SCOPING STUDY OF LOWER HYBRID CURRENT DRIVE FOR CFETR

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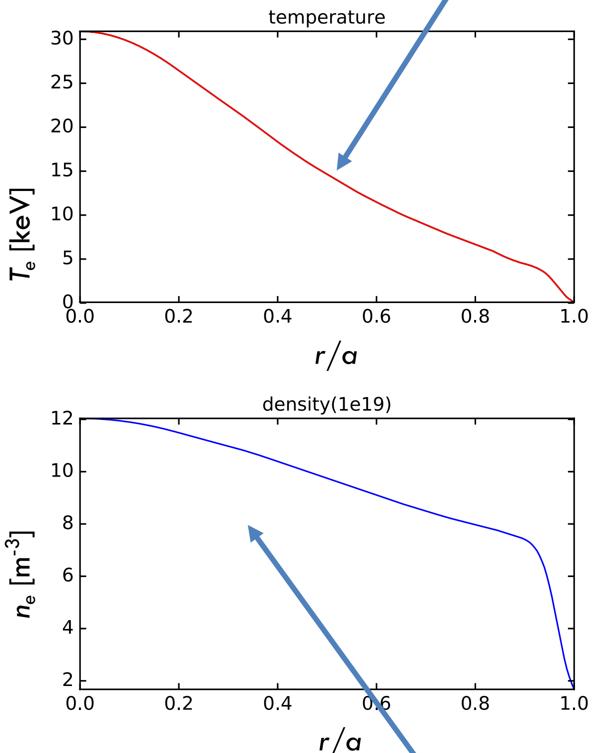
IAEA-TECH/P7-17

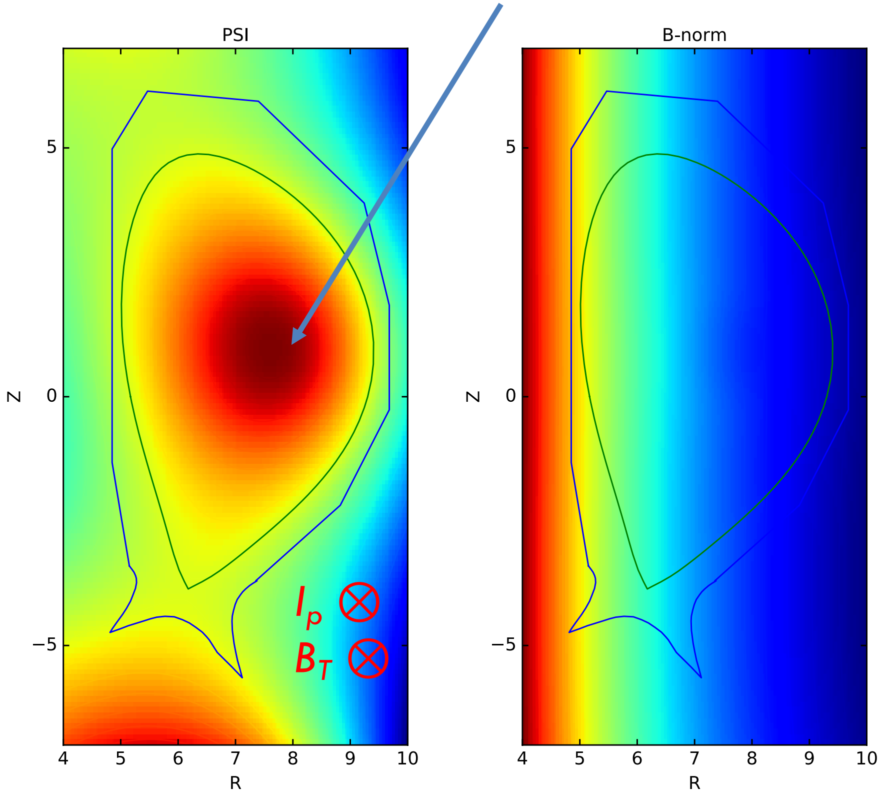
28th IAEA Fusion Energy Conference, 14 May, 2021

The CFETR "hybrid" scenario

Peaked T_e profile



Large Shafranov shift



Low density and flat profile make LFS LHCD a viable option

R_0 = 7.2 m, a = 2.2 m,
B_0 = 6.5 T, I_p = 13 MA,
Q = 8.3, f_{BS} = 0.47

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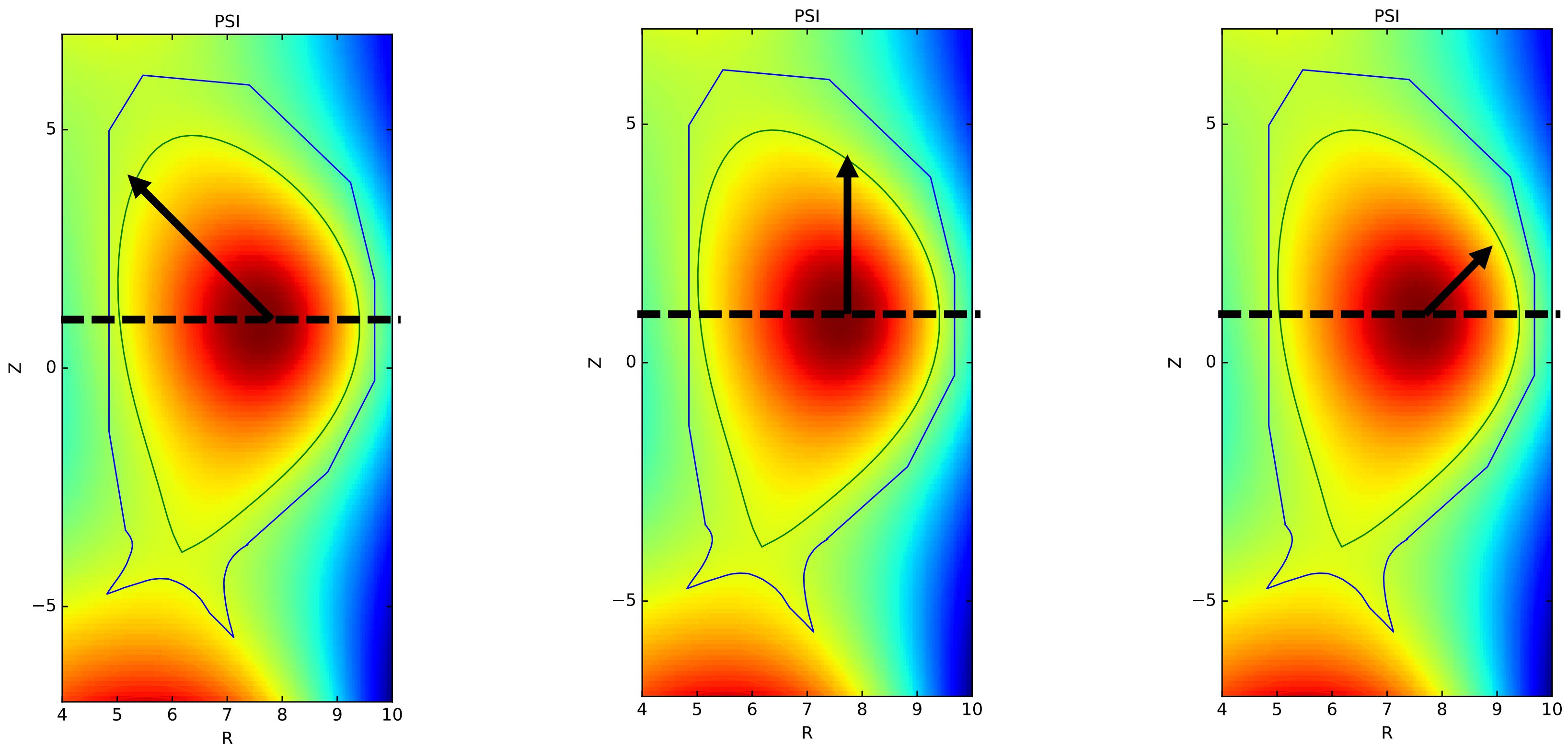
Goal: determine optimal LHRF parameters with parametric scans

