Collective alpha-particle effects in burning plasma experiments.

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Collective effects, such as instabilities driven by fast fusion products, alpha-particles, in the burning plasma experiments are the most critical physics issues for the sustainment of the plasma parameters close to the ignition and for the heat fluxes to the first wall of the reactor. Collective effects are known to result in energetic particle transport and losses in the present day experiments. However, as it will be shown some parameters of the burning plasmas can not be reproduced in present devices. There are specific physical issues, which only arise from at dimensionless parameters relevant to next step burning plasma experiments (BP). In addition alpha particles will have close to isotropic distribution function, which distinguish BP from present day (PD) experiments. This effects the drive for known instabilities in the plasma, such as Alfvén eigenmodes, EPMs, fish-bones, and MHD macro-modes. Other important issue to be considered is the interaction of alphas with multiple Alfvén instabilities, which are difficult to produce in PDs. Even with continued progress in PD experiments extrapolation to BP conditions will remain uncertain without BP experiment.

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Critical Issues in Alpha physics for Burning Experiment

Effects of Alphas in tokamak plasma can be grouped into:

1. single particle
2. collective

⇒ Have to answer: Will alphas be confined in BP? How they will affect plasma performance in BP?

1. single particle effects:
   - ✓ Ripple losses: Present Dev. relevant -PD, and can be extrapolated to Burning Plasma -BP.
   - ✓ background plasma driven MHD activity (PD, BP)
2. collective:
   - ✓ Fish-bone instability (PD, BP)
   - ✓ Alfvén instabilities (TAE/RTAE/EPM/KTAE/KBM) (PD, BP)
   - ✓ High frequency Alfvén instabilities (ST)
     (energy channeling to increase performance???-BPST).

Can we use dimensionless parameters for extrapolation from PD to BP?

Some conditions are qualitatively different from reactor/BP conditions:

1. Alphas distribution function is almost isotropic in BP then fast particle distributions in PD
    - ✓ In PD it is mostly trapped (ICRF) or passing (NBI): Pitch angle width of the distribution is narrow $\Delta\lambda \simeq 0.1$ for ICRF, $\Delta\lambda < 0.5$ for NBI.
    - ✓ $\Rightarrow$ anisotropy can change mode range through extra drive/damping. $n_{min} \Leftarrow \omega_*/\omega$.
2. Machine size scale of ρ_f/a sets upper limit for Alfvén Eigenmodes (AE) mode number and number of modes.
3. Combination of different factors, such as anisotropy and machine scale aree interconneted with mode range and drive & particle transport.

Alpha effects on plasma macro-stability

PD theory predict only trapped particle interaction with $m/n = 1/1$
NOVA-K, NOVA-2 can predict effect of fast particles on ideal mode:

- ✓ Analysis of JET experiments demonstrates strong stabilization by ICRH, NBI, alphas of ideal mode.
- ✓ NOVA-K demonstrates ω_* stabilization in TFTR NBI heated discharges $\omega_* > \gamma_{MHD}$, but not in JET $\omega_* < \gamma_{MHD}$.
  Also plasma rotation is important for NBI stabilization.

How well we can extrapolate sawtooth stabilization to BP?

Not understood:

- ✓ Passing particle stabilization as JT-60U experiments suggest.
  Is it an ω_* stabilization or the trapped particle part of the distribution function issue?
- ✓ Onset of $m/n = 1/1$ mode and role of ω_* and ω_{rot} effects on the mode structure and frequency.

⇒ Need $\omega_{\varphi pr} \gg \omega_*, \omega_{rot}$ for succesfull stabilization of ideal mode, conditions (+anisotropic DF) not observed in PD.

⇒ Alphas effect on sawtooth in BP are challenge for the theory (BP relevant).

JT-60U observes strongly driven chirping Alfvén frequency modes.

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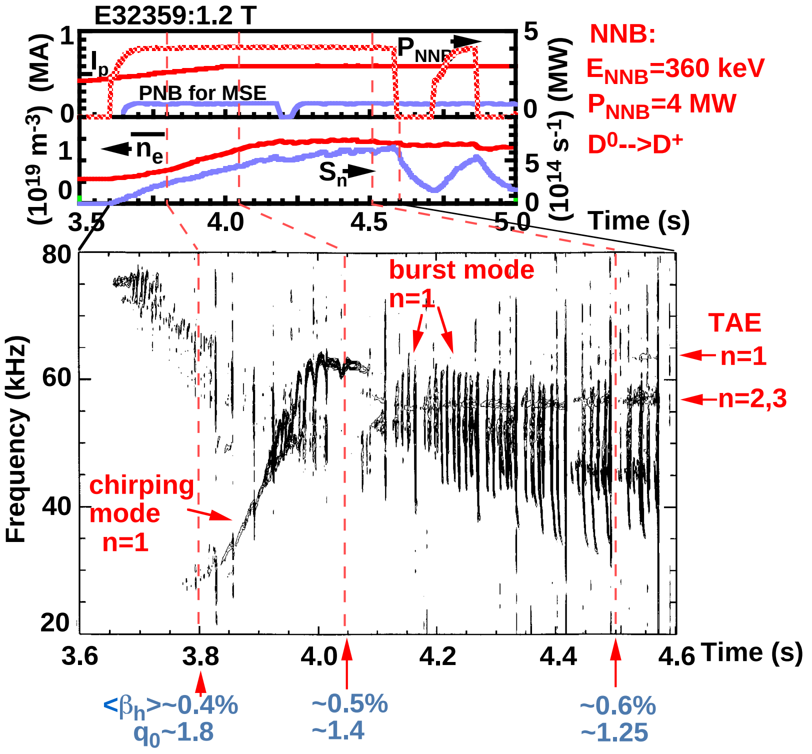
Y. Kusama, IAEA’98.



