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Alfvén-Ion-Cyclotron Instability in the Central Cell of TMX

D. C. Watson and D. E. Baldwin

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Alfvén-Ion-Cyclotron Instability
in the Central Cell of TMX*

D. C. Watson and D. E. Baldwin

1. Distribution-function Modelling
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Abstract

The central cell of TMX may require hot-ion injection. The resulting velocity-space anisotropy together with the length of the central homogeneous region raise the possibility of convective AIC instability. In this report we demonstrate that the Rosenbluth criterion of less than a thousand-fold amplitude amplification per pass can be satisfied by ion distributions which nevertheless have sufficient anisotropy to be confined within the central cell.

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DISTRIBUTION-FUNCTION MODELLING

The central cell of TMX will have an ambipolar potential of -340 eV relative to the plug midplane. Central cell ions with kinetic energy less than 340 eV will all be confined. Ions with kinetic energy between 340 eV and 680 eV will see a mirror-ratio of 5:1, the ratio of the field at the plug midplane to the cell field. Ions with kinetic energy over 680 eV will see a mirror-ratio of 10:1, the ratio of the field at the inner plug throat to the cell field. Graphically the combined magnetic and electrostatic confinement appears as follows

We now turn to the results of Fokker-Planck computations by Rensink et. al. Neutral injection at 15 keV forms a plateau in the ion velocity distribution, extending down to about 3 keV. Below this temperature the velocity distribution is well approximated by a Maxwellian of temperature 260 eV. The electrons are Maxwellian with temperature 353.5 eV. Neglecting the narrow loss-region shown in Fig. (1), one can characterize the two components of the ion velocity distribution, along with the electrons, by their respective number densities,

mean energies, and mean parallel energies:

Hot plateau:

$$\langle E_H \rangle = 6.168 \text{ keV} \quad \langle E_{H\parallel} \rangle = 0.885 \text{ keV} \quad n_H = 0.99 \times 10^{13} \text{ cm}^{-3} \quad (1)$$

Cool bulk:

$$\langle E_C \rangle = 0.390 \text{ keV} \quad \langle E_{C\parallel} \rangle = 0.130 \text{ keV} \quad n_C = 1.495 \times 10^{13} \text{ cm}^{-3} \quad (2)$$

Electrons:

$$\langle E_E \rangle = 0.5606 \text{ keV} \quad \langle E_{E\parallel} \rangle = 0.1868 \text{ keV} \quad n_E = 2.485 \times 10^{13} \text{ cm}^{-3} \quad (3)$$

As an indicator of the relative importance of electron drag and ion-ion collisions note that

$$\langle \cos^2 \theta_H \rangle = 0.1435 > 0.1 = \langle \cos^2 \theta_{inj} \rangle \quad (4)$$

so that the angular extent of the plateau is at least roughly related to the angular extent of the injection. Of course in this approximation

$$\langle \cos^2 \theta_C \rangle = 1/3 \quad (5)$$

An appropriate mathematical model of the ion distribution is the superposition of a hot cone-bounded Maxwellian and a cool isotropic Maxwellian, chosen to duplicate the component densities and energies of (1) and (2) respectively. This choice is performed automatically by the code BALD14, which needs as input just the quantities

$$\beta_H^{vac} = 0.4531 \quad \beta_{H\parallel}^{vac} = \{0.2006\} \quad n_H/n_i = 0.398 \quad (6)$$

$$\beta_C^{vac} = 0.0433 \quad \beta_{C\parallel}^{vac} = 0.0433 \quad n_C/n_i = 0.602 \quad (7)$$

$$\beta_E^{vac} = 0.0622 \quad (8)$$

The vacuum betas are defined with respect to a vacuum field of 1.9 kG. The braces are a reminder that the code scans the variable $\beta_{H''}^{\text{vac}}$ to find the transition from convective to absolute instability. During the scanning, the total $\beta_{\perp}$, the internal magnetic field and the local ion beta are continually recomputed using the long thin approximation. The angular spread required for the plateau is then taken as a guide to the angular spread required for the injected beams, as discussed above.

