Global Stability Issues for a Next Step Burning Plasma Experiment

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with input from

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APS/DPP Meeting

Paper NP1.110

Oct 25, 2000

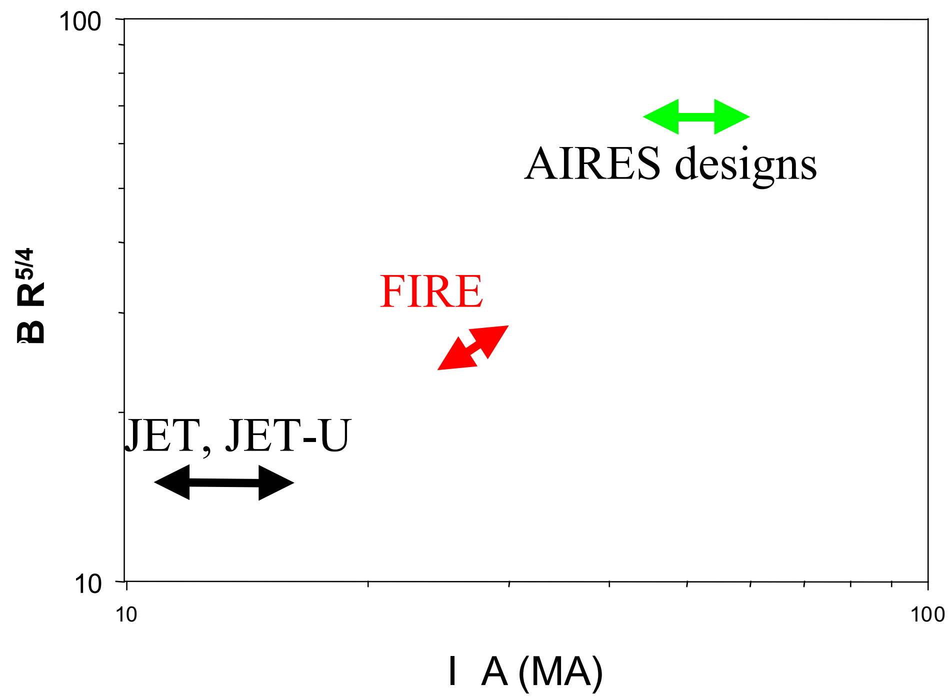
Quebec

Abstract

We present analysis which supports the feasibility of a next-step burning plasma experiment. The FIRE design has R = 2 m, a = .525 m, κ_{95} = 1.77, δ_{95} = 0.4, B = 10(12) T, I = 6.44(7.7) MA, H = 1.2 (1.0) for the reference (high-field) discharge, with monotonic q-profile and sawtoothing ELMy H-mode operation. The primary issues for MHD are associated with (1) the q=1 surface, (2) energetic particle modes (3) edge currents due to the H-mode pedestal, (4) neoclassical tearing modes, and (5) error fields and locked modes. We find (1) the m=1, n=1 mode requires non-linear analysis including energetic-particle effects, (2) α-particle driven Alfven modes, RTAE and KTAE, are expected to be stable for $\beta_\alpha < 0.5$ %, (3) the predicted critical value for the onset of the NTM is very close to the operating point for the high-field option, and may be mediated by self or active control of seed island width or active island current drive, (4) the nominal self-consistent operating point is stable to external kink modes without a conducting wall and (5) error field requirements need to be revisited. Advanced operating modes with q > 2 everywhere and high-bootstrap fraction also hold promise but need to be further developed.

Fire is a logical next step between JET/JET-U and a fusion power plant

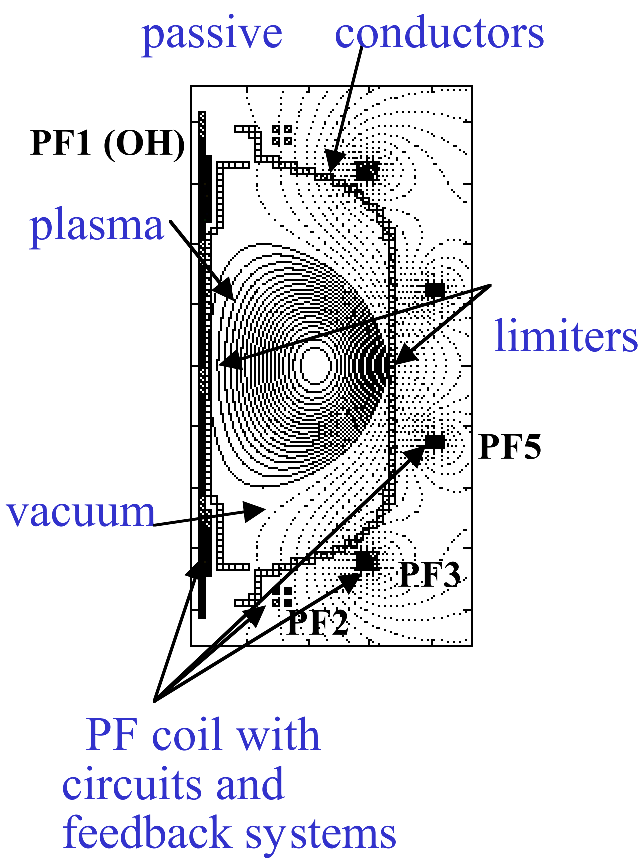
- A major step in the study of alpha-heating dominated plasmas
- Provides critical data for extrapolating to reactors
- Provides data point for critical benchmarking of advanced simulation codes and will
- Stimulate development of even more advanced numerical simulation
- Will provide focus to experimental and theory programs



FIRE operating modes

	I_P(MA)	B_T	T(s)	β_N	f_{BS}
Standard operating mode (LF)	6.5	10	21	2.7	0.3
High-field (shorter pulse mode)	7.7	12	12	1.9	0.2
Advanced Tokamak 1st stability	5.6	9	30	2.9	0.5
Reversed Shear Wall stabilized	4.5	6.7	60	4.5	0.8

Tokamak Simulation Code (TSC) is unique tool for modeling the evolution of a free-boundary axisymmetric plasma on the resistive time scales



- arbitrary transport model
- neoclassical-resistivity
- bootstrap-current,
- auxiliary-heating
- ballooning-mode transport
- current-drive,
- alpha-heating,
- radiation,
- pellet-injection,
- sawtooth model,
- circuit equations for all the poloidal field coils
- induced currents in passive conductors, halo
- feedback systems for I_P, position, and shape.

TSC was chosen by ITER as the standard model for:

- poloidal flux consumption and pulse length
- timescales for current rampup and rampdown
- shape control requirements

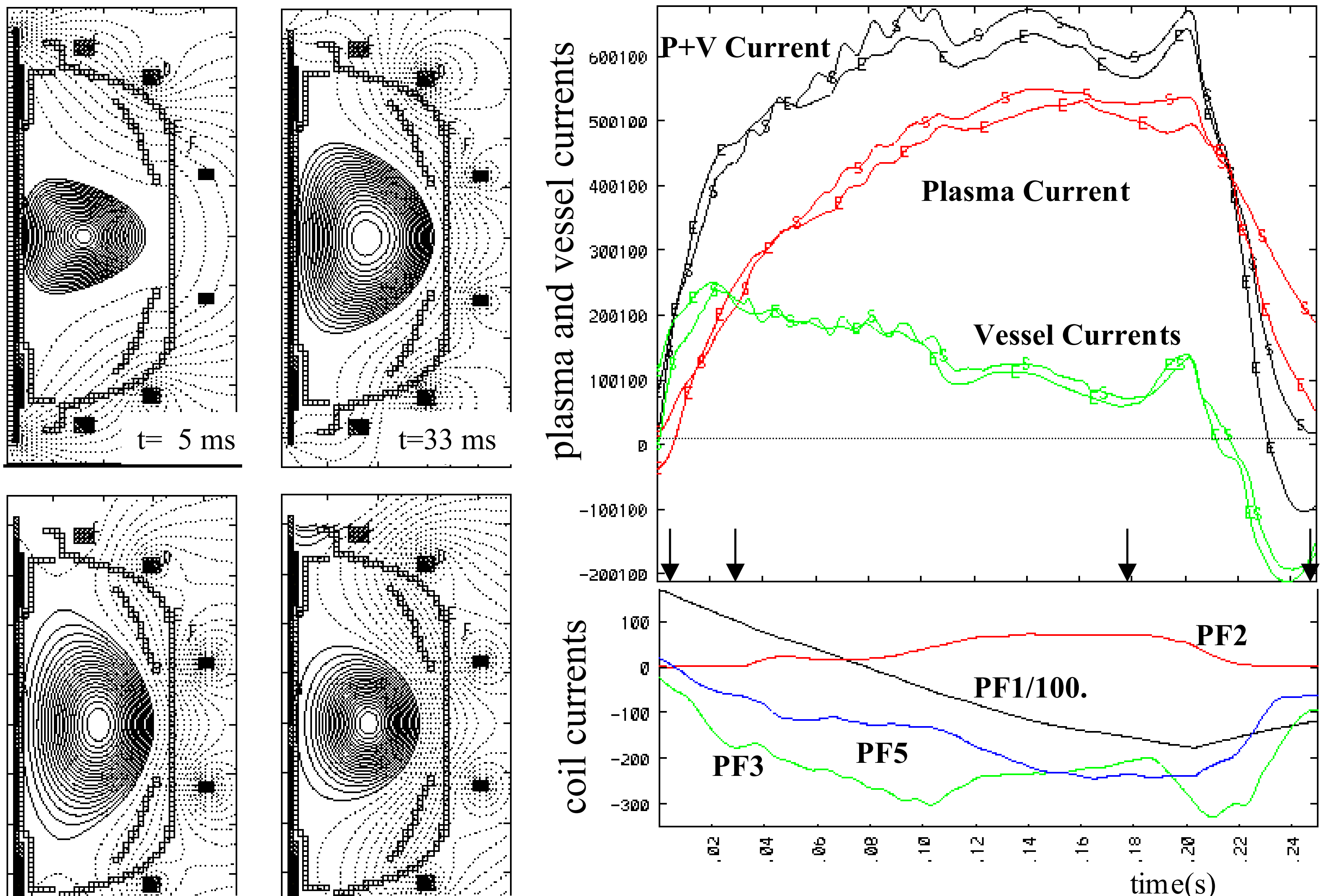
New Directions:

