Using AORSA to simulate helicon waves in DIII-D and ITER

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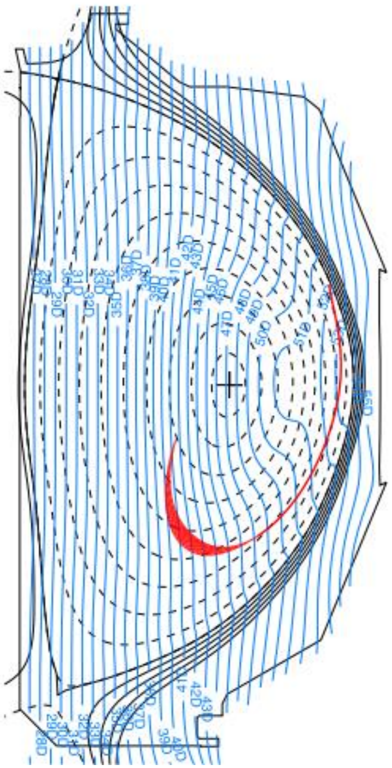
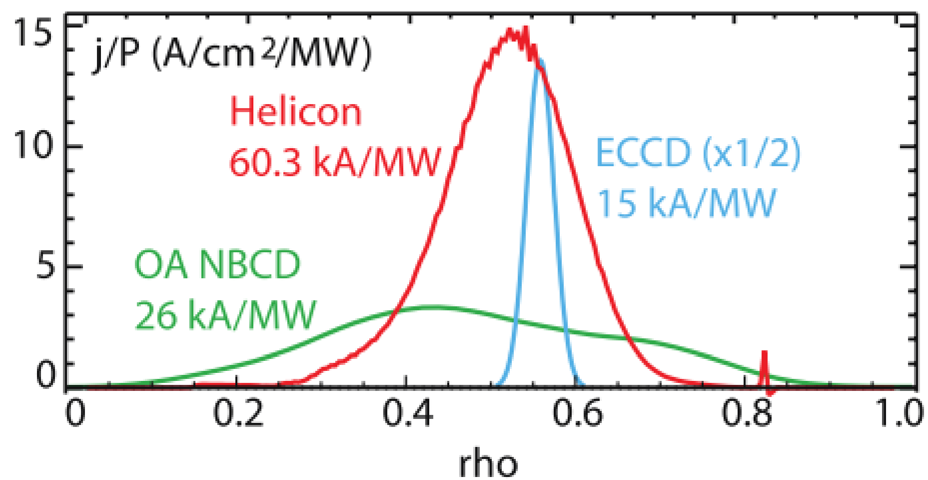
GENRAY has been used to show that helicons can be an effective current drive tool on DIII-D

- Helicons (fast waves at ~ 30-50ω_{ci}) have been numerically investigated by Prater using GENRAY for their current drive efficiency on DIII-D
    - High beta and launched frequencies greatly improve efficiency
    - Variations of $n_{||}$ and antenna location has been done in this study



$n_{||}(a)$ = 3.0, f=500 MHz
$n_e(0)$ = 10.3, $T_e(0)$ = 3.4, $T_i(0)$ = 7.2, Zeff ~ 2.2
$\beta_e(\rho=0.5)$ = 3.2%

I_{CD} = 60.3 kA/MW
η= nIR/P = 0.62x10^{19} A/W/m^2
ζ = 33 n_{20} I R / P T_{keV} = 0.64



Graphics taken from Prater, US-Japan RF workshop 2013

AORSA is an excellent tool to investigate the use of helicon waves for current drive in DIII-D and ITER

- Full wave, PSTELION[1], and ray tracing, GENRAY [2], codes have been used to model helicon wave current drive efficiency off-axis

- GENRAY and PSTELION is likely a reasonably model in this high single pass damping, high frequency scenario
  - main limitation is ability to include absorption of fast ions (deuterium beams, hot alphas) at ~ 30-50ω_{ci} may be inaccurate
    - GENRAY ion absorption model may not be accurate at such high harmonics
    - PSTELION uses a 2nd order finite Larmor radius expansion

- AORSA [3] , a full wave code that is valid for all finite larmor radius and ion cyclotron harmonics, and includes more physics, such as an more accurate fast ion/alpha absorption and possible slow wave effects, but is much more computationally intensive

[1] V. L. Vdovin, Plasma Physics Reports, V.39, No.2, 2013
[2] R. Prater et al, Nucl. Fusion, 52, 083024, 2014
[3] E.F Jaeger et al, Phys. Plasmas, V.7, No.8, 2001

Summary of talk

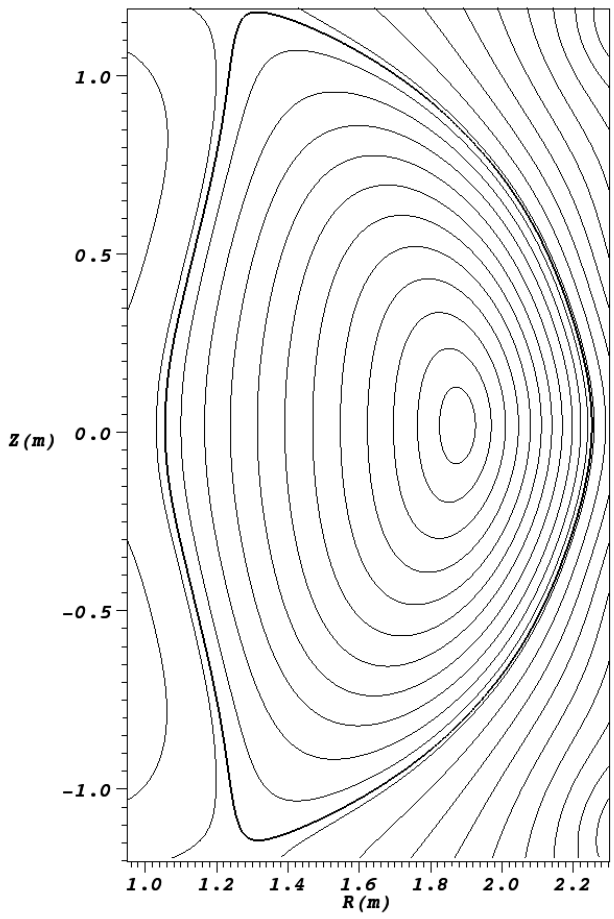
- Comparison between AORSA and GENRAY will be shown to be good for well converged DIIID and ITER cases
  - good agreement in current and power absorption profiles in DIIID and ITER cases at $n_{||}$=3 at antenna between GENRAY and AORSA
  - Electron damping is dominant in all these cases, but there is some ion absorption due to beam ion and alpha population at ITER
  - there may be some difference in fast ion absorption models, but this is not clear in current cases (may require low $n_{||}$)

- Numerical challenges to AORSA simulations at ~ 30-50ω_{ci} will be shown
  - significantly more modes needed due to the shorter wavelengths
  - new analytical Z function seems to significantly reduce numerical noise
  - Cases at lower $n_{||}$ still remain a challenge
  - inclusion of realistic SOL remains a numerical challenge

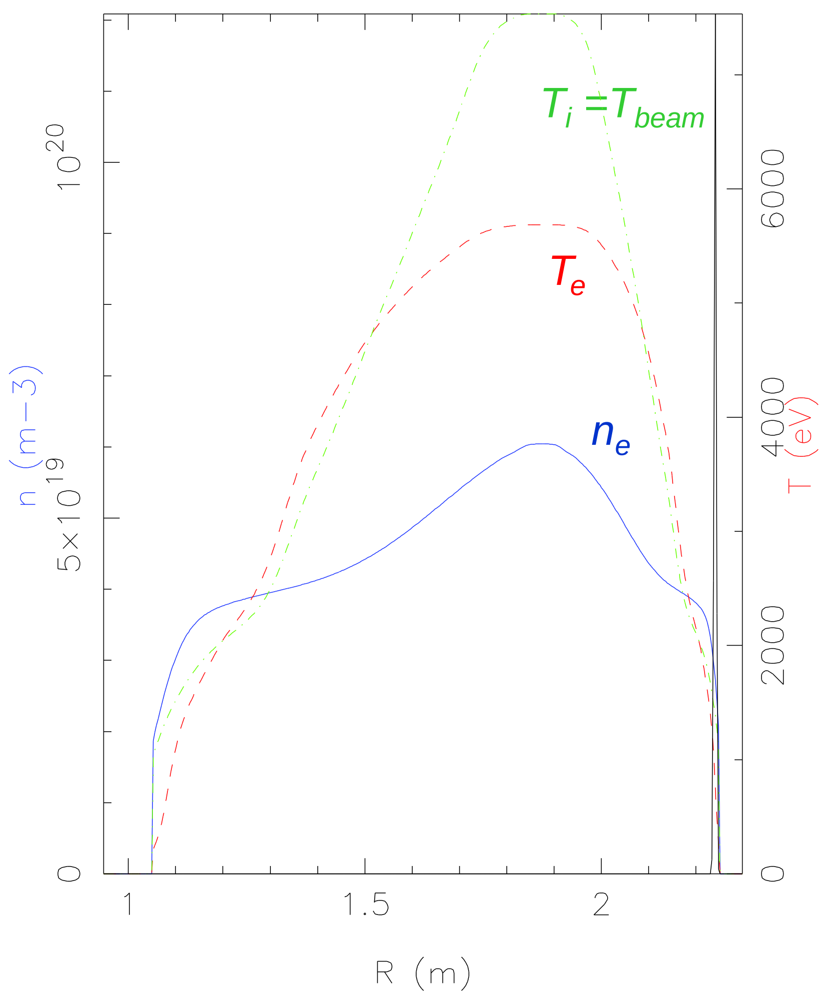
Different DIII-D scenario from integrated plasma simulation is shown here

