QP1.011 HHFW Power Deposition Modeling for NSTX Experiments*

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The physics of RF heating and current drive at high harmonics of the majority ion cyclotron frequency (>10) in high beta plasmas is being explored on NSTX. Though the plasma density and temperatures in NSTX are comparable to those of conventional tokamaks, the magnetic field is an order of magnitude smaller, resulting in high dielectric constants for the high harmonic fast waves (HHFW). Furthermore, the HHFW perpendicular wavelengths are small compared to the ion gyroradius, so that the finite Larmor radius (FLR) assumption used in many RF modeling codes is violated. Transit-time magnetic damping of the waves by electron is predicted to be strong for moderate ion temperatures in this regime[1]. In recent experiments[2,3], electron temperatures up to ~ 3.5 keV have been measured with RF input power up to ~ 4 MW applied at 30 MHz in NSTX plasmas. Radial power deposition profiles predicted by ray tracing codes and 1D and 2D kinetic full wave models will be compared for NSTX parameters. Benchmarking of the codes against measured power deposition profiles will be discussed

[1]M. Ono, Phys. Plasmas 2(1995) 4075.

[2]See contributed oral by J.R. Wilson et al, this conference.

[3]See contributed oral by B. P. LeBlanc et al, this conference

* Work supported by USDOE Contract #DE-AC02 -76CH03073

Six Different Codes Will Be Compared for NSTX Data

Two 2D - ray tracing models: offer fastest analysis method but subject to WKB constraints

- **HPRT** hot electron - cold ion ray paths; WKB full hot plasma absorption model; *2D* EFIT equilibrium; spline fits of measured profiles.

- **CURRAY** hot electron - cold ion ray dispersion relation; WKB full hot plasma absorption with order reduction scheme for $k_\perp$; *2D* EFIT equilibrium; spline fits of measured profiles.

One integrated 2D-ray tracing /Fokker Planck model: offers capability to self-consistently calculate power deposition with co-resonant HHFW and NBI:

- **CQL3D /GENRAY** hot or cold plasma ray paths; *2D* EFIT with polynomial fits to profiles; absorption calculated for all harmonics with 2D-vel / 1D-rad Fokker Planck code (zero banana width, self-consistent NBI and HHFW).

Six Different Codes Will Be Compared …………………..

***Two 2D full wave kinetic models**: offer self-consistent treatment of wave propagation and power absorption, including physical optics effects, but subject to convergence difficulties in some regimes*

- **TORIC** — ***2D*** **full wave hot plasma, FLR approximation used;moments description for equilibrium; polynomial fits of measured profiles.**
  - > *FLR approximation offers compromise between speed of ray tracing and cpu demands for self-consistent all orders wave propagation and absorption*
- **AORSA-2D** — ***2D*** **full wave hot plasma, no FLR approximation; analytically specified equilibrium and gaussian profiles.**
  - > *offers most accurate and self-consistent 2D treatment of wave propagation and absorption to all orders in the ratio of the ion gyroradius to the perpendicular wavelength*

***One 1D full wave kinetic model**: offers all-orders estimate of strength of absorption processes but neglects potentially important 2D effects*

- **METS** — ***1D*** **full wave hot plasma, no FLR approximation; polynomial fits for profiles; $B_T \sim 1/R$; $|B|$ includes B_p specified through q profile.**
  - > *avoids resolution difficulties of 2D codes*
  - > *provides test bed for improved absorption models, such as self-consistent effects of non-Maxwellian particle velocity distributions*

Unique and Important Features of HHFW Heating

NSTX

- **densities and temperatures in ST comparable to conventional tokamak but B field is an order of magnitude smaller so dielectric constant is high**

- **Using $\omega \sim k_\perp V_A \sim N\Omega_{ci}$ and $v_{th} \sim \rho_i \Omega_{ci}$ find:**

  $k_\perp^2 \rho_i^2 \sim N^2 \beta >> 1$ in an ST (FLR questionable)

  Note potential ion absorption occurs for high harmonics

- **Using $\omega \sim k_\perp V_A \sim N\Omega_{ci}$ find:**

$$\frac{\lambda_\perp}{a} \approx \frac{0.45}{N\ a} \frac{\sqrt{A_i}}{Z_i} \frac{1}{\sqrt{n_i / 10^{19}}} << 1$$

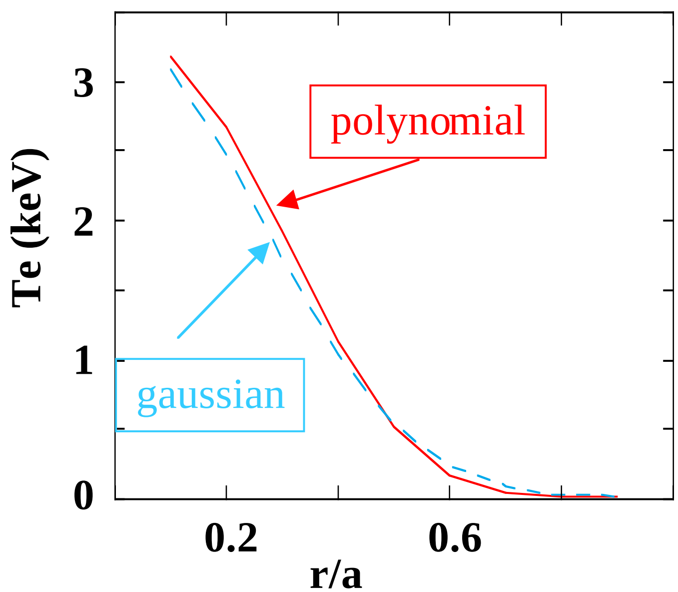
so WKB may be ok for propagation except near cyclotron harmonics?

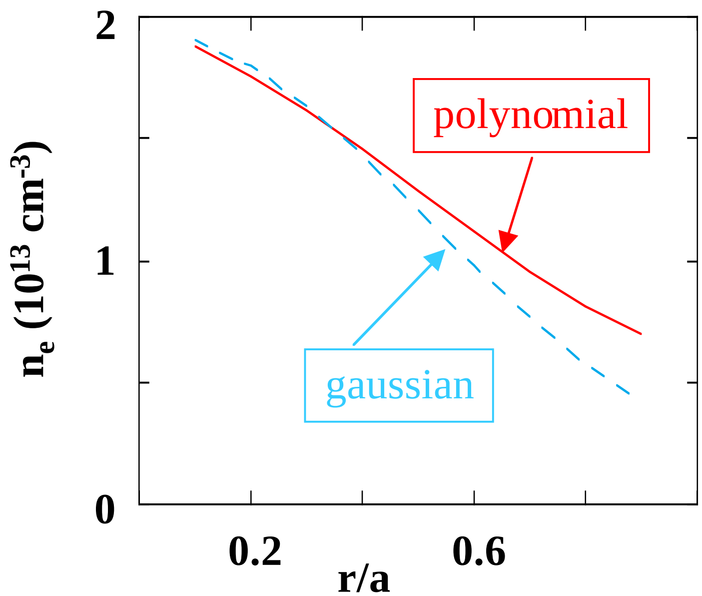
- **Plasma β is high so electron TTMP damping is strong relative to conventional tokamaks**

