Internal m=1 Modes in Ignitor

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Semi-analytical Approach

Generalized potential energy associated with internal kink displacement:

- $\delta W = 2\pi^2 R_0 \xi_{\mathrm{r0}}^2 (B_0^2/\mu_0)(\rho_1 \overline{a}/R_0)^4 \times \delta\overline{W} \qquad \overline{a} = \sqrt{V/(2\pi^2 R_0)} \qquad \rho = r/\overline{a}$

- $\delta\overline{W}$ = $\delta\overline{W}_T(\beta_{\mathrm{p1}}) + \delta\overline{W}_{\mathrm{shape}} + \delta\overline{W}_{\mathrm{KO}} + Re\delta\overline{W}_{\mathrm{k}\alpha}(0)$

- $\delta\overline{W}_T(\beta_{\mathrm{p1}}) = k_0 - k_1\beta_{\mathrm{p1}} - k_2\beta_{\mathrm{p1}}^2$ coefficients k_i (that depend on global characteristics of the q-profile) $\rightarrow$ computed numerically as specified in M. N. Bussac *et* al. *Phys. Rev. Lett.* **35**, 1638 (1975).
  $\beta_{\mathrm{p1}} = -\beta(0)(R_0/\overline{a})^2(1/\rho_1^4)\int_0^{\rho_1} d\rho\, \rho^2\, d\hat{p}/d\rho \qquad \hat{p} = p/p(0)$

- $\delta\overline{W}_{shape}$: shaping contribution $\rightarrow$ computed numerically as specified in J. W. Connor and R. J. Hastie, Rep. CLM-M106, UKAEA, Culham Lab. (1985).

- $\delta\overline{W}_{\mathrm{KO}} = 1.108\frac{15}{8\sqrt{2}\pi}\left(\frac{R_0}{\overline{a}}\right)^{3/2}\beta_{\mathrm{i}}(0)\frac{1}{\rho_1^4}\int_0^{\rho_1} \mathrm{d}\rho\, \rho^{3/2}\, \hat{p}_{\mathrm{i}}$ collisionless thermal trapped ion contribution $\rightarrow$ R. J. Hastie and T. C. Hender *Nucl. Fusion* **28**, 585 (1988).

Hot Alpha Particle Contributions

Two contributions by hot alpha particle population (K. G. McClements, R. O. Dendy, C. G. Gimbeltt, R. J. Hastie and T. J. Martin, *Nucl. Fusion* **35**, 1761 (1995)):

- $\beta_{\mathrm{p1}} = \beta_{\mathrm{p1,core}} + \beta_{\mathrm{p1},,\alpha h}$
  destabilizing term: increases as the $q = 1$ radius increases;

- $Re\,\delta\overline{W}_{\mathrm{k}\alpha}(0) = -\frac{3}{8}\left[\frac{R_0}{\overline{a}}\right]^{5/2} \beta_{\alpha h}(0)\,\frac{1}{\rho_1^4}\int_0^{\rho_1} \mathrm{d}\rho\,\rho^{3/2}\,\{0.6 +$
  $+\,3.2\,[1 - q(\rho) - \hat{s}(\rho)/2]\}\,\frac{\mathrm{d}\hat{p}_{\alpha h}}{\mathrm{d}\rho}$ $\qquad \hat{s} = (\rho/q)dq/(d\rho)$
  stabilizing "kinetic" term contributed by hot trapped alpha particles: decreases as the $q = 1$ radius increases;

Hot alpha particle pressure computed from slowing down distribution function

$$F_{\alpha h} = \frac{<\sigma v>_{\mathrm{DT}}\, n_{\mathrm{i}}^2\ \tau_{\mathrm{sl},\alpha}}{4\,(v^3 + v_{\mathrm{c}}^3)}\,\frac{1}{4\pi}H(v_\alpha - v)$$

Bosch-Hale expression for D-T thermal reactivity.

Modelling of Ignitor Plasmas

$p = p(0)(1-\rho^2)^{\nu_{\rm n}+\nu_{\rm T}} \qquad q = q_0(1+\lambda_{\rm q}\rho^{2\nu})^{1/\nu}$

Fix $q_0 = 0.85, \quad q_a = 3.4$ and vary ν to modify ρ_1. The value of $\beta_{\rm p1,crit}$ ($\delta\overline{W}_{\rm T}(\beta_{p1,crit}) = 0$) drops from 0.215 to 0.136 as the ρ_1 is increased from 0.24 to 0.44.