- Scan comprises 5 parameters:
  - $n_{||1}$, HFS antenna $n_{||}$
  - $n_{||2}$, LFS antenna $n_{||}$
  - θ_1, HFS antenna poloidal position
  - θ_2, LFS antenna poloidal position
  - P_2/P_1, ratio of power between HFS and LFS antennas
- πScope workflow used for parametric scans with GENRAY/CQL3D ray tracing/Fokker-Planck codes
- Takes considerable wall-clock time to run many simulations even with narrow range for each parameter (5 points x 5 parameters = 3125 simulations
- Fully automated n-D parameter scans will also be critical for building lookup table of EAST discharges w/ $n_\perp$ rotation due to scattering

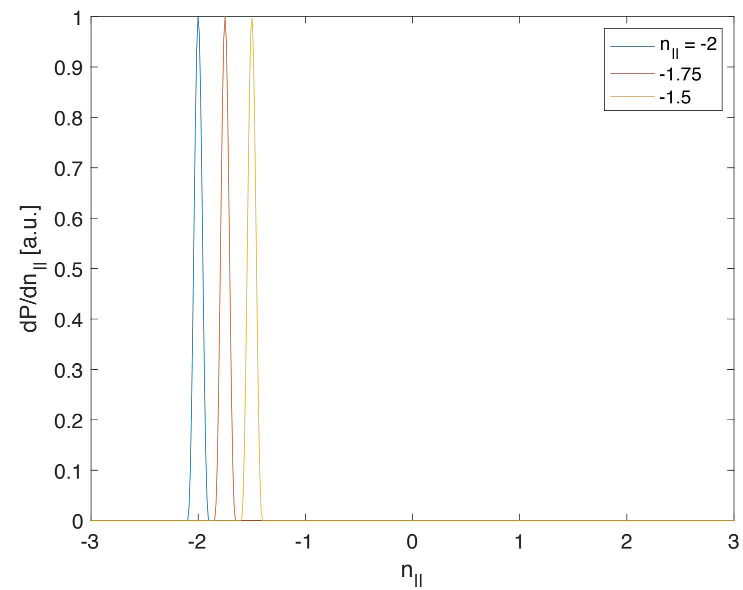
Poloidal launch point defined by angle with respect to magnetic axis; strong Shafranov shift puts 90° on LFS

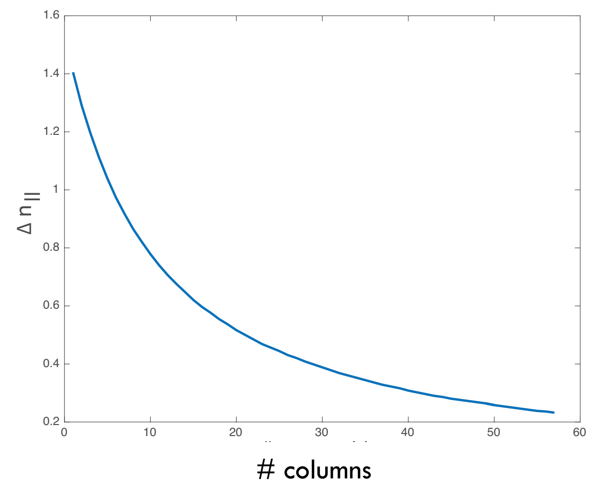
$\theta = 135°$ $\theta = 90°$ $\theta = 45°$



LH system assumptions

- f_0 = 4.6 GHz
  - VKC-7849B klystrons (as used on EAST) at 250 kW each
- P_{LH} = 20 MW not including reverse or side lobes
  - ~30 MW net power required with MJ or PAM antenna
  - ~160 klystrons needed with transmission losses & redundancy
- Full width of $n_{||}$ spectrum = 0.2





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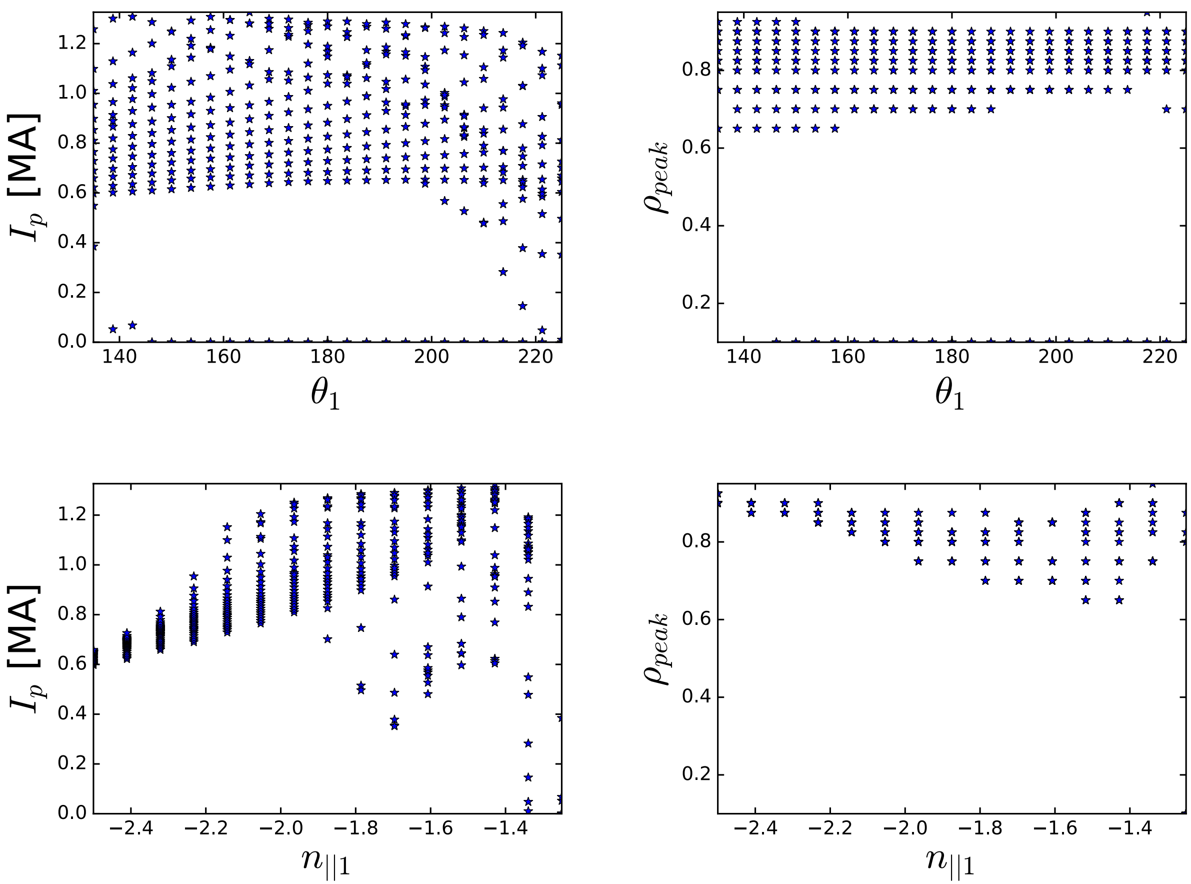
Conservative SOL profiles used in this study

