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Electron-electron collision effects on ISR spectra

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Background

Incoherent scatter radars (ISR) measure the power spectra of radio waves that are Thomson scattered off electrons in the ionosphere. The characteristics of the resulting wave spectra are inverted with theoretical models to calculate the plasma density, electron and ion temperatures, and ion drift speed. When the radar beam points nearly perpendicular to the Earth's magnetic field, Coulomb collisions are the primary mechanism for diffusion across magnetic field lines, and also increase the damping of oblique acoustic modes [1]. This significantly changes the shape of the measured spectra, causing inversion routines to underestimate plasma temperatures. Figure 1 shows the effect of Coulomb collisions on measurements taken at Millstone Hill, and the effect is also present at the Jicamarca and ALTAIR radars.

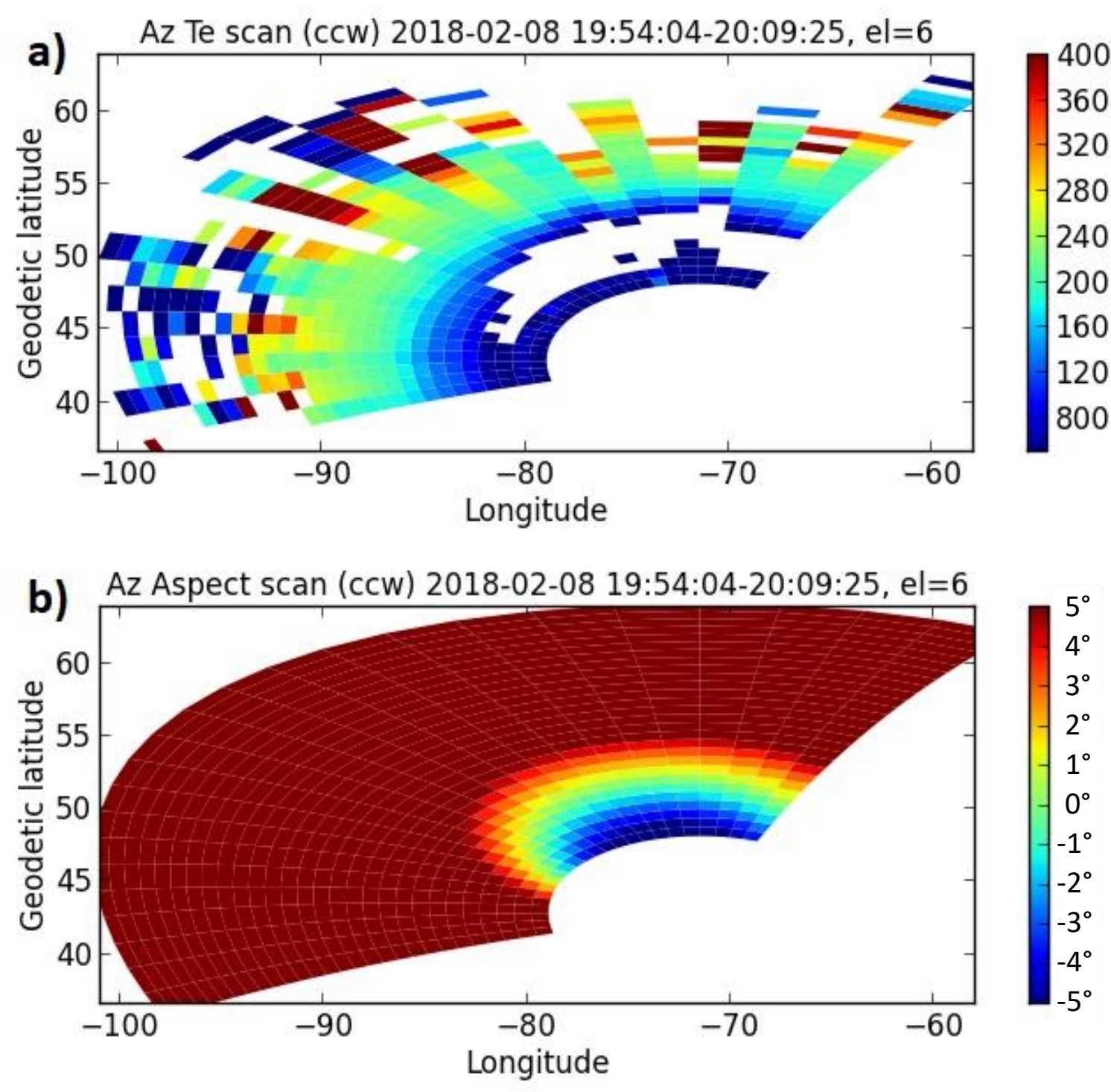

Figure 1: An azimuth scan from the 440 MHz Millstone Hill ISR. The data dropouts in electron temperature (top) close to the radar are where the beam points within 2-3° of perpendicular to the magnetic field (bottom). Standard inversion routines produce non-physical Te/Ti ratios at these aspect angles, and the results are discarded before publication on Madrigal.

This work is the first to use a fully kinetic, self-consistent, Particle-in-Cell (PIC) code to simulate ISR spectra at small magnetic aspect angles. The PIC approach allows for velocity dependent electron-ion and electron-electron collisions, as well as nonlinear wave behavior. Previous results are either restricted to single particle simulations with a velocity dependent collision frequency [1, 3], or approximate the collision process as Brownian motion with a constant collision frequency [2].

ISR Theory

The backscattered power spectra measured by a radar is [2]

$$P(\omega) \propto \left\langle \left| n_e\left(\omega, \vec{k}\right) \right|^2 \right\rangle = 2N_0 \left| 1 - \frac{\sigma_e}{\epsilon} \right|^2 \mathrm{Re}[J_e] + 2N_0 \left| \frac{\sigma_e}{\epsilon} \right|^2 \mathrm{Re}[J_i]$$

where $\epsilon = i\omega\epsilon_0 + \sigma_e + \sigma_i$. The Gordeyev integrals, J_s, and conductivities, σ_s, are calculated either by assuming a velocity-independent Brownian collision operator [2], or by simulating the trajectory of a single particle with a velocity dependent Fokker-Planck collision operator [3].