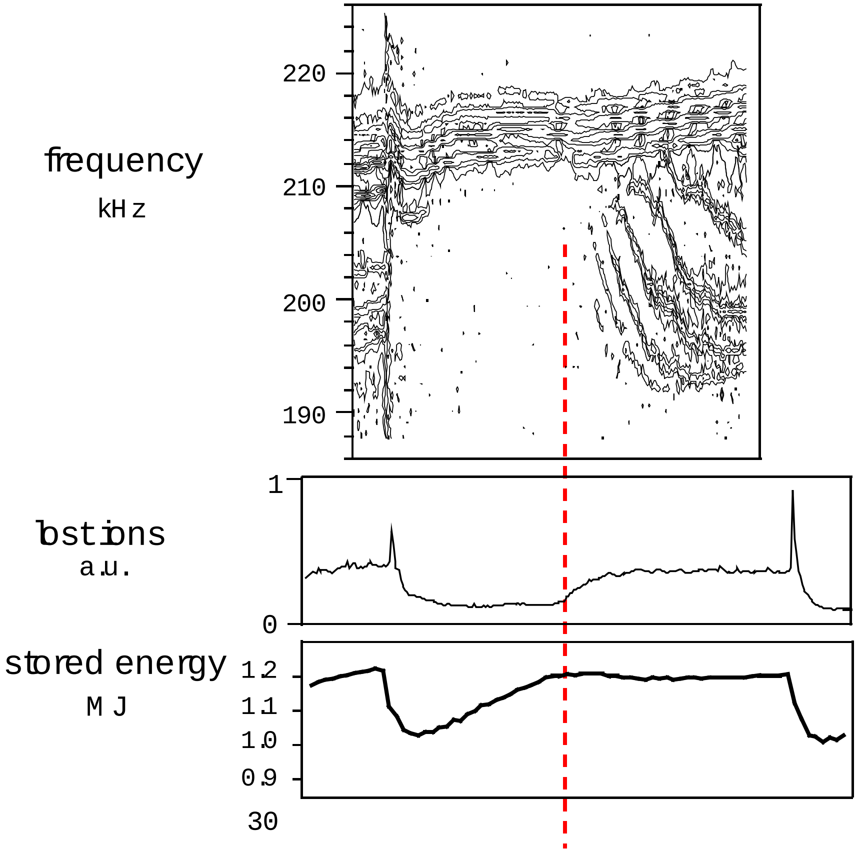
NNB:
E_{NNB}=360 keV
P_{NNB}=4 MW
D^0-->D^+

$<\beta_h>$~0.4%
q_0~1.8

~0.5%
~1.4

~0.6%
~1.25

TFTR core localized RTAEs transport particles and degrade stored energy (Bernabei).

