Physics Analysis of FIRE

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with input from

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General Atomics

PPPL
PRINCETON PLASMA
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Outline

- Rational for the device design
- Nominal operating point and reference discharge
- Perturbation studies
- Heating, CD, and Fueling
- MHD stability and Energetic Particle Modes
- Device Flexibility and AT modes
- Sensitivity to Energy Confinement Time
- Summary

A simple systems power balance analysis provides a rational for optimizing the design point

Confinement (Elmy H-mode) ITER98(y,2):

$$\tau_E = 0.144\ I^{0.93}\ R^{1.39}\ a^{0.58}\ n_{20}^{0.41}\ B^{0.15}\ A_i^{0.19}\ \kappa^{0.78}\ P_{heat}^{-0.69}\ H(y,2)$$

Density Limit: $n_{20} < 0.75\ n_{GW} = 0.75\ I_P/\pi a^2$

H-Mode Power Threshold: $P_{th} > (2.84/A_i)\ n_{20}^{0.58}\ B^{0.82}\ R\ a^{0.81}$

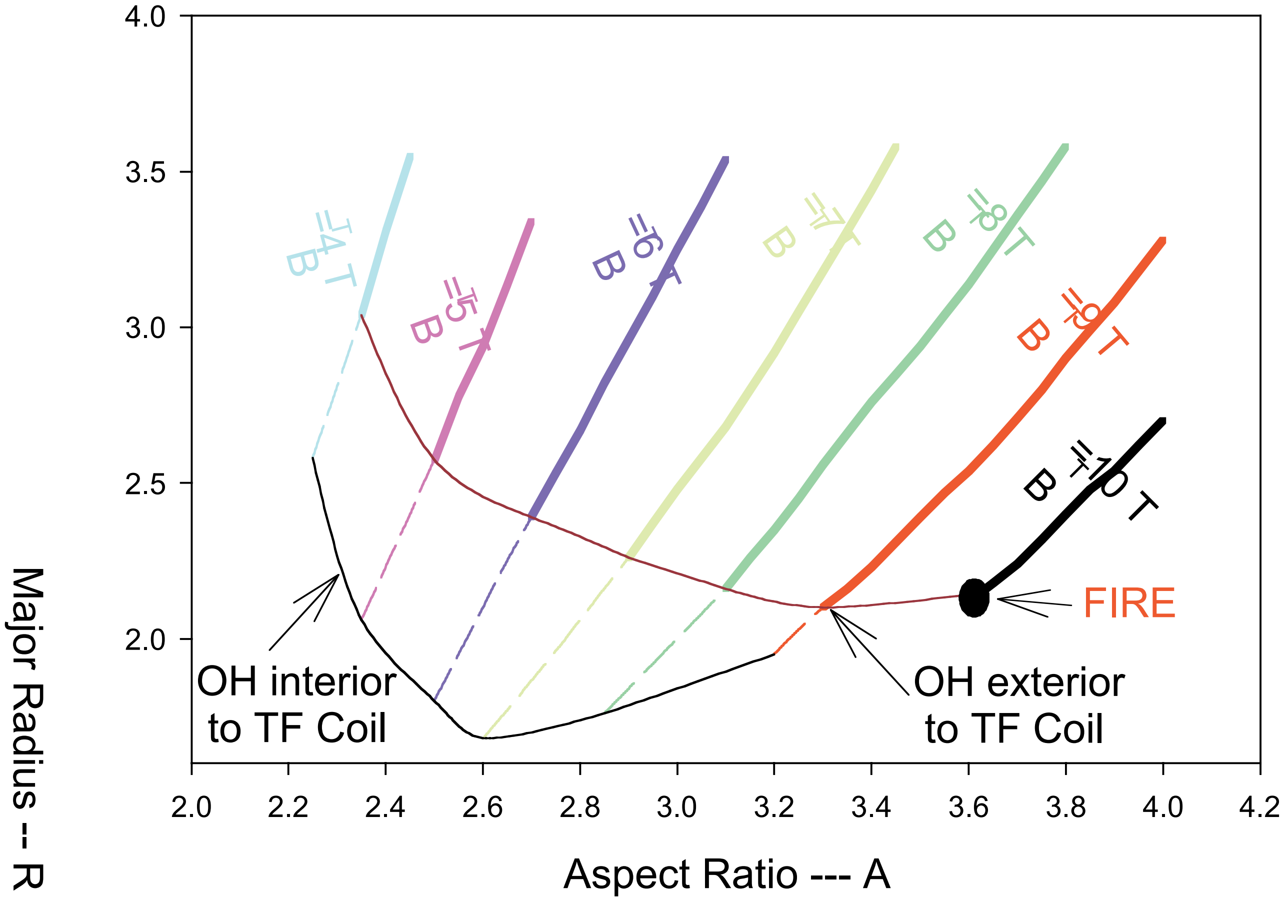
MHD Stability: $\beta_N = \beta / (I_P/aB) < 1.8$

Engineering Constraints:
1. Flux swing requirements in OH coil (V-S)
2. Coil temperature not exceed 373° K
3. Coil stresses remain within allowables

Configuration Concept:
1. OH coils <u>interior</u> to TF coils, or
2. OH coils <u>exterior</u> to TF coils

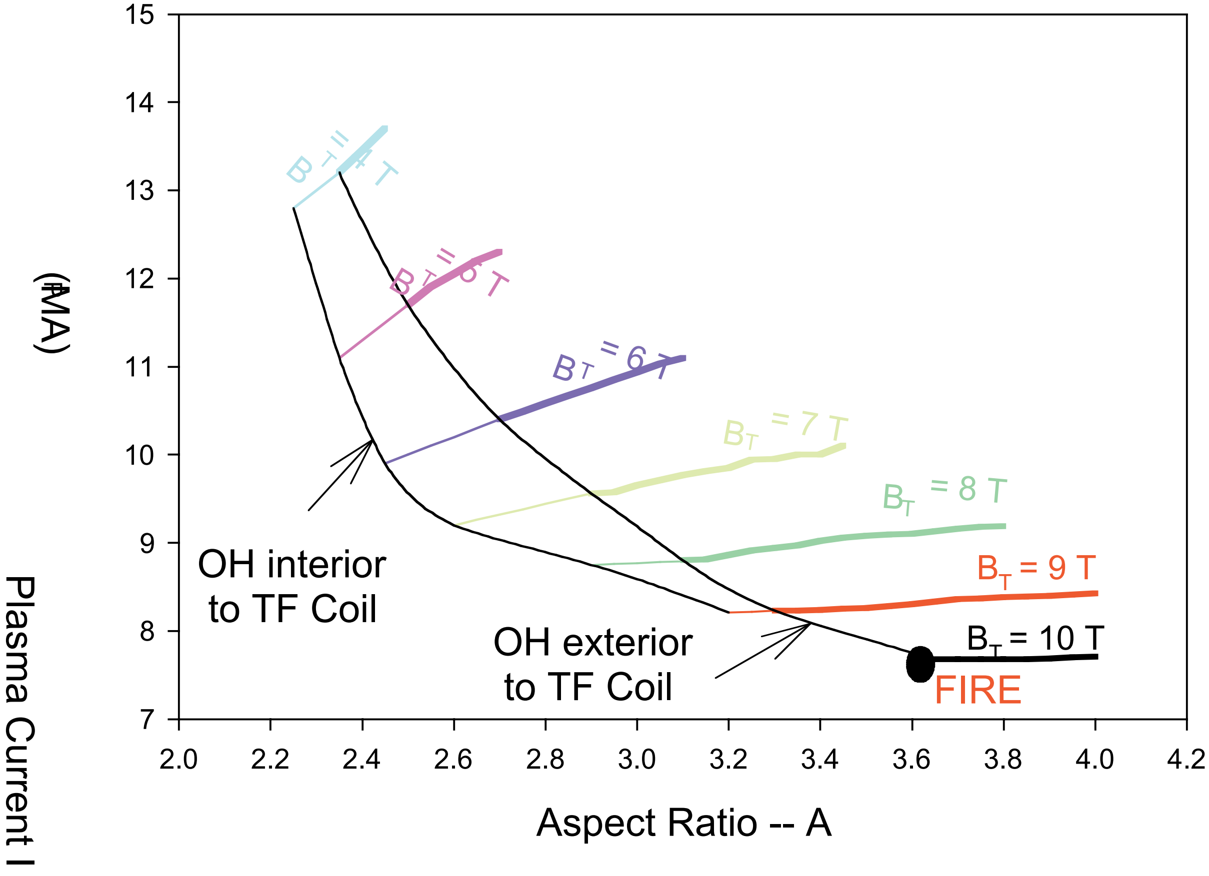
Major Radius required for power balance vs A

