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Building Better Mousetraps

Hollow Cathodes and the

Path to a Plasma Density "Standard Candle"

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Washington, D.C.

Presented to the Michigan Institute for Plasma Science and Engineering (MIPSE)

October 26, 2022

The United States Naval Research Laboratory

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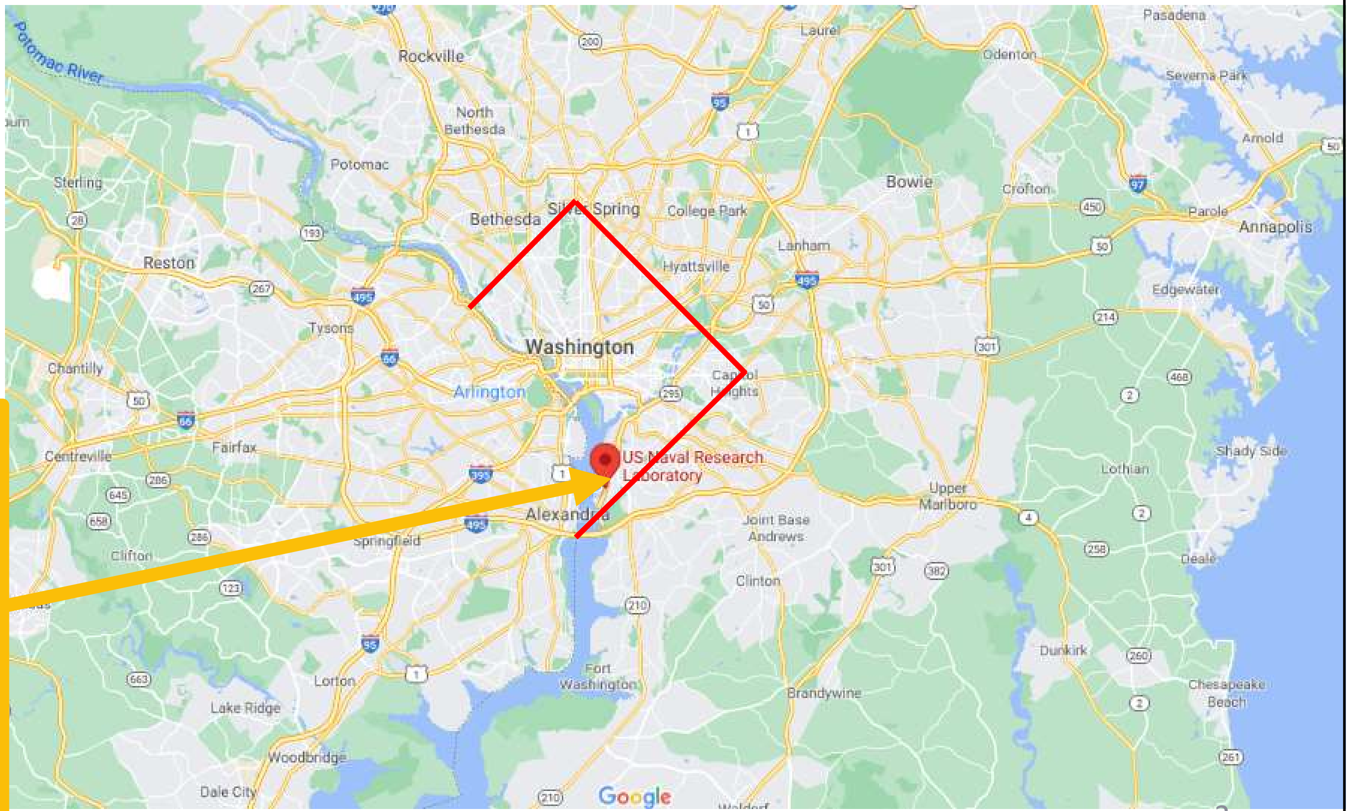


NRL Mission:

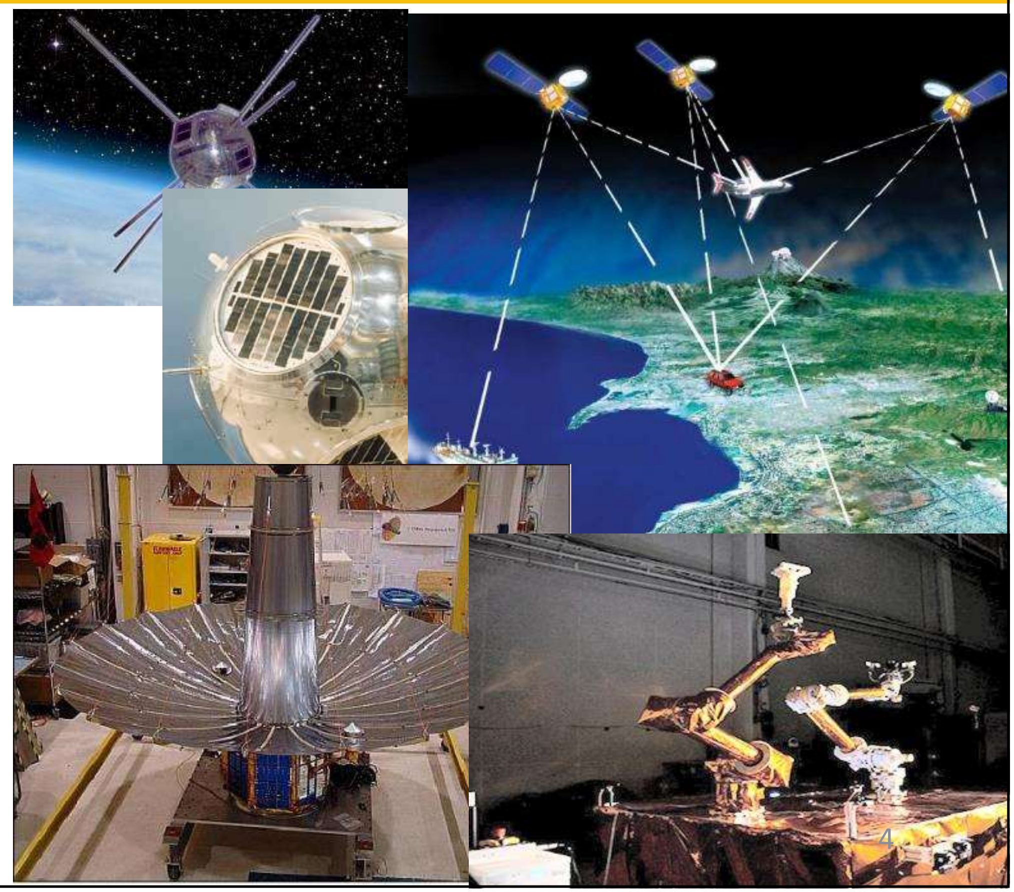
"The Government should maintain a great research laboratory... In this could be developed...all the technique of military and naval progression without any vast expense.“ --Thomas Edison

Naval Research Laboratory Founded 1923
Meet S&T needs of the US Navy and Marines

NRL is a $1B organization employing over 1600 S&Es, over 50% PhDs, conducting basic and applied research spanning the depths of the ocean to the far reaches of space

Naval Center for Space Technology (NCST)

- 50's: Project Vanguard put the first US satellite in orbit.
- 60's: GRAB1 first surveillance satellite
- 70's-80's: Developed initial GPS
- 2000's: TacSat tactical communications
- 2010's: Robotic Servicing of Geostationary Satellites (RSGS)



Plasma Propulsion Personnel

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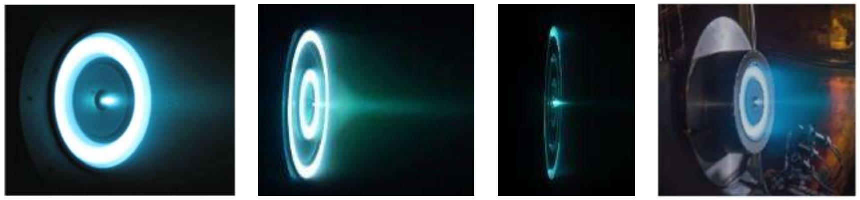
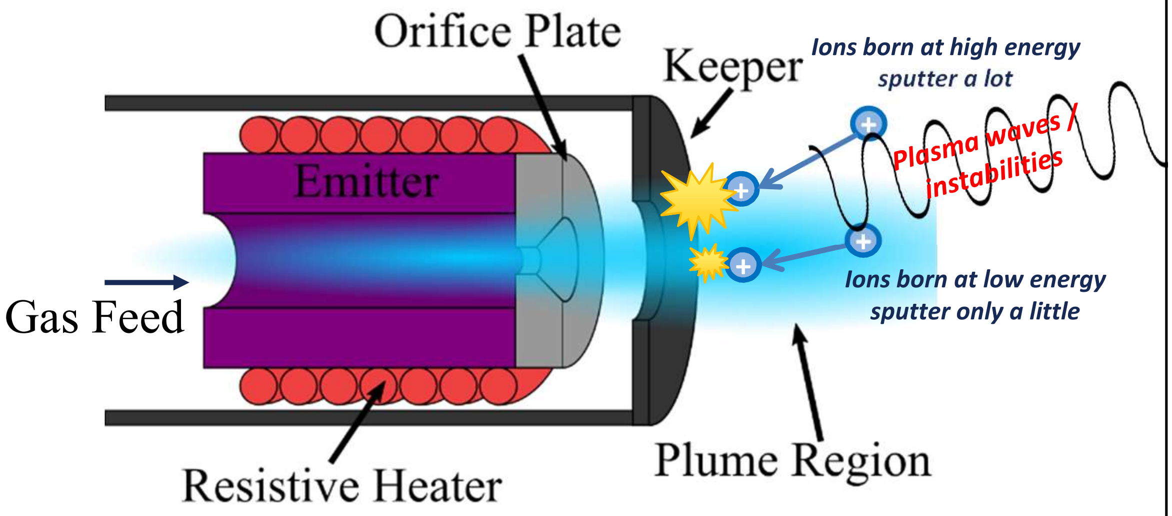
- Special thanks to our NRL Plasma Physics Division collaborators whose work is featured in this talk:
  - **Erik Tejero**
  - Dave Blackwell
  - Ami DuBois
- And to all our intern alumni since 2019!
  - Matt Paliwoda (UIUC→NRL)
  - Margaret Mooney (WMU)
  - Hannah Watts (WMU→Aerojet)
  - Hannah Sargent (WMU)
  - Anil Bansal (UM)
  - Anna Sheppard (UW→JPL)
  - Jacob Halpern (Purdue)
  - Emil Broemmelsiek (UIUC)
  - Austen Thomas (WMU)
  - Adrian Vicente La Lande (GT)
  - Henry Shi (SUNY)
  - Jose Orozco (UC Davis)
  - Moises Angulo-Enriquez (UIUC)
  - Roxanne Pinsky (UM)
  - Arega Margousian (GT)

Background: What is a Hollow Cathode?

- Why work with cathodes?
  - Smaller, cheaper, easier than thrusters
  - They're a common pain point (hot, power-hungry, delicate, single points of failure)
  - Share many similar physics problems
- Operating principle:
  - Gas flows into a long tube
  - An "emitter" at the end is heated to thermionic electron emission
  - Electrons are drawn out toward a "keeper" to ignite a plasma
  - External heaters are turned off; the plasma stably self-heats
- What could go wrong?
  - Plasma instabilities at high ratios of $I_D/\dot{m}$ drive energetic ion bombardment producing keeper erosion

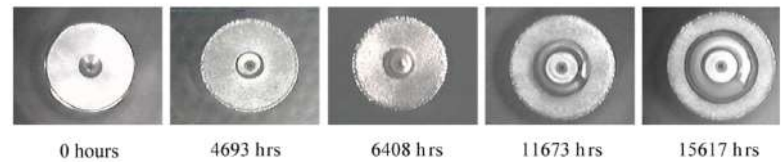


Cathodes: That bright little spike in the middle of cool Hall thruster photos

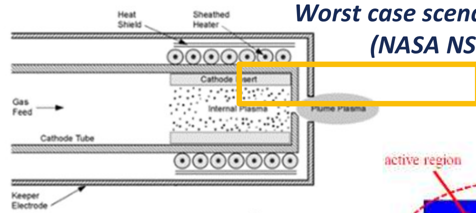


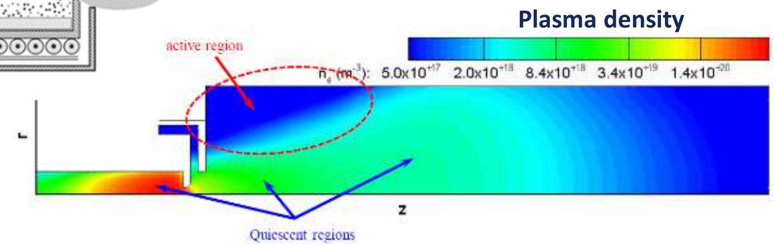
How Might We Suppress That Instability? Try Breaking Up the Keeper Orifice

- We know ion bombardment can destroy cathodes
  - more current or less neutral damping exacerbates instability
- Some results suggest triggering in regions of high radial plasma or neutral gradient
- Could breaking the keeper into a “showerhead” style with multiple orifices help?
  - Lots of hand-wavey reasons to say “maybe”
  - But what a nice toy system!