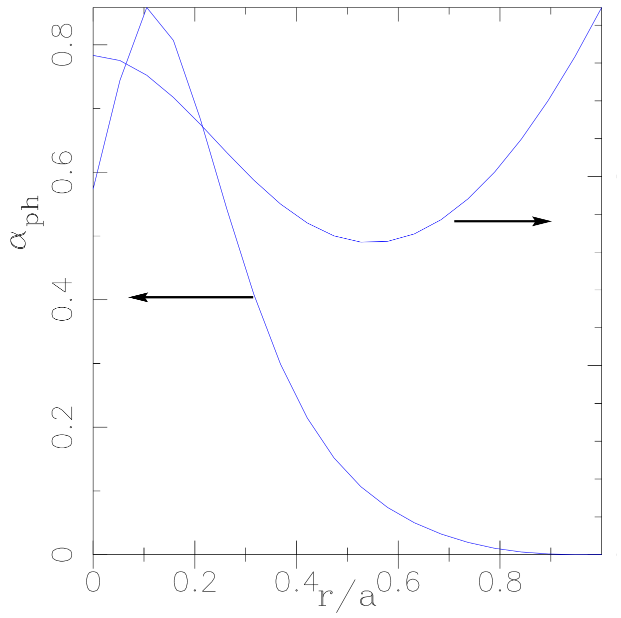


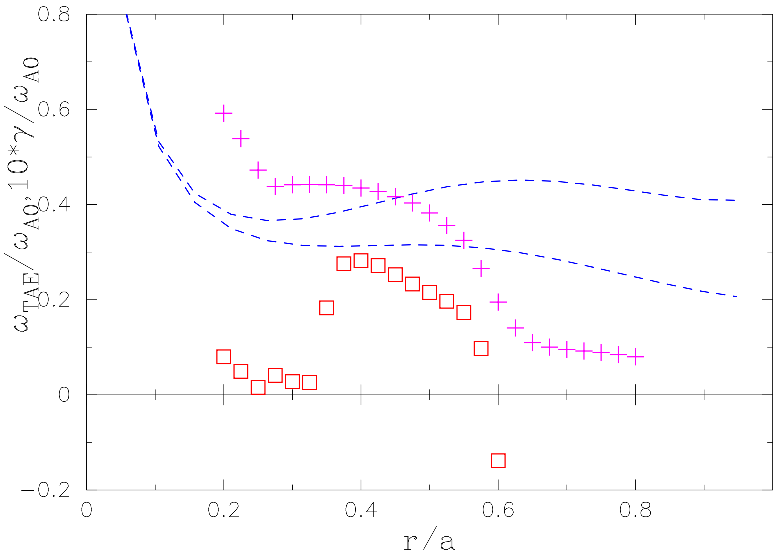
Plasma underperformes due to AE activity.

One needs a combination of modes for efficient transport: Core and Global RTAEs/TAEs.

Similar conclusions follow from DIII-D observations (Bernabei, Heidbrink).

Alfvén Modes are Robustly Unstable in Reversed Shear Configurations in BP & PD





- ✓ RTAE is found near q_{min}at low critical $\beta_{0\alpha crit} = 0.23\%$ at $r/a = 0.4$, (local $\beta_\alpha = 0.047\%$).
- ✓ NO relaxed RTAE stable profiles were found.
- ✓ Modes in AT regimes [BAE in DIII-D, chirping modes in JT-60U, TFTR].

Critical Parameters in AE/RTAE excitation for burning plasma tokamak experiments

Use following parameters for different machines:

	R,m	a,m	B_0, T	$\bar{n}, 10^{14} cm^{-3}$	$v_f, 10^9 cm/sec$	$v_A, 10^9 cm/sec$
ITER-FEAT	6.2	2	5.3	1	1.3	0.82
FIRE$_{base}$	2	0.525	10	5	1.3	0.7
FIRE$_{hiB}$	2	0.525	12	6	1.3	0.77
FIRE$_*$	2.14	0.595	10	5	1.3	0.7
IGNITOR	1.32	0.47	13	5.5	1.3	0.86
DIII-D	1.7	0.63	2	0.3	0.3	0.57
JT-60U(with NNBI)	3.3	0.78	1.2	0.1	0.6	0.58
JET-DT	3.	0.96	3.3	0.3	1.3	0.93
NSTX	0.86	0.68	0.3	0.3	0.27	0.084
DTST	1.2	0.96	3	4(?)	1.3	0.23
ARIES-ST	3.3	2	2	3	1.3	0.18
ARIES-RS	5.52	1.38	7.98	6.3	1.3	0.49

Critical Parameters in AE/RTAE excitation: mode number vs. number of modes.

Use scalings for the growth rate $\gamma_f \sim (\omega - \omega_*)$, and radiative and continuum dampings $\sim k_\perp \rho_i = nq\rho_i/r$.

- ✓ Passing particle drive limit (more tokamak relevant): $qk_\perp\rho_f \simeq 1$ or $n_{max} = r/q^2\rho_f$;
- ✓ Trapped particle limit (more ST relevant): $k_\perp \Delta_f \simeq n_{max} q \Delta_f / r = n_{max} q^2 \rho_f / (r\sqrt{\epsilon}) = 1$. For passing particles in ST one should use instead of $\rho_f \to v_A/\omega_c$, since $v_A \ll v_f$.
- ✓ Low limit for $n_{min} = (v_A/v_f)(L_p/R)(r/\rho_f q^2) < 1$, for estimates and $L_p = r$.
- ✓ RTAEs/EPMs may be driven at highest n - strongest drive as single-modes.
- ✓ We will use $q = 1$ and $r = a/3$.
- ✓ Fast particle to Alfvén speed ratio: $v_f/v_A > 1/3$ is needed for the instability on passing particles.