- integrated modeling of core and edge
- improved models of non-linear saturation of high-β m=1 mode, ELMs, balloon-unstable region

Jardin, et al, Nucl. Fus. 39 (2000) 923

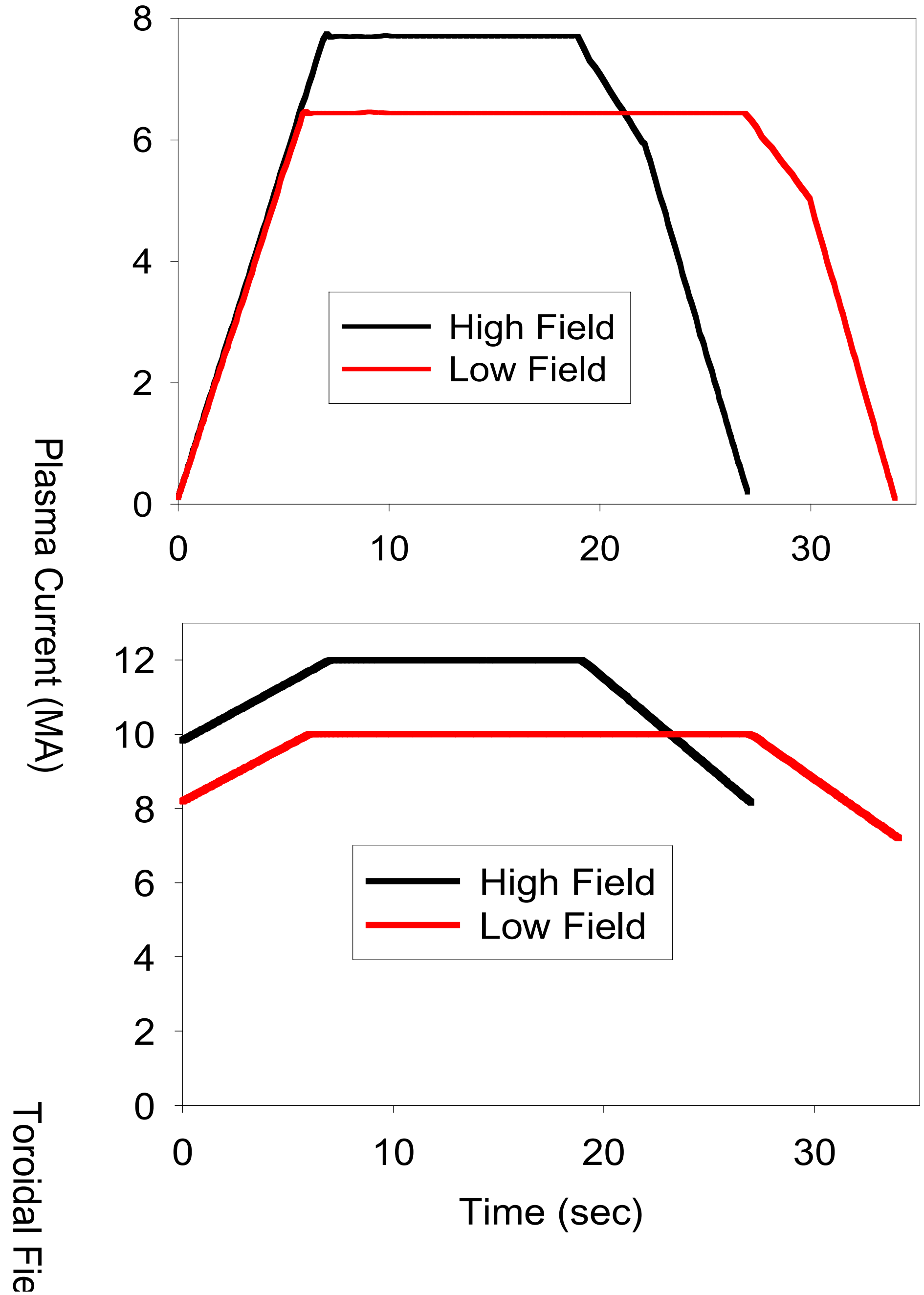
TSC simulation of NSTX shot 100920

E .. experimental data   S..computed by TSC



Simulation uses experimental coil currents:
computes plasma and vessel currents

Plasma Current and Toroidal Field



Guidelines for Predicting Plasma Performance

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

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

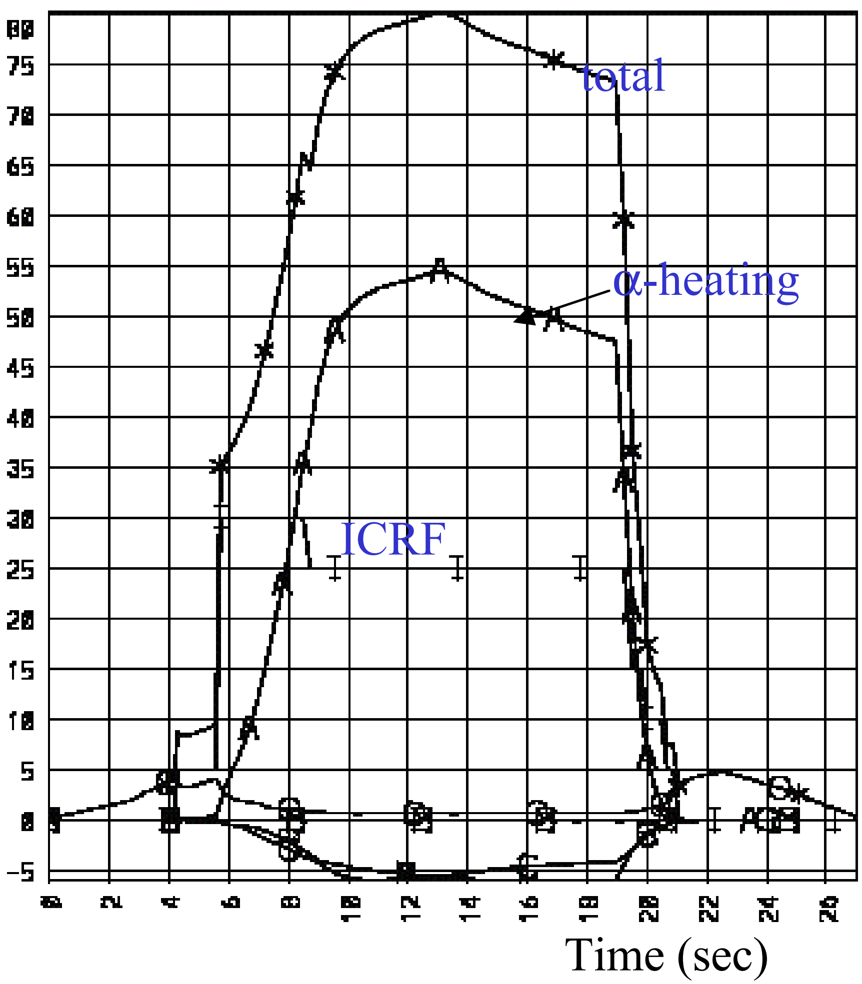
Density Limit:

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

H-Mode Power Threshold:

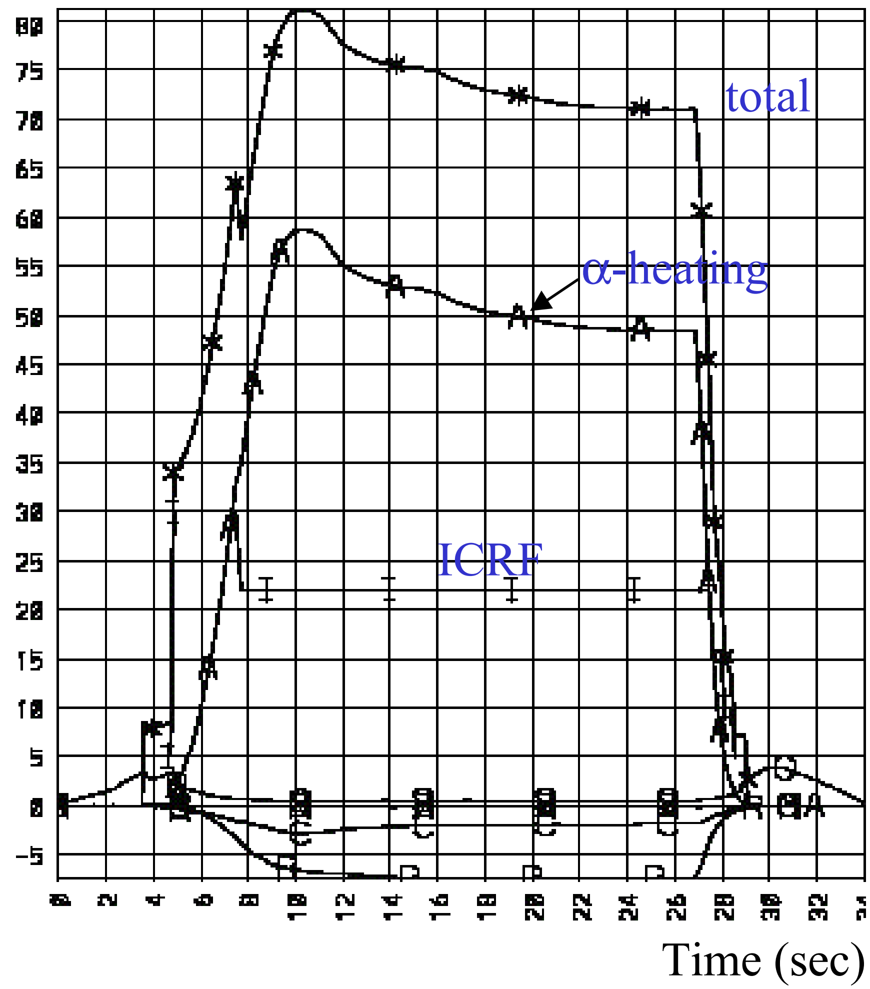
$$P_{th} > (2.84/A_i)\ n_{20}{}^{0.58}\ B^{0.82}\ R\ a^{0.81}$$