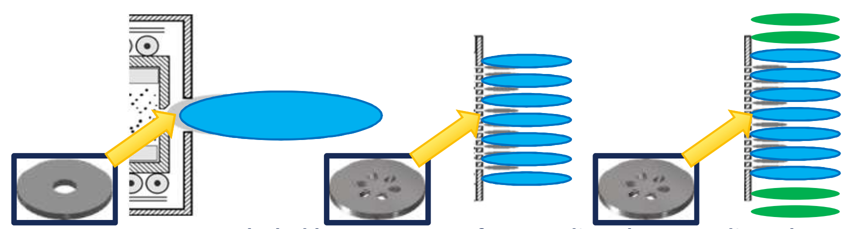


Worst case scenario: Complete keeper erosion (NASA NSTAR extended life test)



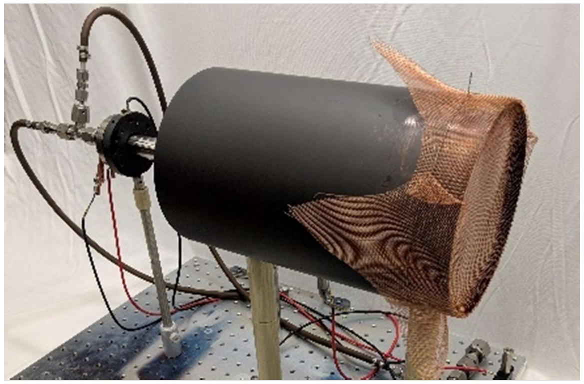


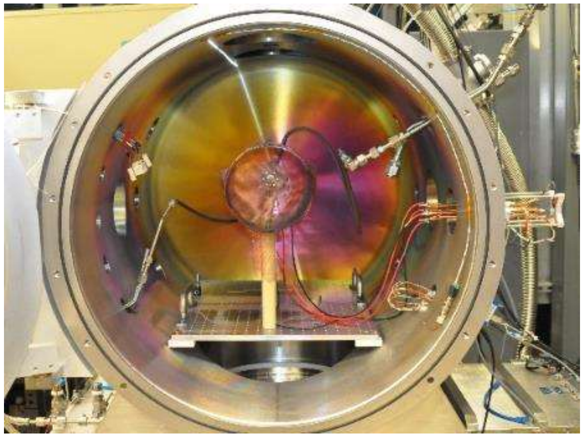
JPL modeling (Mikellides) identifies active region in wings of cathode plume

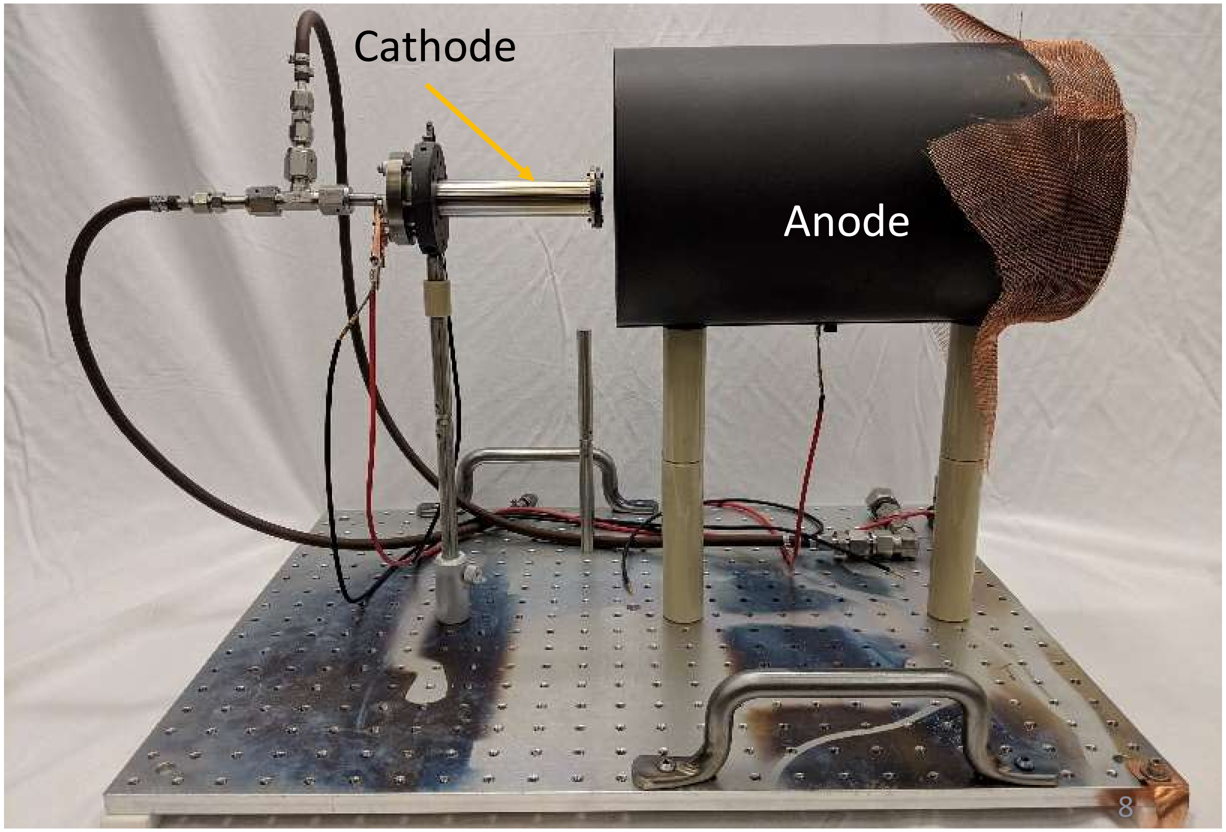


Many-holed keepers can soften gradient by spreading plasma (middle) and/or neutral gas (right)

Experimental Configuration: External Anode Testing







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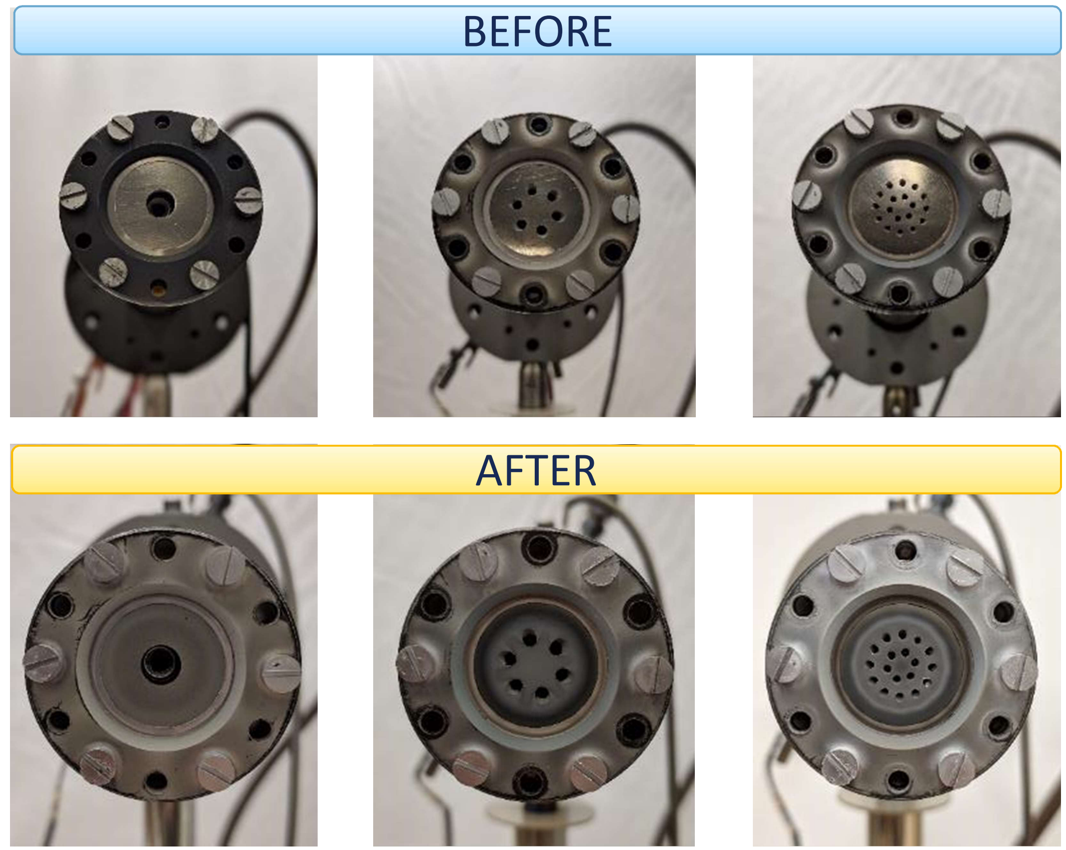
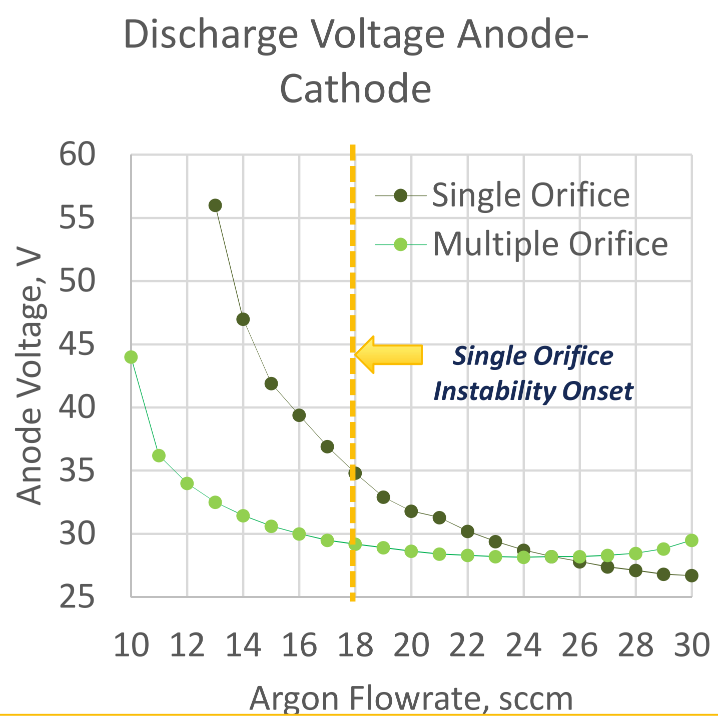
Reduced Erosion on MO Keeper

- Single Orifice:
  - Graphite erosion
  - Stainless scouring

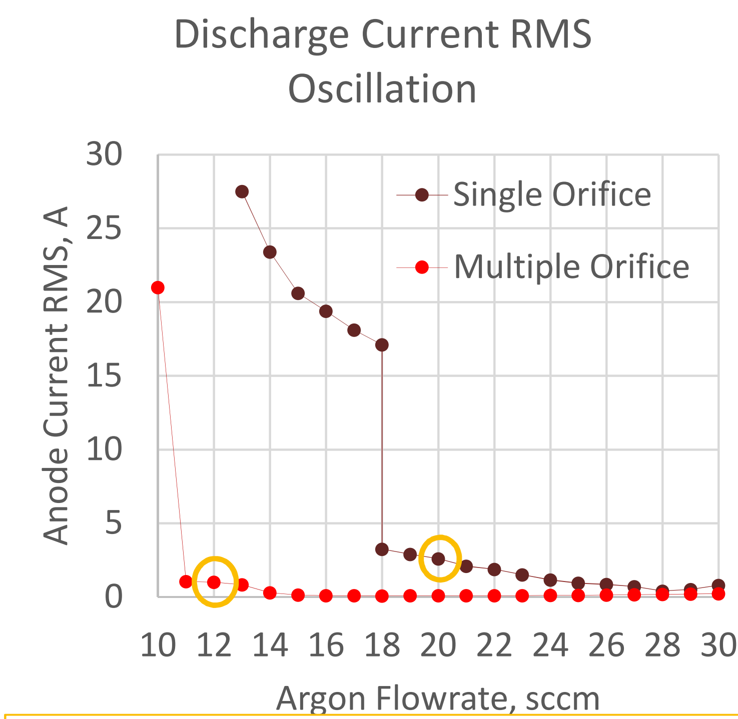
- Multiple Orifice:
  - No erosion of graphite spray seen
  - Net deposition (backsputter) seen instead



Performance Metrics



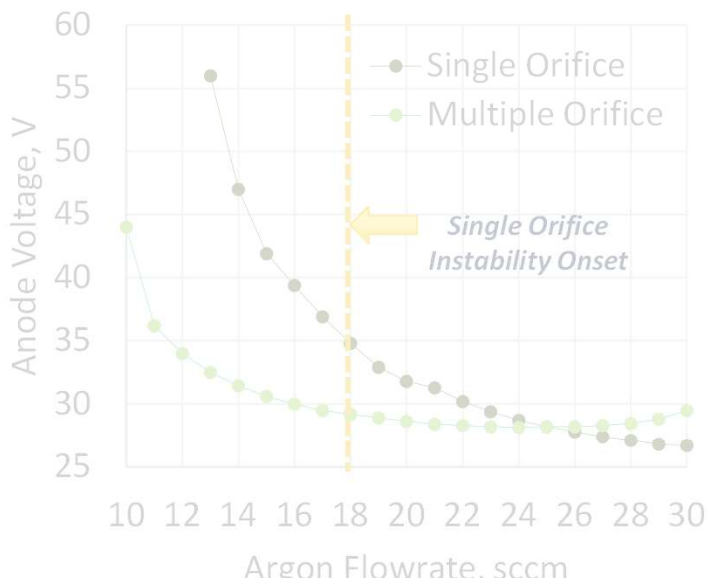
10%-20% lower power



Current delivered more stably

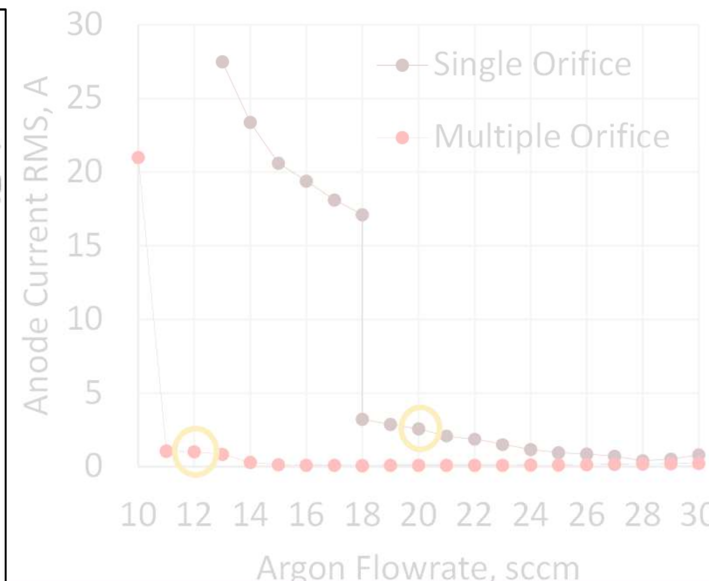
Performance Metrics

Discharge Voltage Anode Cathode



Hey! It Kind of Worked!
But, ummm… Why?

