Using the Magnetized Dusty Plasma Experiment (MDPX) to evaluate dust cloud detection between spacecraft

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Physics Department, Auburn University

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Key points

Motivation:

- Can the presence of clouds of charged dust grains interacting with the solar wind may be responsible for interplanetary field enhancement (IFE)?
- Can a launched, electrostatic fluctuation be used to detect the presence of dust?

Preliminary laboratory experiments:

- Demonstrated *coupling* between launched waves and dusty plasma cloud in a magnetized plasma
- Observed an possible enhancement in *electrostatic plasma* fluctuations due to the presence of dust particles

Evidence for dust-plasma interactions: space and lab

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL085818

Key Points:
- The associated magnetic perturbations detected across the bow shock are explained by a cloud of charged fine dust carried by the solar wind

Magnetized Dust Clouds Penetrating the Terrestrial Bow Shock Detected by Multiple Spacecraft

H. R. Lai[1], C. T. Russell[2], Y. D. Jia[2], and M. Connors[3]

[1]School of Atmospheric Sciences, Sun Yat-Sen University, Zhuhai, China, [2]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, USA, [3]Athabasca University Observatories, Athabasca, Alberta, Canada

JGR Space Physics

Research Article

Magnetic Field Enhancements in the Solar Wind: Diverse Processes Manifesting a Uniform Observation Type?

Ying-Dong Jia, Hairong Lai, Nathan Miles, Hanying Wei, Janet G. Luhmann, C. T. Russell, X. Blanco-Cano, Lan Jian, Chen Shi

First published: 28 February 2024 | https://doi.org/10.1029/2023JA032255 | Citations: 1

H. R. Lai, et al., GRL, **46**, 14282 (2019)

Y. D. Jia, et al., JGR: Space Phys., **129**, e2023JA032255 (2024)

Solar System Observations:

- Interplanetary field enhancements (IFE) - are anomalous enhancements of the interplanetary magnetic field
- IFEs are correlated with dust impacts on spacecraft

Possible Mechanism(s) [Jia, 2024]

- Relative motion between dust cloud and solar wind - leads to anomalous magnetic fields: $\rho_{dust} \approx \rho_{solar\ wind}$
- Colliding magnetic ropes which generate current sheets
- Simulations [Jia, 2024] suggest that both mechanics could lead to IFE

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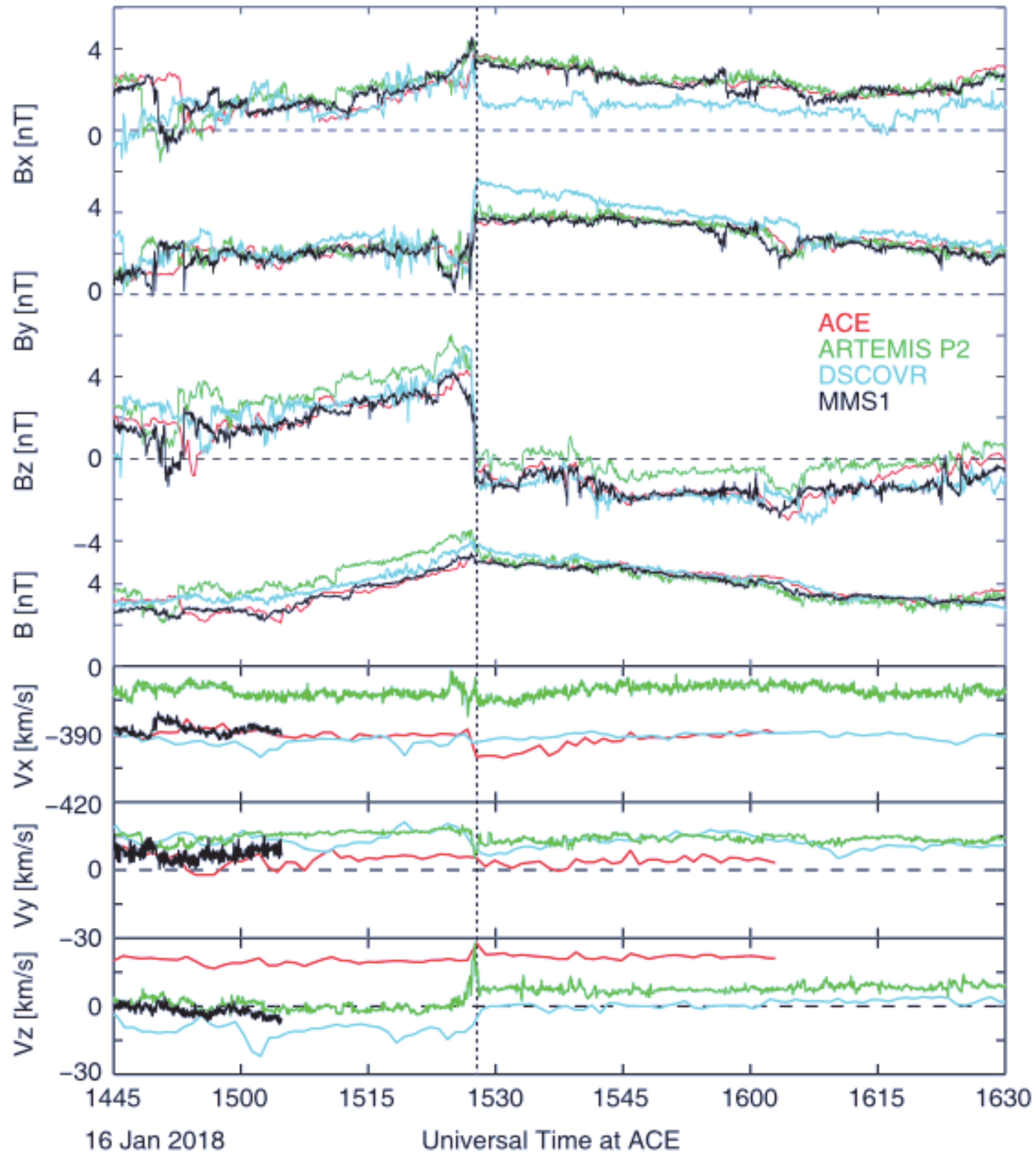
Evidence for dust-plasma interactions: space and lab



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Evidence for dust-plasma interactions: space and lab

Laboratory Observations:

- Presence of dust can local deplete the number of free electrons in a plasma
- Example from a lab experiment looking at self-excited ion fluctuations

PHYSICS OF PLASMAS **17**, 043703 (2010)

Plasma fluctuation spectra as a diagnostic tool for submicron dust

S. Ratynskaia,[1] M. De Angeli,[2] E. Lazzaro,[2] C. Marmolino,[3] U. de Angelis,[4] C. Castaldo,[5] A. Cremona,[2] L. Laguardia,[2] G. Gervasini,[2] and G. Grosso[2]
[1]*Royal Institute of Technology, Stockholm, Sweden*
[2]*Istituto di Fisica del Plasma, CNR "P. Caldirola", Milan, Italy*
[3]*Department STAT, University of Molise, Pesche (IS), Italy*
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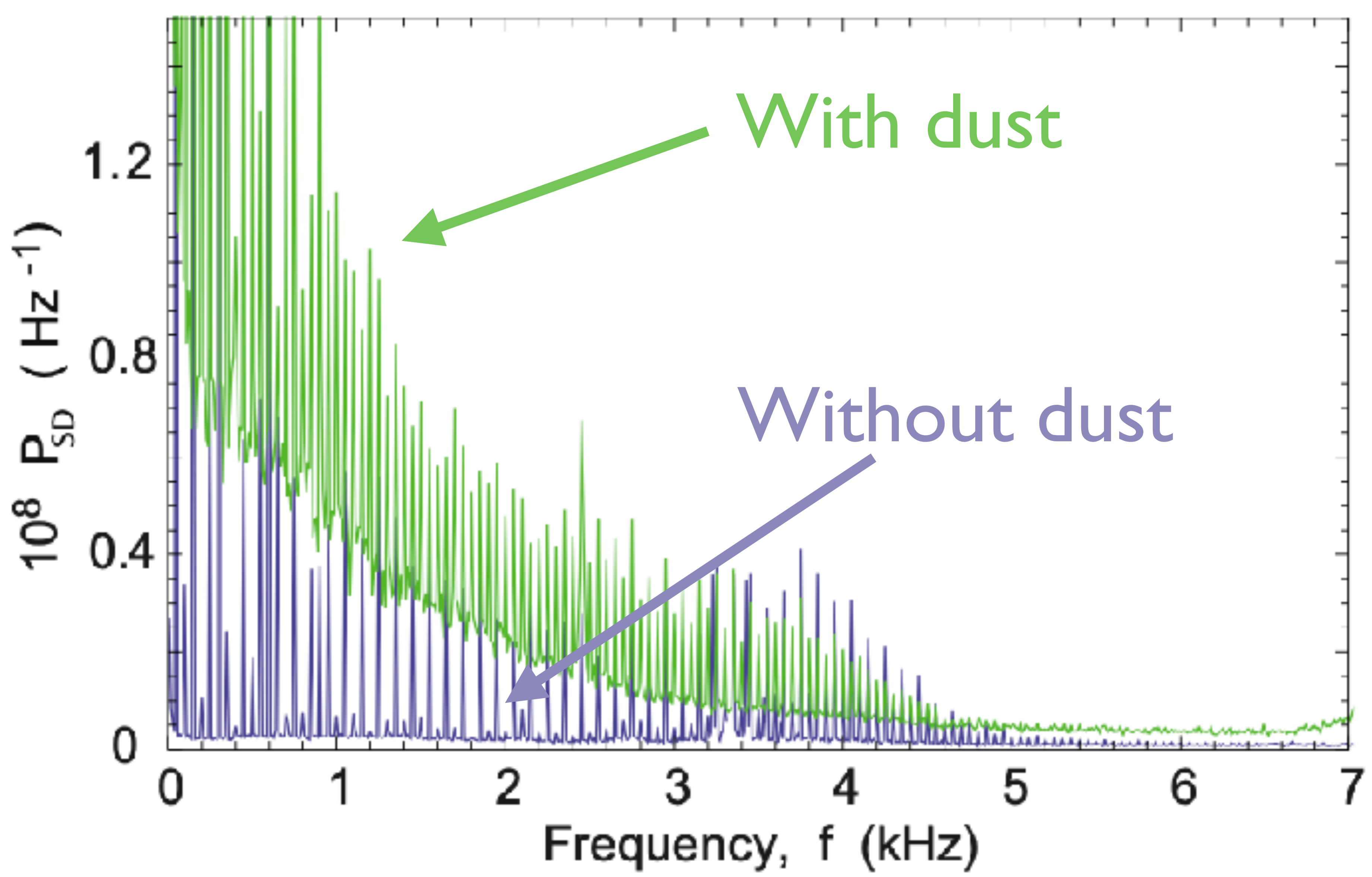
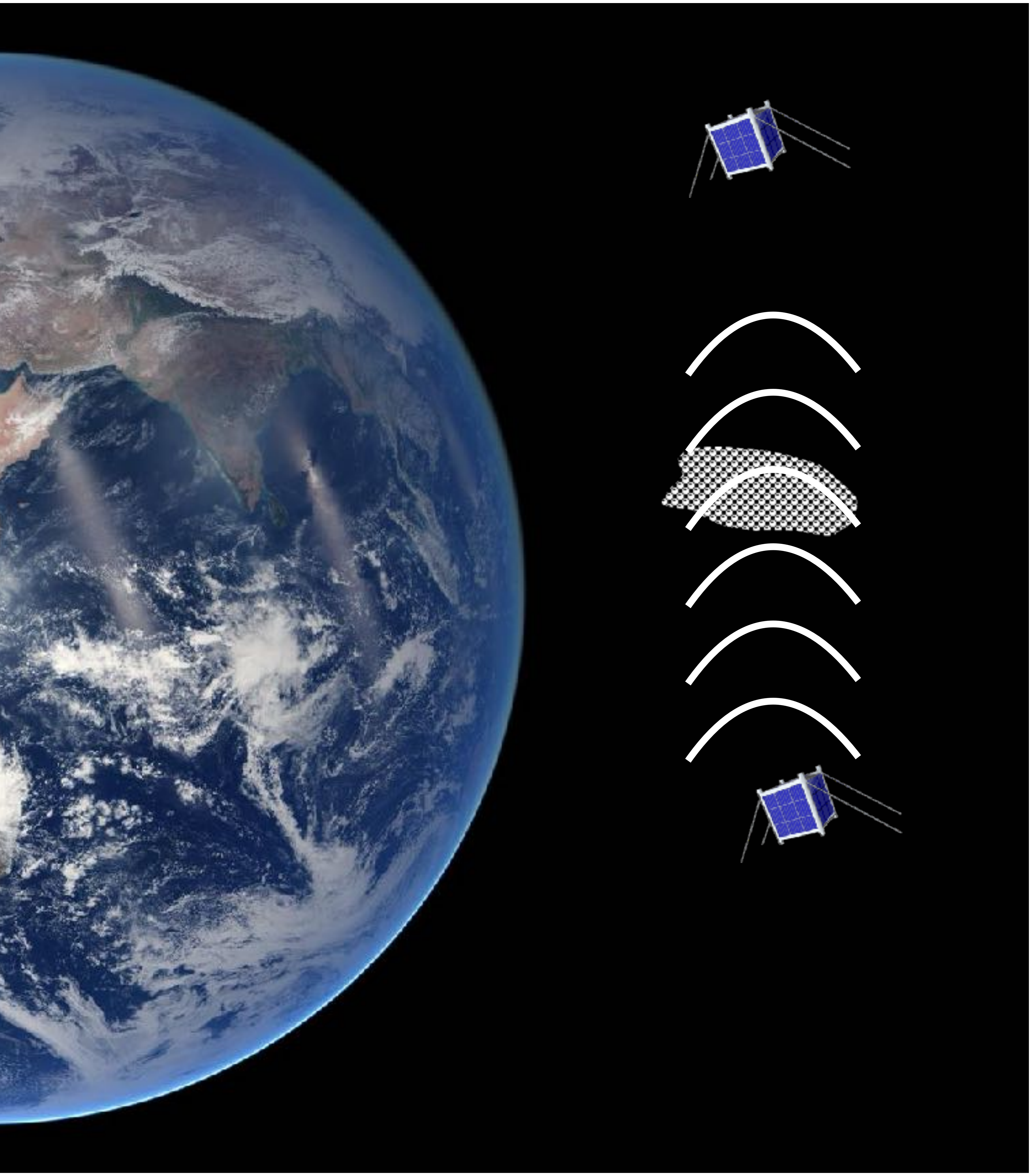
[5]*ENEA-Frascati, Frascati, Italy*

(Received 5 February 2010; accepted 8 March 2010; published online 7 April 2010)

It is shown that the measurements of density fluctuation spectra in dusty plasmas can constitute a basis for *in situ* diagnostic of invisible submicron dust. The self-consistent kinetic theory that includes the charging processes and the natural density fluctuations of the dust particles predicts modifications of the spectra due to the presence of dust. A laboratory experiment was carried out where submicron dust was produced in a gas phase and diagnosed by surface analysis of samples and by measurements of its influence on the plasma density fluctuation spectra. Quantitative comparison of the latter with the theory yields information on dust density, size, and distribution in agreement with the results of the surface analysis. The method can be applied to various plasma environments in laboratory and space. © *2010 American Institute of Physics*.
[doi:10.1063/1.3374035]



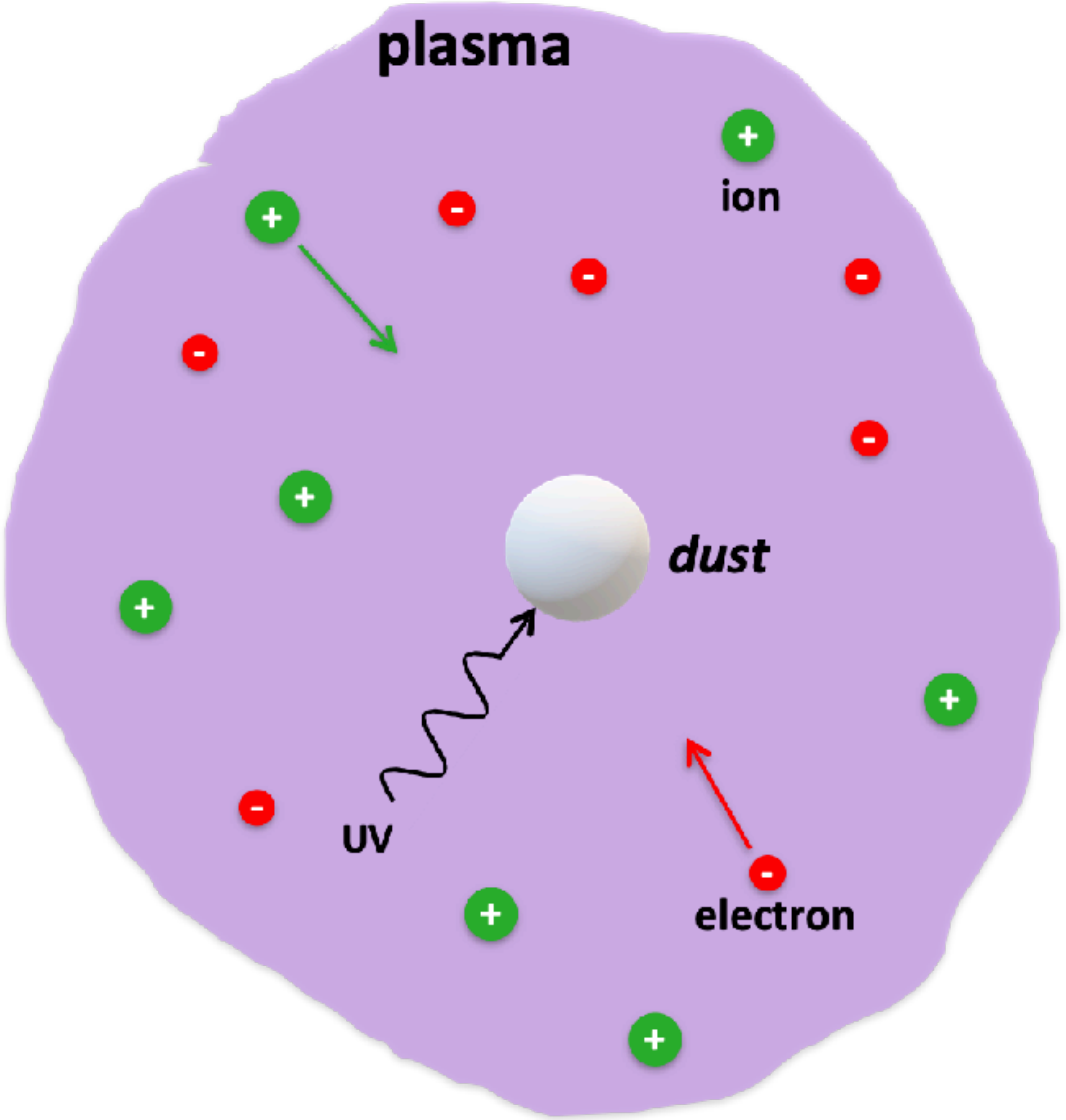
Concept



- Can a pair of spacecraft (e.g., cubists) be used to transmit an electrostatics / electromagnetic wave that interacts with dust particles as a detection mechanism?
- How will the wave be modified by the local plasma and charged dust?
- What would be an appropriate range of frequencies?
- Can laboratory experiments provide insights that can guide the development of a future space experiment/mission?