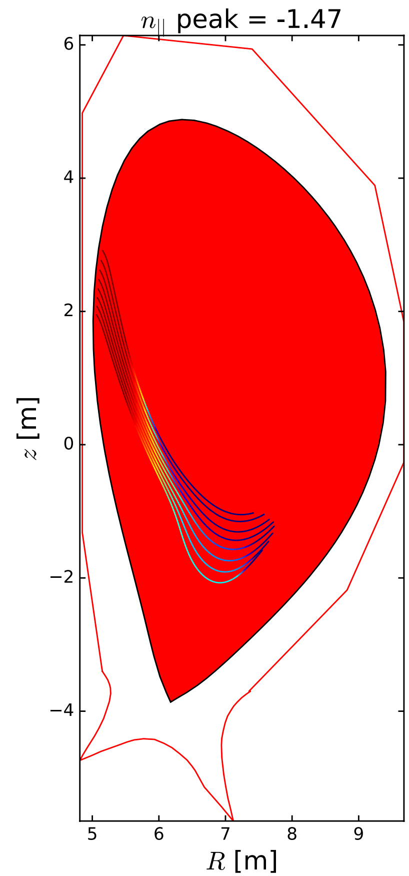
- e-folding width of ~2 cm for n_e and ~5 mm for T_e to increase collision frequency
- High collisionality in SOL results in non-resonant collisional damping of waves which do not absorb on single-pass
- Safeguards against multi-pass damping scenarios for which ray tracing is less trustworthy

HFS scan: 1.3 MA at $\rho = 0.65$ for $(150°, n_{||} = -1.47)$



HFS launch has good accessibility and damps at $\rho \sim 0.65$

- Higher B on HFS allows waves to penetrate directly to core plasma
- Little opportunity for losses in SOL to impact efficiency
- Low $n_{||}$ can be used even with "lossy" SOL



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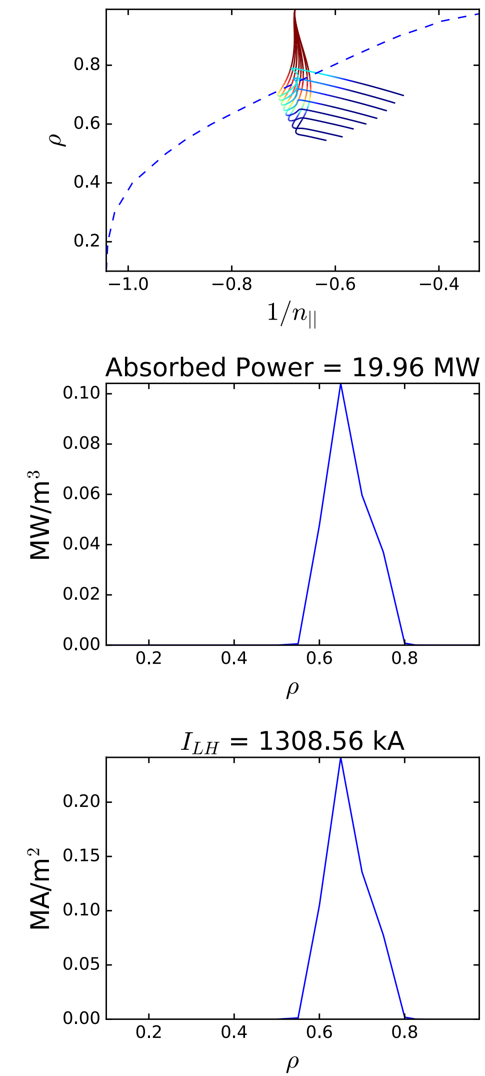
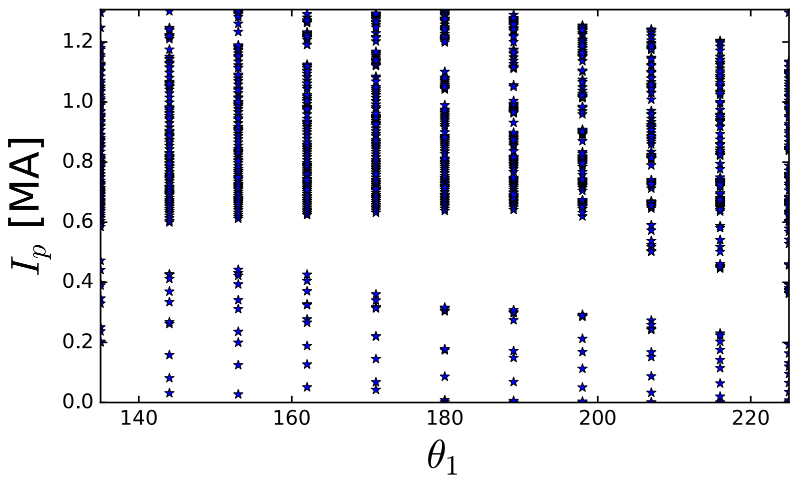
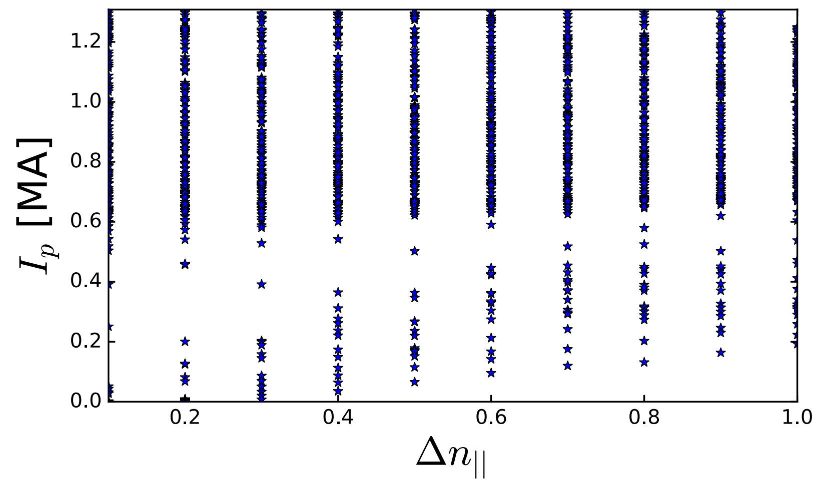
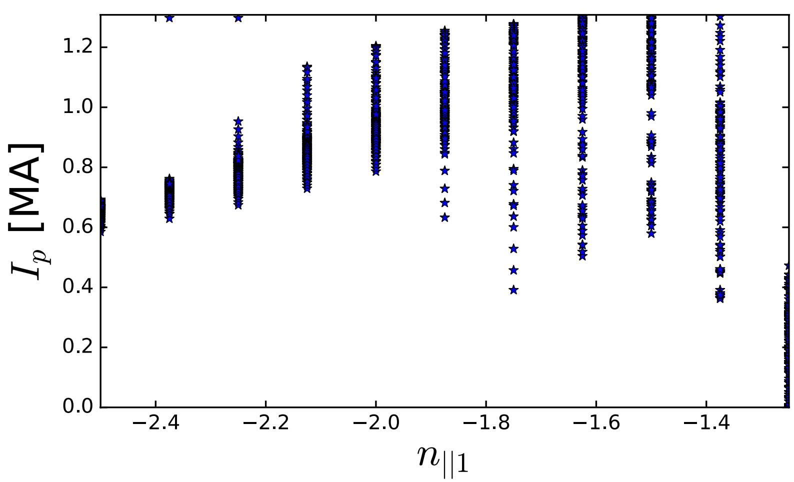


