Geodesic modes driven by auxiliary NB or ICR

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plasma fluxes during heating in tokamaks

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The effect of a minor concentration of energetic ions driven by NB injection or ICR heating on Geodesic Acoustic Modes (GAM) is analyzed using fully kinetic equation for large safety factor $q^2 >> 1$. “Bump on tail like” distribution is used for hot minority ions. It is found that the standard GAM frequency is reduced by the effective mass renormalization by energetic ions. A new energetic GAM branch with higher frequency is found for the case when the mode frequency stays near the bump circulation frequency. Similar equation is found for ICR minority heating. The electron current in combination with NB driven ion flow may overcome the ion Landau damping thus resulting in the GAM instability.
1. Introduction: Geodesic modes in tokamak plasmas

Geodesic Acoustic Modes (GAM) [1] are linear modes driven by the electron and anisotropic ion pressure perturbations, which have the \( N=0 \) axisymmetric toroidal mode that is combined with poloidal side-bands \( M=0, \pm 1, \pm 2 \) in tokamak geometry. The standard theory [2-6] presents two cases of eigenmodes in limit \( \varepsilon=\frac{r}{R}<<0 \):

- high frequency geodesic mode
- and ion-sound branches

\[
\omega_{GAM}^2 \approx \left[ \frac{7T_i}{2} + 2T_e + \frac{23T_i^2 + 4T_e(4T_i + T_e)}{q^2(7T_i + 4T_e)} \right] \frac{1}{R_0^2 m_i}
\]

\( \omega_{GAM} \) (\( R_0 \) is major radius, \( q \) is safety factor, \( m_{ei} \) is mass and \( T_{ei} \) is temperature of plasma species).

Experimentally [7-11], using Reflectometry [8-9] and magnetic probe measurements, the \( M=\pm 2 \) geodesic mode structure is observed. Series of geodesic oscillations have been detected in a relatively wide range of frequencies in different tokamaks with NB and ICR heating JET, JT-60, D-III, as well in Ohm discharger in AUG, Textor, T-10, FT-Ioffe et al. These modes may strongly affect the drift-wave turbulence and plasma transport that has been observed in experiments (specially in L-H transition) and in numerical simulations.

Here, the effect of the minor concentration of the energetic bounce particles on GAM spectrum is analyzed by drift kinetic theory applying method of Jacobi functions and taking into the account the electron current, plasma rotation and diamagnetic drifts in a tokamaks.
1.2 GAM driven NB or ICR in tokamaks (motivation)

ICR and NB heating in JET tokamak


After tangential ctr-NB injection, n=0 magnetic fluctuations detected at 10kHz frequency range in JT-60U

G. Matsunaga et al, P2.062, 39th EPS Conference, July 2012, Stockholm
2.1 Distribution function for ICR and NB injection

\[ E_{cr} = \frac{m_i}{2} v_{cr}^2 = 14.8Z_{ef}^{2/3}T_e \]

**Bump on tail distribution formation (Stix, PFCF, 1972)**

**FIG.** Trapped (banana) guiding-center orbits in the normalized poloidal \((\bar{\chi}, \bar{\eta})\)-plane for \(\kappa = (0.5, 0.99)\)

\[ \Theta = \frac{\left(1 - \frac{\lambda - \lambda_{0b}}{\Lambda^2}\right)H(\lambda - \lambda_{0b} + \Lambda)H(\lambda_{0b} + \Lambda - \lambda)}{1 - \frac{\lambda^2 - \lambda_{0b}^2}{\Lambda^2}} \]

\[ \Theta_{par} = 2/3 \quad \text{in the case of parallel NB injection} \]
3.1 Drift kinetic equation and standard GAMs

To find the GAM continuum for the toroidal mode number \( N=0 \), we will use standard drift kinetic equation for electrons and ions with \( F_{e,i} \) -sifted Maxwell distribution

\[
\frac{\partial f_i}{\partial \mathbf{r}} + i \frac{\mathbf{v}_i k_r}{w k_0} \mathbf{f} \sin \mathbf{\omega} = \frac{e_i F_{a}}{m_i w} \left[ \left( w - w_0 \right) E_3 \right] + \frac{2 + \eta (w^2 + u^2 - 3)}{2 k_0 v_T \omega_c d_r} E_2 - \frac{(w^2 - v_{0i}^2 t_c + u^2/2)}{2 \omega_c R} E_1 \sin \mathbf{\omega}
\]

where \( \Omega = \omega / k_0 v_T >> 1; k_0 = 1 / q R_0 \);

\[
V_{re,i} = -(w^2 - v_{0i}^2 t_c + u^2/2) v_{Te,i} \rho_{e,i} / R; \quad \rho_{e} = v_{Ta} / \omega_c
\]

