Benchmark of ICRF codes in mid and high harmonic regimes in view of NSTX-U operation

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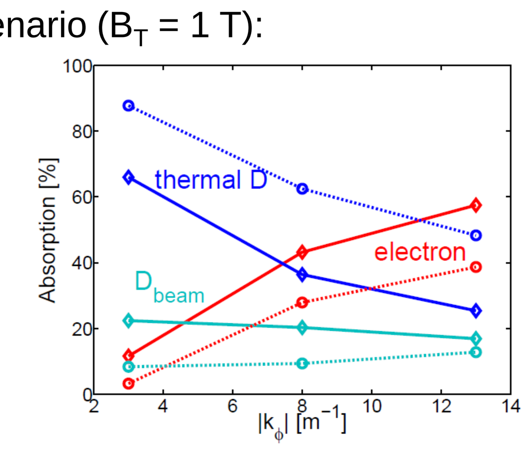
Introduction & motivation

- In previous works [Phillips et al APS 2003 and Bertelli et al., US-Japan RF workshop 2012] found discrepancies between RF codes in HHFW regimes when ion absorption (thermal and fast ions) is significant.

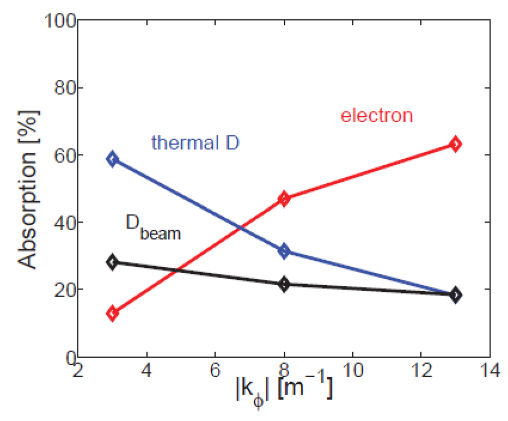
For NSTX-U scenario (B_T = 1 T):



TORIC5: ○ - - - -
GENRAY: ◊ ——

- When $T_i > T_e$ then absorption by thermal ions is large [Bertelli et al., *AIP Conf. Proc.* **1580**, 310 (2014)]

For NSTX-U scenario (B_T = 1 T) with AORSA:



AORSA: ◊ ——

- Important to have an accurate estimate of the fast and thermal ions in NSTX-U experiment
  - Interaction between fast ions and HHFW

Benchmark between ray tracing (GENRAY) and full wave codes (AORSA, TORIC5, and TORIC6) is necessary in order to understand why ion absorption discrepancies occur and the possible limitation of the physics model implemented in each codes

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Ray tracing code GENRAY

GENRAY [A. P. Smirnov and R. W. Harvey, Bull. Am. Phys. Soc. 40, 1837 (1995)] is a ray tracing code, which solves WKB equations for different wave dispersion relations in a tokamak geometry.
Assumptions used in this work:

1) Cold plasma dispersion relation
2) Wave frequency = 30 MHz
3) Same $k_{||}$ for all rays
4) 60 rays
5) Ion absorption given by Chiu et al., NF 29, 2175 (1989):

$$\boxed{2\frac{\mathrm{Im}(k_\perp)_{\rm ion}}{\mathrm{Re}(k_\perp)} = \frac{\mathrm{Im}(\varepsilon_{11}) - \frac{2D\mathrm{Re}(\varepsilon_{33})}{|\varepsilon_{33}|^2}\mathrm{Re}(\varepsilon_{12})}{A_2} + \frac{(S-N_{||}^2)(\mathrm{Im}(\varepsilon_{22})+\mathrm{Im}(\varepsilon_{11})-2D\mathrm{Re}(\varepsilon_{12})}{(S-N_{||}^2)^2-D^2}\frac{A_1}{A_2}}$$

$$A_1 = N_{||}^2 - S + \frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{\mathrm{Re}(Z)}{|Z|^2}\frac{N_{||}^2}{N_{||}^2-S} \qquad A_2 = N_{||}^2 - S + \frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{\mathrm{Re}(\mathcal{Z})}{|\mathcal{Z}|^2}\frac{N_{||}^2+S}{N_{||}^2-S}$$

$$\mathcal{Z} = \mathrm{Re}(\mathcal{Z}) + i\mathrm{Im}(\mathcal{Z}) \equiv 2\xi_e^2(1+\xi_e Z(\xi_e)), \quad \xi_e = \frac{\omega}{k_{||}v_{\rm th,e}}$$