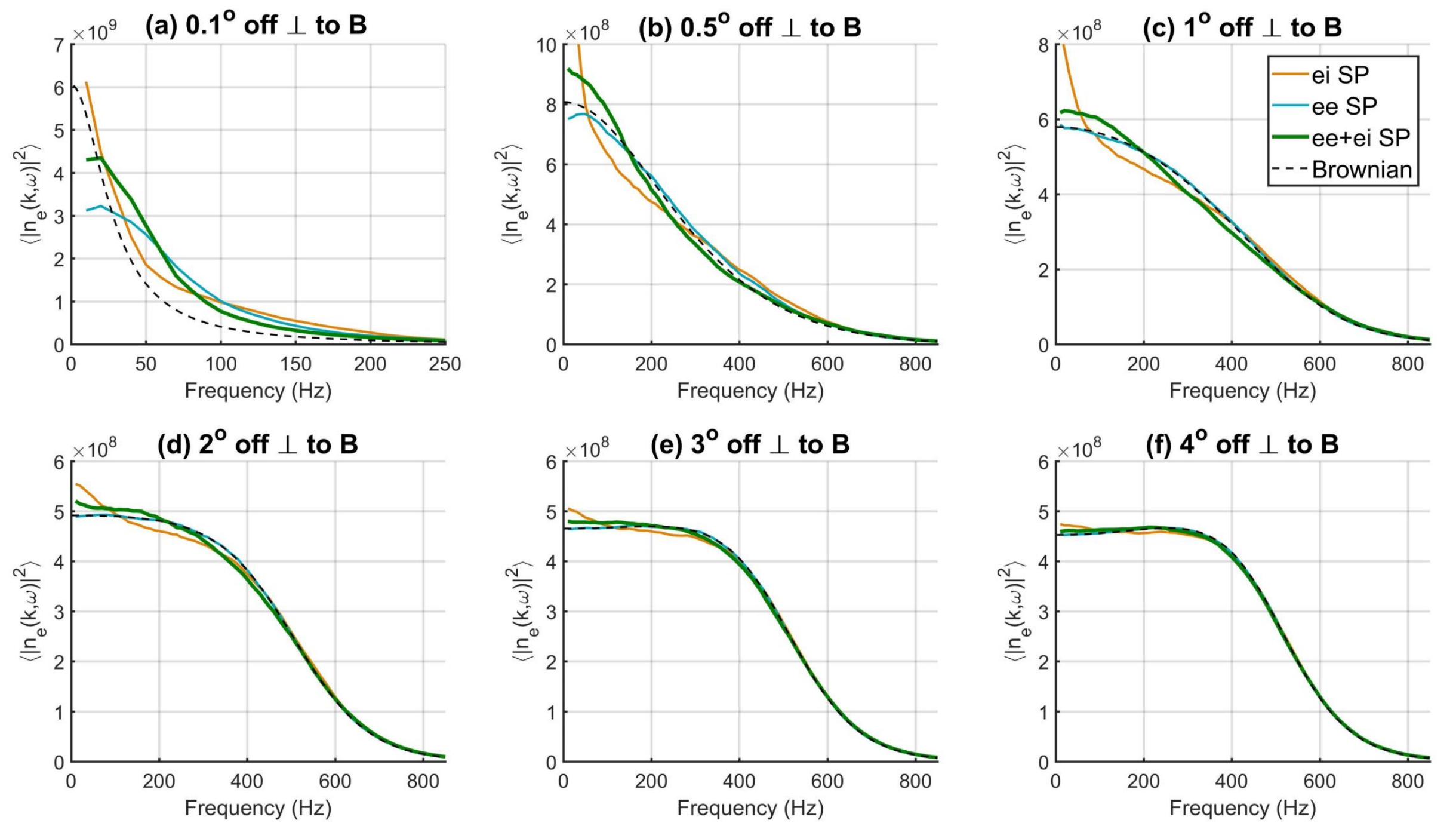

Figure 2: Small aspect angle spectra for a 50 MHz radar. Single particle simulations (SP) with only electron-electron collisions (blue) are well fit by the Brownian theory (black) at most angles. However, simulations with only electron-ion collisions (orange) or both collisions (green) are not well fit by the Brownian theory at aspect angles less than 3°.

PIC Simulations

PIC simulations naturally produce ion-acoustic and Langmuir waves, and output density at each time step. ISR spectra are then calculated by running the PIC code for 100 independent simulations, then Fourier transforming and averaging the density of each run to directly calculate $\left\langle \left| n_e\left(\vec{k}, \omega\right) \right|^2 \right\rangle$. Table one shows the simulation parameters used by the PIC code, which are representative of the nighttime F-region.

Table 1: Parameters used in ISR simulations.

Grid Size	512 x 512	**Electron mass**	$m_e = 2.594 \times 10^{-29}$ kg
Grid Step	$\Delta x = \Delta y = 1$ cm	**Ion mass (O^+)**	$m_i = 2.657 \times 10^{-26}$ kg
Simulation length	t = 40 ms	**Temperature**	$T_e = T_i = 1000$ K
Radar frequency	$f_{rad} = 440$ MHz	**Average density**	$n = 10^4$ cm^{-3}

