Probe-based Measurements of High-Frequency Azimuthal Oscillations in a Magnetically Shielded Hall Thrusters

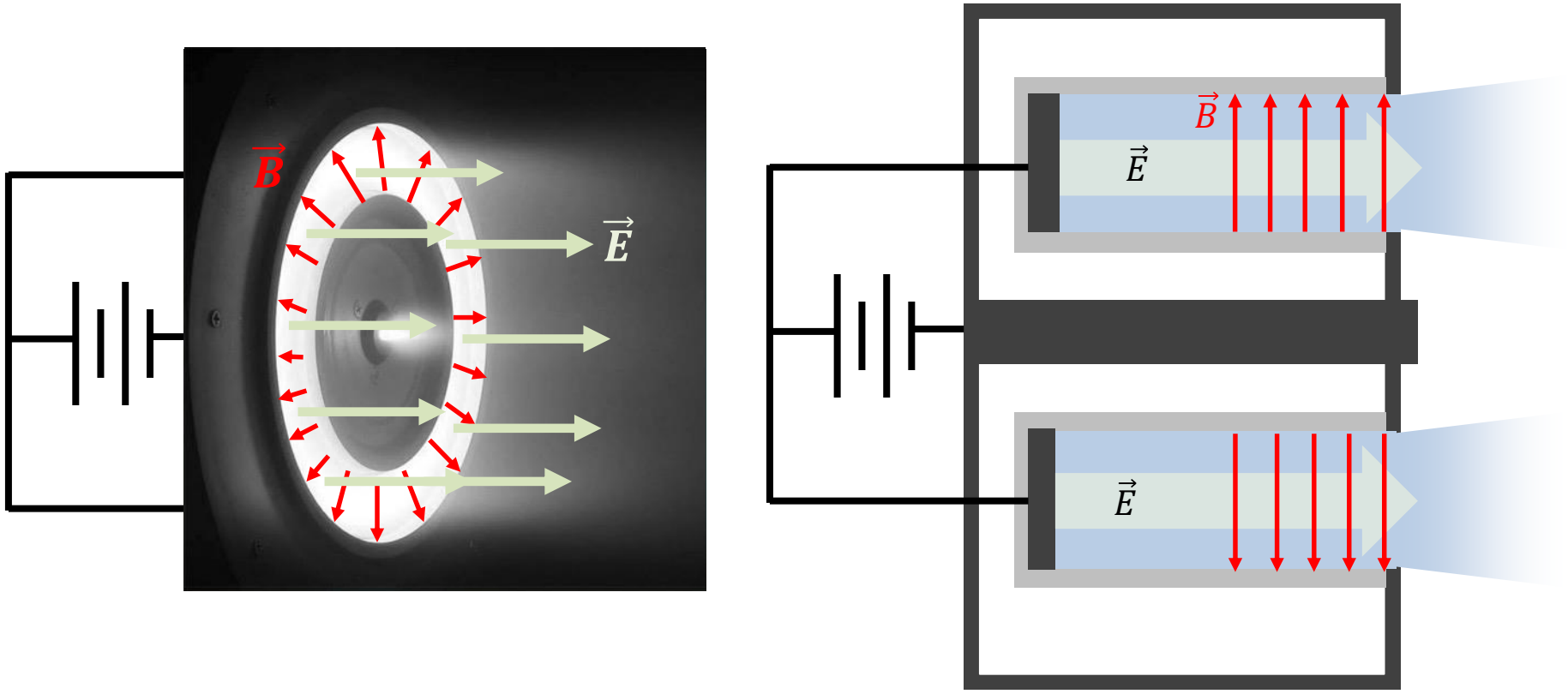
Benjamin Jorns

Zachariah Brown

University of Michigan

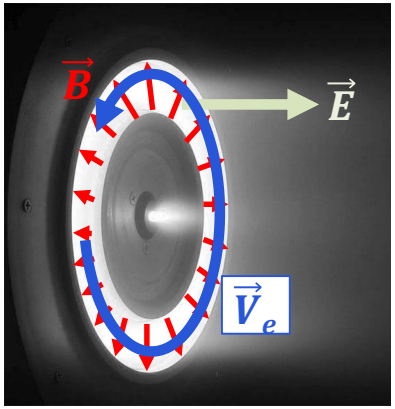
Princeton University ExB Workshop

The Hall effect thruster

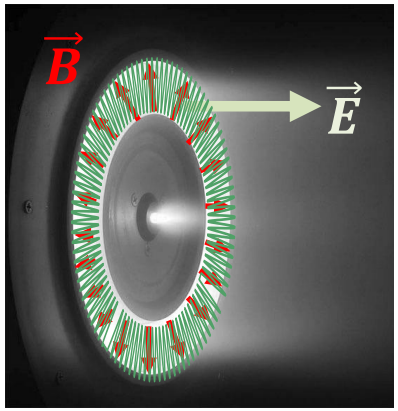


- What drives the anomalous across-field transport?
- **Driving hypothesis:** transport results from onset of microturbulence in E × B direction

Mechanism for how onset of microturbulence can drive cross-field transport

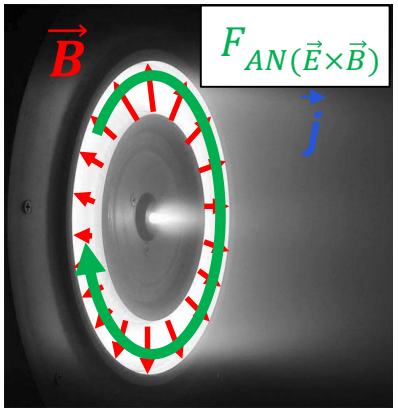


1) Strong E × B drift between electrons and ions

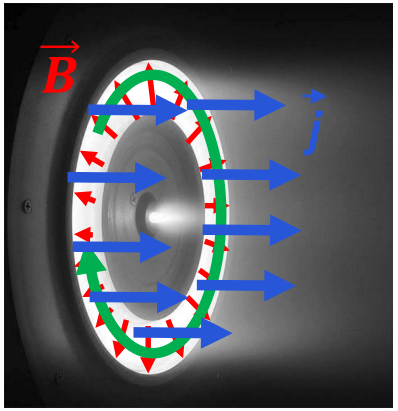


2) Azimuthal electron cyclotron drive instability (ECDI) driven unstable by drift through inverse cyclotron or Landau damping

3) Electrons slowed in E × B direction by wave growth leads to effective drag in Hall direction

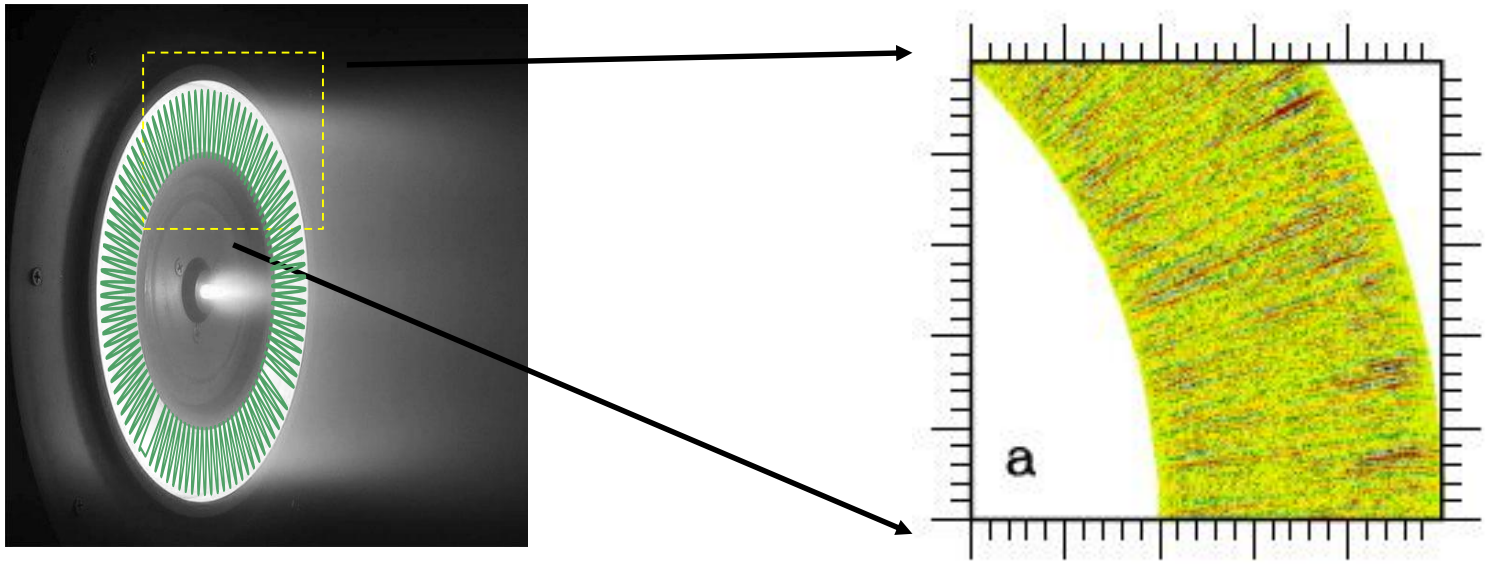


4) Effective drag due to onset of waves gives rise to cross-field electron current



Kinetic simulations predict onset of micro-turbulence

Density fluctuations from PIC, 2D model



* A. Héron and J. C. Adam, "Anomalous conductivity in Hall thrusters: Effects of the non-linear coupling of the electron-cyclotron drift instability with secondary electron emission of the walls."Physics of Plasmas 20 , 082313 (2013);

Sampling of other numerical models showing instability

- J. C. Adam , A. Héron , and G. Laval, Physics of Plasmas 11 , 295 (2004)
- A. Ducrocq , J. C. Adam , A. Héron , and G. Laval, Physics of Plasmas 13 , 102111 (2006);
- J.P. Boeuf. Frontiers in Physics, Vol. 2, No. 74, (2014)
- T. Lafleur , , S. D. Baalrud , and P. Chabert, Physics of Plasmas 23, 053502 (2016);
- V Croes et al. Plasma Sources Sci. Technol. 26 (2017)
- Janhunen, S., et al., Physics of Plasmas 25, (2018)

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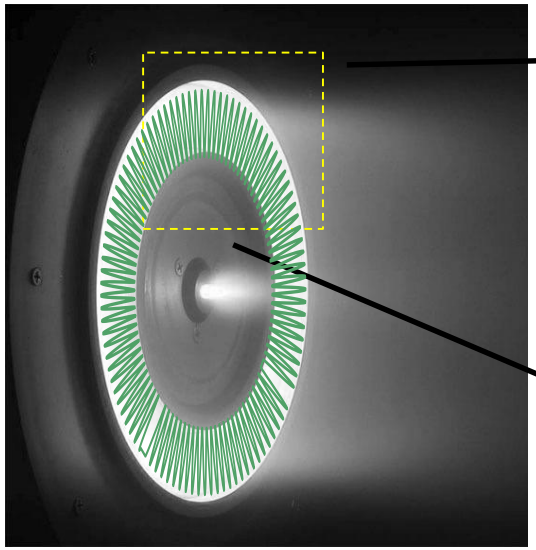

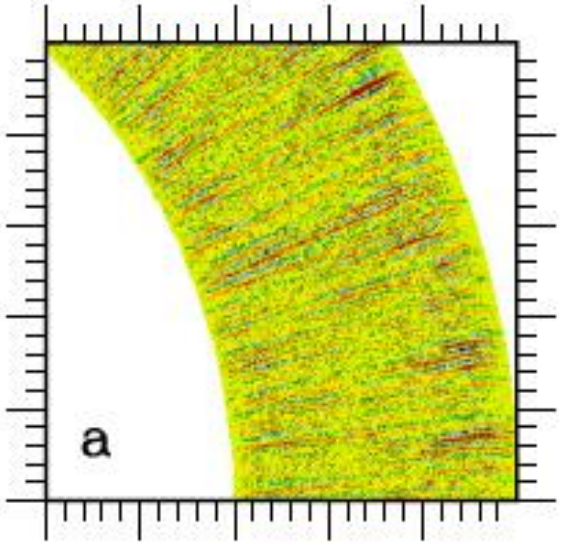

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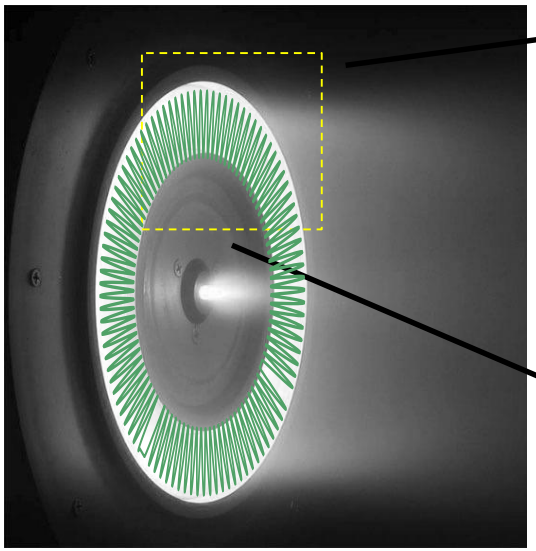
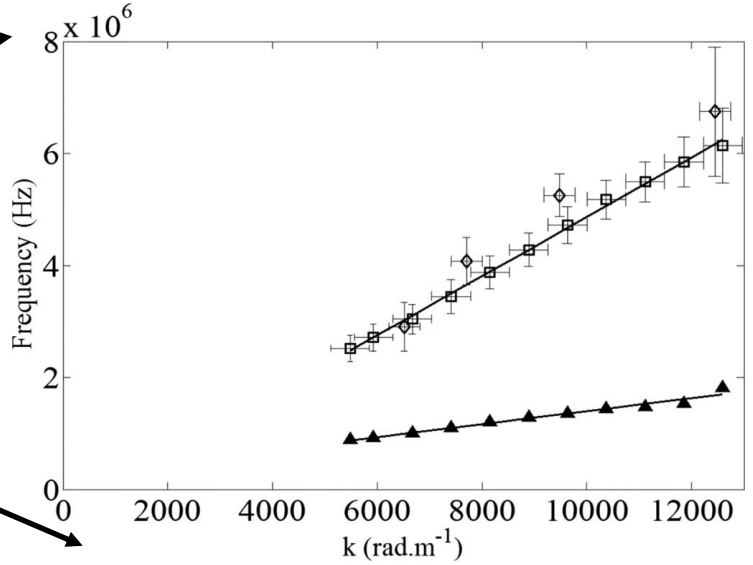
- S. Janhunen et al., *Physics of Plasmas,* 011608 (2018)

Does this type of instability actually exist in Hall thruster discharges?

Experimental evidence of microturbulence



Experimental dispersion relation of small-scale oscillations in Hall direction



S. Tsikata, N. Lemoine, V. Pisarev, and D. Grésillon, *Physics of Plasmas*. Vol. 16., No. 3. 2009.

- Wavelengths < 1 mm
- Dispersion is acoustic-like
- Modes are incoherent

ECDI in the acoustic-like limit

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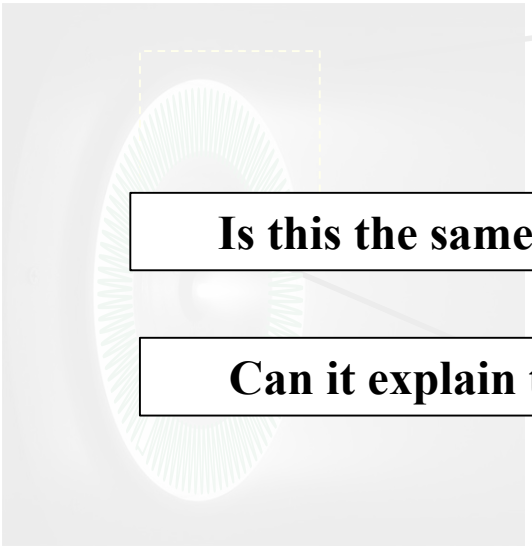

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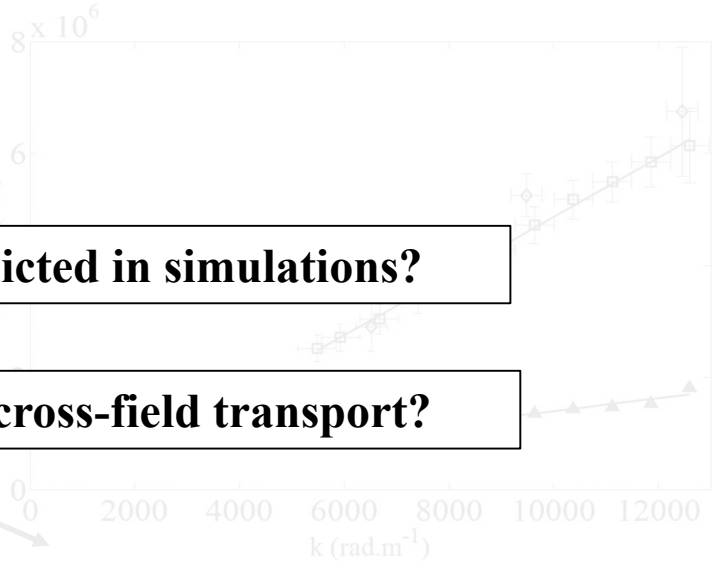

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Is this the same wave as predicted in simulations?

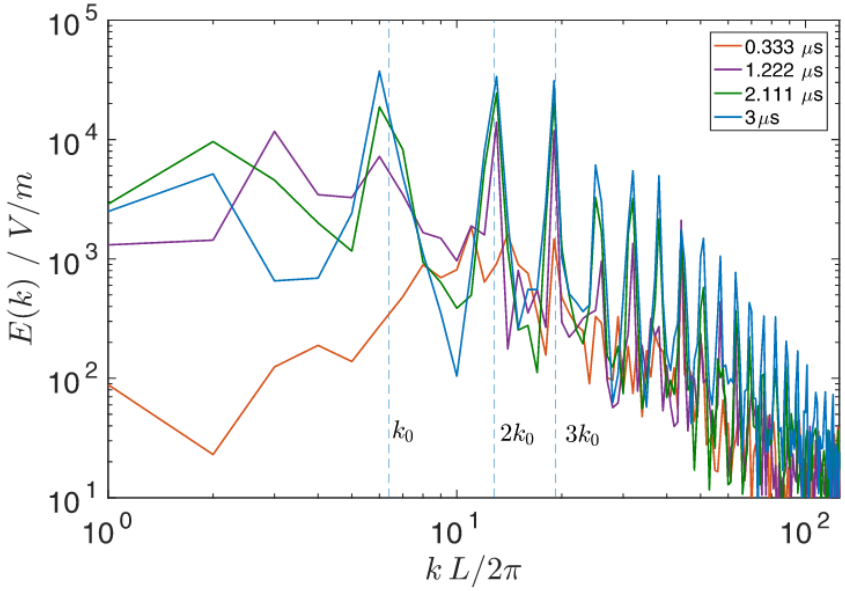
Can it explain the observed cross-field transport?

- Wavelengths < 1 mm
- Dispersion is acoustic-like
- Modes are incoherent

ECDI in the acoustic-like limit

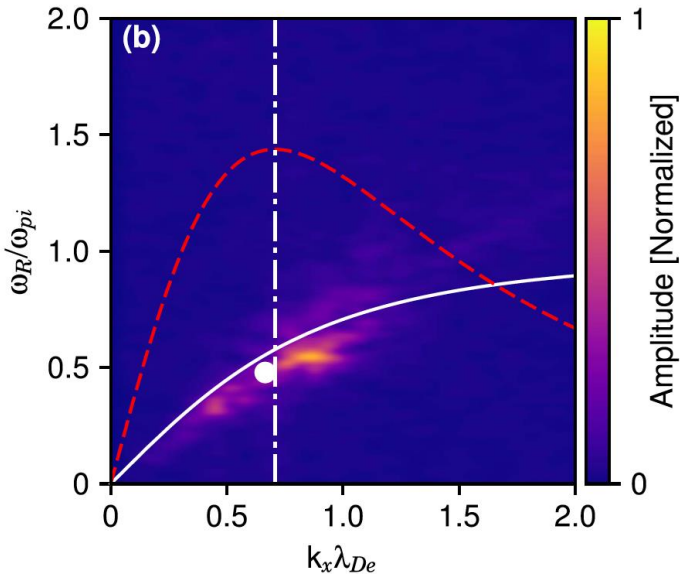
Open experimental questions related to ECDI in Hall thrusters

Is this the same wave as predicted in experiments:
What is the wavelength/frequency of maximum growth?



S. Janhunen et al., *Physics of Plasmas,* 011608 (2018)

Max growth at cyclotron resonance



T. Lafleur and P. Chabert, PSST **27** 015003 (2018)

Max growth on order of Debye length

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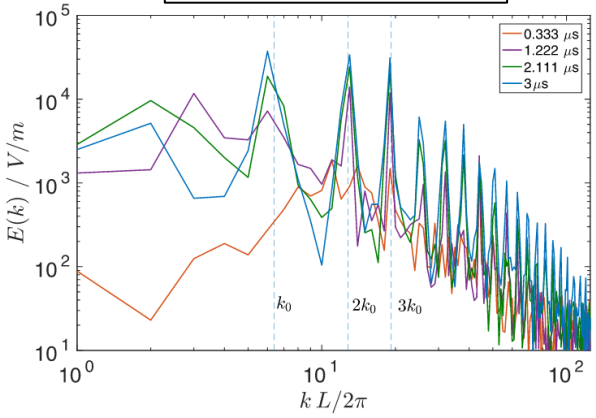
Simulations



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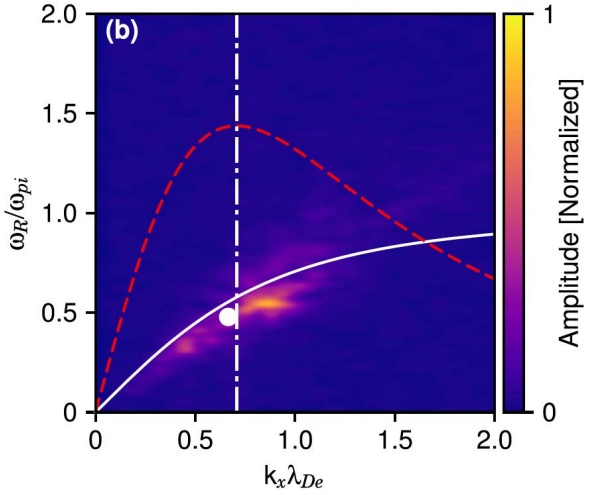

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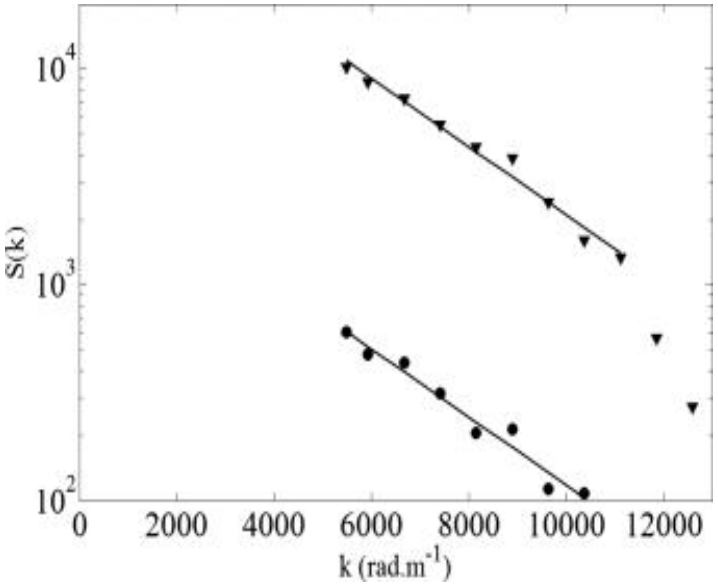
Experimental measurements



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Contradictions with simulations

- Measurements are broadband
- Do not show maximum growth wavelength

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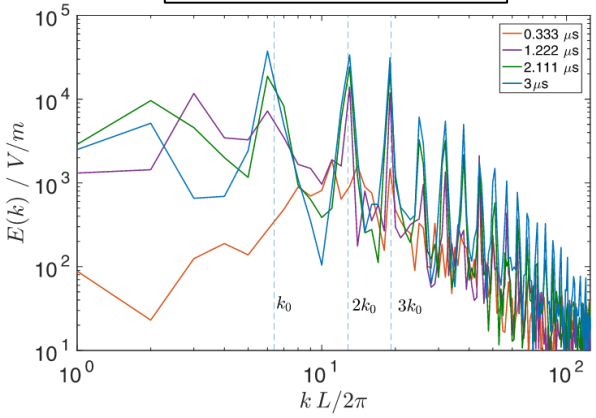

