Connecting particle growth and pattern formation in the Magnetized Dusty Plasma Experiment (MDPX)

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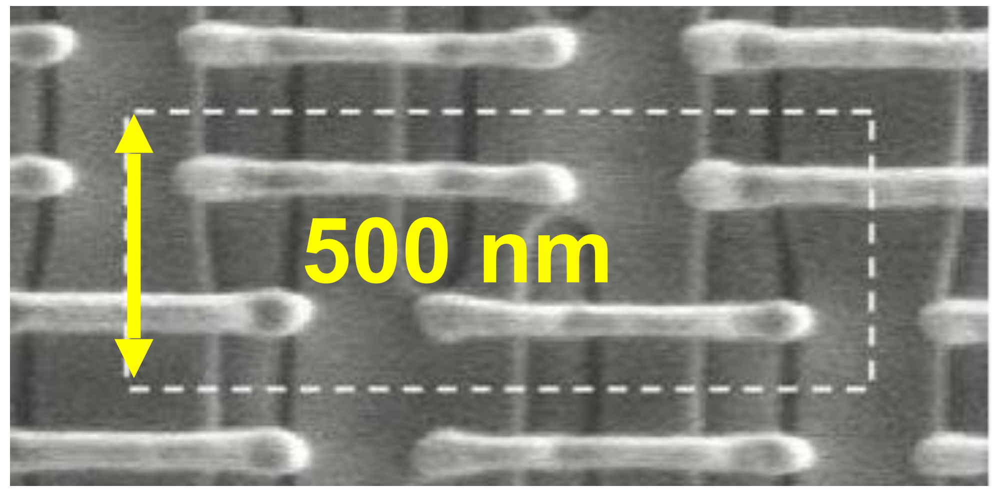
Project support:
Department of Energy: DE-SC0019176
National Science Foundation: PHY-1126067, PHY-1613087 & NSF EPSCoR: OIA-1655280
NASA: JPL-RSA-1571699, JPL-1646773 & NASA EPSCoR: NASA-80NSSC19M0182

Presentation at Online Low Temperature Plasma (OLTP) Seminar
December 14, 2021

Plasmas: natural and man-made occur at all scales (nm to light years)

Man-made

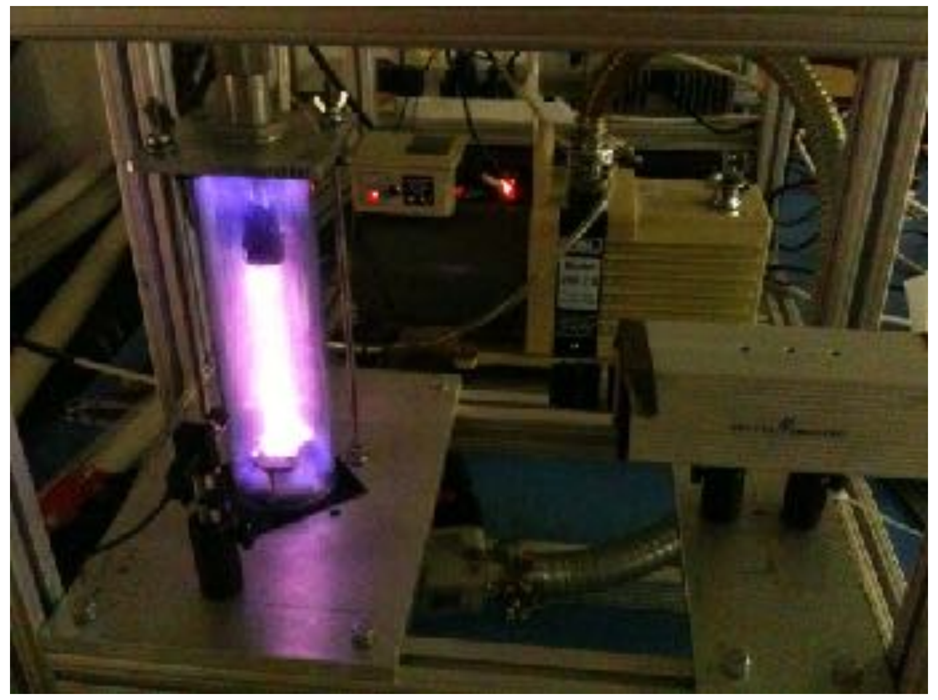


Manufacturing

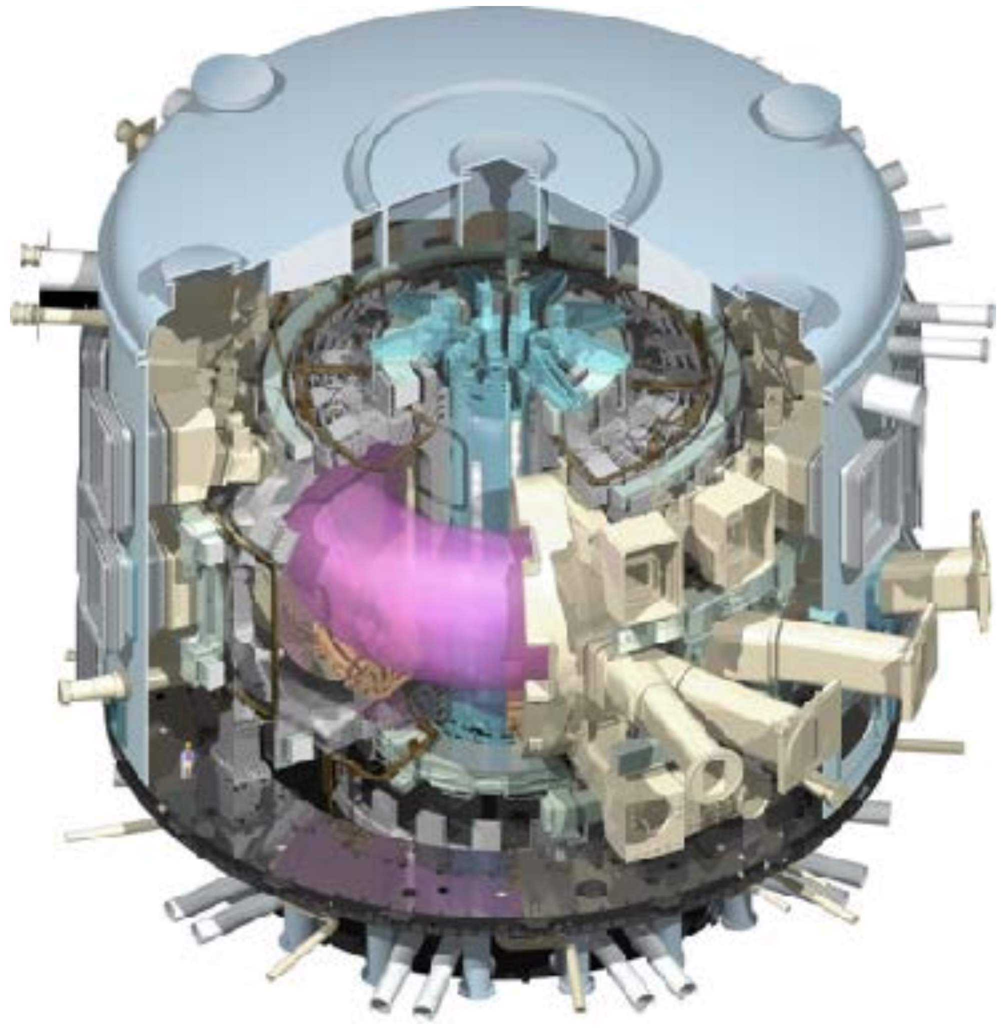
Plasma medicine

Lighting

Plasma agriculture



Lab experiments



Fusion energy

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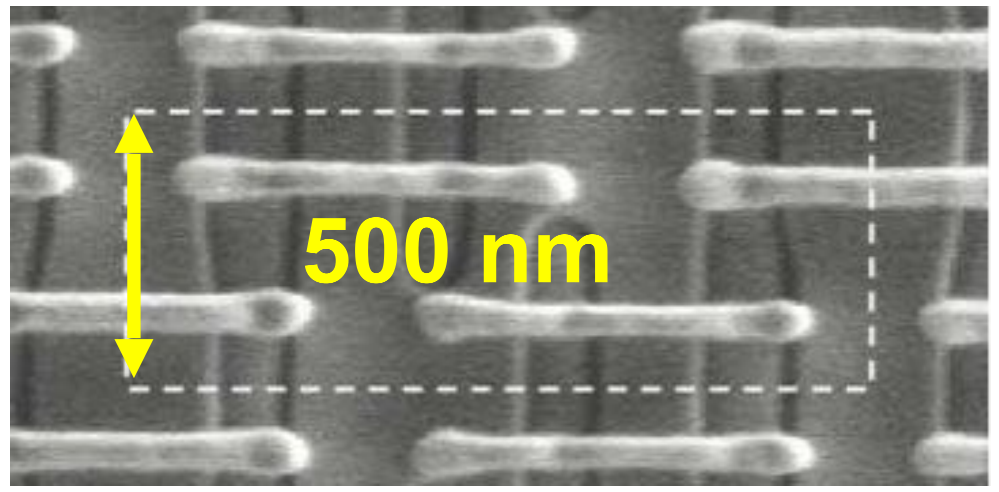

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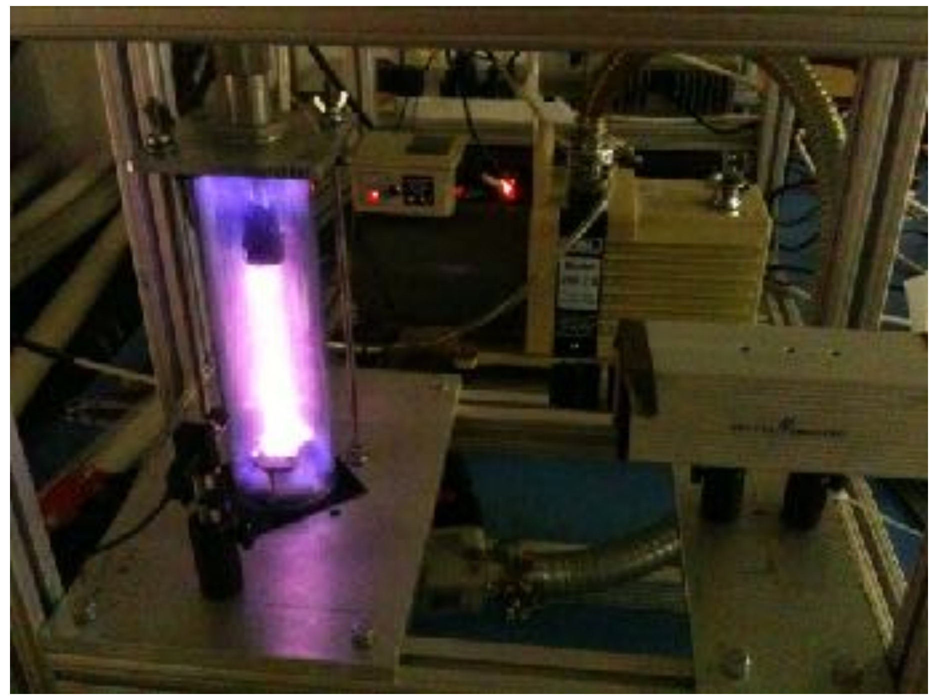

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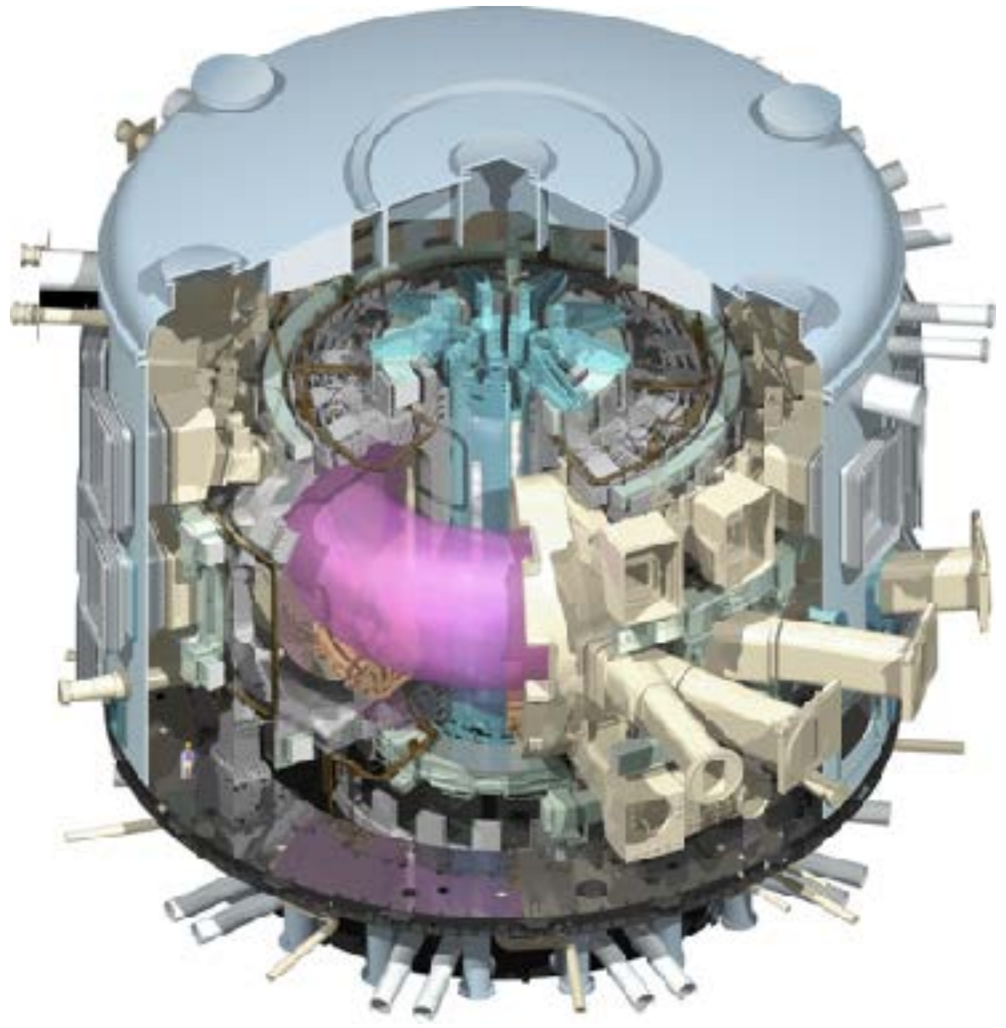
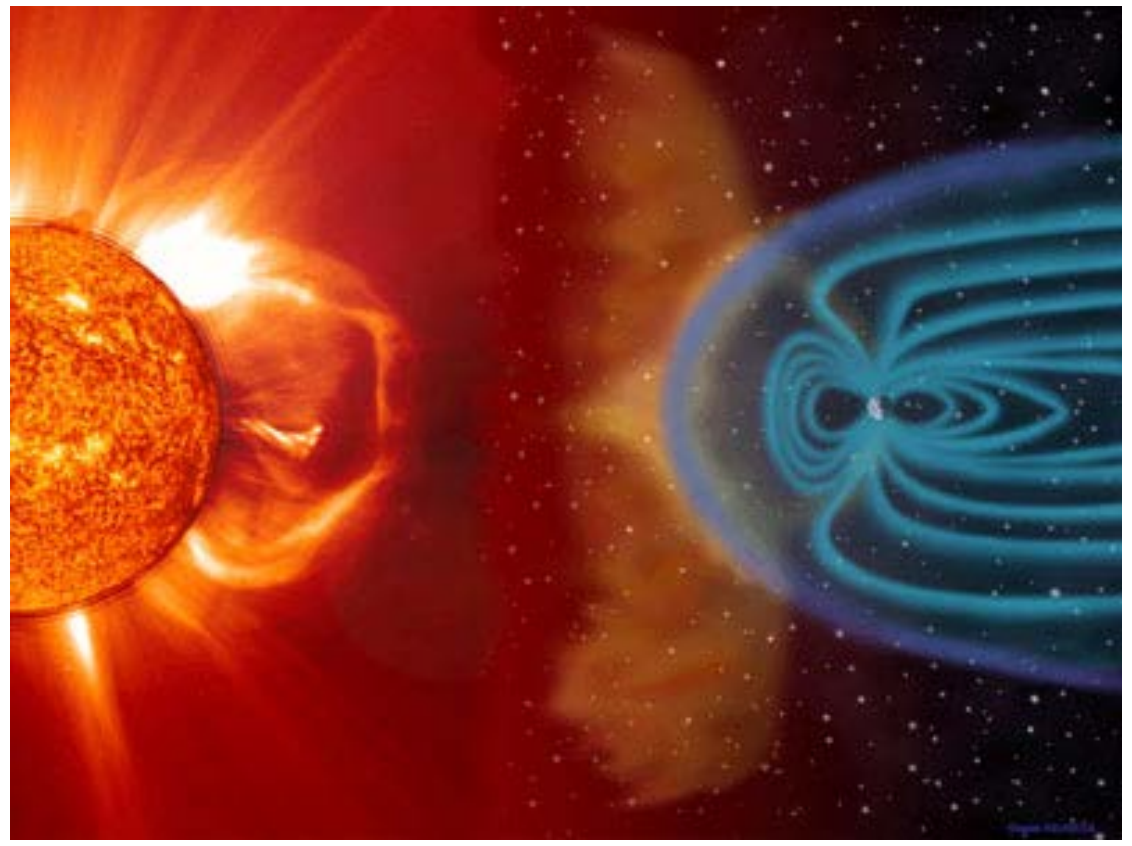


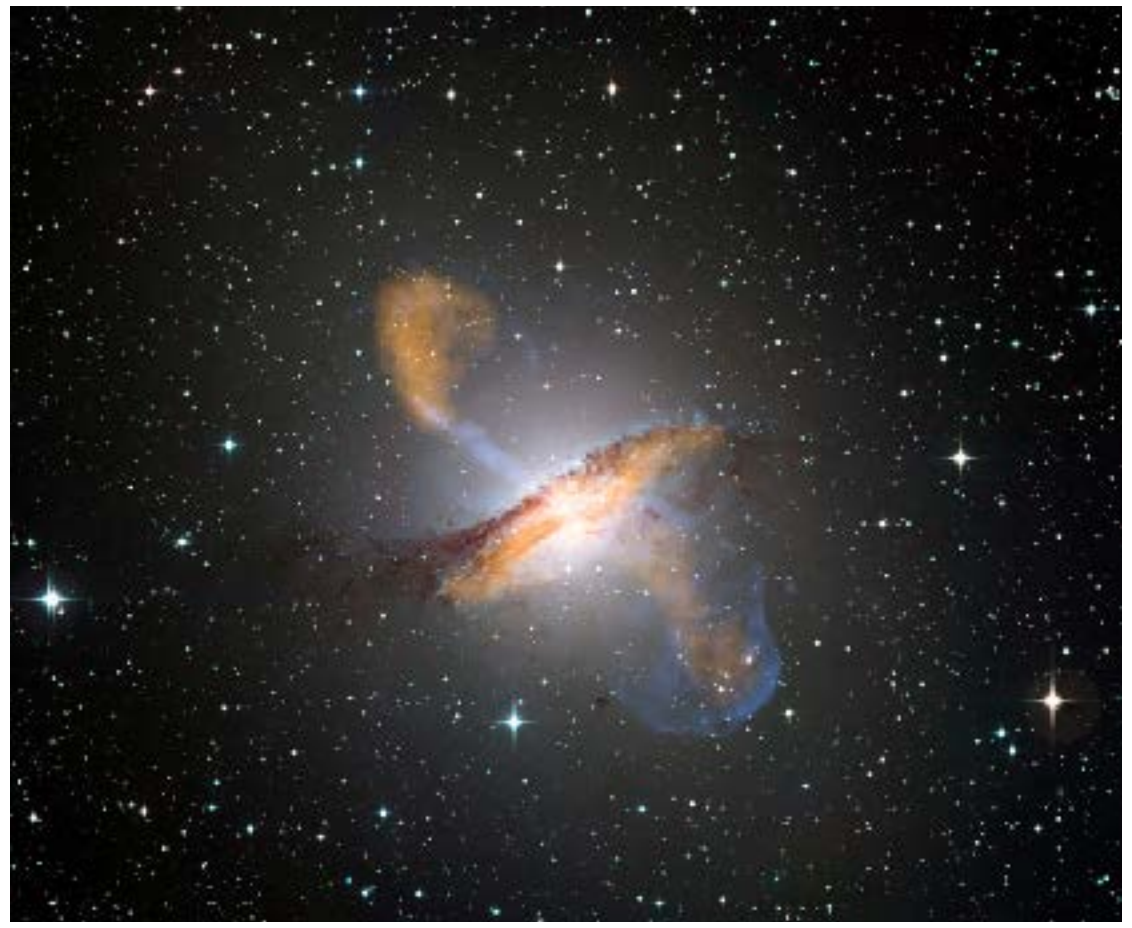
Fusion energy

Naturally-Occurring

Lightning



Sun-Earth connection
"space weather"

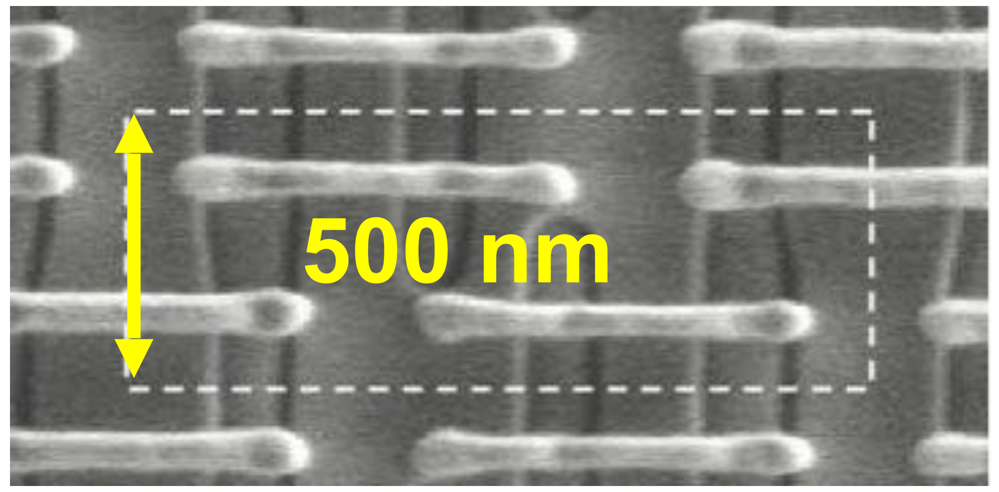


Astrophysical jets powered by black holes

Eta Carina nebula
"star and planet formation"

Plasmas: natural and man-made occur at all scales (nm to light years)

Man-made



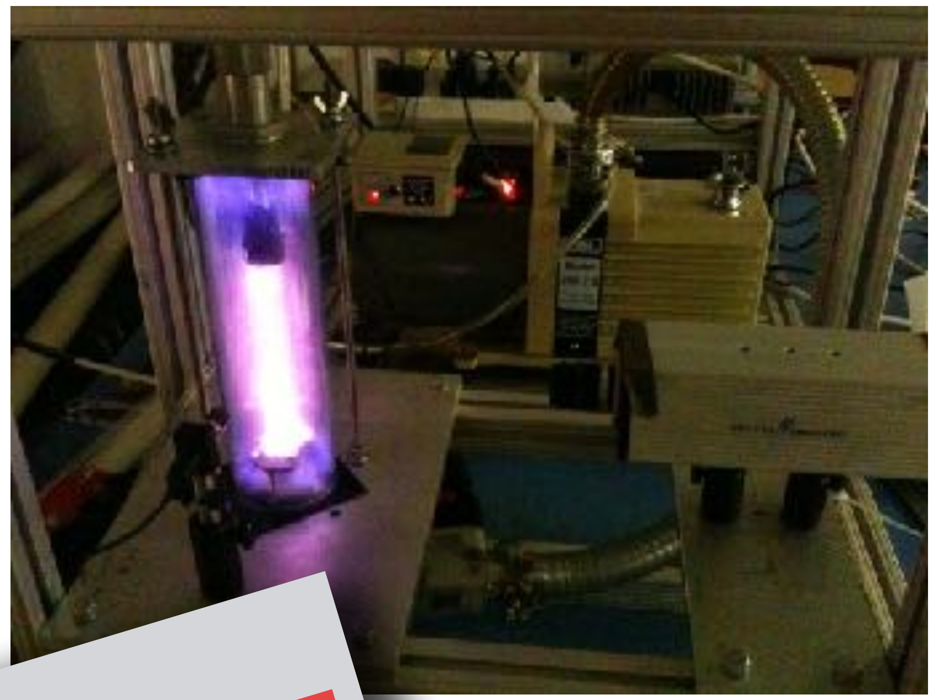
Manufacturing


Plasma medicine


Lighting


Plasma ag

DUST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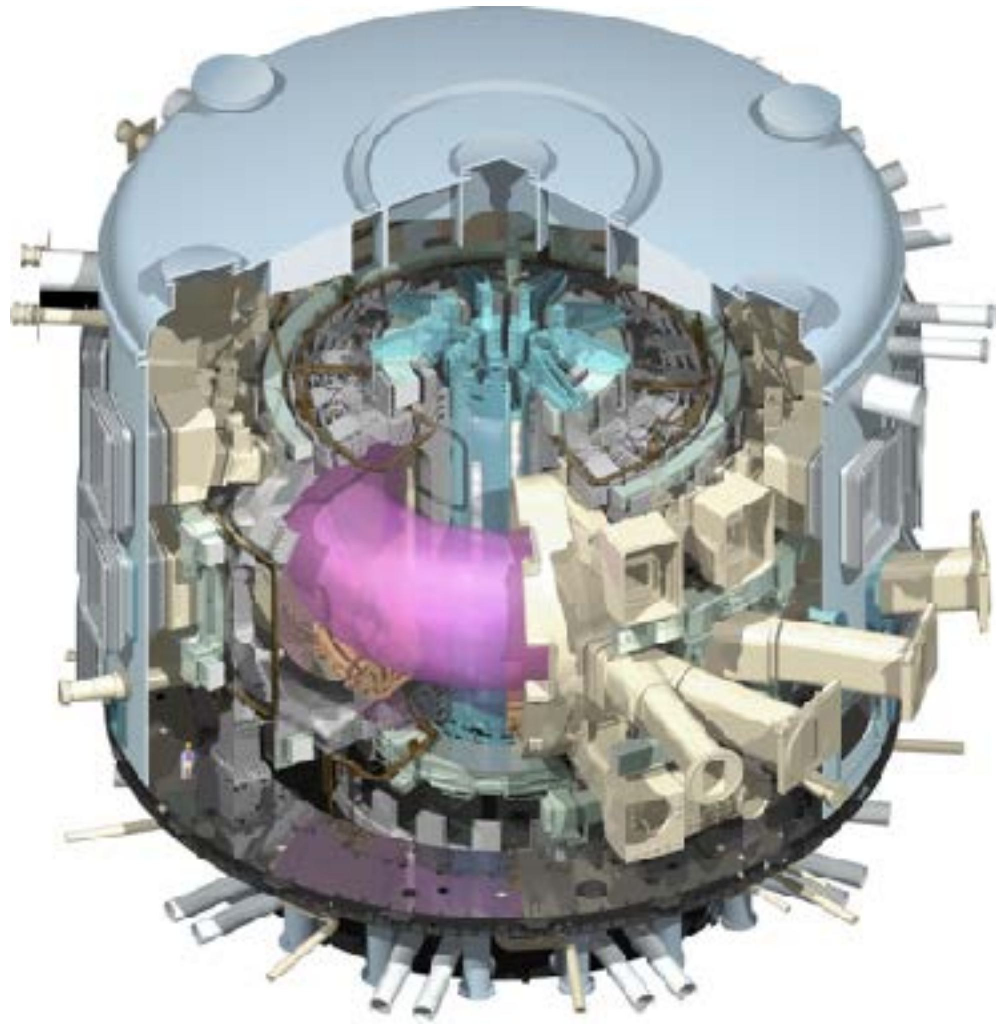
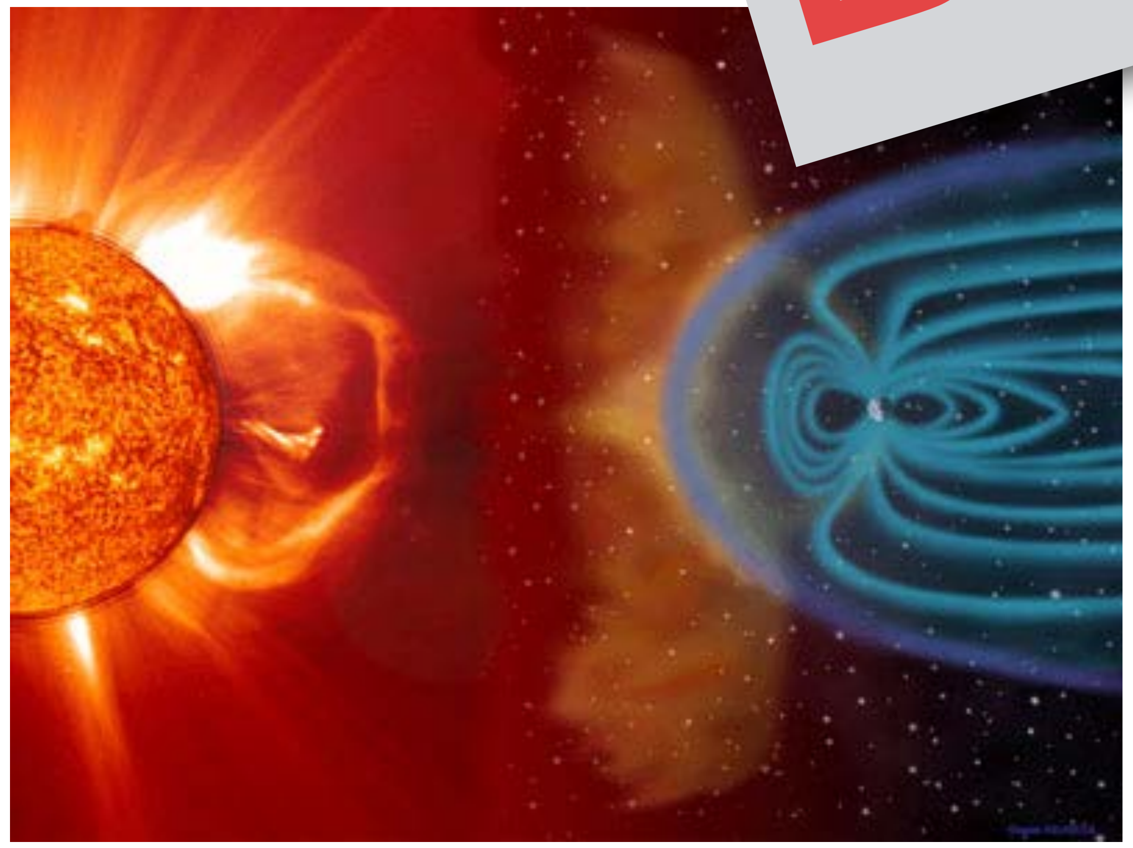

Fusion energy

Naturally-Occurring


Lightning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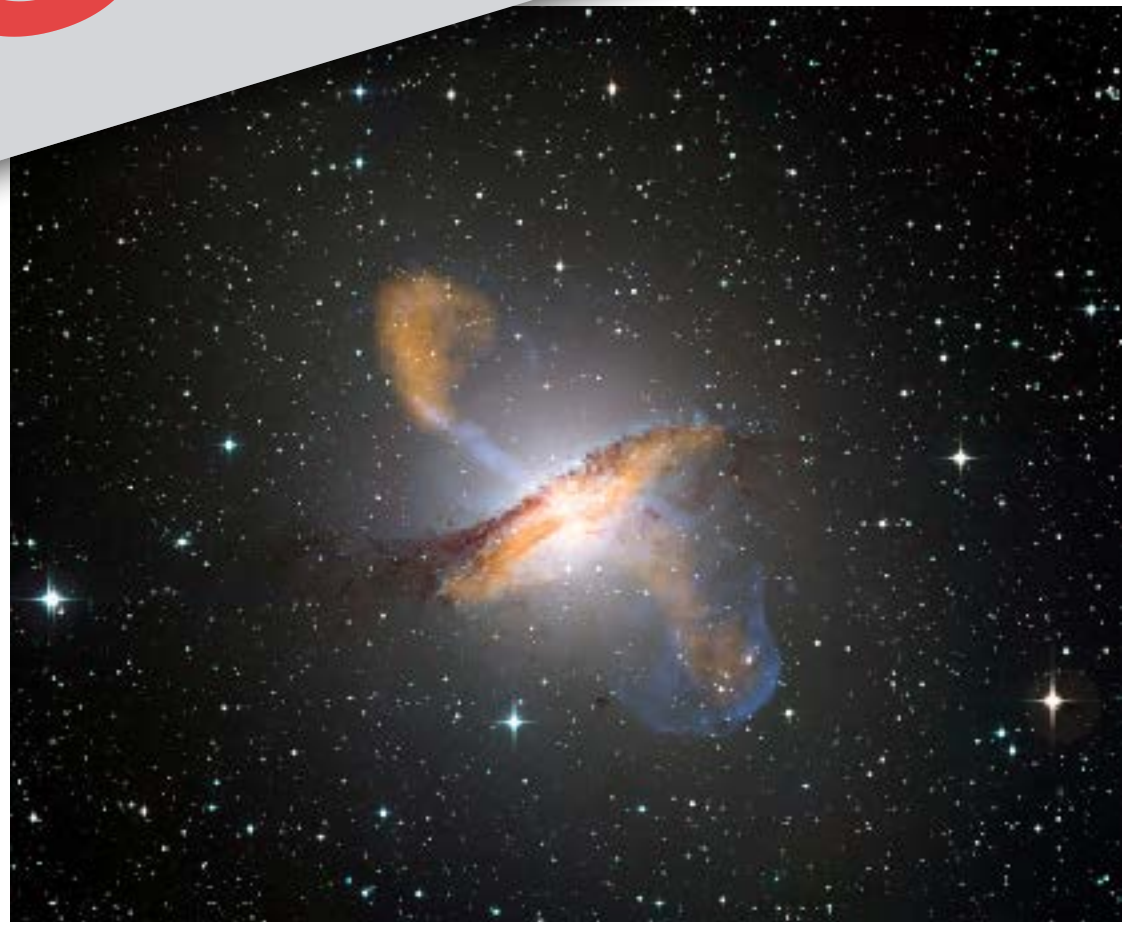
Astrophysical jets powered
by black holes