Ignoring \( V_r \)-magnetic drift and diamagnetic drift are, we find density and current perturbations

\[
\tilde{n}_{as} = \sqrt{2} \frac{e_n n_a R_0 q}{4 m_n v_{Ta}^2} \left\{ \frac{iv_{Ta}}{R_0 \omega_{ca}} \left[ (Z_+ - Z_-) (\Omega^2 + 1 - t_c v_{0i}^2) + 2 \sqrt{2} \Omega \right] E_1 + \left[ (\Omega + v_{0a}) Z_+ - (\Omega - v_{0a}) Z_- + 2 \sqrt{2} \right] E_c + i \left[ (\Omega + v_{0a}) Z_+ + (\Omega - v_{0a}) Z_- \right] E_s \right\}
\]

\[
\tilde{n}_{ac} = \sqrt{2} \frac{e_n n_a R_0 q}{4 m_n v_{Ta}^2} \left\{ \frac{v_{Ta}}{R_0 \omega_{ca}} \left[ 2 \sqrt{2} v_{0a} - (Z_+ + Z_-) (\Omega^2 + 1 - t_c v_{0i}^2) \right] E_1 + \left[ (\Omega - v_{0a}) Z_+ - (\Omega + v_{0a}) Z_- - 2 \sqrt{2} \right] E_s + i \left[ (\Omega + v_{0a}) Z_+ + (\Omega - v_{0a}) Z_- \right] E_c \right\}
\]

\[
\langle \tilde{j}_r^{\alpha} \rangle = - \frac{i e_n n_a q}{8 m_n \omega_{ca}} \left\{ \sqrt{2} (\Omega^2 + 1 - v_{0i}^2 t_c) ((\Omega + v_{0a}) Z_+ - (\Omega - v_{0a}) Z_-) \right\} E_1
\]

\[
- i \left[ 8 + 4 \Omega^2 + \sqrt{2} (\Omega^2 + 1 - v_{0i}^2 t_c) ((\Omega + v_{0a}) Z_+ - (\Omega - v_{0a}) Z_-) \right] E_c
\]

\[
+ \frac{v_{Ta}}{R_0 \omega_{ca}} \left[ \sqrt{2} (Z_+ - Z_-) (2 \Omega^2 + \Omega^4 + 2 - (\Omega^2 + 1) v_{0i}^2 t_c) + 4 (\Omega^2 + v_{0a}^2 - 2 v_{0i}^2 t_c + 3) \right] E_1
\]

where

\[
Z_\pm = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} dt \exp(-t^2)/(x-t)
\]

\[
x = (v_{0a} \pm \Omega) / \sqrt{2}
\]
In the cold limit for main ions and hot minority, 
\[ v_{0e} > v_{0b} >> \omega R_0 q / v_{Ti} > v_{0i} \]
using quasi neutrality \( n_e + n_i = 0 \) with resonance condition
\[ \langle j^e_r \rangle + \langle j^i_r \rangle + \langle j^b_r \rangle + j_p = 0 \]
where \( j_p = -i \omega c^2 E / 4\pi c^2 \) is the polarization current, \( c_A = B / \sqrt{4\pi n_i m_i} \).

We get the GAM continuum equation and increment from the radial current:

\[
\frac{\Omega^2_G}{q^2} = \left( \frac{\omega G R_0^2}{v_{Ti}^2} \right) \approx \left[ \frac{7}{2} + 2\tau_e + 4\nu_0^2 - \frac{n_b \tau_e}{\tau_b} (2\tau_e + \tau_b + \tau_e^2 + \nu_{0i} \nu_{0b}) \right] \\
\frac{1}{1 + n_b q^2 (v_{0b}^2 + 3\tau_b + q^2 \tau_e + 7q^2 / 4) / 2\tau_b}
\]