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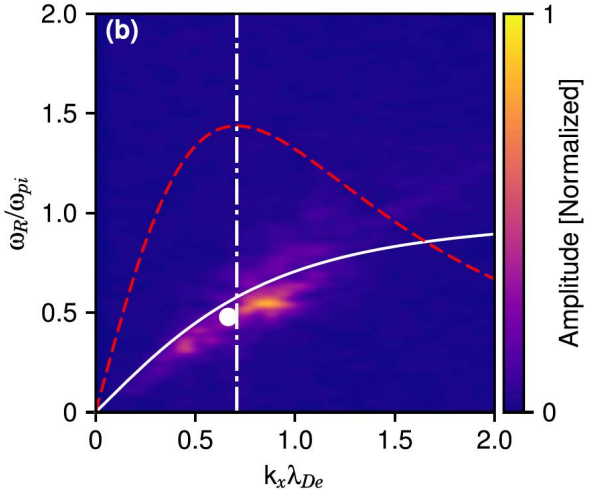

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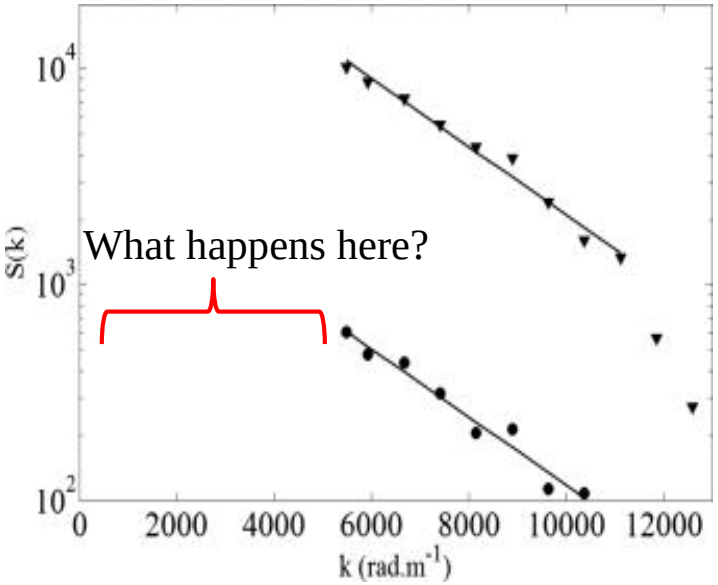

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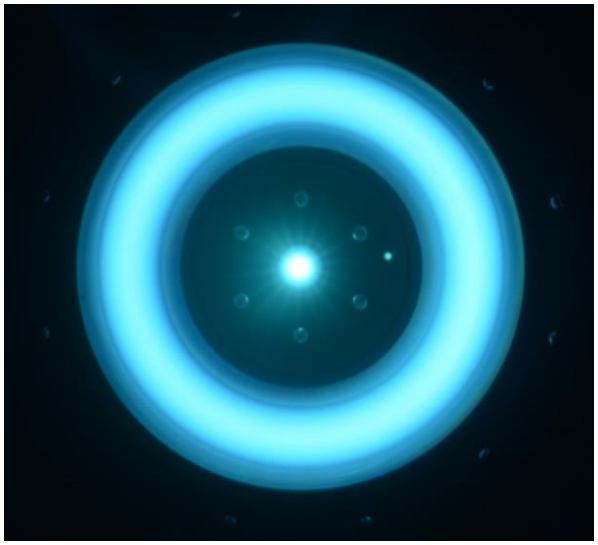
Experimental Setup at UM

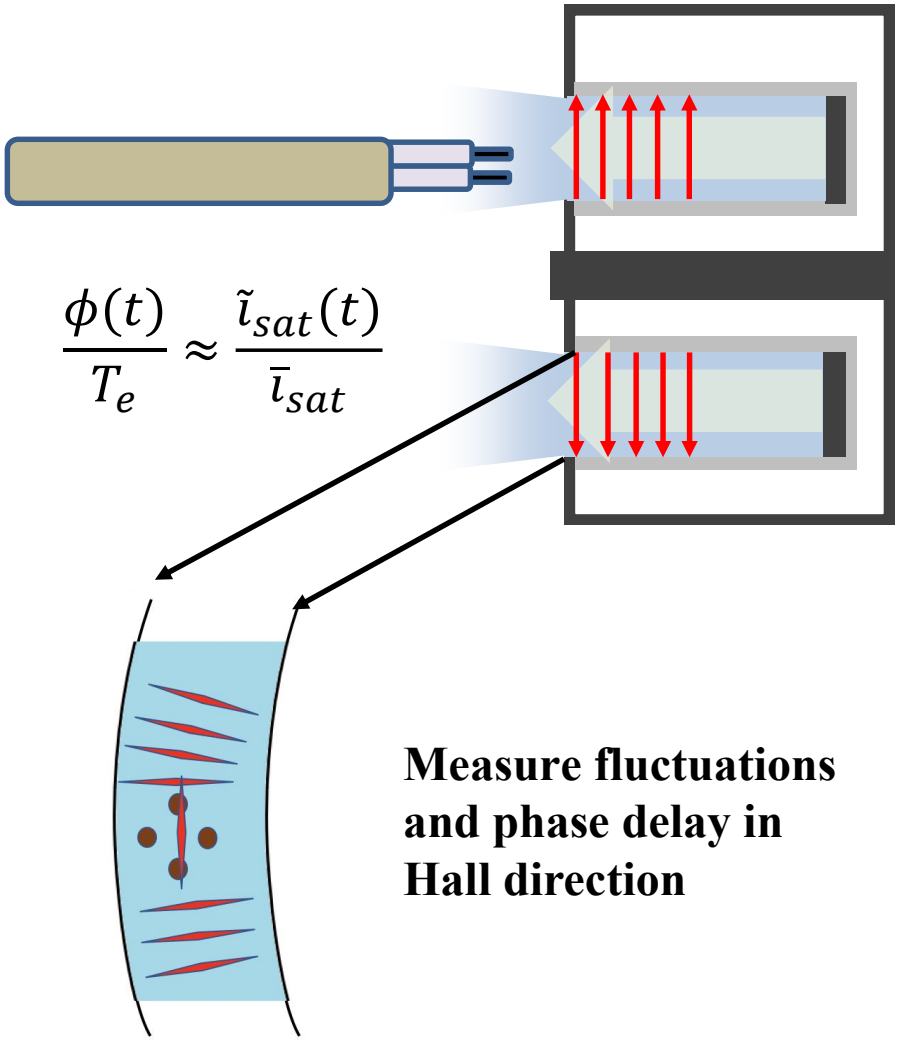
H9: 9kW magnetically shielded Hall effect thruster at 300 V and 4.5 kW



Large Vacuum Test Facility at UM

Experimental Setup at UM

Ion saturation probes

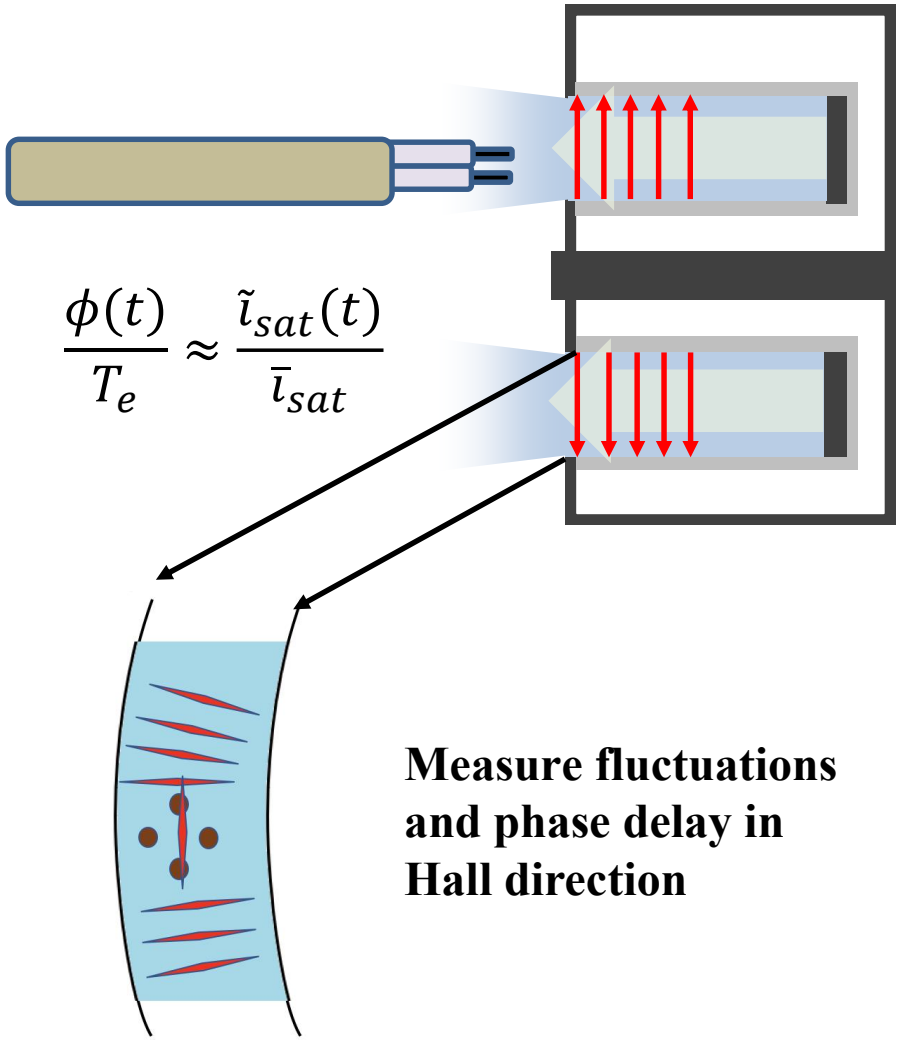


$$\frac{\phi(t)}{T_e} \approx \frac{\tilde{\imath}_{sat}(t)}{\bar{\imath}_{sat}}$$

Measure fluctuations and phase delay in Hall direction

Experimental Setup at UM

Ion saturation probes



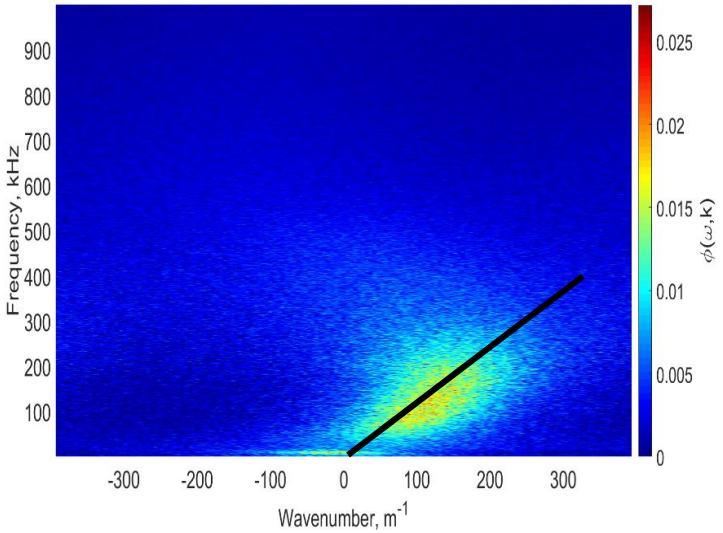
$$\frac{\phi(t)}{T_e} \approx \frac{\tilde{\imath}_{sat}(t)}{\bar{\imath}_{sat}}$$

Measure fluctuations and phase delay in Hall direction

Analysis

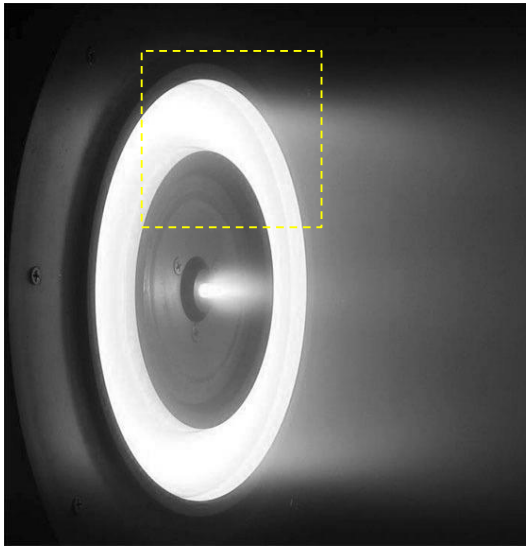
- Fourier analysis to find
  - Power spectrum $\phi(\omega)$
  - Cross-correlation $\omega(k)$
- Averaging yields statistical dispersion relation $\phi(\omega, k)$

Beall Plot

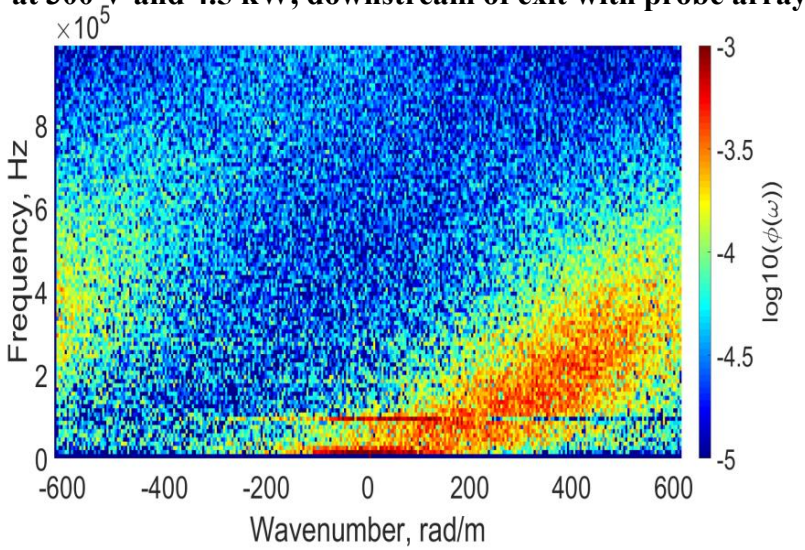


Z. Brown and B. Jorns, AIAA-2018-4423

Experimental results from fixed point measurement



H9 at 300 V and 4.5 kW, downstream of exit with probe array



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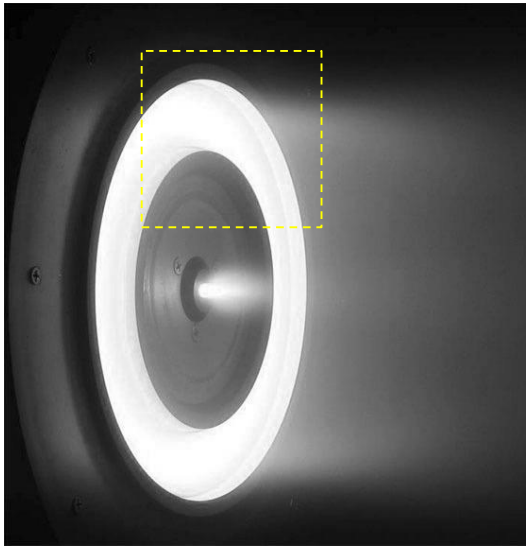

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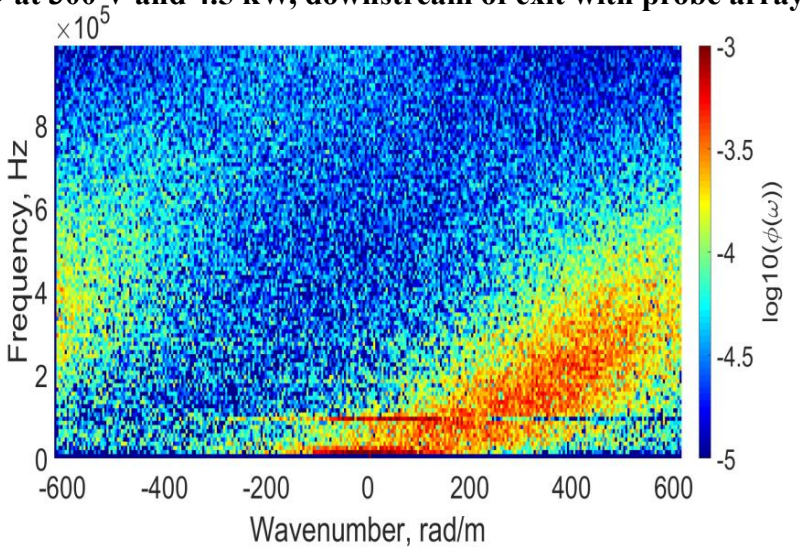
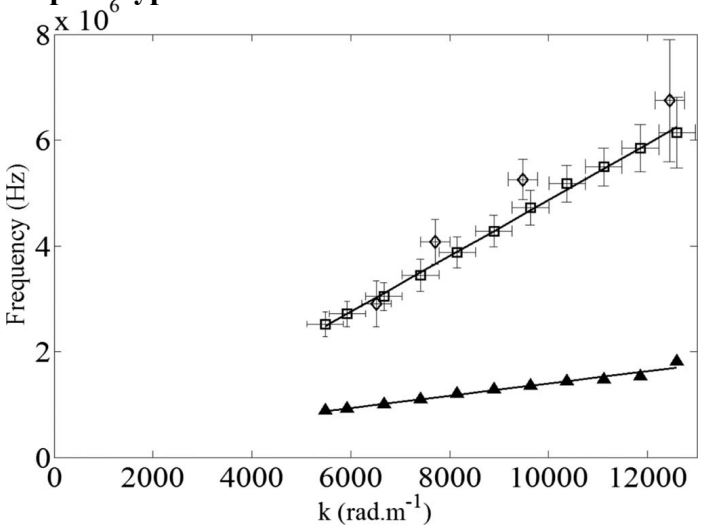


5 kW prototype PPS-X000ML downstream of exit with CTS



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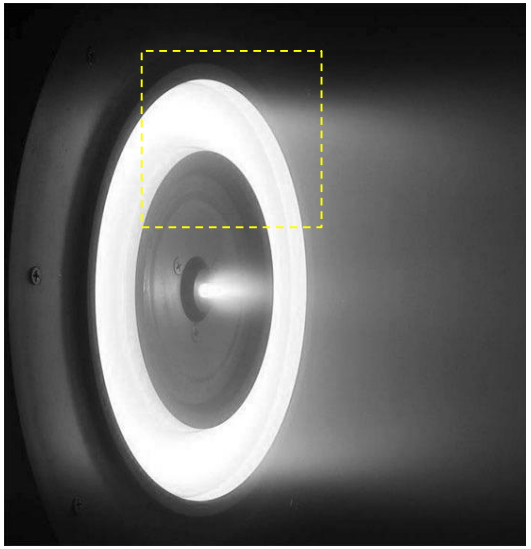

- **Linear dispersion confirmed**
- **Results fill in some missing wavenumber space**

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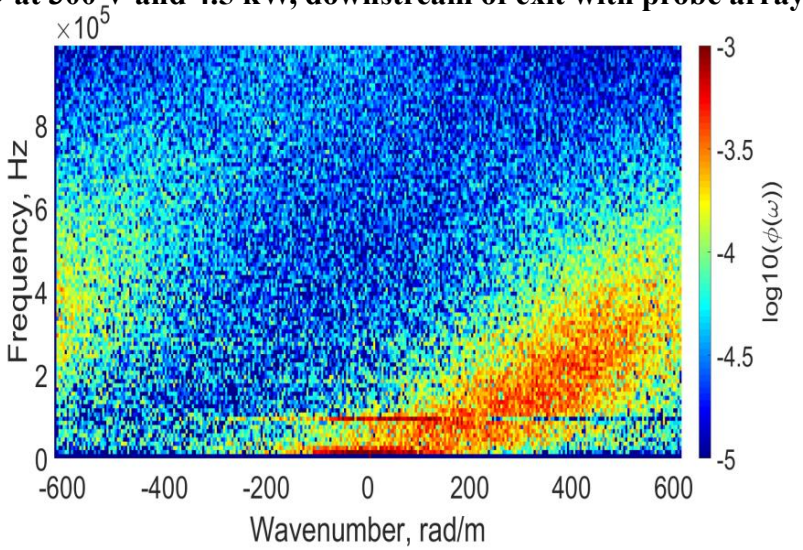

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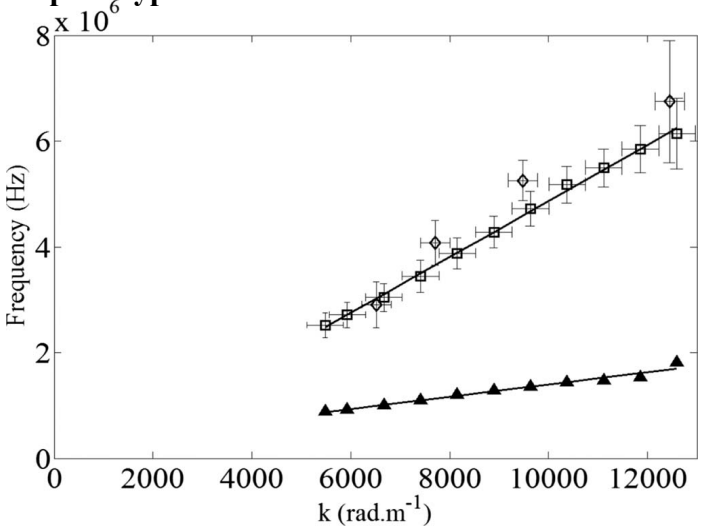

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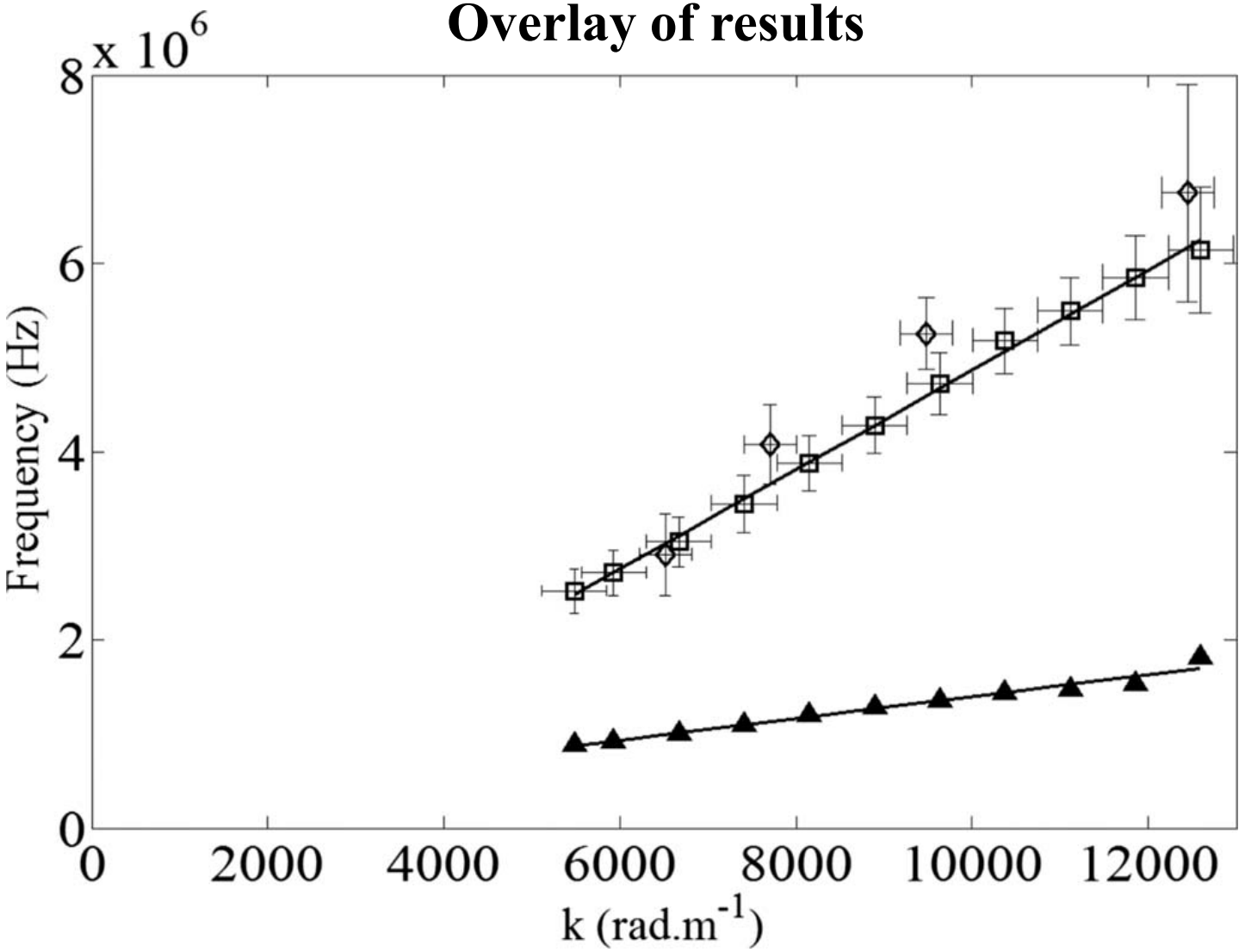
Overlay of results



