Effects of Ionization on Beam Parallel Component and Beam-Driven Perpendicular Modes

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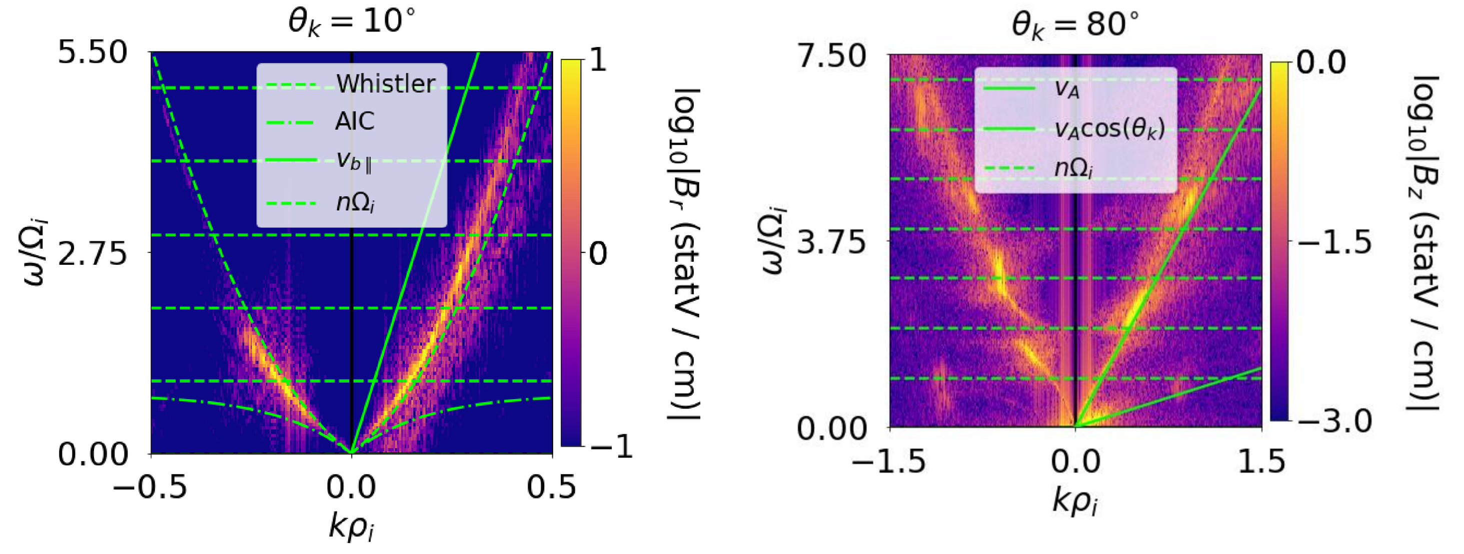
1. Motivation

- Experiments[1] indicate beam-driven mode in the vicinity of the ion cyclotron frequency ($n = 1$) seen at low β—conditions typically found in C2U FRC scrape-off layer and outbound of separatrix.
- 1D PIC simulations with ion beam reproduce ion cyclotron mode for parallel beam/propagation.
- Velocity-space broadening by ionization may create population of beam ions with increased parallel velocity component.
- This work explores the effect of ionization of a neutral beam on perpendicular beam-driven modes and the creation of more strongly parallel beam ions in a uniform magnetic field.

