Competing processes due to microparticle injection and effects on microwave transmission through an overly dense plasma layer

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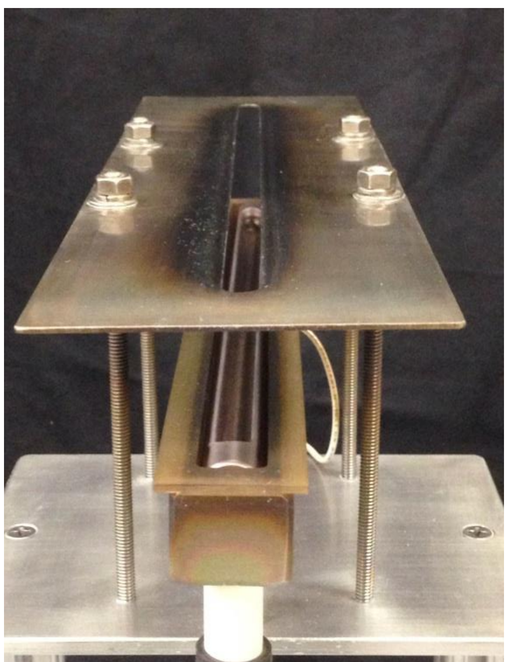


Outline

- Motivation/background
- Communications blackout mitigation approach
- Experimental setup
- Establishing transmission standards/controls
- Single pulse results
- Pulsing pattern effects
- Plasma recovery characteristics
- Particle flux correspondence to transmission
- Concluding remarks

Communications Radio Blackout Remains Problematic

- Dense plasma layer forms around hypersonic vehicles (Mach 7 to 10 or greater)
- Blocks communications
  - **GPS navigation**
  - Command and control
  - Telemetry
  - Electronic countermeasures
- Plasma cutoff frequency

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

- Applications
  - NASA – spacecraft reentry
  - Air Force/DOD – hypersonic defense
  - **NRL – Railgun projectiles (Mach 7+)**

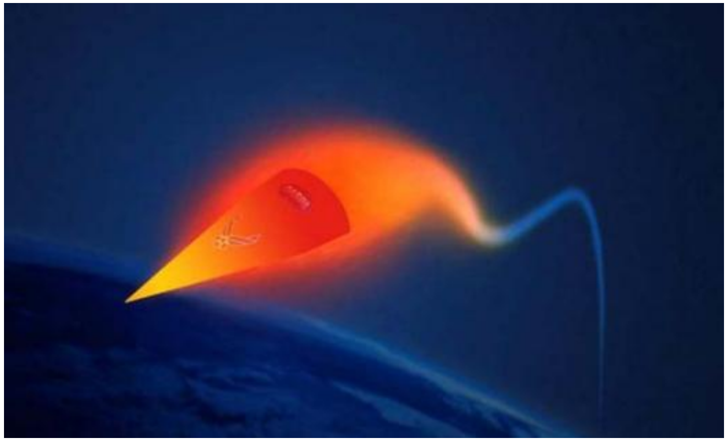
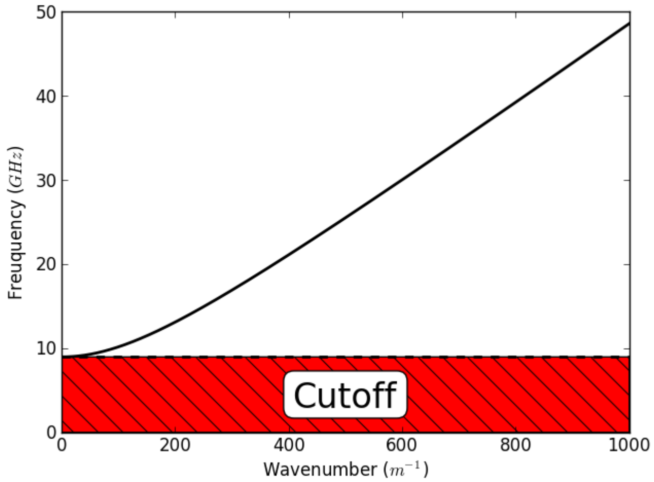


Image: popsci.com



Microparticle Injection Mitigation Approach Shows Promise

- Microparticles collect many electrons

$$Q = 4\pi\varepsilon_0 r_d V_f$$

- Electrons bound to heavy microparticles
- Cutoff frequency dependent on *free* electron density
- Evidence of significant electron depletion in past studies[1-3]
- Microparticle acts as recombination surface after initial charging
- Competing effect:
  - Theory predicts EM wave scattering off of charged particles[4]

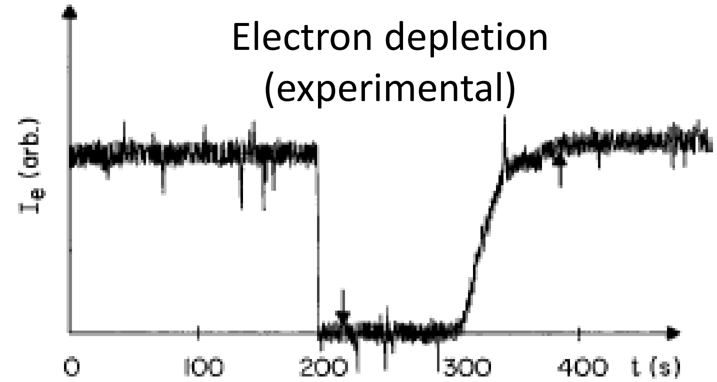


Image credit: Luo and D'Angelo[2]

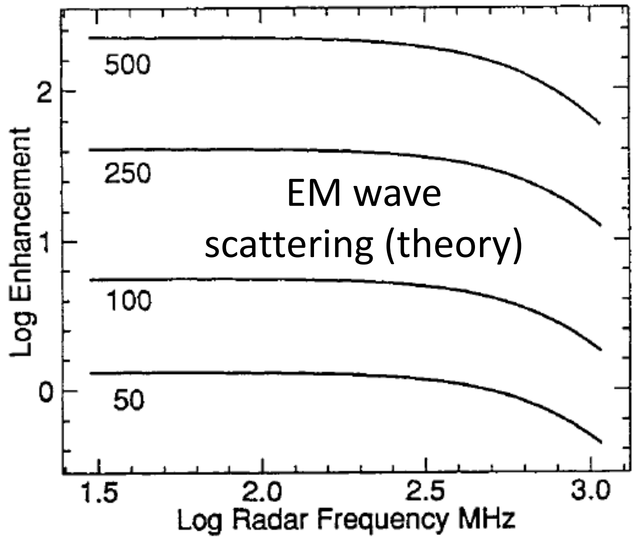
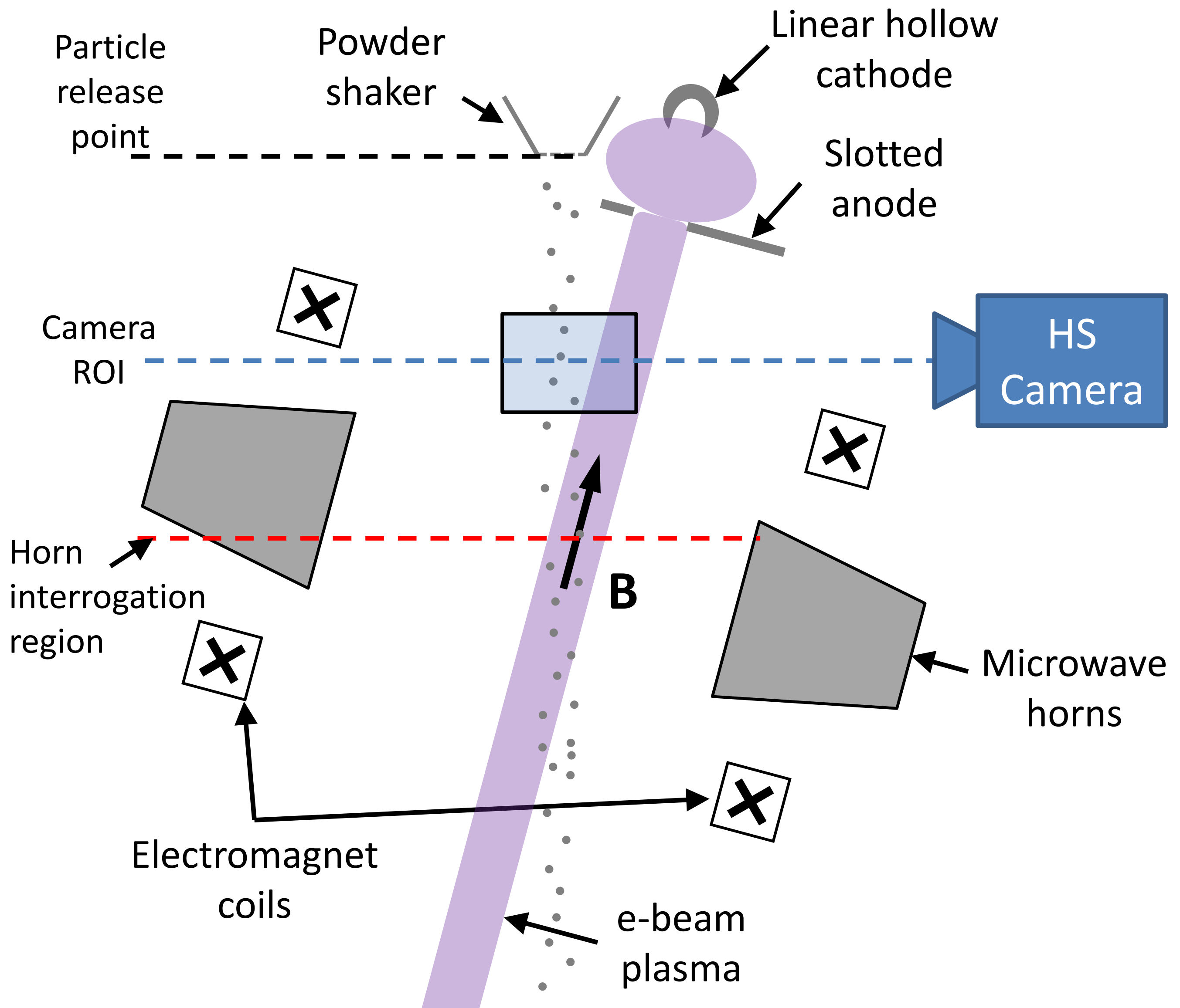


