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Collisionless Interaction of a Magnetized Ambient Plasma and a Field-Parallel Laser Produced Plasma

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Collisionless Parallel Shock Formation

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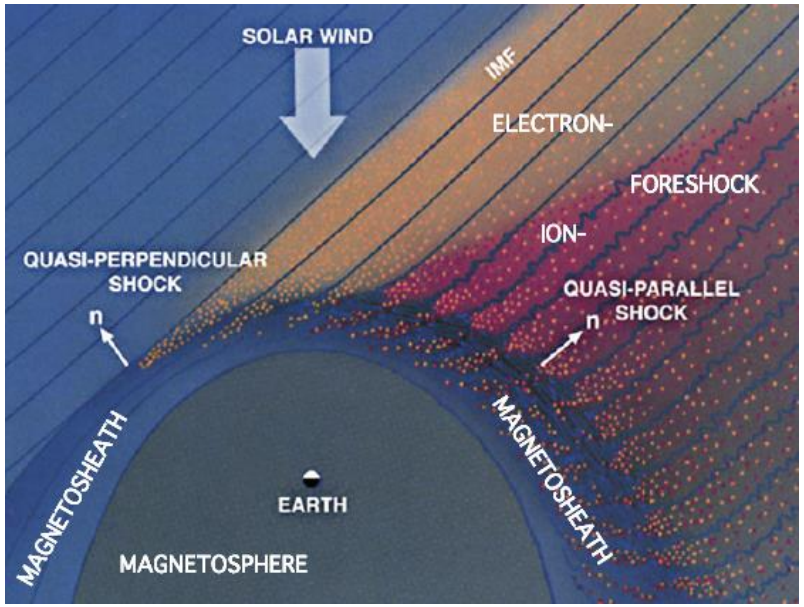
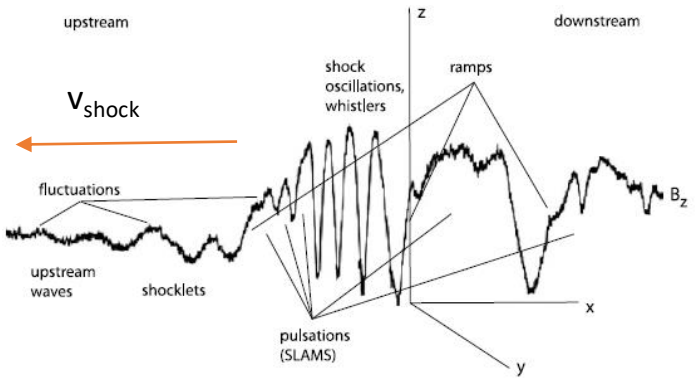
Collisionless parallel shocks are important in many space and astrophysical contexts. Parallel shock formation has been previously studied by hybrid simulations, but has never been observed in the laboratory.

According to simulations:

- Parallel shocks form over large length scales (hundreds of ion-inertial lengths).
- Two beam instabilities play an important role in parallel shock formation: the Right Hand Resonant Instability (RHI) and the Non-Resonant Instability (NRI).





Physics of Collisionless Shocks, Balogh and Treumann

RHI and NRI Beam Instabilities

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Right Hand (Resonant) Instability (RHI)

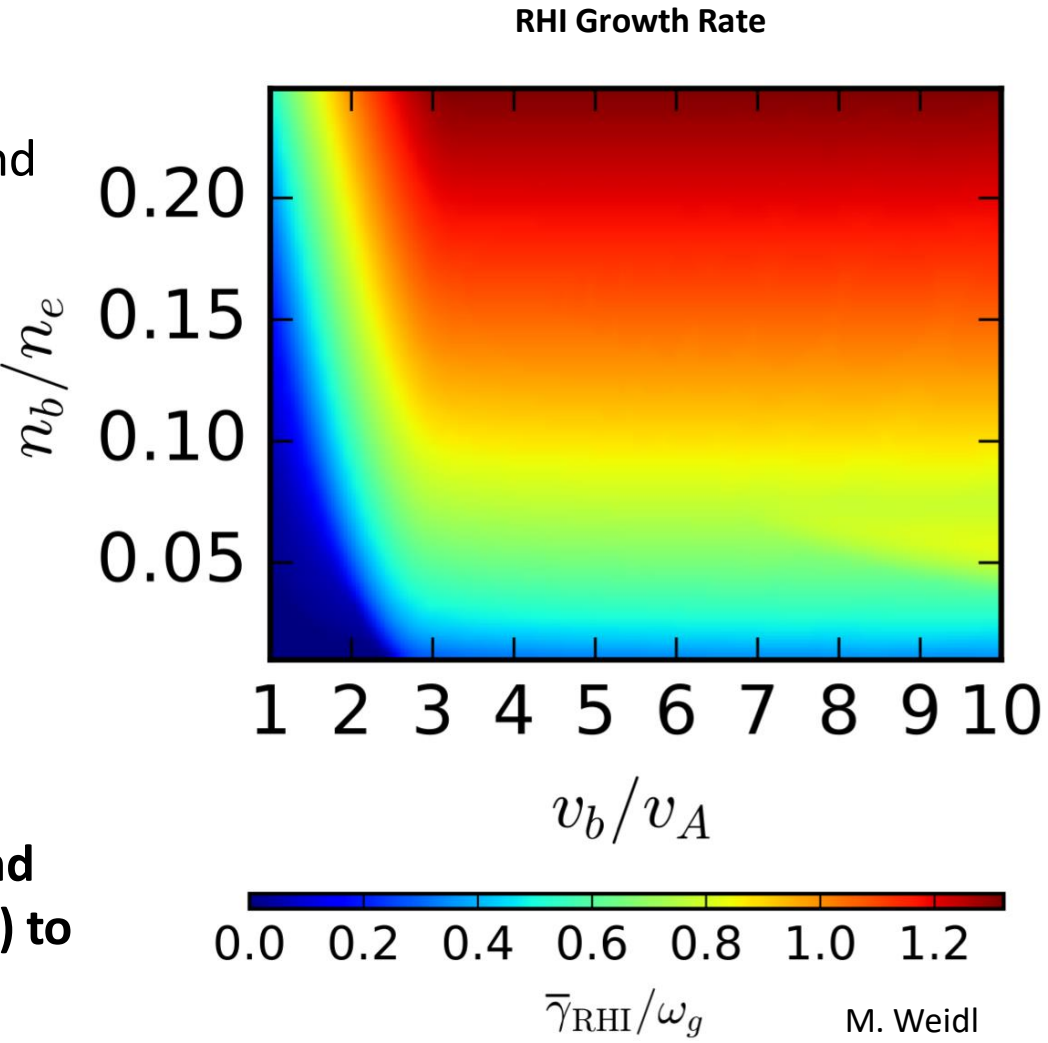
- Gyro-resonances of debris ions with circularly polarized magnetosonic waves with negative helicity in the background plasma.
- Dominant for $\mathbf{n_{debris} \leq n_0}$ when $v_{debris} > v_{A.}$

Non-Resonant Instability (NRI)

- Non-resonant coupling of debris ions to background ions through broadband turbulence with mostly positive helicity.
- Dominant for $\mathbf{n_{debris} \sim n_0}$ when $v_{debris} >> v_{A.}$

Winske1984, Gary1986

Experiment goal: Create field-parallel debris with $M_A > 3$ and debris ≥ 5% n_0 over several meters (and several gyro periods) to excite the RHI.