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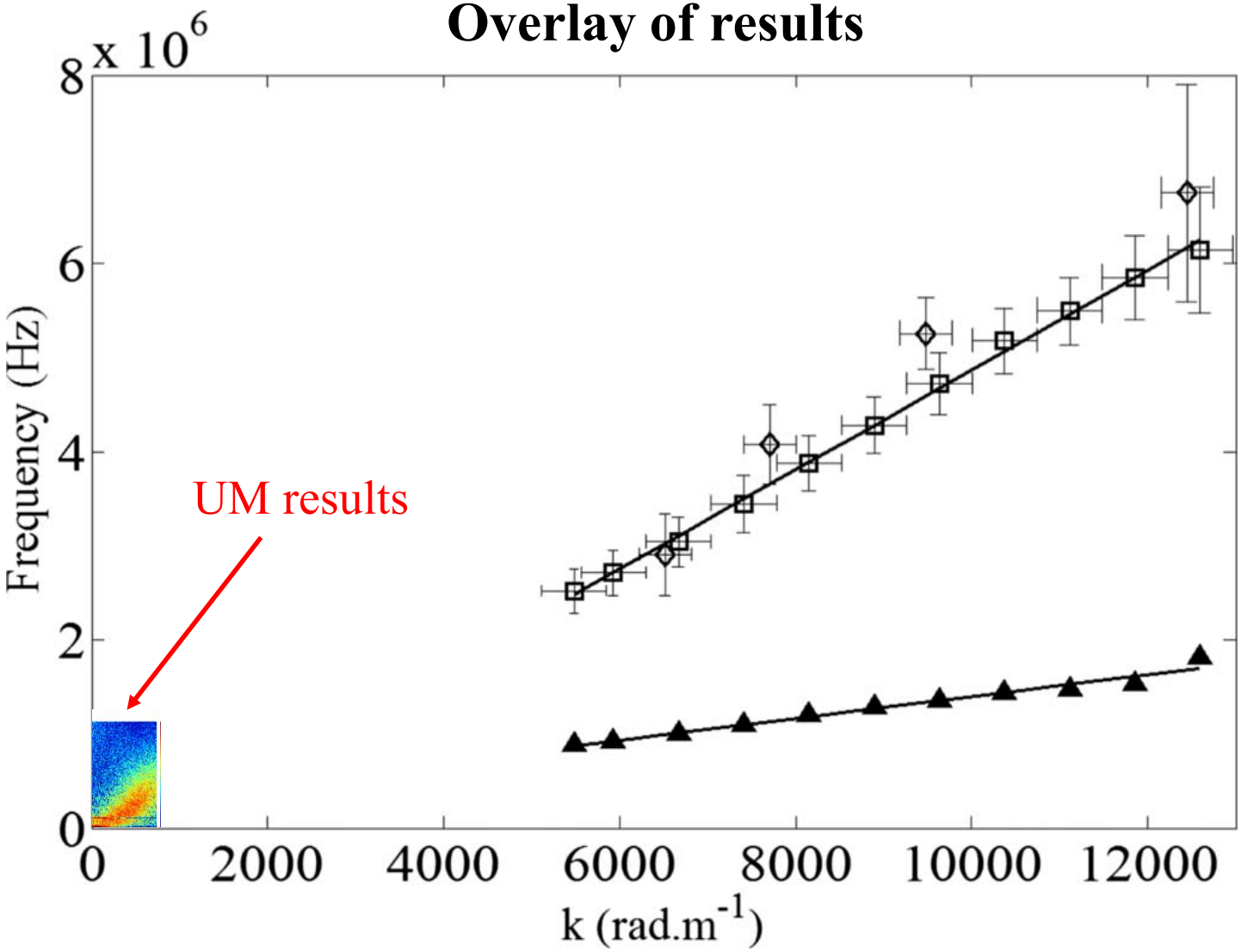

Comparison is not one to one but does illustrate both follow similar linear trends

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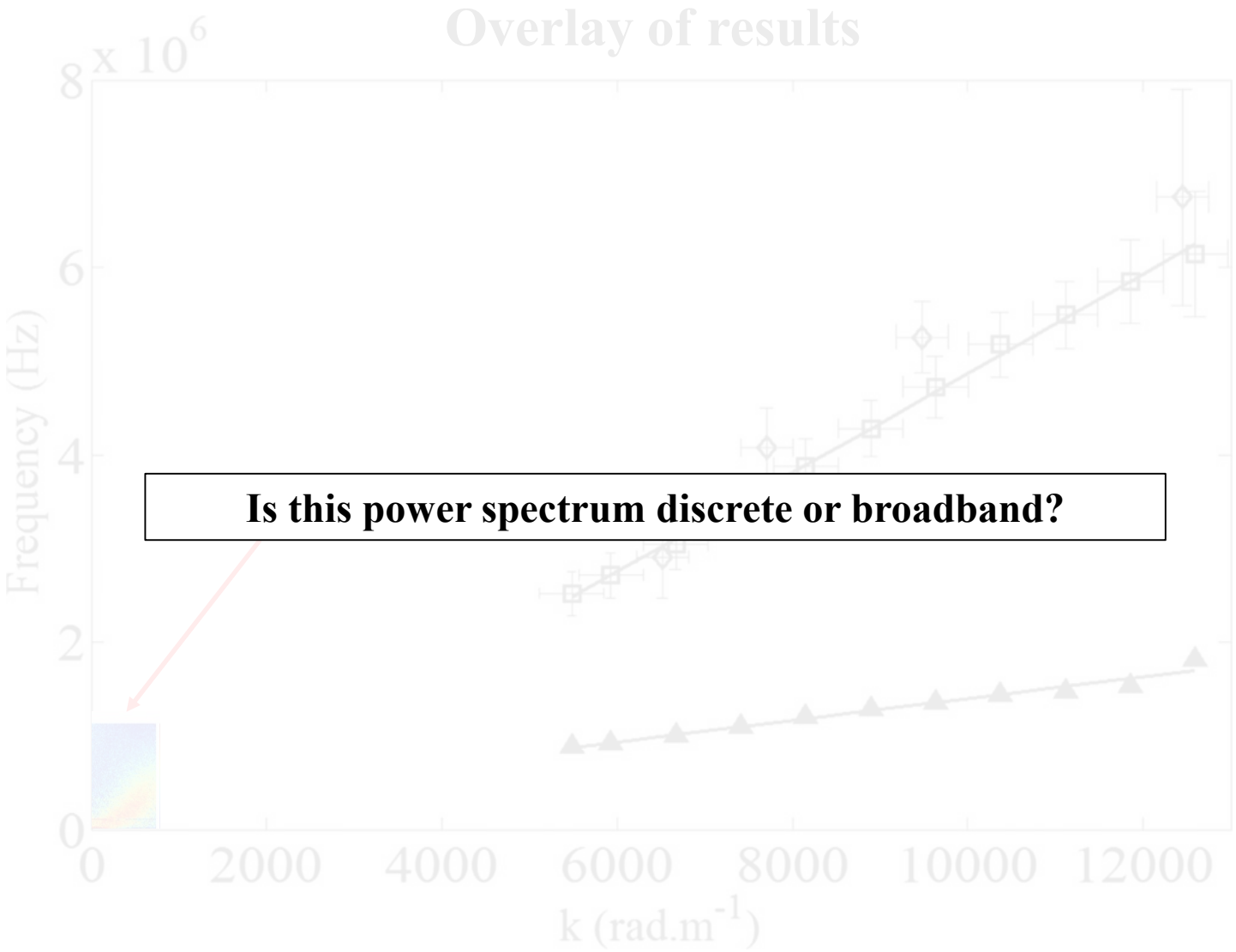

Is this power spectrum discrete or broadband?

Comparison is not one to one but does illustrate both fall on similar linear trends

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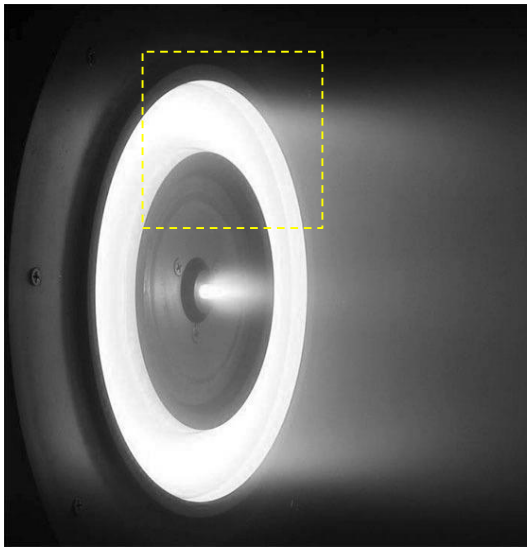

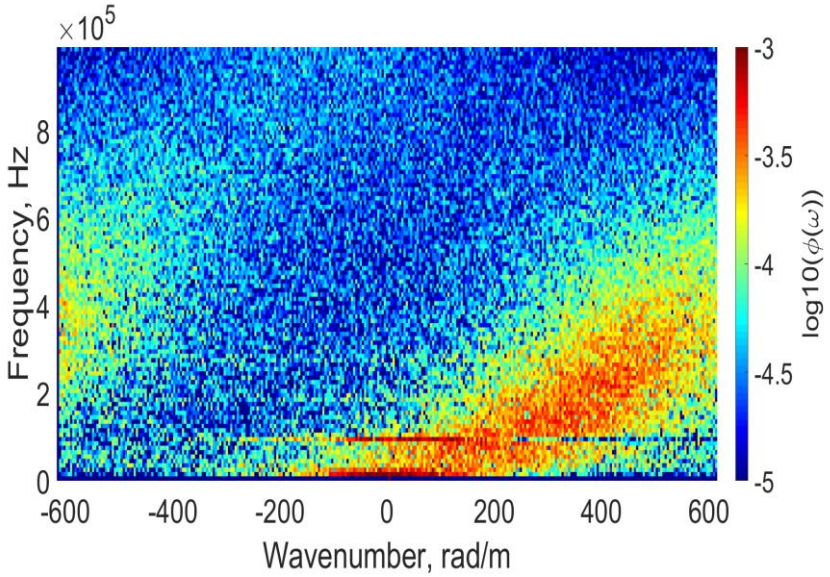

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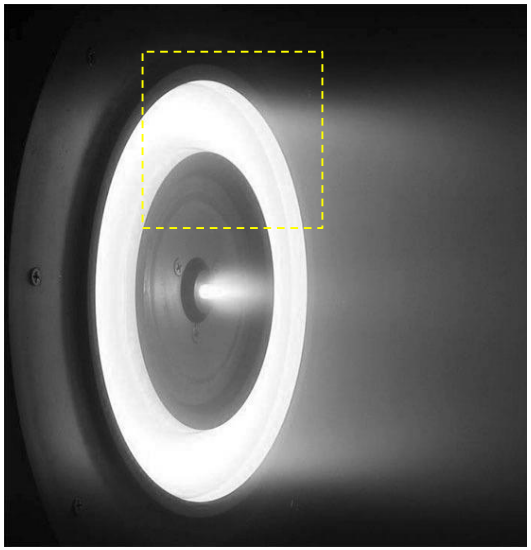

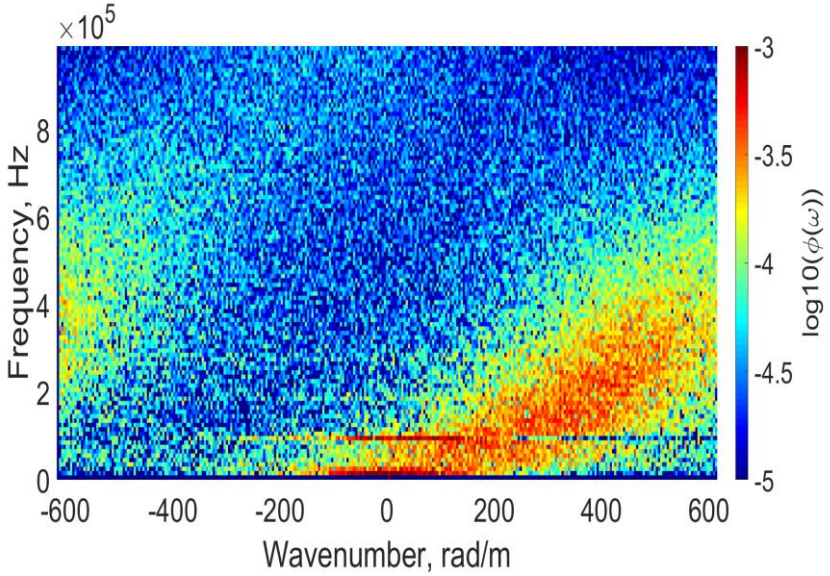

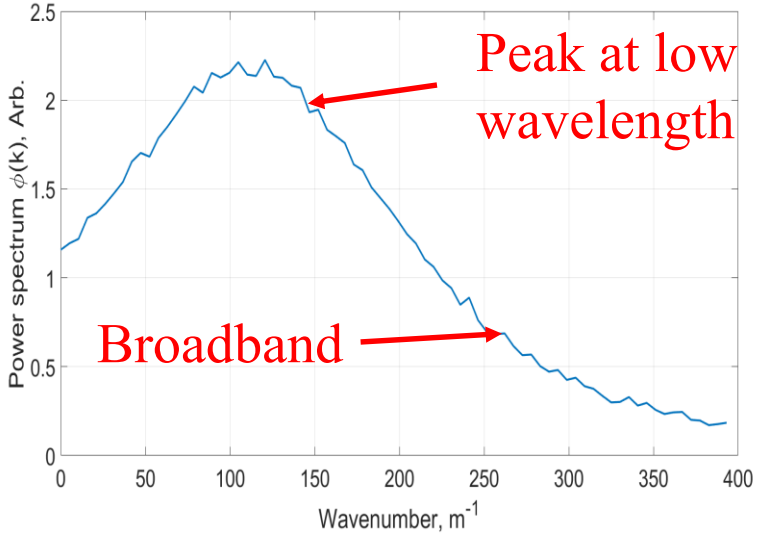

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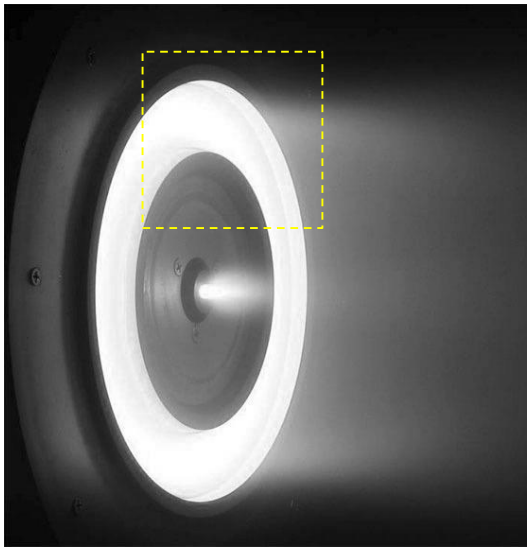

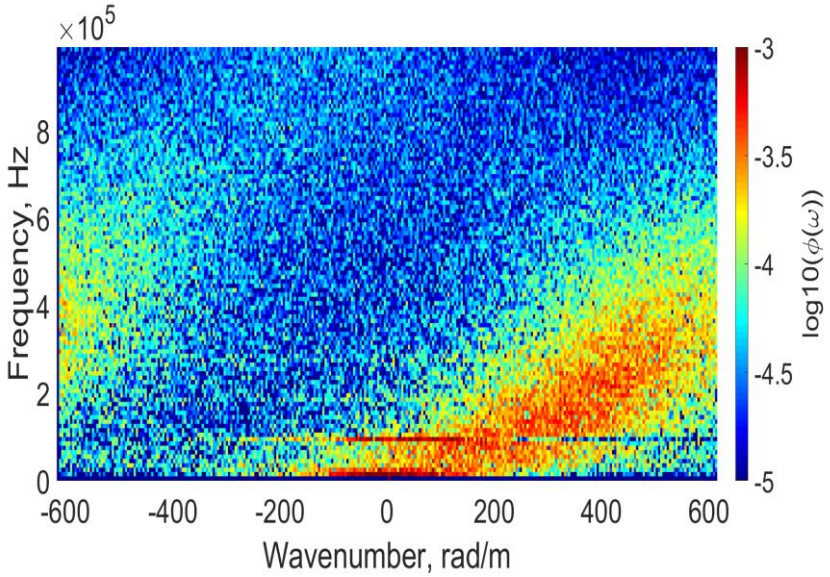

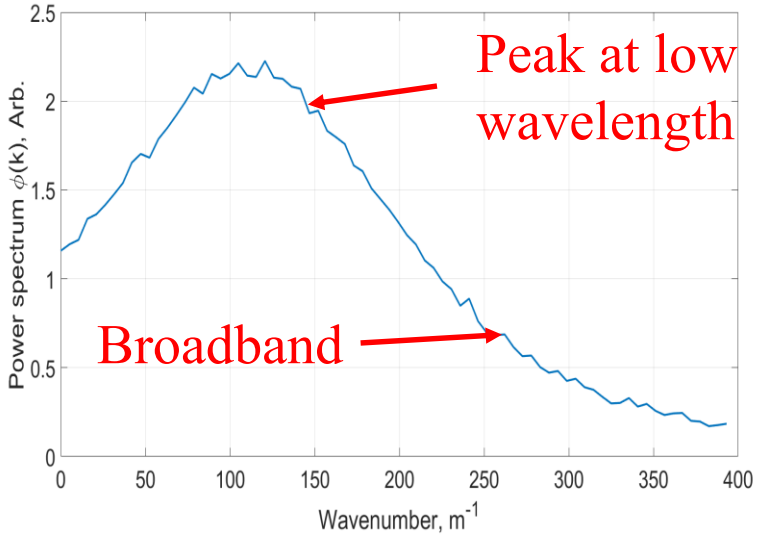

Contradictions with simulations

- Measurements are broadband
- Maximum growth occurs but at order of magnitude longer length-scale

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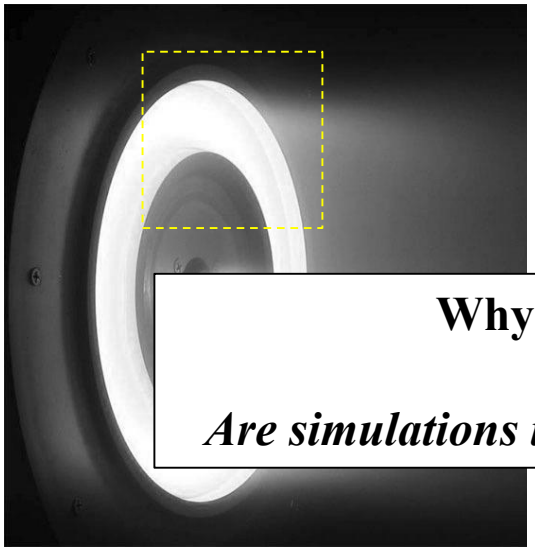

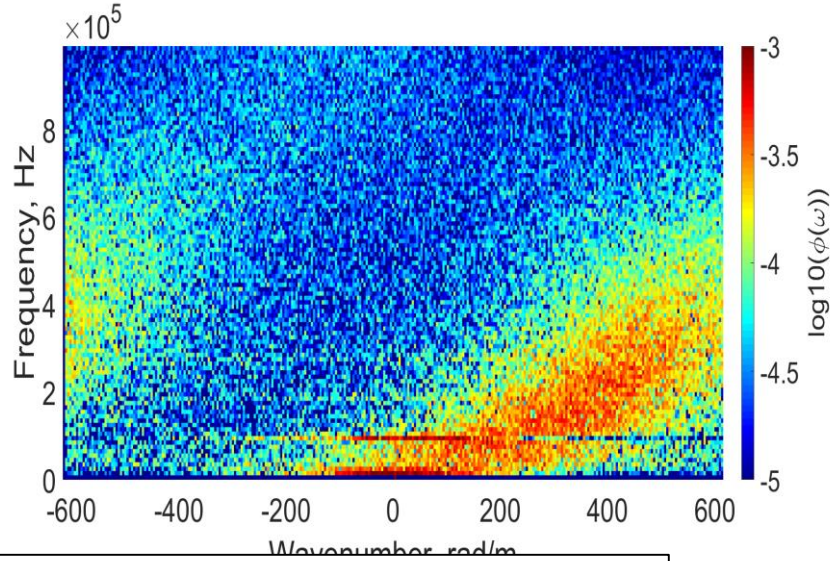

Why is there this discrepancy?

Are simulations inherently missing physical processes?

