Key Aspects of EBW Heating and Current Drive in Tokamaks

J. Urban[1], J. Decker[2], J. Preinhaelter[1], G. Taylor[3], L. Vahala[4], G. Vahala[5]

[1] EURATOM/IPP.CR Association, Prague, Czech Rep.
[2] EURATOM-CEA, Cadarache, France
[3] Princeton Plasma Physics Laboratory
[4] Old Dominion University, Norfolk, VA
[5] College of William & Mary, Williamsburg, VA

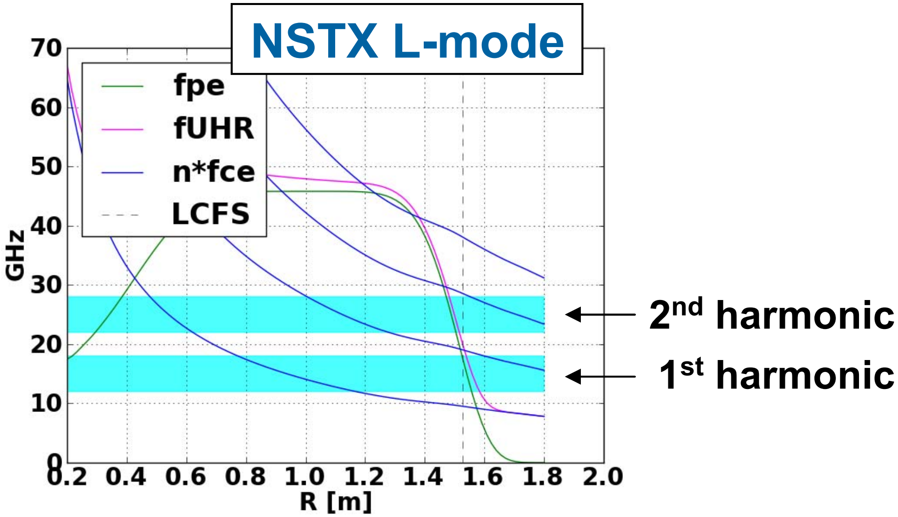
Introduction & motivation

- **EBWs – Electron Bernstein waves**
  - The only waves in the **electron cyclotron (EC) range** that can propagate in **overdense plasmas** ($\omega_{pe} >> \Omega_{ce}$)
  - Must be excited by O/X-modes
  - Strong interaction with the plasma (electrostatic)
- **Potential goals – stabilization, profile shaping**
  - **On/off-axis, localized heating and current drive**
- **How to optimize and control?**

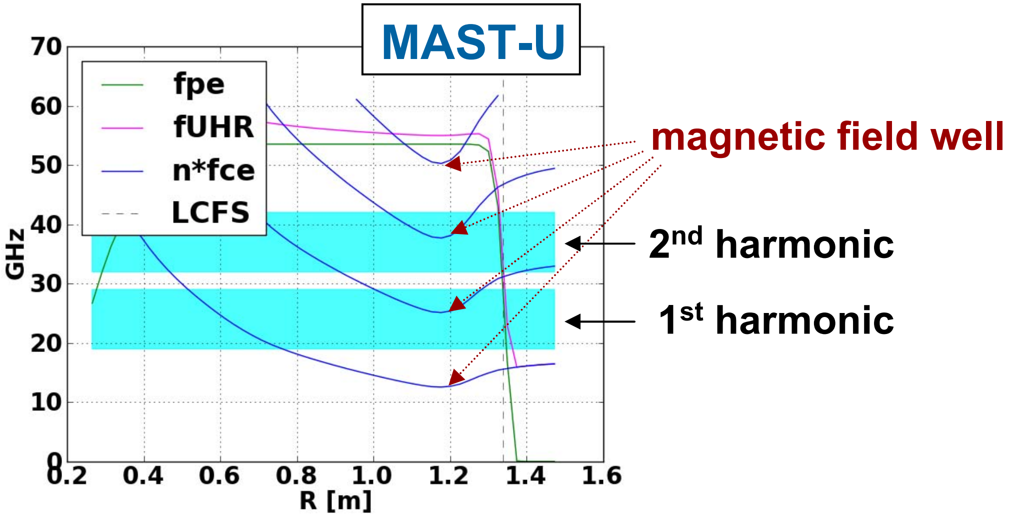
Simulation setup

- **AMR (Antenna, Mode-conversion, Ray-tracing) + LUKE (3D Fokker-Planck) codes**
  - AMR calculates optimum aiming and EBW ray trajectories
  - LUKE calculates quasi-linear damping and current
- **O-X-EBW scheme**
  - Frequency and antenna vertical position can be chosen
  - $N_{||}^2$, N_{pol} determined → 2 $\pm\phi$ injections possible
- **Target plasma**
  - **NSTX L-mode**
  - **MAST-U H-mode** (TRANSP scenario)
  - Z_{eff}=2 for all scenarios
- Antenna parameters
  - **1 MW power** (unless specified)
  - **Varying antenna vertical position** above midplane and **toroidal injection angle sign** (equivalent to below midplane with switched toroidal angles)