β ~ 5%, deuterium beam included, Z_{eff} ~ 1.8, B_0 = 1.49 T

(a) Magnetic equilibrium

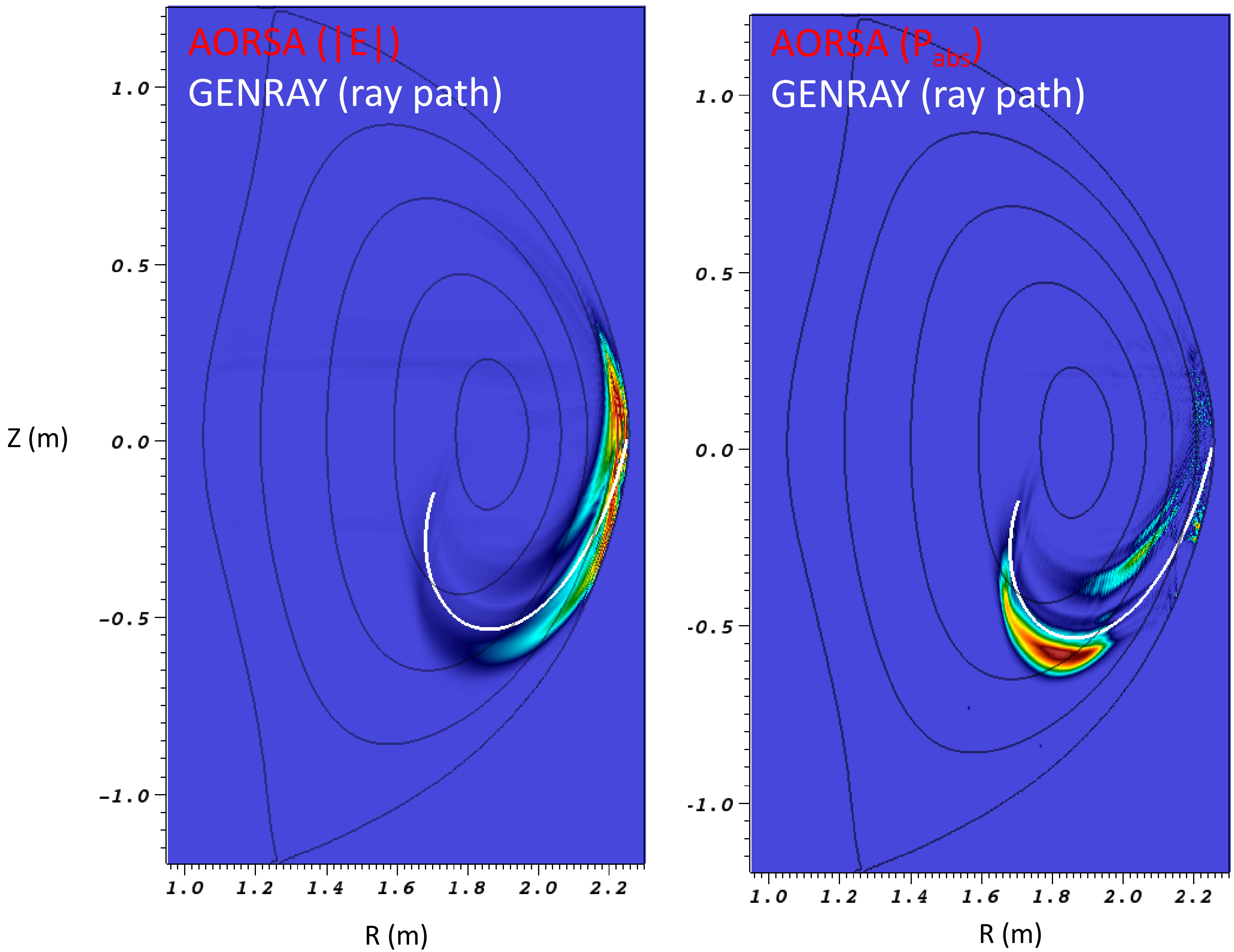


(b) Plasma profiles

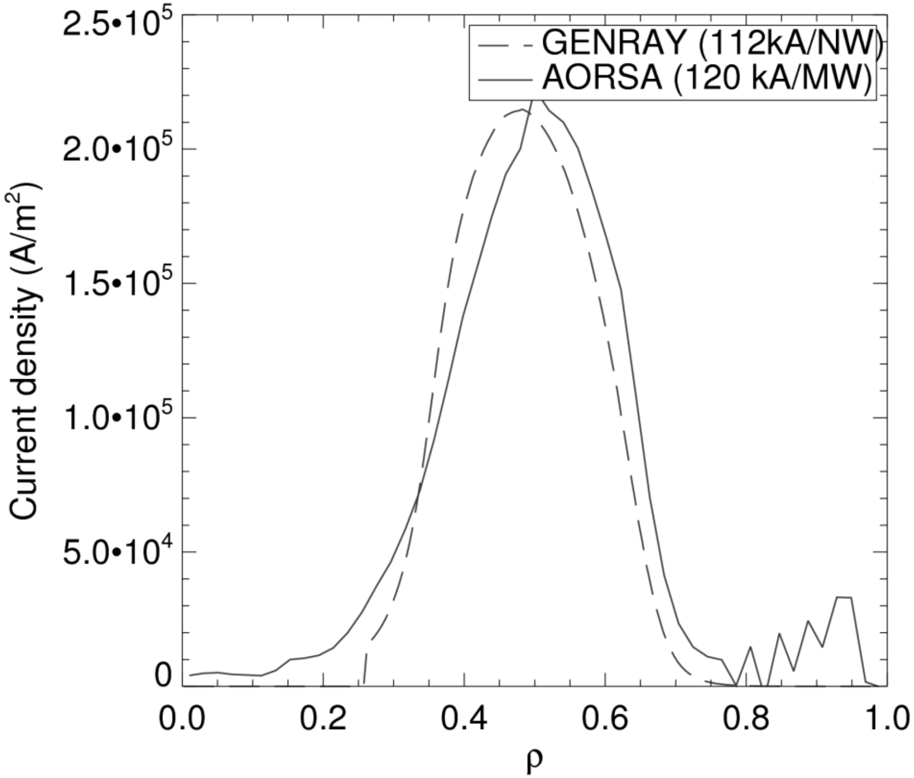


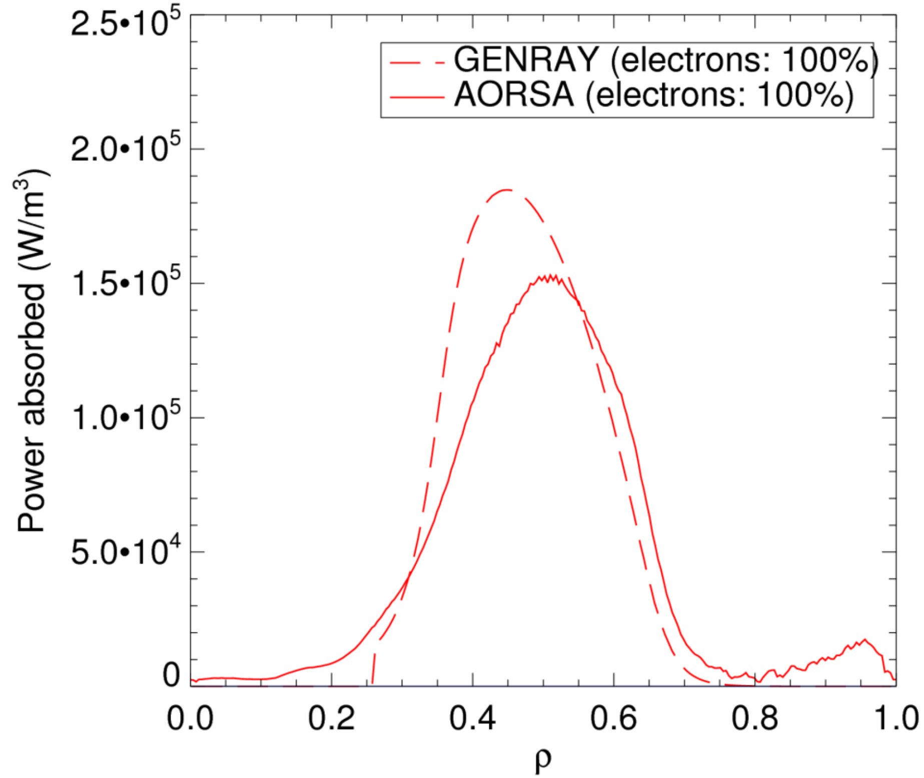
Scenario provided by J.M Park

GENRAY and AORSA compares favorably for DIIID conditions at 500 MHz, $n_{||}$ =3



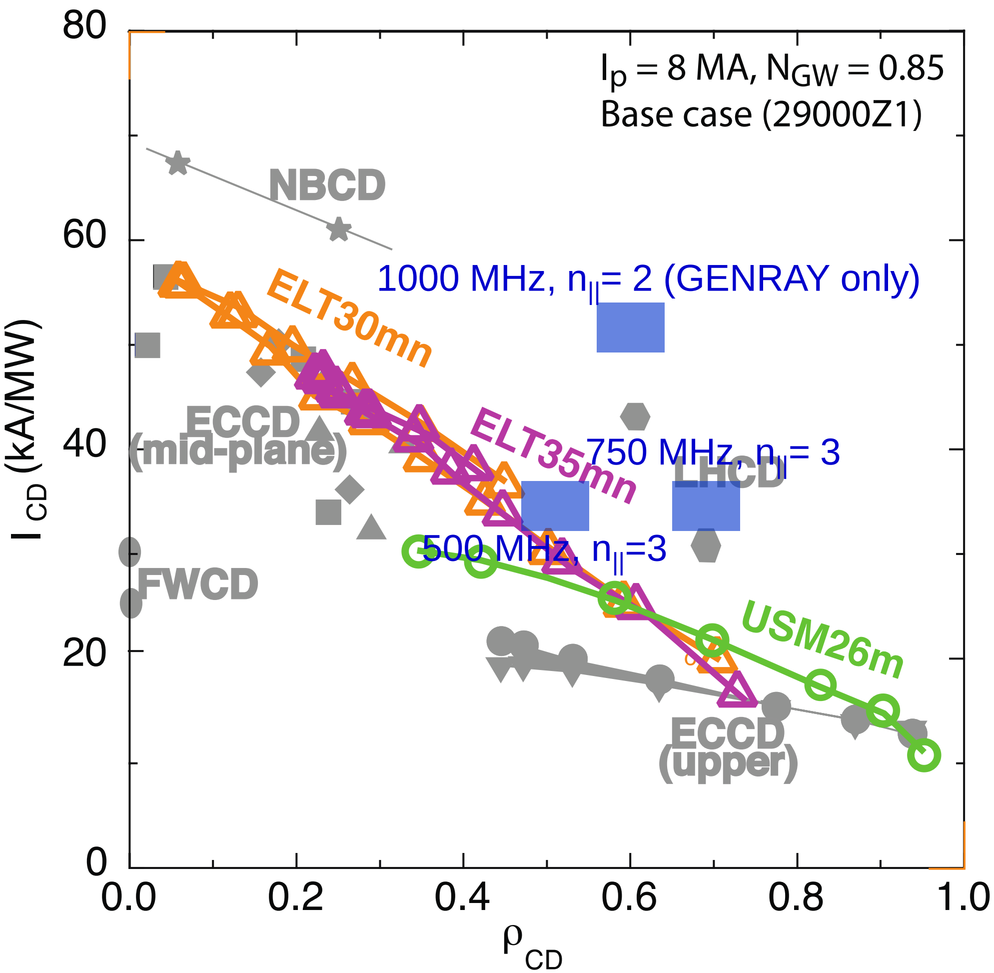
GENRAY and AORSA compares favorably for DIIID conditions at 500 MHz, $n_{||} = 3$





- agreement between AORSA and GENRAY is pretty good for these high beta, high single pass absorption DIII-D cases that have been tried in both magnitude and location of current drive and power absorption channels
- AORSA simulations took 5 hours with 4096 processors
- GENRAY simulations took 3 seconds on standard Linux workstation

Helicon waves have been simulated on ITER



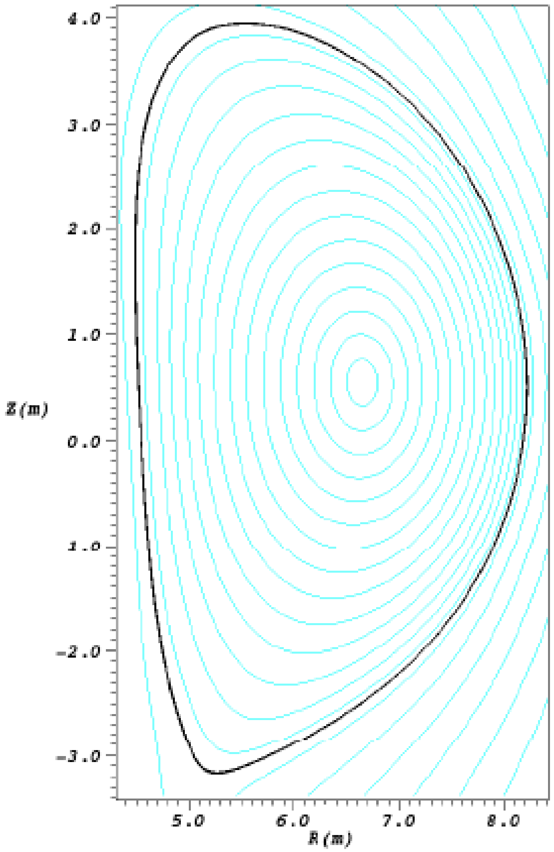
Simulations of different current drive efficiency for ITER SS benchmark (Murakami, ITPA 2014)

- ITER steady state scenario group has simulated different current drive options (NBCD, ECCD, FWCD, LHCD) for ITER steady state benchmark case
- ITER helicon cases comparing AORSA and GENRAY (next few slides) have been added to this plot
    - AORSA has not been able to simulate desired 1000 GHz case, but other cases give favorable results with GENRAY
- GENRAY shows helicon can be effective for higher frequencies
- deuterium beam and alpha particles can have some effect in reducing current drive efficiency