High Field: H = 1.0 (12 T, 7.7 MA)

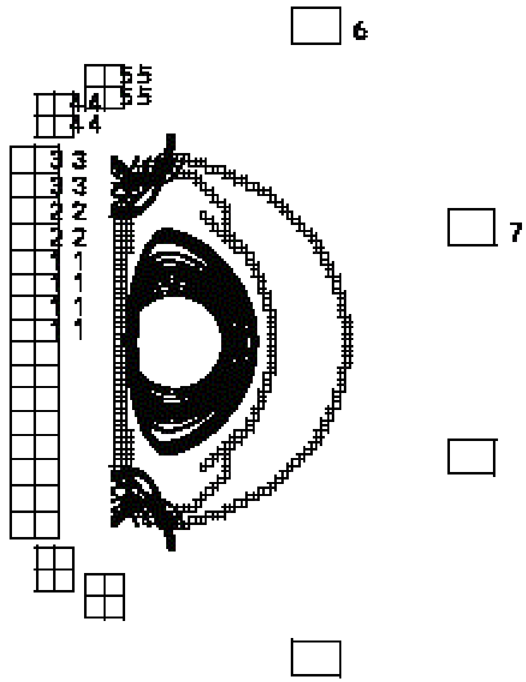


Q > 10 for 9 sec

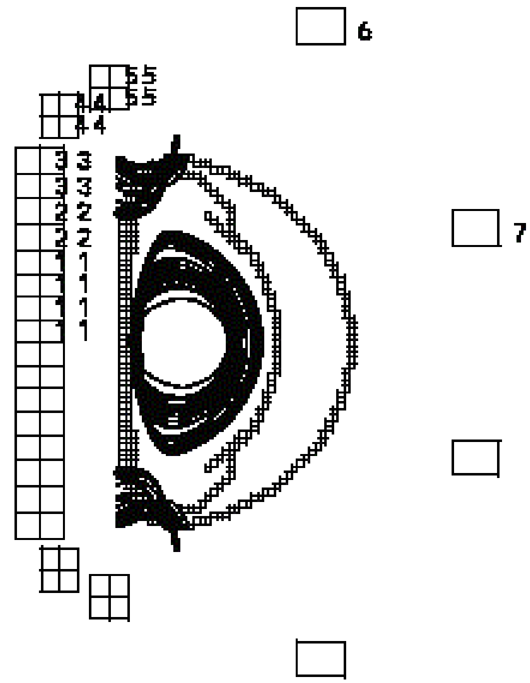
Low Field: H = 1.2 (10 T, 6.5 MA)



