Modeling of HHFW Current Drive Discharges on NSTX with Kinetic and Ray Tracing Codes

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ABSTRACT

Demonstration of high-power (> 4 MW) HHFW current drive has been one of the main goals of the recent NSTX experimental campaign. The aim is to create a high-T_e (>1.5 keV) target plasma first before RF power with a fast spectrum centered at $k_{||} = 3\ m^{-1}$ is applied, in order to maximize the CD efficiency. The driven current can be measured directly by the MSE technique or by inference from the measured loop voltage difference induced while the current is kept constant. In this paper, we examine ways to analyze the CD discharges using a set of kinetic (CQL3D) and ray tracing (CURRAY, GENRAY) codes. First, a detailed benchmarking of results from CURRAY and GENRAY is carried out for a set of standard discharges from a previous campaign at both 90^o and 45^o antenna phasing. The CQL3D/GENRAY package is then run to determine if quasi-linear diffusive effects play a significant role in typical NSTX plasma and RF parameter ranges. Finally, the influence of a back emf on the level of driven current in a constant current discharge will be assessed. The practicality of a CD efficiency table modified based on the adjoint technique will then be addressed.

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$ Work presented here has been slightly altered from what is contained in the abstract.

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Background

- The motivation for this work is to explore the kinetic aspect of current drive (CD) with high-harmonic fast waves (HHFW) on NSTX.
- There are two areas in which kinetic effects may be important:
  - High power HHFW (≤ 6 MW) may induce quasilinear diffusion in velocity space that alters linear local wave damping and current drive
  - During current ramp-up or during current drive experiment when the plasma current is held constant, the induced DC electric field can affect the electron distribution function so as to alter the wave damping and CD dynamics.
- Modeling of current transients during RF power switch-on necessitates the knowledge of $\partial j_{rf} / \partial E_{DC}$ in order to avoid numerical instabilities. [Dave Ignat]

Background (Cont'd)

- We propose to study these effects using the CQL3D kinetic code [Harvey, CompX] in conjunction with a ray tracing code (GENRAY, CURRAY).
- In Ignat's work for lower hybrid waves, he took advantage of the condition that $\square/k_{||}v_e >> 1$ to arrive at a simple integral expression for $j_{rf}(w)$. However, for the fast waves, $\square/k_{||}v_e$ □1-2, and a complete calculation will be required.
- We will like to explore the possibility of deriving a simplified "empirical" expression for the CD efficiency $j/p(E_{DC}, \square, \square, \square)$, or generate a table of j/p for use in the CURRAY code.
- Of course, there is always the possibility of incorporating the CQL3D with either GENRAY or CURRAY into the TRANSP analysis code.

Recent Development in FWCD Experiments

- In the recent HHFW experiments on NSTX, it was found that the power absorbed by the core plasma as a fraction of the launched power decreases as the launched toroidal wave-number $k_{||}$ is lowered, and completely vanishes at $k_{||} = 3\ m^{-1}$.

- Also, there is little evidence of interaction with the thermal plasma and beam ions when HHFW power is coupled into an NBI-heated NSTX plasma at these wavelengths.

- These and other observations have led to the conclusion that three

  edge processes may be partially or totally responsible. such as, and/or coupling to the RF sheaths.
  - parametric decay instabilities
  - turbulence scattering
  - Coupling to surface waves due to non-alignment of antenna current with magnetic field line

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OUTLINE

- **Status of HHFW kinetics studies:**
  - Benchmarking of GENRAY with CURRAY for four earlier HHFW CD discharges on NSTX

    [This is to ensure rigorous comparison between the linear CURRAY result and the kinetic CQL3D/GENRAY prediction.]

- **Comparison of CURRAY and AORSA (full-wave) code CD predictions with experimental data.**

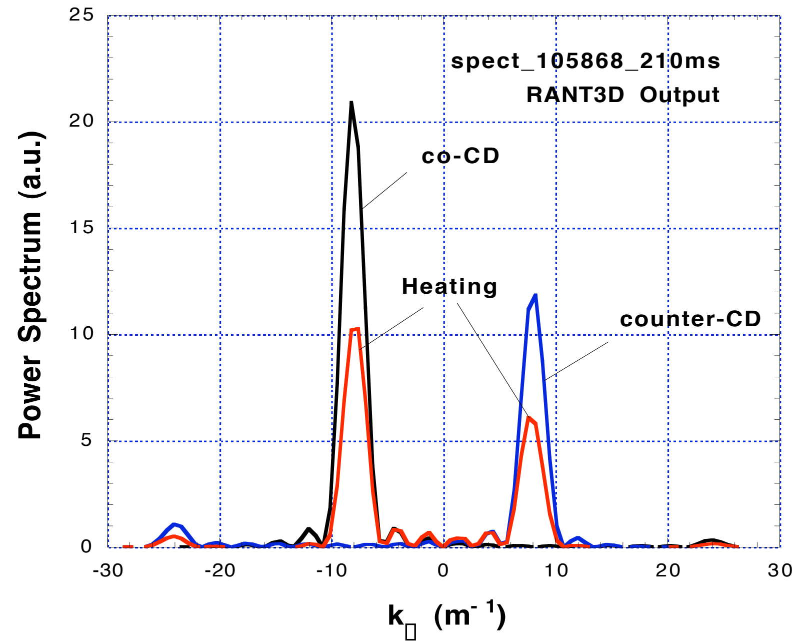
  [This is in response to Phil Ryan's oral paper on Monday.]