Eta Carina nebula
"star and planet
formation"

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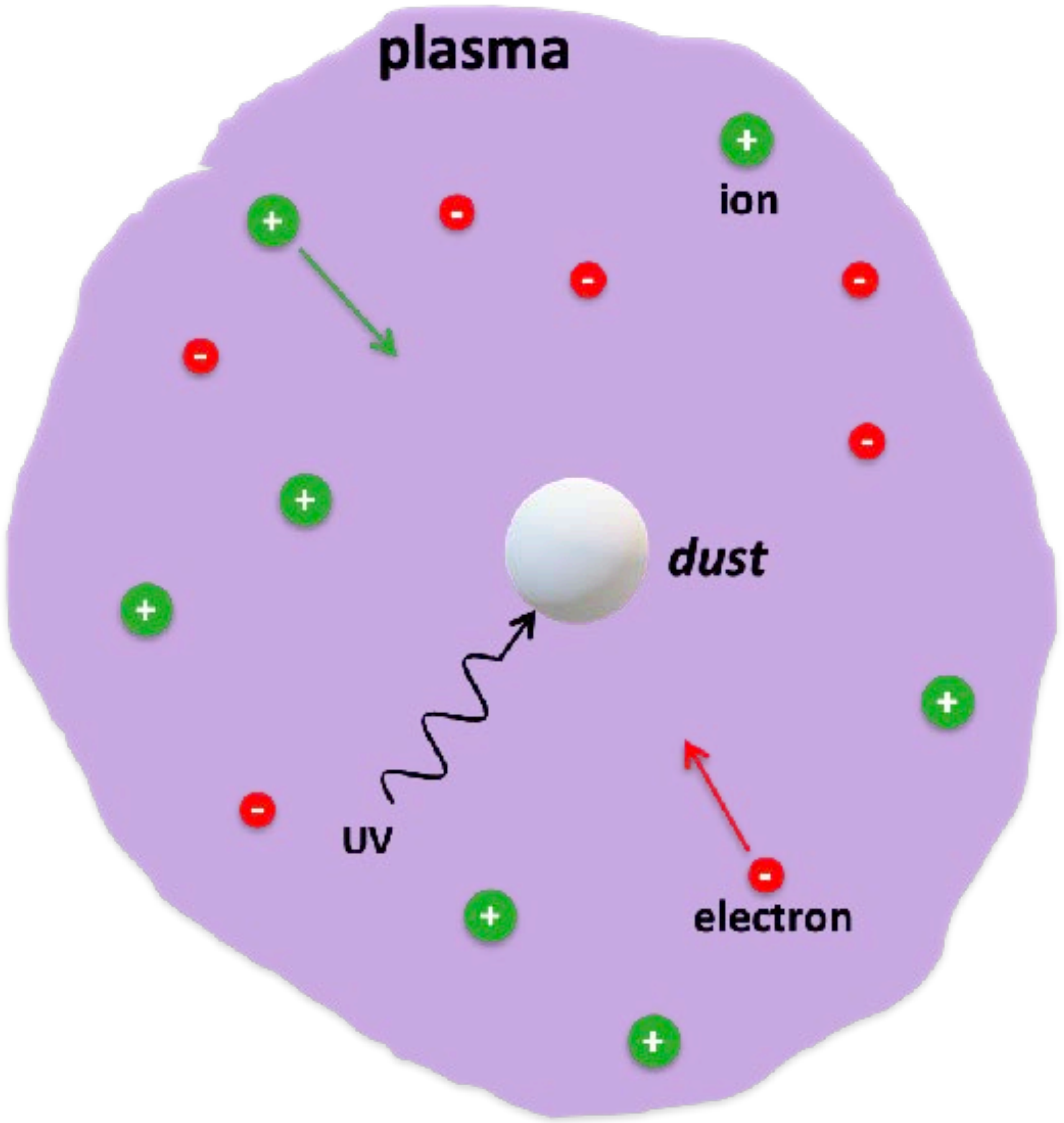
Dusty (complex) plasmas

Dusty plasmas are a four-component plasma system

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



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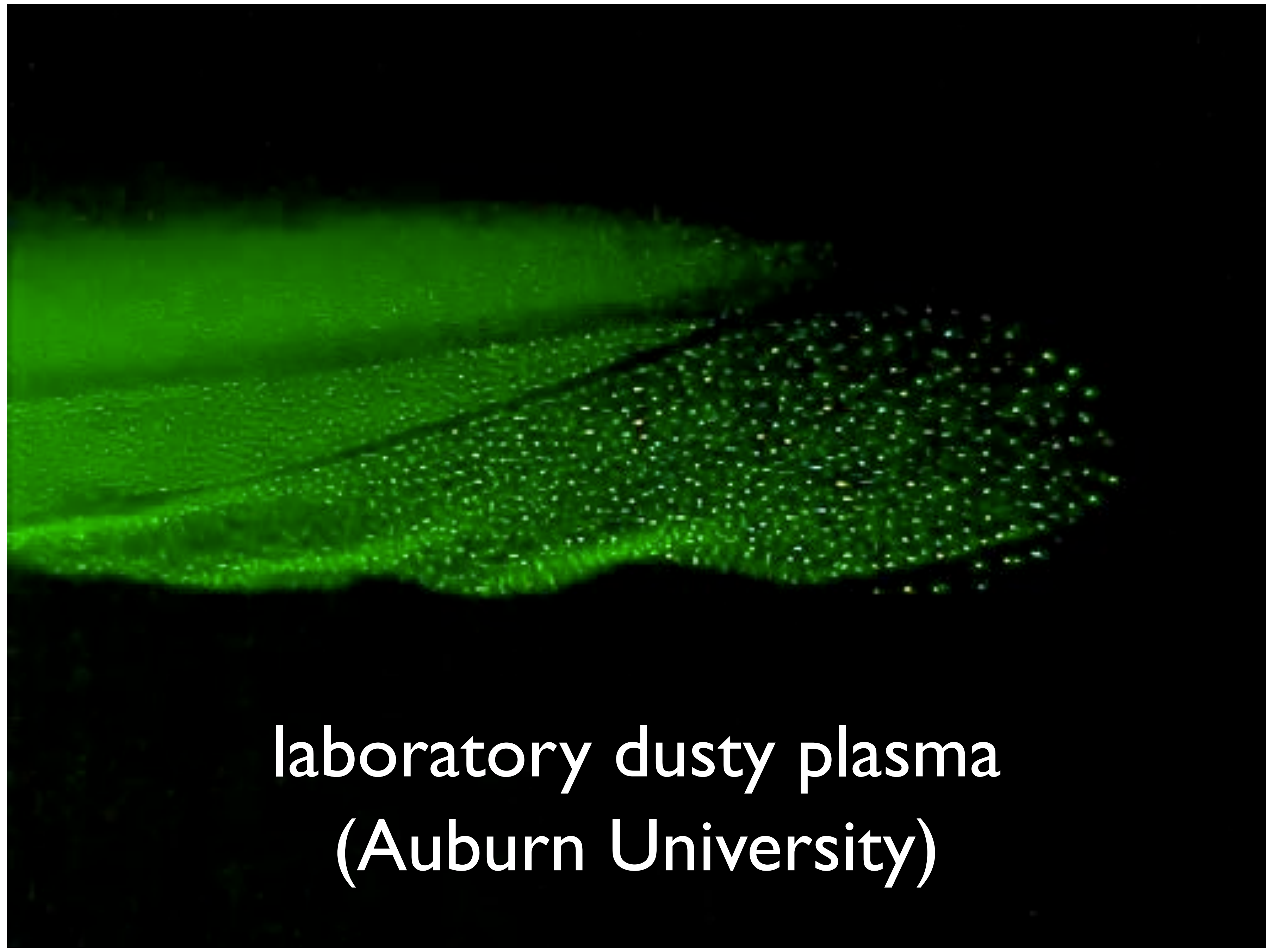
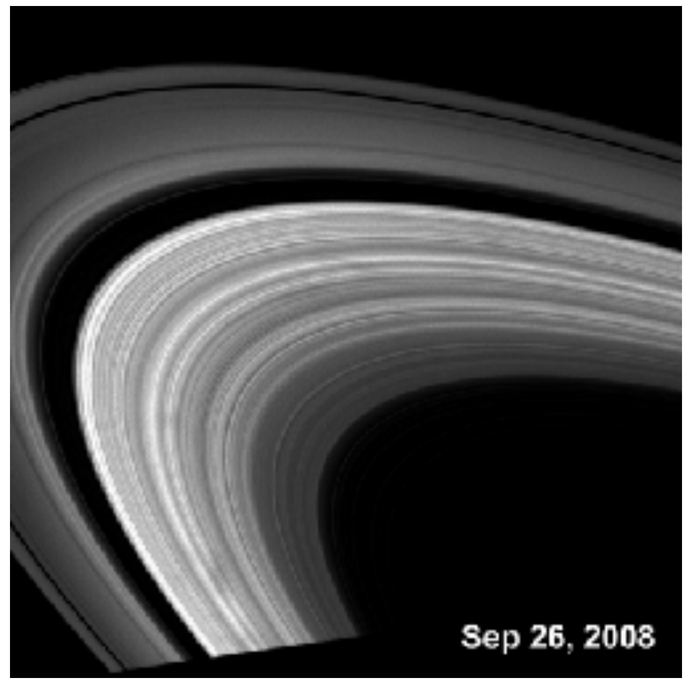
- Dusty plasmas (complex plasma)
  - Ions
  - Electrons
  - Neutral atoms
  - Dust particles (nm to μm)
- Plasma ⇄ dust via charging
- Dusty plasmas occur in space, lab, and industry

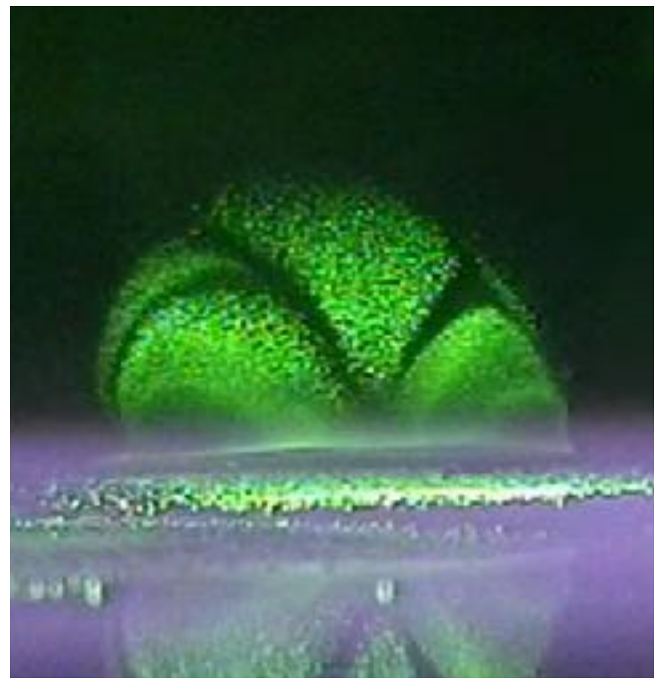

laboratory dusty plasma (Auburn University)



← nebula (ly) —— asteroid (m) →


Plasma processing


Fundamental physics

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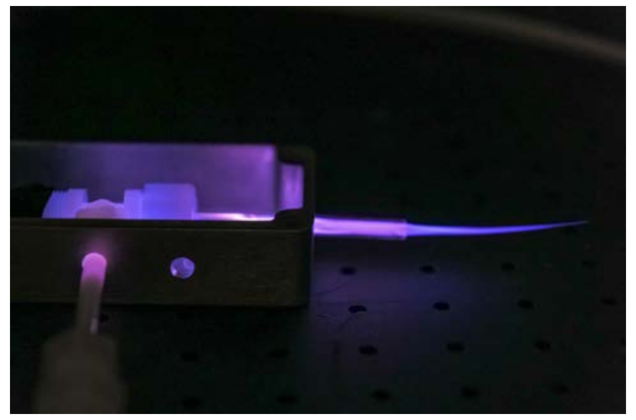
The Magnetized Dusty Plasma Experiment

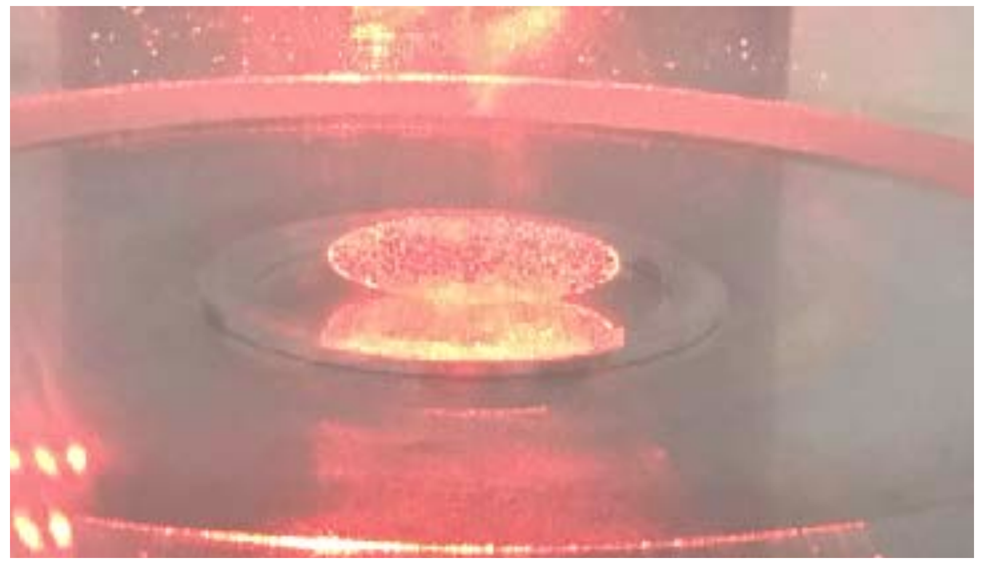
Magnetized Plasma Research Laboratory (MPRL)

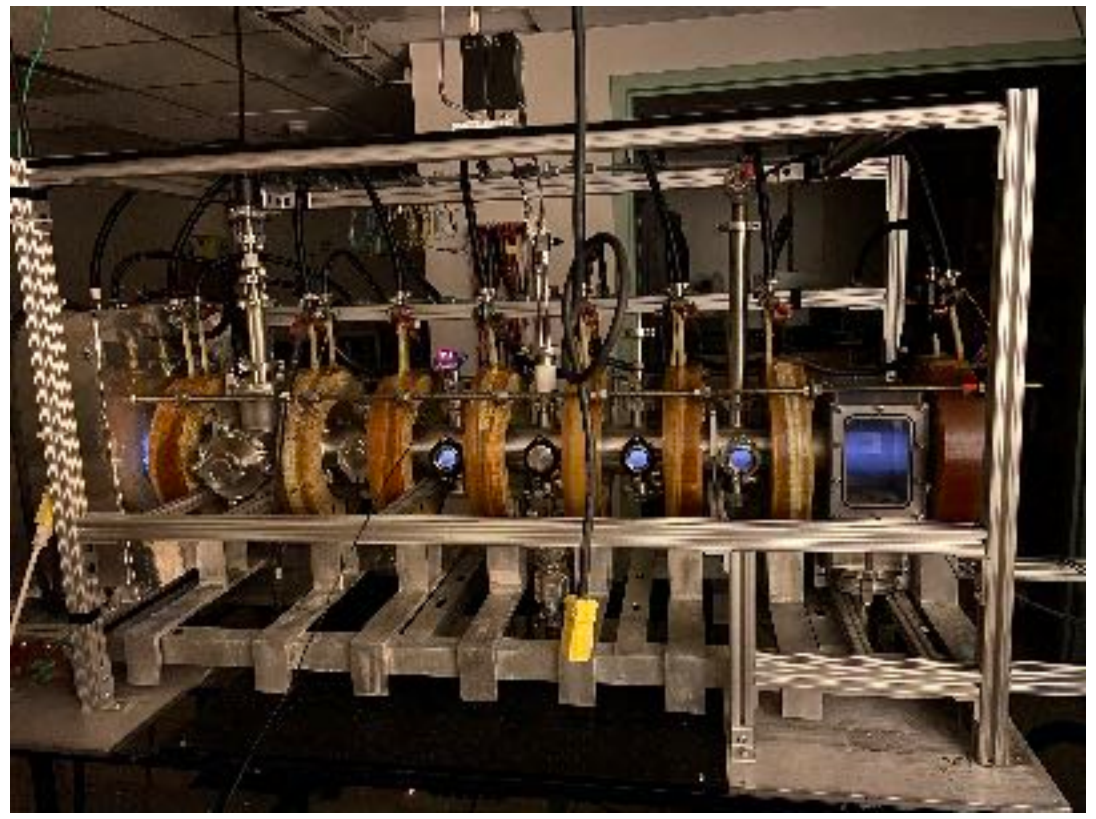
A Department of Energy Collaborative Facility - Operated via Plasma Science Facility Program

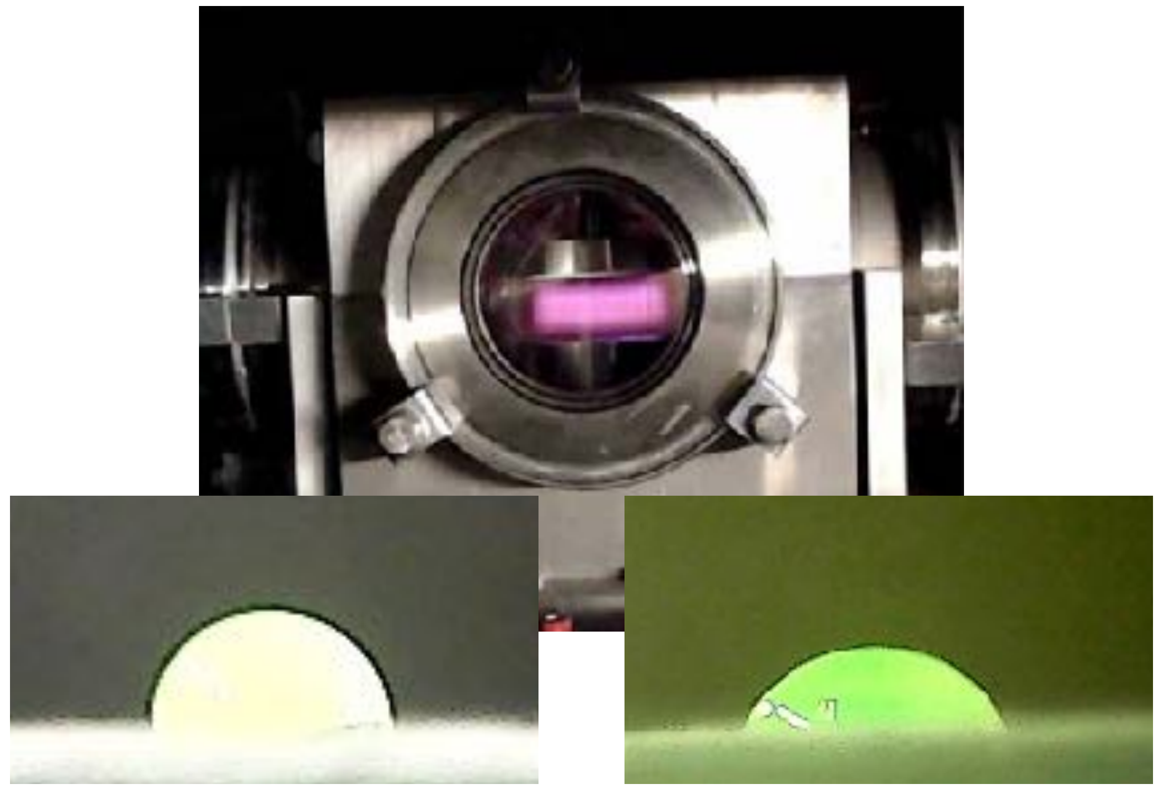
Additional support via the NSF-EPSCoR program - CPU2AL project

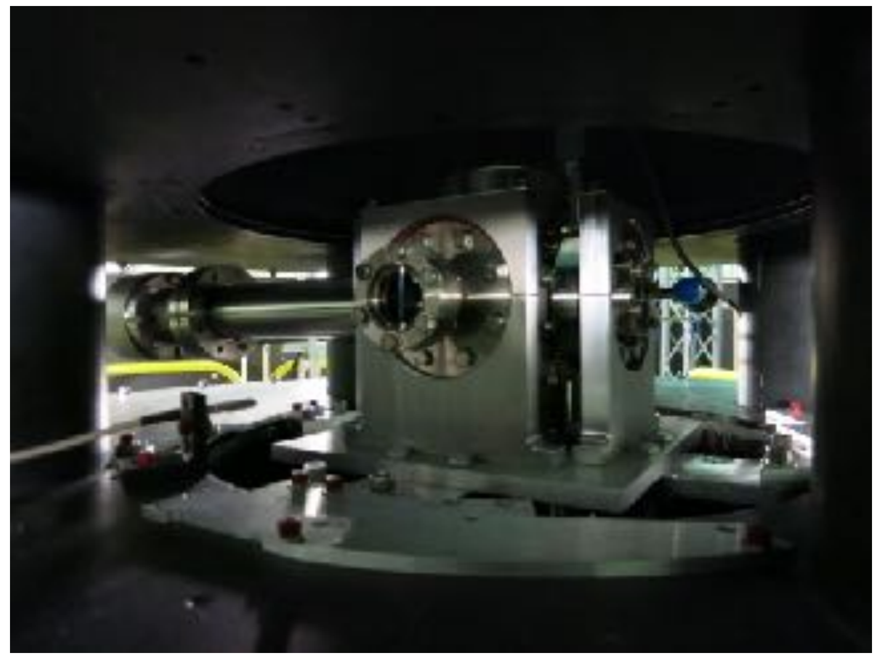
Major equipment funded by the NSF (NSF-MRI), DOE, and NASA











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External Users/Collaborations

Univ. Greifwald*
IPR, India*
Univ. Saskatchewan+
German Aerospace Center (DLR)+

Baylor Univ.
Emory Univ.*
Mississippi State Univ.*
Univ. Alabama - Birmingham (UAB)+
Univ. Alabama - Huntsville (UAH)* +
UCSD
Univ. Iowa
Univ. Maryland - Baltimore (UMBC)*
U. Memphis*
U. South Alabama+
Univ. Wisconsin*
West Virginia Univ.*
Wittenberg Univ.*

* DOE +NSF-EPSCoR

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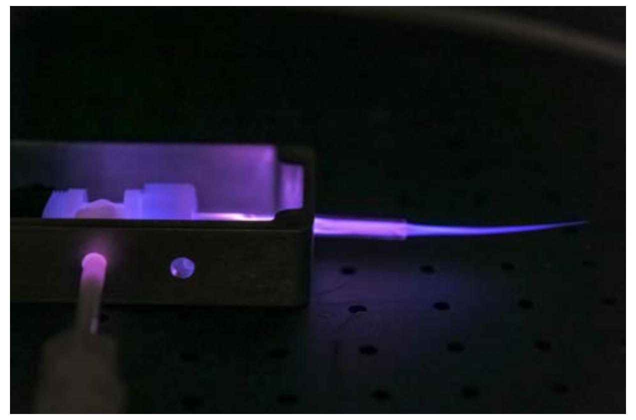

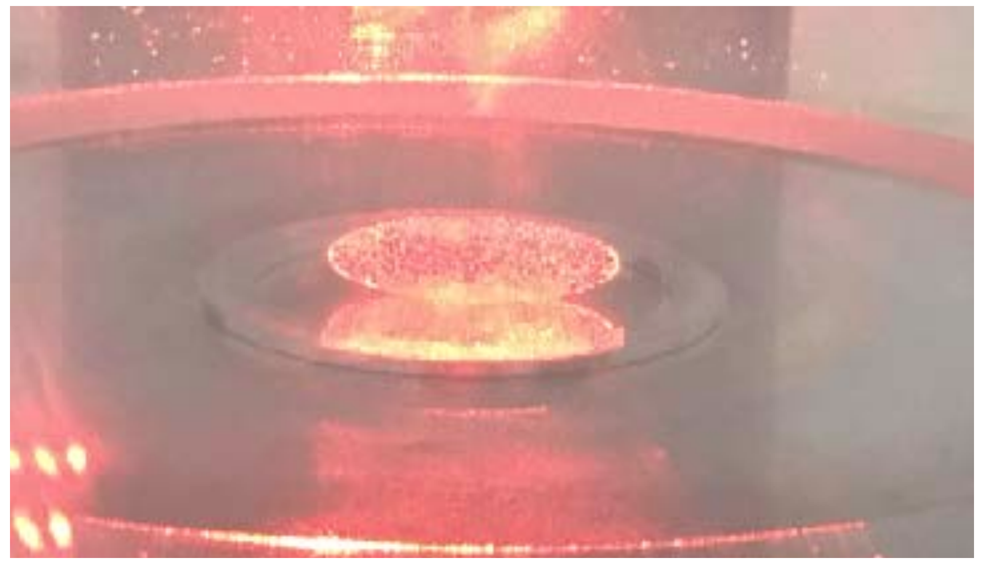

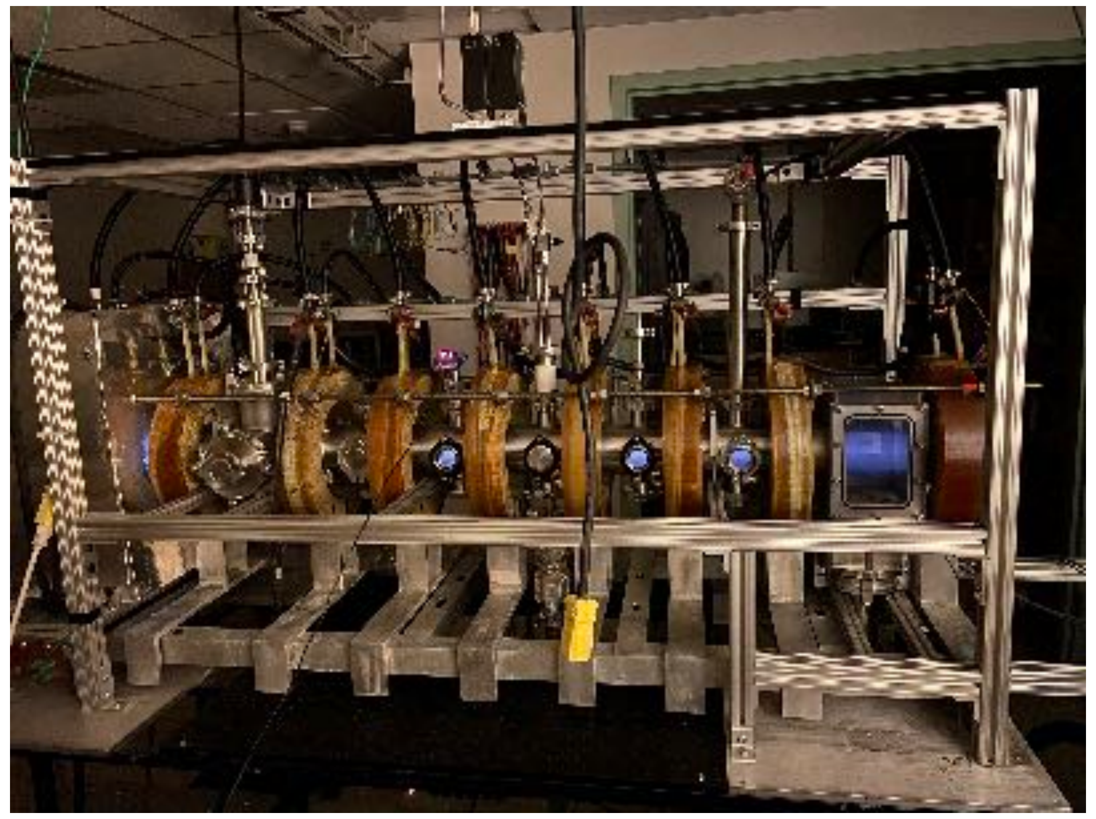

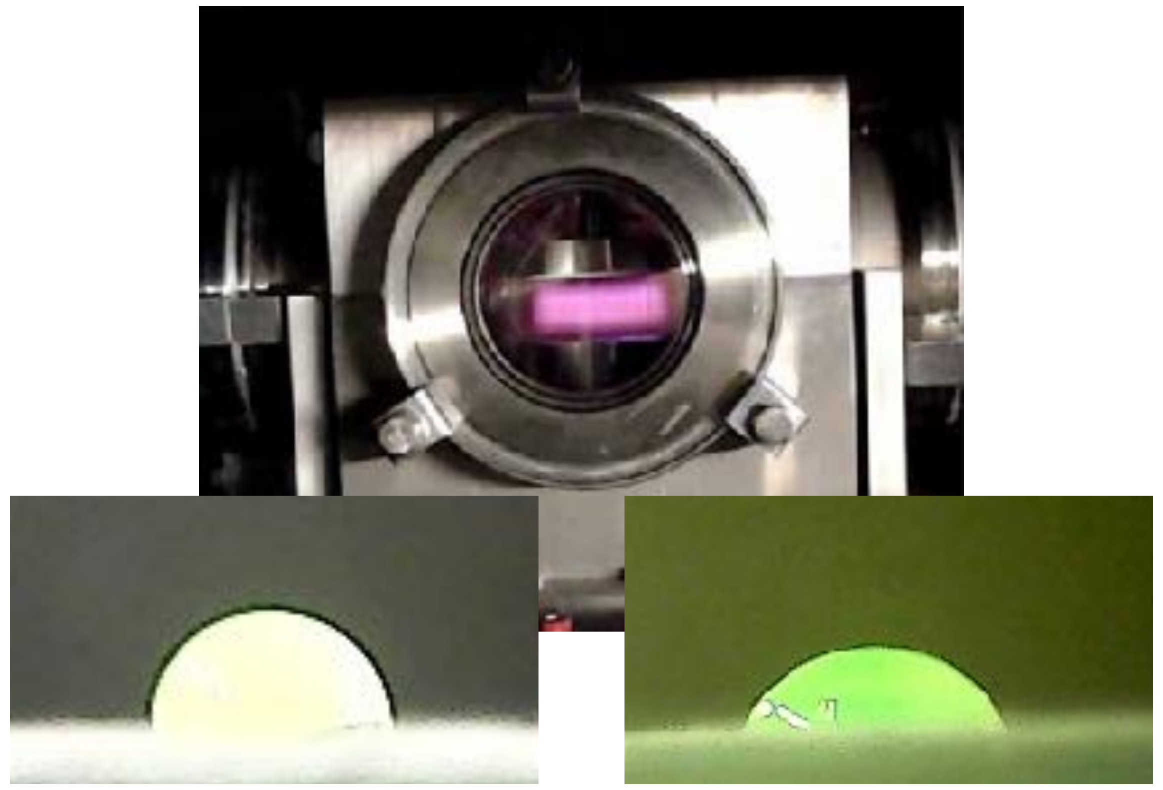

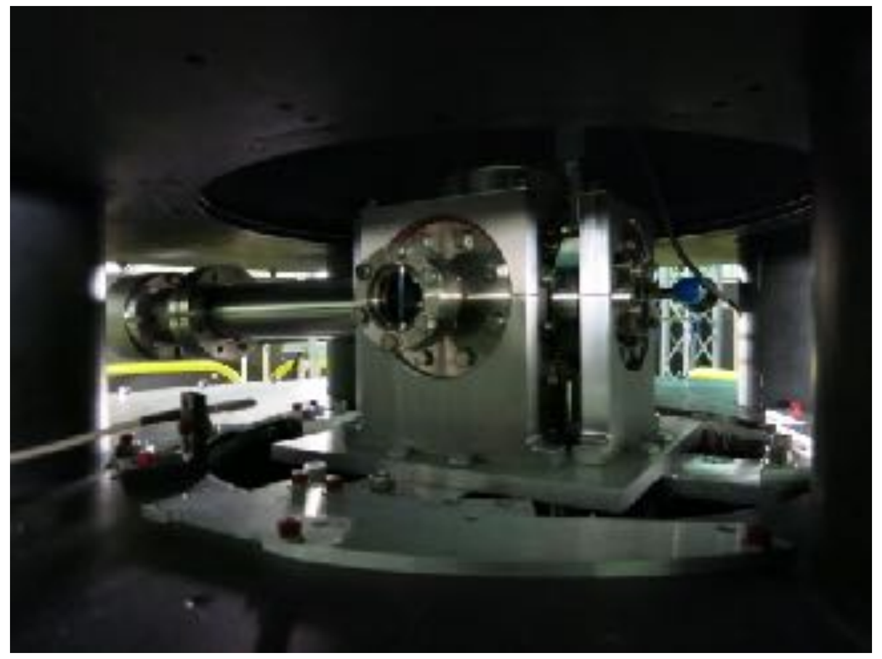

MagNetUS Frontier Plasma Science - Joint Solicitation

http://MagNetUS.net

BAsic Plasma Science Facility
(BAPSF @ UCLA)

DIII-D National Fusion Lab
(San Diego @ General Atomics)

Wisconsin Plasma Physics Lab
(WiPPL @ Univ. of Wisconsin)

Magnetized Plasma Research Lab
(MPRL @ Auburn Univ.)

