INFLUENCE OF THE SCRAPE OFF LAYER ON RF ACTUATOR PERFORMANCE

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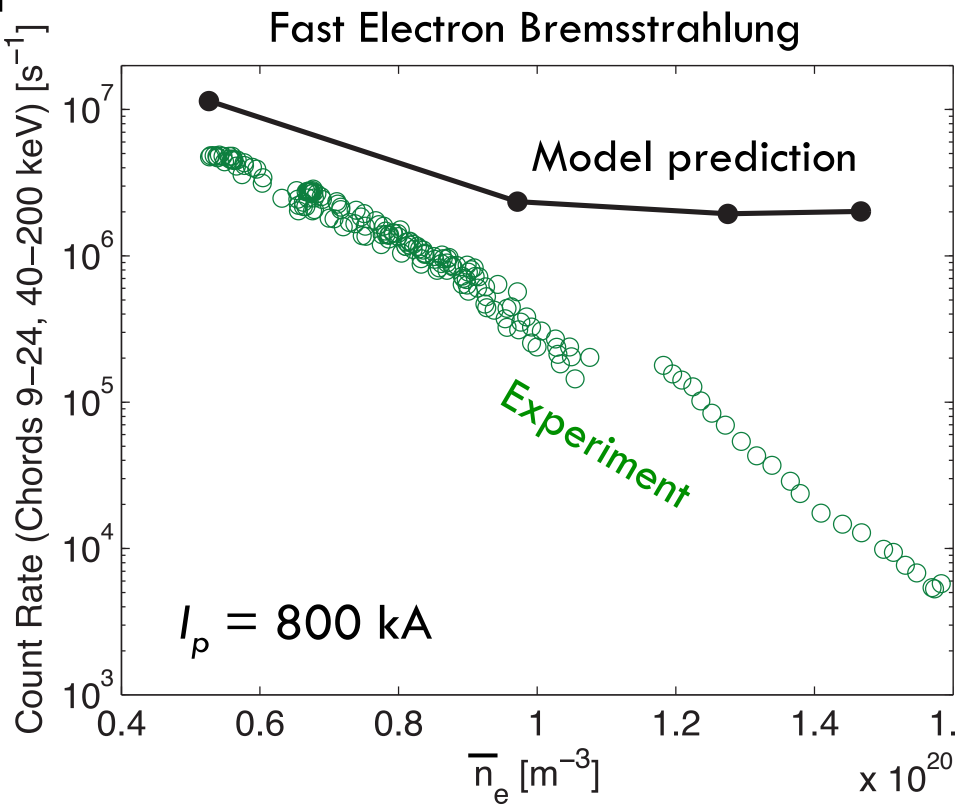
RF actuators will play a major role in fusion reactors → must have confidence they will work

- Steady-state fusion reactors will likely need RF actuators to control current profile and access burning regime
  - Ion cyclotron range of frequency: core heating and current drive
  - Lower hybrid range of frequency: off-axis current drive
- Two case studies where behavior of RF waves in the SOL had unexpected impact on actuator performance
  - LHCD on Alcator C-Mod
  - HHFW on NSTX [Perkins, EX/P4-42]

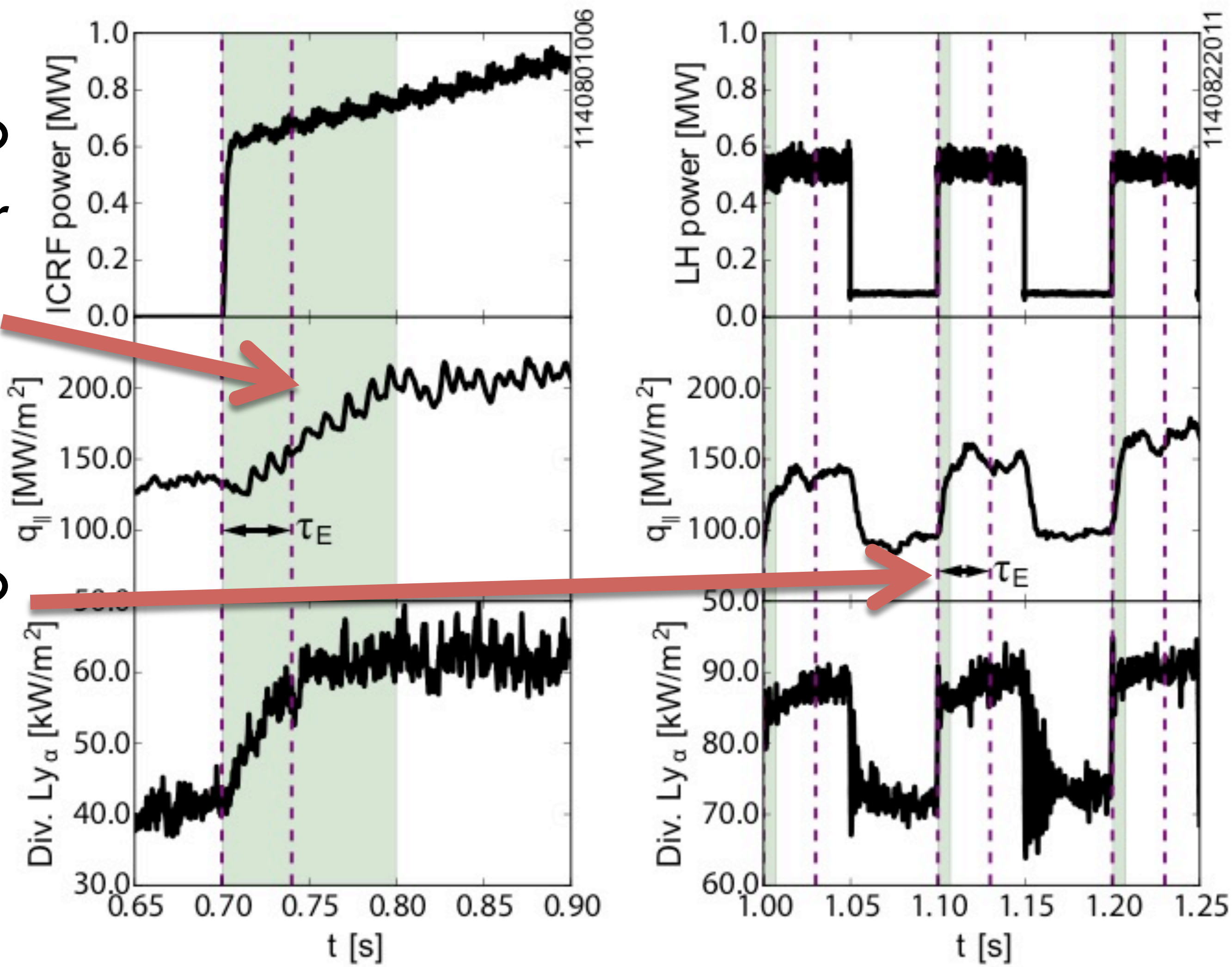
Loss of LHCD effect at high density not predicted by modeling w/o SOL

- Modeling in advance of experiments (w/o SOL) predicted high CD efficiency up to n_e ~ 1.5×10^{20} m^{-3}
- Experiments show very weak non-thermal emission and no CD effect at n_e > ~1.0×10^{20} m^{-3}



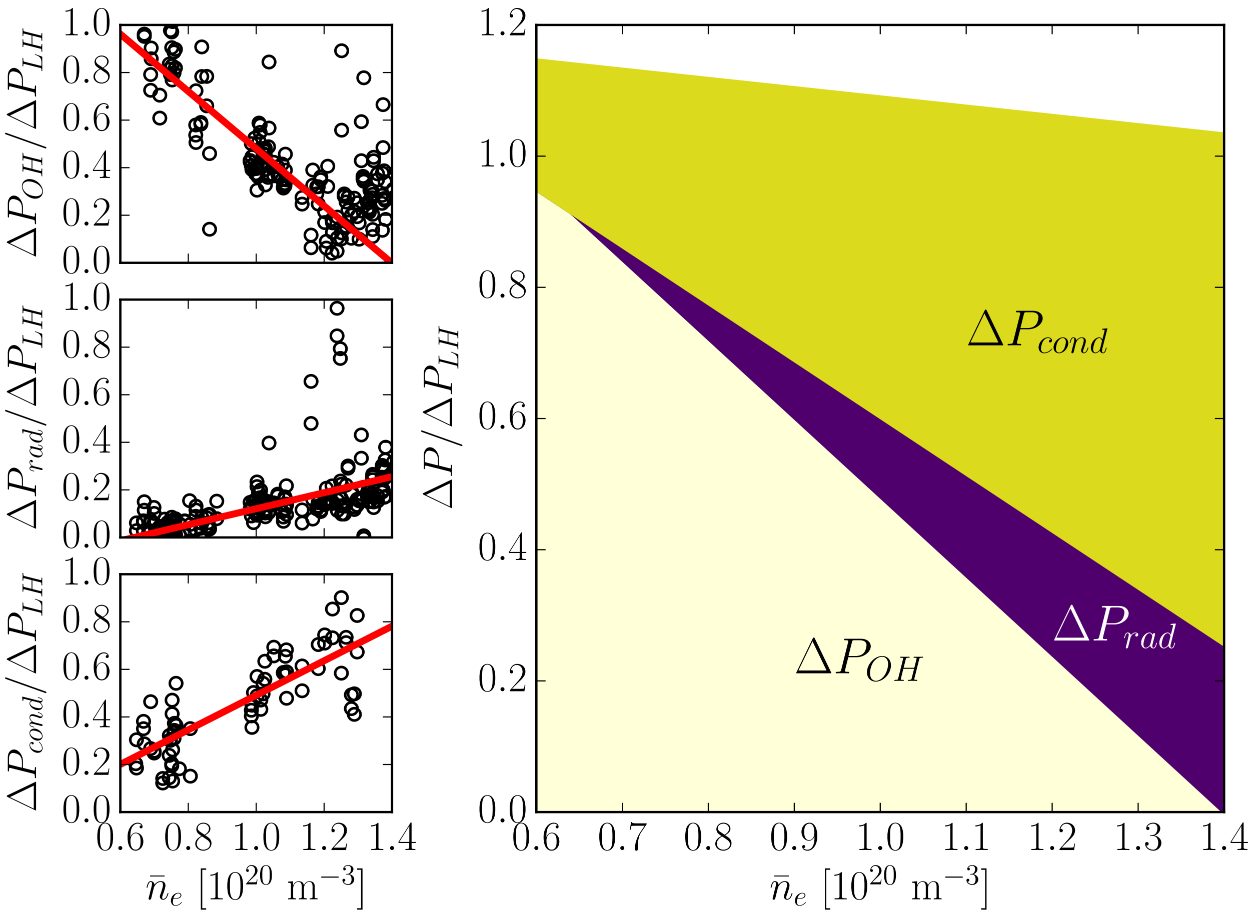
Prompt response of SOL to LHRF power indicates waves are absorbed near LCFS