- **$B_p \sim B_T$ so sheared 2D equilibrium likely to be important**

NSTX Test Case I: High Te observed with 2.4 MW HHFW

Shot #105830 @ 0.193s





η_D = 0.705
η_H = 0.037
η_C = 0.043
Z_{eff} ~ 2.29

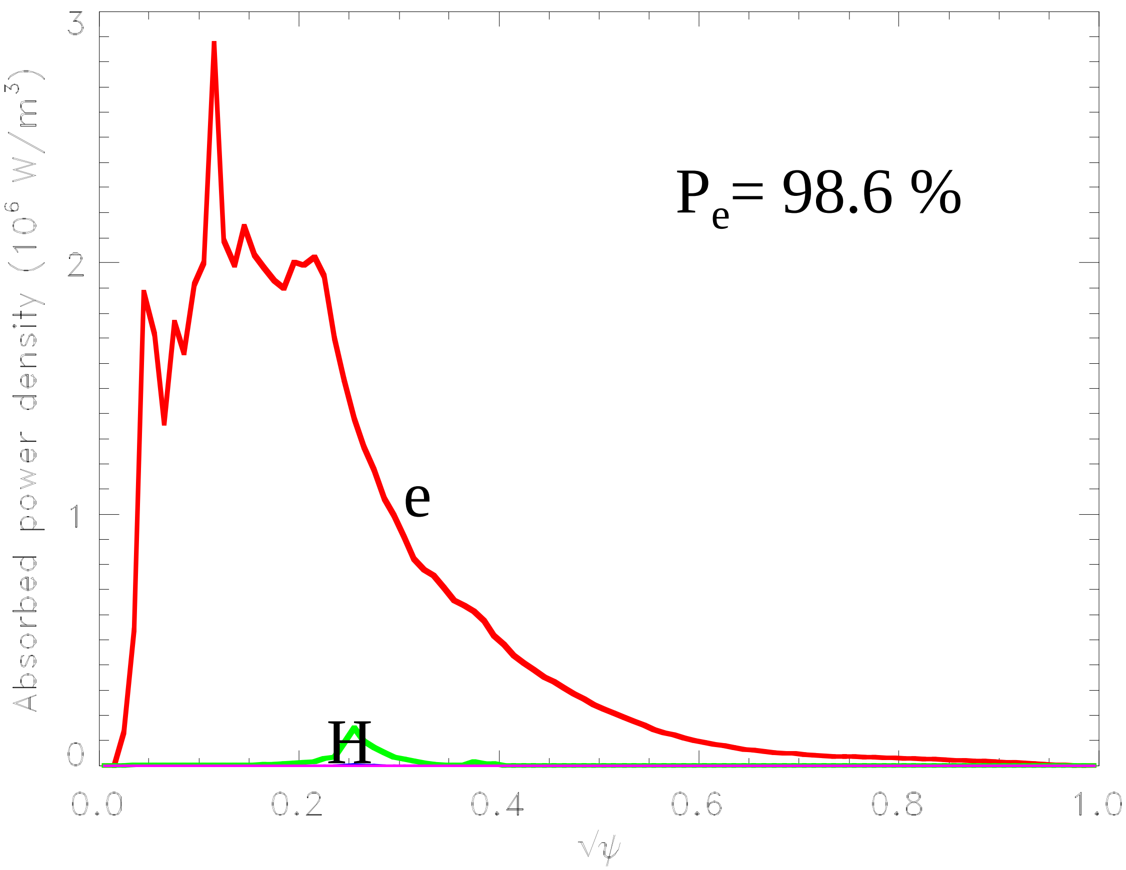
f = 30 MHz | **P_{rf} =2.4 MHz** | **$k_{//,A}$ ~ 14 m^{-1} or N_ϕ = 24**

B_T ~ 0.446T @ R= 99 cm | **"r_{minor}" = 62 cm** | **I_p = 766 kA**

n_{e0} ~ 1.94e13 cm^{-3} | **T_{e0} ~ 3.32 keV** | **T_i ~ 0.68 * T_e**

HPRT Predictions for HHFW Heating in NSTX (Shot 105830)

Shot 105830   Time 193 ms

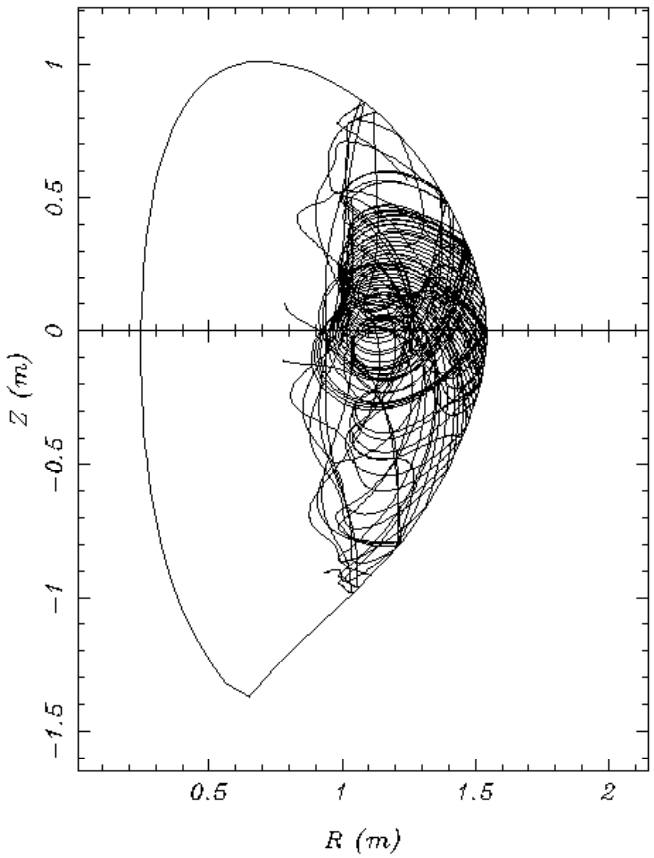


dominant on-axis electron heating

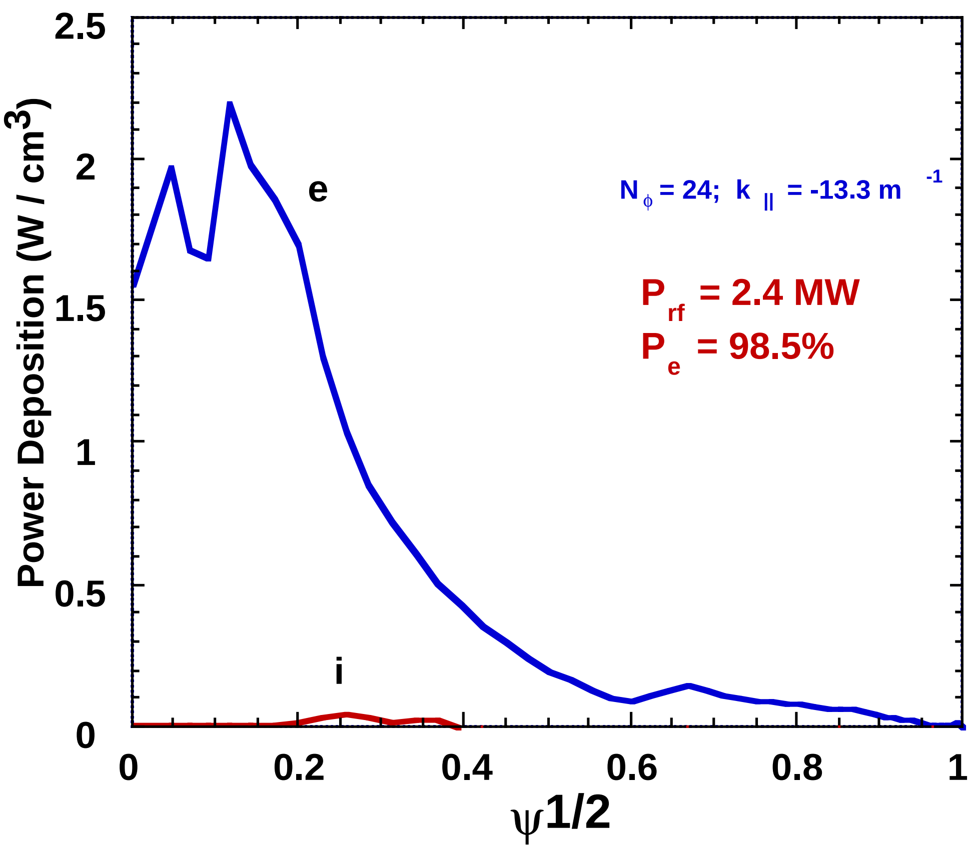
Rosenberg

CURRAY Predictions for HHFW Heating in NSTX (Shot 105830)

- NSTX shot : 105830_0193
- 25 rays along antenna poloidal extent, all starting with $k_{||} \sim -13.3\ m^{-1}$
- 98.5% of power goes to electrons.