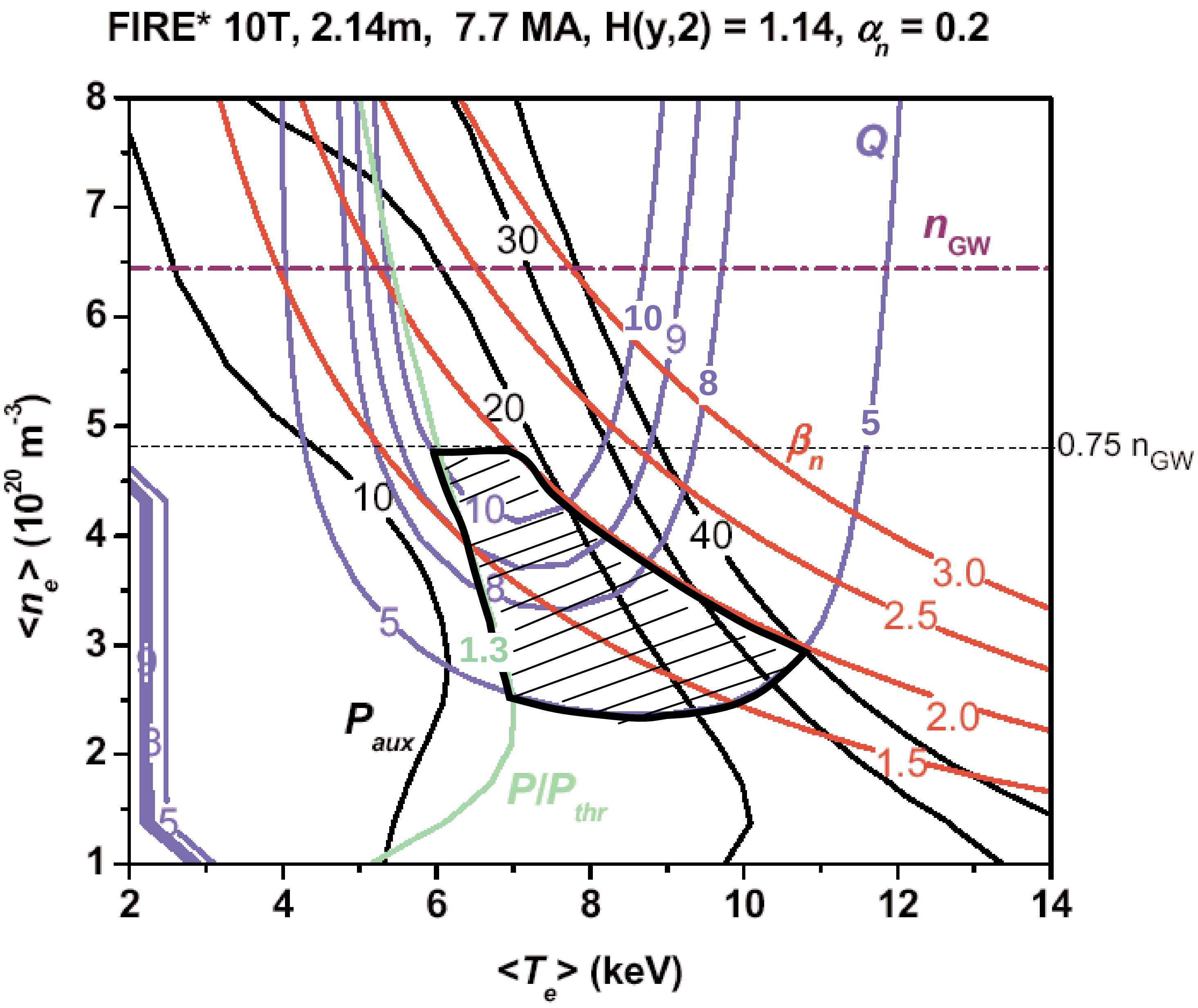
β_N = 1.5, q_e = 3.13, Q=10, κ=1.8, $H_{y,2}$=1.0, τ_{flat} = 20 s



Plasma Current required for power balance vs A

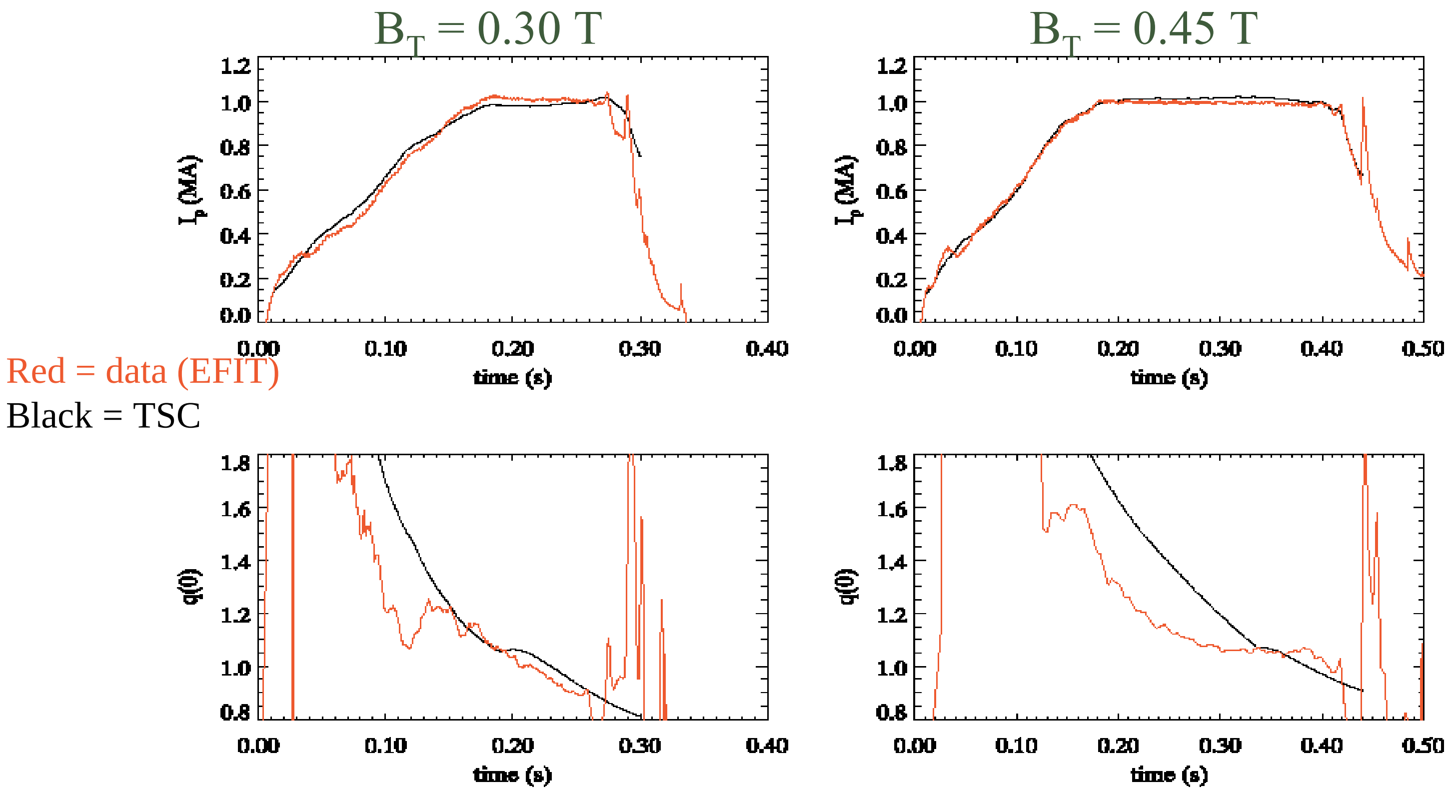
$\beta_N = 1.5$, $q_e = 3.13$, $Q=10$, $\kappa=1.8$, $H_{y,2}=1$, $\tau_{flat} = 20$ s





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

TSC was used recently to model the NSTX current evolution for a Toroidal Field scan series in order to establish the correlation between .


$B_T = 0.30$ T

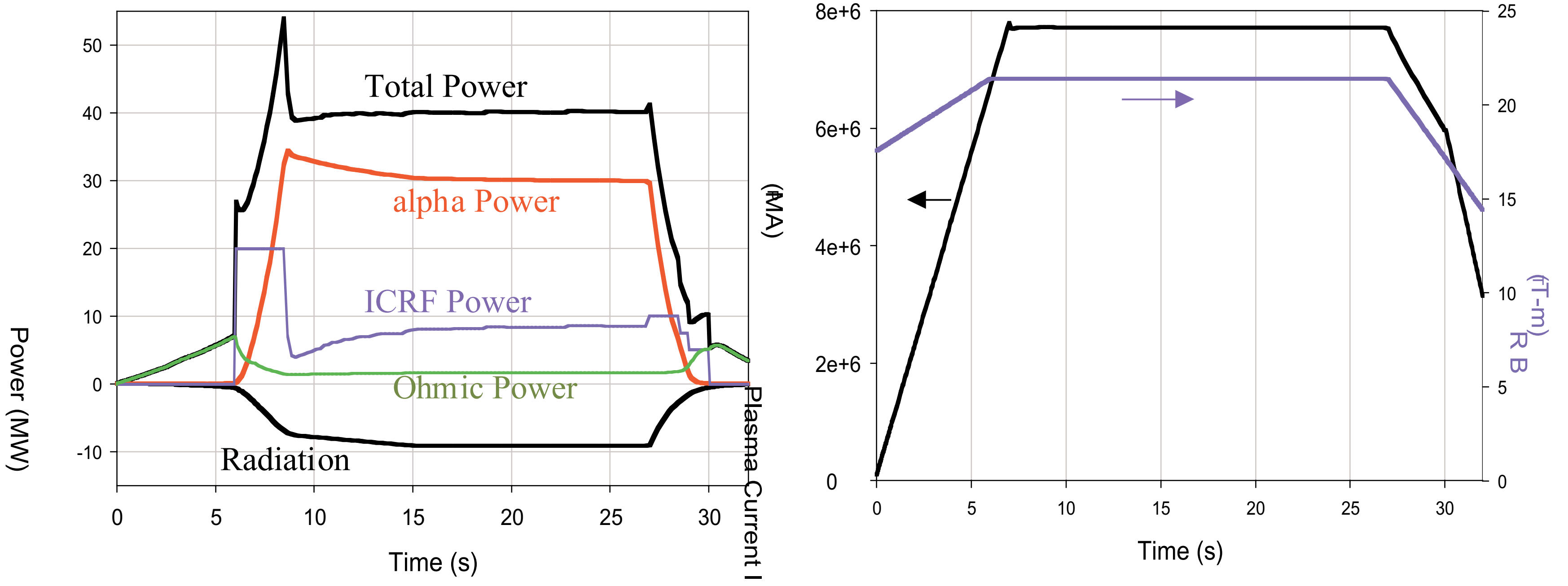
$B_T = 0.45$ T

Red = data (EFIT)
Black = TSC

- TSC could reproduce the plasma current evolution using only the experimental values of the PF current trajectories. Everything else is predictive

- Supported the correlation between the q=1 surface and termination of the current

TSC Simulation of Reference FIRE* Discharge with Burn Control



$\beta_P = 0.70$ $n_e = 5 \times 10^{20}$ $\tau_E = W/P =$ 800 ms $= 0.8\ H_{98(y,2)}$ $n_\alpha = 10^{19}$

$\beta_T = 2.1\%$ $T_{e0} = 11$ keV $= W/(P-P_{RAD}) =$ 1100 ms $= 1.1\ H_{98(y,2)}$ $\beta_\alpha = 0.2\%$

$\beta_N = 1.6\ \%$ $W = 32$ MJ $\ell_i\,(1) = 1.08$ $\ell_i\,(3) = 0.9$

Why a 20 sec discharge ?

