EBW heating and current drive modeling

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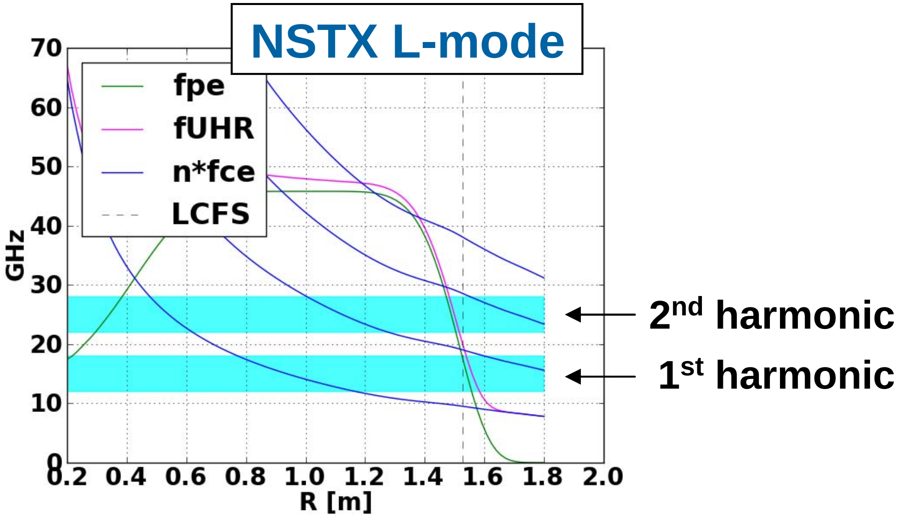
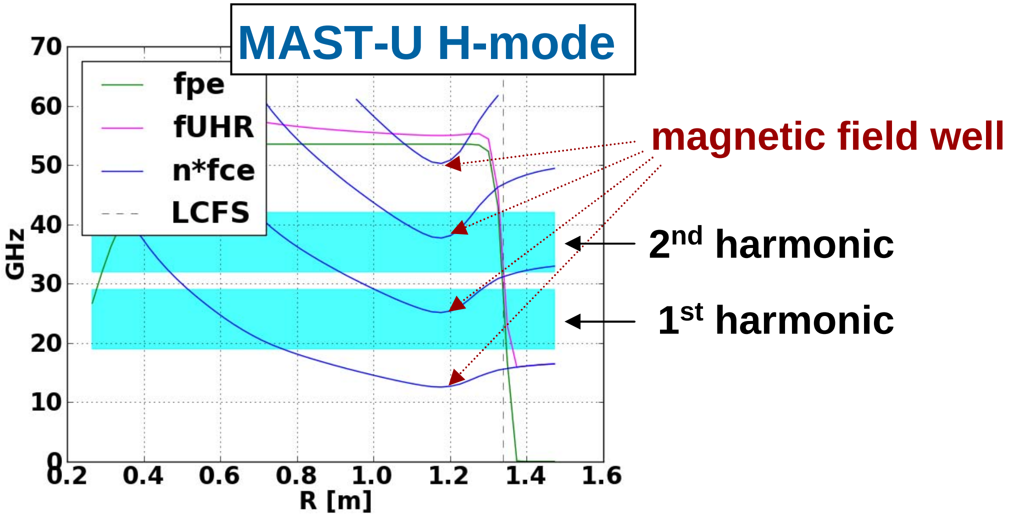
Simulation setup

- **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 (assuming 100% coupling)
- **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** and **toroidal injection angle sign**