- Edge response to ICRF power is delayed
  - $t > \tau_E$
- Edge response to LHRF is prompt
  - $t << \tau_E$

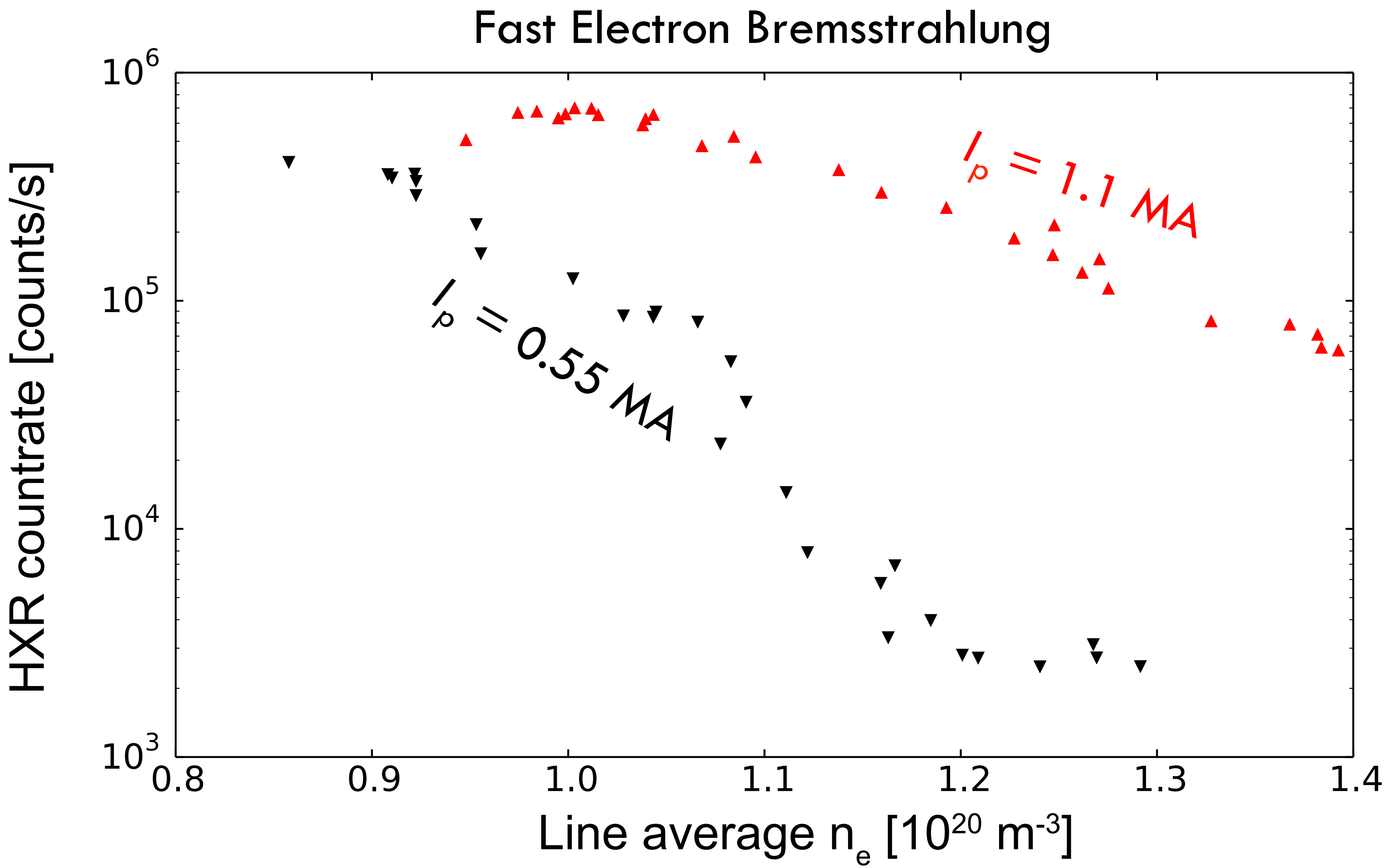


Increasing fraction of LH power damps near the LCFS as density increases

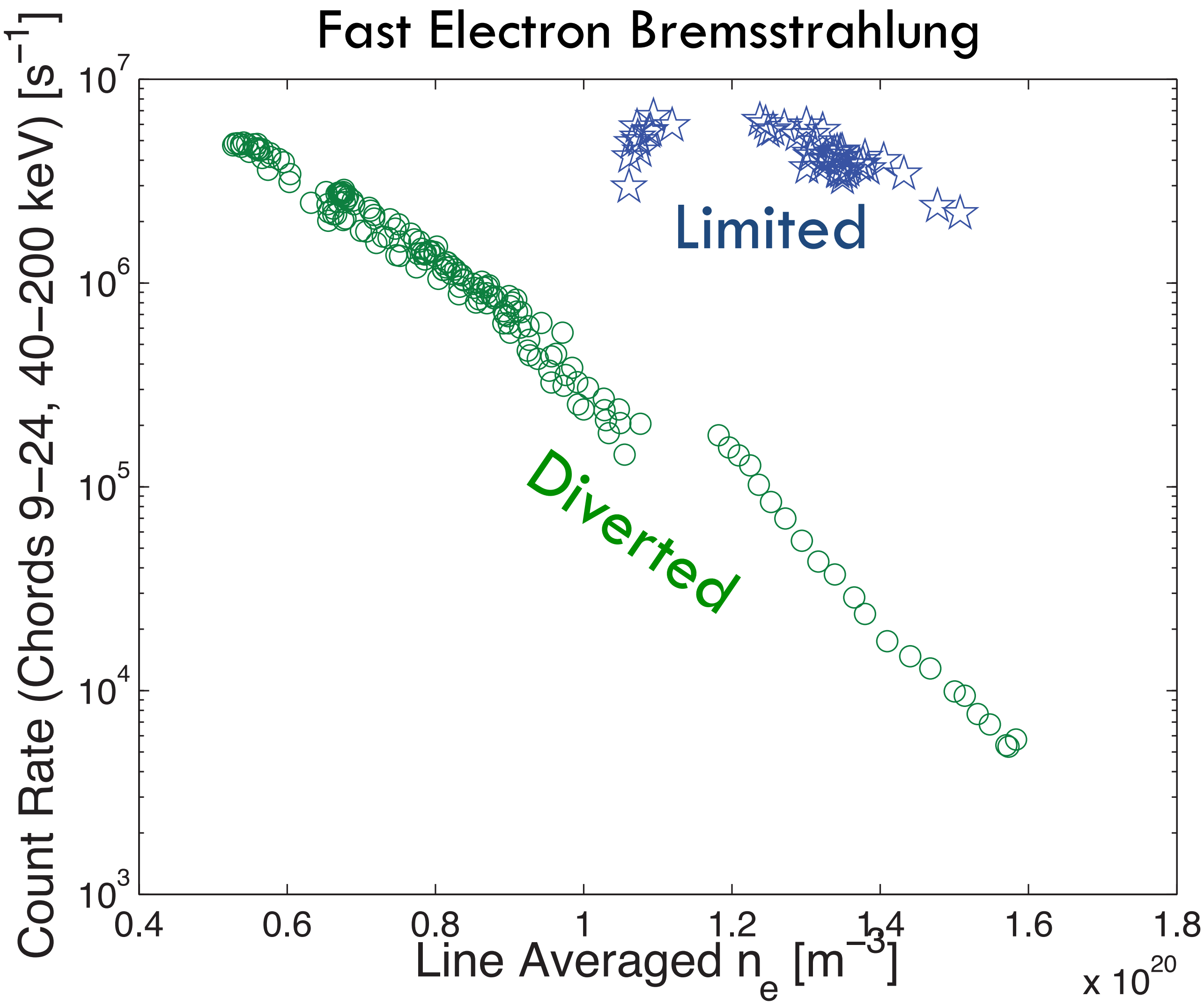
- Majority of LHRF power goes to displacing Ohmic power at low density
- Majority of LHRF power radiated or conducted to divertor at high density