http://aub.ie/mprl

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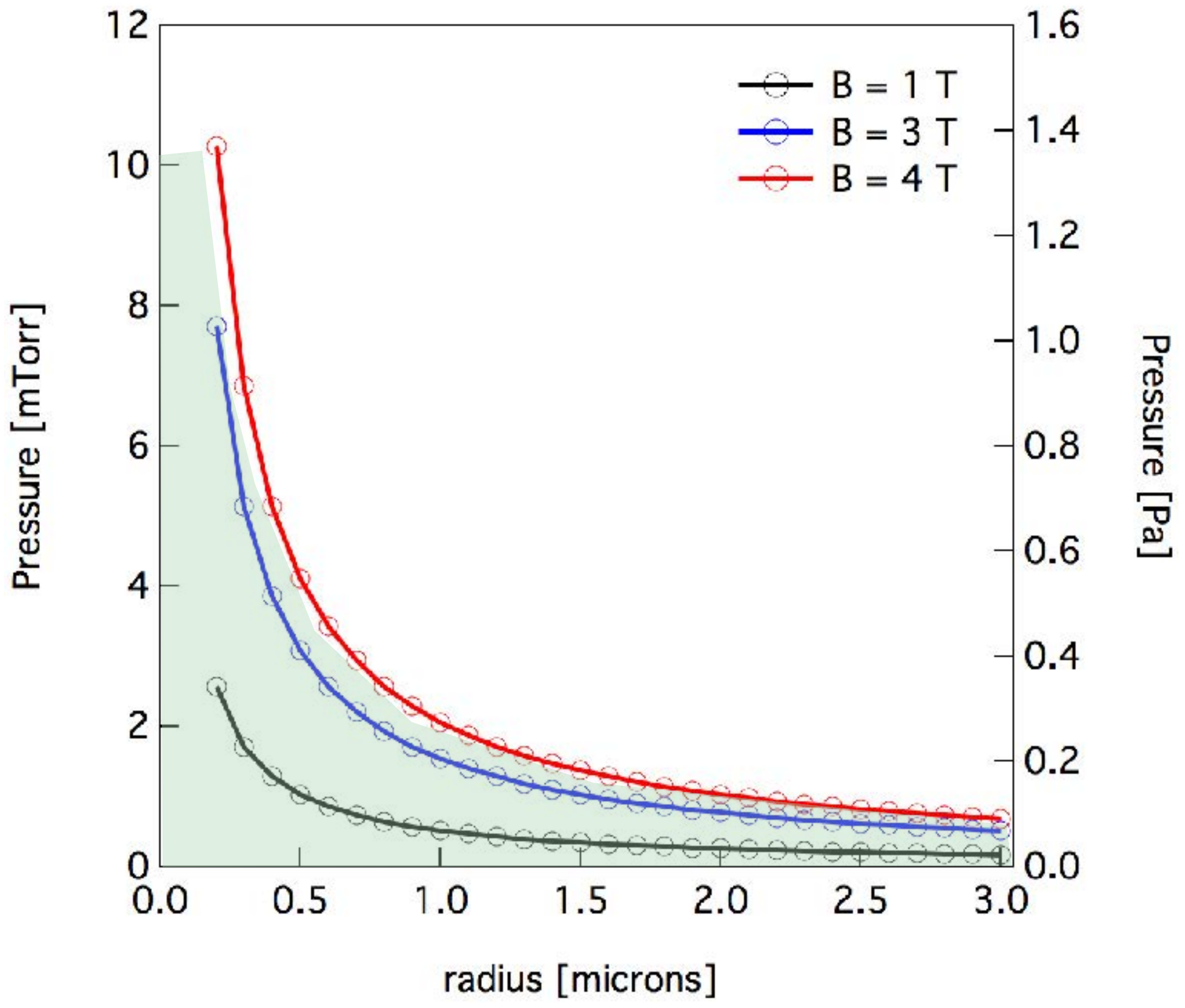
Technical challenges in magnetizing a dusty plasma in the laboratory

- Magnetization criterion
  - Magnetic force will be comparable to the other forces acting upon the dust grain
- Challenges:
  - Dust grain charge, $Z_d \sim 1000$
  - Dust grain mass, $m_d > 10^8\ m_{ion}$
- That is: $q_d/m_d << e/m_{ion} << e/m_{elec}$
- Key parameters:
  - gyroradius to exp. size: $\frac{\rho}{L} \sim \frac{a^2 v_d}{BL} << 1$
  - gyrofreq. to collision freq.: (Hall parameter) $\frac{\omega_c}{\nu_{dn}} \sim \frac{B}{aP} > 1$
  - magnetic to gravitational force: $\frac{F_m}{F_g} = \frac{Q_d v_d B}{m_d g} \sim \frac{v_d B}{a^2} \geq 1$

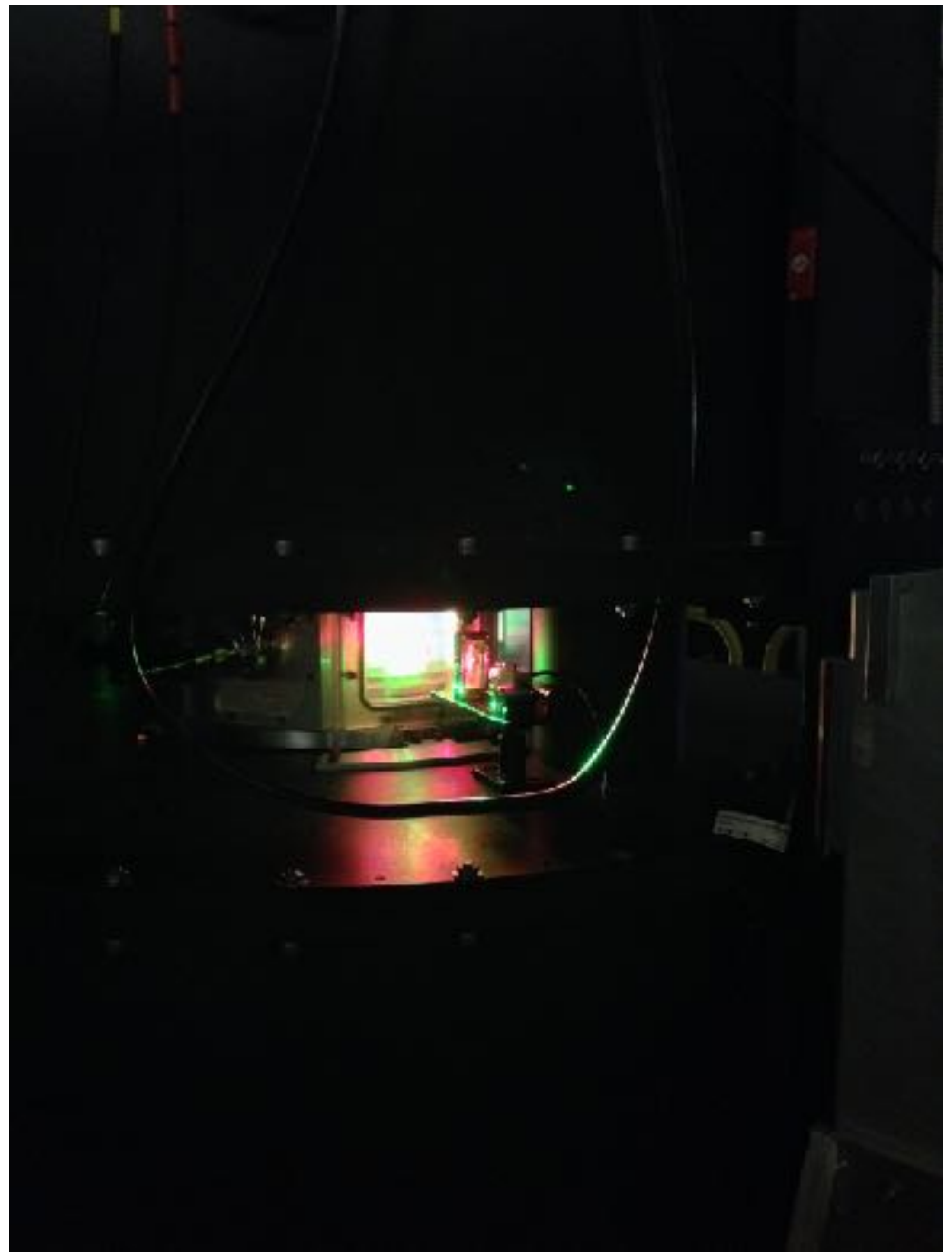
Key result: Maximize B/a

- Scaling of pressure vs. grain radius for the condition: $\tau_{collision} / \tau_{cyclotron} = 1$



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
- Argon:
  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
  High-speed video cameras (300 fps)
- Plasma parameters (@ B = 0 T):
  $T_e = 1$ - 5 eV, $T_i = 1/40$ eV
  $n_e \sim n_i \sim 2$ 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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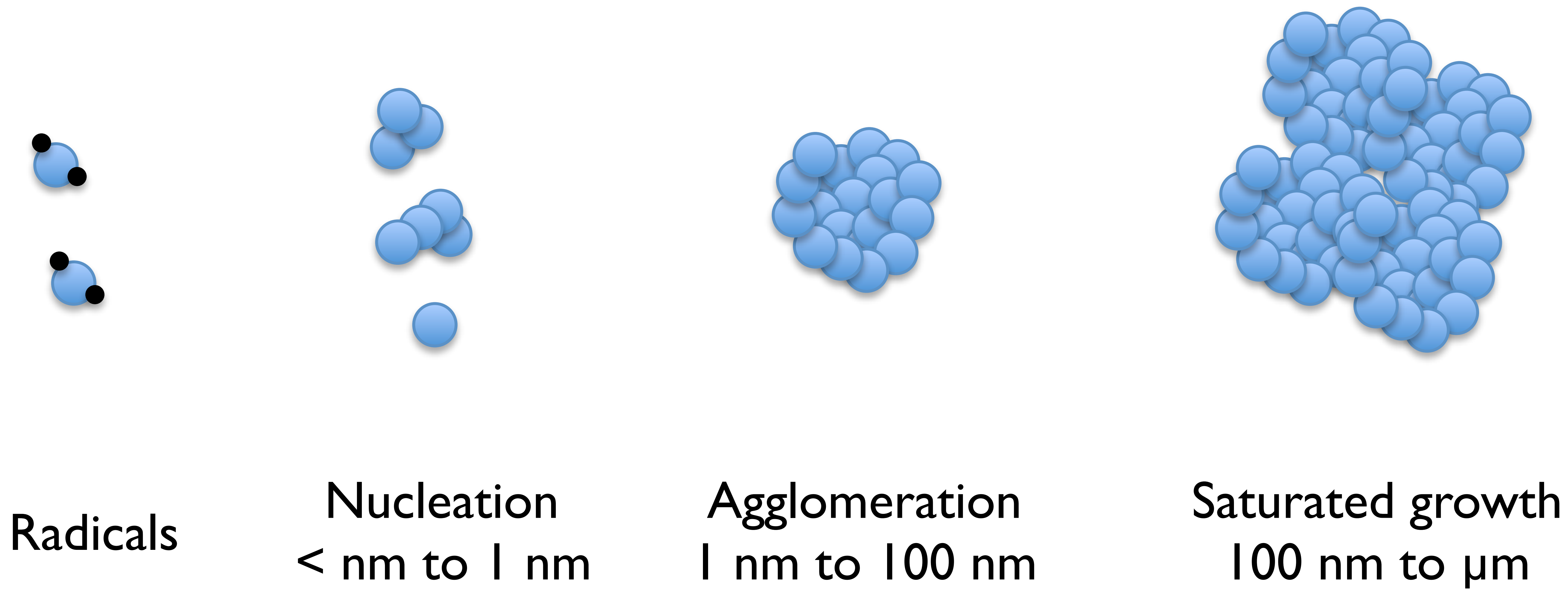
Dust particle growth at high magnetic field

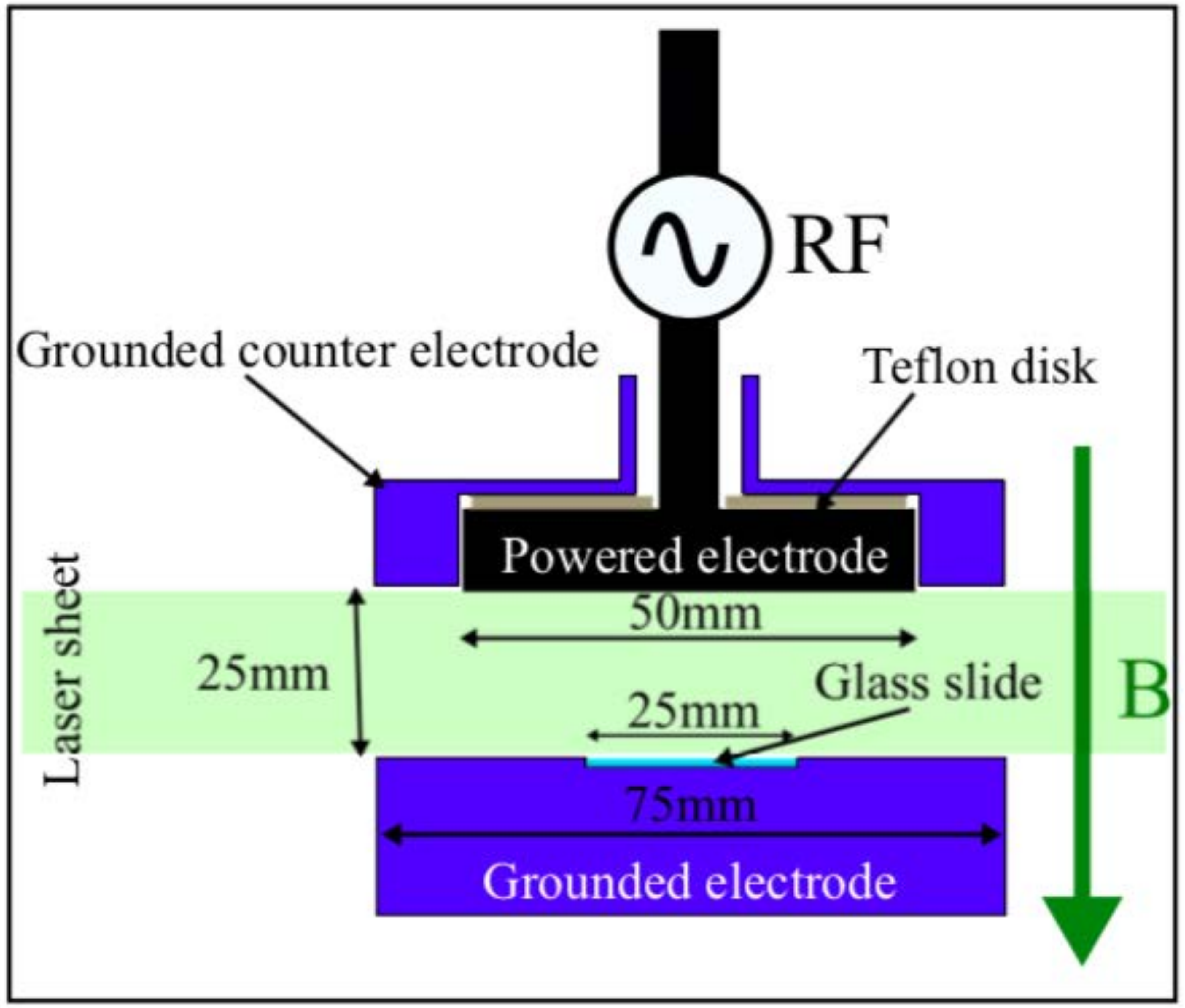
Particle growth in reactive plasmas

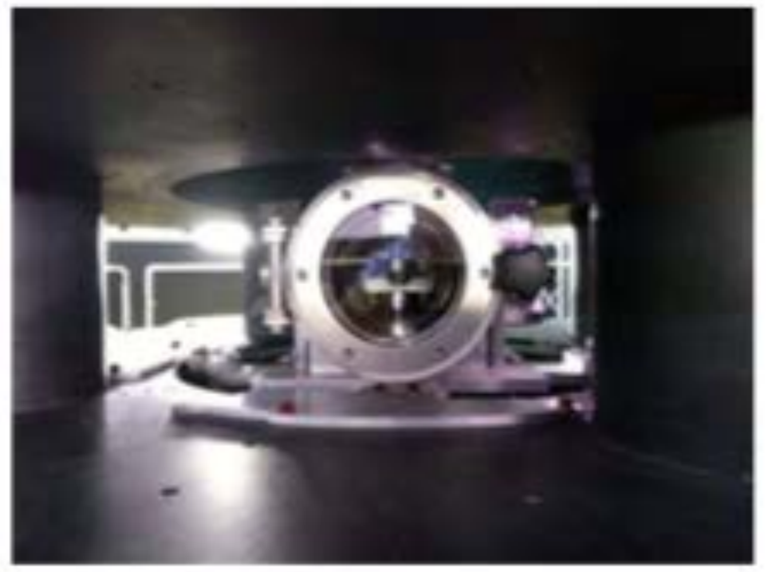
- In a reactive plasma, particles can be formed directly from the gaseous phase.
- It is a multi-step process where the plasma has sufficient energy density to break up complex molecules.
- The resulting ions can undergo a combination of chemical and physical reactions to form nm to μm sized particles.
- These processes can occur in the cooler, denser edge plasma.



Recent results: Dust particle growth is modified by the presence of a strong magnetic field

- Experiments are being performed in MDPX to investigate dust particle growth.
- Initial studies have used an argon plasma seeded with acetylene (C_2H_2) to form a reactive plasma.
- Carbon-rich particles quickly form in the plasma - within seconds.





Plasma glow at B=0T

Plasma glow at B=0.5T

Collaboration with L. Couedel, CNRS / Univ. Saskatchewan

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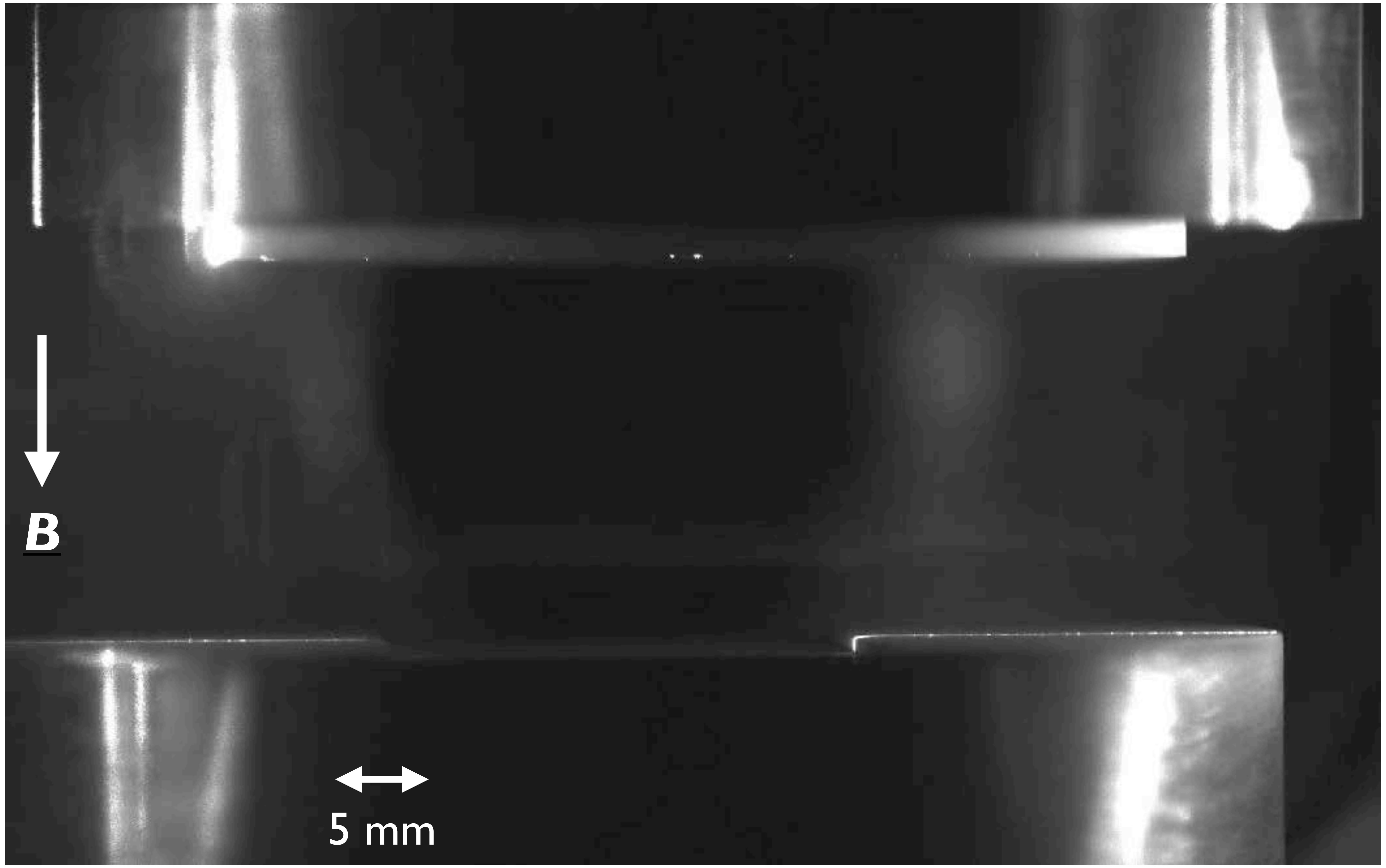


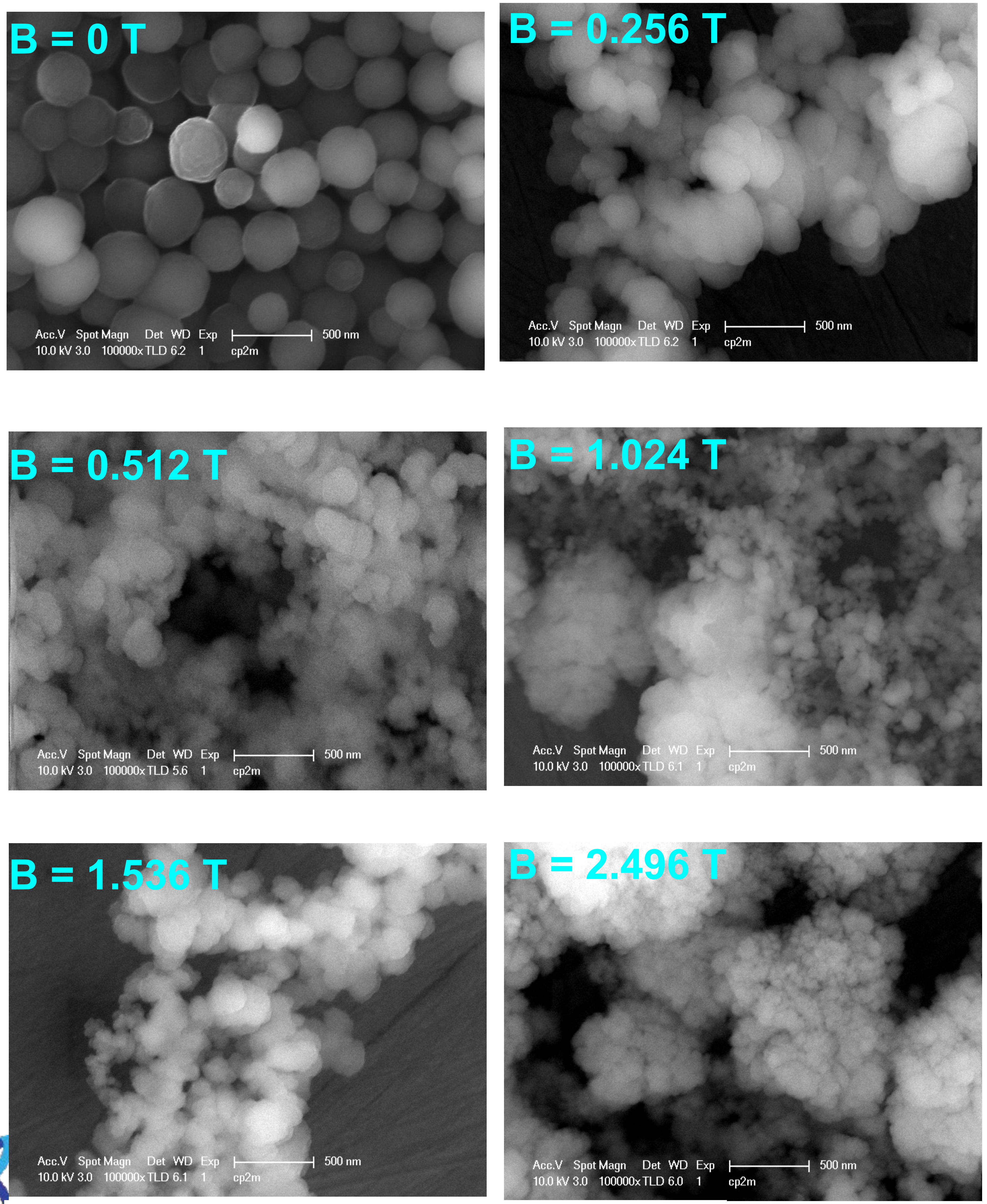
Real-time movie of carbon nanoparticle growth at B = 2.02 T

Collaboration with L. Couedel, CNRS / Univ. Saskatchewan

Characterizing the grown particles

SEM images of grown particles

- At B = 0 T, the particles form mostly uniform spheres approximately 0.25 to 0.3 μm in diameter.
- With increasing magnetic field:
  - Particle size is smaller
  - Large aggregates of small particles form
  - Increasing porosity of assembled particles
  - L. Couëdel, *et al. Plasma Res. Express* **1**, 015012–19 (2019).



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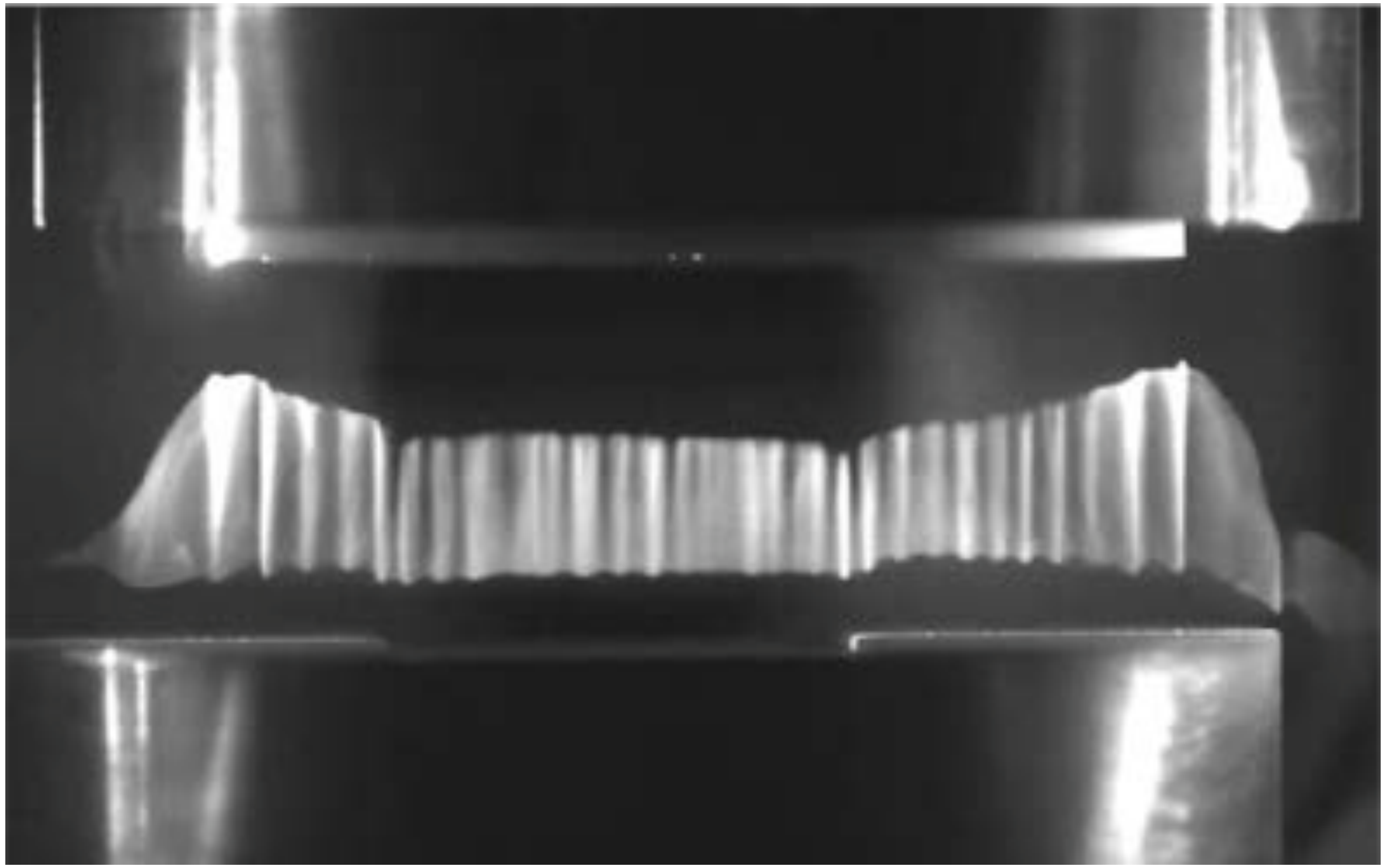
Decoupling: filaments vs magnetic field

- Initial results - show modification of particle growth with increasing magnetic field
- What precisely is the mechanism: is it the magnetic field or is there a contribution due to filaments - or both?