Super Alfvénic Debris Ablated by Lasers

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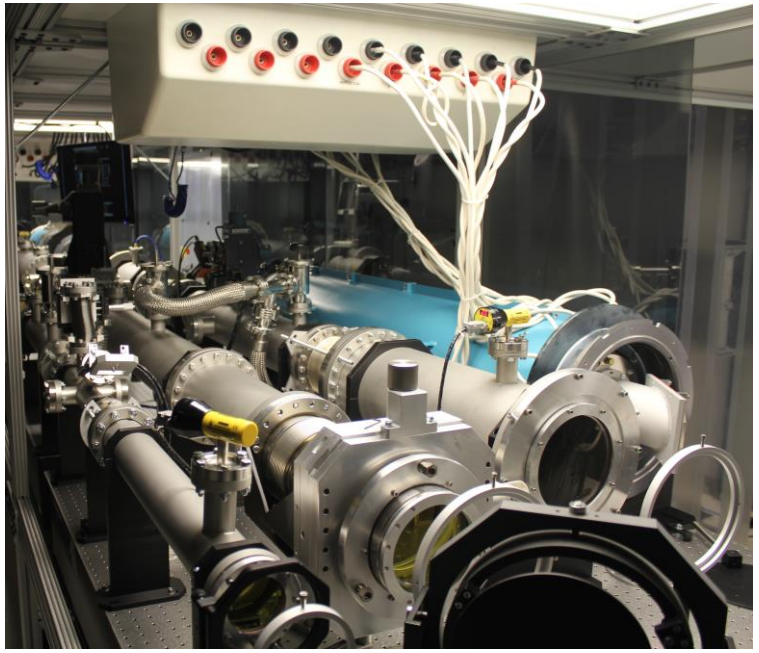
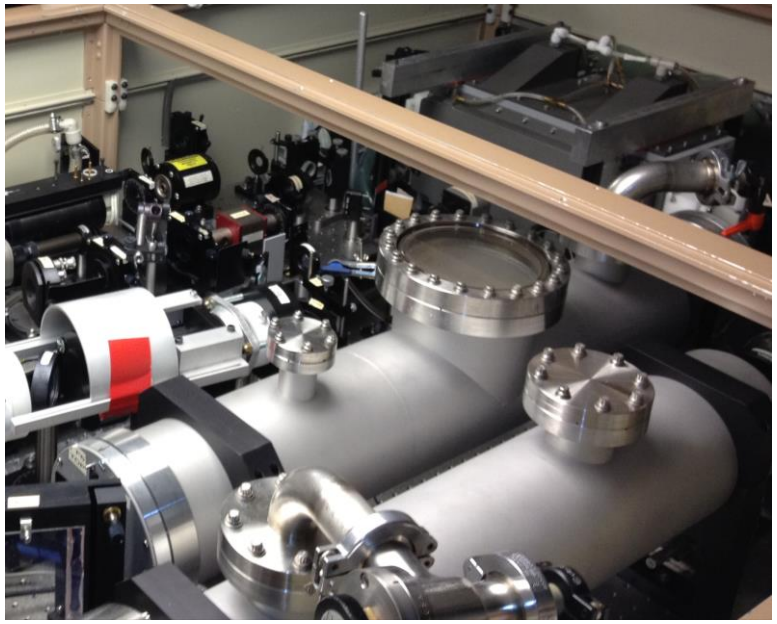
Raptor: High Energy, Low Rep. Rate



- E = 200 J (τ = 25 ns)
- Intensity on target 10^{11} W/cm^2.
- Ablated 10^{17} ions.
- ~ 1 shot per hour.

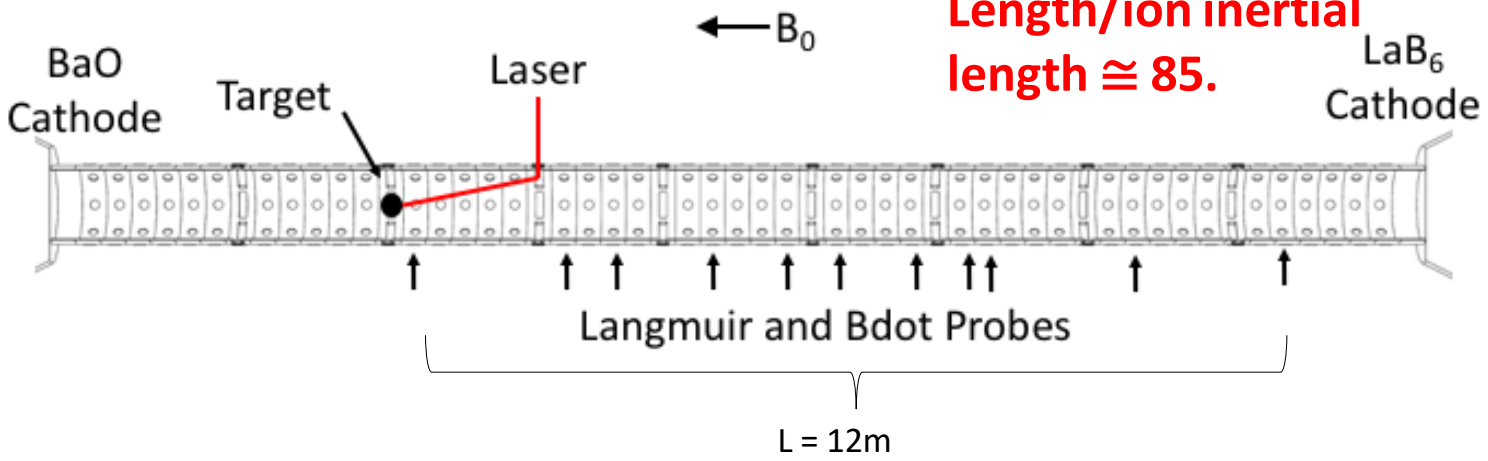
Despite energy difference, similar intensity -> similar debris velocities.

Peening: Lower Energy, High Rep. Rate



- E = 15 J (τ = 15 ns)
- Intensity on target 10^{11} W/cm^2.
- Ablated 10^{16} ions.
- Up to 1 Hz rep. rate.