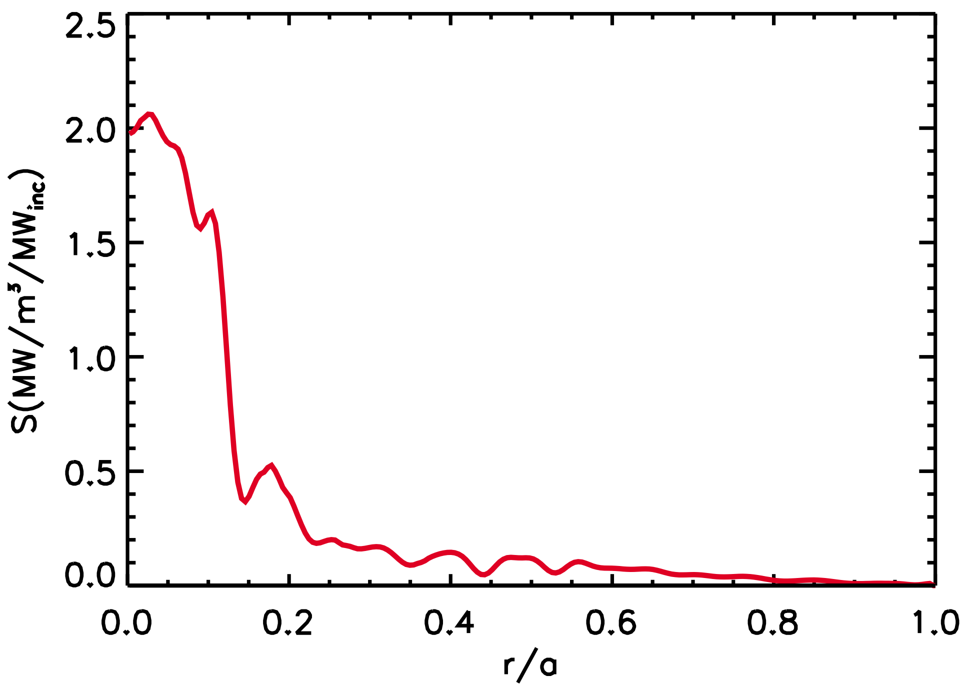
absorption requires a few passes of rays across plasma



dominant on-axis electron heating

T.K. Mau

TORIC Predictions for HHFW Heating in NSTX (Shot 105830)



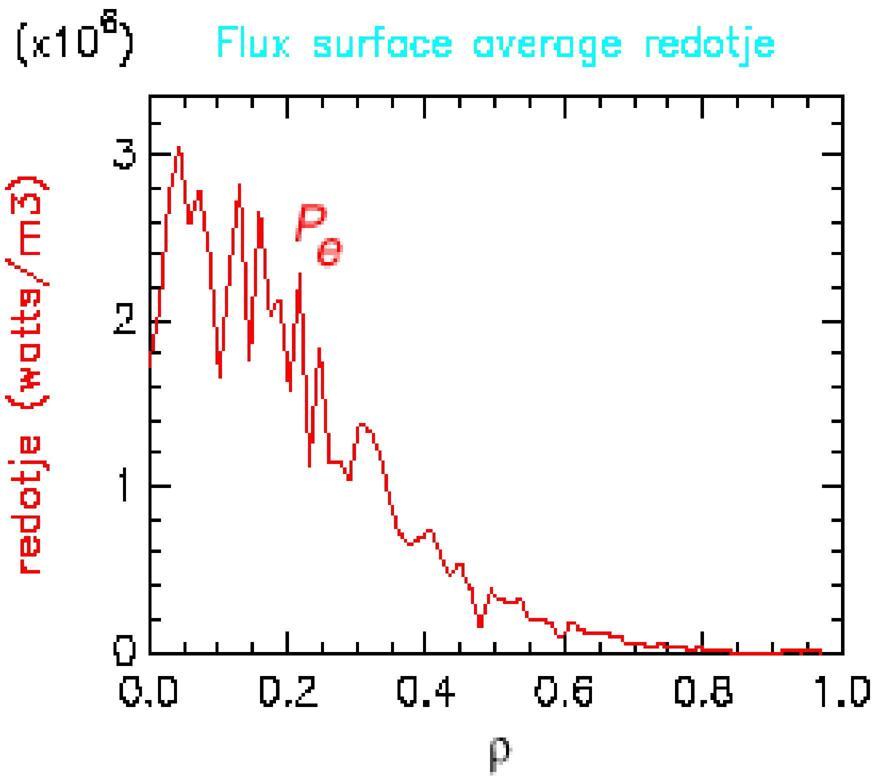
dominant on-axis electron heating

100% of HHFW power absorbed by electron Landau damping and TTMP

AORSA Predictions for HHFW Heating in NSTX (Shot 105830)

NSTX

NSTX (shot #105830) with 3.7% H in D plasma with *Te* = 3.32 keV and *Ti* = 2.25 keV
(140 × 140 modes in *x* and *y*, and 20 cyclotron harmonics) P_rf = 2.4 MW