\[ \gamma \approx \sqrt{\frac{\pi}{2}} \frac{v_{Ti} \tau_e q}{2R_0} \left\{ \frac{\sqrt{\tau_e \mu}}{\Omega^2} \nu_{0e} \left[ 4\nu_{i0} + \nu_* - \left( \Omega^2 + 2\tau_e + 2 \right) \frac{n_b \nu_{0b}}{2\tau_b} \right] \\
- \frac{1}{\tau_e} \left[ \frac{\Omega^4}{2} + (2\tau_e + 1) \Omega^2 + 3\tau_e^2 + 4\tau_e + 1 \right] \exp \left( -\frac{\Omega^2}{2} \right) \right\}
\]

where \( \tau_\alpha = T_\alpha / T_i \) is the temperature relations, \( \nu_{\alpha 0} = V_{\alpha 0} / v_{Ti} \) is the normalized parallel velocity, \( n_b \) is the ratio of hot ion to main plasma density, \( \nu_* = (2 + 2d \ln T_i / d \ln n_i + 3\tau_e) \rho_{Li} / d_i h_g \).
4.1. Energetic GAMs

In the case of $\Omega \sim w_{ob} \sim \Omega_G \gg 1$, using approach we get dispersion equation at the phase resonance

$$\Delta = 1 - \Omega_G^2 (1 - i\gamma)/W_{ob}^2, \quad \Omega = w_{ob}(1 + \delta) \quad \text{and} \quad \delta^2 < < 1$$

where

$$\eta = \frac{2}{5} \frac{T_b^{5/2}}{q^2 n_b W_{ob}^5}, \quad \Omega_G^2 \approx q^2 \left( \frac{7}{2} + 2 \frac{T_e}{T_i} + 4v_{0i}^2 \right)$$

$$\gamma \approx \sqrt{2\pi} \left[ n_b \frac{q^2 W_{ob}^3}{8T_b^{3/2}} + \frac{\Omega_G^3}{q} \exp \left( -\frac{\Omega_G^2}{2} \right) \right]$$

Approximate GAM dispersion $|\Delta| < < 1$

$$\delta = \delta_{\text{split}} \pm \sqrt{\delta_{\text{split}}^2 (1 - \Omega_G^2 (1 - 2i\gamma)/\Omega_G)/W_{ob}^2}$$

where $\delta_{\text{split}} = \frac{2\eta - 1}{8} + \frac{1}{4} \sqrt{7(\eta - \frac{1}{80})}$

One root will be unstable independently from $\gamma$ sign

GAM frequency modification by energetic particles found from in Eq.1.
4.2. GAM continuum modification by NB injection

GAM continuum in the case of the phase resonance with bump velocity

\[ \omega_{\text{cont}} = (1 + \delta)W_{0b}/R_0q, \Delta = 1 - q^2 R^2 \omega_G^2/W_{0b}^2 \text{ and } \delta^2 << 1 \]

\[ \Omega \sim W_{0b} \sim \Omega_G >> 1 \]

GAM continuum extremum equation

\[ \frac{d\omega_{\text{cont}}}{dr} = \frac{(1 + \delta)W_{0b}}{R_0q} \left[ \frac{d \ln W_{0b}}{dr} - \frac{d \ln q}{dr} - \frac{q^2 R^2 \omega_G^2}{W_{0b}^2} \left( 2 \frac{d \ln q}{dr} + \frac{d \ln \left( \frac{\omega_G^2}{W_{0b}} \right)}{dr} d\delta \right) \right]_{r=r_0} = 0 \]

Assuming

\[ W_{0b} \approx u_{cr} = 5.5 Z_{\text{ef}}^{1/3} \sqrt{T_e/m_i} \text{ and } dT_e/dr < 0 \]

We get estimation of continuum minimum position

\[ 2 \left( 2q^2 R^2 \frac{\omega_G^2}{W_{0b}^2} d\delta \right)_{r=r_0} + 1 = \frac{d \ln T_e}{d \ln q} \approx O(-1), \]

or\[ \frac{d\delta}{d\Delta} \bigg|_{r=r_0, \delta=\delta_{\text{split}}} < 0 \]

Normalized GAM continuum frequency over radius for different conditions: (dot) no beam, (blue) small NB
density \( f < f_{\text{crit}} \), (black) for \( \eta = \frac{2}{5} \frac{T_e^2}{q^2 n_b W_{0b}^4} = 0.3 \)

\[ T_e = T_0((1-x)^{2.5} + 0.04), q = q_0 + (q_a - q_0)x \]

\[ T_i = 0.6T_0((1-x)^{1.5} + 0.06); \eta = 0.3 \]
5.2 Discussion of GAM observations