Q > 10 for 18 sec

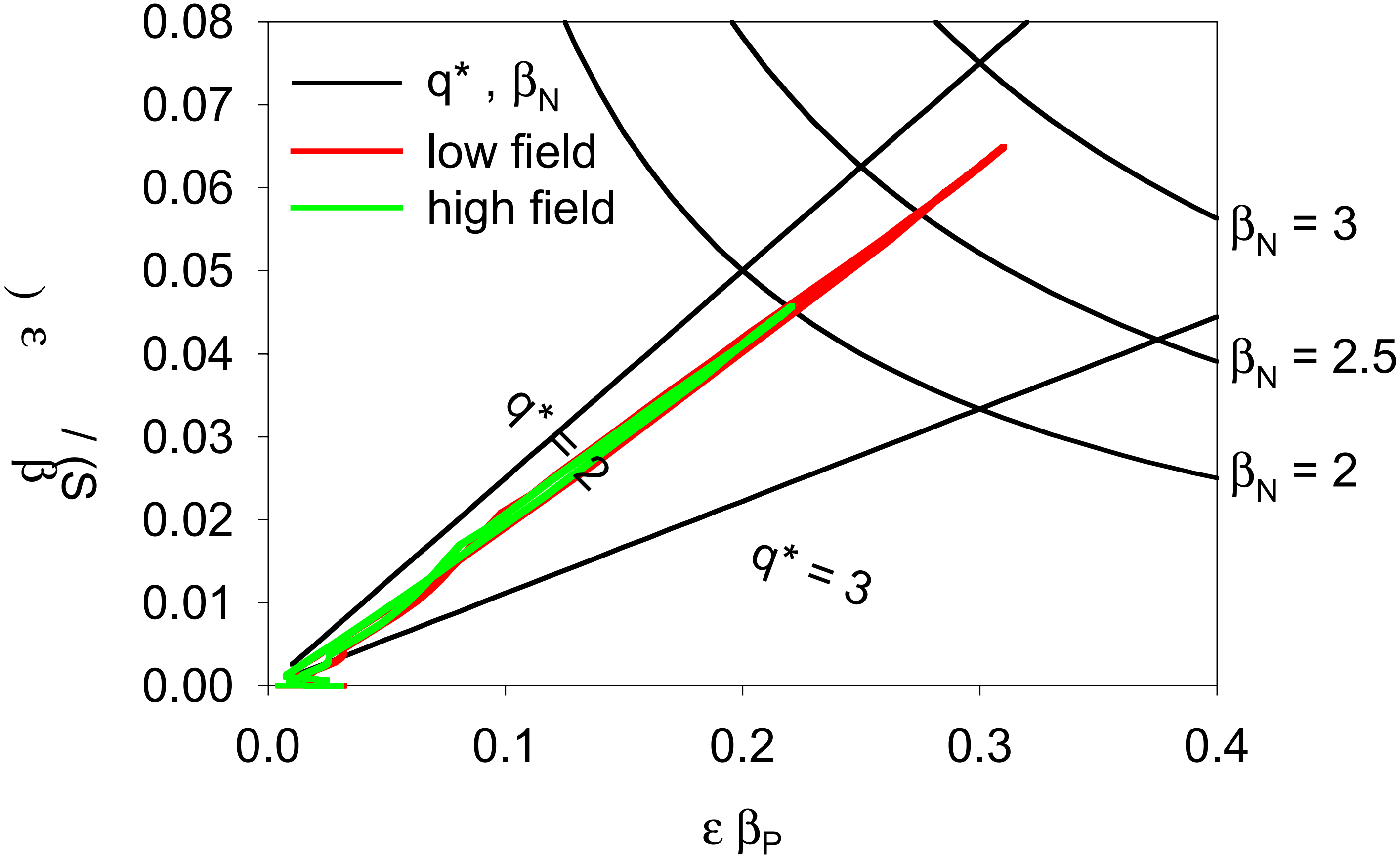


High Field



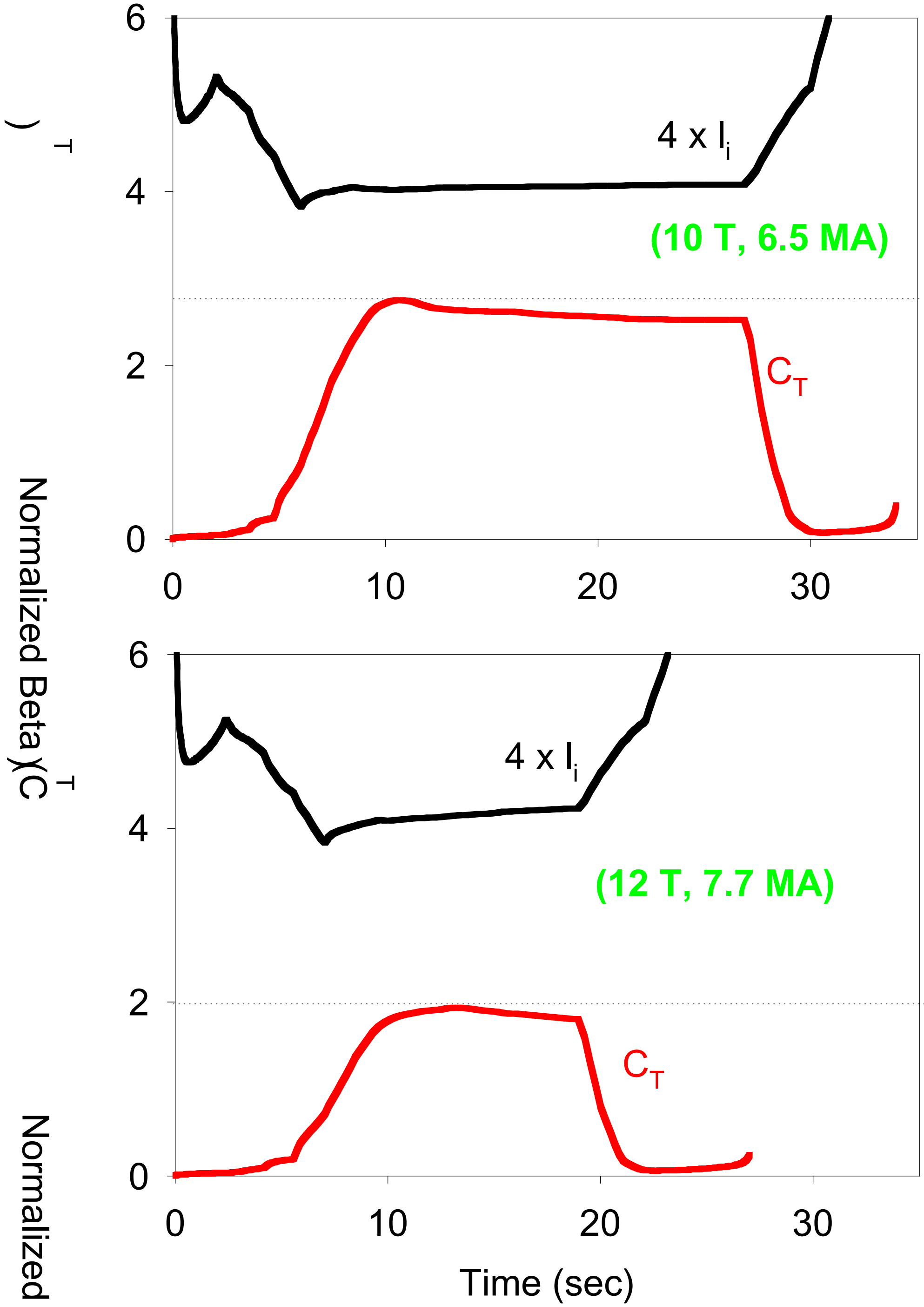
Low Field

FIRE Discharge Trajectories in Stability Space

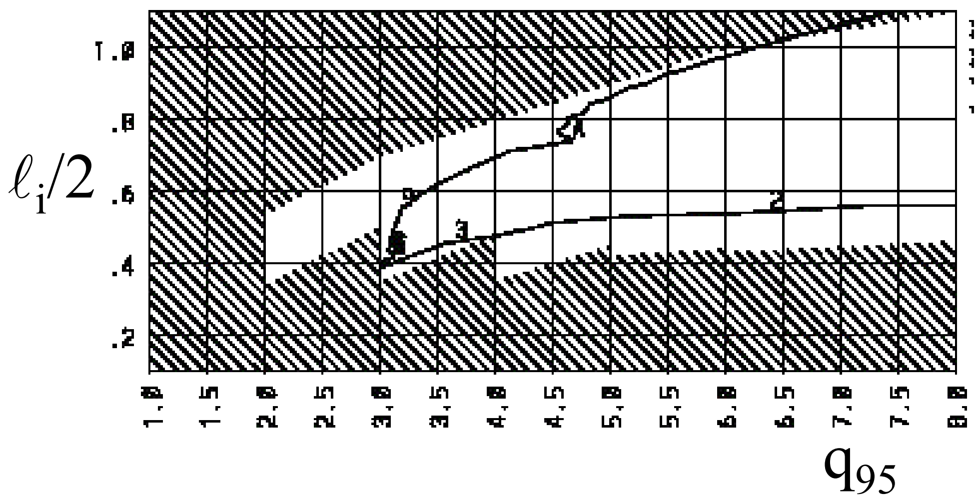


$S = (1+\kappa^2)/2$

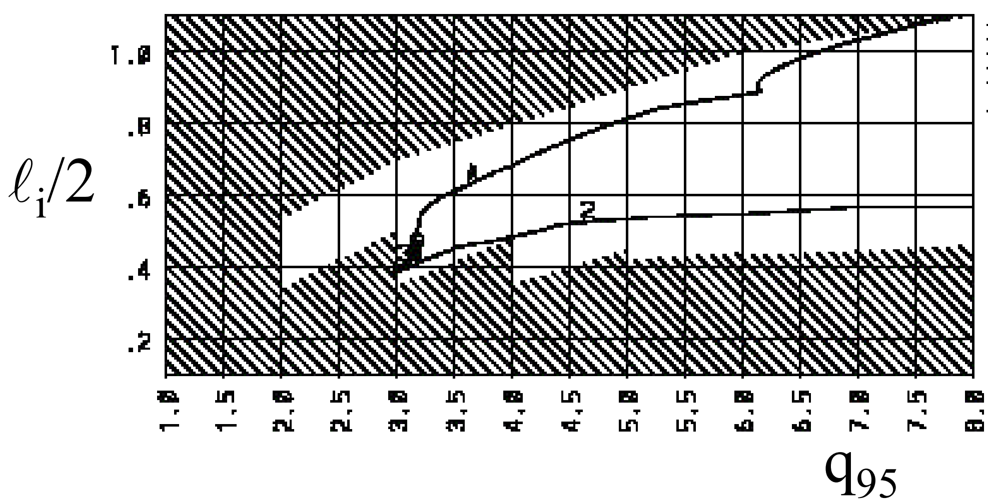
$\varepsilon = a/R$



Normalized Beta (C_T)
4 x I_i
(10 T, 6.5 MA)
C_T
4 x I_i
(12 T, 7.7 MA)
C_T
Time (sec)



High Field

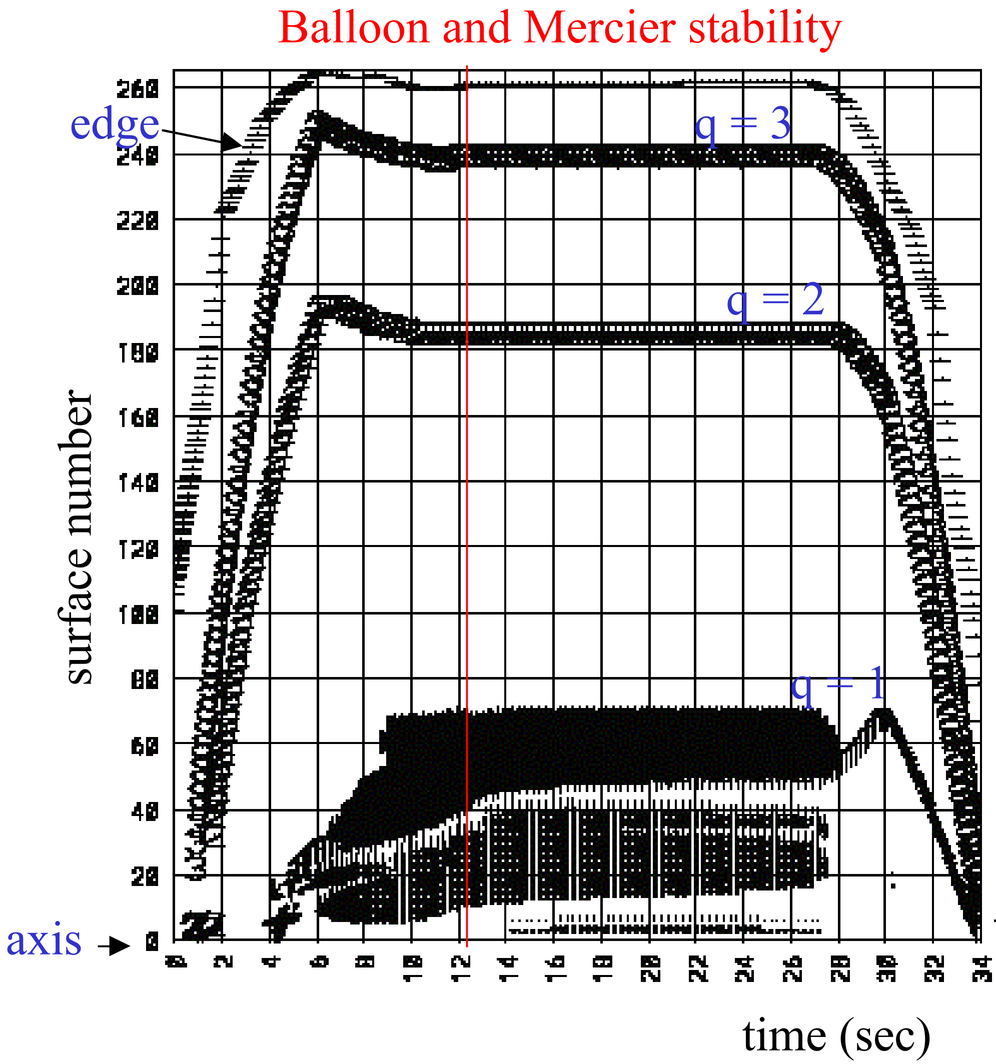


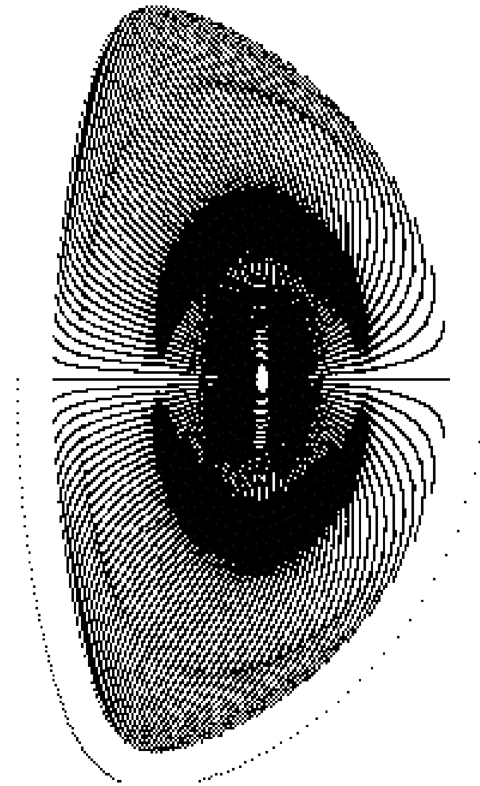
Low Field

Physics Question: Role of the m=1 mode

- Ideal MHD theory predicts m=1,n=1 mode unstable at high β for $q_0 < 1$
- High-n ballooning modes also predicted to be unstable in the vicinity of and interior to the q=1 surface
- Proper physics description must take into account energetic particle drive, kinetic stabilization, 2-fluid effects, and non-linear saturation mechanism
- This should be [and is] one of the major thrusts of the 3D macroscopic simulations communities
- FIRE will provide critical data point for both extrapolations and for code benchmarking

