Projection of Plasma Performance for FIRE

Response to NSO-PAC1

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Presented to
NSO-PAC2 Meeting
MIT-PSFC, Cambridge, MA

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NSO-PAC Recommendations on Plasma Performance Projections

Recommendation R1-7: To more clearly understand the cost/benefit tradeoffs in designing a lower cost machine for the investigation of self-heated fusion-dominated plasmas, the PAC recommends the examination of at least one variation of FIRE at somewhat larger size. The design point of the larger device could be an increase in the device size by 50% or an increase in the cost by 50% to reach Q=5, using the ITER Y2 scaling and flatter density profiles.

Recommendation R1-8: In defining baseline performance and in comparing the performance of FIRE to that of ITER and other devices, the PAC recommends that common design criteria (with respect to ITER) be used. We expect that this would involve the use of the best available confinement scaling, including ITER Y2, and also a range of density profiles, including flatter profiles with a peaking factors down to ~ 0.1. The PAC further recommends that the performance variation be examined as a function of the density. If performance projections are cited for FIRE based on assumptions that differ from those for ITER (or other comparison devices, *e.g.* Ignitor), these different assumptions should be made clear and justified.

Recommendation R1-11: We also recommend that the performance margin needed to meet the science objectives be discussed at a future meeting.

FIRE Performance Projection Activities

Design Guidelines

- Similar to ITER-FEAT
  - Campbell APS paper on FIRE, ITER-FEAT presentation to TAC 7/00
  - Uckan, Wesley ANS paper
  - Meade, IAEA, ANS papers

Confinement Database Meeting (DB4)

- Collection of random vs library of repeatable (eg Barabaschi EPS paper)

FIRE Specific Assumptions

- JET H-mode data base of FIRE-like shots (55)

  $\kappa \geq 1.7$, $\beta_N > 1.7$, $2.7 < q_{95} < 3.5$, $Z_{eff} < 2$, $0.3 < n/n_{GW} < 0.8$

  - $\langle H(y,2\rangle = 1.1$, $\langle n(0)/\langle n\rangle_v\rangle = 1.2$

- density peaking ≈ 1.2 consistent with 1-D modeling (e.g., Houlberg-ANS)

- Impurity assumption needs more analysis. Not taking credit for reduction at high density, but must make sure hi-Z ions do not get into core plasma.

Starting interactions with first principles modeling groups .

Guidelines for Estimating FIRE 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 tokamak data base (IPBDB4)

$$n_{20} \leq 0.80\ n_{GW} = 0.80\ I_p/\pi a^2$$

Beta Limit - theory and tokamak data base

$$\beta \leq \beta_N (I_p/aB), \quad \beta_N < 2.5 \text{ conventional}, \ \beta_N \sim 3 - 4 \text{ advanced}$$

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

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

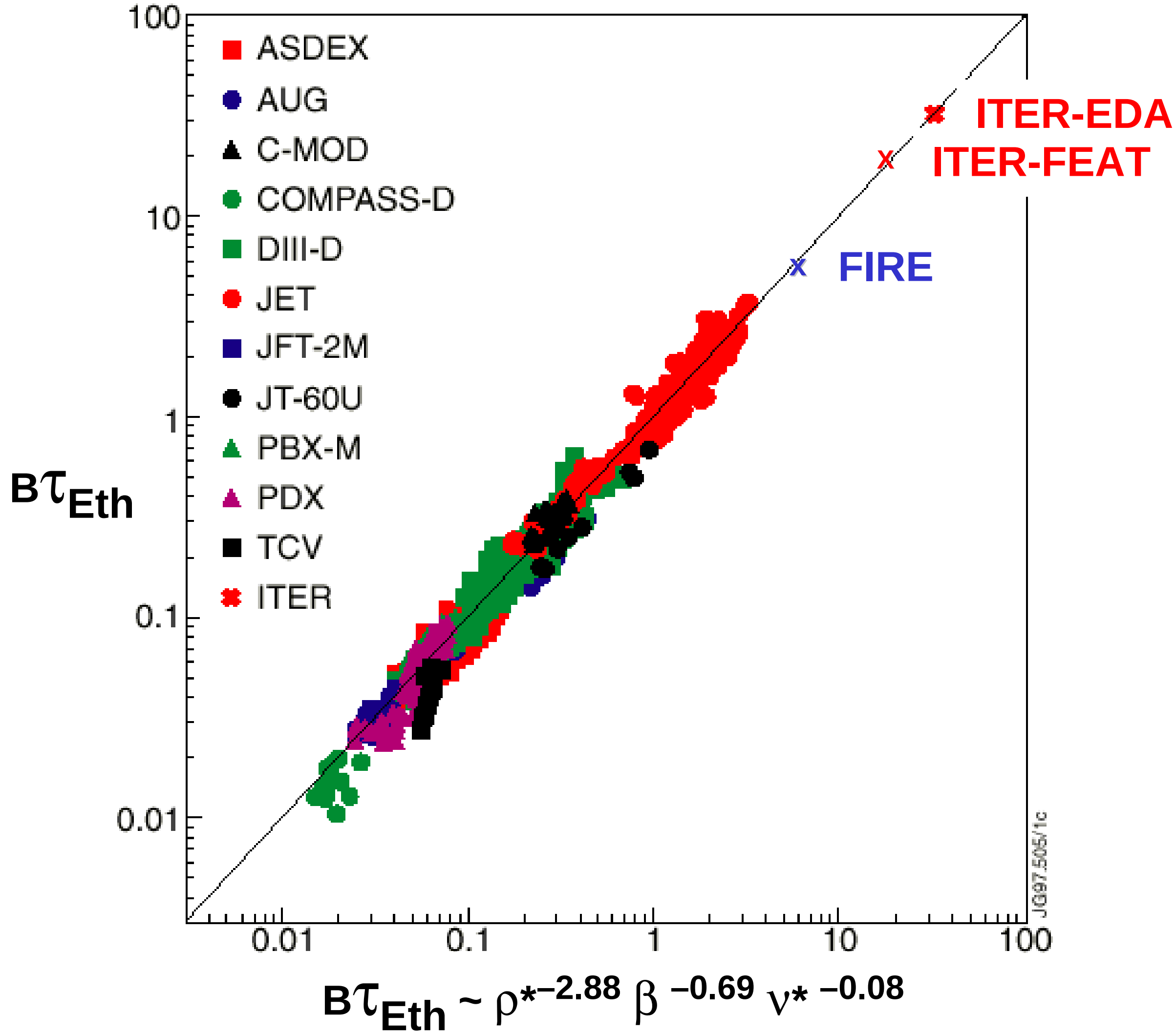
Helium Ash Confinement $\tau_{He} = 5\ \tau_E$, impurities = 3% Be

Most analyses published for FIRE have 3% Be while ITER at 1/6 the operating density has 2% Be. Some very recent cases for FIRE assume nBe ~ 1/n relative to ITER or 0.4% Be.