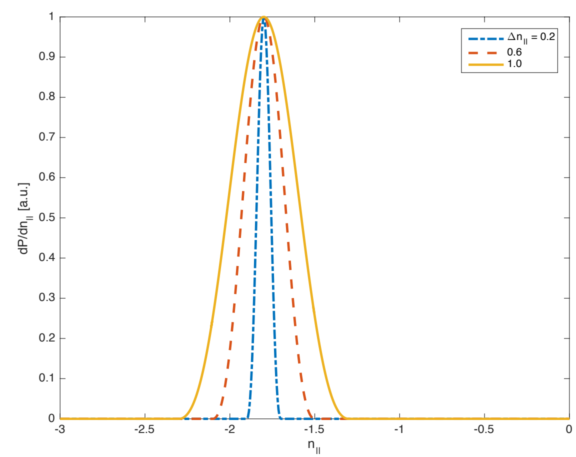
HFS launch insensitive to width of $n_{||}$ spectrum ($\Delta n_{||}$)

CFETR antenna spectral width ~ 0.13





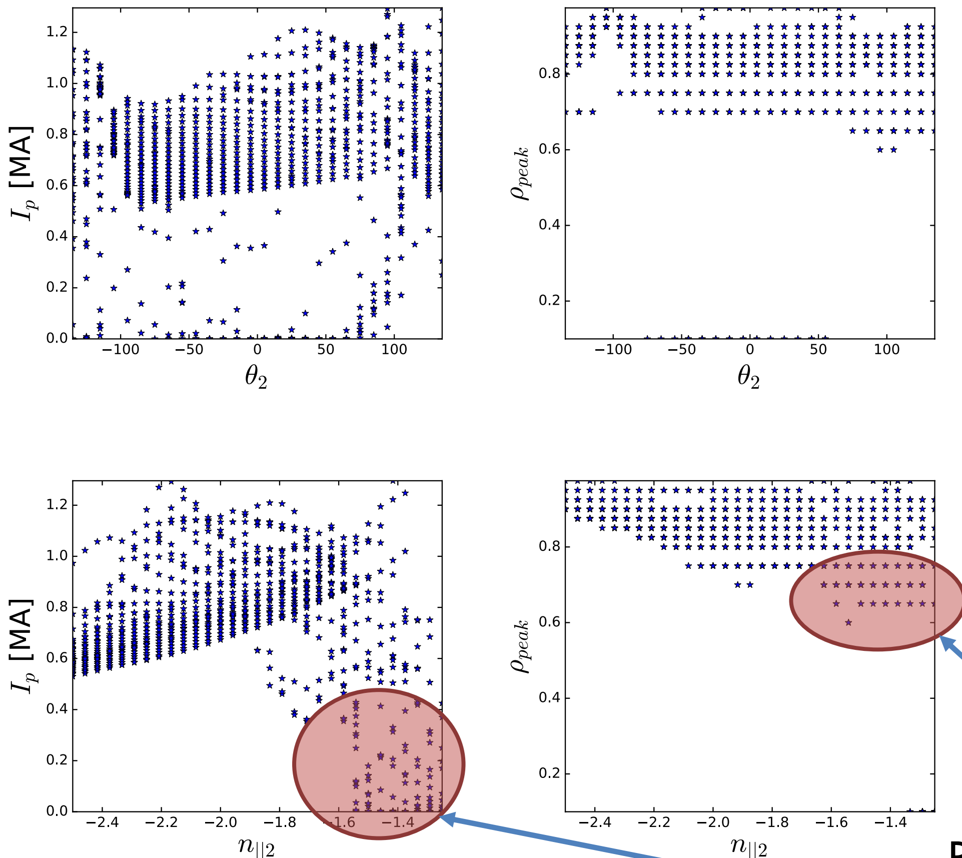




HFS scan summary

- Good wave accessibility even at low $n_{||} \sim 1.47$ with launch position above midplane (150°)
- Peak of current profile around r/a ~ 0.65
- Results invariant to SOL losses due to good accessibility and strong single-pass damping
- Peak current drive efficiency of 1.3 MA / 20 MW
  - $\boldsymbol{\eta} \sim 4.0\mathrm{x}10^{19}$ $\mathrm{AW^{-1}m^{-2}}$ for local n_e of $8\mathrm{x}10^{19}$ $\mathrm{m^{-3}}$

LFS scan: I_p max of 1.3 MA at $\rho \sim$ 0.85 for (90°, $n_{||}$ = -2.17)



Results at small ρ are multi-pass with low efficiency

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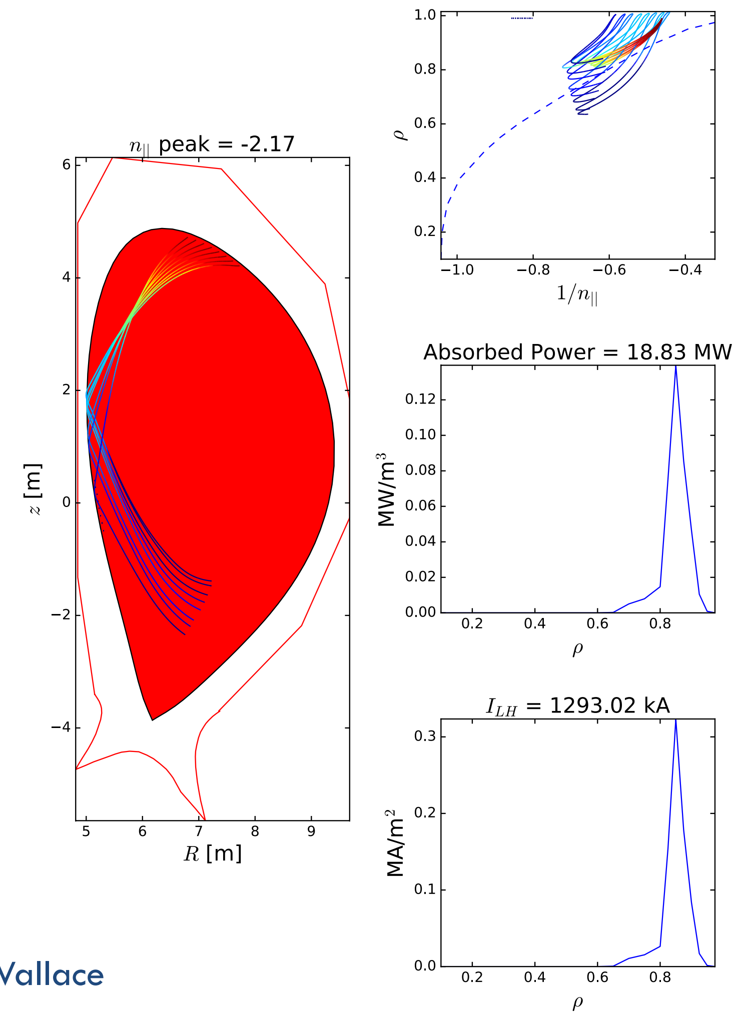
LFS antenna location gives similar efficiency, but larger damping ρ