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Full wave code AORSA & TORIC: wave field modeled with linear wave equation

Full field linear wave equation (inhomogeneous plasma):

$$\nabla\times\nabla\times\mathbf{E} - \underbrace{\frac{\omega^2}{c^2}\left(\mathbf{E}+\frac{4\pi i}{\omega}\mathbf{J}_p\right)}_{=\boldsymbol{\varepsilon}\cdot\mathbf{E}} = \frac{4\pi i}{\omega}\mathbf{J}_A$$

where

$\boldsymbol{\varepsilon}$ is the dielectric tensor, $\mathbf{J}_A$ is the antenna current

$$\mathbf{J}_p(\mathbf{r}) = \int dr'\boldsymbol{\sigma}(\mathbf{r},\mathbf{r}')\cdot\mathbf{E}(\mathbf{r}')$$

- AORSA includes the complete non-local, integral operator for ε that is valid for "all orders" ($k_\perp\rho_s > 1$) [E. F. Jaeger *et al*, *Phys. Plasmas* **9,** 1873 (2002)]
- TORIC utilizes a quasi-local differential operator for ε that is valid in the HHFW regime but assumes that one dominant mode is propagating [M. Brambilla, Plasma Phys. and Control. Fus. 44 (2002) 2423]

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Both full wave codes utilize spectral decomposition to solve for the wave fields

- AORSA utilizes a local Cartesian grid in the poloidal plane and a Fourier decomposition in the toroidal direction of symmetry:

$$\mathbf{E}(x,y,\phi) = \sum_{n_\phi}\sum_{n,m}\mathbf{E}_{n_\phi,n,m}e^{in_\phi\phi}e^{i(k_n x + k_m y)}$$

where $x = R - R_0$ and y is the distance from the midplane

- TORIC utilizes a poloidal mode expansion and radial finite elements inthe poloidal plane and a Fourier decomposition in the toroidal direction:

$$\mathbf{E}(\mathbf{r}) = \sum_{n_\phi}e^{in_\phi\phi}\sum_{m=-n_{\rm mod}/2}^{n_{\rm mod}/2}\mathbf{E}_m(\psi,n_\phi)e^{im\theta}$$

and $\mathbf{E}_m(\psi,n_\phi)$ is solved with $n_{\rm elm}$ cubic Hermite polynomials.

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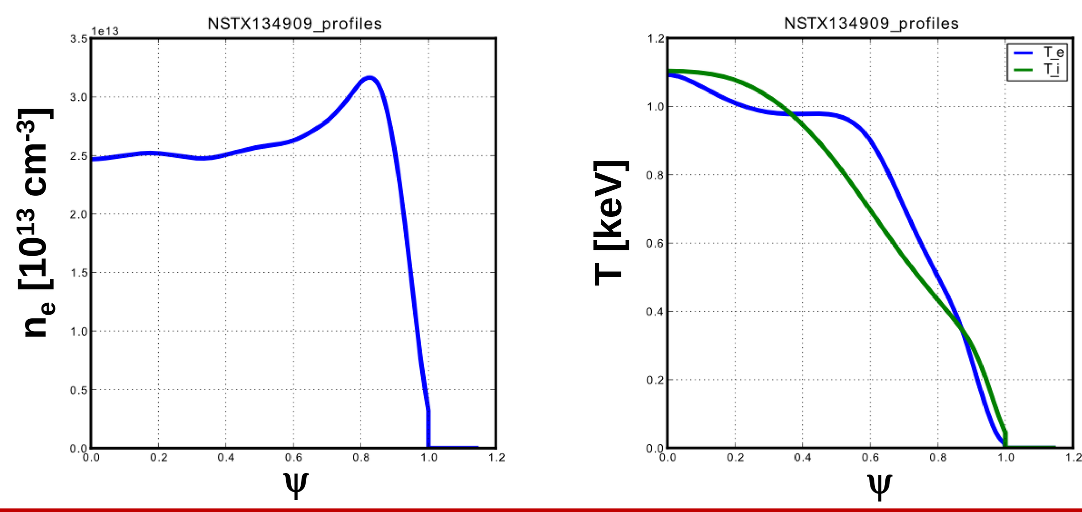
NSTX discharge 134909 (high harmonic regime): density and temperatures profiles

