Alpha driven instabilities in FIRE.

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Critical Issues in Alpha physics

Effects of Alphas in tokamk plasma can be grouped into:

1. single particle
2. collective

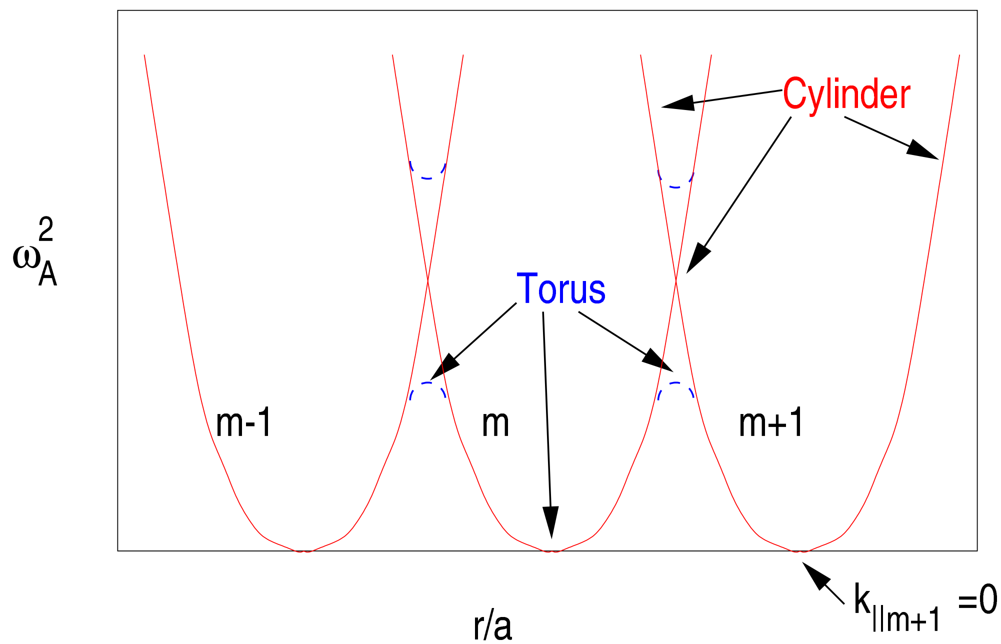
Most critical issue: Will alphas be confined?

1. single particle: Ripple losses
   - ✓ MHD activity
2. collective:
   - ✓ Fishbone instability (if $q_0 < 1$)
   - ✓ Alfvén instabilities (TAE/RTAE/EPM/KTAE/KBM)

- ✓ Alfvén wave dispersion $\omega_A = k_\parallel v_A$.
- ✓ In tokamak

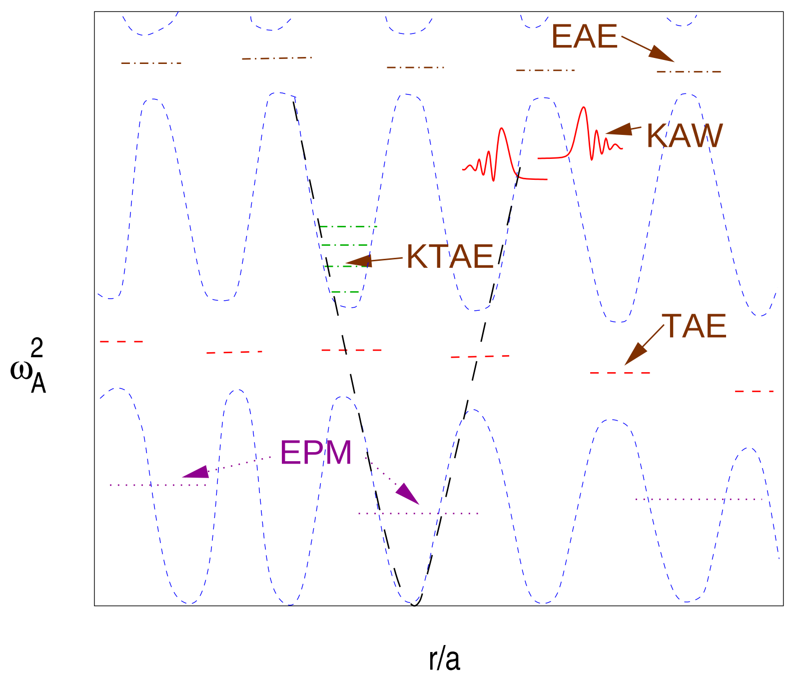
$$k_\parallel = -i\frac{\mathbf{B}}{B}\nabla = -i\frac{\mathbf{B}_\theta}{B}\nabla\theta\frac{\partial}{\partial\theta} - i\frac{\mathbf{B}_\varphi}{B}\nabla\varphi\frac{\partial}{\partial\varphi} \Rightarrow$$