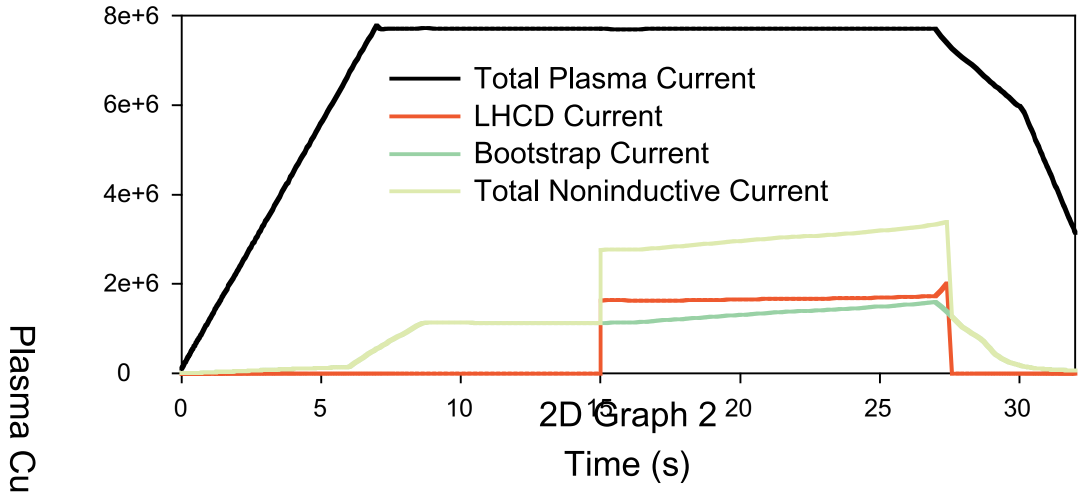
$\tau_E \sim 1$ sec (energy confinement time)

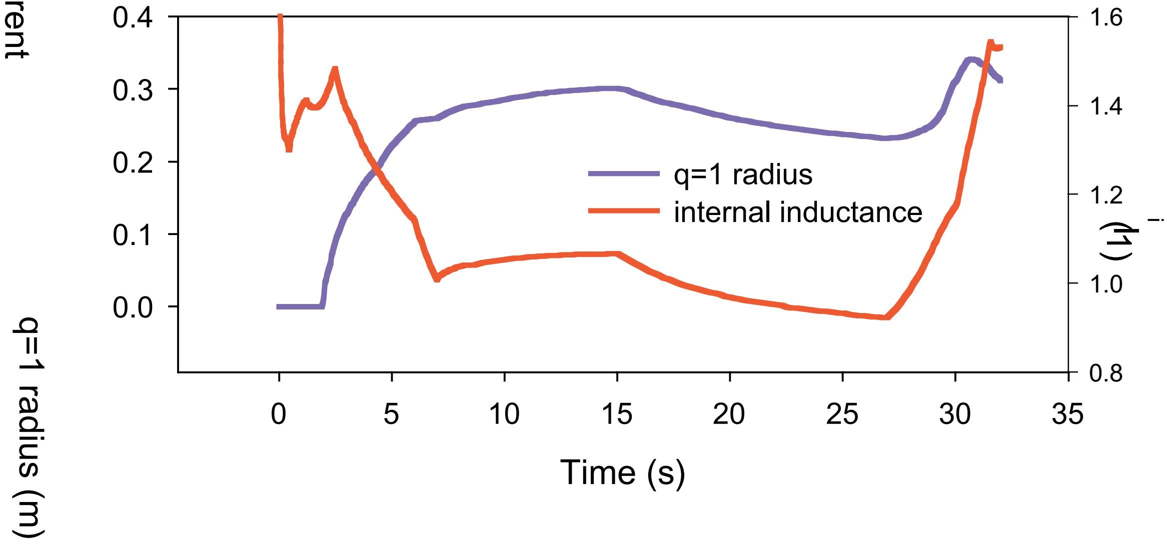
Other timescales of interest:

- Current redistribution time ~ 10 s
- Burn control time ~ 5-10 s
- Helium Ash buildup time ~ 5-10

These transient phenomena and others being studied with TSC

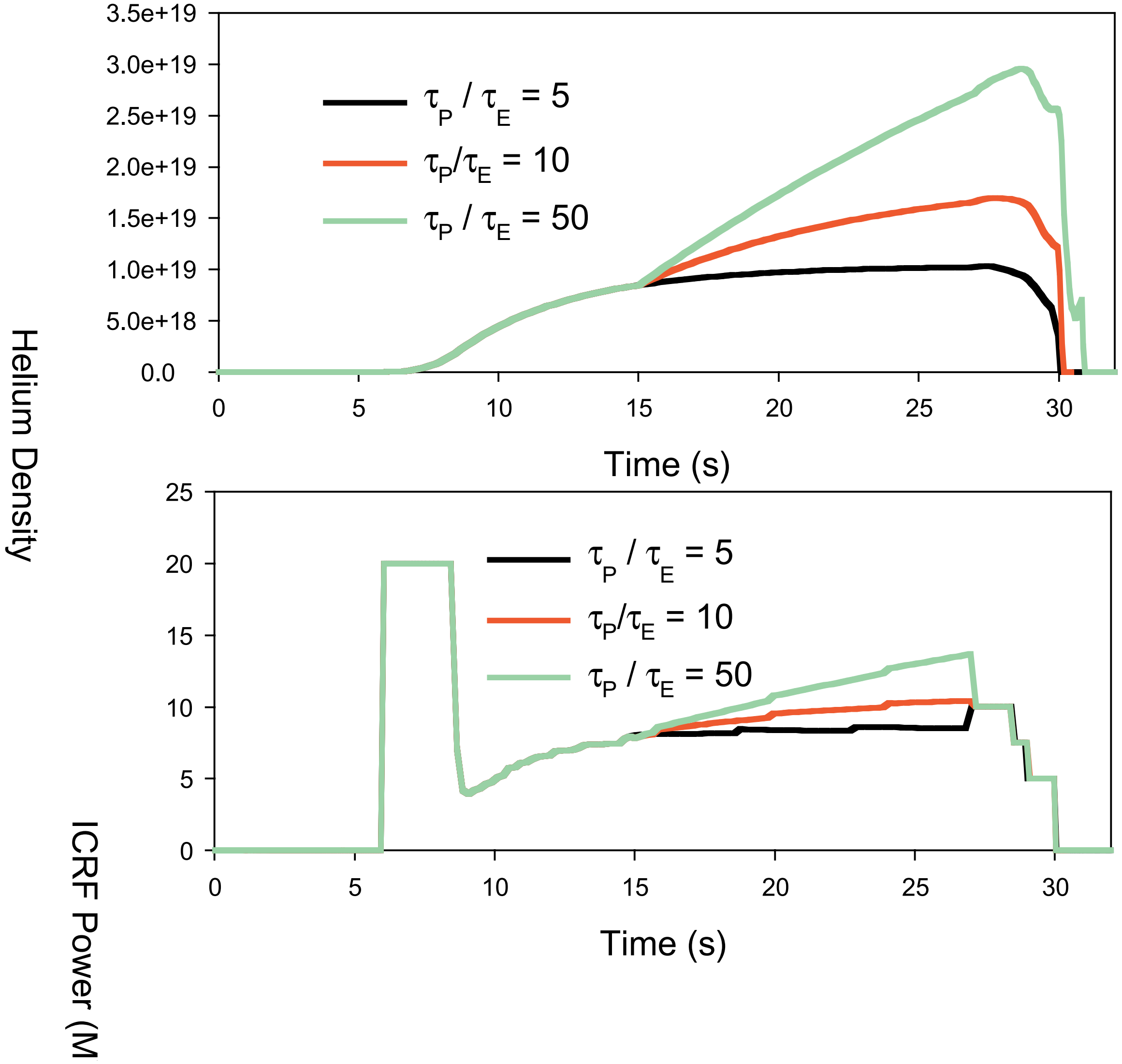
TSC simulation of LHCD added to reference discharge shows it takes 10-20 sec to equilibrate





- 1.75 MA LHCD turned on at t=15 s
- requires over 10 sec for current profile to adjust as seen by q=1 radius and l_i

Comparison of 3 TSC FIRE simulations where τ_P is changed suddenly at t=15 from $5\tau_E$ to $10\tau_E$ or $50\tau_E$

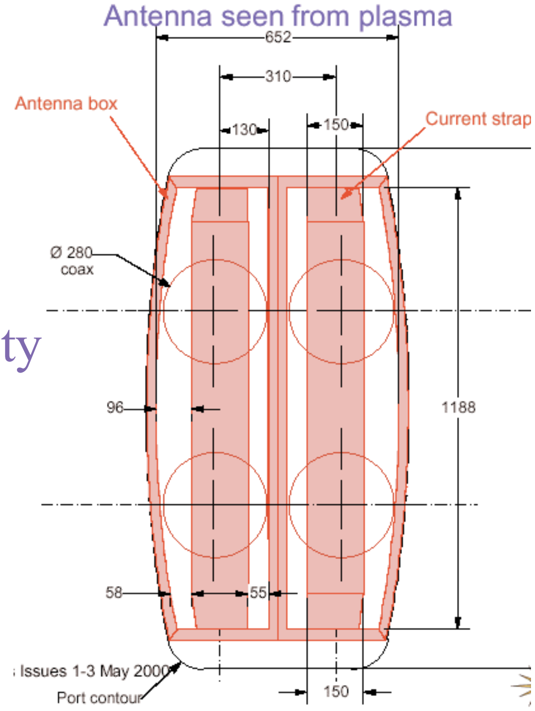


- natural equilibration time for helium ash is 10-20 sec
- note, shows the importance of particle control in divertor

← Power required to keep stored energy at 40 MJ

Fire Heating and CD systems

- **Ion Cyclotron system**
    - Baseline system, heating only
    - 30 MW to the plasma
    - 100 – 150 MHz for $2\Omega_D$ Ω_T , H or He^3 minority
- **High Frequency Fast Wave**
    - Optional /Partial replacement for ICRH
- **Lower Hybrid System**
    - Possible upgrade
    - 8 GHz , 2-ports for 25 MW total