Current drive at high density recovers with high plasma current on C-Mod

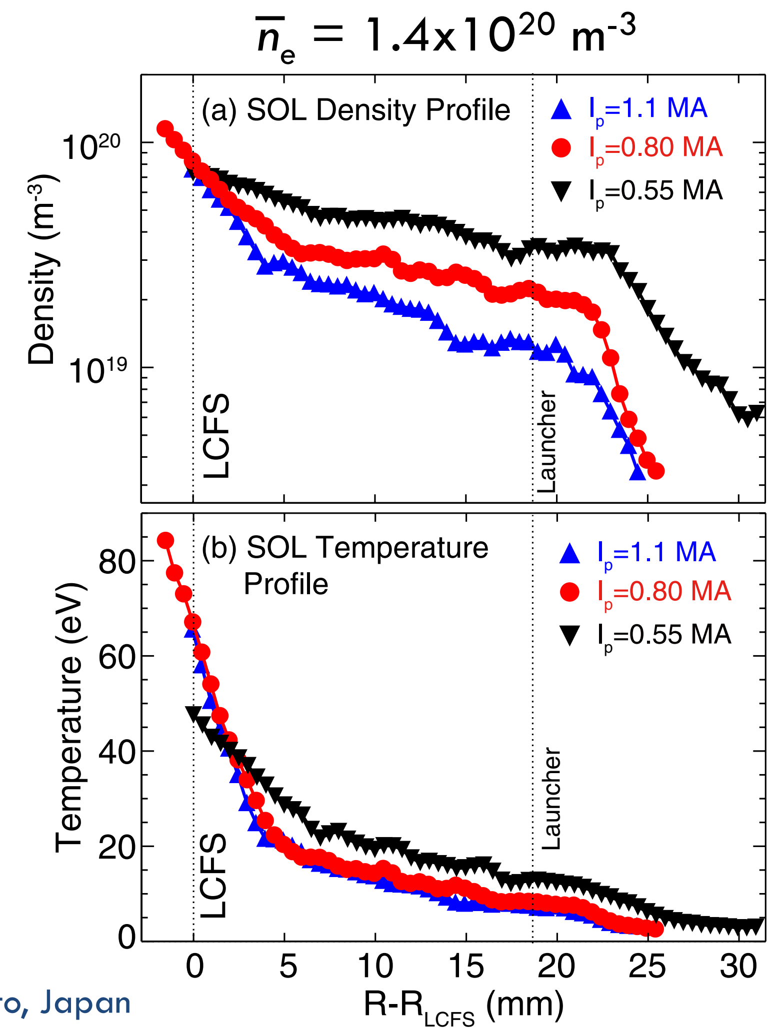


Current drive at high density recovers in inner wall limited discharges on C-Mod

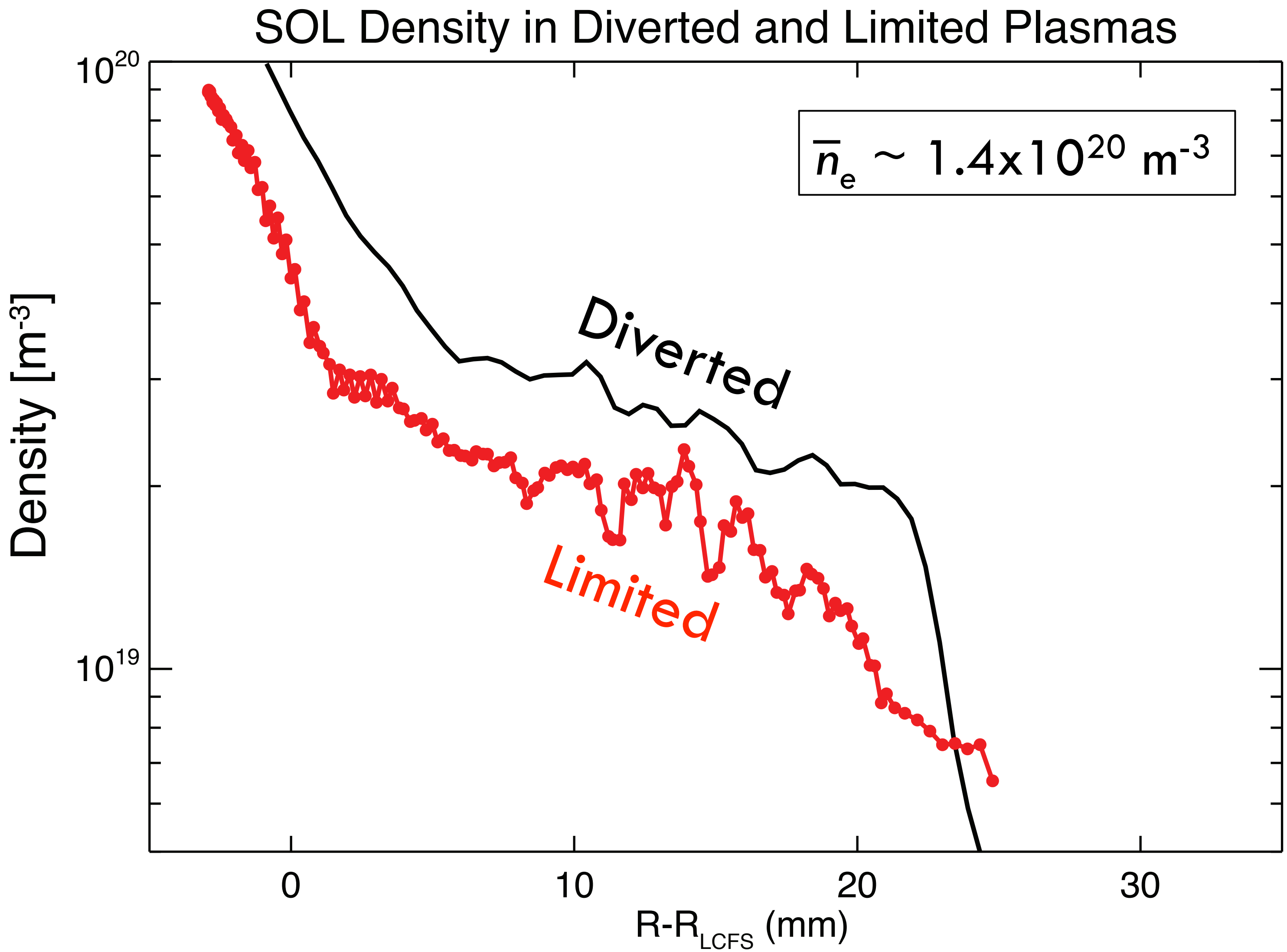


SOL profiles differ considerably for limited and high current discharges

- Larger poloidal field affects ray trajectories/ upshifts at higher current
- Density gradient in SOL is steeper at high current
  - Profiles for inner wall limited discharges are similar to higher current discharges