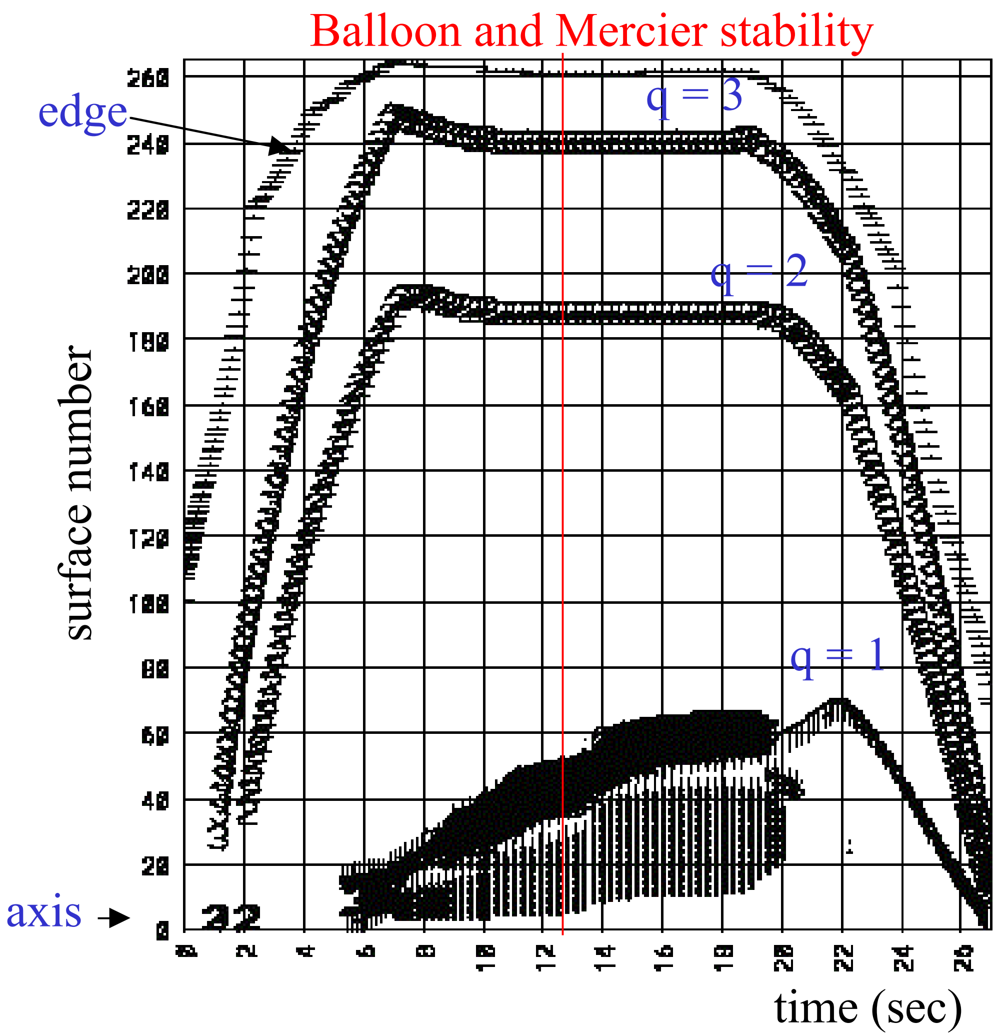
Low Field: 10 T, 6.5 MA

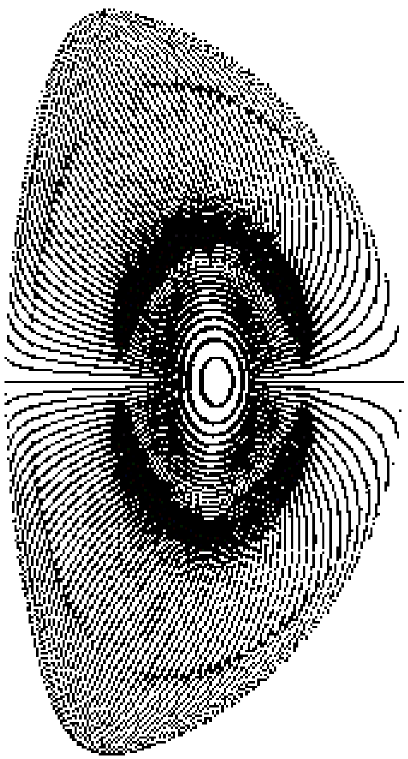




PEST unstable eigenfunction at t=12.5 sec

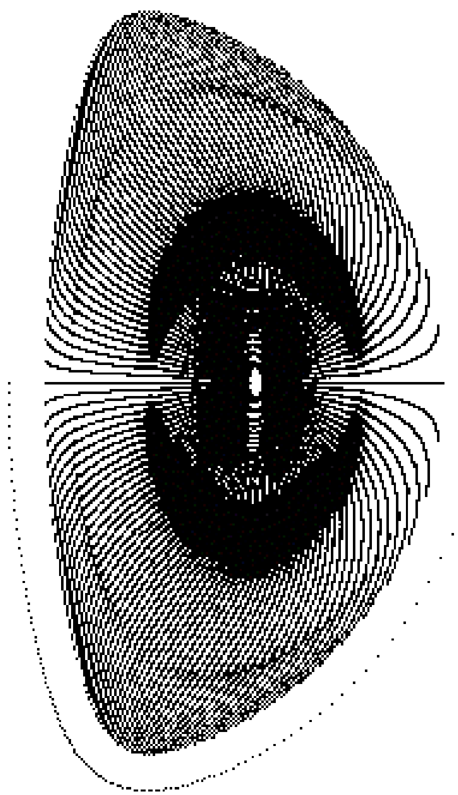
High Field: 12 T, 7.7 MA





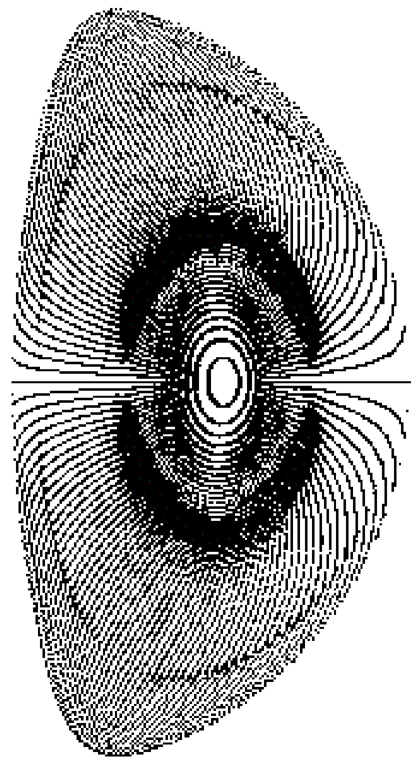
PEST unstable eigenfunction at t=12.5 sec