The code BALD14 assumes an ion distribution function, normalized to unity in the uniform-field region of the central cell, of the form

$$f_0(v_{\perp}, v_{\parallel}) = \sum_{j=1}^5 \frac{n_j/n_0}{m_j!} \frac{\alpha_{j\parallel}}{\pi} \sqrt{\frac{\alpha_{j\parallel}}{\pi} + \frac{\alpha_{j\perp}}{\pi(R_j-1)}} \times e^{-\alpha_{j\perp} v_{\perp}^2 - \alpha_{j\parallel} v_{\parallel}^2 + \alpha_{j\perp} v_{jh}^2} \alpha_{j\perp}^{m_j} \left[v_{\perp}^2 - \frac{v_{\parallel}^2}{R_j-1} - v_{jh}^2 \right]^{m_j} \quad (9)$$

wherever the square bracket is positive and zero elsewhere. Here

$$1 = \int d^3v f_0(v_{\perp}, v_{\parallel}) = \sum_{j=1}^5 n_j/n_0 \quad (10)$$

The parameters of the component subdistributions are chosen to satisfy

$$\frac{\beta_j}{\beta_{j\parallel}} = \left(\frac{1}{R_j-1} + \frac{\alpha_{j\parallel}}{\alpha_{j\perp}} \right) \left(1 + \frac{2}{3} m_j + \frac{2}{3} \alpha_{j\perp} v_{jh}^2 \right) - \frac{1}{3} \left(\frac{\alpha_{j\parallel}}{\alpha_{j\perp}} - 1 \right) \quad (11)$$

For our case

$$n_3 = n_4 = n_5 = 0 \quad (12)$$

$$\alpha_{j\parallel} = \alpha_{j\perp} \quad (13)$$

$$v_{jh}^2 = 0 \quad (14)$$

$$m_j = 0 \quad (15)$$

$$\frac{1}{R_c - 1} = 0 \quad \frac{1}{R_H - 1} = \tan^2 \left(\theta_{\min}^{\text{plateau}} \right) \quad (16)$$

AIC STABILITY IN HOMOGENEOUS PLASMA

In terms of the parameters introduced in (6) through (10), the AIC dispersion function for parallel propagation assumes the form

$$D(K_{\parallel}, W) = \frac{K_{\parallel}^2}{\beta_i^{\text{loc}}} + \frac{W^2}{W - 1} + \frac{1}{2} \sum_{j=1}^5 \frac{n_j}{n_0} \left\{ \frac{1}{R_j - 1} \left(\xi_j^2 Z'(\xi_j) - 1 \right) + \left[\frac{1}{W - 1} + \frac{\alpha_{j\parallel}}{\alpha_{j\perp}} \left(1 + m_j + \alpha_{j\perp} v_{jh}^2 \right) + \frac{1}{R_j - 1} \left(m_j + \alpha_{j\perp} v_{jh}^2 \right) \right] Z'(\xi_j) \right\} \quad (17)$$

Here the local ion beta is defined by

$$\beta_i^{\text{loc}} = \beta_i^{\text{vac}} / (1 - \beta_{\perp}^{\text{vac}}) \quad (18)$$

where the perpendicular vacuum beta is found from

$$\beta_{\perp}^{\text{vac}} = \frac{3}{2} \beta_i^{\text{vac}} - \frac{1}{2} \beta_{i\parallel}^{\text{vac}} + \beta_e^{\text{vac}} \quad (19)$$

The dimensionless wavenumber and frequency are normalized to the average ion energy and local magnetic field:

$$K_{\parallel} = \frac{k_{\parallel}}{\omega \sqrt{\alpha_{\text{phys}}}} \quad \langle \alpha_{\text{phys}} v_i^2 \rangle \equiv \frac{3}{2} \quad W = \frac{\omega}{\omega_{ci}} \quad (20)$$

The finite electron temperature is ignored in the electron term of the dispersion function, namely the second term on the right of (17). However it is included in the finite-beta correction (18) - (19). The arguments of the Fried-Conte function are

$$\xi_j = \frac{W - 1}{K_{||}} \sqrt{\frac{n_j}{n_0} \frac{\beta_i^{\text{vac}}}{\beta_{j||}^{\text{vac}}}} \quad (21)$$

The program BALD14 finds the saddle point defined by

$$D(K_{||}, W) = 0 \quad \partial D / \partial K_{||} = 0 \quad (22)$$

and adjusts the parallel ion energy of the hot plateau $\beta_{H||}^{\text{vac}}$ until

$$\text{Im}(W_{\text{saddle}}) = 0 \quad (23)$$

This marks the transition from convective to absolute instability. For hot ion populations more closely clustered around $\theta = 90^\circ$, the AIC mode is absolutely unstable. For hot ion populations more widely spread in angle, the convective growth length for seven exponentiations (a thousandfold increase) in wave amplitude is given by

$$\frac{L_7}{a_i^{\text{vac}}} = \frac{7.0}{\text{Im}(K_{\text{conv}}) \sqrt{1 - \beta_{\perp}^{\text{vac}}}} \quad (24)$$

