Quasioptical propagation and absorption of electron cyclotron waves from both numerical and experimental point of view

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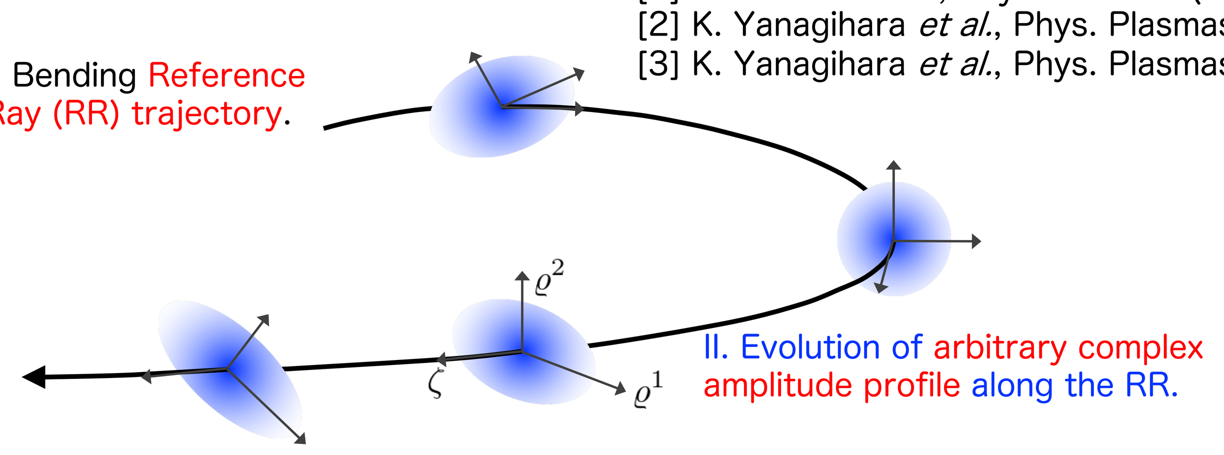
Introduction

- Shear-driven mode conversion at the peripheral affects to the mode purity of electron cyclotron (EC) waves in the core. Inhomogeneous dissipation in spatial resonant structure affects to the power deposition profile.
- Both effects should be considered for highly precise ECRH predictions, but have not considered sufficiently in conventional EC codes.
- We newly developed quasioptical ray tracing code PARADE, which can capture both effects simultaneously.
- PARADE predictions of EC wave beams are validated for the first time, by comparing with experiments in Large Helical Device.

Quasioptical ray tracing code PARADE

Simulate wave beam propagations with those quasioptical envelopes in inhomogeneous anisotropic media [1-3].

[1] I. Y. Dodin *et al.*, Phys. Plasmas (2019)
[2] K. Yanagihara *et al.*, Phys. Plasmas (2019a)
[3] K. Yanagihara *et al.*, Phys. Plasmas (2019b)



PARADE simultaneously captures
1) refraction
2) diffraction
3) mode conversion
4) inhomogeneous dissipation

Basic equations governing PARADE

Hamilton RR eq. to fix the RR trajectory.

$$\frac{dX^\alpha}{d\zeta} = \frac{1}{V_\star}\frac{\partial H_\star}{\partial K_\alpha},\quad \frac{dK_\alpha}{d\zeta} = -\frac{1}{V_\star}\frac{\partial H_\star}{\partial X^\alpha},\quad V_\star = |\boldsymbol{V}_\star| \doteq \left|\frac{\partial H_\star}{\partial \boldsymbol{K}}\right|$$

$H_\star$: Ray Hamiltonian $\boldsymbol{X}$: Position of the RR $\boldsymbol{K}$: Wave vector of the RR

Quasioptical partial differential eq. to integrate complex amplitude profile.