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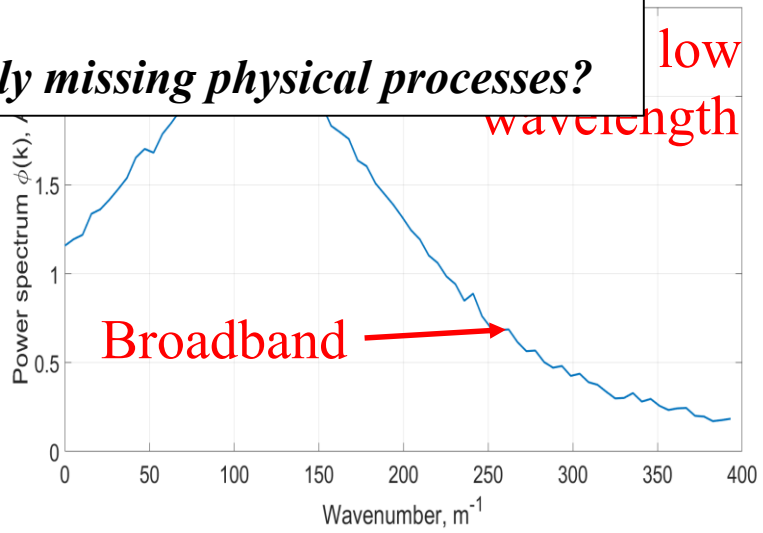
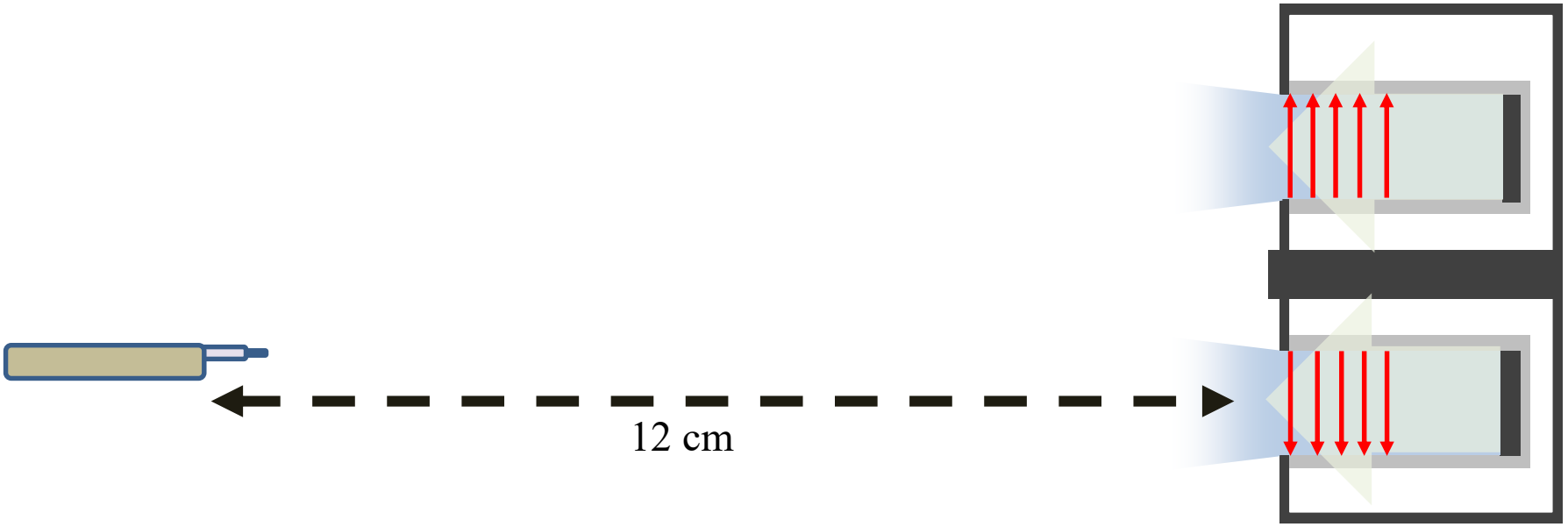


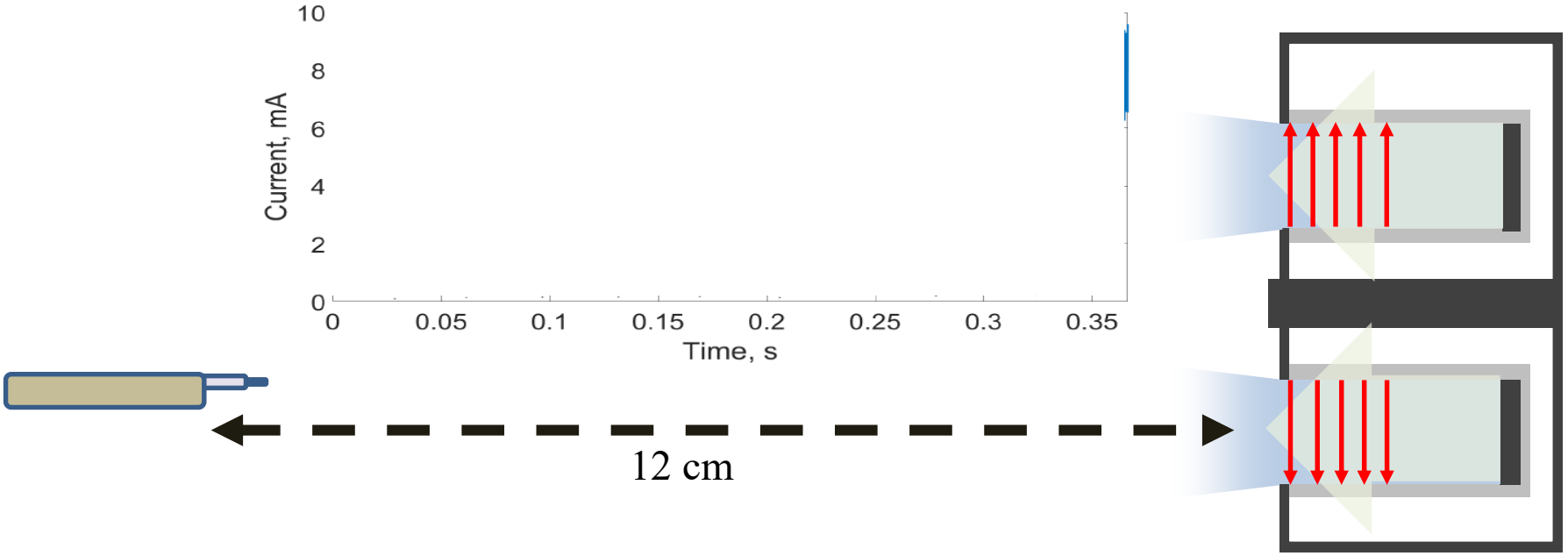
Spatial mapping of dispersion in H9

- Record continuously as probe is injected at high speed
- Chop waveform into position bins based on injection trajectory



Spatial mapping of dispersion in H9

- Record continuously as probe is injected at high speed
- Chop waveform into position bins based on injection trajectory



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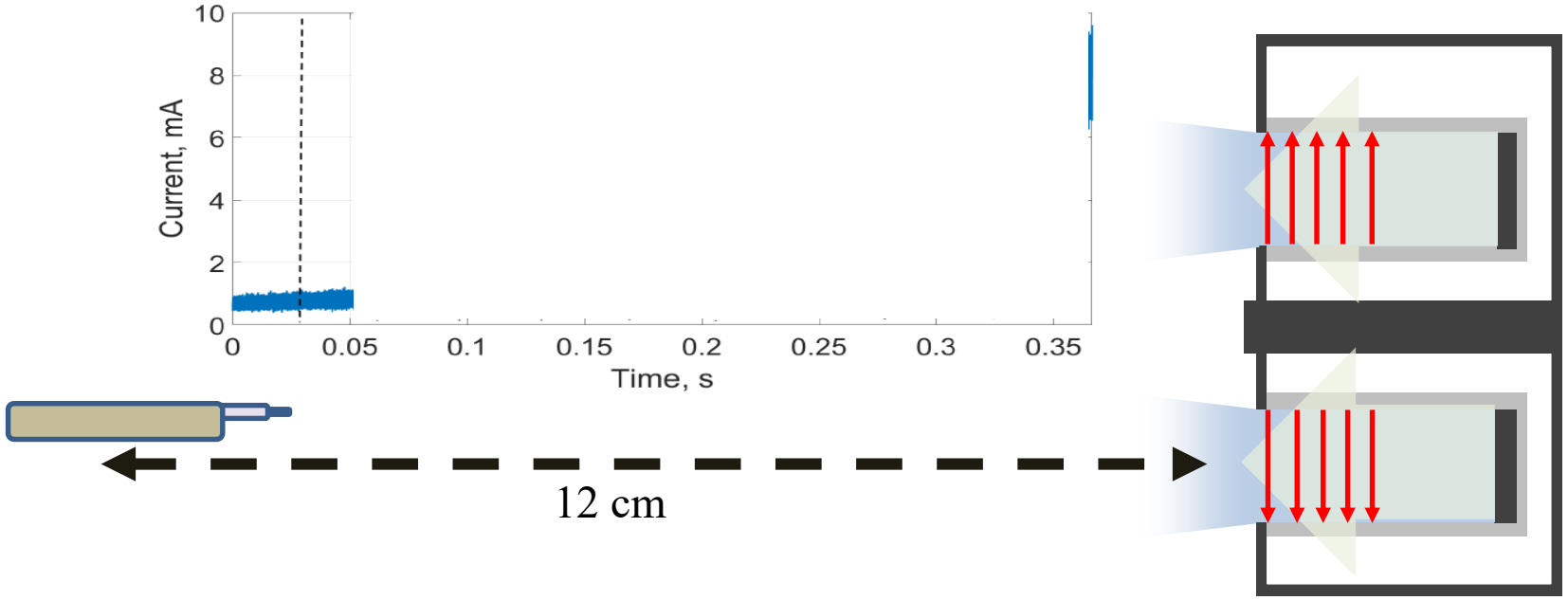

Spatial mapping of dispersion in H9

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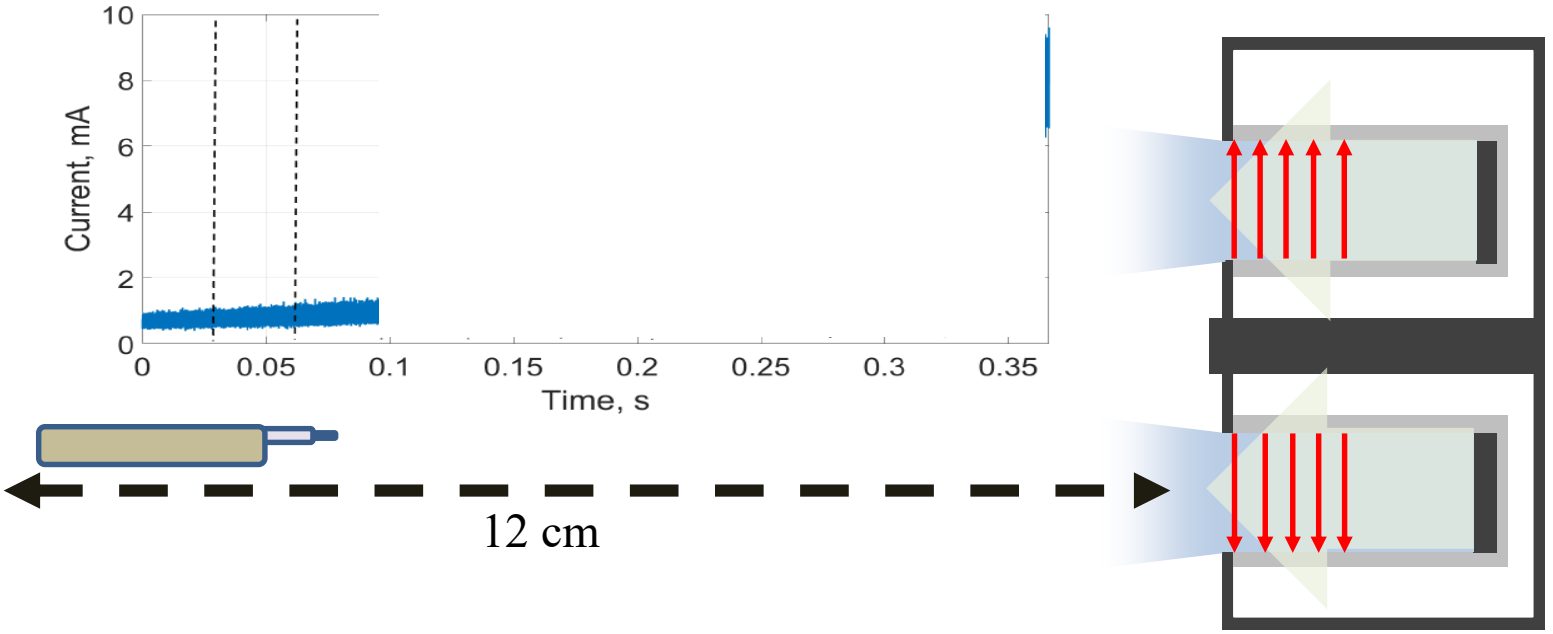

Spatial mapping of dispersion in H9

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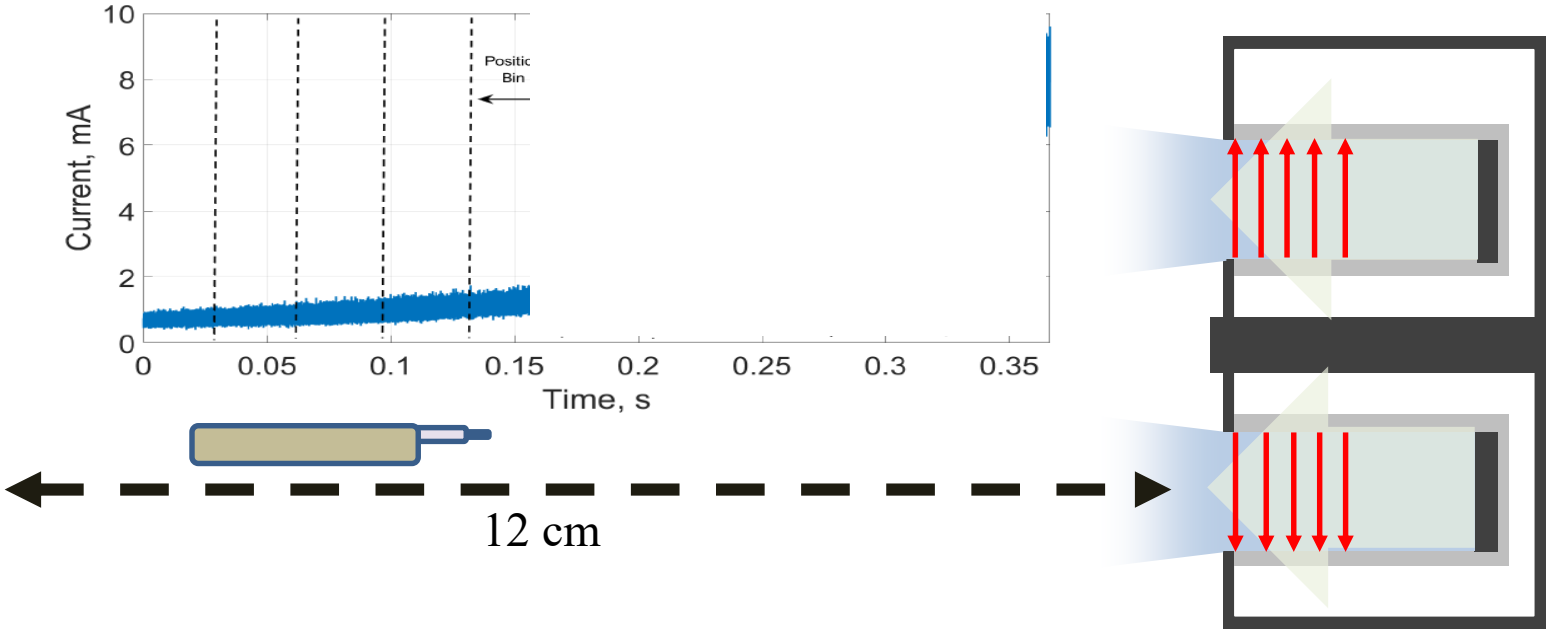

Spatial mapping of dispersion in H9

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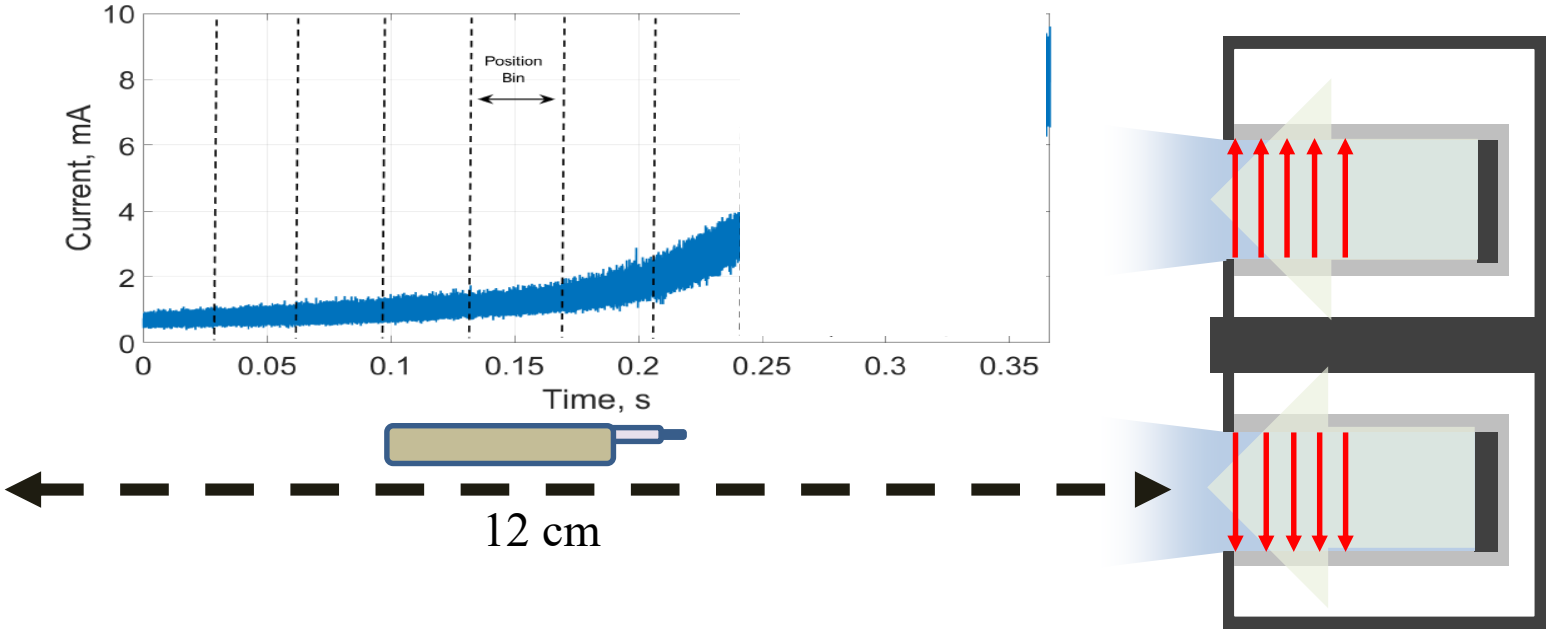

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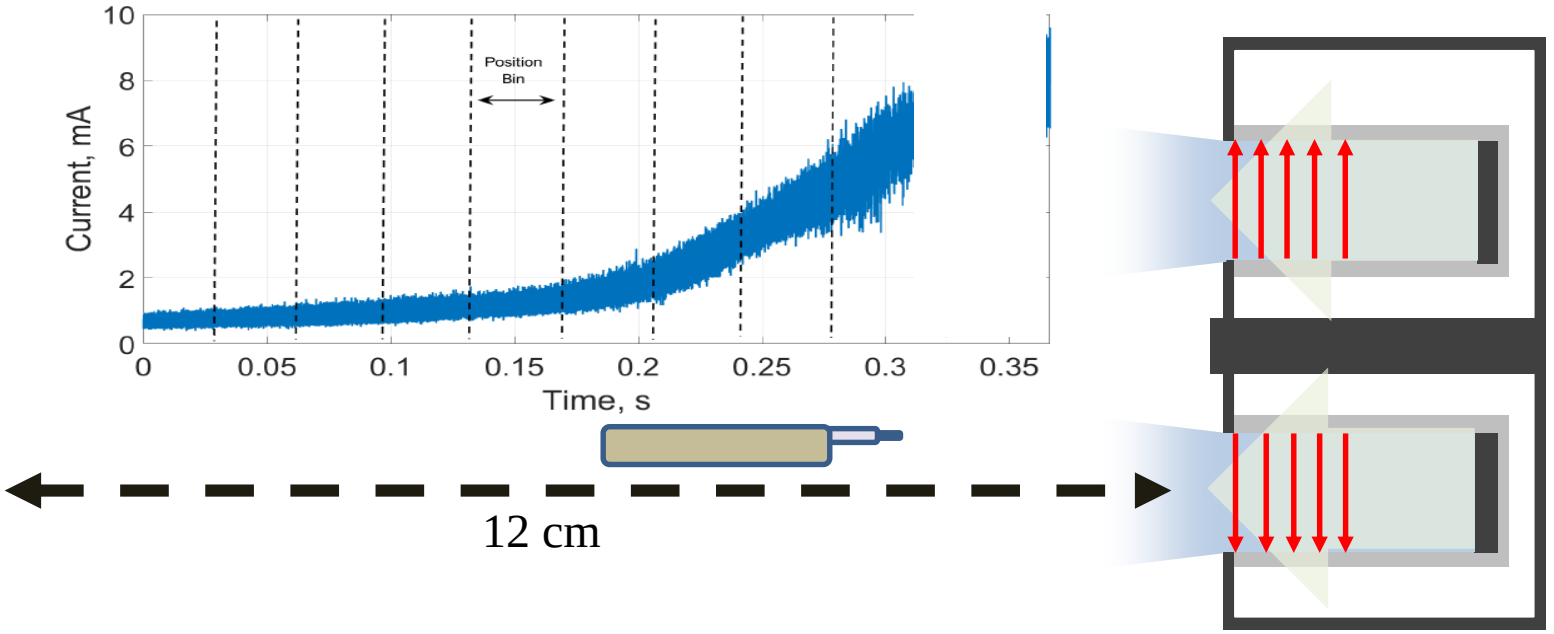