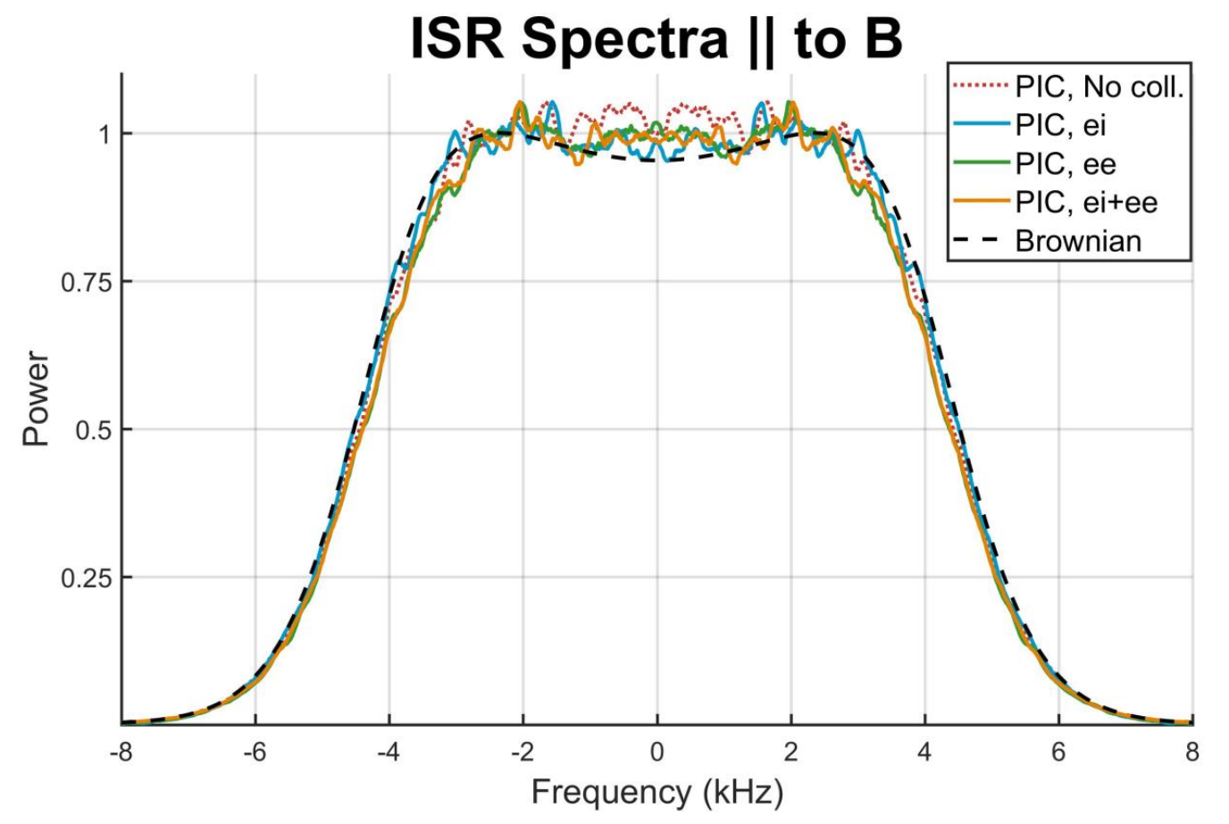

Figure 3: ISR spectra parallel to the magnetic field. The spectra at aspect angles larger than 5° is dominated by the high mobility along the magnetic field lines, and collisions have no effect on the propagation of the ion-acoustic mode [1].