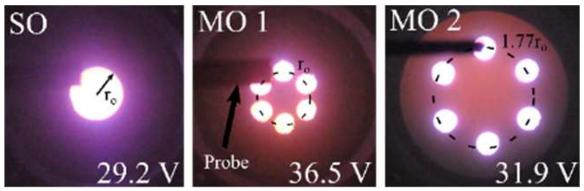
Discharge Current RMS Oscillation



10%-20% lower power

Current delivered more stably

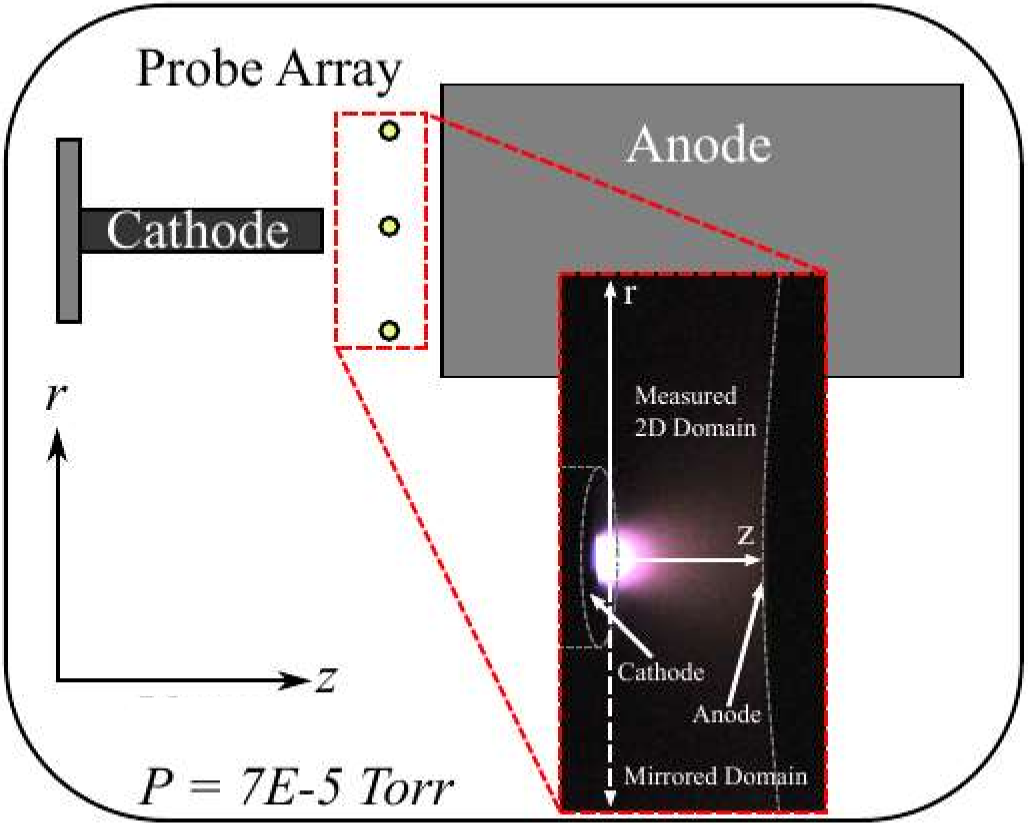
Experimental Apparatus



Hollow cathode operating parameters

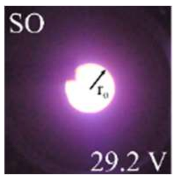
- $\dot{m}$ = 20 sccm Ar
- I_{dc} = 15 A
- V_{dc} = 29.1 V

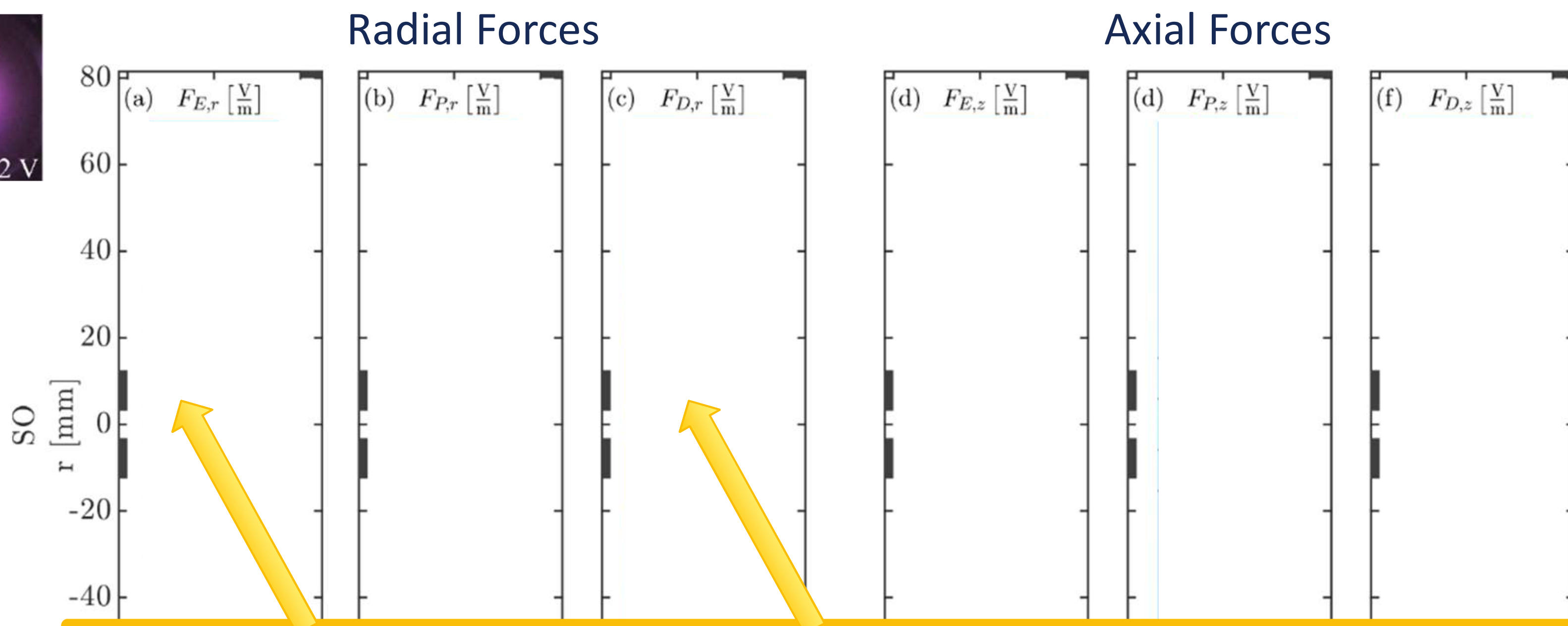
- Langmuir Probe (n, T_e)
- Emissive probe (V_p)
- Ion saturation probe (ν_e^{IAT})
- Can use to evaluate Ohm's law and determine flow field for electrons



See: Georgin, Electron Transport in Multiple Orifice Hollow Cathodes, J. App Phys 2021

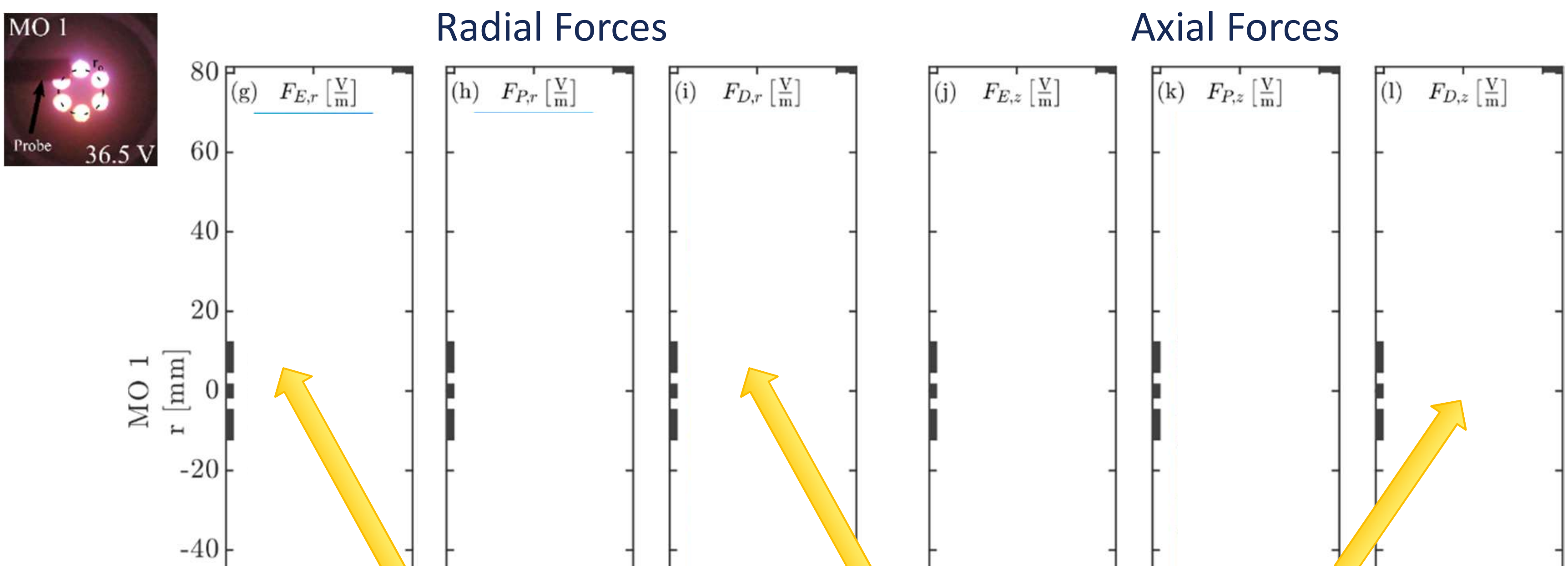
SO: Forces Influencing Electron Flow Direction





Radial electric and drag forces dominate in the plume region for the standard cathode

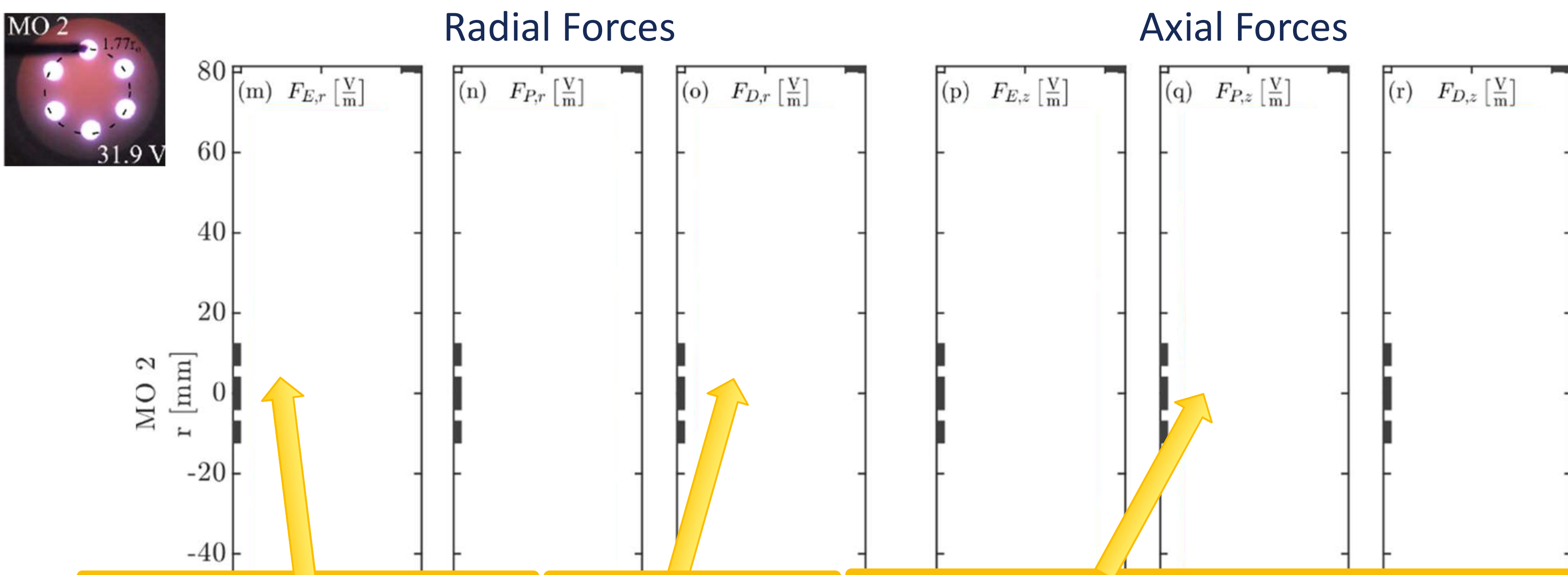
MO1: Forces Influencing Electron Flow Direction



Radial electric and drag forces are strong

Axial component of drag is comparable

MO2: Forces Influencing Electron Flow Direction



Radial electric force reversed

Drag reduced

Axial pressure contribution dominates the plume.