FIRE is a Modest Extrapolation in Plasma Confinement

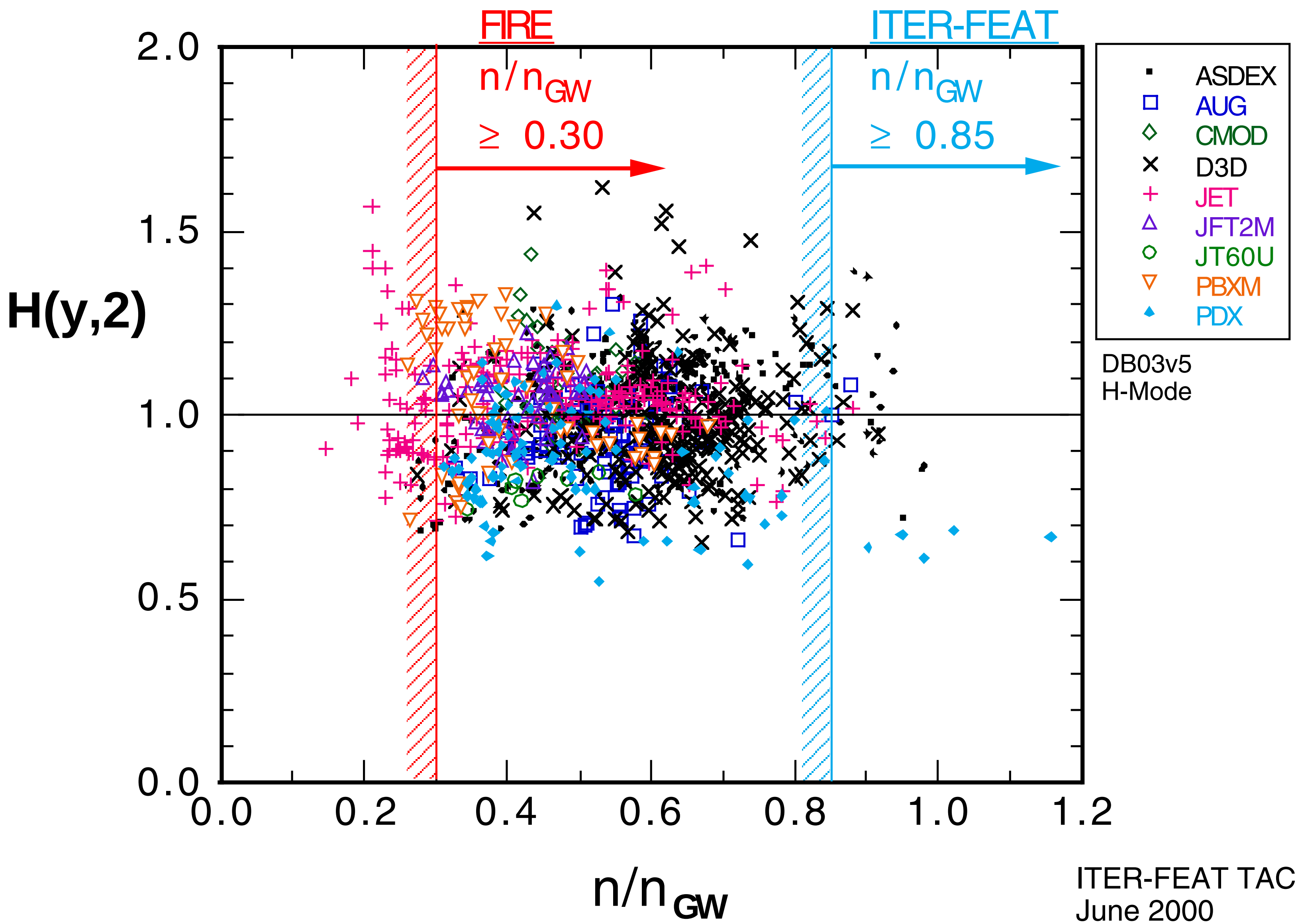
Dimensionless Parameters
$\omega_c \tau$ $\rho^* = \rho/\mathbf{a}$ $\nu^* = \nu_c/\nu_b$ β