$$k_\parallel = \frac{B_\theta}{rB}m - \frac{B_\varphi}{RB}n \simeq \frac{m - nq(r)}{q(r)R} \Rightarrow k_{\parallel gap} = \frac{1}{2qR}$$



Zoo of Alfvén modes.

Noncircularity and nonideal effects introduce new types of modes:



Ideal MHD theory for TAE are not satisfactory for the majority of fast particle driven Alfvén instabilities observed in experiments.

Nonideal effects are important, when:

(1) Plasma FLR corrections are large: new KTAE branch (Mett, Mahajan '92).

(2) Fast particles introduce strong drive for the modes $\Rightarrow$ strong modification

Strong drive introduces new types of modes: RTAE/EPM (Cheng, Gorelenkov '95; Chen '94, Zonca and Chen '96).

New tools are urgent to understand and analyse Alfvén type modes excitations in TFTR, DIII-D, JT60, START, NSTX, JET and FIRE.

Nonlinear Physics in Mode Excitation

Linear mode apearance may be strongly effected by nonlinear effects:

✓ frequency splitting (JET, pitchfork TAE effect)

✓ frequency chirp - rapid frequency evolution (Berk & Breizman, 1998).

Mode amplitude saturation to evaluate particle losses, can be calculated using nonlinear theory:

✓ theory (Berk & Breizman 1992 -1997).

✓ numerical application in NOVAK for TFTR (Gorelenkov *et.al.* 1999).

Nonlinear physics can be critical in such cases as many radially displaced weakly unstable modes:

“Domino” effect. Maybe relavant to FIRE with KTAE often unstable.

Nonperturbative Analysis of Mode Excitation

Fast particles have strong beta (ICRF, NBI). For Alfvén modes locally:

$$k_{\|}^2 v_A^2 - \omega^2 + \beta_\alpha(\omega - \omega_*)\left[\ln\left(\frac{\omega_{\varphi 0}(\mathcal{E},\lambda,P_\varphi)}{\omega} - 1\right) + i\pi\right] = 0$$

To excite the nonperturbative mode one needs:

✓ + $\beta_\alpha^{'} \simeq \beta_c^{'}$

✓ Resonant particles with $\omega_\varphi(\mathcal{E},\lambda\, P_\varphi) = \omega$, and strong pressure gradient to overcome Landau damping $\omega_* > \omega$

✓ Drive stronger that damping from the plasma, which includes:

- background plasma ion & electron Landau damping
- electron collisional damping
- continuum radiative damping

Frequency of RTAE/EPM is $\omega \simeq \omega_{\varphi 0}$

Numerical simulation of nonperturbative Alfvén modes. HINST analysis.

HIgh-N Alfvén modes STability code developed at PPPL is used.
HINST is:

- ✓ nonperturbative,
- ✓ fully kinetic,
- ✓ uses Fourier-Ballooning formalism,
- ✓ can produce $2D$-mode structure for high-n modes,
- ✓ $s-\alpha$ analytic equilibrium with circular magnetic surfaces,
- ✓ now include fast particles with Maxwellian, slowing down, beam and slowing down + beam distributions.
- ✓ Also has local version, very usefull for medium-n analysis and first guess of the modes lcoation.

High-n TAE Eigenmode equation

- Assume analytical $s - \alpha_{pc}$ equilibrium
- Based on Gyro-Kinetic Equations, we obtain

High-n 2D Eigenmode Equation

(see Cheng, Gorelenkov, Hsu, Nucl.Fusion 1995).