$$V_\star \partial_\zeta \phi = -(\tilde{u}^\sigma_\star + \tilde{\vartheta}^\sigma_{\star\bar{\sigma}}\tilde{\varrho}^{\bar{\sigma}})\partial_\sigma\phi - \frac{\tilde{\vartheta}^\sigma_{\star\sigma}}{2}\phi + \Gamma\phi$$

$$-i(\tilde{\mathfrak{L}}_{\star\sigma\bar{\sigma}}\tilde{\varrho}^\sigma\tilde{\varrho}^{\bar{\sigma}} + \tilde{\mathfrak{M}}_{\star\sigma}\tilde{\varrho}^\sigma + M_\star - U_\star)\phi + \frac{i}{2}\tilde{\Phi}^{\sigma\bar{\sigma}}_\star\partial^2_{\sigma\bar{\sigma}}\phi.$$

$\phi = \sqrt{V_\star}a$: Re-scaled complex amplitude
ζ : Coordinate along the RR
$\tilde{\varrho}$: Coordinate perpendicular to the RR
$U_\star$: Mode conversion
Γ : Dissipation
$\tilde{\Phi}^{\sigma\bar{\sigma}}_\star$: Diffraction

Concrete representation of each terms are derived and summarized in [1-3].

Direct measurement of EC wave beam in the LHD

The purpose of this work ; Validate new quasioptical code "PARADE", by simulating target plate experiments in LHD.

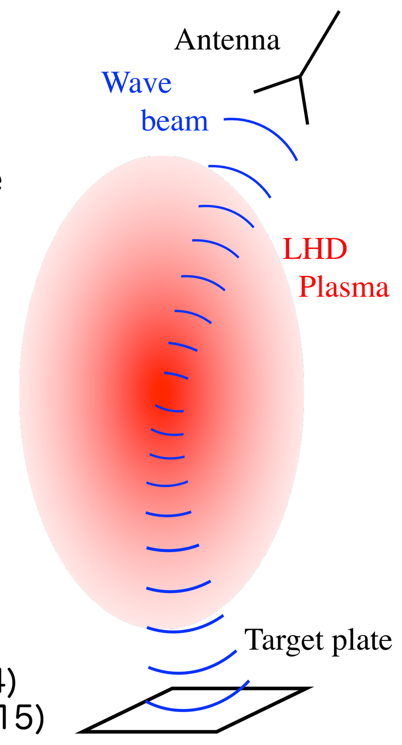
Overview of the Experiment [5,6]

Target plate is installed to face an antenna in vacuum vessel of the Large Helical Device (LHD).

Top-launched wave beams (77 GHz, 2nd O mode) are affected by the LHD plasma, reach to the plate, and heat the plate.

By using IR camera, measuring the ΔT profiles of the plate, which is proportional to the beam power profiles.

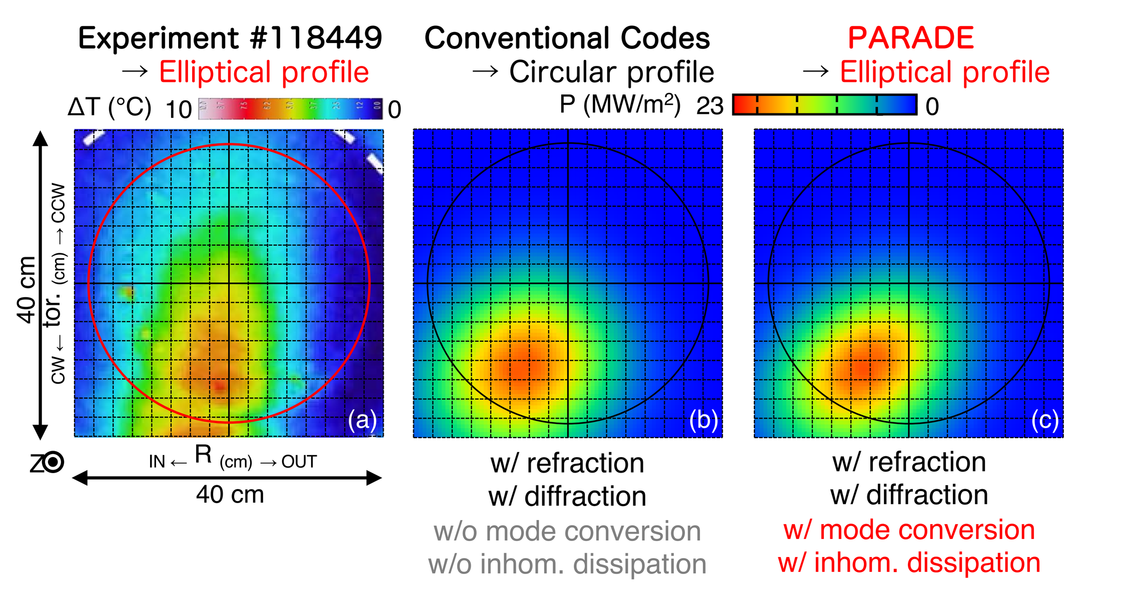
Validate our model, by comparing Numerical intensity profiles and Experimental ΔT profiles on the plate.