2001 DPP-APS

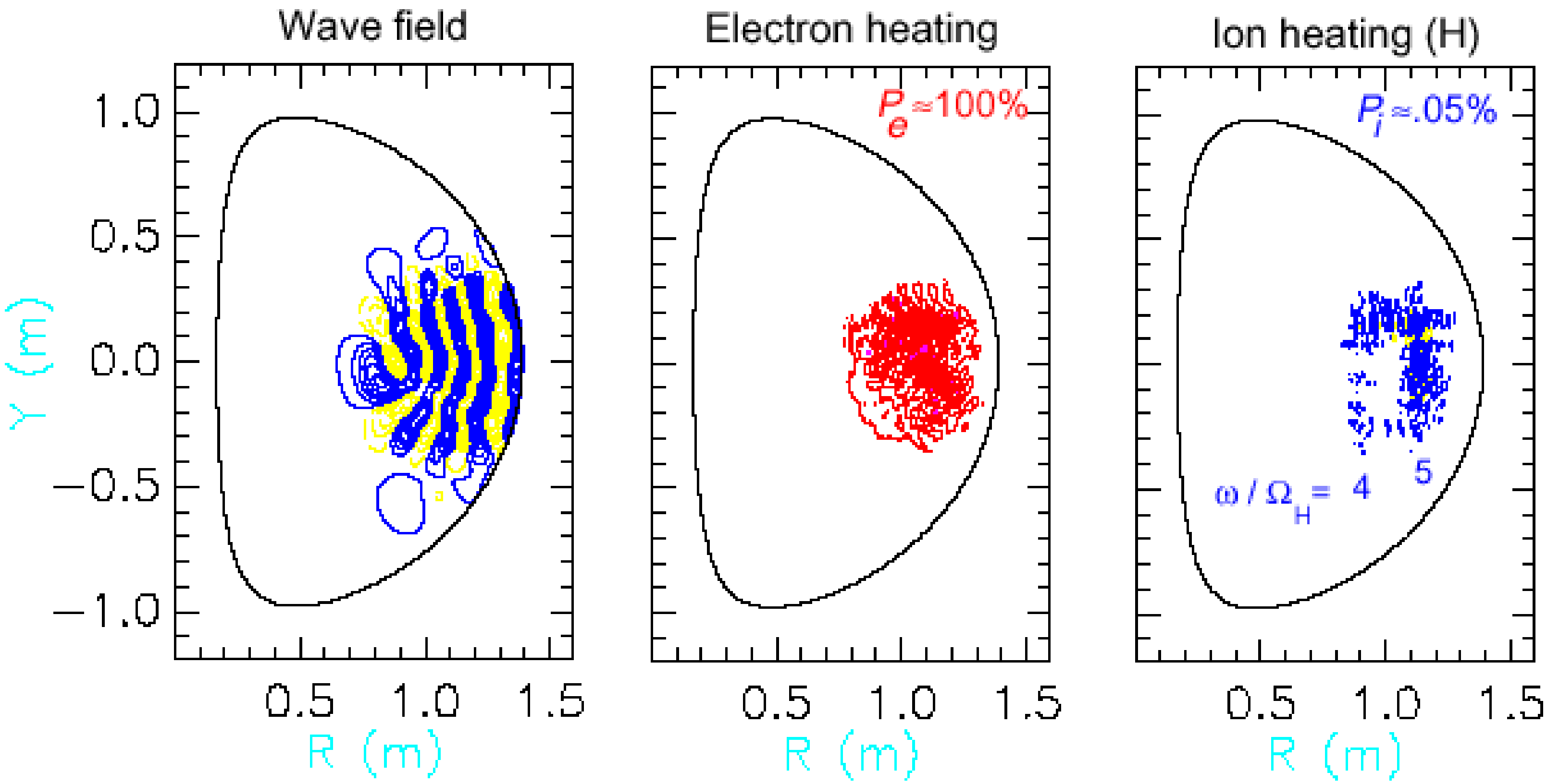
dominant on-axis electron heating

ornl

Jaeger, Batchelor, and Berry

AORSA 2D HHFW full wave fields qualitatively consistent with WKB ray paths

NSTX



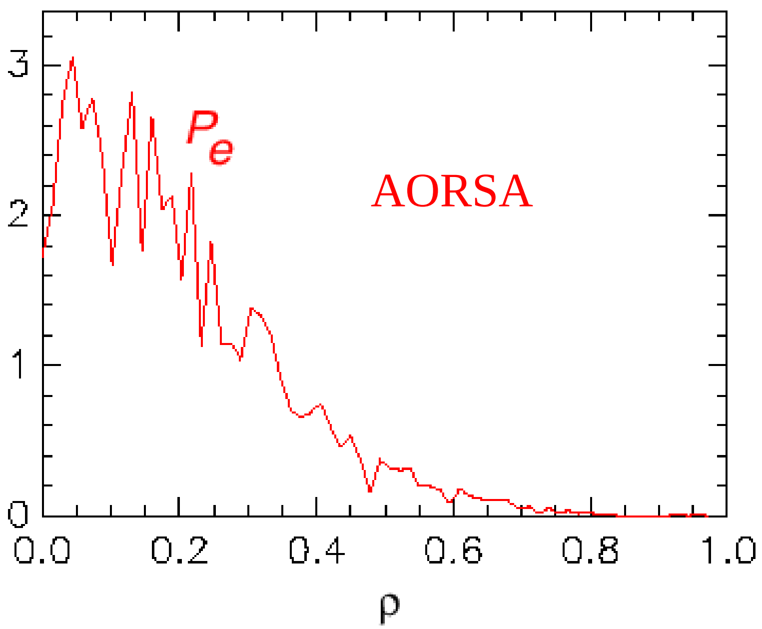
field structure consistent with relatively strong single pass damping

electron absorption structure consistent with ray paths

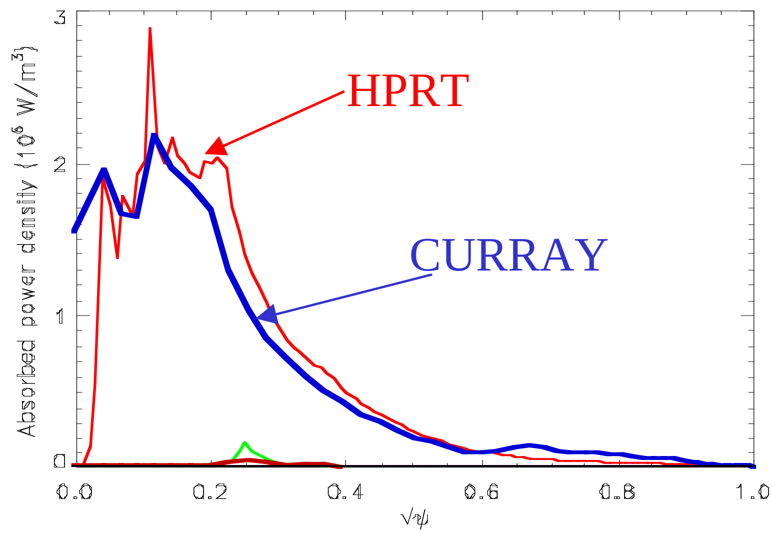
“no” ion absorption

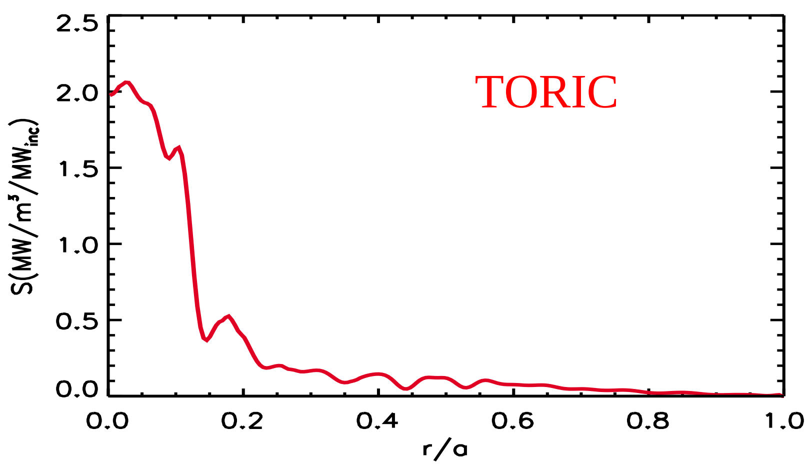
Excellent agreement found in this regime between ray tracing codes and 2D FLR and all-orders full wave codes for HHFW test case

dominant on-axis electron heating predicted by 2D codes



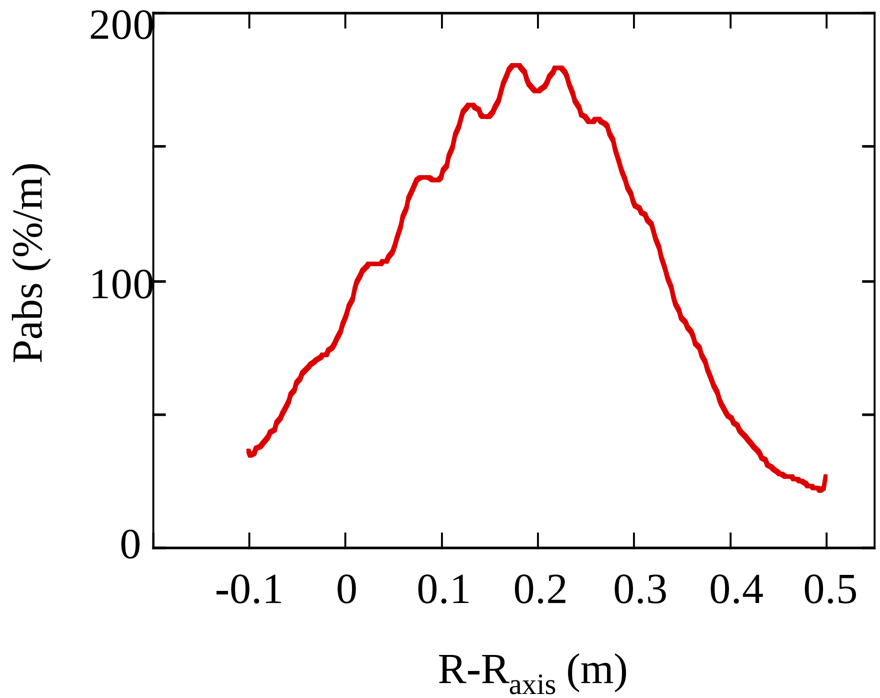
figures drawn to same physical scale

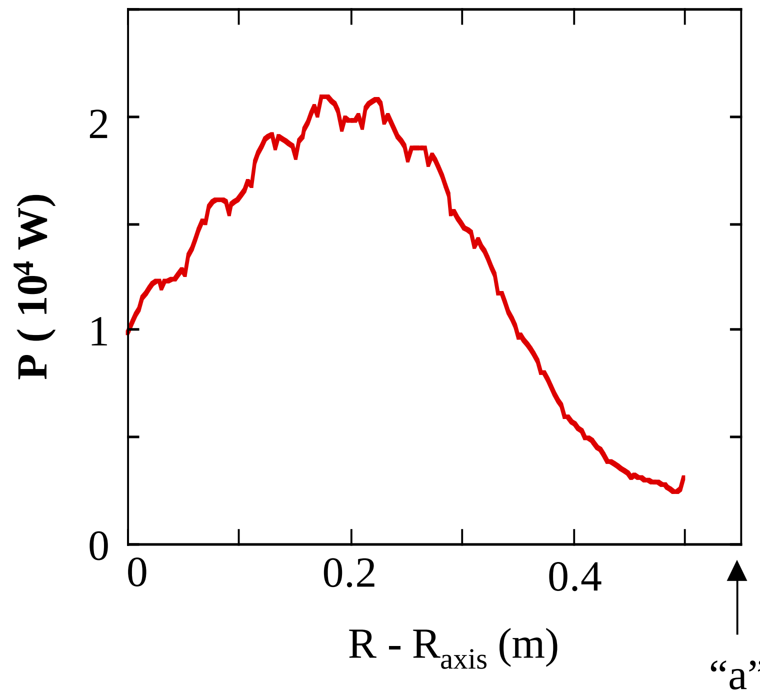




TORIC profile is a bit narrower

METS Predictions for HHFW Heating in NSTX (Shot 105830)





METS predicts 62.7% per pass absorption on electrons over midplane radius shown in figure

METS predicts normalized power per meter in a slab aligned along midplane

>> mapping to flux surface is ill-defined due to neglect of 2D wavestructure

>> profile above is broad with most power absorbed within r/a ~ 0.5

>>stronger core absorption found in 2D codes likely due to B_{pol} modifications of $k_{//}$

CQL3D / GENRAY Predictions for HHFW Heating in NSTX (Shot 105830)

- **CQL3D / GENRAY modeling *in progress***

  (joined code comparison campaign just 2 weeks ago!)