2-strap ICRH antenna in each of 4-ports

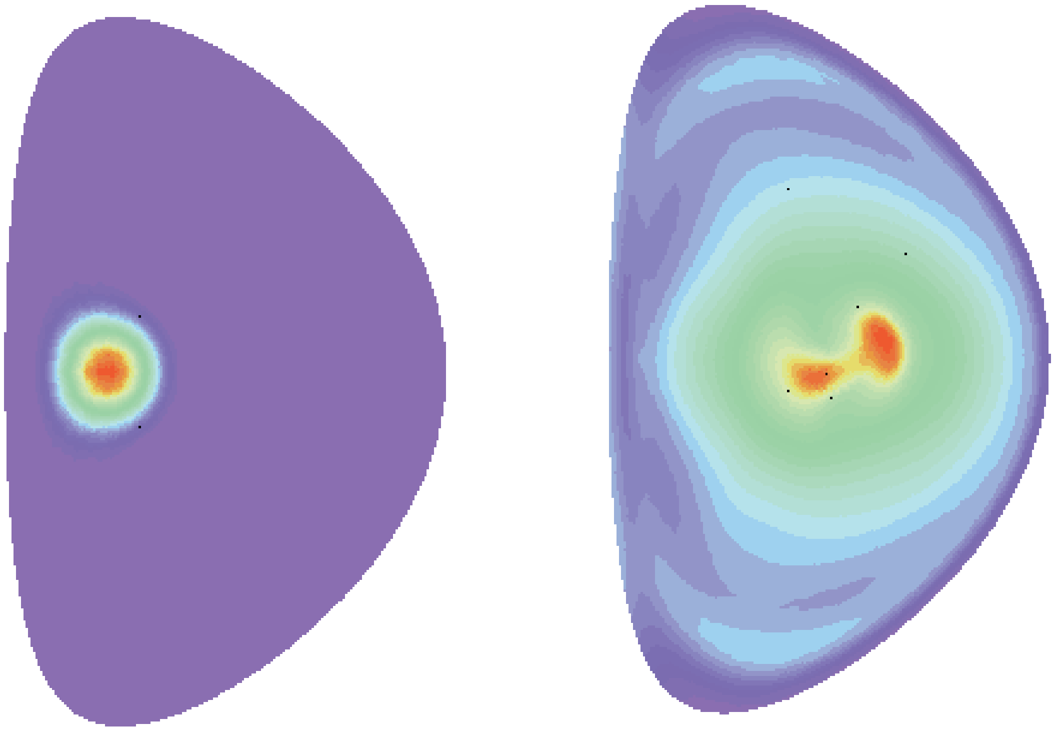
FIRE is considering both vertical and inside launch to allow deep pellet penetration

- first 3D simulation of this experimentally discovered phenomena was in M3D

[Strauss, Park, et al, Phys. Plasmas **7** (2000) 250]

- led to development of 2D model now in **TSC** code

[Jardin, Schmidt, et al, Nucl. Fusion **39** (2000) 923]



MHD Stability of Baseline Discharge

➔ Baseline operating regime has very low β_N (~1.5 to 2.0) and qe > 3.1, and therefore has good stability margins

However, there are areas requiring additional R&D:

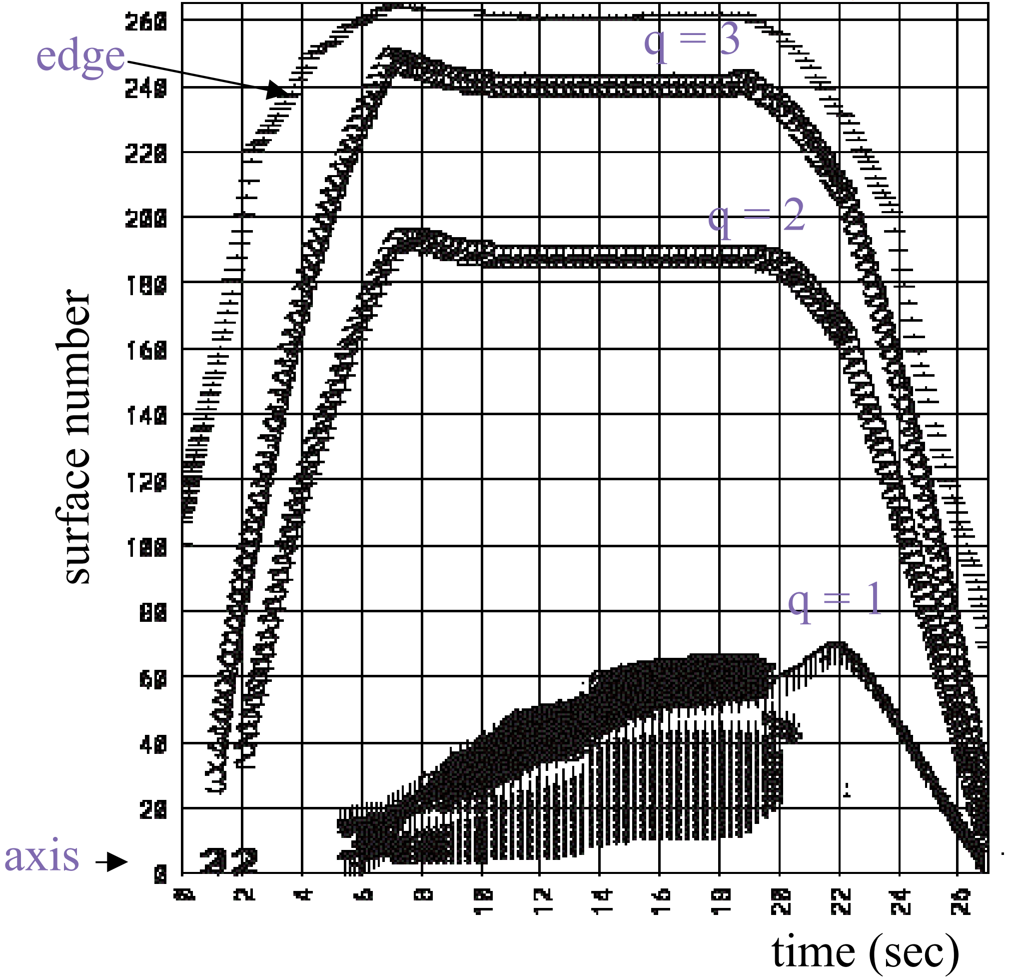
- m=1 internal mode (monster sawtooth)
- Neoclassical tearing mode (NTM)
- Edge Localized Modes (ELMs)
- Energetic particle modes
- MHD stability limits for AT modes

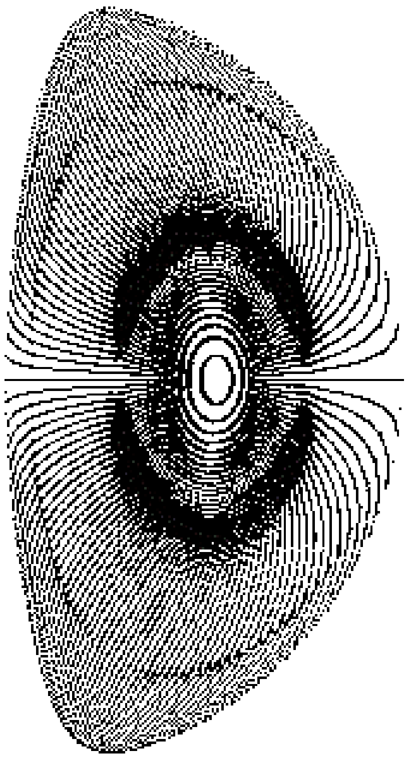
Physics Question: Role of the m=1 mode

- FIRE will have a q=1 surface at 0.3 < r/a < 0.5 and will exhibit m=1 (sawtooth)
- The question is when this mode couples to other modes and leads to a NTM or a disruption
- 3D Extended MHD simulation taking part as part of the SCIDAC initiative are studying the m=1 mode in a burning plasma, taking into account:
  - energetic particle drive,
  - kinetic stabilization,
  - 2-fluid effects, and
  - non-linear saturation mechanism
- This is one of the major thrusts of the 3D macroscopic simulations communities..similar to turbulent transport simulations in transport community
- LHCD can provide some control on this by decreasing the q=1 radius

