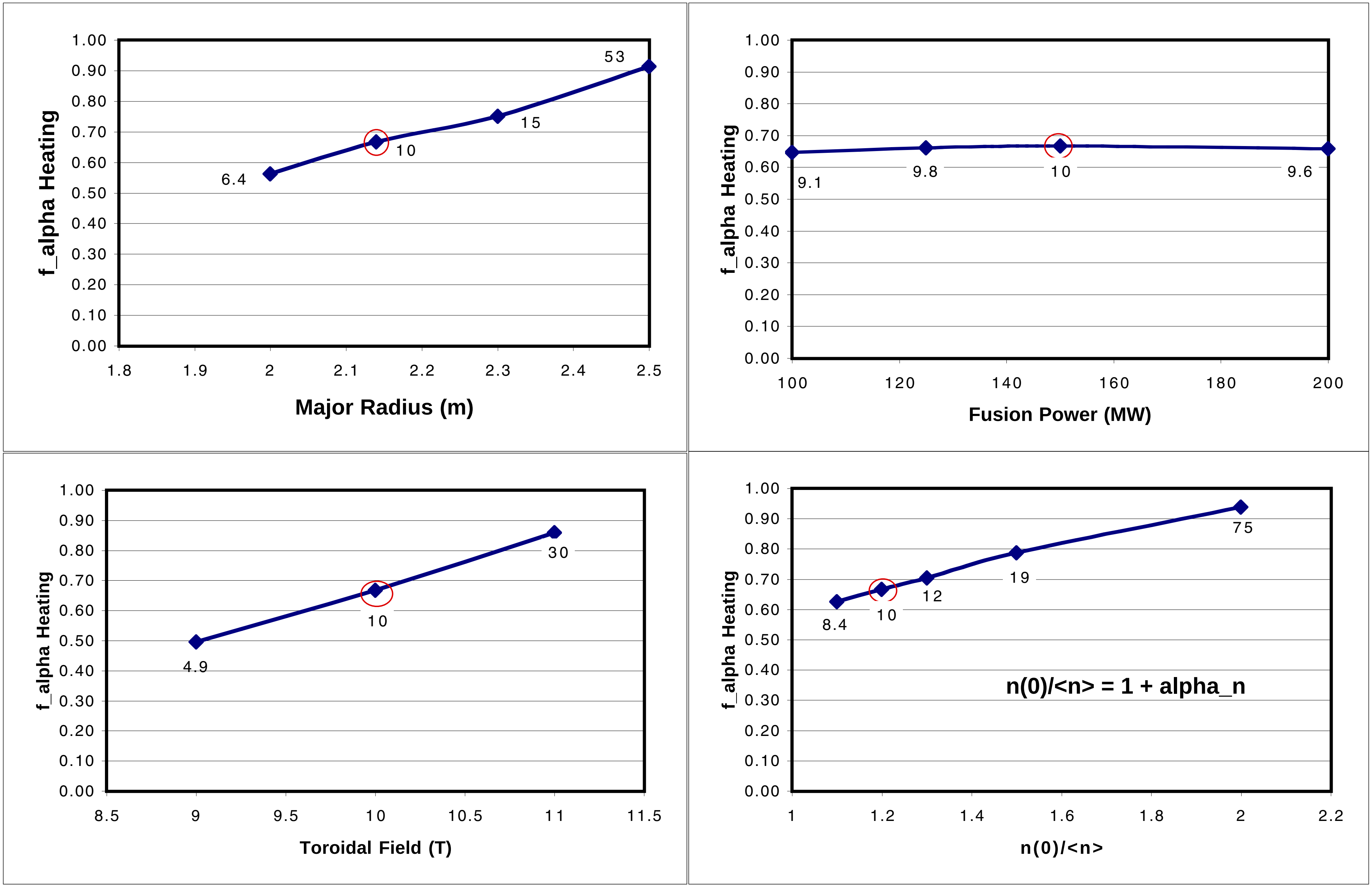
c) What breadth of parameters can be expected, given fixed values of Q (e.g., Q=5, Q=10, Q>10)?
PopCon Plot attached

d) Density and density profile are two very strong controlling parameters for determining the fusion power production. What tools will be available for density and density profile control?

Pellet fueling and divertor pumping has ongoing contact with people involved in present experiments DIII-D, C-Mod, JT-60U, ASDEX, JET.