Physics Learned from HHFW simulations

- Electron damping is strong as predicted by Ono (> 60% per pass)

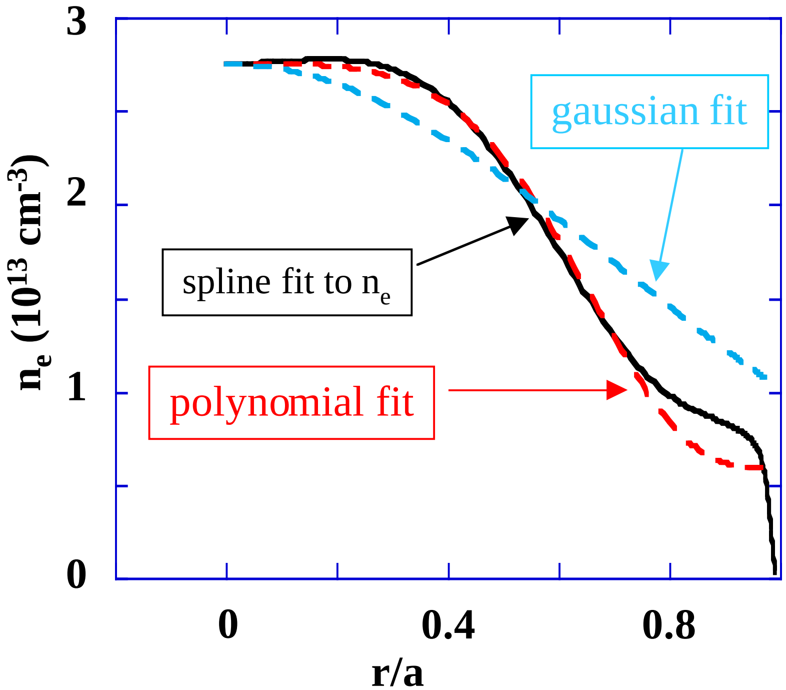
- Electron damping is peaked on-axis in lower density regime

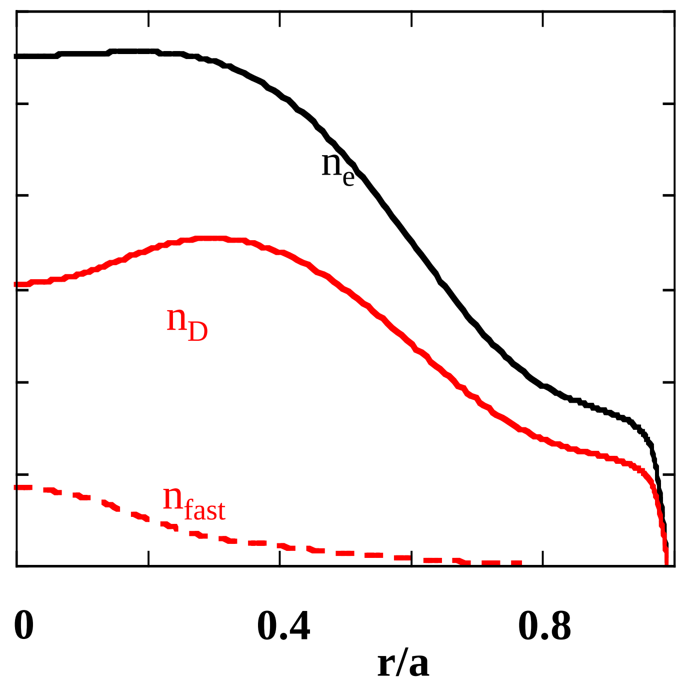
- Excellent quantitative agreement is found between 2D full wave codes and 2D ray tracing codes
  - ion absorption is negligible
  - no evidence of mode conversion to ion Bernstein waves near cyclotron harmonics
  - WKB is satisfied over remainder of plasma cross-section

- 2D effects on power deposition are significant
  - B_{pol} effects on $k_{//}$ evolution may account for differences in absorption profiles found between 1D and 2D codes

NSTX Test Case II: HHFW combined with DNBI (shot #105913)

See poster QP1.010 by A. Rosenberg for more experimental and theoretical details



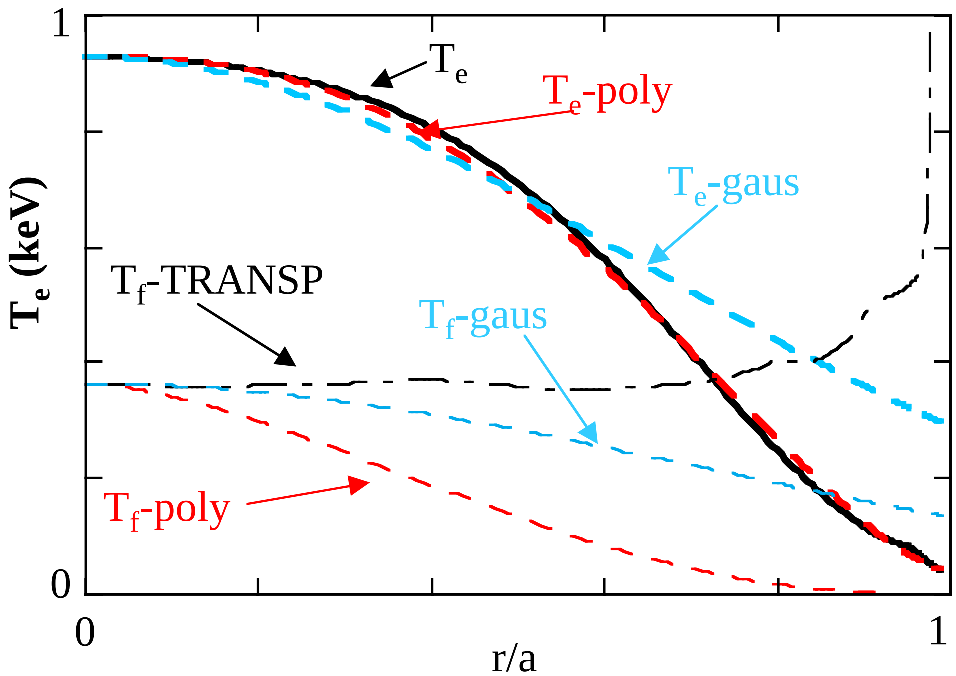


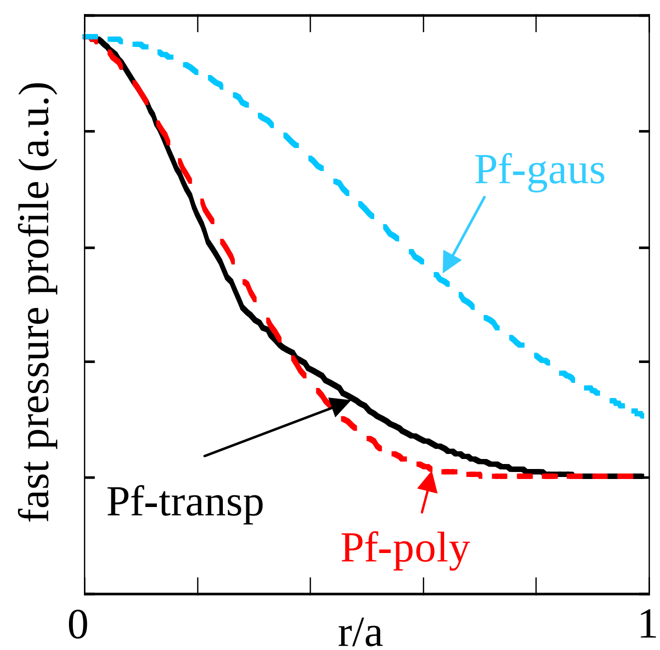
η_D = 0.553
η_F = 0.152
η_H = 0.037
η_C = 0.043
Z_{eff} ~ 2.29

fast ion density oeaks on axis but thermal ion density peaks off-axis
>> full wave codes currently assume all ion species have same radial density profile as electrons

f = 30 MHz	**P_{rf} =2.92 MHz**	**$k_{//,A}$ ~ 14 m^{-1} or N_ϕ = 24**
B_T ~ 0.447T @ R= 98.4 cm	**"r_{minor}" = 62 cm**	**I_p = 896 kA**
n_{e0} ~ 2.8e13 cm^{-3}	**T_{e0} ~ 0.926 keV**	**T_i ~ T_e**