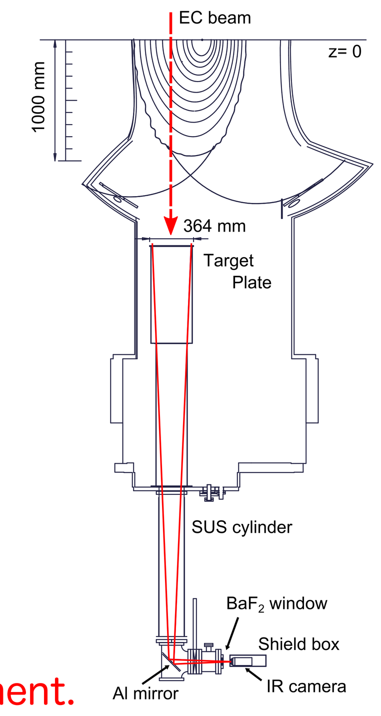


[5] S. Kamio *et al.*, Rev. Sci. Instrum. (2014)
[6] H. Takahashi *et al.*, EPJ Web Conf. (2015)

Intensity and ΔT profiles on Target-plate

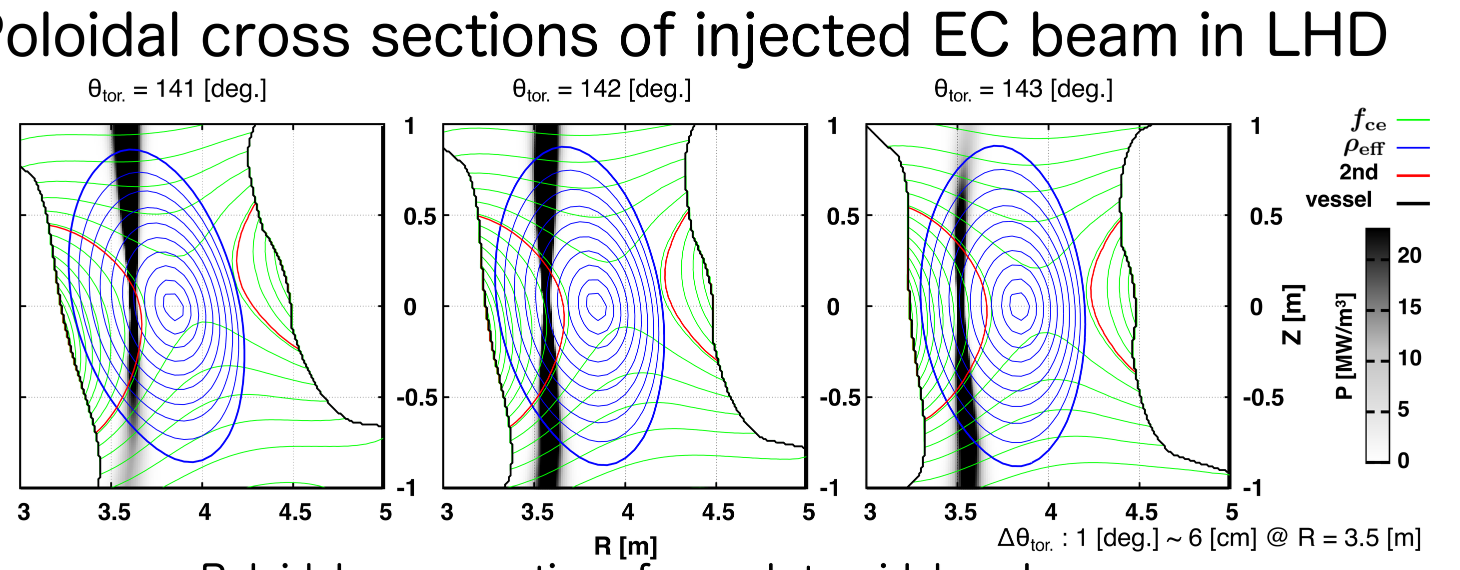
Experimentally verified that PARADE's predictions are more realistic than conventional quasioptical codes in the past.