- $B(R_0)$ = 0.55 T
- $n_e(0) = 2.5\times10^{19}$ m^{-3}, , $T_e(0) \sim T_i(0) \sim 1.1$ keV
- Fast ions (D beam) concentration ~ 8 %



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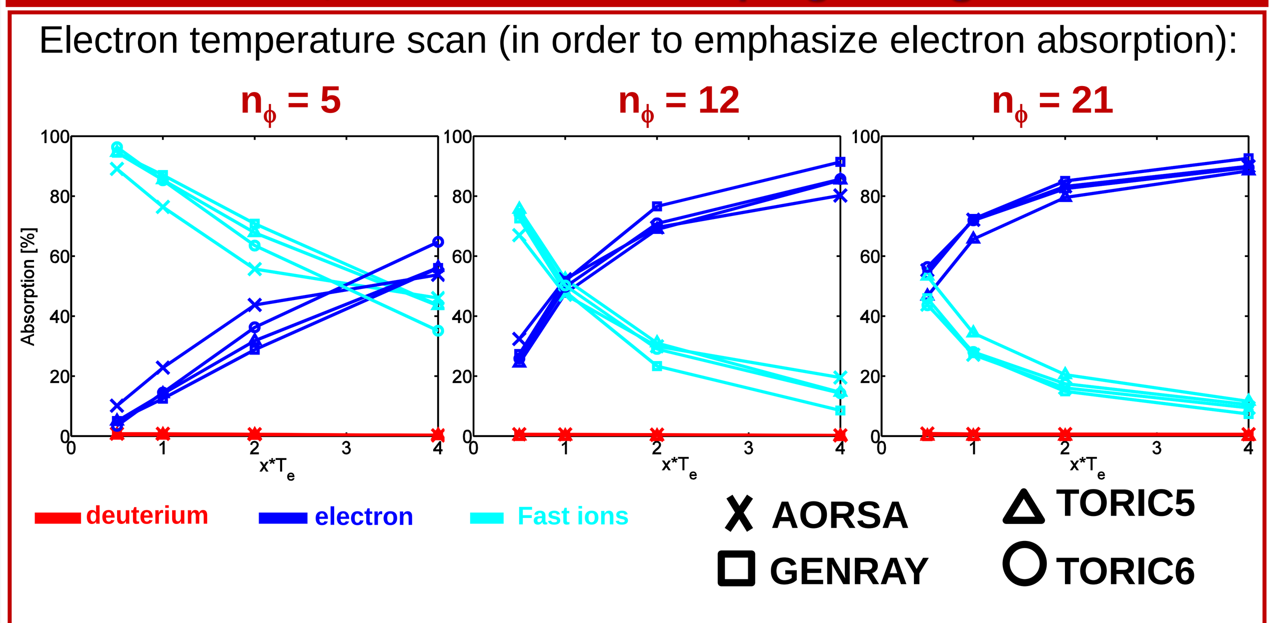
Agreement between codes improves when increasing n_ϕ, i.e., when Landau damping is larger

Electron temperature scan (in order to emphasize electron absorption):