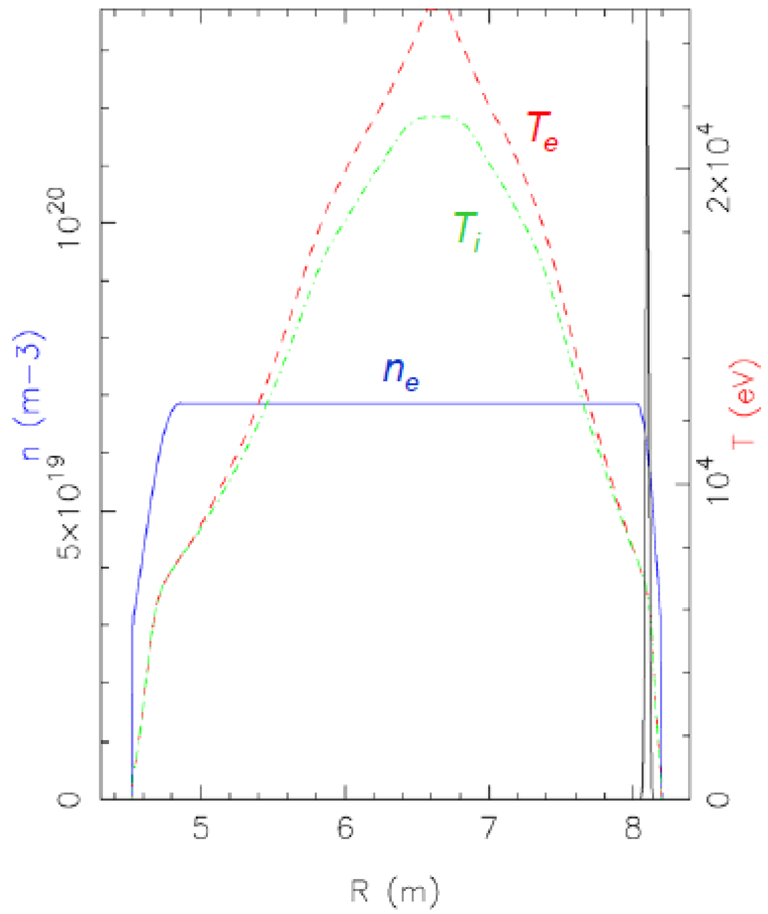
ITER advanced scenario equilibrium and profiles