Properties of dust-containing plasmas: space and lab

- Dusty plasmas (complex plasmas)
  - Ions
  - Electrons
  - Neutral atoms
  - Dust particles (nm to μm)
- Plasma ⇄ dust via charging



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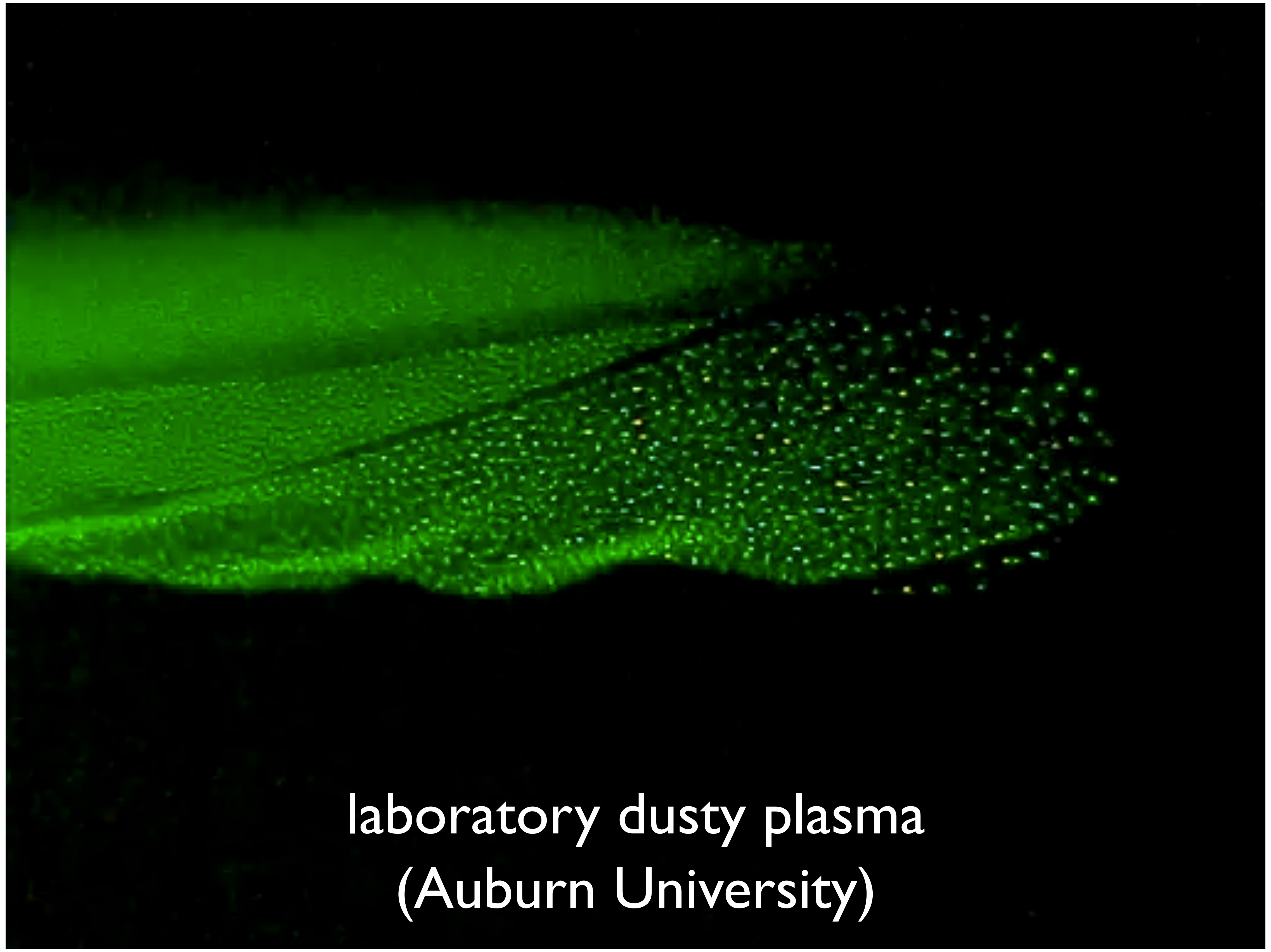

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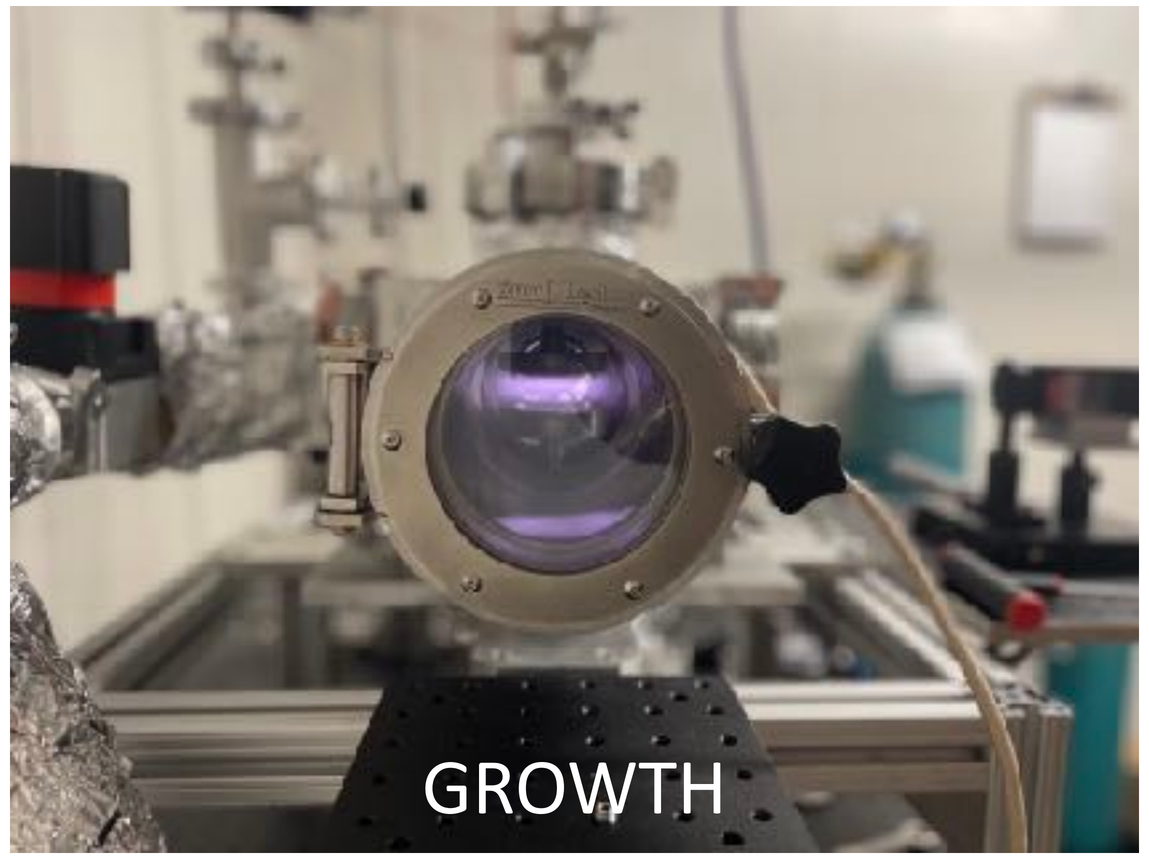