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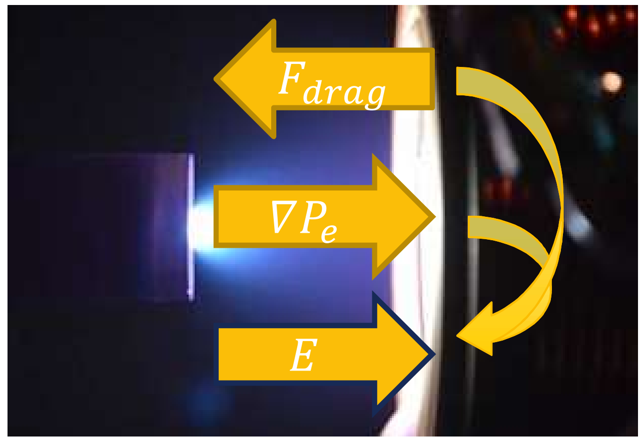
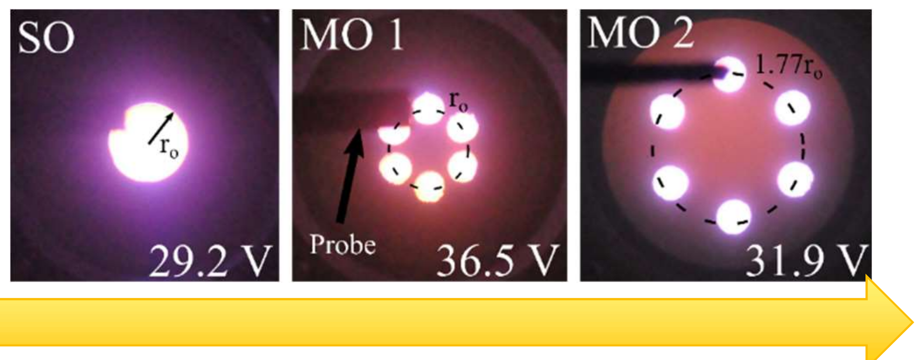
Electron Transport Physical Picture



$\vec{E}$ is a response in the plasma due to changing pressure and drag conditions.

Electric field dominated



Pressure dominated

$\vec{E}$ is suppressed because design increases pressure and reduces drag

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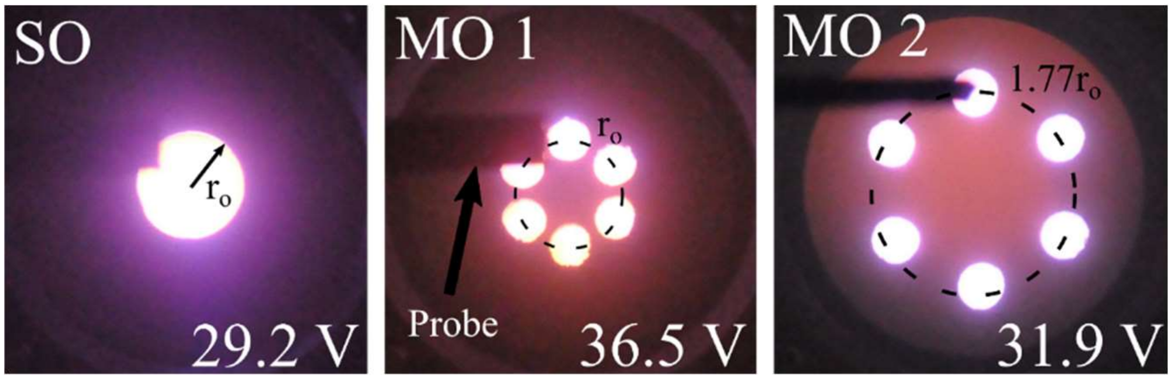
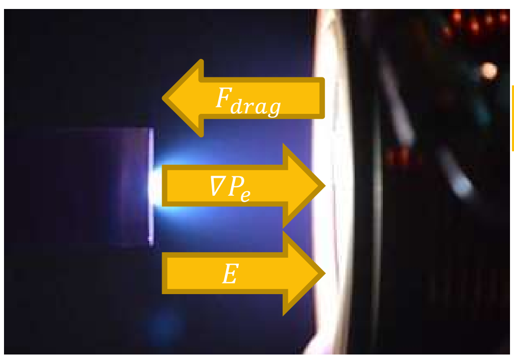
…Now What?

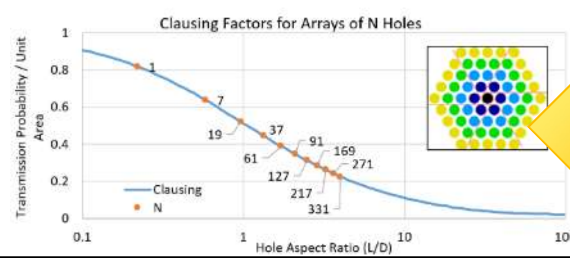


Goal: learn to manipulate forces for future designs

Existing Designs



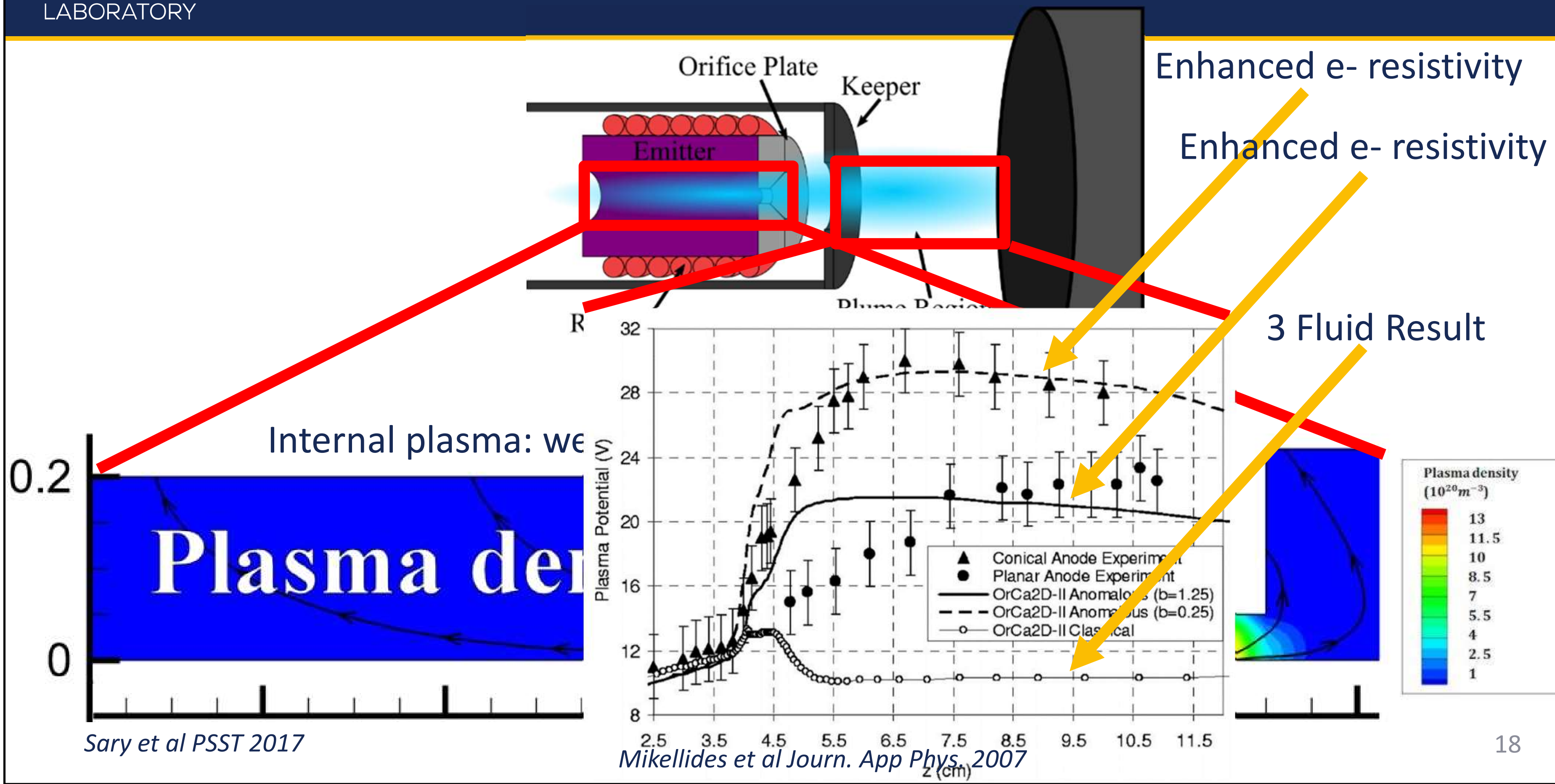
Physical Principles of Operation



Modeling

?

Cathode Physics



Sary et al PSST 2017

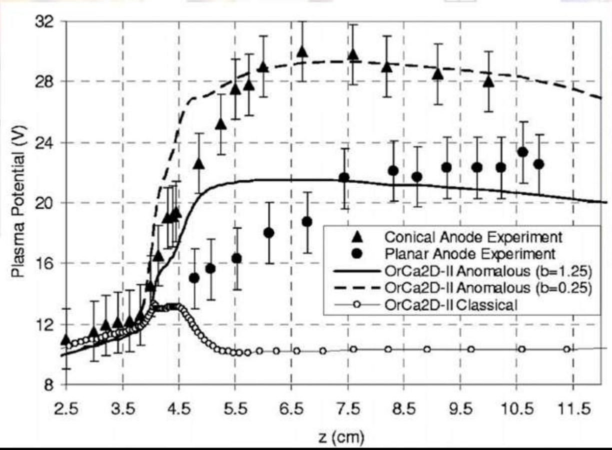
Mikellides et al Journ. App Phys. 2007

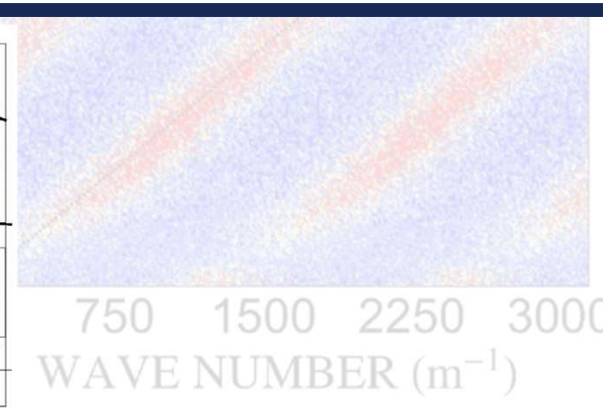
Streaming instabilities

IAWs cause effective drag force on electrons by distorting the distribution function

The effective collision frequency can be 10-100X Coulomb collisions

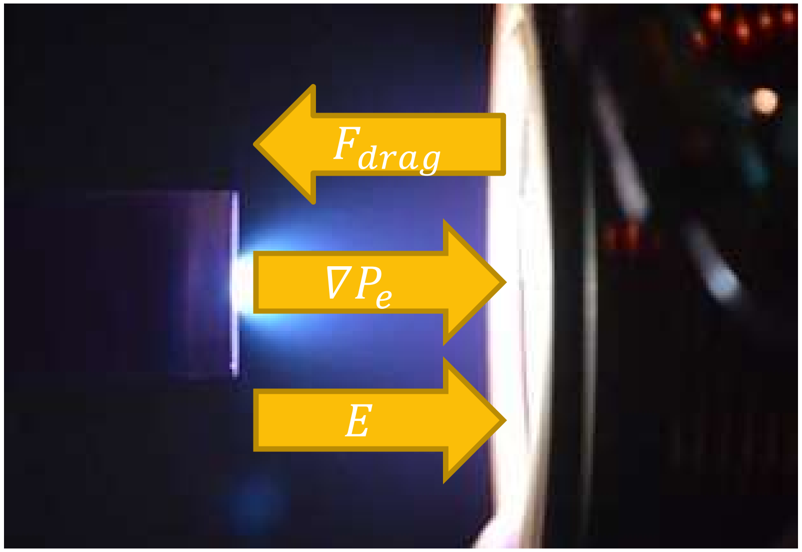
Jorns et al Phys Rev E 2017





Jorns et al Phys Rev E 2014

Anomalous Electron Transport Physical Picture



(1) (2) (3)

$$-\frac{\nabla(P_e)}{n} - m_e u_e \nu_e = \vec{E}$$

1. P_e pushes electrons from cathode to the anode

The next several slides draw from:
M.P. Georgin, "Comparison of the quasilinear theory of anomalous electron transport with Ohm's law in a thermionic hollow cathode", submitted to Plas. Source Sci. Tech Oct. 2022

How do we model this turbulence effect?

$$\frac{\partial f_e}{\partial t} + \nabla_r \cdot (\vec{v} f_e) - \frac{q\vec{E}}{m_e}\nabla_v(f_e) = C[f_e]$$

Time variations

Convection

Forces

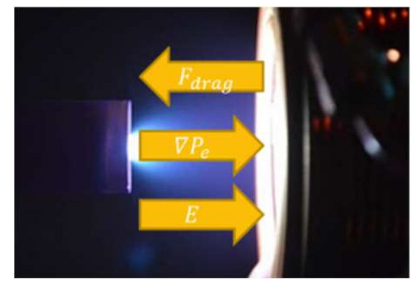
Collisions

Fourier Decomp. + Time Avg.

