Hot Plasma Ray Tracing of HHFW in NSTX

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Prolog:

- GENRAY is an all frequencies (HHFW, EBW, LH, ...) ray tracing code giving RF deposition and current drive in toroidal devices.
- It has been modified in accord with recent theory to properly treat ray tracing and absorption near cyclotron harmonics.

Outline:

- The usual ray tracing equations will be described.
- Problems exist near cyclotron harmonics. Possible solutions: Westerhof-Tokman theory.
- Results for ray tracing and comparisons will be shown.

Ray Tracing Equations fo $\hat{\mathbf{E}}(\mathbf{r},t) = \mathbf{Re}(\mathbf{E}\exp \mathbf{i}(\mathbf{k}.\mathbf{r} - \omega \mathbf{t}))$

$$\frac{d\mathbf{r}}{dt} = \frac{\partial \omega}{\partial \mathbf{k}}, \quad \frac{d\mathbf{k}}{dt} = -\frac{\partial \omega}{\partial \mathbf{r}}$$, where

where $\omega = \omega(\mathbf{k}, \mathbf{r})$ is a **real** Hamiltonian for rays, derived from the local solution of the EM wave and plasma equations.

Assumptions: 1. $\lambda \ll L$
2. $|\varepsilon_{ij}^{aH}| \ll |\varepsilon_{ij}^{H}|$

Problems near cyclotron harmonics:
1. $|\varepsilon_{ij}^{aH}| \sim |\varepsilon_{ij}^{H}|$
2. Group velocity can become anomalous (i.e., > c, or < 0).

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Solutions to $|\varepsilon_{ij}^{aH}| \sim |\varepsilon_{ij}^{H}|$ Problem

1. Use cold plasma rays [$\varepsilon_{ij}^{aH} = 0$] and hot plasma dispersion absorption based on cold $n_{\parallel}$. This gives no problems at harmonics, but trajectories may not be accurate.

2. Ignore the problem and use only Hermitian part of dielectric tensor, which gives real Hamiltonian, but ignores effect of $\varepsilon_{ij}^{aH} \neq 0$ on trajectory and polarizations.

3. Use complex Hamiltonian from the solution of the wave equation, but there are questions on how to project the ray onto real space.

4. GENRAY has option to use recently developed ray theory including the effect of $|\varepsilon_{ij}^{aH}| \sim |\varepsilon_{ij}^{H}|$ by Westerhof (1997) and Tokman (2000) for electron cyclotron range, following work of Piliya and Federov (1984). (Good for $Im(k_{\perp}) \ll Re(k_{\perp})$.)

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Westerhof-Tokman Ray Tracing

Westerhof (1997):

From $D(\omega, k) \equiv \|D_{pm}\| = 0$, the condition for soln to the wave equation,

$D = \lambda_1 \lambda_2 \lambda_3$ (the three eigenvalues solving $D_{pm}E_m = \lambda E_m$),

take the ray Hamiltonian to be = $Re(\lambda)$. (This accnts for $\left|\varepsilon_{ij}^{aH}\right| \sim \left|\varepsilon_{ij}^{H}\right|$).

Tokman, Westerhof, Balakina (2000):

$$\nabla . \mathbf{S}_M + \tilde{\mathbf{Q}} = 0$$

where.

$$\mathbf{S}_M \equiv \frac{c^2}{16\pi\omega} |E|^2 \frac{\partial \left(D^H e_p^* e_m\right)}{\partial \mathbf{k}} \Big|_{\mathbf{k}_{real}}$$

$$\mathbf{Q} \equiv \frac{ic^2}{8\pi\omega} |E|^2 \left(D_{pm}^{aH} e_p^* e_m\right) \Big|_{\mathbf{k}_{real} + \nabla\phi}$$