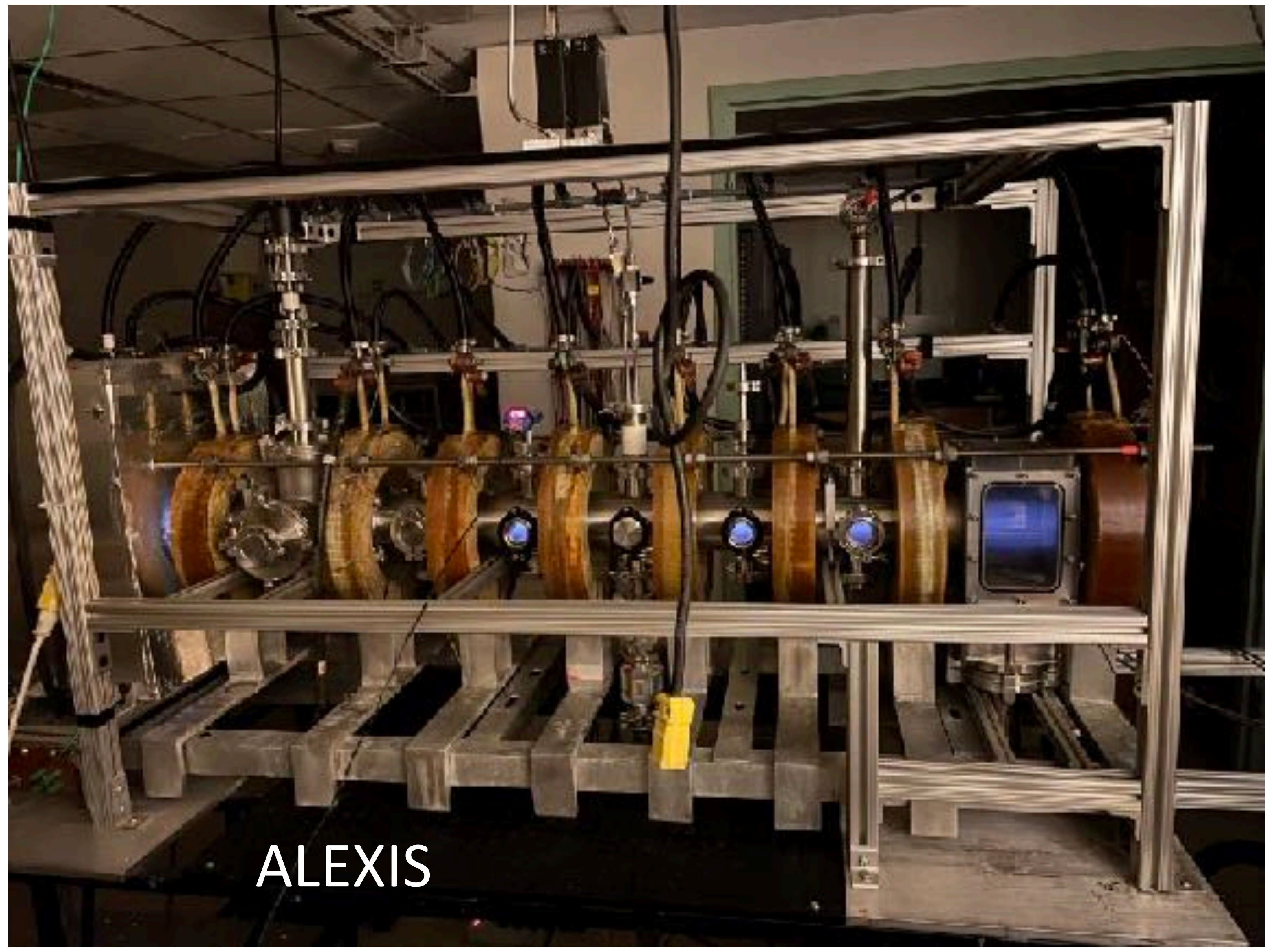

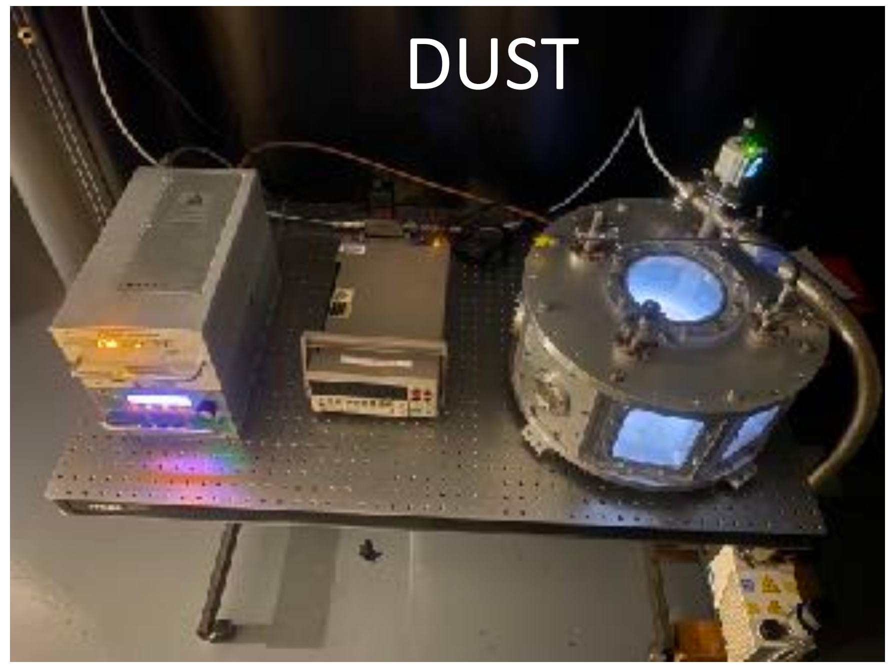

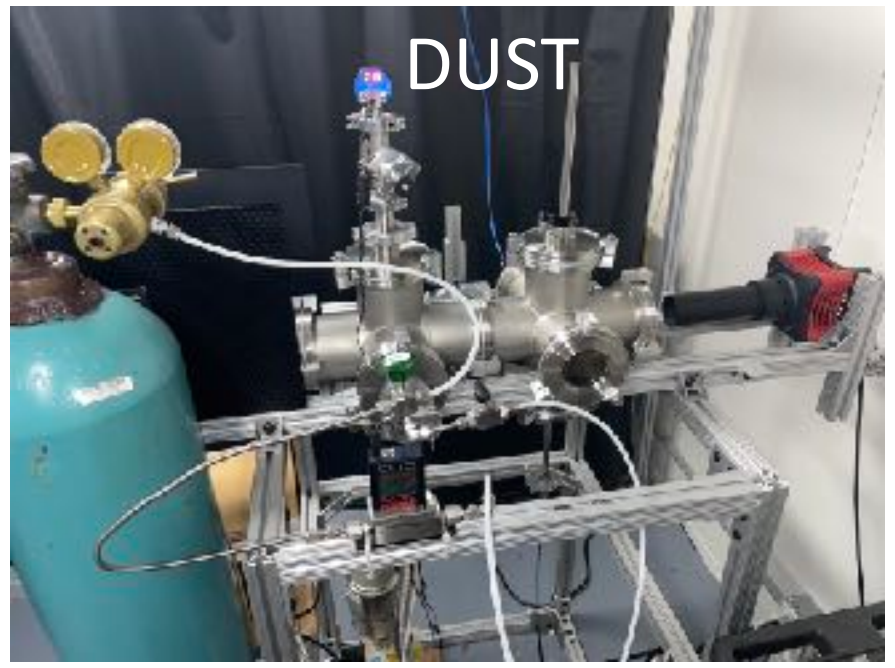

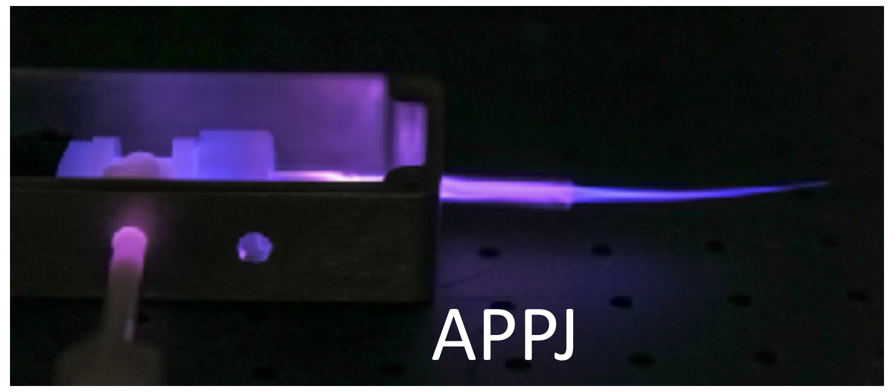

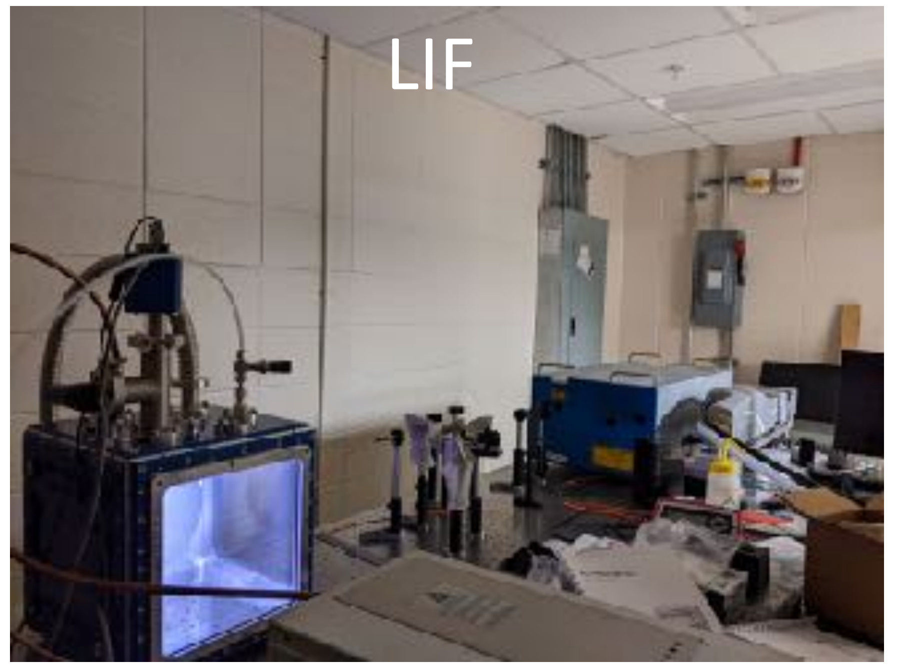

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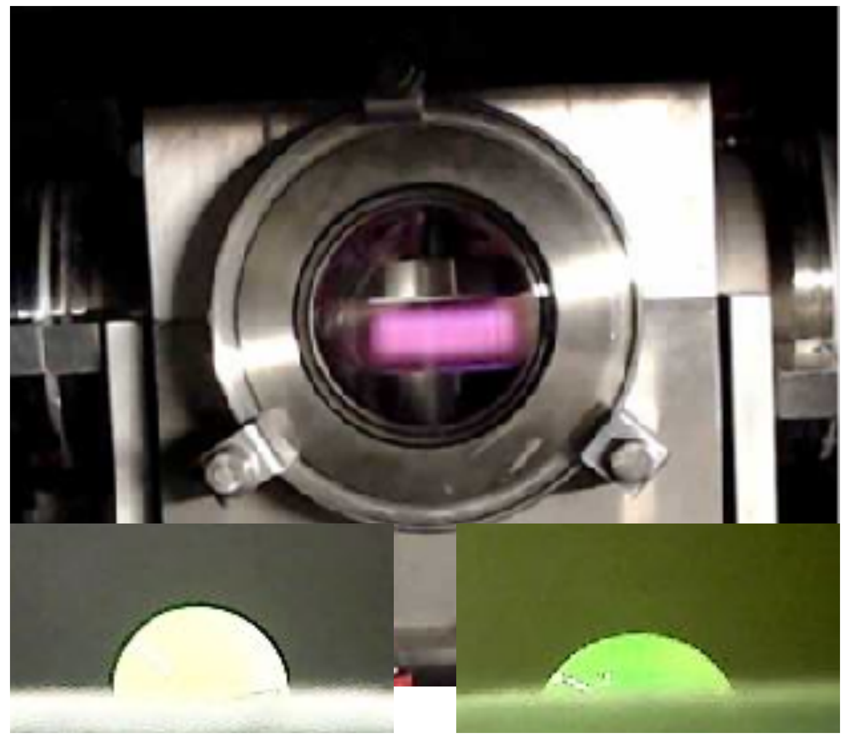

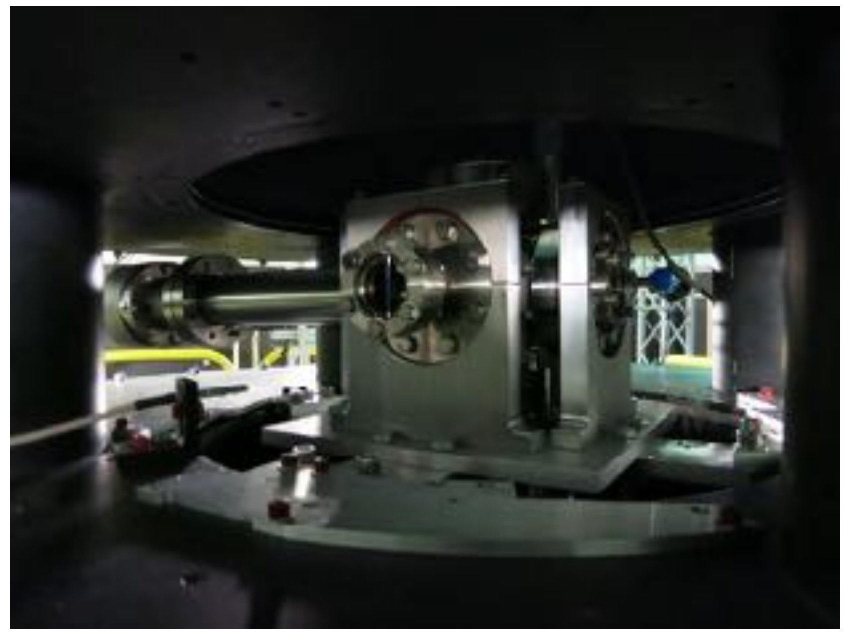

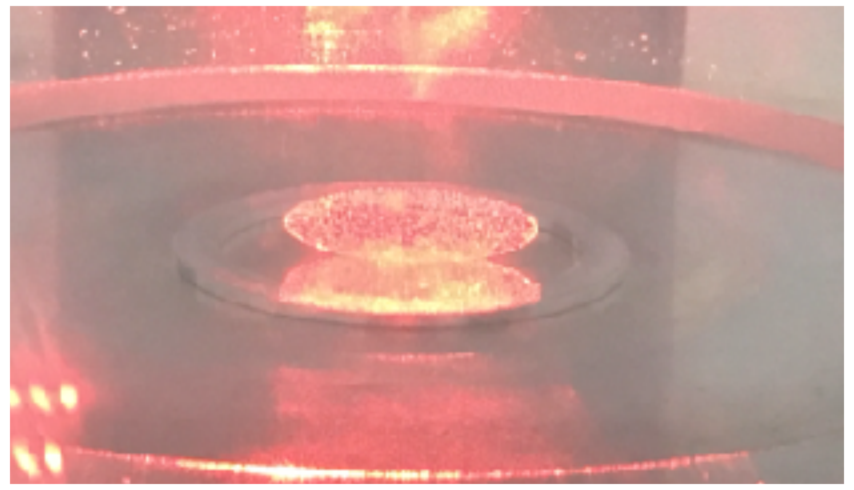

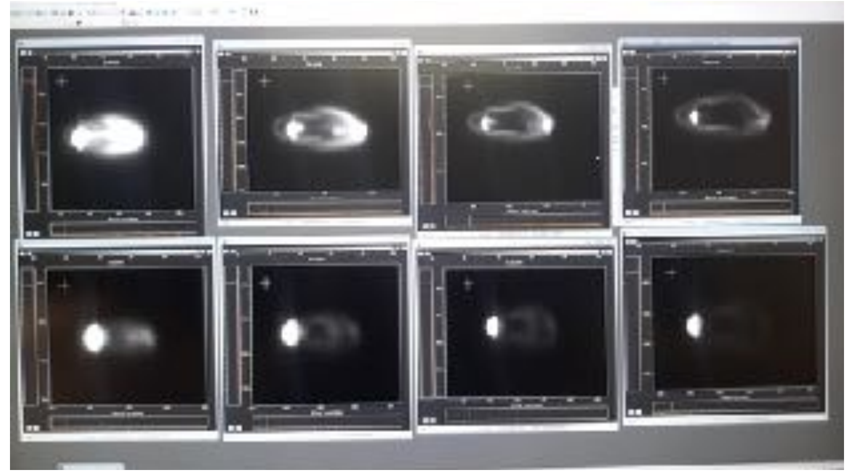

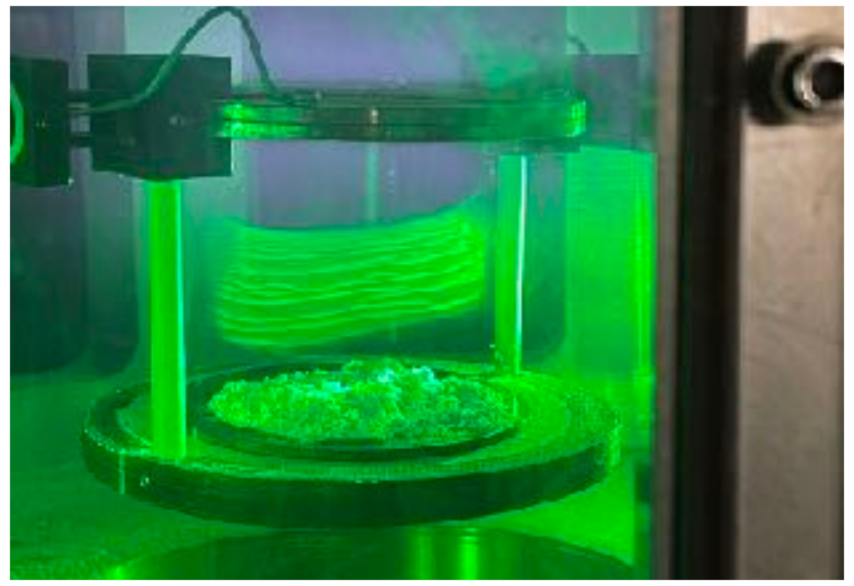

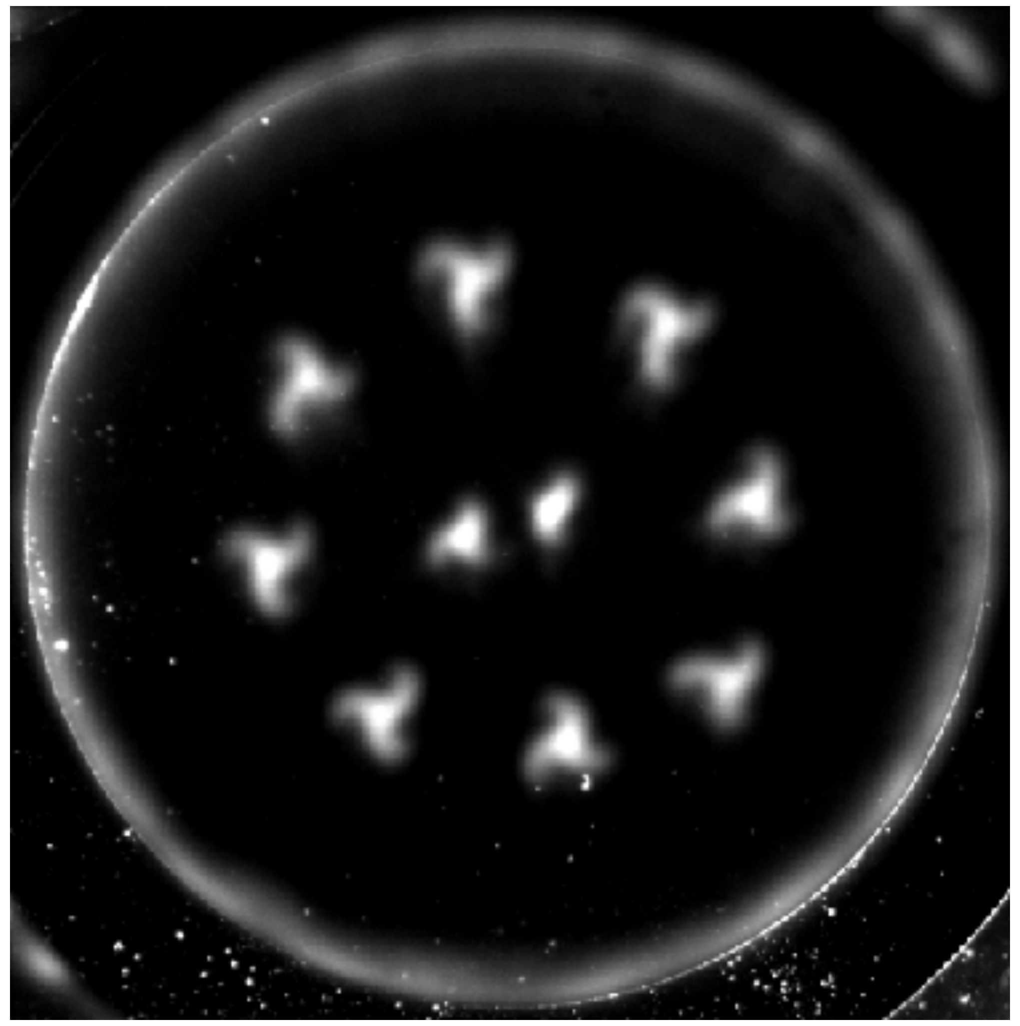

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MPRL facilities can provide access to selective scaled space-relevant parameters

	Geospace	Solar wind	MDPX	ALEXIS
Density [m^{-3}]	1×10^{5}	5×10^{6}	1×10^{15}	5×10^{15}
Ion temp. [eV]	1000	10	0.03	0.03
Electron temp. [eV]	150	10	3.00	5
Magnetic field [T]	2×10^{-8}	5×10^{-9}	0.5	0.1
Gas pressure [Pa]	7×10^{-8}	3.2×10^{-5}	6.67	1.07
Gas species	Hydrogen	Hydrogen	Argon	Helium
Ionization fraction, χ	2.4×10^{-7}	2.8×10^{-7}	6×10^{-7}	2×10^{-5}
Plasma scaling [Debye length / Gryoradius]				
Electrons	0.123	0.004	97.7	0.69
Ions	0.003	0.0001	0.36	0.008
Magnetization (Hall parameter) [Mean free path / Gyroradius]				
Electrons	1.0×10^{5}	2.1×10^{3}	4.6×10^{3}	8.8×10^{3}
Ions	19	0.97	3.9	29.1

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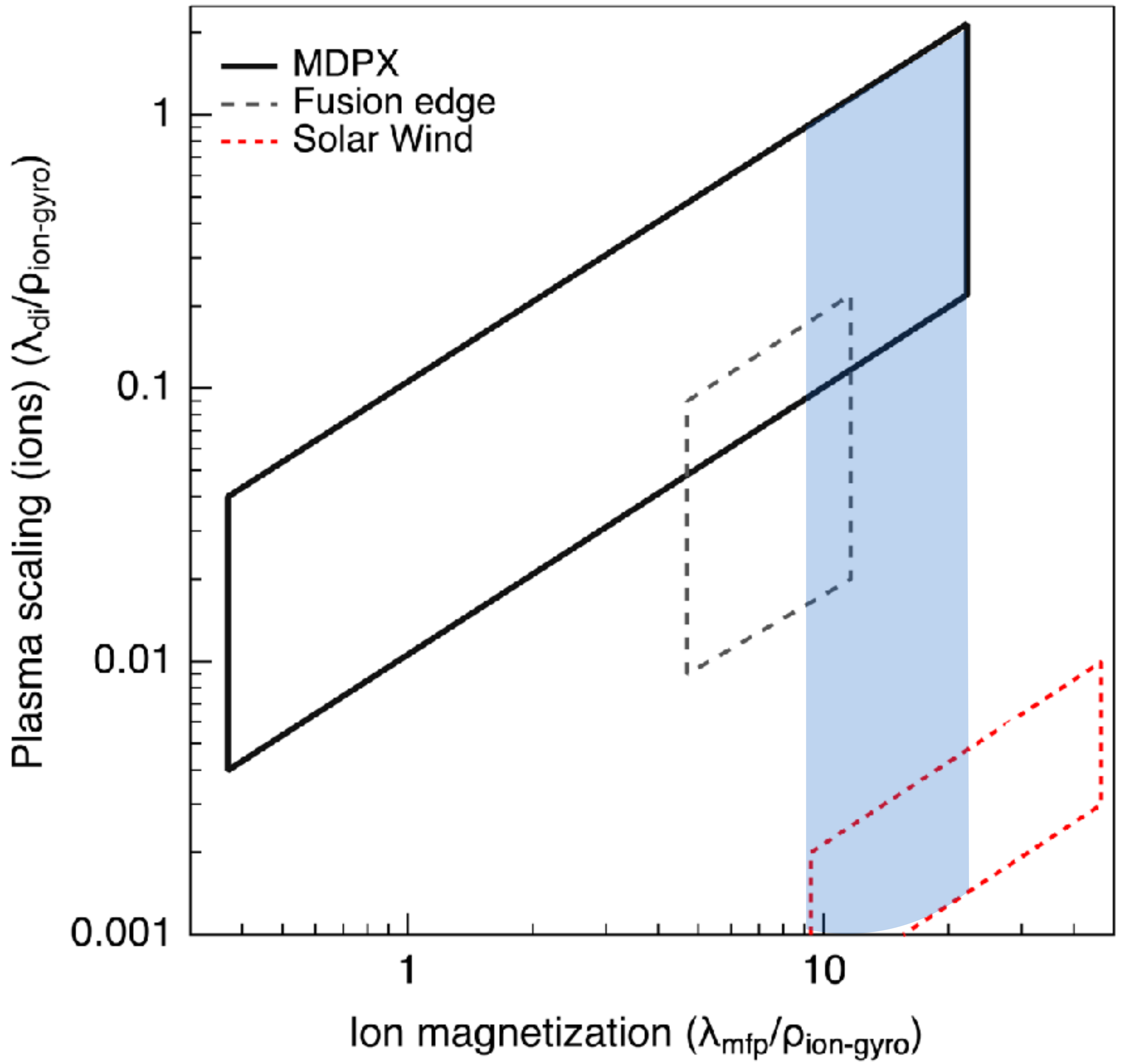
MPRL facilities can provide access to selective scaled space-relevant parameters