Pressure | Collisions | E Field | Effective force

$$-\nabla(n_0 T_{e0}) - m_e n_0 u_{e0} \nu_{cl} - n_0 q \vec{E}_0 = q \sum_\omega n_\omega \vec{E}_\omega^*$$

Integrate first moment



Time-average quantities

Time-average effect of oscillations (quasilinear theory)

Convection

Forces

Collisions

$$\nabla_r \cdot (\vec{v} f_0) - \frac{q\vec{E}_0}{m_e}\nabla_v(f_0) - C[f_0] = \frac{q}{m_e}\sum_\omega \nabla_v\left(f_\omega \vec{E}_\omega^*\right)$$

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What are we interested in knowing?

Fluid
Pressure + E field

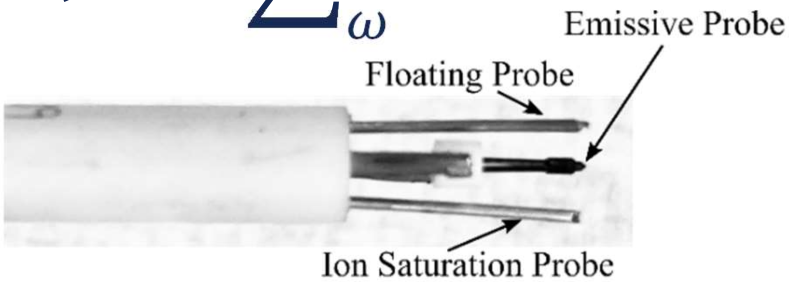
Kinetic
Wave effect

$$-\left(\nabla(n_0 T_{e0}) + n_0 q \vec{E}_0\right) \simeq q \sum_{\omega} n_{\omega} \vec{E}_{\omega}^{*}$$

How does the fluid picture compare with the kinetic picture?

What must we measure?

$$-\left(\nabla(n_0 T_{e0}) + n_0 q \vec{E}_0\right) \simeq q \sum_{\omega} n_\omega \vec{E}_\omega^*$$



Integrated triple probe design

- DAQ: 12 bit oscope
- Probe is calibrated with a chirped reference signal.

Need to measure:

1. For Ohm's law (Fluid)
   1. Density
   2. Electron Temperature
   3. Plasma potential → E field
2. For QLT (Kinetic)
   1. Density oscillations
   2. Plasma oscillations → E field

   ($E_\omega = -ik\phi_\omega$ and $k = \frac{\omega}{c_s + u_i}$ is assumed)

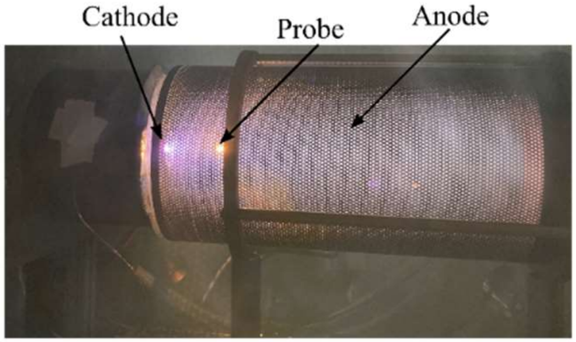
Need to determine:

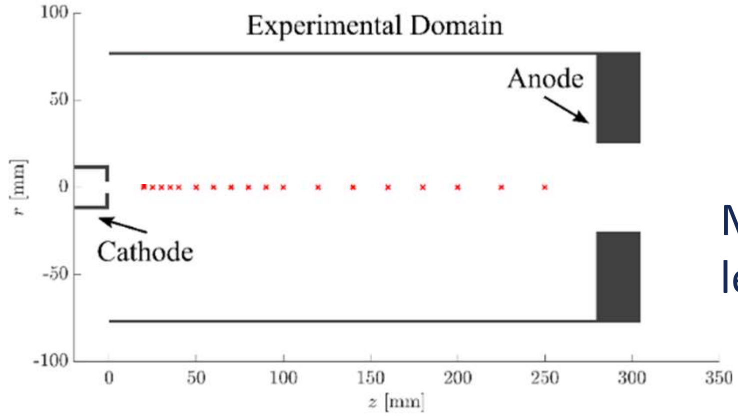
1. Fourier amplitudes
2. Phase delay between field and density

Experimental setup

Operating Conditions

$$I_{dc} = 20\ A$$
$$V_{dc} = 27.4\ V$$
$$\dot{m} = 20\ sccm$$
$$P = 400\ \mu Torr$$

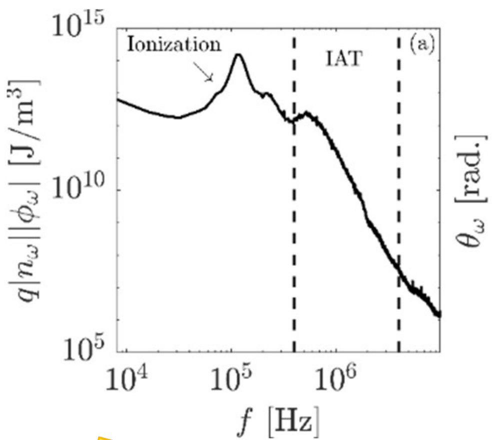




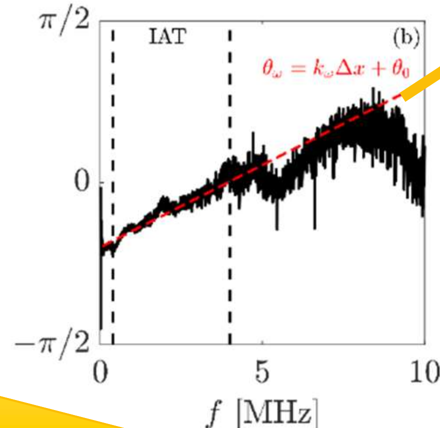
Measure on axis along the length of the anode

Oscillation data analysis process

Fourier amplitudes

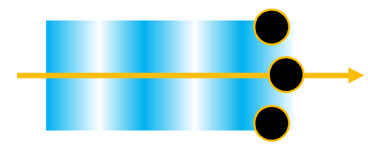


Phase delay correction

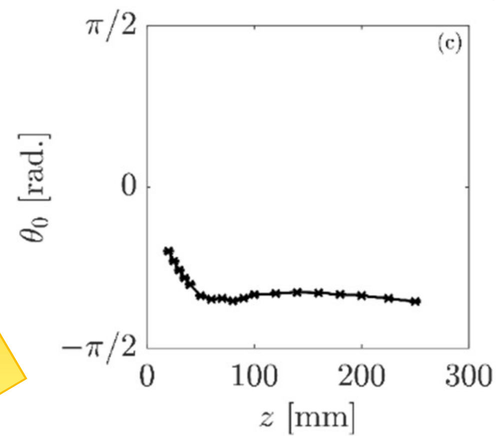


Wave fronts coincident on probes

Phase delay introduced by small misalignments

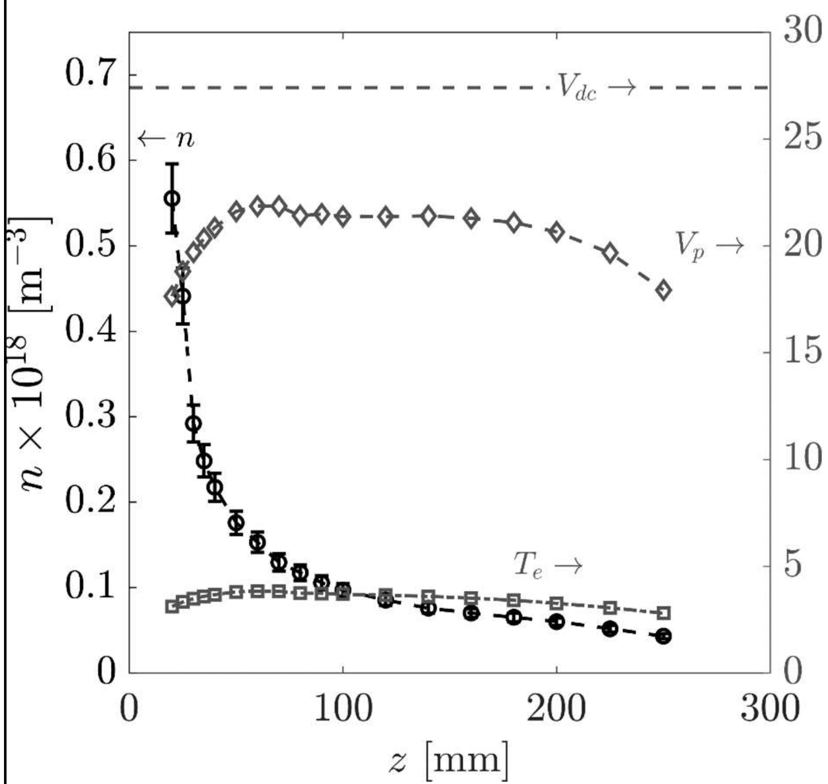


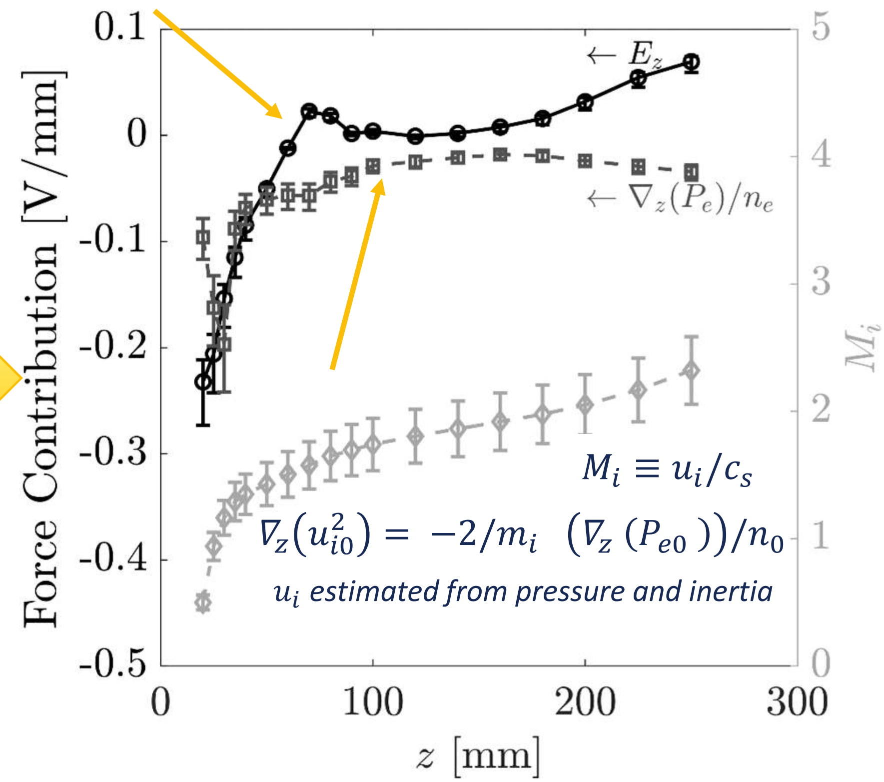
Corrected Phase Delay



Data Analysis Process

Experimental Results: Ohm's law (Fluid)