Debris Expands Parallel to Field over 12m



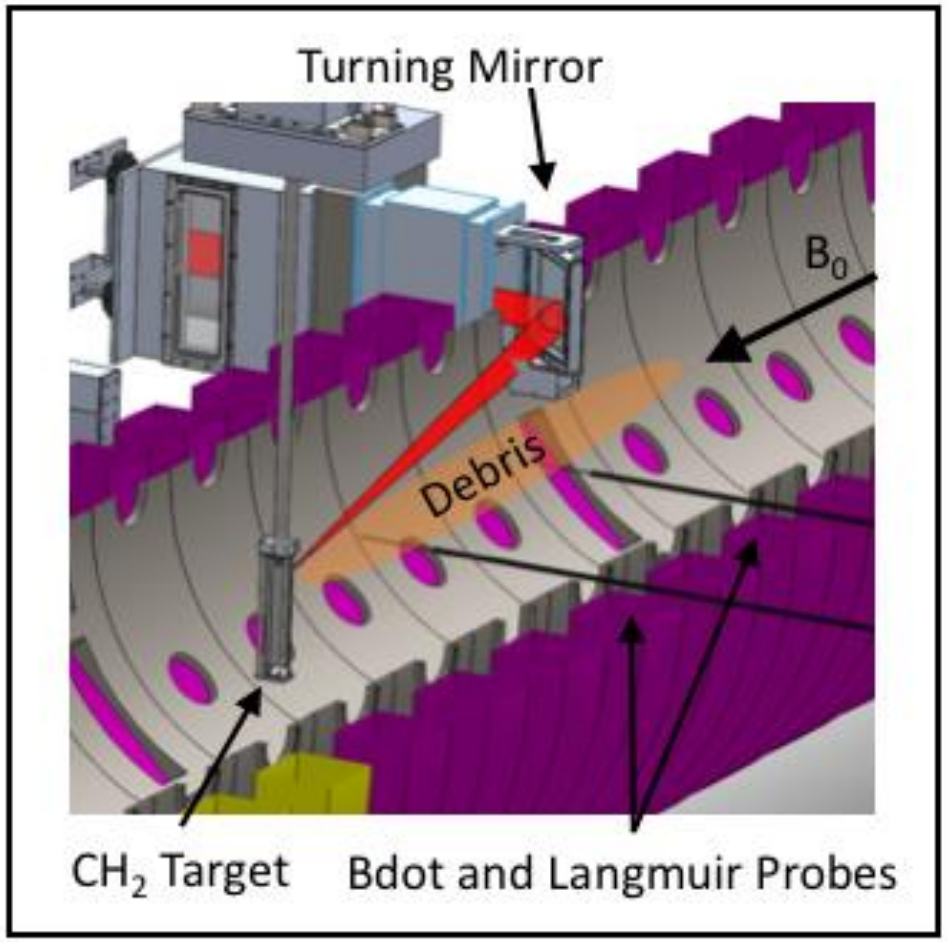
Length/ion inertial length ≅ 85.

Large Plasma Device (LAPD)

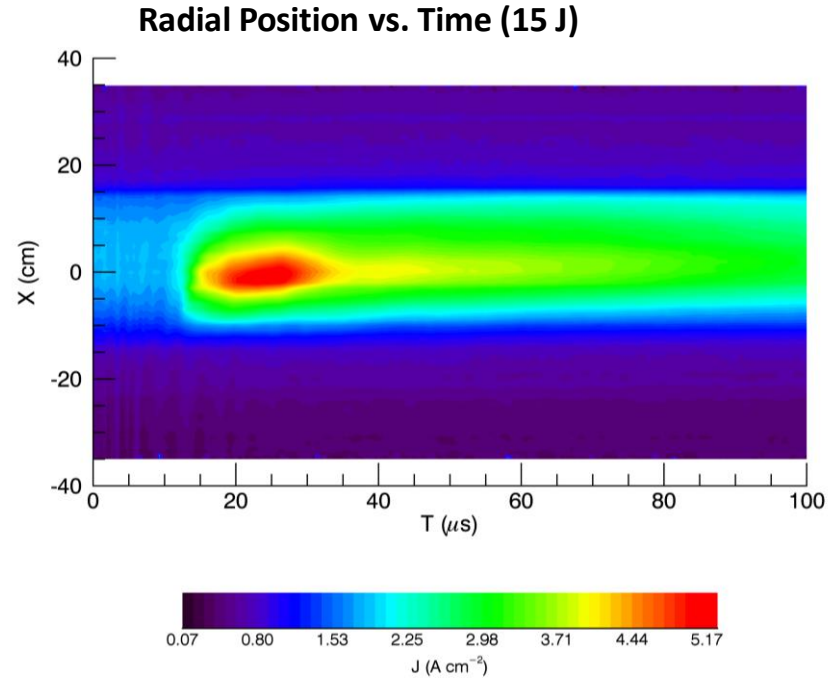
- B_0 =300 G.
- Helium Plasma.
- $n_0 \sim 10^{13}$ cm^{-3}.

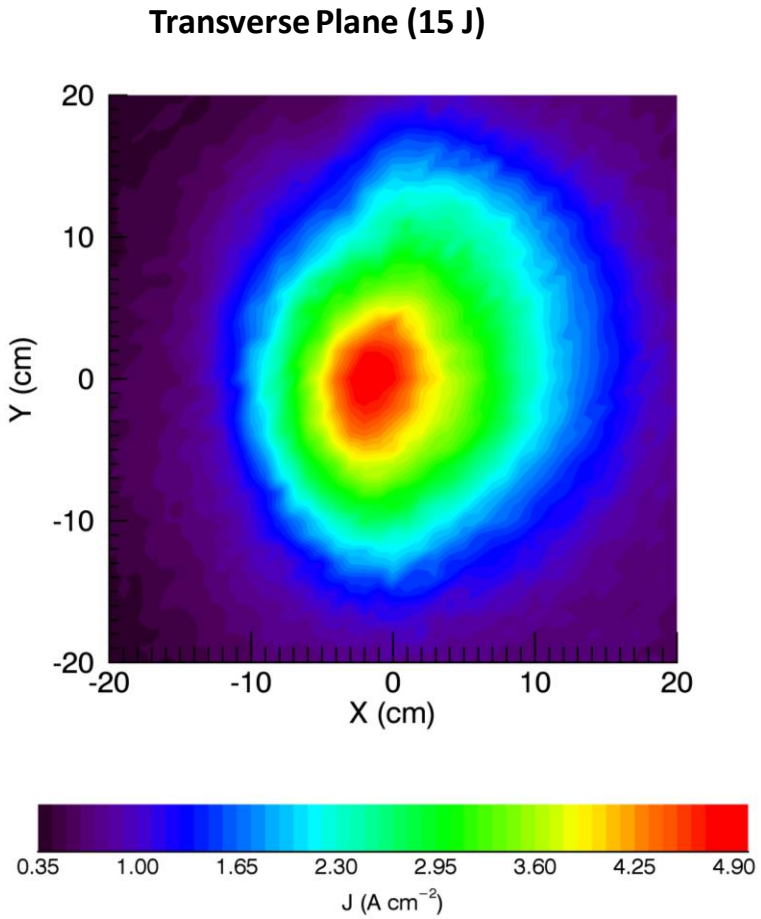
Debris

- Carbon and Hydrogen ions.
- Collisionless: $\lambda_{ii,mfp} > 100$ m.
- ~ 10^{17} particle blowoff.



Debris Density Meets Goal Up To 2 m From Target





- Measurements with a Langmuir probe 2 m from the target show that $\mathbf{n_{debris} \sim 8\% n_0}$ in the dense center of beam.
- Results are consistent between both lasers.