Absorption of thermal D is negligible

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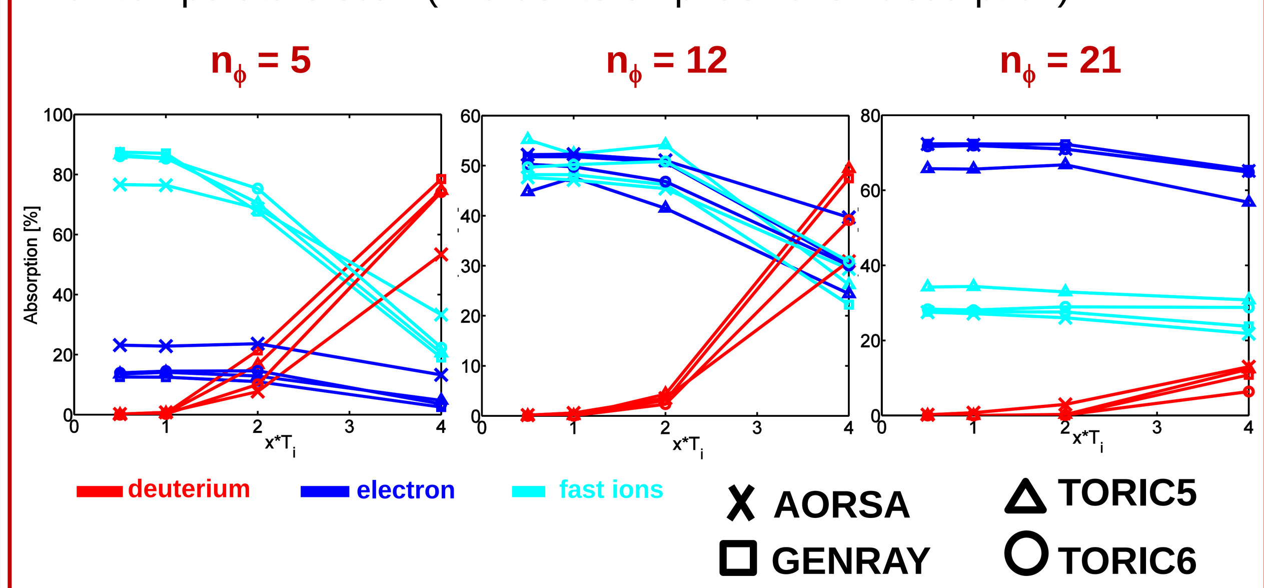
Discrepancies between codes increase when absorption of thermal D increases

Ion temperature scan (in order to emphasize ion absorption):



Absorption of thermal D is significant when $T_i/T_e \geq 2$

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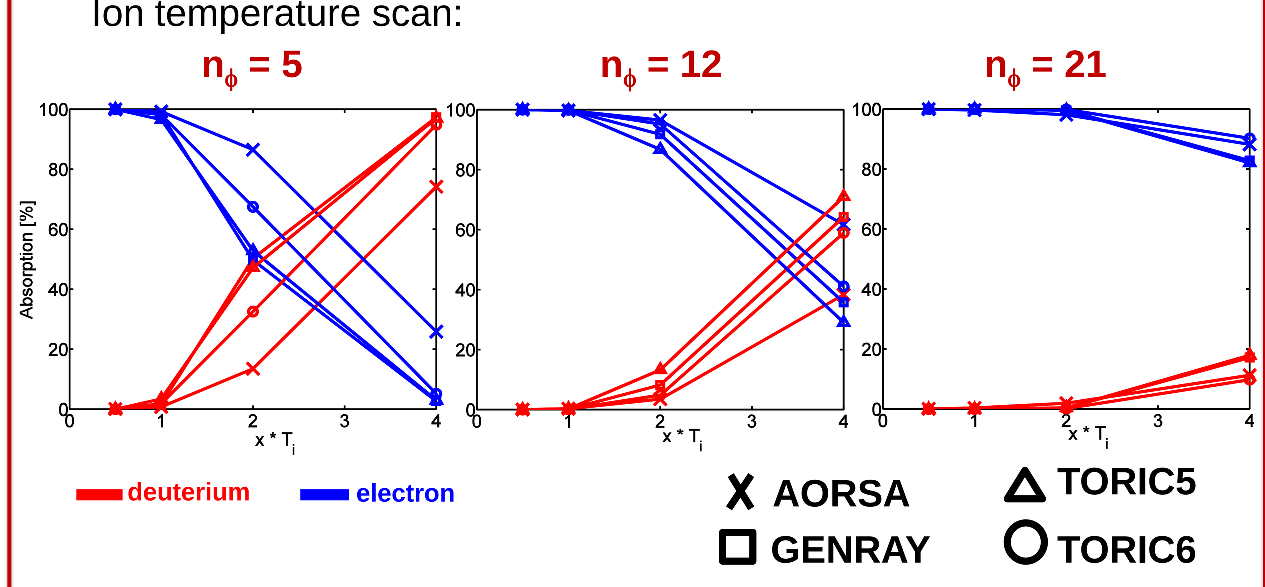
Discrepancies between codes increases when T_i increases in absence of D beam

Only electron and D species to simplify the problem

Ion temperature scan:



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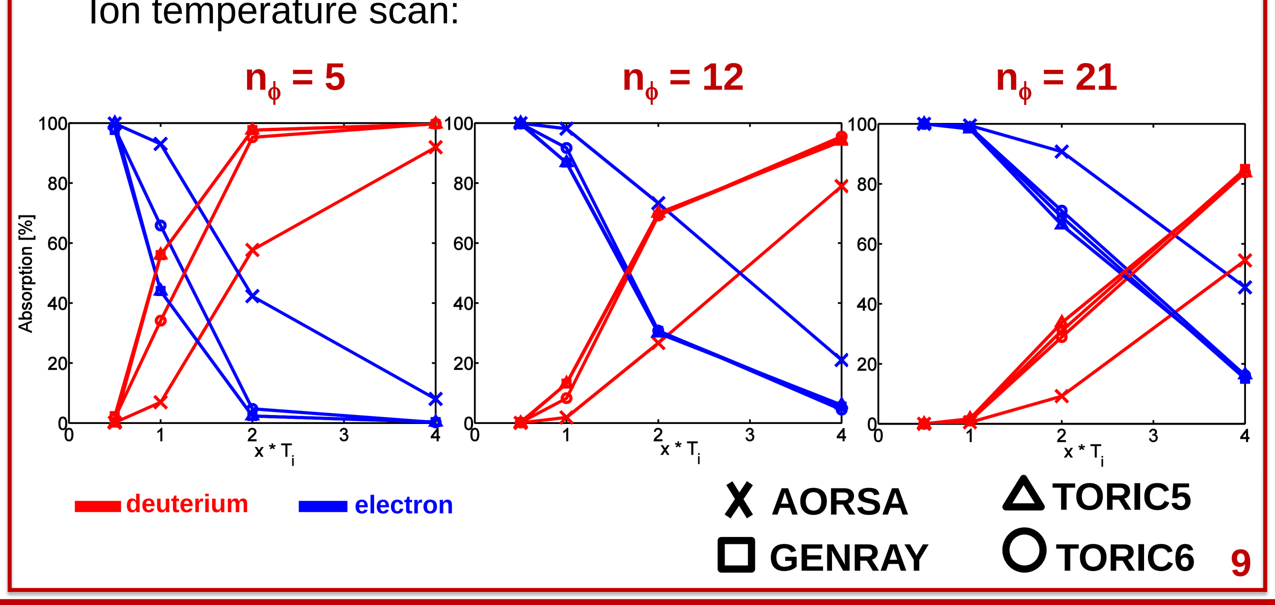
Discrepancies between codes increases when T_i increases in absence of D beam when doubling the density

Only electron and D species to simplify the problem
& double density to make even stronger single pass absorption

Ion temperature scan:



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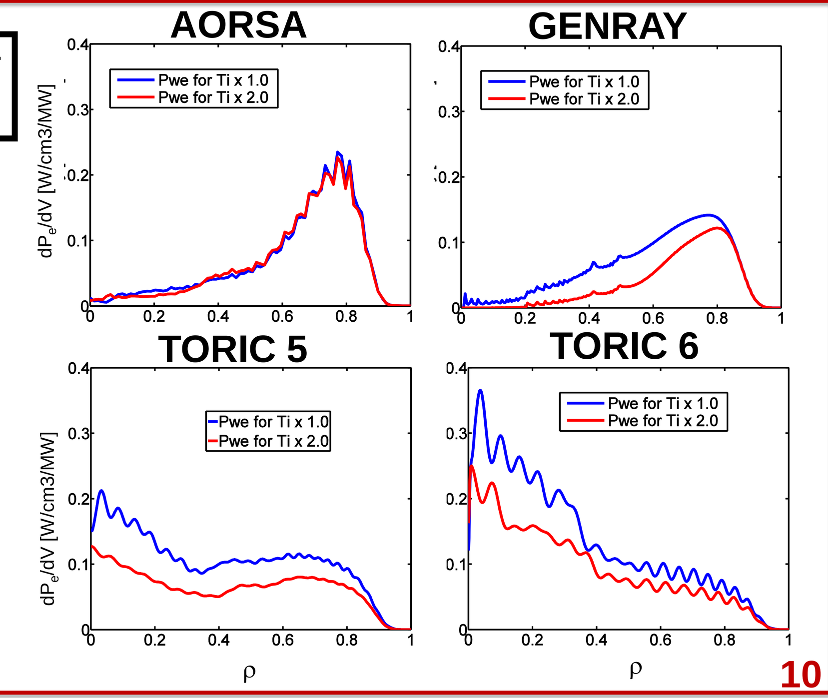
Electron power density profiles from TORIC5/6 largely differ from AORSA and GENRAY profiles