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



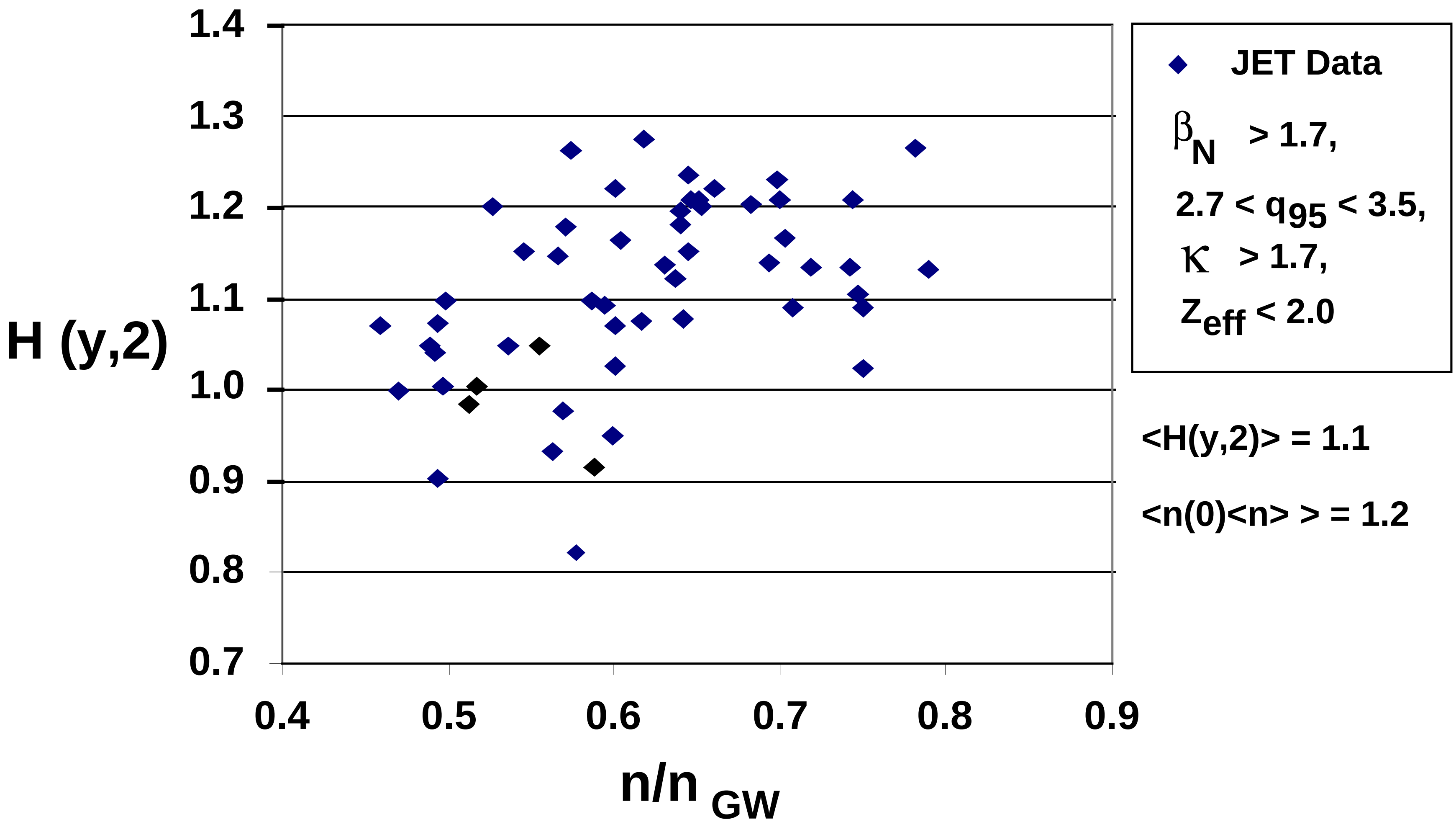
Kadomtsev, 1975

FIRE can Access Most of the H-Mode Database



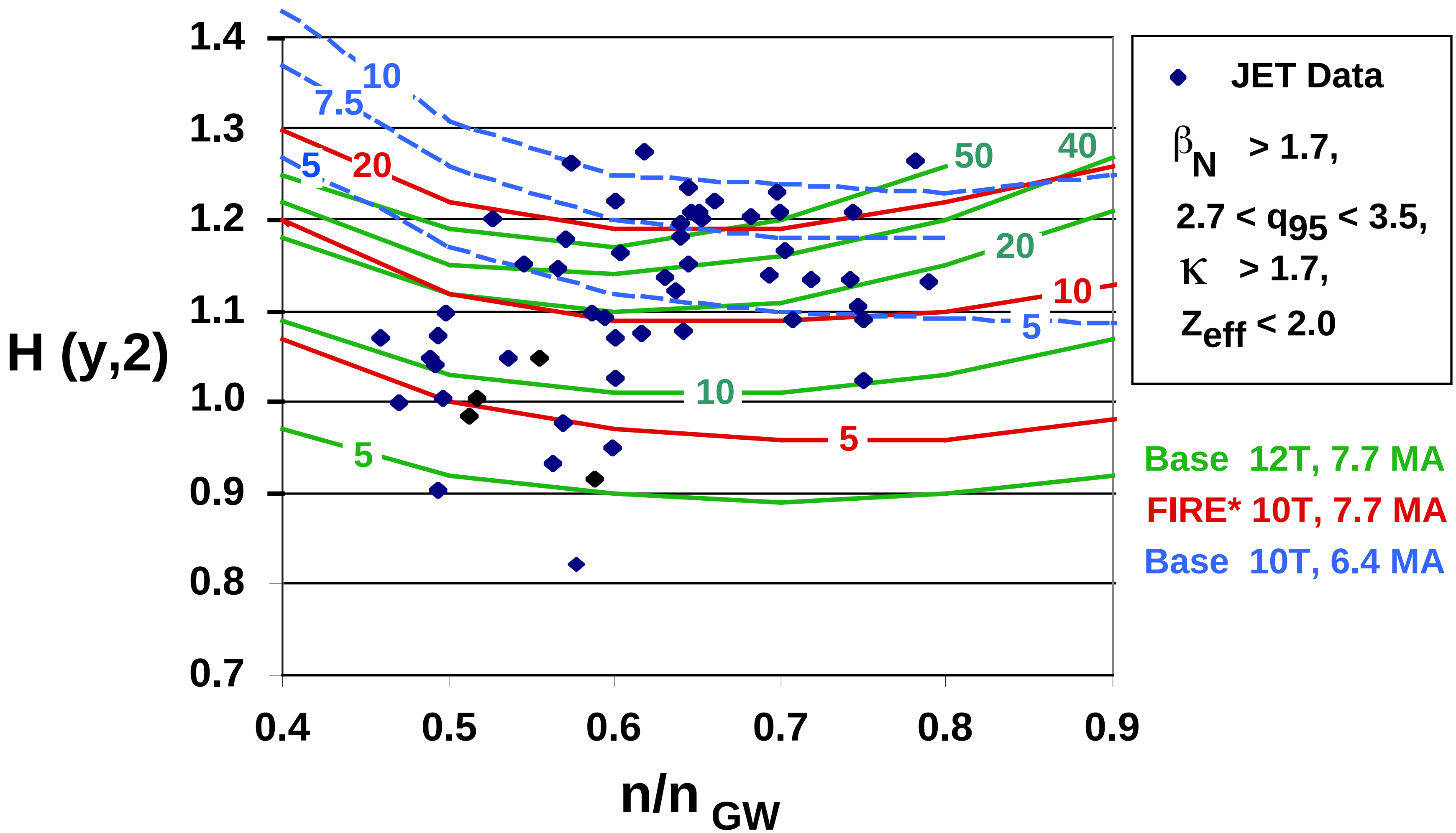
ITER-FEAT TAC Meeting
June 2000

JET H-Mode Data Selected for FIRE-like Parameters

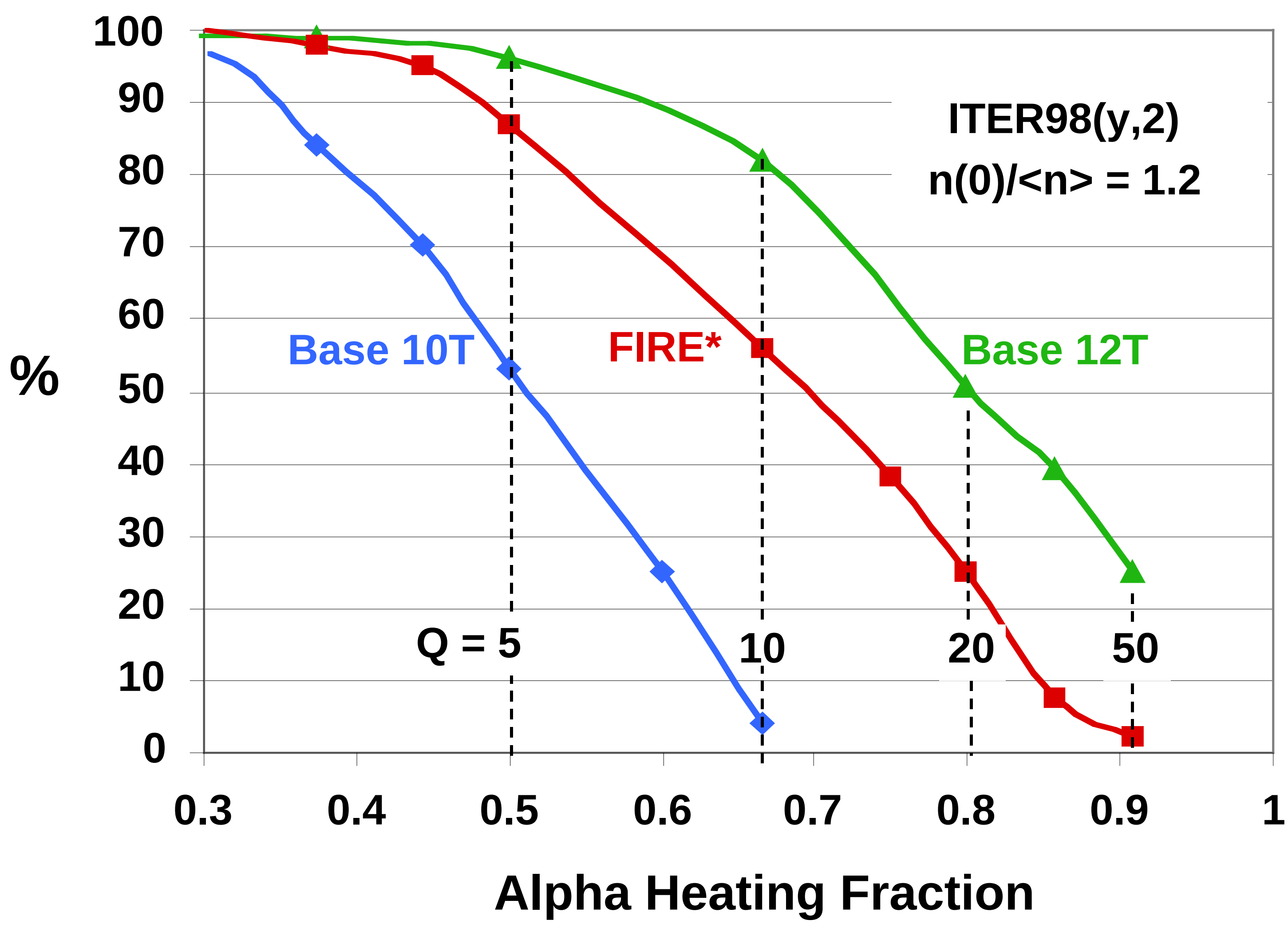


This approach discussed at IAEA(Sorrento) and at the International Confinement Database meeting (Frascati).