GAM like oscillations (N=0, M=0-3) in the frequency band $f=30-37$kHz were detected by the magnetic and Langmuir probes [8] with high coherence level (at the position $\Delta r \approx 1-2$ cm deep from the last magnetic surface) during the stable part of ohmic discharges in COMPASS deuterium plasmas ($I_p=180$ kA, $n_0=4-5 \times 10^{19}$ m$^{-3}$, $T_{e0}=800-900$eV). Series of discharges with co (#11035, $I=12$ A, $U_{NB}=40$ keV, $P_{NBI}=360$ kW) and counter NB injection (#11502, 12A, $U_{NB}=40$ keV, $P_{NBI} \sim 370$ kW) is used to study NB heating effect on GAM.
5.3 Discussion of GAM observations

With NB application, it is observed that the GAM frequency increases $\Delta f \approx 20\%$ for co and $\Delta f \approx 16\%$ for counter injection. Dramatic changes in the GAM amplitude occur during the NB injection period $t_{NB}=1090-1170$ ms. While the GAM amplitude increases moderately during the counter injection, the GAM instability is strongly suppressed by the co-injection. This GAM frequency corresponds to theoretically predicted one [1,3] assuming the ion temperature $T_{ia} \approx T_{ea} = 30-35$eV at the border and rotation $V_{0i} \approx 0.4v_{Ti}$ shown in Eq.of slide 4.1. We note that there is no phase resonance between the beam circulation and GAM frequency.
The frequency increase with NB application may be partly attributed to estimates of the electron/ion temperature variation, which is not enough to explain the GAM frequency increasing that needs to have $\Delta T_e + \Delta T_i \approx 35-40\%$. Here, we propose that part of the variation may be attributed to plasma rotation induced by NB that should be $V_{e0} \approx 0.4 v_{Ti}$ according to Eq. in slide 4.1. To explain the GAM amplitude variation, we assume that it should be proportional to the instability increment in Eq. in slide 4.1. In the ohmic stage, the instability may be driven by the cross term between the electron velocity and ion drift corresponding to the first term in that Eq. A condition for the instability, large electron current speed $V_{e0} >> R q \omega G > V_{i0}$, is satisfied for the entire tokamak cross-sections, calculating the current profile with EFIT code. For counter injection, the electron and ion velocities have the same direction and their cross term might increase the instability, whereas this term may strongly reduce it for co-injection, when rotation velocity is larger than drift velocity $V_{i0} > \rho_{Li} v_{Ti} / d_r h_g$.
6. Trapped-untrapped ion kinetic equation

To study hot particle effect on GAM continuum, we use the drift kinetic equation via integrals of motion \( u^2 = v^2/v_I^2, \lambda = v_\perp^2 B_0/v_I^2 B \) and \( w_\parallel = s u \sqrt{1 + \epsilon \cos \theta - \lambda}; \ s = \pm 1 \)

\[
\frac{w \partial f}{\partial \theta} - i \Omega_\alpha f = \frac{e_\alpha qR}{m_\alpha} F_\alpha \left[ \frac{w E_3}{v_T^2} + \frac{2 + \eta_\alpha (u^2 - 3)}{2v_T \omega_{ca} d_r} E_2 - u^2 \frac{(2 - \lambda + \epsilon (2 + \lambda) \cos \theta)}{2R \omega_{ca} v_{Ta}} \right] E_1 \sin \theta
\]

Taking solution of the equation, we have to calculate the \( \sin \theta/\cos \theta \) density and radial current

\[
n_{s,\epsilon}^{(a)} = \int_{v_{Ta}^3 u^2 du} \int_{\sin \theta d \theta} \sum_{s=\pm 1} \left( \int_{1-\epsilon}^{1+\epsilon \cos \theta} \frac{f_{s,a}^2}{\sqrt{1+\epsilon \cos \theta - \lambda}} \right)
\]