Ti x 1.0 and Ti x 2.0 for n_e x 2.0, and n_ϕ = 21

- Strong single pass absorption
  - good for ray tracing
- Peak location of AORSA & GENRAY is off-axis
- Peak location of TORIC5/6 is on the magnetic axis
- **Unclear and unexpected differences.**

Still under investigation



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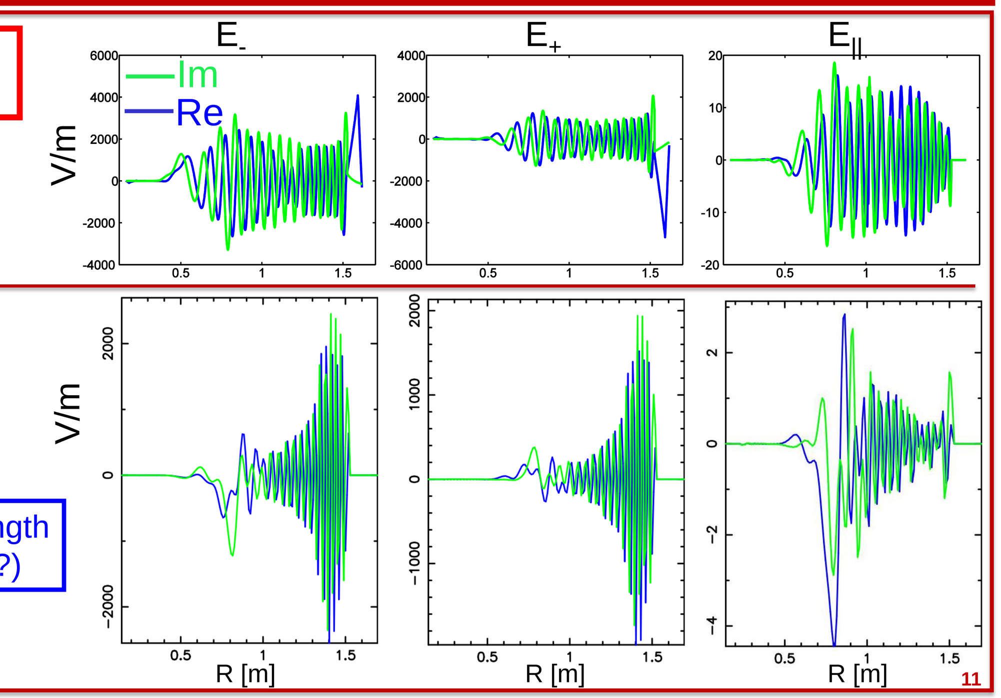
Despite the agreement in the absorption percentages, large differences in the electric field obtained from AORSA and TORIC6

T_i x 1.0, n_e x 2.0, and n_ϕ = 21



Different wavelength between codes (?)

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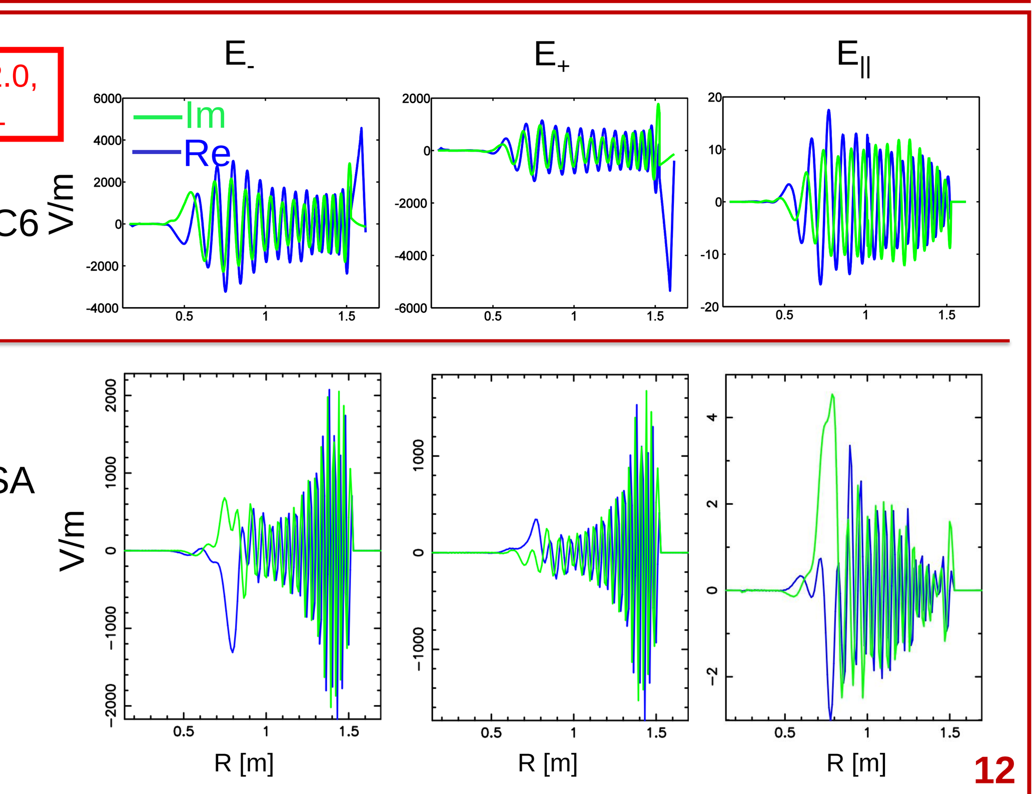
Similar discrepancies as above when the absorption percentages are different