Fast ion profiles obtained from TRANSP simulation





From TRANSP simulation, deduce effective fast ion density and temperature (equivalent Maxwellians)

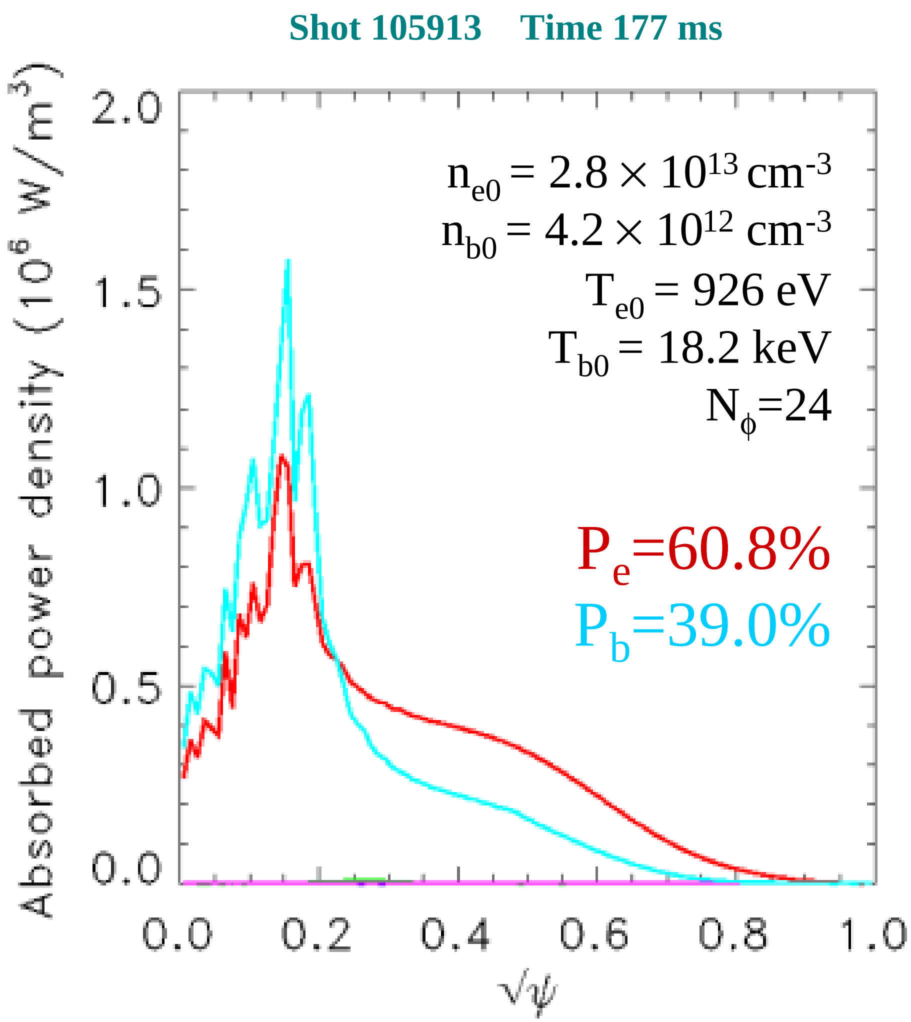
In full wave codes, modify fast ion temperature to match against fast ion pressure (full wave codes can't match fast ion density profile without recoding)

Note that: $P_{abs} \sim \omega_{ps}^2 * \left\{ \sum_{n=-\infty}^{n=\infty} e^{-\lambda} \frac{n^2 I_n(\lambda)}{\lambda} |E_x|^2 + \ldots \right\} \sim nT^{\alpha}$

where "α" depends on the cyclotron harmonic

Note: gaussian fit to fast pressure used in AORSA is broad due to typo in fit parameters sent by CKP - *sorry*!

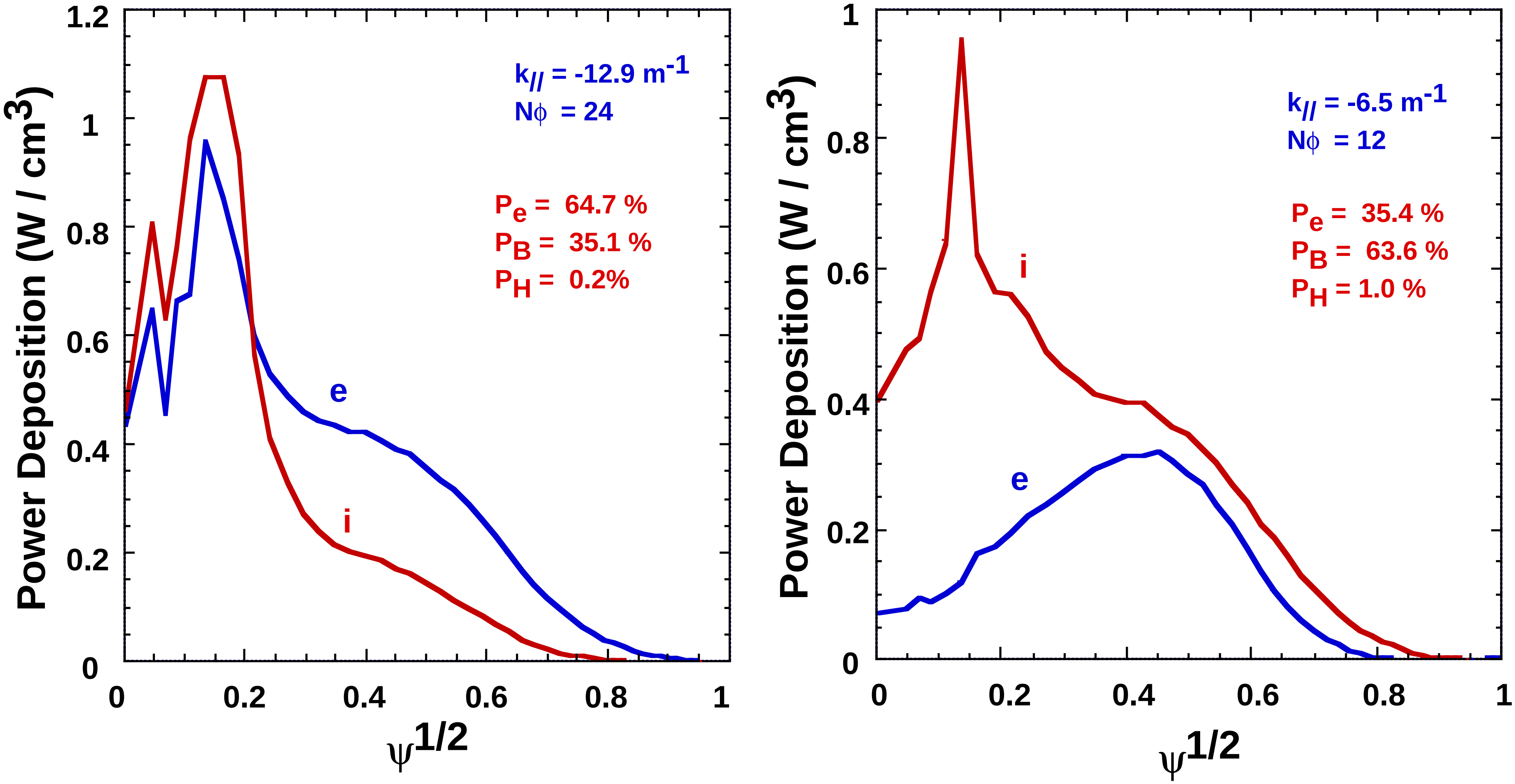
HPRT Predictions for HHFW+DNB Heating in NSTX (Shot 105913)