Bulk Debris is Super-Alfvénic

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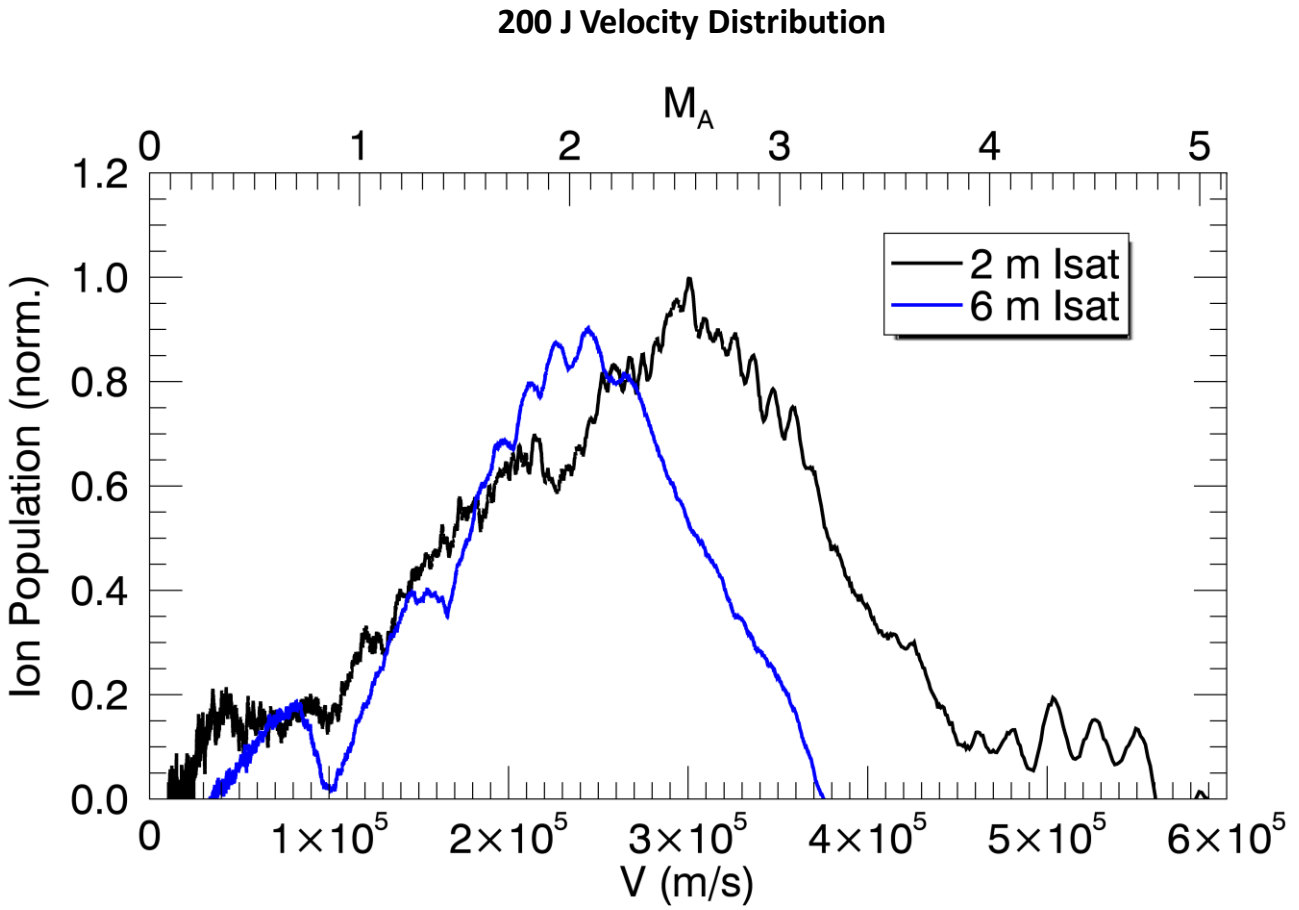
- LAPD Alfvén speed measured to be ~100 km/s.
- Time of flight velocities calculated from a Langmuir probe 2m from the target show ions as fast as **$M_A = 5$** (500 km/s) for the Raptor laser, and **$M_A = 2.5$** (250 km/s) for the Peening laser.



Experiment Parameters In RHI Regime

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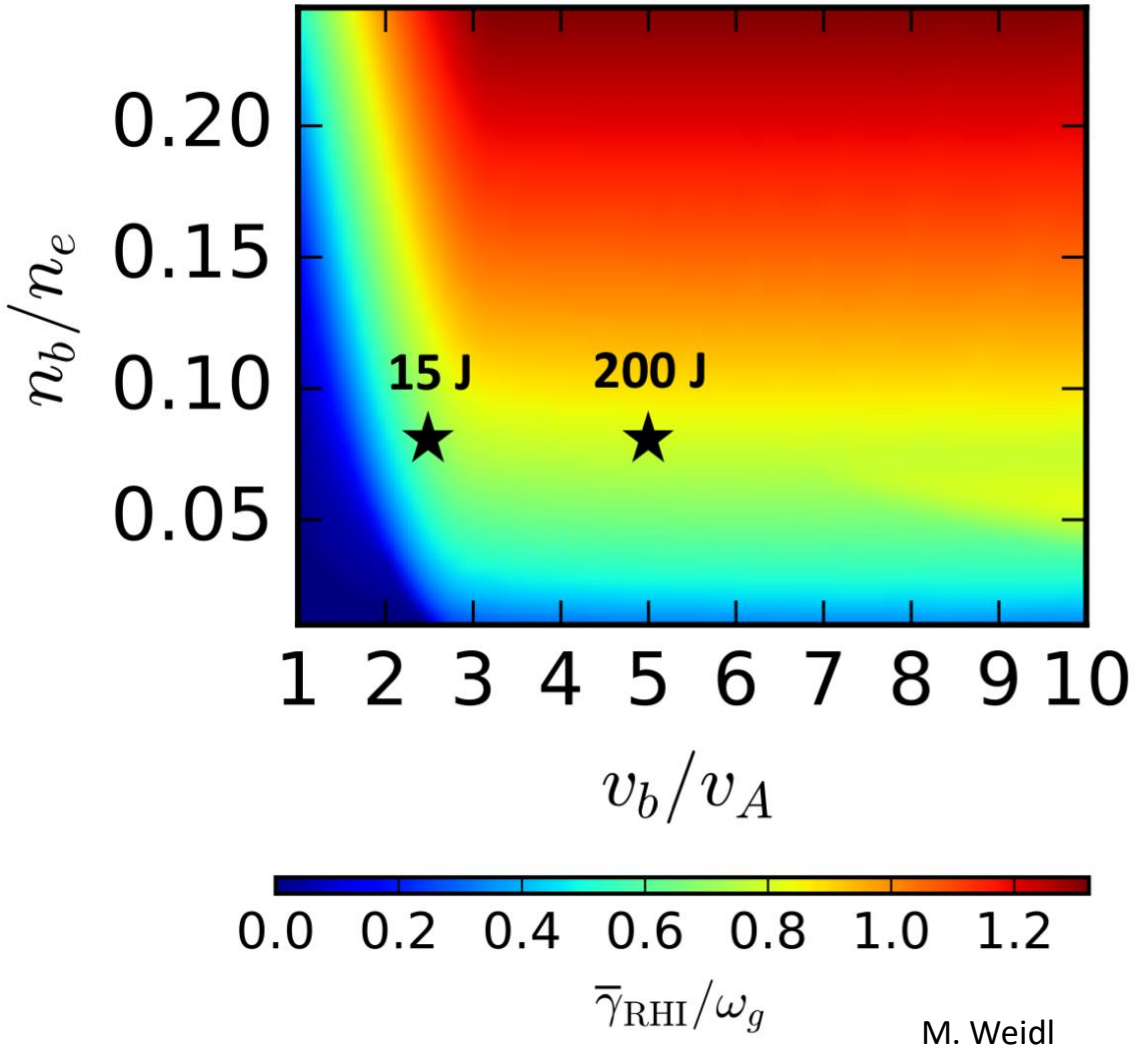
Experiment goal: Create field-parallel debris with $M_A > 3$ and debris ≥ 5% n_0 over several meters (and several gyro periods) to excite the RHI.