Image credit: La Hoz[4]

1. Gillman and Foster, JVST A **31**, 2013
2. Luo and D'Angelo, J. Phys. D **33**, 2000
3. Rosen, Phys. Fluids **5**, 1962
4. La Hoz, Physica Scripta. **45**, 1992

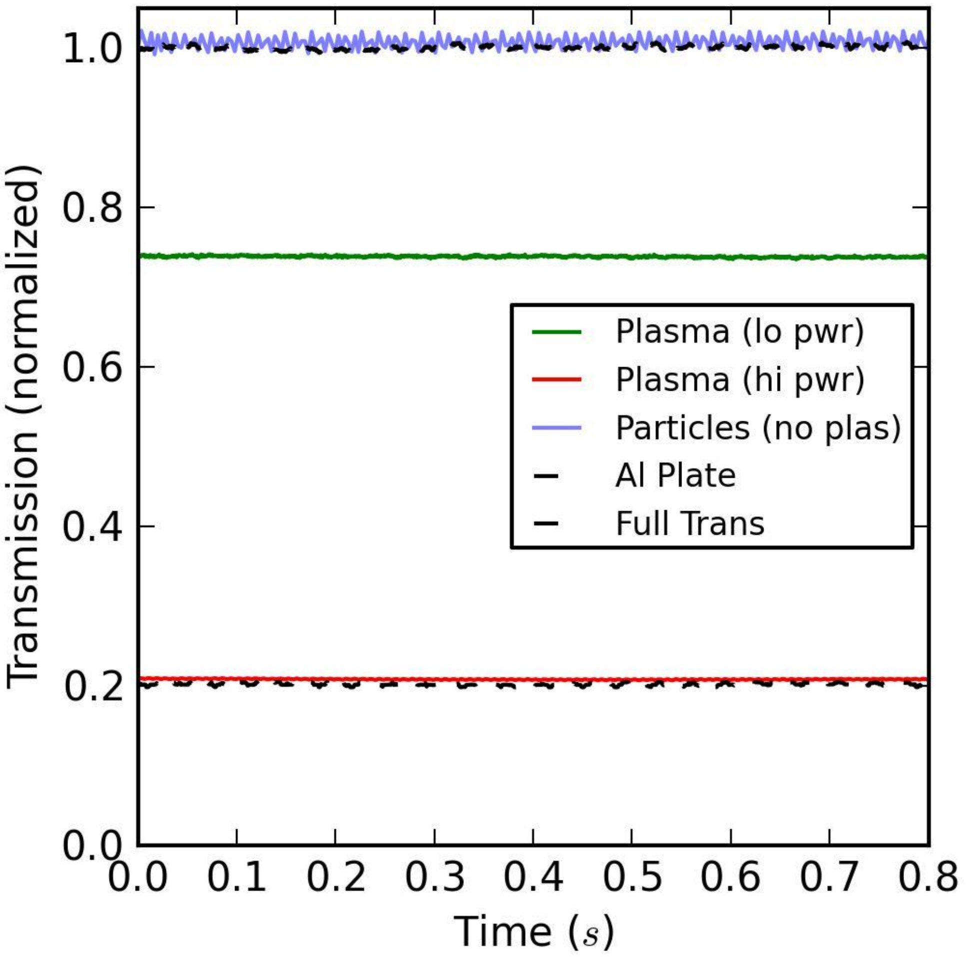
Tilted Plasma Allows For Temporally Comprehensive Investigations

- Plasma sheet simulates reentry plasma layer
- Diagnostics:
  - Microwave horns
  - Langmuir probe
- Microparticles:
  - Aluminum-oxide (Al_2O_3) powder
  - 60 μm diameter
- Near GPS freq (1.25 GHz)
- High-frame-rate camera images at 1500 fps



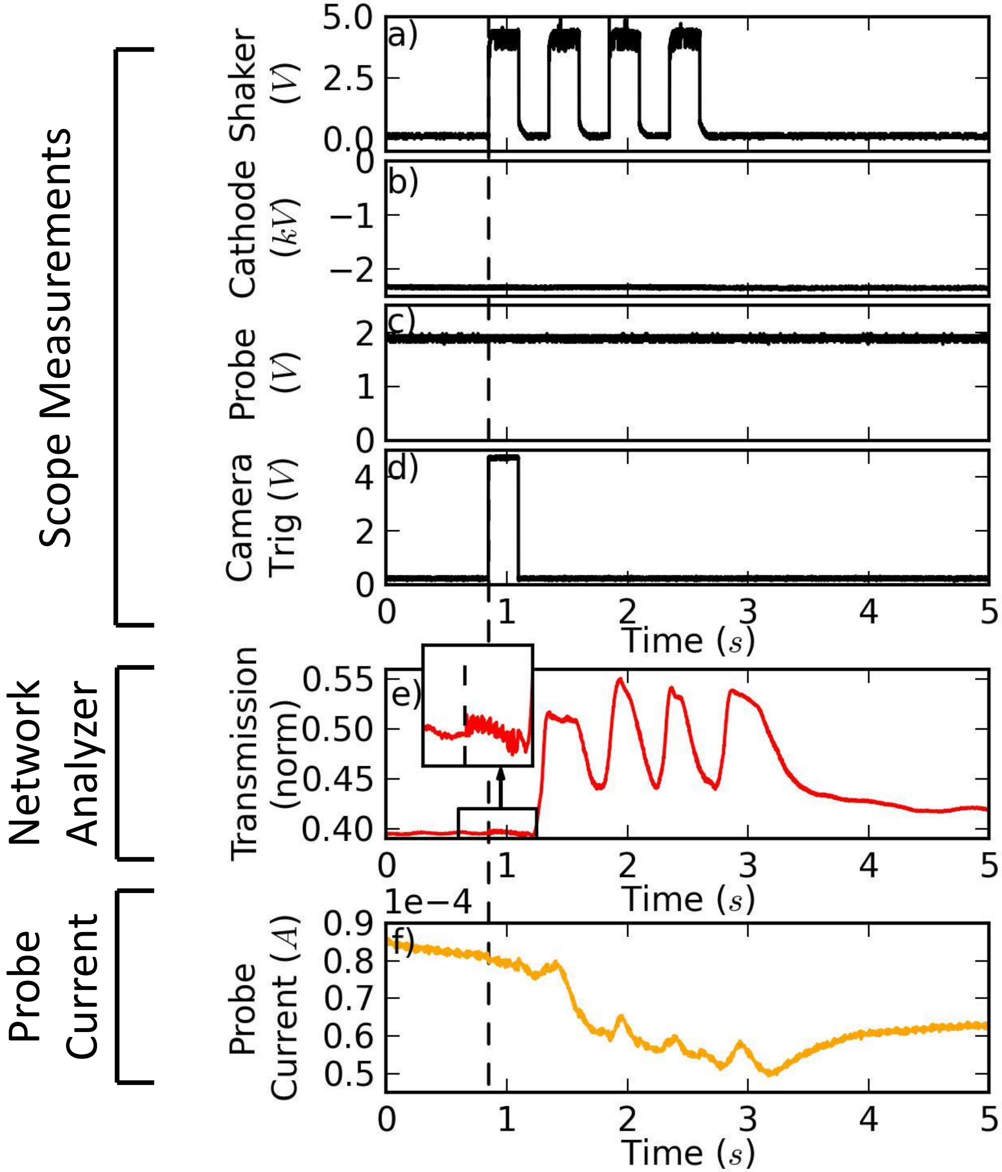
Limits of Transmission Established

- Transmission limits:
  - **Full transmission:** no obstructions (only chamber) between horns
  - **Ideal/complete cutoff:** Aluminum plate covered in microwave absorbent material
  - **High density plasma:** above cutoff (no powder)
  - **Low density plasma:** below cutoff (no powder)
  - **Powder/particle injection**: uncharged particle scattering



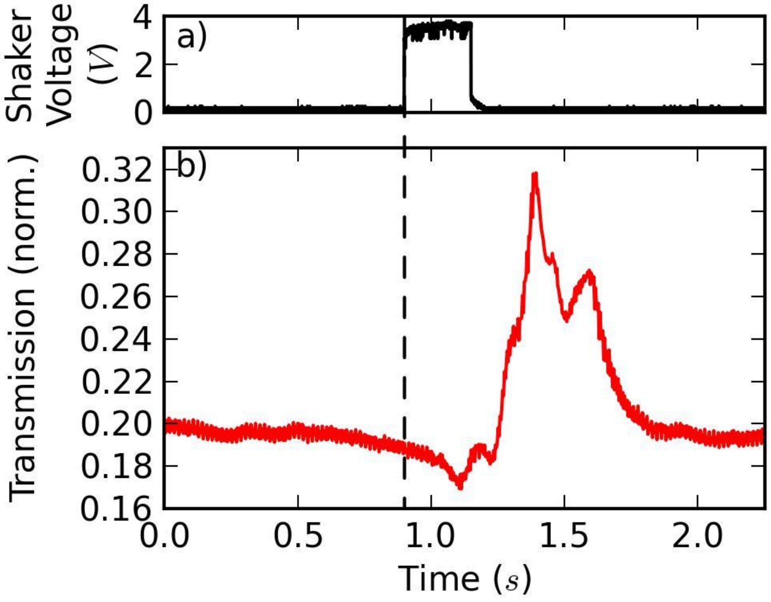
Tests Designed to Investigate Parameter Variation Temporally

