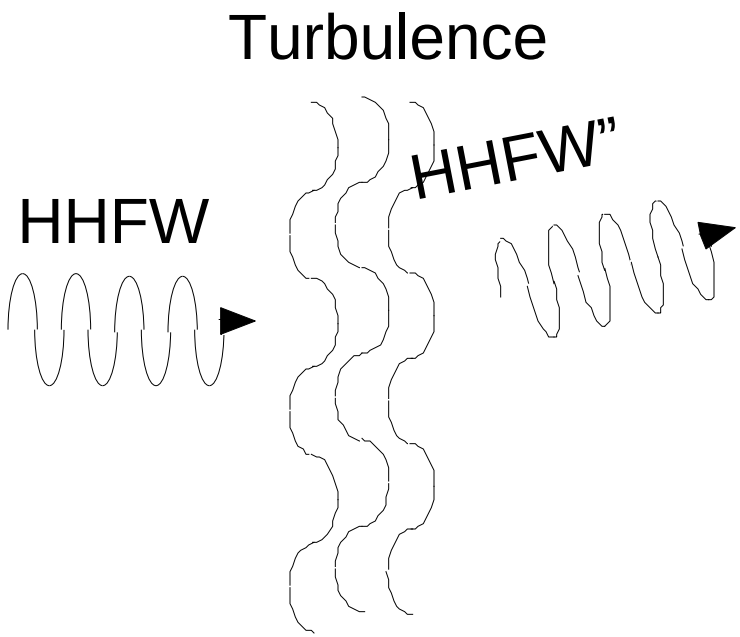
Scattering of HHWF by Drift Turbulence in NSTX



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Motivations

- HHFW does indeed seem to work on NSTX!

- But there are puzzles not easily explainable by linear theory.

  - Helium plasmas seems to heat better than deuterium plasmas though the HHFW wave propagation physics should be nearly identical.
  - The slowest waves ($k_{||}$ = 14 m^{-1}) heat better than the faster waves ($k_{||}$ = 7 m^{-1}) though the linear theory suggests good heating for both cases.
  - Diverted plasmas seems to be better than limited plasmas.
  - For the $k_{||}$ = 14 m^{-1} case, the observed heating may be more central than linear theory predictions. $k_{||}$ down shift?
  - In general, the HHFW heating seems to be not as robust as we would like it to be.

- Can we understand the underlying physics of observations so that we can make meaningful improvements on HHFW?

Basic HHFW Wave Dispersion Relations

- HHFW Cold Dispersion Relation:

$$\varepsilon \quad K_{xx}\frac{n^2}{n^2} - \frac{K_{xy}^2}{n^2 - K_{xx}}\frac{n^2}{n^2} + \frac{n_{II}^2\, K_{zz}}{(n^2 - K_{zz})}\frac{n^2}{n^2} = 0 \qquad (1)$$