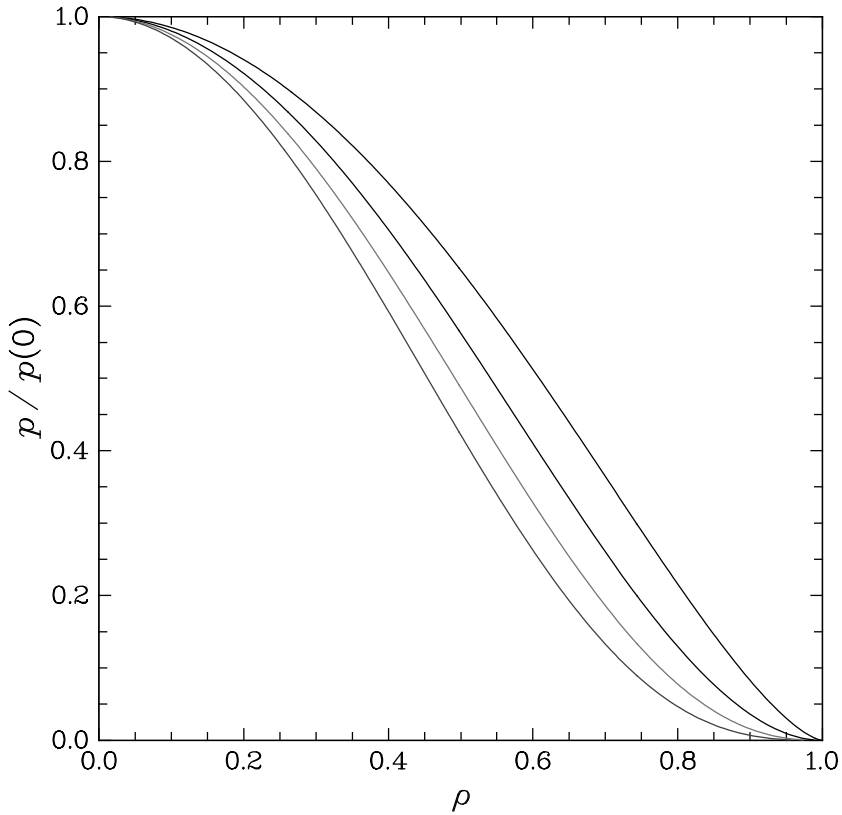
Different types of pressure profiles (coefficients $\nu_{\rm n}$, $\nu_{\rm T}$) are considered.

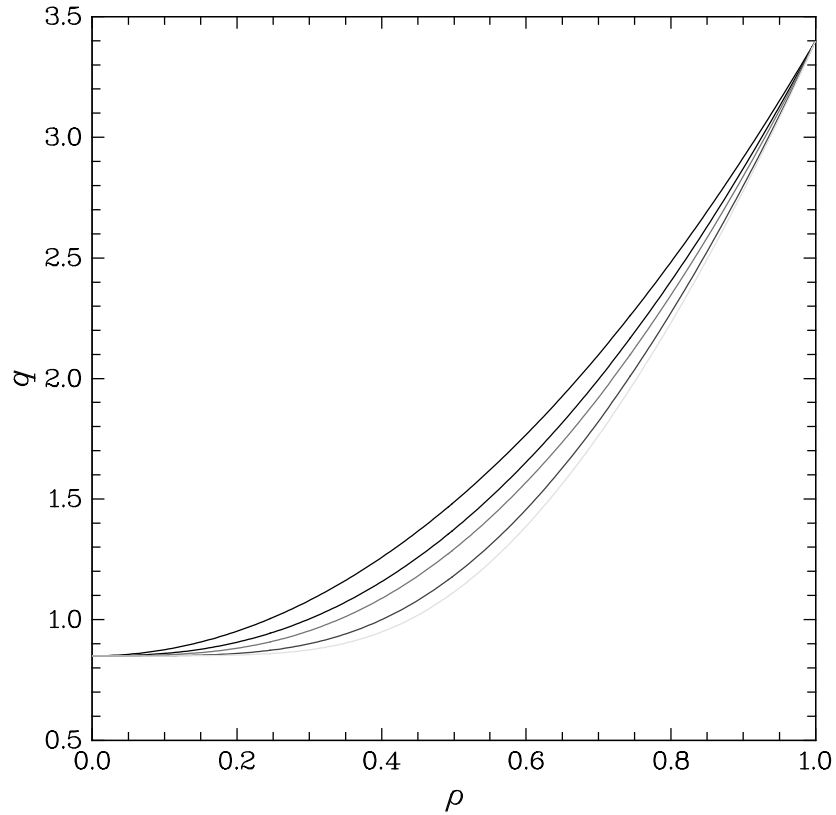
$T_{\rm e}/T_{\rm i} = 1.1$ and $n_{\rm i}/n_{\rm e} = 0.97$ is assumed.