- **Summary and future work**

CD Antenna Power Spectrum

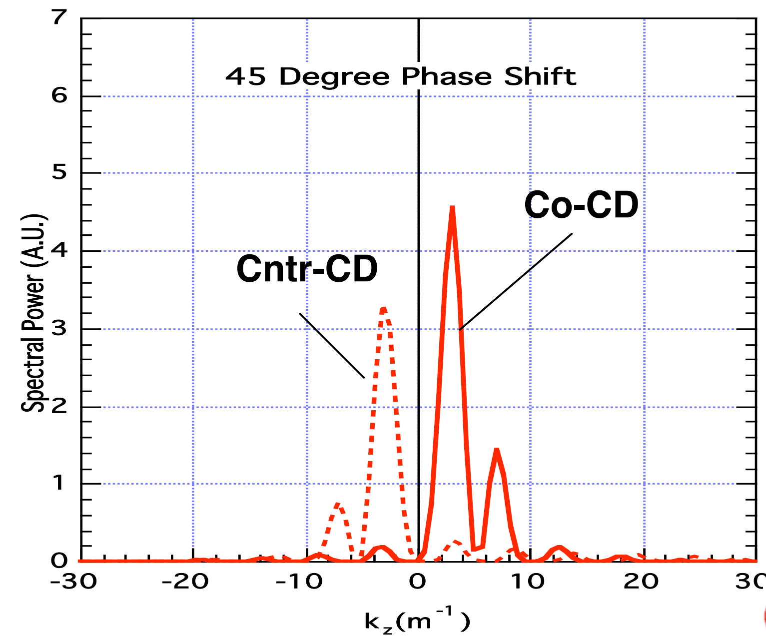
Slow spectrum:

- **Co-CD**: Phase shift = $-\pi/2$; peaks at $k_{\parallel} = -8\ m^{-1}$, $m = 1$
- **Cntr-CD**: Phase shift = $+\pi/2$; peaks at $k_{\parallel} = +8\ m^{-1}$, $m = 1$



Fast Spectrum:

- **Co-CD**: Phase shift = $-\pi/4$ Peak at $k_{\parallel} = -3\ m^{-1}$ $m = 0$
- **Cntr-CD**: Phase shift = $+\pi/4$ Peak at $k_{\parallel} = +3\ m^{-1}$ $m = 0$



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A Quick Comparison between CURRAY and GENRAY

	CURRAY	**GENRAY**
Frequency range	ICRF, LH	ICRF, LH, ECRF, EBW
Dispersion relation	hot electron, cold ion	cold plasma (used) other forms available
Damping	weak damping model all orders in $k_{\square}\ \square_i$	solves for Im($k_{\square}$) all orders in $k_{\square}\ \square_i$
CD efficiency	Ehst-Karney (used) adjoint available	Ehst-Karney (used) Fokker Planck CQL3D
Fast ion treatment	Maxwellian equivalent slowing down distribution	Maxwellain equivalent Fokker Planck CQL3D
Coupled Equilibrium	EFIT	EFIT
Plasma profiles	spline-fit of data analytic form	spline-file of data analytic form

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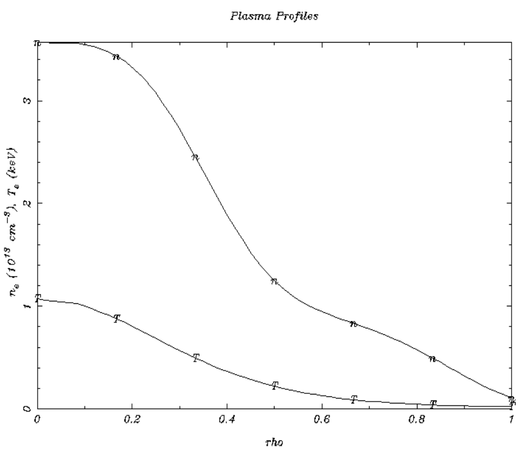
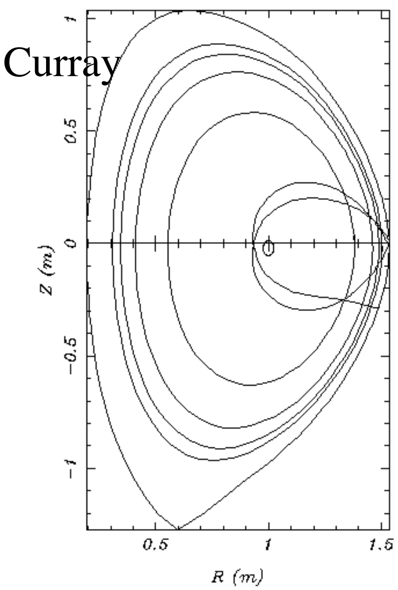
Comparison of Single Ray Trajectory
NSTX Shot 108903.00301