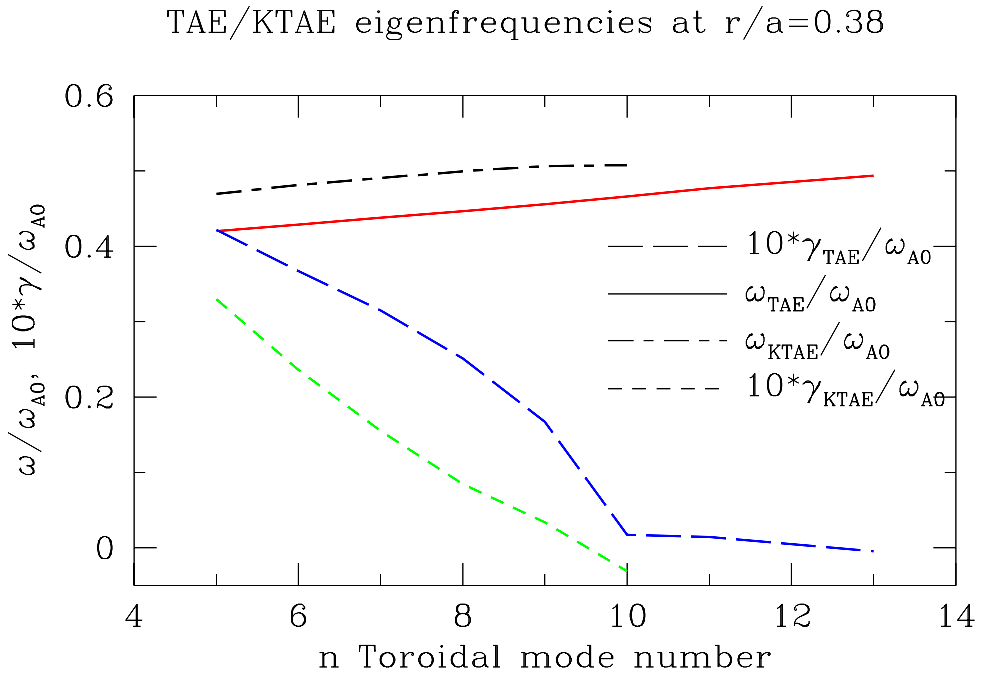
Critical Parameters in AE/RTAE excitation: estimates.

	ρ_f/a	v_f/v_A	n_{max}	$\beta(0)\,\%$	$\beta_f(0),\%$
ITER-FEAT	0.0257	1.6	13	10	1.5
FIRE$_{base}$	0.052	1.86	6	11	1.5
FIRE$_{hiB}$	0.043	1.7	8	11?	1.5
FIRE$_*$	0.046	1.86	7	11?	1.5
IGNITOR	0.044	1.5	8		1.2
DIII-D	0.054	0.53	6	7.	3.
JT-60U(with NNBI)	0.127	1	2.5	0.8	0.5
JET-DT	0.086	1.4	4	2	~ 0.5
NSTX	0.28	3.2	2(4,r=a)	60	30
DTST	0.093	5.7	4	60	30
ARIES-ST	0.066	7.2	5	60	30?
ARIES-RS	0.0248	2.65	13	11	0.8?

Global TAEs should be a problem for multiple n drive $n \geq 10$ (BP), but still maybe a concern for lower $n > 5$.

Alphas in DTST are similar to NBI ions in NSTX.

Drive vs. toroidal mode number for RTAE in FIRE RS.



Lowest n number is the most unstable, but global study may change this result.

DIIID shows similar behavior and is supported by HINST.

Drive and Saturation.

- ✓ For strongly driven RTAE/EPMs:

  $$\alpha_f \simeq \alpha_p = \beta q^2/\epsilon(L_\beta/r) \simeq 1$$

  is achievable in PD. But good confined alphas can produce more steeper gradients of betas and subsequent AE instabilities.
- ✓ Many modes can be excited at single n.
- ✓ Nonlinear physics can be critical in cases with many modes through the “Domino”-like effect. Maybe relevant to ITER and FIRE with global TAE and KTAE often unstable.
- ✓ Multimode instabilities are poorly diagnosed in PD especially for particle losses.

Summary remarks for Discussion

1. Critical issue for BP is multi-mode AE excitation and possible alpha transport associated with it. This can not be extrapolated from PD to BP: robust transport prediction.
2. Alphas effect on macro-stability is BP relevant. Hard to extrapolate: due to distribution function issue and $\omega_*, \omega_{rot} \sim \omega_{pr}$ in PD.
3. To do now:
    (a) Urgent need to concentrate on fast particle physics including more internal measurements of distribution and instabilities.
    (b) Develop robust linear and nonlinear models for strongly driven AE instabilities. National initiative in fast particle physics area to develop a nonlinear code dedicated to study nonlinear dynamic of fast particles is necessary + benchmark it to existing experiments.