PARADE's 2 advantages improve the profile to suit for the experiment.

Poloidal cross sections of injected EC beam in LHD

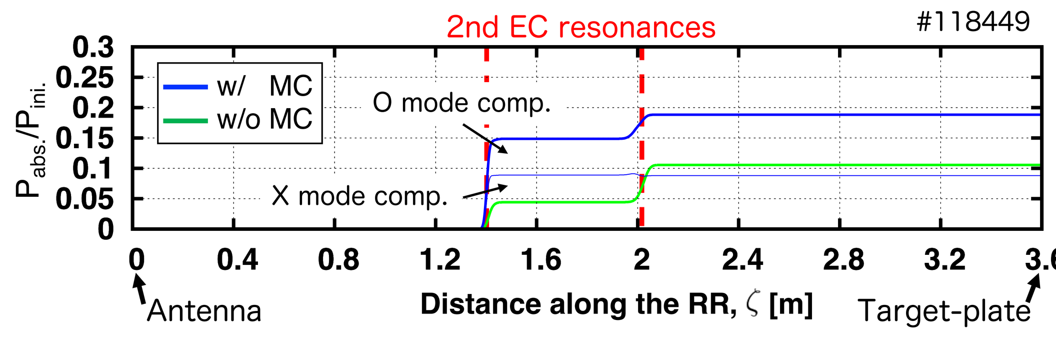


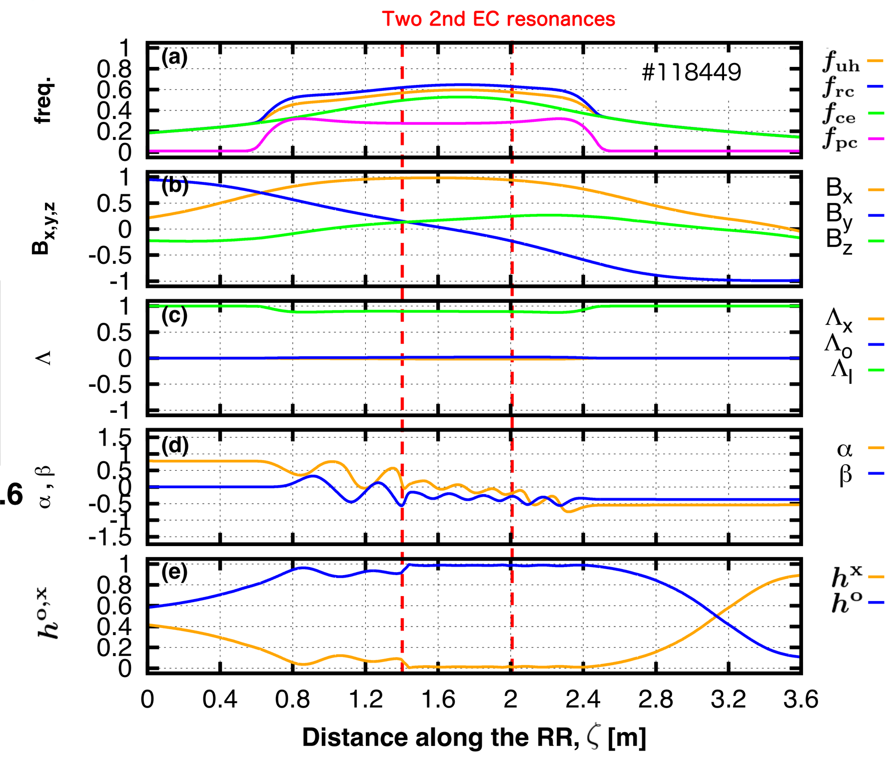
Poloidal cross sections for each toroidal angles.