$$e_p \equiv E_p / |\mathbf{E}| \text{, polarizations}$$

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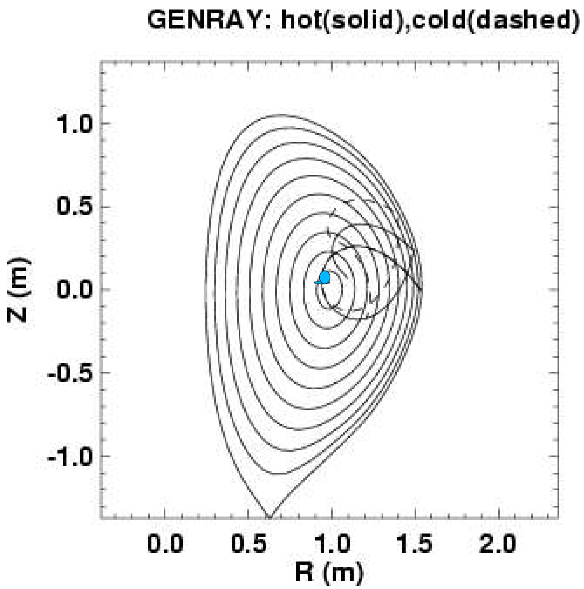
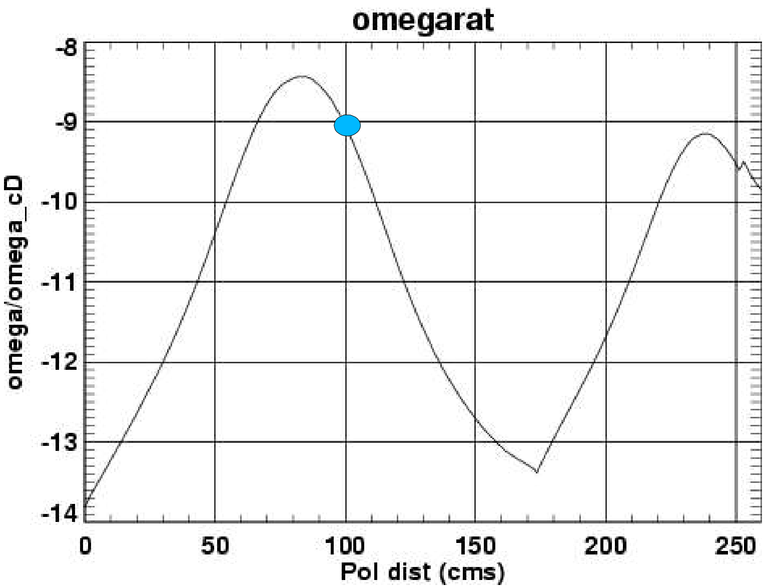
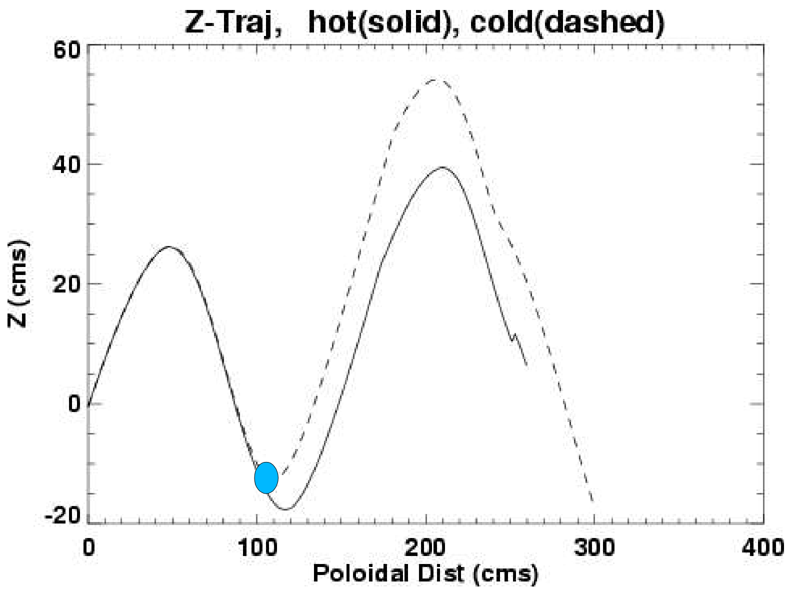
Main new effect: Polarizations effected by grad-k. This removes anomalous group vel prblm

Comparison of Hot and Cold Ray Trajectory

(Rosenberg hot Ti test case)







Conclusion: Significant deviation of hot ray from cold path at point it traverses cyclotron resonance in hot central plasma.

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Conclusions

- HHFW ray tracing with full (Stix) hot plasma dispersion has been implemented in GENRAY.
- Significant deviations of the rays from cold plasma trajectories are calculated as the ray passes through a cyclotron harmonic in the hot plasma center.
- Future work will explore range the range of new physics for the hot plasma rays.