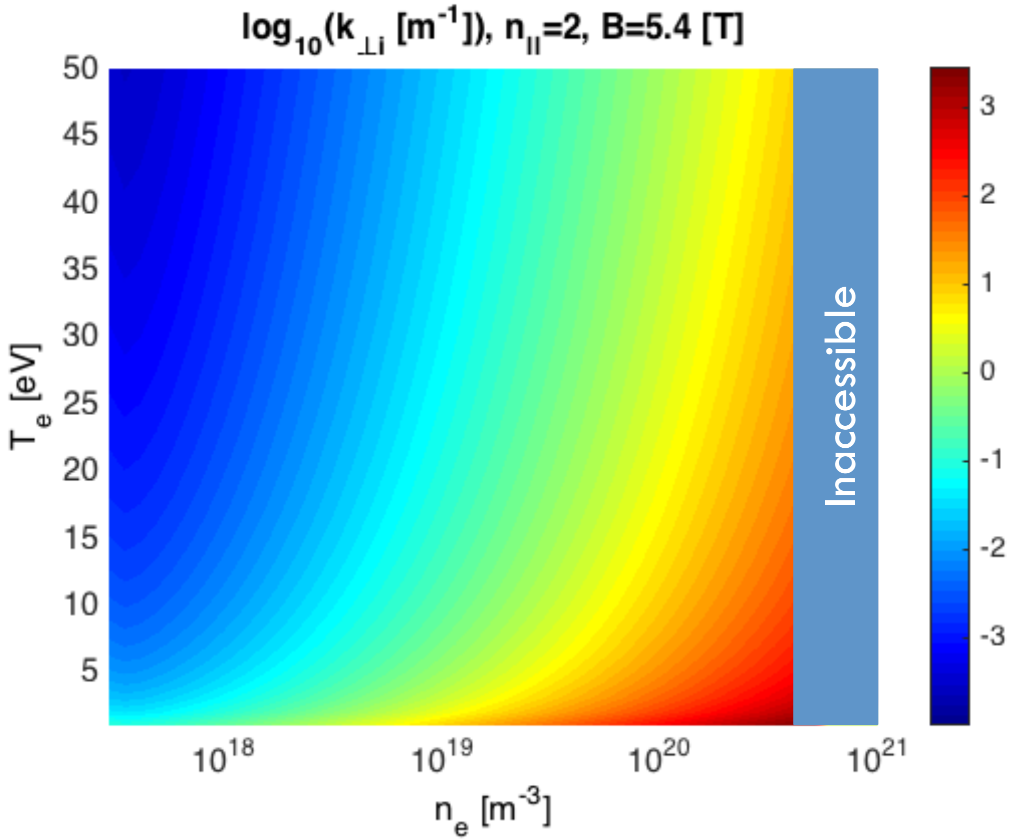


Inner wall limited SOL profiles also steeper than diverted profiles

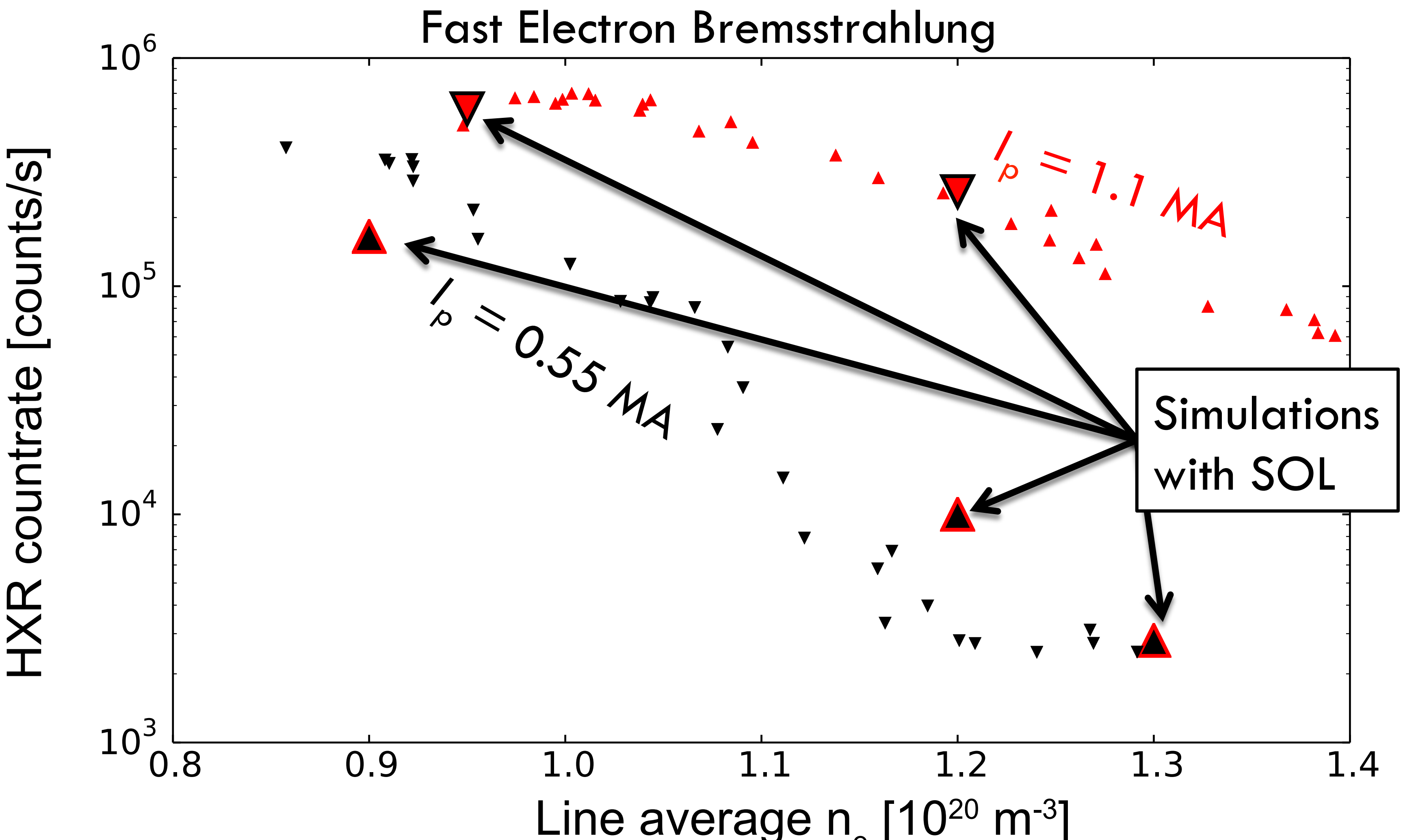


Collisional damping is strong in cold, dense regions of SOL

- Electron-ion collisions lead to significant power loss where ν_{ei} is large
- Conditions near active divertor lead to e-folding lengths of ~ cm's

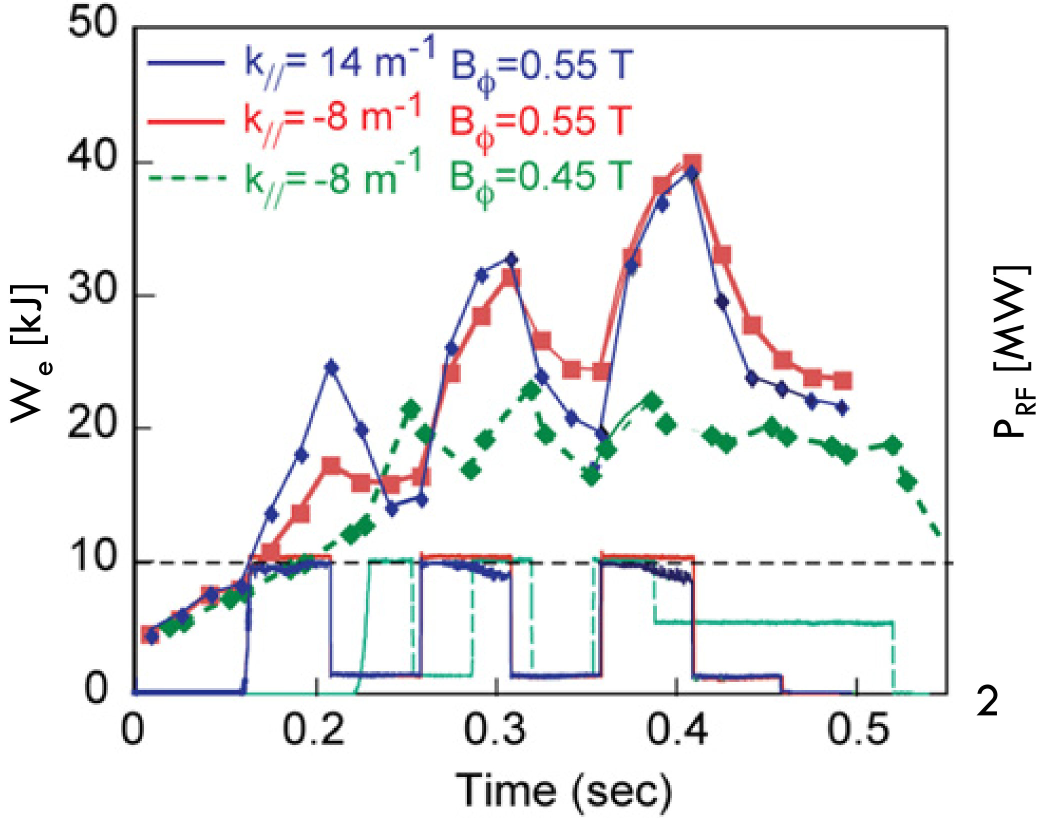


Modeling including collisional SOL model reproduces experimental trends

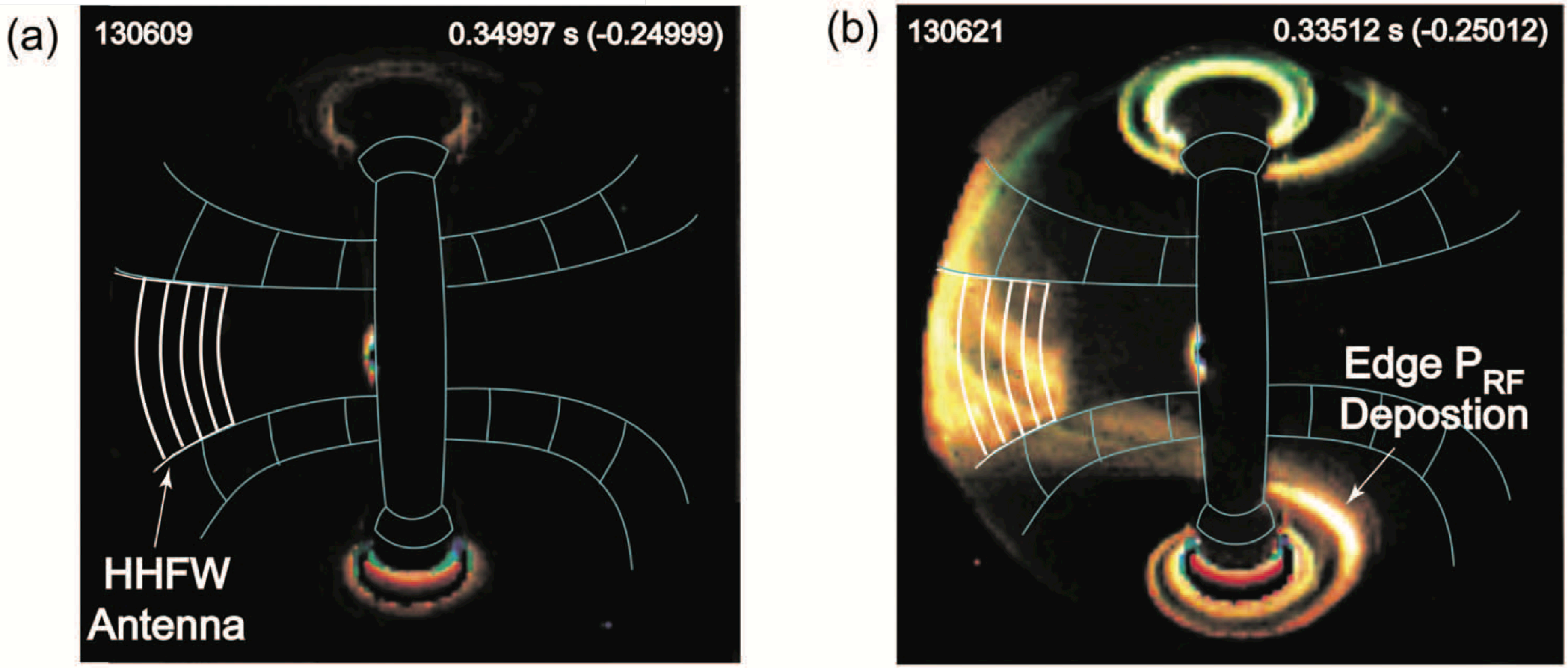


HHFW core heating on NSTX is sensitive to B_φ, n_e, and $k_{||}$

- Strong heating effect at higher B_φ and $k_{||}$
- Core heating effect reduced at lower $k_{||}$ and B_φ