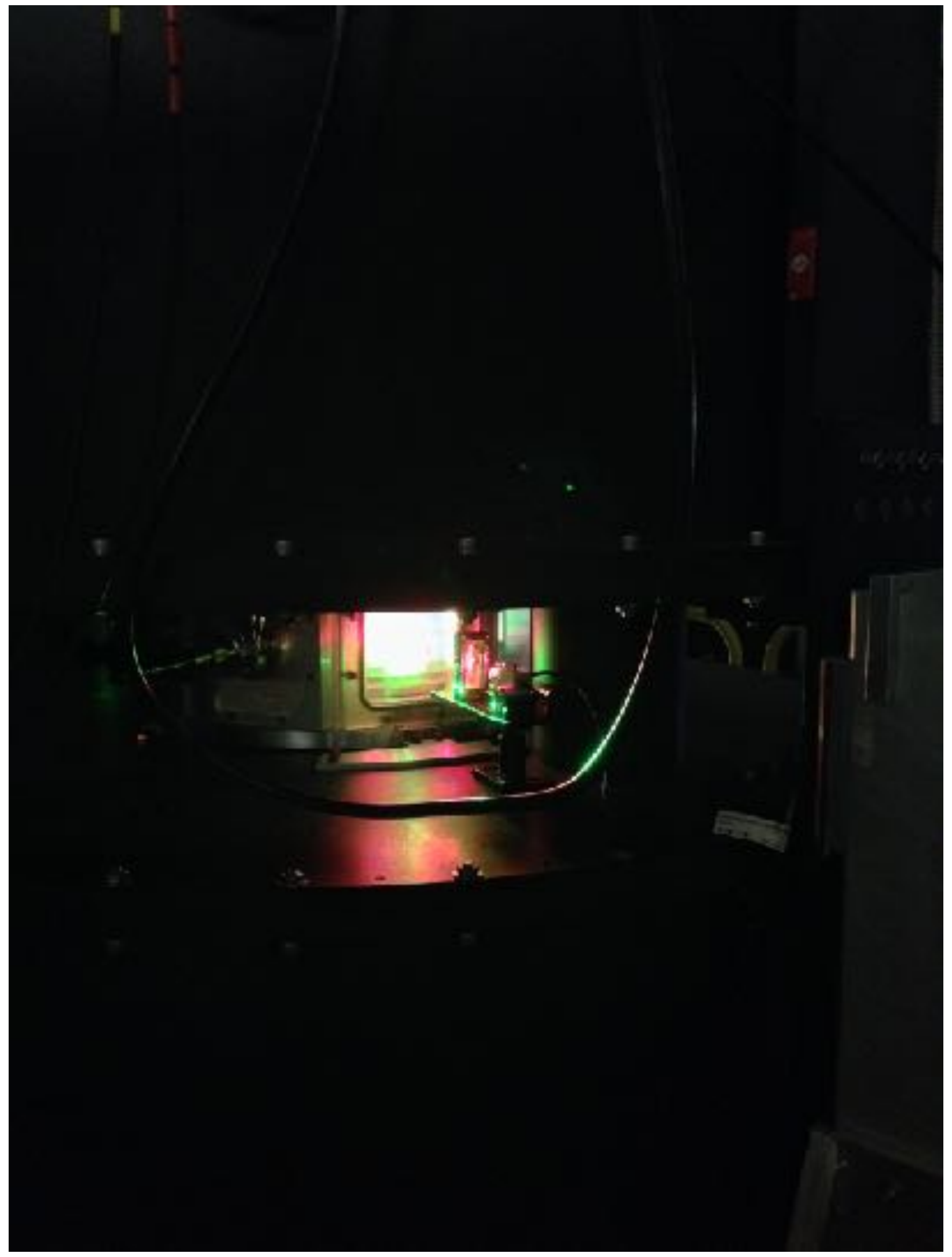


Operating parameters

- Operating space of MDPX device compared to normalized fusion edge plasma and solar wind parameters
- Y-axis: ion Debye length / ion gyro-radius
  X-axis: ion mean free path / ion gyro-radius
- Focus is on strongly magnetized regimes - both electrons and ions are magnetized

MDPX: A cryogen-free, superconducting, multi-configuration magnetic field system

- Radial and axial diagnostic access
- RF generated plasmas:
  f = 13.56 MHz, P_{RF} = 1 to 10 W
- Helium, Neon, Argon, Krypton
  P = 5 to 300 mTorr (0.6 to 40 Pa)
- Silica microspheres
  <dia> = 0.1 μm to 8 μm
- Diagnostics:
  Langmuir probes
  Triple probe (n_e, T_e, V_p)
  DPSS lasers
  Ximea cameras (300 fps)
  Photron high speed (>100kfps)
- Plasma parameters (@ B = 0 T):
  T_e = 1- 5 eV, T_i = 1/40 eV
  $n_e \sim n_i \sim 0.1$ to 8×10^{15} m^{-3}



Magnetic field:	3.5 T (to date); 4 T (max)
Magnetic field gradient:	1 - 2 T /m
Magnet cryostat:	50 cm ID / 127 cm OD / 158 cm axial
Magnet material:	NbTi superconductor; cryogen-free

C. E. Miller, et al., *IEEE Trans. Appl. Supercond.*, **24**, 1 (2014)
E. Thomas, et al., *J. Plasma Phys.*, **81**, 345810206 (2015)

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MDPX "octagon" chamber - experimental configuration

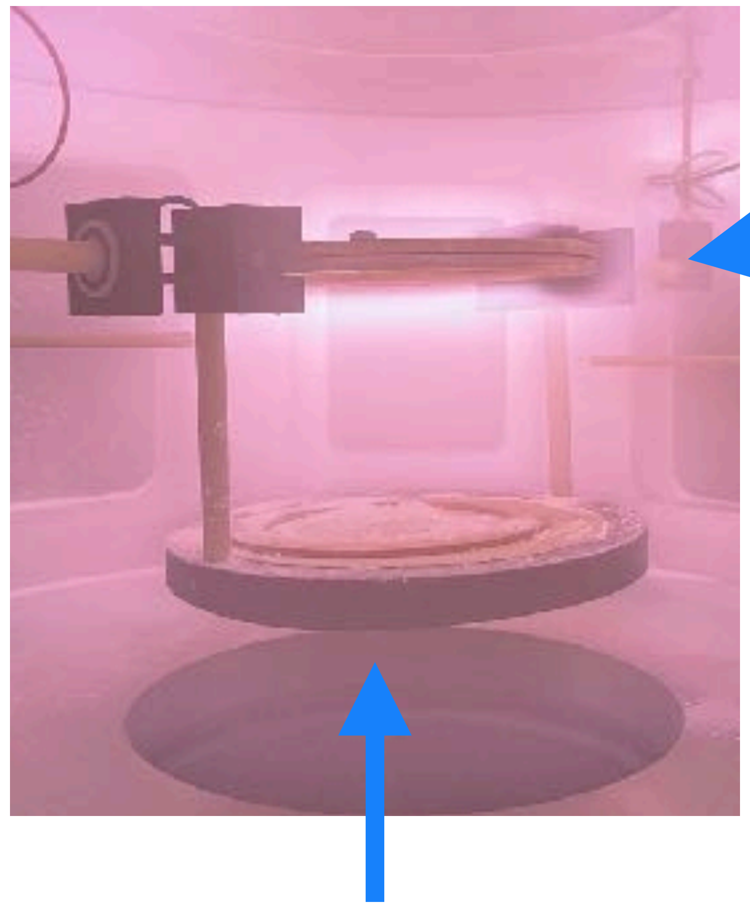
<u>Setup parameters:</u>

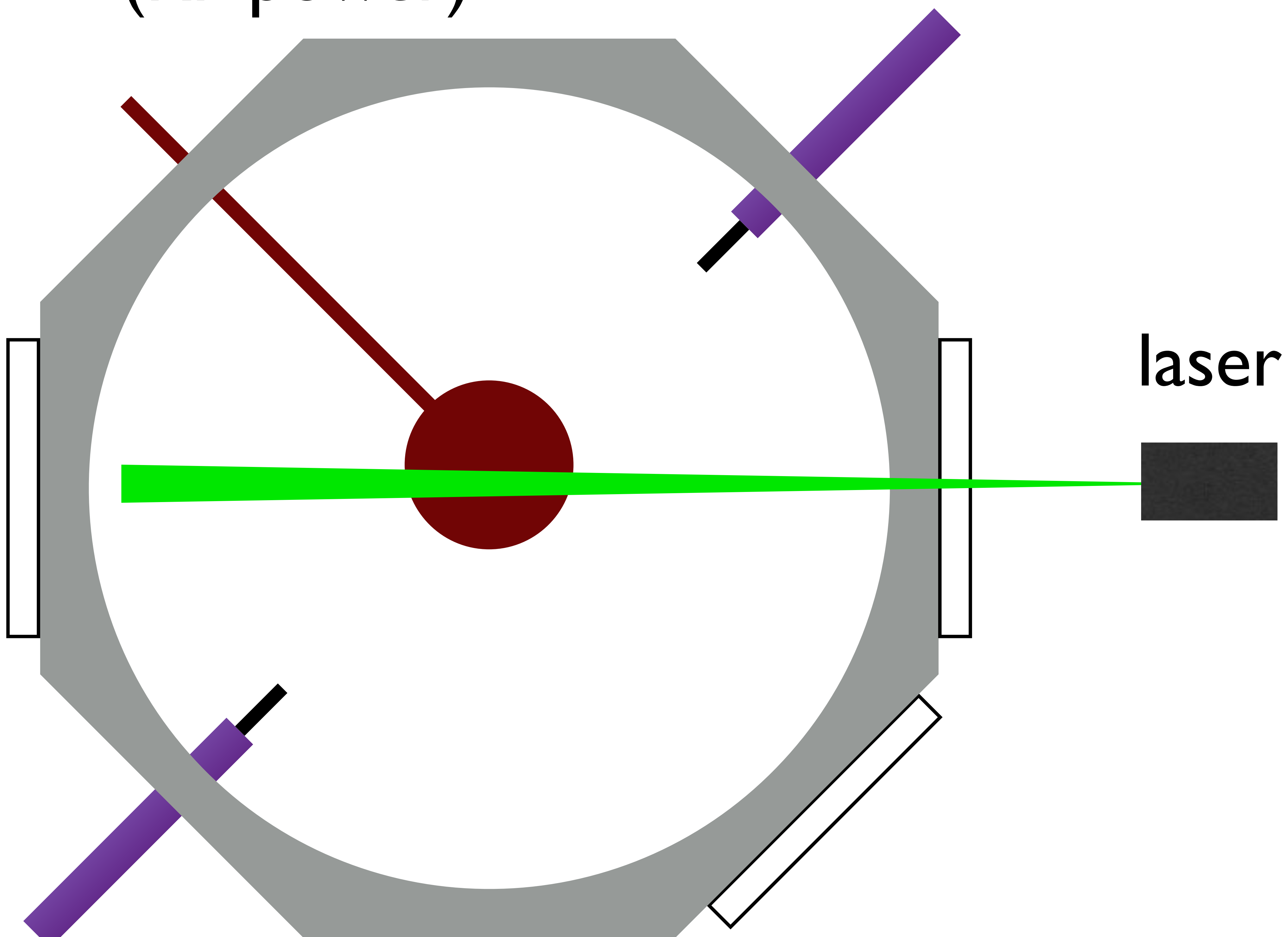
Silica particles: 1 μm (nominal dia.)
Gas: Argon
Pressure: 88.3 mTorr (11.8 Pa)

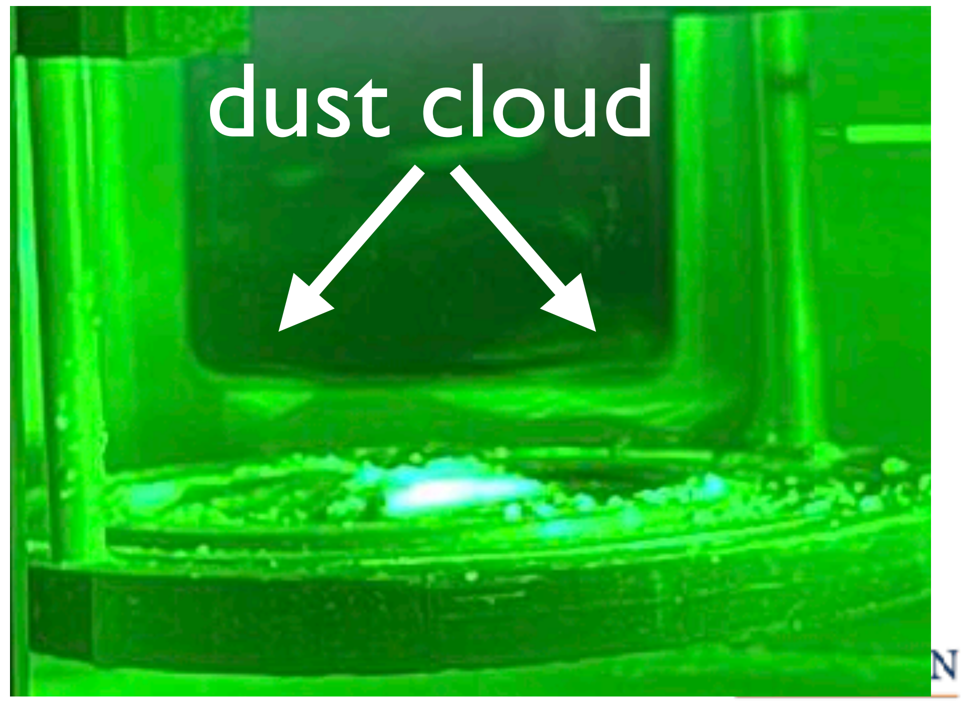
4-Channel Oscilloscope
Ch 1: Input to amplifier
Ch 2: Transmit (V_{bias}, Probe 1)
Ch 3: Receive (V_{float}, Probe 2)
Ch 4: Lower electrode ($I_{sat\text{-}elec}$)

Transmit: 26 V_{pp}, +43.8V dc offset

Electrode: V = +30 V







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MDPX "octagon" chamber - experimental configuration

<u>Setup parameters:</u>

Transmit and detect low frequency potential fluctuations

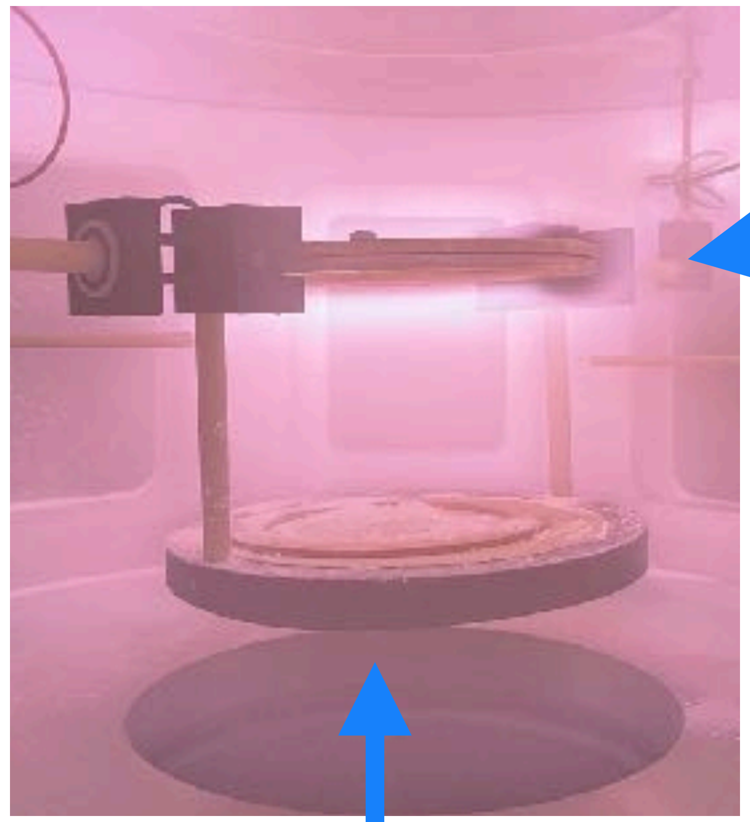
$f_{ion\text{-}neutral} \sim 6 \times 10^5$ Hz

$\omega_{dust\text{-}plasma} \sim 220$ rad/sec (36 Hz)