Regimes 1D PIC Beam-Driven Modes

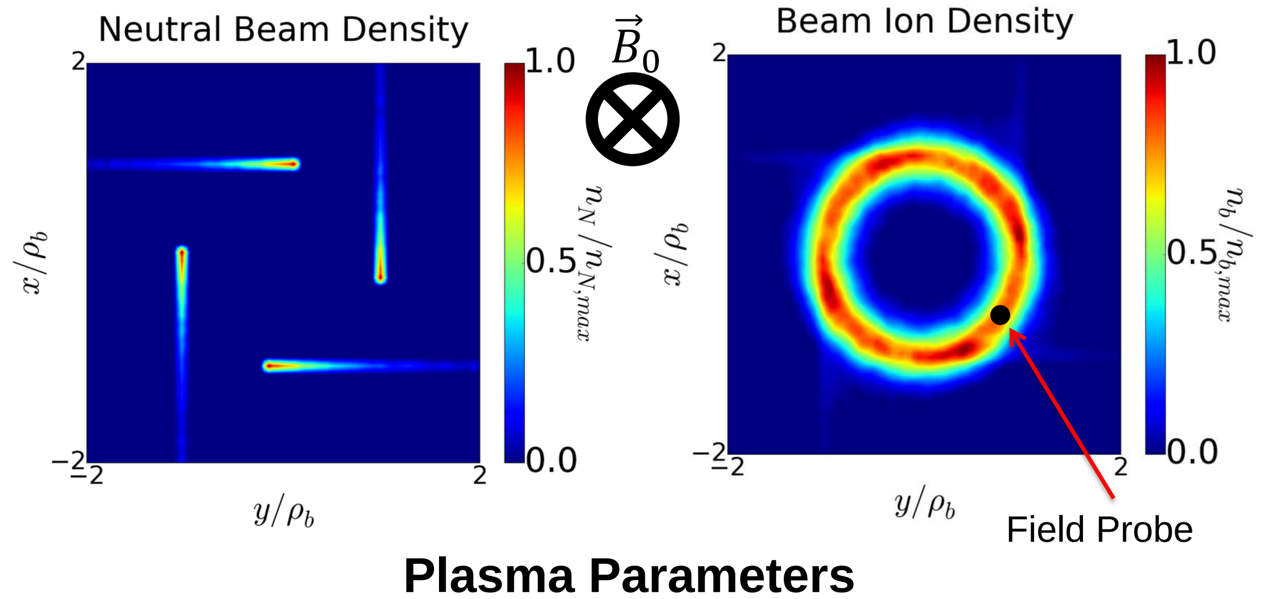


Parallel: Right-handed Alfven mode dominates with peak at ion cyclotron fundamental

Perpendicular: Harmonics of beam ion-Bernstein modes and excitation of shear Alfven dominate

2. Setup

- Implicit PIC code LSP
- Ambient magnetic field $\vec{B}_0 \parallel \hat{z}$
- 2D simulation domain: x, y plane
- Conducting boundaries; impacting particles lost
- Uniform background: electrons, deuterium plasma
- Probe measures time evolution of fields in beam ring
- Neutral hydrogen beam injected with local density of 10% of background electron density n_e
- Beam has $v_\perp$ and $v_\parallel$; $\rho_b = 22$ cm $\approx 10\rho_i$
- Charge-exchange not included; ionization σ multiplied by 50 to approximately compensate



Plasma Parameters

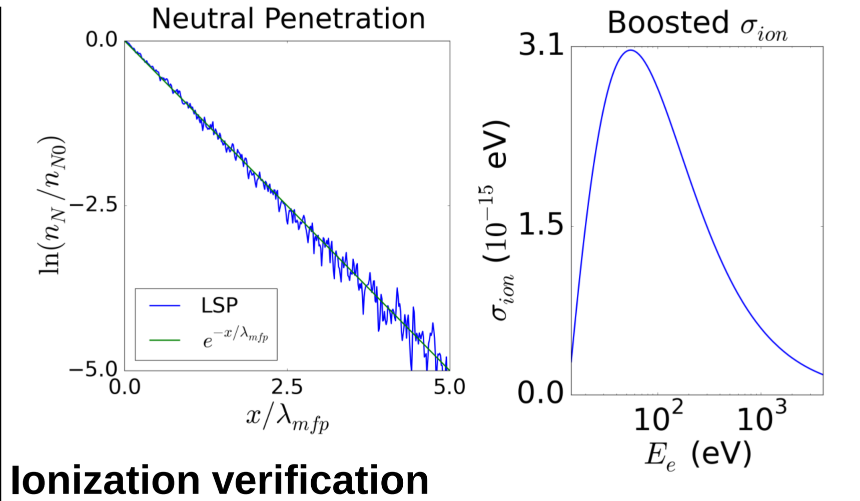
B_0	$T_{i,e}$	T_b	E_b	n_e	θ_b	β
0.075 T	200 eV	0 eV	15 keV	7E18 m^{-3}	70°	10%

3. 1D Verification of Ionization Model

- Geometry reduced to 1D and neutral beam injected at edge of domain, directed along x axis
- Periodic boundary conditions
- Same boosted ionization model as 2D setup with no charge exchange
- Penetration of neutrals shows good agreement with theoretical mean free path λ_{mdp} derived from assumption that $v_b \ll v_{Te}$.