where

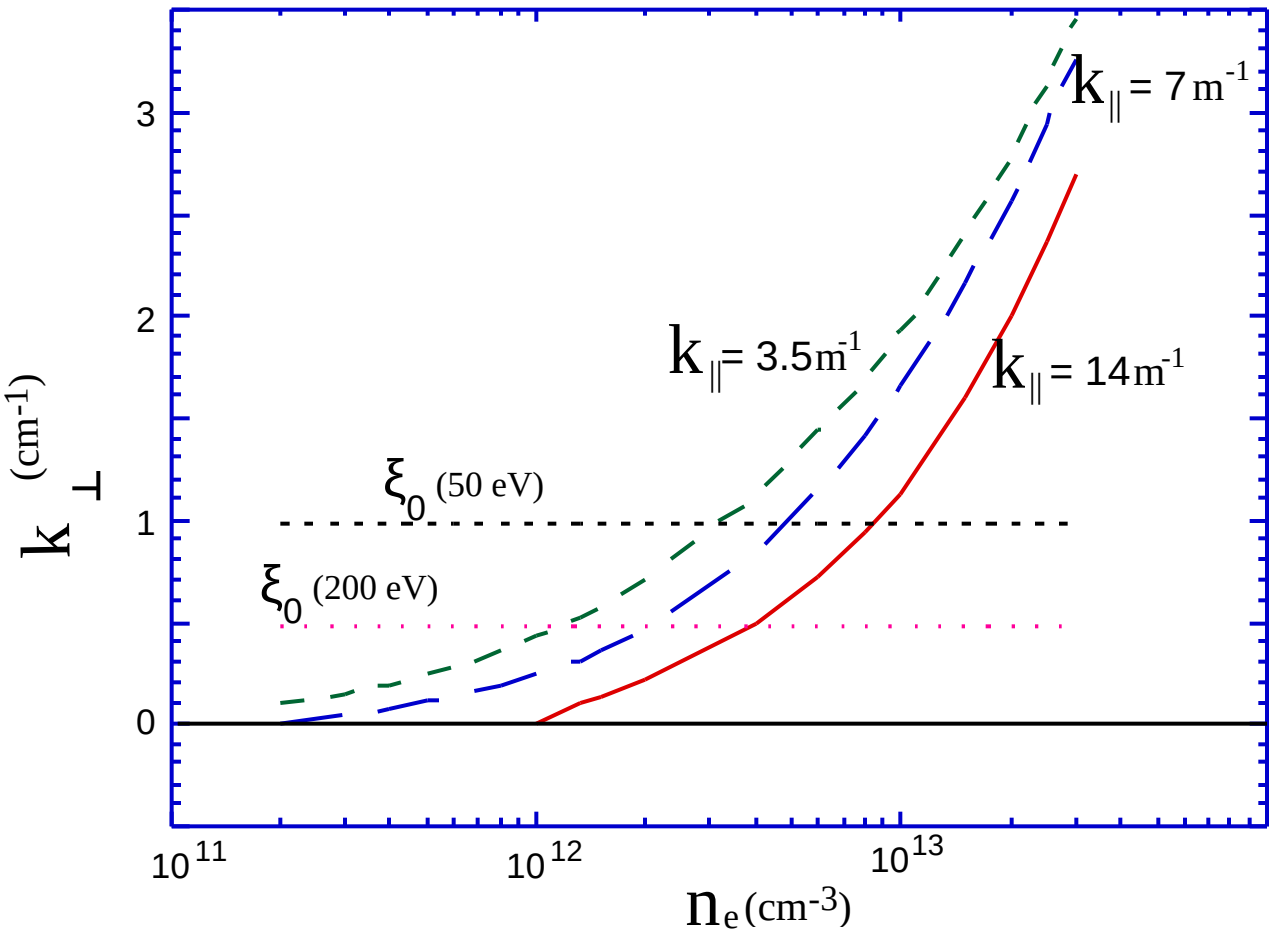
$$K_{xx} \quad 1 + \frac{\omega_{pe}^2}{\Omega_e^2} - \frac{\omega_{pi}^2}{\omega^2}, \quad K_{xy} \quad i\left[\frac{\omega_{pe}^2}{\omega\,\Omega_e} - \frac{\Omega_i\,\omega_{pi}^2}{\omega^3}\right] \quad i\frac{\omega_{pe}^2}{\omega\,\Omega_e}, \quad \textit{and} \quad K_{zz} \quad 1 - \frac{\omega_{pe}^2}{\omega^2}.$$

- A useful form for this problem:

$$n^2 = \frac{-A + \sqrt{A^2 - 4K_{xx}\,C}}{2\,K_{xx}} \qquad (2)$$

$$A = -(K_{xx} + K_{zz})(K_{xx} - n_{||}) + |K_{xy}|^2 \quad \textit{and} \quad C = K_{zz}(K_{xx} - n_{||}^2)^2 - |K_{xy}|^2 K_{zz}.$$

HHFW Wave Dispersion Relation



HHFW perpendicular wave number as a function of n_e for various $k_{\parallel}$ as labeled. B = 2.0 kG, f = 30 MHz, and deuterium plasma.