T_i x 2.0, n_e x 2.0, and n_ϕ = 21



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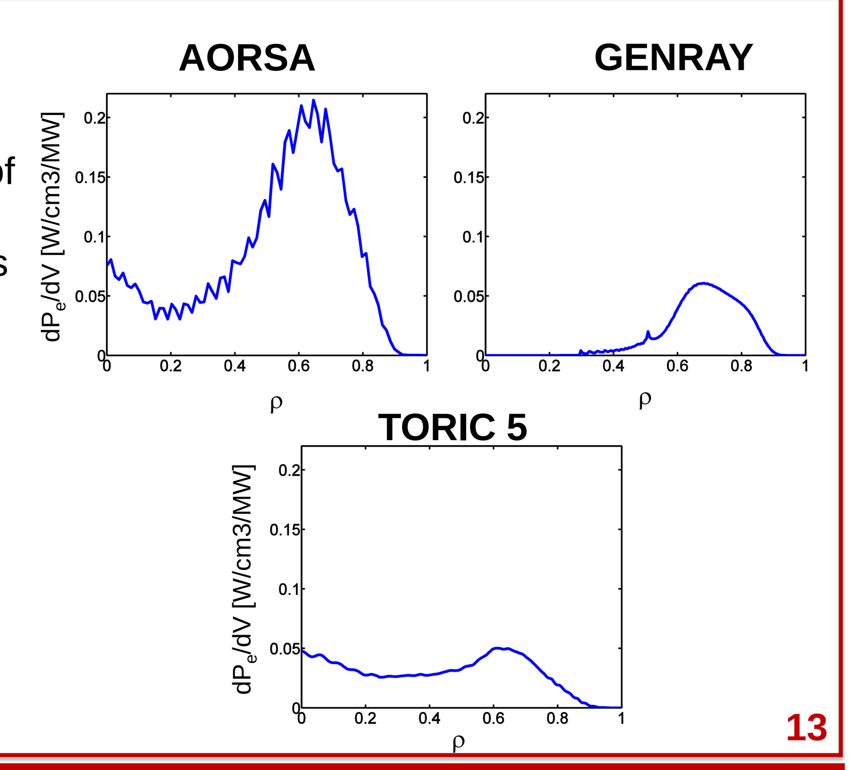
T_i x 2, ne x 2, and n_ϕ = 12 case confirms same differences in the electron power density profiles

- Similar peak position of the electron power density between codes
- GENRAY and TORIC5 results are closer than AORSA results



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Conclusions

An initial benchmark between AORSA, GENRAY, TORIC 5 & 6 in the high harmonic regimes have been presented.

- This benchmark confirms
  - a significant thermal D absorption when $T_i/T_e \geq 2$
  - a significant fast ion absorption, in particular, for lower n_ϕ
- Reasonable agreement between codes has been found for large n_ϕ and when the absorption of thermal D is negligible
- Significant differences have been found between codes in the case of two species plasma (D and e^-) both in terms of percentage of absorption for each species and the electric power density profiles
  - The reason behind these differences is still under investigation

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