Spatial mapping of dispersion in H9

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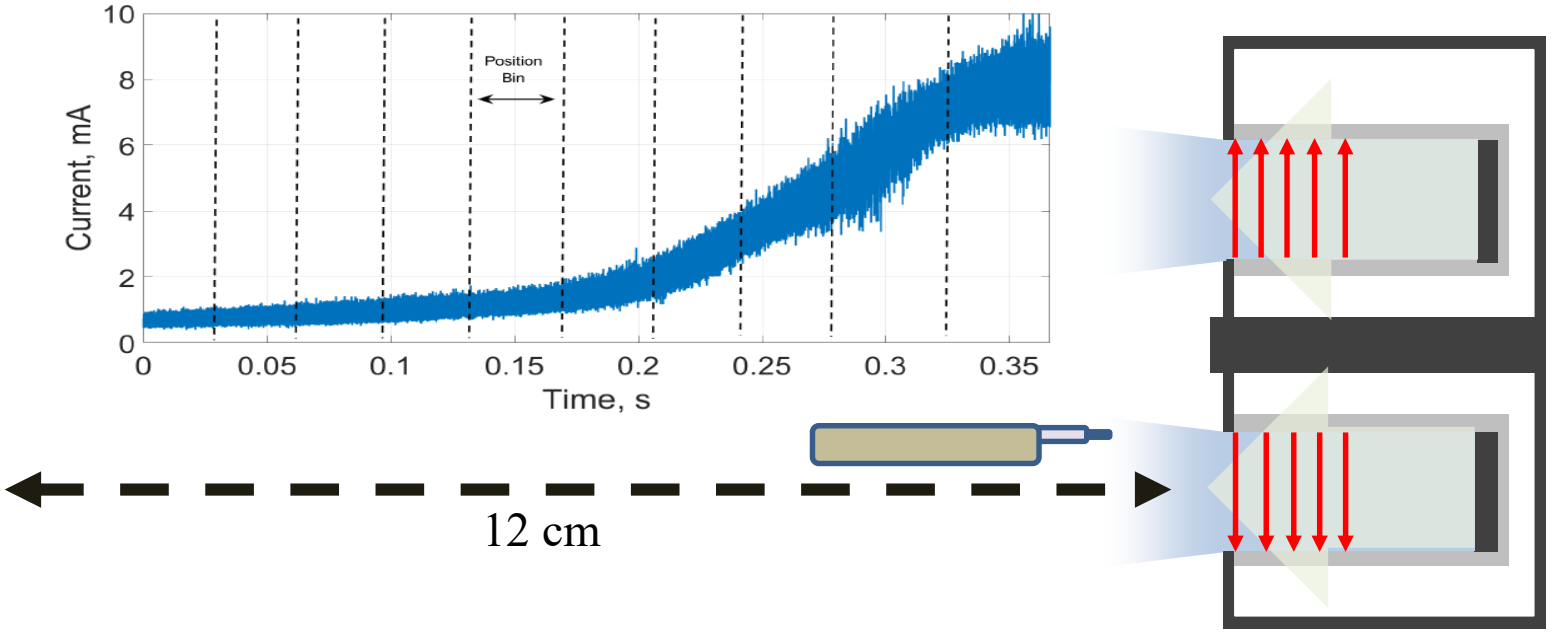
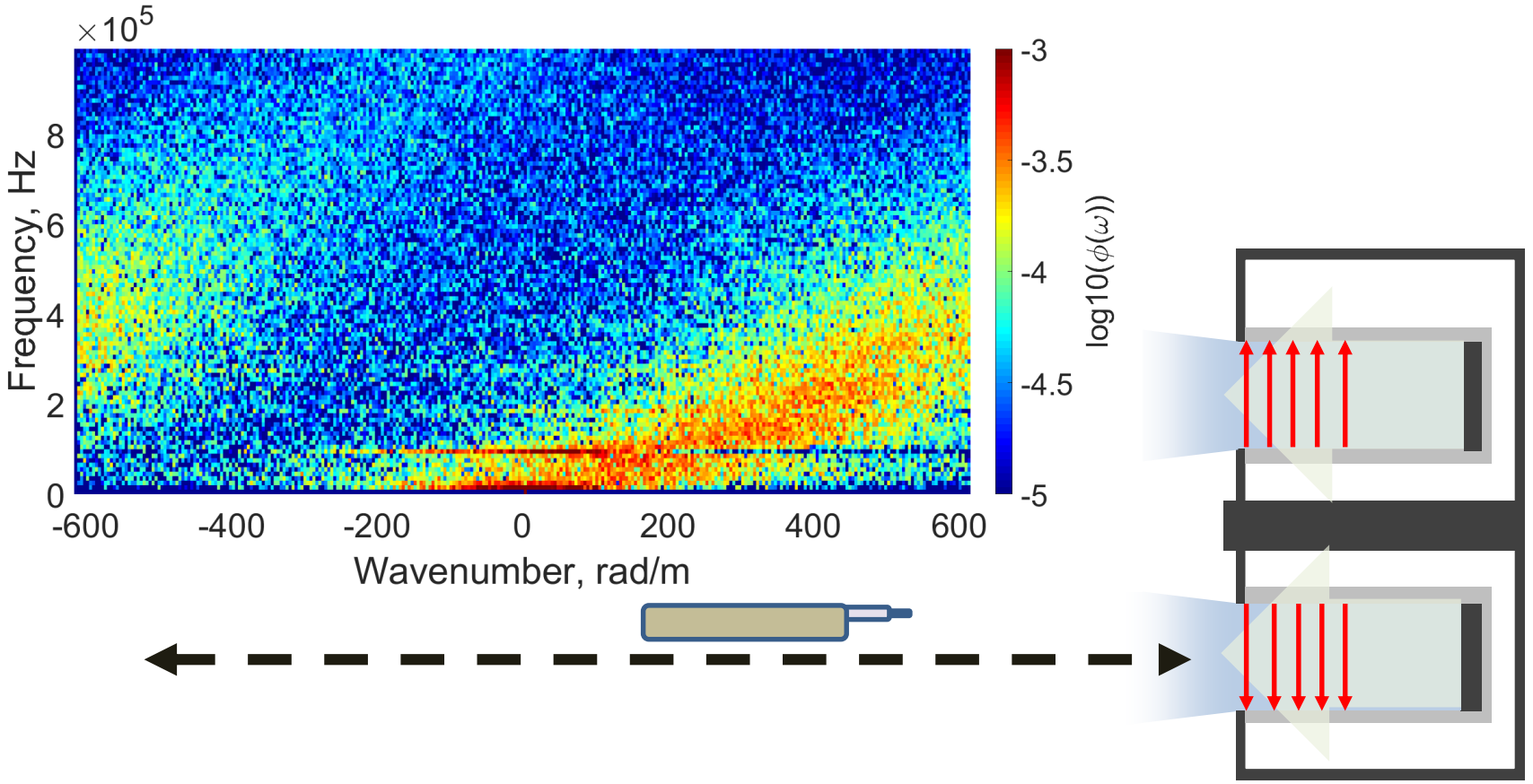
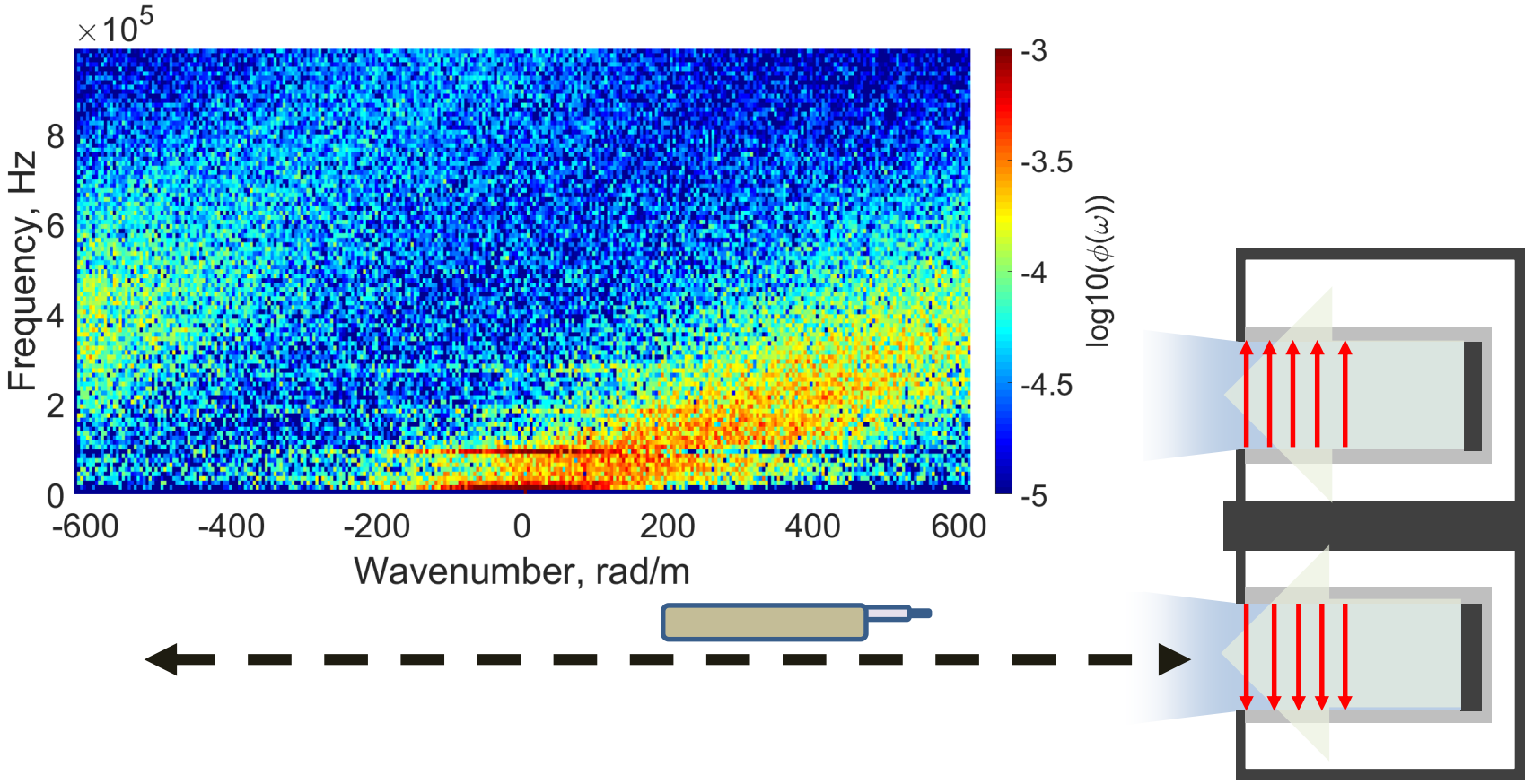