Sensitivity Scans on FIRE*

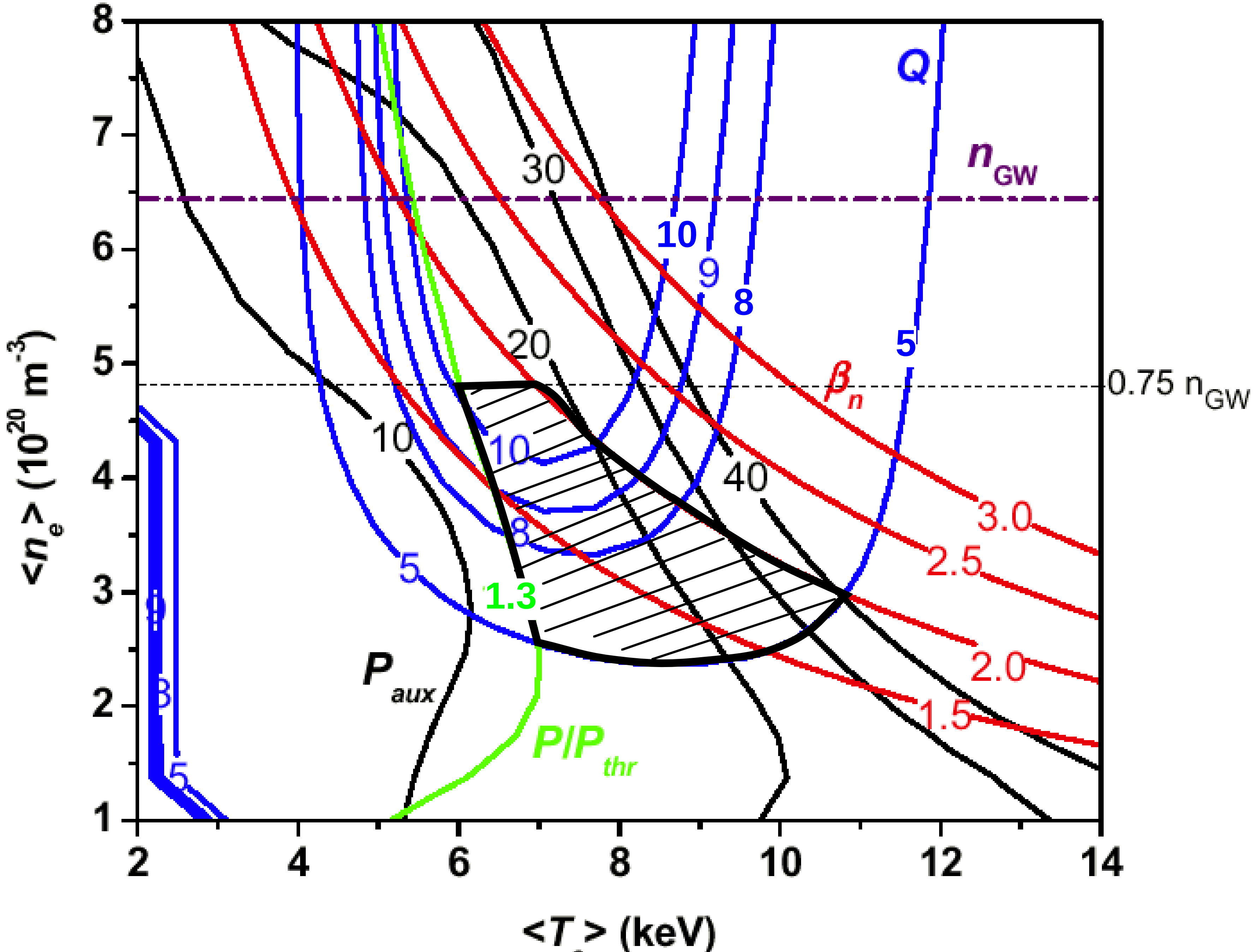
(A = 3.60, κ95 = 1.77, δ95 = 0.4, ITER98(y,2), H = 1.027, n/nGW = 0.7, nBe = 0.4%)