Feasible frequency ranges determined by the equilibria



B_0=0.5 T
I_P=0.6 MA
n_{e0}=2.6x10^{19} m^{-3}
T_{e0}=2.9 keV



B_0=0.78 T
I_P=1.2 MA
n_{e0}=3.5x10^{19} m^{-3}
T_{e0}=2.4 keV

EBW coupling details are neglected in this study

1D

OXB optimum angle: $N^2_{||\mathrm{opt}} = \left(1+\omega/\omega_{\mathrm{ce}}\right)^{-1}$, $\mathbf{N}\cdot\left(\mathbf{B}\times\nabla n_{\mathrm{e}}\right)=0$

Theoretical dependence: $C_{\mathrm{OXB}} = e^{-\pi k L_n \sqrt{\omega_{\mathrm{ce}}/2\omega}\left(2\left(1+\omega_{\mathrm{ce}}/\omega\right)\left(N_{||\mathrm{opt}}-N_{||}\right)^2+N_y^2\right)}$

Additional full wave effects:
parasitic SX-FX tunneling, magnetic shear dependence
Non-linear effects – parametric decay

2D

Non-parallel O- and X-mode cutoff surfaces
Beam curvature should be adjusted to plasma surface
Beam size matters as it determines $N_{||}$ spectrum
Density fluctuations

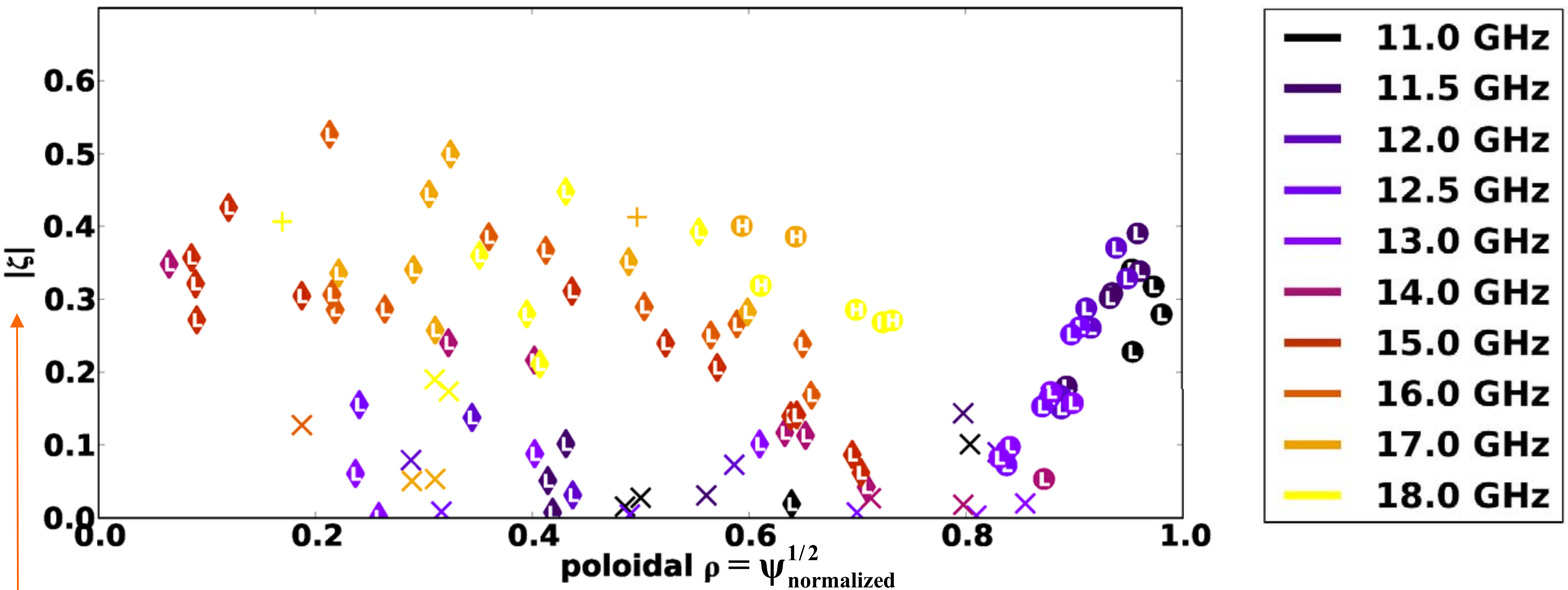
collisions

Collisional damping at the mode conversion region can cause significant coupling efficiency decrease

OUR SOLUTION

1. Determine **optimum angle**
2. Prescribe **Rayleigh range** rather than beam waist radius
3. Assume **100% conversion**
4. **Remember** that the reality can be different