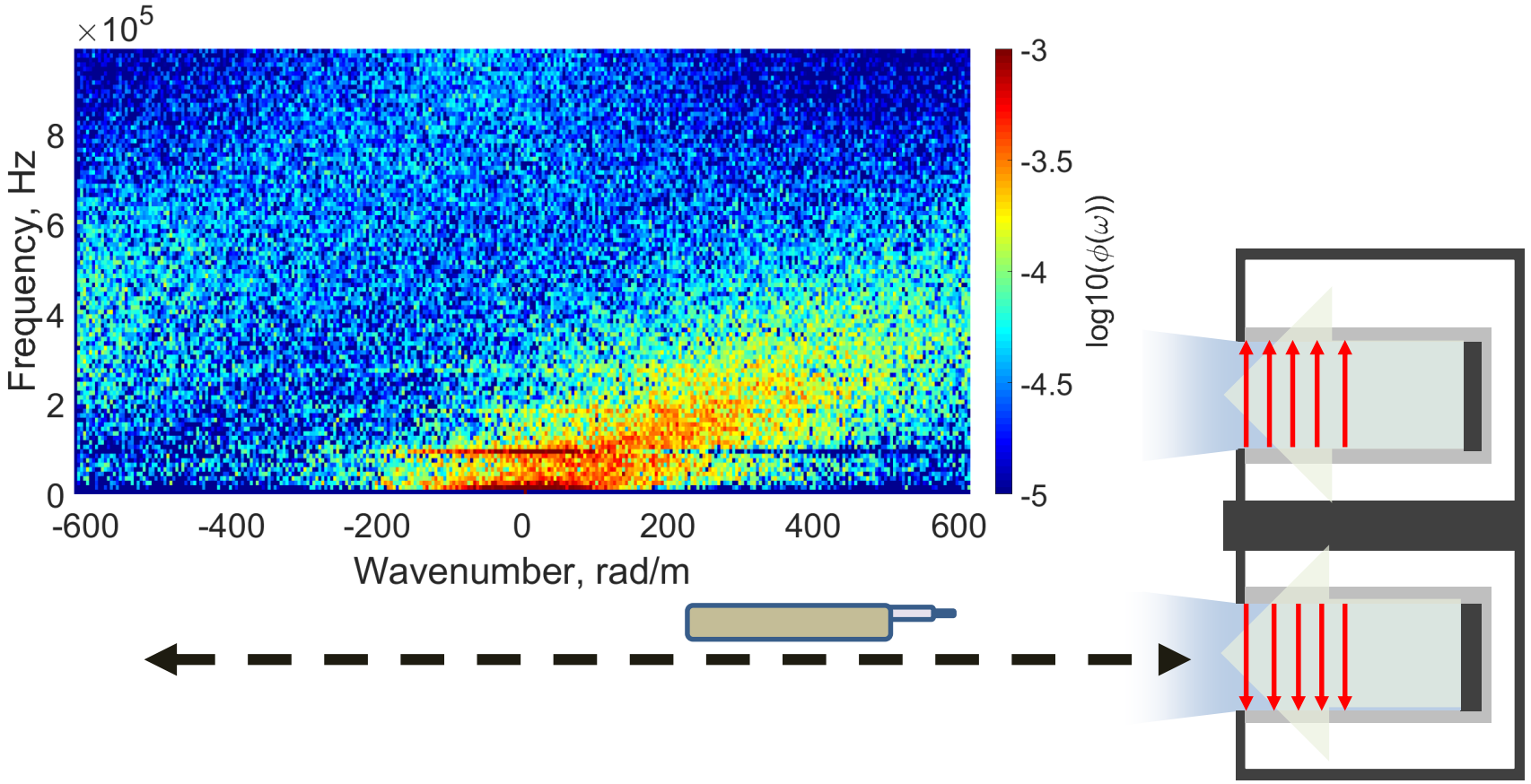
Near-Field Plume



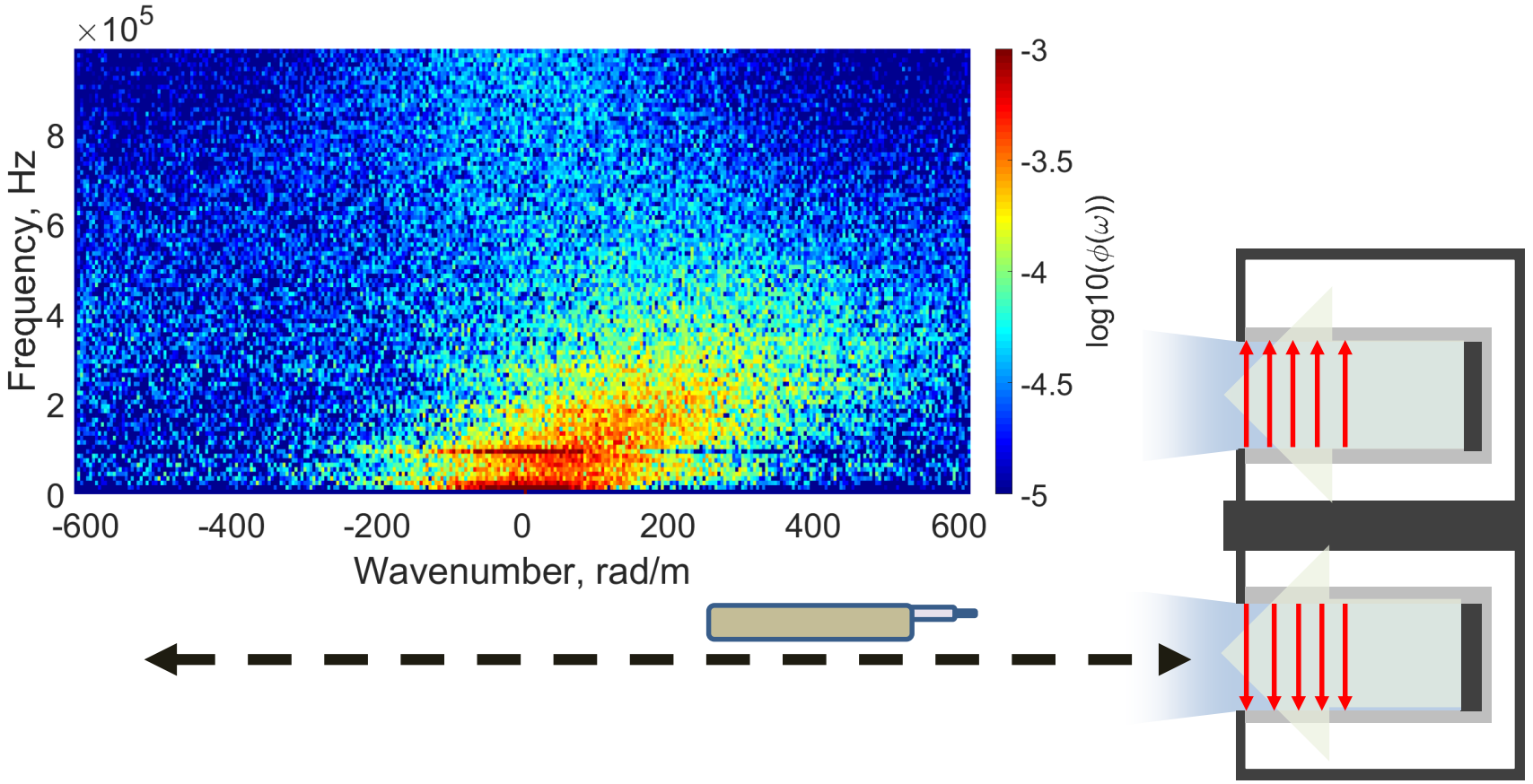
Near-Field Plume



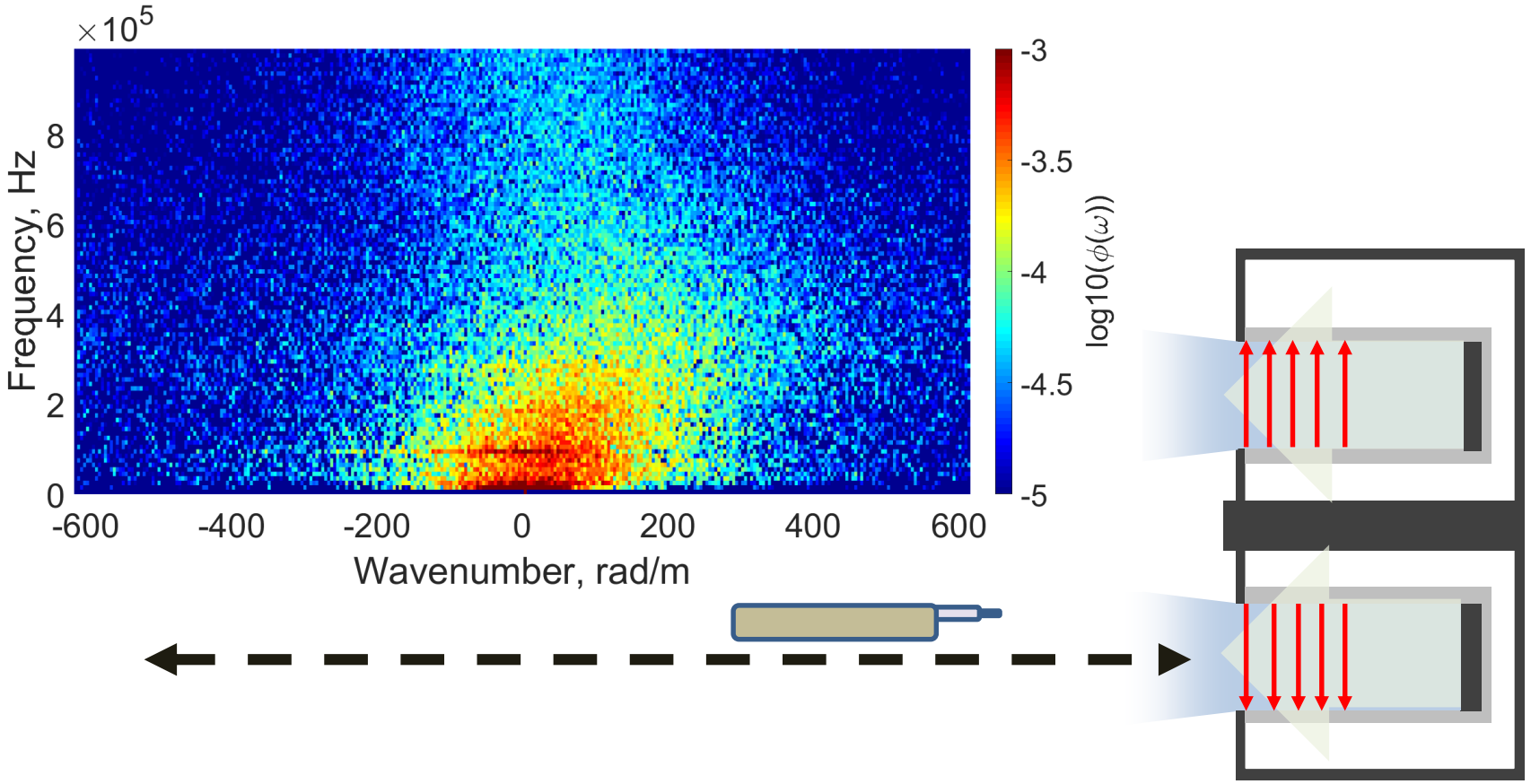
Near-Field Plume



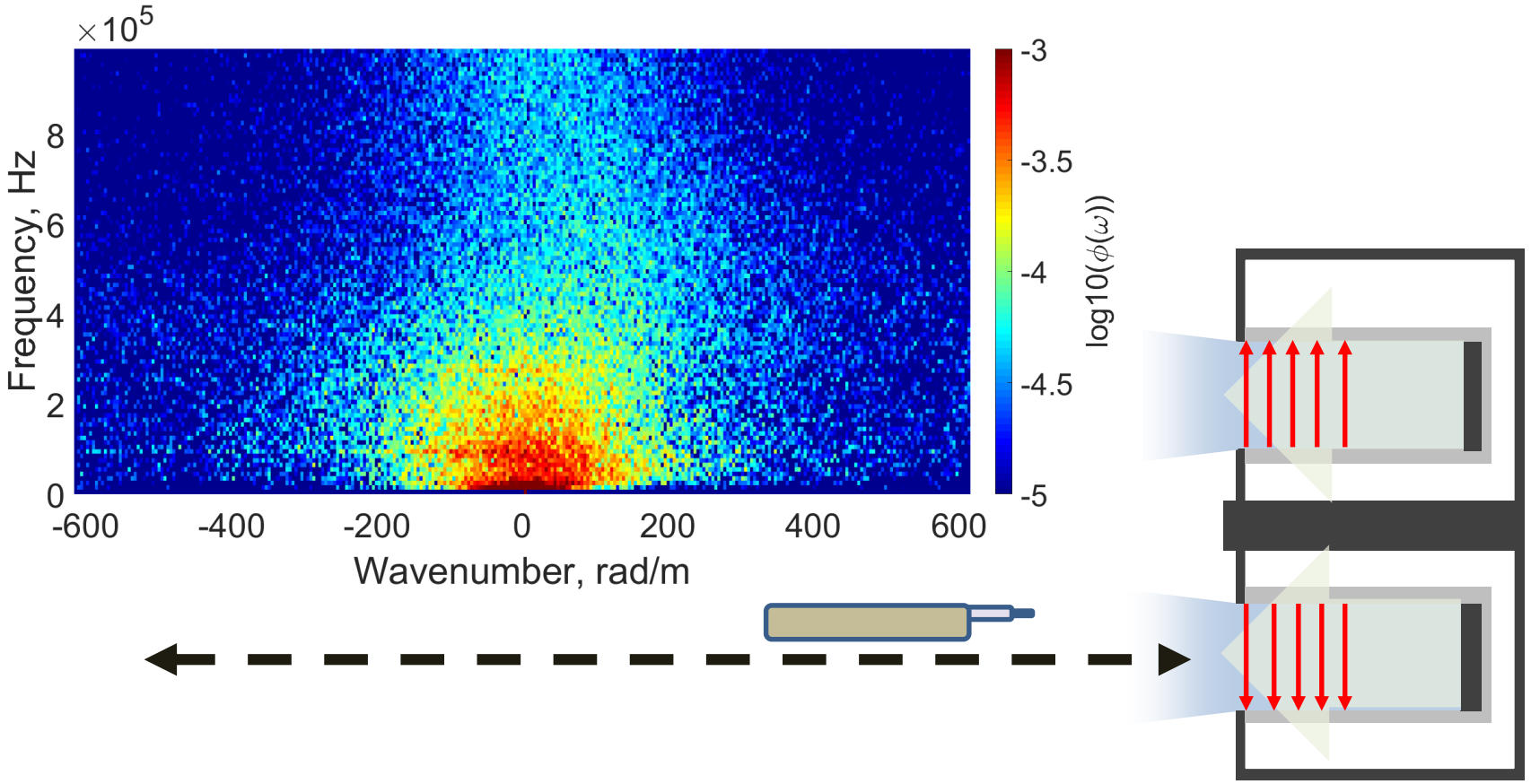
Near-Field Plume



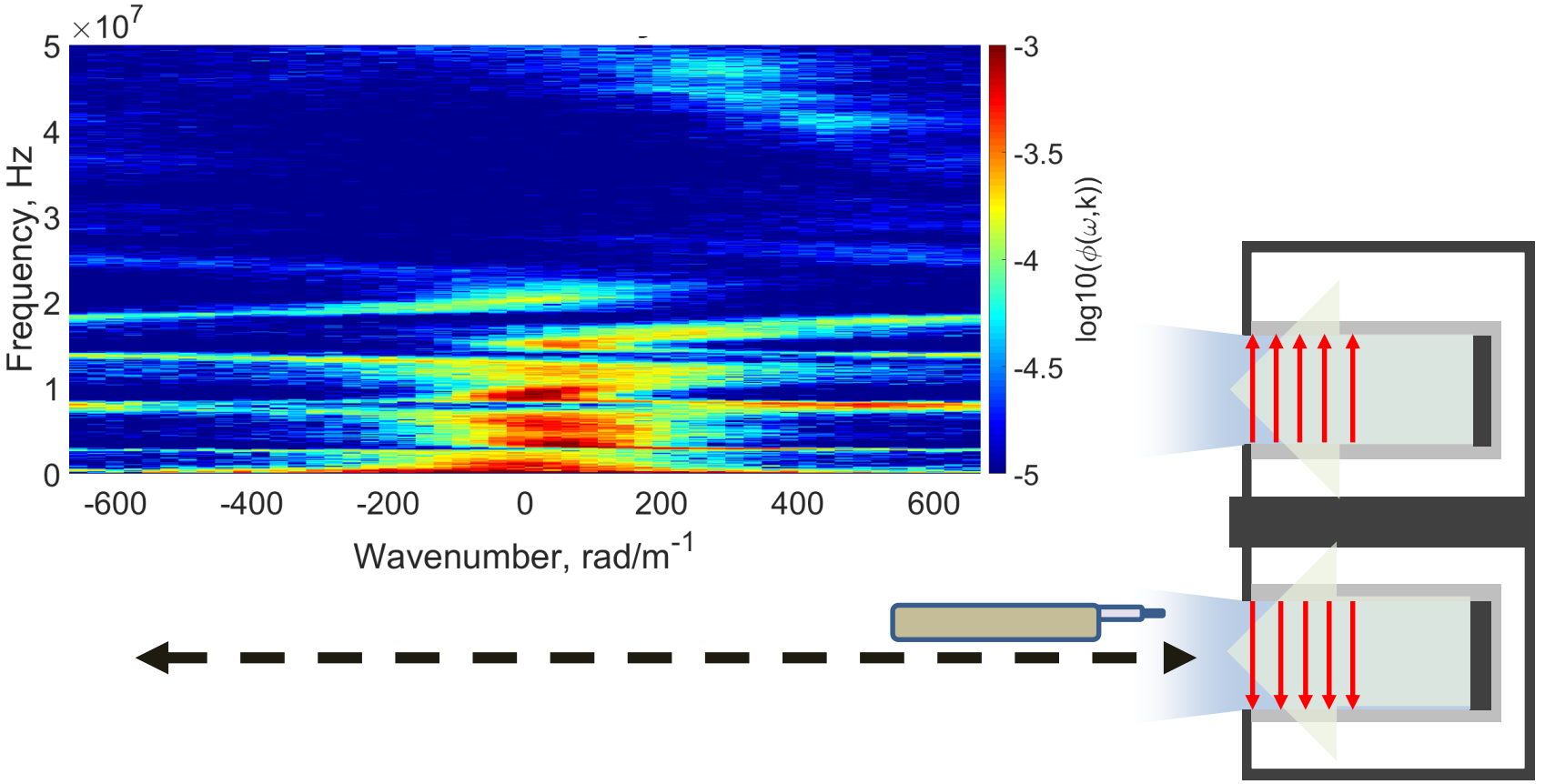
Near-Field Plume



Near-Field Plume



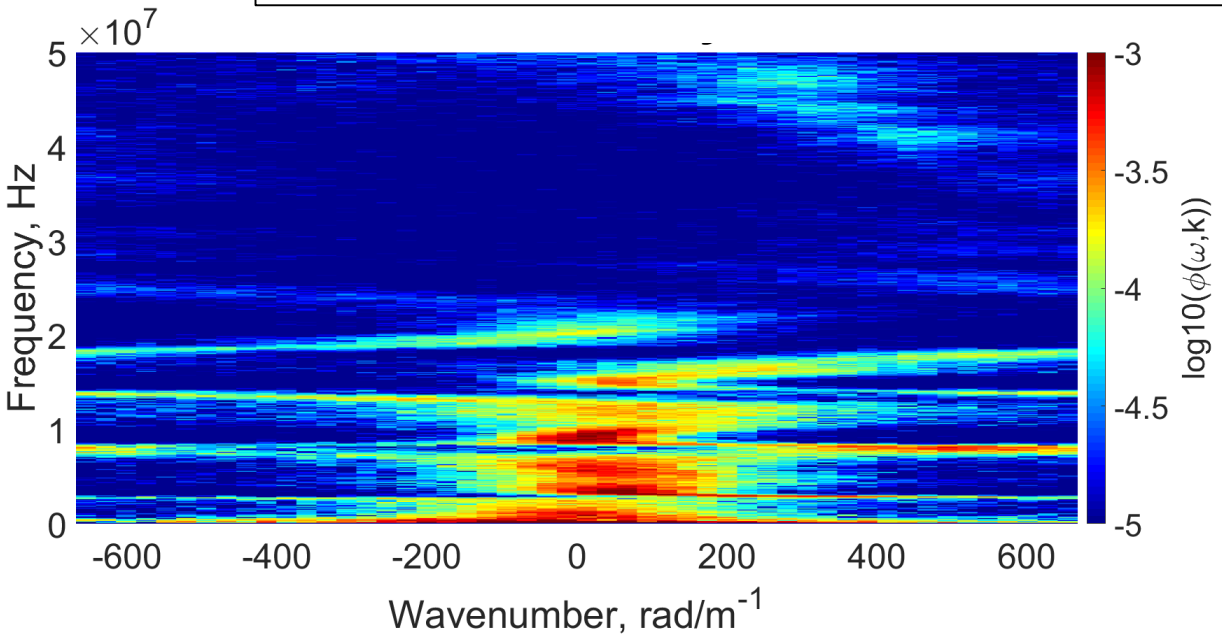
Near-Field Plume



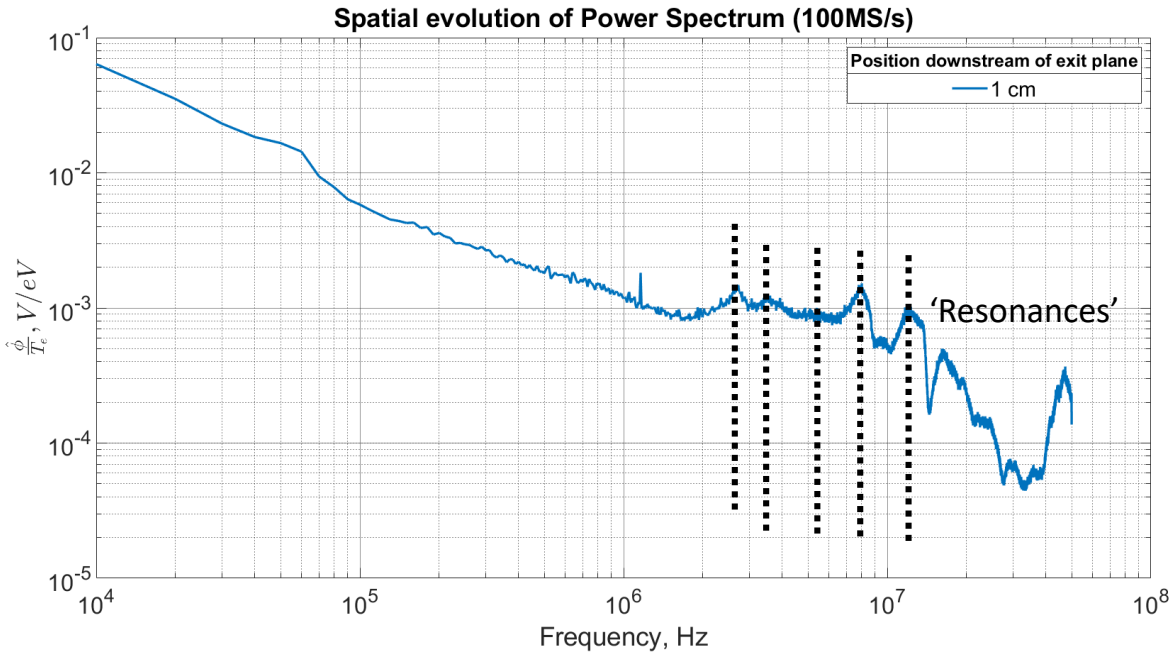
Near-Field Plume

The dispersion relation fundamentally changes nature showing discrete structure upstream

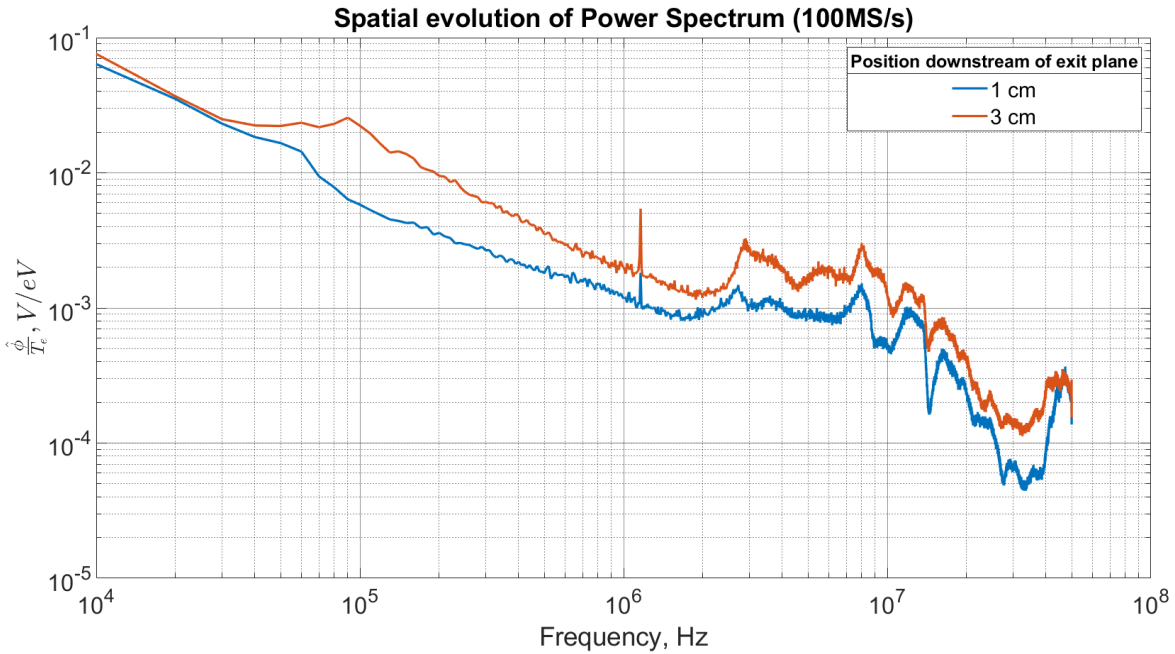
Could discrete structure transitioning into broadband explain discrepancy with experiments?



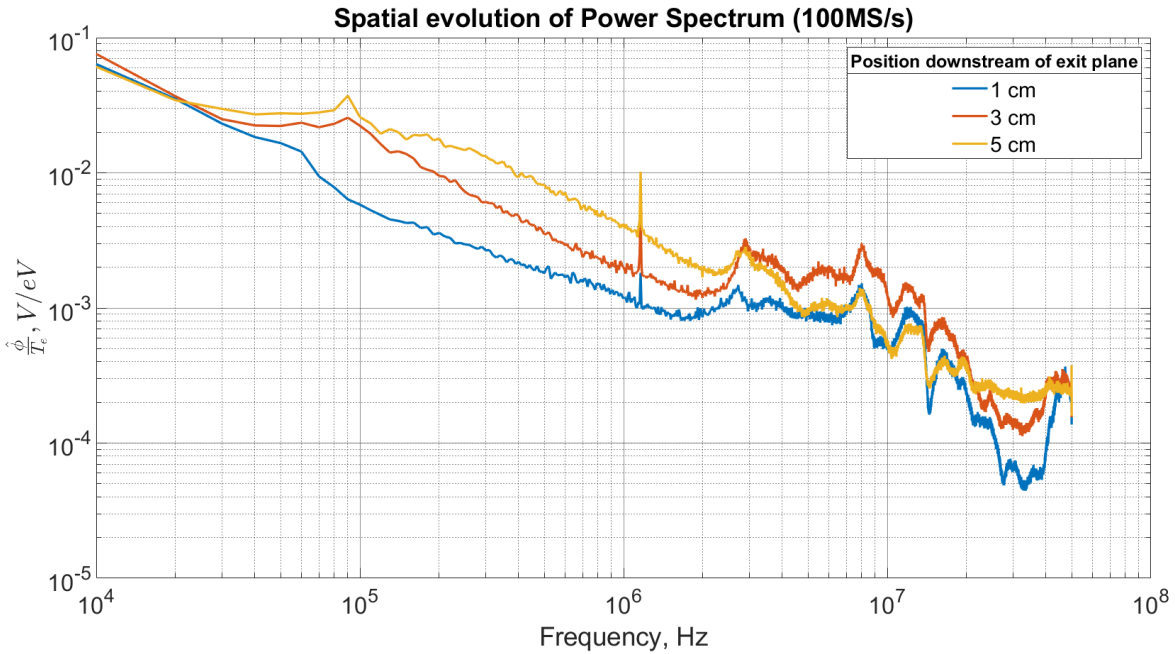
Near-Field Plume



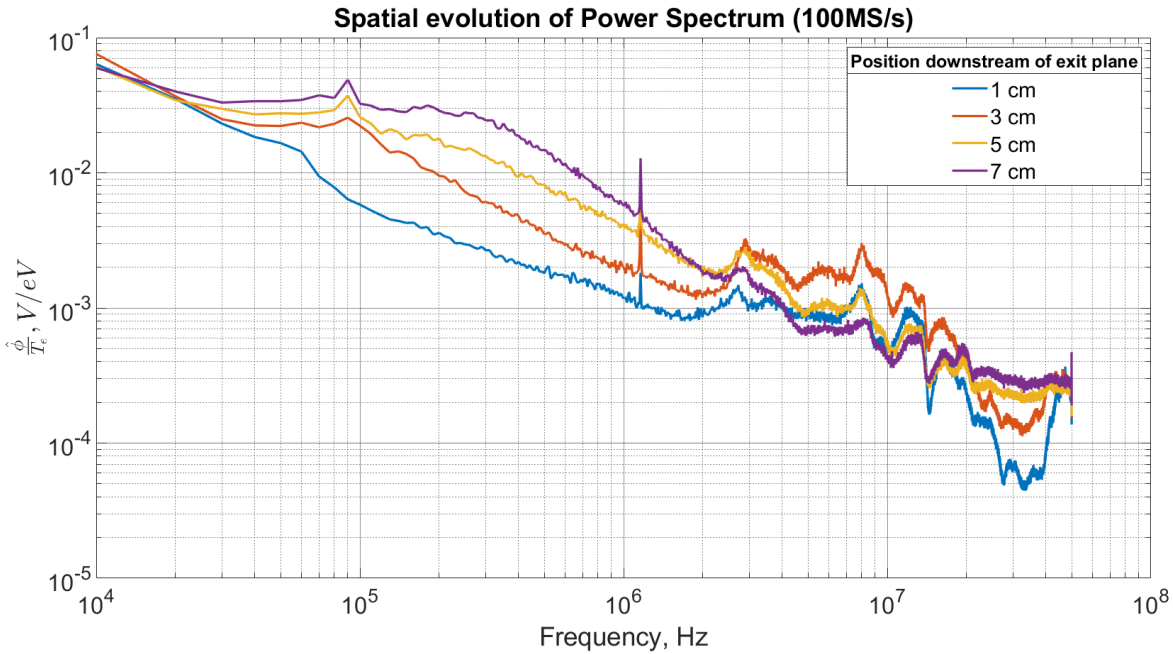
Near-Field Plume

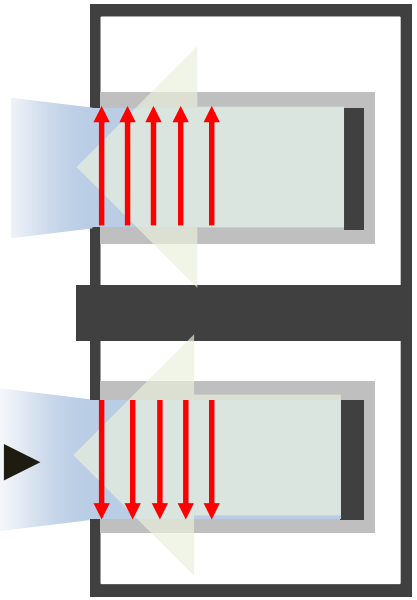


Near-Field Plume

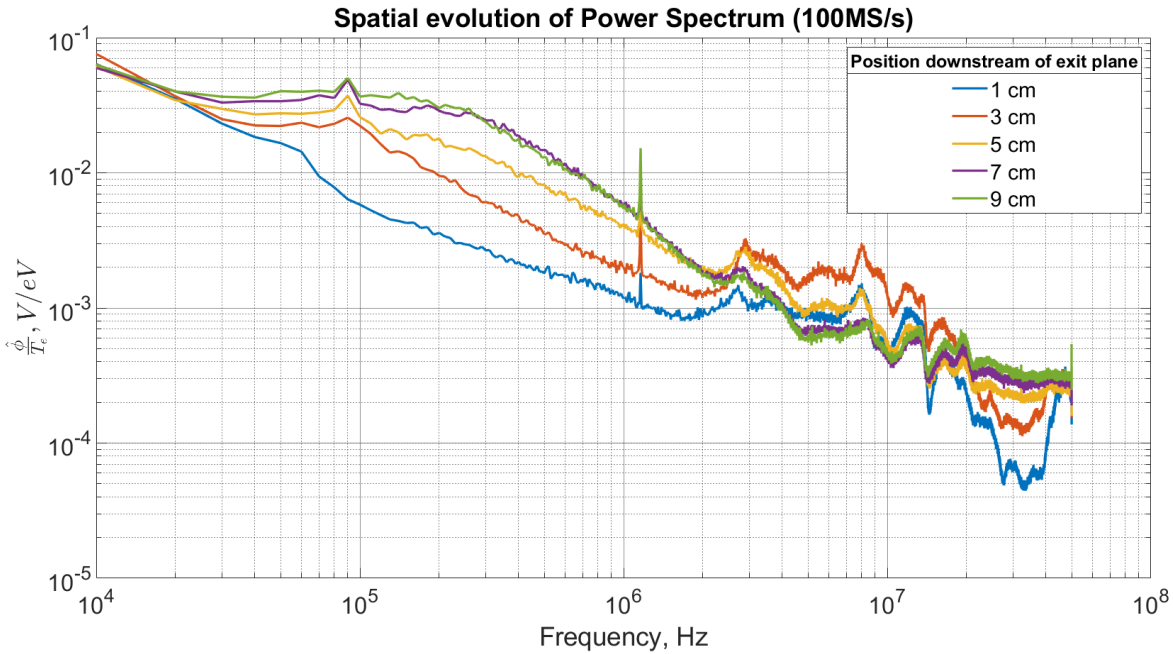


Near-Field Plume

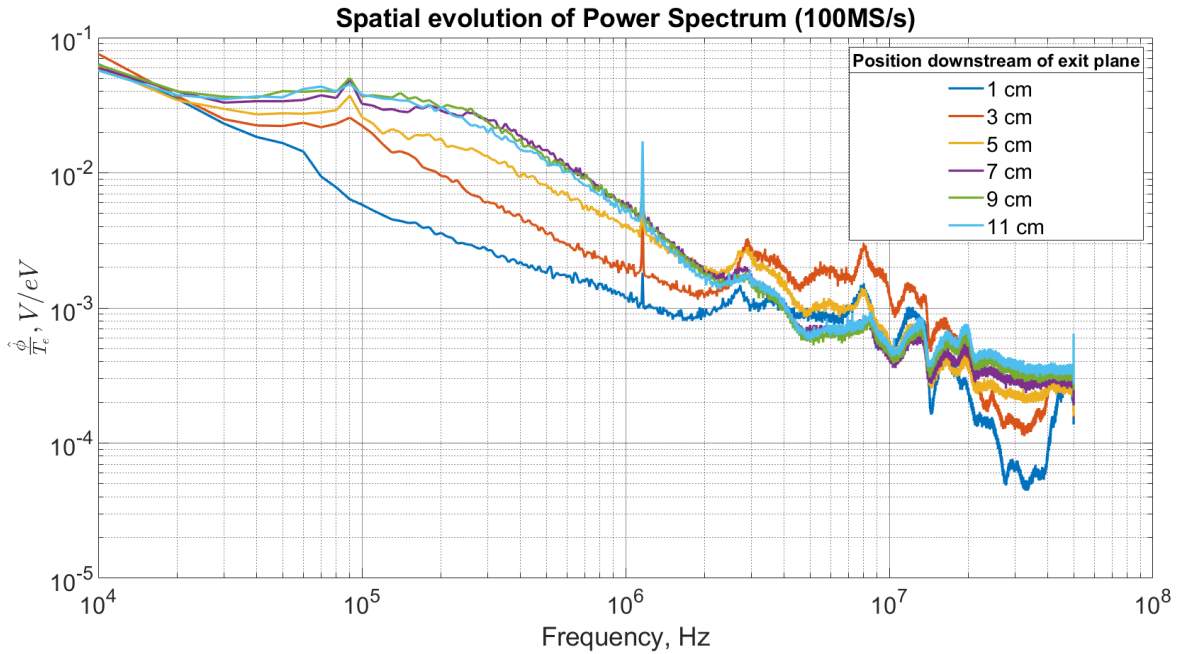




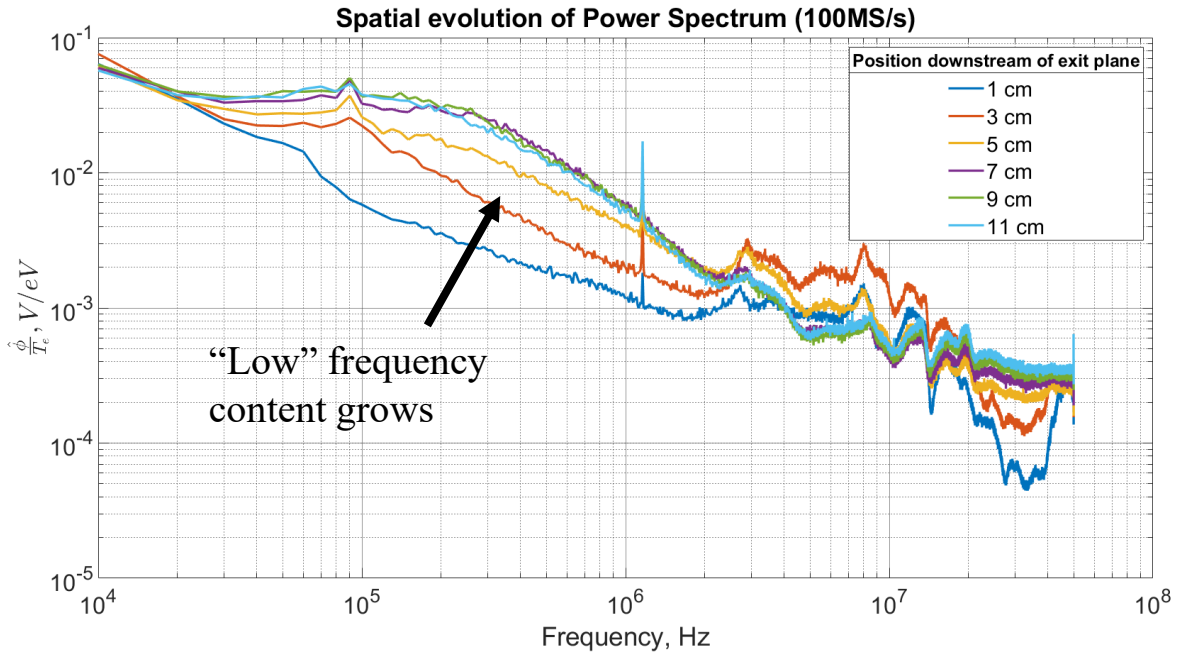
Near-Field Plume



Near-Field Plume



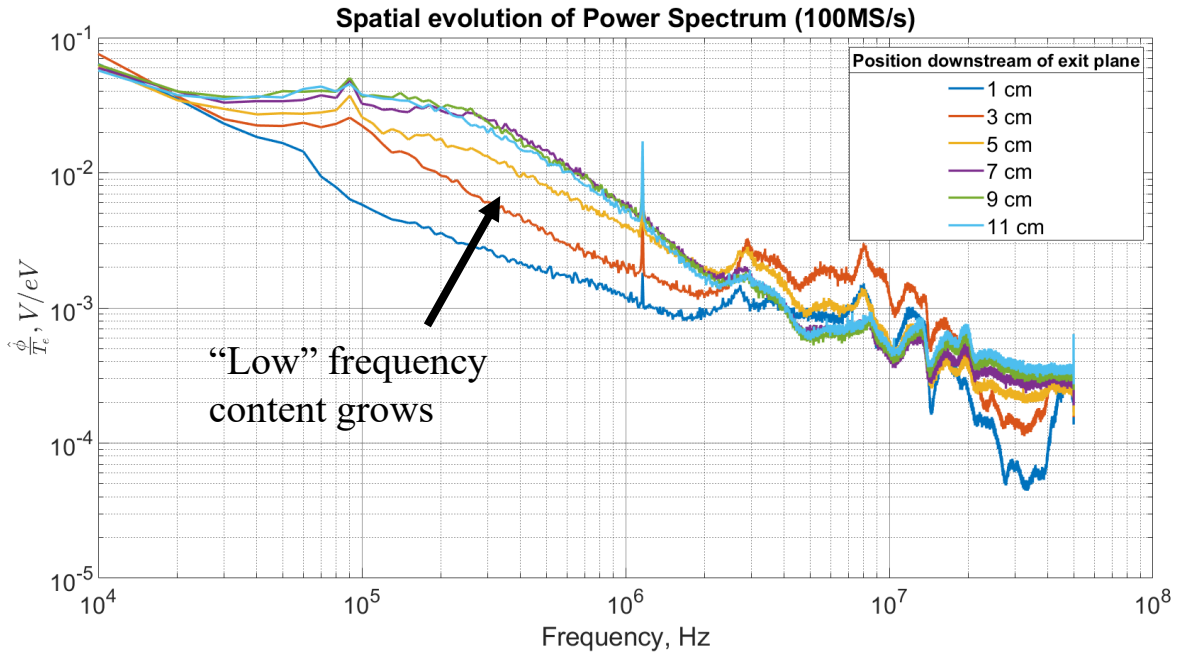
Near-Field Plume



Near-Field Plume

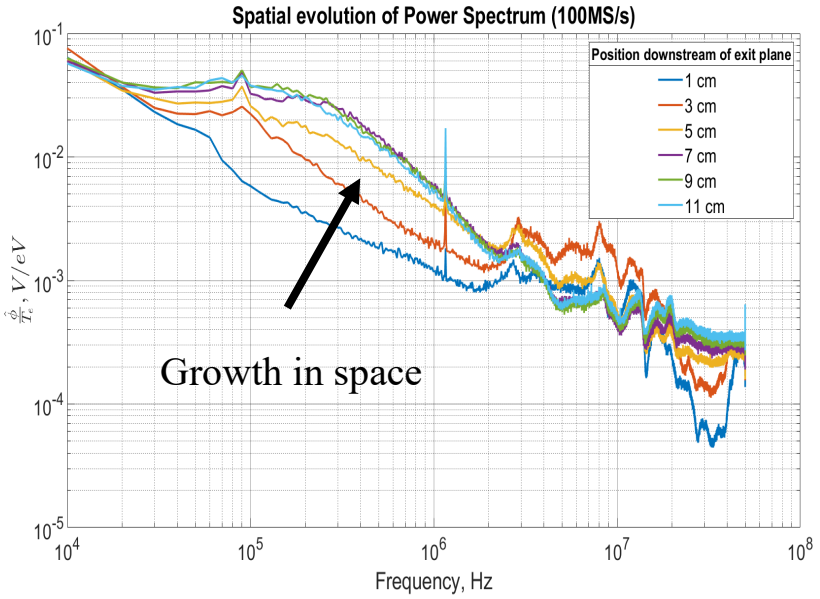
Hypothesis: experiments to date have been performed too far downstream of acceleration zone to image formation of ECDI where discrete structure is present

How could this transition occur?