Shear-driven mode conversion and Multi-mode absorption

PARADE can predicts the variation and absorption of excited O/X mode ratio of quasi-degenerated wave beams [1,3,7,8].

PARADE revealed that almost 10% power of the injected beam is absorbed as 2nd X mode at the cyclotron resonance on ζ=1.4 m.

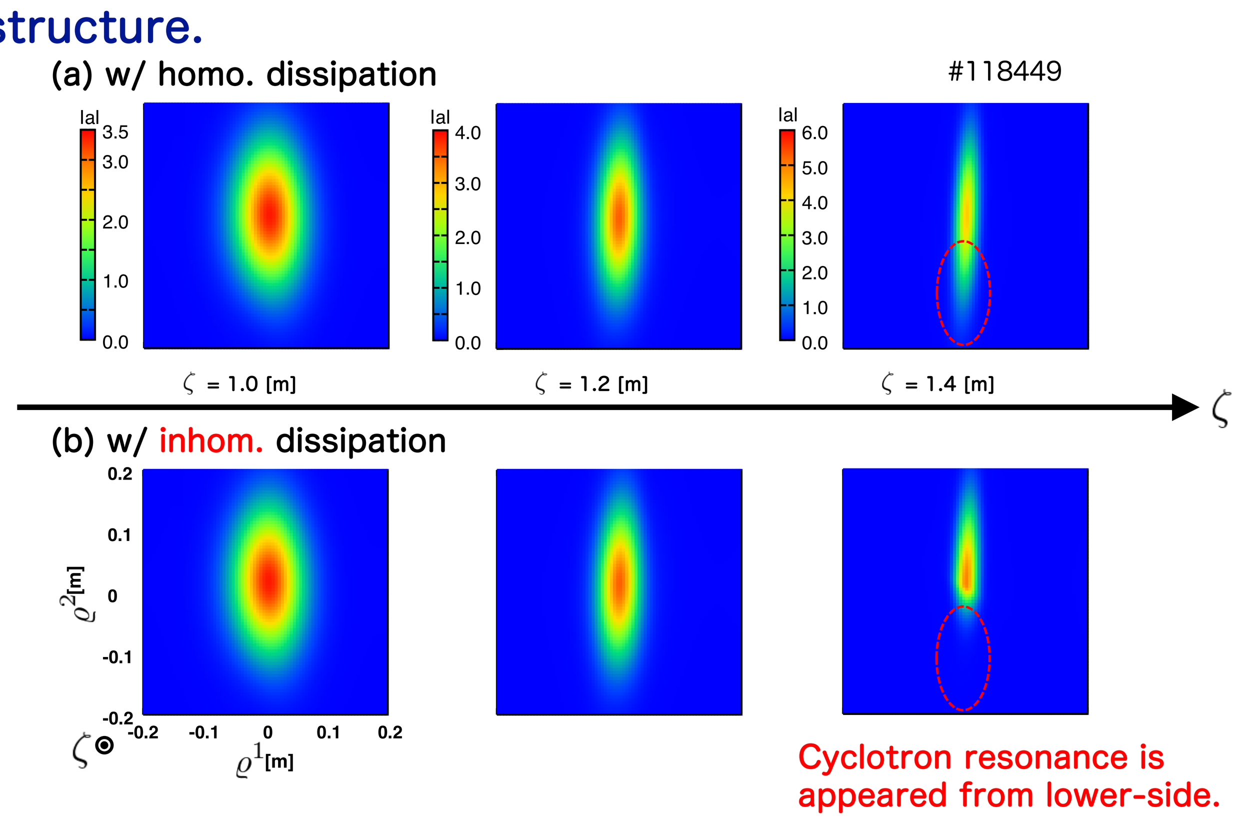




[1] I. Y. Dodin *et al.*, Phys. Plasmas (2019)
[3] K. Yanagihara *et al.*, Phys. Plasmas (2019b)
[7] K. Yanagihara *et al.*, Phys. Plasmas (2017)
[8] K. Yanagihara *et al.*, Plasma Fusion Res. (2019)