HHFW Scattering Due to Turbulence

- 90° scattering of HHFW in weak turbulence approximation:

$$L_s = q \frac{(k \quad \partial\varepsilon / \partial k \;)^2}{(4\pi k^3) \int_{-\pi}^{\pi} |V|^2 \; S\left[2k \;\; \sin(\alpha/2)\right] \sin^2(\alpha/2)\, d\alpha} \qquad (3)$$

M. Ono, Phys. Fluids 25, 990 (1982).

where

$$|V|^2 = a_1 + (2a_1 a_2 - a_3^2)\sin^2(\alpha/2) + (a_2^2 + a_3^2)\sin^4(\alpha/2),$$

$$a_1 = 1 + \frac{n_{II}^2}{(n^2 - K_{zz})}, \quad a_2 = -2 - \frac{2\, n_{II}^2 \; K_{zz}}{(n^2 - K_{zz})}, and \quad a_3 = 2K_{xy} + \frac{2\, K_{xy}(K_{xx} - 1)}{n^2 - K_{xx}}.$$

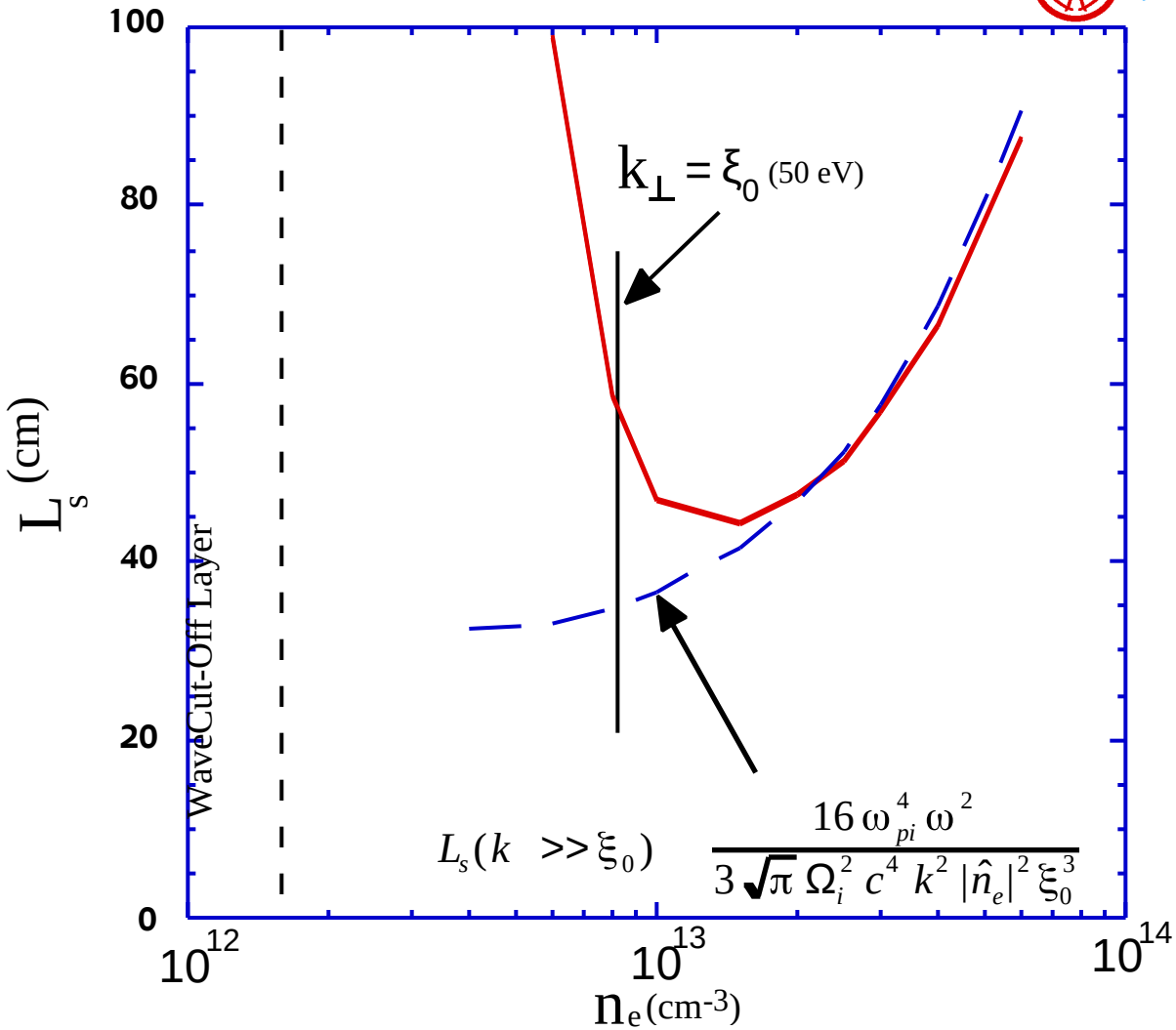
- For this exercise, we will use a model turbulence spectra:

$$S(\xi) = [\pi \xi_0^2]^{-1} \, |\hat{n}_e|^2 \, \exp(-\xi^2 / \xi_0^2)$$

where

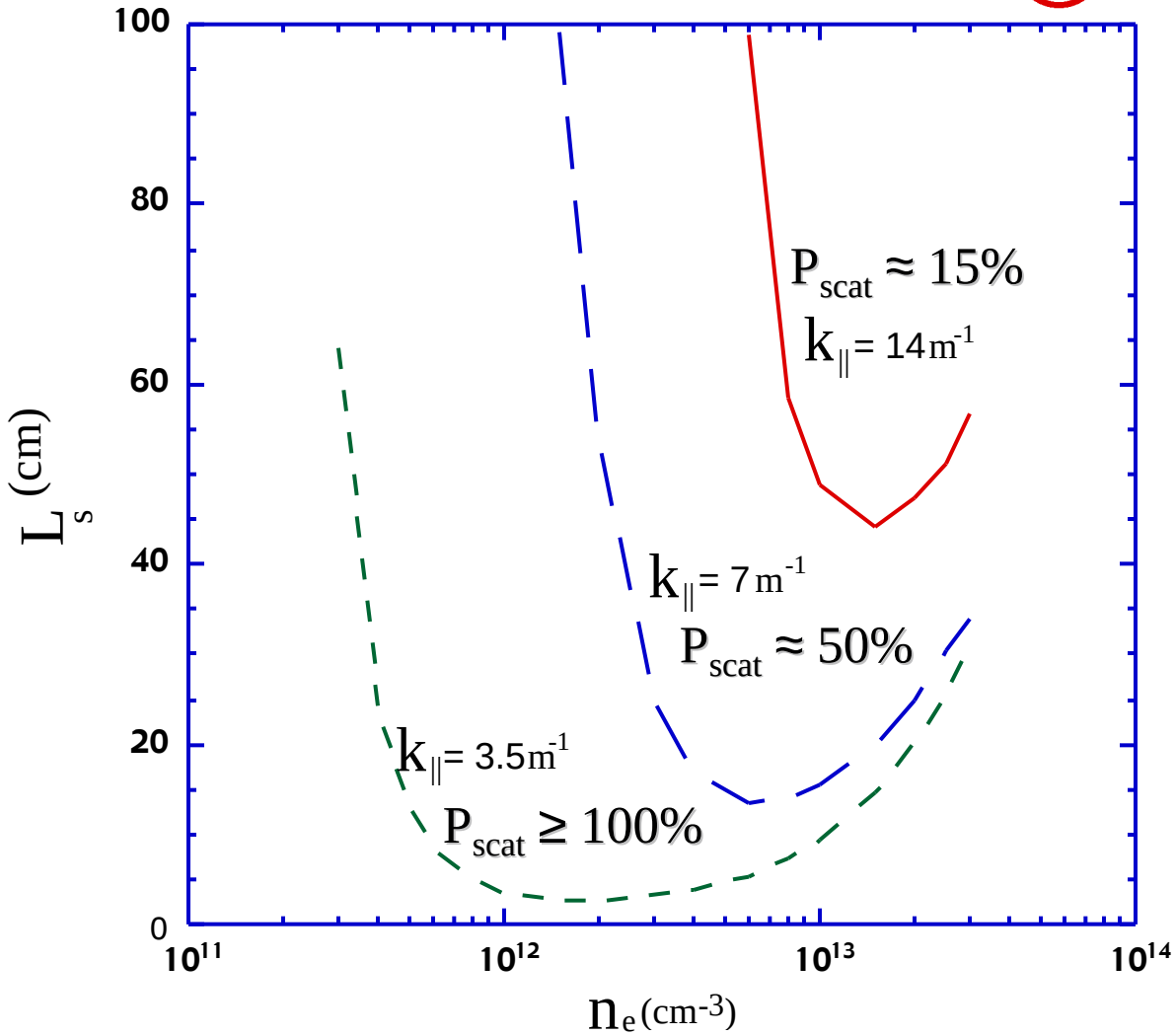
$$\xi_0 \rho_i = C_D \approx 0.25 - 1.0$$