Here a_i^{vac} is the ion Larmor radius in the vacuum field for an isotropic distribution with the same average energy as the actual distribution. Explicitly it is the radius of the Larmor orbit described by an ion with

$$E_{\text{ion}} = \frac{2}{3} \langle E_i \rangle = 1.7946 \text{ keV} \quad (25)$$

$$B = B_{\text{vac}} = 1.9 \text{ kg} \quad (26)$$

and has the value

$$a_i^{\text{vac}} = 4.554 \text{ cm.} \quad (27)$$

The input data (6) - (8) yield a value for the angular spread of the hot-ion component at the onset of absolute instability which is

$$\beta_{H_{\parallel}}^{\text{vac}} = 0.3964 \quad \cos^2(\theta_H) = \beta_{H_{\parallel}}^{\text{vac}} / \beta_H^{\text{vac}} = .8749 \quad (28)$$

$$\theta_H = 20.72^\circ \quad \text{from magnetic field direction.} \quad (29)$$

This 20° off-axis cone implies 70° of inclination off the mid-plane for the injectors. This discouraging result motivates us to look at the stabilizing influence of finite width, described in sections 3 and 4.

At these low anisotropies convective growth is no problem, indeed even at the onset of absolute instability

$$L_7 = 205.32 a_i^{\text{vac}} = 935.1 \text{ cm.} \quad (30)$$

AIC STABILITY IN FINITE-WIDTH PLASMA

We model the effect of finite width by requiring a non-zero $k_{\perp}$ such that a half-wavelength fits across the diameter of the cell i.e.

$$x_j \equiv \frac{k_{\perp}^2 a_{j\perp}^2}{2} = \frac{\pi^2}{8} \frac{a_{j\perp}^2}{R_p^2} = \frac{\pi^2}{8} \frac{(a_{j\perp}^{\text{vac}})^2 / R_p^2}{1 - \beta_{\perp}^{\text{vac}}} \quad (31)$$

The $a_{j\perp}$ will be defined mathematically in terms of the $\alpha_{j\perp}$ appearing in (9).

$$(a_{j\perp}^2)_{\text{math}} = \frac{1}{\alpha_{j\perp} \omega_{ci}^2} \quad (32)$$

For the components of the distribution which are restricted in angle, this definition yields a smaller value than the physical Larmor radius

$$(a_{j\perp}^2)_{\text{phys}} = \frac{\langle v_{j\perp}^2 \rangle}{\omega_{ci}^2} \quad (33)$$

The quantities x_H , x_C serve as expansion parameters for the hot-ion and cool-ion parts of the AIC dispersion tensor. Their values are

$$x_i = \frac{\pi^2}{8} \frac{n_i \beta_{ij}}{n_j \beta_i} \frac{(a_i^{\text{vac}})^2 / R_p^2}{1 - \beta_{\perp}} \left(\frac{\alpha_{j\parallel}}{\alpha_{j\perp}} + \frac{1}{R_j - 1} \right) \quad (34)$$

where $\beta_{\perp}^{\text{vac}}$ must be recomputed using (18) each time the angular spread of the hot ions is changed. For the most general distributions, $\alpha_{j\parallel}/\alpha_{j\perp}$, R_j and $\alpha_{j\perp} v_{jh}^2$ must also be recomputed using (11). For our case (13) and (14) hold so that

$$x_H = \frac{\pi^2}{8} \frac{0.4531}{0.398 \times 0.4964} \frac{(4.554)^2 / (16.0)^2}{1 - \beta_{\perp}} = \frac{0.2286}{1 - \beta_{\perp}} \quad (35)$$

$$x_C = \frac{\pi^2}{8} \frac{0.0433}{0.602 \times 0.4964} \frac{(4.554)^2 / (16.0)^2}{1 - \beta_{\perp}} = \frac{0.0144}{1 - \beta_{\perp}} \quad (36)$$

The overall isotropized equivalent Larmor radius a_i^{vac} was obtained from (25) - (27).

We now have to decide whether to include coupling to the ion-sound wave as well as to the whistler wave. This complication can be avoided provided $T_e/T_i \ll \beta, 1$. This is certainly true for the total ion distribution. Thus we only require coupling to the LH polarized (whistler) wave, i.e., we solve in the usual notation

$$D_{k\perp}(k_{\parallel}, \omega) \equiv D_{LL} - \frac{D_{LR} D_{RL}}{D_{RR}} = 0 \quad (37)$$

Each of D_{LL} , $D_{LR} = D_{RL}$ and D_{RR} has a free-space term, an electron term and a cold-fluid ion term which are the same as for a one-part ion distribution.