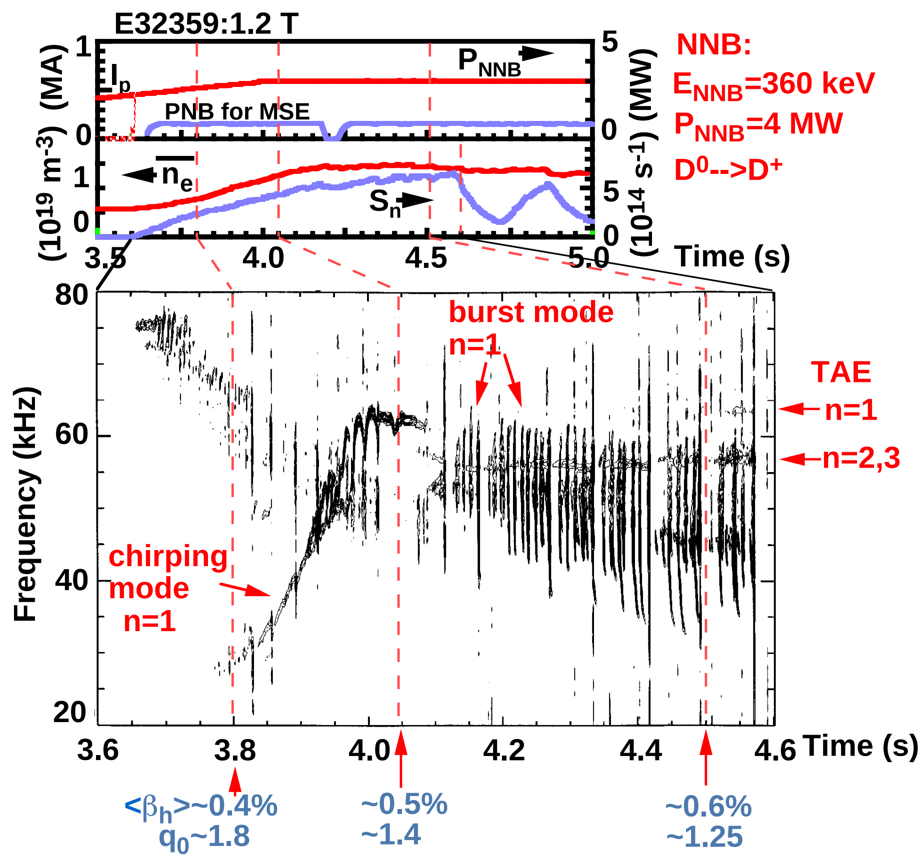
$$\begin{aligned}
&\int dx e^{i\eta_k' x}\left[\frac{\partial}{\partial\eta} h(\eta,\eta_k)\frac{\partial}{\partial\eta}\Phi\right.\\
&+\frac{\omega^2}{\omega_A^2}\left(1-\frac{\omega_{*i}}{\omega}\right)(1+2\hat{\epsilon}\cos\eta)\frac{h^2(\eta,\eta_k)(1+G_1)}{1+b_i}\Phi\\
&+\left[\cos\eta+(s(\eta-\eta_k)-\alpha_{pc}\sin\eta)\sin\eta\right]\\
&\left.\times\left\{(\alpha_{pc}-\alpha_{ph}G_3)[1+G_1]+G_4\right\}\Phi\right]=0
\end{aligned},$$

where

- ✓ $h(\eta,\eta_k)=\left[1+(s(\eta-\eta_k)-\alpha_{pc}\sin\eta)^2\right]$,
- ✓ G_1, G_4 - electron and ion Landau and trapped electron collisional damping,
- ✓ G_3, fast particle contribution
- ✓ $b_i = k_\perp^2\rho_i^2/2$, Full FLR with Padè approximation
- ✓ $\alpha_{ph,c} = -2p_{h,c}' Rq^2/B^2$.

Example of Chirping RTAE in JT-60U

Y. Kusama, IAEA'98.



DIII-D analysis in progress

Experimental evidence of Alfvén mode activity in RS discharges (Greenfield talk at APS, 99):

✓ Plasma underperformance due to AE activity

✓ NBI ion losses

✓ Sawteeth are more frequent due to the lack of stabilization from fast particles.