90° Scattering Length vs. Plasma Density



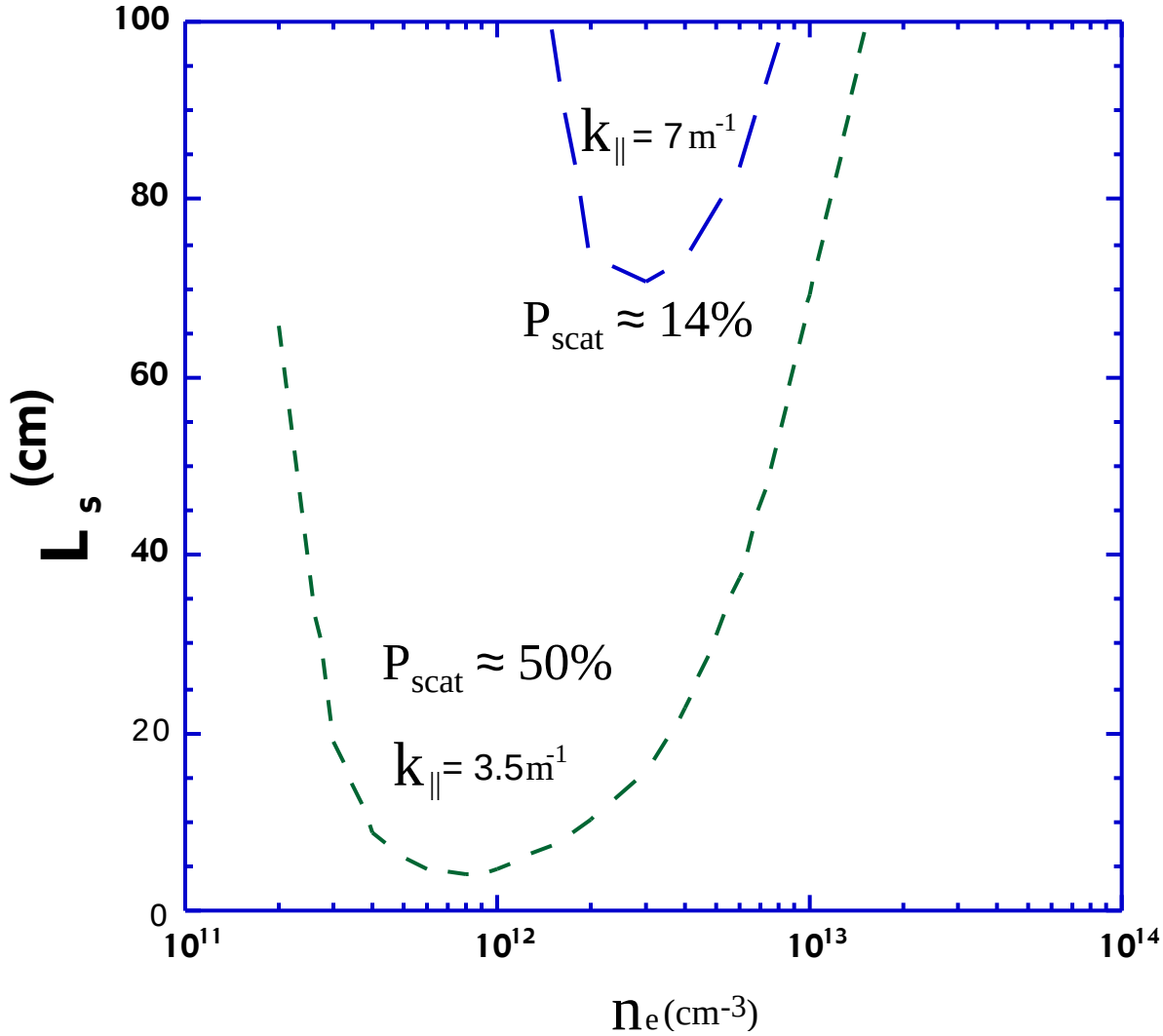
Low frequency scattering length L_s as a function of n_e. $k_\parallel$ = 14 m^{-1}, B = 2.0 kG, T_i = 50 eV, C_D = 0.5, $|\hat{n}_e|$ = 0.05, and f = 30 MHz, and deuterium plasma. Analytical expression for $k >> \xi_0$ is plotted as a dashed curve.