The term describing the effects of ion temperature and anisotropy is the density-

weighted sum of the terms of the two parts of the ion distribution.

In the case of a single isotropic maxwellian, the dispersion tensor for the AIC mode assumes the form

$$D = \frac{K_{\parallel}^2}{\beta_i} \frac{1}{10c} + \frac{K_{\perp}^2}{2\beta_i} \frac{1}{10c} + W + \sum_{\ell} x_{\ell}^{LL} Z_{\ell} \quad (38)$$

$$D_{RR} = \frac{K_{\parallel}^2}{\beta_i} \frac{1}{10c} + \frac{K_{\perp}^2}{2\beta_i} \frac{1}{10c} - W + \sum_{\ell} x_{\ell}^{RR} Z_{\ell} \quad (39)$$

$$U_{LR} = - \frac{K_{\perp}^2}{2\beta_i} \frac{1}{10c} + \sum_{\ell} x_{\ell}^{LR} Z_{\ell} \quad (40)$$

$\underbrace{\hspace{10em}}_{\text{free-space contributions}} \quad \underbrace{\hspace{10em}}_{\text{electron contributions}} \quad \underbrace{\hspace{10em}}_{\text{ion contributions}}$

where

$$Z_{\ell} = \frac{W}{W - \ell} \underbrace{\left(1 + \frac{1}{2} Z'(\xi_{\ell})\right)}_{\substack{\text{cold ion} \\ \text{contribution}}} \quad \underbrace{\hspace{10em}}_{\substack{\text{temperature and} \\ \text{anisotropy contribution}}} \quad (41)$$

and

$$\xi_{\ell} = \frac{W - \ell}{K_{\parallel}} \quad (42)$$

Here the normalized variables (20) have been employed, and

$$x_{\ell}^{LL} = \left(\frac{x}{2} - \ell\right) \Gamma_{\ell-1} + (x - \ell) \Gamma_{\ell} - \frac{x}{2} \Gamma_{\ell+1} \quad (43)$$

$$x_{\ell}^{RR} = \frac{x}{2} \Gamma_{\ell-1} + (x + \ell) \Gamma_{\ell} - \left(\frac{x}{2} + \ell\right) \Gamma_{\ell+1} \quad (44)$$

$$x_{\ell}^{LR} = \frac{x}{2} \Gamma_{\ell-1} - x \Gamma_{\ell} + \frac{x}{2} \Gamma_{\ell+1} \quad (45)$$

$$\Gamma_{\ell} = I_{\ell}(x) e^{-x} \quad (46)$$

Expand (43) - (46) to first order in x and substitute in (38) - (40). One

obtains

$$D_{LL} = \frac{K_{ii}^2}{\beta_i} \frac{1}{10c} + \frac{K_{+}^2}{2\beta_i} \frac{1}{10c} + W + (1 - 2x) Z_1 + xZ_0 \quad (47)$$

$$D_{RR} = \frac{K_{ii}^2}{\beta_i} \frac{1}{10c} + \frac{K_{+}^2}{2\beta_i} \frac{1}{10c} - W + (1 - 2x) Z_{-1} + xZ_0 \quad (48)$$

$$D_{LR} = - \frac{K_{+}^2}{2\beta_i} \frac{1}{10c} + \frac{x}{2} Z_1 + \frac{x}{2} Z_{-1} - xZ_0 \quad (49)$$

Now assume a more general but still tractable distribution, namely

$$f_0 = \frac{\alpha_{+}}{\pi} \sqrt{\frac{\alpha_{ii}}{\pi} + \frac{\alpha_{+}}{(R-1)\pi}} e^{-\alpha_{+} v_{+}^2} e^{-\alpha_{ii} v_{ii}^2} e^{+\alpha_{+} v_h^2} \quad (50)$$

$$v^2 - v_h^2 > \frac{v_{ii}^2}{R-1} \quad (51)$$

$$D_{LL} = \frac{K_{ii}^2}{\beta_i} \frac{1}{10c} + \frac{K_{+}^2}{2\beta_i} \frac{1}{10c} + W + D_1^{\text{ion}} - 2xE_1^{\text{ion}} + xE_0^{\text{ion}} \quad (52)$$

$$D_{RR} = \frac{K_{ii}^2}{\beta_i} \frac{1}{10c} + \frac{K_{+}^2}{2\beta_i} \frac{1}{10c} - W + D_{-1}^{\text{ion}} - 2xE_{-1}^{\text{ion}} \quad (53)$$