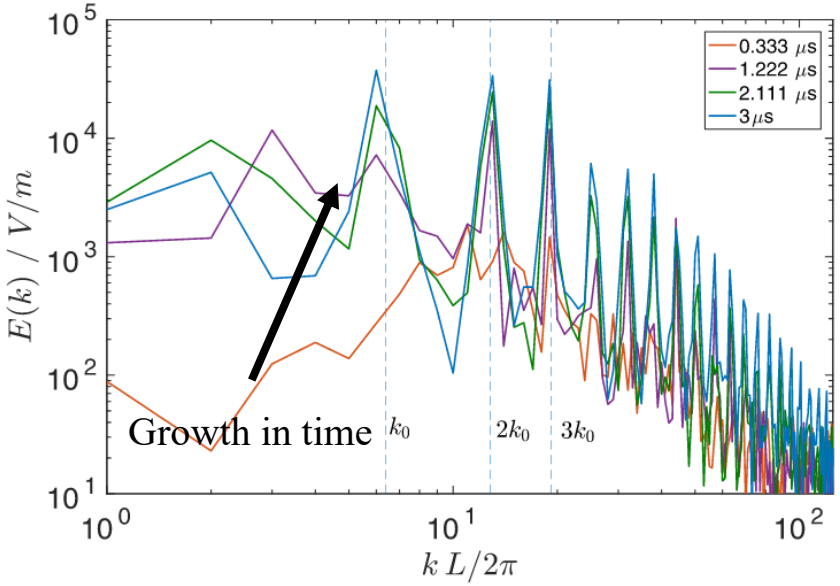
Qualitative comparison with simulation results

Experiment



Z. Brown and B. Jorns (submitted) 2018.

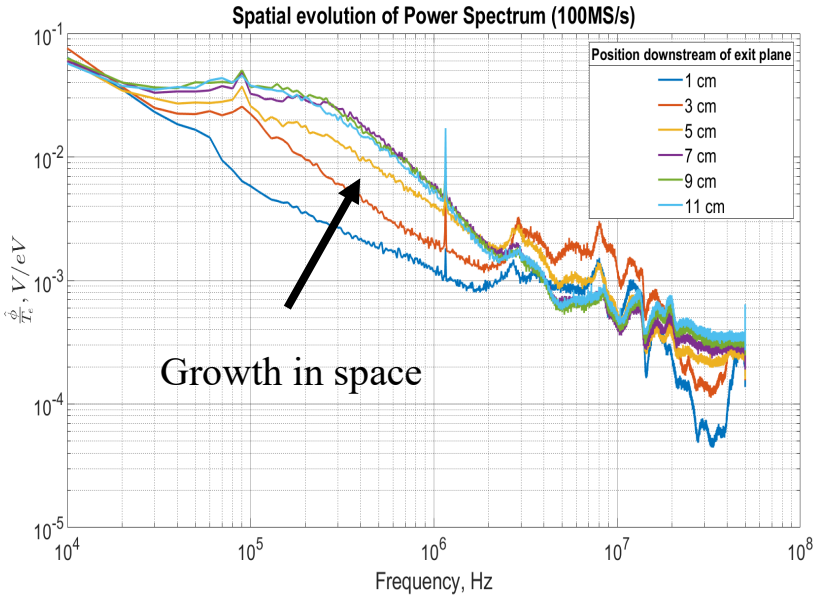
Simulation



S. Janhunen et al., *Physics of Plasmas,* 011608 (2018)

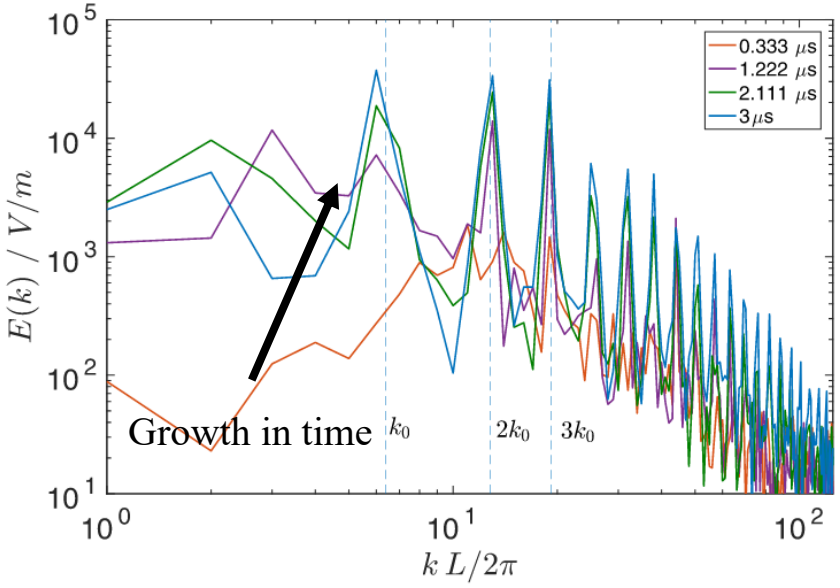
Qualitative comparison with simulation results

Experiment



Z. Brown and B. Jorns (submitted) 2018.

Simulation

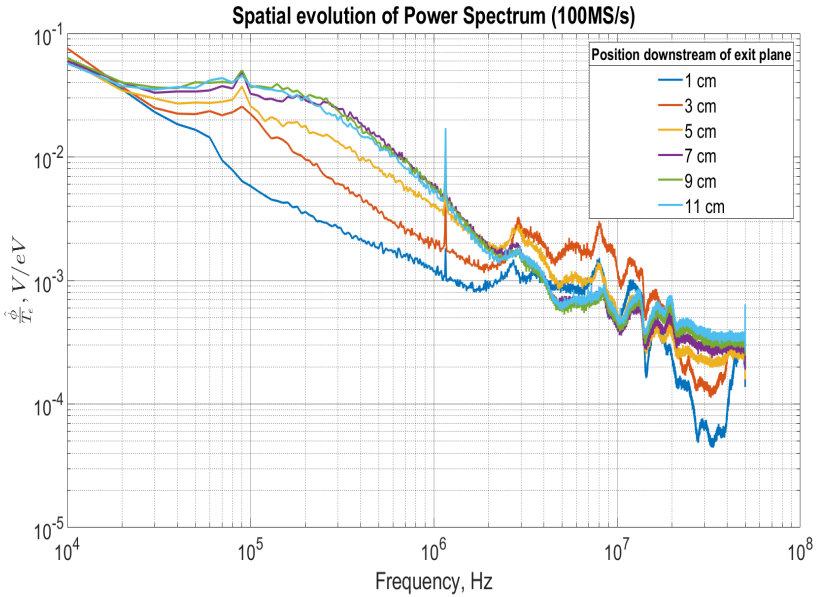


S. Janhunen et al., *Physics of Plasmas,* 011608 (2018)

Could there be a non-linear inverse energy transfer from short to long wavelength?

Qualitative comparison with simulation results

Power spectra



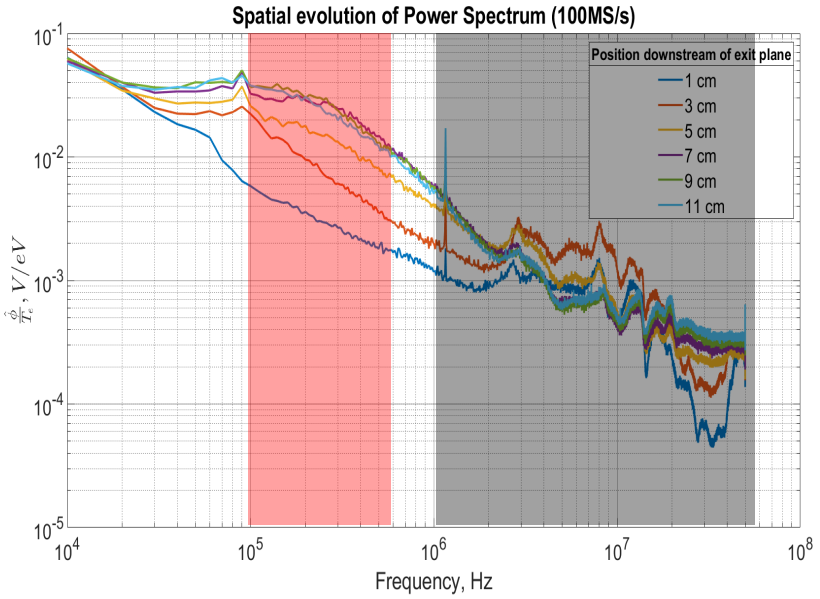
Z. Brown and B. Jorns (submitted) 2018.

Increase in low wavelength content energy (acoustic modes) increases with position as energy in resonant modes decreases

Efforts underway to quantify and understand this transfer

Qualitative comparison with simulation results

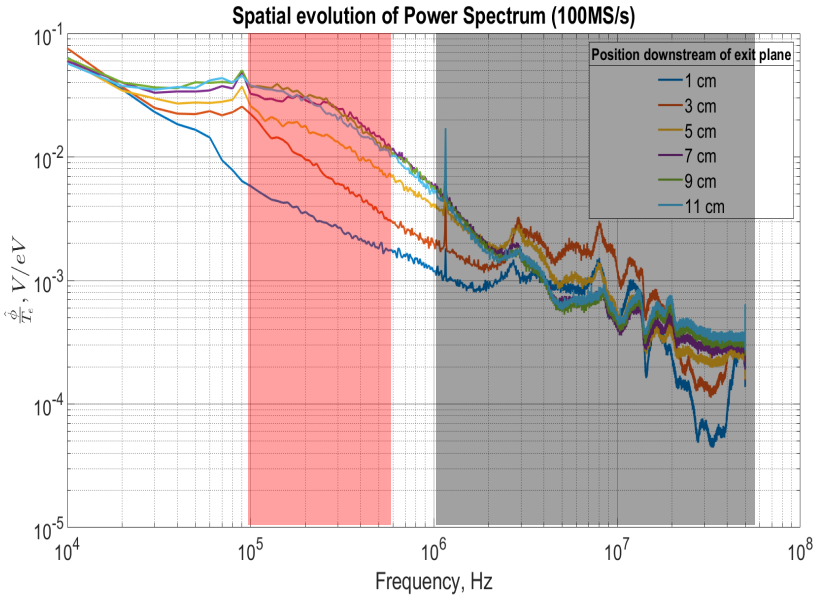
Power spectra



Z. Brown and B. Jorns (submitted) 2018.

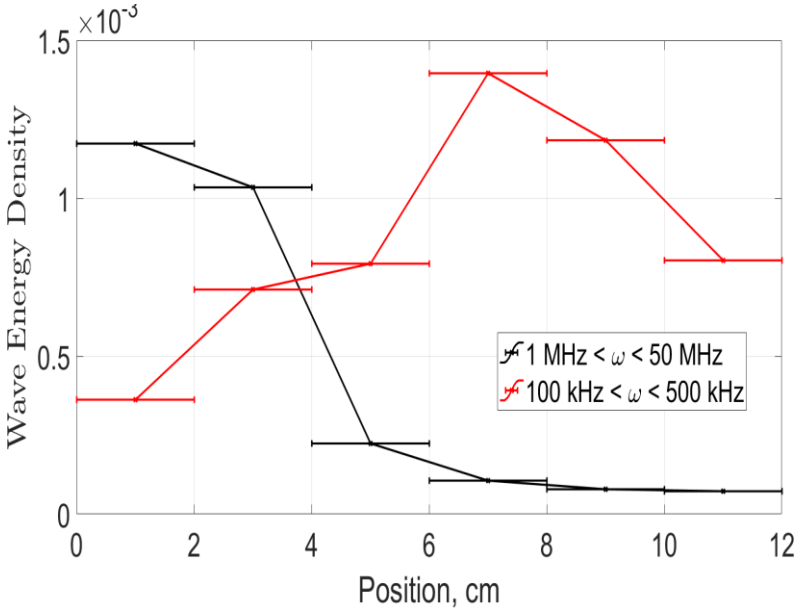
Qualitative comparison with simulation results

Power spectra



Z. Brown and B. Jorns (submitted) 2018.

Evolution of wave energy density



Qualitative comparison with simulation results

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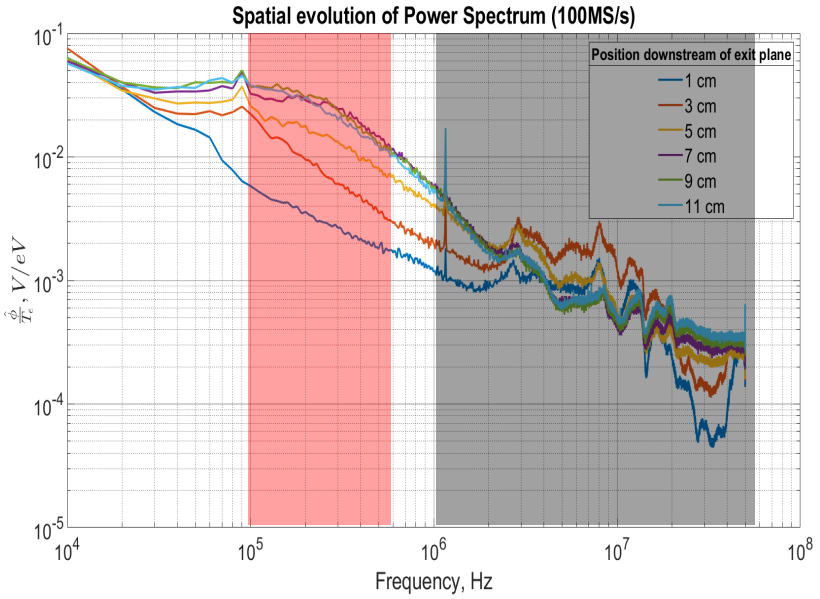

Z. Brown and B. Jorns (submitted) 2018.

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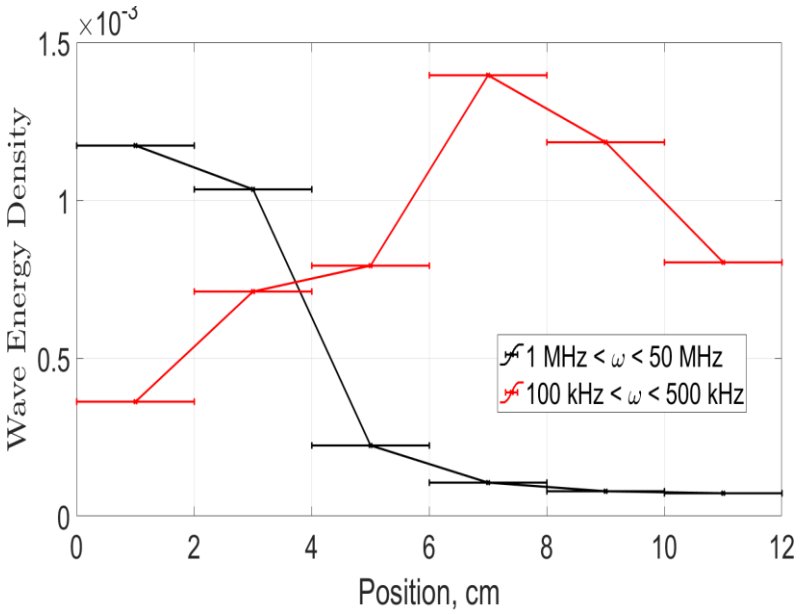
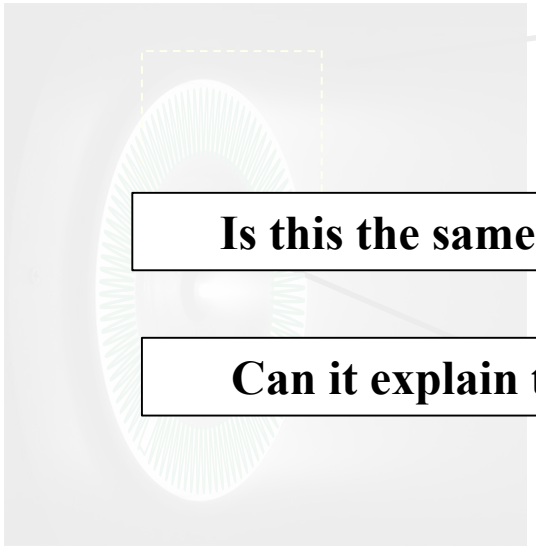


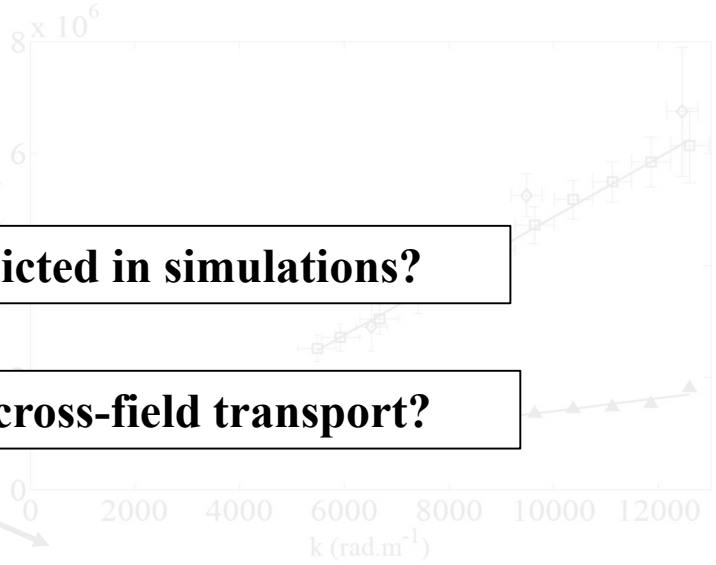
Increase in low wavelength content energy (acoustic modes) increases with position as energy in resonant modes decreases

Efforts underway to quantify and understand this transfer

Experimental evidence of microturbulence



Experimental dispersion relation of small-scale oscillations in Hall direction



Is this the same wave as predicted in simulations?

Can it explain the observed cross-field transport?

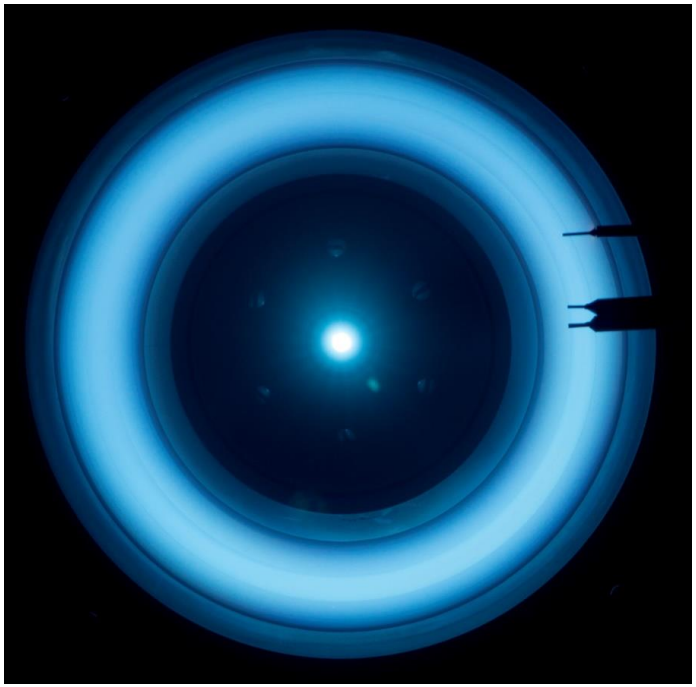
S. Tsikata, N. Lemoine, V. Pisarev, and D. Grésillon, *Physics of Plasmas*. Vol. 16., No. 3. 2009.

- Wavelengths < 1 mm
- Dispersion is acoustic-like
- Modes are incoherent

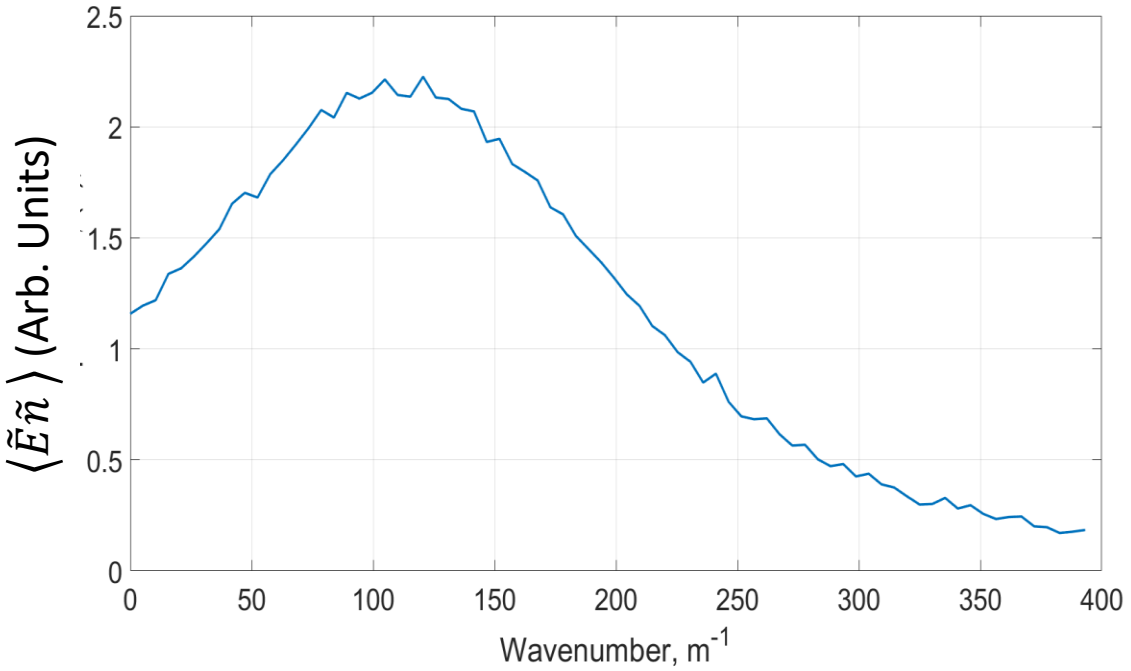
ECDI in the acoustic-like limit

Experimental evidence of electron transport driven by instabilities

9kW Magnetically Shielded Hall thruster



Power spectrum of ECDI-like oscillations



Z. Brown and B. Jorns, "Dispersion relation measurements of plasma modes in the near-field plume of a 9-kW magnetically shielded thruster," IEPC-2017-387