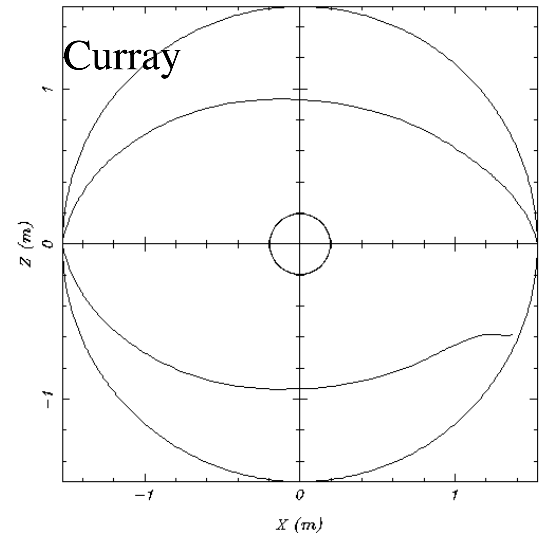
$T_i / T_e = 0.7$
$Z_{eff} = 3.25$
D : H : C : Cu =
0.93 : 0.046 : 0.02 : 0.0025

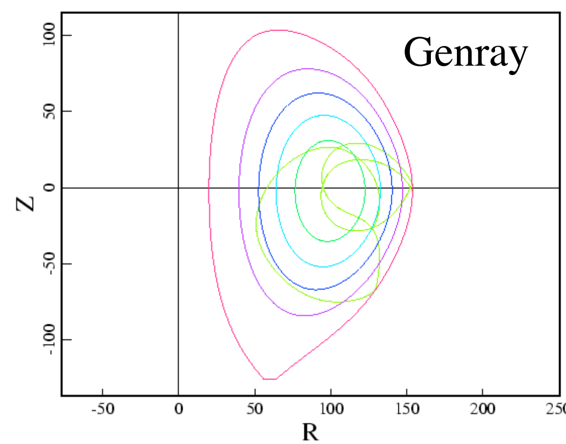


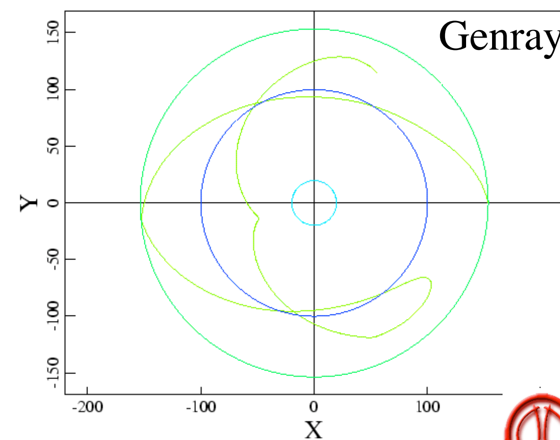
Cross section view



Top view



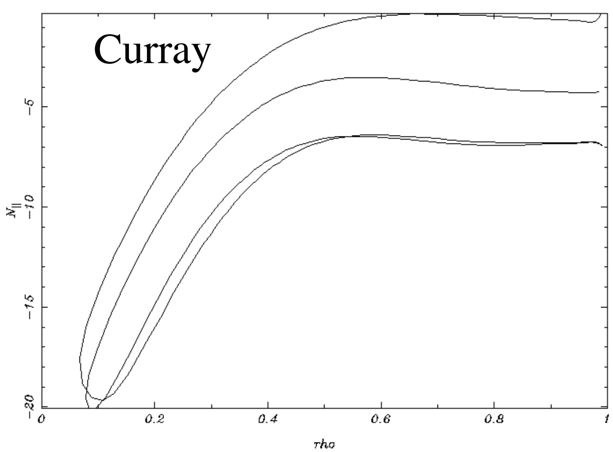


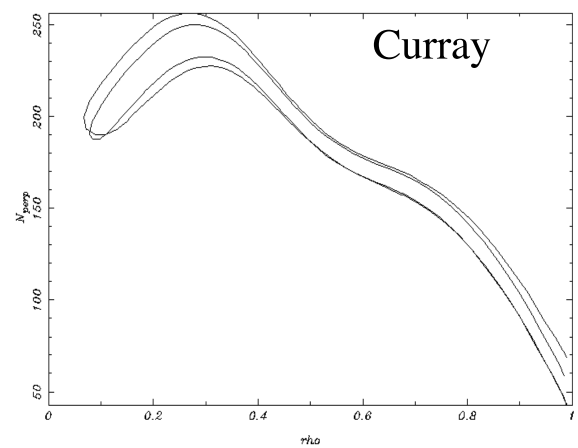


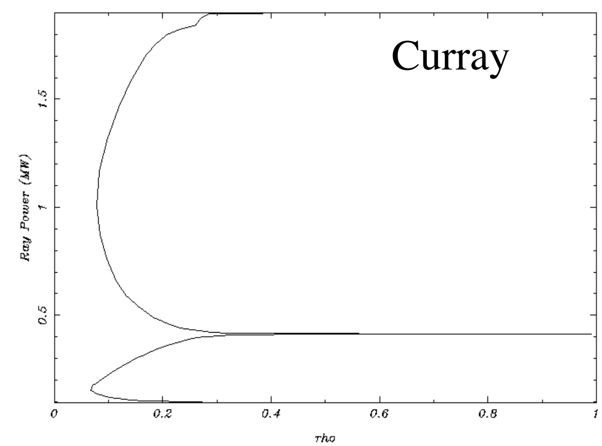
Comparison of Wave Dispersion and Damping