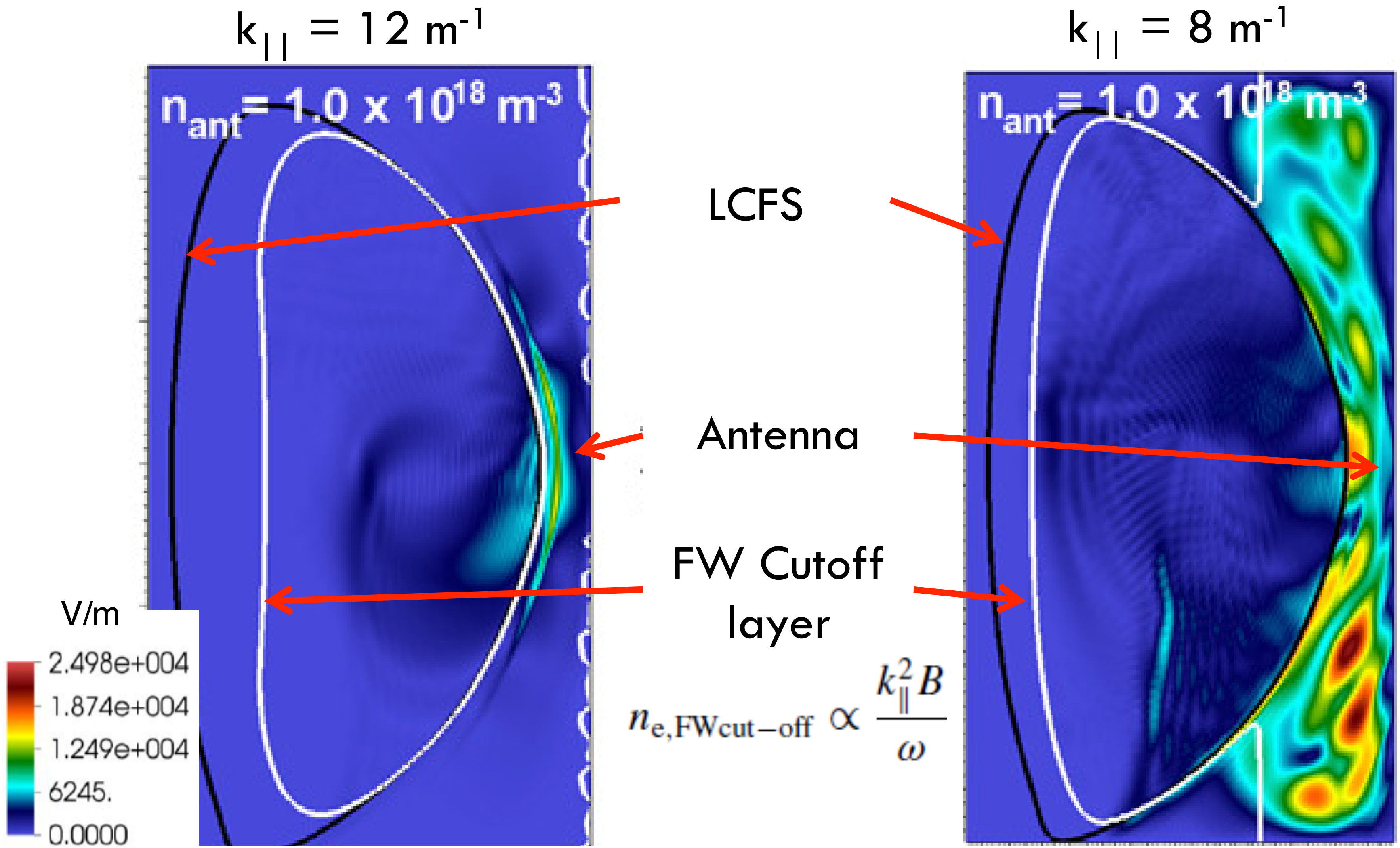
Spirals observed leaving HHFW antenna indicate localized power deposition in SOL of NSTX



- Probe and IR measurements consistent with localized power sink in divertor region

AORSA shows enhanced RF fields in SOL when cutoff layer opens in front of antenna