Feasible frequency ranges determined by the equilibria

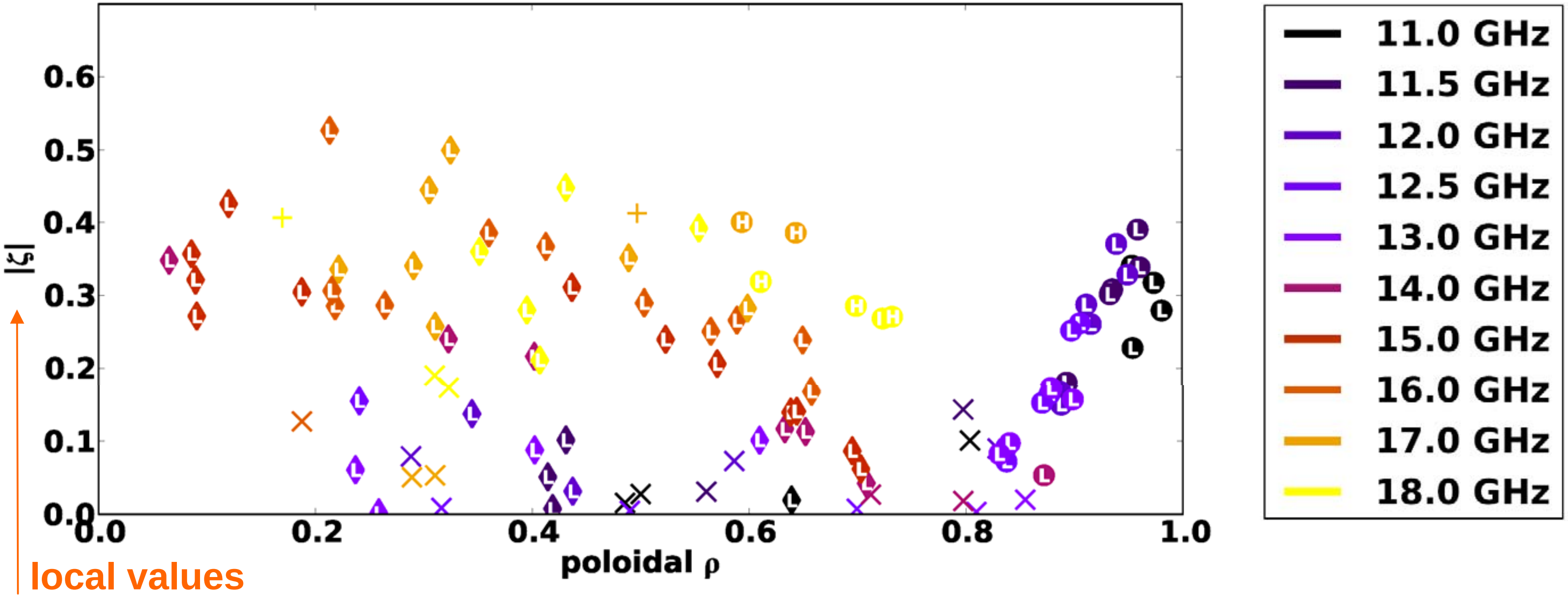


B_0=0.5 T
I_P=0.6 MA
n_{e0}=2.6x10^{19} m^{-3}
T_{e0}=2.9 keV



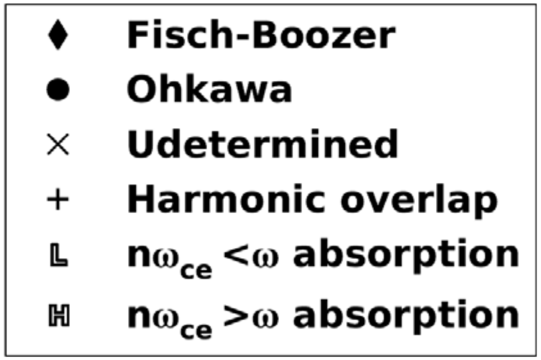
B_0=0.78 T
I_P=1.2 MA
n_{e0}=3.5x10^{19} m^{-3}
T_{e0}=2.4 keV

NSTX L-mode 1st harmonic

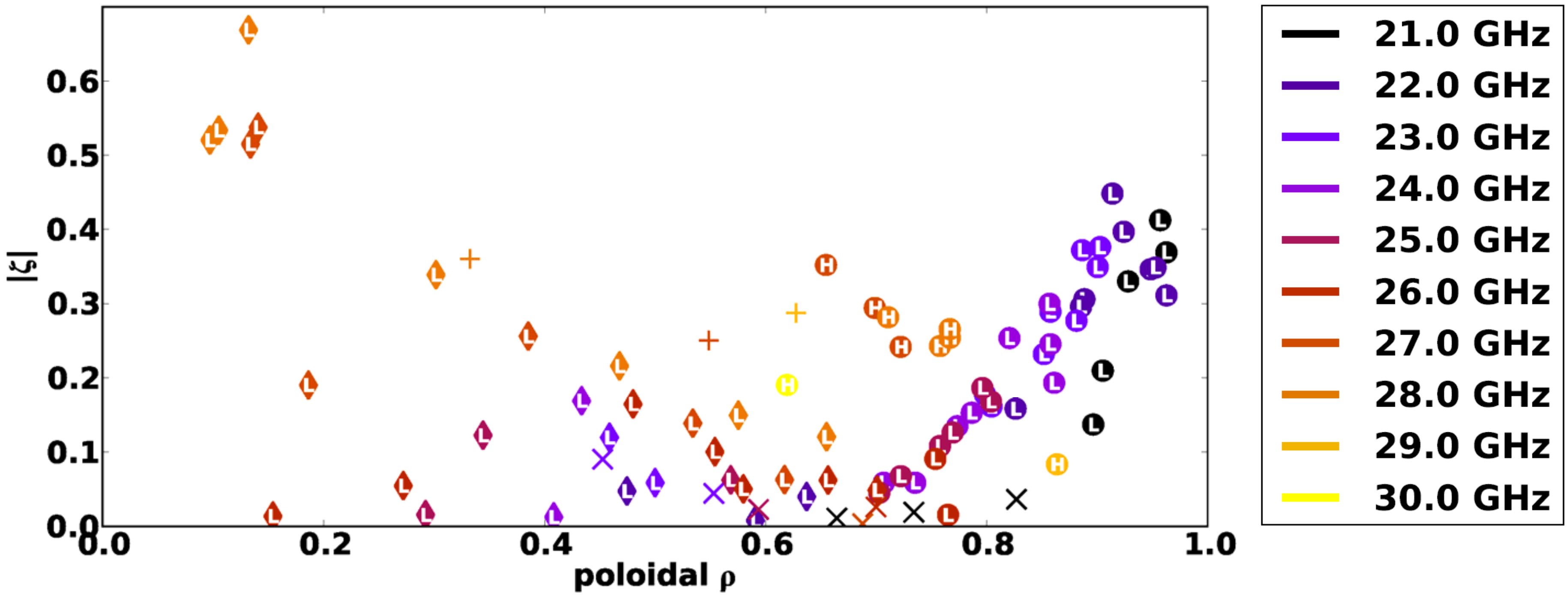


$$\zeta = \frac{e^3}{\epsilon_0^2}\frac{Rn_e}{kT_e}\frac{I}{P} \cong 3.27\frac{I[\mathrm{A}]}{P[\mathrm{W}]}\frac{R_0[\mathrm{m}]n_e\left[10^{19}\,\mathrm{m}^{-3}\right]}{T_e[\mathrm{keV}]}$$