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Waves and Alfvénic pulse observed in B-field

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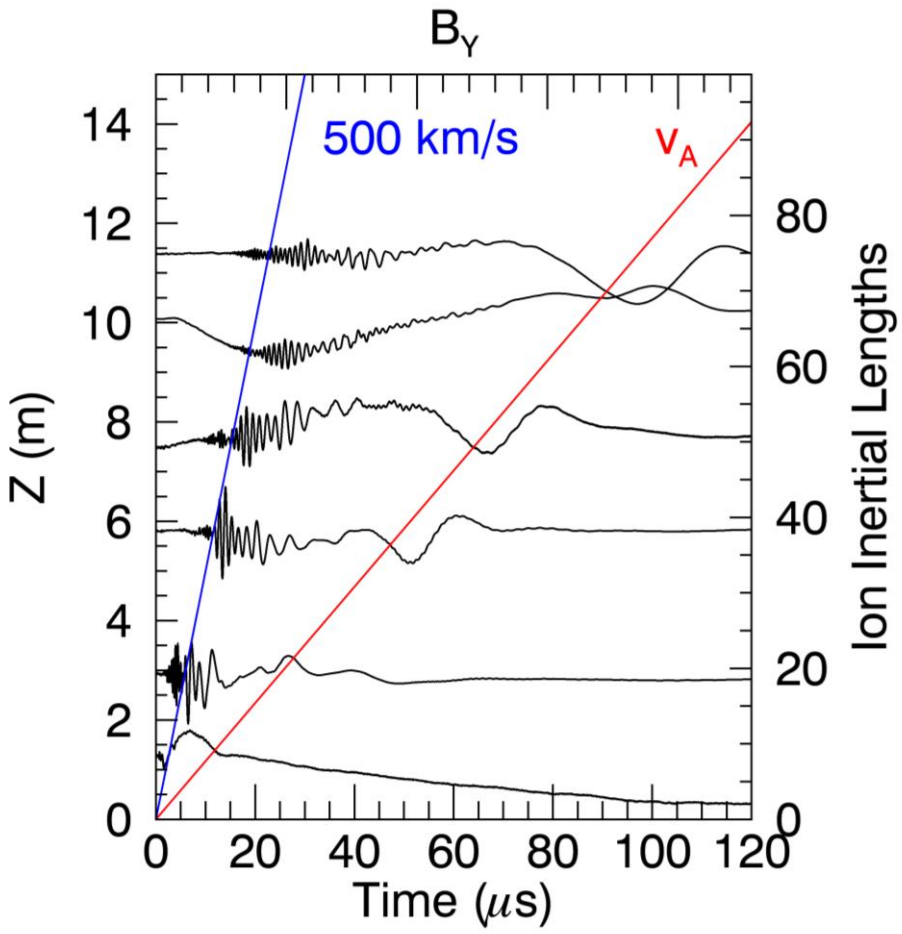
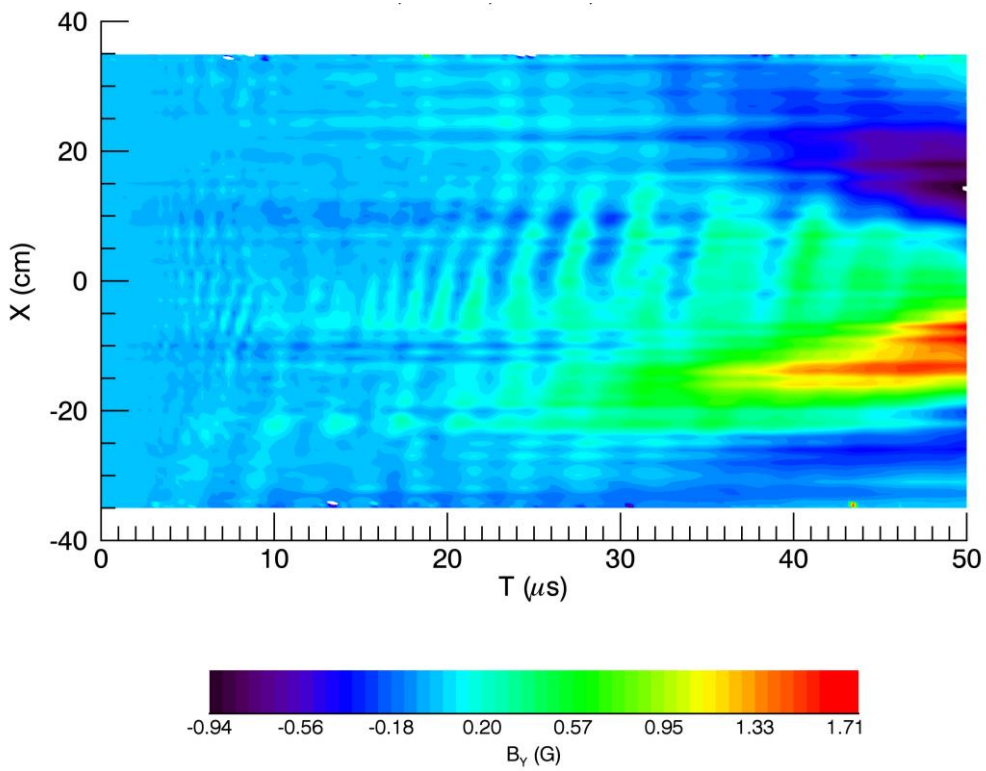
- A shear Alfvén wave follows traveling at V_A (red line) is observed on each probe.
- A high frequency chirp (10^7 Hz down to $\Omega_0 = 2 \times 10^5$ Hz).