Note: kappa area would make H = 1.01

FIRE* Scans Compare

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



7.0 FIRE* versus FIRE Decision

7.1 Selection criteria for Choosing among possible engineering solutions

Physics Requirements: Q ≈ 10 [ITER98(y,2)], 2 τ_{CR}, flexibility for AT upgrade

Engineering Requirements: Margin needed in permanent items

Cost: ≈$1B for initial construction including site credits, US site

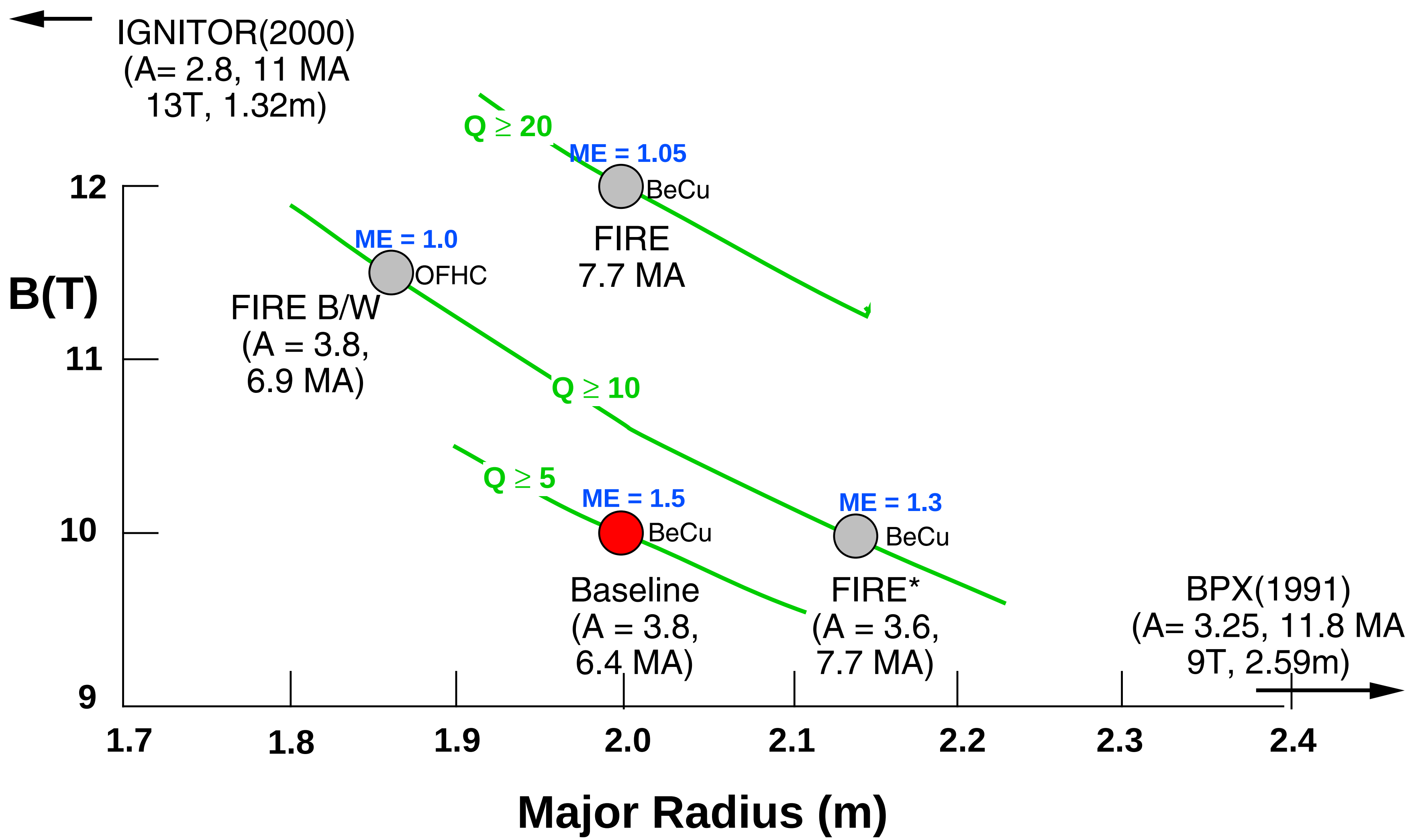
FIRE Options being Evaluated for Physics and Engineering (see next VG and table below)

	R (m)	A	B (T)	TF (mat/Config)	Ip (MA)	Q	Flattop (s/τ_{skin})	Cost ($B) Tok/Total
Base	2.0	3.8	10	BeCu/Wed	6.44	5	18.5	0.34/1.2
Hi B Base	2.0	3.8	12	BeCu/Wed	7.7	20	12	
FIRE*	2.14	3.6	10	BeCu/Wed	7.7	10	20	
FIRE**	1.86	3.8	11.5	OFHC/B&W	6.9	10	16	