D_{beam}, alpha profiles included here, B_0 = 4.92 T

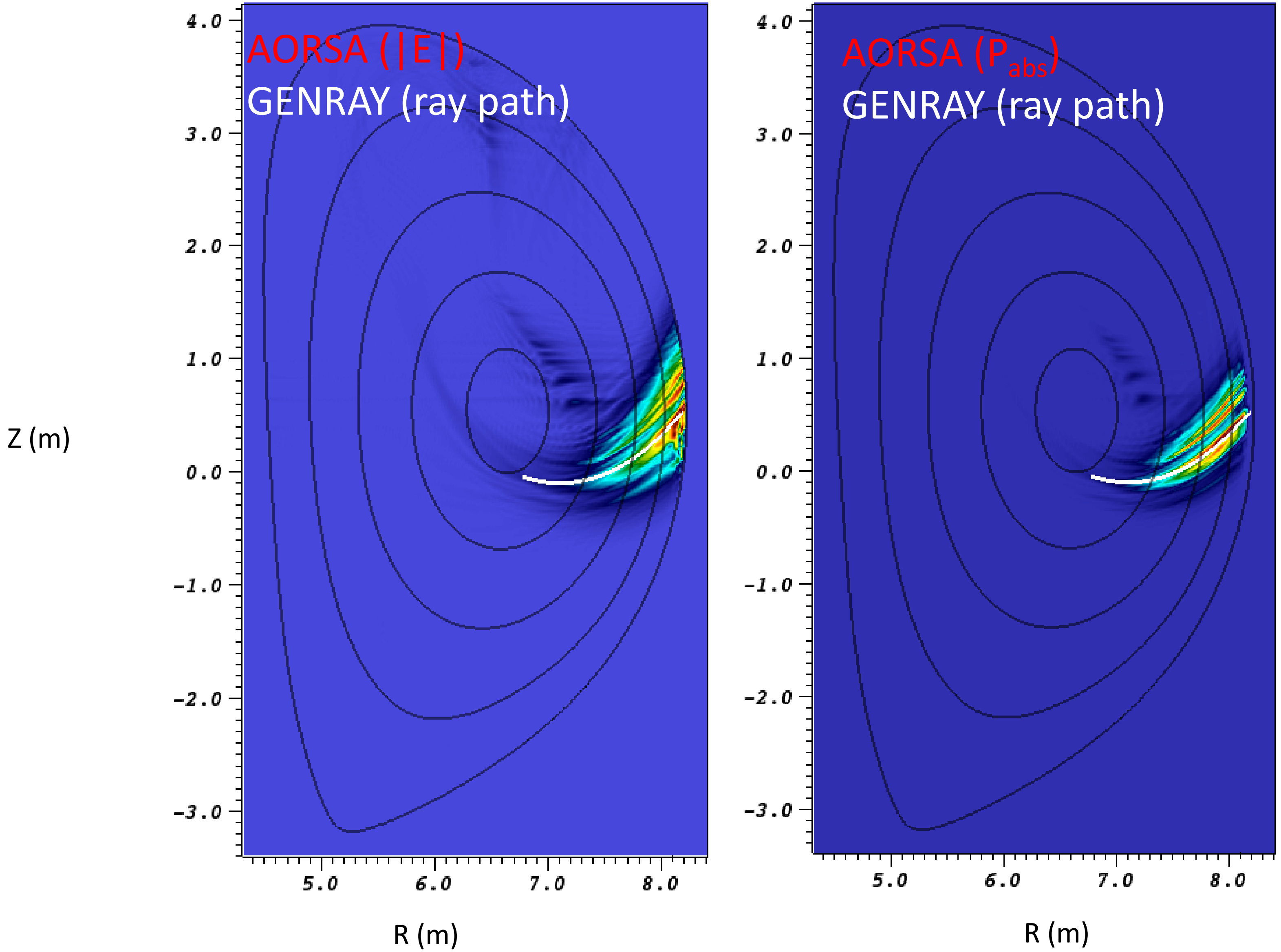
(a) Magnetic equilibrium



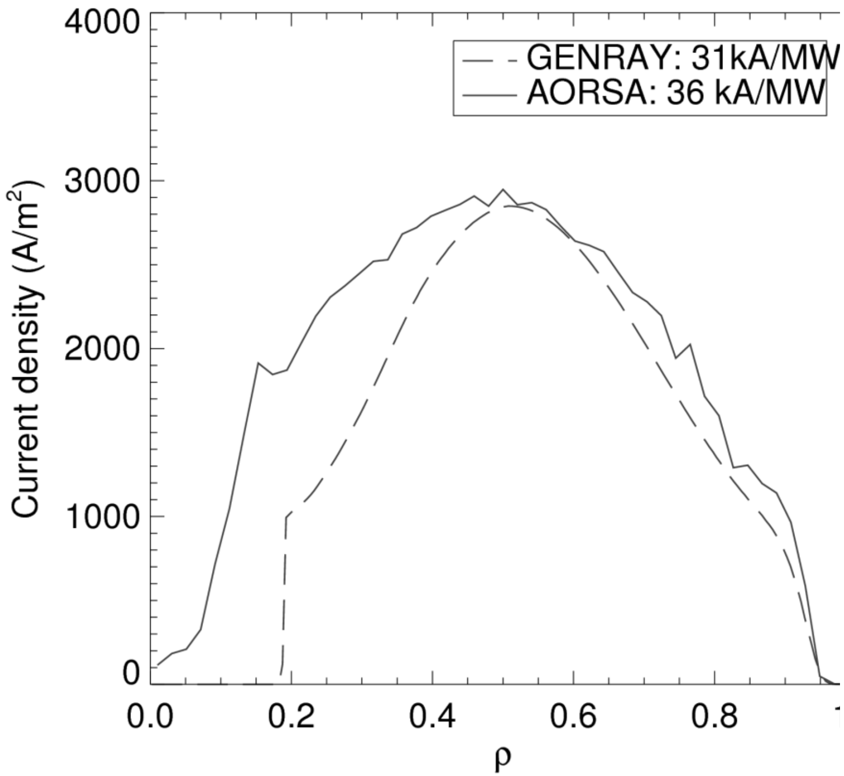
(b) Plasma profiles

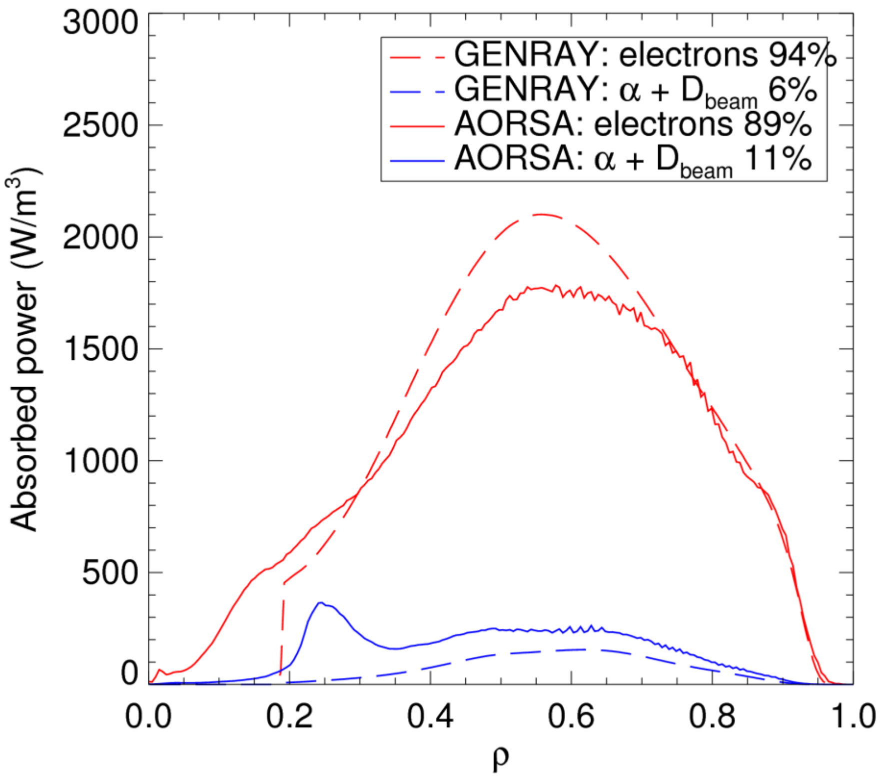


GENRAY and AORSA compare reasonably for ITER at 500 MHz, $n_{||}$ =3.0



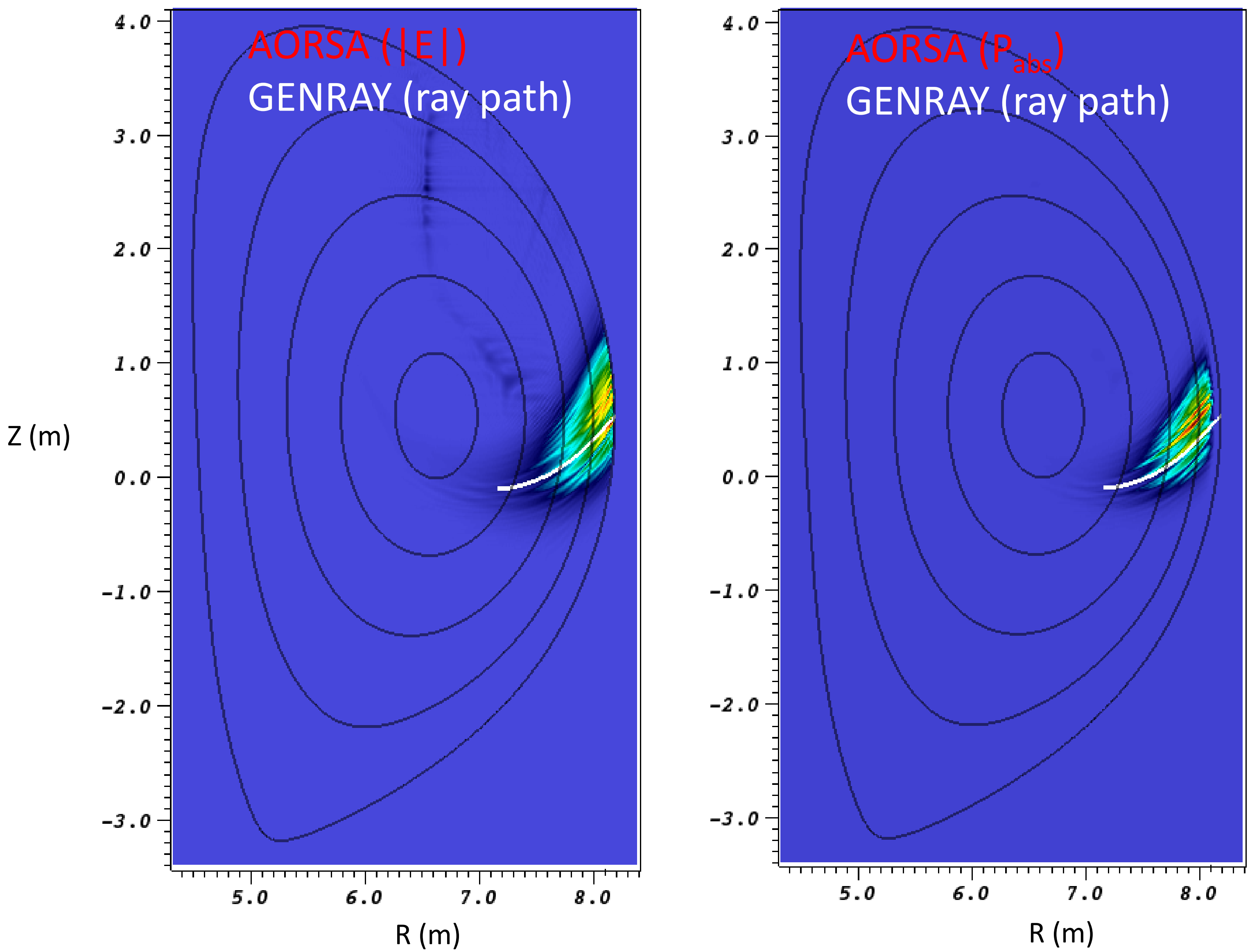
GENRAY and AORSA has comparable current drive efficiency for ITER at 500 MHz, $n_{||}$=3



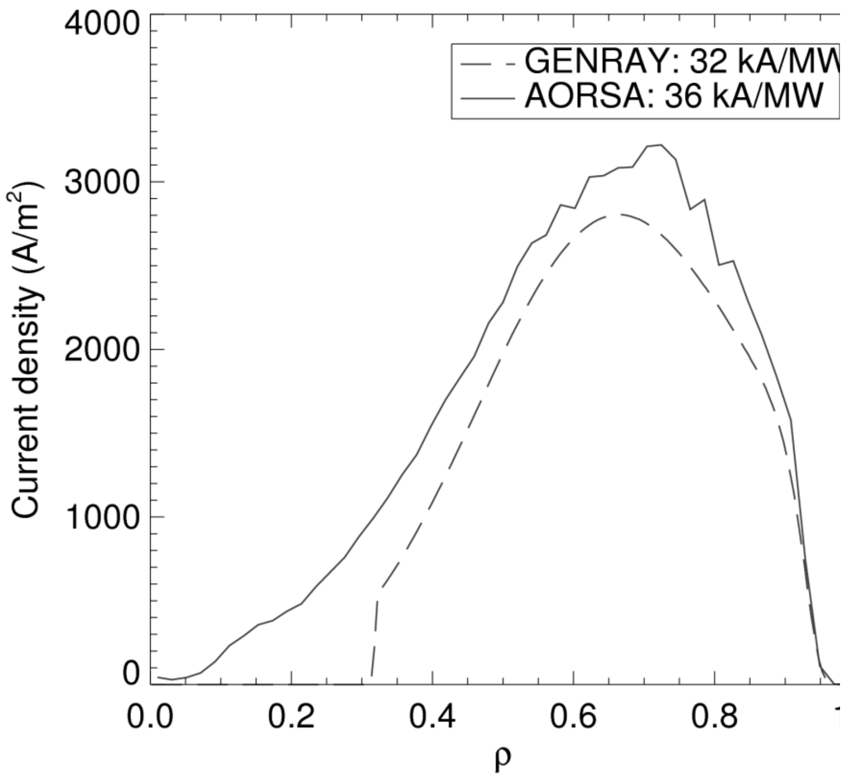


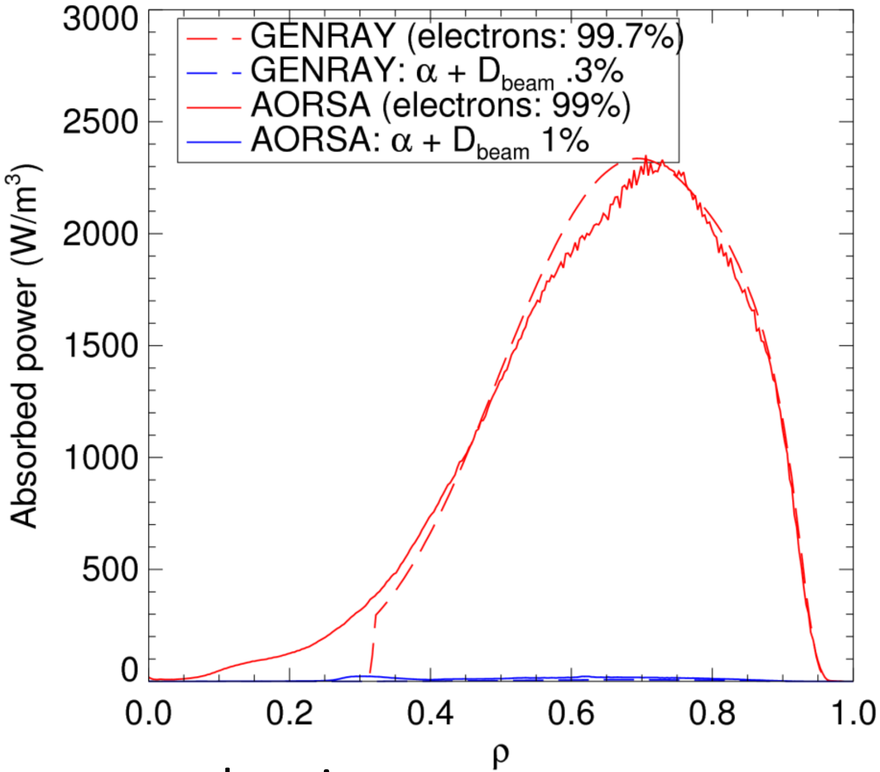
- agreement between AORSA and GENRAY is pretty good, but there are slight differences in width of current drive, absorption profiles
- high fast ion absorption at ρ = .2 is possibly numerical noise
    - D_{beam} density also peaks at this location

GENRAY and AORSA has comparable current drive efficiency for ITER at 750 MHz, $n_{||}$ =3



GENRAY and AORSA has comparable current drive efficiency for ITER at 750 MHz, $n_{||}$=3





- agreement between AORSA and GENRAY is very good again
- higher frequencies seem to decrease ion absorption profile
- possible difference in ion absorption models in AORSA and GENRAY is not so important in these high absorption issues

converged AORSA simulations require numerous numerical tinkering

- AORSA simulations at ~ 30-50ω_{ci} required considerably more modes and numerical methods to get a reasonable answer
  - major difficulty is numerical noise pollution for high $k_\perp$ near $k_{||}$=0
- inclusion of up to 50 harmonics are necessary in conductivity to converge and get correct answer
- 2 methods for Z function has been derived to reduce numerical noise
  - $k_{||}$ has significant variation along field line, so an "averaging" of Z function along field line orbits is done to reduce numerical noise near $k_{||}$=0
- Small $n_{||}$ cases (high ion absorption) are still a work in progress
  - 1000 MHz, $n_{||}$=2 case is desired
  - numerical solution is harder at low $n_{||}$
- SOL effects are still a work in progress

New Z function takes advantage of expanding and averaging AORSA basis functions along field line

For each k_x and k_y, evaluate the AORSA basis function along a field line length of $2\pi R_0 q$ (i.e. $l = -q\,\pi\,R_0$ to $q\,\pi\,R_0$)

$$E(l) = e^{i[k_x R(l) + k_y Z(l) + n_\varphi \varphi(l)]} = e^{i\Psi(l)}$$

where $R(l)$, $Z(l)$, and $\varphi(l)$ are found by tracing field line orbits.
Next, Fourier expand $E(l)$ along the field line to find the spectrum in $k_{||}$

$$E(l) = \sum_n E_n e^{ik_{\parallel,n}\, l}$$ typically n = 256 or 512 modes

and evaluate the electron conductivity $\sigma^{e}_{3,3}$ (0th harmonic) at each $k_{||,n}$ in this spectrum. The parallel electron current can then be calculated as a sum over $k_{||,n}$

$$J_e(l) = \sum_n \sigma^{e}_{3,3}(k_{\parallel,n})\, E_n e^{ik_{\parallel,n} l}$$

$$\sigma^{e,new}_{3,3}(0) = \frac{\mathrm{J}(0)}{\mathrm{E}(0)}$$

Use this to replace the 0th harmonic term in the usual sum over harmonics for $\sigma^{e}_{3,3}$

Alternately, Taylor expand the phase along field line orbits

Taylor expand ψ about $l = 0$: $$\Psi(l) = k_R R(l) + k_Z Z(l) + n_\varphi \varphi(l)$$

$$\Psi(l) = \Psi(0) + \frac{d\Psi}{dl} l + \frac{1}{2}\frac{d^2\Psi}{dl^2} l^2$$

$$\frac{d\Psi}{dl} = k_R \frac{dR}{dl} + k_Z \frac{dZ}{dl} + n_\varphi \frac{d\varphi}{dl} = k_R b_R + k_Z b_Z + \frac{n_\varphi}{R} b_\varphi = k_\parallel \quad \text{(field line orbits)}$$

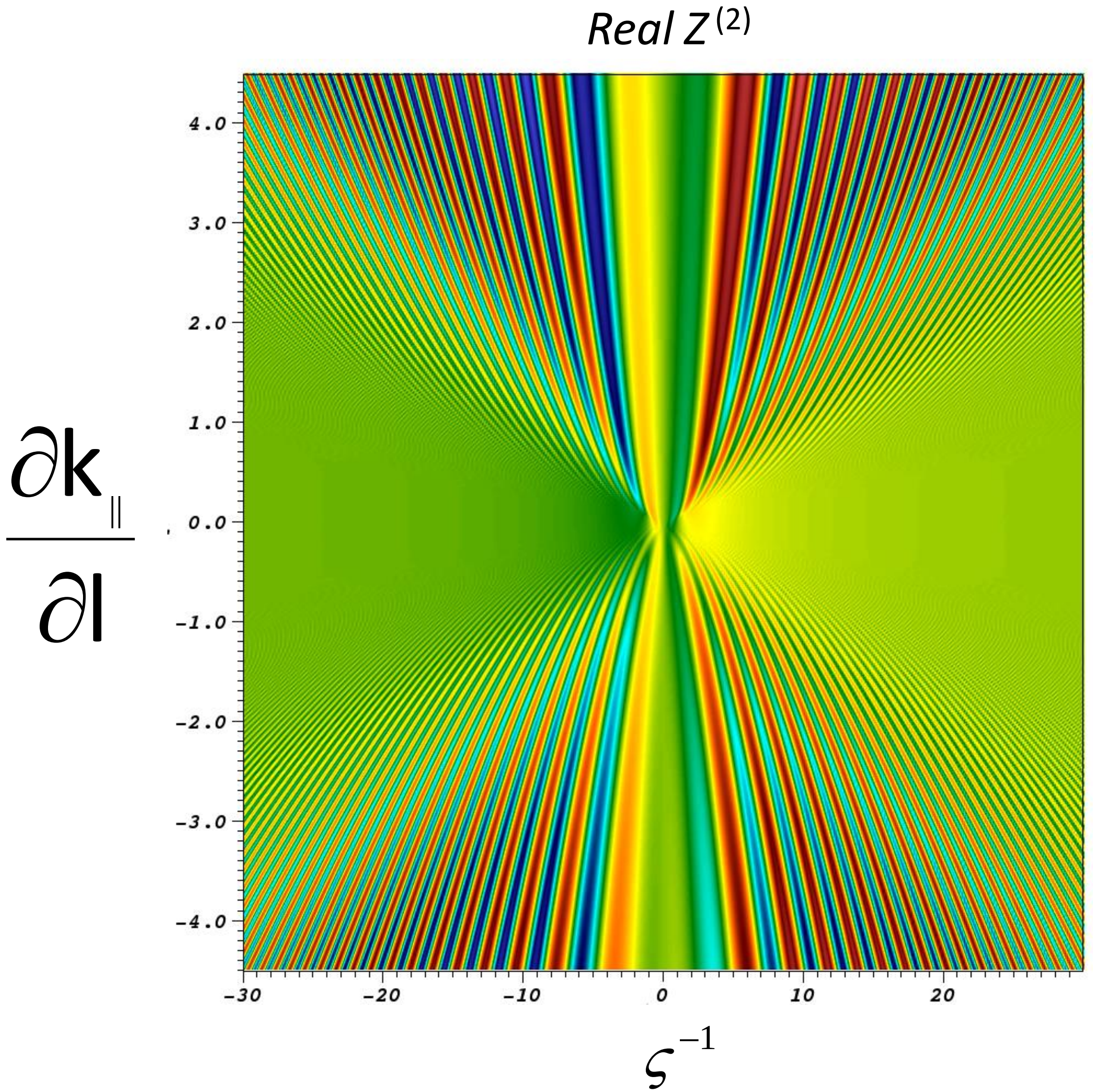
$$\frac{d^2\Psi}{dl^2} = \frac{dk_\parallel}{dl}$$