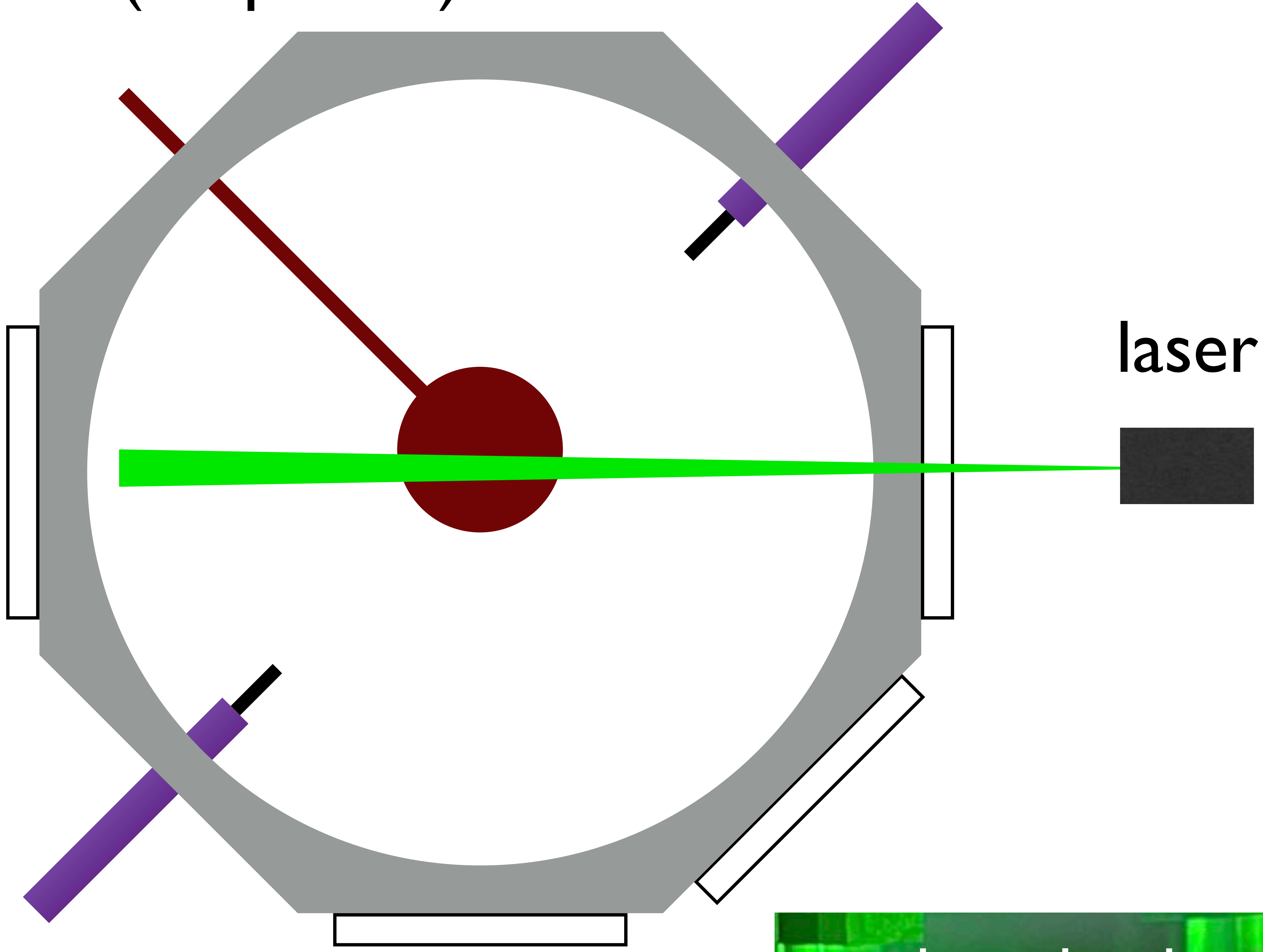
$\lambda_{mfp} / d_{inter\text{-}dust} \sim 2$

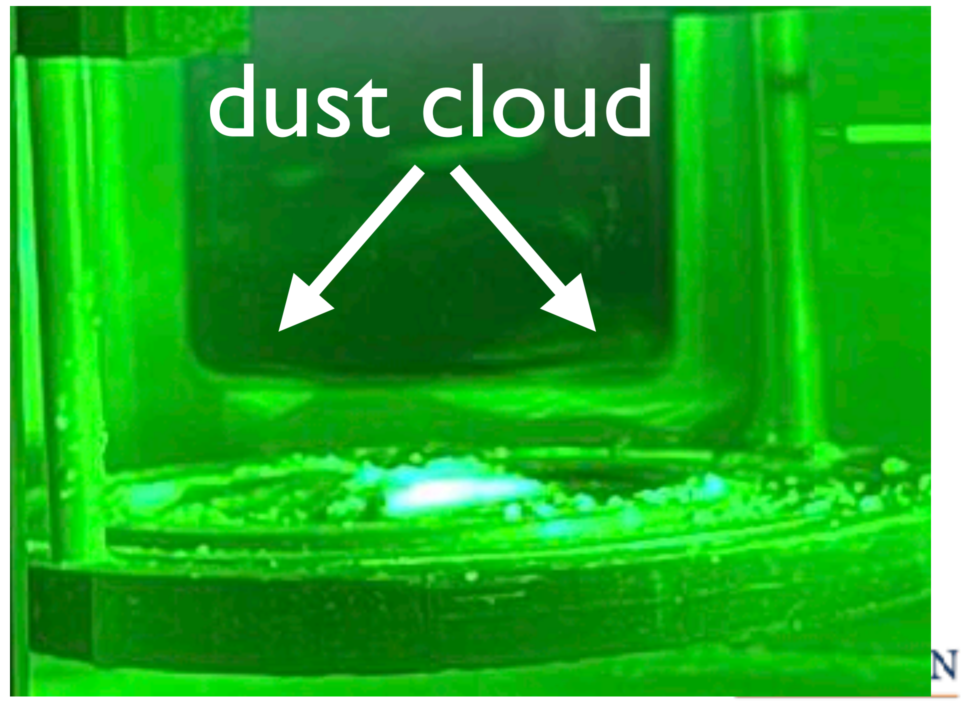
f_{launch} = 10 Hz to 1500 Hz

$f_{launch} / f_{dust\text{-}plasma}$ = 0.28 to 42



Lower electrode
(Electron current)





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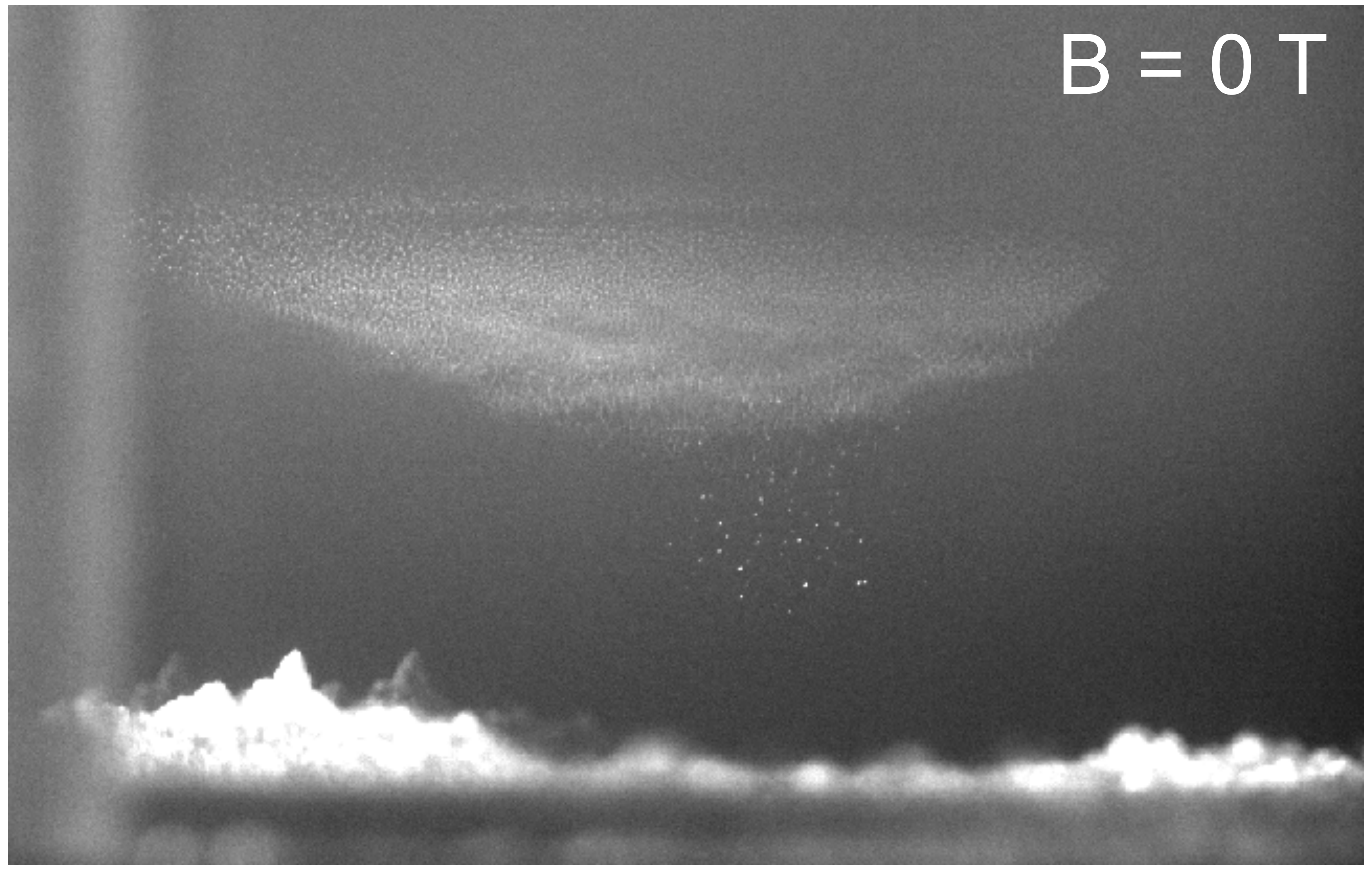
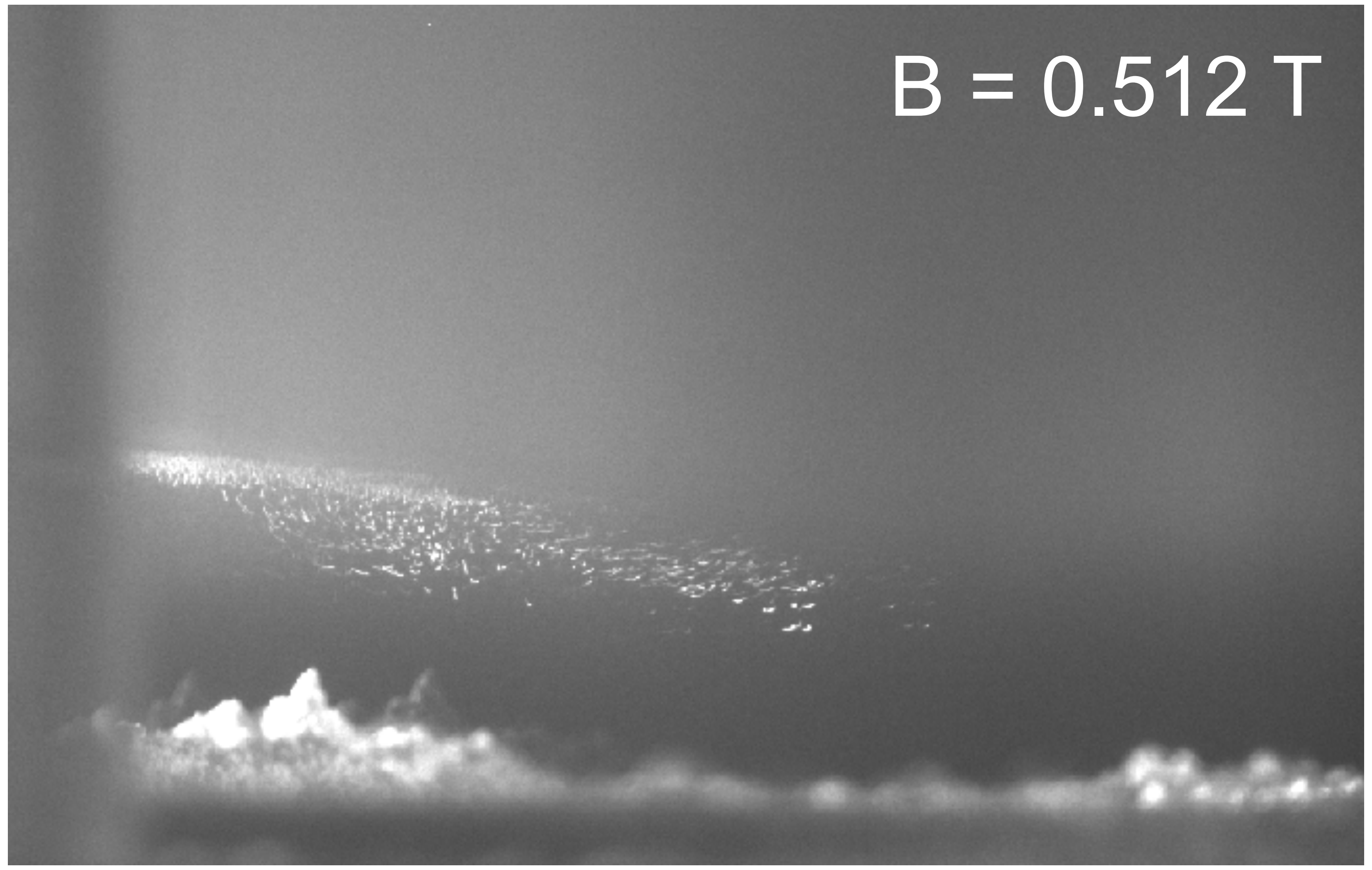
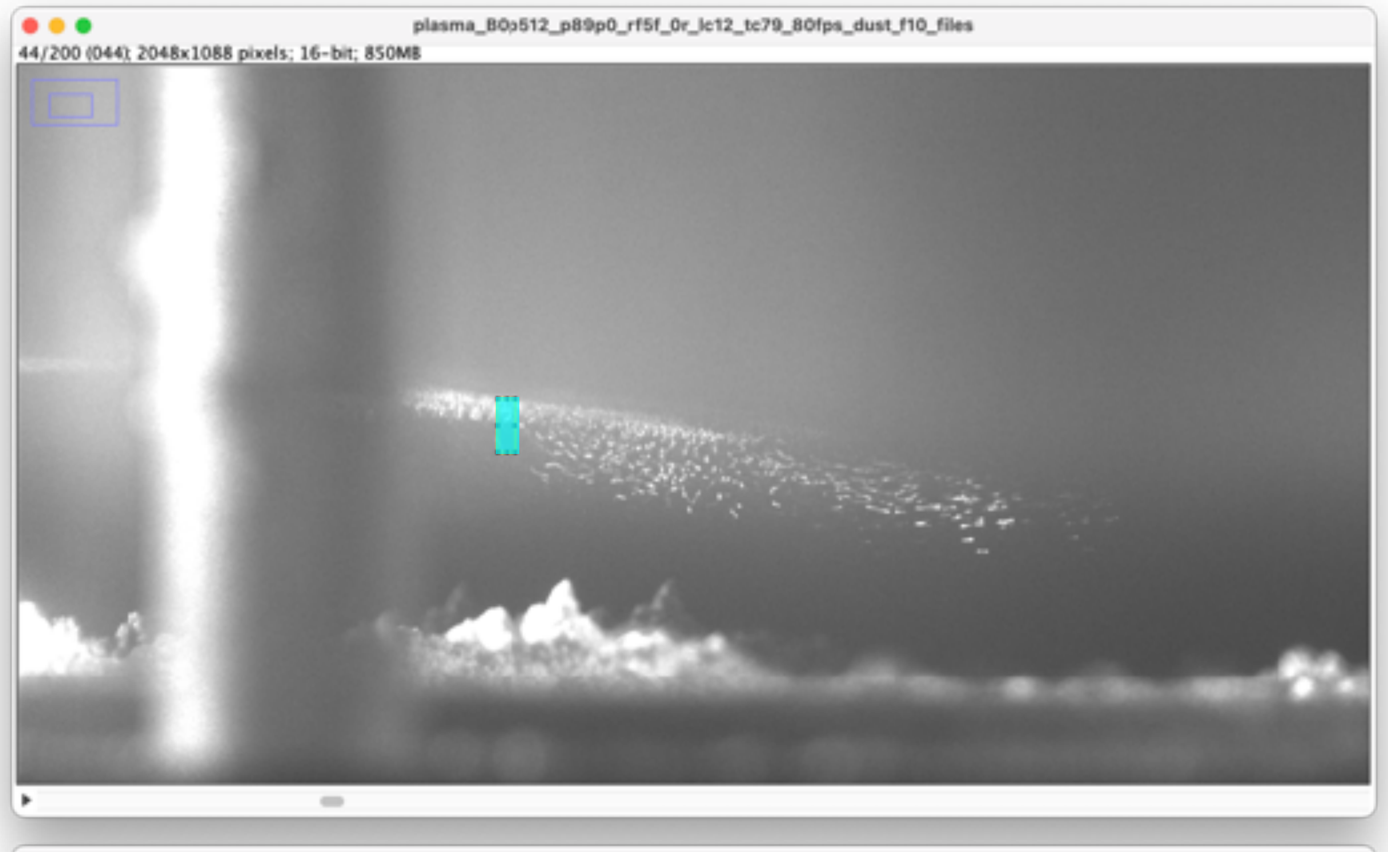
Measurement of launched electrostatic fluctuations: plasma and dust







Methods:

- Use imaging to characterize plasma and dust fluctuations (Ref: blue boxes)
- Use probe measurements to characterize floating potential and electron saturation current fluctuations
- Compute ratio of fluctuation amplitude with and without the presence of dust