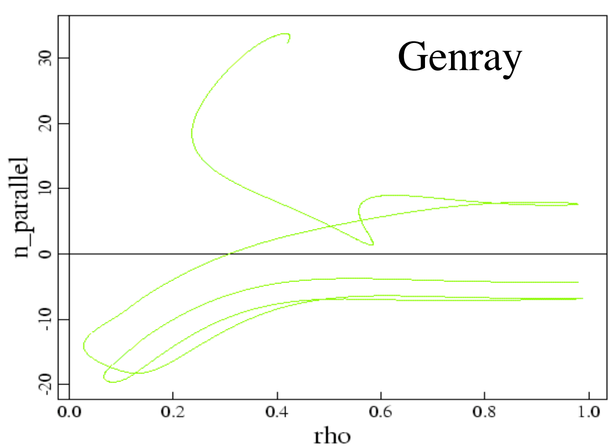
NSTX Shot 108903.00301

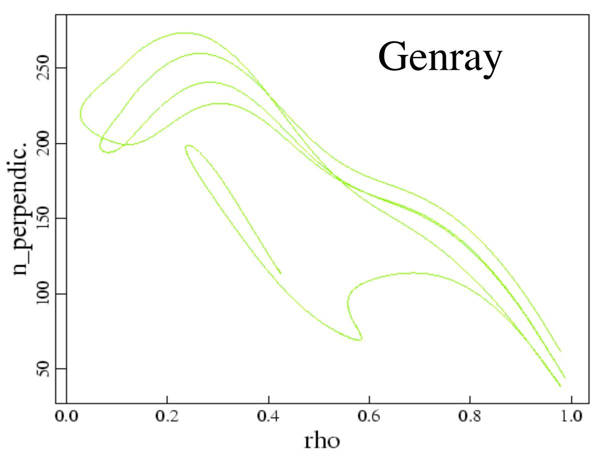
Parallel Wavenumber | Perpendicular Wavenumber | Power along ray