NSTX L-mode 1st harmonic



$$\zeta = \frac{e^3}{\epsilon_0^2} \frac{R n_e}{k T_e} \frac{I}{P}$$

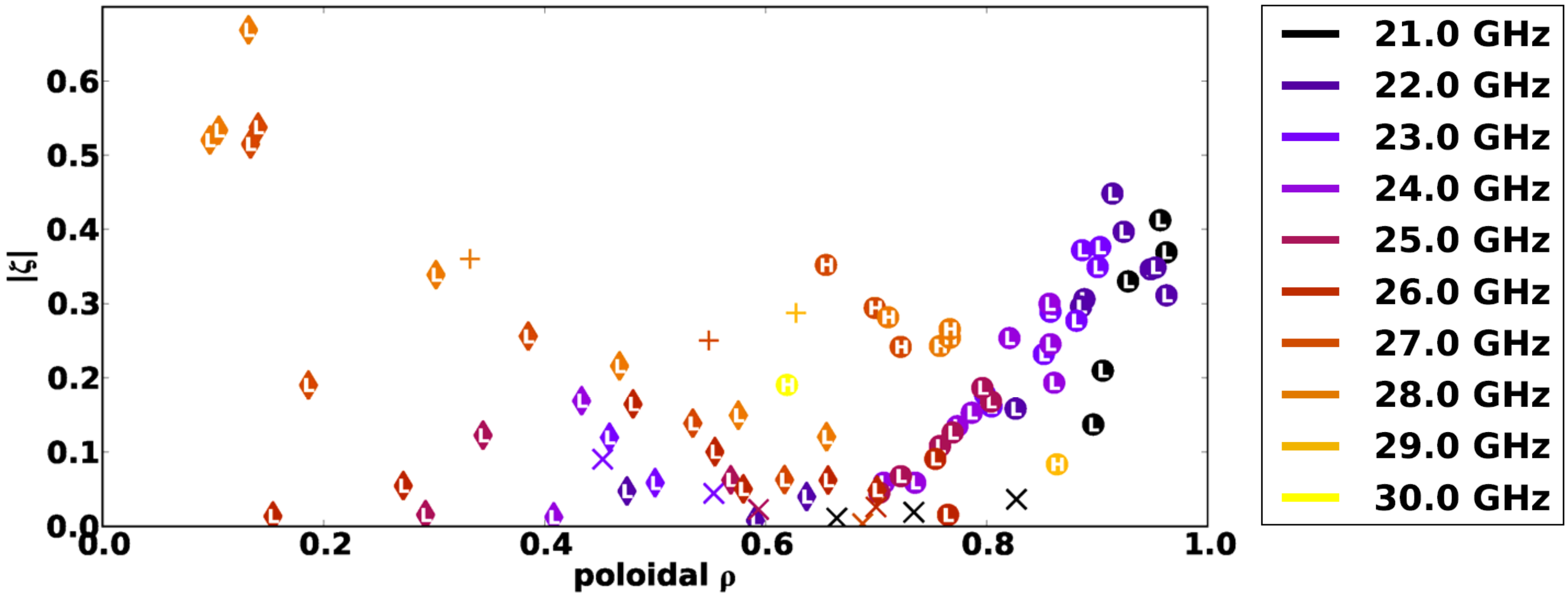
local values

C. C. Petty *et al.*, Nucl. Fusion **42**, 1366 (2002)

- **CD efficiency varies** with the frequency, the vertical antenna position and the initial N_ϕ sign
- **ζ ~ 0.4 can be reached across the whole plasma**

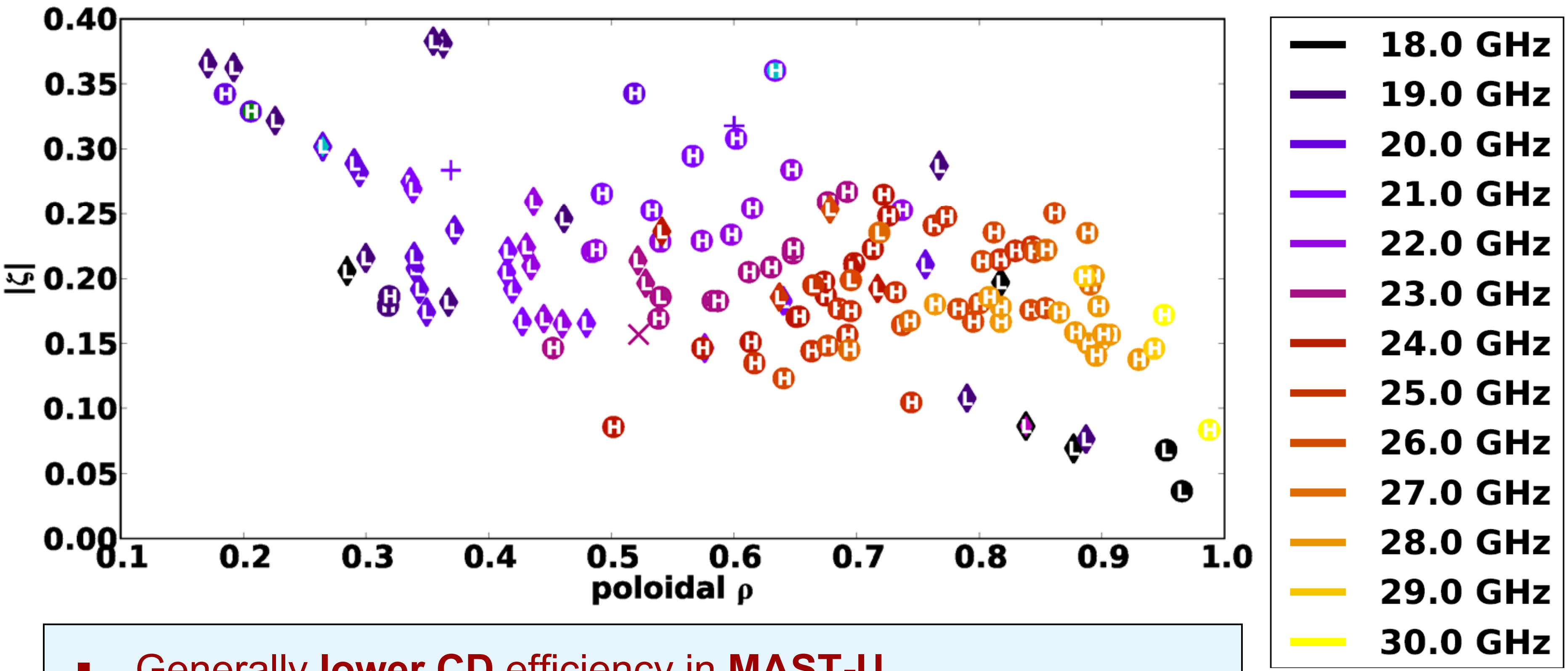
- ♦ Fisch-Boozer
- ● Ohkawa
- × Udetermined
- \+ Harmonic overlap
- L $n\omega_{ce} < \omega$ absorption
- H $n\omega_{ce} > \omega$ absorption