Confinement Enhancement Required to Access Various Q-values Compared with JET H-Mode Data



Percentage of JET FIRE-like Data Points that Project to a Specific Alpha Heating Fraction (Q)

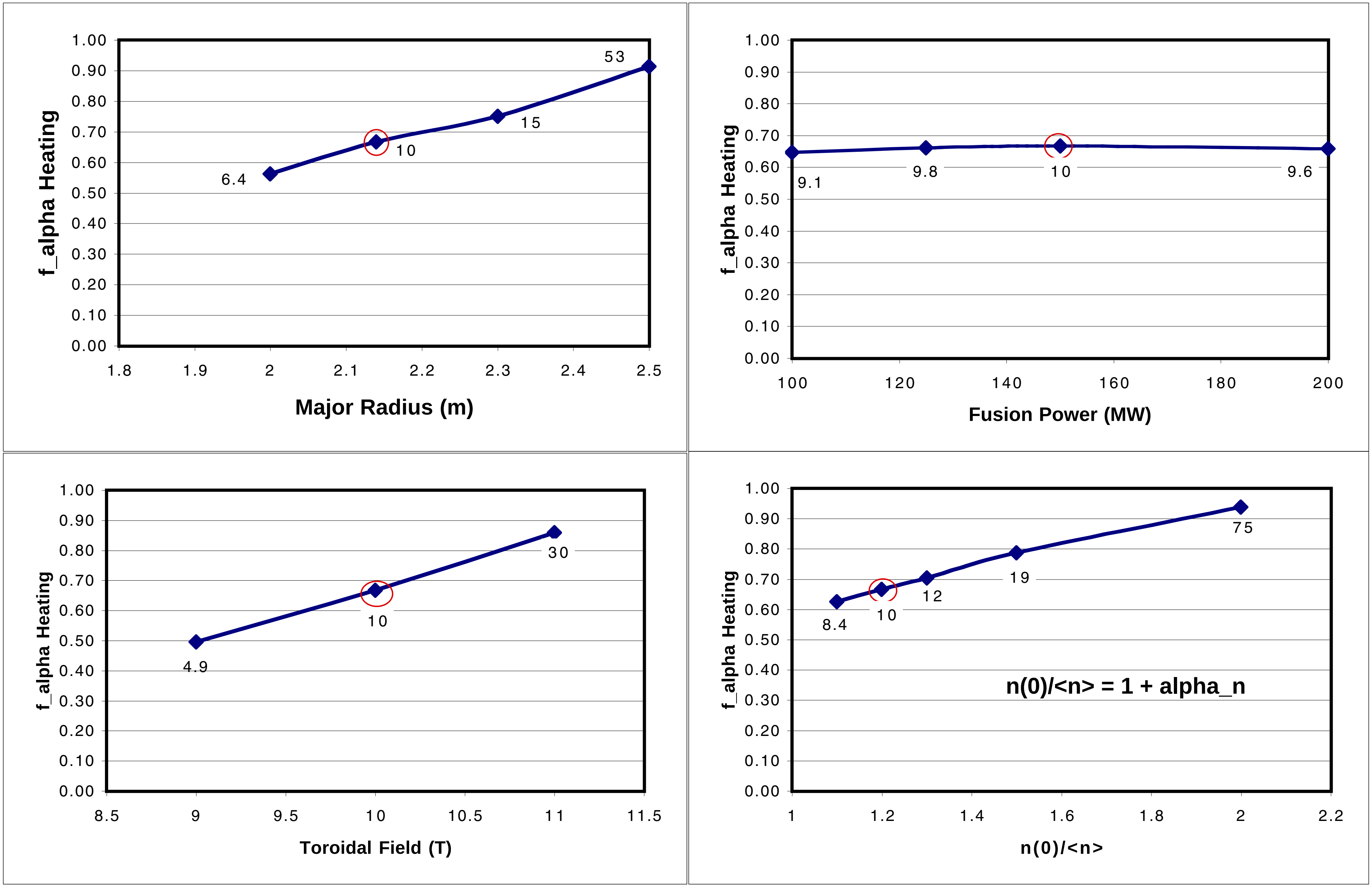


Optimizing The FIRE Design Point

	Base	Base	Higher B	Shaping	Size	FIRE*
R_o, plasma major radius, m	**2.00**	**2.00**	**2.00**	**2.00**	**2.14**	
a, plasma minor radius, m	**0.525**	**0.525**	**0.525**	**0.556**	**0.595**	
R_o/a, aspect ratio	**3.81**	**3.81**	**3.81**	**3.60**	**3.60**	
κ_{95}, plasma elongation at 95% flux	1.77	1.77	1.77	1.77	1.77	
δ_{95}, plasma triangularity at 95 % flux	**0.40**	**0.40**	**0.40**	**0.50**	**0.4**	
q95	3.03	3.03	3.03	3.05	3.05	
Bt, toroidal magnetic field at R_o, T	**10**	**10**	**12**	**10**	**10**	
Ip, plasma current, MA	**6.44**	**6.44**	**7.71**	**7.71**	**7.7**	
li(3), internal plasma inductance	0.80	0.80	0.80	0.80	0.80	
Bootstrap current fraction, approx.	0.31	0.31	0.24	0.26	0.27	
<ne>, 10^20 /m^3, volume average	4.22	4.22	5.40	4.83	4.22	
α_n, densiy profile peaking = 1 + α_n	**0.5**	**0.5**	**0.2**	**0.2**	**0.2**	
<n>l/Greenwald	**0.65**	**0.65**	**0.65**	**0.65**	**0.65**	
<T>n, density weighted average temperature, keV	7.3	7.4	6.4	6.7	6.84	
T(0), central temperature, keV	11.6	11.7	10.9	11.4	11.7	
α_T, temperature profile peaking = 1+ α_T	1	1	1	1	1	
Impurities, Be; Hi Z, %	3;0	3;0	3;0	3;0	3;0	
taup*(He)/tauE	5	5	5	5	5	
Alpha ash concentration, %	1.69	2.40	2.25	2.28	2.3	
Zeff	1.39	1.41	1.41	1.41	1.41	
ν*, collisionality at q = 1.5	0.051	0.049	0.06	0.048	0.048	
Pext (MW)	30	15	15	15	15	**27**
P_fusion (MW)	150.6	151.5	149.2	150.6	150	
Pheat = Pext + Palpha - Prad(core), (MW)	52.0	37.0	34.2	35.3	35.6	**47.6**
Pheat/P_{th}(L->H)	**2.33**	**1.66**	**1.20**	**1.46**	**1.41**	
tauE	0.52	0.73	0.88	0.89	0.97	
ITER98H(y,2)-Multiplier	**1.03**	**1.16**	**1.01**	**1.09**	**1.11**	**1.00**
ITER89P-Multiplier	2.10	2.52	2.37	2.52	2.52	**2.16**
nd(0)T(0)tau_E, 10^20m^-3 kev s	31.9	45.3	51.9	49.3	47.9	
Q_DT	**5.0**	**10.1**	**9.9**	**10.0**	**10.0**	**5.5**
Plasma current redistribution time, s	11.7	11.8	9.6	11.2	13.3	
W(MJ), plasma kinetic energy	26.8	27.1	30.1	31.6	34.6	
Fast alpha energy/Plasma W, %	7.8	7.9	6.1		7	
Beta_total, %	2.5	2.56	1.94	2.62	2.35	
Beta_N	**2.1**	**2.1**	**1.58**	**1.89**	**1.82**	