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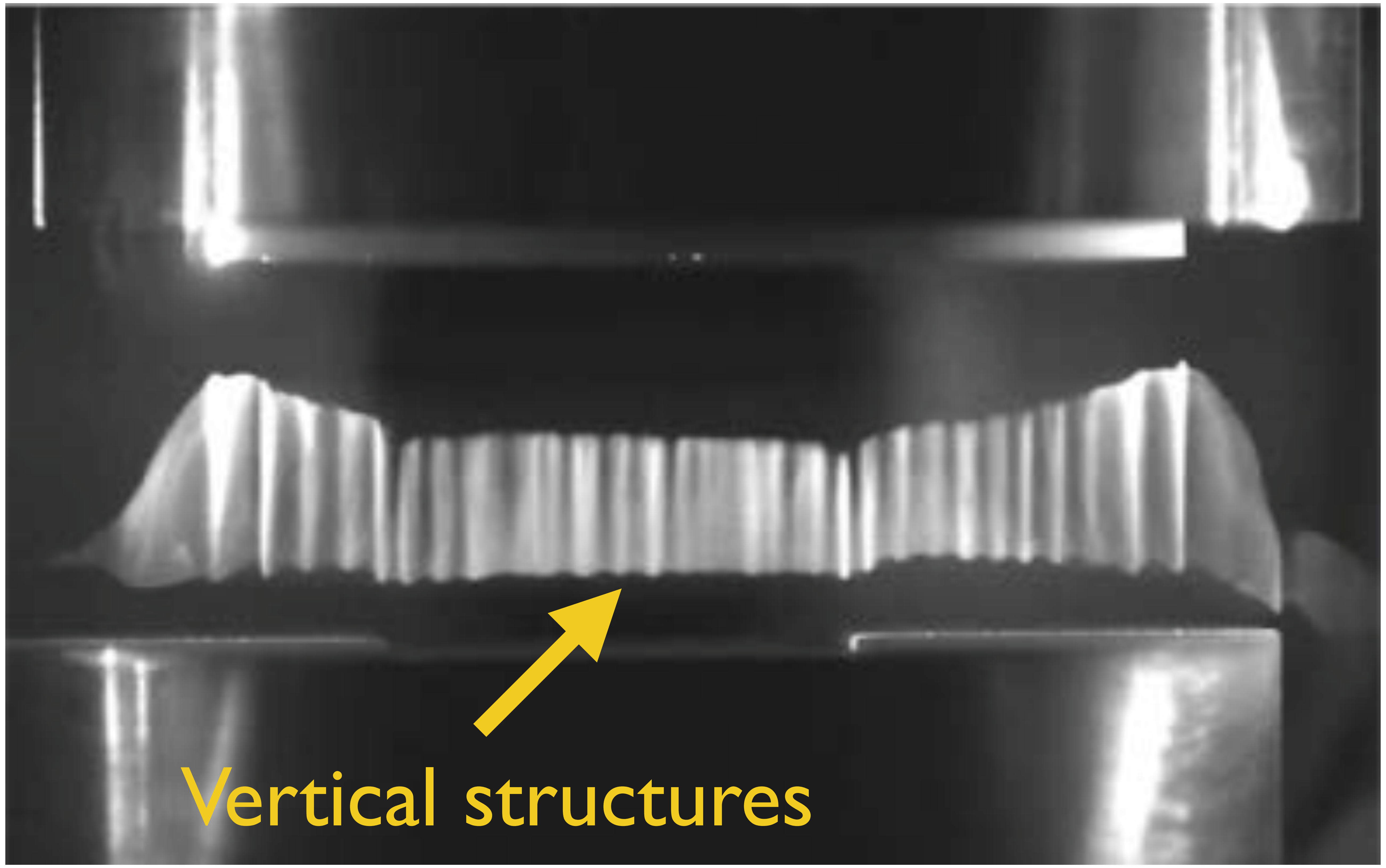
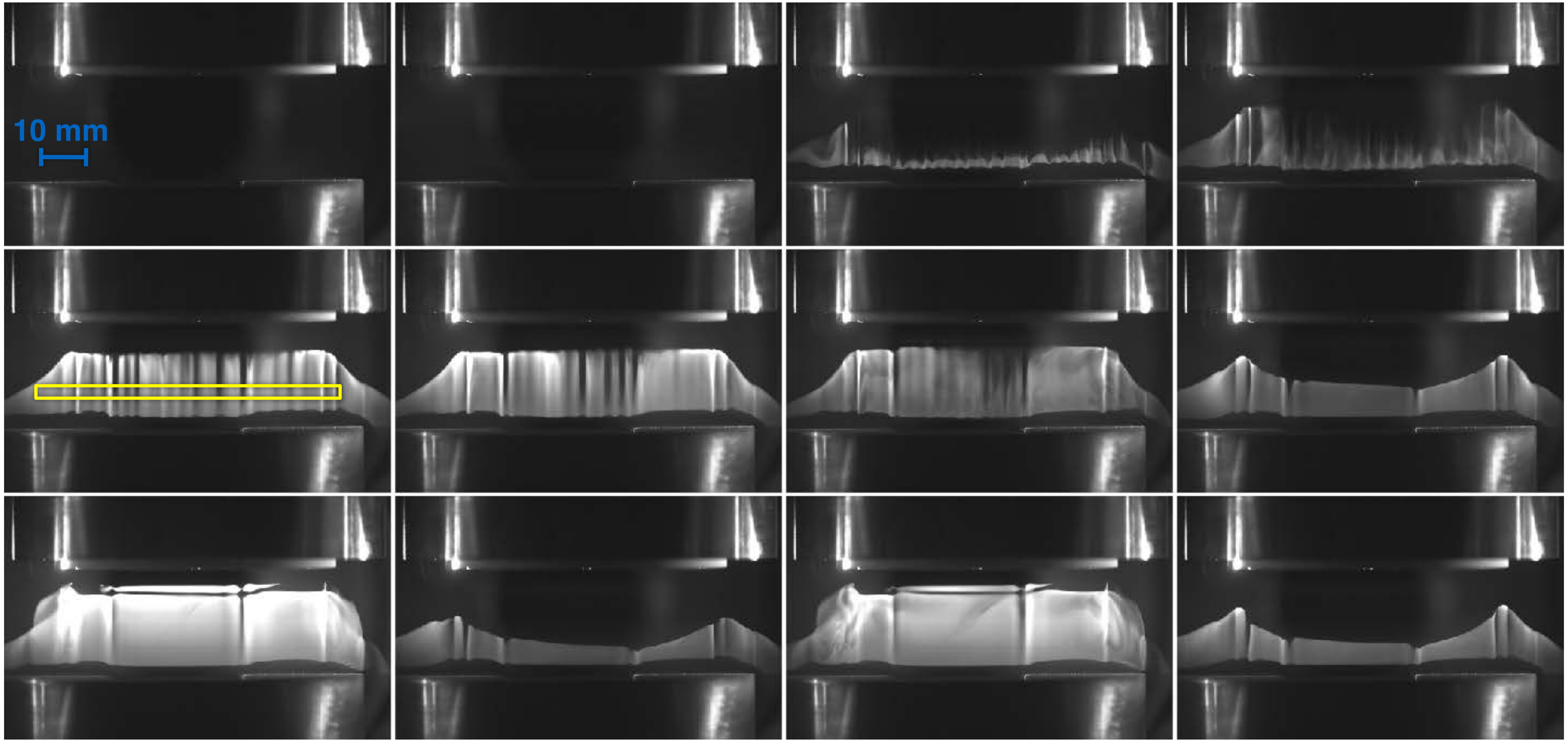


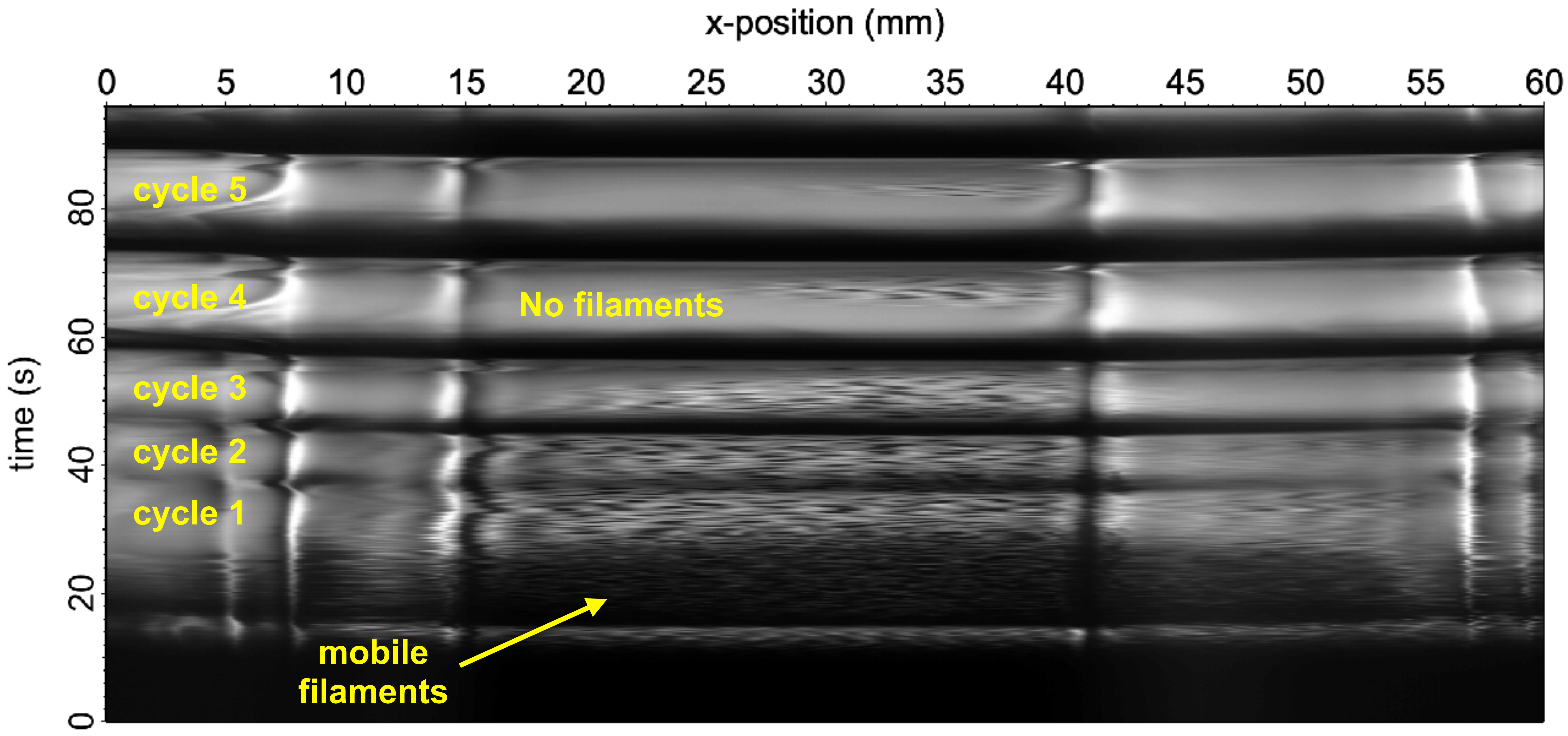
Redesign of growth experiment



- An electrode redesign was performed to localize the formation of filaments
- S. Jaiswal, et al., *Jpn. J. Appl. Phys* **59**, SHHC07 (2020)

Redesign of growth experiment

- Time/space sequence showing the time evolution of the filaments.
- Particularly, note the localization of a few filaments.



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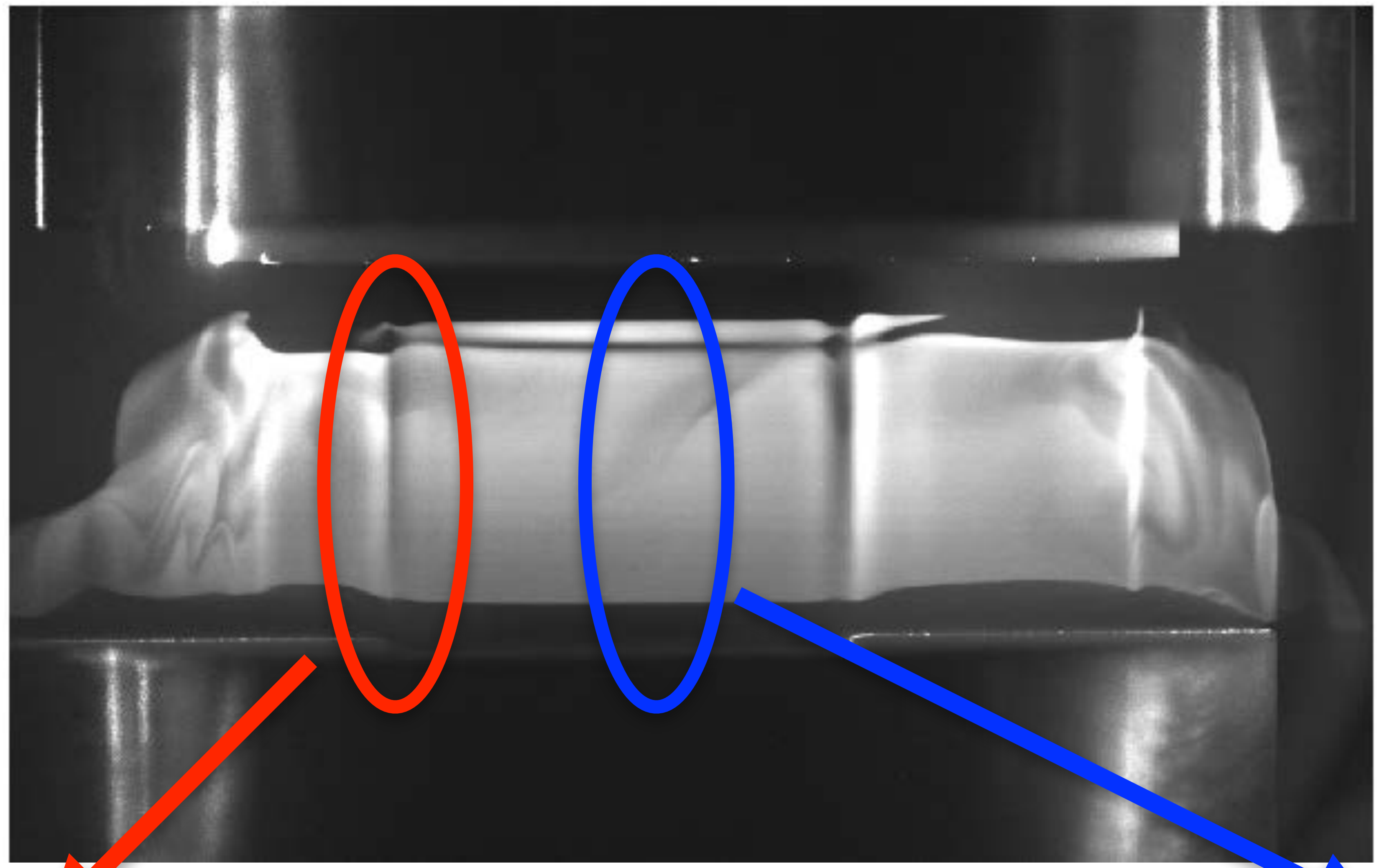
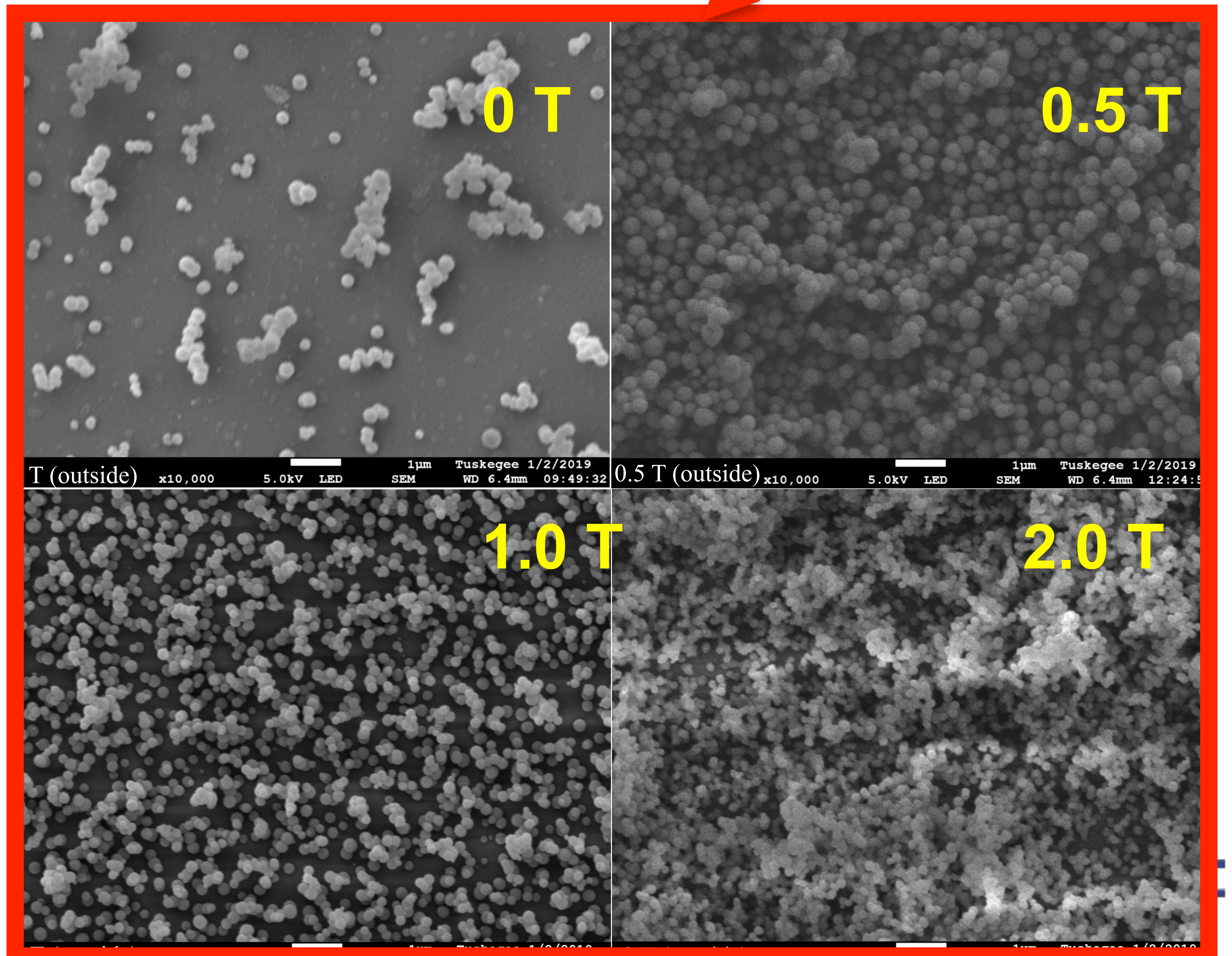
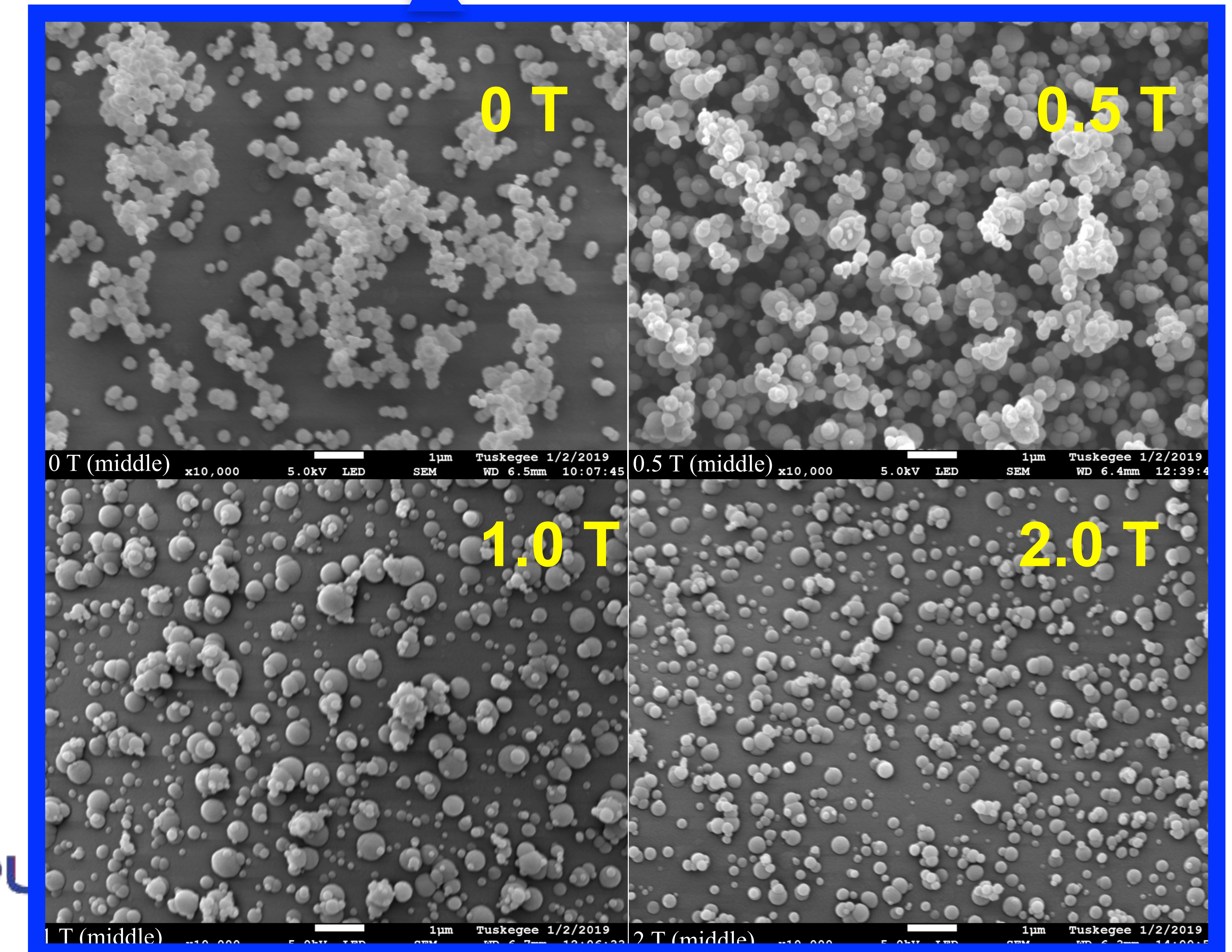
Decoupling: filaments vs magnetic field

Electrode modification to reduce filamentation near the center.



Evolution of particle growth in regions with filaments and reduced filaments





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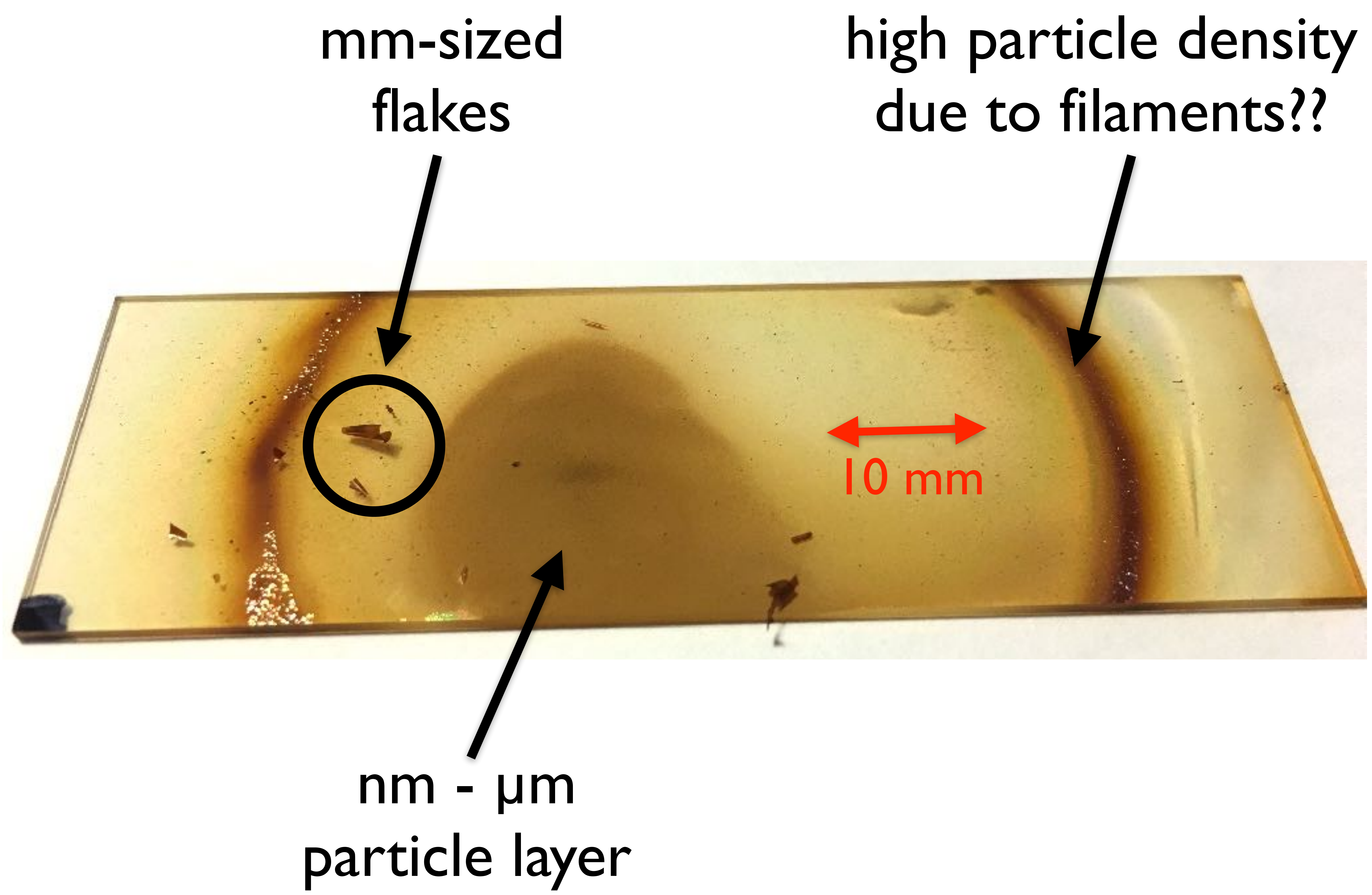
Future directions: Determine the characteristics of the magnetized plasma that lead to the modification of the particle growth

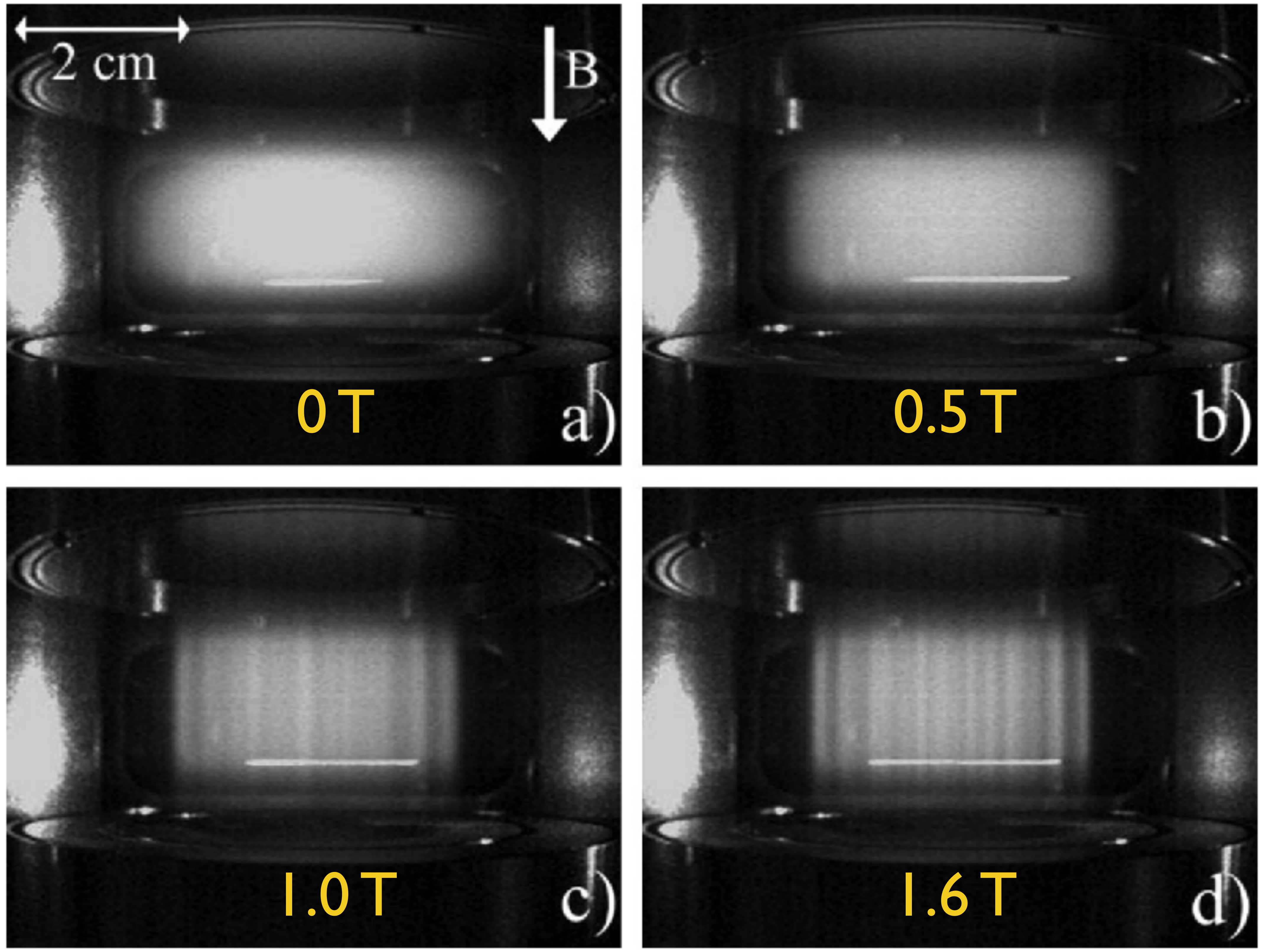
- The initial studies have demonstrated that the particle growth process in the magnetized plasma differs from the unmagnetized case.
- However, the magnetized plasma has a number of different characteristics:
  - presence of filaments
  - modified density
  - modified electron temperature
- Is it possible to "direct" particle growth using a combination using plasma pattern formation?



Pattern formation (filamentation) in magnetized plasmas

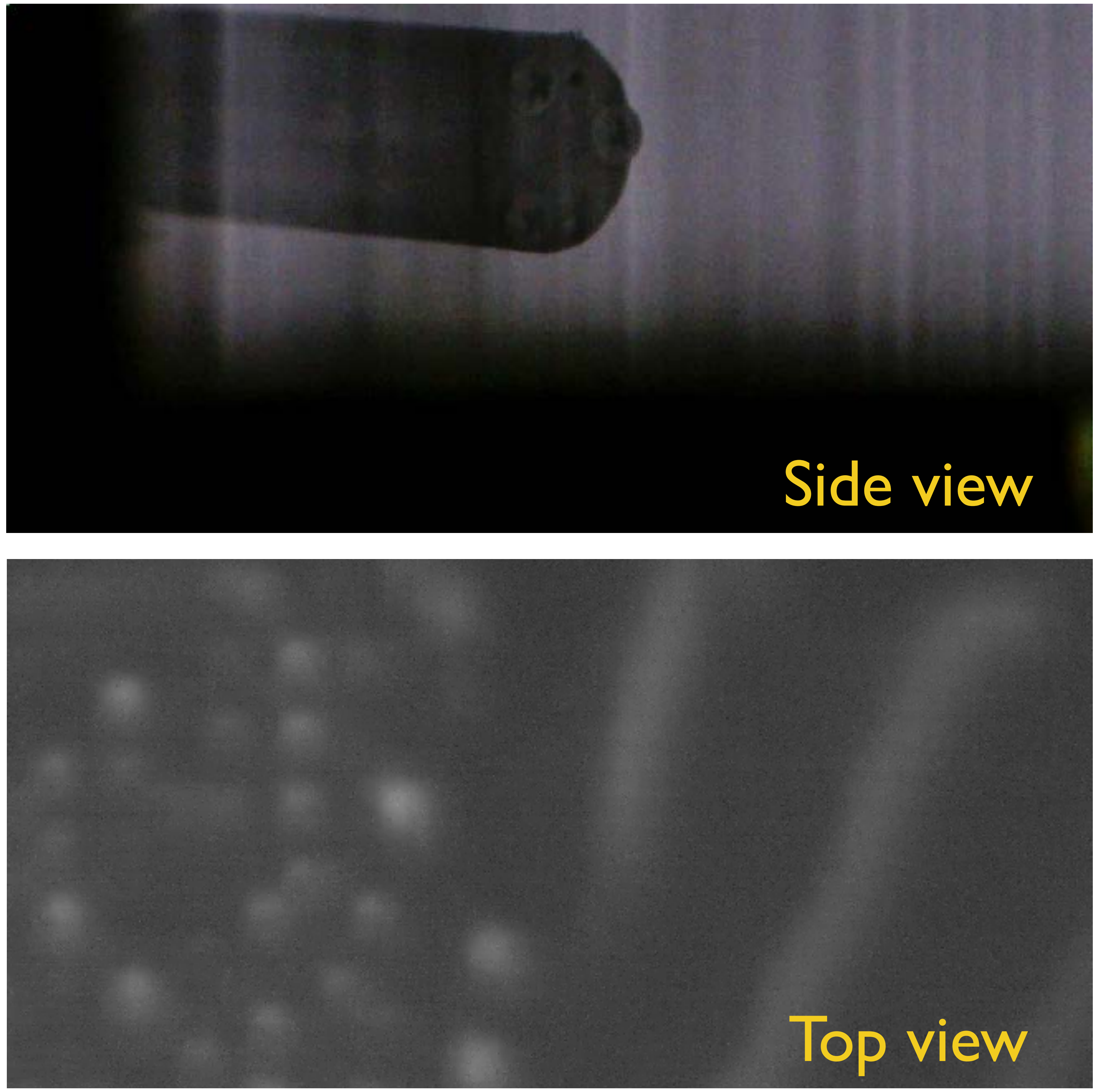
A brief aside on plasma filaments - observations

- First reported at MPE
- Structures in the plasma glow aligned to the magnetic field



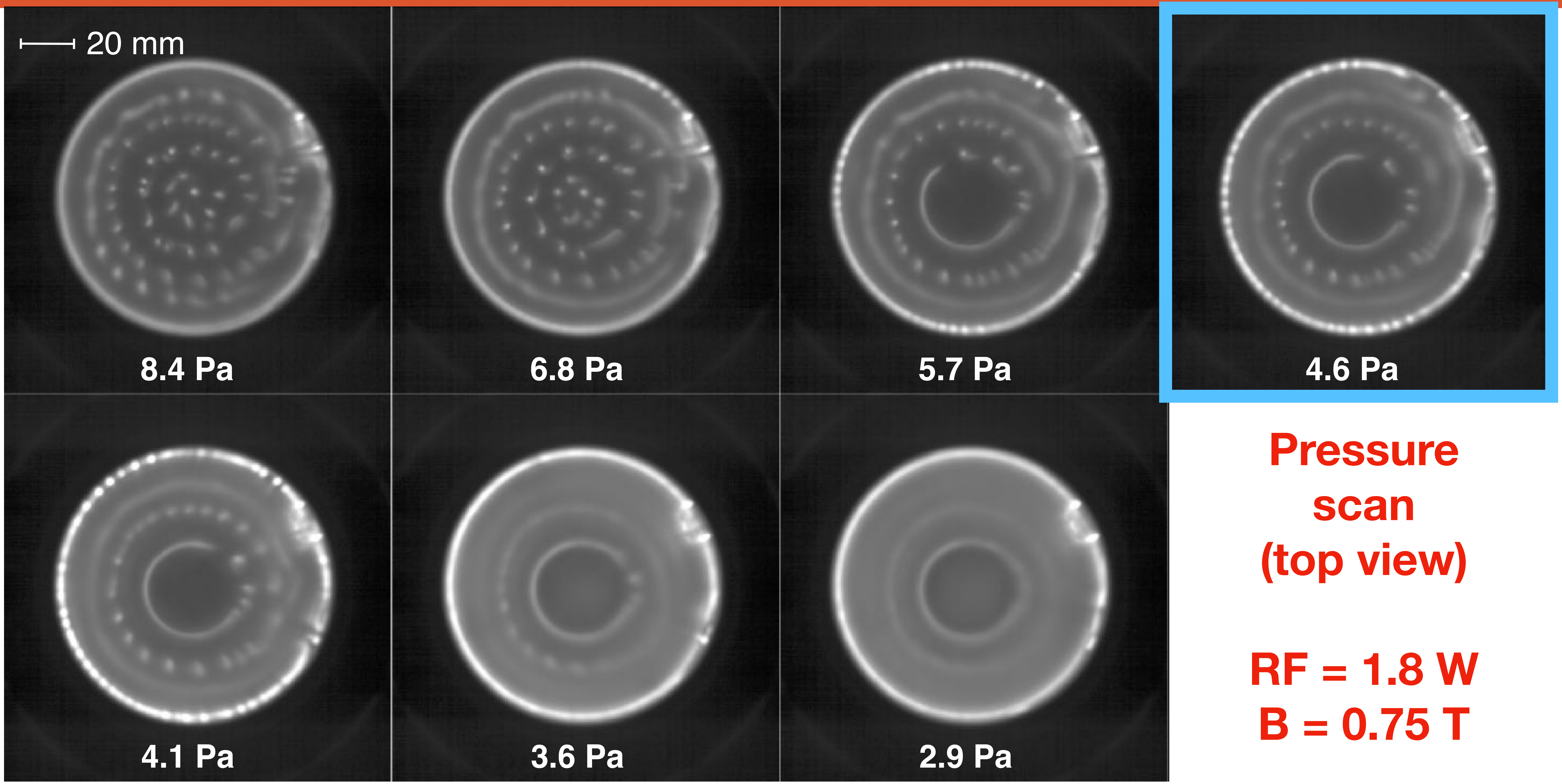
M. Schwabe, et al., PRL, **106**, 215004 (2011)

MDPX: Argon plasma at B = 0.75 T, P = 2.9 Pa, and RF = 1.8 W



E. Thomas, et al., PPCF, **62**, 014006 (2020)

Filamentation: Ordered, plasma structures



Pressure scan (top view)

RF = 1.8 W
B = 0.75 T

- The presence of filaments (plasma structures aligned parallel to the magnetic field) has been reported in earlier works [e.g., *M. Schwabe, et al., PRL, 2011*].
- Filaments generally appear at low pressure, at low rf power, and at higher magnetic fields; <u>filaments dissipate due to enhanced collisions with neutrals</u>.