$$\Psi(l) = \Psi(0) + k_\parallel l + \frac{1}{2}\frac{dk_\parallel}{dl} l^2 = \Psi(0) + k_\parallel v_\parallel \tau + \frac{1}{2}\frac{dk_\parallel}{dl} {v_\parallel}^2 \tau^2$$

$$Z_l^{(2)} = \frac{|k_\parallel| i}{\alpha^2\sqrt{\pi}} \int_{-\infty}^{\infty} v_\parallel^2 dv_\parallel e^{-v_\parallel^2/\alpha^2} \int_{-\infty}^{0} d\tau\, e^{i\psi(\tau) - i\omega\tau}$$

The $v_{||}$ integral can be done analytically (Smithe: phase function of order $v_{||}^2$ or less) and the τ integral numerically. Z is obtained as a table in terms of $\varsigma = (\omega - n\Omega) / k_{||} v_{th}$ and $dk_{||}/dl$ (next slide).

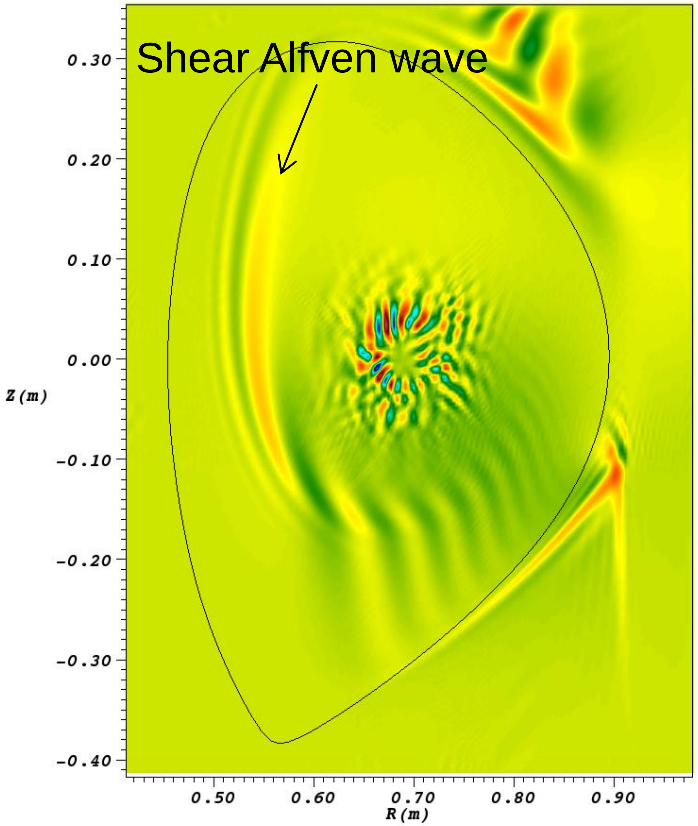
Tabulated Z_2 function for electrons



New $Z_{2,e}$ reduces numerical pollution caused by $k_{//}$ passing through zero

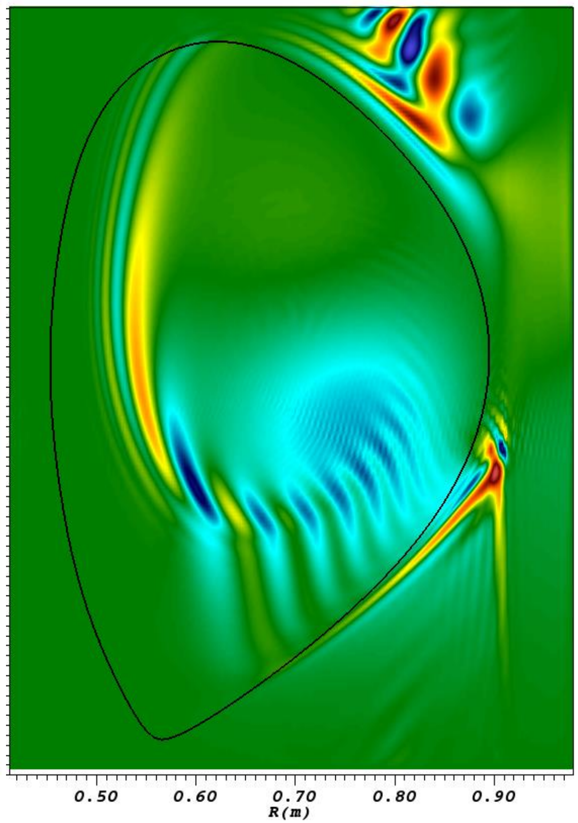
C-Mod: #1051206002.01120, 200x200, f = 30 MHz, B_0 = 5.29 T, n_ϕ = 12, cold ions $\delta_0 = 1\times10^{-4}$

Original $Z_{2,e}$



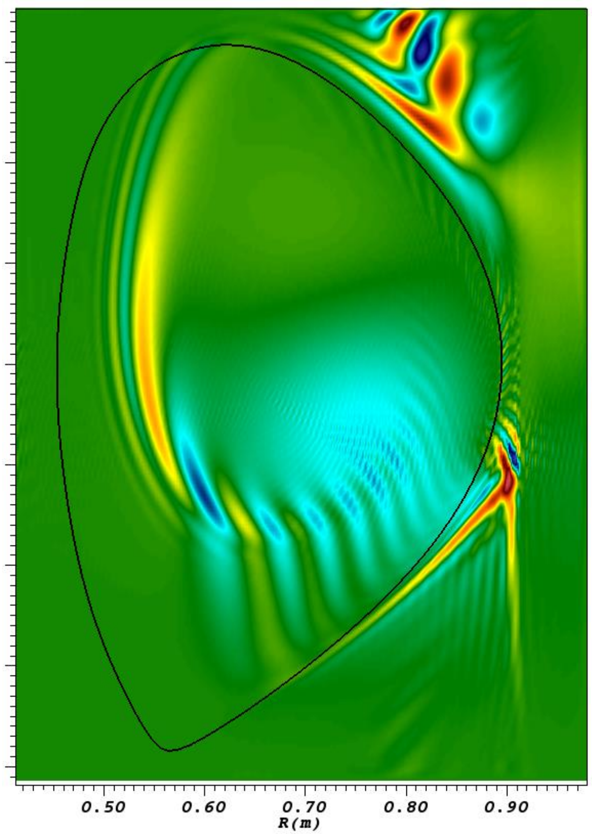
14.5 mins (Edison, 1296)

New $Z_{2,e}$ (tabulated)



14.6 mins (Edison, 1296)

Fourier $Z_{2,e}$ (orbits)

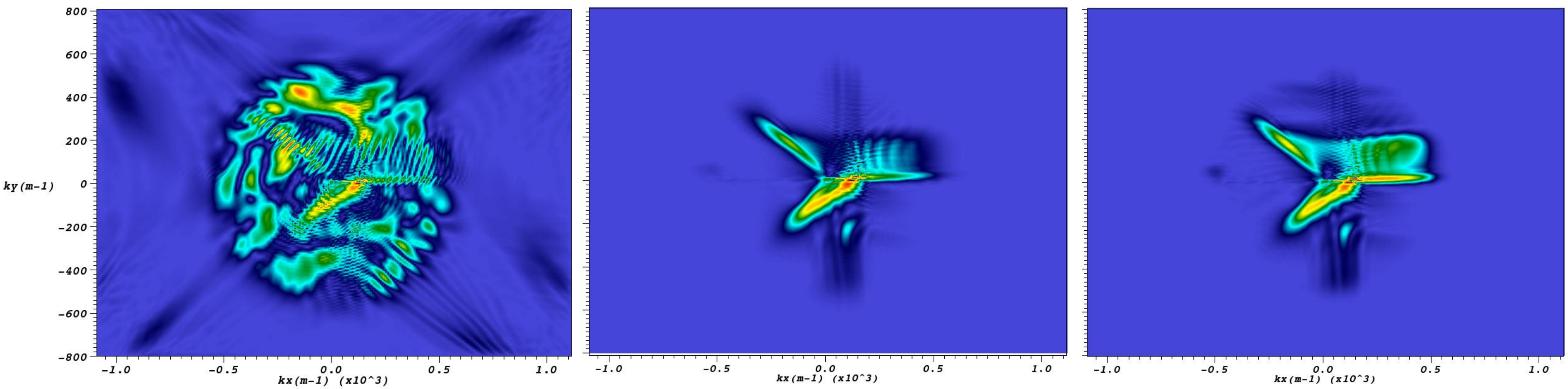


31 mins (Edison, 2304)

New $Z_{2,e}$ reduces numerical pollution in $E_{//}$ spectrum

C-Mod: #1051206002.01120, 200x200, f = 30 MHz, B_0 = 5.29 T, n_ϕ = 12, cold ions $\delta_0 = 1\text{x}10^{-4}$

Original $Z_{2,e}$ | New $Z_{2,e}$ (tabulated) | Fourier $Z_{2,e}$ (orbits)