Next, the variable \( \lambda \) is changed to the new \( \kappa \)-variable for the untrapped \( \kappa^2 = 2\epsilon/1 + \epsilon - \lambda \) and trapped particles \( \kappa^2 = (1 + \epsilon - \lambda)/2\epsilon \). The untrapped equation is rewritten via the \( \text{cn}, \text{sn}, \text{dn} \) Jacobi functions

\[
\frac{\partial f_{\text{un}}}{\partial \Theta} - \sqrt{2is} \frac{\partial f_{\text{un}}}{u \sqrt{\epsilon}} + \sqrt{2s e_\alpha q u F_\alpha} (\kappa^2 + 2\epsilon - H\kappa^2) E_1 \text{sn}(\kappa,\Theta) \text{cn}(\kappa,\Theta)
\]

\[
= \frac{4e_\alpha R q F_\alpha}{m_\alpha v_{Ta}^2} \left[ E_s \text{sn}(\kappa,\Theta) \text{cn}(\kappa,\Theta) - E_c (\text{sn}(\kappa,\Theta)^2 - 1/2) \right] \text{dn}(\kappa,\Theta)
\]

Using Q-series \( Q = [1 - (1 - \kappa^2)^{1/4}]/2[1 + (1 - \kappa^2)^{1/4}] < 1/2 \) of the Jacobi functions, we get solution

\[
f_{1,\text{un}}^{(a)} = i\sqrt{2\pi} e_\alpha q F_\alpha E_1 \sum_{p=1}^N \frac{(\kappa^2 + 2\epsilon - H\kappa^2) Q_p^p u^2 \tilde{\Omega}_{\alpha,p}^2}{K(\kappa) K^3 (1 + Q^2 p)(u^2 - \tilde{\Omega}_{\alpha,p}^2)} \sin \left( \frac{\pi \kappa \Theta}{K(\kappa)} \right)
\]

The density and current may be obtained via the dispersion function \( Z = \int_{-\infty}^{\infty} dt \exp(-it^2)/(t - x) \) where \( x = \tilde{\Omega}_{\alpha,p}^2 / \sqrt{2} \) but rest of integration has problem:
6.1 Density & current for hot and cold ions

Assuming that the bounce frequency is larger than the GAM frequency $\Omega_h = \omega q R / v_{Th} < \sqrt{\varepsilon}$, hot ions have small fraction $n_h \ll 1$ and taking into account the order $O(1/\sqrt{\varepsilon})$ of terms, we perform integration that gives

Untrapped particles:

$$
n_{un}^{(h)} = \frac{e_h n_0 n_h q R_0}{6 m_h v_{Th}^2} \left( 0.9 \frac{i \omega E_1}{\sqrt{\varepsilon} \omega_{ch}} + E_c \right) \sin \vartheta; \quad -\text{small}
$$

$$
< j_{un}^{(h)} > \approx -\frac{e_h^2 n_0 n_h q}{10 m_h \omega_{ch}} \left\{ 4.5 \left[ 1 + 0.23i \left( \frac{\omega q R_0}{\sqrt{\varepsilon} v_{Th}} \right)^5 \exp \left( -\frac{(\omega q R_0)^2}{2 \varepsilon v_{Th}^2} \right) \right] E_c \\
+ \frac{\omega}{\sqrt{\varepsilon} \omega_{ch}} \left[ 3i - \left( \frac{\omega q R_0}{\sqrt{2 \varepsilon v_{Th}}} \right)^5 \exp \left( -\frac{(\omega q R_0)^2}{2 \varepsilon v_{Th}^2} \right) \right] E_1 \right\}
$$

Trapped particles:

$$
n_t^{(h)} = 0.53i \frac{e_h q R_0 n_0 \omega R_0}{\sqrt{\varepsilon} m_h \omega_{ch} v_{Th}^2} E_1 \quad -\text{small}
$$

$$
< j_t^{(h)} > = -\frac{e_h^2 n_0 n_h q^2 \omega}{\sqrt{\varepsilon} m_h \omega_{ch}^2 v_{Th}^2} \left[ i \left( 1.2 + 0.56 \frac{\Omega_h^2}{\varepsilon} - 2.94 \frac{\Omega_h^4}{\varepsilon^2} \right) + 14.4 \frac{\Omega_h^5}{\varepsilon^{5/2}} (0.35 - \Omega_h^2) \exp \left( -2 \frac{\Omega_h^2}{\varepsilon} \right) \right] E_1
$$