- Similar efficiency vs. HFS launch, but damping at larger ρ due to higher $n_{||}$
- Can't use lower $n_{||}$ due to poor accessibility

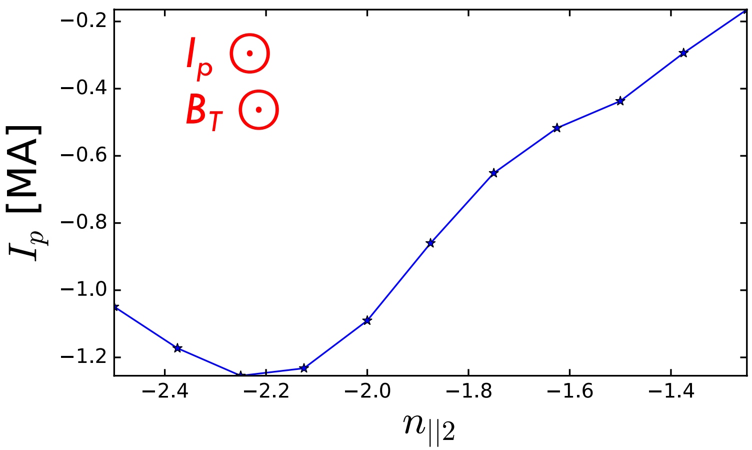


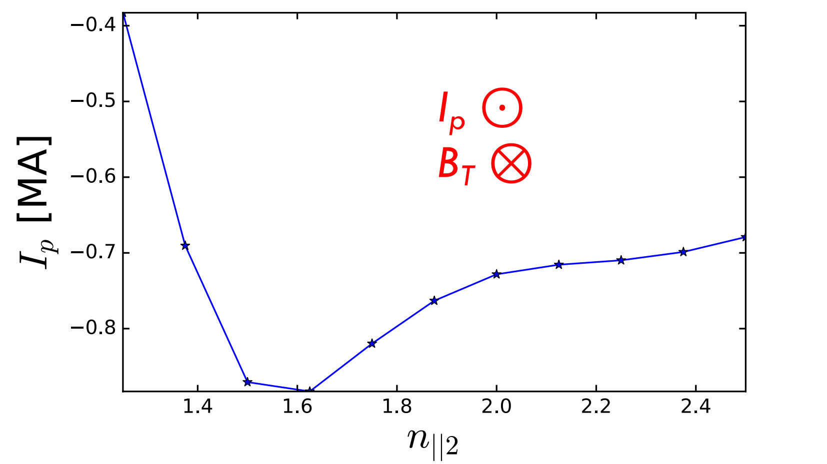
LFS scan summary

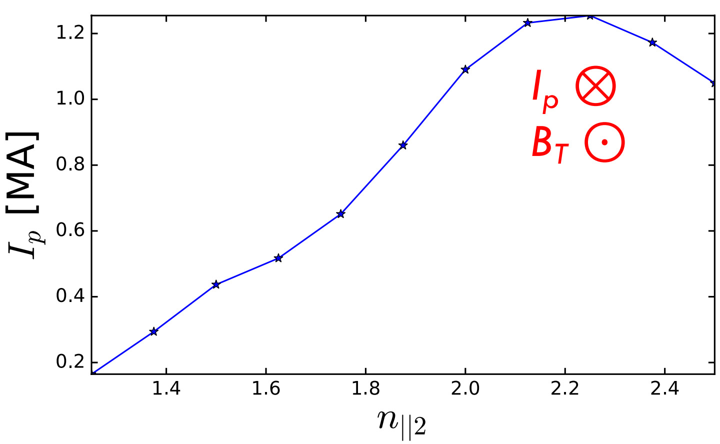
- Best case efficiency is nearly identical to HFS launch, but at larger $r/a \sim 0.85$
- Poor accessibility limits penetration of lower $n_{||}$ rays into the core plasma
- Multi-pass nature of the rays opens door to parasitic losses in the SOL at lower $n_{||}$
- Peak current drive efficiency of 1.3 MA / 20 MW
  - $\eta \sim 3.8\times10^{19}$ AW^{-1}m^{-2} for local n_e of 7.6×10^{19} m^{-3}

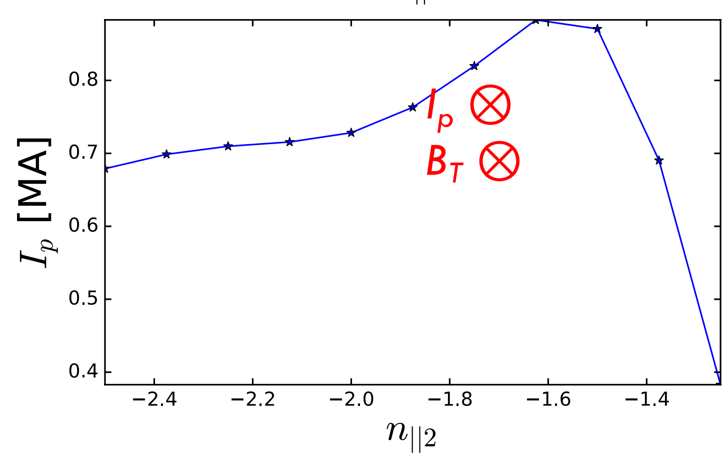
Efficiency depends on B_T sign for off mid-plane launch points (e.g. 150°)

$$n_{\|} = \frac{c}{\omega}\left(\frac{mB_\theta}{rB} + \frac{n_\phi B_\phi}{RB}\right) \;\Rightarrow\; \frac{dm}{d\theta} \propto -n_{\|} q(r)\sin(\theta)$$