$$D_{LR} = \frac{K_{+}^2}{2\beta_i} \frac{1}{10c} + \frac{x}{2} E_1^{\text{ion}} + \frac{x}{2} E_{-1}^{\text{ion}} - xE_0^{\text{ion}} \quad (54)$$

$$\text{where } D_{\ell}^{\text{ion}} = \frac{W}{W - \ell} + \frac{1}{2} \left[\frac{\ell}{W - \ell} + \frac{h^2}{R - 1} + (1 + h^2) \frac{\alpha_{ii}}{\alpha_{+}} \right] Z'(\xi_{\ell}) + \frac{1}{2} \frac{1}{R - 1} \left[\xi_{\ell}^2 Z'(\xi_{\ell}) - 1 \right] \quad (55)$$

$$E_{\ell}^{\text{ion}} = \frac{W}{W - \ell} \left[1 + h^2 + \frac{1/2}{R - 1} \left(\frac{\alpha_{ii}}{\alpha_{+}} + \frac{1}{R - 1} \right)^{-1} \right] + \frac{1}{2} \left[(1 + h^2) \left(\frac{\ell}{W - \ell} + \frac{\alpha_{ii}}{\alpha_{+}} \right) + \frac{1}{2} h^4 \left(\frac{\alpha_{ii}}{\alpha_{+}} + \frac{1}{R - 1} \right) \right] Z'(\xi_{\ell}) + \frac{1}{4} \frac{1}{(R - 1)^2} \left(\frac{\alpha_{ii}}{\alpha_{+}} + \frac{1}{R - 1} \right)^{-1} \left(\xi_{\ell}^4 Z'(\xi_{\ell}) - \xi_{\ell}^2 - \frac{3}{2} \right) \quad (56)$$

$$\xi_\ell = \frac{W - \ell}{K_{||}} \sqrt{\frac{\beta}{\beta_{||}}} \quad h^2 = \alpha_\perp v_h^2 \quad (57)$$

Distributions of type (9) can be accommodated in the oblique - propagation formalism (52) - (54) provided $m_j = 0$ for all j . One has

$$D_{LL} = \frac{K_{||}^2}{\beta_i} + \frac{K_\perp^2}{2\beta_i} + W + \sum_{j=1}^5 \frac{n_j}{n_0} \left(D_1^j - 2x_j E_1^j + x_j E_0^j \right) \quad (58)$$

$$D_{RR} = \frac{K_{||}^2}{\beta_i} + \frac{K_\perp^2}{2\beta_i} - W + \sum_{j=1}^5 \left(D_{-1}^j - 2x_j E_{-1}^j + x_j E_0^j \right) \quad (59)$$

$$D_{RL} = - \frac{K_\perp^2}{2\beta_i} + \sum_{j=1}^5 \frac{n_j}{n_0} \left(\frac{x_j}{2} E_i^j + \frac{x_j}{2} E_{-1}^j - x_j E_0^j \right) \quad (60)$$

where

$$D_\ell^j = D_\ell \left(h_j^2, \frac{\alpha_{||j}}{\alpha_{\perp j}}, R_j, \xi_j \right) \quad (61)$$

$$E_\ell^j = E_\ell \left(h_j^2, \frac{\alpha_{||j}}{\alpha_{\perp j}}, R_j, \xi_j \right) \quad (62)$$

are obtained from (55) and (56) by making the indicated replacements, and where the arguments ξ_j of the Fried-Conte function are obtained from (21), and where the parameters x_j are obtained from (34).

The program BALD21 finds the transition from convective to absolute stability as defined by (22) and (23). The result in terms of the hot-ion plateau-angle differs little from the homogeneous medium case (29). The result is

$$\theta_H = 30.87^\circ \quad (63)$$

Again the convective growth is not an issue, since even at the onset of absolute

instability

$$L_7 = 635.8 \text{ cm.} \quad (64)$$

The growth length is shorter than in the homogeneous case (30), since the increased attainable anisotropy (63) outweighs the finite-width stabilization.

From Fig (1) we see that for the hot ions to be contained in the central cell

$$\cos^2(\theta_H) < 1/10 \quad (65)$$

$$\theta_H > 18.43^\circ \quad (66)$$

From (63) we see that for the hot ions to avoid AIC instability

$$\theta_H < 30.87^\circ \quad (67)$$

Thus it is possible for the injected hot ions to be magnetically confined without incurring the penalty of AIC instability, provided the injector inclinations reach up to 60° away from the mid-plane. Alternatively, injection restricted to the mid-plane could allow the development of AIC turbulence which would broaden the hot-ion angular distribution to a point short of breaching magnetic confinement. At this point the AIC turbulence would switch itself off.

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