Slightly better convergence and energy conservation than orbits

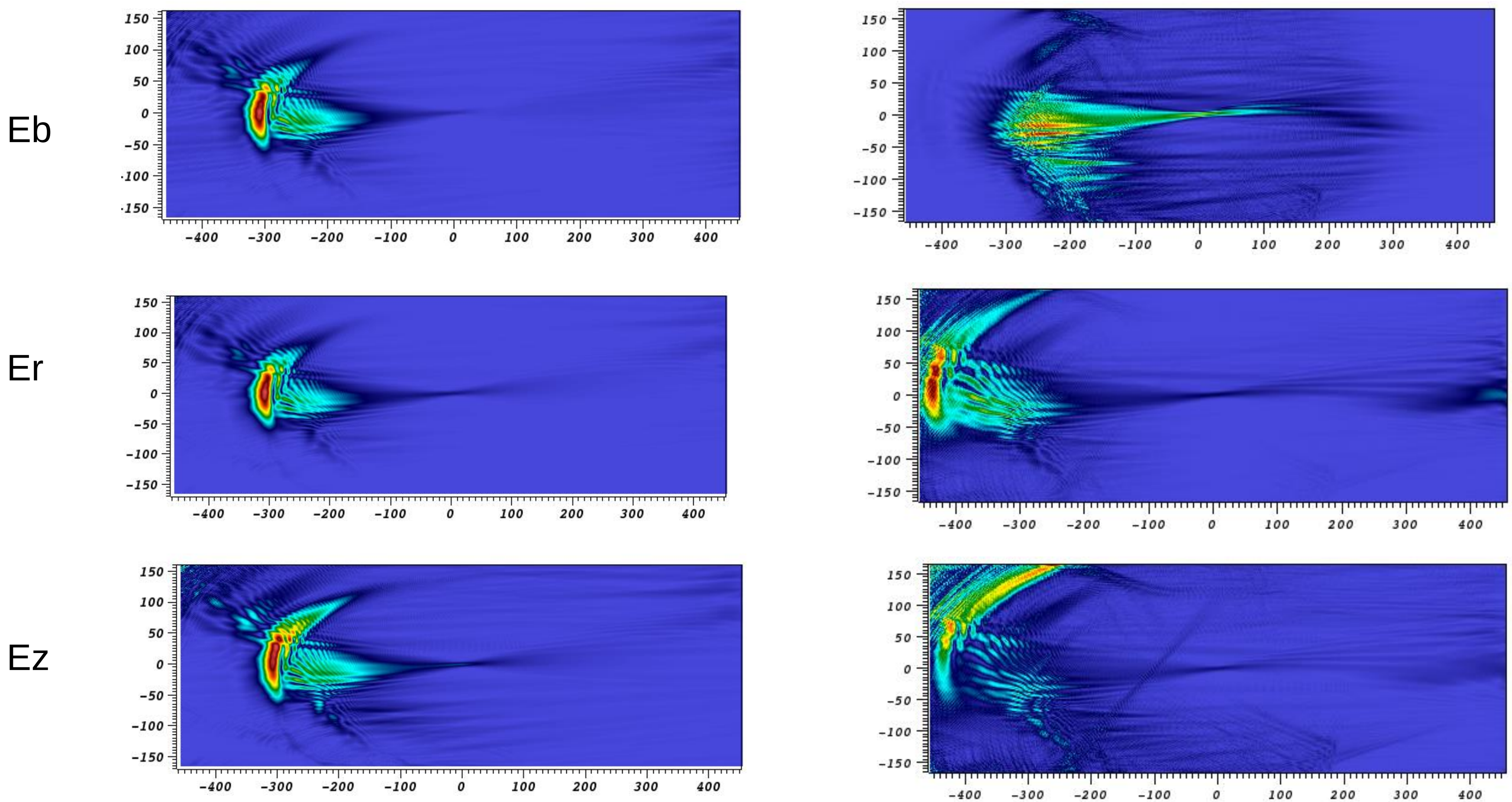
14.5 mins (Edison, 1296

14.6 mins (Edison, 1296)

31 mins (Edison, 2304)

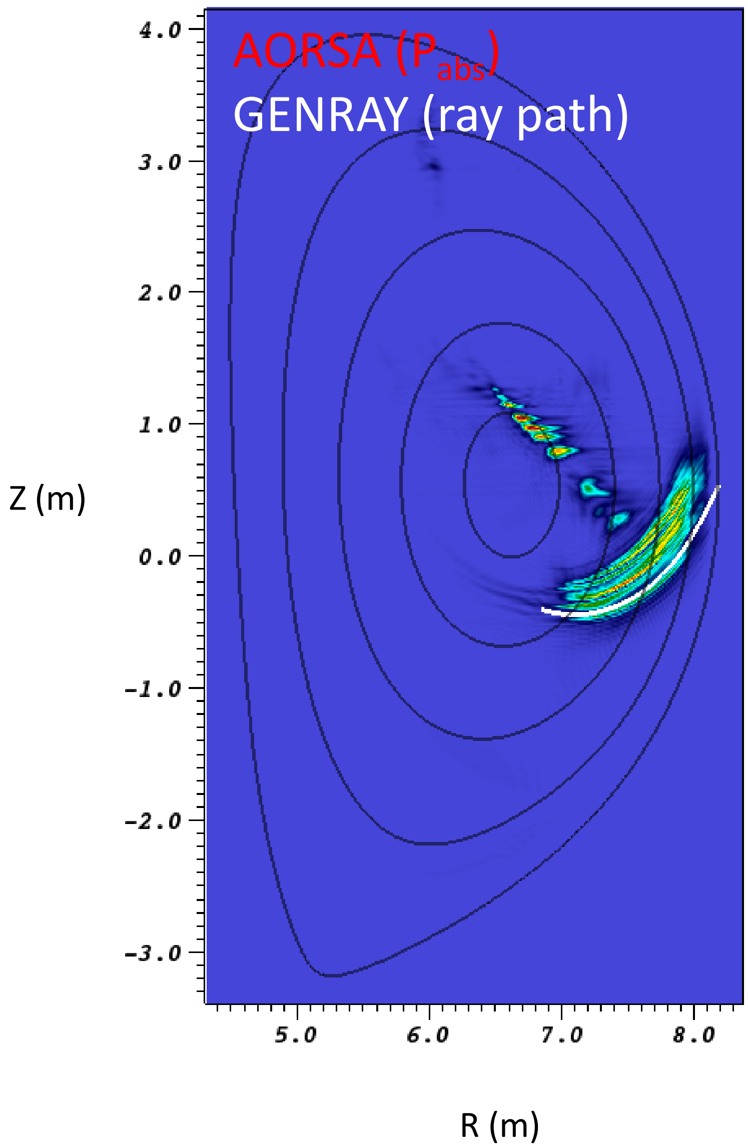
Small $n_{||}$ case are more difficult for numerical convergence

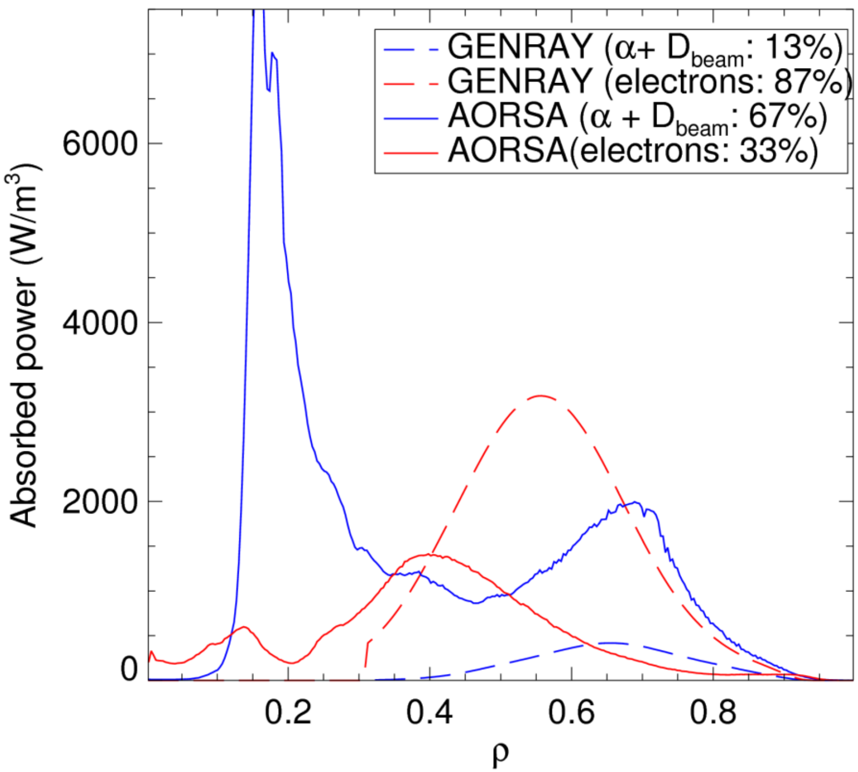
ITER 750 MHz $n_{||}$=3 | ITER 750 MHz $n_{||}$=2



- AORSA simulations with 600x400 modes took 9 hours with 9192 processors
- numerical damping used in $n_{||}$=2 case
    - damping helps with convergence, but did change answer for $n_{||}$=3 case
- More modes, other solutions may be necessary for $n_{||}$=2 case

$N_{||}$=2 case currently does differ between GENRAY and AORSA





- effects of fast ions is expected to be more important for $n_{||}$=2 cases
- Significant differences between GENRAY and AORSA
  - needs to be resolved
  - AORSA may require numerical tinkering

Future steps using AORSA for helicon simulations is inclusion of SOL effects

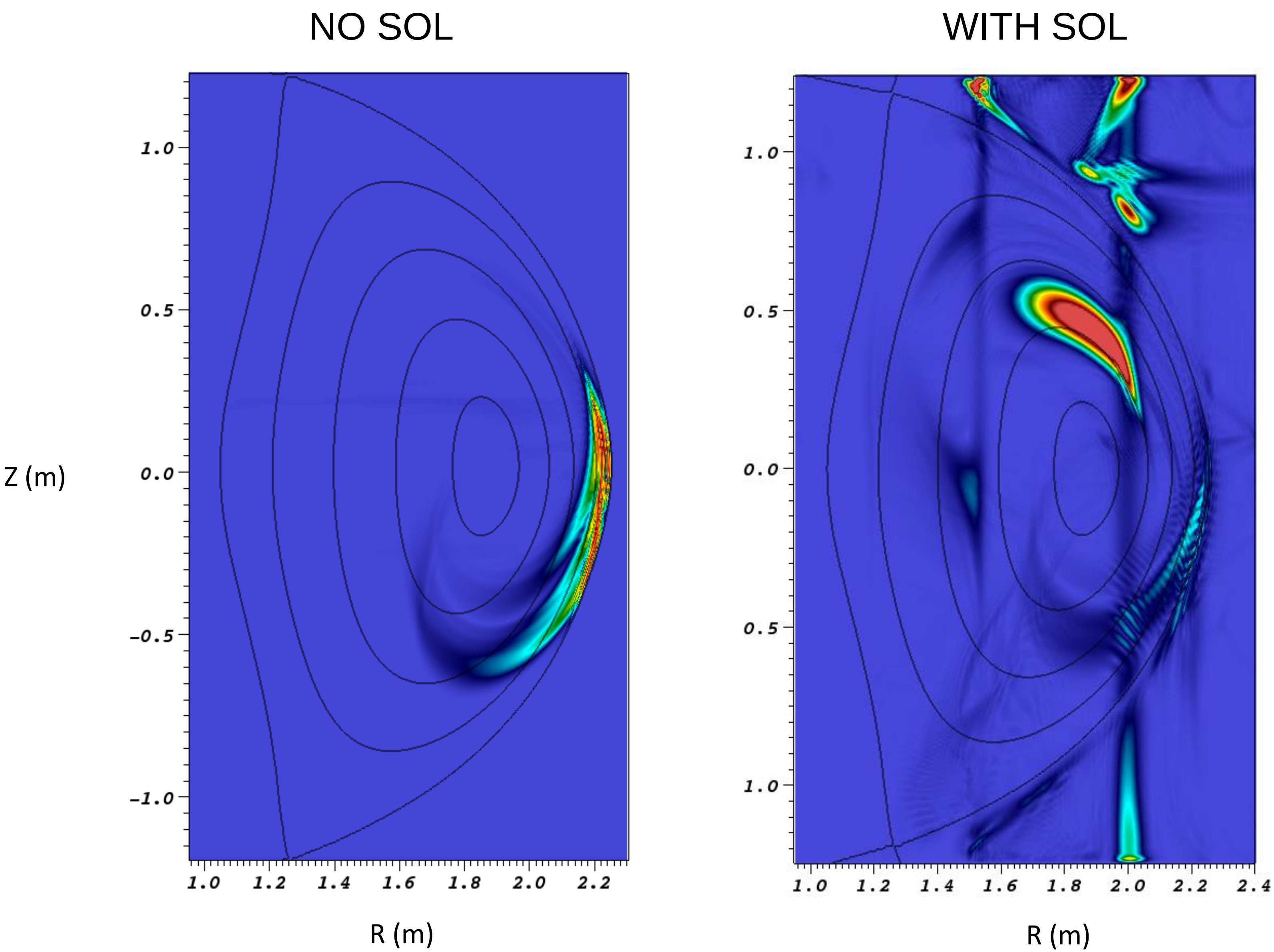
- Current simulations focuses on RF physics within LCFS
  - SOL effects are very important, as there is significant concern that power would not be coupled to bulk plasma
  - coupling to slow waves, collisional absorption, PDI, scattering from density fluctuations are possible SOL issues that may lower current drive efficiency