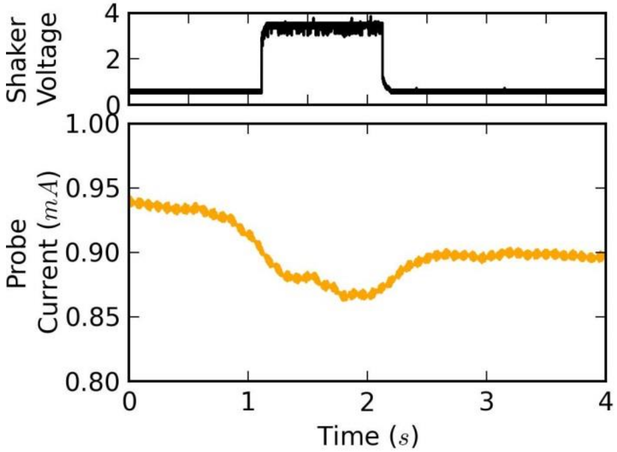
- Temporal measurements:
  - Dust shaker motor voltage pulse
  - Cathode bias voltage
  - Langmuir probe voltage (at plasma potential)
  - Camera trigger (TTL)
  - EM wave transmission
  - Electron saturation current
- Time-resolved high-frame-rate images (1500 fps) are captured
- Testing focused on GPS freq range (1.25 GHz)



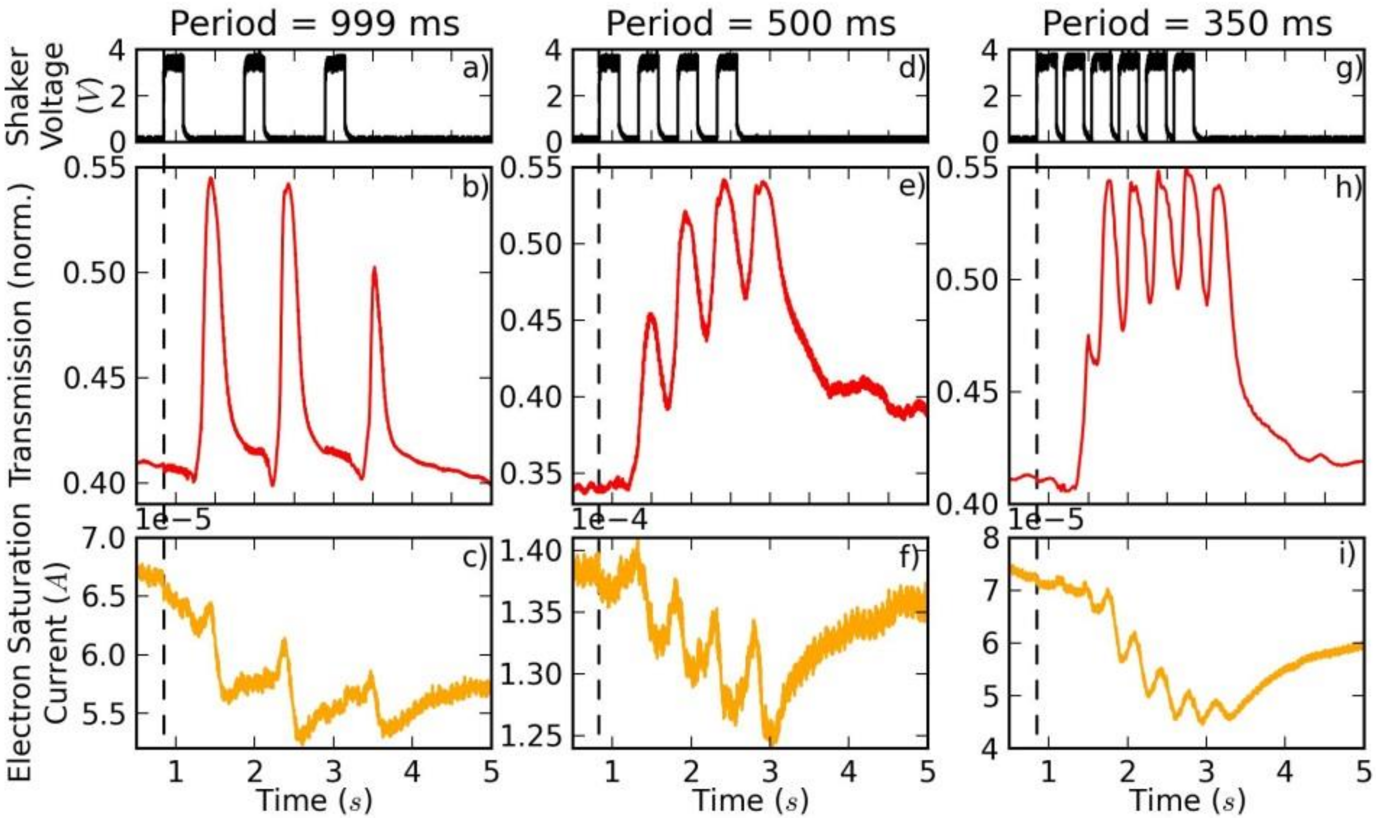
Single Pulse Tests Show Both Competing Effects

- Transmission response
  - Reduction in transmission: scattering effect – occurs early on
  - Transmission increases as charged microparticles begin leaving
  - Peak FWHM is approximately equal to dust shaker pulse width
- Electron current response
  - Current reduction indicates electron depletion
  - Difference in pre and post-pulse current is due to powder on probe





Pulsing Patterns: Multiple Pulses Can Compound Effects



- Subsequent pulses build on each other
- Plasma recovery is impeded by subsequent pulses
- Leads to increase in transmission magnitude as well as length of time of increased transmission

Plasma Electron Recovery Is Slow Compared to Transmission

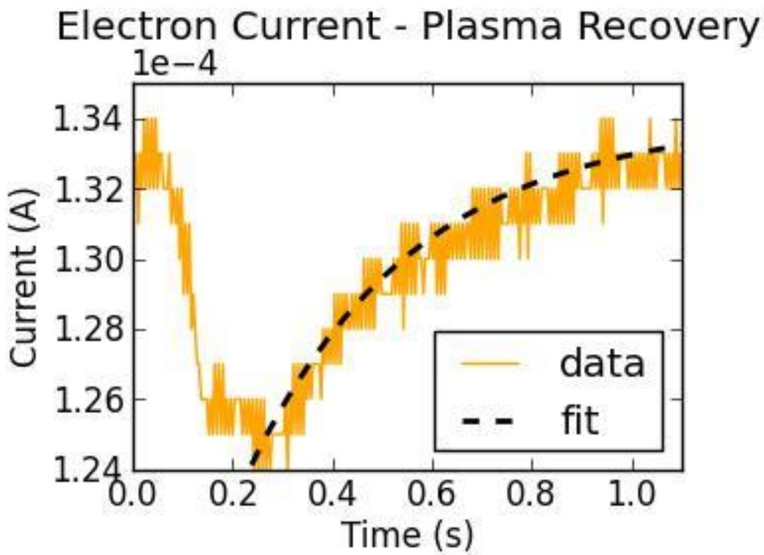
- Transmission and electron current recovery
- Transmission recovery time:

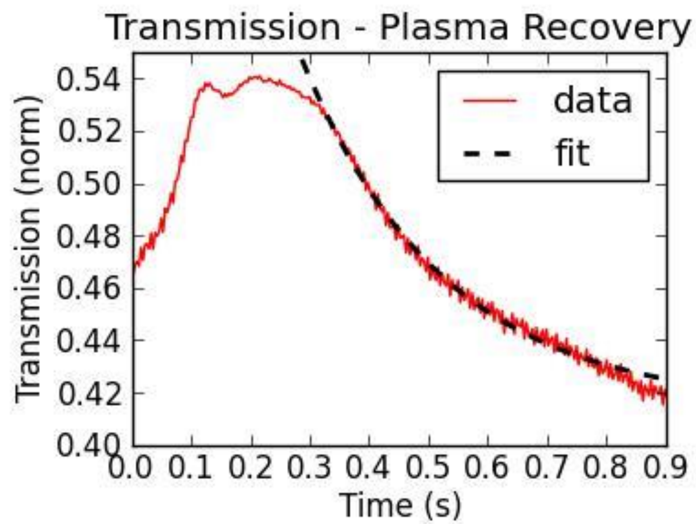
  τ_T = 100 ms

  σ_T = 50 ms
- Electron current recovery time:

  τ_i = 560 ms

  σ_i = 310 ms
- Expected recovery time is several orders of magnitude smaller (when accounting for cross-field diffusion)