Sensitivity Scans on FIRE*

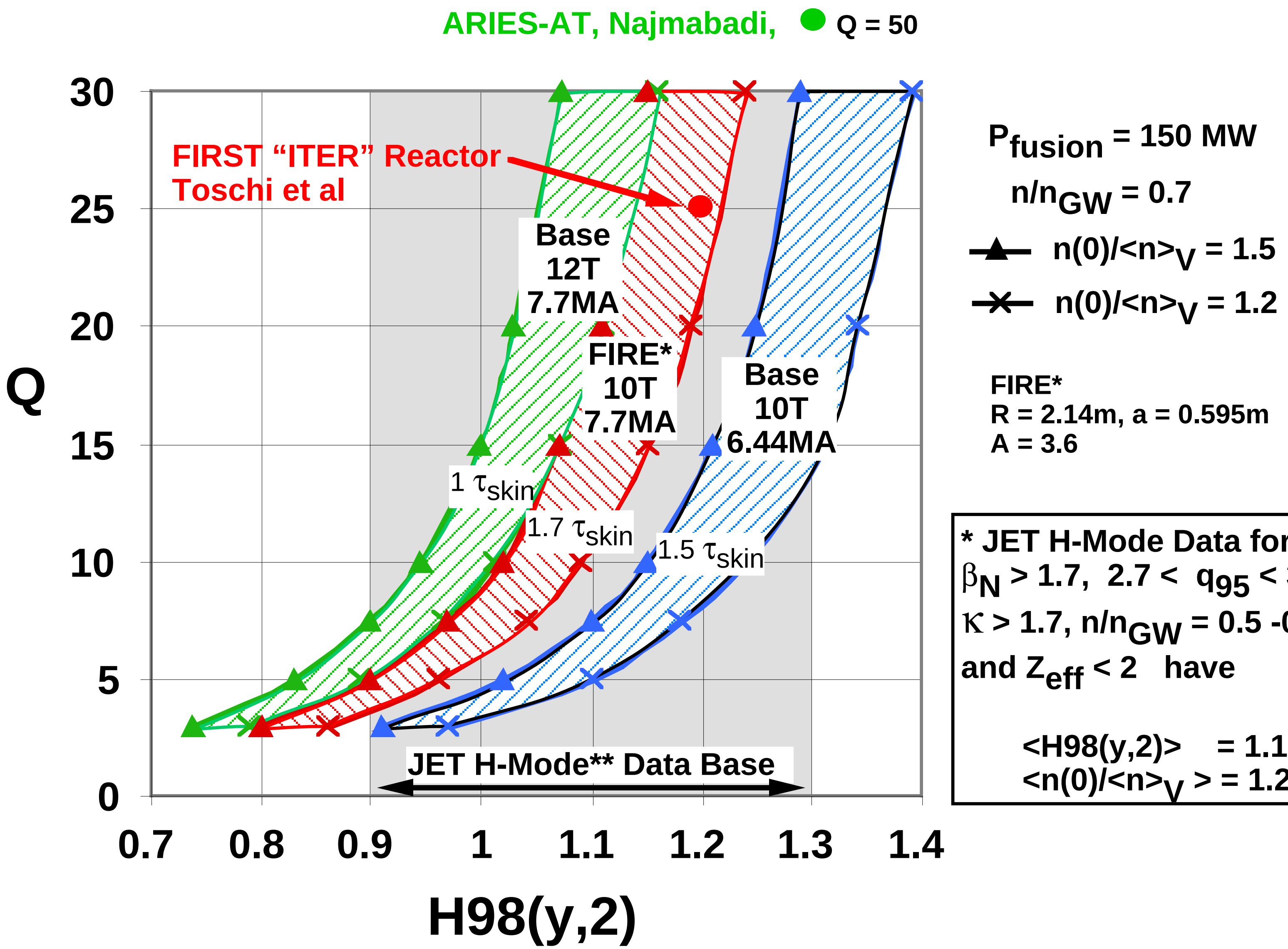
(A = 3.60, κ95 = 1.77, δ95 = 0.4, ITER98(y,2), H = 1.027, n/nGW = 0.7, nBe = 0.4%)



Note: kappa area would make H = 1.01

FIRE* Scans Compare

Projections of FIRE Compared to Envisioned Reactors

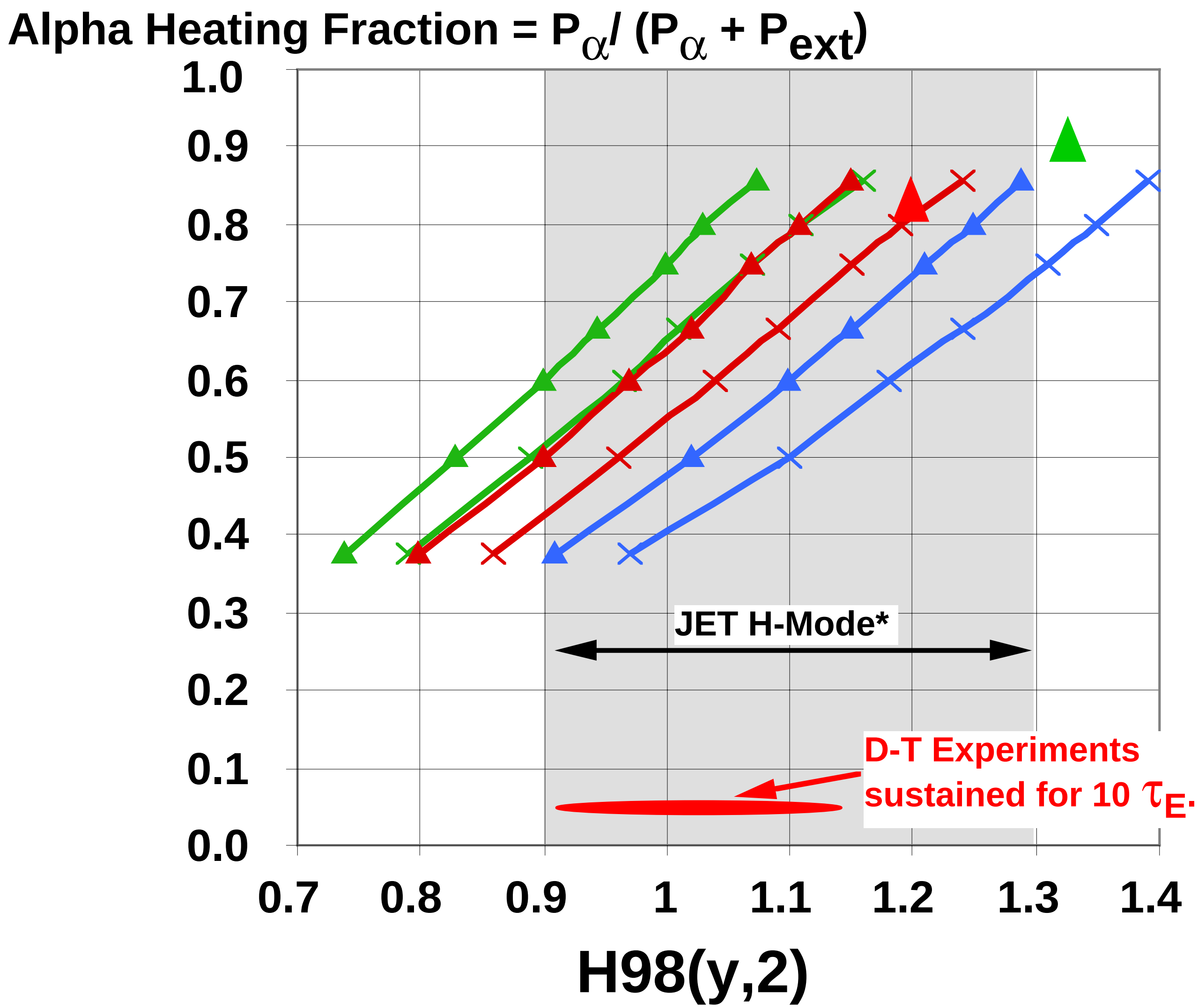


FIRE*
R = 2.14m, a = 0.595m
A = 3.6

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

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

Projections of FIRE Performance as Confinement is Enhanced Toward that Required for Attractive Reactors



ARIES-AT
Najmabadi, IAEA 2000

FIRST "ITER" Reactor
Toschi, SOFT 2000

FIRE Projections

- Base 12T, α_n = 0.5
- Base 12T, α_n = 0.2
- FIRE* 10T, α_n = 0.5
- FIRE* 10T, α_n = 0.2
- Base 10T, α_n = 0.5
- Base 10T, α_n = 0.2