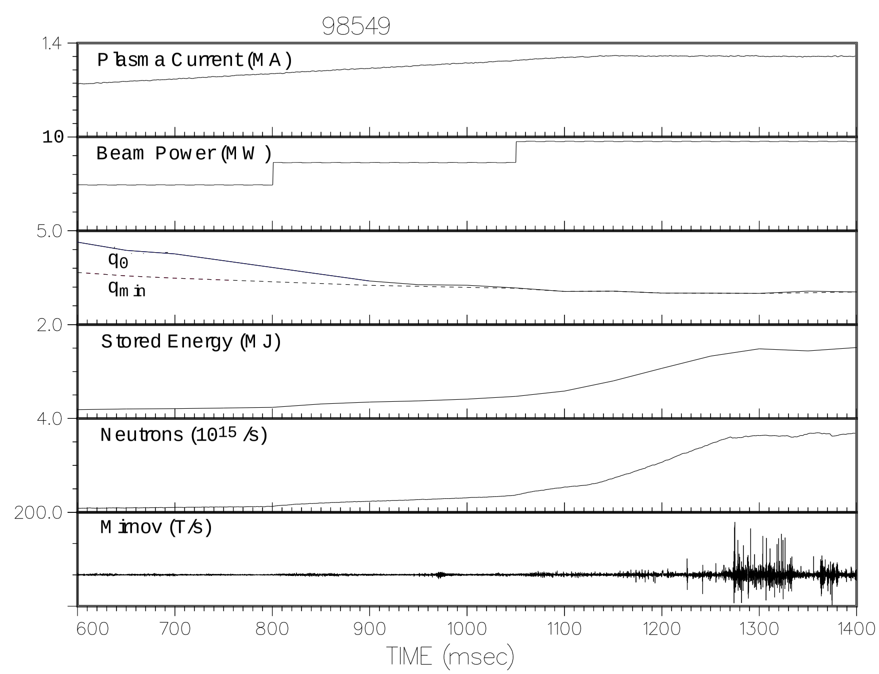
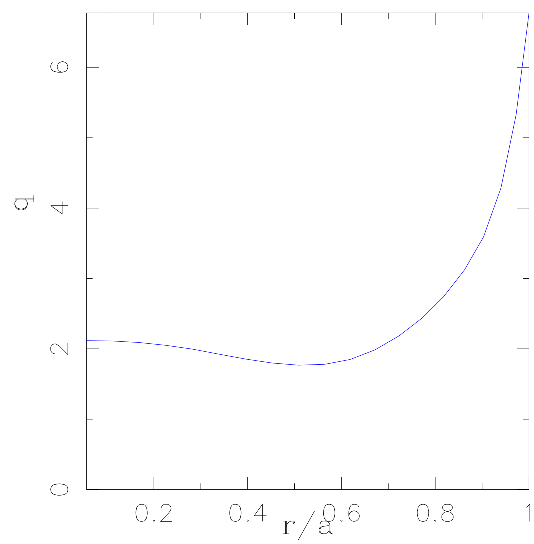
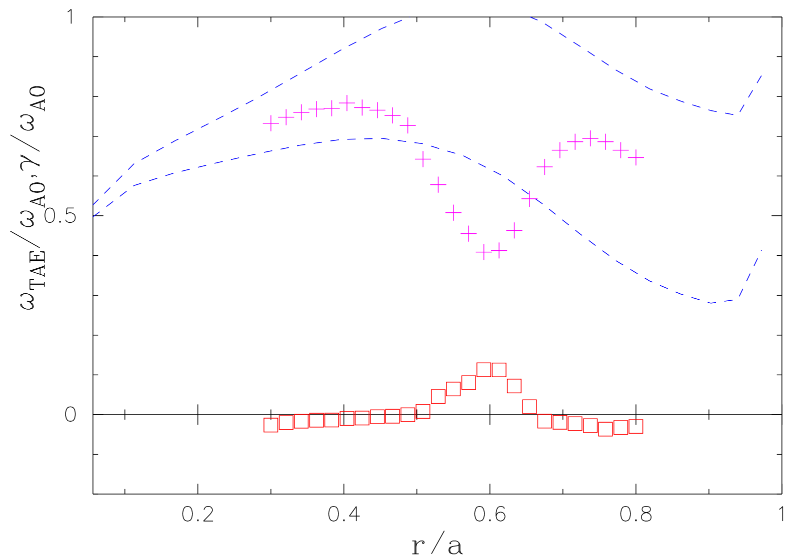


Figure 1:

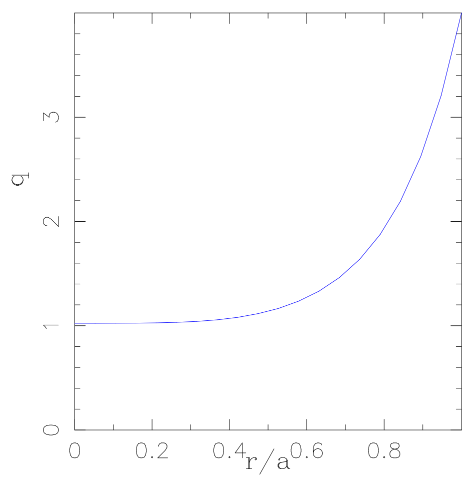
Preliminary HINST DIII-D analysis

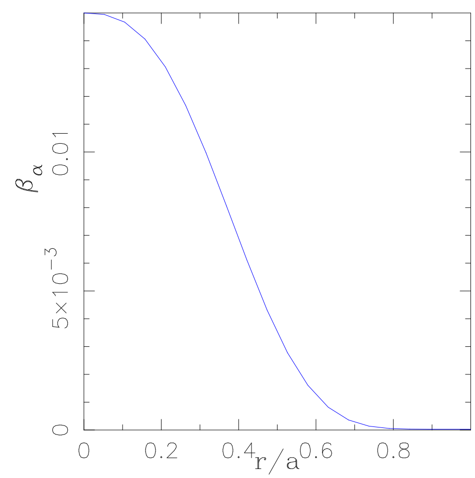


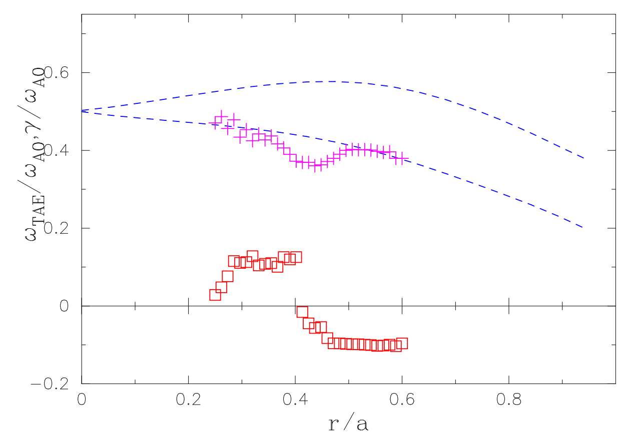


- ✓ Alfvén mode is strongly coupled to the continuum - RTAE.
- ✓ RTAE has maximum growth rate at small slightly positive shear minor radius.
- ✓ Mode can be stabilized by negative shear.

FIRE regular q-profile







Other parameters:

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

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

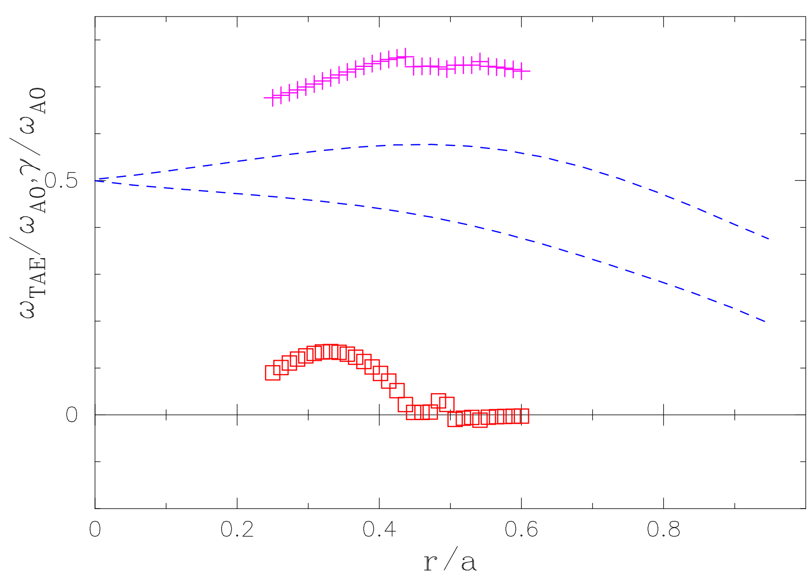
Critical Alpha $\beta_{0crit} = 0.65\%$ (local $\beta_\alpha = 04\%$).