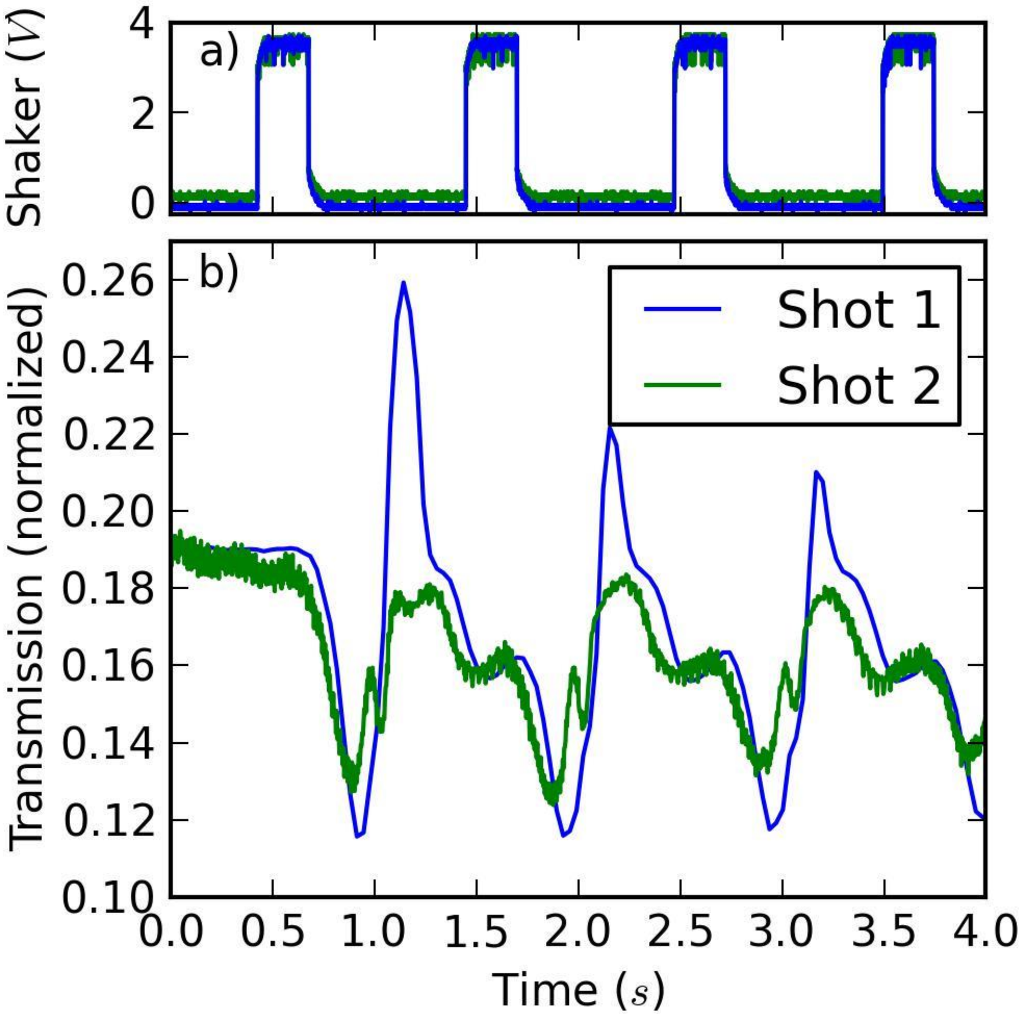




What Causes Shot-to-Shot Variation?

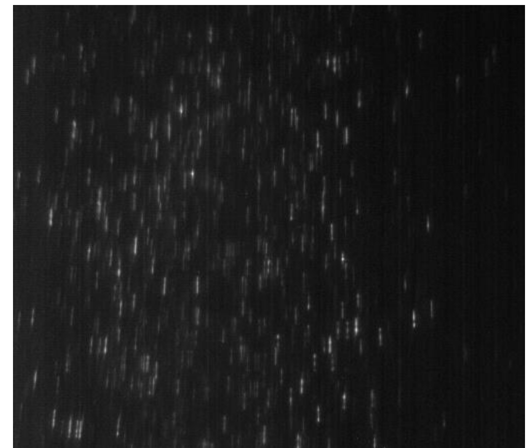
- Shot 1 and 2 were taken with same settings
- Shaker pulse is identical
- Transmission has similar qualitative characteristics
- Why the difference in peak transmission?
  - **Shot 1:** 6% *increase* in transmission
  - **Shot 2:** 1% *decrease* in transmission

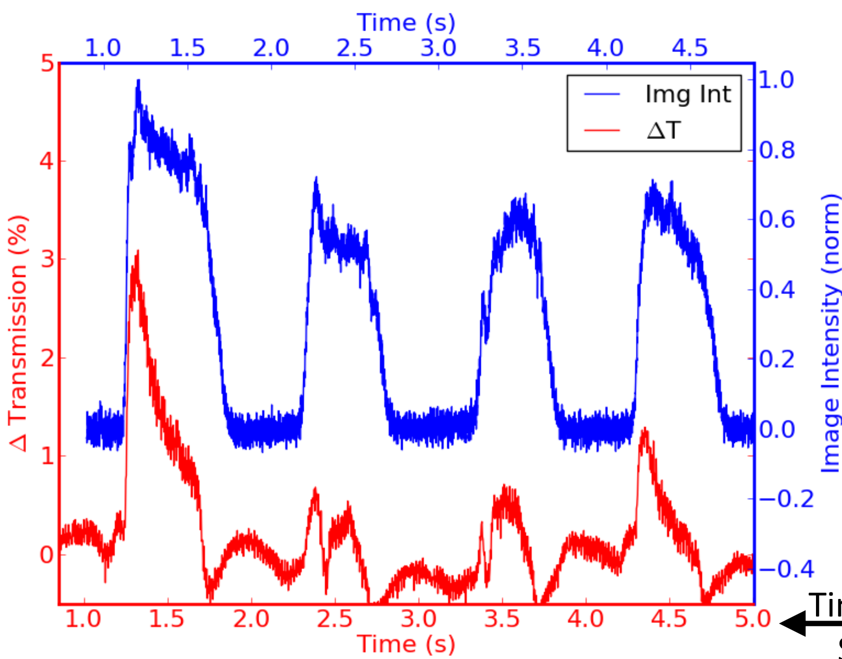
- **High-speed imaging of microparticles answers this question**



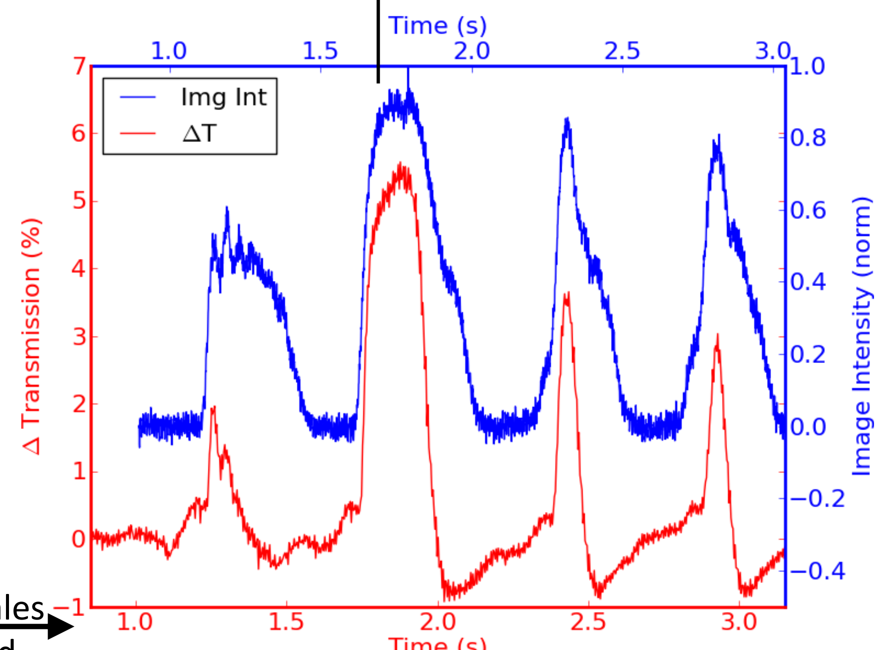
Shape of Transmission Peak Determined by Particle Flux

- Shape of transmission peak follows the pixel intensity spike (microparticle flux) closely
- General features: transmission peak width, magnitude of peak
- Fine features: eg - tapering of particle flux is reflected in transmission (see pulse 1 on left)

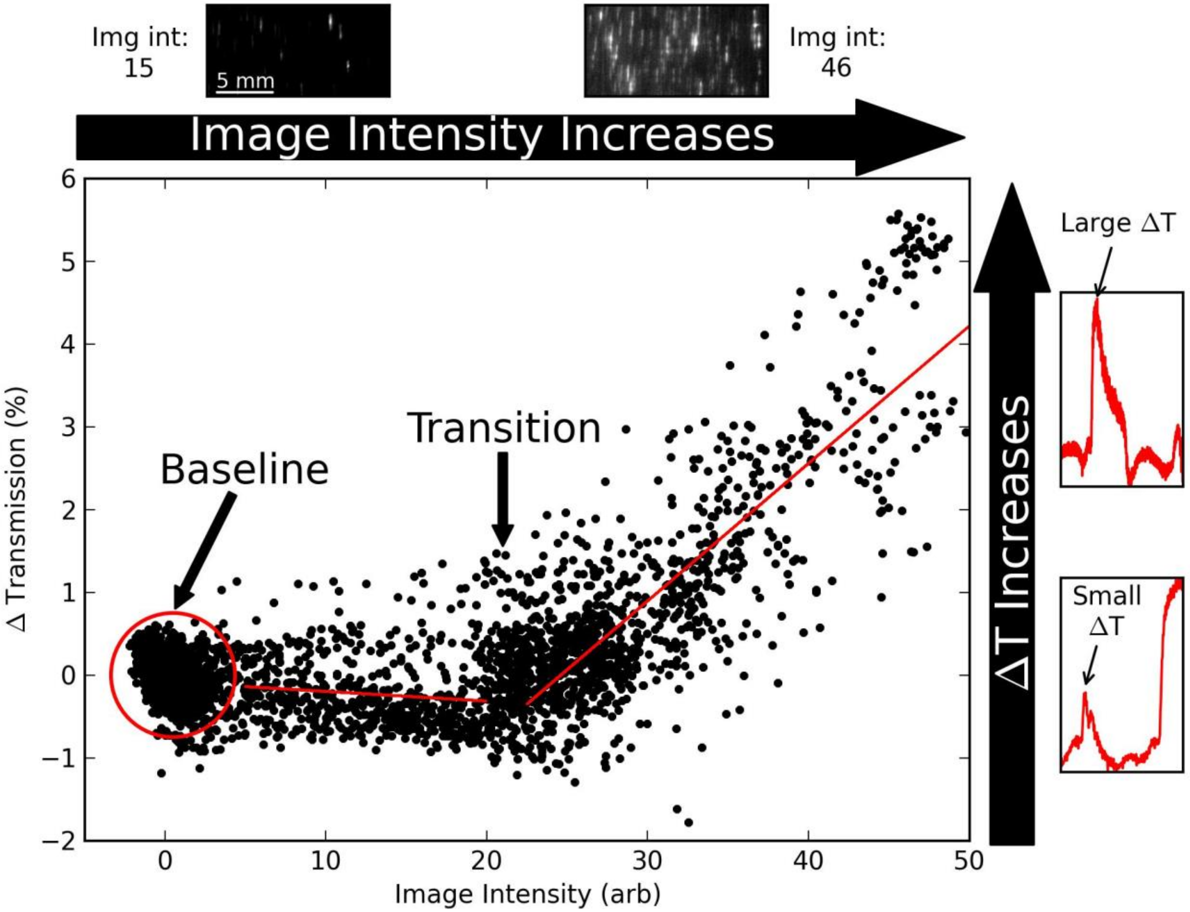




Timescales
Shifted



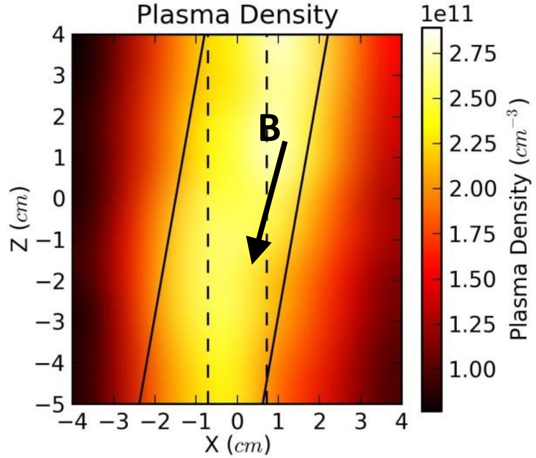
Increased Particle Flux Results in Increased Transmission