Spatial structure of a resonance collapse beam profile

PARADE captures anti-symmetric beam profile due to the spatially inhomogeneous resonance structure.



|a| profile of X mode component on beam-cross section.

Distorted envelope structure directly affects the profile on the target plate.

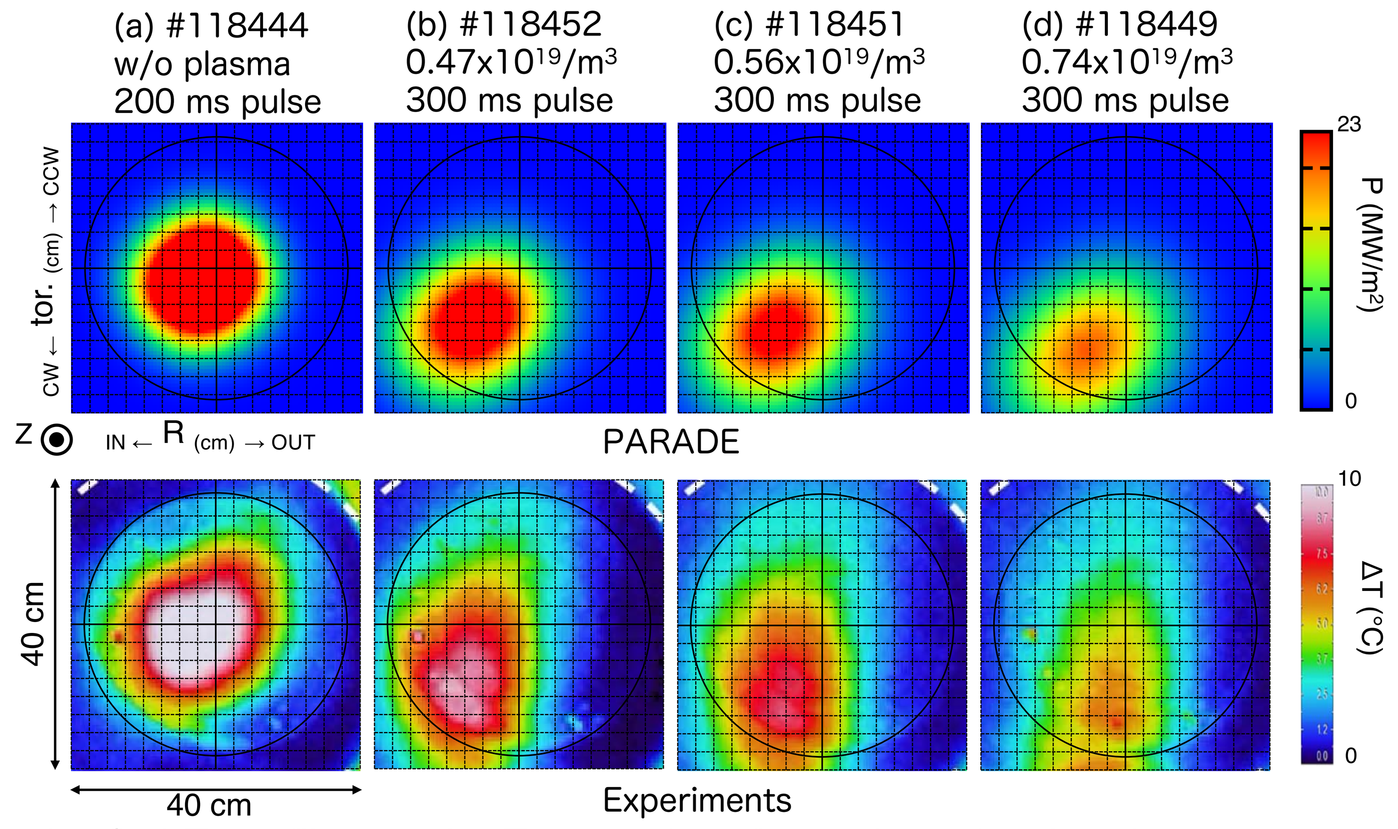
Qualitative agreement between PARADE and Exp.