- **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**

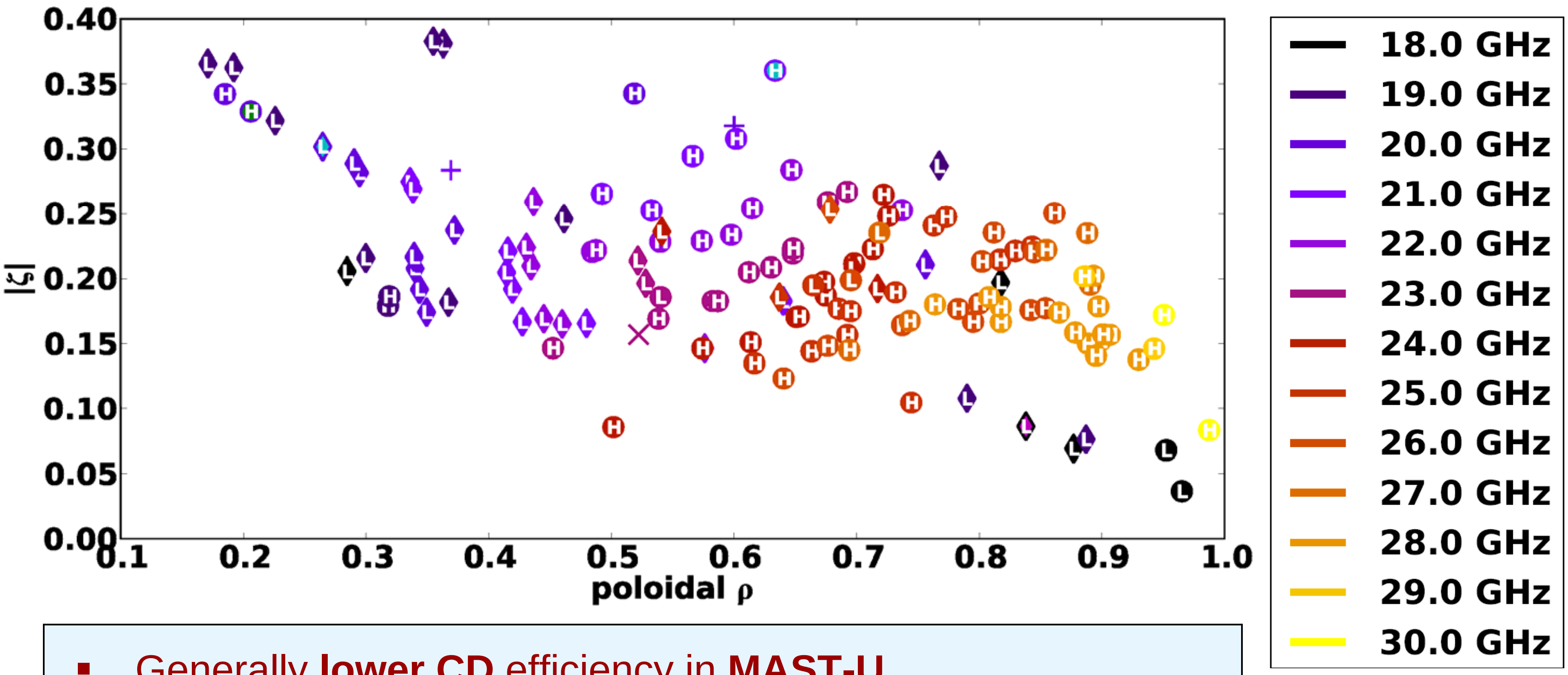


NSTX L-mode 2nd harmonic



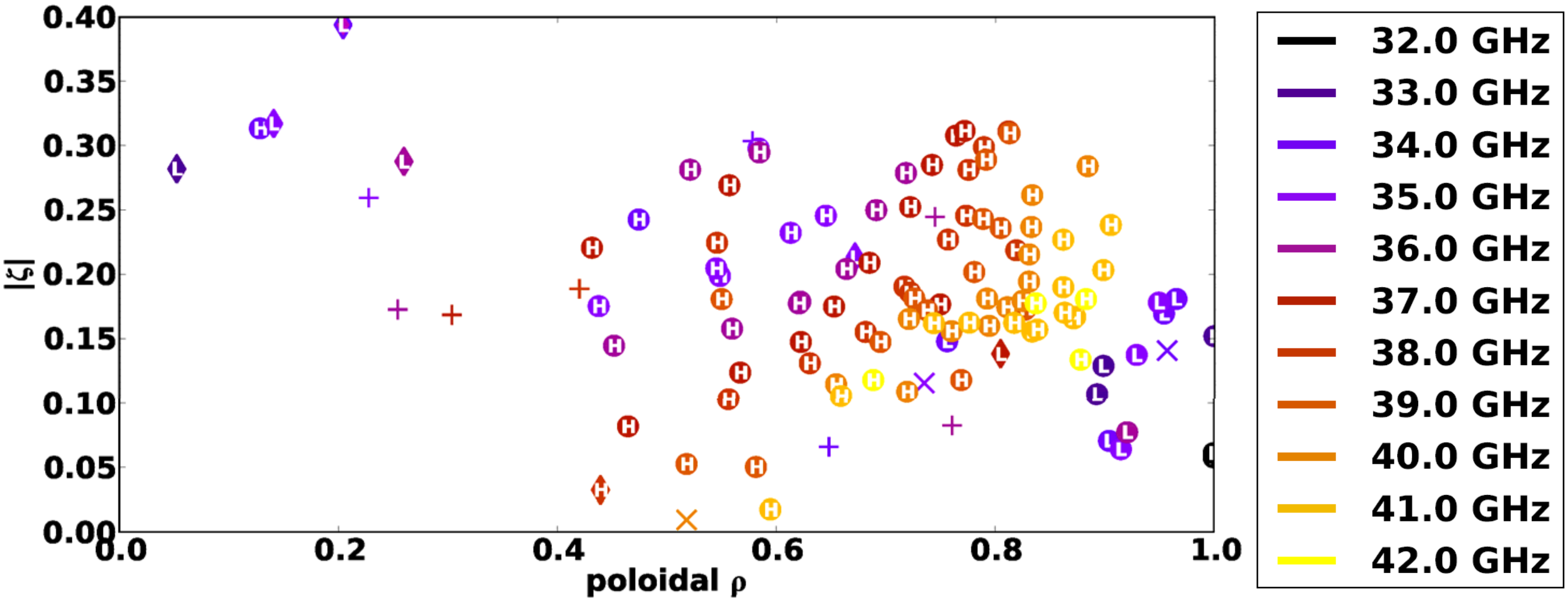
- **Fisch-Boozer** CD is favored in the **central region**
- **Ohkawa** CD is favored at the **edge region**
- A region of high-efficiency Ohkawa with high B-field side absorption occurs
- **Low-efficiency** typically caused by **$N_{||}$ sign mixing**