A typical regime with $n_{\rm e}(0) = 10.0 \times 10^{20}$ m^{-3} as well as one with lower density $n_{\rm e}(0) = 7.3 \times 10^{20}$ m^{-3} - to explore effects of “higher temperatures” - are considered.

For given values of $\nu_{\rm n}$, $\nu_{\rm T}$, the value $T_{\rm e}(0)$ is then chosen so that $P_{\rm fus} \approx 100$ MW.

Plasma Profiles Considered





Higher density: $n_{\rm e}(0) = 10.0 \times 10^{20}$ m^{-3}

$$p(0)/\langle p \rangle = 1 + \nu_{\rm n} + \nu_{\rm T}$$

$\nu_{\rm n}$	$\nu_{\rm T}$	$T_{\rm e}(0)$ (keV)	ν_α	$\beta(0)$ %	β %	$\beta_{\rm p}$	$\beta_{\rm p1,core}$ $(\rho_1 = 0.34)$	$\beta_{\alpha h}(0)$ %	$\beta_{\rm p1,\alpha h}$ $(\rho_1 = 0.34)$
1.0	2.0	11.6	9.3	5.20	1.30	0.21	0.30	0.32	0.037
1.0	1.5	10.8	7.4	4.84	1.38	0.22	0.24	0.30	0.026
1.0	1.0	10.0	5.4	4.48	1.49	0.24	0.19	0.19	0.016
0.5	1.0	9.1	3.3	4.08	1.63	0.26	0.14	0.15	0.010

Low values of β, $\beta_{\rm p}$. However, $\beta_{\rm p1}$ can be relatively high for peaked pressure profiles.

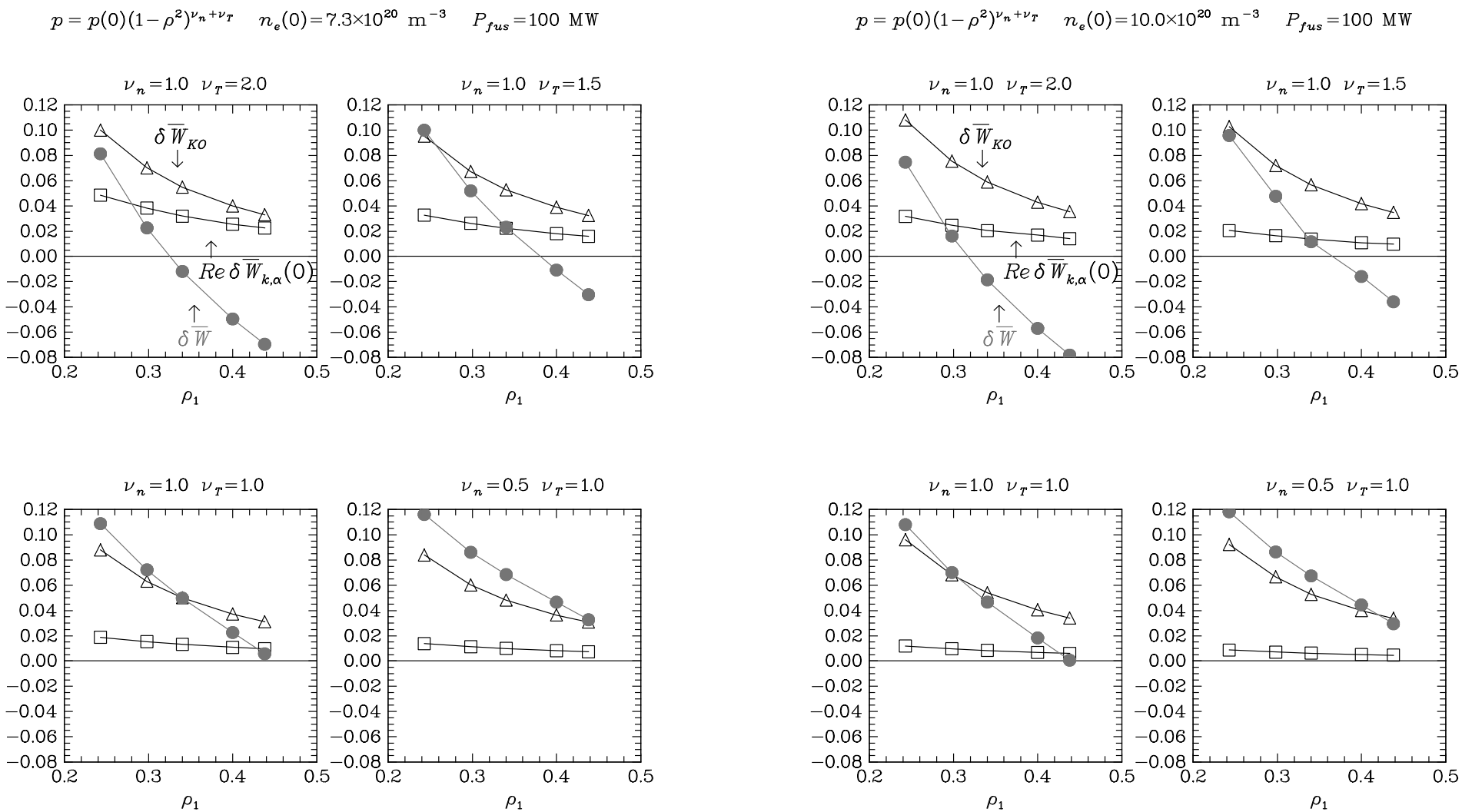
Lower density: $n_{\rm e}(0) = 7.3 \times 10^{20}$ m^{-3}