Rosenberg

strong absorption of HHFW by fast ion component
electron and fast ion absorption relatively broad and peaked somewhat off-axis

CURRAY Predictions for HHFW+DNB Heating in NSTX (Shot 105913)

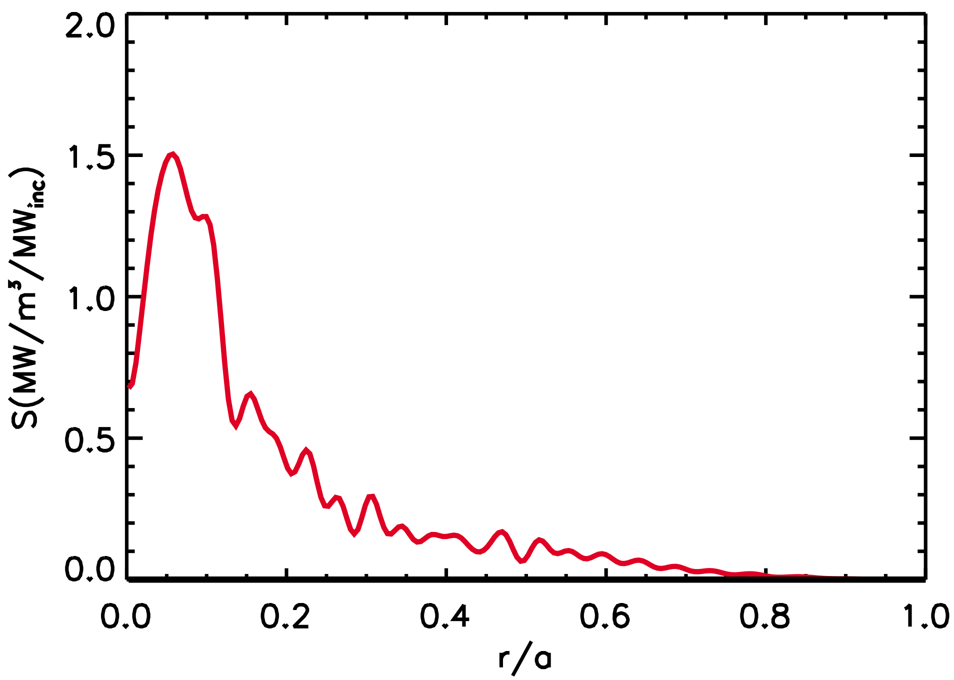


strong absorption of HHFW by fast ion component
electron and fast ion absorption relatively broad and peaked somewhat off-axis

energetic ion absorption increases for lower $k_{//}$

T.K. Mau

TORIC Predictions for HHFW+DNB Heating in NSTX (Shot 105913)

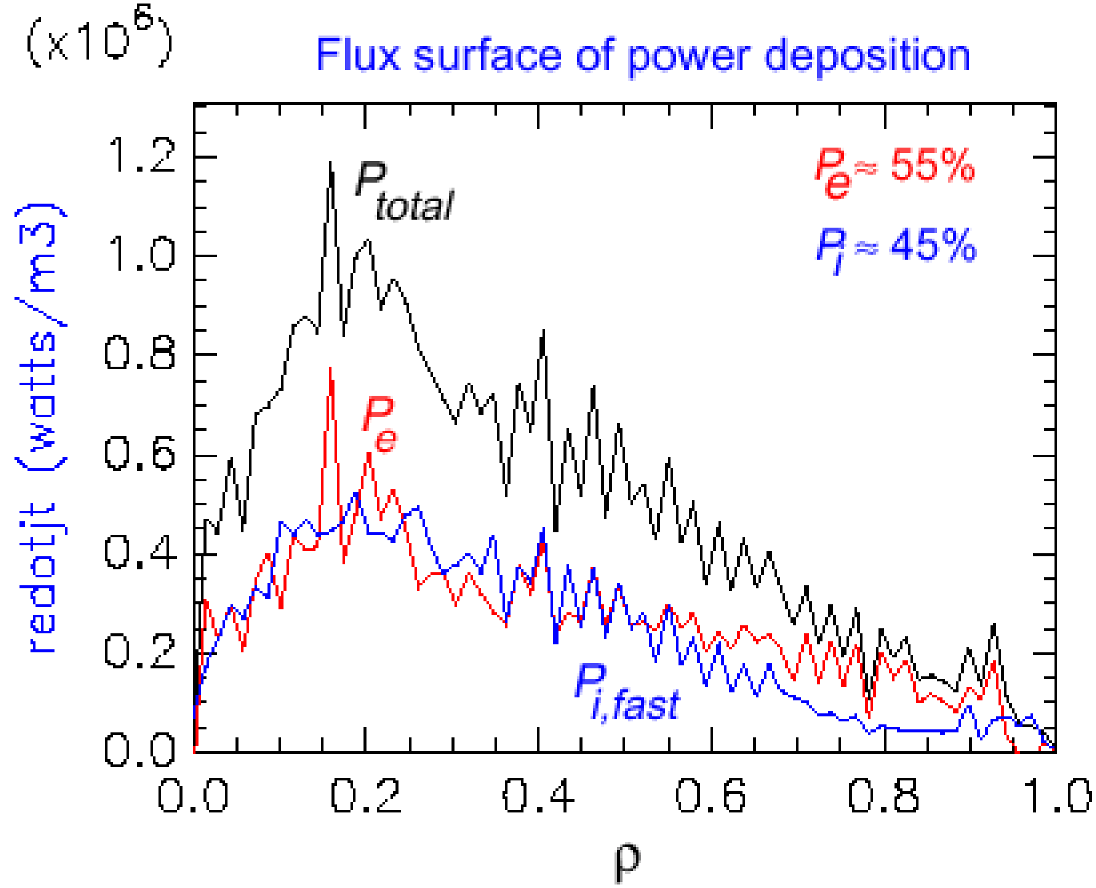


Because of FLR assumption, high ion cyclotron harmonic damping terms are omitted, so 100% of HHFW power is absorbed via ELD.

Modifications are being incorporated which will estimate high harmonic ion damping using full hot plasma damping coefficients but FLR wave fields

AORSA Predictions for HHFW+DNB Heating in NSTX (Shot 105913)