FIRE regular q-profile plasma variations

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

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

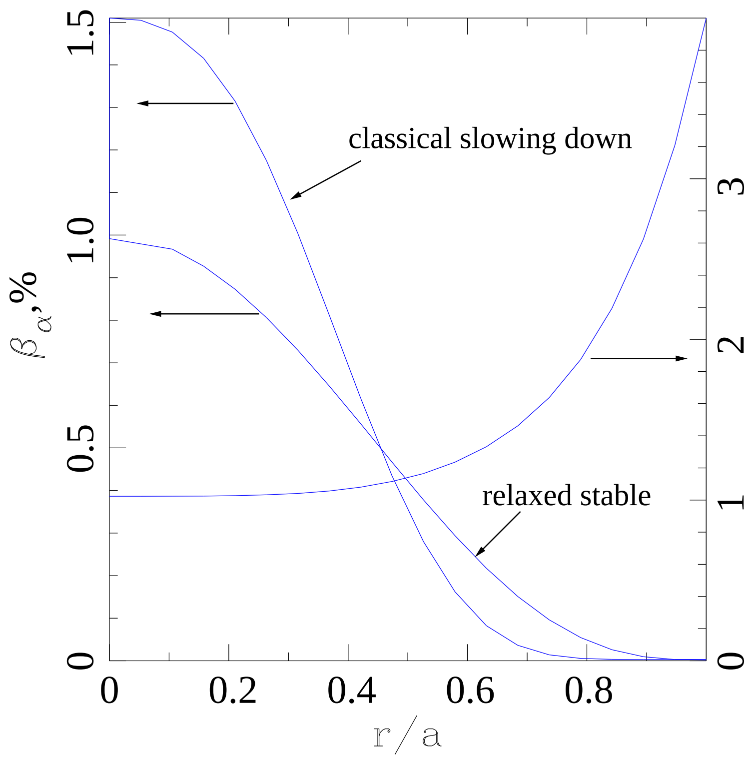
KTAE are still unstable.

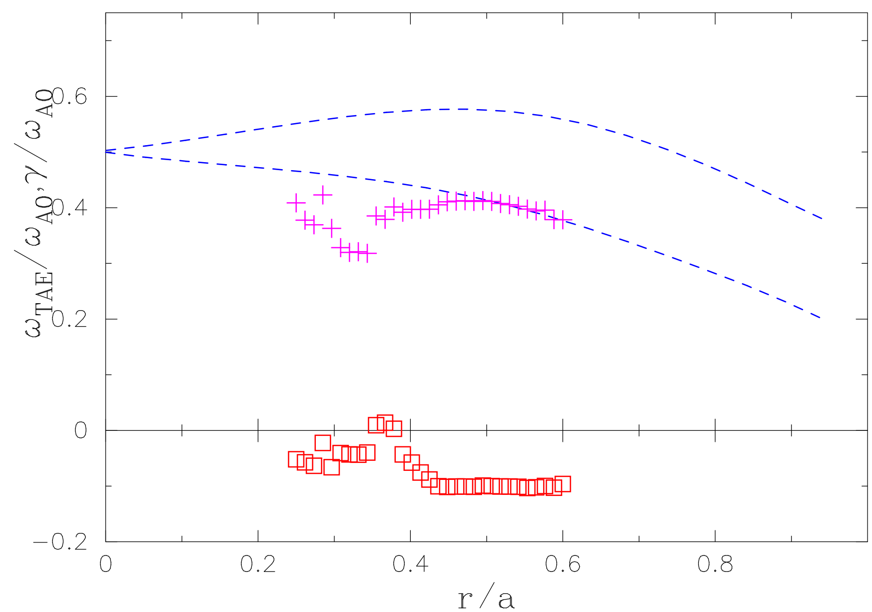


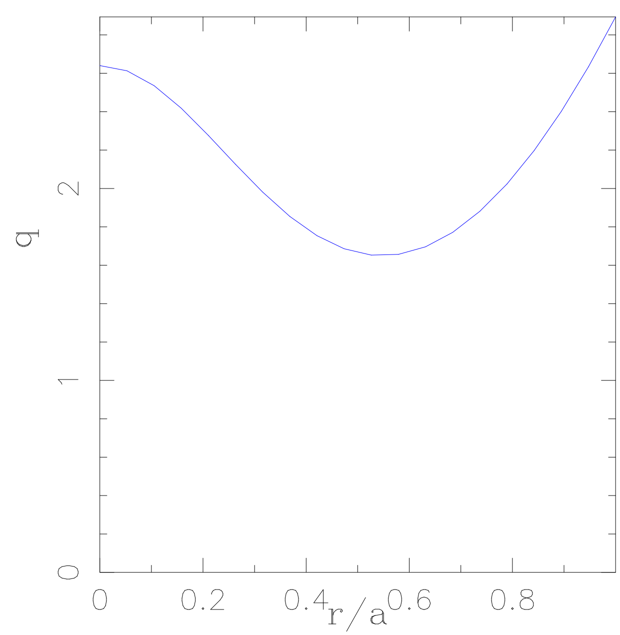
KTAE: $\beta_{0\alpha crit} = 0.5\%$ at $r/a = 0.35$ analysis and $\beta_{\alpha crit} = 0.33\%$