200 J



15 J



Observed Waves are Right-Handed

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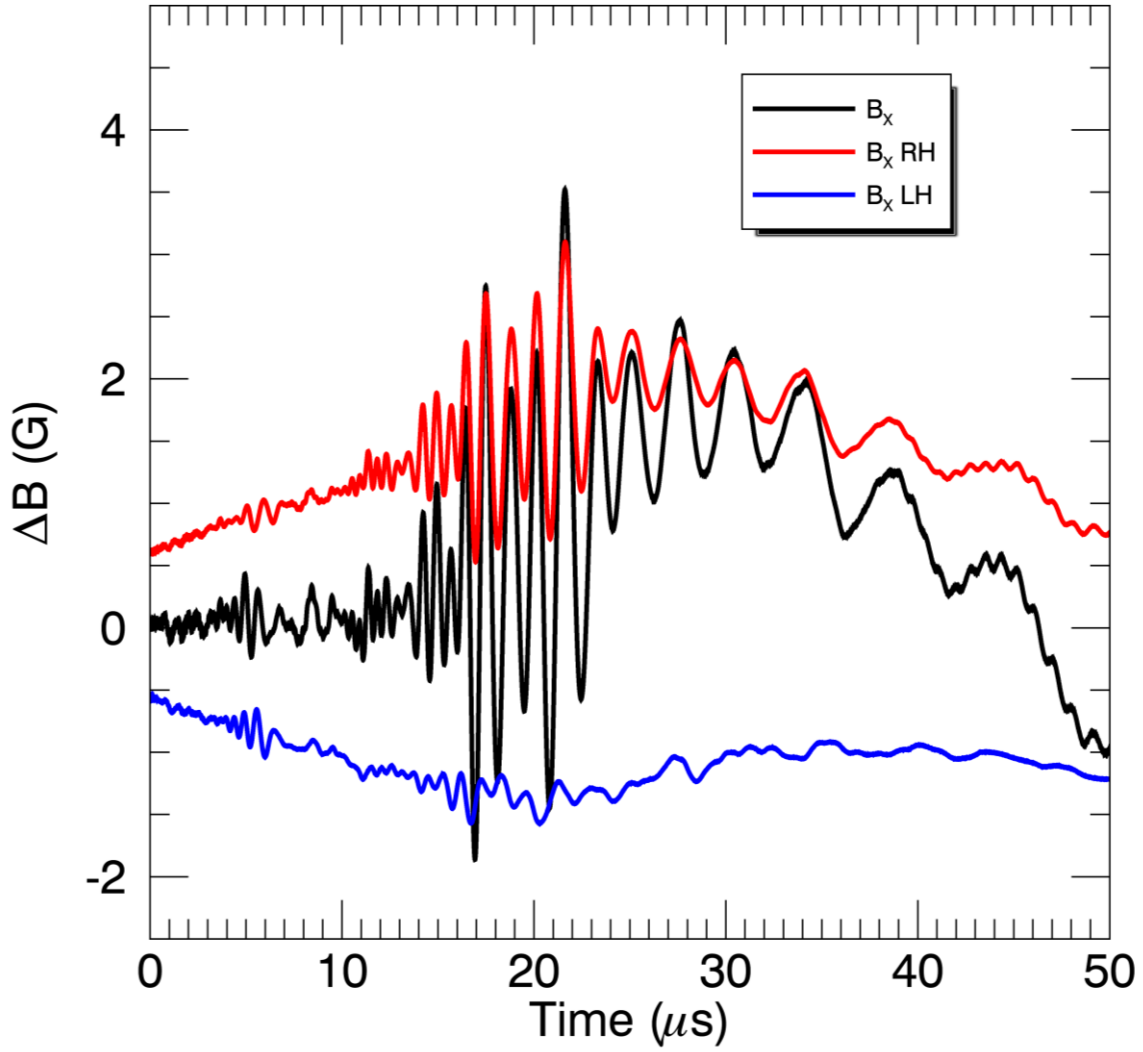
- Decomposition onto circularly polarized basis vectors shows that the waves are predominantly right-hand polarized.

- This fact is consistent with these waves being driven by the RHI.

$$B_R(k) = \frac{1}{2}(B_x(k) + iB_y(k))$$



Fitting with an Analytic RHI Model

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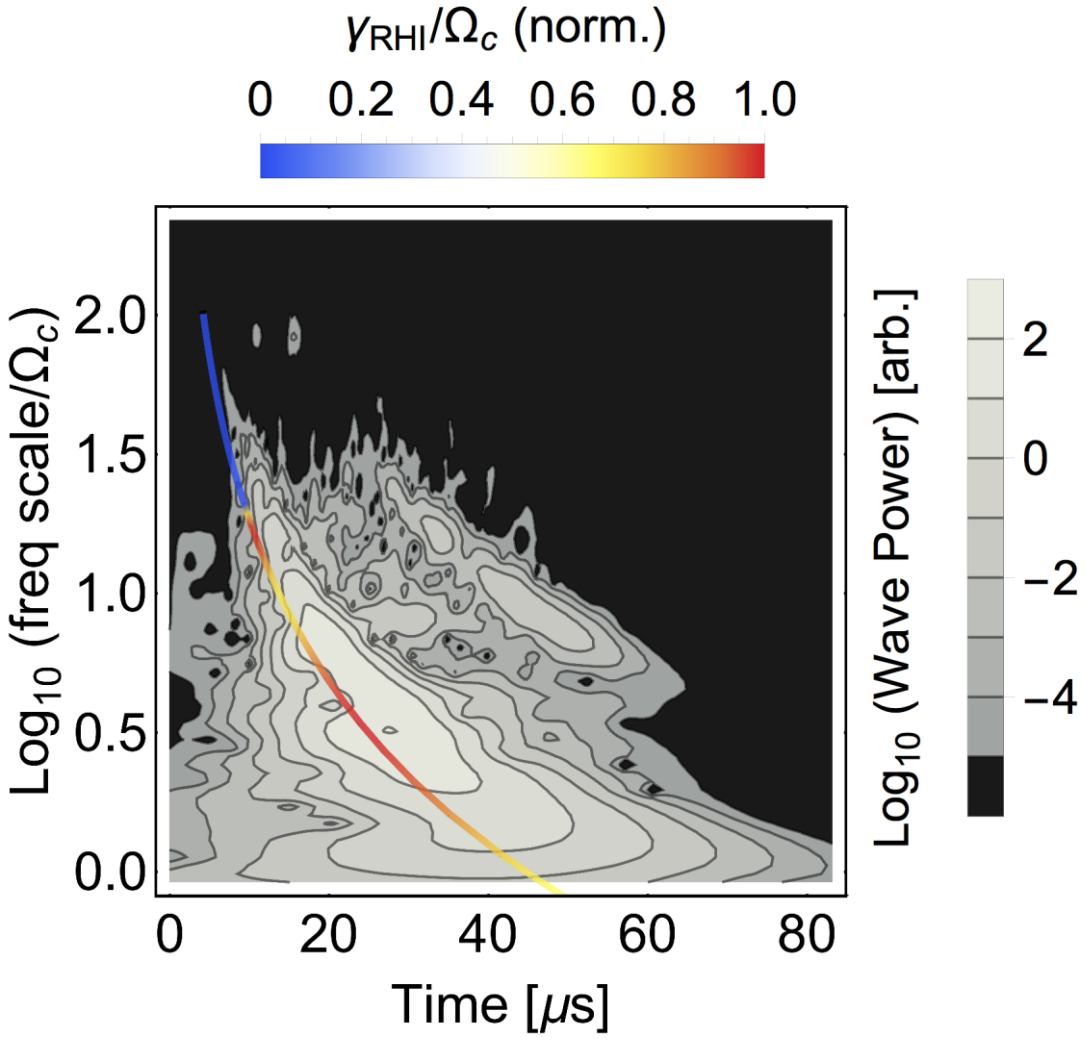
- Wavelet analysis shows frequency chirp.
- Analytic model approximates beam as monoenergetic, and assumes waves propagate according to a cold plasma dispersion relation from near the target.
- Model agrees with data over a range of magnetic fields and background gases.