$$p(0)/\langle p \rangle = 1 + \nu_{\rm n} + \nu_{\rm T}$$

$\nu_{\rm n}$	$\nu_{\rm T}$	$T_{\rm e}(0)$ (keV)	ν_α	$\beta(0)$ %	β %	$\beta_{\rm p}$	$\beta_{\rm p1,core}$ $(\rho_1 = 0.34)$	$\beta_{\alpha h}(0)$ %	$\beta_{\rm p1,\alpha h}$ $(\rho_1 = 0.34)$
1.0	2.0	14.8	8.4	4.84	1.21	0.20	0.28	0.54	0.059
1.0	1.5	13.8	6.8	4.51	1.29	0.21	0.23	0.43	0.043
1.0	1.0	12.6	5.0	4.12	1.37	0.22	0.17	0.32	0.027
0.5	1.0	11.8	4.6	3.86	1.54	0.25	0.13	0.25	0.020

Alpha particle betas almost doubled with respect to previuos case.

Results


$p = p(0)(1-\rho^2)^{\nu_n+\nu_T}$ $n_e(0)=7.3\times10^{20}$ m^{-3} $P_{fus}=100$ MW
$p = p(0)(1-\rho^2)^{\nu_n+\nu_T}$ $n_e(0)=10.0\times10^{20}$ m^{-3} $P_{fus}=100$ MW
$\nu_n=1.0$ $\nu_T=2.0$
$\nu_n=1.0$ $\nu_T=1.5$
$\nu_n=1.0$ $\nu_T=1.0$
$\nu_n=0.5$ $\nu_T=1.0$
$\delta\overline{W}_{KO}$
$Re\,\delta\overline{W}_{k,\alpha}(0)$
$\delta\overline{W}$
ρ_1

Discussion

- as expected, stability (i.e. $\delta\overline{W} > 0$) depends on the peakedness of pressure profile and on the location of the $q = 1$ surface: peaked pressure profiles and large $q = 1$ radii are unfavourable;
- the stabilizing contribution of collisonless thermal trapped ions (Kruskal-Oberman term) is more important than than of hot alpha particles: this is partly due to the relatively "low" temperatures characteristic of Ignitor but also to the destabilizing effect of hot alpha particles through $\beta_{p1,\alpha h}$ (so the expectaction that "hotter is better" need to be qualified);
- in the case of $p(0)/\langle p\rangle = 2.5$, stability is found even without the Kruskal-Oberman term, while for $p(0)/\langle p\rangle = 3.0$ this term is important for stability when $\rho_1 > 0.3$;
- with more peaked pressure profiles, stability is limited to $\rho_1 < 0.36$ for $p(0)/\langle p\rangle = 3.5$ and $\rho_1 < 0.30$ for $p(0)/\langle p\rangle = 4.0$.
- while appealing - many potentially important terms can be computed self-consistently -, this semi-analytical approach has its shortcomings as the various terms in the generalized potential energy are computed in an approximated way (albeit significantly improved with respect to other formulations, such as that implemented in the so-called Porcelli model). More analysis is required to benchmark approximations, in particular for the fluid MHD term that represents the effects of shaping of the magnetic surfaces.