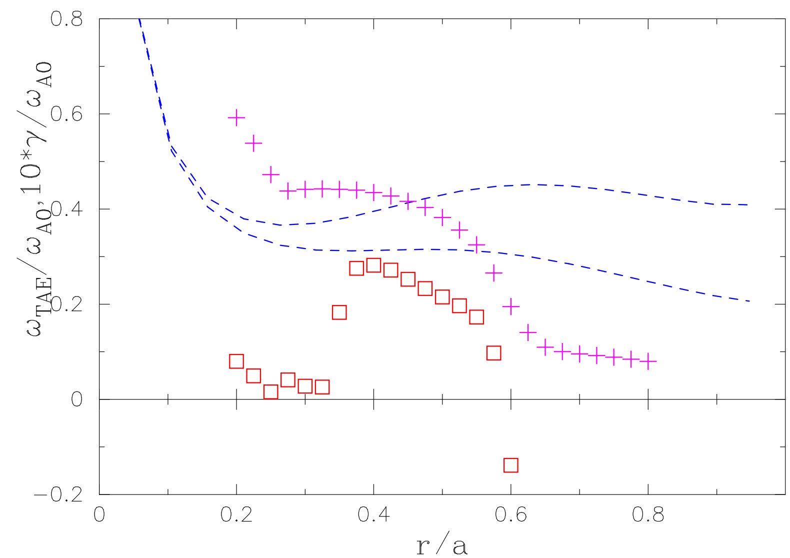
Regular q-profile with relaxed fast particle pressure.

If the profile is allowed to relax without particle loss, stability to these Alfven waves is achieved.





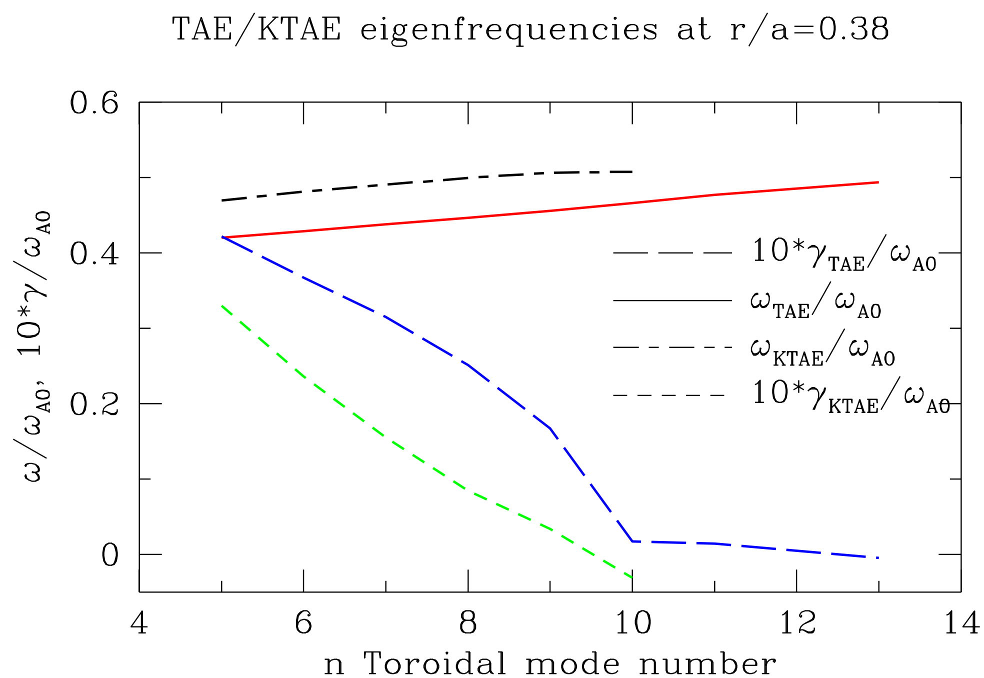




RTAE is found near q_{min} at critical $\beta_{0\alpha crit} = 0.23\%$ at $r/a = 0.4$, (local $\beta_\alpha = 0.047\%$).