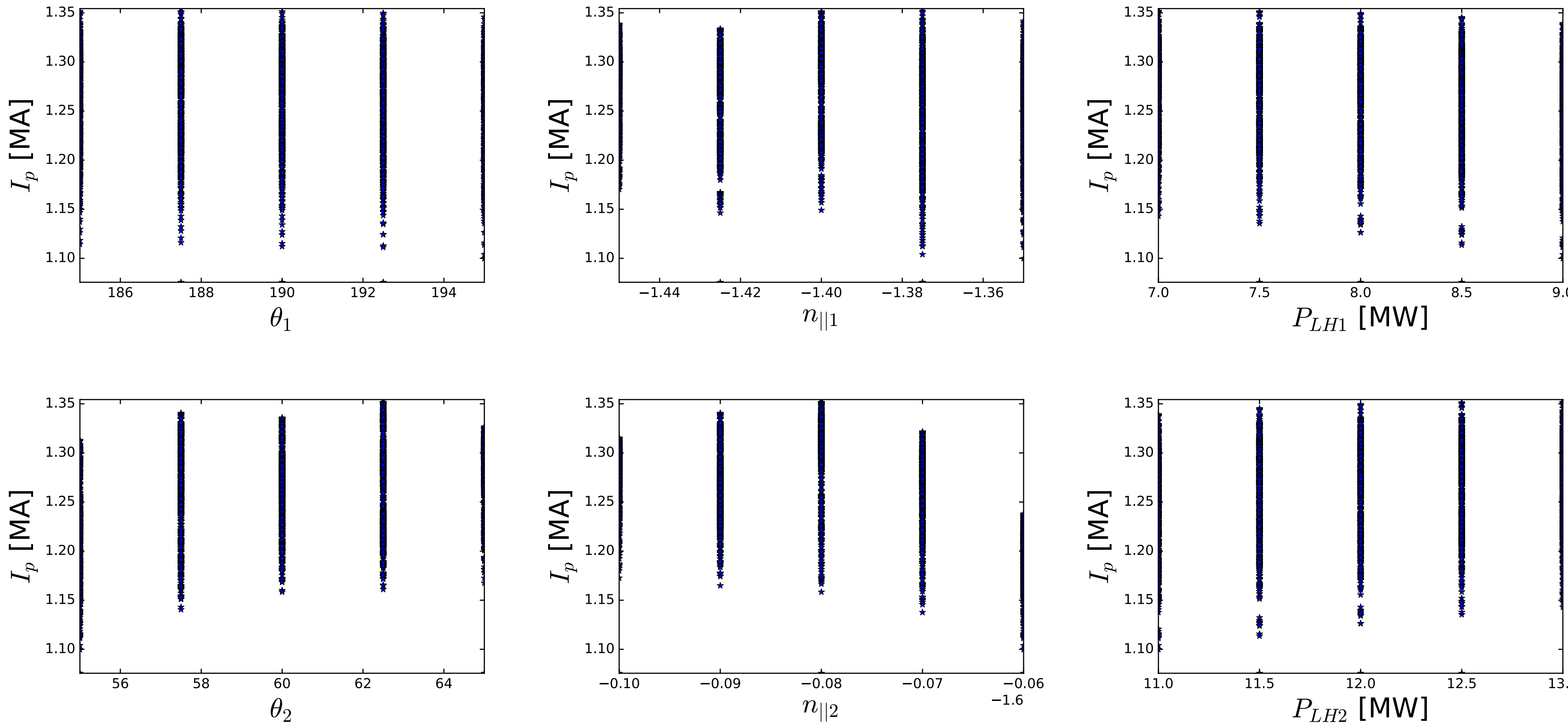




Best results for HFS + LFS synergy with 65% power from LFS, 35% from HFS

With enhanced collisions

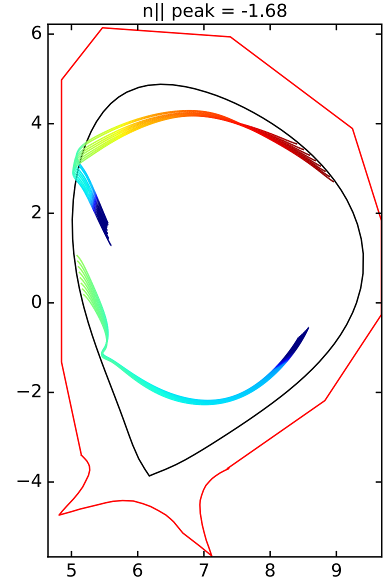
I_p max of 1.35 MA at (187.5°, 62.5°, $n_{||1}$ = -1.375, $n_{||2}$ = -1.68, 7 MW, 13 MW)

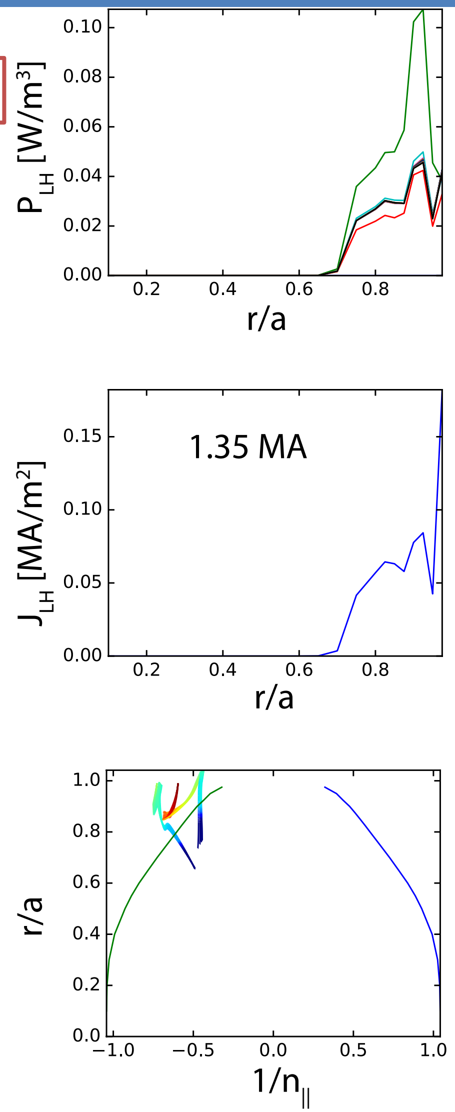


HFS + LFS synergy current profile far off-axis for hybrid scenario

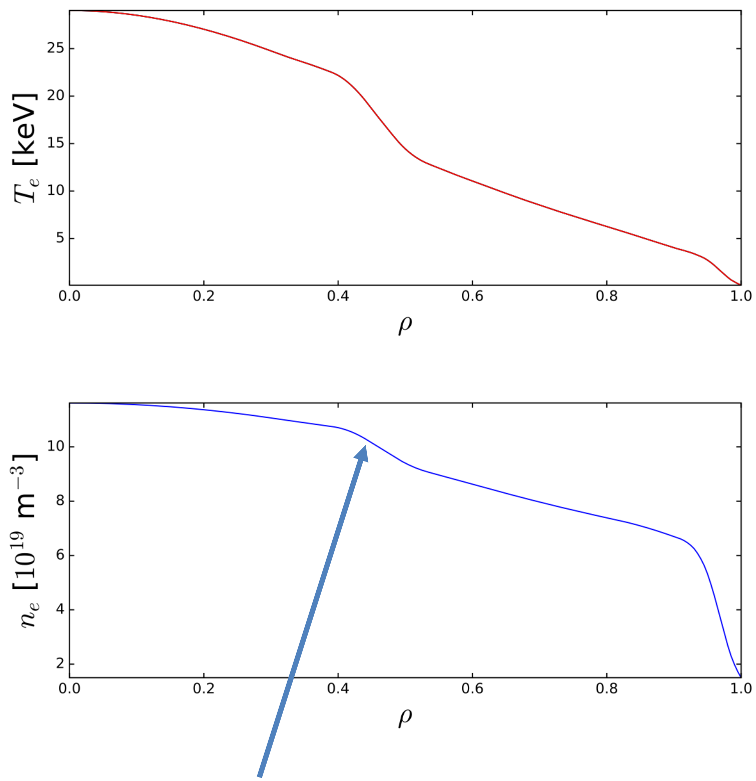
- Current efficiency remains high for HFS + LFS combined
- Current profile is peaked very far off axis
- No significant benefit as compared to LFS only