90° Scattering Length Dependence on $n_{||}$



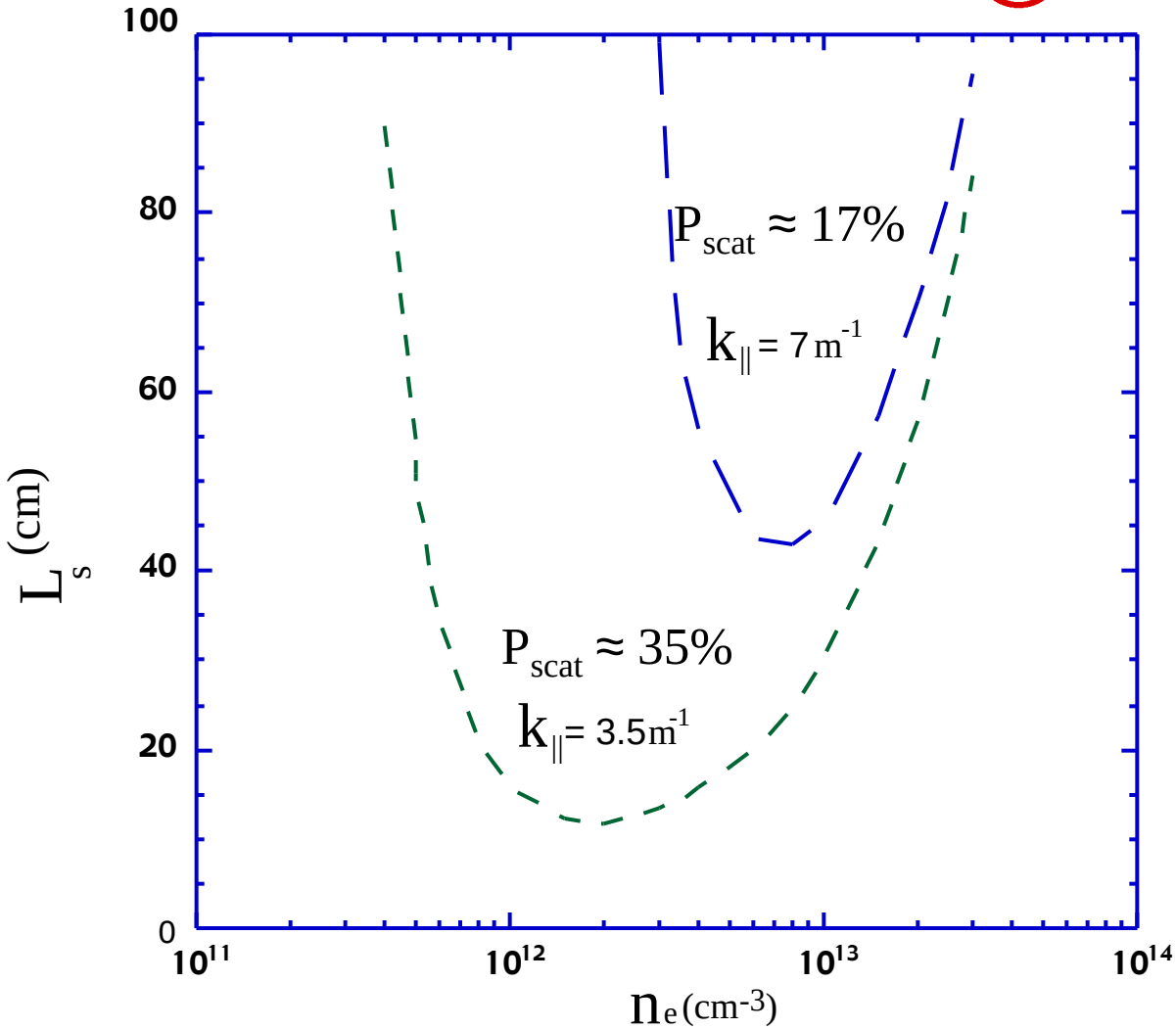
Low frequency scattering length L_s as a function of n_e. for various $k_{||}$ as labeled. B = 2.0 kG, T_i = 50 eV, C_D = 0.5, $|\hat{n}_e|$ = 0.05, and f = 30 MHz, and deuterium plasma.