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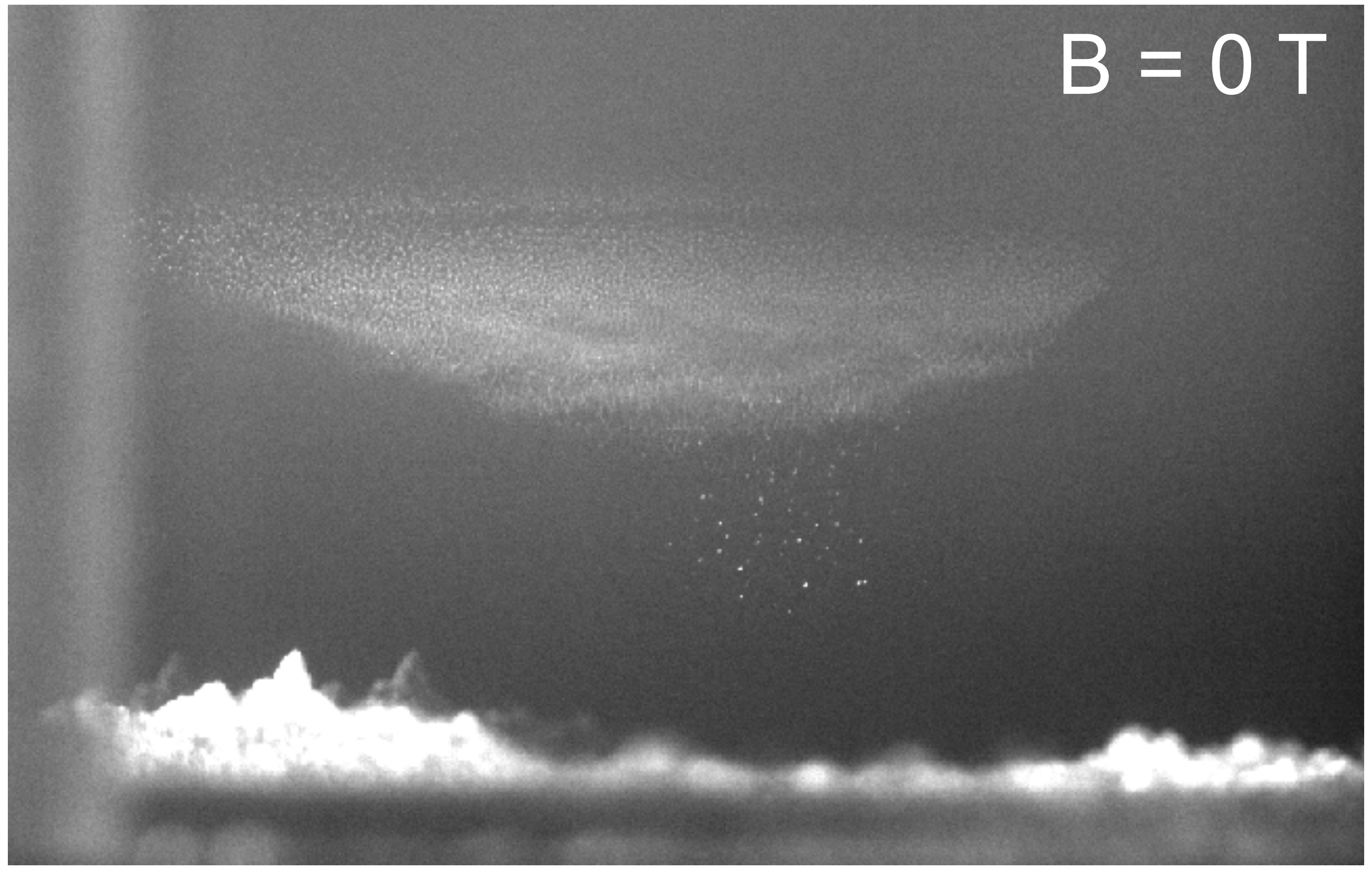
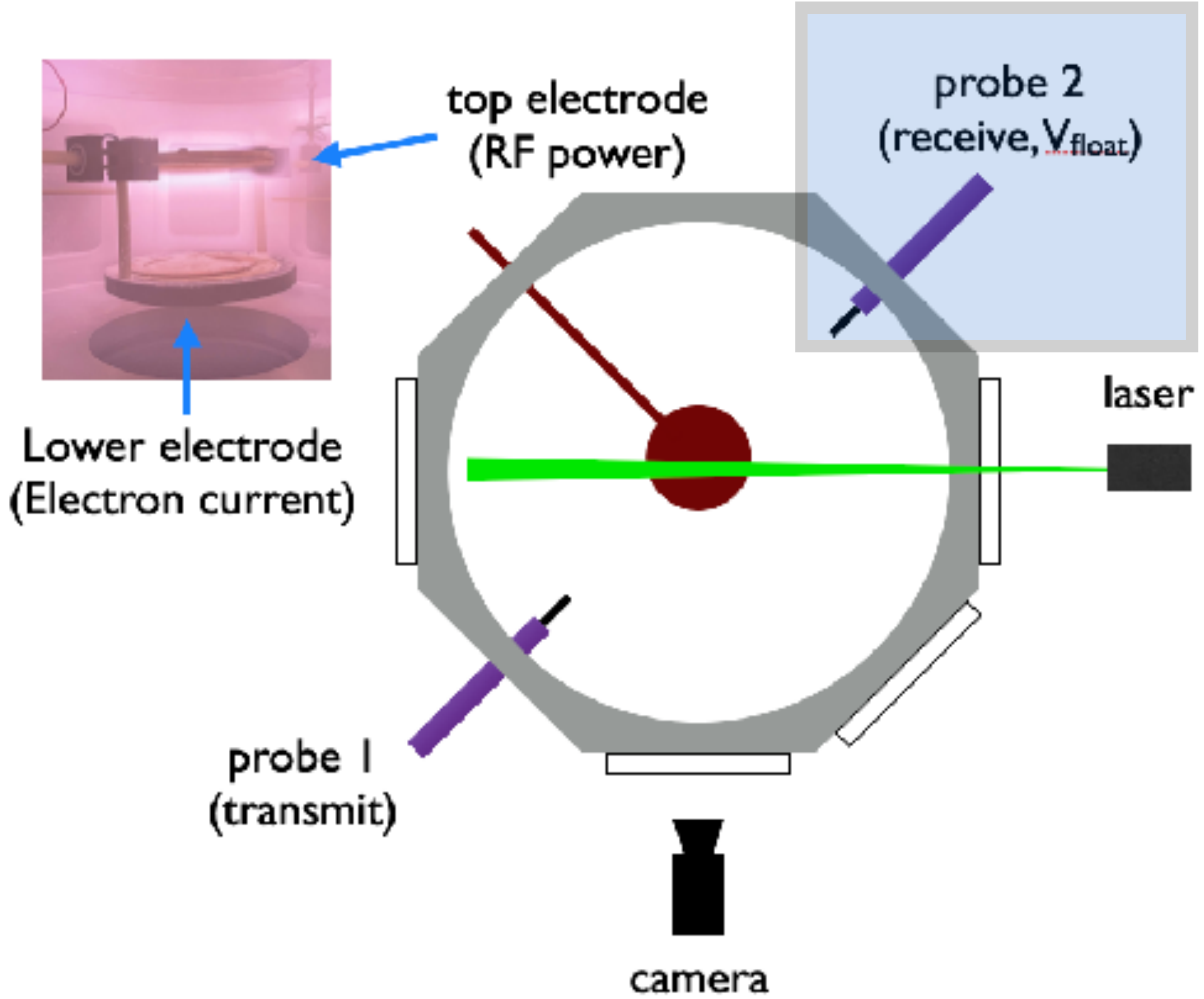
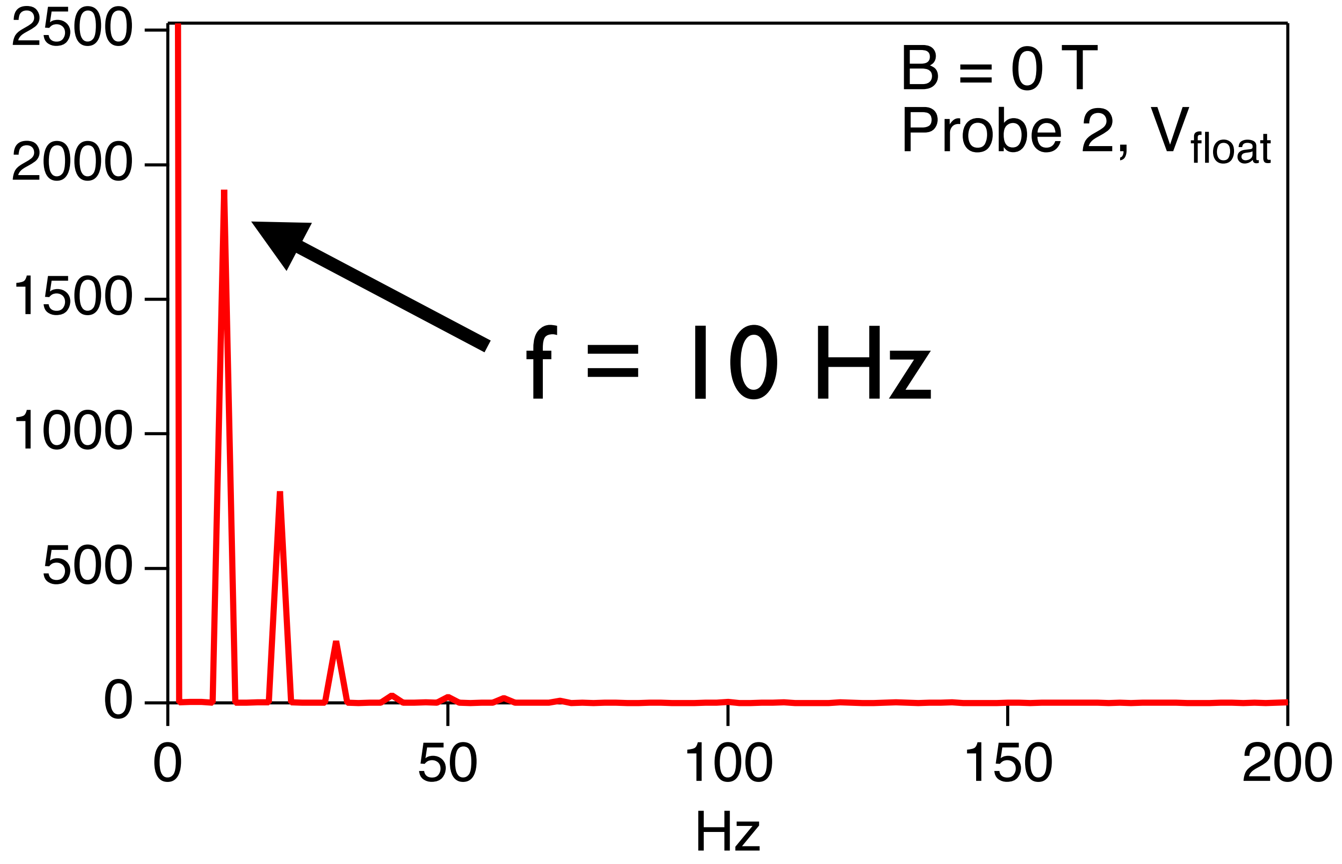
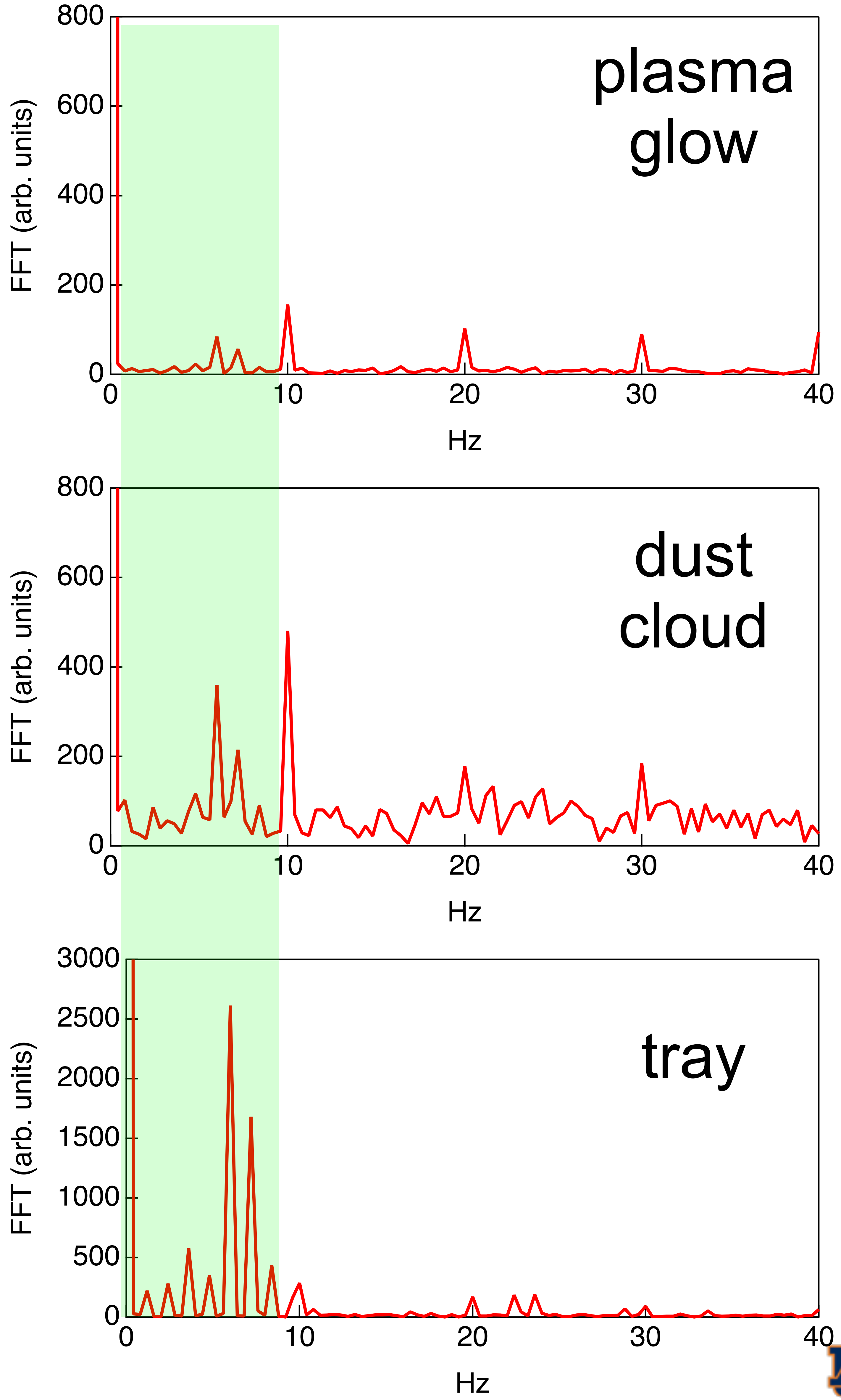
Effect of dust particles on the propagation of launched waves



