SCOPING STUDY OF LOWER HYBRID CURRENT DRIVE FOR CFETR

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The CFETR “hybrid” scenario

Peaked $T_e$ profile

Low density and flat profile make LFS LHCD a viable option

Large Shafranov shift

$T_e [\text{keV}]$

$n_e [\text{m}^{-3}]$

$R_0 = 7.2 \text{ m}, \alpha = 2.2 \text{ m},$

$B_0 = 6.5 \text{ T}, I_p = 13 \text{ MA},$

$Q = 8.3, f_{BS} = 0.47$
Goal: determine optimal LHRF parameters with parametric scans

- Scan comprises 5 parameters:
  - $n_{||1}$, HFS antenna $n_{||}$
  - $n_{||2}$, LFS antenna $n_{||}$
  - $\theta_1$, HFS antenna poloidal position
  - $\theta_2$, LFS antenna poloidal position
  - $P_2/P_1$, ratio of power between HFS and LFS antennas

- $\pi$Scope 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

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Poloidal launch point defined by angle with respect to magnetic axis; strong Shafranov shift puts $90^\circ$ on LFS

$\theta = 135^\circ$

$\theta = 90^\circ$

$\theta = 45^\circ$
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
  - \( \sim 30 \) MW net power required with MJ or PAM antenna
  - \( \sim 160 \) klystrons needed with transmission losses & redundancy
- Full width of \( n_{||} \) spectrum = 0.2
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 $(150^\circ, n_{||} = -1.47)$
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 $\sim 0.13$
HFS scan summary

- Good wave accessibility even at low $n_{||} \sim 1.47$ with launch position above midplane ($150^\circ$)
- Peak of current profile around $r/a \sim 0.65$
- Results invariant to SOL losses due to good accessibility and strong single-pass damping
- Peak current drive efficiency of $1.3 \text{ MA} / 20 \text{ MW}$
  - $\eta \sim 4.0 \times 10^{19} \text{ AW}^{-1} \text{m}^{-2}$ for local $n_e$ of $8 \times 10^{19} \text{ m}^{-3}$
LFS scan: $I_p \max$ of 1.3 MA at $\rho \sim 0.85$ for $(90^\circ, n_{||} = -2.17)$

Results at small $\rho$ are multi-pass with low efficiency
LFS antenna location gives similar efficiency, but larger damping $\rho$

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

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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 $1.3 \text{ MA} / 20 \text{ MW}$
  - $\eta \sim 3.8 \times 10^{19} \text{ AW}^{-1} \text{ m}^{-2}$ for local $n_e$ of $7.6 \times 10^{19} \text{ m}^{-3}$
Efficiency depends on $B_T$ sign for off mid-plane launch points (e.g. 150°)

\[ n_{\parallel} = \frac{c}{\omega} \left( \frac{mB_\theta}{rB} + \frac{n_\phi B_\phi}{RB} \right) \Rightarrow \frac{dm}{d\theta} \propto -n_{\parallel} q(r) \sin(\theta) \]
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 $(187.5^\circ, 62.5^\circ, n_{\|1} = -1.375, n_{\|2} = -1.68, 7$ 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

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Steady-state scenario

\[ I_p \otimes B_T \otimes R_0 = 7.2 \text{ m}, \quad \alpha = 2.2 \text{ m}, \quad B_0 = 6.5 \text{ T}, \quad I_p = 11 \text{ MA} \]

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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.
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

$$k_\perp = \sqrt{k_\rho^2 + (k_\theta \frac{B\phi}{B})^2 + (k_\phi \frac{B\theta}{B})^2} \approx \sqrt{k_\rho^2 + k_\theta^2}$$

$$\xi_{n\perp} \approx \tan^{-1} \frac{k_\theta}{k_\rho}$$

- $\xi_{n\perp}$ impacts evolution of $k_{||}$ along ray through poloidal mode number $M_\theta$

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

Impact of scattering from edge density fluctuations can be compensated

HFS Launch ($\theta = 150^\circ$)

LFS Launch ($\theta = 90^\circ$)

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

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Conclusions

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

- CFETR scenario development favors mid-radius current drive vs far-off-axis current drive


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