90° Scattering Length for Higher Temperature



Low frequency scattering length L_s as a function of n_e. for various $k_{||}$ as labeled with T_i = 200 eV. B = 2.0 kG, , C_D = 0.5, $|\hat{n}_e|$ = 0.05, and f = 30 MHz, and deuterium plasma.

90° Scattering Length at Higher Field



Low frequency scattering length L_s as a function of n_e. for various $k_{\|}$ as labeled for B = 3.0 kG. T_i = 200 eV, C_D = 0.5, $|\hat{n}_e|$ = 0.05, and f = 30 MHz, and deuterium plasma. .

Summary Table of Scattering Probability (%)

$$P_s \equiv \int_{r_1}^{r_2} L_s^{-1}\, dr$$

	$n_{\|\|} = 14\ m^{-1}$	$n_{\|\|} = 7\ m^{-1}$	$n_{\|\|} = 3.5\ m^{-1}$
Case I*			
Lin.	17	56	100
Exp	13	51	200
Case II*			
Lin.	small	14	34
Exp	small	12	88
Case III*			
Lin.	small	16	28
Exp	small	18	47

Case I: B = 2.0 kG, T_i = 50 eV, C_D = 0.5.
Case II: B = 2.0 kG, T_i = 200 eV (or C_D = 0.25).
Case III: B = 3.0 kG, T_i = 200 eV (orC_D = 0.25).
All cases: 10 cm ramp distance, = 0.05, and f = 30 MHz, and deuterium.

Summary & Discussions

- HHFW could be subjected to low frequency fluctuation scattering
  - Scattering increases with decreasing $n_{||}$.
  - Increasing temperature reduces scattering.
  - Increasing magnetic field also reduces scattering for the fastest mode.

- How can we improve the situation?
  - Clearly quieter edge is desirable. (Is the fluctuation level generally lower for helium compare to deuterium?)
  - Steeper density gradient is better. (Is the density gradient diverted discharge steeper than the limited discharge? How does the heating efficiency depends on the scrape-off length?)
  - Hotter edge is better. (H-mode?)
  - With scattering, there are considerable up and down shifts of wave spectra (broadening - more core heating?).

Possible HHFW Turbulence XP(s)

- **Clearly we need to characterize the edge:**
  - Density and Temperature Profiles (MPTS, Reflectometry, CHERS, Edge Probe, etc.)
  - Fluctuations (Reflectometry, Edge Probe, etc.)

- **Parametric dependence of interest:**
  - Helium vs. deuterium.
  - Diverted vs. limited.
  - Distance to the LCFS.
  - Magnetic field scan (3 - 6 kG)
  - L-mode vs. H-mode

- **Analysis opportunity:**
  - More precise geometry
  - Input experimental measurements.
  - Ray-tracing + scattering. ($n_{||}$ Up-shifts + downshifts)