Observed and Simulated Frequency Chirps Agree

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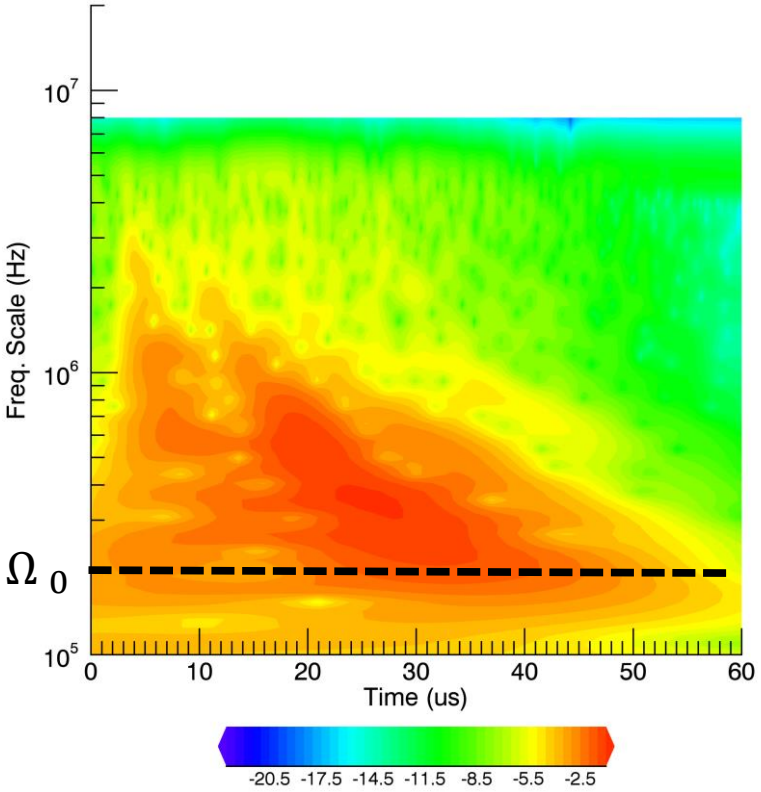
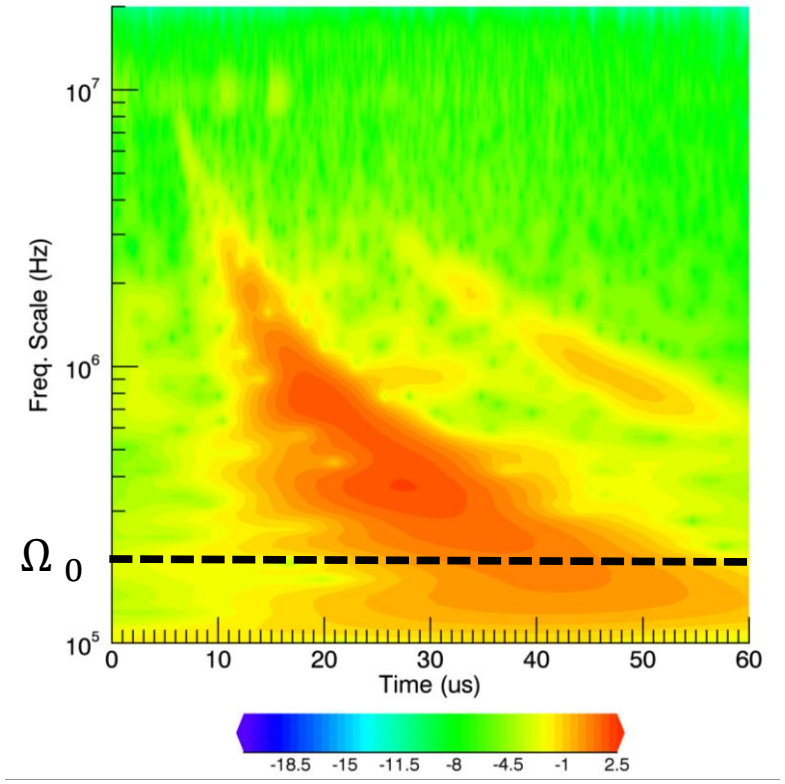
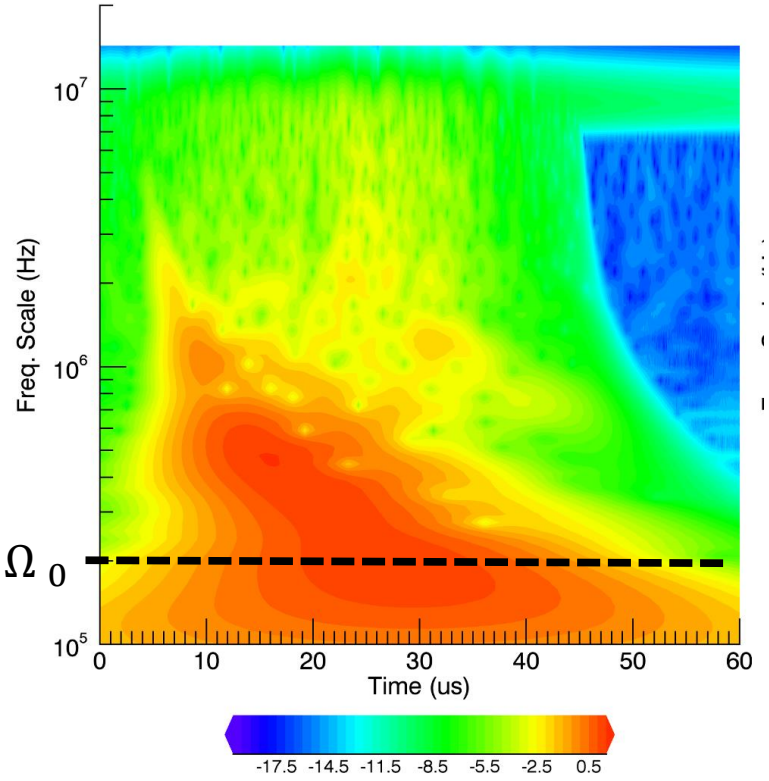
15 J Peening



200 J Raptor



Simulation (200 J)