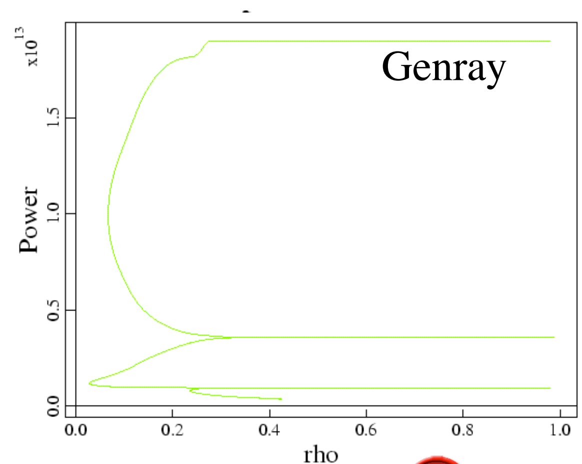






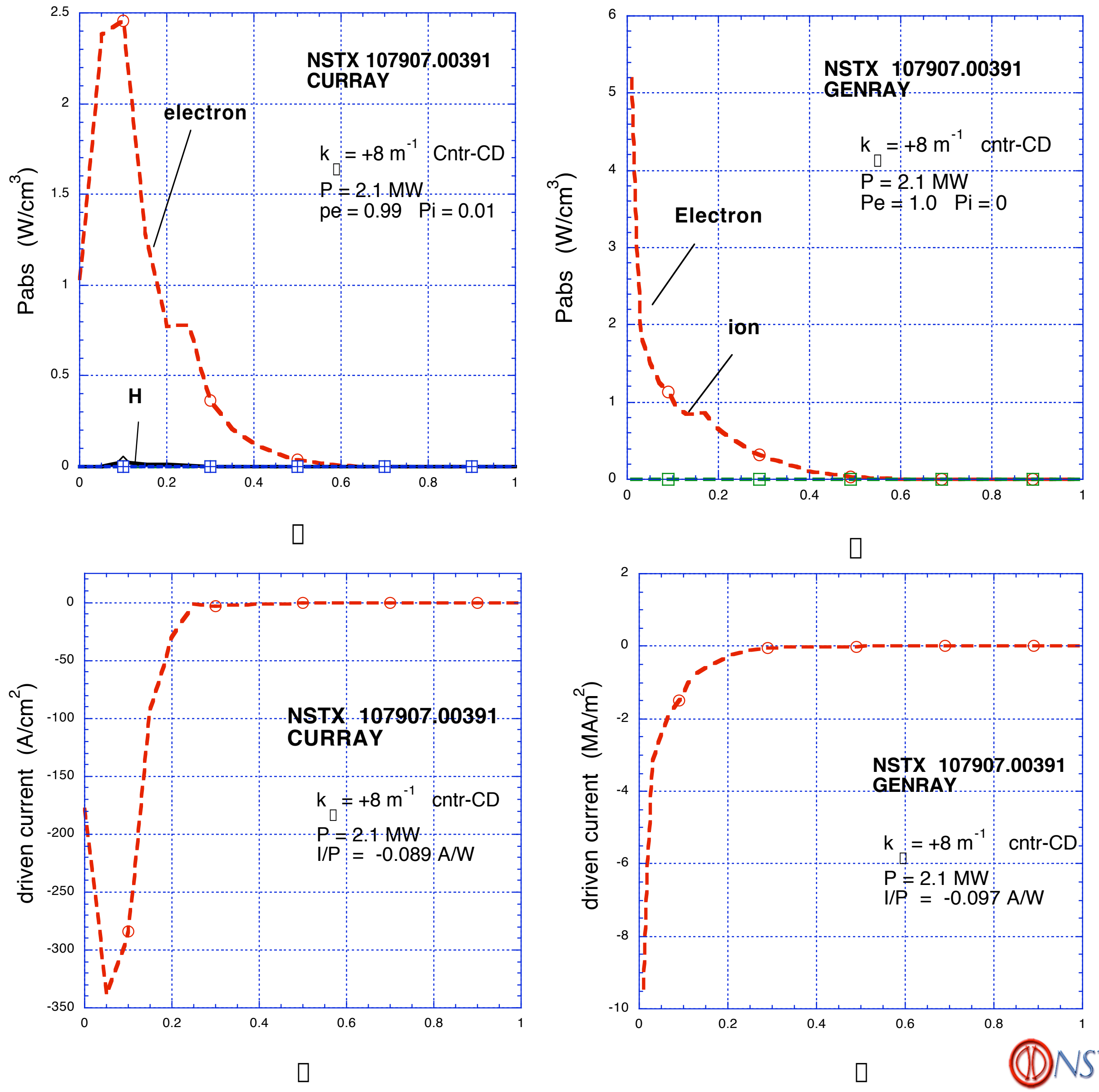






Comparison of Wave Absorption and Current Drive
for Shot 107907.00391

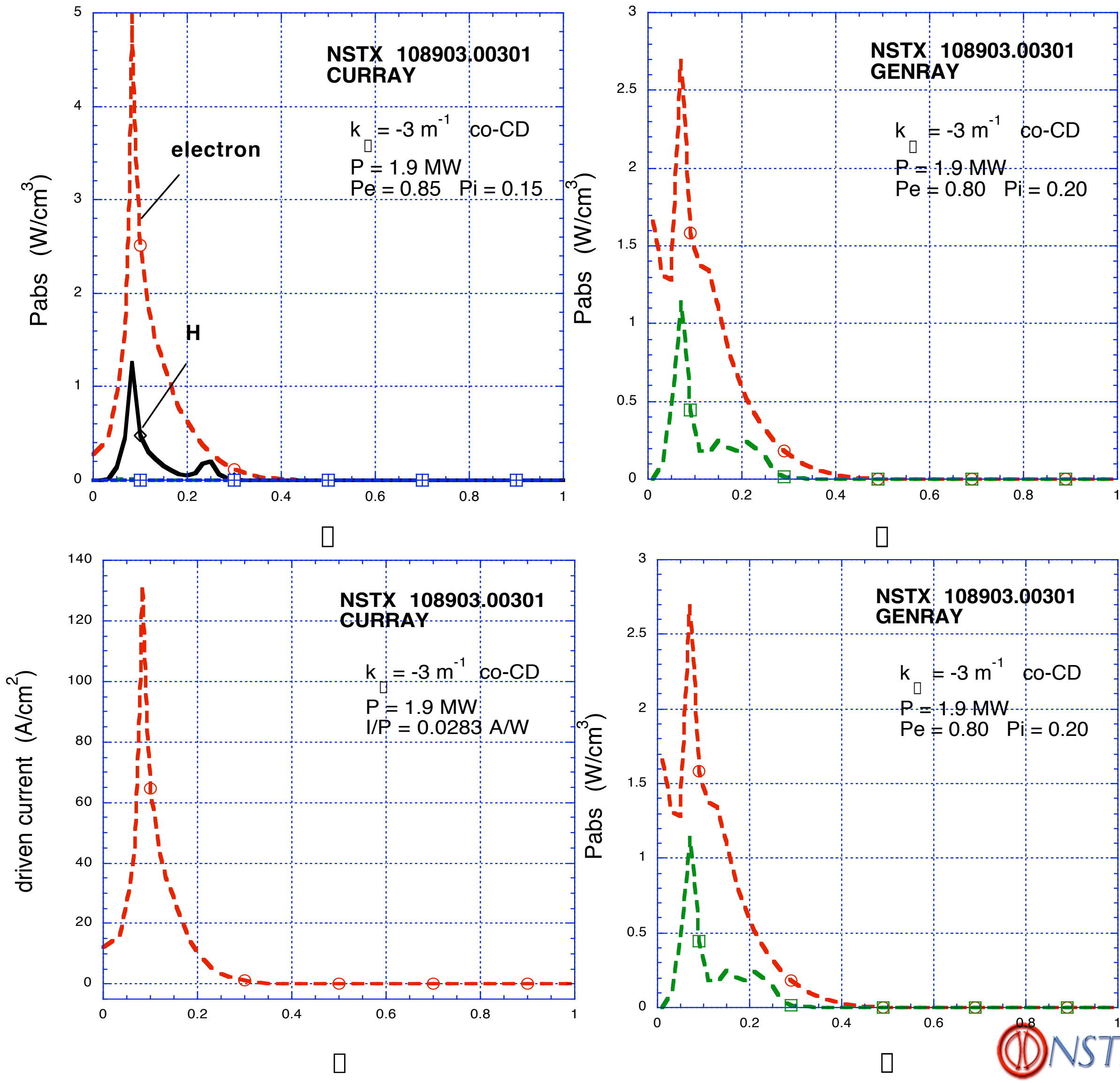
- Generally good agreement in absorption and j_{rf} profiles, except for slightly off-axis peaks in CURRAY.