MAST-U 1st harmonic



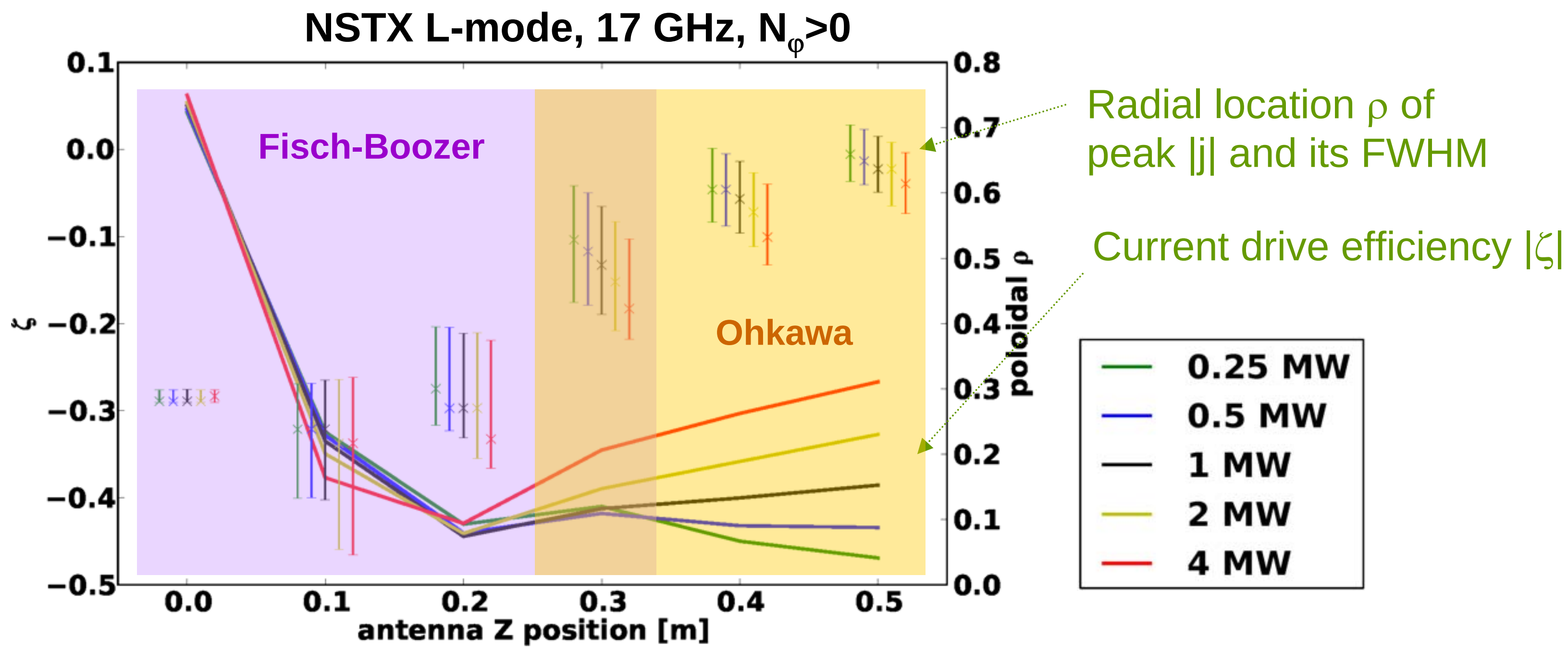
- Generally **lower CD** efficiency in **MAST-U**
- Large number of cases are damped on **high B-field side** because of the magnetic field well at the edge, driving **Ohkawa** current
- **Central region less accessible** (same reason)