- AORSA can handle some of these problems, but so far, a complete solution including the SOL eludes us (see next slide)

- Short wavelength modes that require extremely high resolution seems to be the culprit in reaching numerical convergence

- goal for next year is to find some converged helicon solution for DIII-D that includes the SOL plasma either by resolving the slow waves or by absorbing them

Inclusion of SOL in helicon for DIIID case gives significant numerical noise



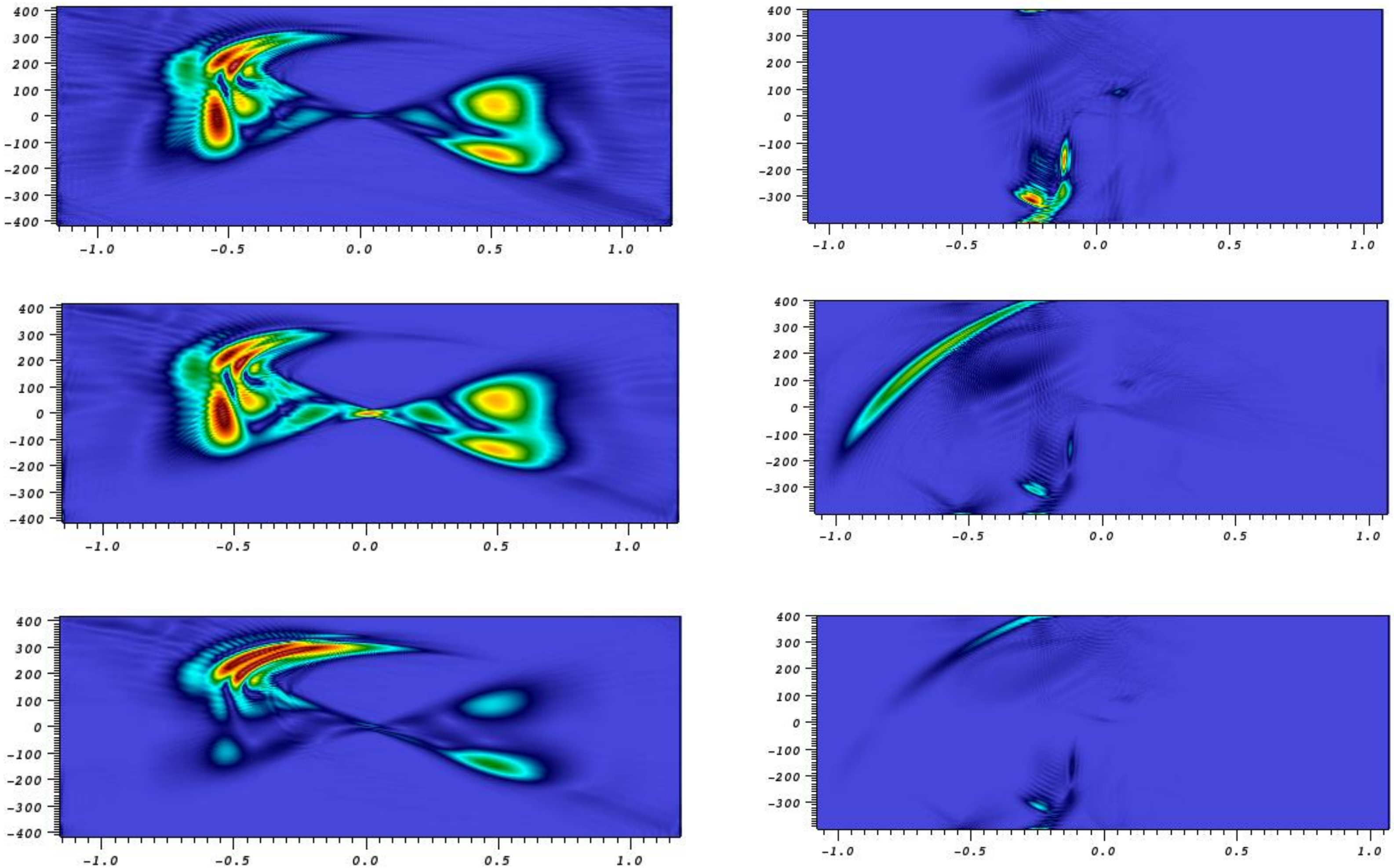
Significant work is necessary to resolve the SOL in DIII-D case

no SOL | SOL

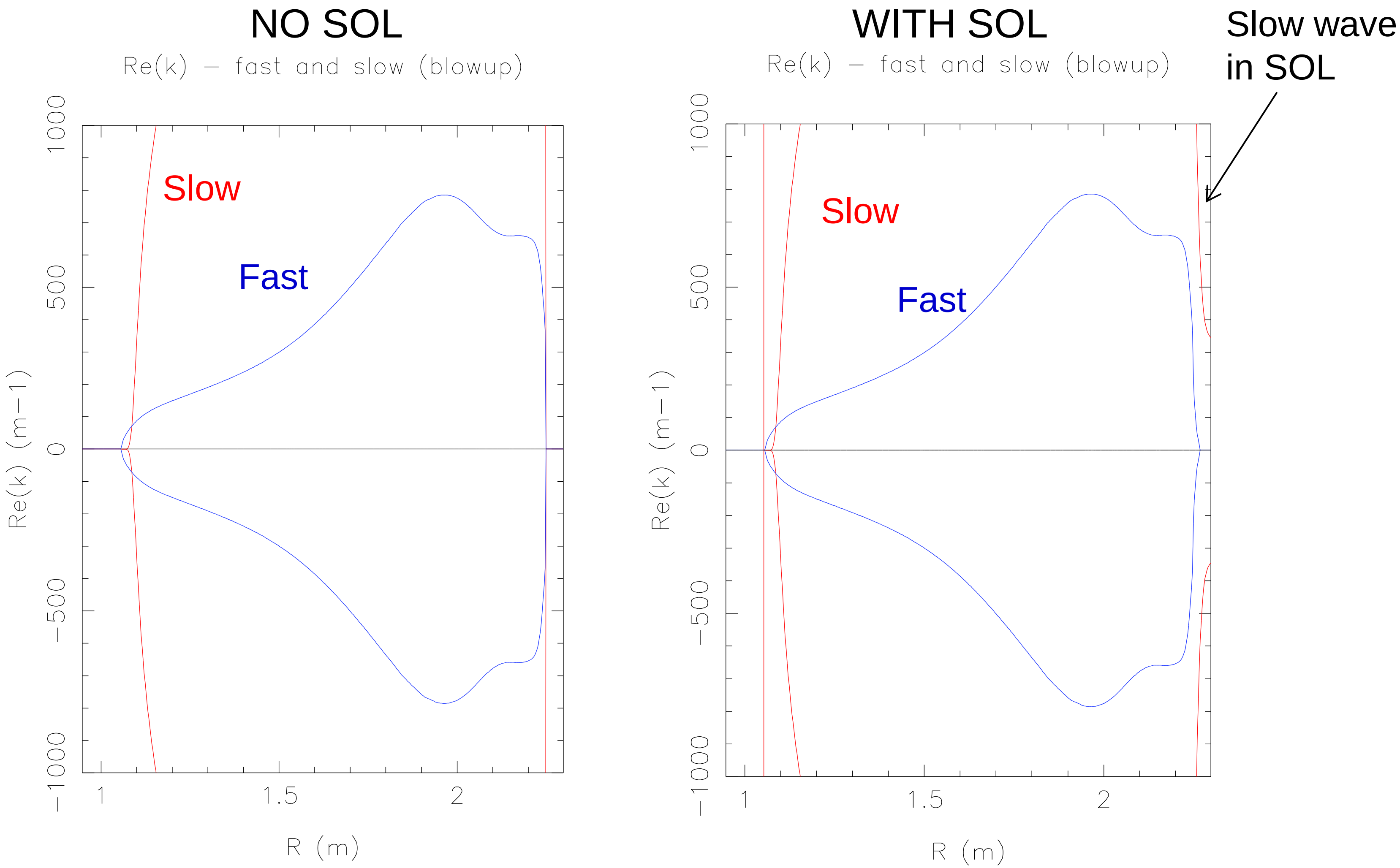
Eb

Er

Ez



Cold plasma dispersion shows slow wave in the edge



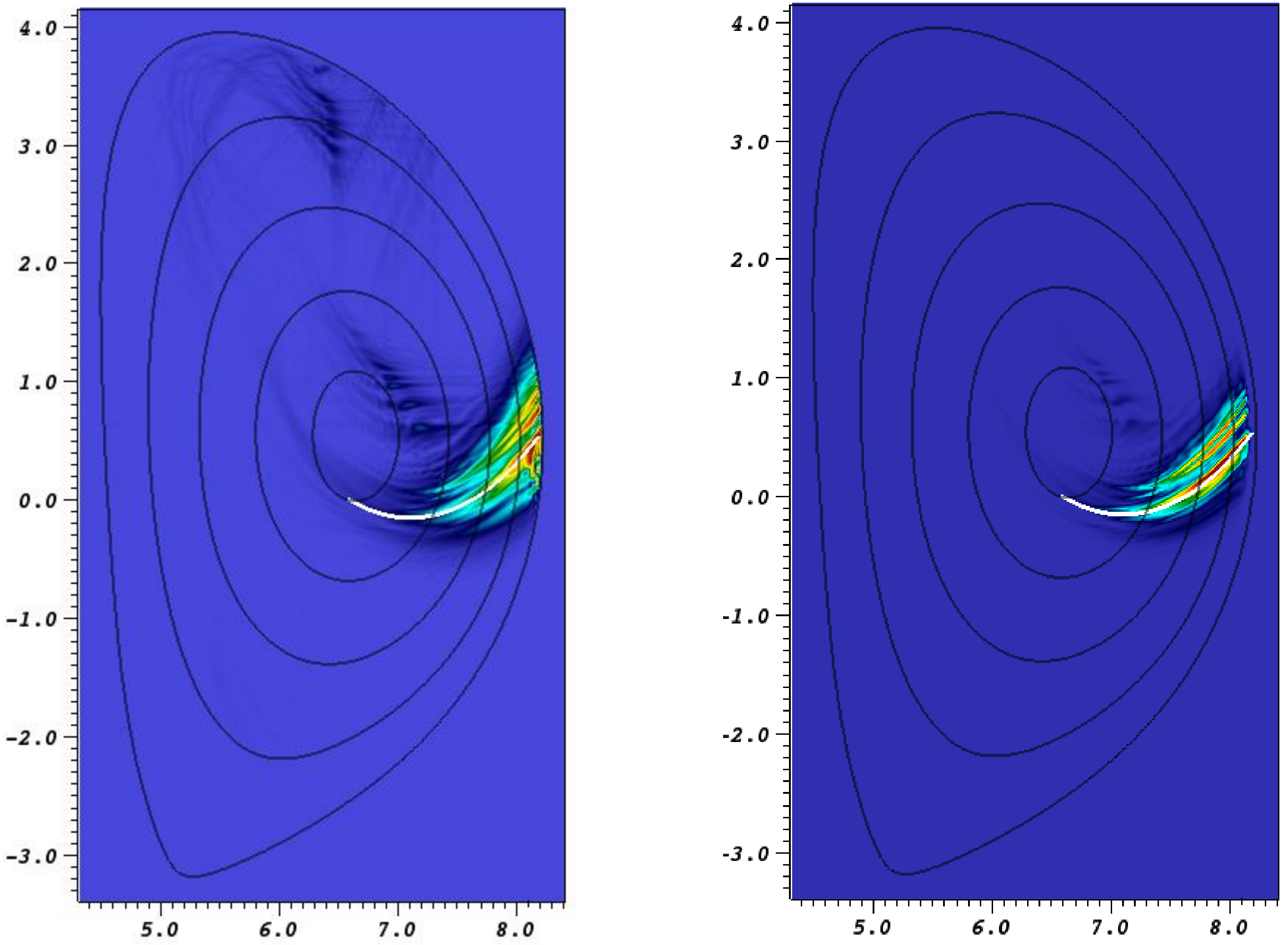
Summary of talk

- Comparison between AORSA and GENRAY will be shown for DIIID and ITER cases
  - good agreement in current and power absorption profiles in DIIID and ITER cases at $n_{||}$=3 at antenna between GENRAY and AORSA
  - Electron damping is dominant in all cases tried, but there is some ion absorption due to beam ion and alpha population at ITER
  - there may be some different fast ion absorption models, but this is not clear in current cases with low fast ion absorption (may require low $n_{||}$)
  - helicon current drive efficiency using “core ICRF physics models” looks promising