High Field: 12 T, 7.7 MA

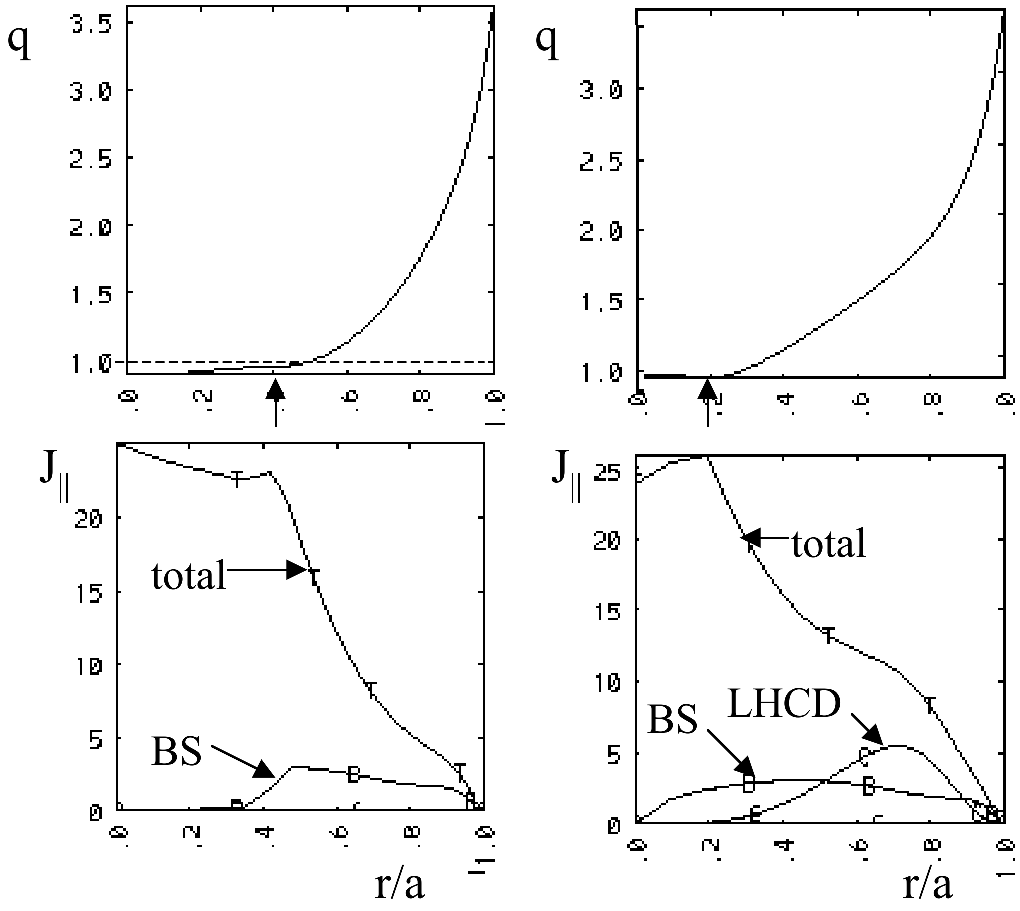
Balloon and Mercier stability





PEST unstable eigenfunction at t=12.5 sec

Radius of q=1 surface can be decreased by application of LHCD near edge

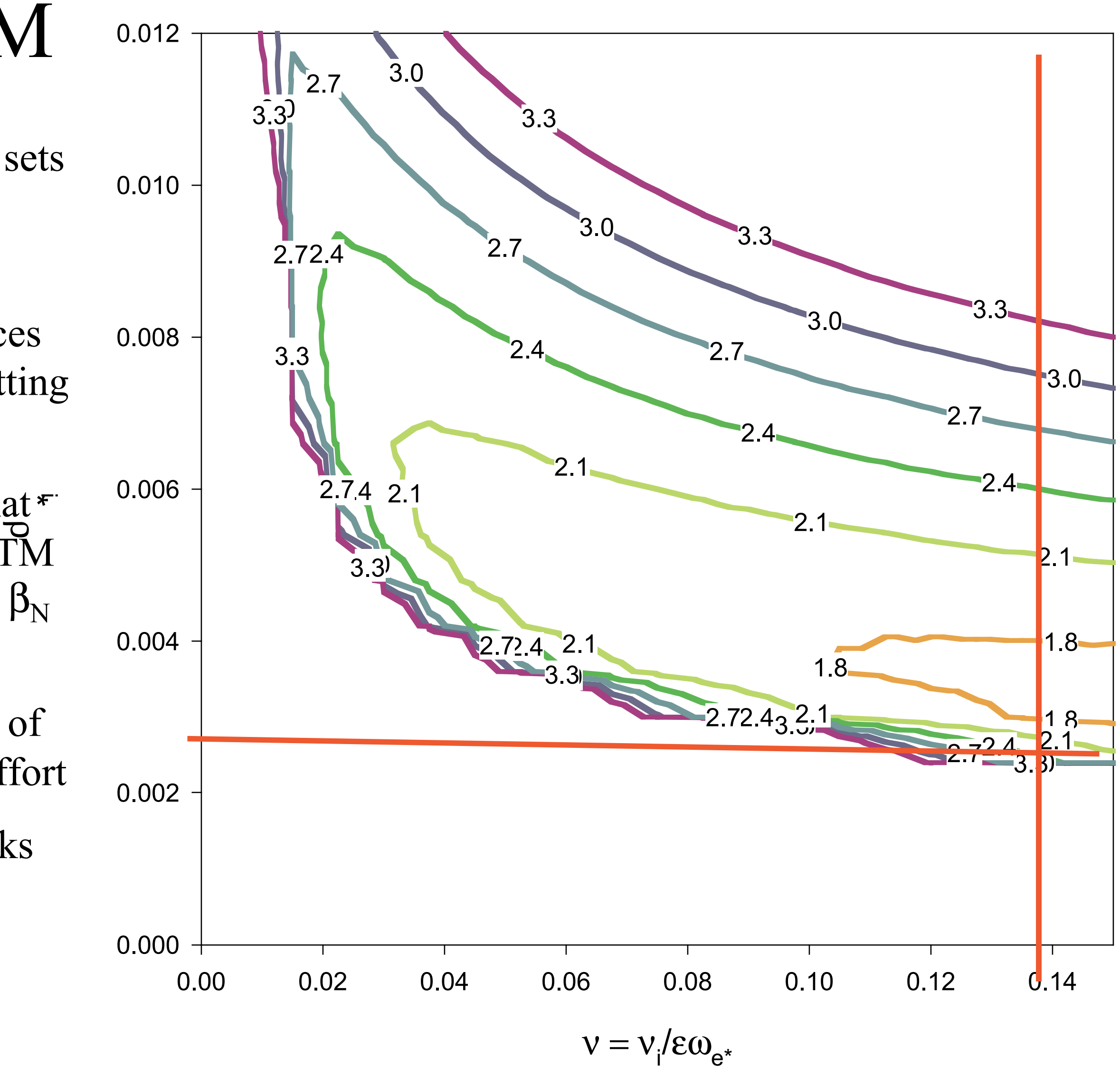


I(LHCD)	r/a(q=1)
0.0	0.425
1.0	0.35
1.5	0.30
2.0	0.20
2.35	0.10
2.55	0.00

Physics question: NTM

- neoclassical tearing mode sets β limits in many long-pulse discharges
- scaling of this to new devices largely result of empirical fitting of quasi-linear formula
- present scaling indicates that FIRE will be stable to the NTM in the ignition regimes $1.5 < \beta_N < 1.8$
- this is another major thrust of 3D macroscopic modeling effort
- LHCD active feedback looks feasible if needed (PHR)

Critical β_N fit for q=1 sawtoothed induced m/n=3/2 NTM

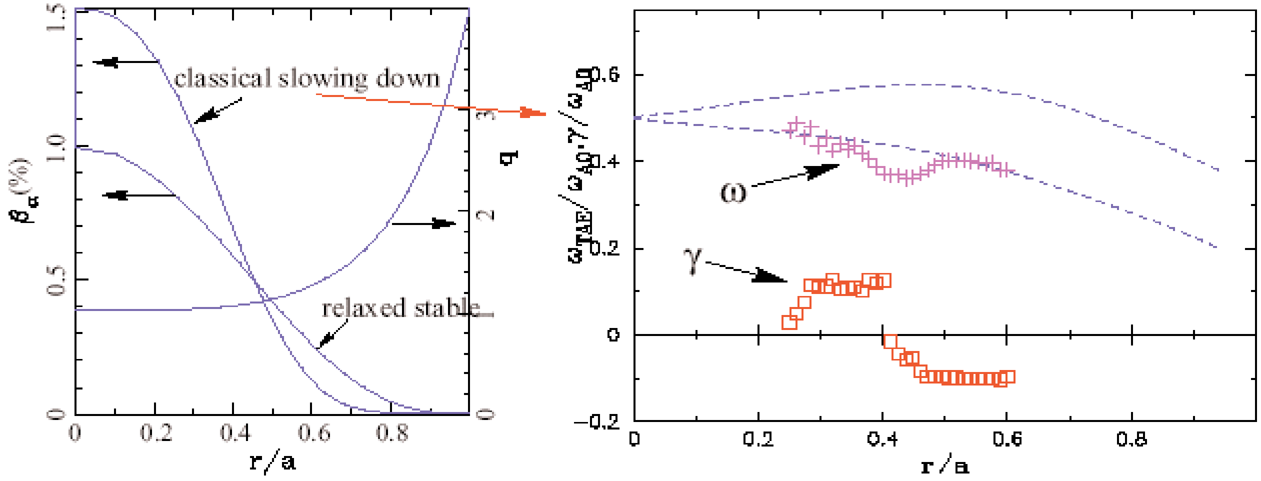


(From LaHaye, Butter, Guenter, Huysmans, Marashek, and Wilson)

High-N non-perturbative Alfven mode Stability Calculations (HINT)

Apply fully kinetic code HINST for baseline FIRE parameters:

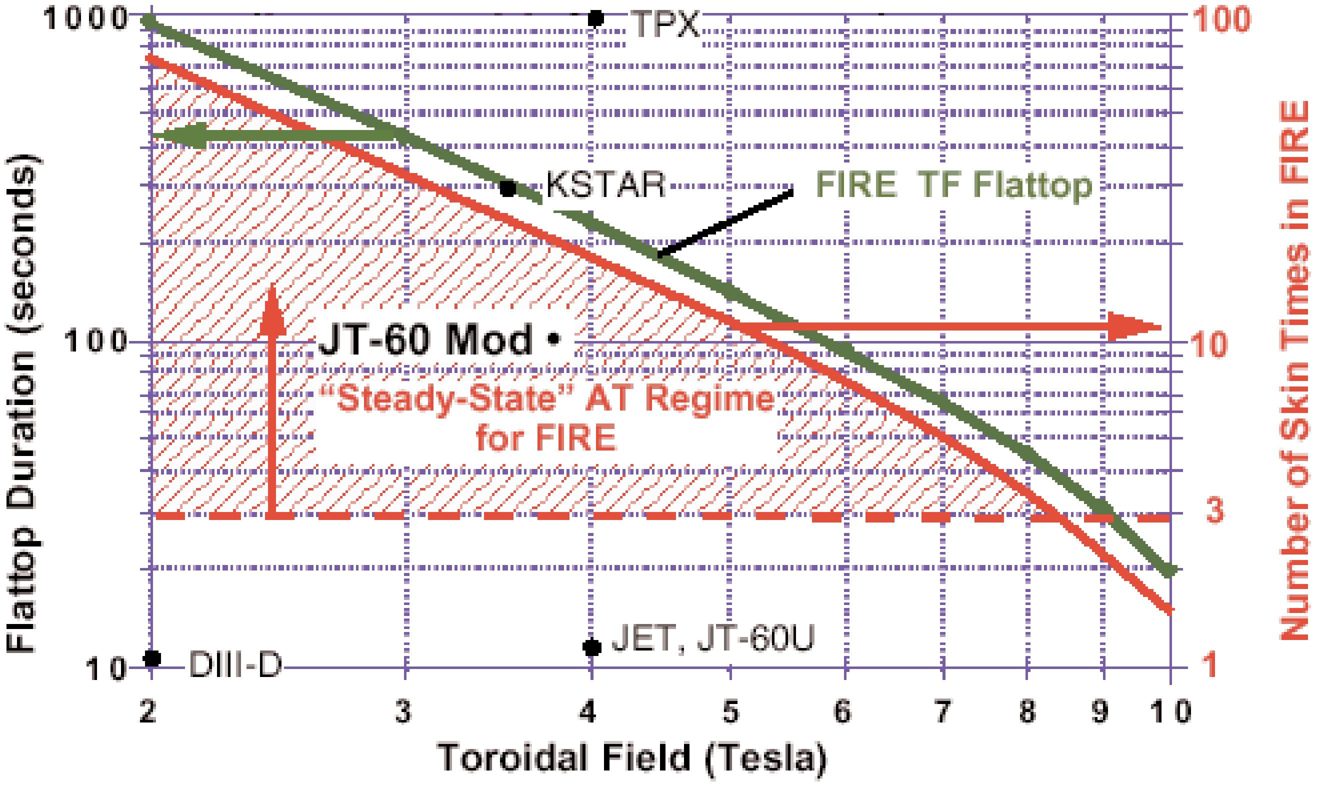
Convetnional shear profile & $R = 2, m$, $a = 0.525m$, $B = 10T$, $I_p = 6.45MA$; $n_e = 5\times10^{14}(1-\Psi^{0.281})^{0.1384}, cm^{-3}$, $n = 7$.