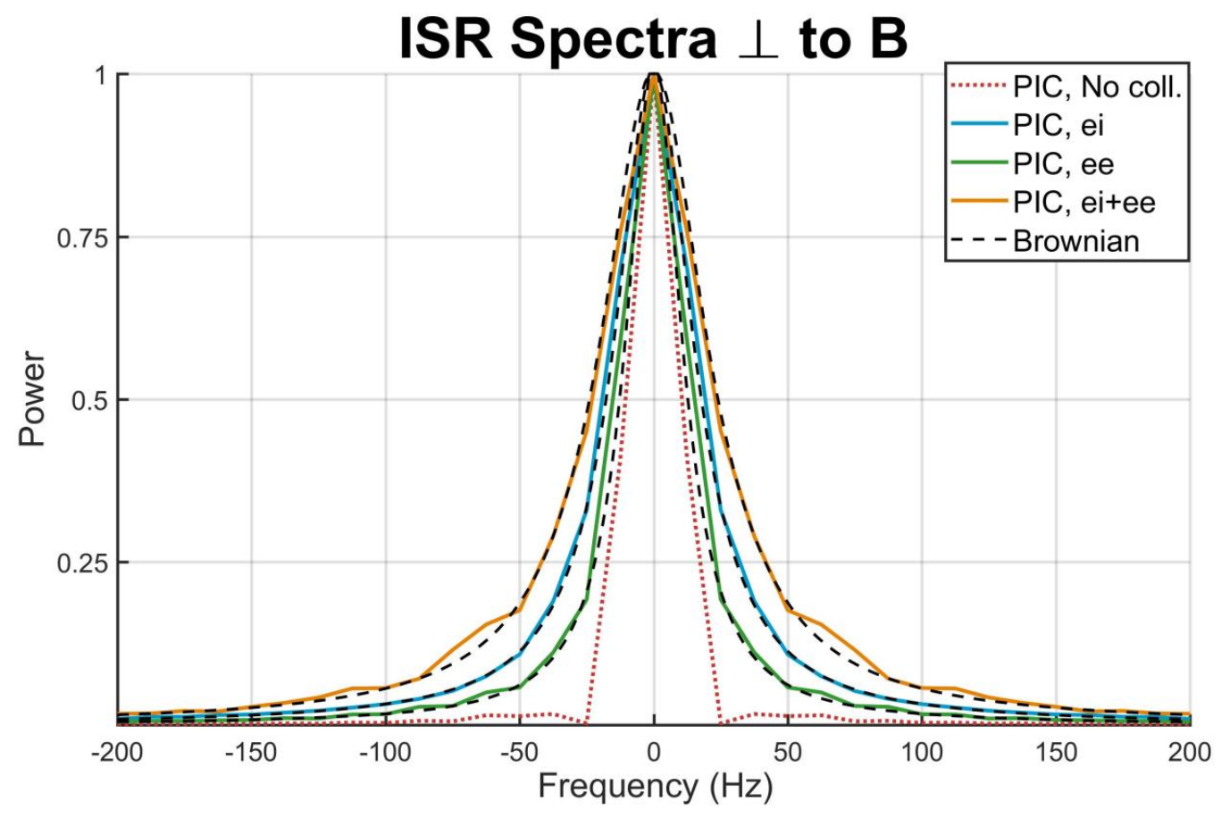

Figure 4: ISR spectra exactly perpendicular to the magnetic field. Without collisions (red) there is no diffusion across field lines and the spectra is narrower than the frequency resolution. The simulated collisional spectra (solid colors) are well fit by the Brownian model (dashed black) from [2].