assuming: H(y,2) = 1.1,

7.2 Main engineering review completed June 5-7, 2001. Thome talk

FIRE Options that have been Considered



ME = Allowable Stress / TF Stress

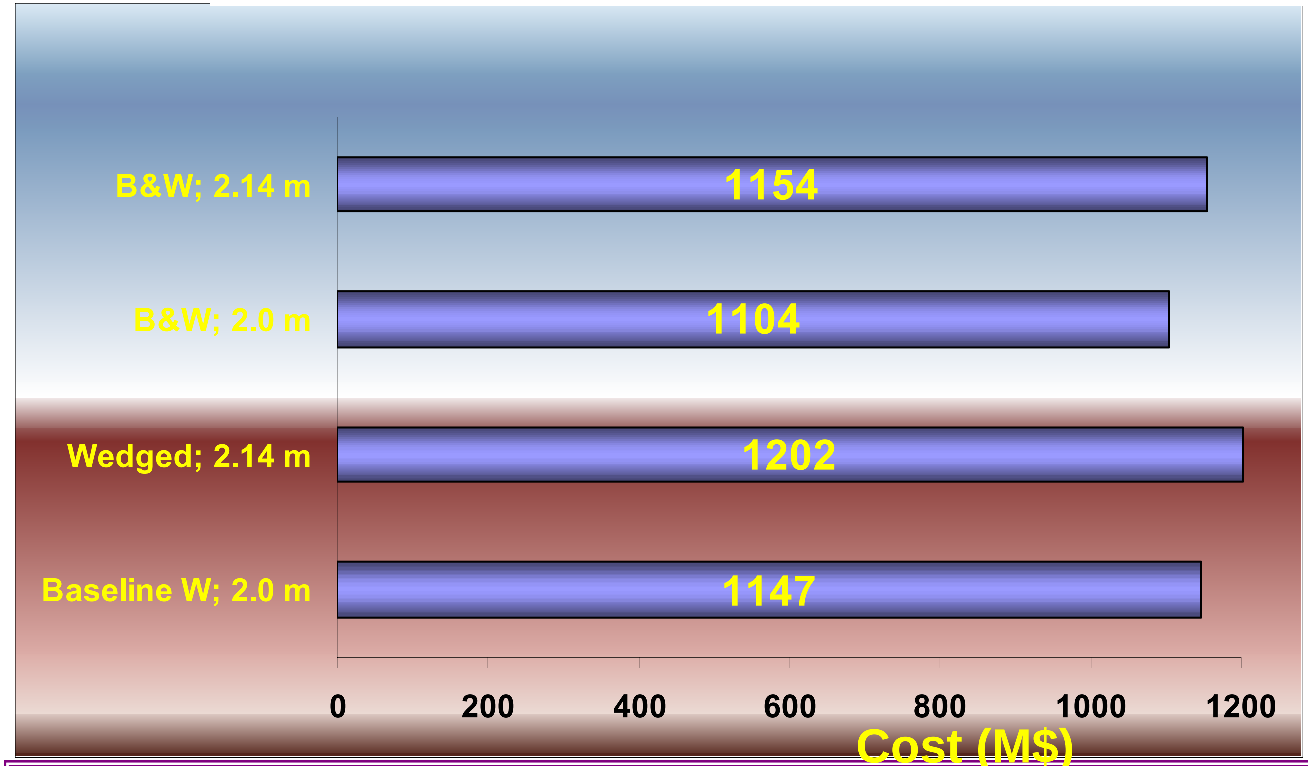
Preliminary FIRE Cost Estimate (FY99 US$M)

	Estimated Cost	Contingency	Total with Contingency
1.0 Tokamak Core	266.3	78.5	343.8
1.1 Plasma Facing Components	71.9	19.2	
1.2 Vacuum Vessel/In-Vessel Structures	35.4	11.6	
1.3 TF Magnets /Structure	117.9	38.0	
1.4 PF Magnets/Structure	29.2	7.2	
1.5 Cryostat	1.9	0.6	
1.6 Support Structure	9.0	1.8	
2.0 Auxiliary Systems	135.6	42.5	178.1
2.1 Gas and Pellet Injection	7.1	1.4	
2.2 Vacuum Pumping System	9.6	3.4	
2.3 Fuel Recovery/Processing	7.0	1.0	
2.4 ICRF Heating	111.9	36.6	
3.0 Diagnostics (Startup)	22.0	4.9	26.9
4.0 Power Systems	177.3	42.0	219.3
5.0 Instrumentation and Controls	18.9	2.5	21.4
6.0 Site and Facilities	151.4	33.8	185.2
7.0 Machine Assembly and Remote Maintenance	77.0	18.0	95.0
8.0 Project Support and Oversight	88.8	13.3	102.2
9.0 Preparation for Operations/Spares	16.2	2.4	18.6
Preconceptual Cost Estimate (FY99 US$M)	**953.6**	**237.8**	**1190.4**

Assumes a Green Field Site with **No** site credits or significant equipment reuse.