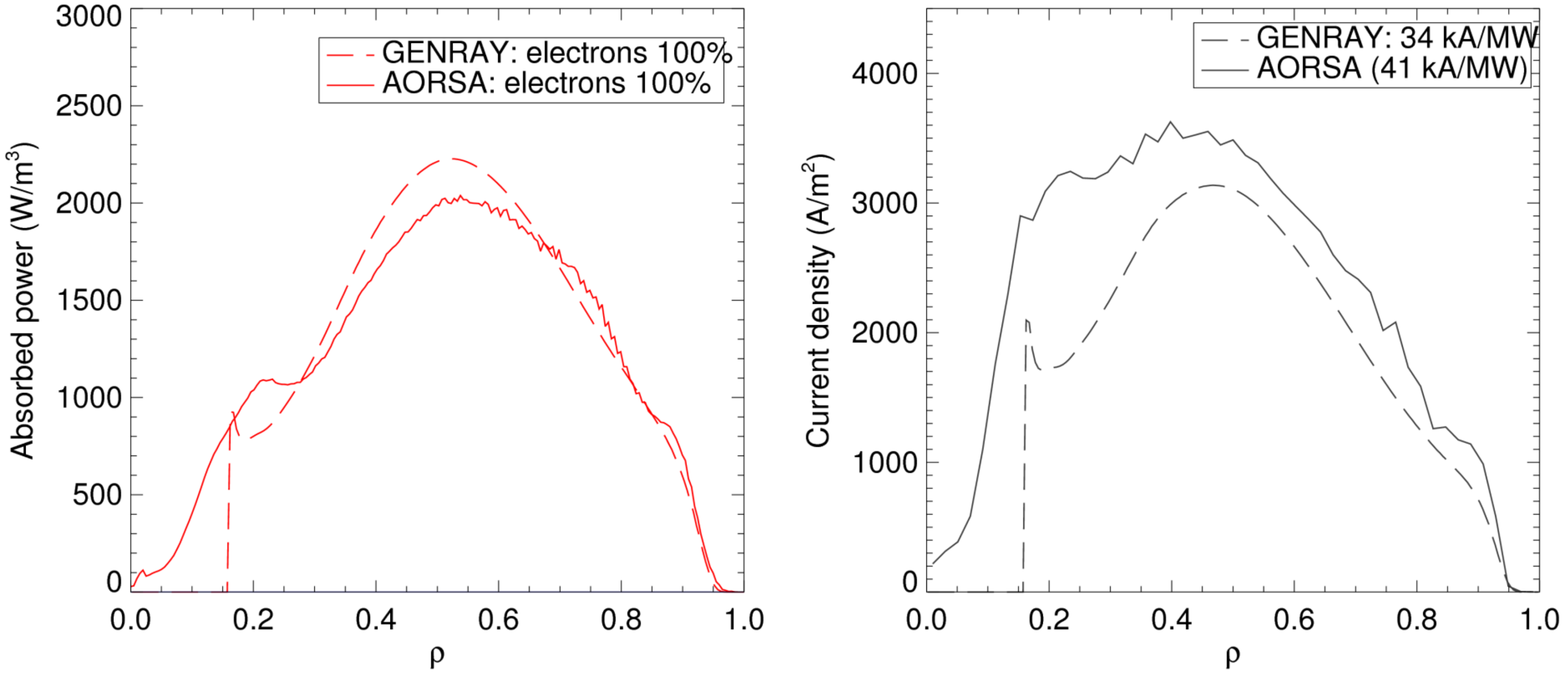
- Numerical challenges to AORSA simulations at ~ 30-50ω_{ci} are significant
  - significantly more modes needed due to the shorter wavelengths
  - new analytical Z function seems to significantly reduce numerical noise
  - Cases at lower $n_{||}$ still remain a challenge
  - inclusion of realistic SOL remains a numerical challenge

Backup slides

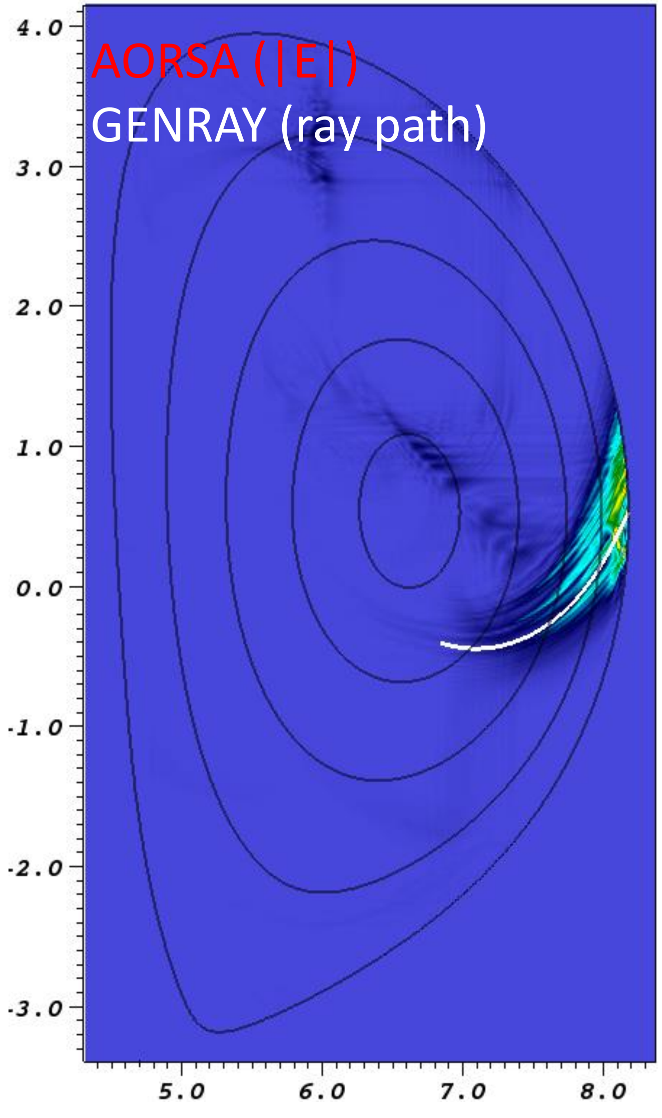
GENRAY and AORSA compare favorably for ITER at 500 MHz, no ions

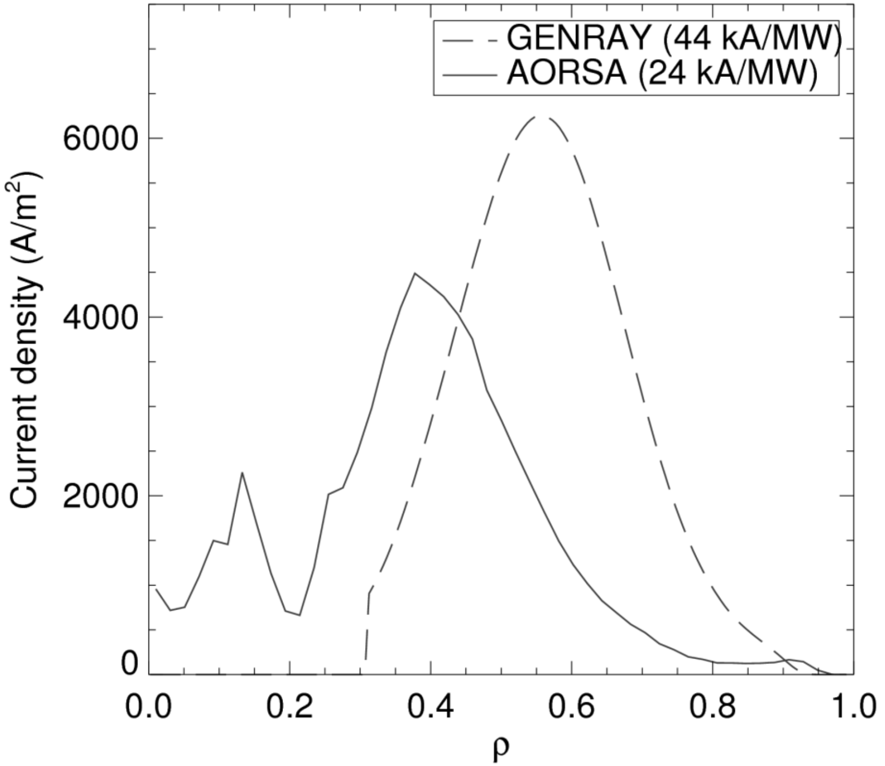


GENRAY and AORSA compare favorably for ITER at 500 MHz, no ions



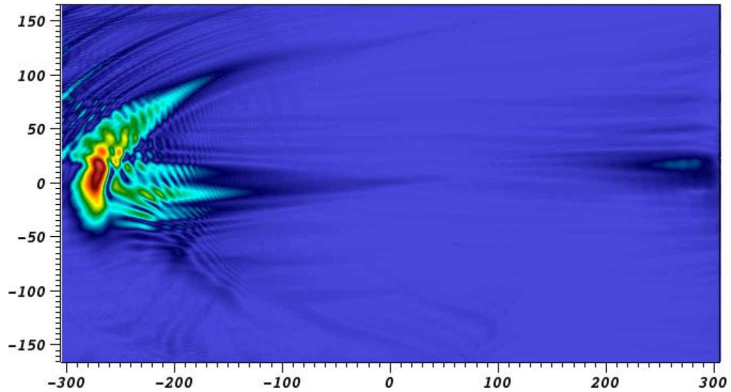
GENRAY and AORSA has different current drive efficiency for ITER at 750 MHz, seemingly due to effect of fast ions/alphas



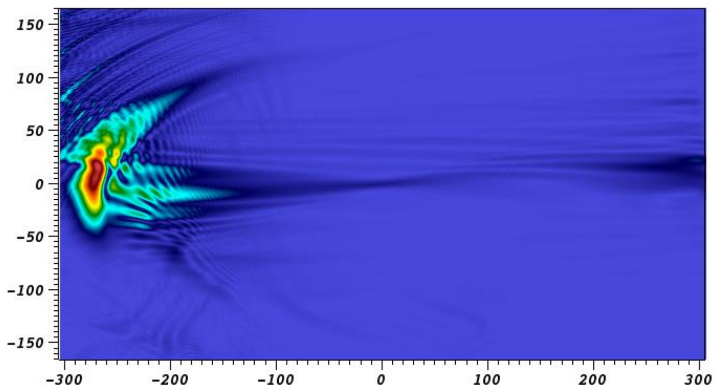


ITER 500 MHz n||=3 case, no ions

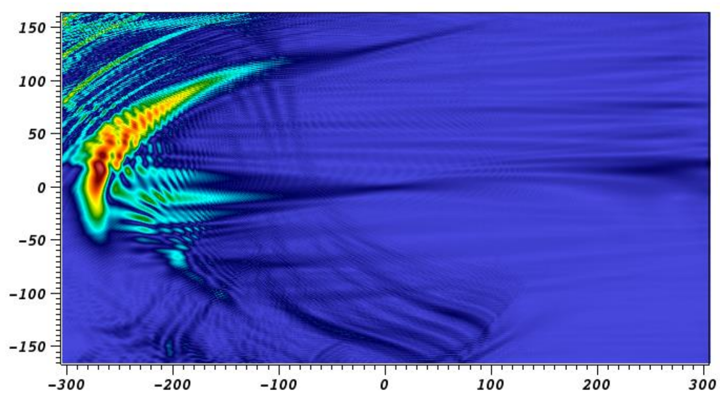
Eb



Ex



Ey



ITER 500 MHz n||=3 case, ions