Comparison of unstable Eigenvalues



Low Field

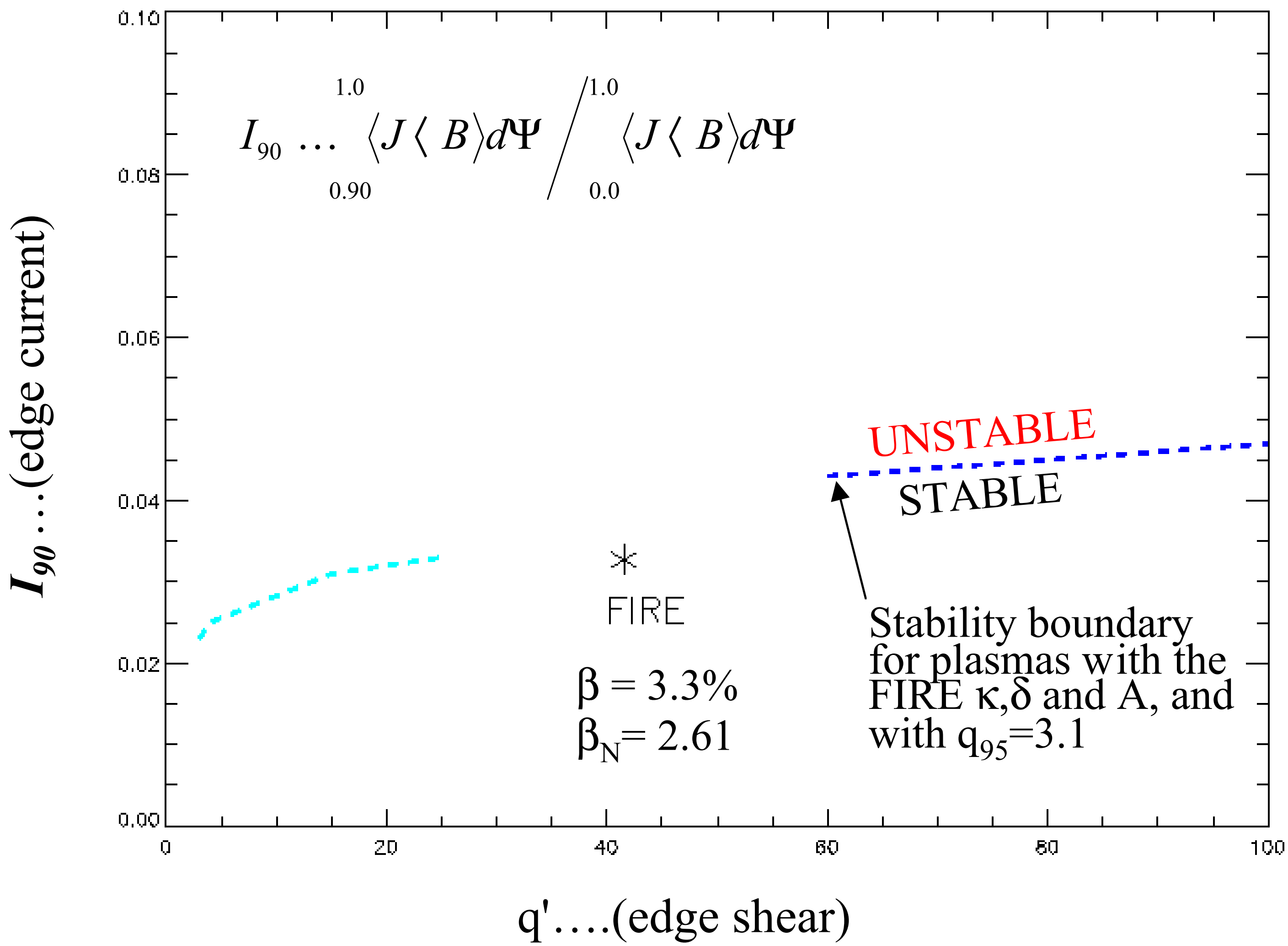
$\gamma^2 = -.0083$



High Field

$\gamma^2 = -.0039$

FIRE nominal operating point is stable to kink modes

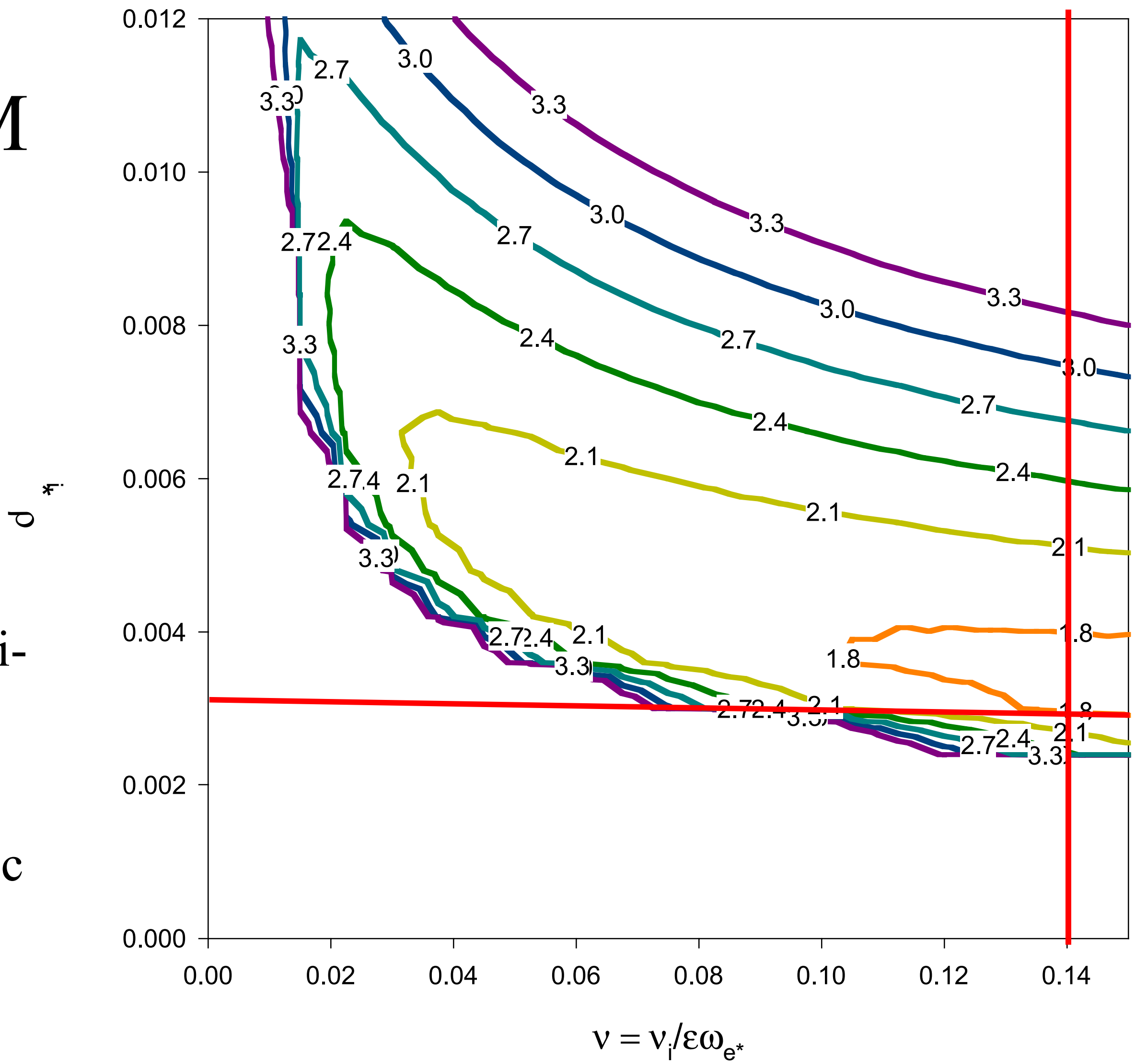


Manickam

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
- this is another major thrust of 3D macroscopic modeling effort
- FIRE will provide critical data point

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



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

Kinetic MHD is becoming much more capable

TFTR Equilibrium

R=2.62 m, a=0.95 m,

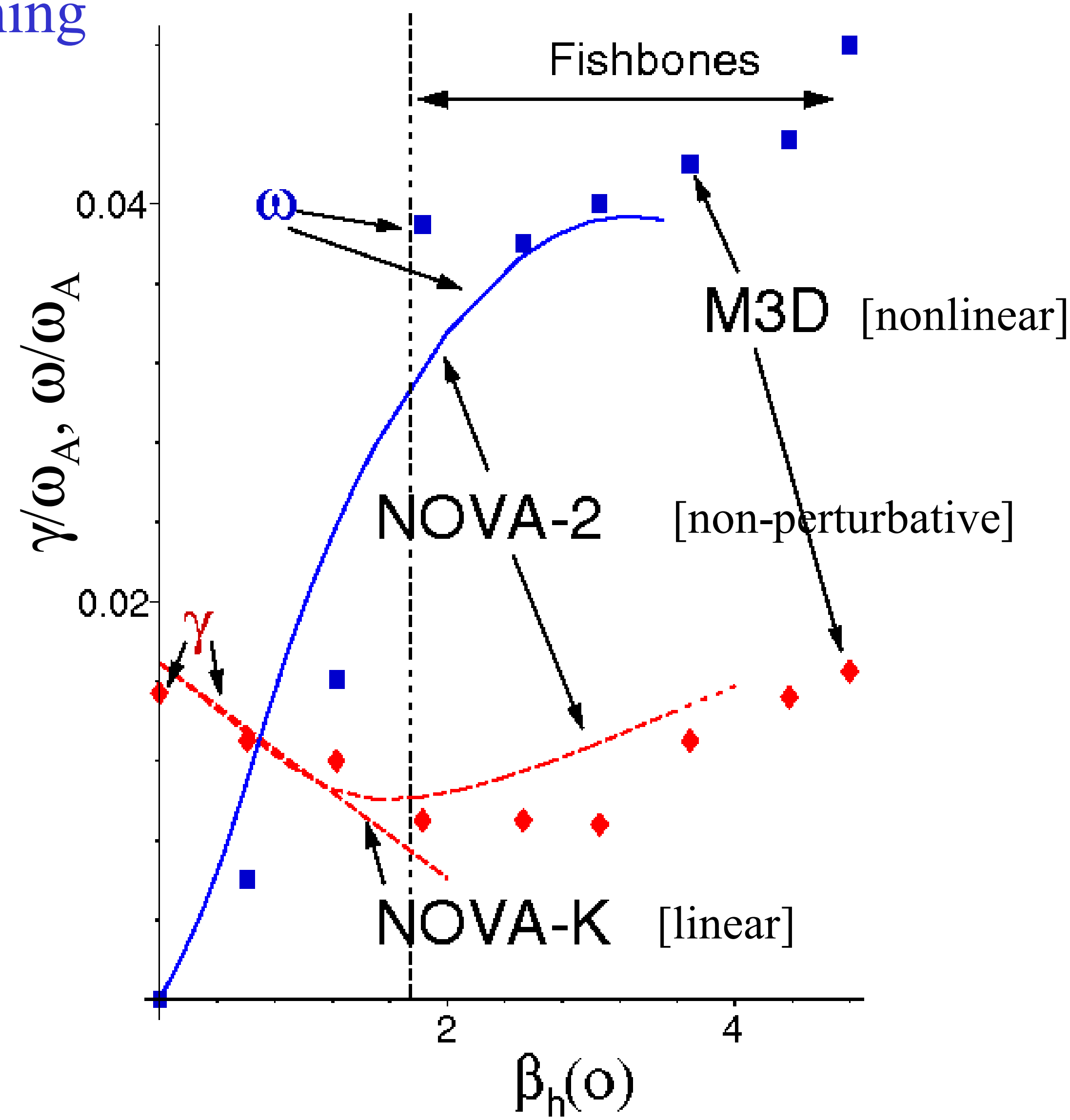
$\beta_{pl}(0) = 5\%$, $\beta_{pl} + \beta_h = \text{const}$,

B=4.45 T

Deuterium hot slowing down ions $v_h = 10^9$ cm/sec, $v_h/v_A=1$, $R/\rho_h = 55.6$

Fishbone branch reproduced by NOVA-2 and M3D

Linear stabilization phase of n=1 mode agrees for 3 codes

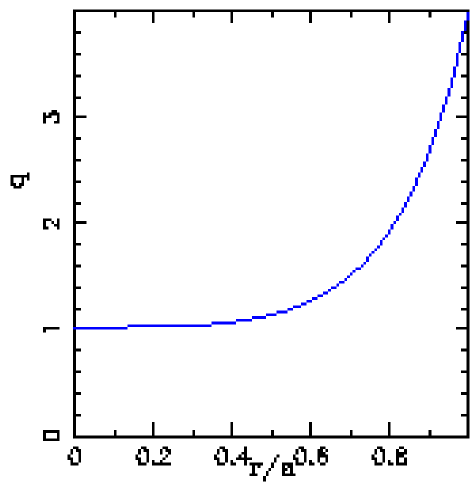


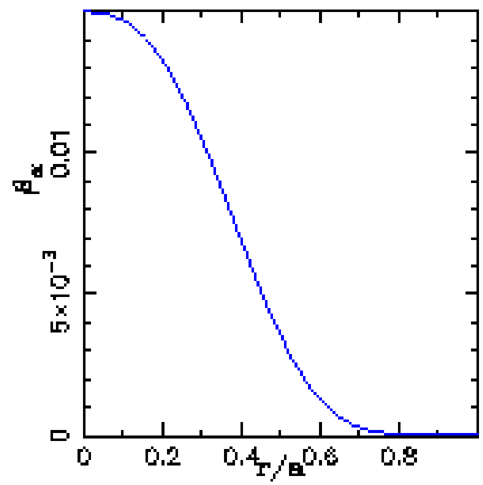
Fu, Gorelenkov

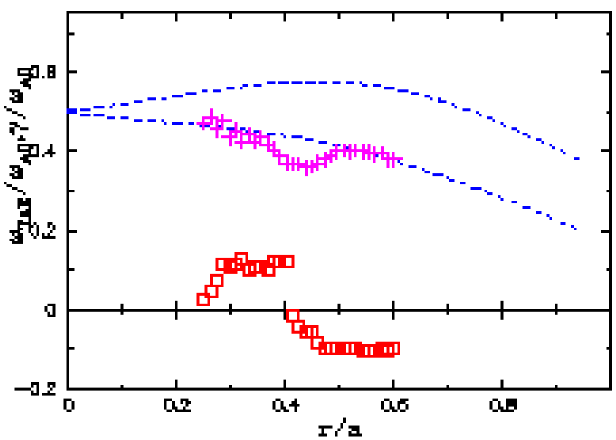
FIRE regular q-profile

NOVA-2 analysis

PPPL







Other parameters:

$R = 2, m$, $a = 0.525m$, $B = 10T$, $I_p = 6.45MA$;

$n_e = 5 \times 10^{14}(1 - \Psi^{0.281})^{0.1384}$, cm^{-3}, $\beta_{th}(\Psi) = 9.7(1 - 0.876\Psi^{0.557})^{1.73}\%$.