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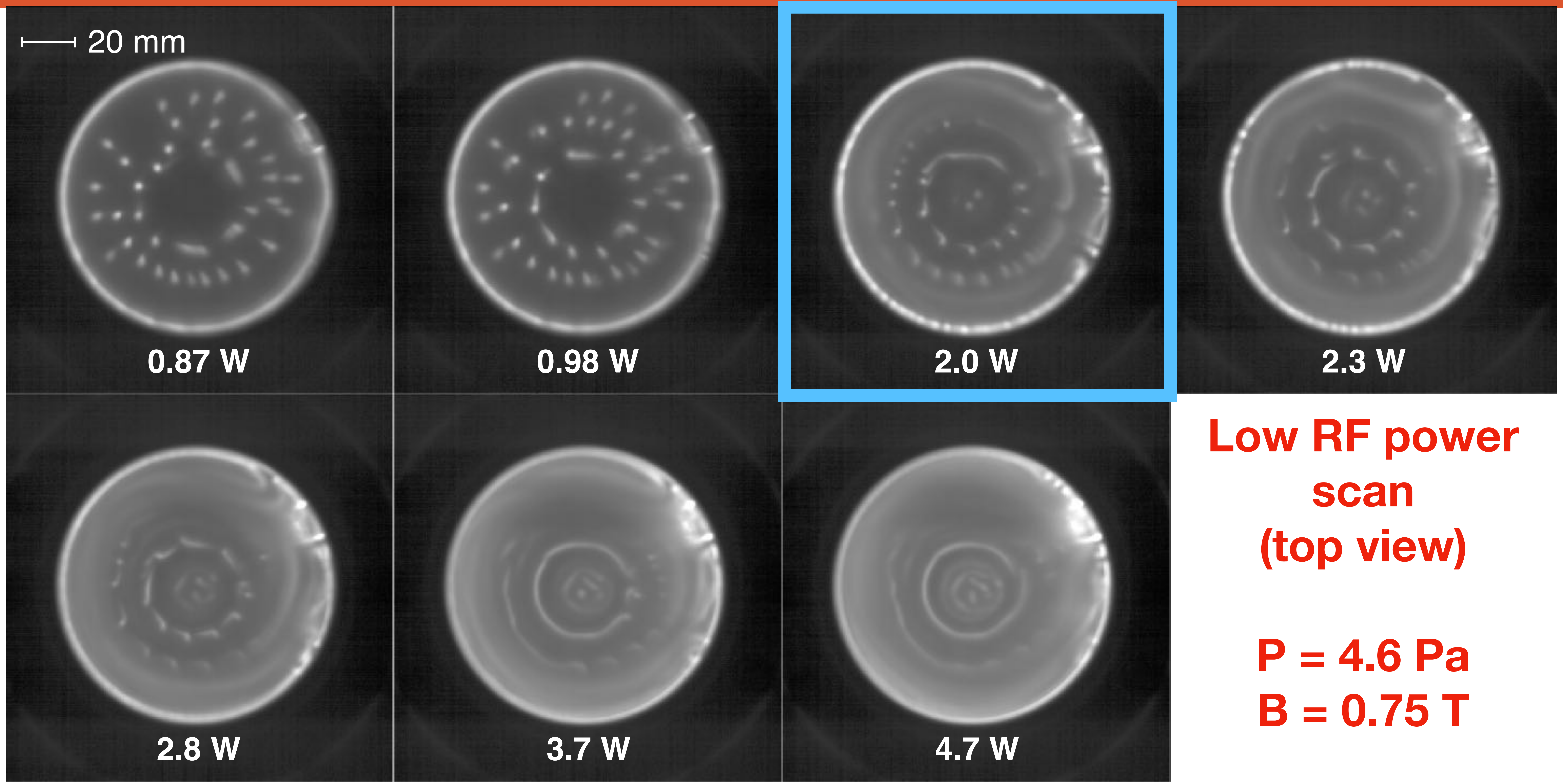
Filamentation: Ordered, plasma structures

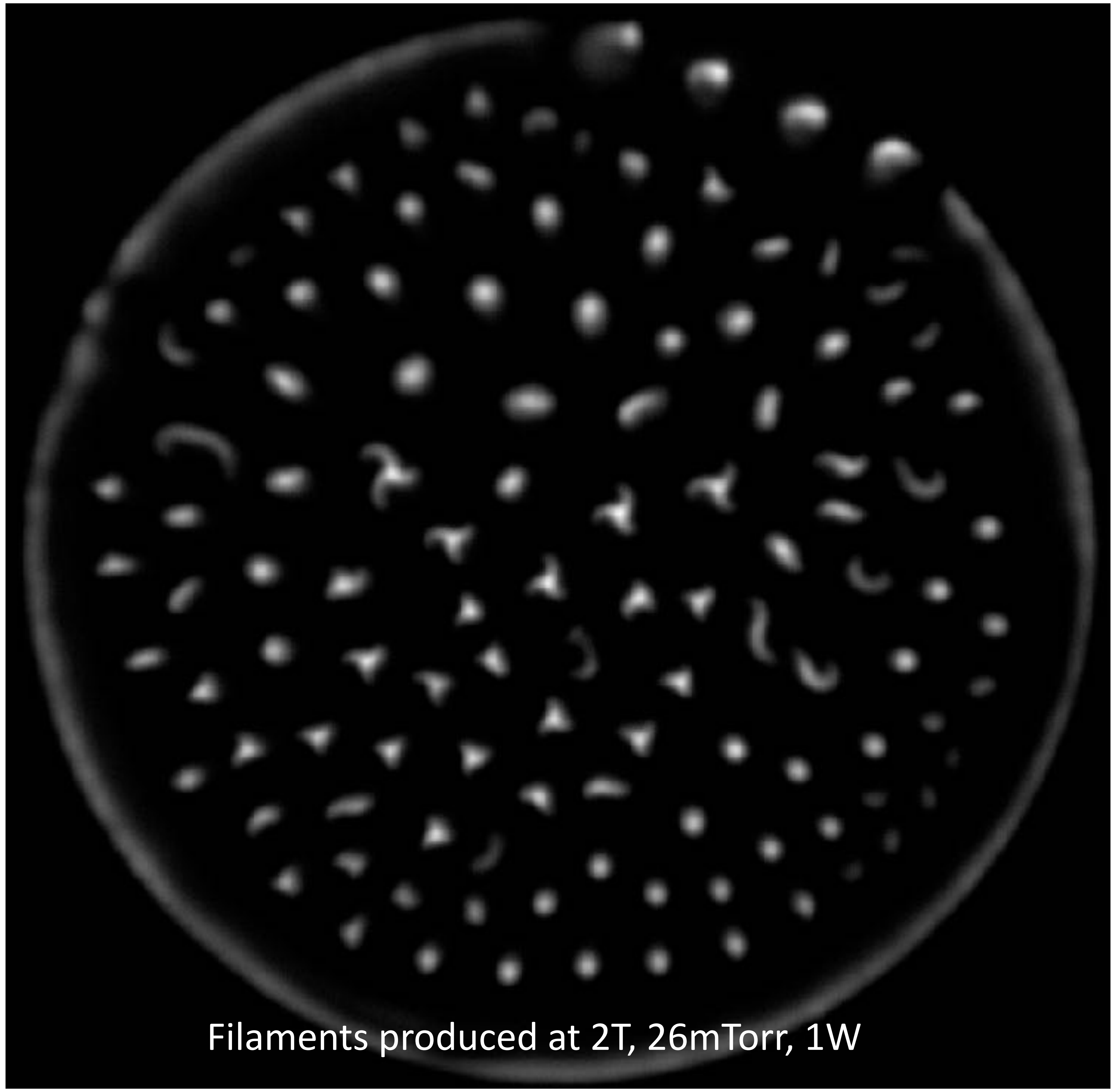


Low RF power scan (top view)

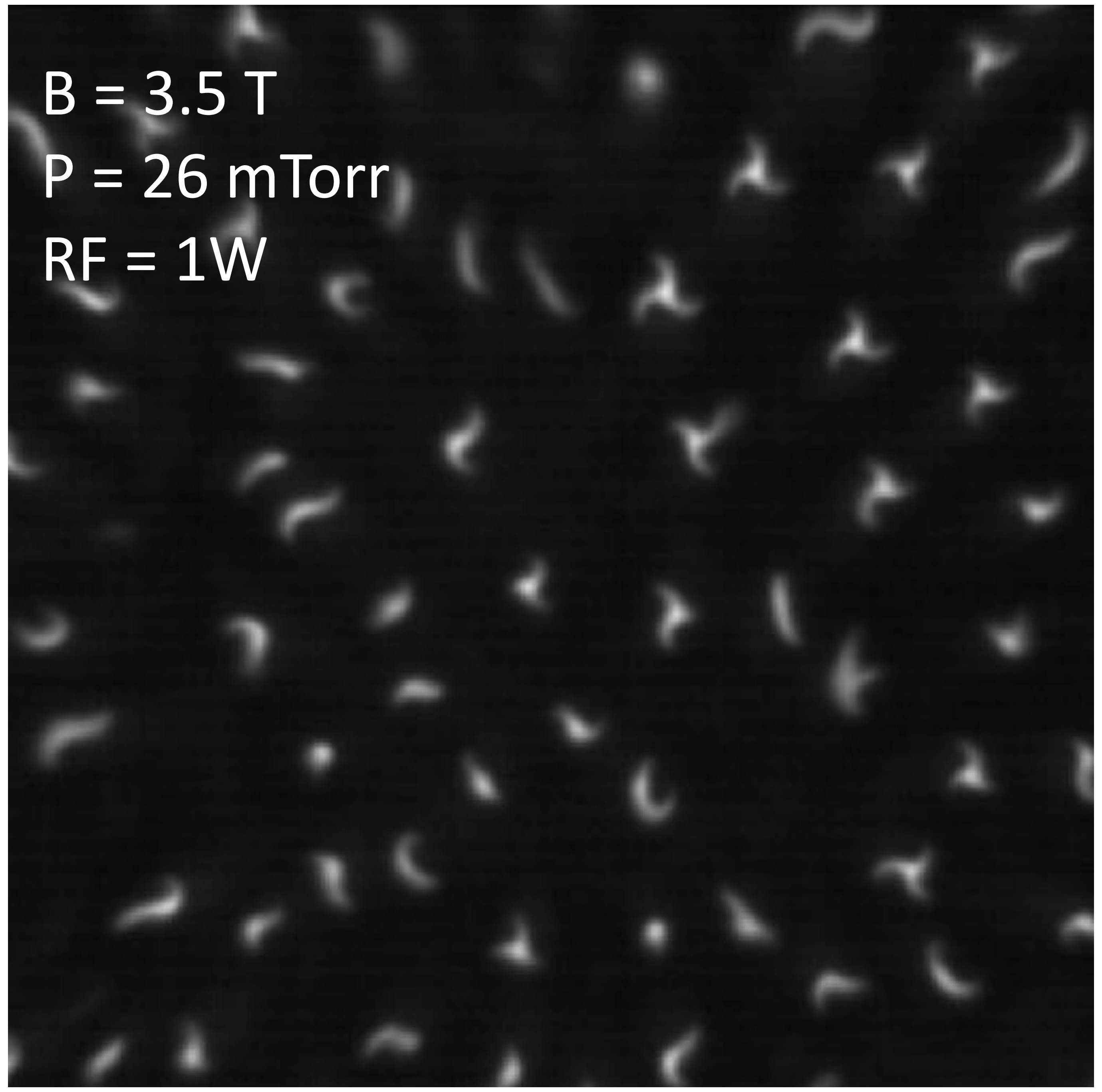
P = 4.6 Pa
B = 0.75 T

- RF power scan shows qualitatively similar results with increasing power; .
- One difference - appearance of single, smaller filaments at center.
- But, physical process must be quite different - because pressure is constant.

Filaments in **Argon** at different magnetic field strengths and pressures



Filaments produced at 2T, 26mTorr, 1W

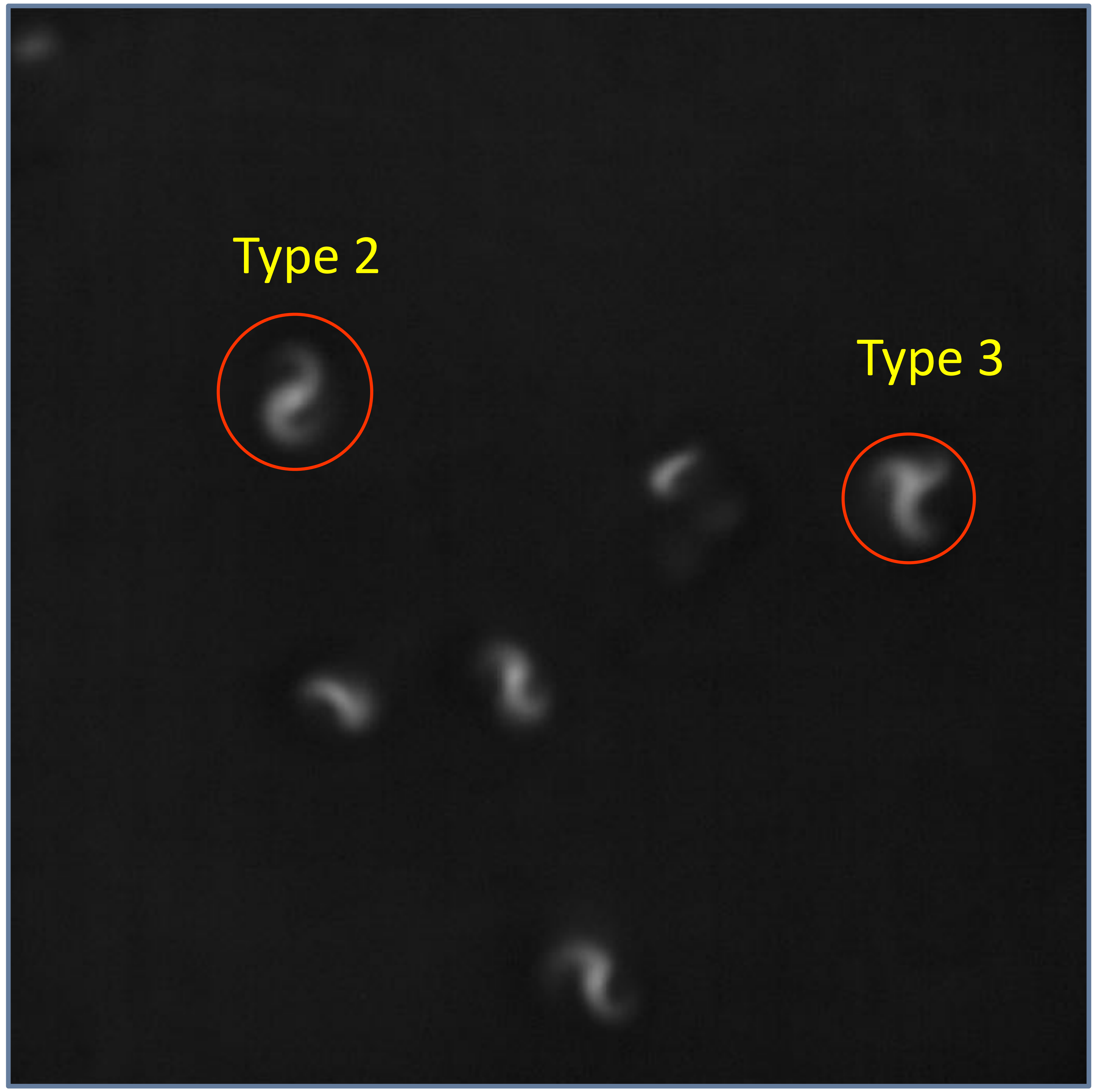


- Individual filaments were observed in argon plasma at low pressures between 5-45mTorr (~0.66-6Pa)
- Confirmed the existence of filaments with new experiment configuration.
- Reproducible!

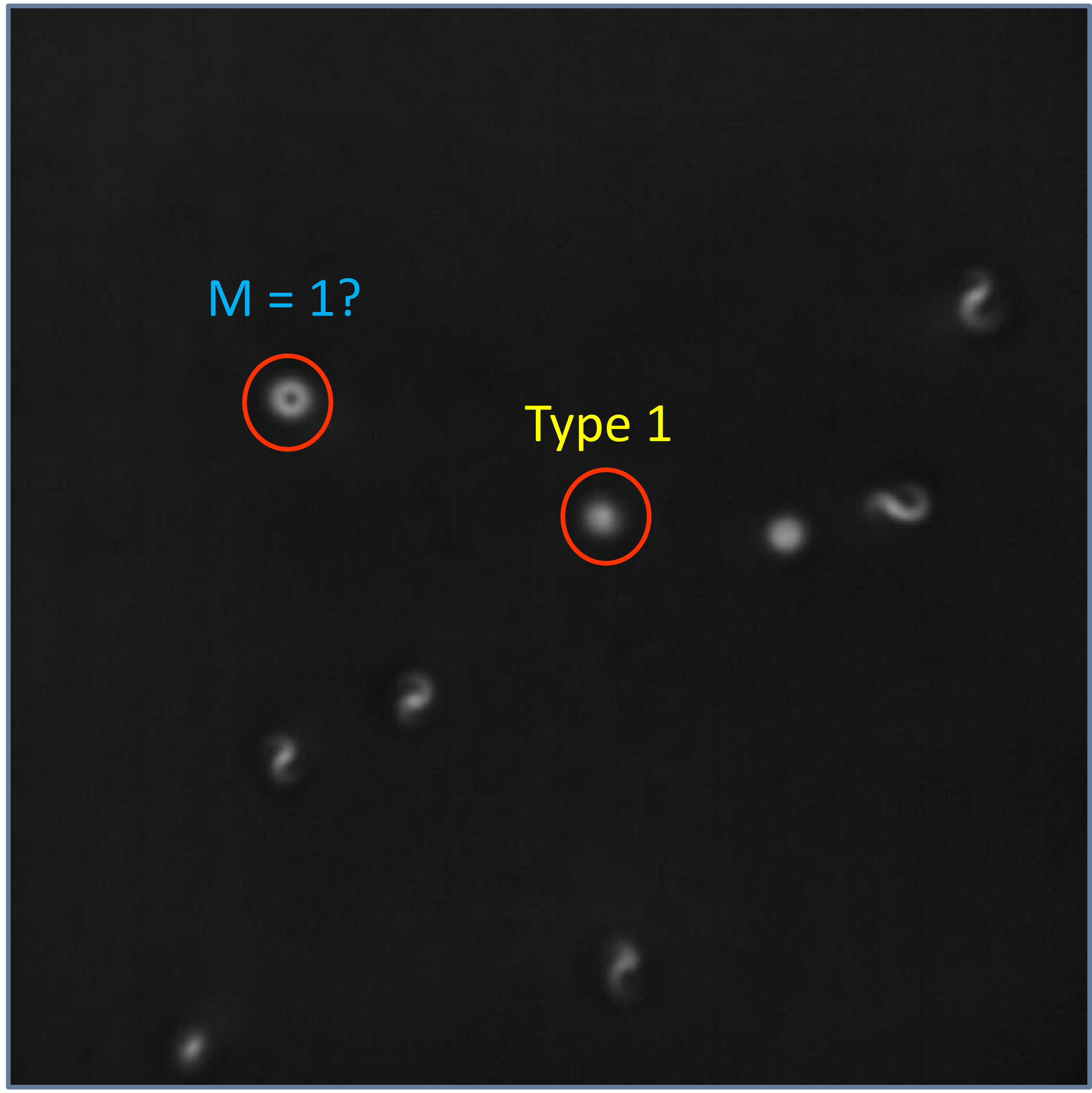
Exploring Hall parameter space with changing ion mass

Reproducible!

Filaments observed in **Neon** gas



B discharge: 3T – 1T
Pressure: 30mTorr (~4 Pa)
Power input: 1W



B discharge: 3T – 1T
Pressure: 26mTorr (~3.3 Pa)
Power input: 1W

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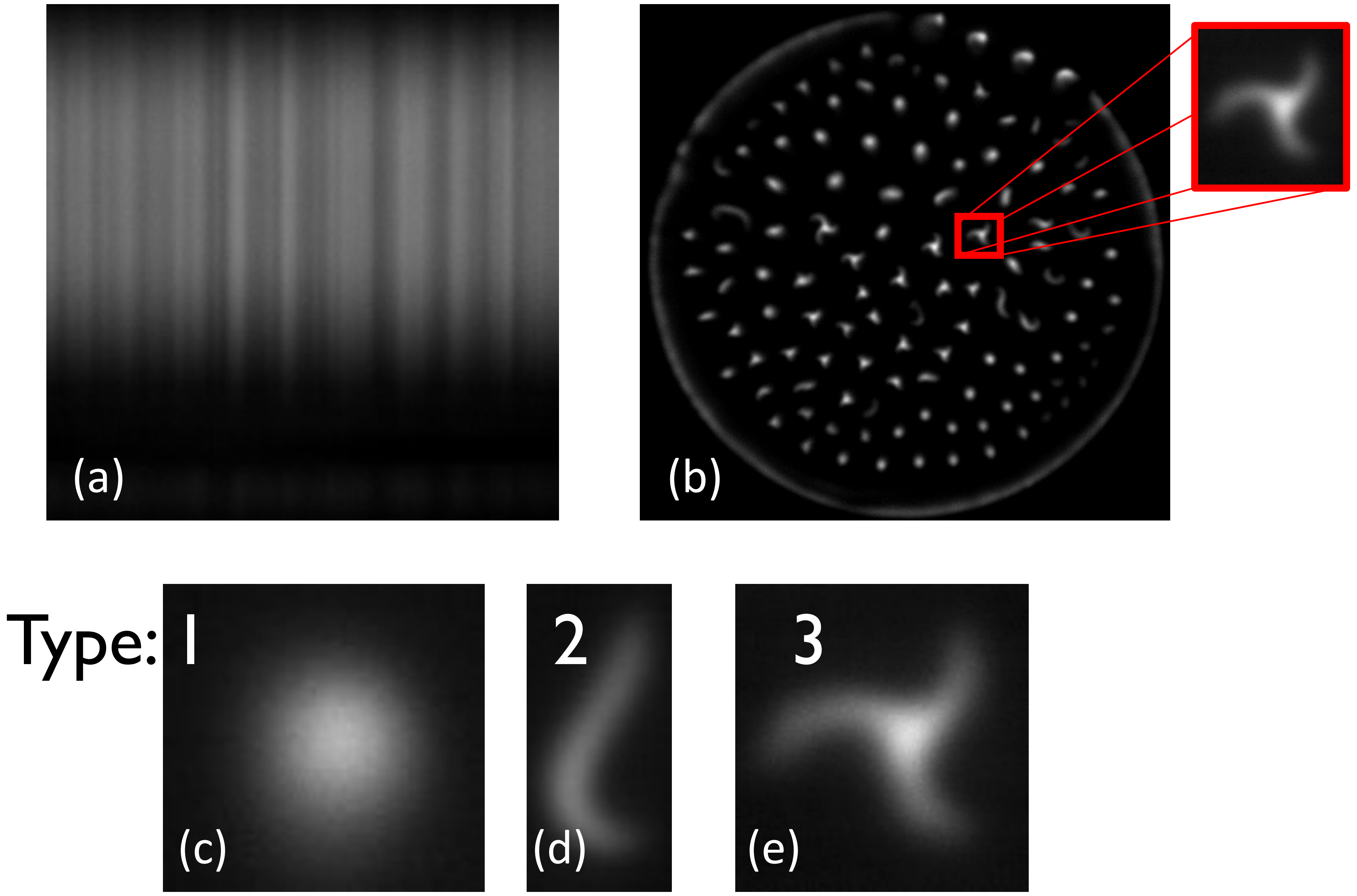
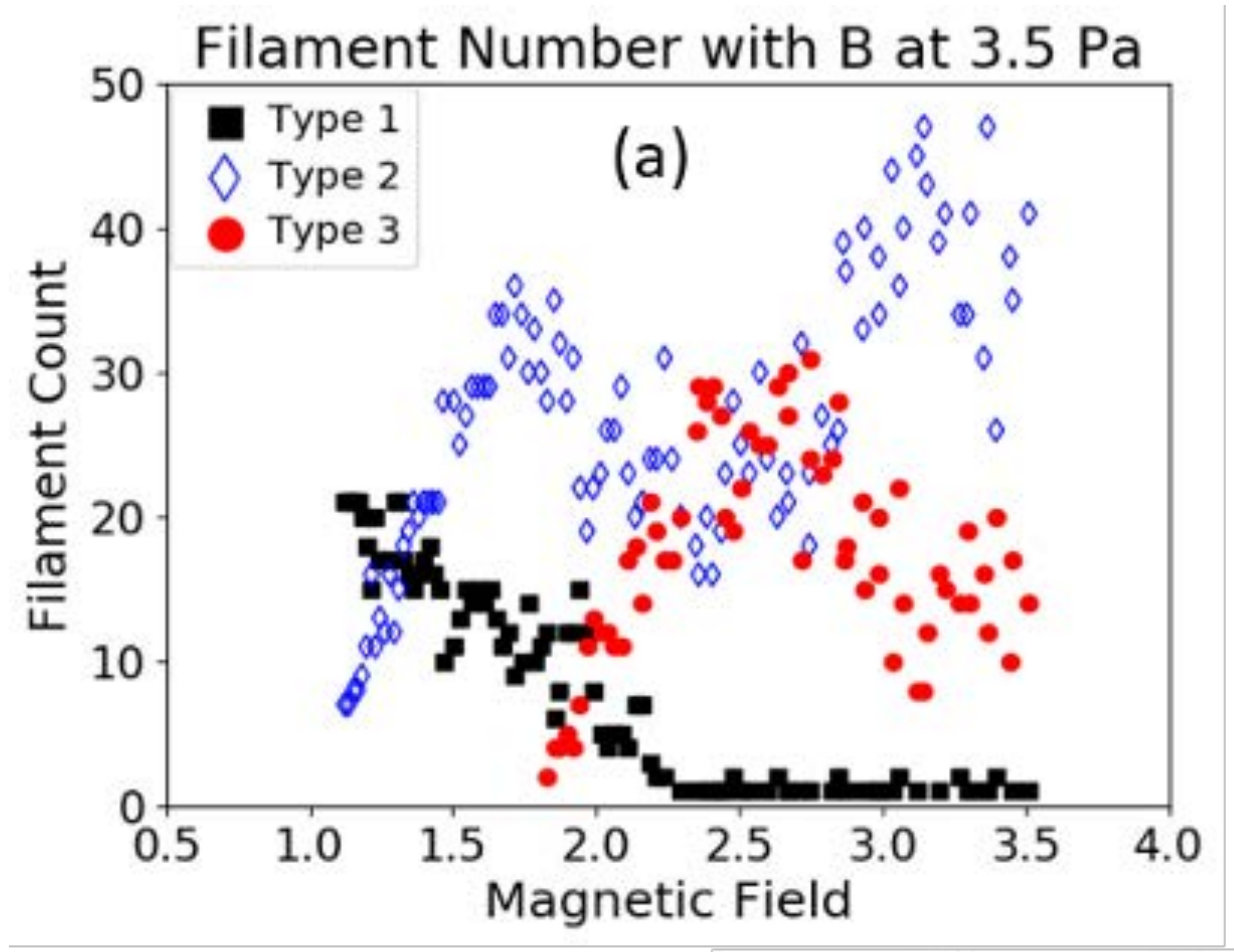
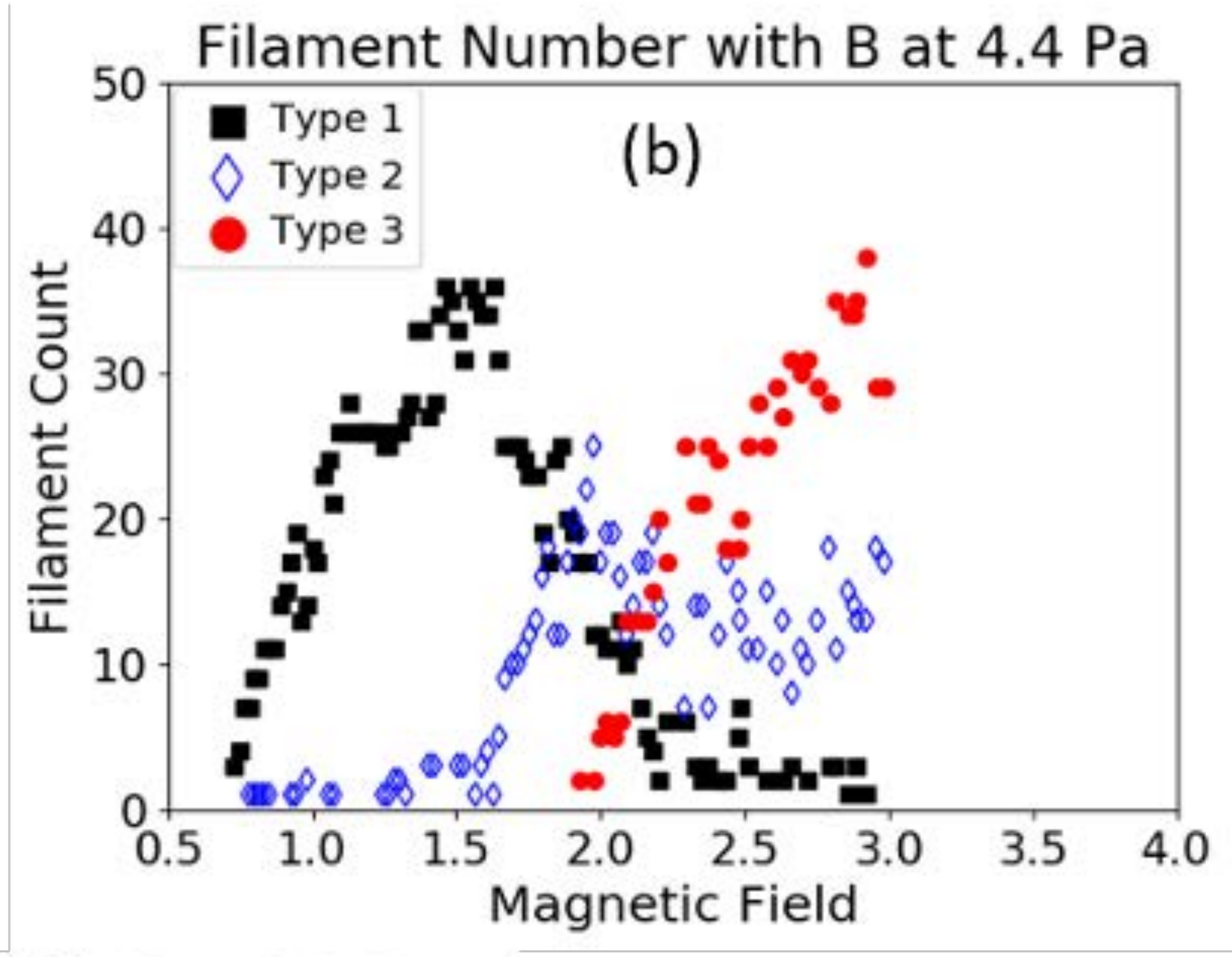
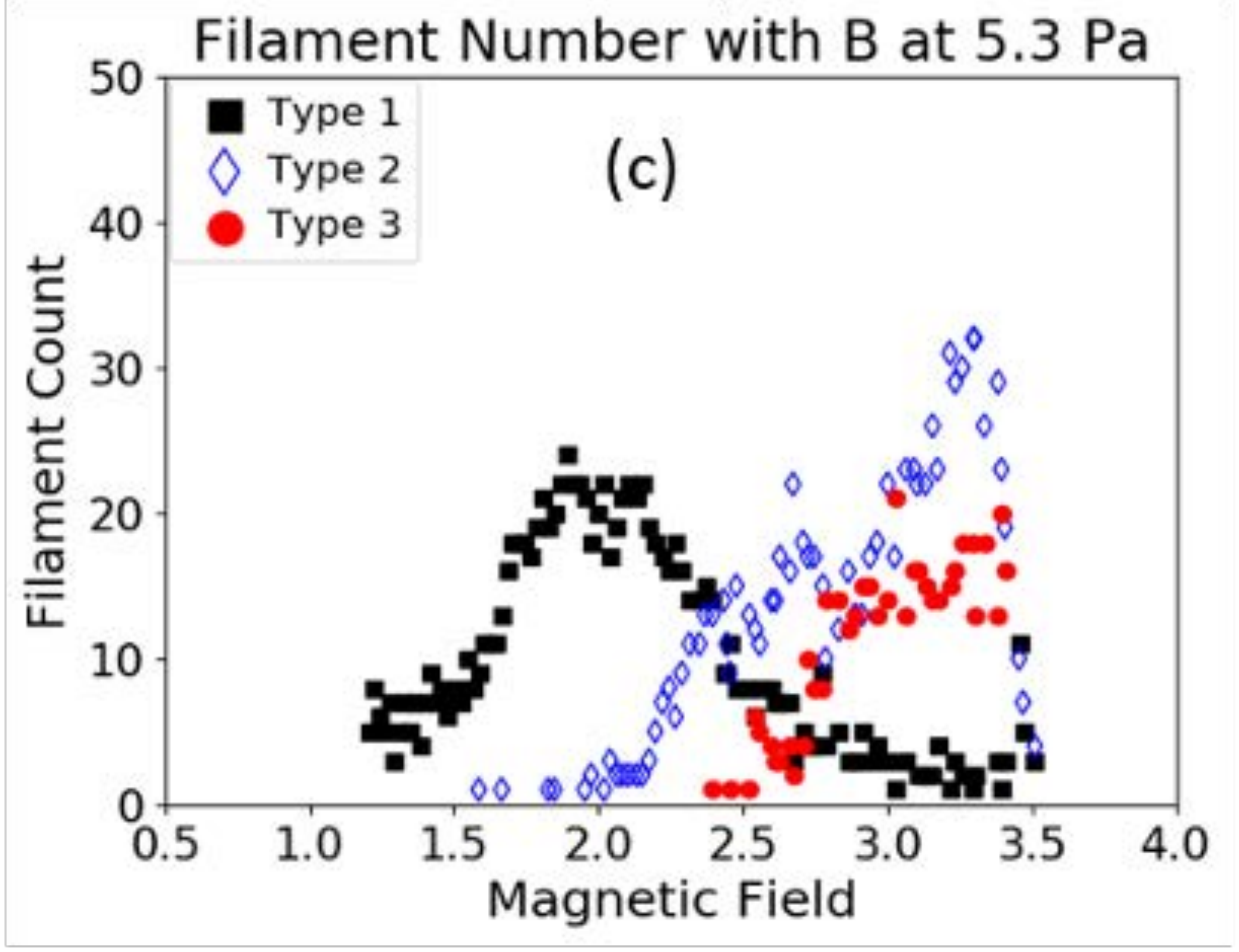
Exploring Hall parameter space with changing ion mass