Experimental Results: Comparison

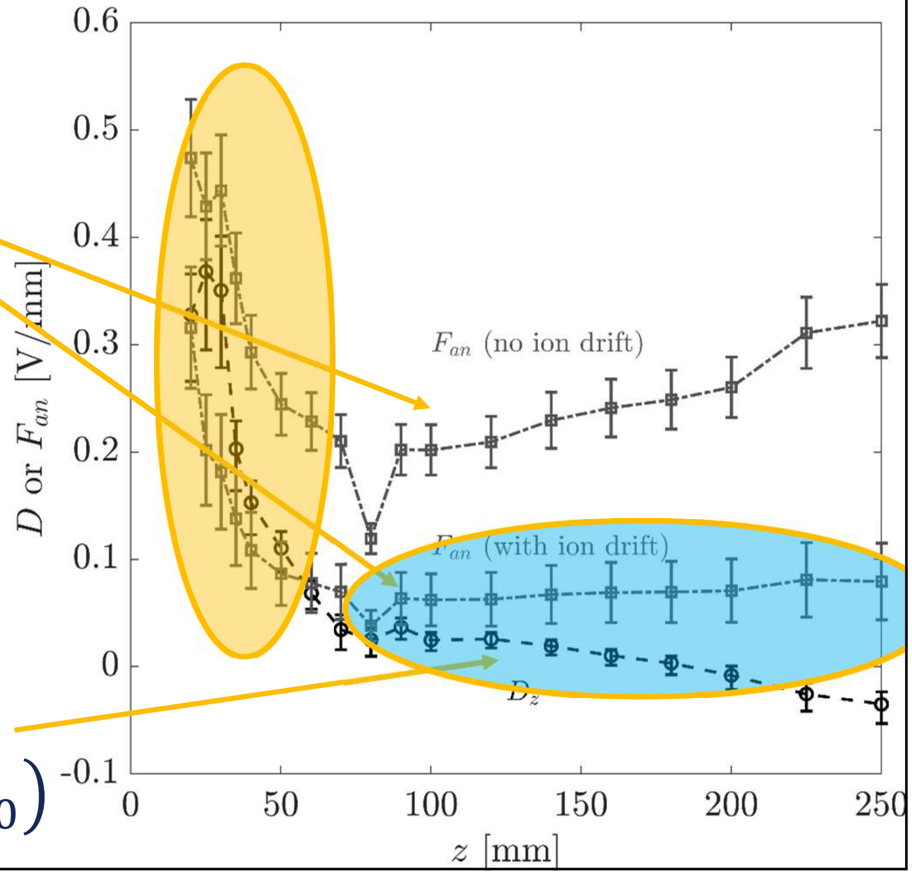
Kinetic

$$q\sum_{\omega} n_{\omega}\vec{E}_{\omega}^{*}$$

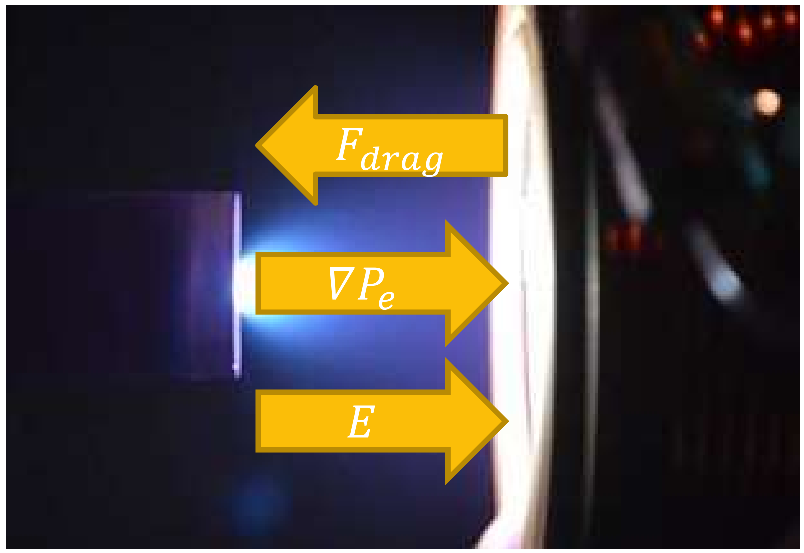
- Excellent agreement is found near the cathode.
- Improved agreement downstream when accounting for ion drift.

Fluid

$$-\left(\nabla(n_0 T_{e0}) + n_0 q\vec{E}_0\right)$$



Anomalous Electron Transport Physical Picture



(1) (2) (3)

$$-\frac{\nabla(P_e)}{n} - m_e u_e \nu_e = \vec{E}$$

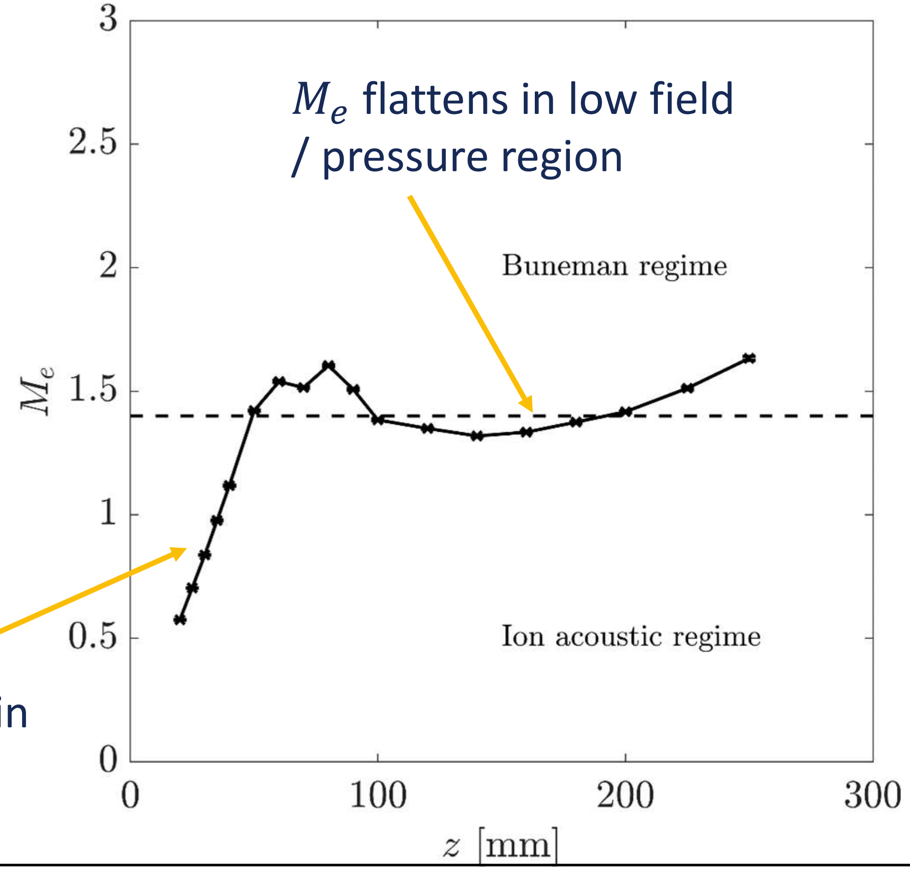
Kinetic

$$q\sum_{\omega} n_{\omega}\vec{E}^{*}_{\omega}$$

1. P_e pushes electrons from cathode to the anode
2. F_{drag} (resistance) from **turbulence** slows them down
3. E pulls electrons to conserve I_{dc} but requires more V_{dc}

Experimental Results: Electron drift velocity

$$M_e = -\sqrt{\frac{2}{\pi}}\tan(\theta_0)$$



M_e flattens in low field / pressure region

Acceleration of electrons in high field/pressure region

Experimental Results: Anomalous Collision Frequency

There are large variations in anomalous collision frequency

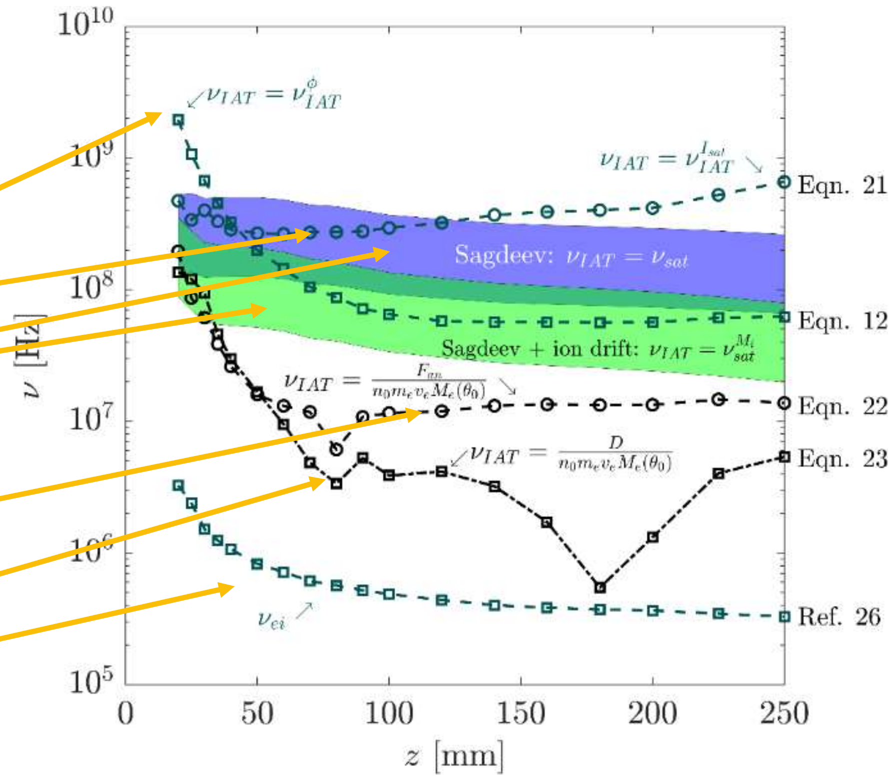
Estimate from single probes

Sagdeev Models

Collision frequency from QLT (Kinetic)

Collision frequency from Ohm's law (Fluid)

Classical collision frequency



What Should You Take From All This?

- Understanding anomalous electron transport is important!
  - Critical for cathode lifetime and performance prediction in EP devices
  - Also “kind of a big deal” in other plasma systems

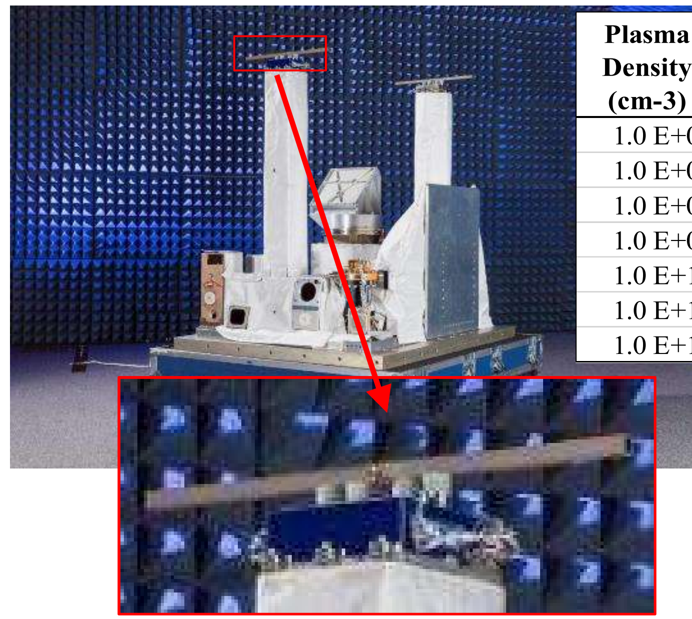
- Our measurements show that the force deficit from the **fluid Ohm’s law picture is well represented by the kinetic quasilinear theory**
  - We can experimentally measure electric and pressure forces to infer drag
  - We can estimate drag via Coulomb collisions in the IAT framework using probe spectra
  - The results line up pretty well!

- However, when cast as an anomalous collision frequency, the **results highlight the spread** in different estimation methods
  - It’s not yet clear how best to shoehorn this kinetic effect into a fully fluid framework

Plasma Impedance Probes:
Shifting from Flux to Frequency in Plasma Diagnostics

- The Langmuir probe (LP): the original plasma diagnostic
  - Density ne calculated indirectly from flux; errors up to… ?
  - Flux is a multi-variable function $f(V_p, n_e, T_e, A_p, Z)$
  - Density calculation affected by beams, EEDF, B-field, etc.
- However, most NIST-traceable measurements rely on time and length
  - No such thing as a plasma "standard candle" to calibrate probes
  - Could we use the plasma frequency instead?

- Some history on the plasma impedance probe (PIP)?
  - NRL has developed PIPs since 2005[1,2], flown on ISS since 2019
    - Max $n_e = 10^8$ cm^{-3} (f_p = 100 MHz); time resolution τ = 100 ms
  - Could we use them for higher density plasmas?
    - Would like $n_e \geq 10^{10}$ cm^{-3} (f_p = 1 GHz), $\tau \leq 10$ μs



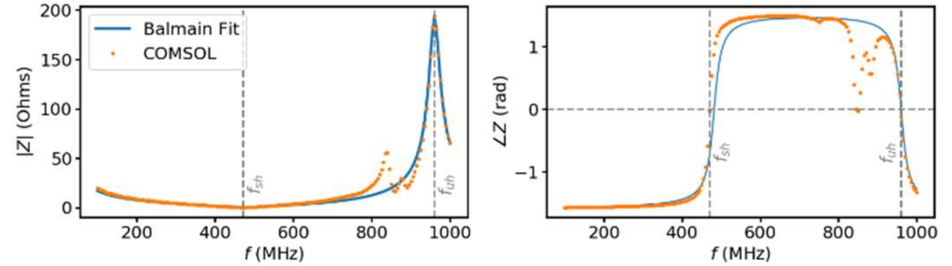
Plasma Density (cm-3)	Plasma Frequency (MHz)
1.0 E+06	9
1.0 E+07	30
1.0 E+08	90
1.0 E+09	300
1.0 E+10	900
1.0 E+11	3000
1.0 E+12	9000

NRL's large plasma impedance probe on the International Space Station measures static (τ = 100 ms) plasma densities up to 10^8 cm^{-3}. It would be nice to make dynamic (τ = 10 μs) measurements up to 10^{10} cm^{-3}!