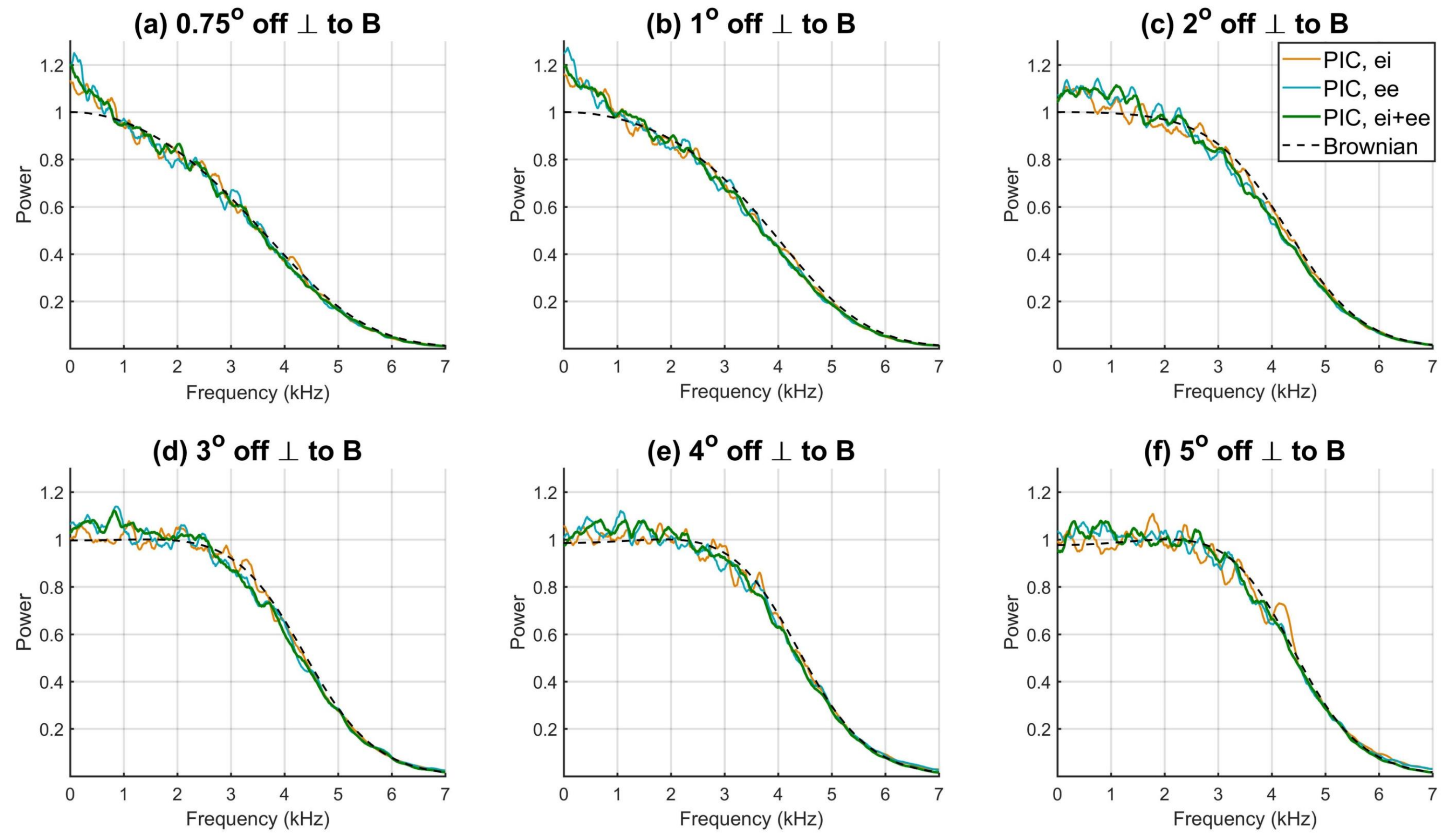

Figure 5: Spectra for a 440 MHz radar at a range of aspect angles near perpendicular to B. The Brownian collision theory (black) predicts wider spectra than any of the collisional simulations at aspect angles of 2° or less. At 3° the simulation with only electron-ion collisions (orange) converges on the Brownian theory. However, the simulations with only electron-electron collisions (blue) and both collision types (green) do not converge on the Brownian theory until 5°. In the PIC code electron-electron collisions damp the ion-acoustic mode at a larger range of angles compared to the Brownian theory. This is in contrast to the single particle simulations in Figure 2, which show electron-electron collisions are well modeled by the Brownian theory.