7MW HFS + 13 MW LFS

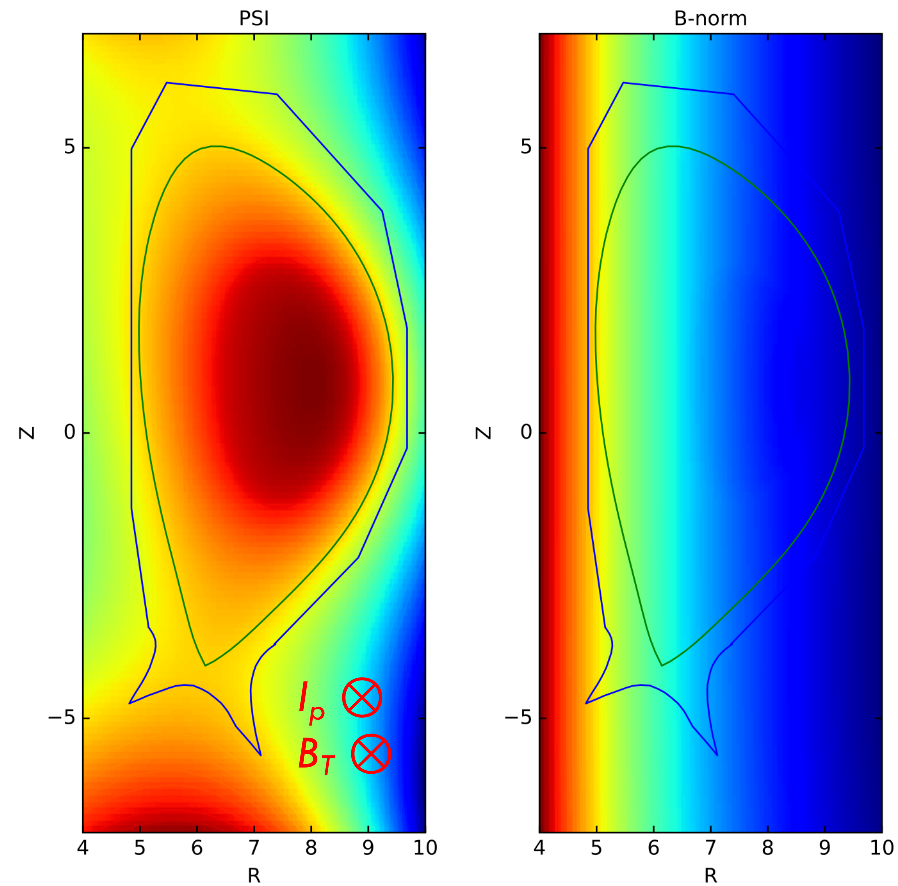




Steady-state scenario



ITB at mid-radius



R_0 = 7.2 m, a = 2.2 m,
B_0 = 6.5 T, I_p = 11 MA

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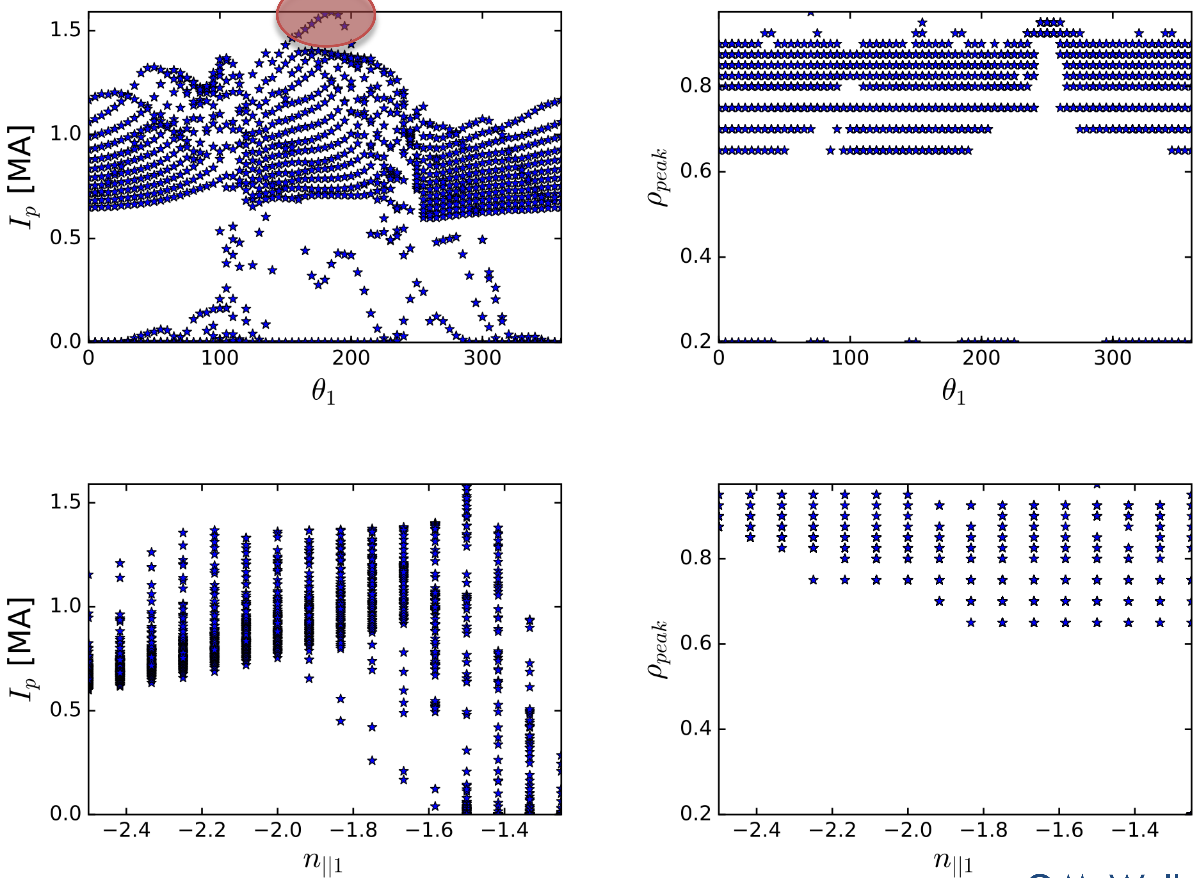
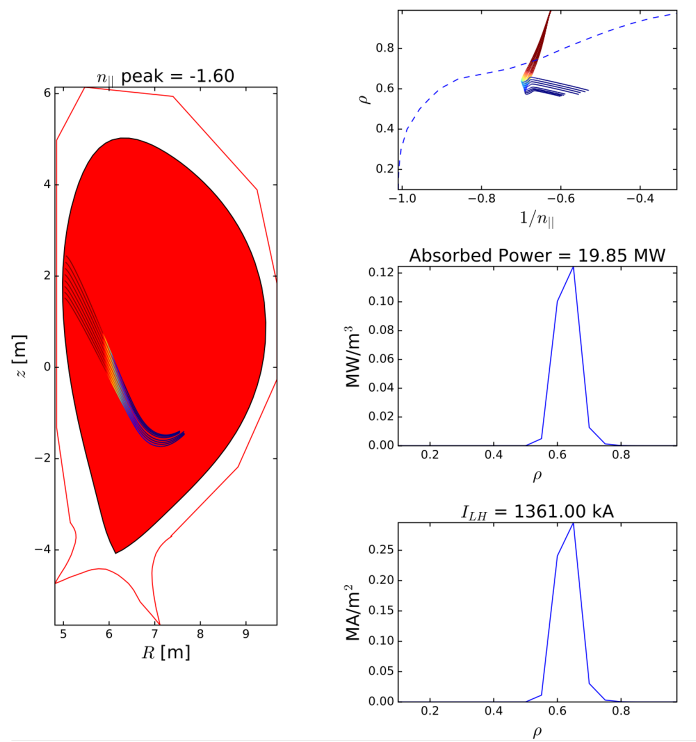
Parametric scan for SS scenario shows similar optimal point as for the hybrid