NSTX L-mode 2nd harmonic



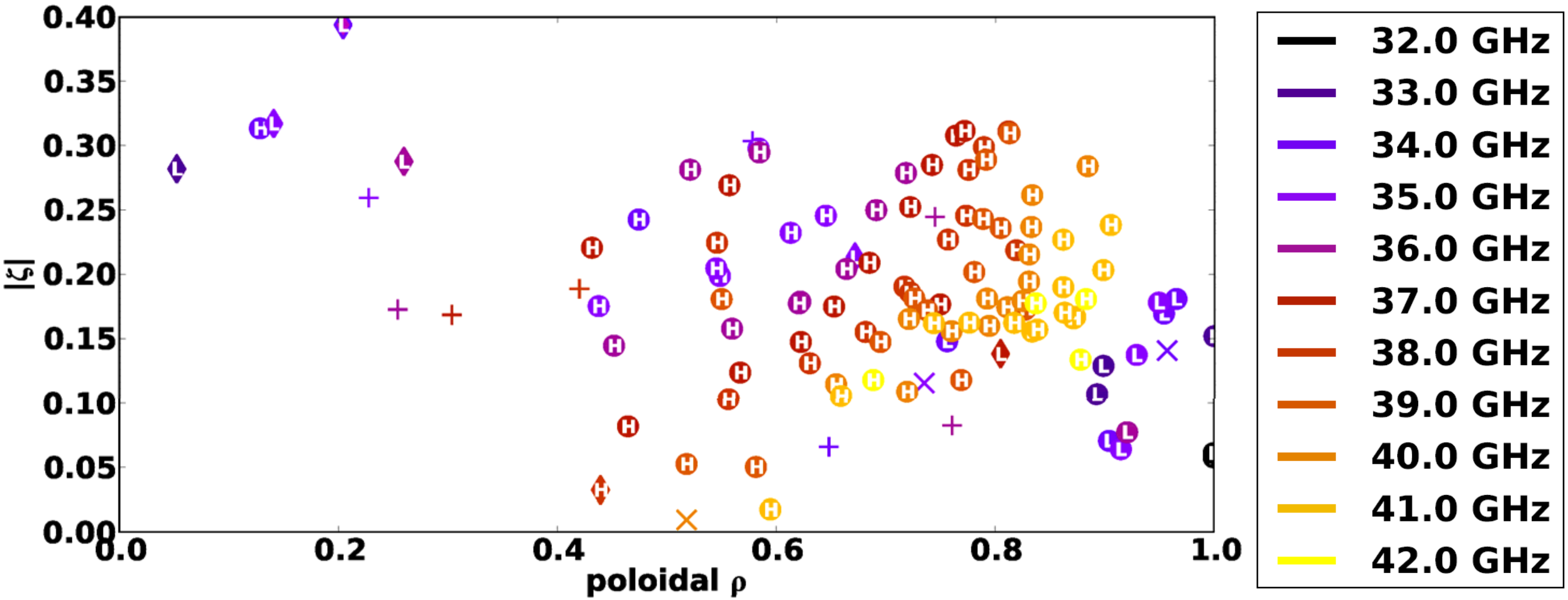
- **Fisch-Boozer** CD is favored in the **central region**
- **Ohkawa** CD is favored at the **edge region**
- A region of high-efficiency Ohkawa with high B-field side absorption occurs
- **Low-efficiency** typically caused by $\mathbf{N_{||}}$ **sign mixing**