PARADE successfully captures three density dependence of exp.,

(i) beam position
Shift to left and lower side from (a) to (b), and right and lower from (b) to (d),

(ii) profile elongation
Circler profile is distorted to elliptical profile from (a) to (d),

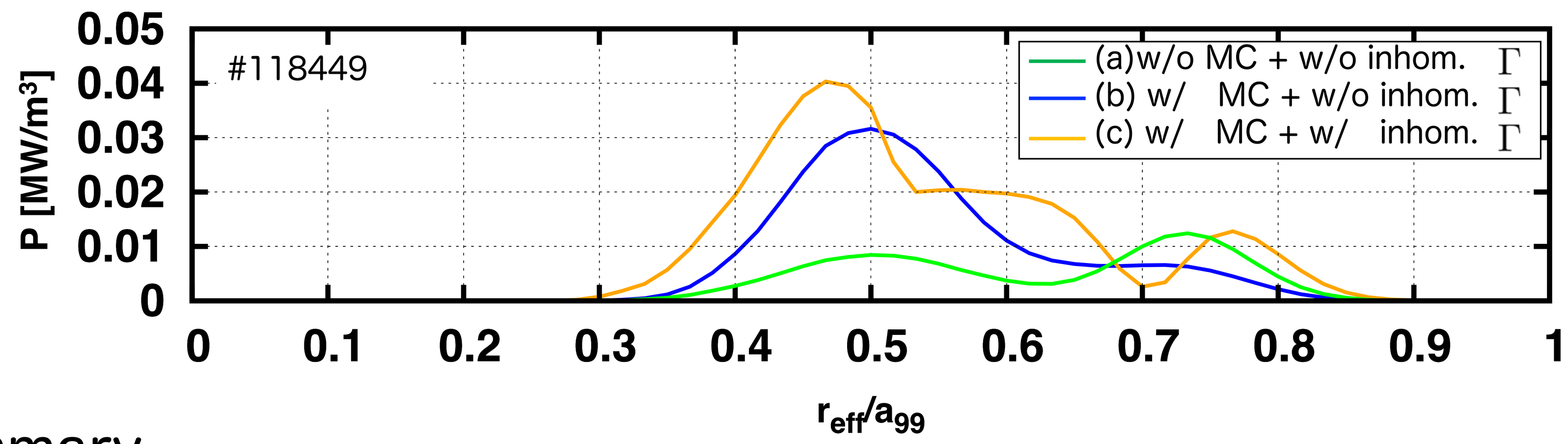
(iii) power decrease
Both intensity and temperature are decreased from (a) to (d).



Intensity & ΔT profiles on the Target-plate for various density plasmas.

Power deposition profiles w/ PARADE's 2 advantages

- Larger deposition near r_{eff}/a_{99} ~ 0.5 of (b) than (a) is due to the X mode absorption ignored in (a).
- Detailed profile of (c) than (b) is obtained by capturing the spatial structure of resonant absorption in (c).



Summary

- PARADE is a quasioptical ray tracing code, that captures refraction, diffraction, mode conversion, and inhomogeneous dissipation, simultaneously.
- Quasioptical propagation of EC wave beams obtained numerically are validated for the first time, by comparing with experiments conducted in Large Helical Device.
- PARADE's results are in qualitative agreement with the LHD experimental results.
- By introducing two unique advantages of PARADE, numerical results are improved to suit for the LHD experimental results.
- Power deposition profile is also improved by two advantages.