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

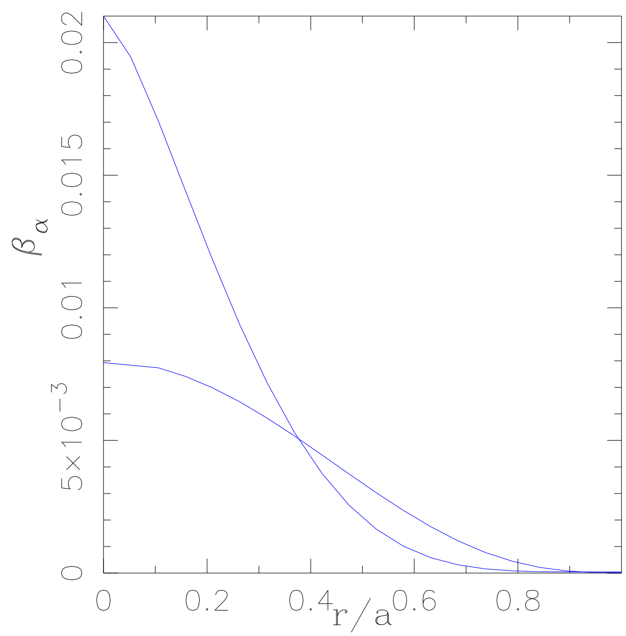
Toroidal mode number dependence

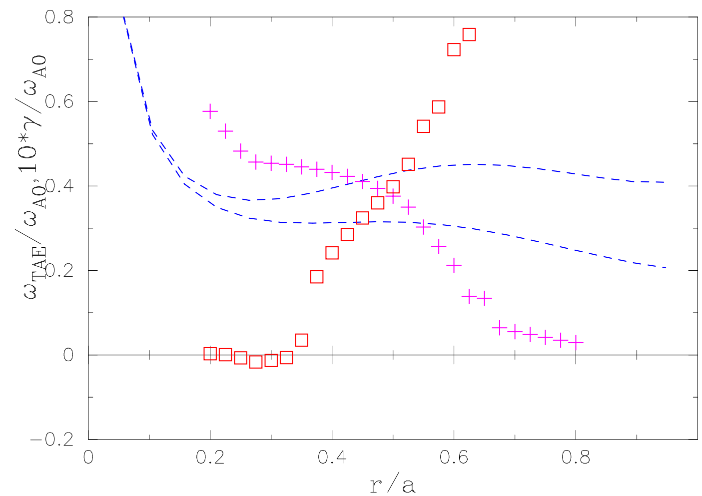


Lowest n number is the most unstable.

DIIID gives the same result and is supported by HINST.

Relaxed $\beta_\alpha-$profile couples RTAE to KBM





Relaxed critical $\beta_{0\alpha} = 0.37\%$ at $r/a = 0.6$ analysis and $\beta_\alpha = 0.09\%$ for KBM. KBM probably were seen in DIIID, where shear is larger outside q_{min}.

Summary and Future plans

1. Regular $q-$profile case in FIRE can be stable against RTAE if alpha particle $\beta_{0\alpha} < 0.65\%$.
   KTAE seems to be unstable if $\beta_{0\alpha} > 0.5\%$. Alphas transport is not expected large due to KTAE except in case of "domino" effect, but needs to be studied.
2. Inversed $q-$profile plasma is very unstable.
   (a) Low threshold.
   (b) Coupling to KBM outside q_{min} surface.
3. DIIID provides similar plasma conditions for studying RTAEs effects on fast particles. Shear effect may be studied at DIIID.
4. Multiple modes effect on fast particles is very probable to be studied in NSTX.
5. New code with capabilities of HINST but for low-n numbers is urgent to understand modes with strong drive, such as EPM/RTAE, BAE.
6. Nonlinear mechanism may introduce enhanced losses even in weakly instable modes suhch as KTAE. Numerical study is nesessary for quantitative analysis, with codes such as M3D.
   Numerical calculations need to be understood with the help of theory.