MAST-U 1st harmonic



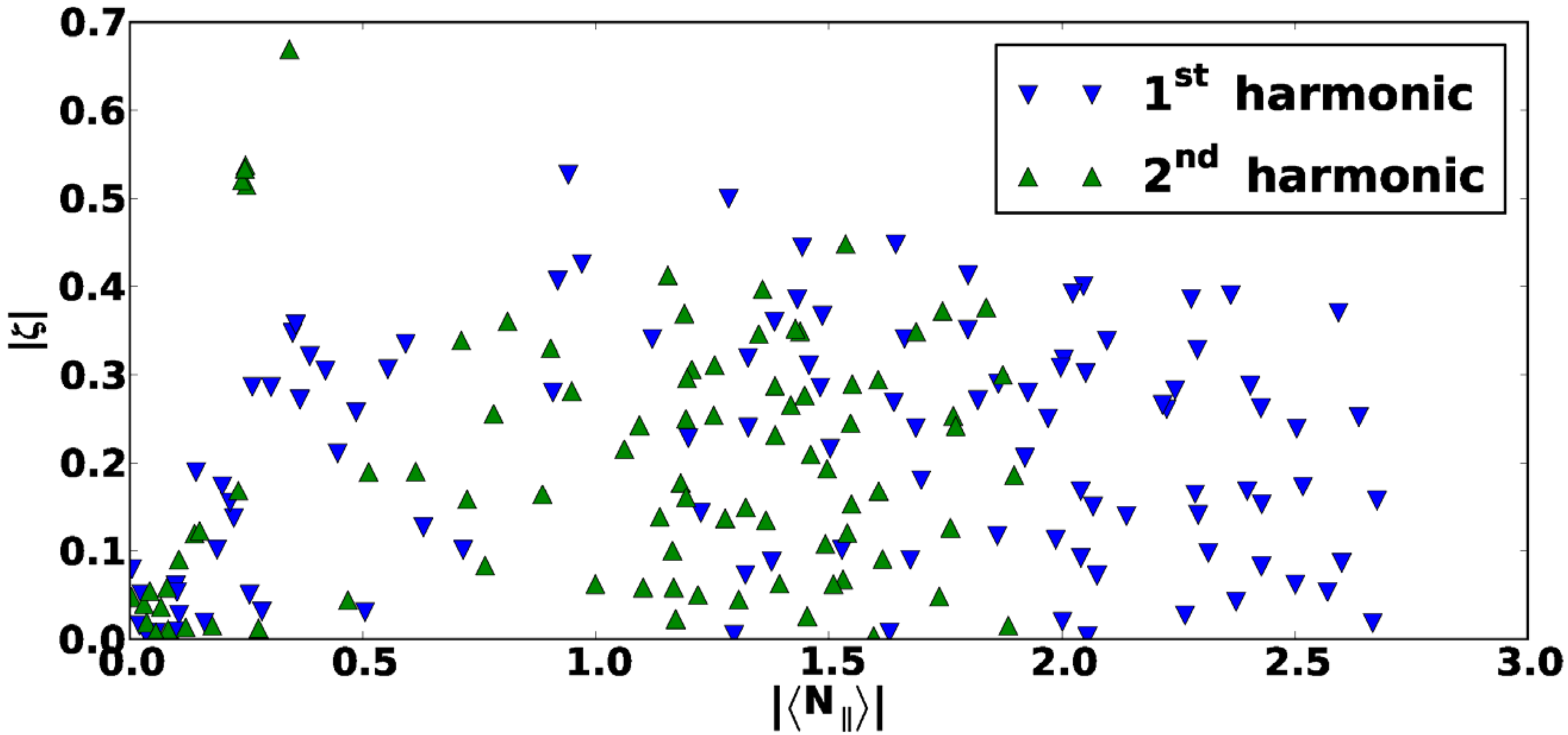
- Generally **lower CD** efficiency in **MAST-U**
- Large number of cases are damped on **high B-field side** because of the magnetic field well at the edge, driving **Ohkawa** current
- **Central region less accessible** (same reason)

MAST-U 2nd harmonic



- The space between the **2nd and 3rd harmonic** is more **narrow → worse central region accessibility**
- Ohkawa CD at 3rd harmonic is the dominant scenario