P_{fusion} = 150 MW

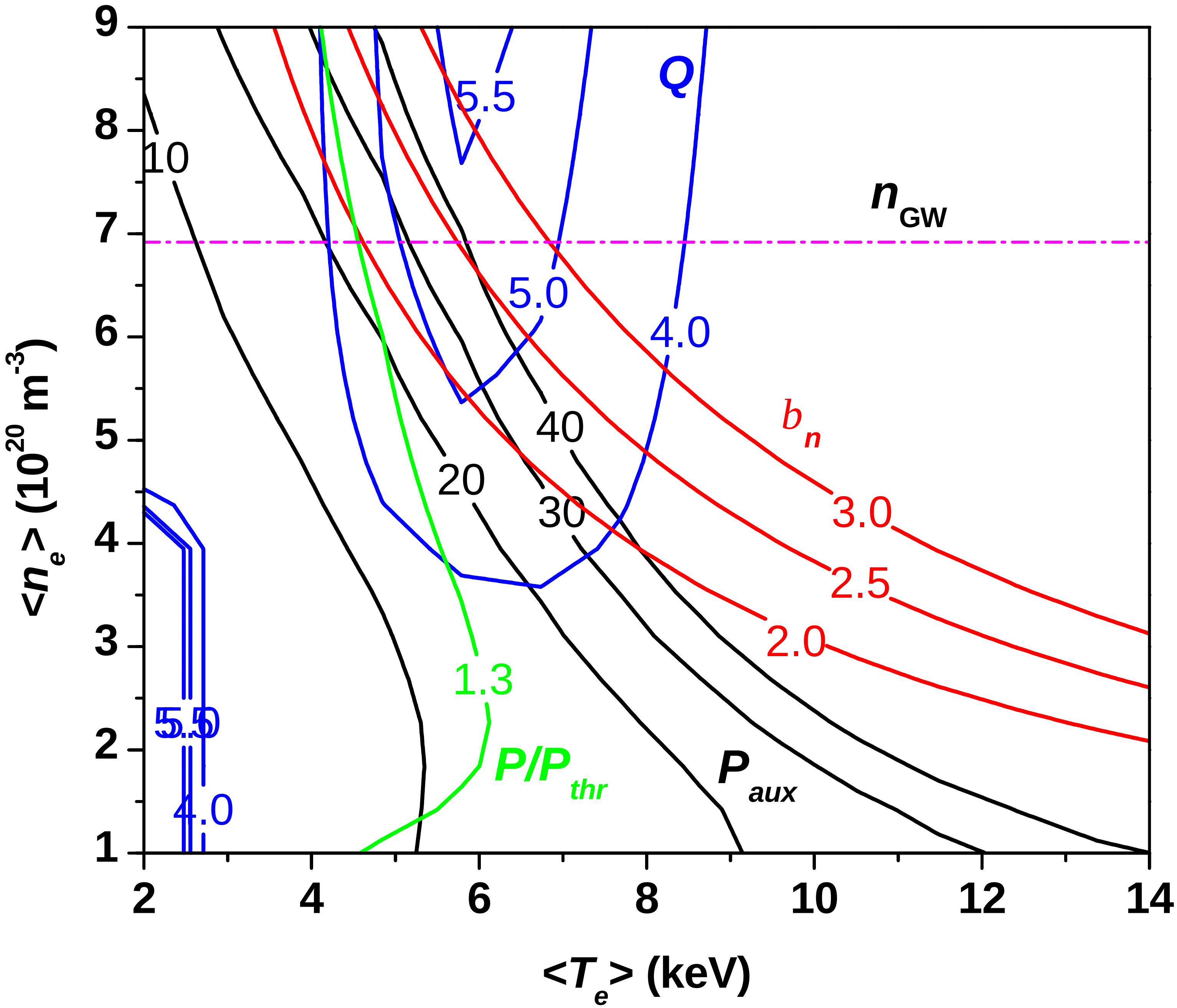
n/n_{GW} = 0.7

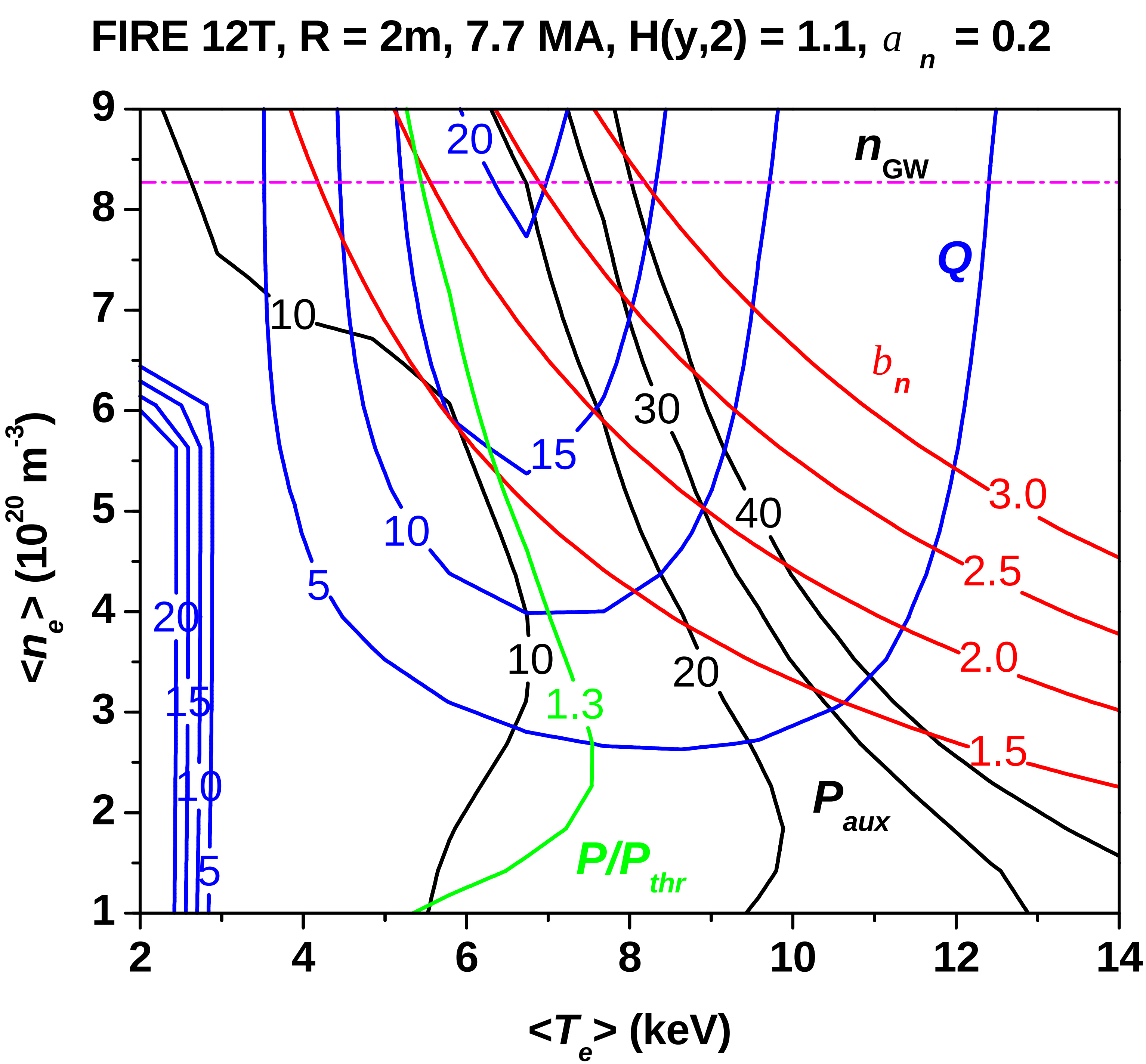
$n(0)/\langle n \rangle_V = 1 + \alpha$_n

* JET H-Mode Range for
$\beta_N > 1.7$, $2.7 < q_{95} < 3.5$
$\kappa > 1.7$, $Z_{eff} < 2$