Resonant TAEs are stable if $\beta_{\alpha 0} < \beta_{\alpha 0crit} = 0.66\% \Rightarrow n_{e0} > 7.5 \times 10^{20}$

Relaxed profiles are stable up to $\beta_{\alpha 0crit} = 1\%$, $n_{e0} > 6.3 \times 10^{20}$

FIRE Can Access Various Pulse Lengths by Varying BT

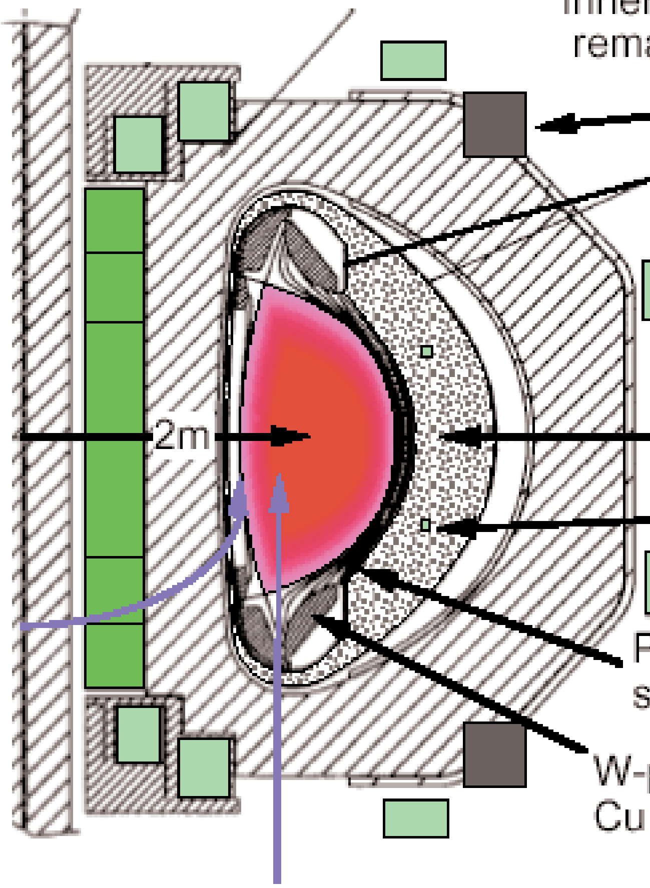


Note: FIRE is ≃ the same physical size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT .

FIRE will have many features for AT operation

AT Features

- DN divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



Wedged TF Coils (16), 15 plates/coil*
Inner Leg BeCu C17510,
remainder OFHC C10200

Compression Ring

Double Wall Vacuum Vessel (316 S/S)

All PF and CS Coils*
OFHC C10200

Internal Shielding
(60% steel & 40%water)

Vertical Feedback Coil

Passive Stabilizer Plates
space for wall mode stabilizers

W-pin Outer Divertor Plate
Cu backing plate, actively cooled

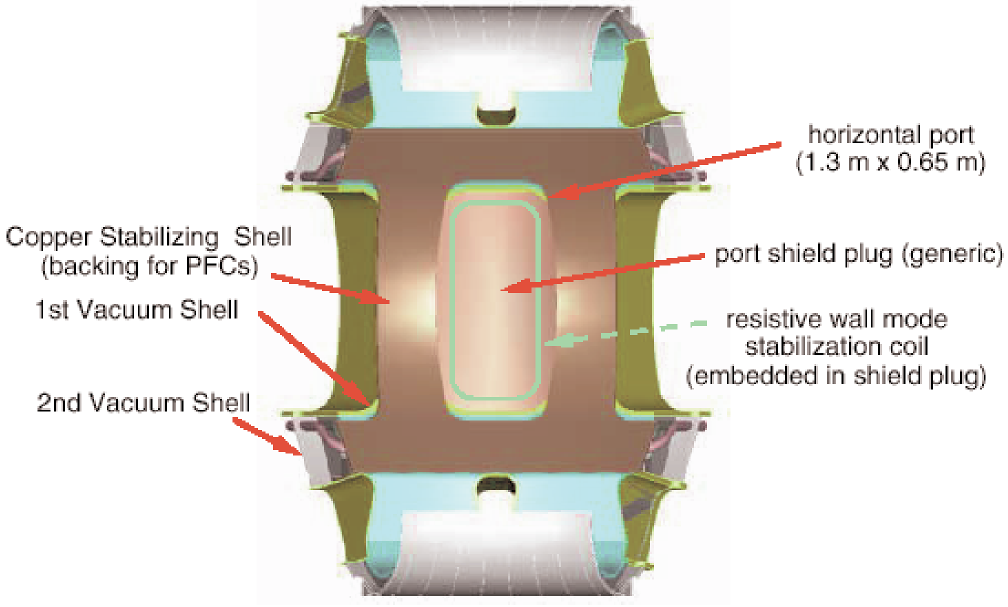
Direct and Guided Inside Pellet Injection

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

FIRE is Examining Ways to Feedback Control RWM/Kink Modes

- Design will incorporate what is learned from DIII-D and Columbia experiments

view of hoizontal port front looking from plasma side



Identification of AT Targets for FIRE

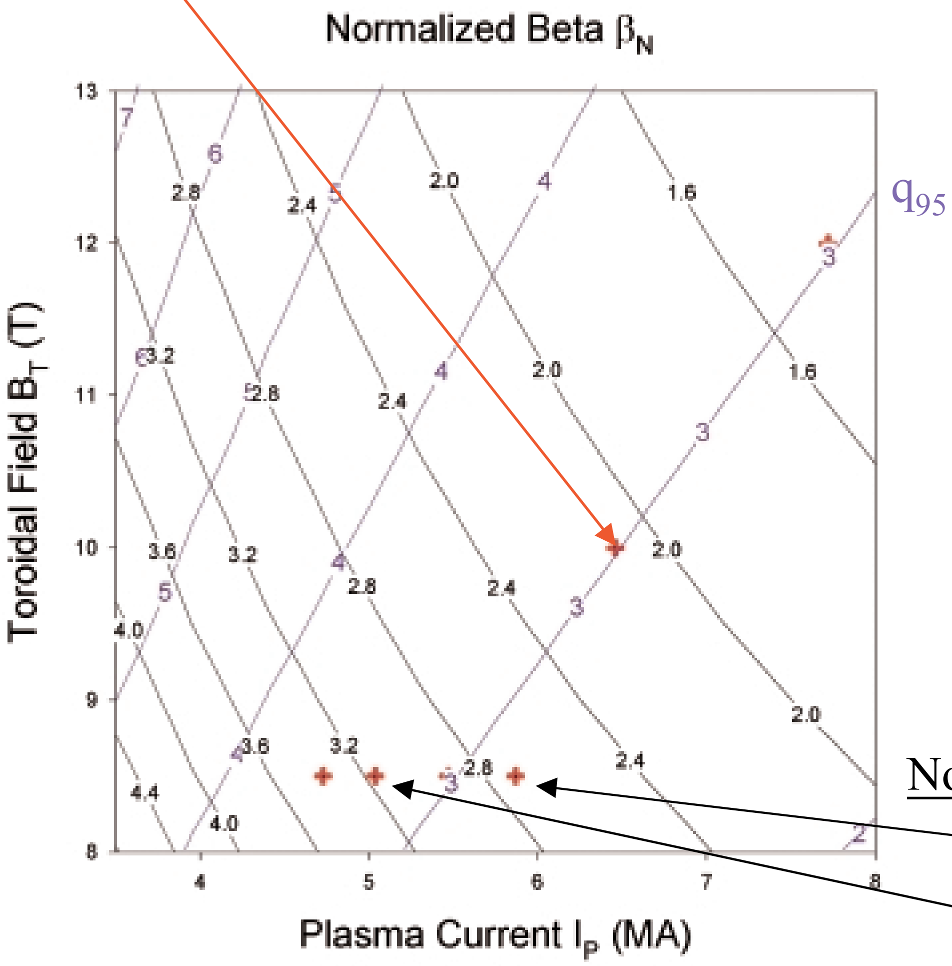
- Long pulse AT modes are targeted to operate at reduced field (8.5T) for about 40 sec (> 3 Skin Times)
- We can project backwards from Standard Operating Modes to get requirements on β_N and H(y,2) for AT modes:

Stored Energy: $W \sim \beta B^2 \sim \beta_N I B$

Energy Confinent time: $\tau_E \sim H(y,2)\, I_P^{.93}\, n^{.41}\, B_T^{.15}$

$\sim H(y,2)\, I_P^{1.34}\, B_T^{.15}$

$Q=5$, $B_T=10$, $I_P=6.44$, $H=1$, $\beta_N=2.1$ base case



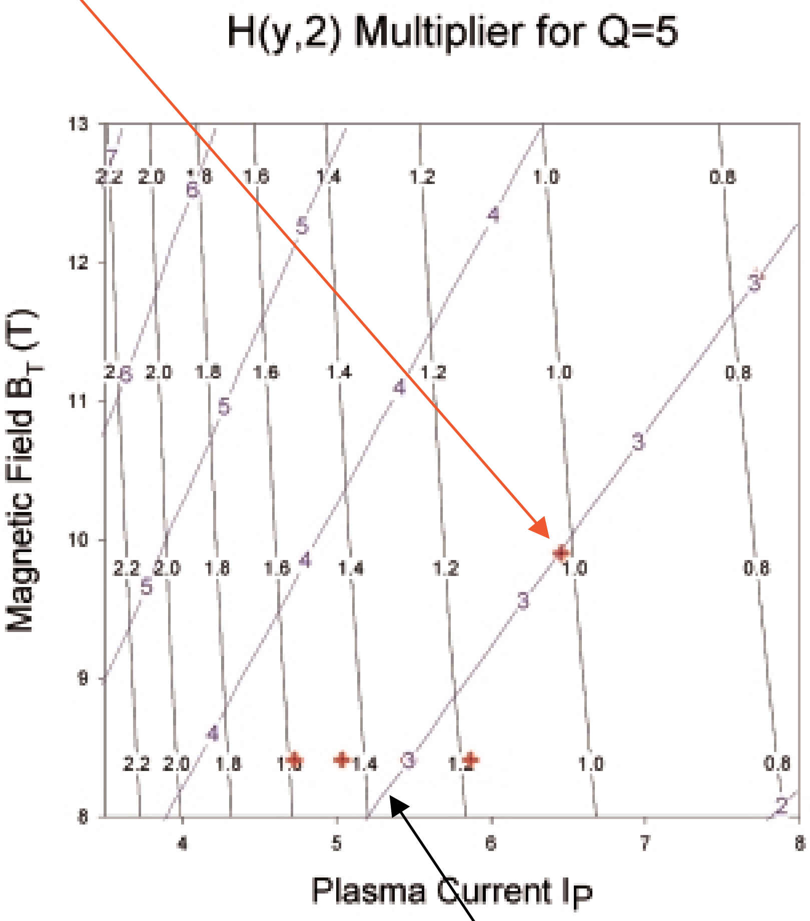
$$W \sim \beta B^2 \sim \beta_N I B$$

The operating points on this graph will have the same stored energy for the β_N values shown on the contours.