Acknowledgements

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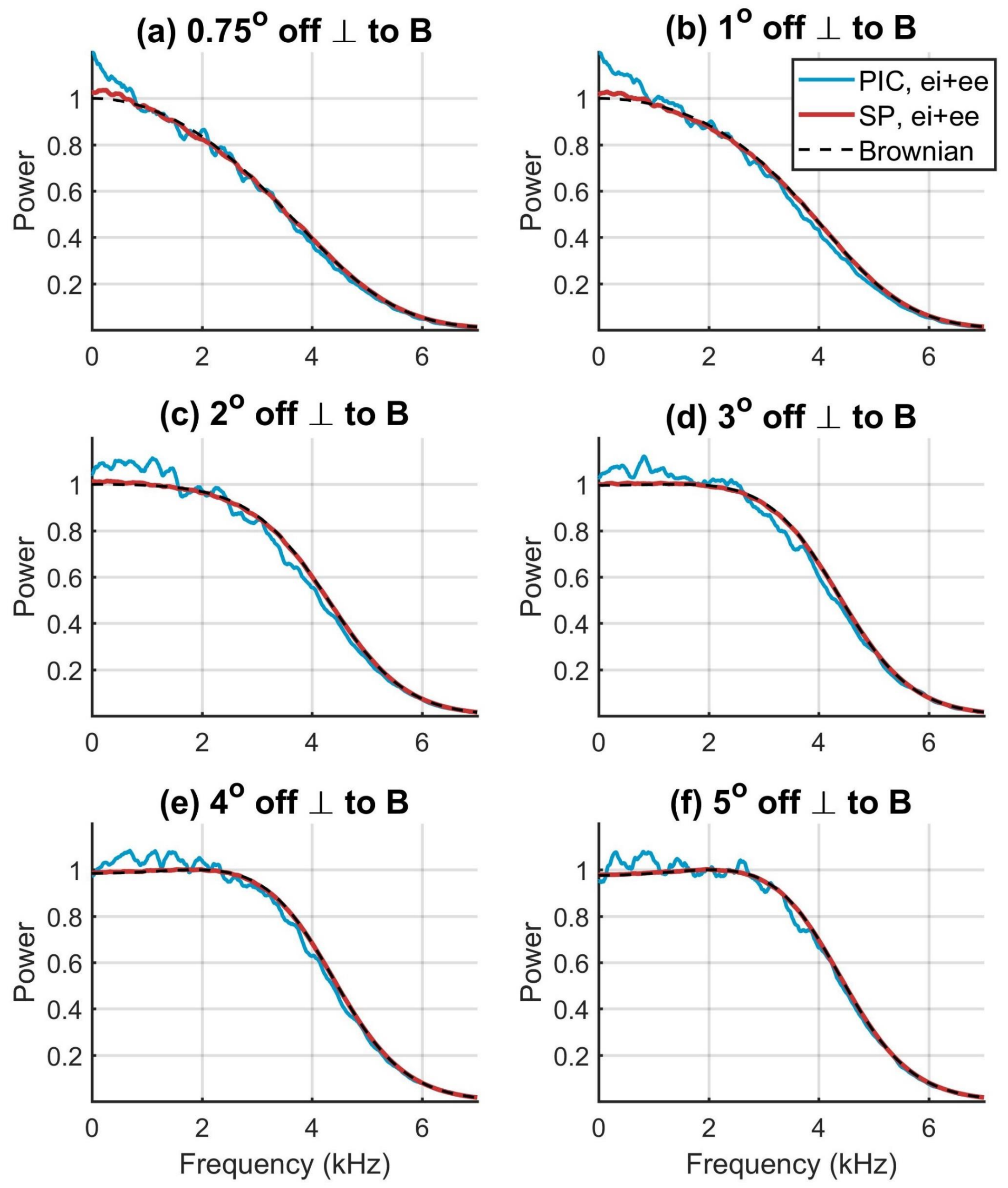
Comparison to Radar Data

Figure 6: The combined effects of electron-ion and electron-electron collisions are compared between the different simulation methods for a 440 MHz radar. At aspect angles of 2° and larger the spectra from single particle simulations (red) are well fit by the Brownian theory (black). However, the PIC simulations (blue) show collisional effects are important at aspect angles as large as 4°. This discrepancy is due to how electron-electron collisions are modeled in the PIC approach versus the single particle approach.