$$\lambda_{mfp} = \frac{v_b}{n_e\langle v_e\sigma(v_e)\rangle}$$

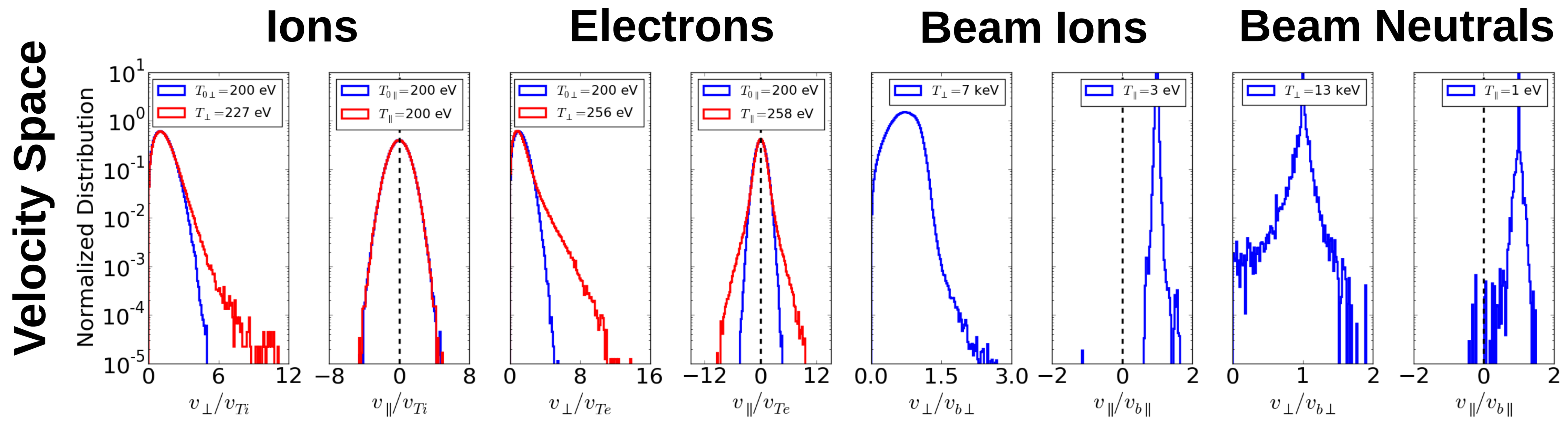
$$\langle v_e\sigma(v_e)\rangle = \left(\frac{2}{\pi}\right)^{1/2}\frac{1}{v_e^3}\int_0^\infty v_e^3\sigma(v_e)\exp\left[-\frac{1}{2}\left(\frac{v_e}{v_{Te}}\right)^2\right]dv_e$$



Ionization verification

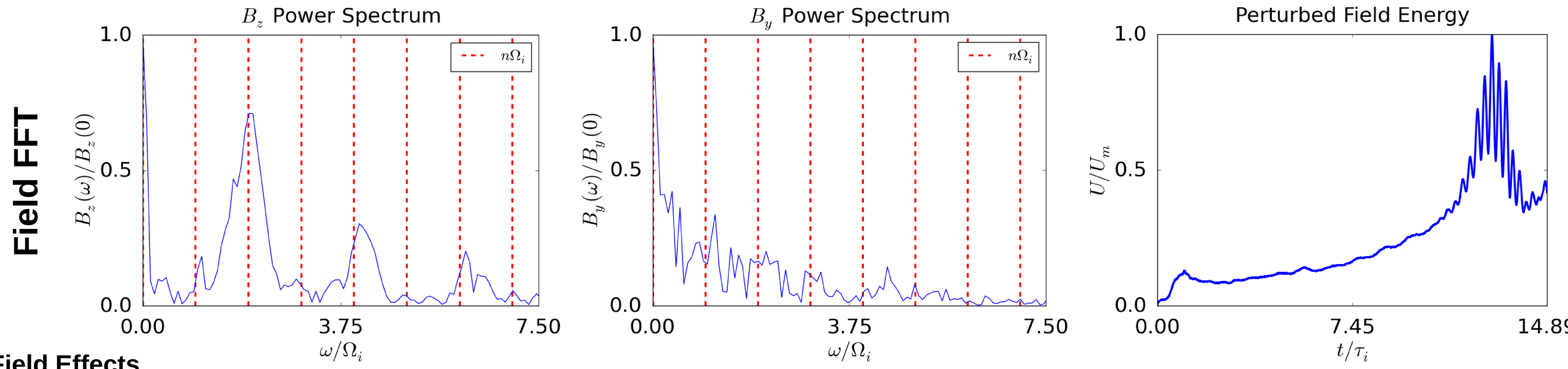
- The functional form of the cross section is taken from NIST (right), and boosted by a factor of 50.
- The simulated mean free path agrees well with the calculated value above through $x/\lambda_{mfp} = 5$.