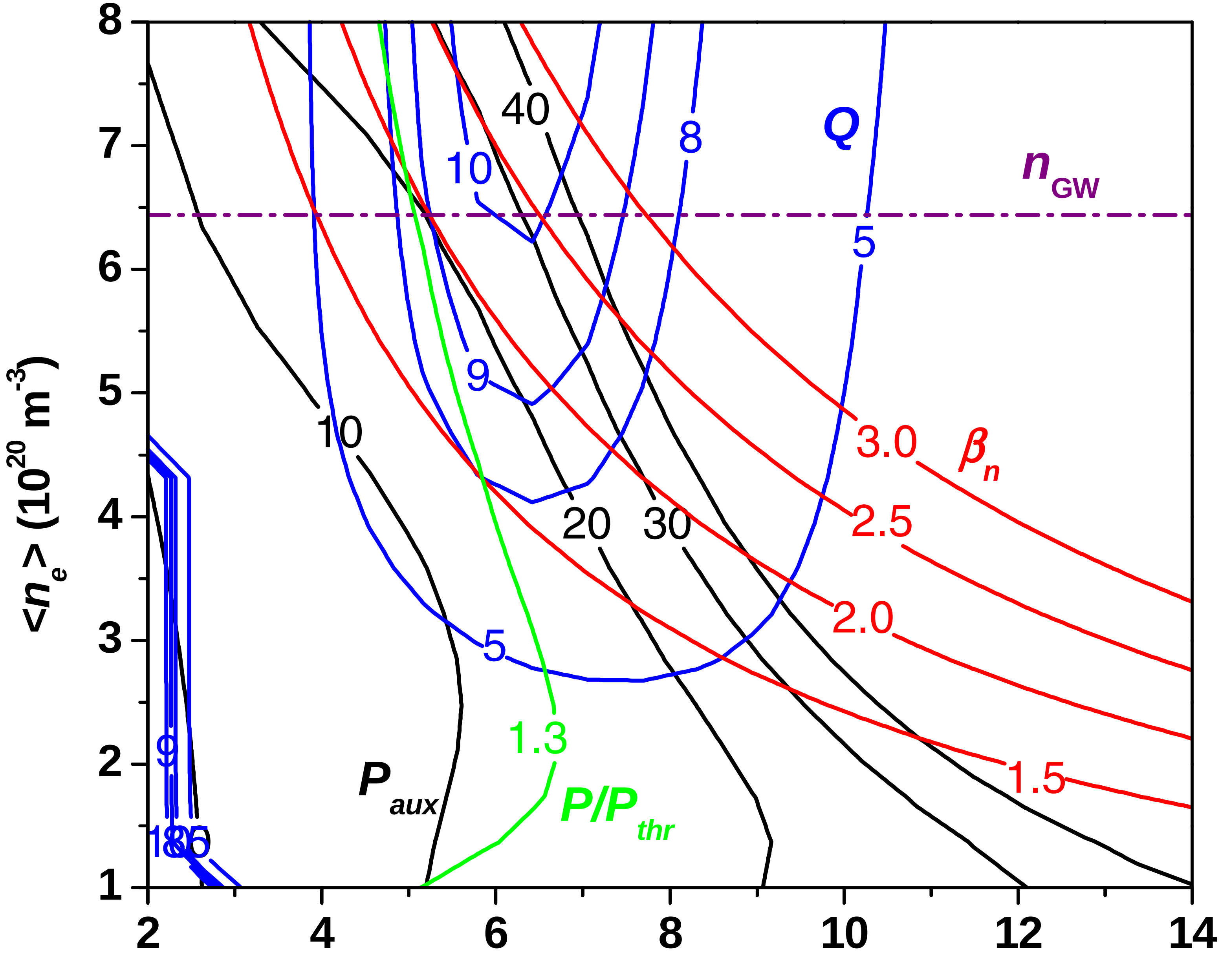
Alpha heating fraction, the science goal, is less sensitive to confinement uncertainty.

FIRE Baseline 10T, R = 2.0m, H(y,2) = 1.1, a_n = 0.2




FIRE 12T, R = 2m, 7.7 MA, H(y,2) = 1.1, a n = 0.2
n GW
Q
b n
P aux
P/P thr
<n e > (10 20 m -3)
<T e > (keV)
10
30
40
20
10
20
15
10
5
20
15
10
5
1.3
3.0
2.5
2.0
1.5
9
8
7
6
5
4
3
2
1
2
4
6
8
10
12
14

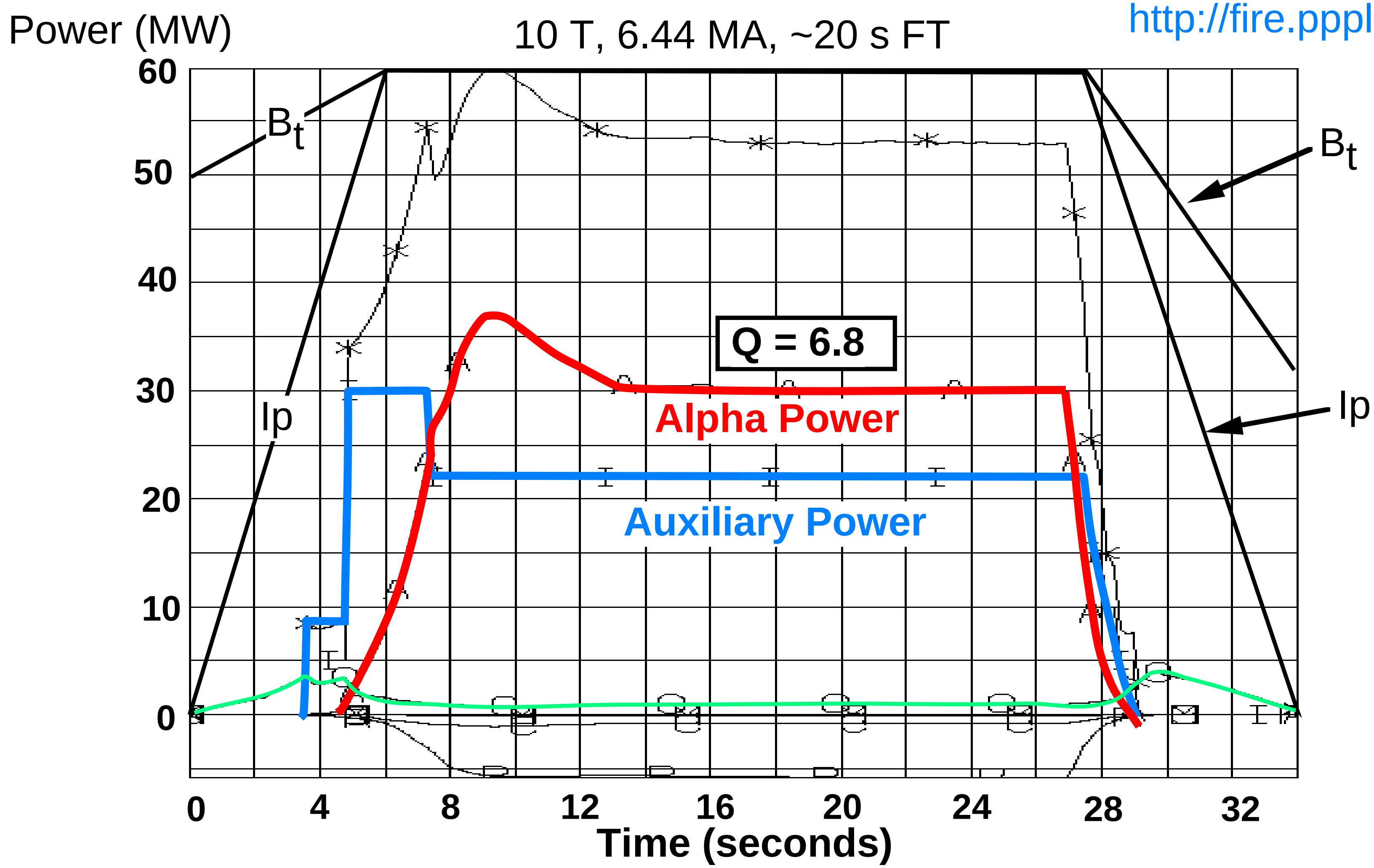
FIRE* 10T, R=2.14m, 7.7 MA, H(y,2) = 1.1, α_n = 0.2



pop*H1p1an02.pdf

1 1/2-D Simulation of Burn Control in FIRE

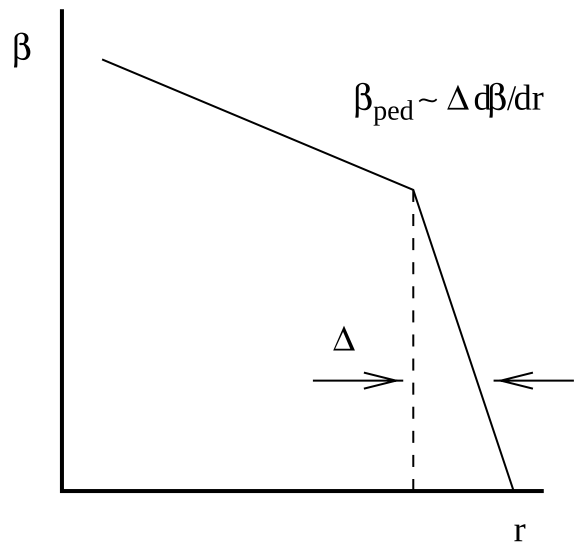
http://fire.pppl.gov



- ITER98(y, 2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.25 and n/n_{GW} = 0.59
  - Pulse Duration ≈ 30 τ_E, 6 τ_{He} and ~1.5 τ_{skin}