Then, taking into account the Maxwell distribution for electrons and ions where bounce effect is absent, (Chavdarovsky, Zonca (2009) PPCF, 115001), we have

$$
E_c = \frac{2i \tau_e v_{Te}}{R_0 \omega_{ei} \Omega_i} \left\{ 1 - i \frac{\sqrt{2\pi}}{4} \Omega_i^3 \exp \left( -\frac{\Omega_i^2}{2} \right) \right\} E_1
$$

$$
< \tilde{j}_r^{(i)} + \tilde{j}_r^{(e)} > \approx \frac{i e_i^2 v_{Te} n_{i0}}{m_i \omega_i R_0^2} \left\{ \frac{7}{2} + 2 \tau_e - i \frac{\sqrt{2}}{4} \left( \frac{\omega q R_0}{v_{Te}} \right) \left( \frac{\omega q^2 R_0^2}{v_{Te}^2} + 2\tau_e \right) \exp \left( -\frac{\omega^2 q^2 R_0^2}{2 v_{Te}^2} \right) \right\} E_1
$$

Then, the dispersion equation from the condition $< j_r^e > + < j_r^i > + < j_r^{tr} > + < j_r^{un} > + j_p = 0$

$$
\left( \begin{array}{c} 1 + 1.5 \frac{m_h n_h q^2}{m_i \sqrt{\varepsilon}} \left( 1 + 0.37 \frac{\omega q^2 R_0^2}{\varepsilon v_{Th}^2} - 2 \frac{\omega^4 q^4 R_0^4}{\varepsilon^2 v_{Th}^4} \right) \end{array} \right) \omega^2 = \left( \frac{7}{2} + 2 \tau_e \right) \frac{v_{Te}^2}{R_0^2}
$$

Hot ion mass effect on GAM

$$
\omega^2 = \left( \frac{7}{2} + 2 \tau_e \right) \frac{v_{Te}^2}{R_0^2} \left( 1 + 1.5 \frac{m_h n_h q^2}{m_i \sqrt{\varepsilon}} \right)
$$

If all hot ions are trapped, the effect is stronger $n_h => n_h^{(tr)} / \sqrt{\varepsilon}$
6.2 Energetic ion effect on GAM stability

Using \( \sqrt{\varepsilon} > \Omega_h = \omega q R_0 / v_{Th} \), increment/decrement is defined by the dissipative part of the radial current

\[
\sum_{\alpha=e,i,h} j^\alpha_r E_1^\alpha / |E_1|^2 \approx \sqrt{2} e_i^2 n_0 q^2 \omega / m_i \omega^2 c_i \left\{ \frac{\sqrt{\pi}}{4} \left( \frac{\omega R_0 q}{v_{Ti}} \right) \left( \frac{\omega^2 R_0^2 q^2}{v_{Ti}^2} + 2 \tau_e \right) \exp \left( -\frac{\omega^2 q^2 R_0^2}{2v_{Ti}^2} \right) \right. \\
- \frac{m_i n_h}{\sqrt{\varepsilon} m_h} \left( \frac{\omega q R_0}{\sqrt{\varepsilon} v_{Th}} \right)^4 \left\{ 3.5 - 10 \left( \frac{\omega q R_0}{\sqrt{\varepsilon} v_{Th}} \right)^2 \exp \left( -2 \left( \frac{\omega q R_0}{\sqrt{\varepsilon} v_{Th}} \right)^2 \right) \right. \\
- \frac{1}{32} \left( 1 - \left( \frac{\omega q R_0}{\sqrt{2 \varepsilon} v_{Th}} \right)^2 \left( 1 + \sqrt{2} \right) \exp \left( -\frac{(\omega q R_0)^2}{2 \varepsilon v_{Th}^2} \right) \right) \right\}
\]

Evan in the best case of trapped current minimum,

\( \omega_{min} = \sqrt{\varepsilon} v_{Th} / 2 q R_0 \)

the instability is hard to be driven

- basic ions
- trapped hot ions
- untrapped hot ions

[Graph showing trapped and untrapped current]
Conclusions

- “Bump on tail like” distribution of energetic ions with temperature comparable to the critical energy is used to analyze geodesic mode stability during parallel NB injection and ICR heating.
- A novel method of Jacobi functions has been successfully applied to solve the drift kinetic equation for the energetic particles with high bounce frequency.
- It is shown that the standard GAM continuum frequency is reduced by mass factor of energetic particle. \[ \frac{1 + 1.6 m_h r_h q^2 / m_i \sqrt{\varepsilon}}{1} \]
- The calculations demonstrate that the standard geodesic mode is driven by NB when the current electron velocity of the Ohm’s current is above the wave phase velocity \( V_0 \gg \omega_{GAM} R q \).
- Found GAM instability, which is induced or suppressed by plasma ion flux, results from the cross term of the electron and ion fluxes induced by the NB injection that stays in qualitative agreement with COMPASS experiments.