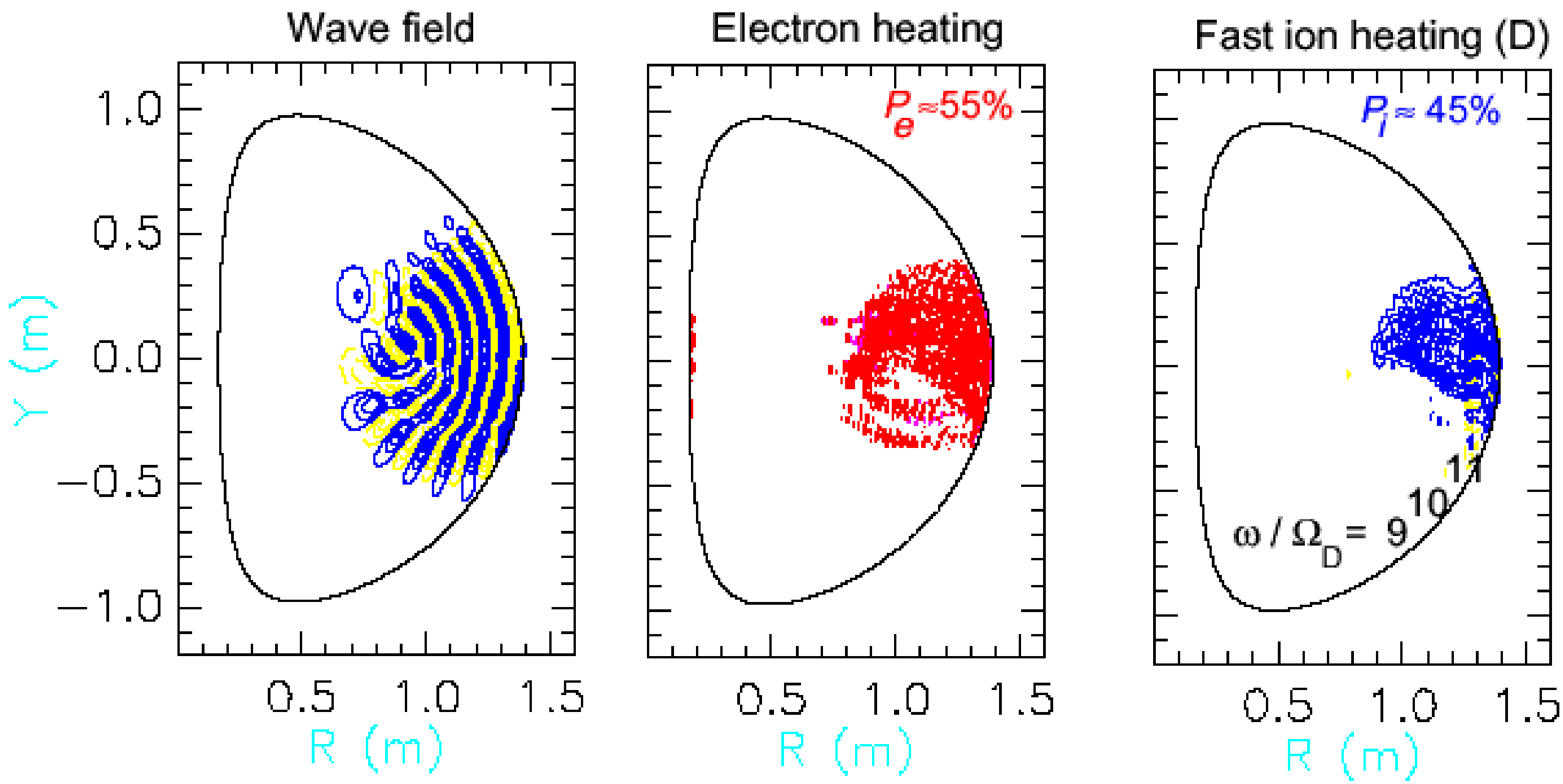
NSTX (shot #105913) with 15.2% fast D with *Te* = .926 keV, *Ti,fast* = 18.22 keV
(140 × 140 modes in *x* and *y*, and 20 cyclotron harmonics) P_rf = 2.92 MW



strong absorption of HHFW by fast ion component
electron and fast ion absorption relatively broad and peaked off-axis

Jaeger, Batchelor, and Berry

AORSA calculates high harmonic wave absorption and propagation in 2D for arbitrary ratios of ion gyroradius to perpendicular wavelength

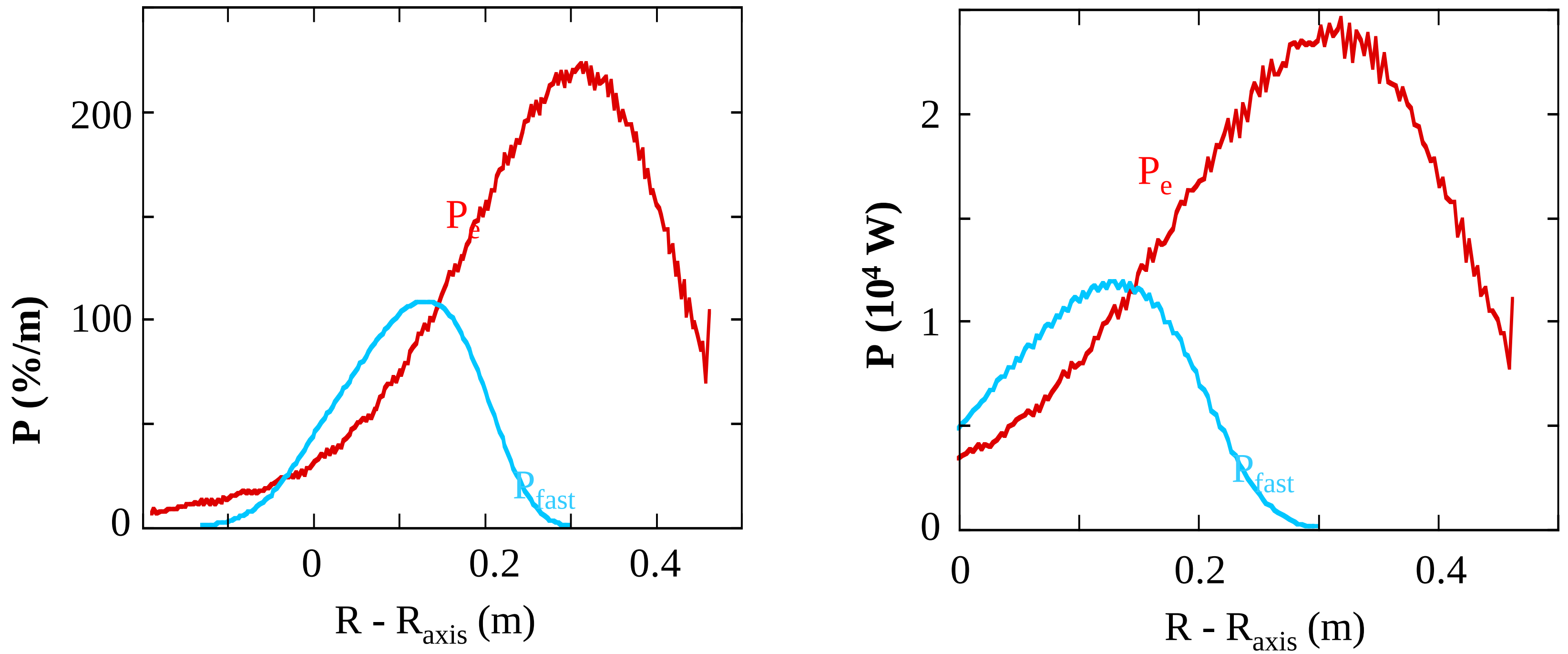


note no evidence of IBW excitation

fast ion absorption peaks near 10th and 11th harmonics

ornl Jaeger, Batchelor, and Berry

METS Predictions for HHFW+DNB Heating in NSTX (Shot 105913)



METS predicts strong single pass absorption ~ 87.6%, with P_e ~ 75% and P_{fast} ~ 25% of total (with a broader fast ion pressure profile, METS predicts the fast ions can absorb > 50% of power)

METS electron absorption profile is peaked more off-axis than 2D codes
METS fast ion absorption profile peaks in the core similar to 2D codes
Differences with 2D codes due to:

- use of different fast ion density and temperature profiles
- neglect of 2D geometry in METS, particularly effects of Bpol
- possible inaccuracies in ion damping calculation in ray codes

CQL3D / GENRAY Predictions for HHFW+DNB Heating in NSTX (Shot 105913)

- **CQL3D / GENRAY modeling *in progress***

  (joined code comparison campaign just 2 weeks ago!)

Physics learned from HHFW + DNBI simulations

- **Fast ion absorption is sensitive to assumed fast ion density and temperature profiles**
  - ***must compare codes using same input profiles (will require some code modifications)***

- **No significant mode conversion observed near IBW-fast wave coupling regions in both 1D and 2D all-orders kinetic models**

and

- **WKB approximation satisfied over remainder of fast wave fields**

$\Rightarrow$ ***ray tracing models with full hot plasma WKB absorption terms may provide fast and accurate tools for data analysis***

$\Rightarrow$ ***FLR full wave model may also provide reasonably fast and accurate model for use in TRANSP***

Summary and Plans

- **Code predictions compared for 2 NSTX discharges:**
  - **105830 high T_{e0} case**
  - **105913 HHFW combined with DNBI**

- **Quantitative agreement found among the various codes:**
  - **Strong single pass core electron damping predicted for high T_{e0} HHFW-only test case (#105830)**
  - **Broad off-axis absorption profiles with significant fast ion absorption predicted for combined HHFW + DNBI test case (#105913)**

- **Codes to be benchmarked against experimentally measured power deposition profiles when data is available**
  - **Accuracy of fast ion absorption obtained from ray tracing codes will be verified using better match of input equilibrium profiles in all codes**
  - **Effects of non-Maxwellian fast ion distributions will be explored experimentally (thesis research by A. Rosenberg) and theoretically (RF-SciDAC initiative)**