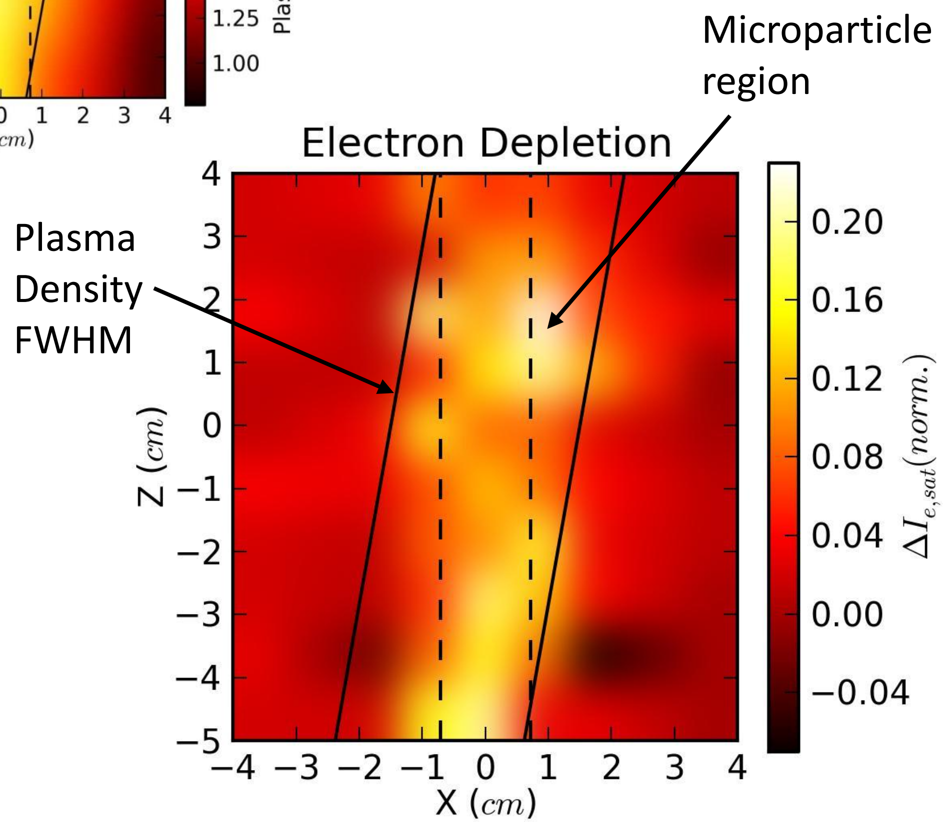


- Upward trend in transmission beyond average image intensity of ~25 (arb. units)
- Downward trend in transmission below ~20 (arb. units) average image intensity
  - Due to effects at beginning and end of microparticle injection pulses?
  - Due to signal scattering off of charged particles?

Electron Density and Depletion Spatial Dependency

- Plasma remains well collimated downstream
- Electron depletion in stream of microparticles
- Microparticles do not affect electron population along field lines
- Charged microparticles may provide efficient cross-field diffusion mechanism





Concluding Remarks

- Competing effects are both observed
  - Periods of increased scattering off of charged particles
  - Increased penetration through the plasma layer due to electron depletion
- Patterned pulses of dust are reflected in transmission
- Plasma recovery time is longer than expected
- Shot-to-shot variation is caused by inconsistent particle injection flux
- Transmission pulse follows the general shape of the particle injection flux
- Trends suggest particle flux need to reach a critical point to increase transmission
- Particle flux is the only apparent limiting factor for increasing signal transmission (in these experiments)
- Electron depletion does not extend along field lines

- Overall, microparticle injection has shown success in reducing the cutoff frequency and increasing microwave penetration of an overly dense plasma slab

Questions?

Recent publication with more details:

Gillman et al., Phys. Plasmas **22**, 043706 (2015).

Acknowledgement:

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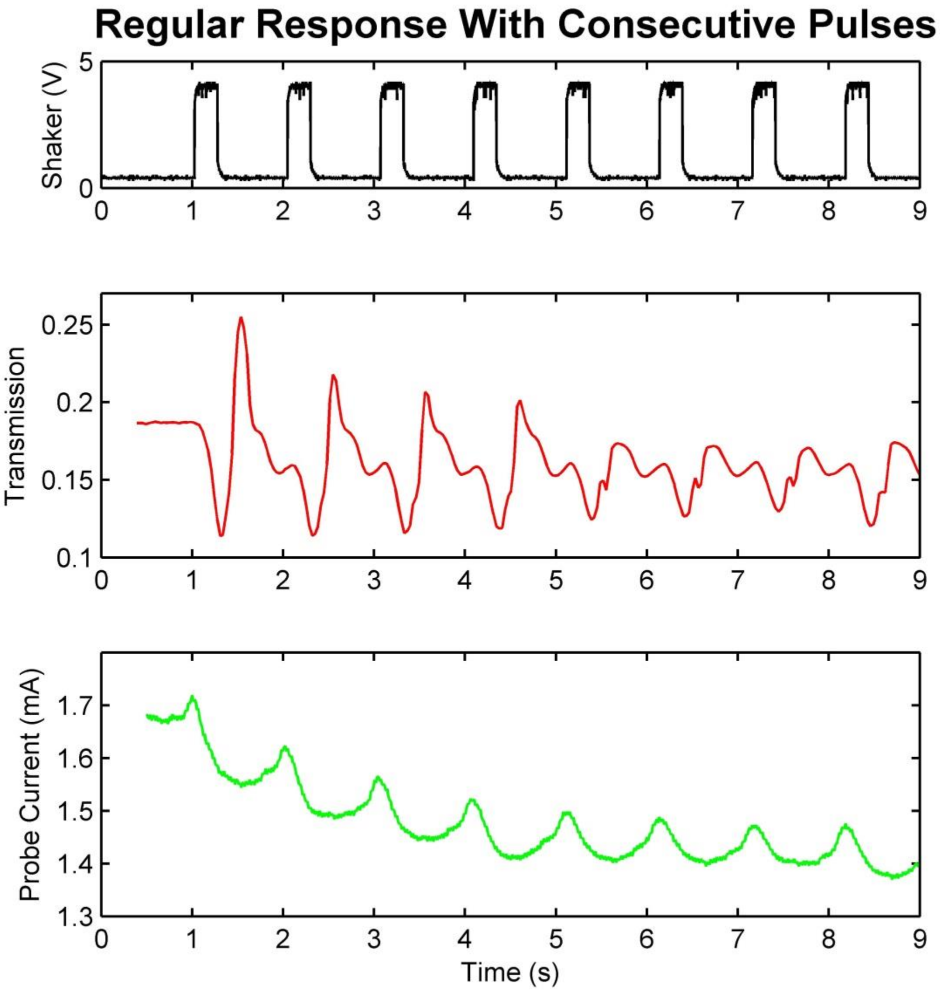
Consistent Response For Discrete Pulses

- 250 ms pulse, 1 Hz rep rate
- While powder is falling:
  - Transmission decreases
  - Probe current decreases
- Recovery period:
  - Transmission increases
  - Current continues to decrease as powder exits plasma
  - As current begins to recover, transmission drops
- Very regular, repeatable pattern evident in transmission and probe current
- Complex structure in transmission