Comparison of Absorption and Current Drive
for Shot 108903.00301

- Electron absorption profiles both peak at same location.
- Somewhat broader absorption and j_{rf} profiles for GENRAY, which also have ox-axis component.

Difference in damping?

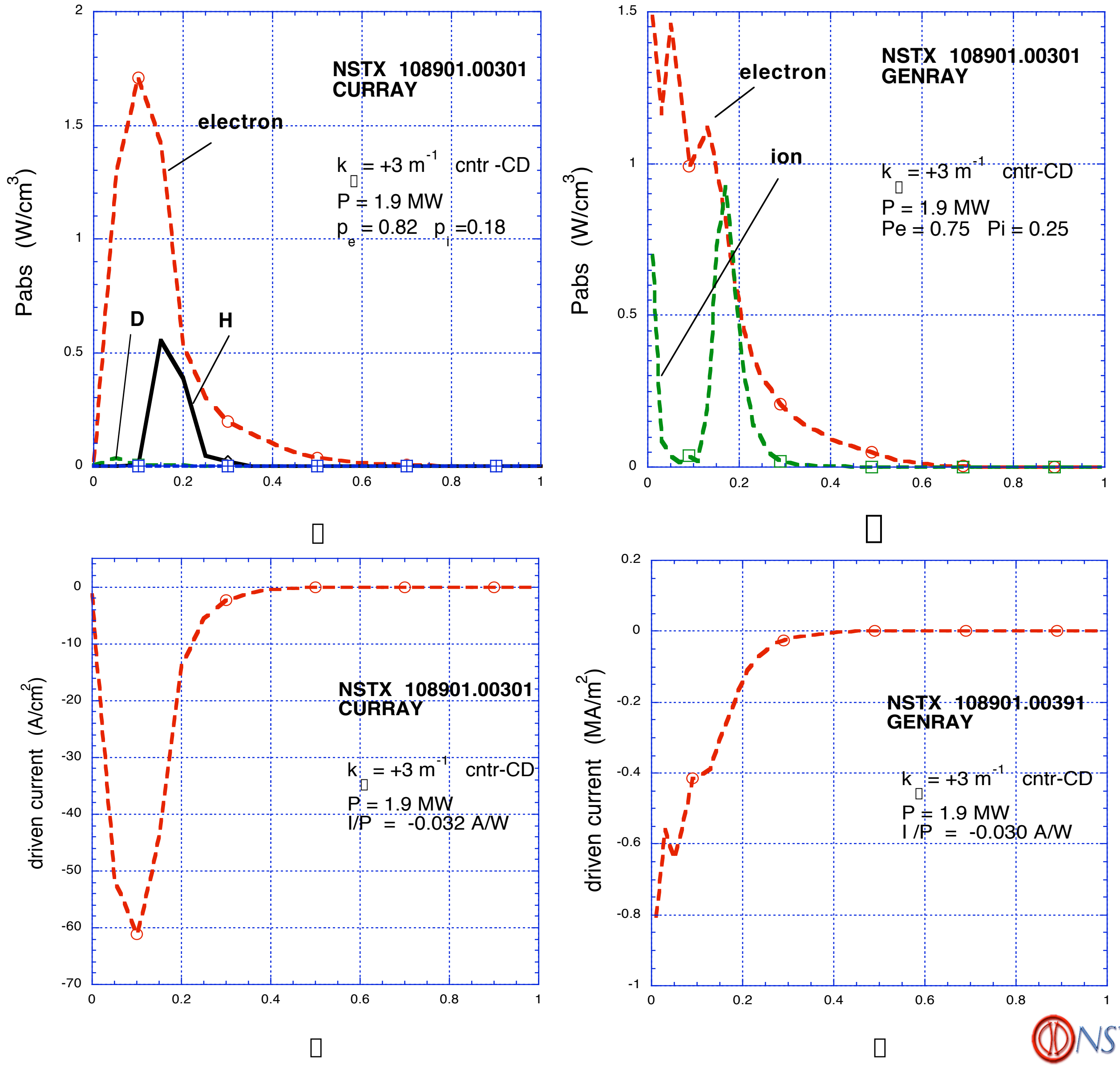


Comparison of Absorption and Current Drive
for Shot 108901.00301

- Peak electron absorption is located at different radii.
- Ion absorption profiles are also different.

Rays in CURRAY do not pass through axis, while those in GENRAY do.

This may be caused by differences in damping along rays.