Data Exhibits Features Similar to Simulations

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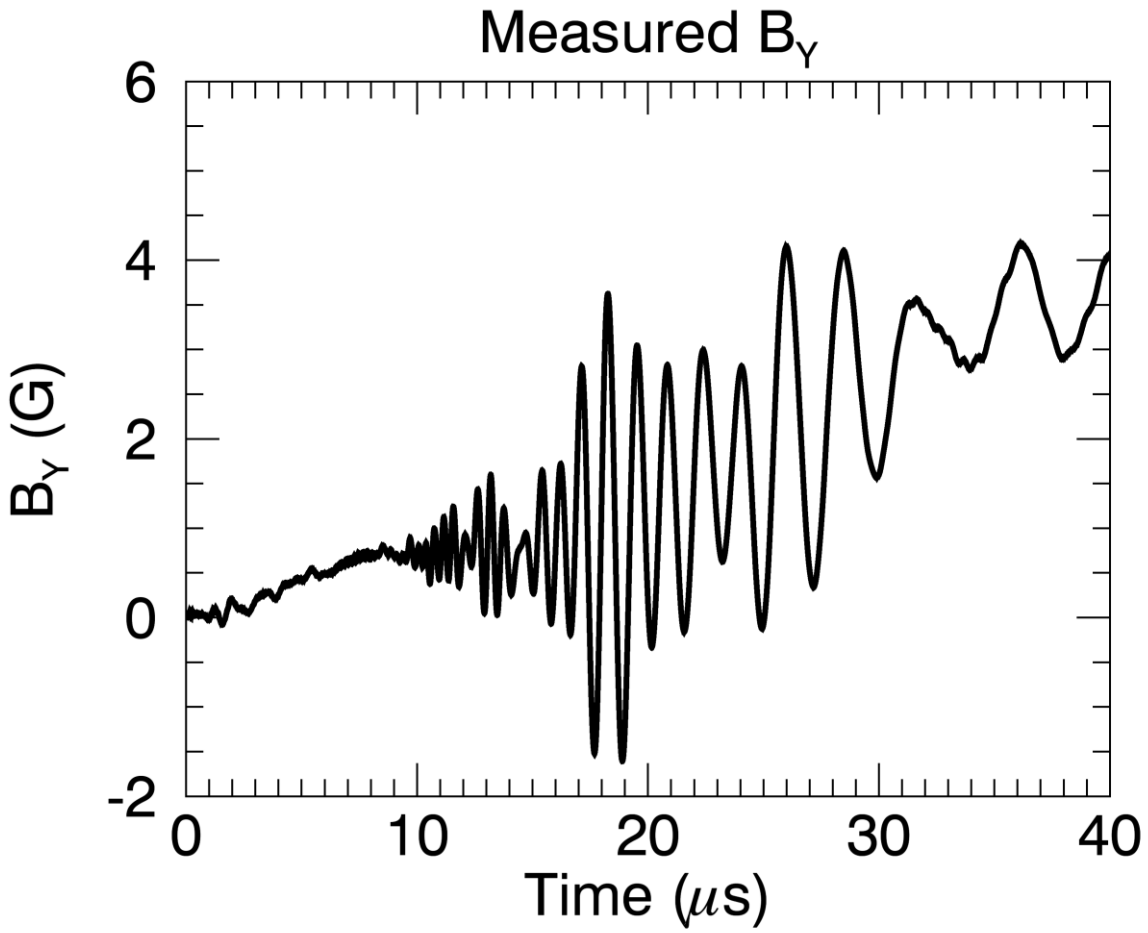

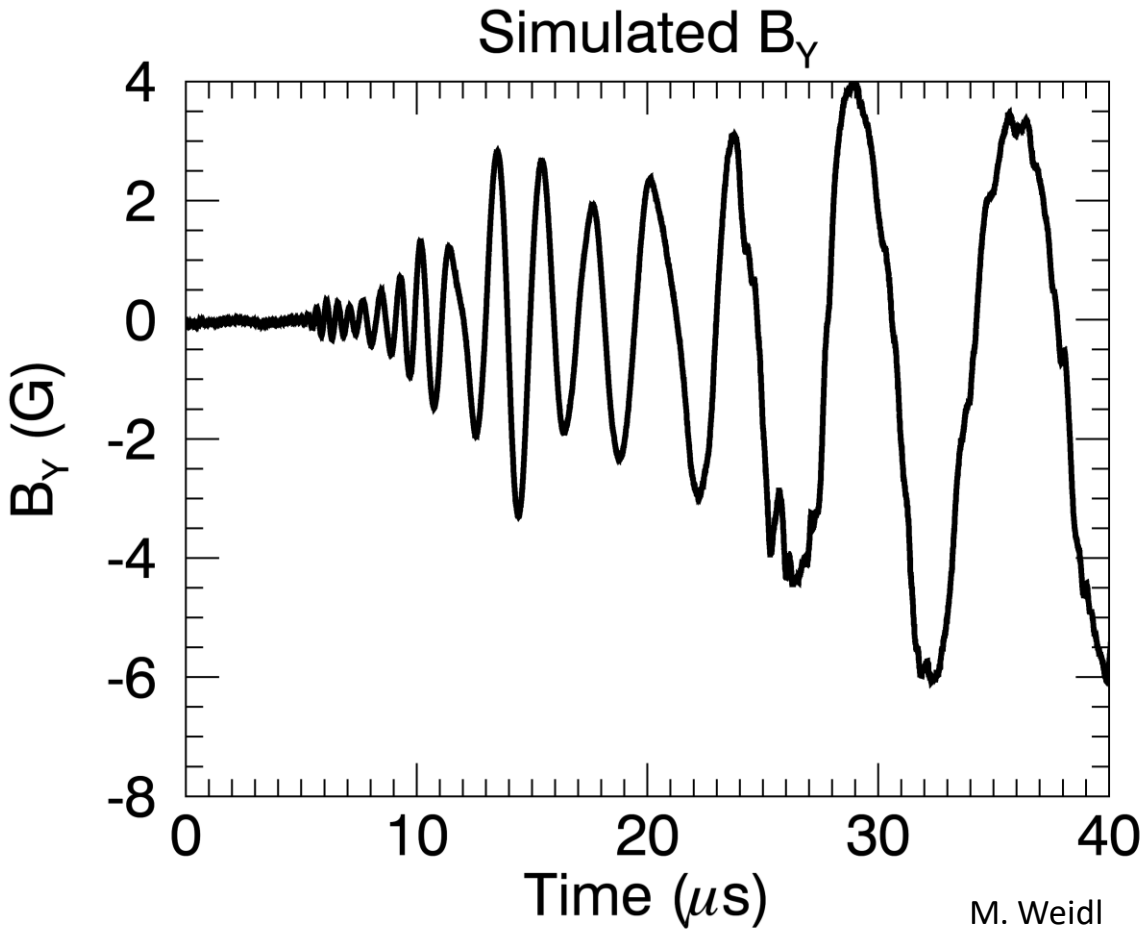

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Summary

- Directed a super-Alfvénic debris cloud through a magnetized background plasma over ~85 ion inertial lengths.
- Observed waves that are consistent with RHI theory.
- Future work will focus on understanding energetics and debris geometry with the goal of tuning the experiment to produce the NRI and eventually a parallel shock.

References

- RHI and NRI: Winske and Leroy, *Journal of Geophysical Research*, 1984
- LPP Distribution: Schaeffer, e. al., *Journal of Applied Physics,* 2016
- Shocks in LAPD: Niemann, et al., *Geophysical Review Letters,* 2014

Acknowledgements

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