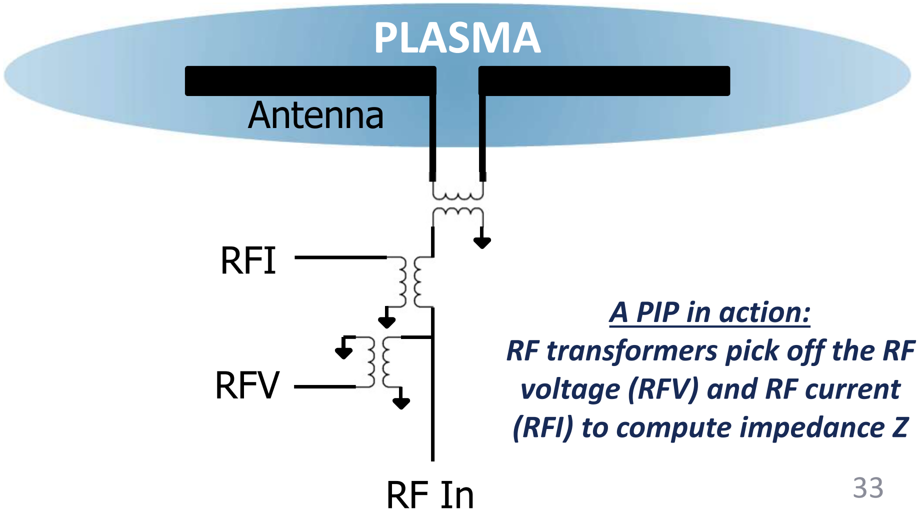
[1] Blackwell et al, Rev. Sci. Inst. **76**, 023503 (2005)
[2] DuBois et al, Rev. Sci. Instrum. 92, 015118 (2021)

How Does a PIP Work? In the Ideal World…

- Sweeping an antenna through a plasma's upper hybrid frequency f_{UH} produces:
  - A maximum in impedance magnitude
  - A 180° phase shift in phase
- If you know B, you know n:
  - ${\omega_{UH}}^2 = \omega_{pe}^2 + \Omega_{ce}^2$
  - $\omega_{pe}^2 \propto n$ and $\Omega_{ce} \propto B$
- Fundamental questions:
  - Is this method accurate?
  - Can you measure a useful density range?
  - Can you get good spatial resolution?
  - Can you get good time resolution?
  - Can you do it cheaply?



The PIP impedance spectrum both peaks and phase shifts at f_{UH}

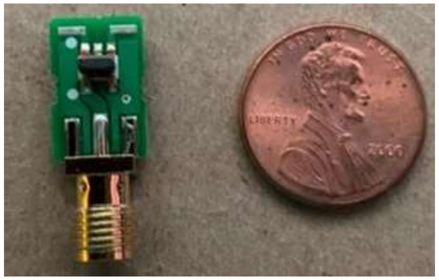


A PIP in action:
RF transformers pick off the RF voltage (RFV) and RF current (RFI) to compute impedance Z

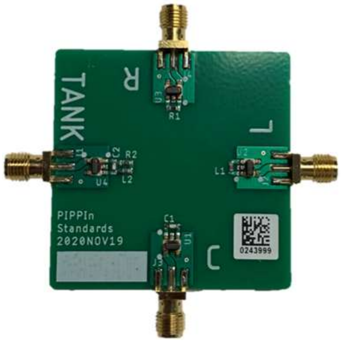
The Three Most Important Rules of Antennas: Calibrate, Calibrate, Calibrate

1. Choose an antenna design
2. Measure Z=Z(f) with R/L/C standards in place of antenna
3. Verify individual R, L and C calibrations applied jointly to a known RLC circuit

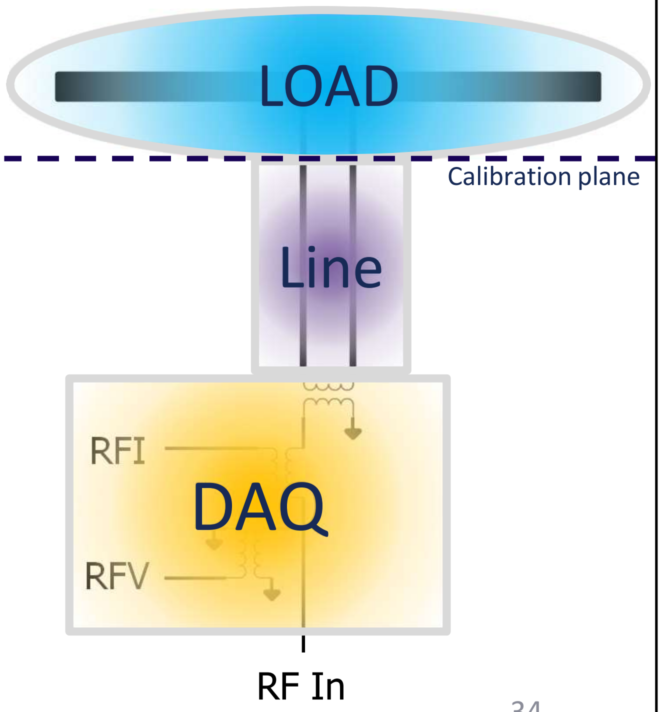
Goal: Isolate line effects to measure only the load at your DAQ (despite the stuff in between)



The PIP v1 above uses a 0.75 cm dipole to minimize ∇n error with a 1.25 GHz balun



This calibration standards board mimics the PIP layout, but replaces it with known R / L / C standards

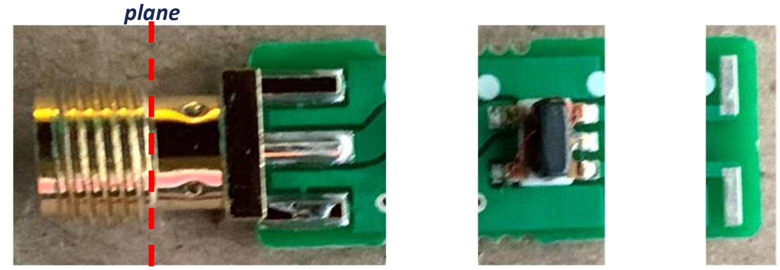


Lessons Learned #1: Resonances are Bad

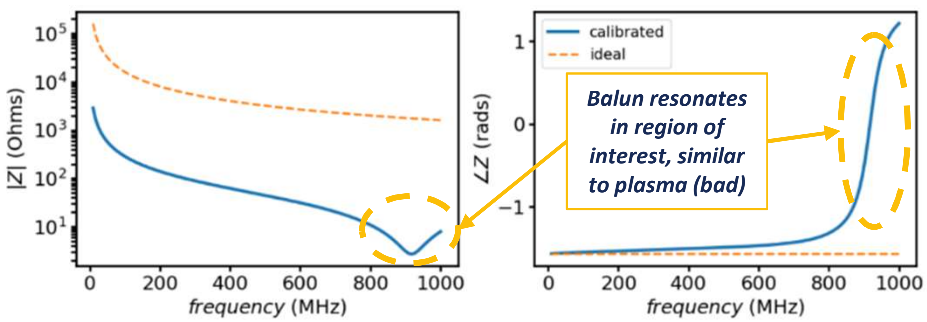
- A **balun** transitions from a **bal**anced dipole to **un**balanced (i.e., grounded shield) coax line
  - But beware if it has a resonance in your range of interest!
  - Options:
    - Test far away from the resonant regions
    - Calibrate/de-embed the resonance
    - Choose a different balun
    - Eliminate the balun entirely

- De-embedding: a technique to analytically remove circuit elements you can't otherwise calibrate out
  - Many RF circuit elements have datasheet S-parameters
  - Fun reality check: Build a back-to-back copy to check!

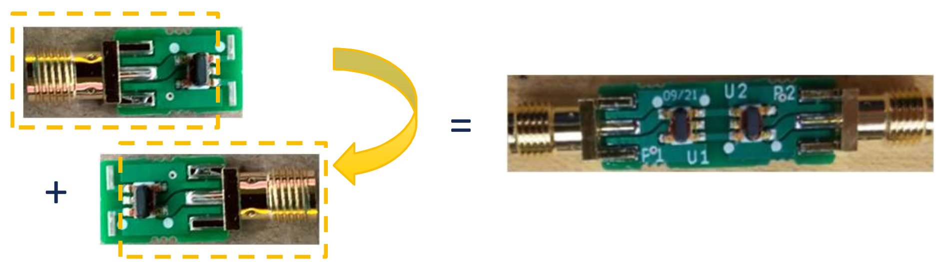
Some Sources of Non-Ideal Behavior



Antenna Vacuum Measurement Comparison



End-to-End Balun Calibration Board



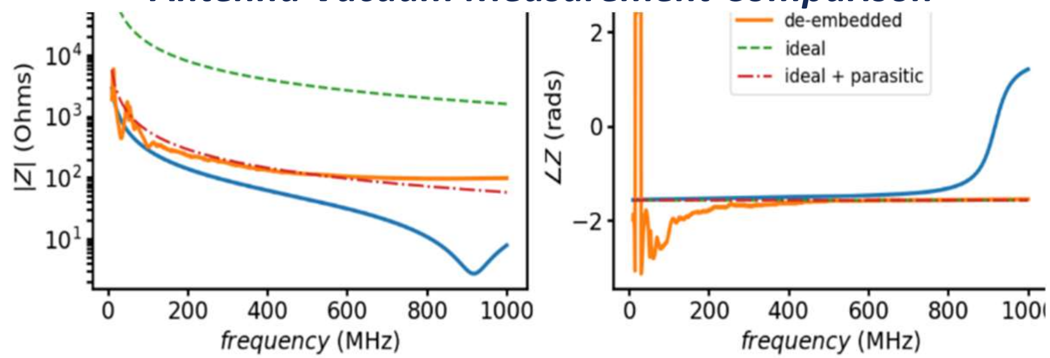
Lessons Learned #2: Parasitic Impedance is Annoying Too

- De-embedding worked great
  - Now we can see the next problem

- Even after de-embedding, we are way off (orange vs. green)
  - To get good agreement, we need to add a lot of capacitance

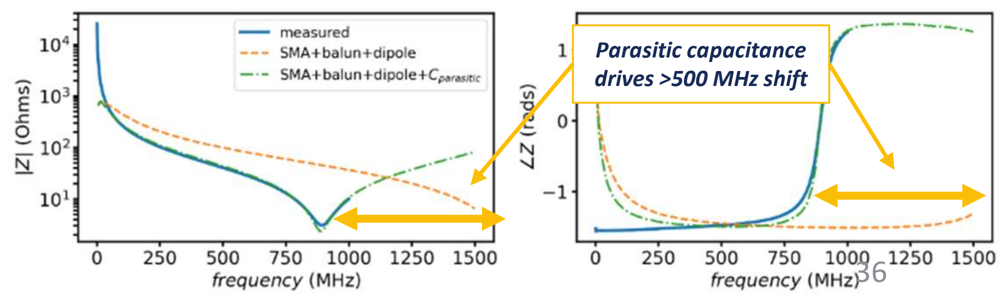
- We will come back to this problem in a few slides!

Antenna Vacuum Measurement Comparison



Modeling Effects of Circuit Components

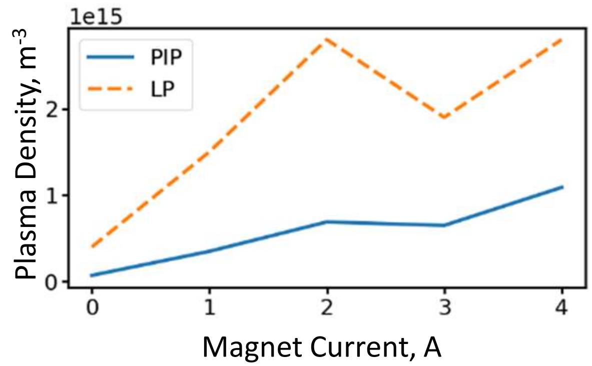
Even after removing balun, parasitic capacitance is still significant



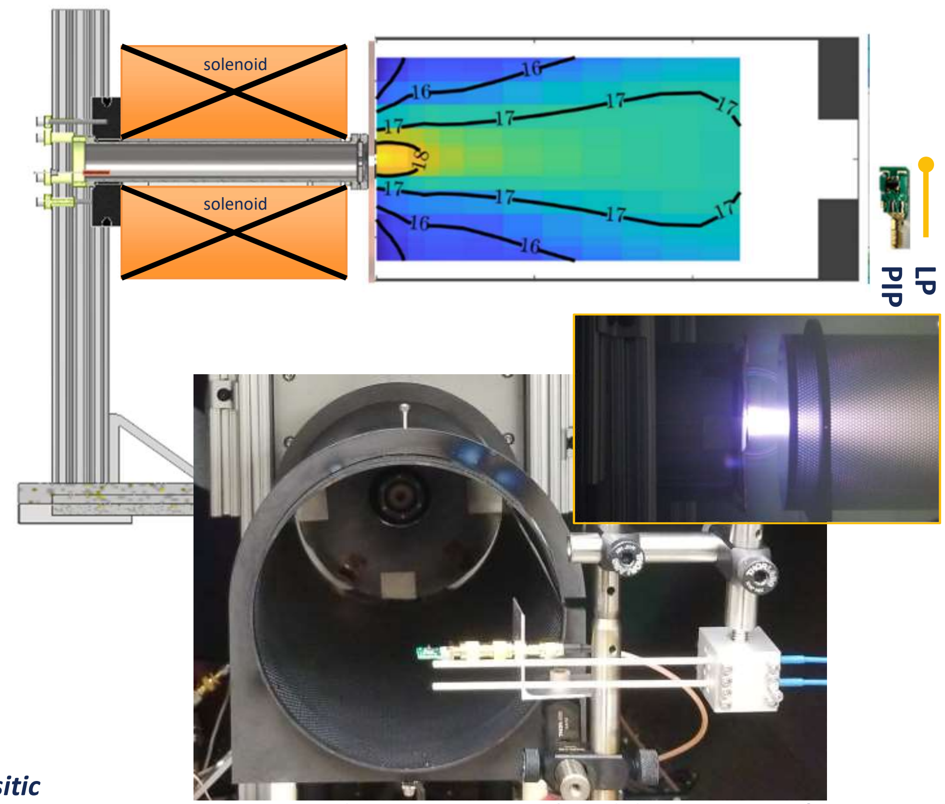
36

A Quick Look at Some Data: PIP vs. LP in a Cathode Plume

- Experimental setup:
  - Plasma Test Facility (PTF): 0.7m x 1m, 4000 L/s
  - Argon-fed LaB_6 hollow cathode, 10-20 sccm
  - Applied magnetic field ~100s G
  - Cylindrical mesh anode
  - Fixed measurement far downstream