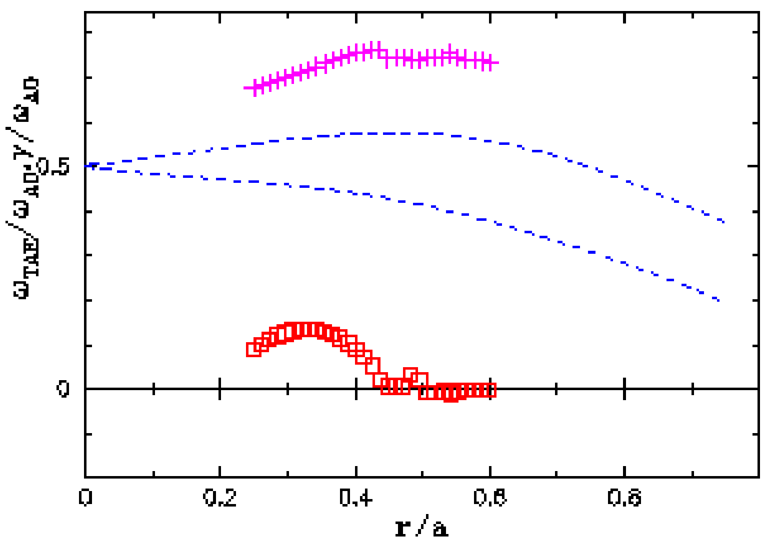
Critical for RTAE $\beta_{0\alpha crit} = 0.65\%$ (local $\beta_\alpha = 0.4\%$).

FIRE regular q-profile plasma variations

case	$n_e(0), 10^{14} cm^{-3}$	$n_{DT}(0), 10^{14} cm^{-3}$	$T_e(0), keV$	n/n_{Gr}	P_{fus}, MW	$\beta_\alpha(0), \%$
1-unst.	5.59	4.22	20	0.66	257	1.5
2-unst.	6.39	4.82	17.5	0.75	262	1.05
3-stab.	7.45	5.62	15	0.89	263	0.69
4-stab	8.94	6.74	12.5	1.06	250	0.4

In regular q-profile there is window for RTAE free operation.

KTAEs are still unstable.

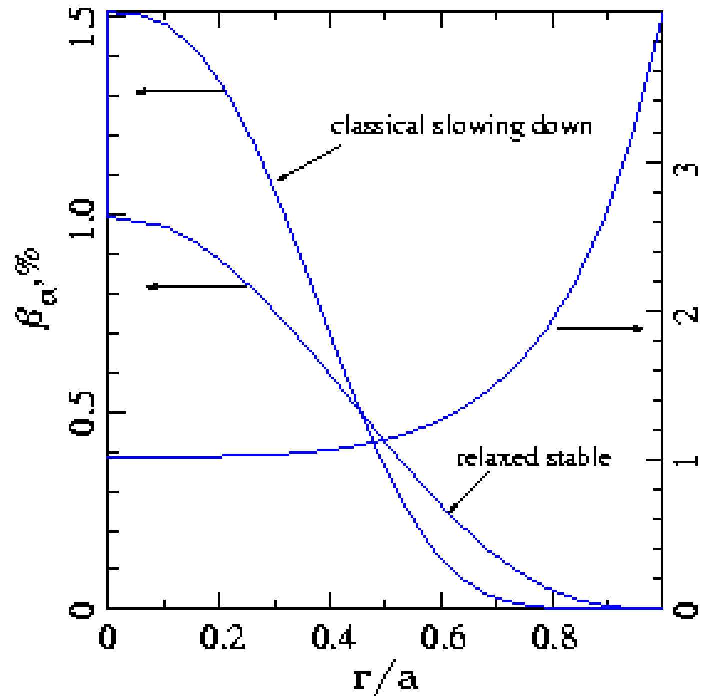


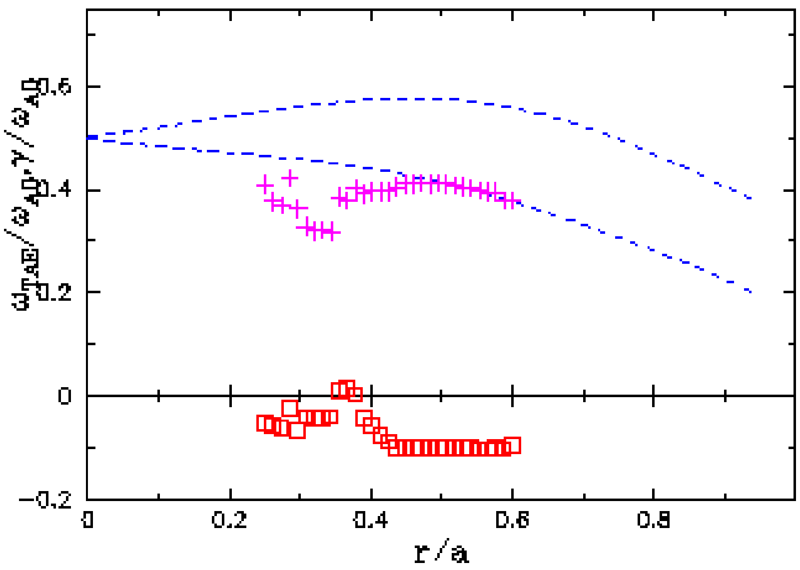
KTAE: $\beta_{0crit} = 0.5\%$ at $r/a = 0.35$ analysis and $\beta_{crit} = 0.33\%$

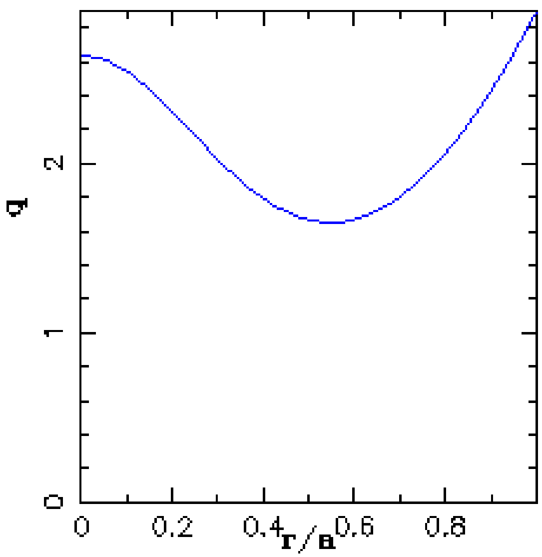
Regular q-profile with relaxed fast particle pressure.

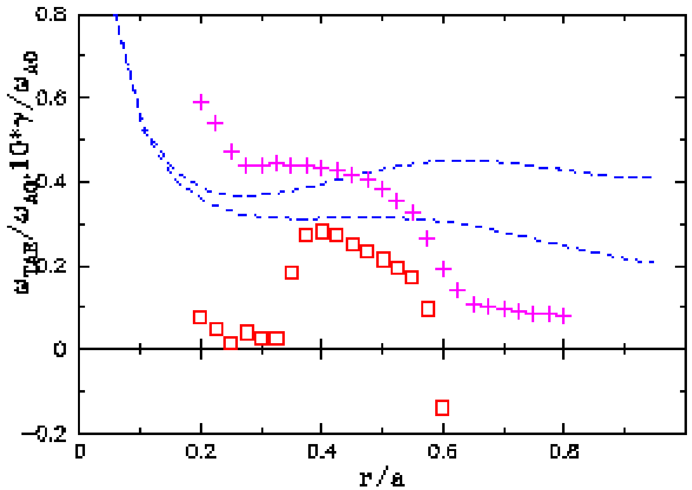
PPPL

If the profile is allowed to relax without particle loss, stability to these Alfven waves is achieved at higher $\beta_{0crit} - 1\%$.







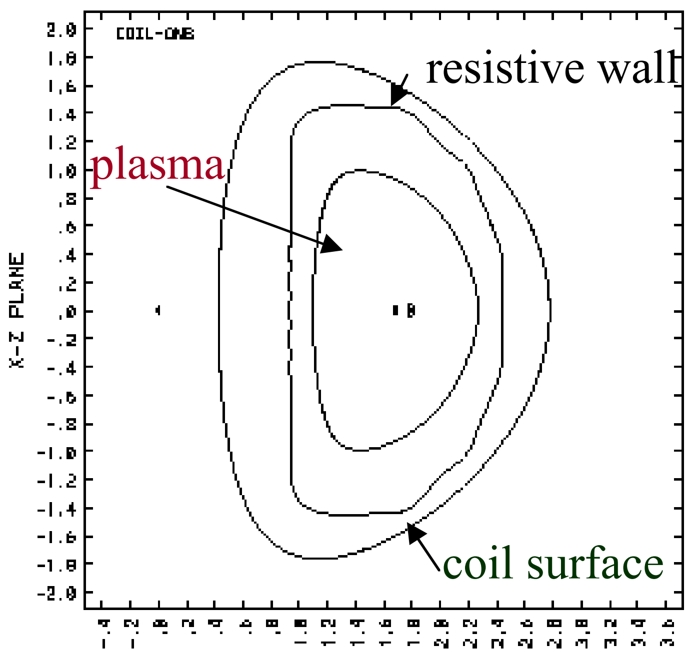


RTAE is found near q_{min} at critical $\beta_{0\alpha crit} = 0.23\%$ at $r/a = 0.4$, (local $\beta_\alpha = 0.047\%$).