Measurements
B = 0 T
f = 10 Hz
ImageJ, 80 fps







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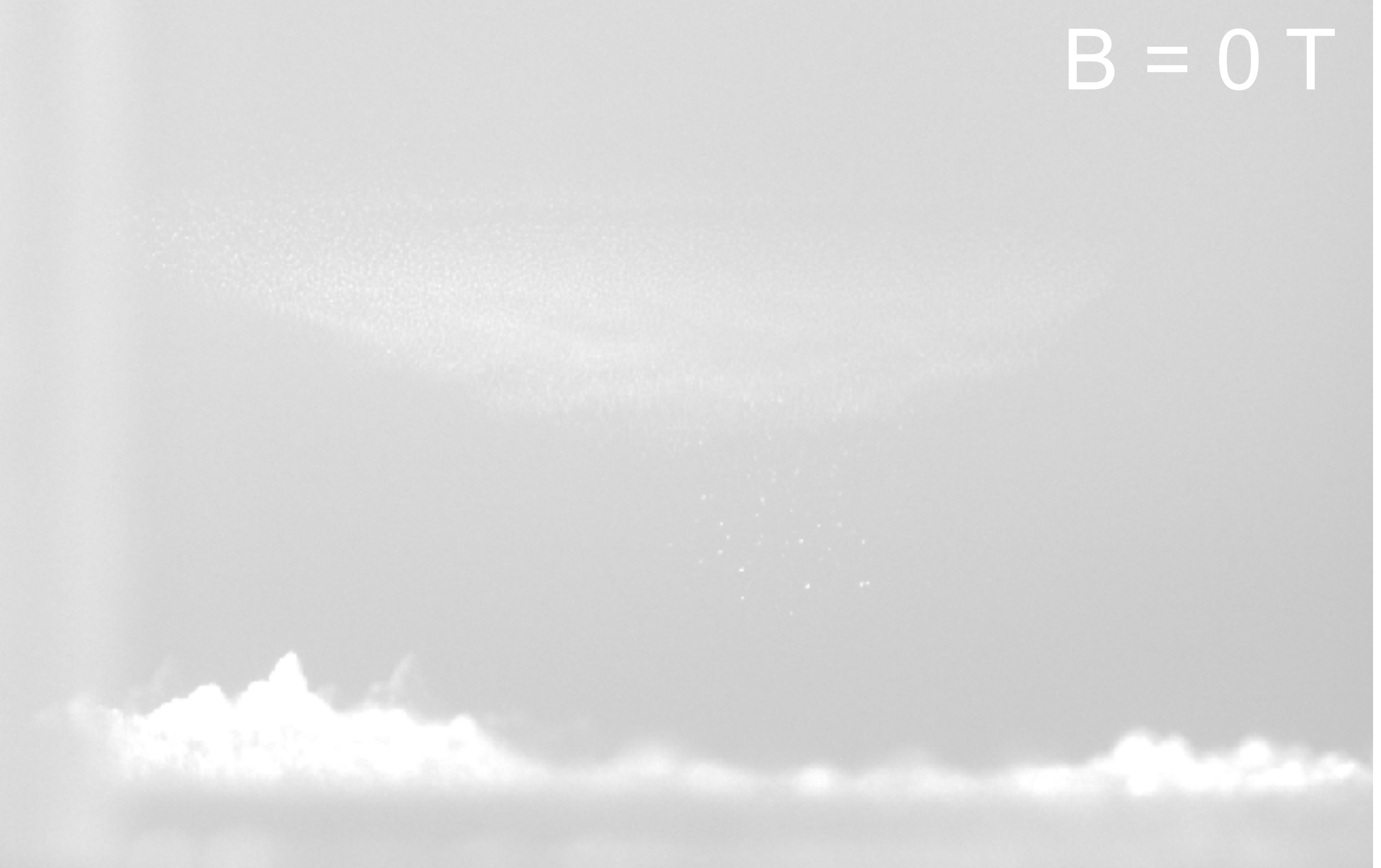
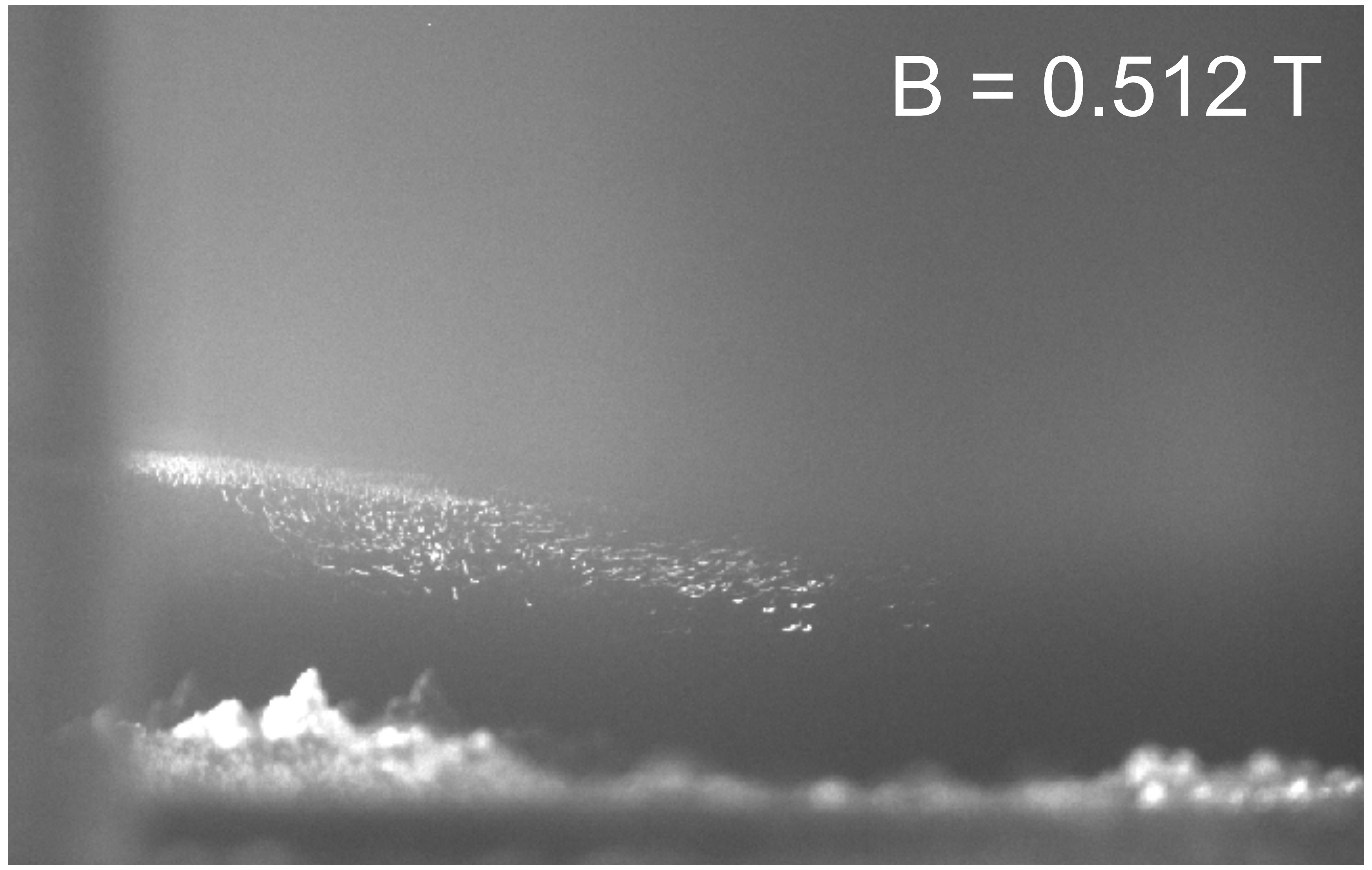
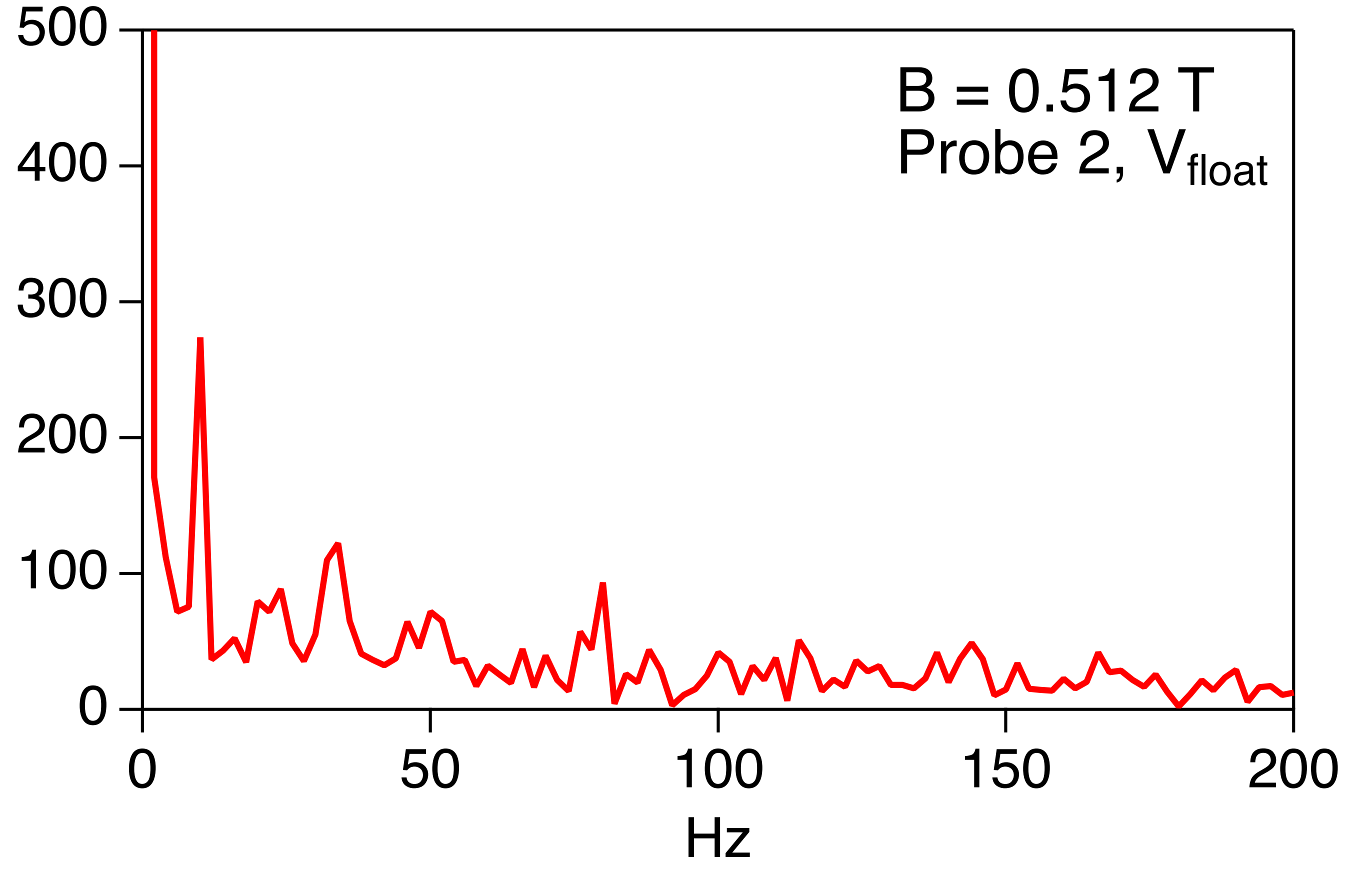
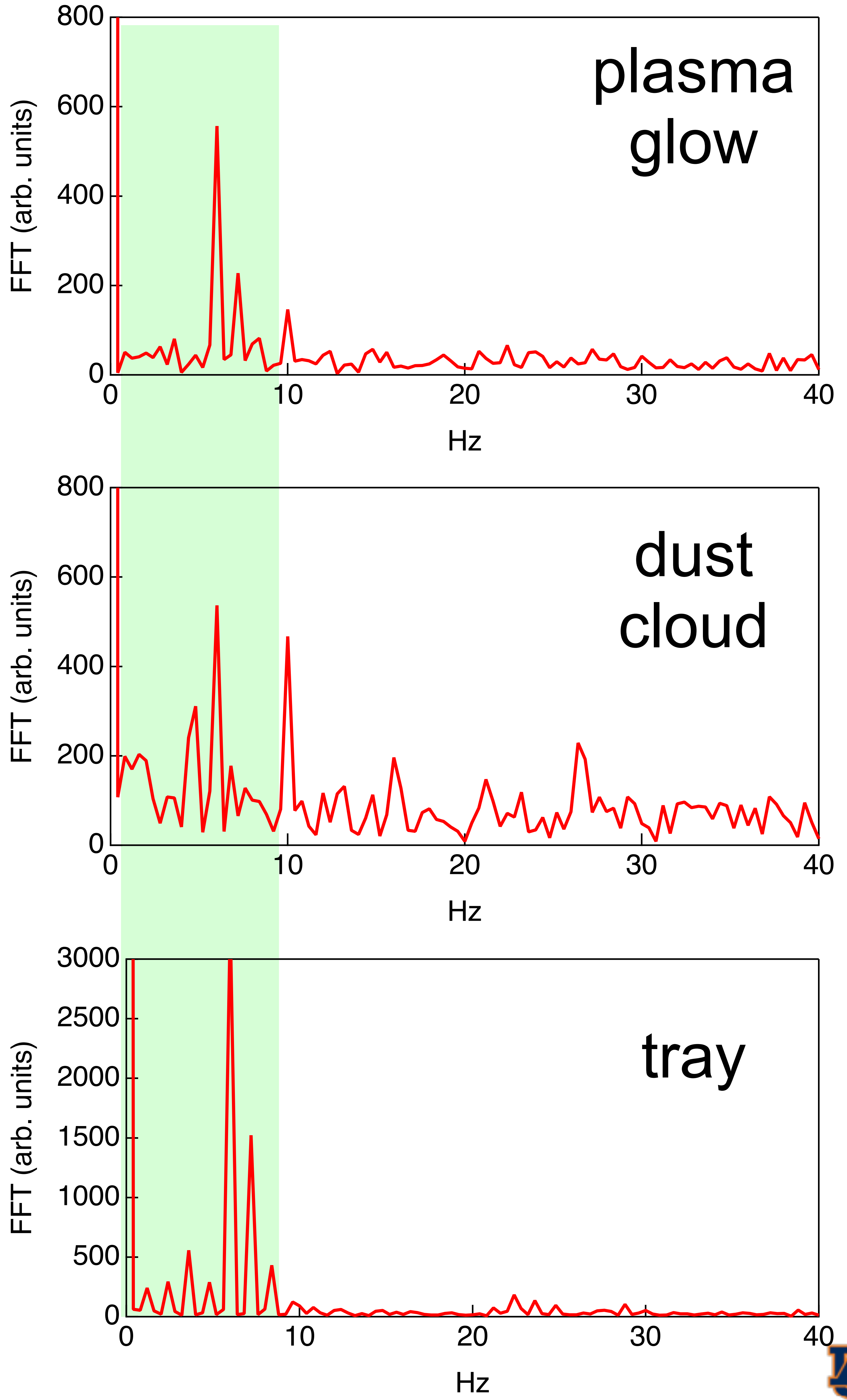




Measurements
B = 0.512 T
f = 10 Hz
ImageJ, 80 fps



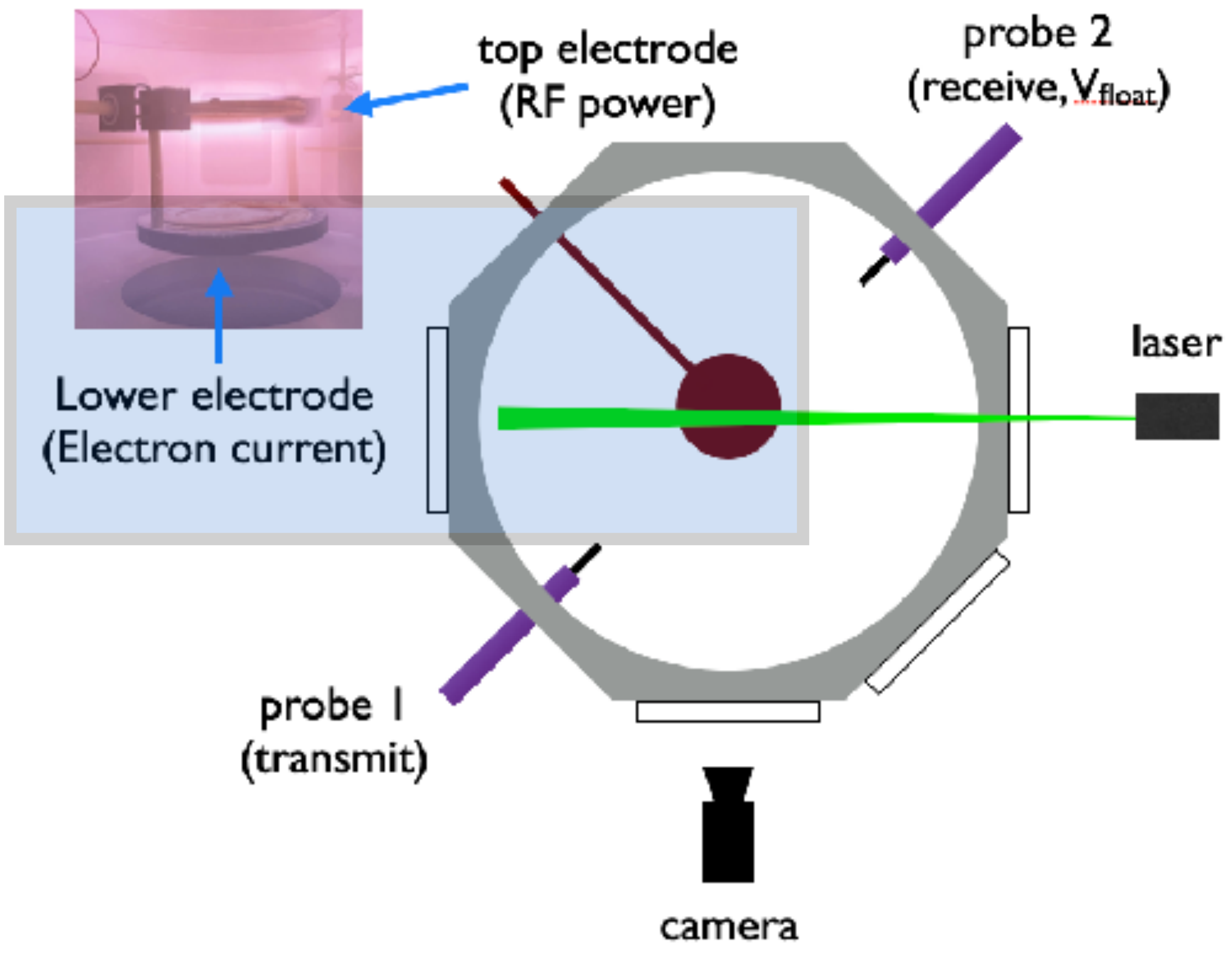
From B = 0 to B = 0.512 T, observe coupling of driven fluctuation to plasma AND dust