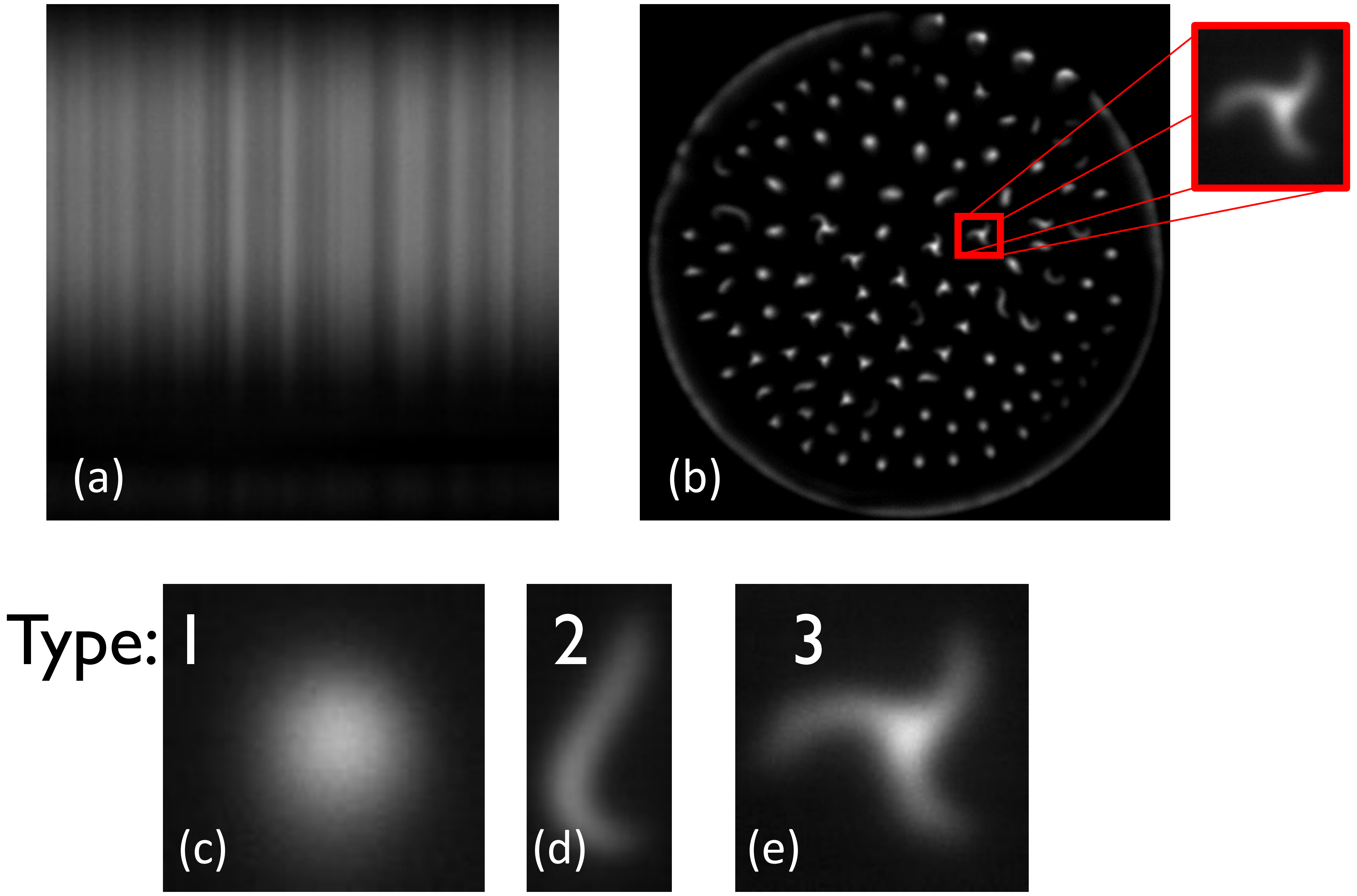


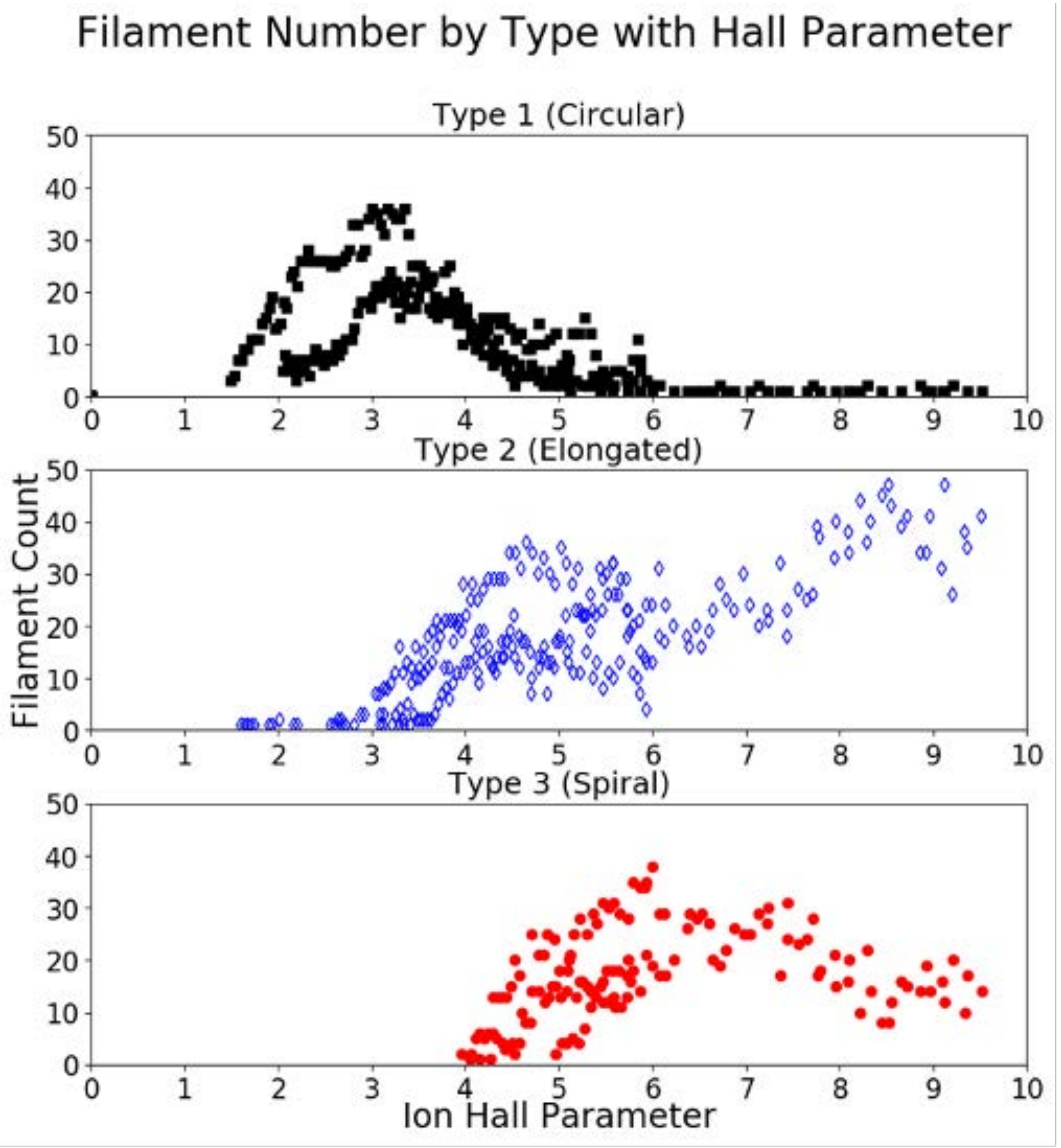






Exploring Hall parameter space with changing ion mass





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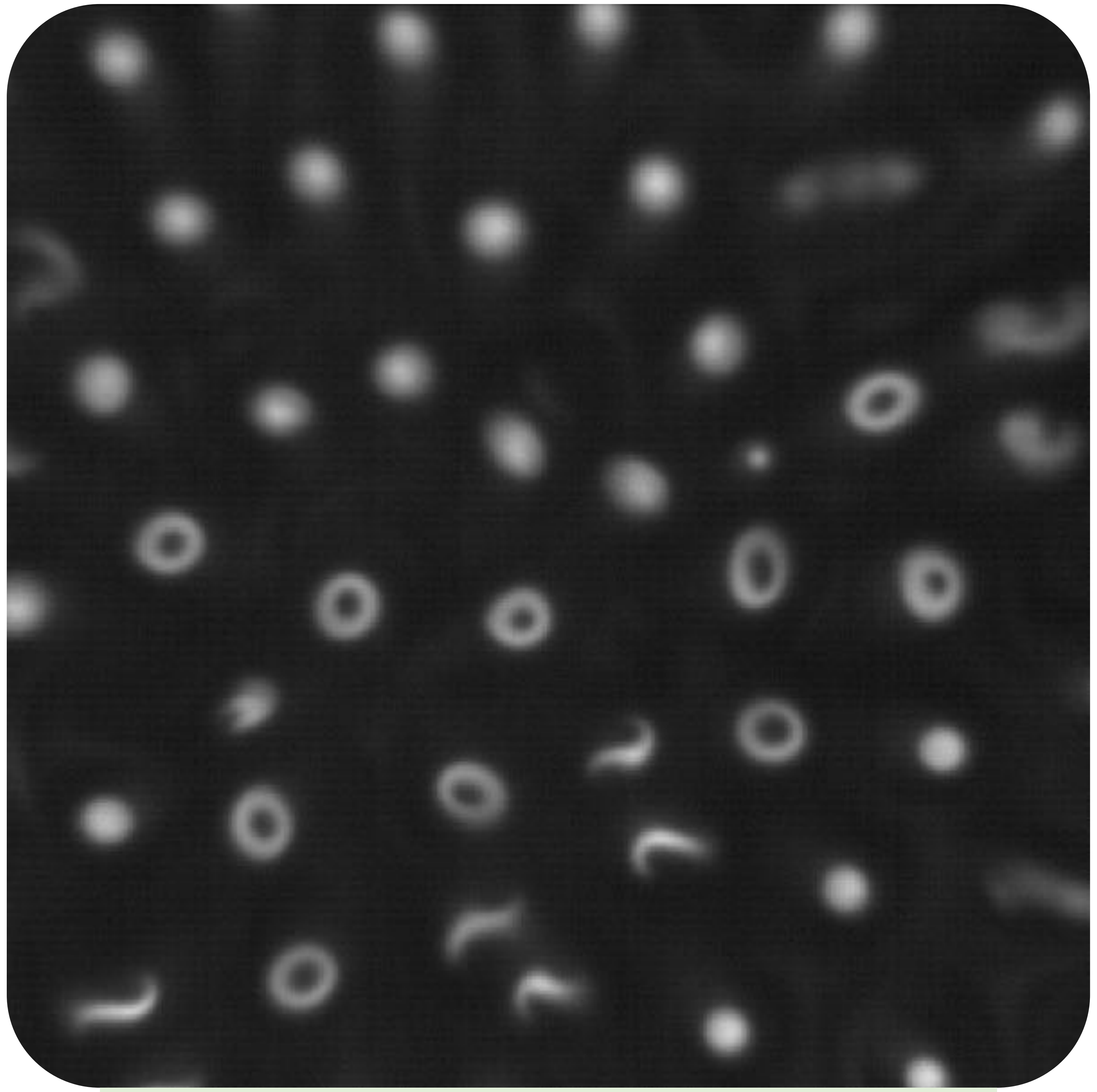
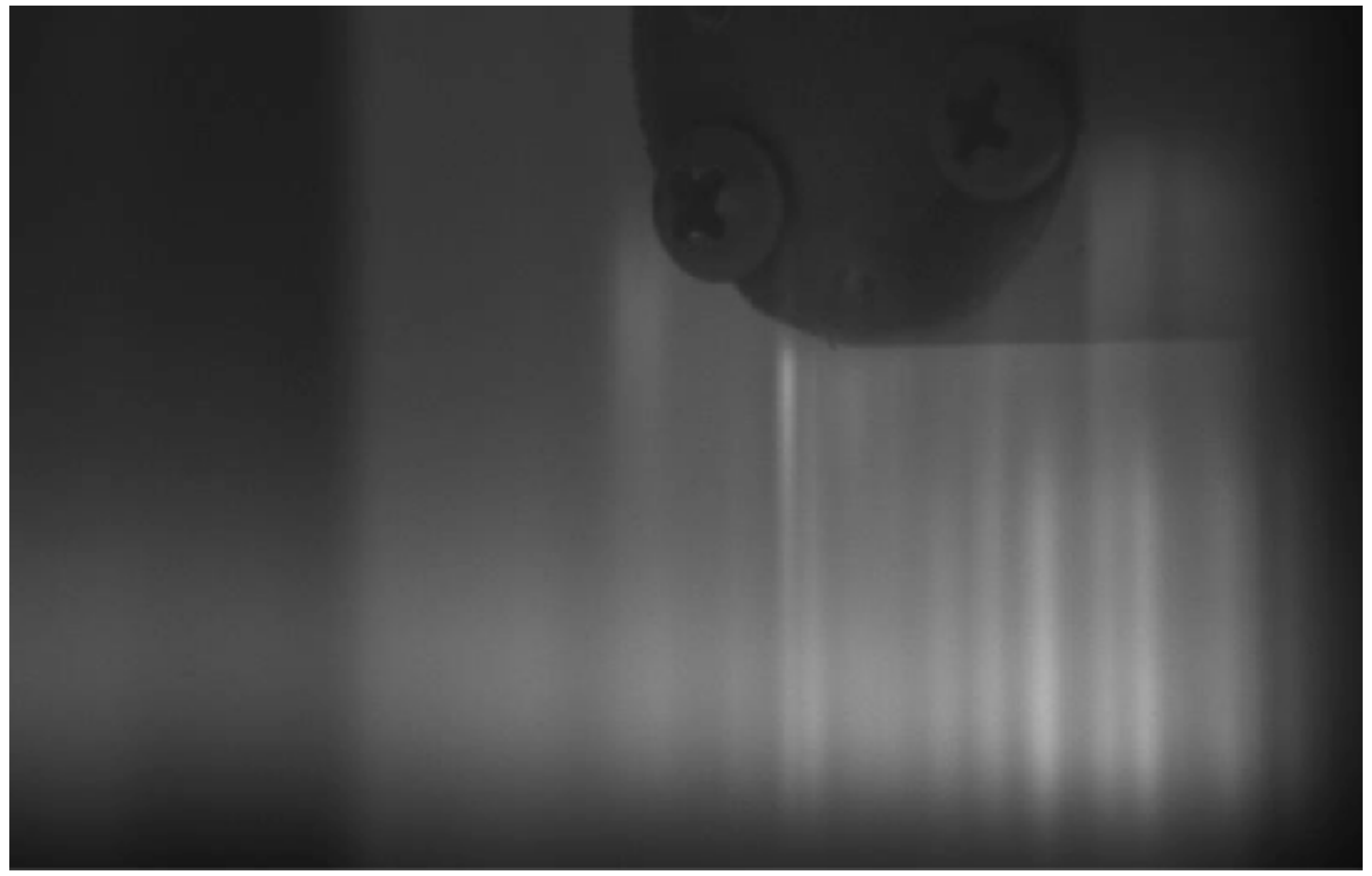
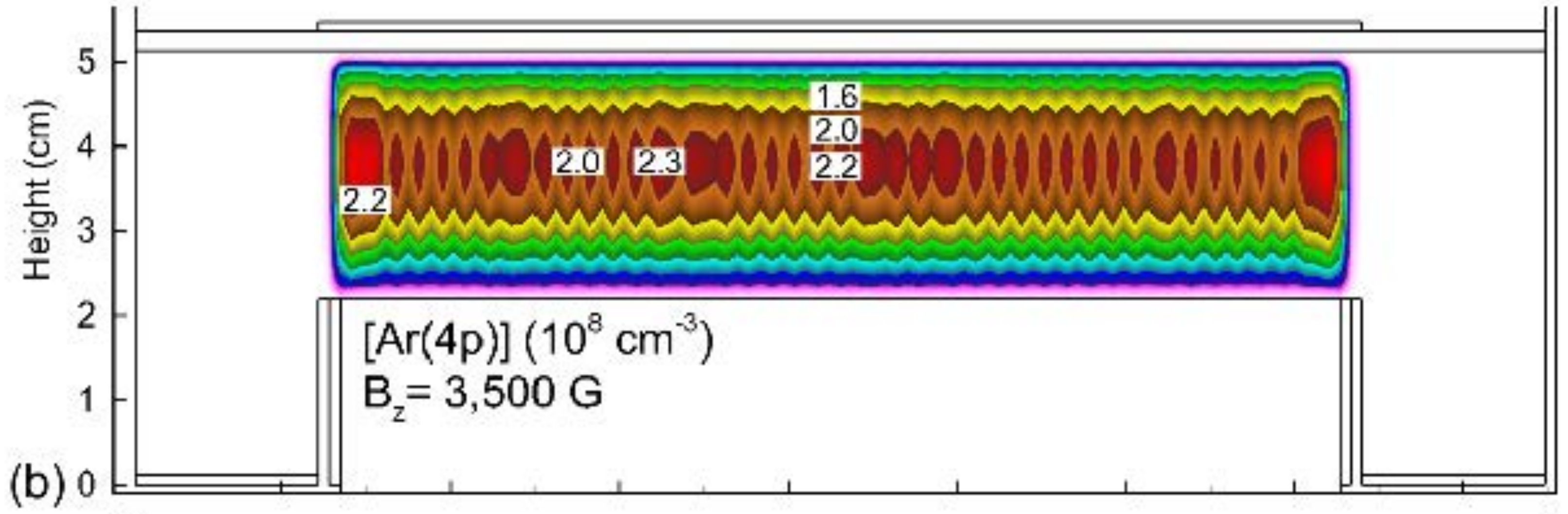
M = 1 filaments observed in multiple gases


Type 4 cheerio found in Neon


Type 4 cheerio found in Argon

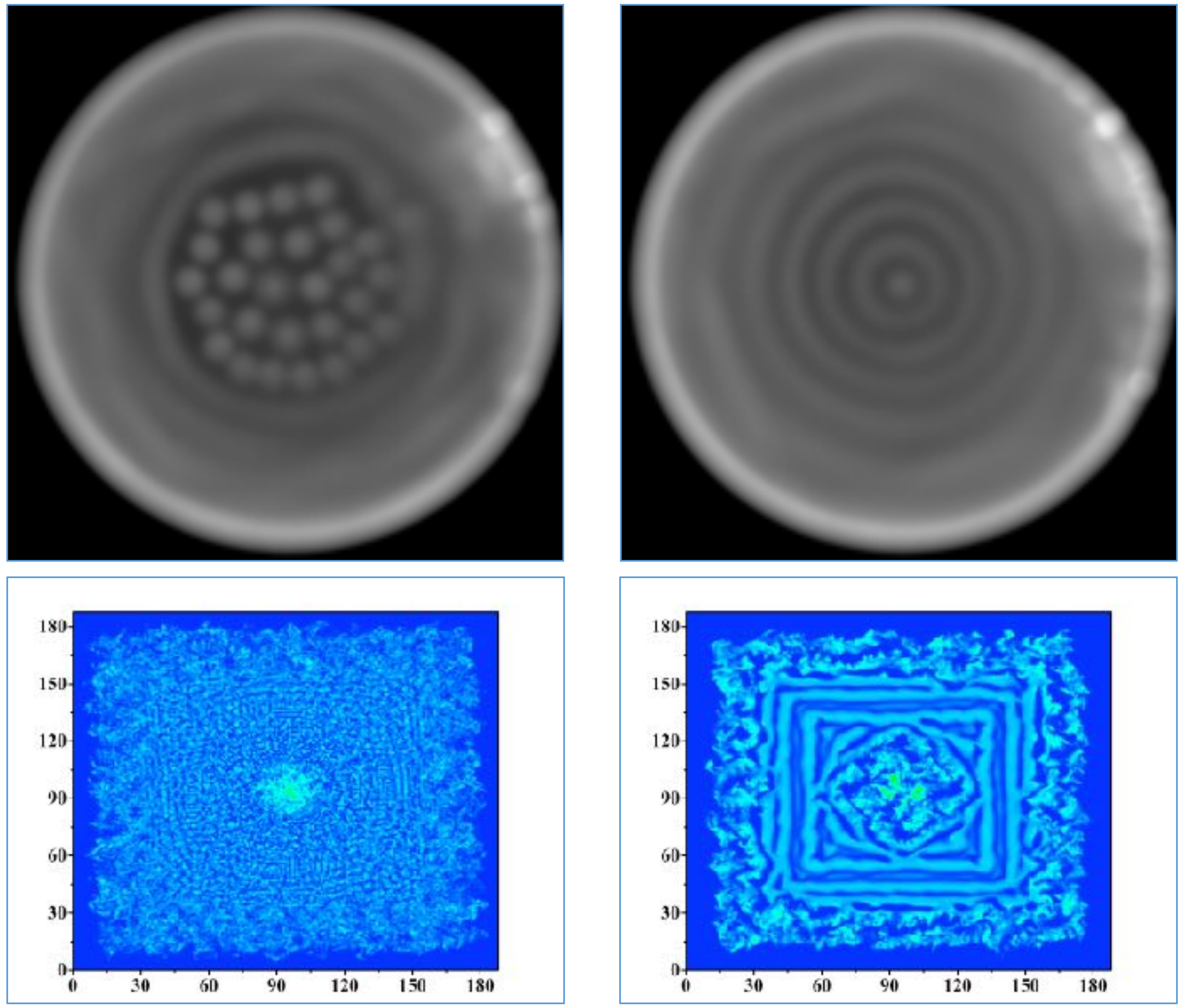
Filamentation: Ordered, plasma structures - initial modeling





2-D modeling of filaments
Using M. Kushner
Hybrid Plasma Equipment Model (HPEM)

M. Menati, et al.,
Phys. Plasmas, 26, 063515 (2019)



3-D modeling of filaments
Using Menati fluid code

Menati, Konopka, Thomas (in prep)

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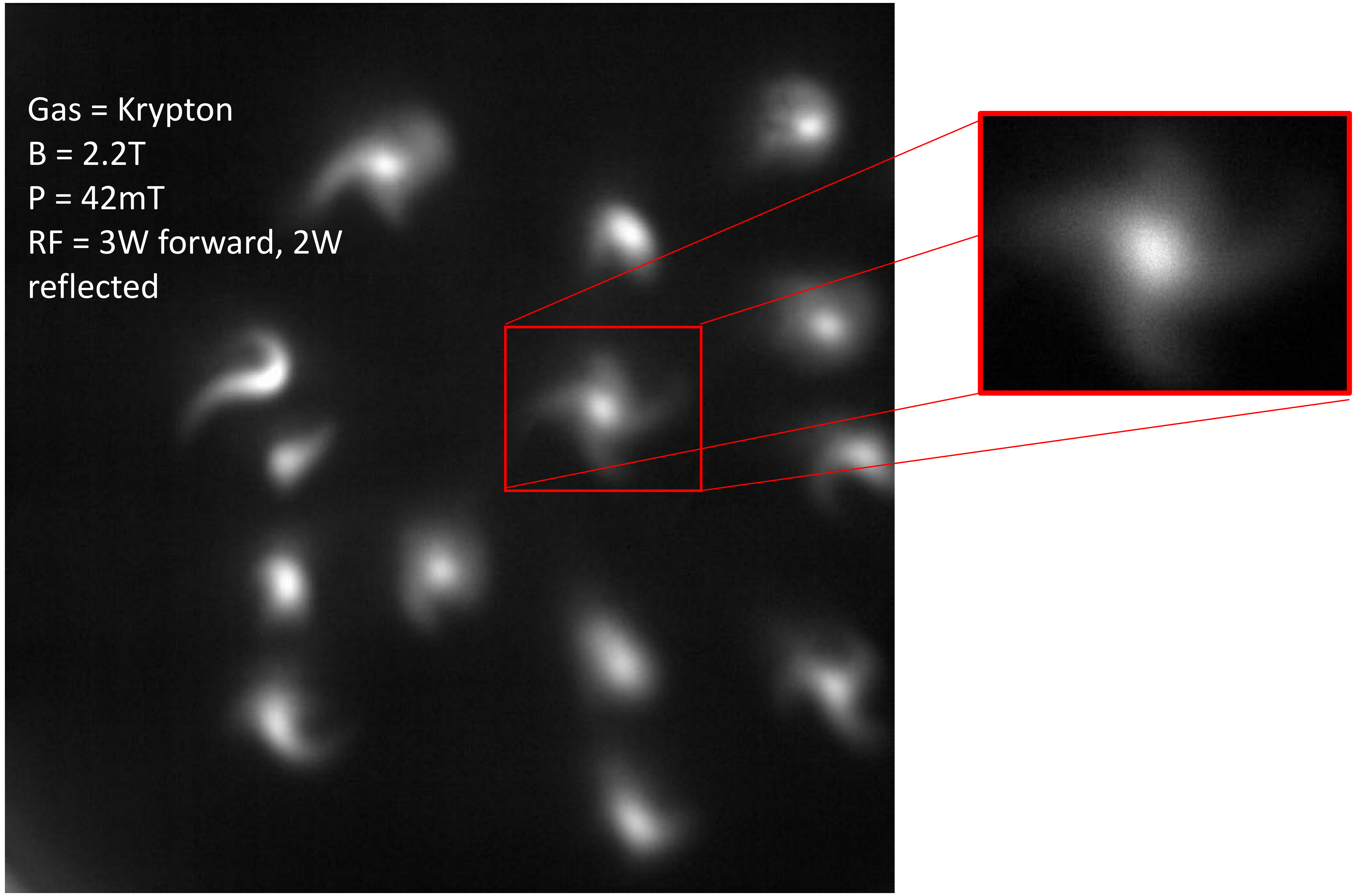
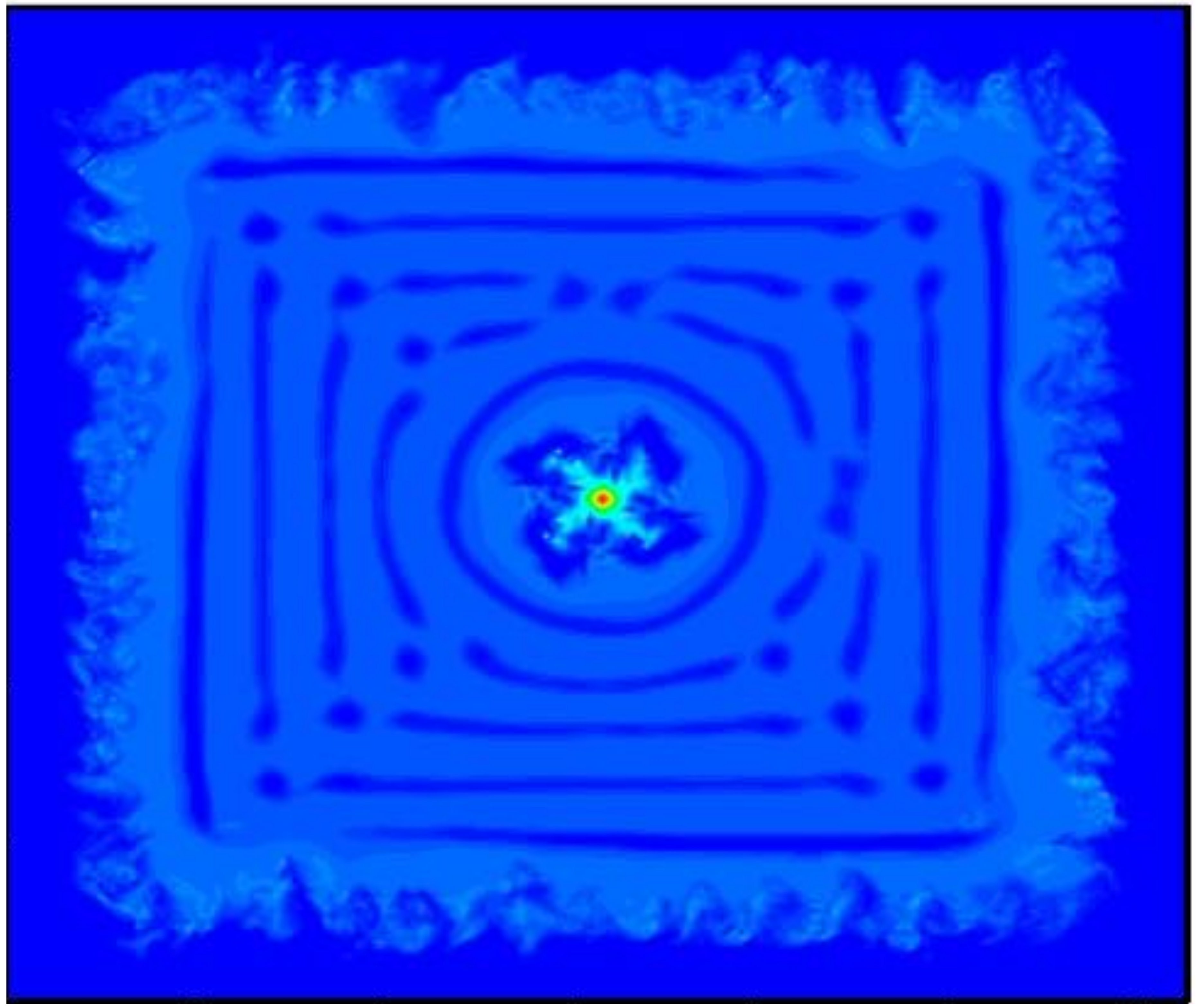
Experimental observations show behavior predicted by simulation





Simulation by Mohamad Menati, et al., Phys. Plasmas **27**, 022101 (2020) in argon plasma.

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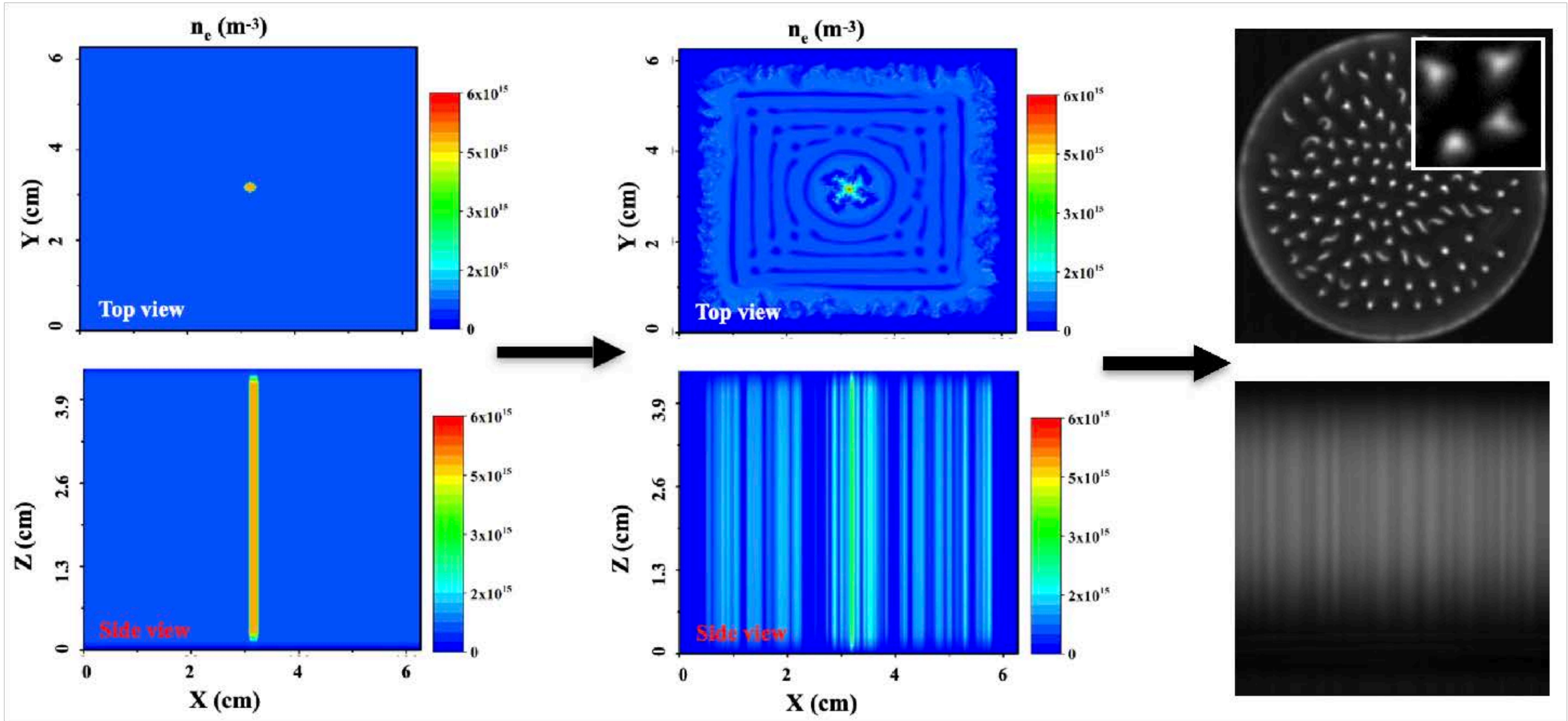
Filamentation model using 3-D fluid codes develop at Auburn

- A three-dimensional, two-component fluid model has been developed to model the ion and electron dynamics at high magnetic field.
- Model allows for neutral collisions and ionization.
- After the initial perturbation, there is a competition between electron fluxes (parallel) and ion fluxes (parallel and perpendicular).
- Equations take the form of an activator-inhibitor system, which we believe may be responsible for the pattern formation.