MAST-U 2nd harmonic



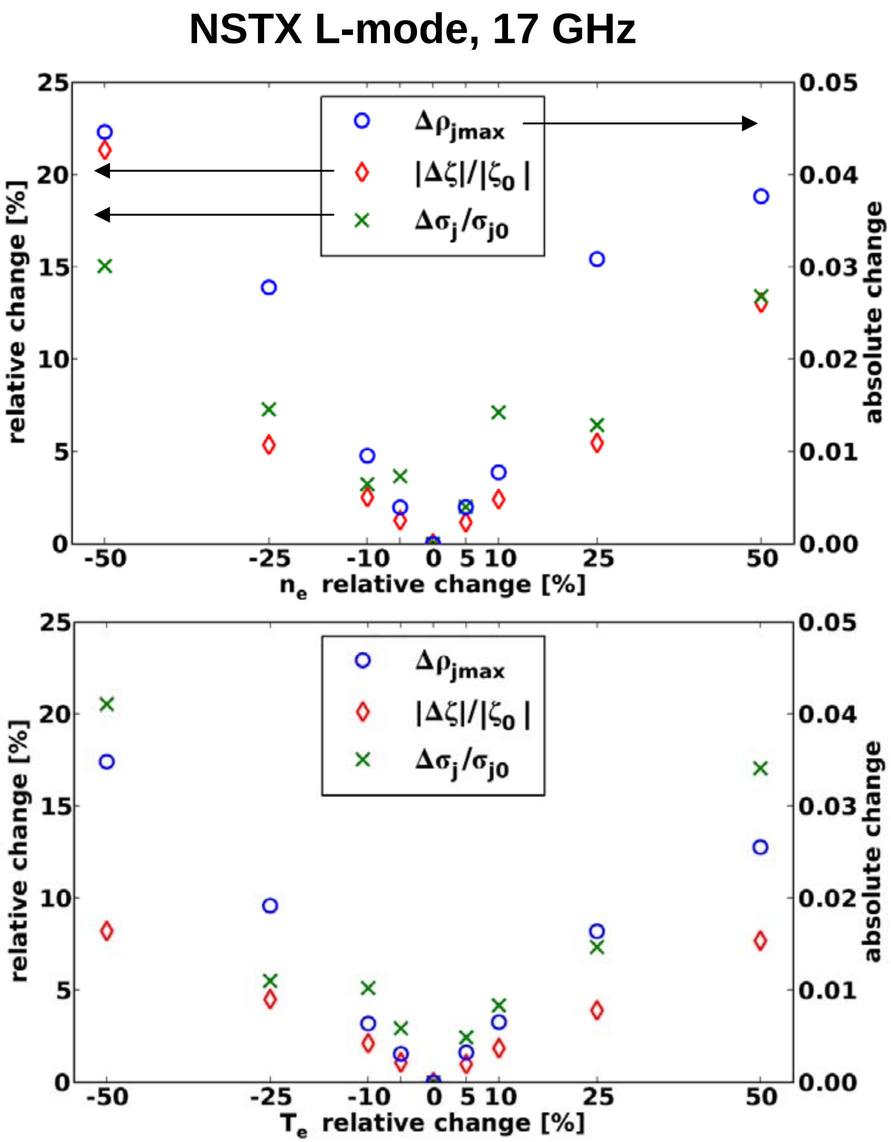
- The space between the **2nd and 3rd harmonic** is more **narrow → worse central region accessibility**
- Ohkawa CD at 3rd harmonic is the dominant scenario