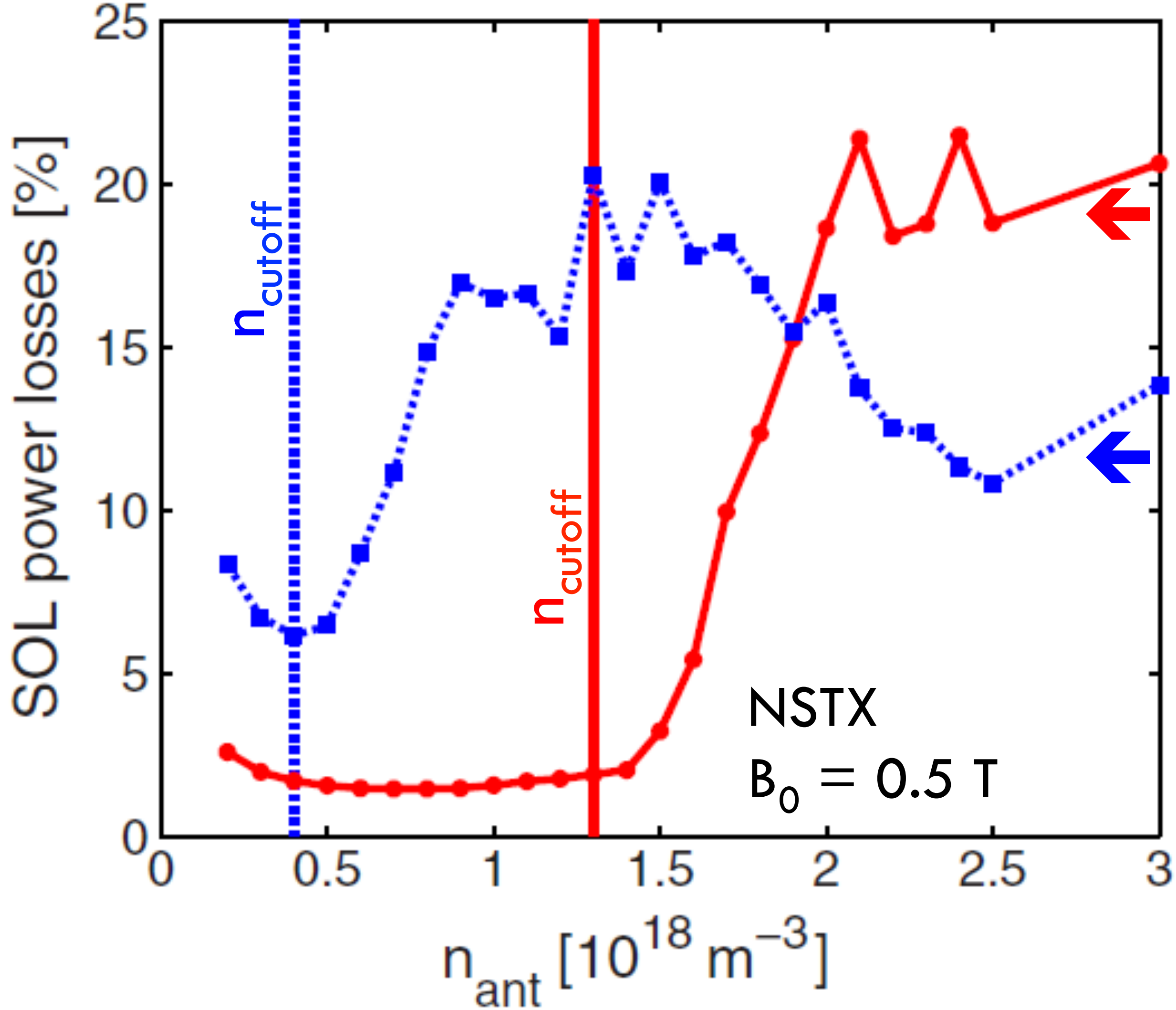
NSTX-U



$$n_{e,\mathrm{FWcut-off}} \propto \frac{k_{\parallel}^2 B}{\omega}$$

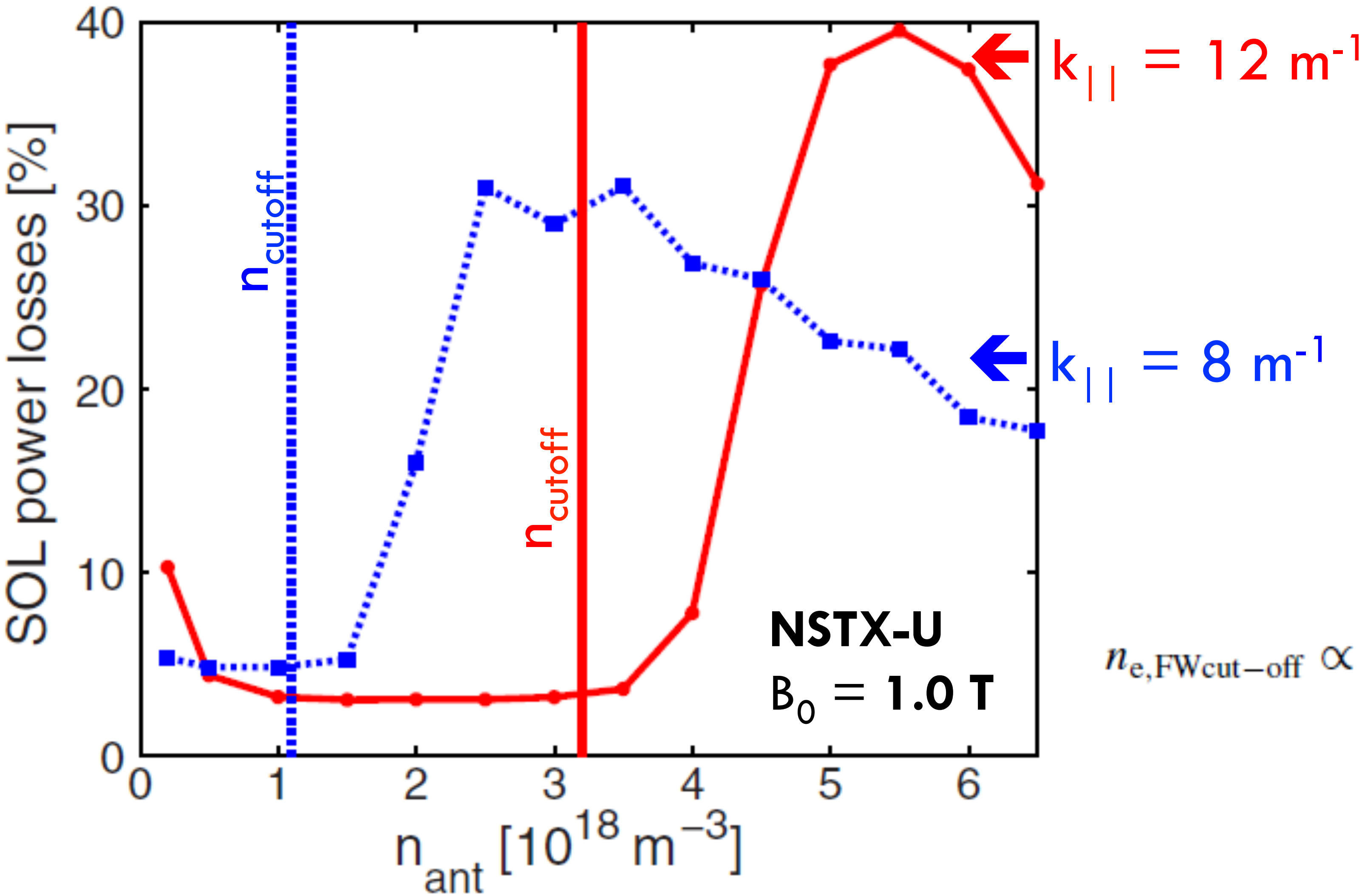
SOL power losses increase as wave transitions from evanescent to propagating

NSTX-U



$$n_{e,\mathrm{FWcut-off}} \propto \frac{k_\parallel^2 B}{\omega},$$

Increased B-field of NSTX-U predicted to reduce SOL losses at high density



$$n_{\mathrm{e,FWcut-off}} \propto \frac{k_{\parallel}^2 B}{\omega},$$

Need to consider SOL impacts when assessing RF actuators for reactors

- SOL profiles are important for more than just antenna coupling
- Other deleterious effects are also sensitive to SOL
  - Parametric decay instabilities (PDI) [Ding EX/P7-5]
  - Impurity generation with high-Z walls
- SOL and core should be considered together when modeling new experiments/reactors [Shiraiwa, TH/P4-27]
- As discussed in previous talk [Bonoli, TH/5-1], HFS SOL profiles are very different from LFS SOL profiles

Conclusions

- Current drive efficiency of LHCD on Alcator C-Mod is reduced when power is absorbed close to the LCFS
- Heating efficiency of HHFW on NSTX suffers from SOL losses if FW is allowed to propagate in the SOL
- Wave propagation/absorption in SOL can lead to unexpected consequences and must be considered in modeling of RF actuators for future reactors

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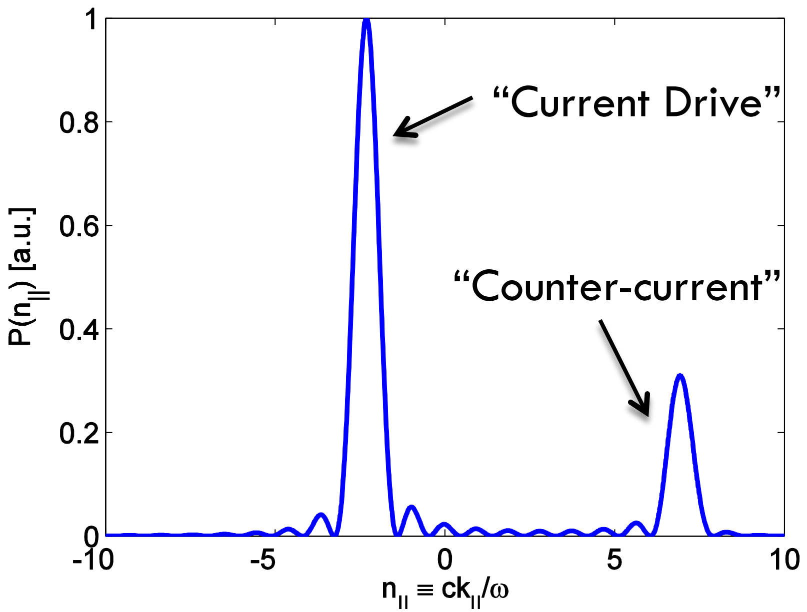
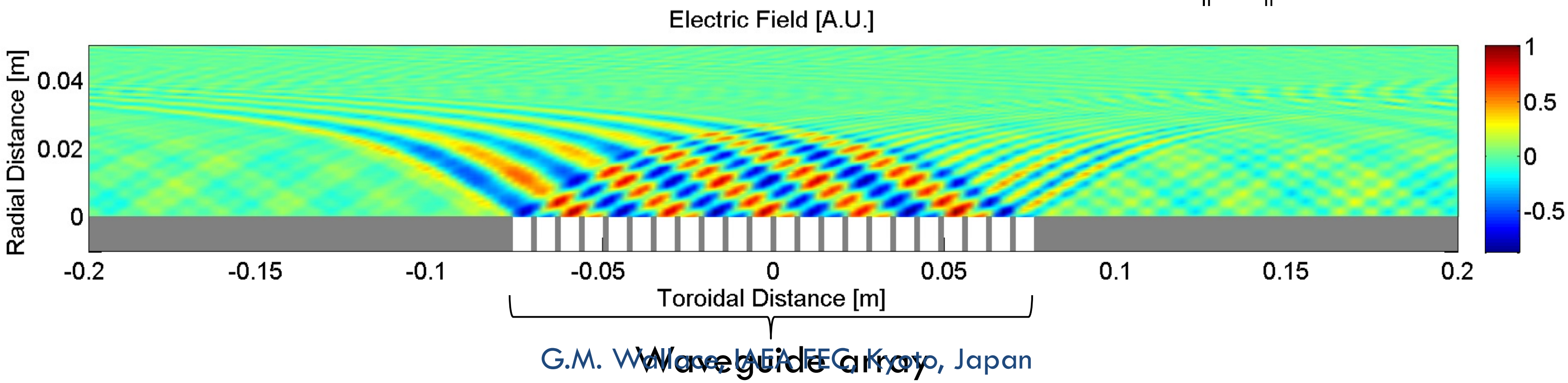
Extra slides

LH waves launched by slow wave structure at plasma edge

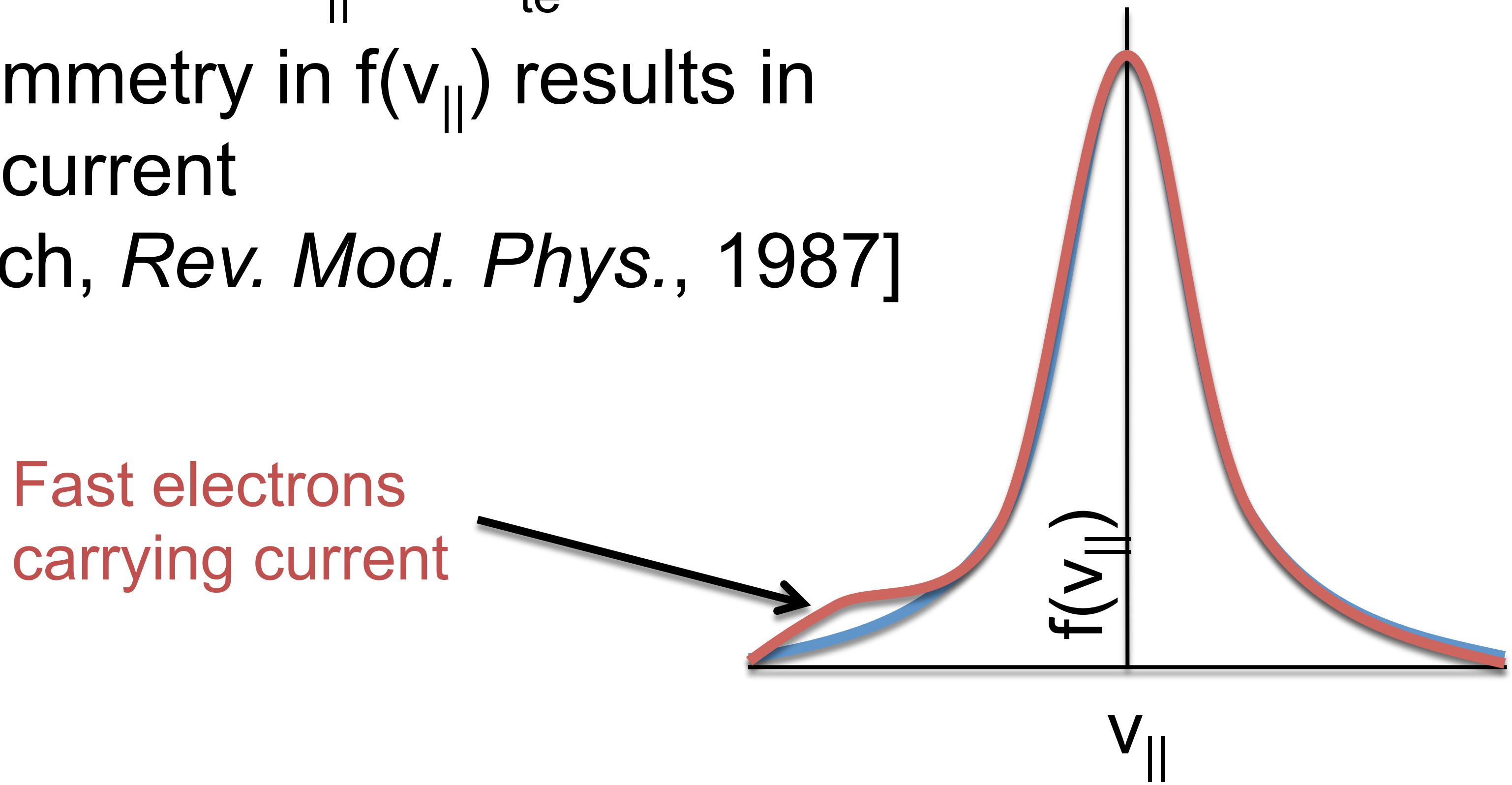
- $\omega \sim 3 - 5 \times \omega_{LH}$
  - $\omega_{LH} = \omega_{pi}(1+ \omega_{pe}^2/ \omega_{ce}^2)^{-1/2}$
- LH launcher couples electrostatic slow mode
- Waves launched preferentially in counter-current direction