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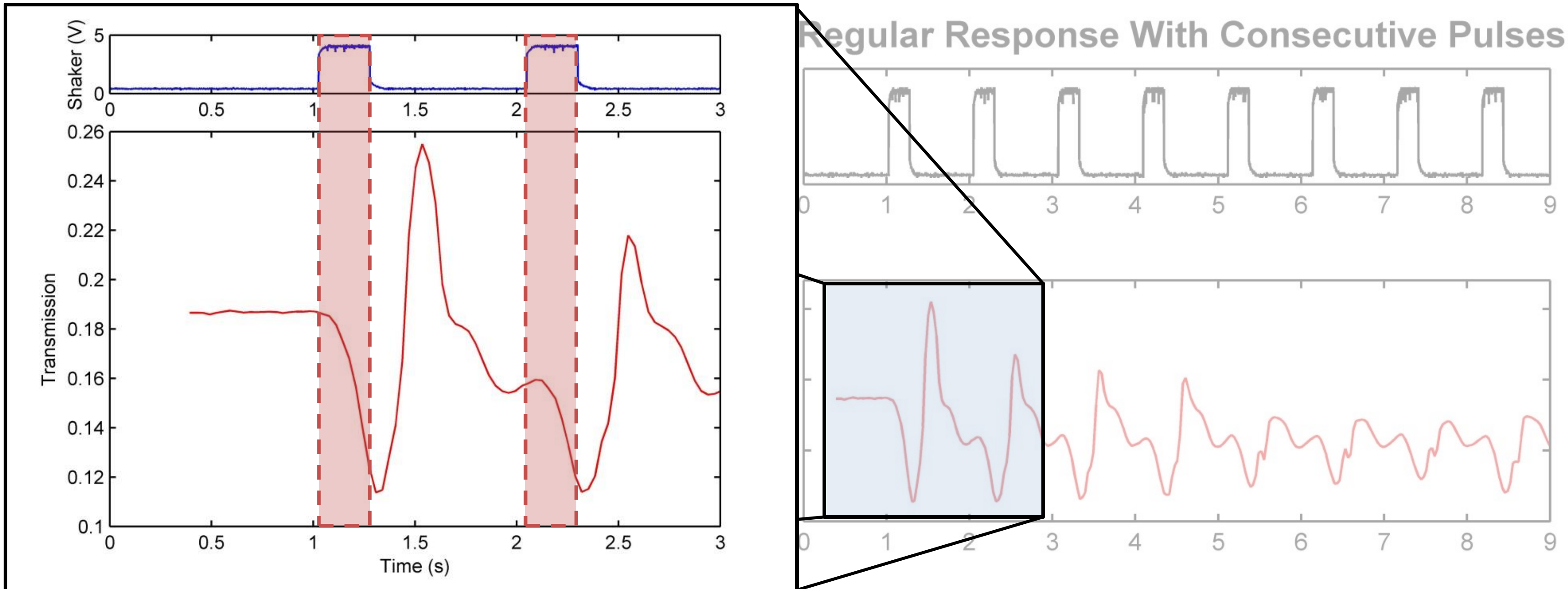

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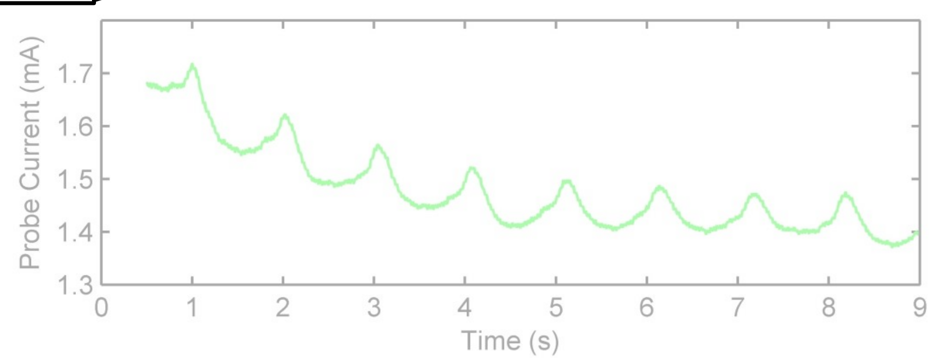
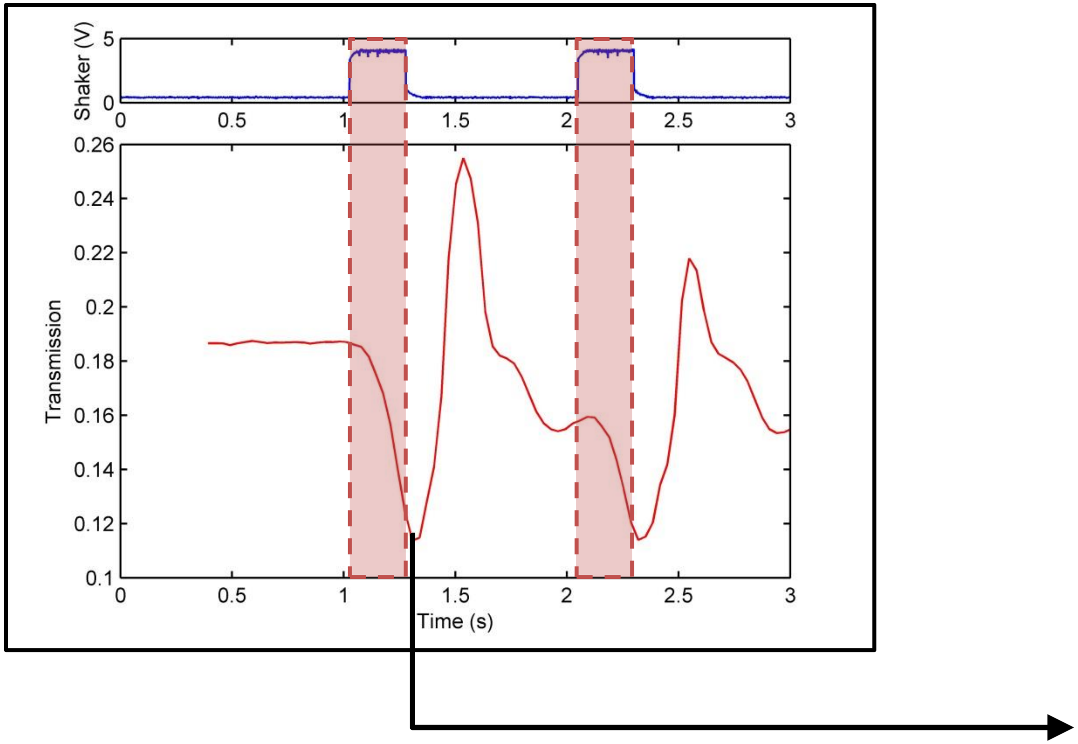
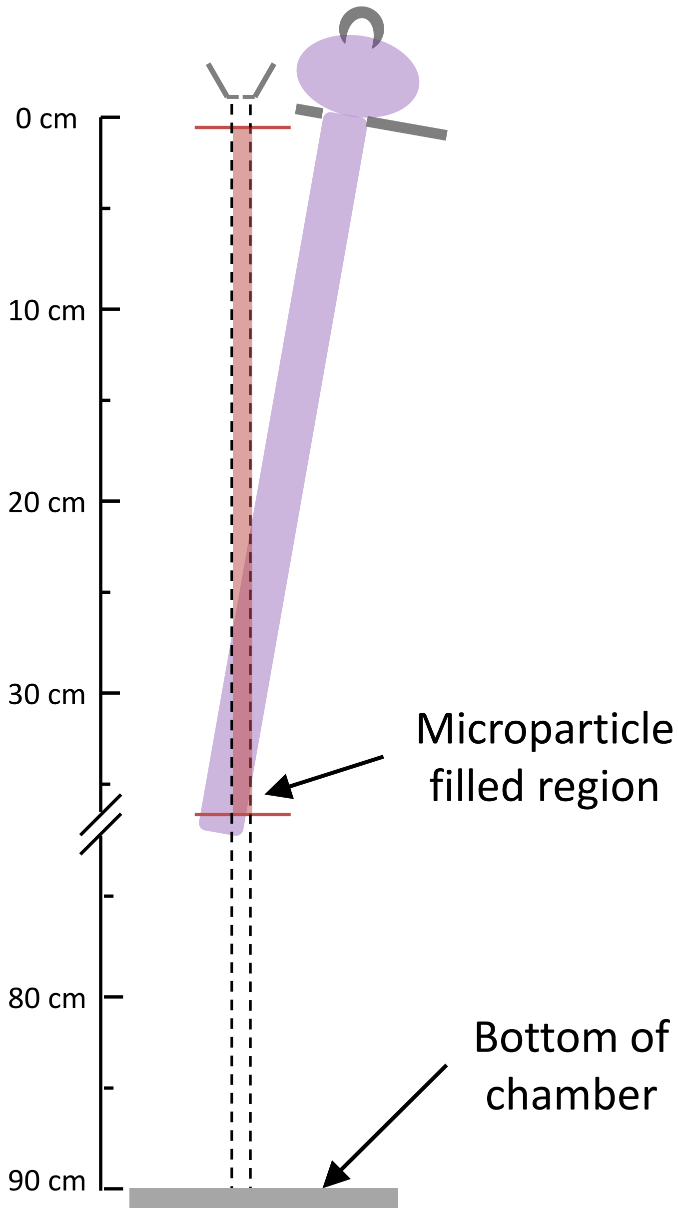
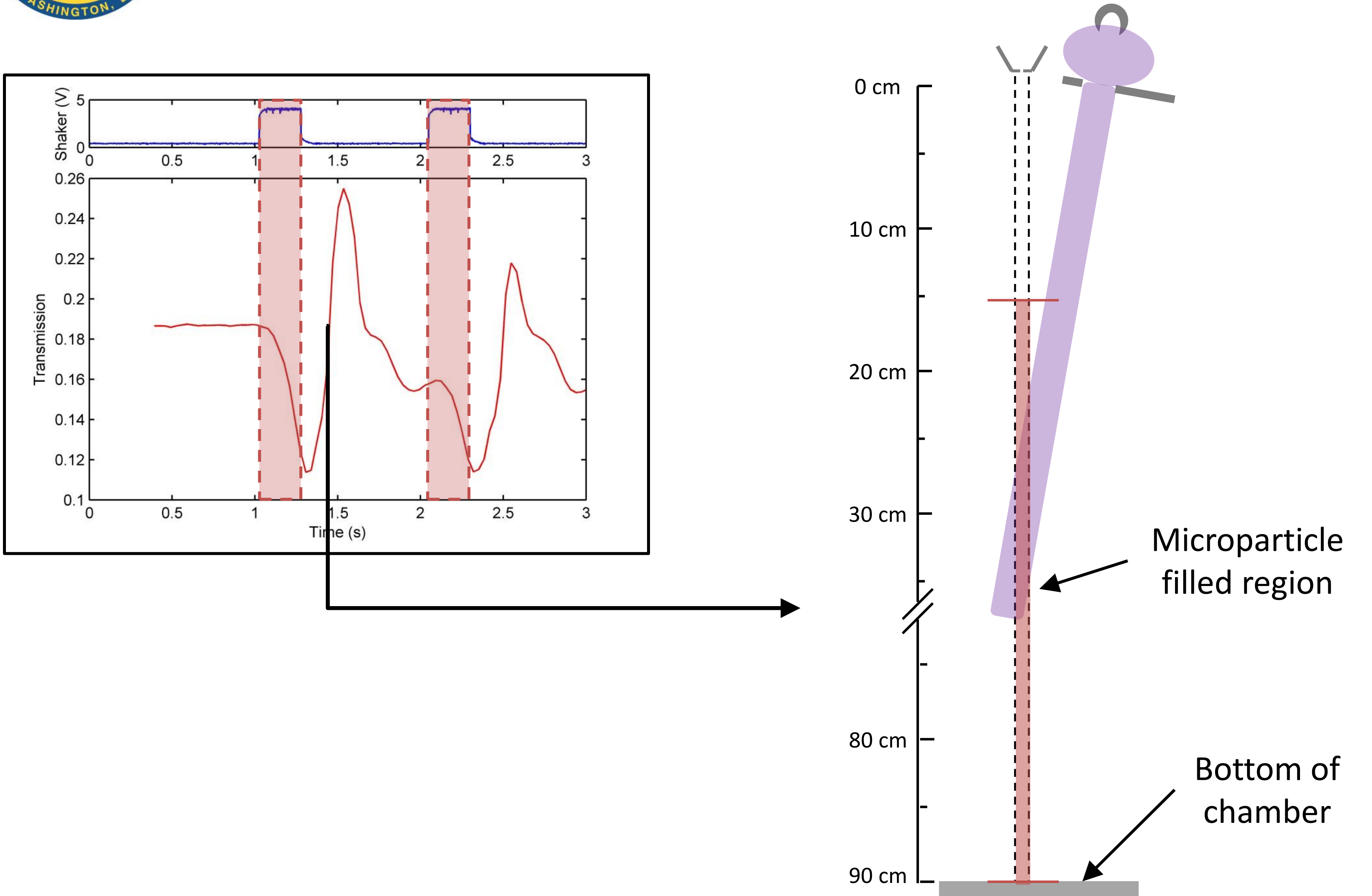