Far off-axis current drive for these points





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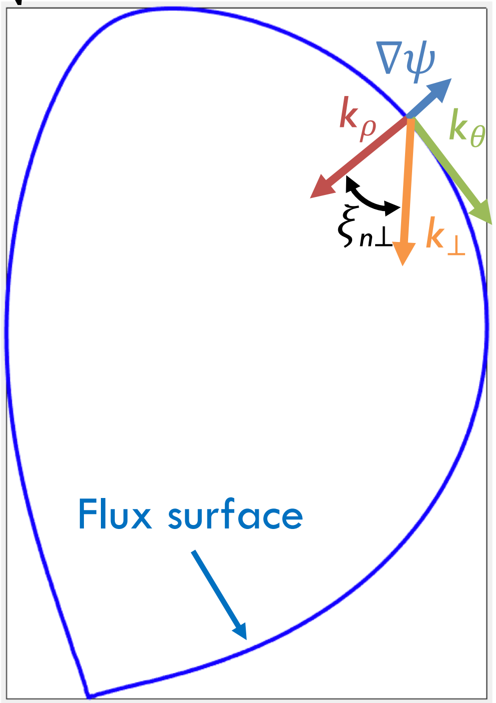
Scattering from n_e fluctuations can change angle $\xi_{n\perp}$ between $k_\perp$ and $\nabla\psi$

- Perpendicular wavenumber typically assumed to be aligned with $\nabla\psi$ based on antenna spectrum
- $k_\perp = \sqrt{k_\rho^2 + \left(k_\theta \frac{B_\phi}{B}\right)^2 + \left(k_\phi \frac{B_\theta}{B}\right)^2} \approx \sqrt{k_\rho^2 + k_\theta^2}$
  - $\xi_{n\perp} \approx \tan^{-1} \frac{k_\theta}{k_\rho}$
- $\xi_{n\perp}$ impacts evolution of $k_{||}$ along ray through poloidal mode number M_θ

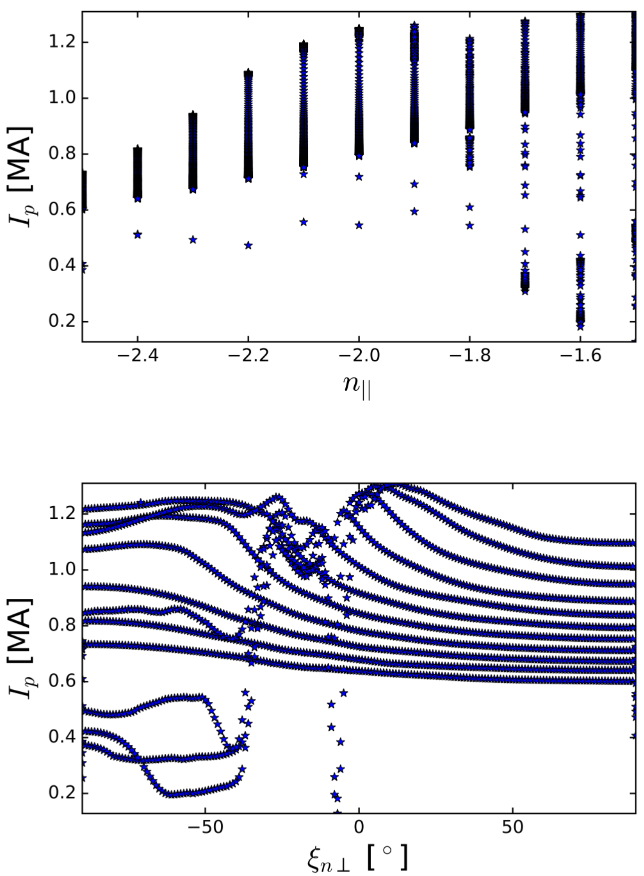
$$k_{||} = \left(\frac{M_\theta}{r}\frac{B_\theta}{B} + \frac{N_\phi}{R}\frac{B_\phi}{B}\right)$$

  - Bonoli and Ott, Physics of Fluids **25**, 359 (1982)
  - Baek *et al*, AIP Conference Proceedings **2254**, 030006 (2020)

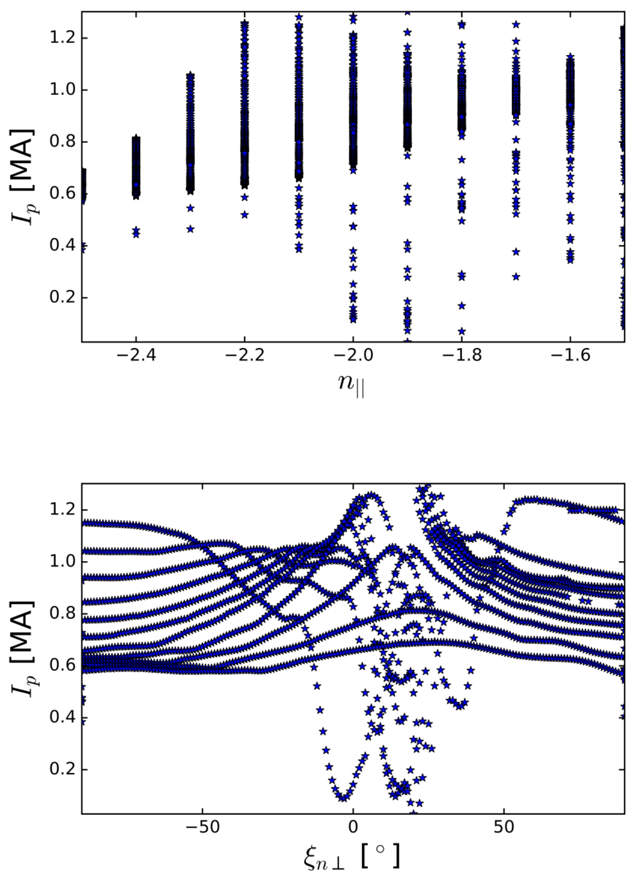


Impact of scattering from edge density fluctuations can be compensated

HFS Launch (θ = 150°)



LFS Launch (θ = 90°)



Adjusting $n_{||}$ can maintain high current drive efficiency for any value of $\xi_{n\perp}$

Conclusions

- $>10^4$ simulations performed with GENRAY/CQL3D to determine optimal LHCD launch point and $n_{||}$
- HFS and LFS launch LHCD both generate ~ 1.3 MA / 20 MW LHRF power
  - Efficiencies similar
  - HFS current profile peaks at $\rho \sim 0.65$
  - LFS current profile peaks at $\rho \sim 0.85$

  Smaller ρ would be even better!
- CFETR scenario development favors mid-radius current drive vs far-off-axis current drive
  - J. Chen, et al *Nuc Fus* 61 (2021) 046002