LH waves transfer energy and parallel momentum to fast electrons to drive current

- LH waves Landau damp on electrons at $v_{||} \sim 3v_{te}$
- Asymmetry in $f(v_{||})$ results in net current
  [Fisch, *Rev. Mod. Phys.*, 1987]



Parallel index of refraction, $n_{||} \equiv ck_{||}/\omega$, impacts wave damping, propagation, & CD

- LH wave damps strongly at

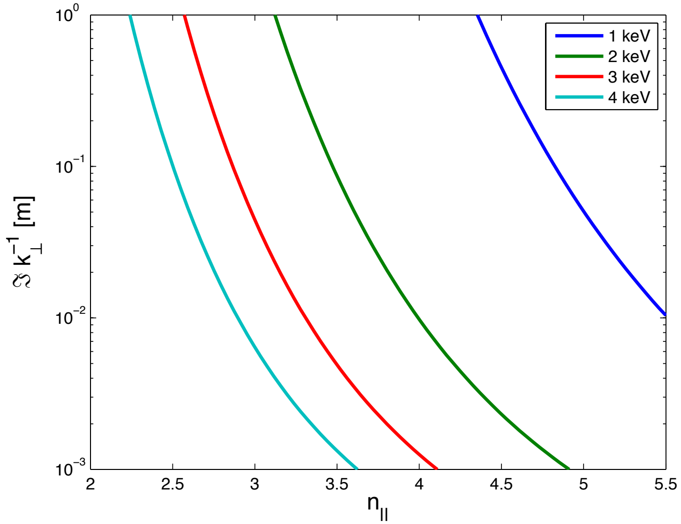
$$n_{\|} \approx \sqrt{30 / T_e}$$

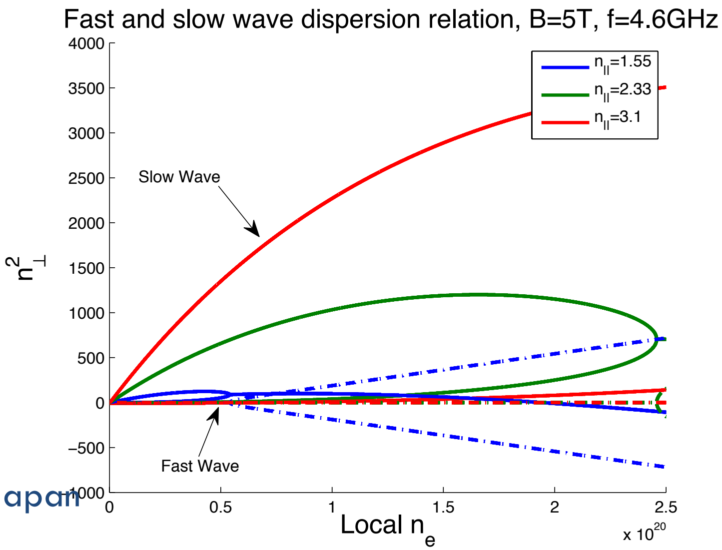
- LH wave cannot propagate unless:

$$n_{\|} > \sqrt{1 - \frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2} + \frac{\omega_{pe}}{|\omega_{ce}|}}$$