Explanation of Complex Structure: Microparticles Enter Plasma Sheet

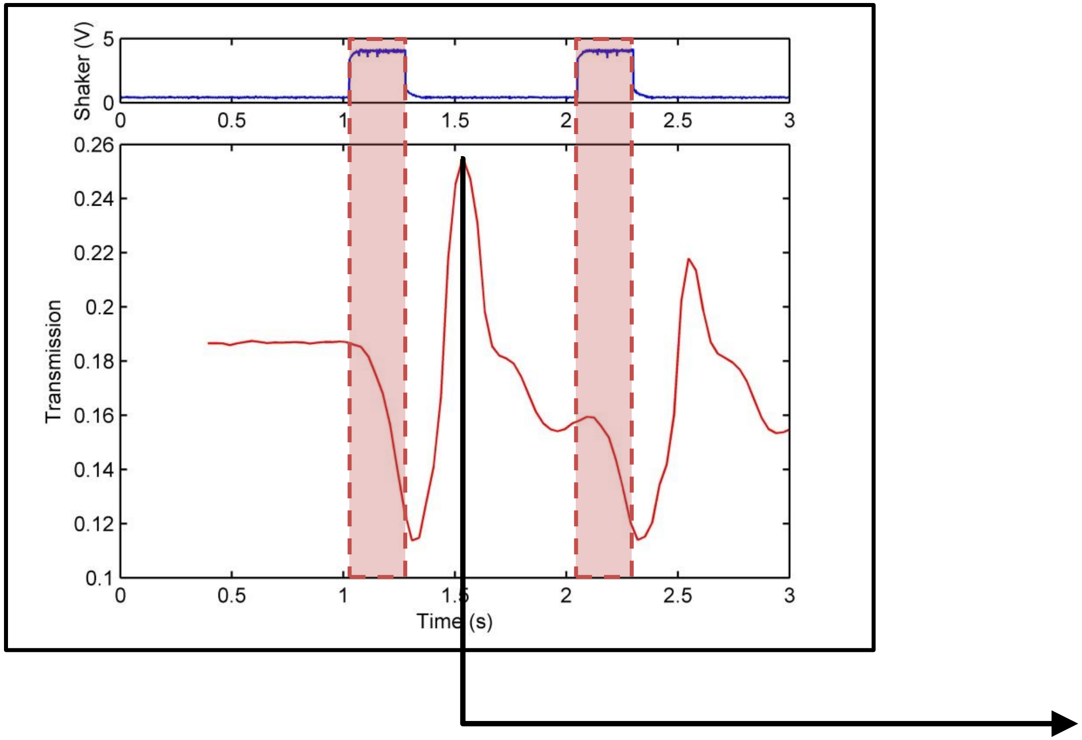


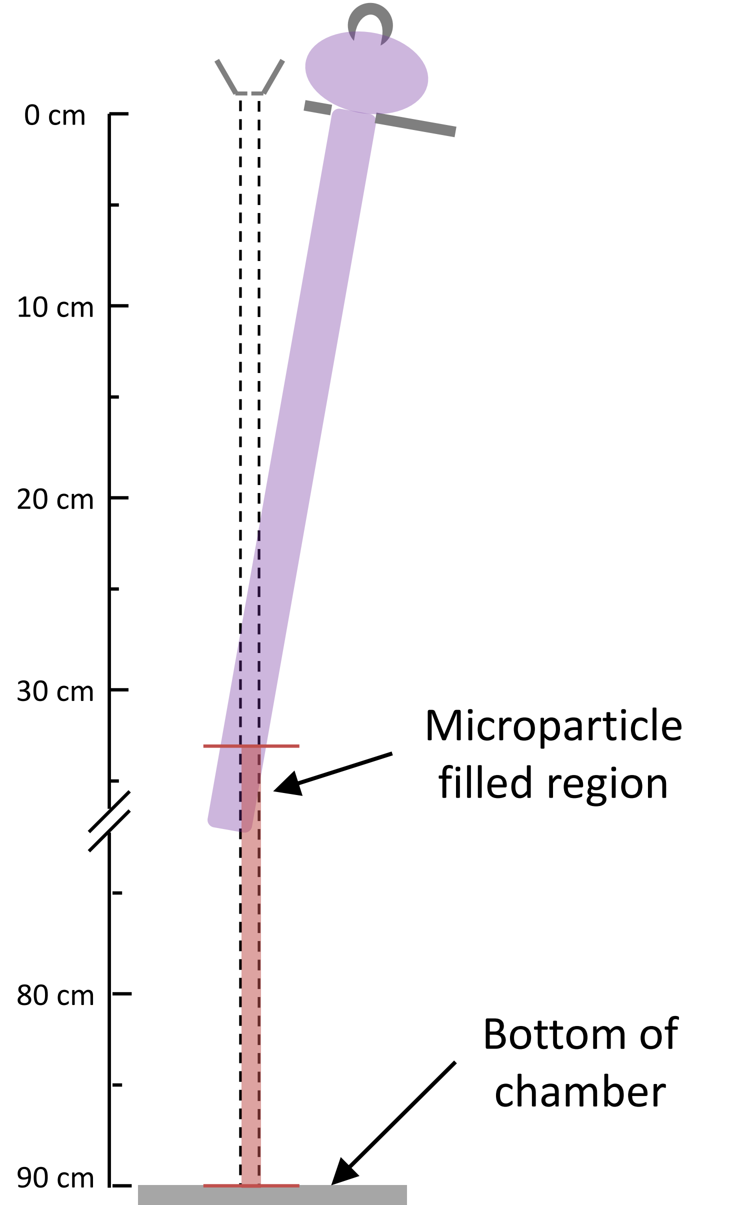


Explanation of Complex Structure: Microparticles Begin Exiting System

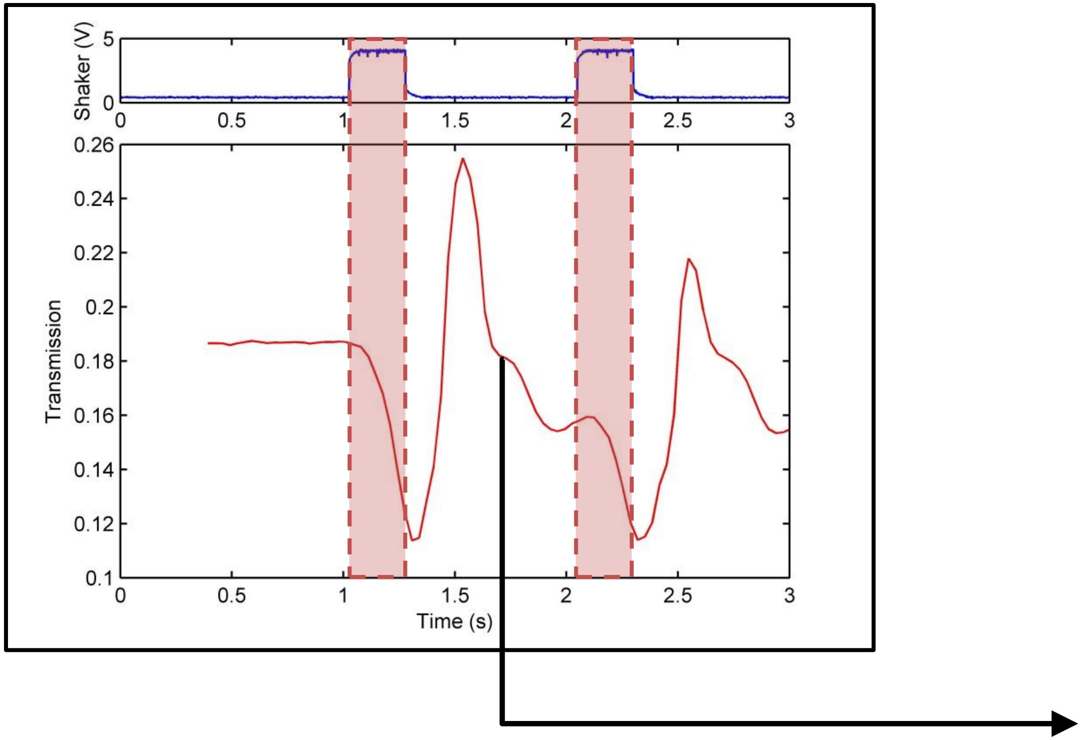


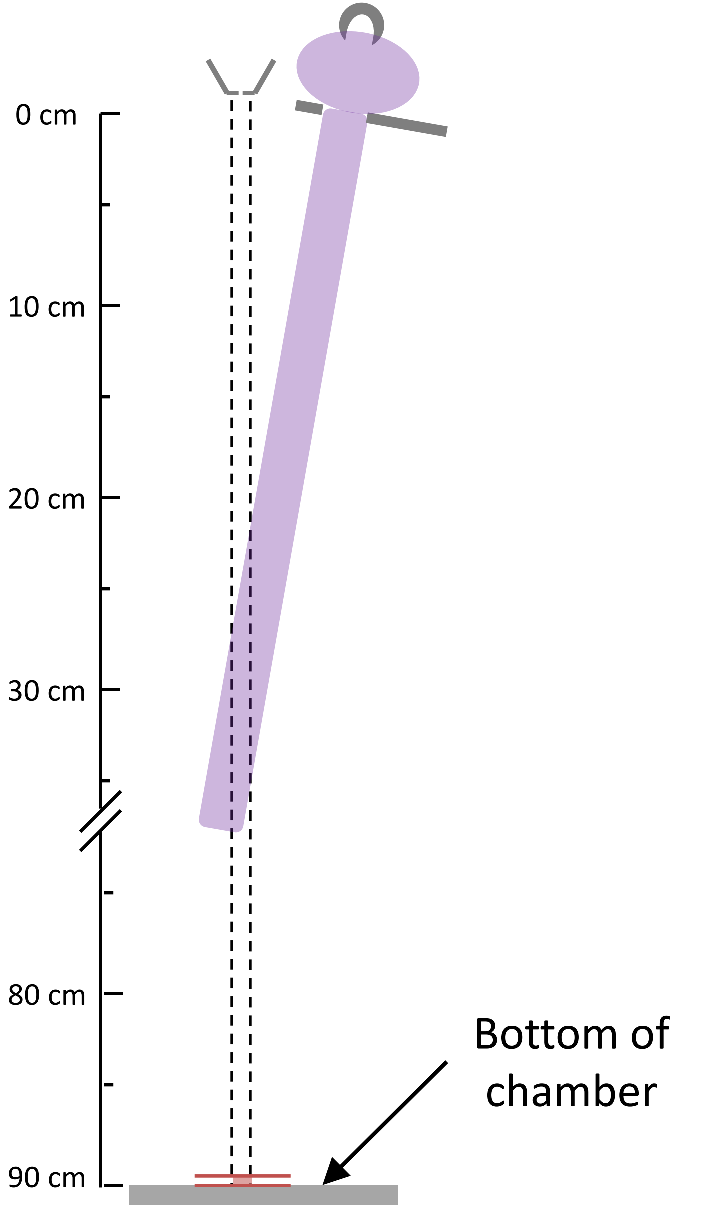
Explanation of Complex Structure: Microparticles Leave Plasma Sheet





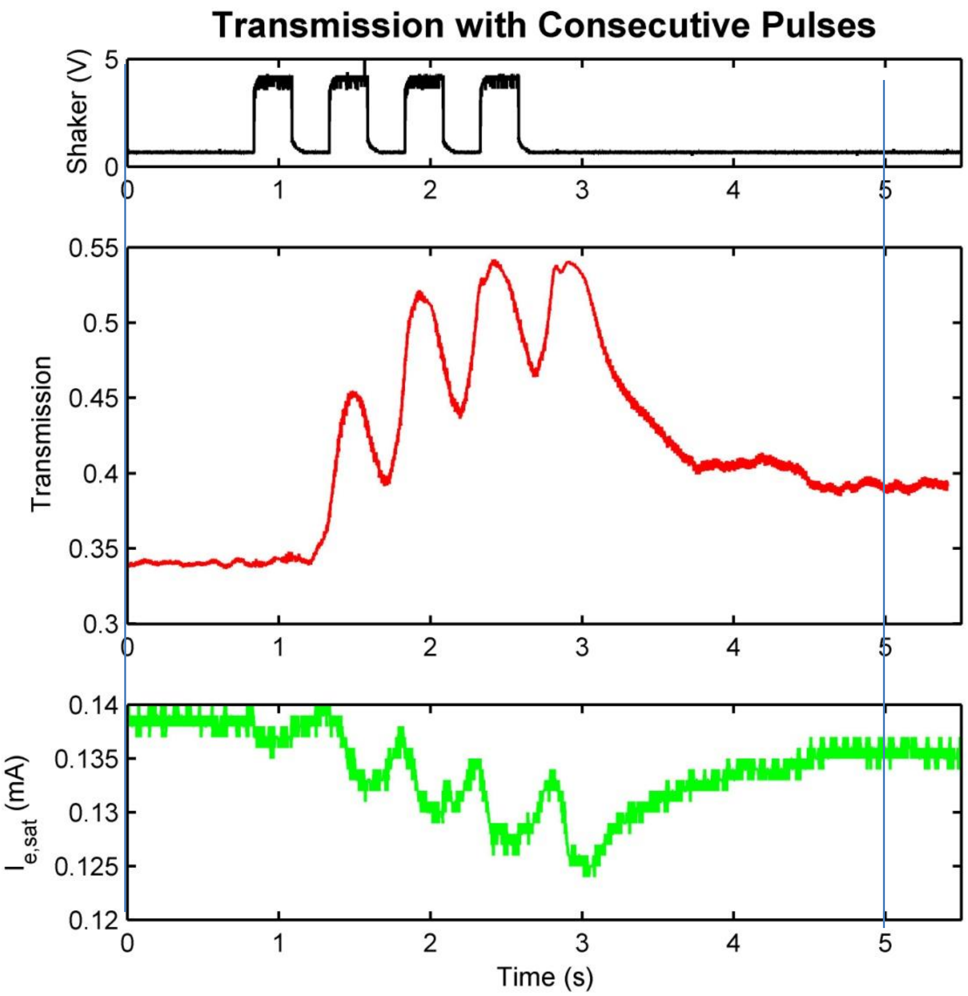
Explanation of Complex Structure: All Microparticles Exit System



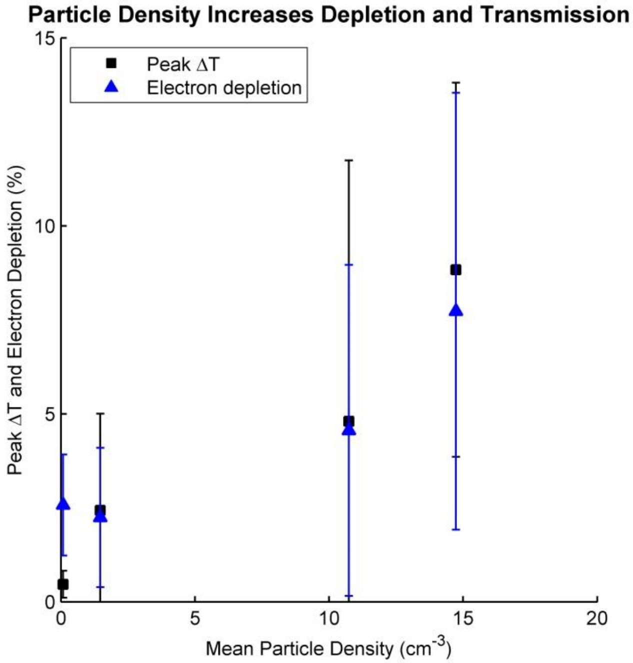


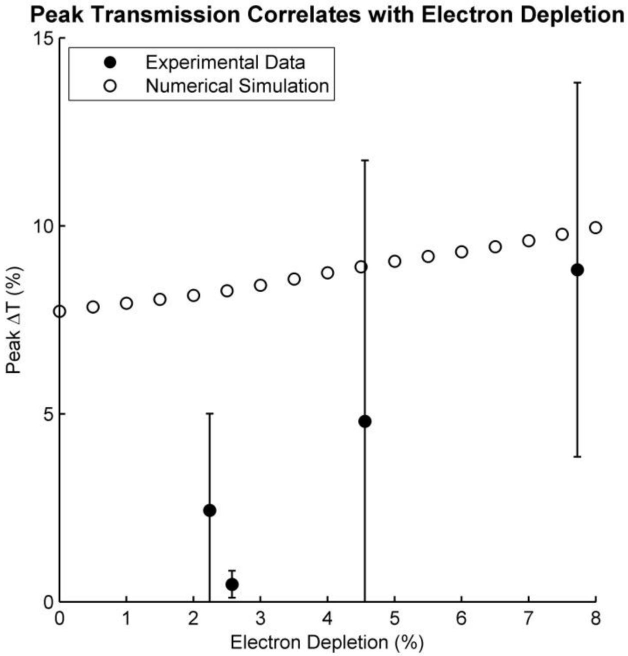
At Fast Rep Rate, Transmission Can Increase With Consecutive Pulses

- 250 ms pulse, 2 Hz rep rate
- Plasma recovery is longer than shaker “off” time
- Each pulse builds on the previous pulse
- Peak transmission continues to increase with each pulse
- Saturation of peak transmission was observed after 4 to 8 pulses



Electron Depletion and Transmission Are Correlated





- Peak transmission and electron depletion correspond well
- Transmission and depletion increase with increasing particle density
- Numerical results correlating transmission with electron depletion correspond well at higher depletion rates to the experimental results
- Further tests are required to reduce experimental error

Magnitude of Transmission Correction

- With plasma tilted, entire length is not fully depleted
- Length that is depleted depends on plasma density profile

Width of Overly Dense Plasma (cm)	Length Depleted (%)	Transmission Correction Factor
0	6.9	14.4
0.5	10.4	9.7
1.0	13.8	7.3
1.5	17.2	5.8
2.0	20.6	4.9
3.0	27.4	3.6