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

EBW H&CD is rather robust

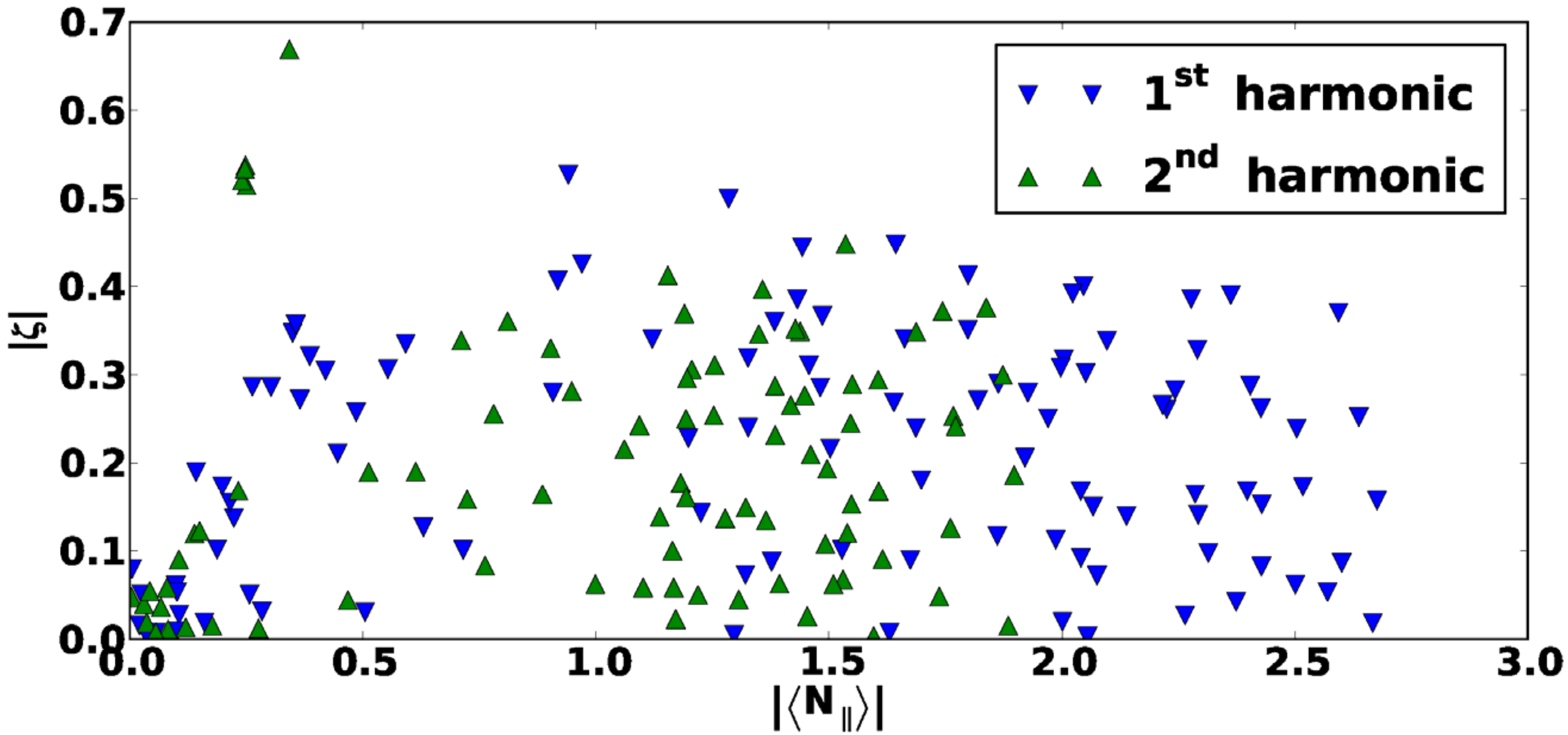


- Shown here are **medians** of absolute peak current location ρ and relative current drive efficiencies and current profile widths
- The median change in **CD efficiency** is **<5%** for **<25% variations**
- The **deposition locations** are **not changed considerably**
- Large changes (not shown here but taken into account) are predicted for mid-plane cases (oscillating, low-z)

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(=3.27×I/P×$R_0 n_{e19}/T_{ekeV}$) ~0.4** can be reached
    - (on-axis 140 kA/MW NSTX L-mode, 90 kA/MW MAST-U)
  - 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**
- **EBW H&CD is rather robust with respect to n_e and T_e variations**
  - **More sensitive to B_{pol}—possibly compensated by B_{tor}**

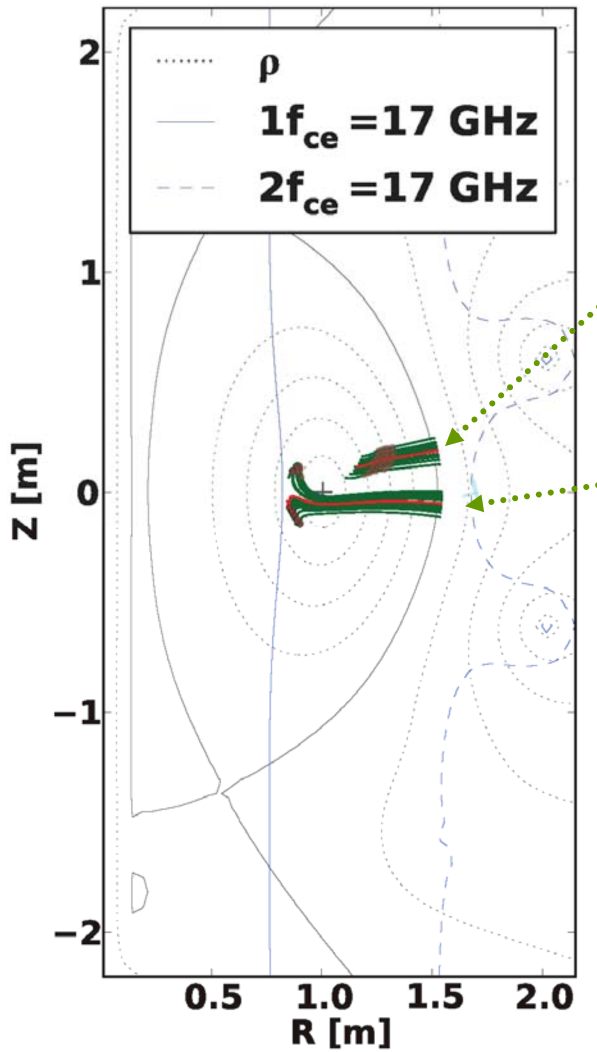
CD efficiency independent of $N_{||}$ in general