- Lower $n_{||}$ improves current drive efficiency

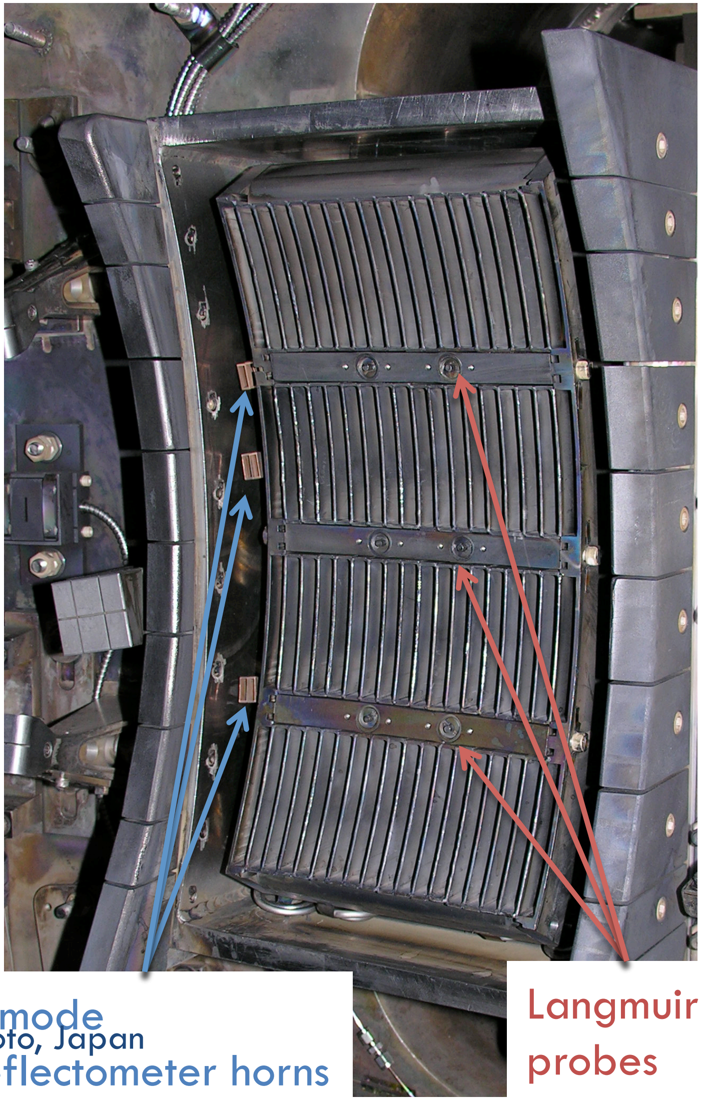
$$\eta \propto \frac{1}{n_{\|}^2}$$

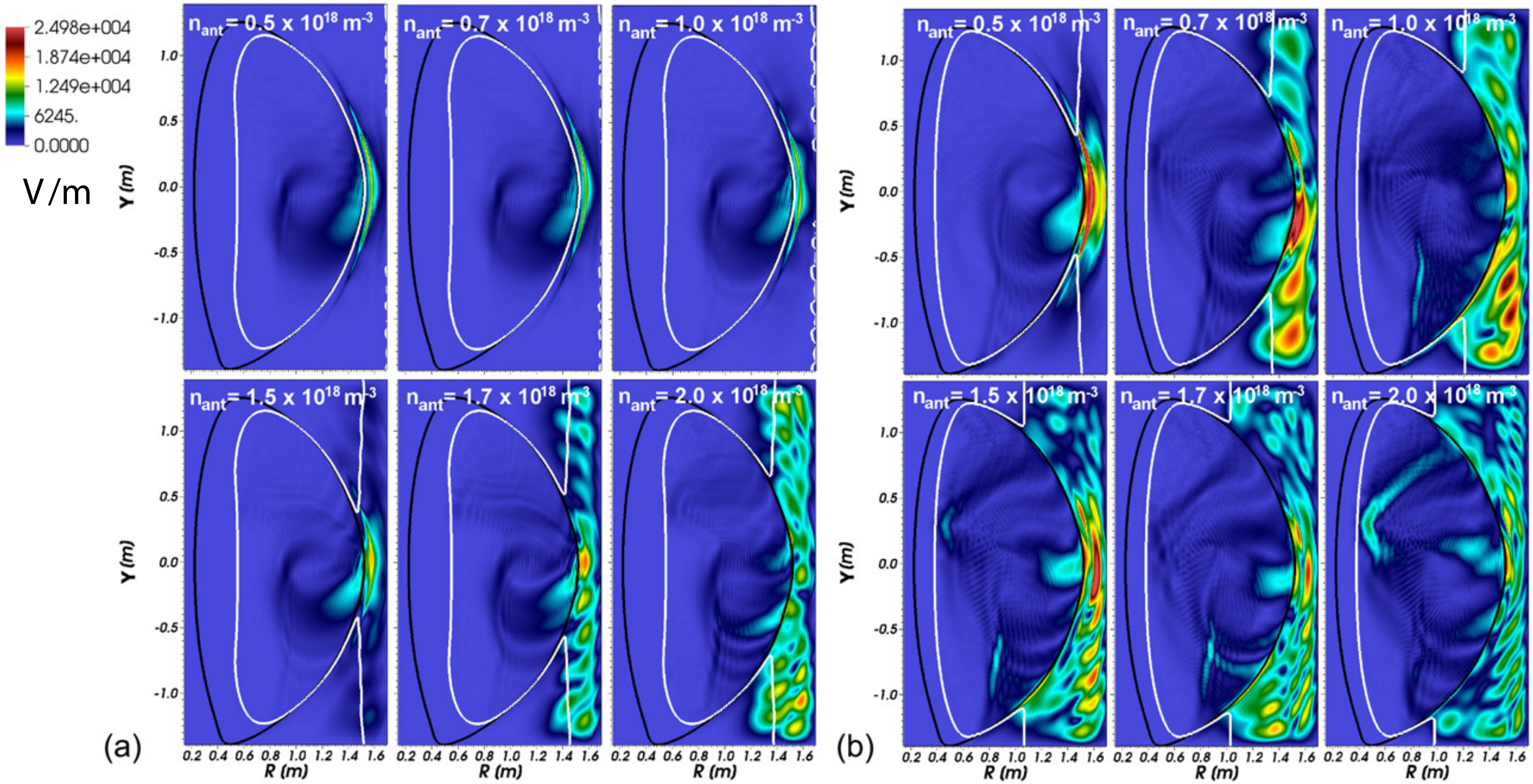




LHCD system on C-Mod investigates LH physics with ITER-like parameters

- $n_e = 0.5\text{-}5\times10^{20}\ m^{-3}$ (ITER = $0.5\text{-}1\times10^{20}\ m^{-3}$)
- $B_T = 3 - 8$ T (ITER = 5 T)
- Diverted plasma configuration (ITER = Lower Single Null)
- $n_{||} = 1.5 - 3$ co- or counter-current (ITER ~ 2)
- $f_{LHCD} = 4.6$ GHz (ITER = 5 GHz)
- 4 rows of 16 waveguides
- $P_{Source} = 2.5$ MW



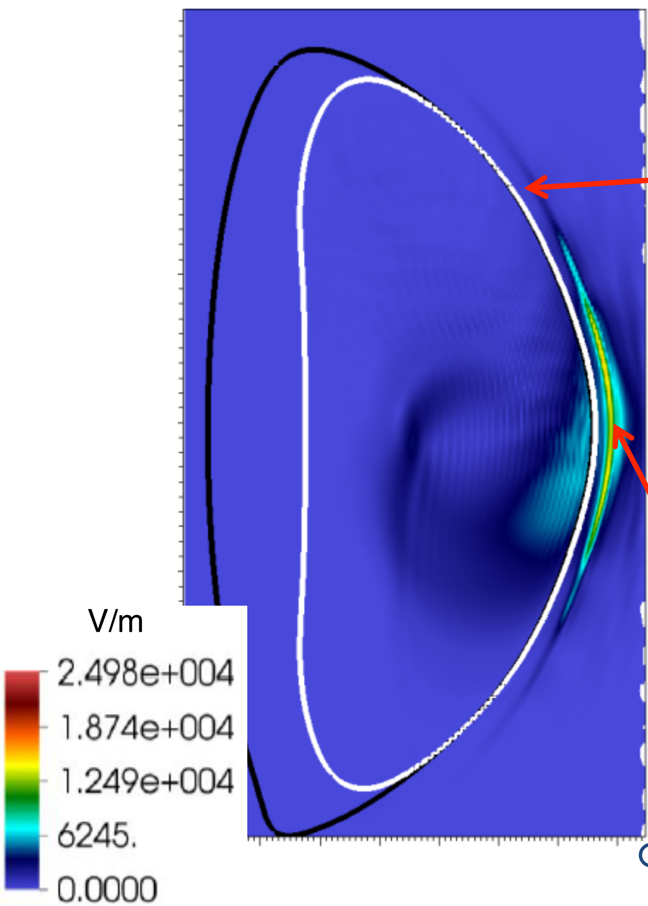


2.498e+004
1.874e+004
1.249e+004
6245.
0.0000
V/m
n_ant = 0.5 x 10^18 m^-3
n_ant = 0.7 x 10^18 m^-3
n_ant = 1.0 x 10^18 m^-3
n_ant = 1.5 x 10^18 m^-3
n_ant = 1.7 x 10^18 m^-3
n_ant = 2.0 x 10^18 m^-3
Y (m)
R (m)
(a)
(b)

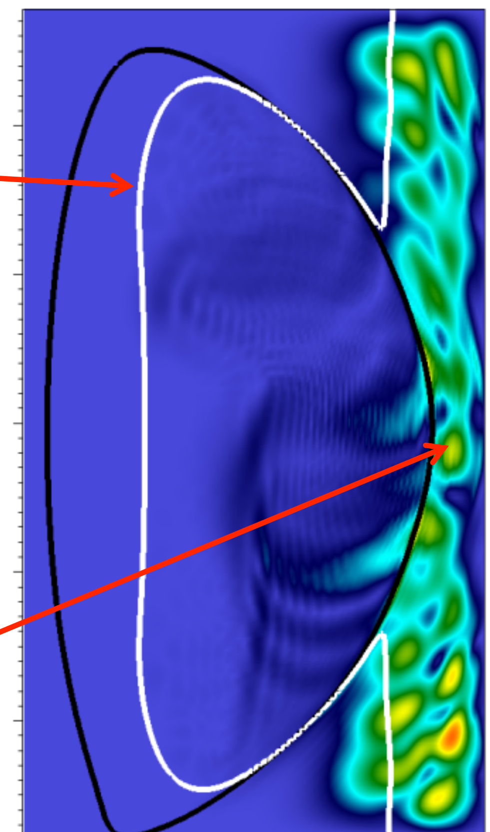
AORSA shows enhanced RF fields in SOL when cutoff layer opens in front of antenna

NSTX-U

Lower SOL density (n_{ant} = 1e12 cm^{-3})



Higher SOL density (n_{ant} = 2e12 cm^{-3})

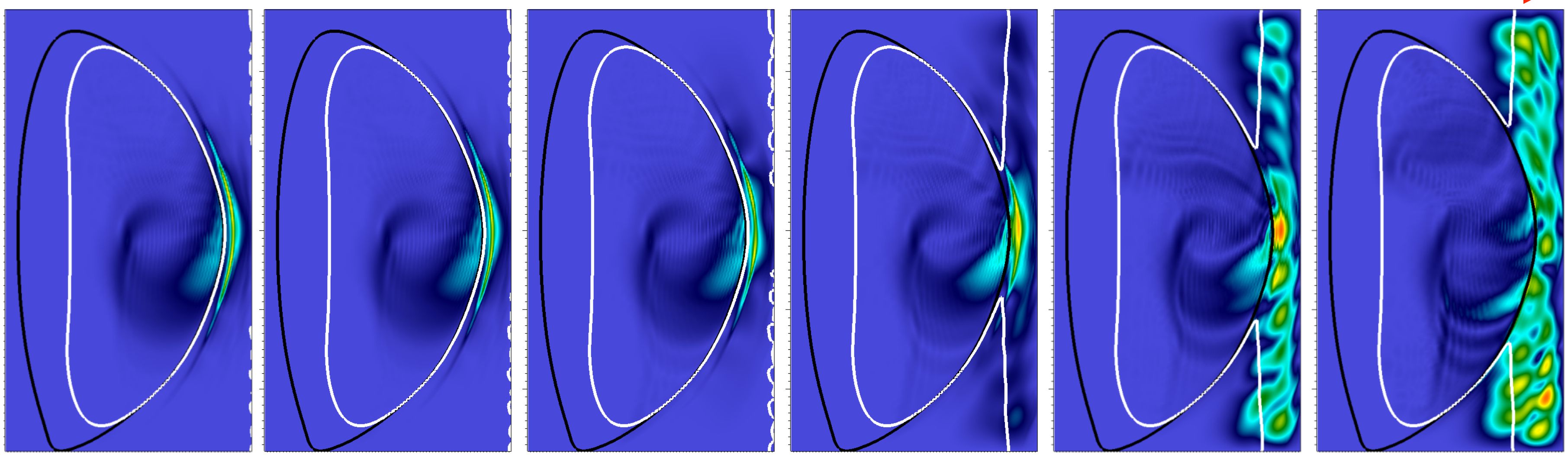


$$n_{e,\mathrm{FWcut-off}} \propto \frac{k_{\parallel}^{2} B}{\omega},$$

RF field amplitude in the SOL increases as soon as the FW cut-off is removed from in front of the antenna

$|E_{tot}|$ is shown for n_ϕ = -21, $\Delta\phi$ = -150° ("2D" ↔ single dominant mode), # 130608

$n_{ant}[m^{-3}]$ = 0.5×10^{18} 0.7×10^{18} 1.0×10^{18} 1.5×10^{18} 1.7×10^{18} 2.0×10^{18}



- For very low density the RF field is strongly localized in front of the antenna

- Standing wave appears at higher density