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)**



- **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))

Some of the new reactor designs may have significantly improved pedestal temperatures

Using this T_{ped} formula (with a $\Delta \propto \rho_\theta$ assumption), and other pedestal scalings also, to scale from JET to some proposed reactor designs:

	R m	a m	B T	I_p MA	n_{ped} $10^{20}/m^3$	$\frac{n_{ped}}{n_{Gr}}$	$\frac{n_{ped}}{\langle n\rangle}$	κ_{95}	δ_{95}	T_{ped} keV if $\Delta \propto \rho_\theta\sqrt{\epsilon}$	T_{ped} keV if $5\delta^2$	T_{ped} keV if $\Delta \propto \sqrt{Rq\rho}$
JET-norm	2.92	0.91	2.35	2.55	0.4	0.40	~ 1	1.61	.17	2.1	2.1	2.1
ITER-96	8.14	2.80	5.68	21.0	1.3	1.52	1	1.60	.24	0.20*	0.18*	1.5*
lower n_{ped}	8.14	2.80	5.68	21.0	0.6	0.70	.70	1.60	.24	0.94*	0.83*	4.2*
ITER-FEAT	6.20	2.00	5.30	15.1	0.58	0.48	.65	1.70	.33	2.9	2.1	7.4
FIRE	2.0	0.53	10.0	6.44	3.6	0.48	.65	1.77	.40	4.8	3.0	6.7

* should add $(nT)_{sol}/n_{ped}$ which could be as high as ~ 0.5 keV.

Encouraging that even with the pessimistic pedestal scaling ($\Delta \propto \rho_\theta$), it may be possible to get high pedestal temperatures by going to stronger plasma shaping, higher field, smaller size, and modest density peaking.

Important to have ability at low density relative to Greenwald while maintaining confinement and detached divertor.

From G. Hammett , W. Dorland , M. A. Beer, M. Kotschenreuther at the UFA_Burning Plasma Science Workshop December 11, 2000

(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.

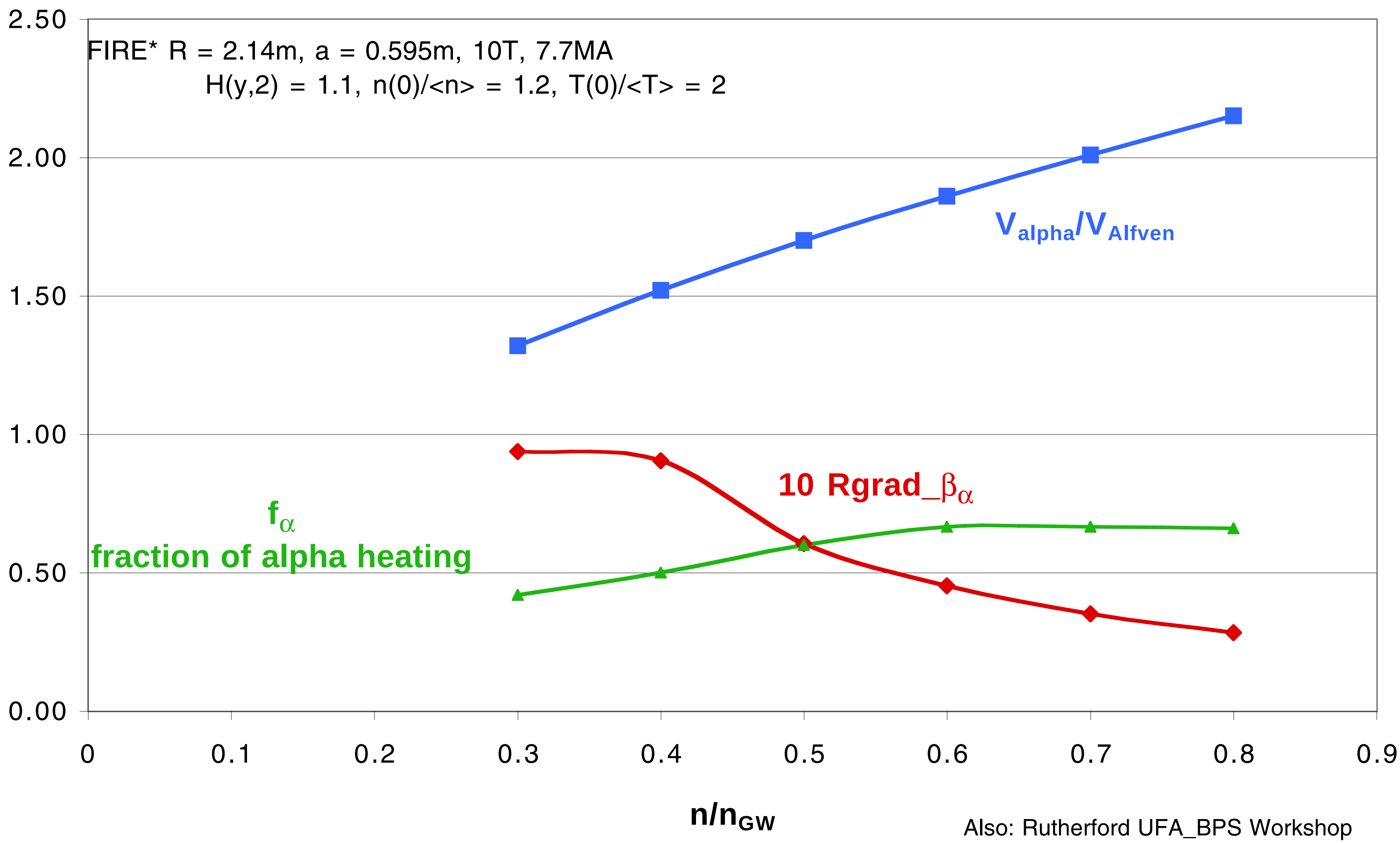
$\langle n_e \rangle / n_{\mathrm{Greenwald}} = 0.74$. **Modest density peaking,** $n_0/\langle n_e \rangle = 1.18$, $n_{ped}/\langle n_e \rangle = 0.65$.
$n(r) = (n_0 - n_{ped})(1 - (r/a)^2)^{0.5} + n_{ped}$.

P_{aux} **adjusted to keep** $P_{net} \geq 1.2 P_{99L \to H}$ **= 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

From G. Hammett , W. Dorland , M. A. Beer, M. Kotschenreuther
at the UFA_Burning Plasma Science Workshop December 11, 2000

Fast Alpha Parameters for FIRE*



Also: Rutherford UFA_BPS Workshop

Summary of Confinement Projections and Impact on Design Point

- The performance of the 6.44 MA baseline using ITER98H(y,2) scaling is not adequate to address the FIRE mission needs.

- Increasing the capability of FIRE to 7.7 MA appears to give adequate performance while not significantly increasing the cost.

- There are two possibilities under consideration that require only straightforward changes.

    1. Baseline FIRE(R = 2.0m, a = 0.525m) at 12T provides 7.7 MA and a flat-top of 12 s (~ 1skin time)

    2. FIRE* (R = 2.14m, a = 0.595m) at 10T provides 7.7 MA and a flat-top time of ~ 20 s (1.7 skin times)

- Higher payoff(higher risk) design options like bucking and wedging are under consideration with the goal of reducing power needs while extending the pulse.