M. Menati, PhD. Dissertation (2020)
M. Menati, et al., PoP, **27**, 022101 (2020)
M. Menati, et al., PSST, **29**, 085015 (2020)



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Similar framework is used to explain imposed, ordered pattern formation in dust

Image spatial resolution

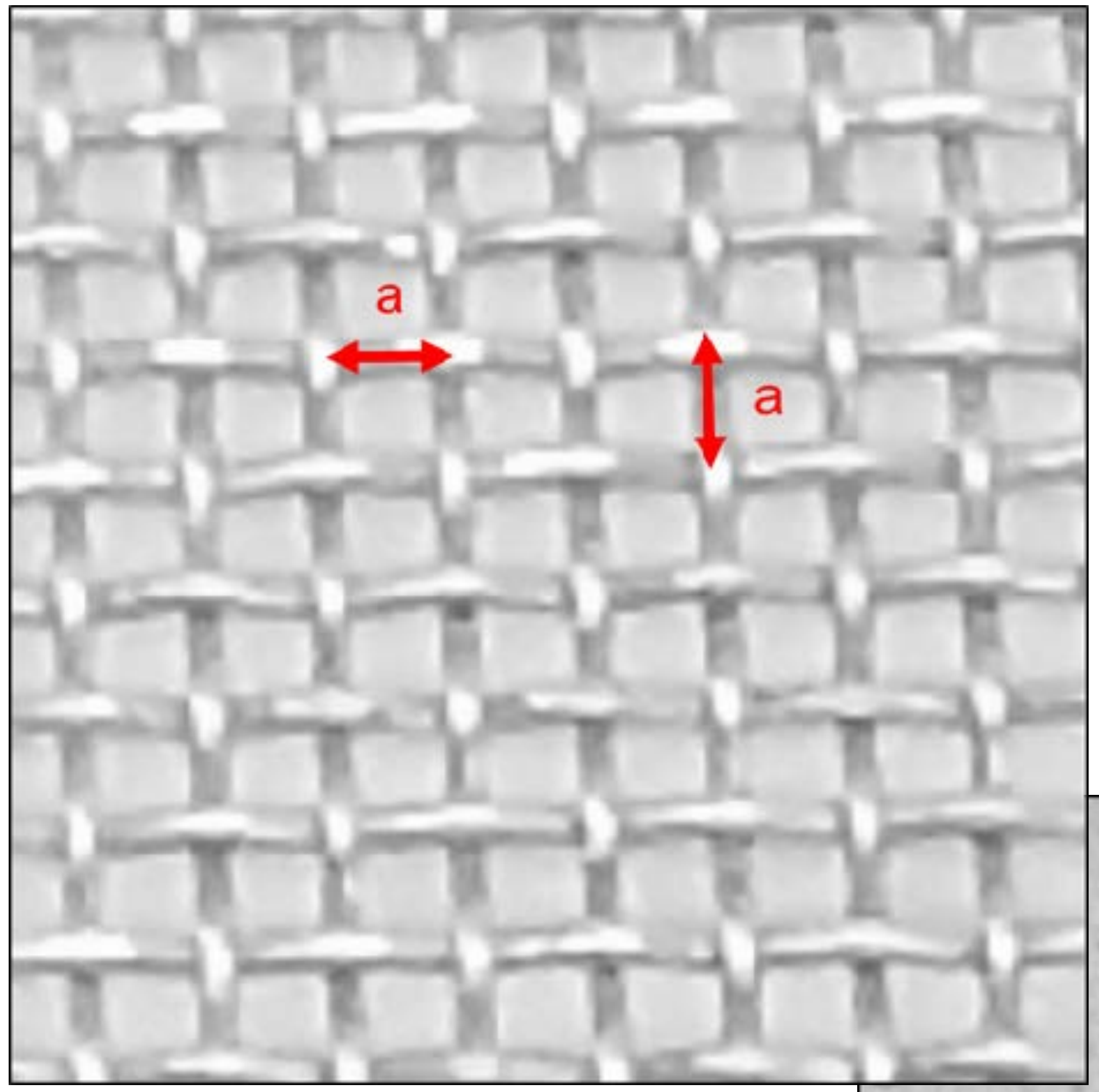
45.5 µm/pix

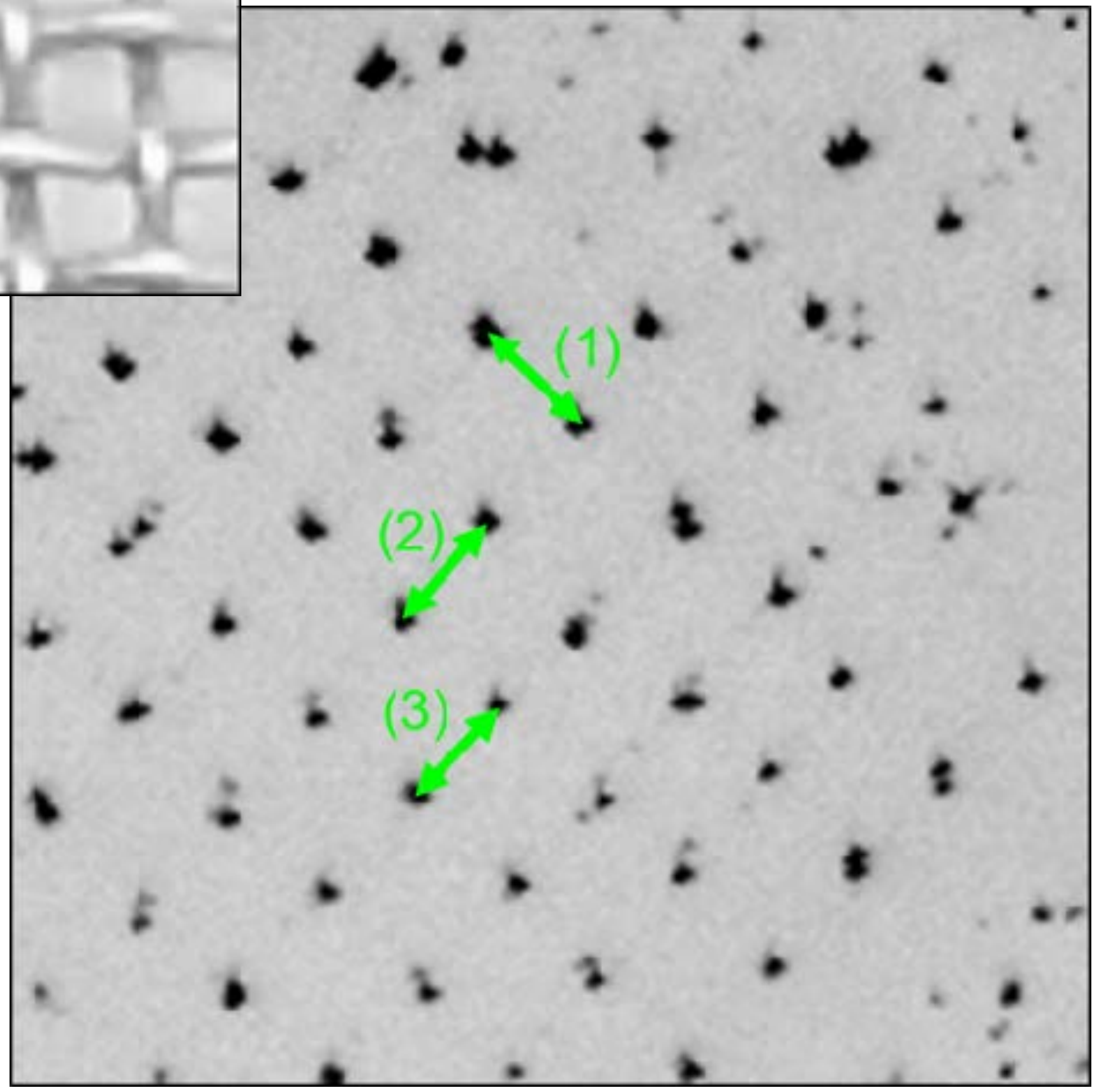
Wire center-to-center spacing

a = 838.2 ± 139.7 µm

Sample measurements

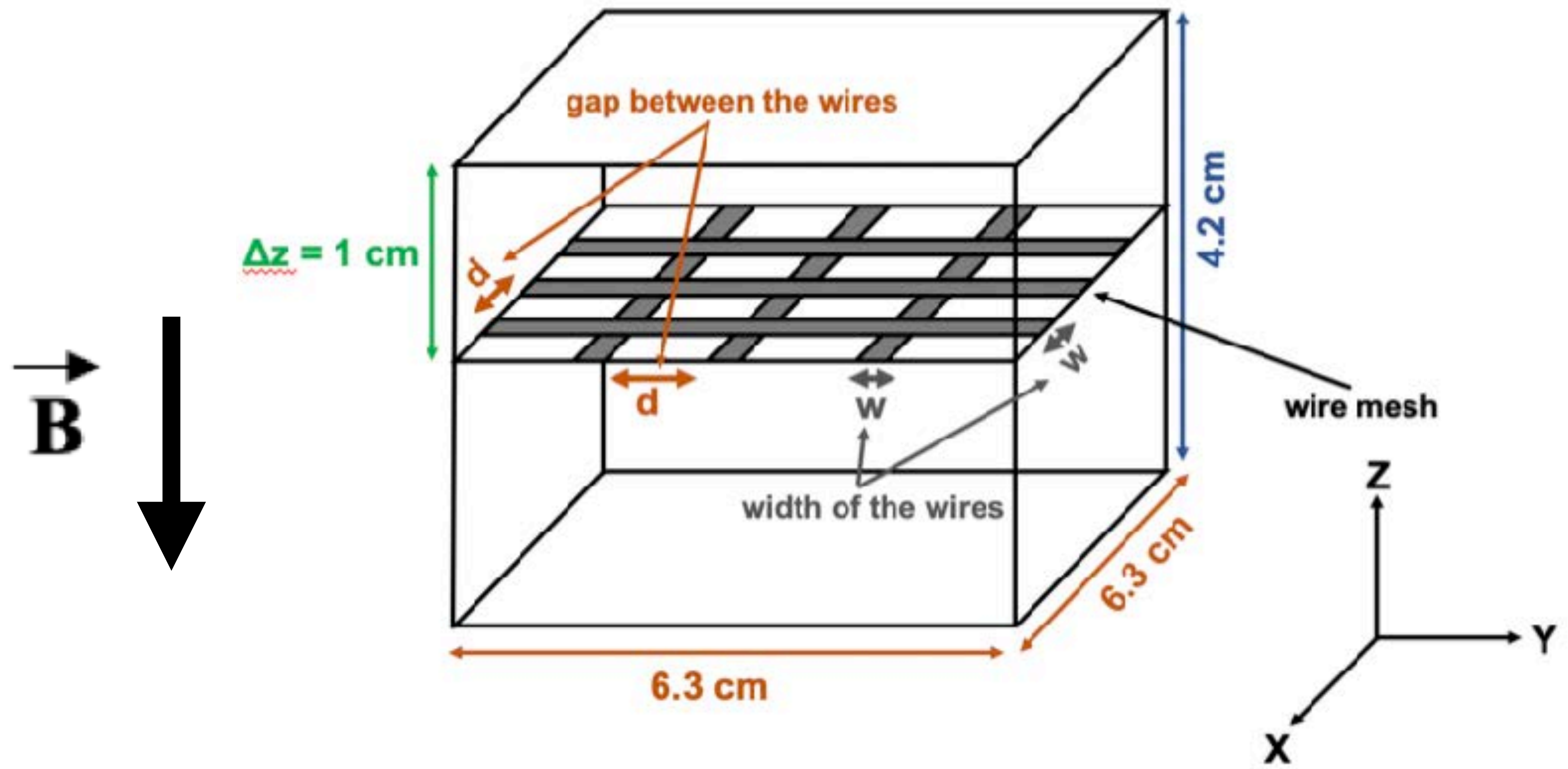
(1) 19.80 pix ~ 900.9 µm
(2) 19.91 pix ~ 908.6 µm
(3) 18.77 pix ~ 854.0 µm

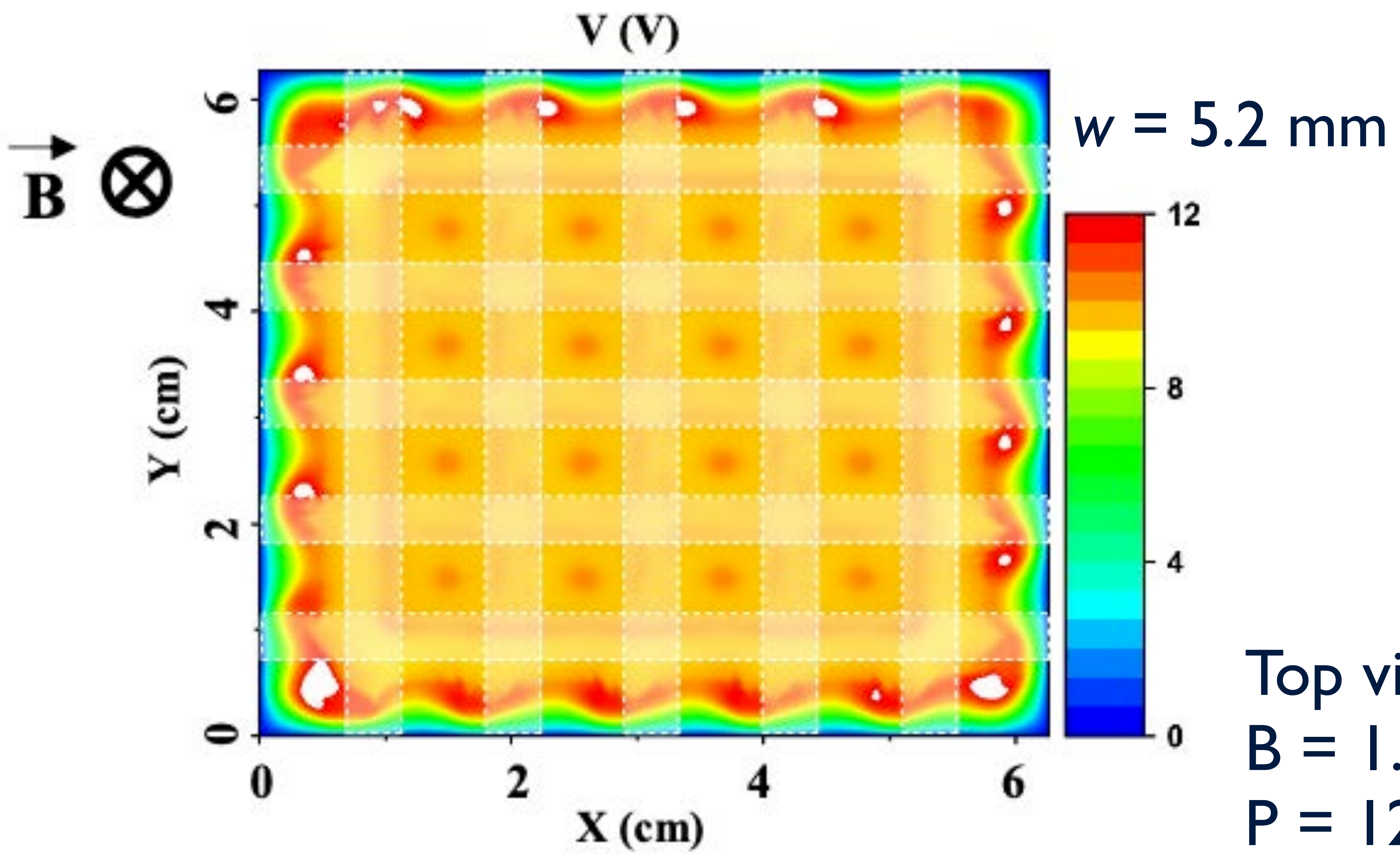




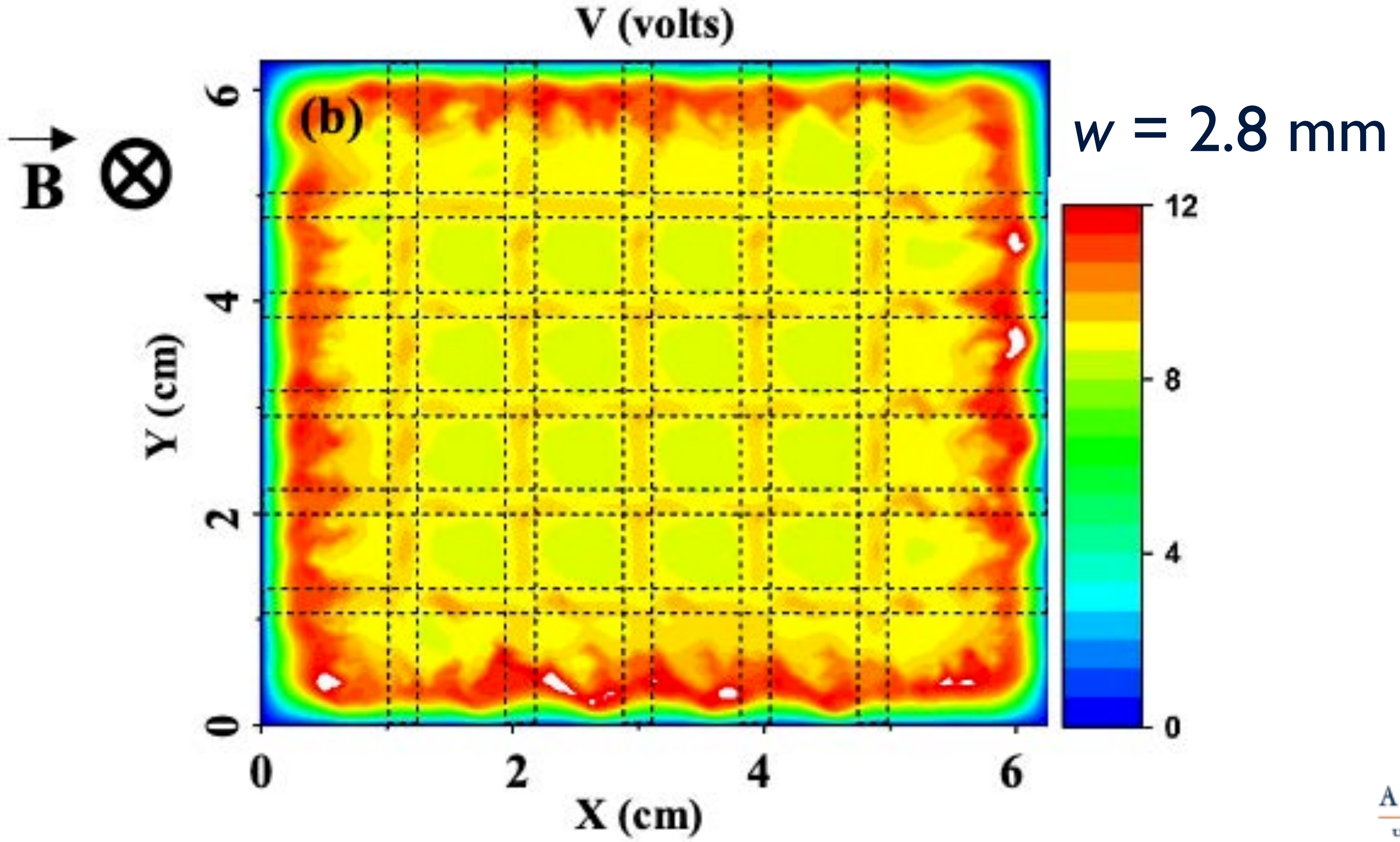
Observations of the dust particles using a macroscopic mesh gives a new view of how they are becoming trapped in the plasma

- A three-dimensional, two-component fluid model has been developed to model the ion and electron dynamics at high magnetic field.
- Model allows for neutral collisions and ionization.
- A grounded, conducting wire mesh is placed in the plasma.
- Trapping is dependent upon *B*, *w*, *d*, *P*, generally consistent with experiments.





Top view:
B = 1.0 T
P = 12 Pa



M. Menati, PhD. Dissertation (2020)
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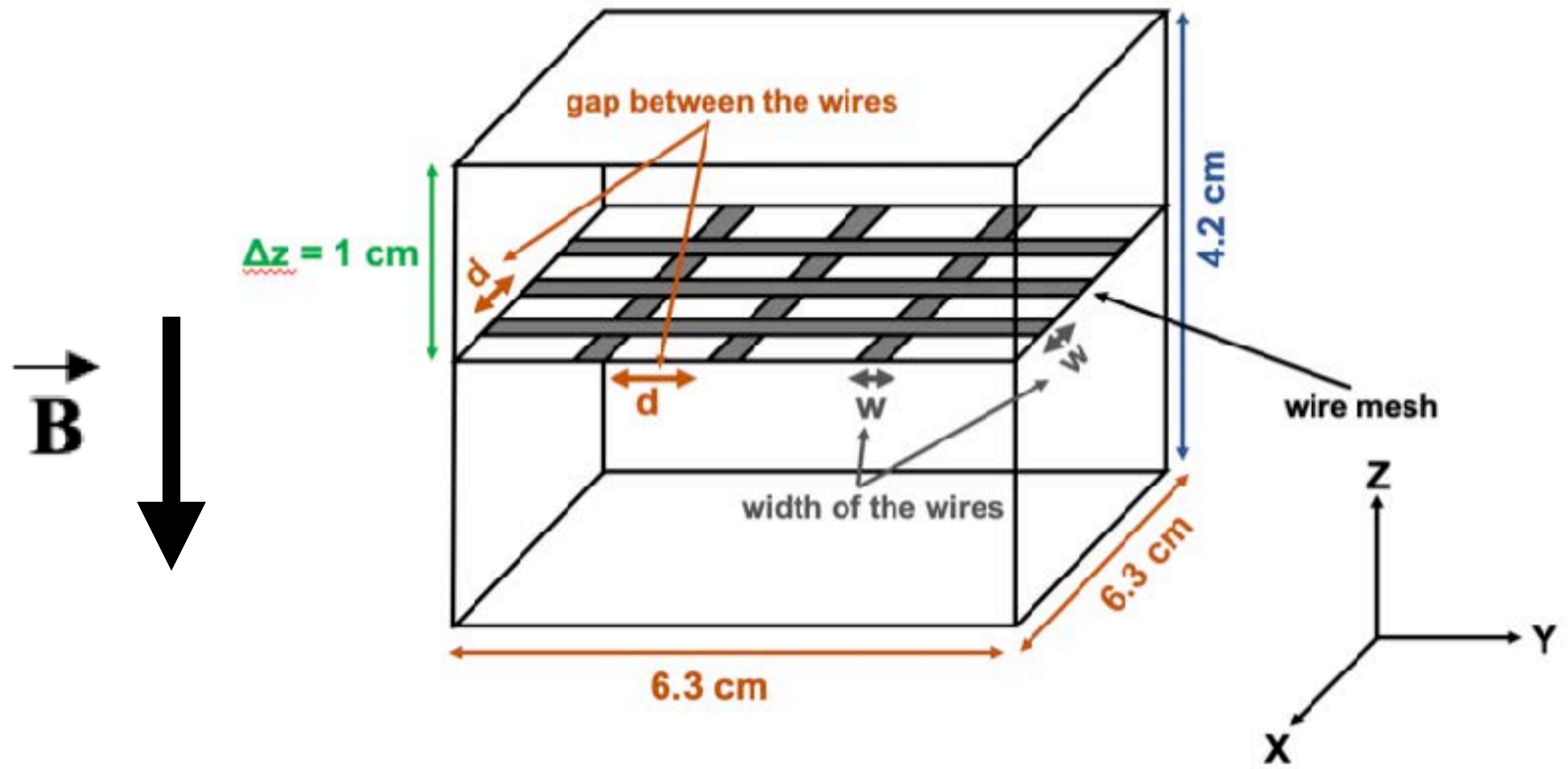
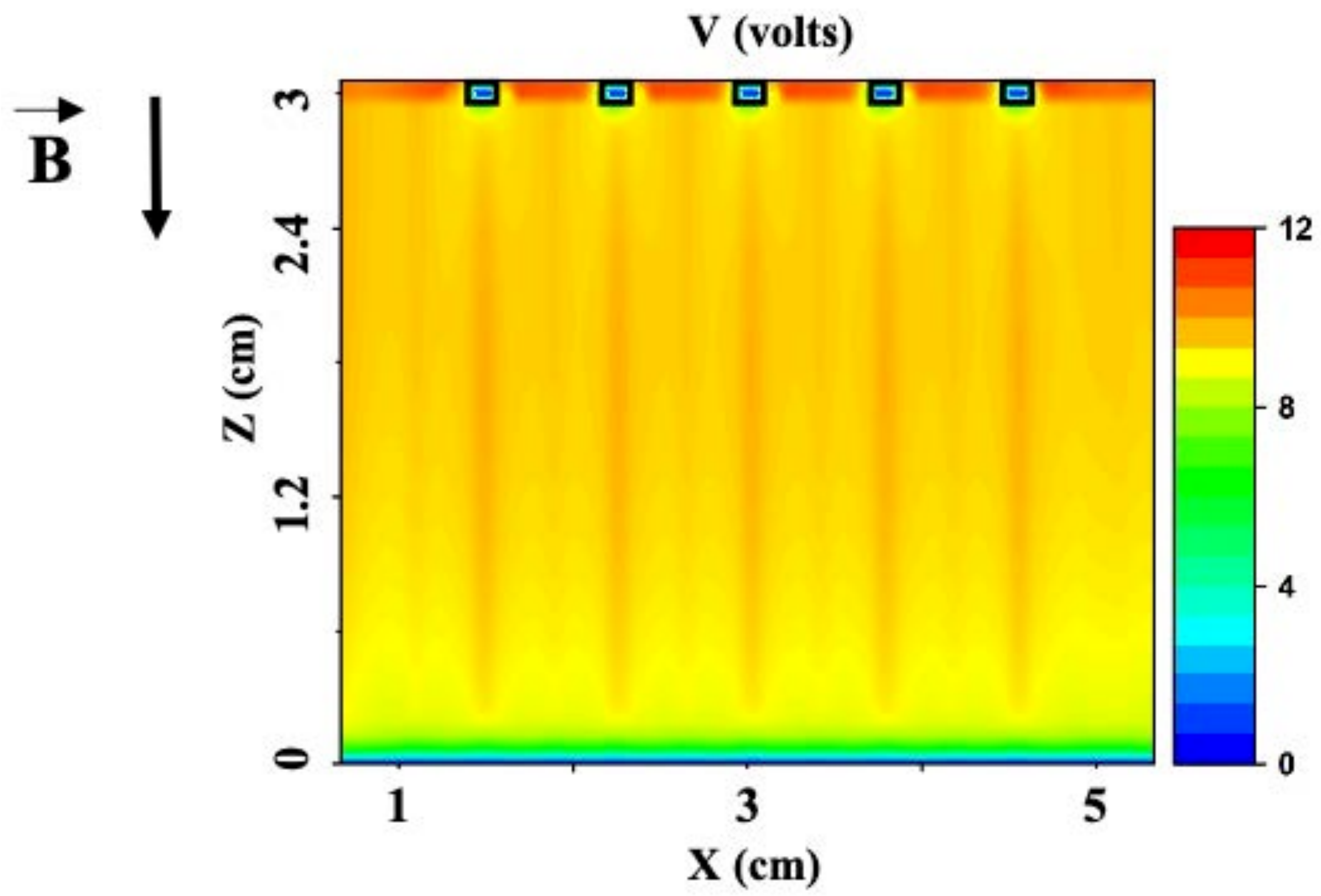
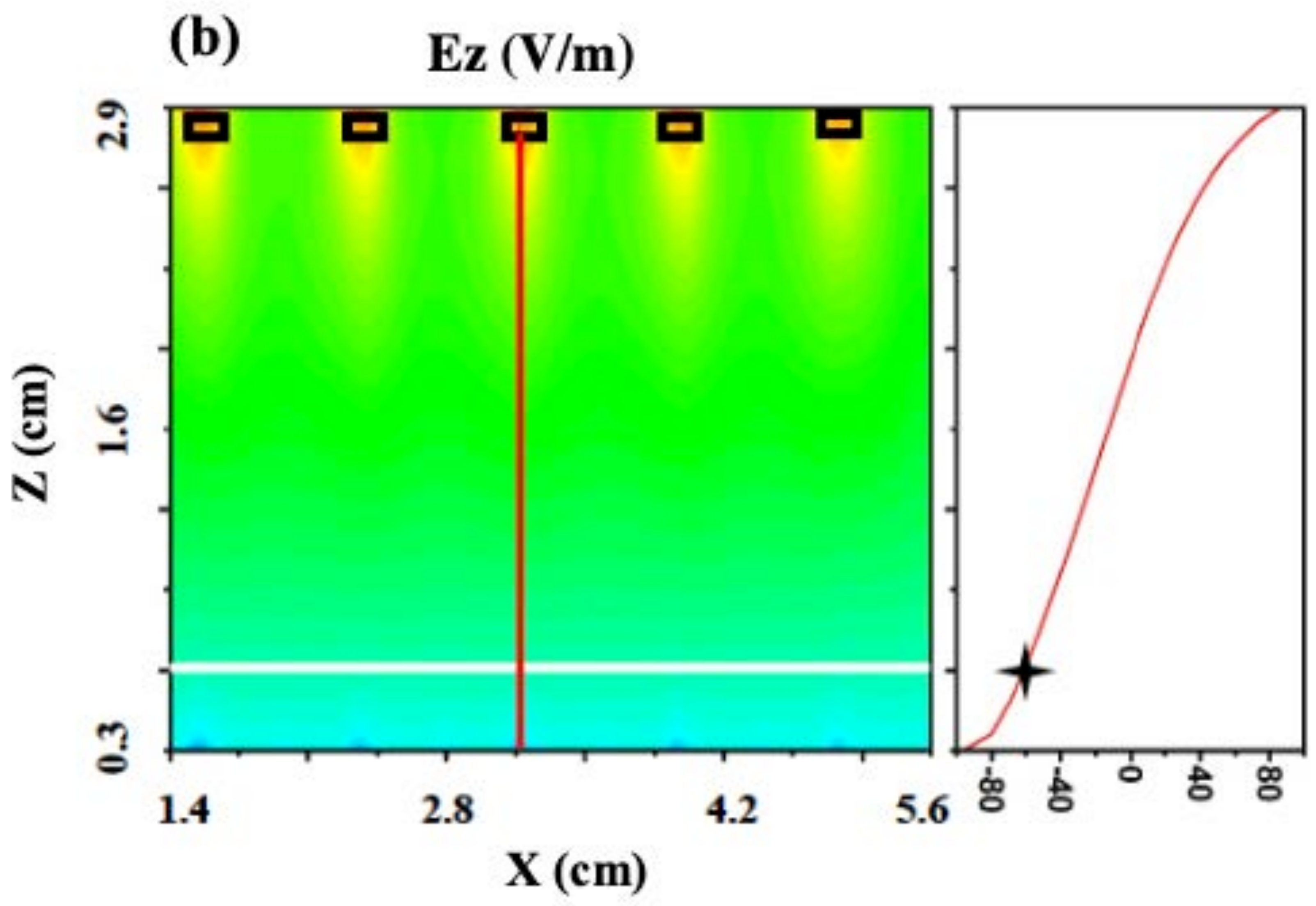