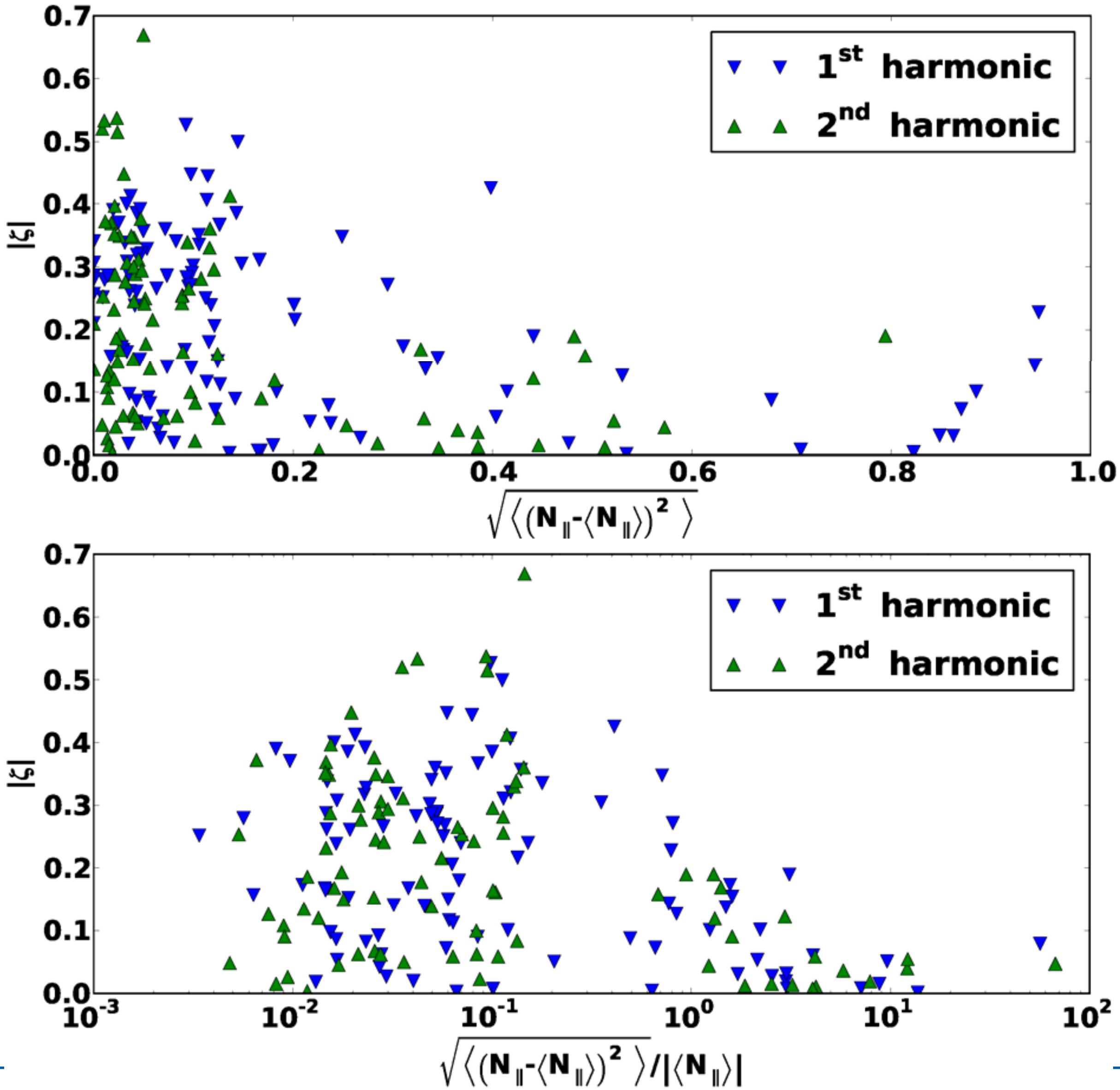
CD efficiency independent of $N_{||}$ in general



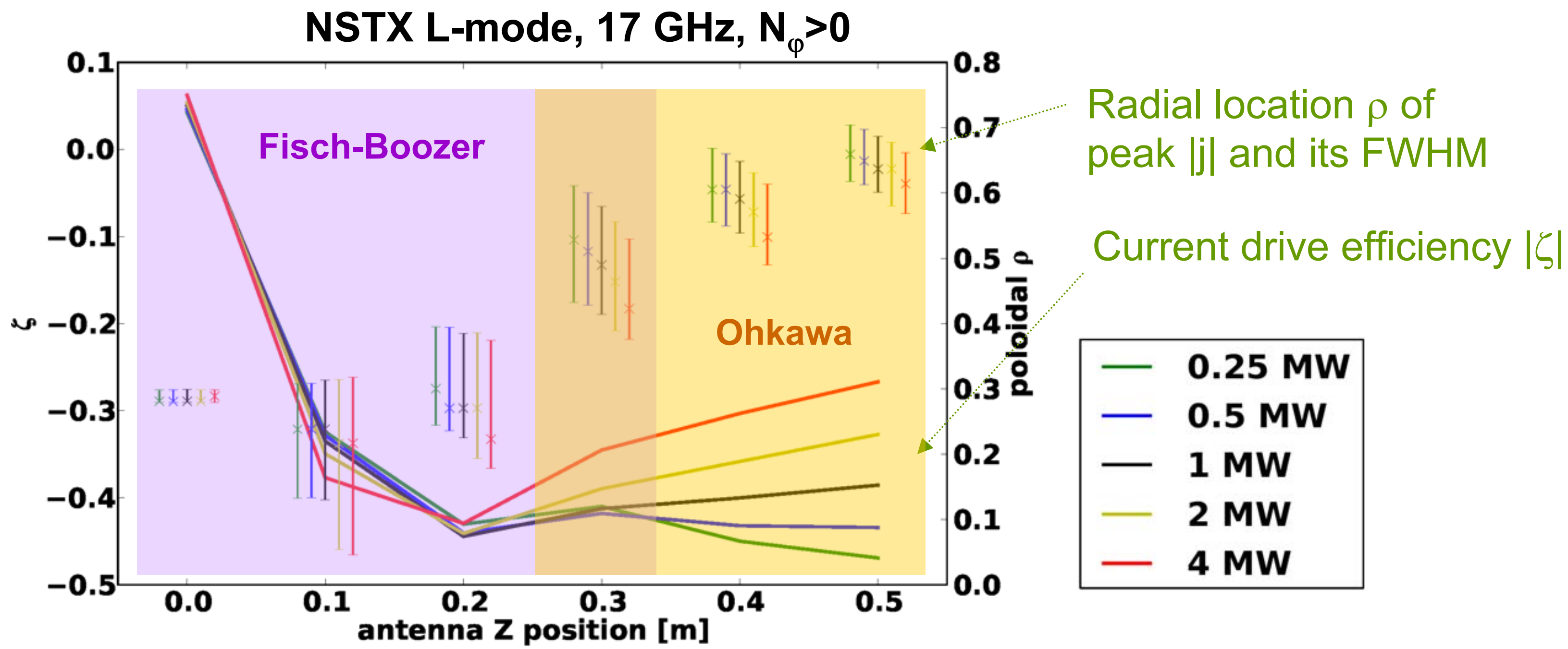
$$\langle N_{||} \rangle = \sum_{i \in \text{F-P bins}} \left(\Delta P(\Gamma_i) \frac{\sum_{\text{rays, } \rho \in \Gamma_i} N_{||} \Delta P_{\text{ray}}(N_{||}, \rho)}{\sum_{\text{rays, } \rho \in \Gamma_i} \Delta P_{\text{ray}}(N_{||}, \rho)} \right) \Bigg/ \sum_{i \in \text{F-P bins}} \Delta P(\Gamma_i)$$