June 5, 2001

Cost of 4 Design Options



None of these machines has (quite) the same mission

Even (seemingly) identical plasmas, have different engineering margins

2.14 m ~ $100 M more than 2.0 m

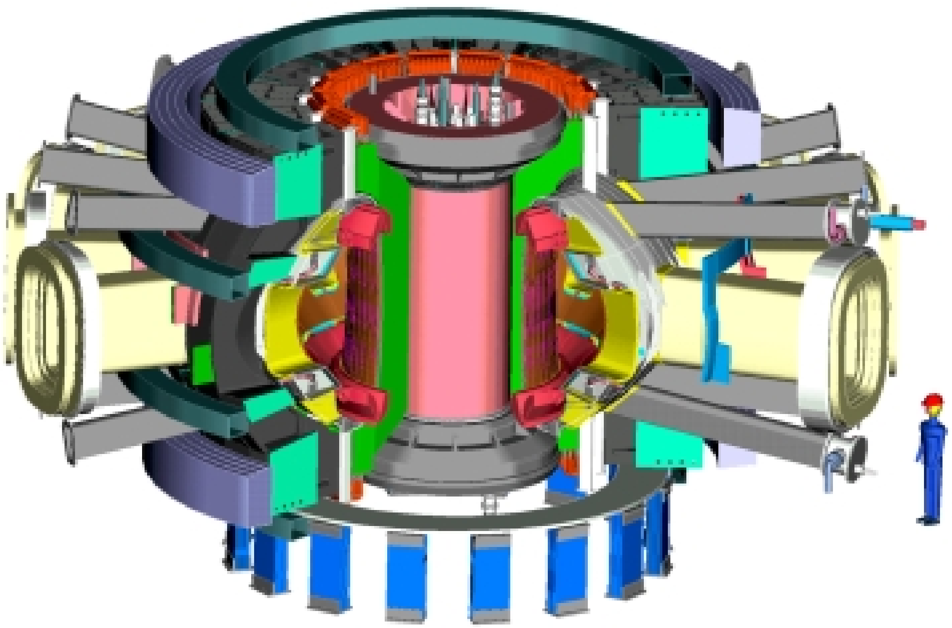
- saves $50 M, because 20 MW, not 30 MW P_{aux}

B&W $50 M less than Wedged

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.

Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.

FIRE* Parameters

R_plasma/ a_plasma	2.14 / 0.595
A	3.6
κa	1.81
δ95	0.4
<ne>, 10^20 /m^3	4.55
Paux (MW)	14.5
Pheat (MW) = Ploss	34
Bt(T) / Ip(MA)	10 / 7.7
Ion Mass	2.5
H(y,2)-ITER98	1.11
H-ITER 89P	2.61
alpha_n / alpha_T	0.2 / 1.0
li(3)	0.8
τaup*(He)/τauE	5
Cbs	0.7
f_bs	0.27
ν*	0.058
1/ρ*(uses To)	352
β (thermal only), %	2.24
q95	3.05
<n>l/greenwald	0.70
P_fusion (MW)	150.7
Pheat/P(L->H)	1.29
Q_DT*= Pfusion/Paux	10.39
Q_DT =Pf/(Pext + Poh)	10.01
fraction_alpha heating	0.67
τauE	1.04
ni(0)τ_ETi(0)	52.27
skin time	12.23
W(MJ), thermal / W alpha (MJ)	35.3 / 2.3
beta_alpha, %	0.15
Rgradbeta_alpha	0.04
v_alpha/v_alfven	2.01
beta_total, %	2.38
beta_N	1.84
eps*betap	0.20
<T>n / To	6.47 / 11.04
Zeff	1.41
Be concentration,%	3.00
Ar concentration, %	0.00
He concentration, %	2.30
Ploss/2πRx/ndiv (MW/m)	1.48

8.0 Physics Analysis and Device Flexibility

Recommendation 8.2(a): Further time-dependent plasma evolution studies are required in order fully explore the range of current profiles accessible to the base design and the further scientific benefit of profile control systems such as LHCD. A realistic lower hybrid current drive model needs to be used to assess the LHCD power requirements. **Kessel**

Recommendation 8.2(b): The assessment of additional profile control tools should be based on more detailed physics analysis of the phenomena (e.g., Alfvén eigenmodes) that can be studied. **Future**

Recommendation 8.2(c): It is recommended to assess the MHD stability with stronger edge pedestals than used in the simulations. **Future**.