No wall n=1 stab	AT rule*	need
3.1	3.4	2.7
3.5	3.7	3.2

*AT rule: lower of 4×ℓi and 1.15 β_N

Q=5, B_T=10,I_P=6.44, H=1, β_N=2.1 base case



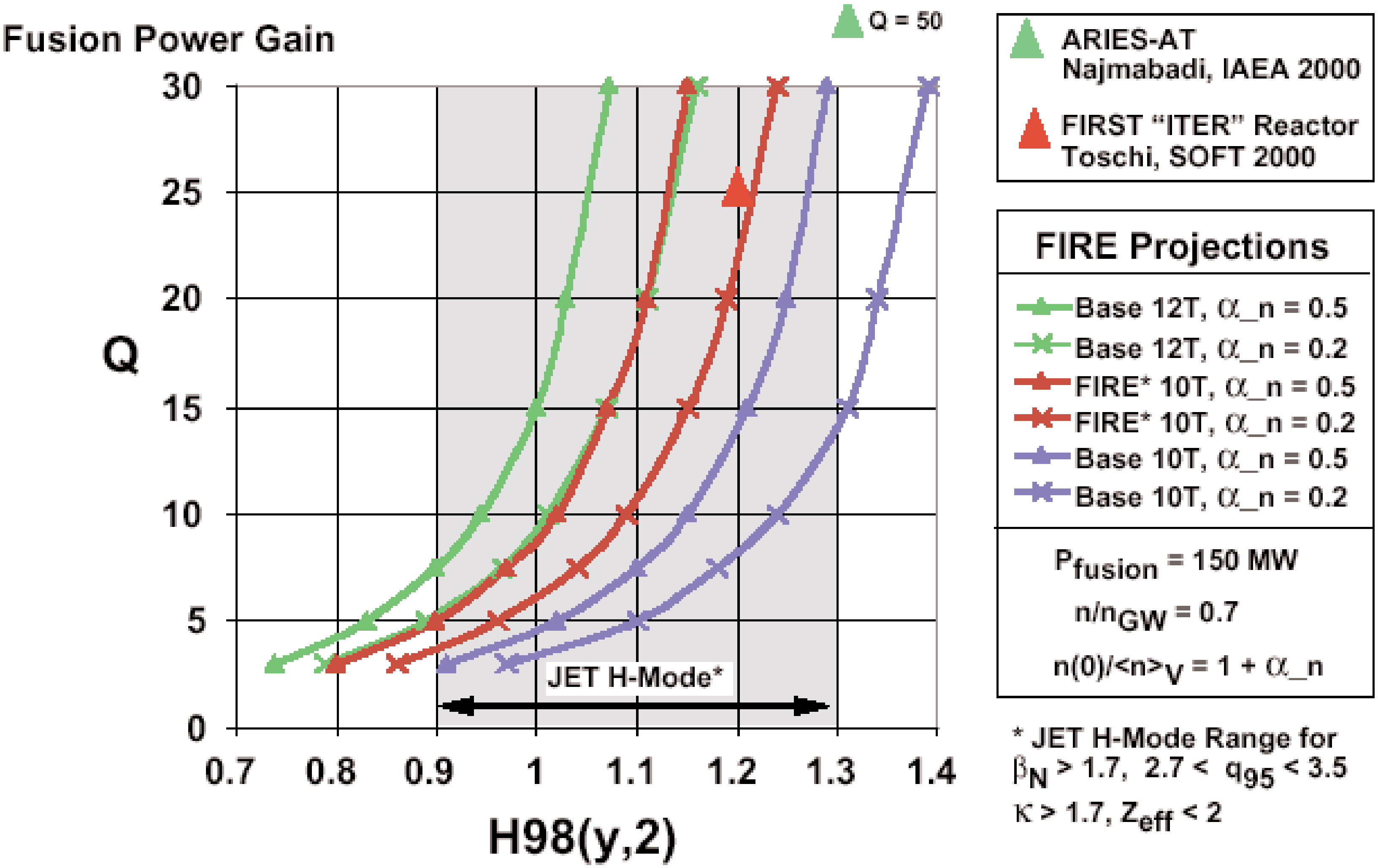
$$\tau_E \sim H(y,2)\ I_P^{.93}\ n^{.41}\ B_T^{.15}$$

$$\sim\ H(y,2) I_P^{1.34}\ B_T^{.15}$$

The operating points on this graph will have the same energy confinement times for the H(y,2) values shown on the contours.

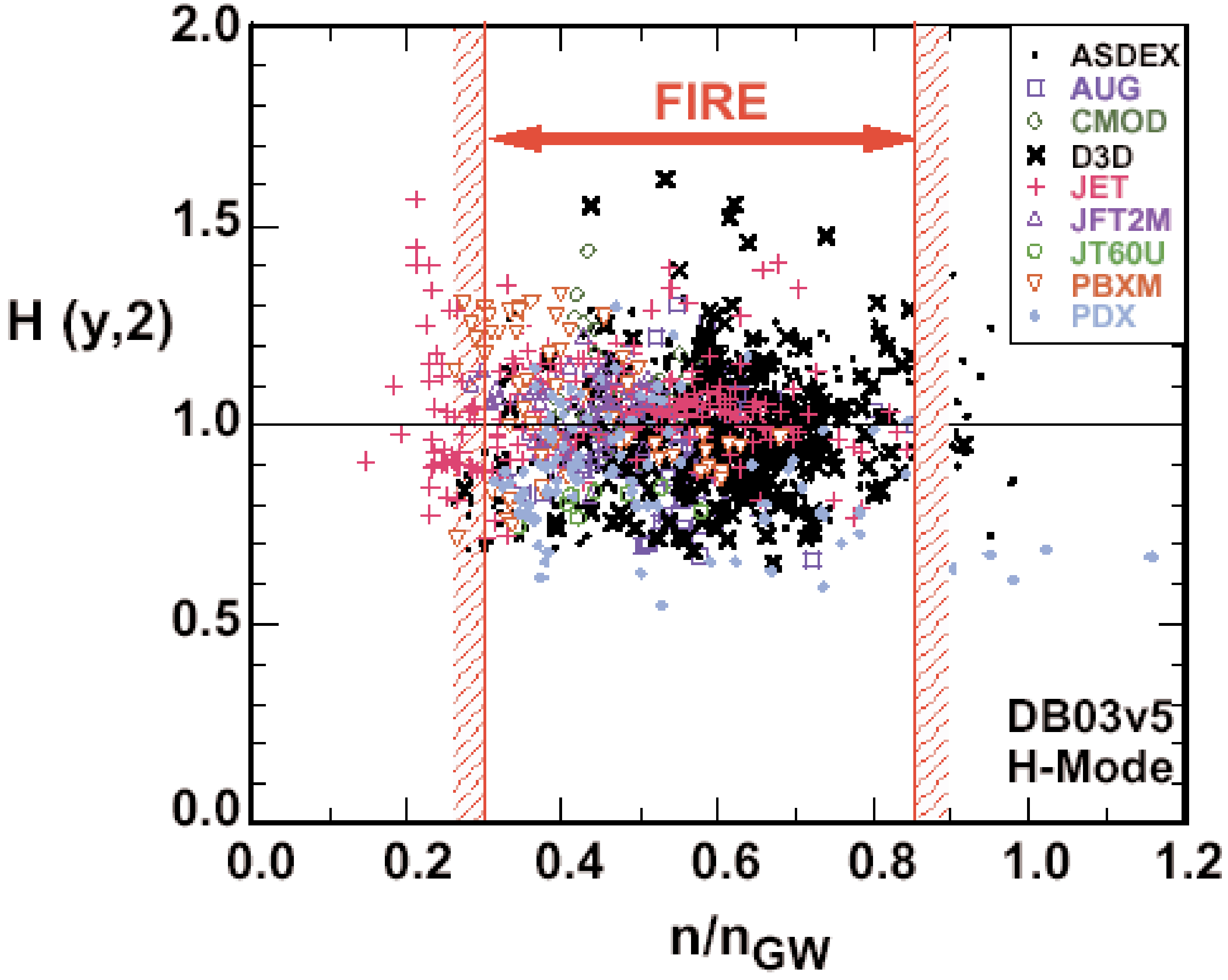
AT modes need H factor in range 1.2 – 1.6 for same confinement time in sec.