$N_{||}$ at the damping location!

No dependence on $N_{||}$ variation either

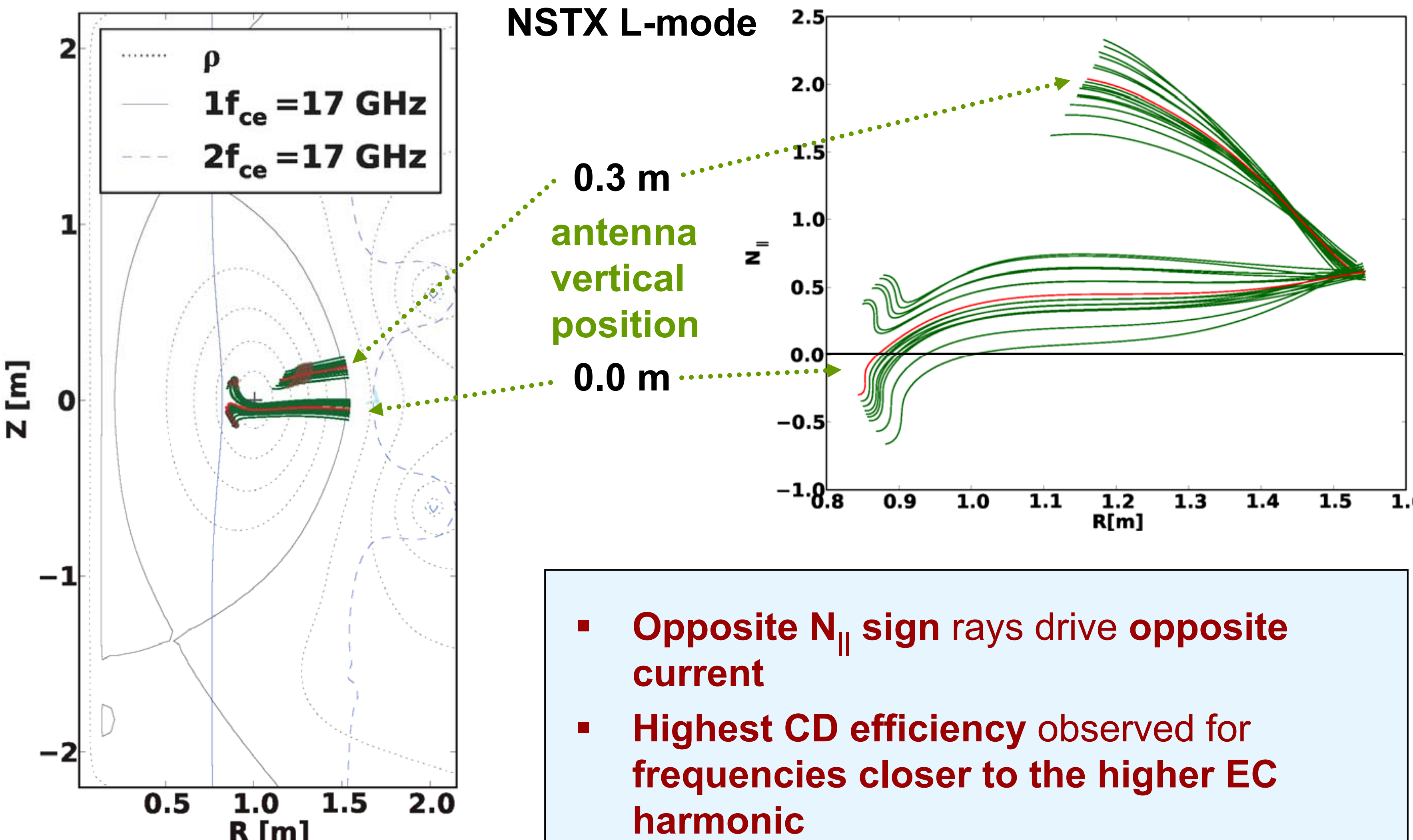


Quasilinear effects play a role



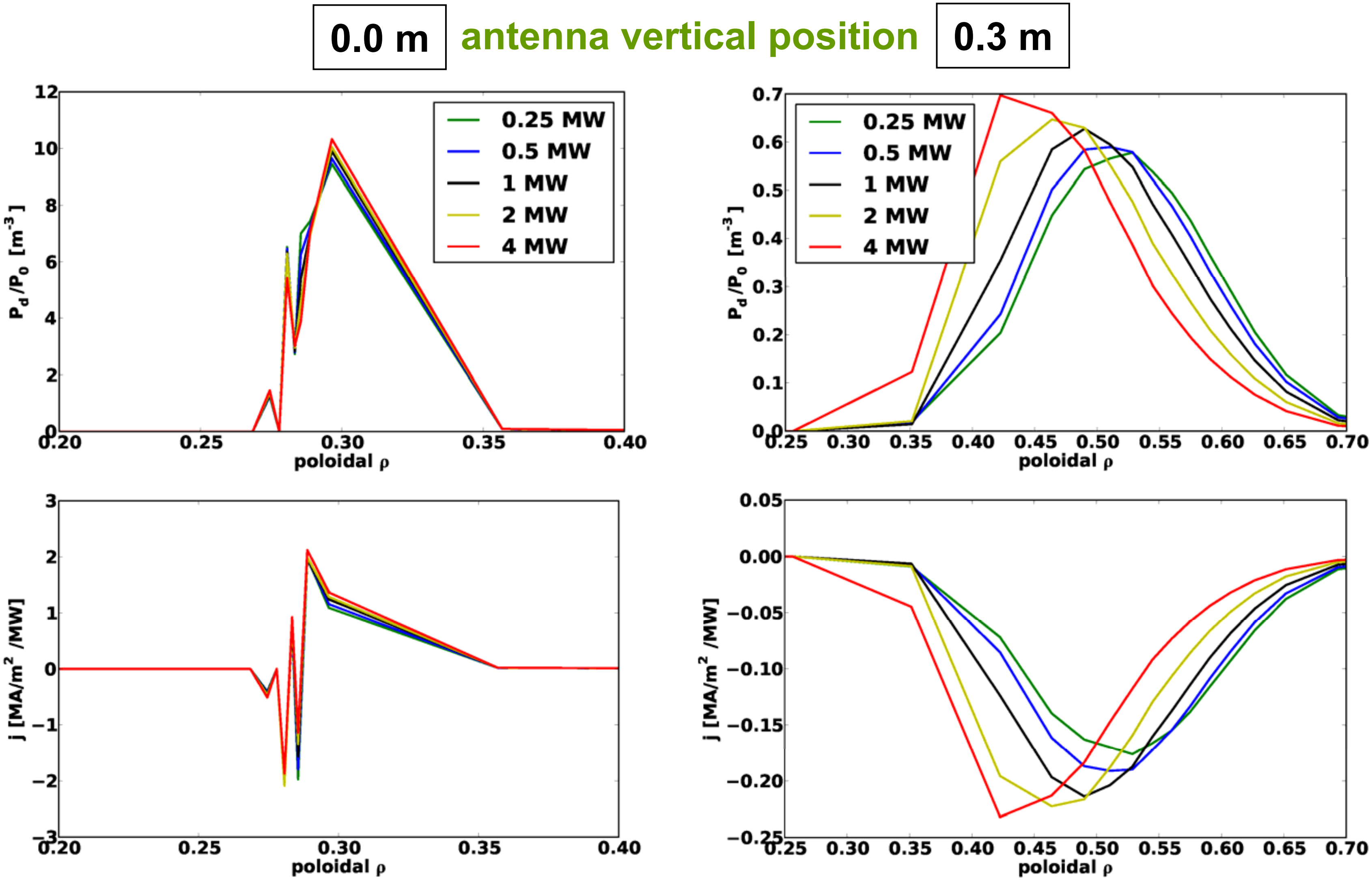
- **Quasilinear absorption typically shifts inwards** with **higher power** because of **distribution function flattening**
- **CD efficiency can either increase or decrease** with power

$N_{||}$ spread causes low CD efficiency



- **Opposite $N_{||}$ sign** rays drive **opposite current**
- **Highest CD efficiency** observed for **frequencies closer to the higher EC harmonic**

Low and high CD efficiency cases compared



Summary & conclusions

- **EBW heating & current drive investigated with AMR + LUKE codes**
  - Large number of different cases examined
- **Power can be deposited and current driven at any radius**
  - **CD efficiency ζ~0.4** can be reached
  - Quasilinear effects must be considered
- **Antenna vertical position and/or frequency are the key parameters**
  - **Various H&CD scenarios possible**
  - **EBWs can be optimized for a specific goal**

Supported by

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DoE DE-AC02-09CH11466

AS CR project AV0Z-20430508

Czech Science Foundation grant 202/08/0419

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