Side view:
B = 1.0 T
P = 12 Pa



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M. Menati, et al., PoP, **27**, 022101 (2020)
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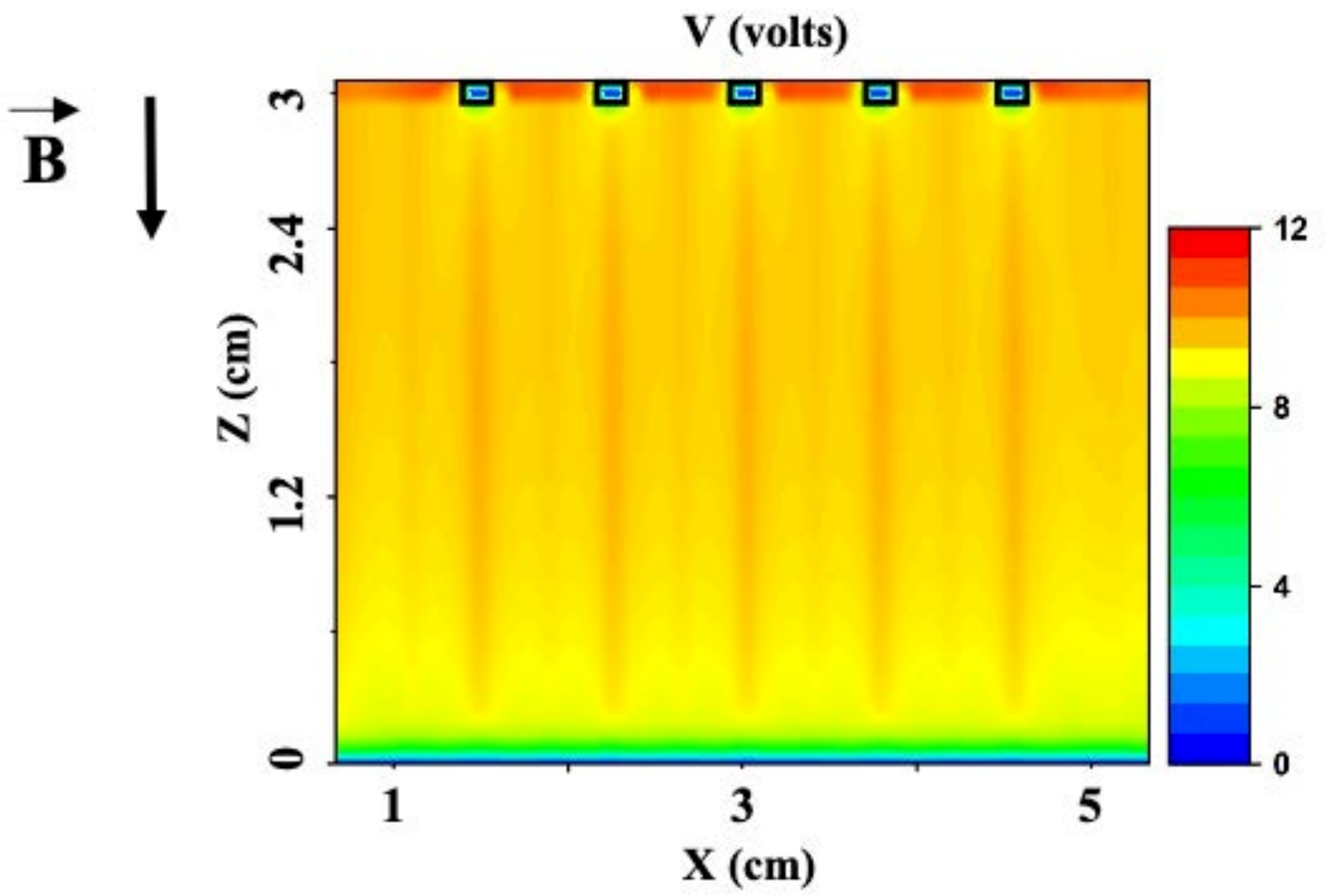
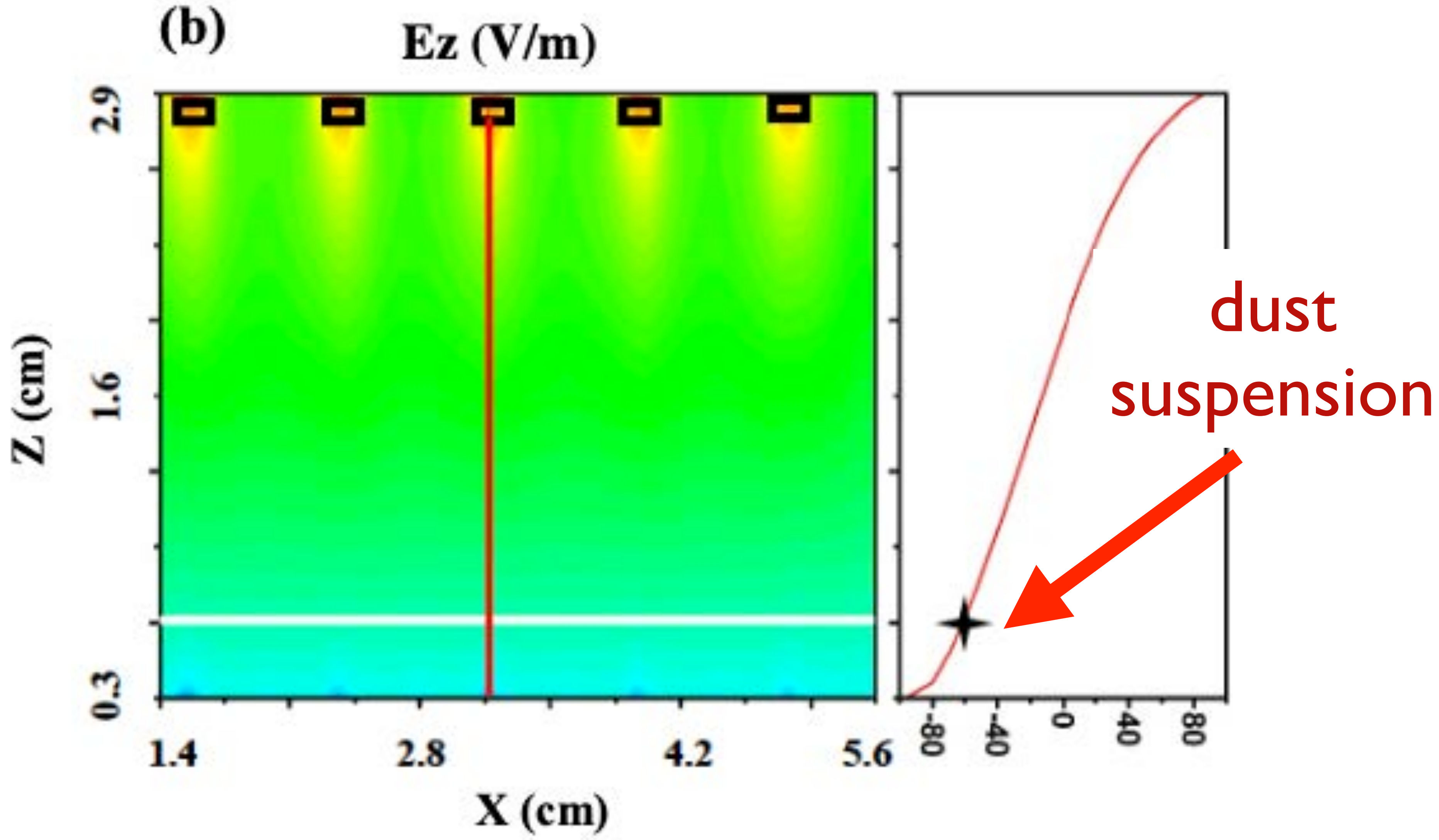
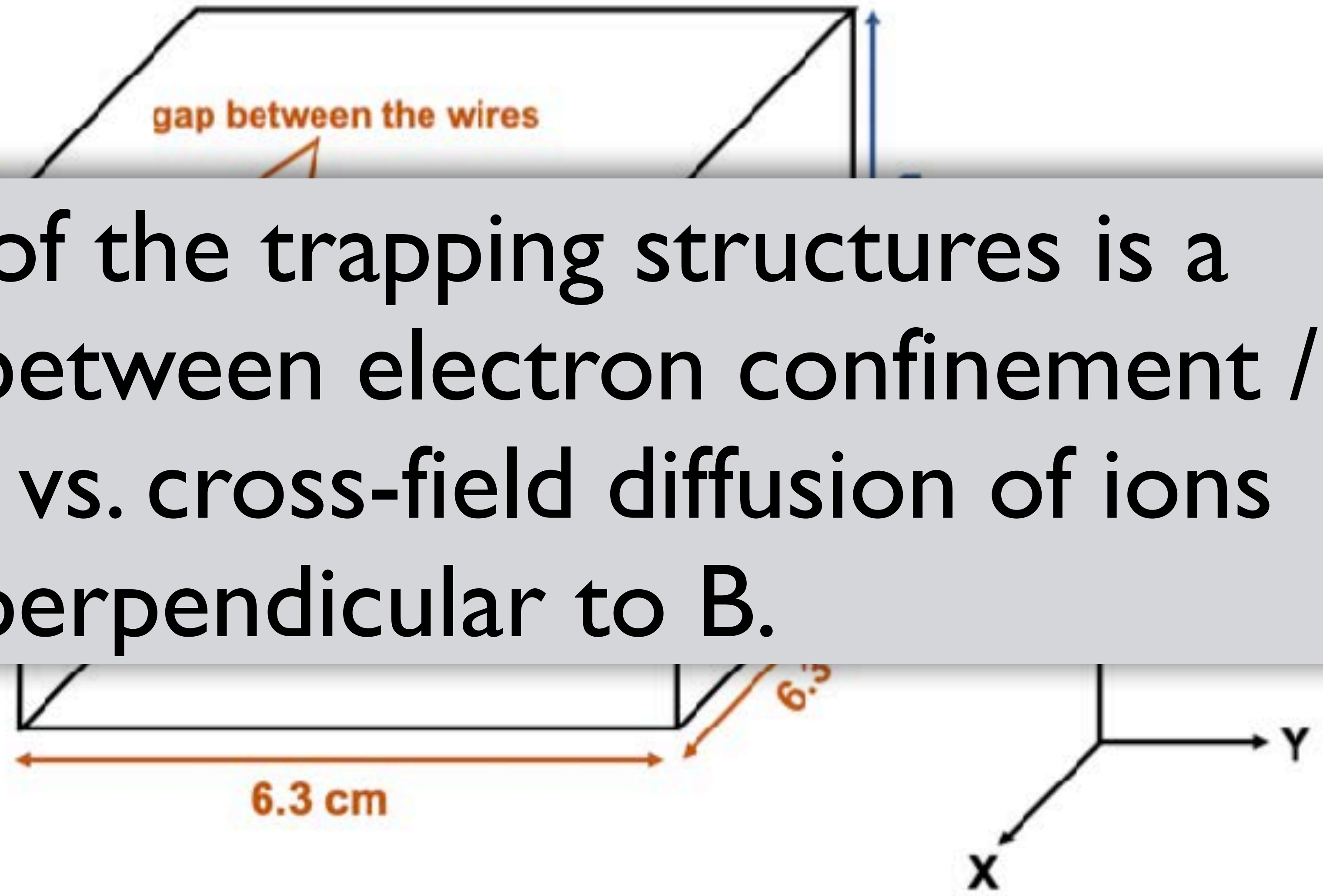


Side view:
B = 1.0 T
P = 12 Pa





Formation of the trapping structures is a competition between electron confinement / flow along B vs. cross-field diffusion of ions perpendicular to B.

M. Menati, PhD. Dissertation (2020)
M. Menati, et al., PoP, **27**, 022101 (2020)
M. Menati, et al., PSST, **29**, 085015 (2020)

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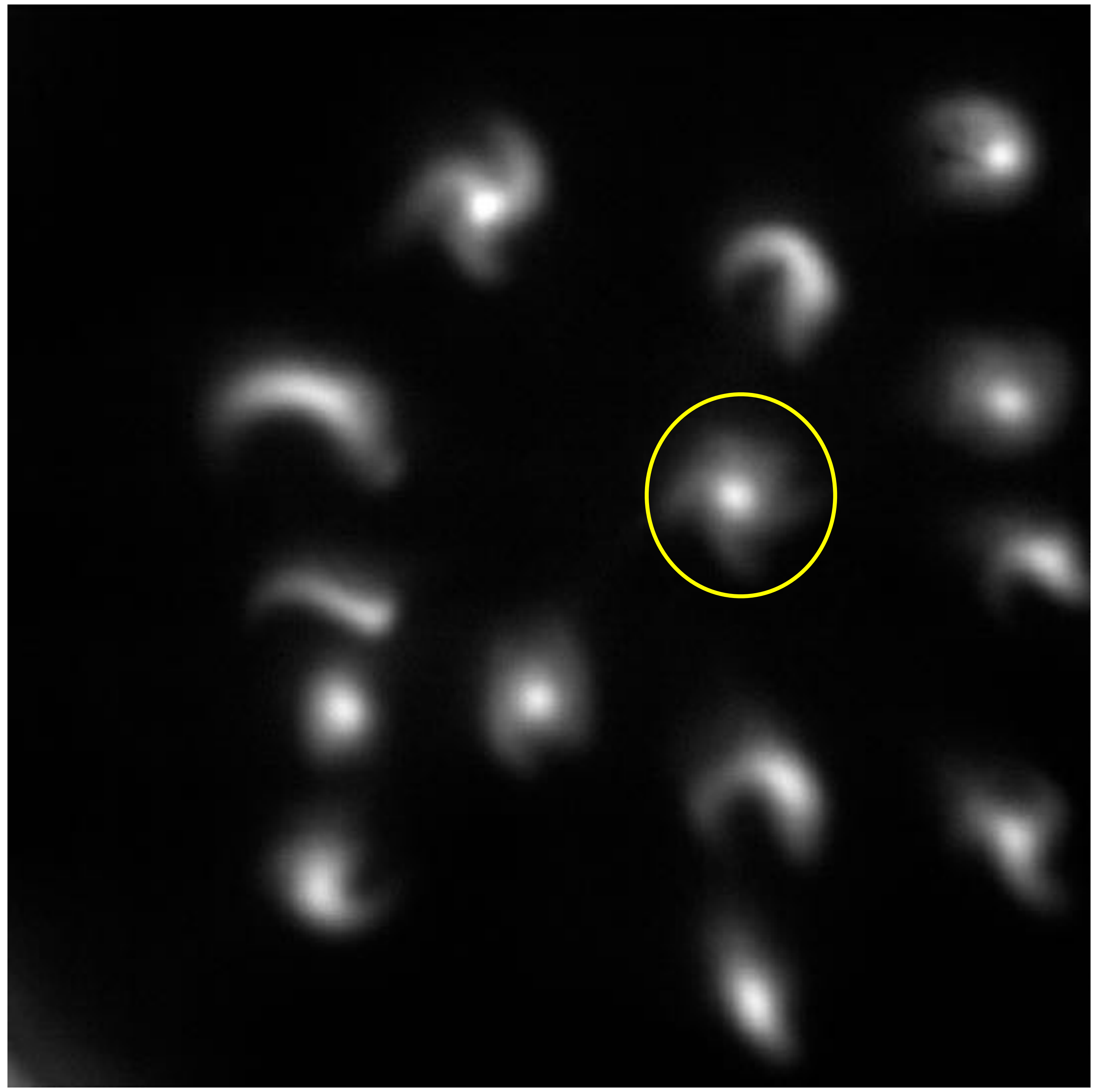
Even higher filamentary modes may exist

4 arm filaments

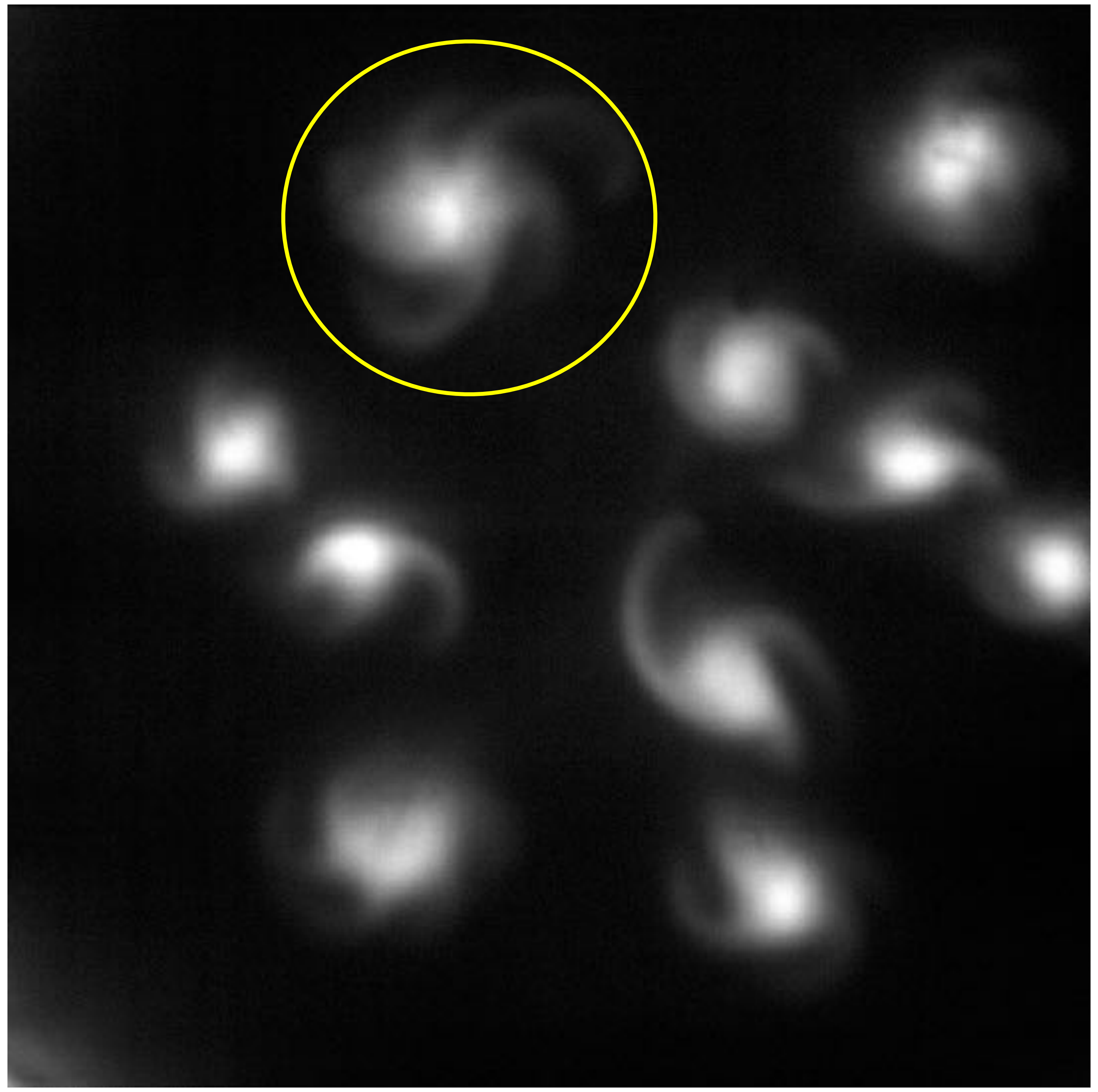
Gas = Krypton
B = 3.25T
P = 50mTorr
RF = 3W forward, 2W reflected

5 arm filaments



Gas = Krypton
B = 2.2T
P = 42mTorr
RF = 3W forward, 2W reflected

5/6 arm filaments



Gas = Krypton
B = 2.2T
P = 42mTorr
RF = 2W forward, 1W reflected

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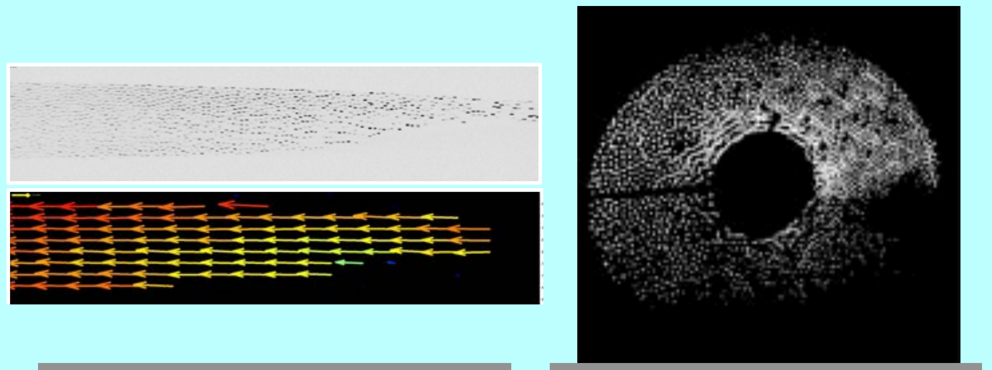
A last few words…

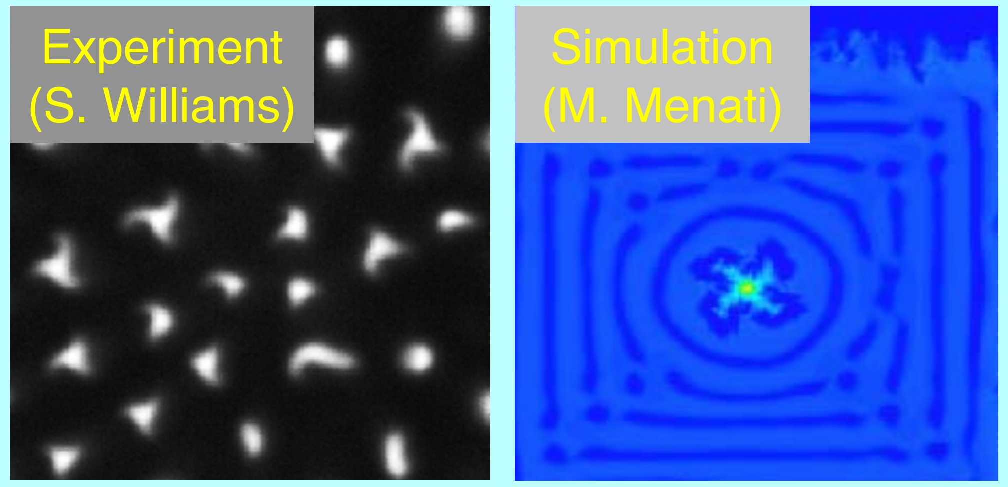
Magnetized Plasma Research Laboratory (MPRL) at Auburn University:
Advancing the study of magnetized plasmas, dusty plasmas, and magnetized dusty plasmas



Thermal properties in dusty plasmas

Studying strongly vs. weakly coupled plasmas in lab, magnetized, and microgravity plasmas.

Collaborations: Baylor, UCSD, ESA, Roscosmos

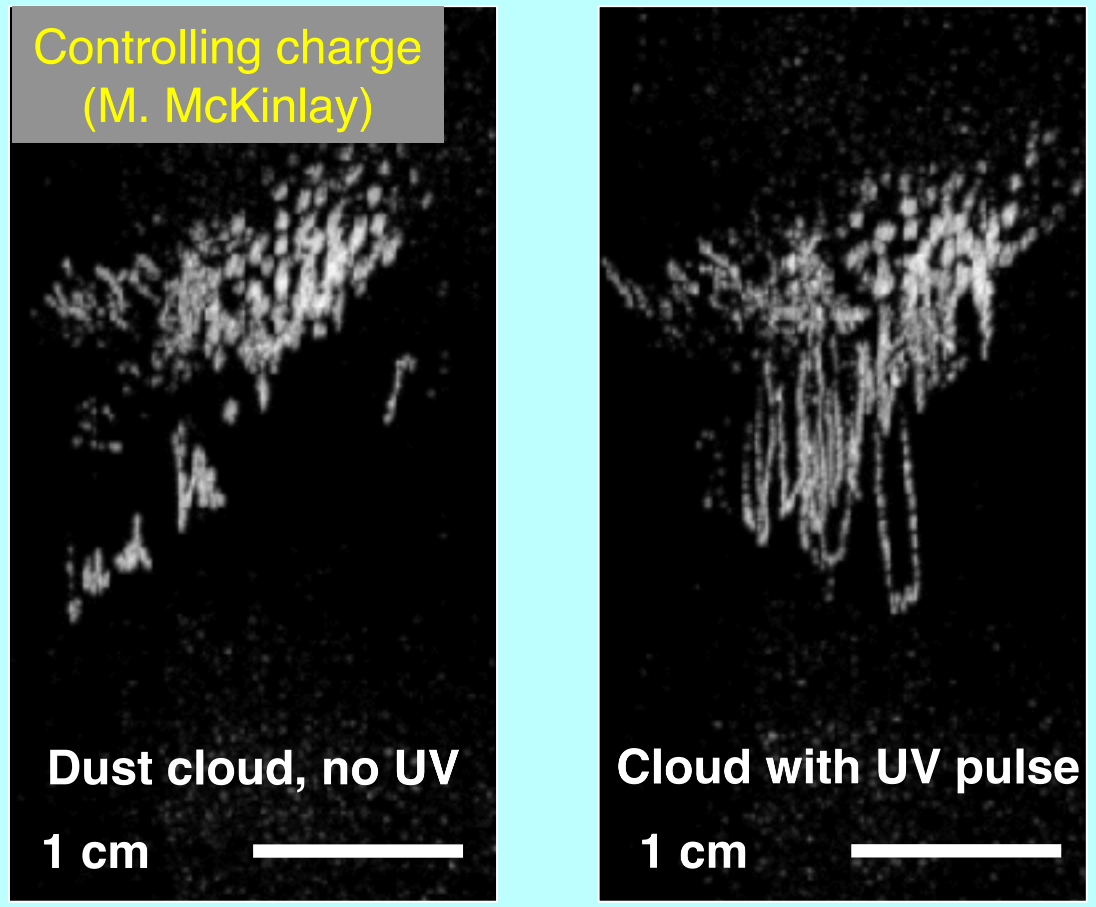


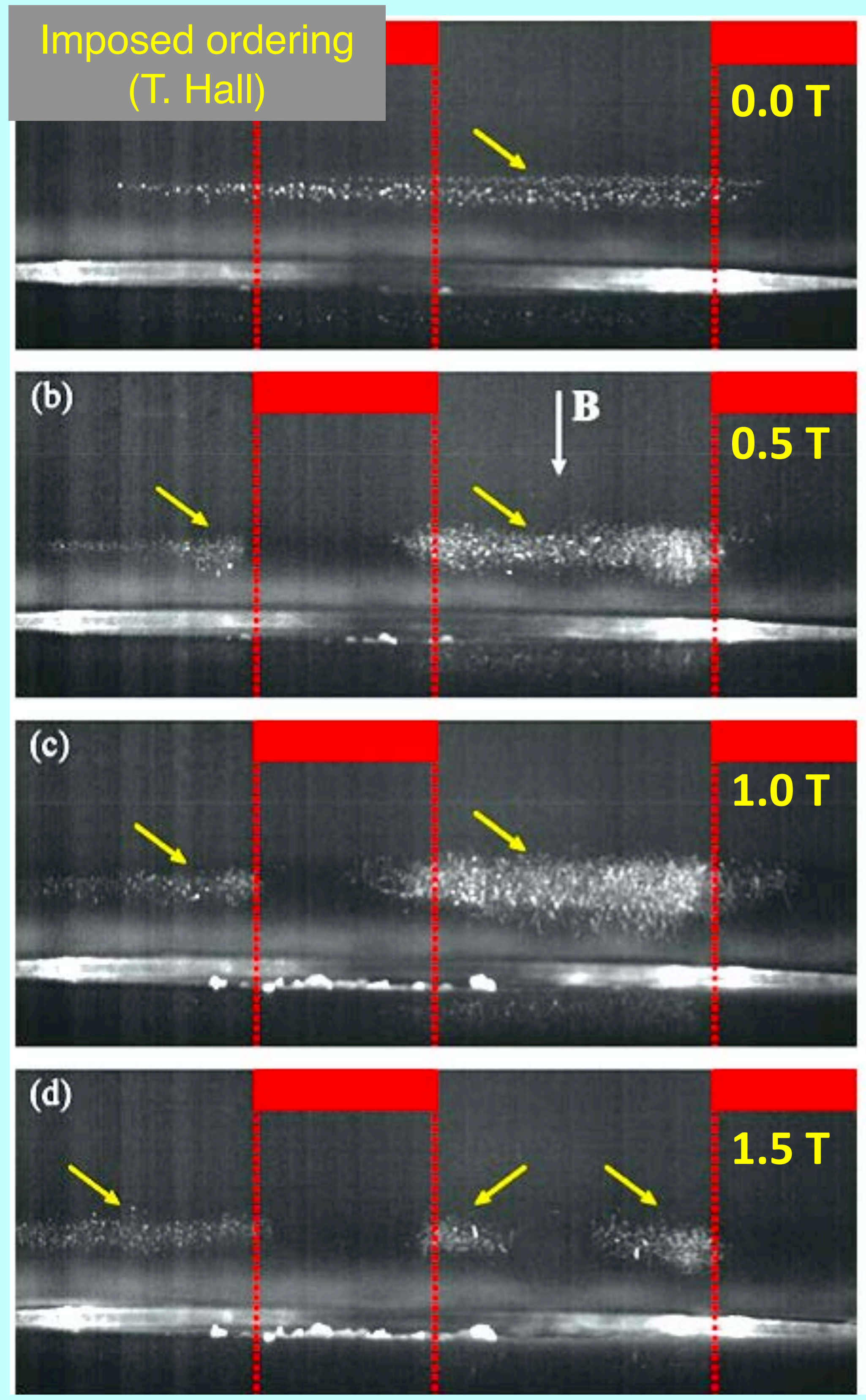
Plasma filaments and plasma self-organization

Experiments and modeling of plasma pattern formation show good qualitative agreement.

Controlling charge

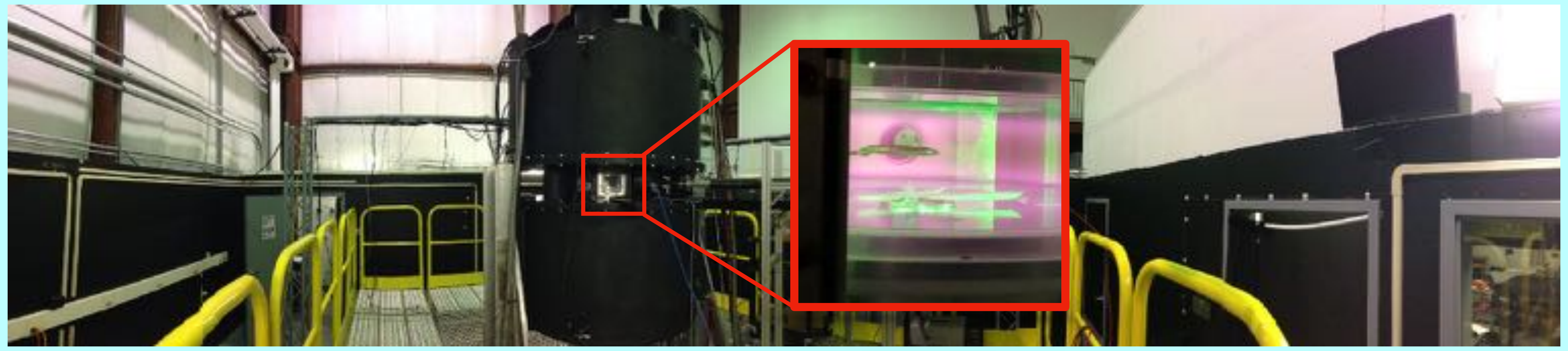
Using UV to control dust without modifying background plasma.



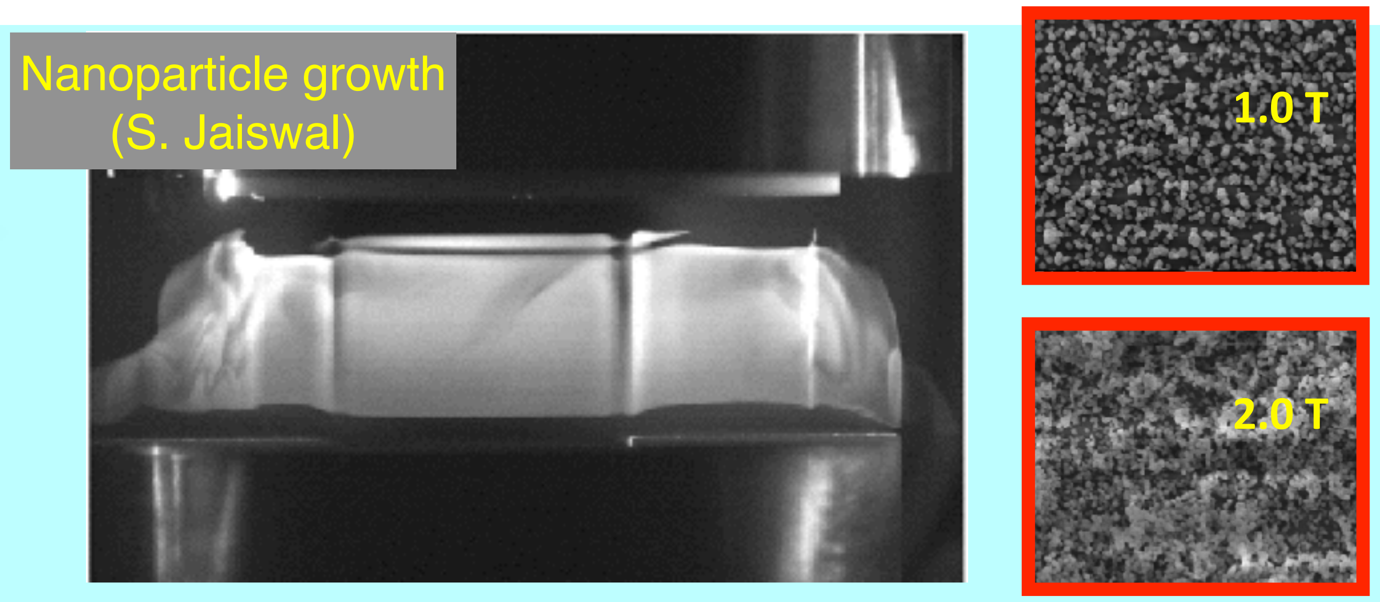


Imposed ordering

Using dust particles as a diagnostic for sheath and filament formation in magnetized plasmas.



Panoramic view of the Magnetized Dusty Plasma Experiment (MDPX) device. Insert of plasma and dust cloud.



Particle growth

Nanoparticle growth in magnetized plasmas filaments leads to control over morphology.

Collaborations: CPU2AL, Tuskegee Univ., U. Saskatchewan, Univ. of Alabama - Birmingham

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http://aub.ie/mprl

CPU2AL

NSF NASA AUBURN UNIVERSITY

MPRL Research Team

MDPX design/construction

Uwe Konopka, Auburn

Robert Merlino, Iowa, Marlene Rosenberg, UCSD

Mark Cianciosa, Ross Fisher, Ami DuBois

Saikat Chakraborty Thakur, MPRL Project Scientist

Cameron Royer, MPRL Manager

Charging

Brian Lynch, Michael McKinlay

Plasma filamentation

Mohamad Menati, Stephen Williams

Particle growth

Bhavesh Ramkorun, Surabhi Jaiswal

Lenaic Couedel - CNRS / University of Saskatchewan*

Dust ordering

Taylor Hall, Spencer LeBlanc

Microgravity

Lori Scott, Eva Kostadinova, Auburn

Truell Hyde, Lorin Matthews, Baylor

Jeremiah Williams, Wittenberg

Mikhail Pustylnik, Hubertus Thomas, DLR

Andrey Lipaev, Sasha Usachev, Russian Academy of Sciences

Diagnostics and instability experiments

N. Ivan Arnold, Jared Powell, Leo Nofs, Evan Aguirre

http://aub.ie/mprl

Open to receive 2022 proposals

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