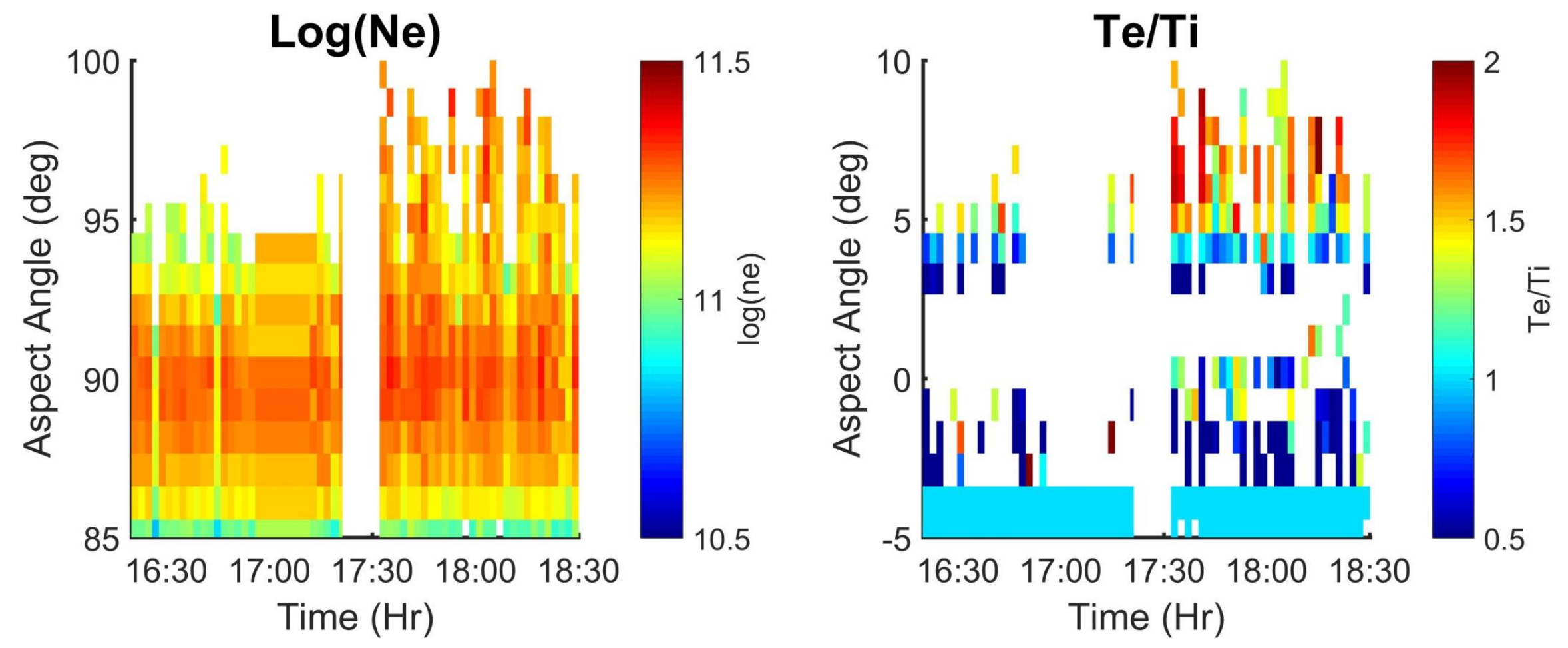


Figure 7: Density and temperature ratio measurements taken April 20, 2018 at Millstone Hill, plotted against magnetic aspect angle. Electron density measurements are less affected by spectral shape at small aspect angles. However, the Te/Ti ratio has data dropouts or nonphysical values at aspect angles as large as 3.6°, where collisions affect the inversion routine. Figure 6 shows PIC simulations predict collisional effects are important at aspect angles as large as 4°, whereas single particle simulations predict collisional effects are important only up to 2°.

Conclusions

- ○ Velocity dependent electron-ion and electron-electron collisions are implemented in a self-consistent PIC code to simulate ISR spectra
- ○ PIC simulations show different collisional effects compared to simulations using single particle displacement statistics
- ○ **PIC simulations show electron-electron collisions cause temperature underestimates at magnetic aspect angles as large as 4°**

References

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[2] Kudeki, E. and M. Milla (2011), Incoherent Scatter Spectral Theories – Part 1: A general framework and results for small magnetic aspect ratios, *IEEE Trans. on Geosci. and Remote Sens.*, Vol. 49, Num 1
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