FIRE’s Performance With Projected Confinement

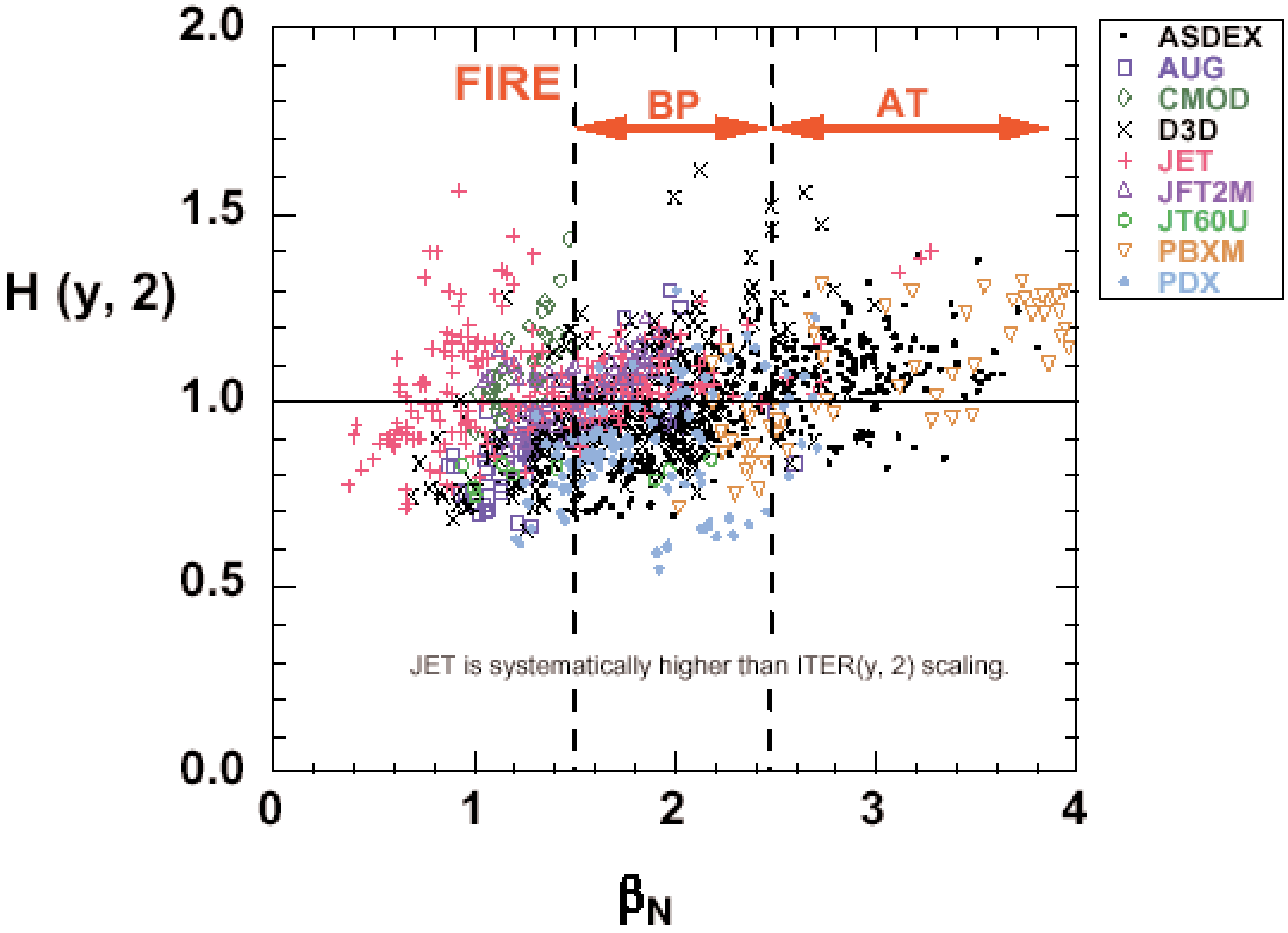


* JET H-Mode Range for
$\beta_N > 1.7$, $2.7 < q_{95} < 3.5$
$\kappa > 1.7$, $Z_{eff} < 2$

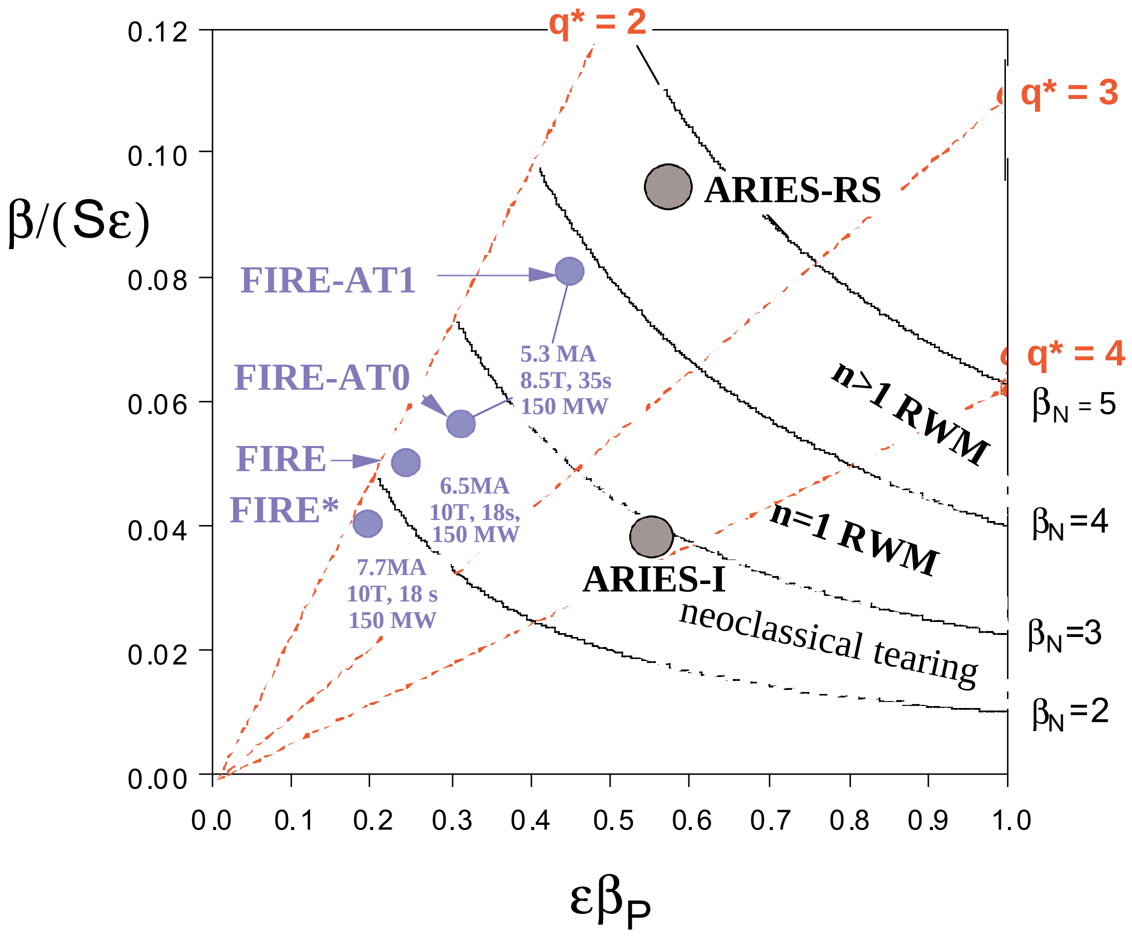
FIRE Operating modes are within the Existing H-mode Database for both density and energy confinement



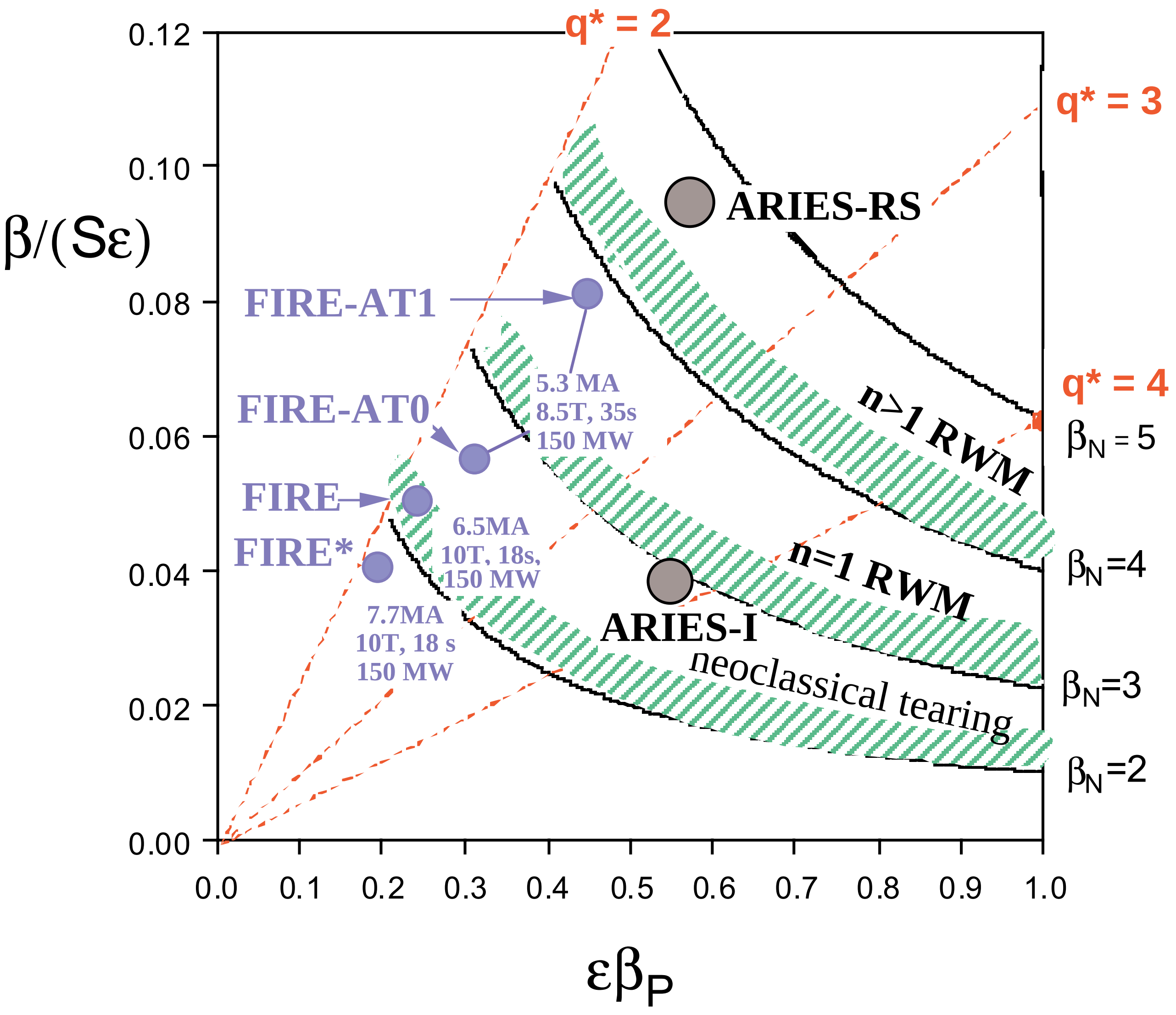
FIRE should be able to access AT Plasmas requiring both high β_N and high H(y,2)



Progress Toward ARIES-like Plasmas will Require a Sequence of Steps



FIRE can test advanced modes used in advanced reactor designs



Summary

- **There are no apparent physics showstoppers**
- **FIRE design is near optimal for Next-Step Mission**
- **FIRE will demonstrate and study high Q operation over a broad range of parameters for all relevant physics timescales**
- **High Q operation at low β_N values down to ~1.5 greatly increase credibility of the device**
- **There is great science to be learned. Eg., in the MHD area:**
    - How does core self-organize with α's and m=1 mode?
    - How does edge self-organize with bootstrap and ELMs
    - Behavior of the neoclassical tearing mode at low (ρ^*,ν^*)
    - How well can our codes predict these nonlinear events ?