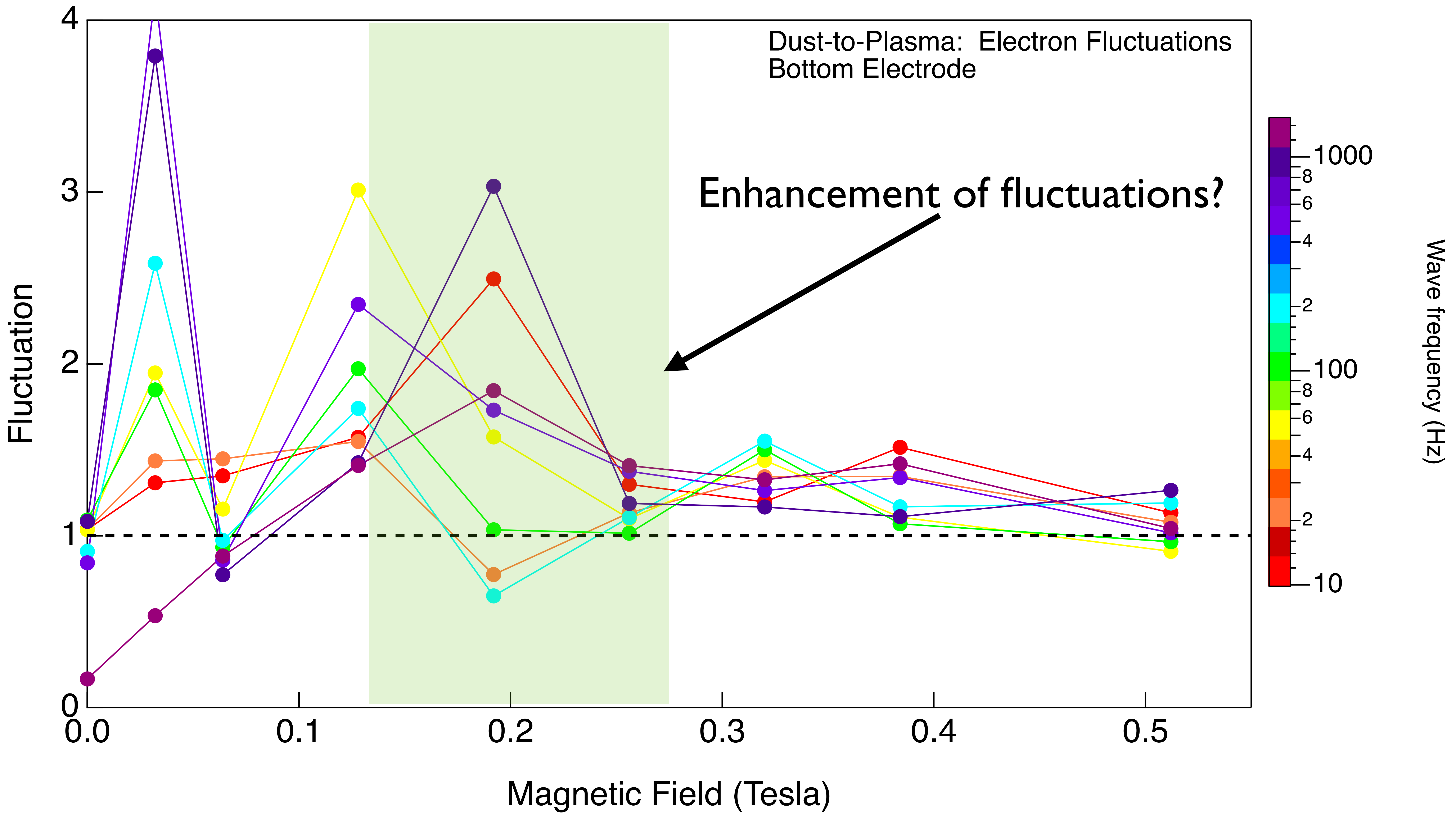


Effect of dust particles on the propagation of launched waves

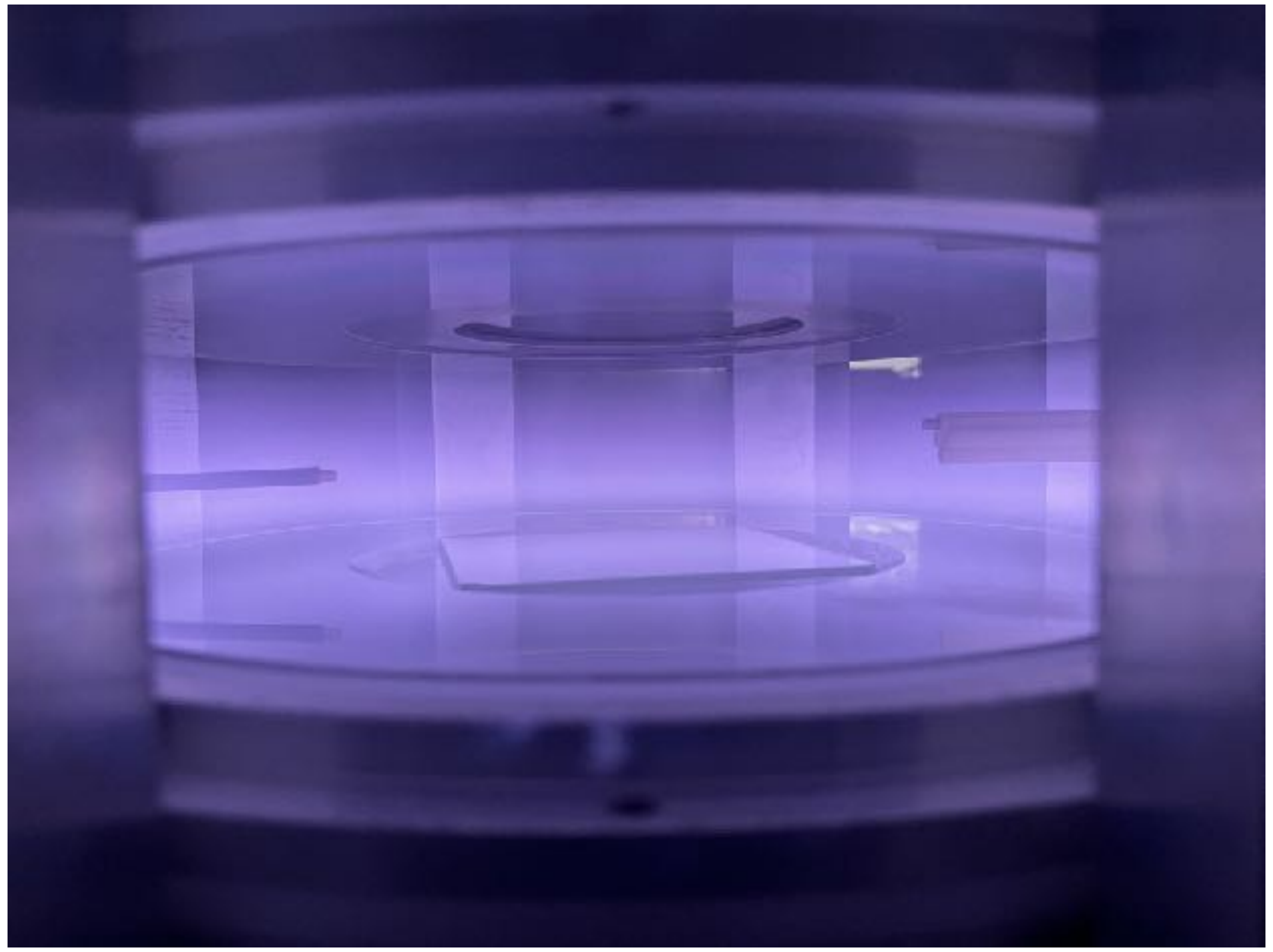
- Measurement of ratio of electron fluctuations: dust vs. no dust

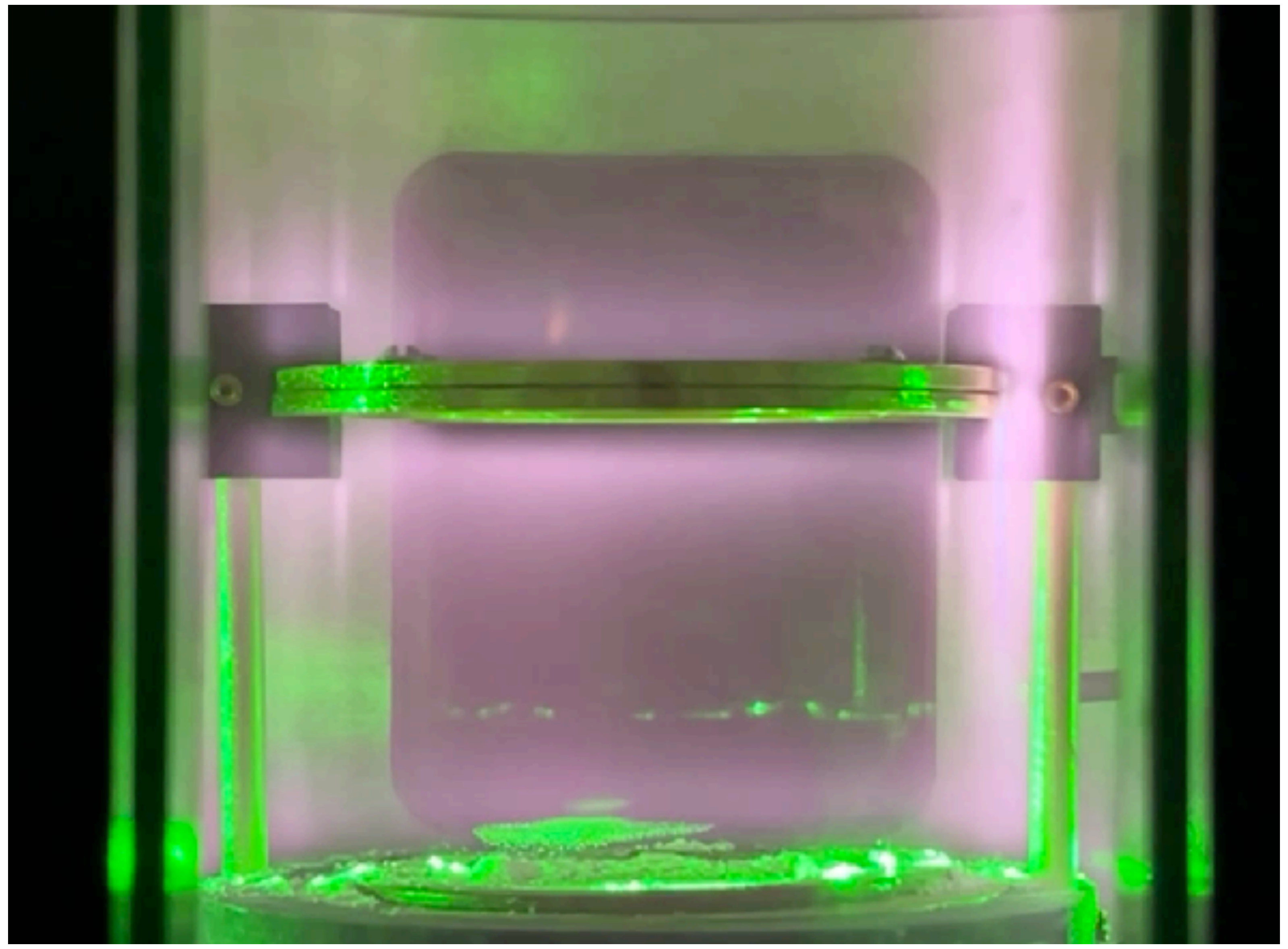
- Normalized to fluctuation level at B = 0 T

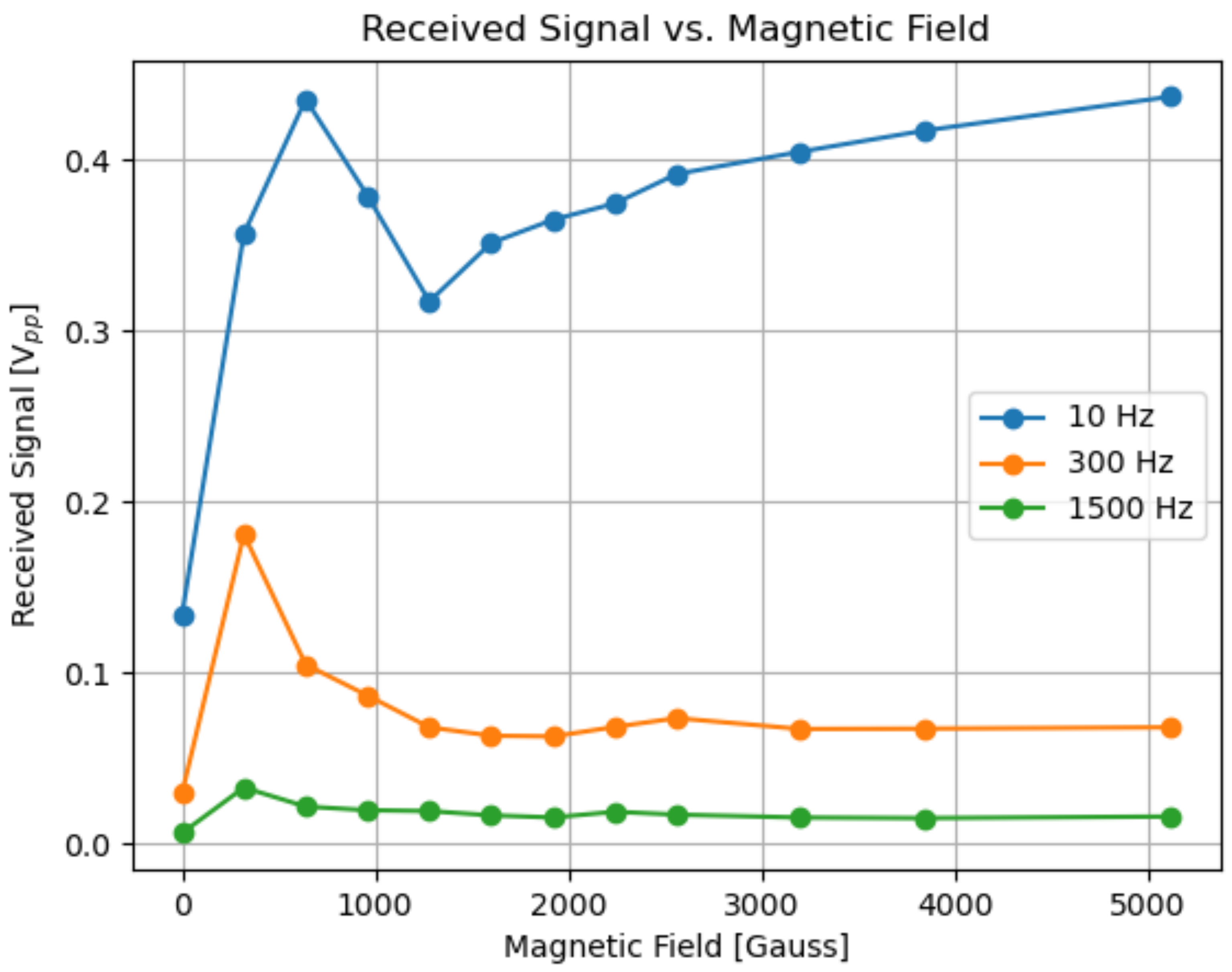




Next steps: development of new setup for electric field measurements parallel and perpendicular to the magnetic field







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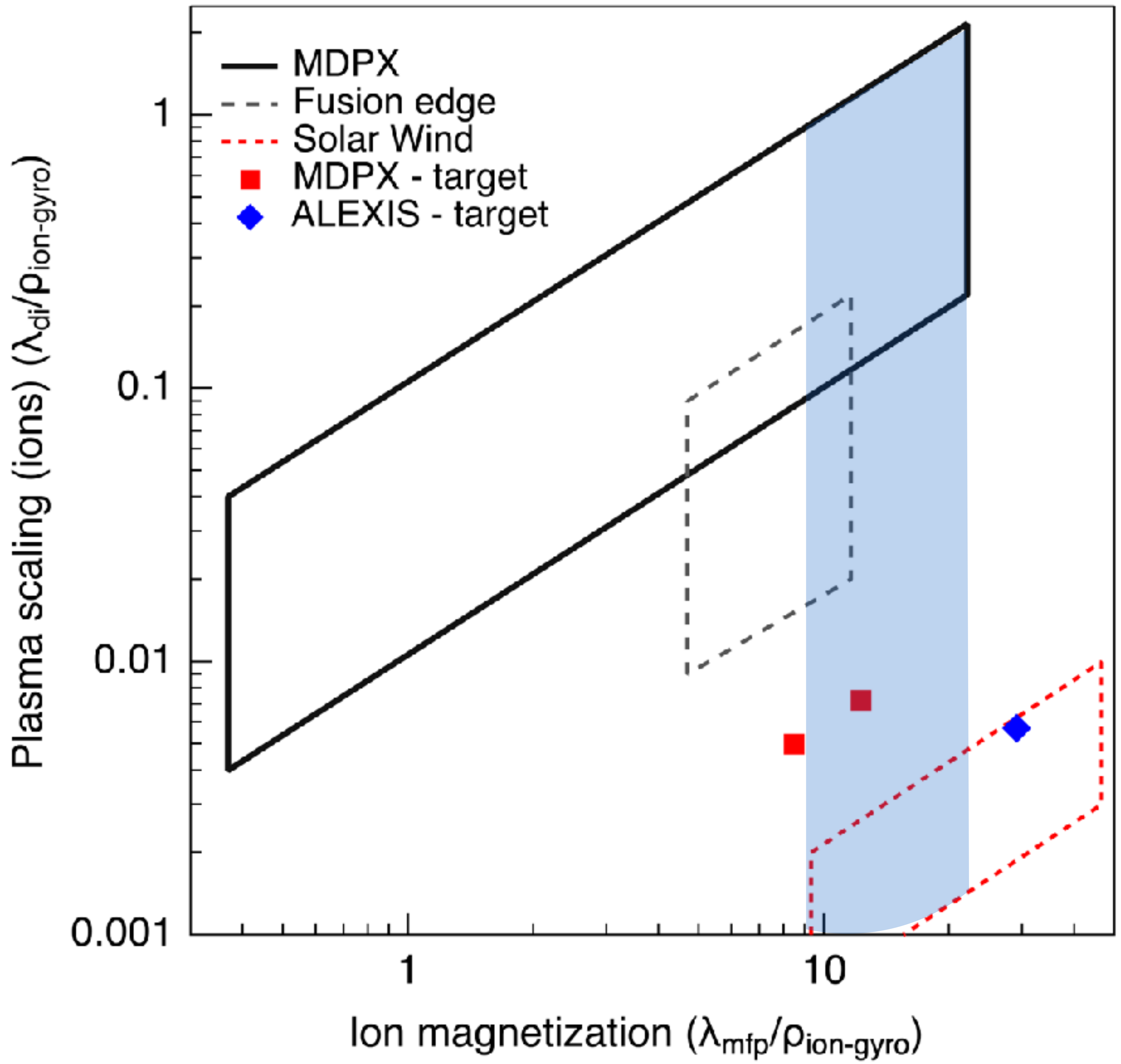
MPRL facilities can provide operating conditions that are scaled to geospace parameters



Expansion of operating regimes

- MDPX:
  - Improved pumping to lower operating pressure ($p \leq 5$ mTorr)
  - Improve electrode design/input power to increase density ($n \sim 10^{16}\ m^{-3}$).
- ALEXIS:
  - Shift operations to helium
  - How to introduce dust without full chamber contamination?

Summary

- The presence of dust can modify wave propagation in laboratory, space and astrophysical plasmas.
- Use the laboratory facilities in the Magnetized Plasma Research Laboratory to perform scaled space-relevant experiments.
- Experiments show that the introduction of the dust particles (i.e., reduction of free electrons) may contribute to enhancement of driven, low frequency electrostatic fluctuations.
- <u>Outstanding issues:</u>
  - Why is there a particular enhancement in the plasma response as magnetic field approaches B ~ 0.2 T?
  - Can we reliably expand the operating regimes of MDPX and other MPRL devices?
  - Need to confirm electric field measurements.

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