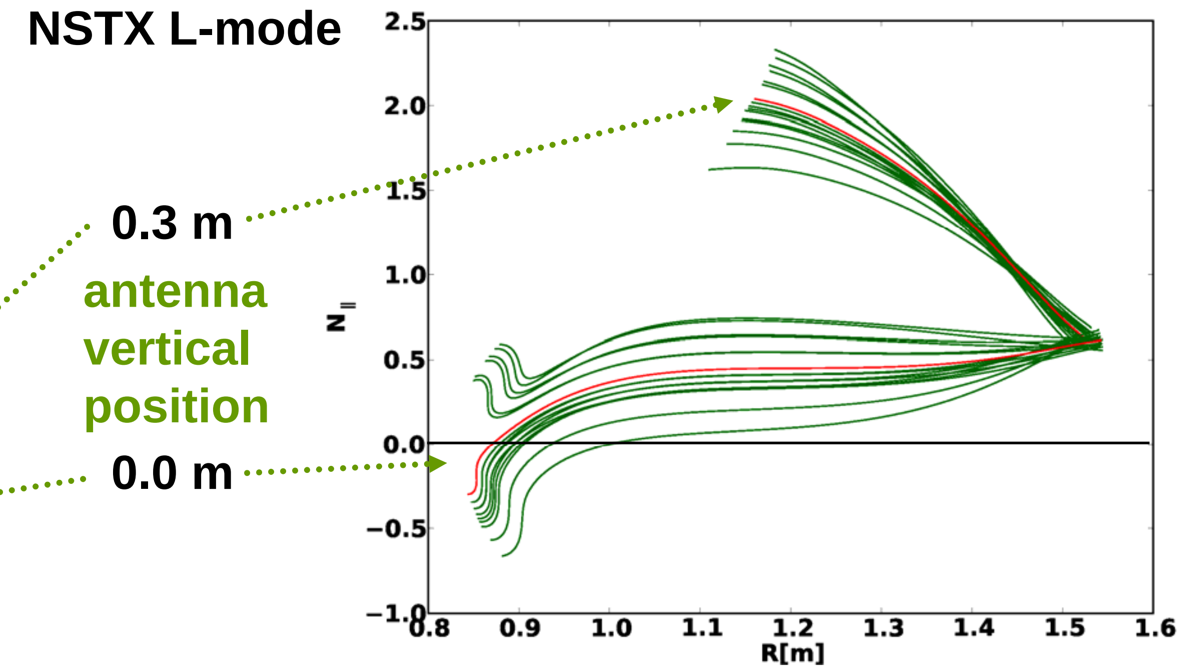


$$\langle N_{||} \rangle = \sum_{i \in \text{F-P bins}} \left(\Delta P(\Gamma_i) \frac{\sum_{\text{rays}, \rho \in \Gamma_i} N_{||} \Delta P_{\text{ray}}(N_{||}, \rho)}{\sum_{\text{rays}, \rho \in \Gamma_i} \Delta P_{\text{ray}}(N_{||}, \rho)} \right) \Bigg/ \sum_{i \in \text{F-P bins}} \Delta P(\Gamma_i)$$

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

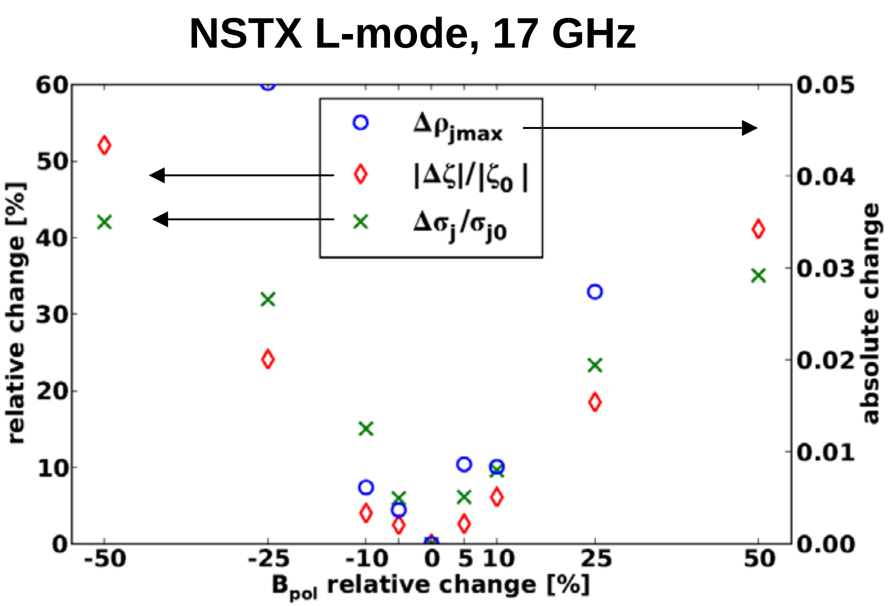
$N_{||}$ spread causes low CD efficiency