Recommendation 8.3(a): A strong recommendation of our committee was to assess the maximum feasible I/aB accessible for FIRE (i.e., maximize δ, κ, ε). This would allow the design to maximize the confinement and plasma pressure and to take advantage of recent developments in the optimization of the AT concept. δ, κ, **are at maximum values consistent with the divertor and feedback stabilization, ε is being optimized. (Jardin)**

Recommendation 8.2(b): The committee recommends the study of AT scenarios at higher q-95 and I_{BS} in order to reduce the current drive requirements. **Ongoing, Kessel.**

Recommendation 8.2(c): The trade-off between enhanced physics capability and additional cost needs to be assessed in the light of the PAC-1 recommendation that the primary burning plasma mission be preserved within the foreseen capital cost. **Agreed.**

Recommendation 8.4(a): Define the range of parameters (e.g. alpha pressure, q-profile) needed to access relevant physics regimes, and express these in terms of POPCON diagrams for AT and H-mode regimes. **Under development, status report PAC3.**

9.0 Diagnostics

Recommendation 9.1(a): The diagnostic planning and resource requirements need to be defined within the context of the scientific mission. The strategy for phased funding and implementation of the diagnostics needs to be clarified. **Draft R&D plan developed by K. Young. Critical Diagnostic R&D issues will be discussed at NSO-PAC3 by K. Young.**

Recommendation 9.1(b): A machine layout and port allocation needs to be determined early in the design process, and port plugs designed to be consistent with the later requirements. **Draft layout made by K. Young. Integration of diagnostics and machine design recognized as key issue.**

Recommendation 9.2: Assess the cost of a diagnostic neutral beam incorporated into the baseline design, or assess how profiles can be measured without it. **K. Young to discuss at NSO-PAC3.**

10. Bucked/Wedged Toroidal Field Design

Recommendation 10.1: We recommend that the cost and risk trade-offs be more clearly detailed at the next PAC meeting. **Thome to discuss at NSO PAC3**

Items from NSO-PAC1

Dimensionless Parameter Table - now, FIRE and reactor - Meade
AT Modes Kessel - report this meeting -ongoing
Identify Upgrades- FWCD, LHCD, RWM stabilization, rotation?
Tritium System Costs-small due to low inventory and TFTR system reuse
Ranges to explore NTMs/RWM/TAE - MHD graph for NTM/RWM, TAE ongoing
Transport Simulations (GLF23TSC, WHIST) have been run for design points
He Ash Accumulation in AT - Future, generic AT issue.
DN power split during disruption - Physics R&D need
Disruption/VDE effects - Ulrickson results presented at Eng. Rev.
Runaway electrons - TSC has module with Rosenbluth model
Pumping Requirements- Ulrickson- base pumping to be increased.
Insitu Be coating - Ulrickson - future, also following ASDEX and C-Mod
Effect of ELMs - Ulrickson - anticipate 3 change outs of divertor targets
Low Shot Rate: M. Bell will review BPX plans and TFTR/JET DT experience
Lifetime limits (fatigue vs dose) - Thome/Meade - goal is to be ≈ equally limiting
Error field correction coils for n = 1feedback - future (Kessel/Columbia)
Power supply requirements for control coils - Kessel
Tangential port access - possible if all ports are same direction.

Summary

- Most issues are being resolved, others are soluble and will take time and resources.
- The design point is in about the right place wrt to feasibility and BP mission. The AT mission and capability is very promising but needs additional work.
- The cost needs to be thoroughly reviewed and scrubbed. The tokamak is ≈ $350M, with a total cost ≈ $1.2B. Need to begin assessing possible sites.
- Need a physics R&D List/Plan.
  - Many generic or ITER specific items are being worked.
  - Need work on FIRE specific items; e.g.,
    - double null effects on confinement, stability, power handling,
    - all metal PFCs, W divertor targets, Be first wall
    - optimized confinement at $n \sim 0.7\ n_{GW}$
    - AT mode development $q_{min} \approx 2.2$, $q_{95} \sim 3.7$
- Need to begin work on Engineering R&D items.
- Community interest is increasing, need stronger community involvement and organization of this effort will need resources to carry this forward.