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Summary of CURRAY and GENRAY Comparison

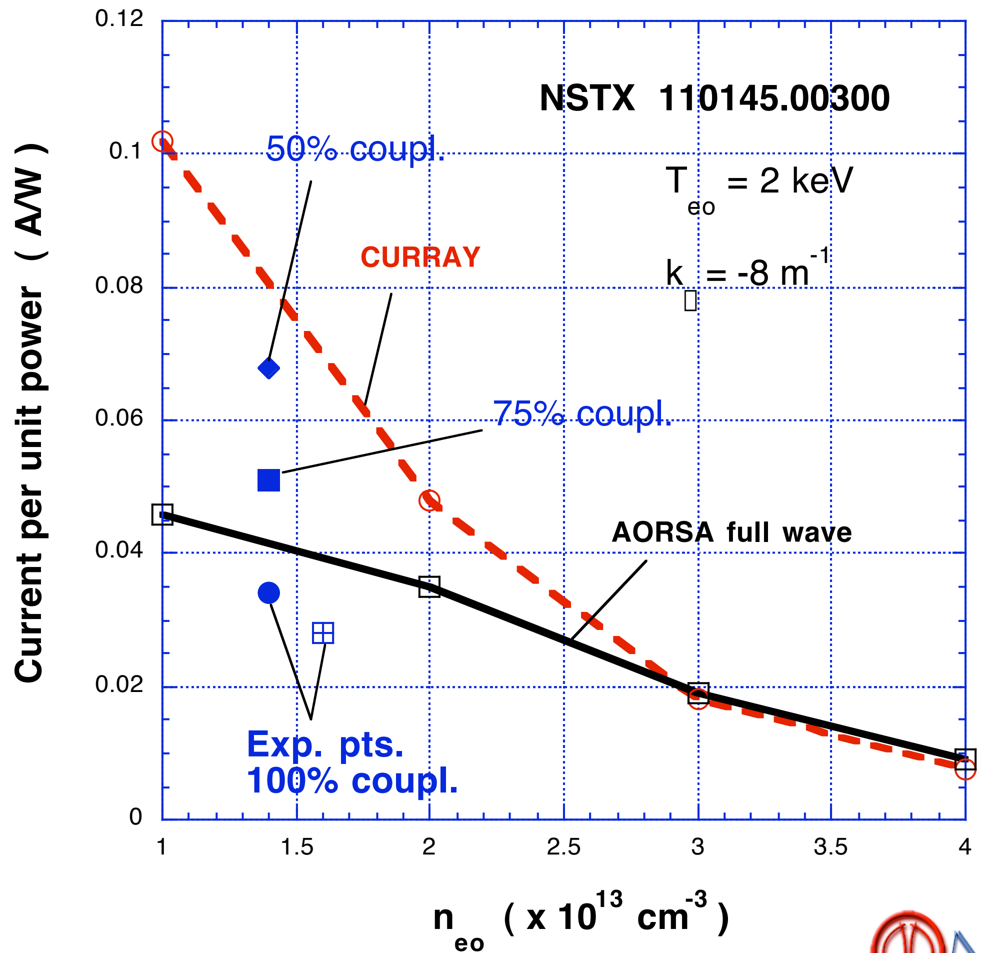
- Initial studies indicate the following global results of CURRAY and GENRAY for four NSTX discharge points :

$k_{\parallel}$ (m^{-1})	P_e / P		I/P (A/W)	
	CURRAY	GENRAY	CURRAY	GENRAY
-8 [co-CD]	0.99	0.99	0.072	0.099
+8 [cntr-CD]	0.99	1.0	-0.089	-0.097
-3 [co-CD]	0.85	0.80	0.028	0.060
+3 [cntr-CD]	0.82	0.75	-0.032	-0.030

- The partition of absorbed power between electrons and ions compares quite well, even though GENRAY give somewhat stronger ion absorption at lower $k_{\parallel}$.
- Reasonable agreement in CD efficiency is obtained for the counter-CD cases, but the results deviate for the co-CD cases.
- The difference in the electron peak absorption location is most likely caused by the deviation in ray paths for those rays carrying the bulk of the power. These may translate into difference in $k_{\parallel}$ evolution, damping location and resultant driven current. Intrinsic difference in the damping model may also be a cause.