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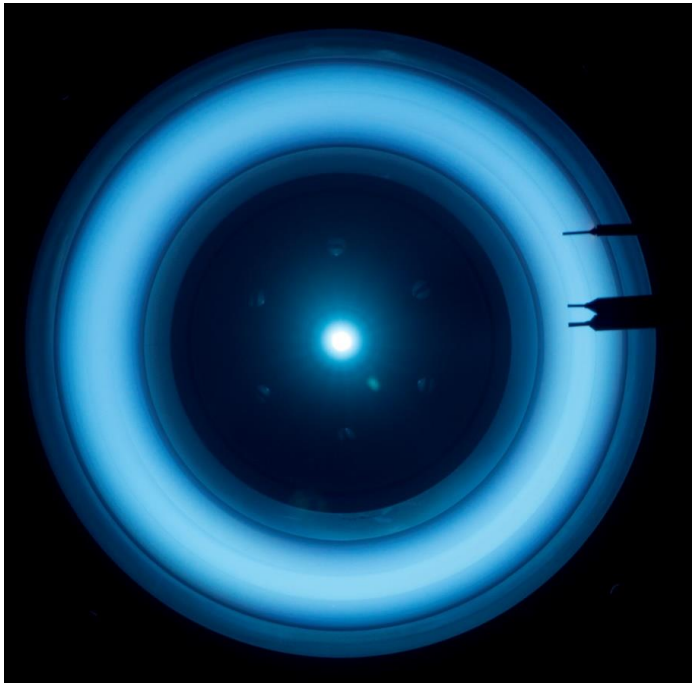
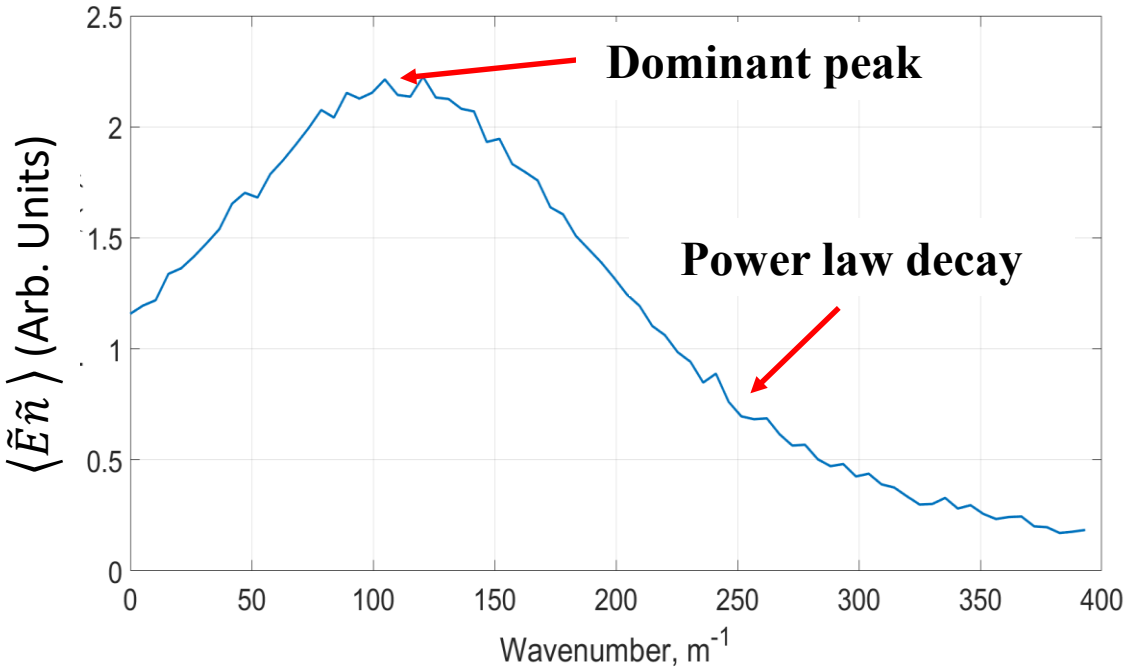


Power spectrum of ECDI-like oscillations



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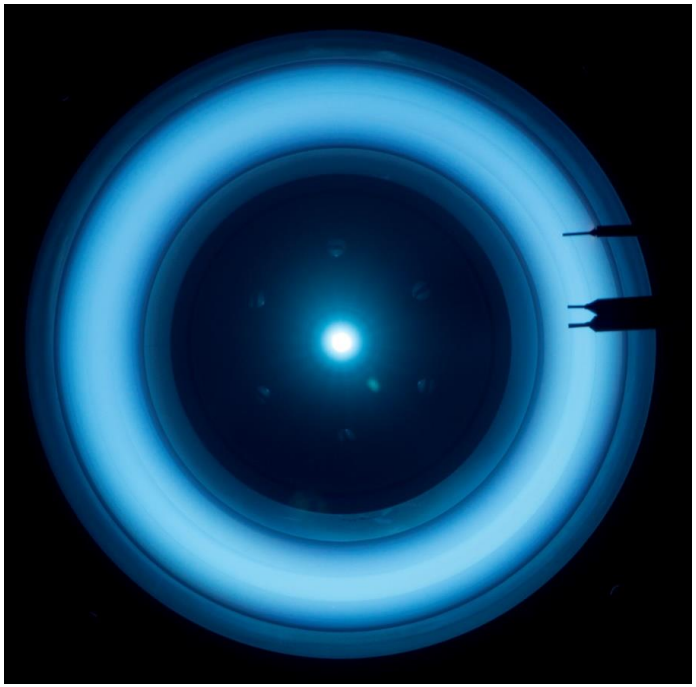
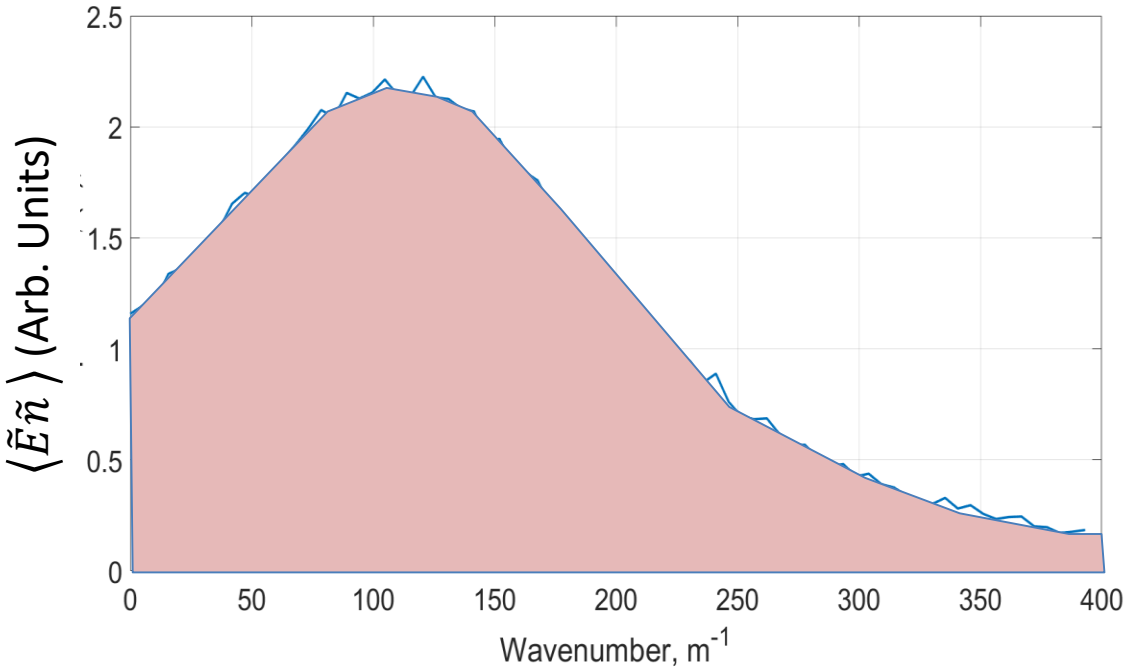


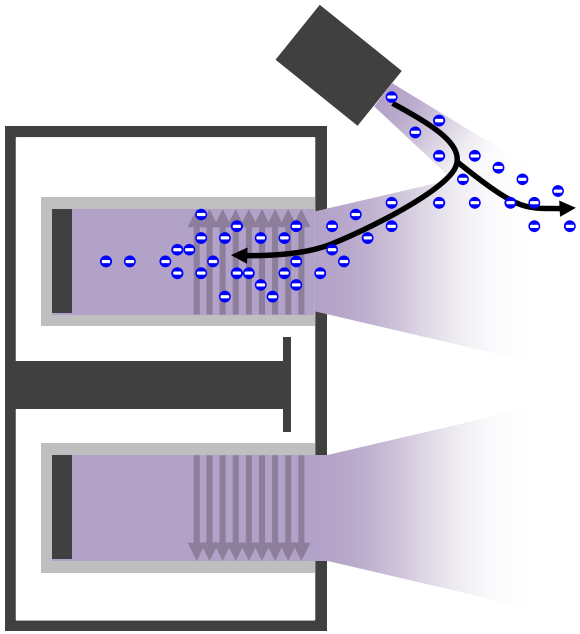
Power spectrum of ECDI-like oscillations



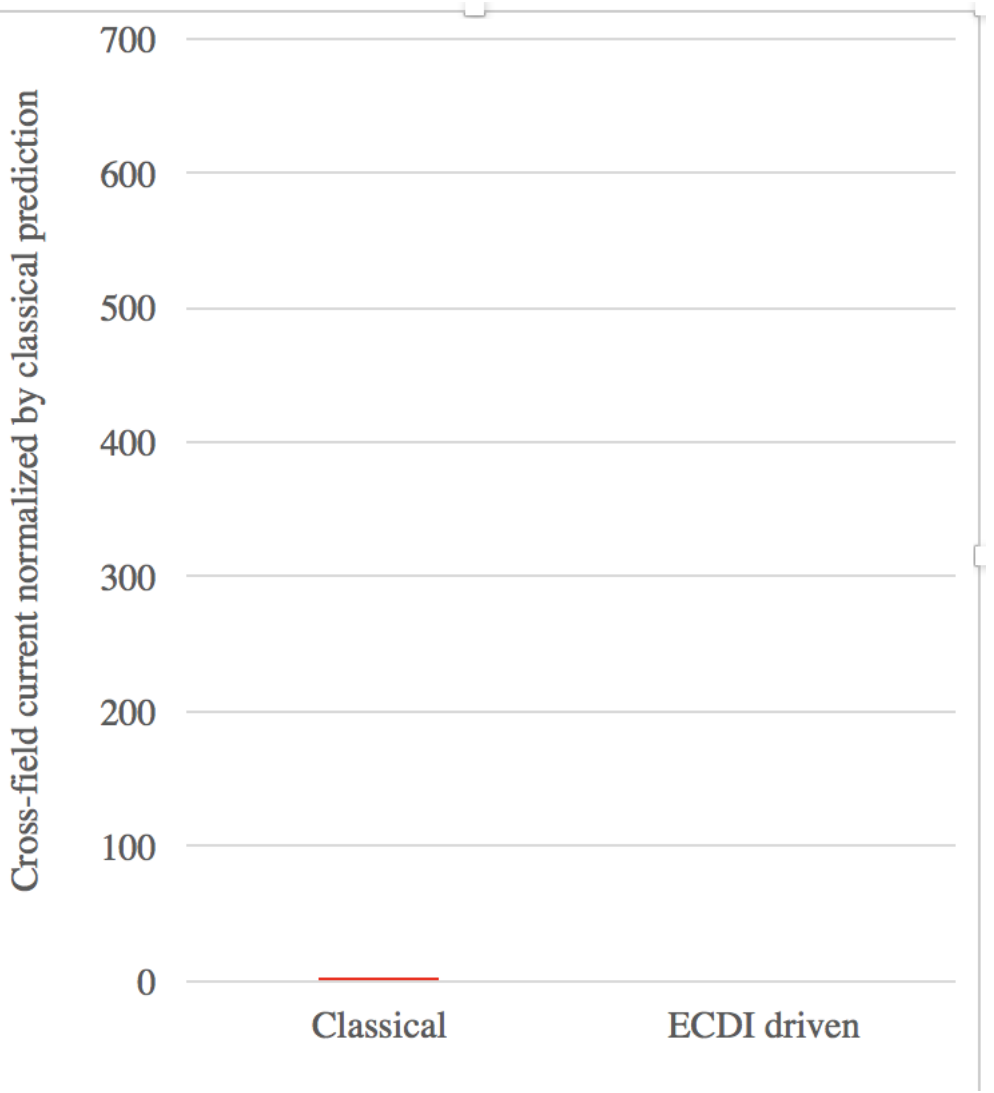
Z. Brown and B. Jorns, "Dispersion relation measurements of plasma modes in the near-field plume of a 9-kW magnetically shielded thruster," IEPC-2017-387

$$I_e \propto \frac{q}{B}\langle \tilde{E}\tilde{n} \rangle$$

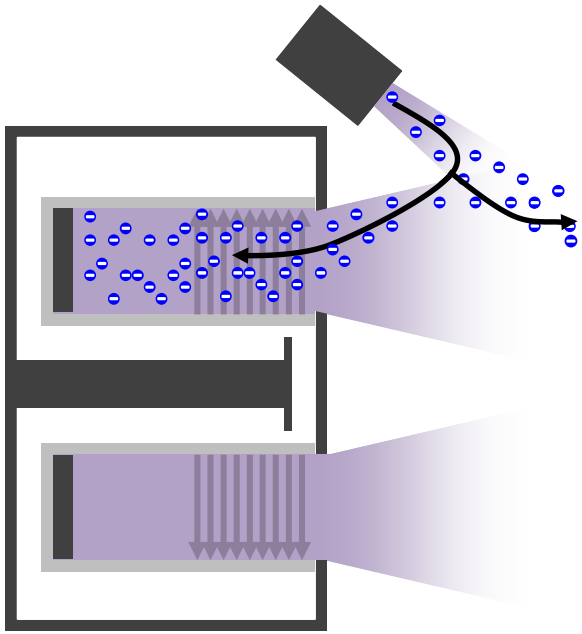
Experimental evidence of electron transport driven by instabilities



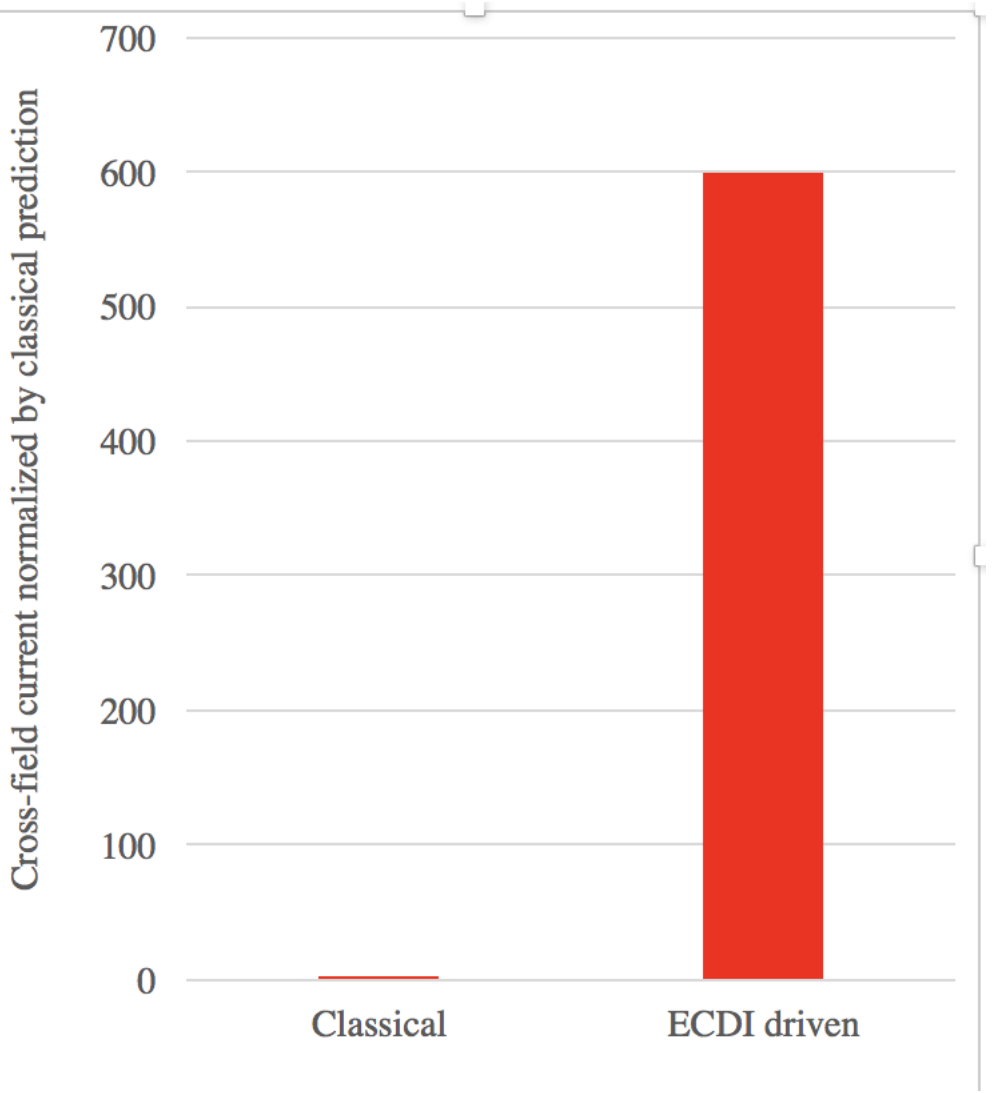
Classical transport from particle collisions



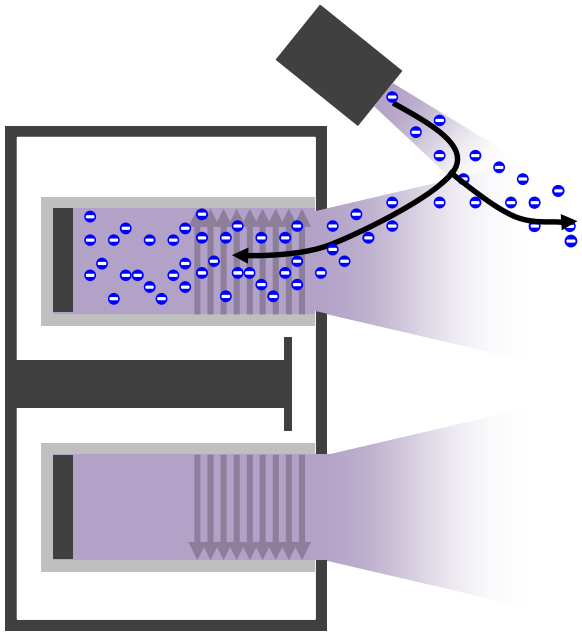
Experimental evidence of electron transport driven by instabilities



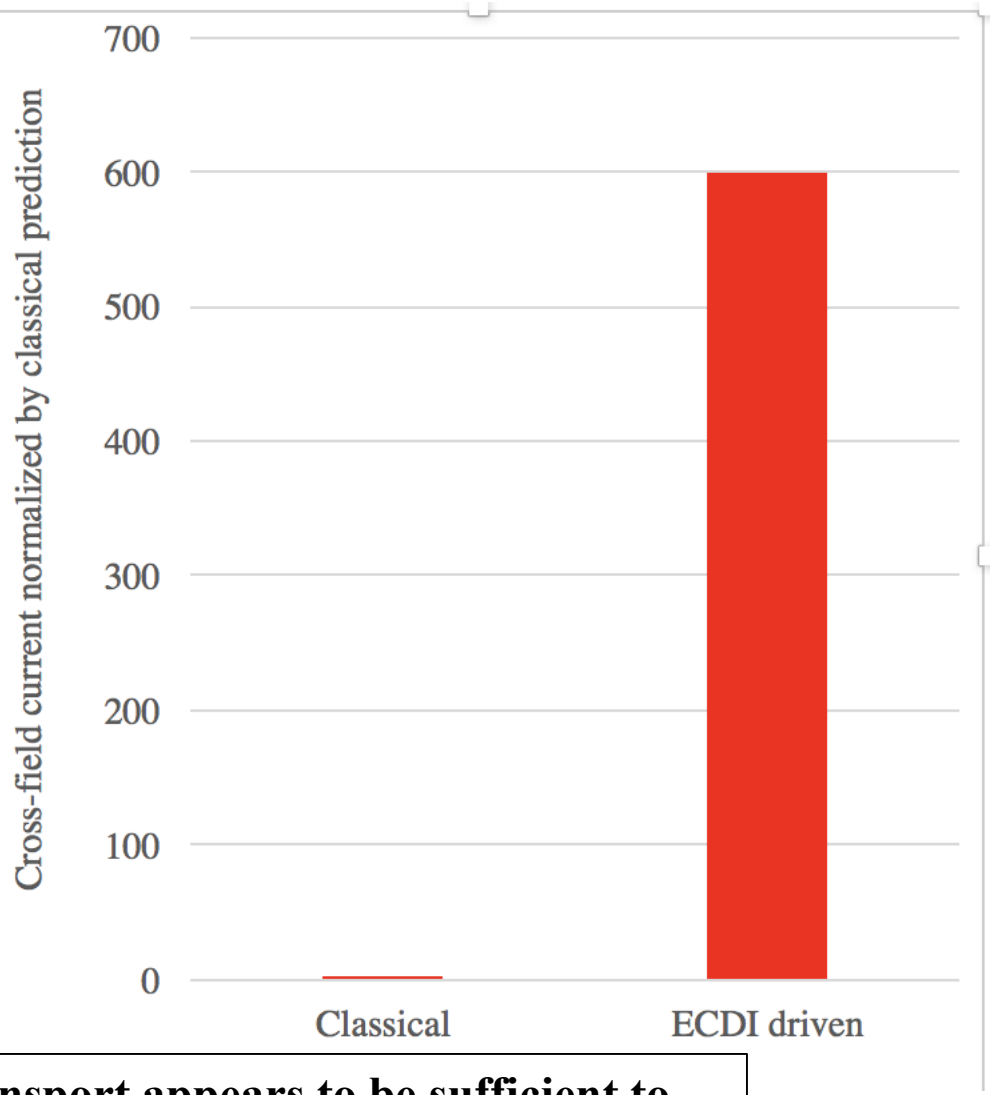
Anomalous transport



Experimental evidence of electron transport driven by instabilities

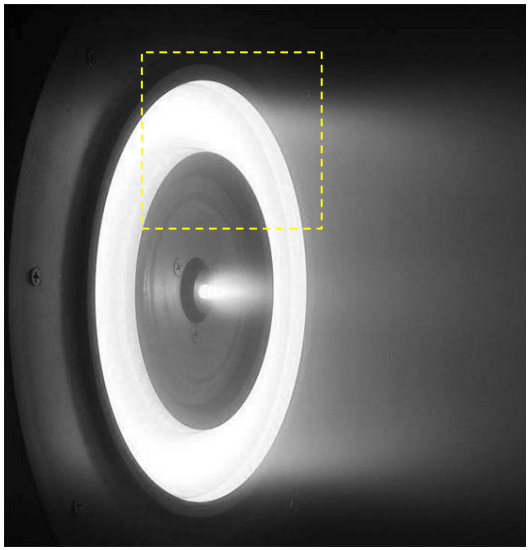


Anomalous transport



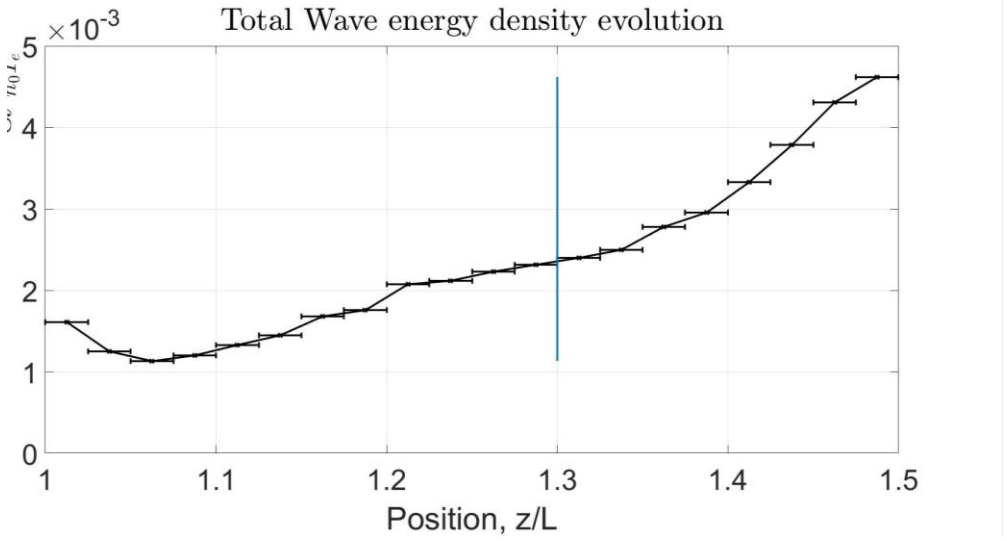
Instability driven transport appears to be sufficient to explain electron dynamics in plume (with caveats)

Other experimental insights into ECDI



ECDI energy density in thruster channel

$\frac{W_T}{nT_e}$



$$\nu_{AN} = \alpha\, \gamma_e \frac{W_T}{nT_e} \approx \alpha\, \gamma_e$$

Critical information for fluid-closure

Summary

- **A number of simulations suggest that ECDI exists and should exhibit distinct, measureable features**
  - Discrete
  - Maximum growth at small wavelength
- **Experimental measurements to date have not supported this**
- **Probing has shown that discrepancy may in part be due to fact ECDI spectrum transitions from upstream discrete nature to downstream broadband spectrum**
- **The nature of this transition is not known but is currently being studied**
- **Other experimental insights are guiding investigations into closure, e.g. the observation modes may be saturated**

Follow on experimental questions

- **How does the energy cascade occur and can we measure it?**
- **Can we measure shorter wavelengths inside the channel with necessary spatial resolution?**
- **Can we use experiments to guide closure for simulation results?**
- **Can kinetic codes ever capture all the nuanced effects (like nonlinear energy cascade in 3D) likely occuring in this geometry?**
- **What other experimental measurements can we make to characterize predictions related to ECDI:**
  - Ion azimuthal drift (on-going at UM)
  - Direct measurements of electron transport (on-going at UM)