4. 2D Simulation Results



Velocity Effects

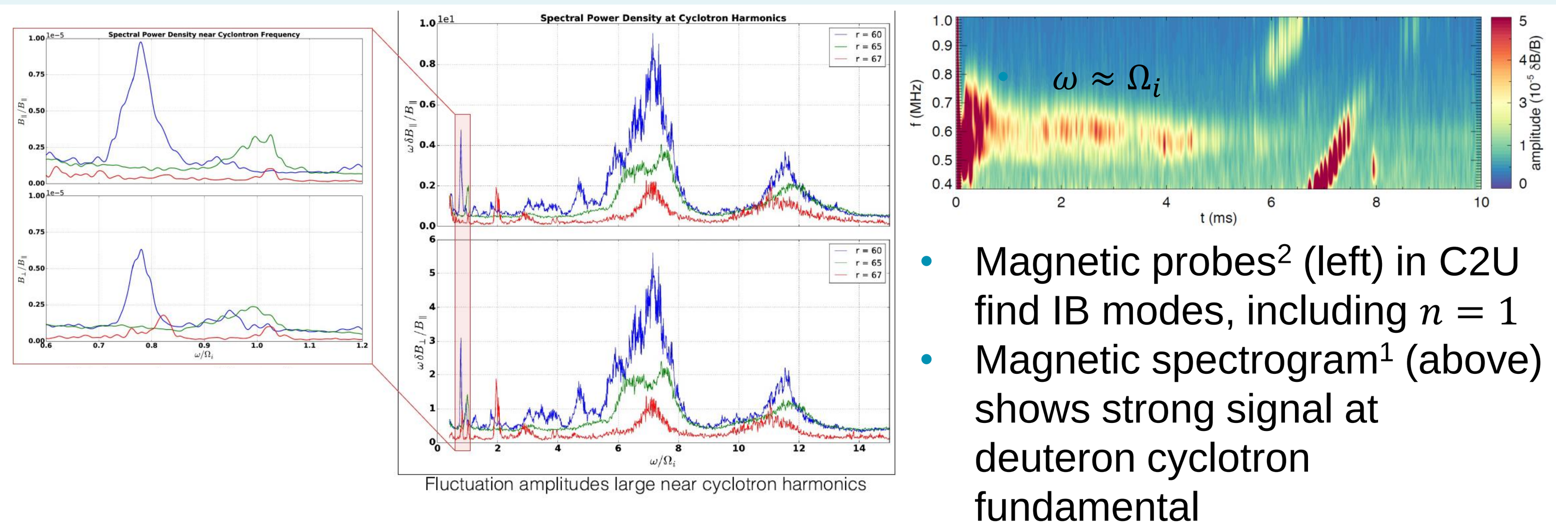
- Tail of fast background ions produced from beam-driven wave interaction
- Electrons warmed from collisions during ionization
- **Ionization broadens beam ion distribution in both perp. and parallel directions, mitigating micro-instability growth**



Field Effects

- Proton ion-Bernstein modes of beam excited, roughly consistent with 1D dispersion, and leads to ion heating.
- Low-frequency activity seen in B_y, which is consistent with shear Alfven mode seen in 1D.
- Growth rate of mode is much slower than in 1D case, where mode saturates at $t \sim 2\tau_i$, because of velocity broadening.

5. Experimental Results[1,2]



- Magnetic probes[2] (left) in C2U find IB modes, including $n = 1$
- Magnetic spectrogram[1] (above) shows strong signal at deuteron cyclotron fundamental

6. Summary and Continuing Work

- Beam-driven modes from 1D PIC simulations with Maxwellian beams motivate moving to 2D PIC geometry. Currently, only simulation of perpendicular plane is possible.
- Perpendicular modes seen in 1D are reproduced in 2D, but ionization of neutral beam introduces a significant broadening (slow-down) in beam distribution, mitigating these modes.
- Ionization also introduces population of beam ions with enhanced parallel velocity, which could possibly account for observed $n = 1$ mode through a parallel-propagating fast Alfven wave.
- The next step: inject beam in similar manner into 2D C2U-like FRC.

7. References

1. R. Magee, "Collective Phenomena in the Advanced, Beam-Driven FRC", IAEA, 2017
2. T. Roche, "Edge/SOL Plasma Parameter/Magnetic Field Profile and Fluctuation Measurements at C2U Midplane", poster, APS DPP 2016