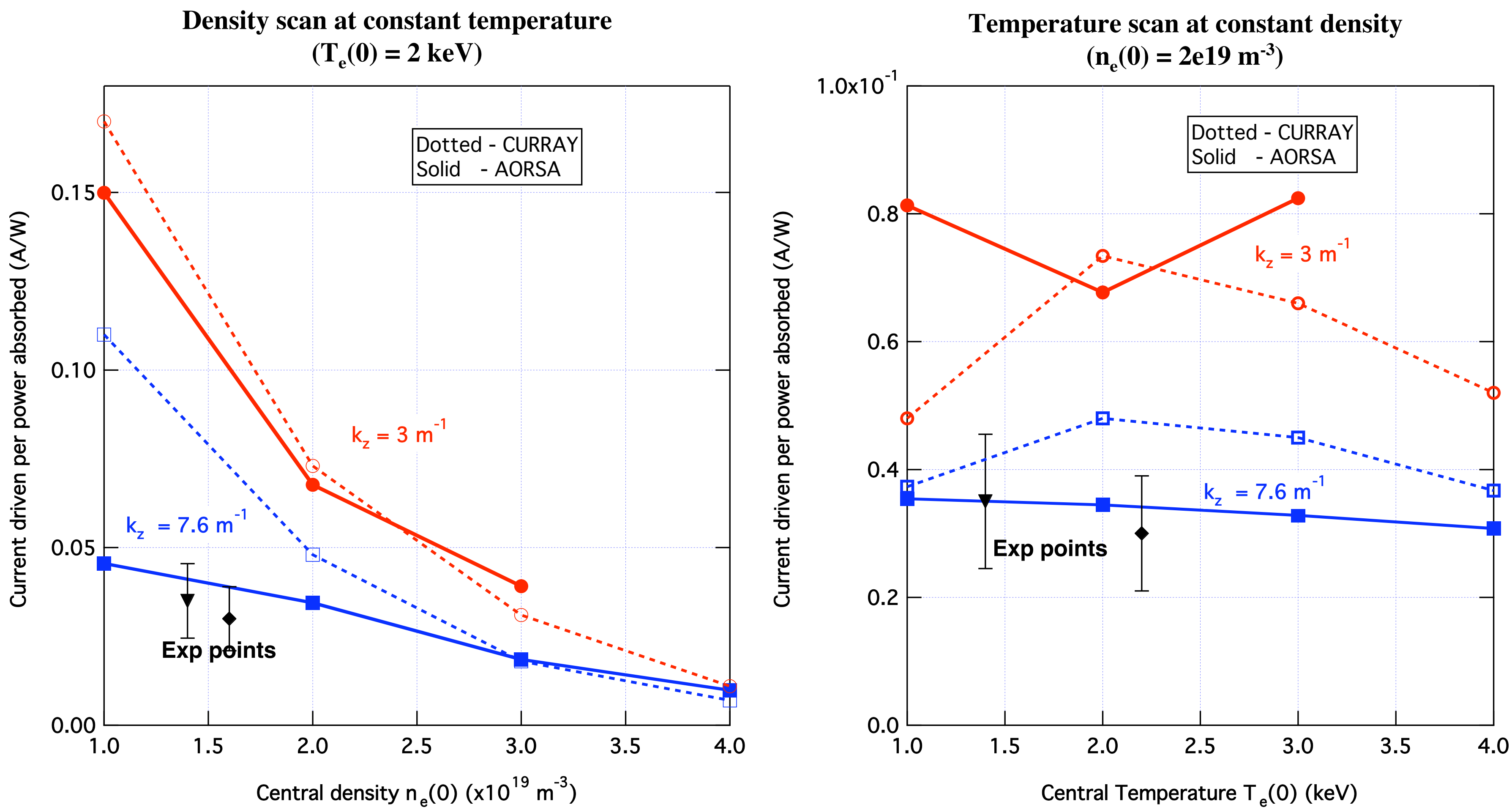
Comparison of CURRAY and AORSA Predictions with Experimental Data

- CURRAY ray tracing prediction of I/P scales inversely with density, and becomes higher than AORSA full wave prediction as $n_{eo} < 2.5 \times 10^{13}$ cm^{-3}.
- Experimental data points with 100%, 75% and 50% assumed core coupling efficiency are plotted, and are in general agreement with predictions.



Full-wave code and ray tracing calculations both predict better CD efficiency for 3 m^{-1}

Scaling study based on T_e, n_e profiles from shot 110145, T_i/T_e = 0.7, D:H::0.96:0.04



CURRAY (Mau) and AORSA (Jaeger) calculations

Summary

- It is argued that rf kinetic effects may be non-negligible in the presence of high-power HHFW heating and/or during RF current ramp-up at low densities.
- A plan is laid out to make use of the CQL3D/GENRAY package to study these effects, and incorporate them into CURRAY for simulating plasma discharges.
- Initial comparison between CURRAY and GENRAY for four HHFW CD discharges show generally good agreement in global heating results but some differences in CD results that need to be sorted out. There are also minor discrepancies in the absorption and CD profiles that need further investigation.
- CURRAY and AORSA CD predictions show good agreement at high densities ($n_{eo} > 2.5 \times 10^{13}$ cm^{-3}), but deviate at lower densities.
- True comparison of experimental data to code predictions requires accurate knowledge of the fraction of RF power coupled to the plasma core.

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Future Work

- The first task is to pinpoint the causes for the differences between CURRAY and GENRAY results, and make appropriate rectifications.
- Use CQL3D/GENRAY to evaluate if quasilinear diffusion plays a role in HHFW damping and CD in NSTX discharges and at what power level.
- Include a DC electric field in CQL3D/GENRAY to elucidate the its effect on damping and CD in typical NSTX parameter regimes.
- Devise an algorithm to include these effects into CURRAY for time-dependent discharge simulations and analysis.
- More detailed comparison between CURRAY and AORSA CD predictions at low densities by comparing plasma profiles used, absorption profiles and driven current profiles.
- **The most important task is to resolve the issue about partial coupling of RF power to the core at low parallel wave numbers.**

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