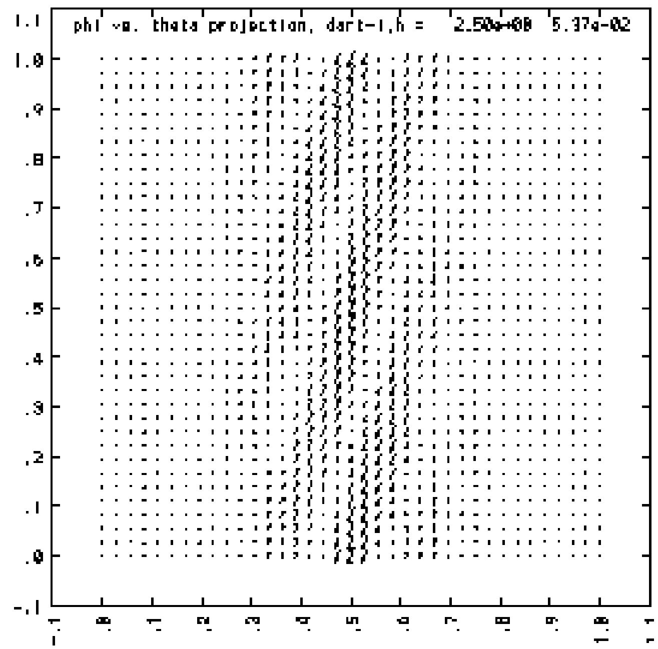
NO relaxed RTAE stable profiles were found. Alphas will be trasported outside q_{min} surface.

Resistive Wall Mode and Active Feedback Stabilization

We are developing a major extension of the linear stability codes to include resistive walls, coils, circuit equations, feedback systems, with self-consistent plasma response…interface with both PEST and GATO—also benchmark with Columbia VALEN code



VACUUM model includes plasma, wall, and coil surface



Induced currents in wall in absence of feedback

Chance, et al. IAEA 2000, Phys. Plasmas 4 (1997) 2161

ω^2 vs q_{edge} for various $\gamma\tau_s$ using GATO + VACUUM: for a conformal resistive shell at b = 0.5 a.

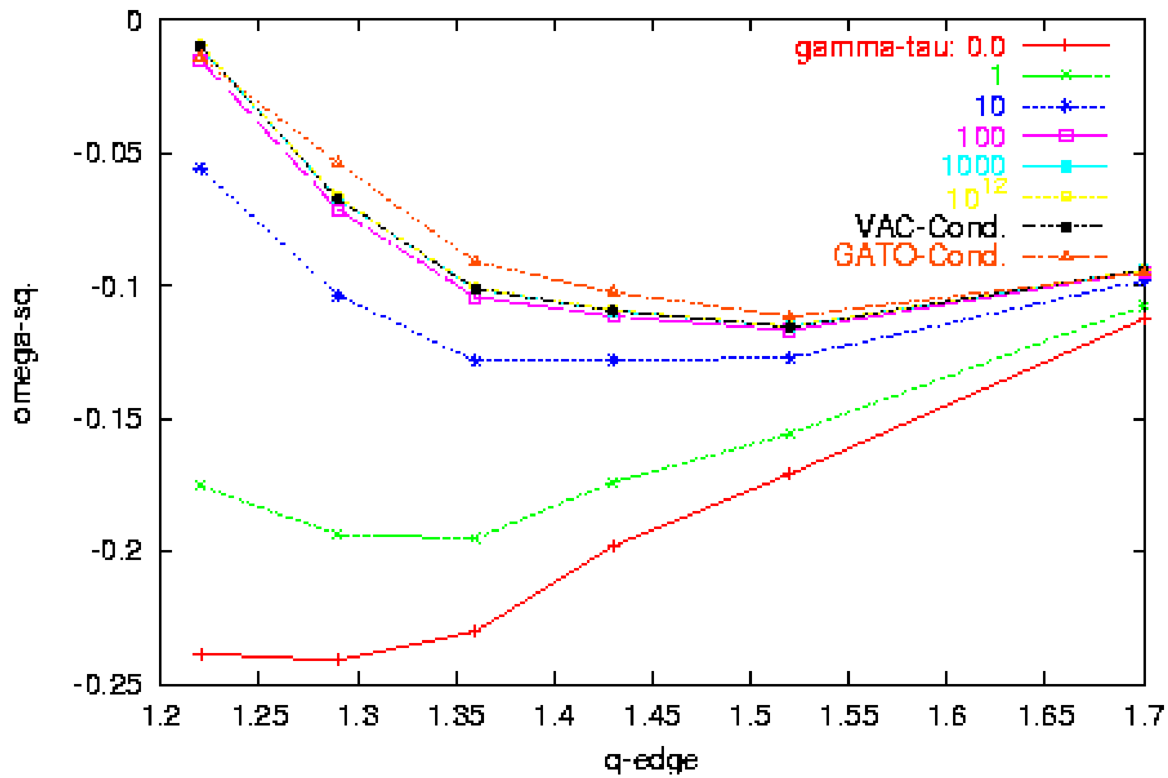
•$\gamma\tau_s \rightarrow \infty$ reproduces perfectly conducting shell results

•$\gamma\tau_s \rightarrow 0$ gives no-wall limit

•$\gamma\tau_s$ in between gives intermediate result

Future Plans:

• include sensor and feedback coils in system while keeping the self-adjoint property



M.Chance, PoP, 4 (1997) 2161

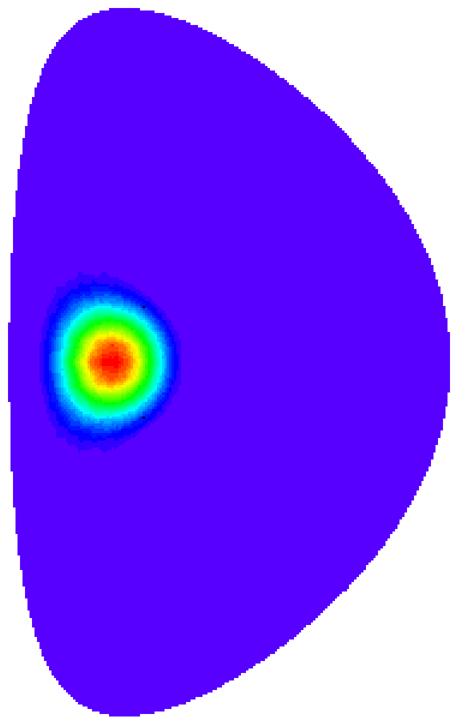
M3D code is being applied to explain physical mechanism for deep penetration of inside pellet launch

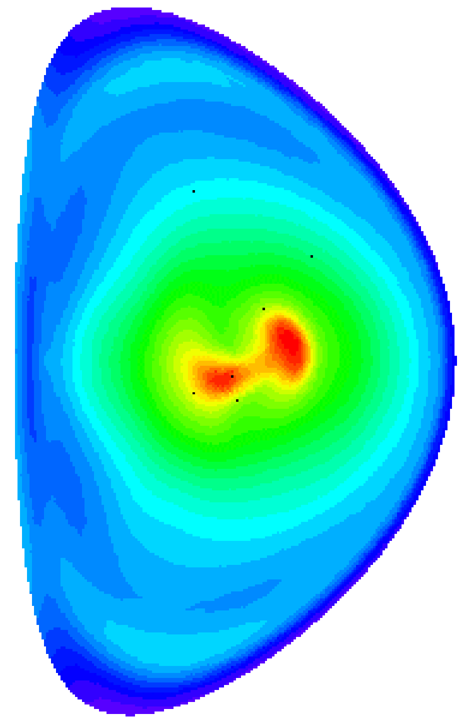
- first 3D simulation of this experimentally discovered phenomena

[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]





Energy Confinement

- Empirical scaling laws predict FIRE will achieve Q=10 at H_{98}=1.2 (LF) or H_{98}=1.0 (HF) using ITER98-H(y,2) fit to data
  - Need to examine scaling of narrower subsets of data: eg. With $n/n_{GR} > 0.6$, $T_i/T_e < 1.5$, $q_{95} < 3.2$, $\beta_\theta > 0.5$
- Good theory based model of plasma confinement would increase confidence…such as what is coming from Gyrokinetic codes
  - FIRE would provide invaluable calibration point for such codes
- Good theory based model of physics of L-H transition would increase confidence: threshold power, edge pedestal height and width
- Some uncertainties regarding impact of sawtooth, NTM, and other MHD on energy confinement

Other Physics Issues for FIRE

conventional operating modes

- the effect of H-mode profiles on MHD stability (Manickam)
    - relation to ELMS, n ~ 5-10 peeling modes, bootstrap currents
- error fields and locked modes (LaHaye, et al)
- need to assess disruption effects

reversed shear operating modes

- characterization of no-wall advanced mode for entire discharge (Ramos)
- wall stabilized advanced modes (GA/PPPL/Columbia experiments on DIII)

other advanced modes

- off axis CD to raise q_0 (Kessel)
- edge current drive to improve stability (?)

Summary

- **No physics "showstoppers" have been identified, but lots of interesting physics issues will come into play**

- **Self-consistent TSC discharge simulations exist for both the high-field (12 T, 7.7 MA, H=1.0) and low-field (10T, 6.75 MA, H=1.2) operating modes**

- **Overall, MHD stability looks favorable. Primary uncertainty due to:**
    - MHD activity near q=1 surface
    - edge currents due to H-mode pedestals
    - neoclassical tearing modes
    - error fields and locked modes

- **Experimental prototyping of the FIRE operating modes would be very beneficial**

- **"Advanced Modes" need to be further developed**