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

Changing B_{pol} (I_P) has larger effect

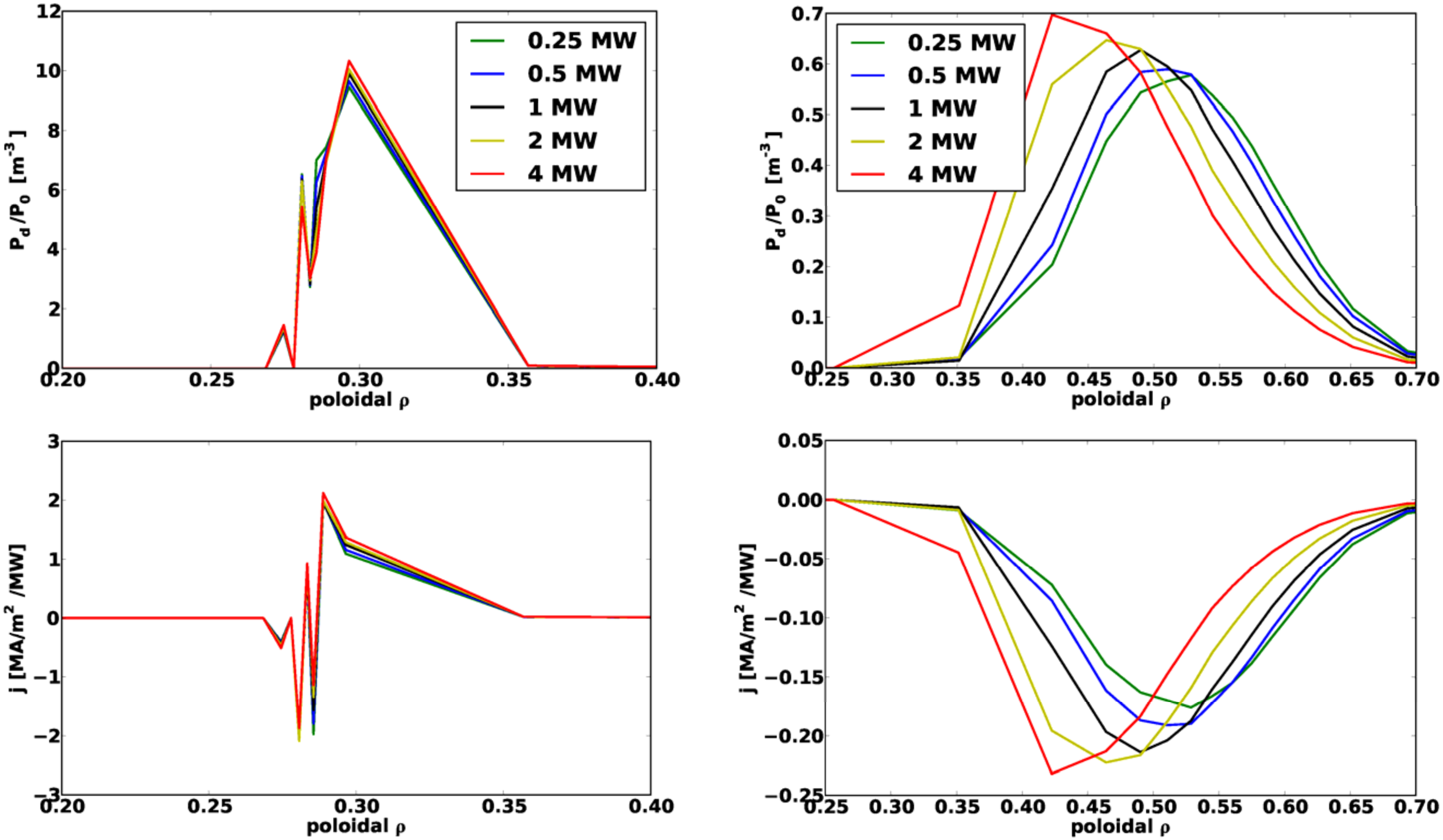


- Shown here are **medians** of absolute peak current location ρ and relative current drive efficiencies and current profile widths

- The median change in **CD efficiency** is **<25%** for **<25% variation**
- The **deposition locations** are **not changed considerably**
- **Can be possibly compensated by changing B_{tor}**

Low and high CD efficiency cases compared

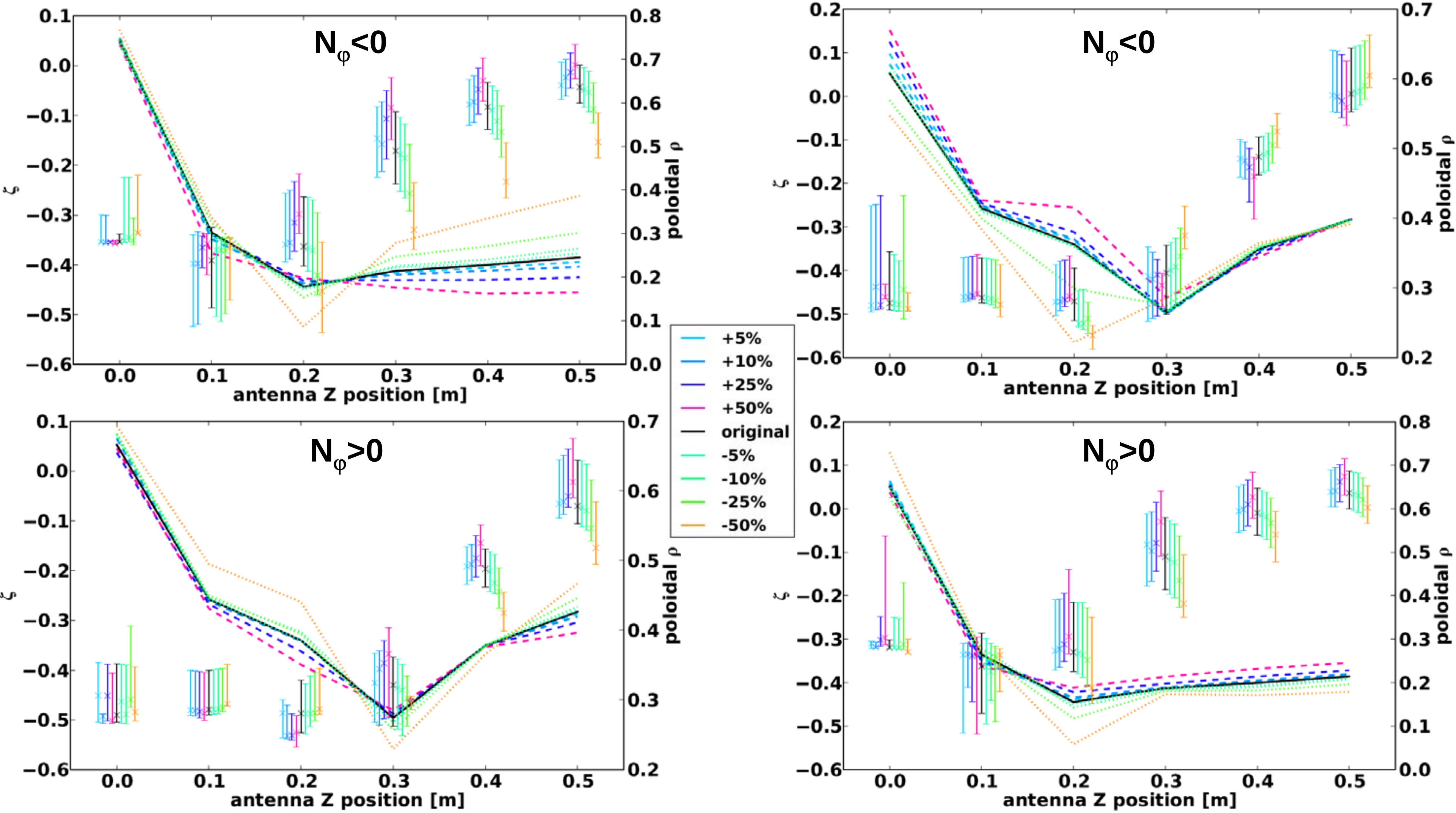
0.0 m antenna vertical position **0.3 m**



n_e/T_e variations details

n_e variation

T_e variation



B_{pol} variations details