Result: We see the right general trend in PIP vs. LP, but parasitic capacitance matters a lot! Uncorrected, it gives values off by ~3X



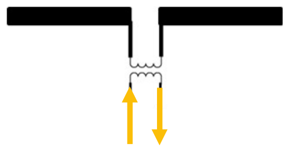
NRL PIP and comparison LP placed downstream of anode on axis in n_e ~ 10^9 cm^{-3} = 10^{15} m^{-3} plasma

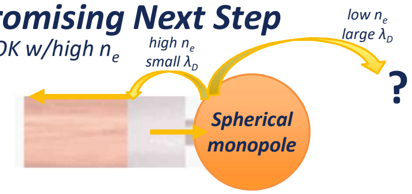
Making Our Lives Easier: Transition from PIP Dipole to Monopole

- When a system is complicated, what do you do? Simplify!
  - The dipole has balun and parasitic capacitance problems
  - What if we go to a monopole "ball on stick" design?
- Why use a ball on a stick?
  - Analytically tractable
  - Simple parasitic modeling
  - Heavily developed pre-ISS for NRL PIPs
    - Drawback was uncertain return path in low n_e environment (sounding rockets or ISS)
    - Promising for high n_e thruster environments
  - Benefits IN survivability and sizing
    - 1-cm spherical monopole can be as "big" as a 3-cm dipole
- Results:
  - Improved modeling allows dynamic range ~10^3
  - Cathode static plume mapping looks good against LP comparison
  - Capable of time resolution better than 100 kHz

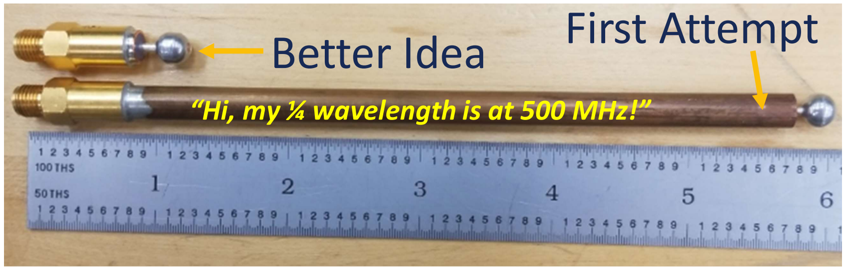
Balun-less Monopole: Promising Next Step

Return path predictability OK w/high n_e

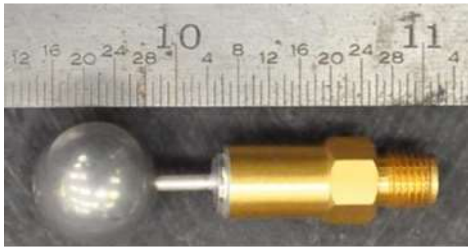




Reminder: resonances in your frequency range of interest are bad



PIP Monopole: ½" "Ball on a Stick"



Even a Really Short Coaxial Stem Still Needs De-embedding to Measure Plasma

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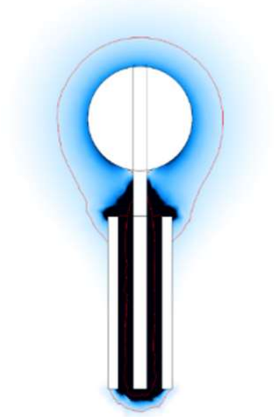
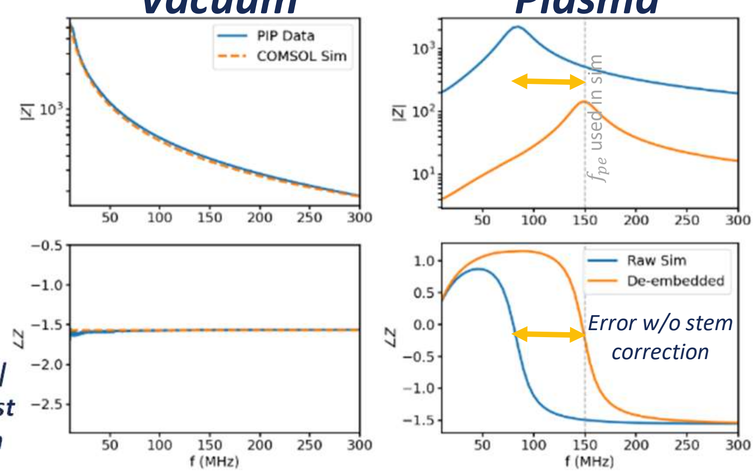
- Let's compare two cases:
  - Sphere model: free-floating sphere in infinite uniform plasma
  - Monopole: Include coaxial stem and center conductor length
  - No sheath effects in either case
- In vacuum, they agree well!
  - Only datasheet coax values and measure ball/stick geometry required
  - No free parameters or fitting
- However, plasma case is quite different
  - Major difference in f_p ~50%
  - Largely resolved by de-embedding stem



COMSOL simulation of |E| for ½" monopole. Strongest fields observed near stem end. Black = saturated.

Monopole Impedance:

Vacuum | **Plasma**

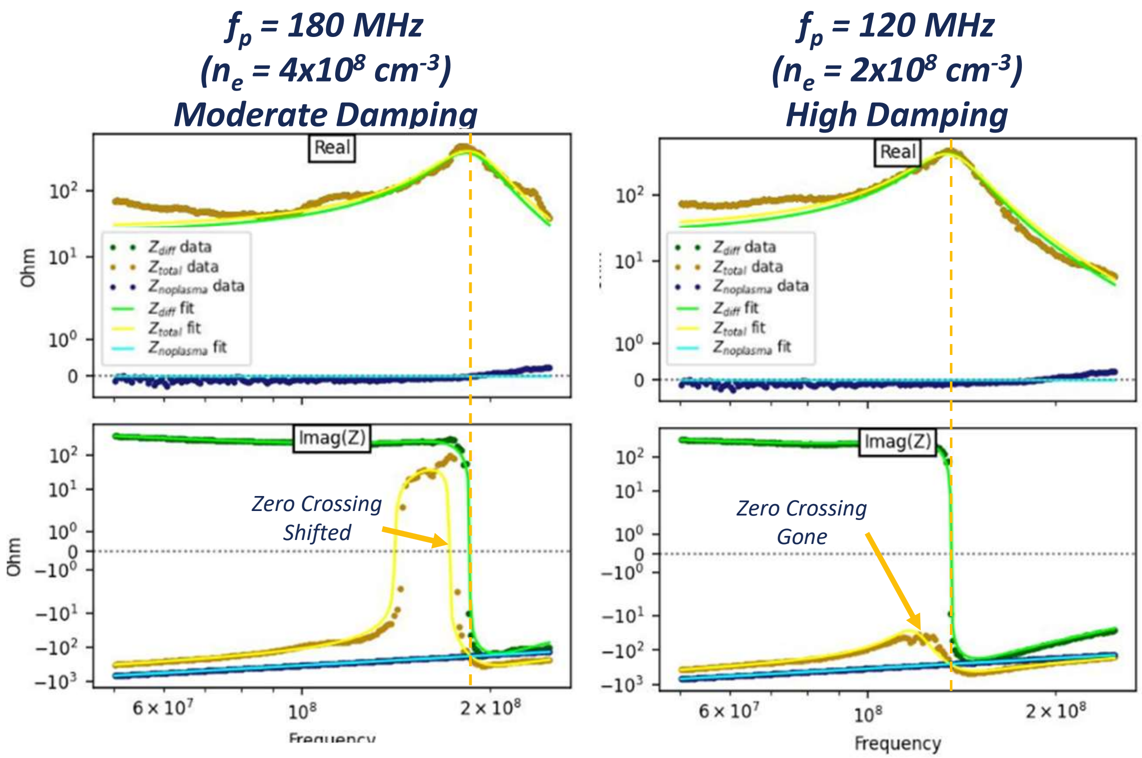


Simulation captures vacuum impedance very well with no fit

Accurate plasma impedance requires stem de-embedding

Aside: An experimental oddity

- Ideally, Re[Z] and Im[Z] show identical plasma frequency
  - So why don't they always in practice?
- Damping of the plasma resonance affects result
  - Shifts or even eliminates zero crossing in Im[Z]
  - Also shifts peak in Re[Z] (less obvious)
- Unexpected finding:
  - Subtracting vacuum impedance ($Z_{diff} = Z_{total} - Z_{noplasma}$) resolves the issue very effectively
  - Great, but *why*?



Resuming our regular programming:
Remember how we were missing some capacitance?

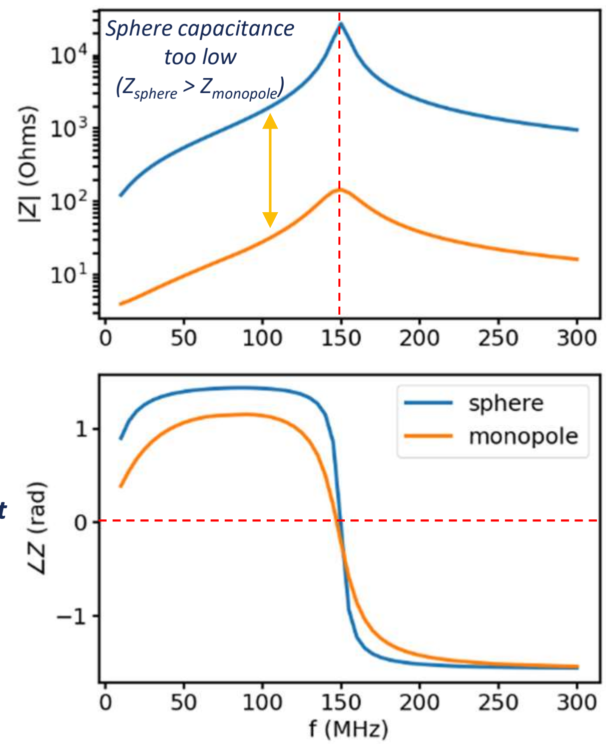
- De-embedding the stem helps, but it's not enough. The sphere model:
  - captures f_{pe} well, but…
  - overestimates impedance magnitude (i.e., has too little capacitance)

- Where is the extra capacitance?
  - Look at difference between top and bottom halves of "lollipop"
  - These strong fields are a region that will also have quite a bit higher capacitance
  - Effect increases as sphere size decreases

- De-embedding the stem helps, but it's not enough. The sphere model:
  - captures f_{pe} well, but…
  - overestimates impedance magnitude (i.e., has too little capacitance)
- Where is the extra capacitance?
  - Look at difference between top and bottom halves of "lollipop"
  - These strong fields are a region that will also have quite a bit higher capacitance
  - Effect increases as sphere size decreases

COMSOL simulation of |E| for ½" monopole. Strongest fields observed near stem end. Black = saturated.

Plasma Impedance (no sheath)

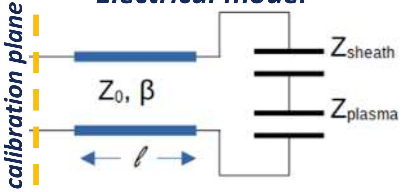


Finding the Capacitance Permits Better Design, Modeling and Experimental Practice

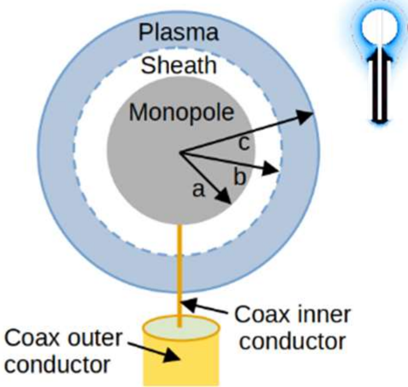
- How does this change our understanding of the monopole capacitive coupling?
  - Initial NRL models[1] assumed the grounded tank, effectively letting c → infinity
  - But it's actually the grounded coax shield
- To fix this we:
  - Constrain "c" as the "effective " spherical radius of the sphere – coax interaction
  - Subtract this new more capacitive (negative) vacuum impedance
    - We can approximate this pretty well experimentally by subtracting the vacuum impedance!
- Result:
  - Much better isolation of f_p and n_e
  - Extends dynamic range over which we can analyze a given sized probe[2]

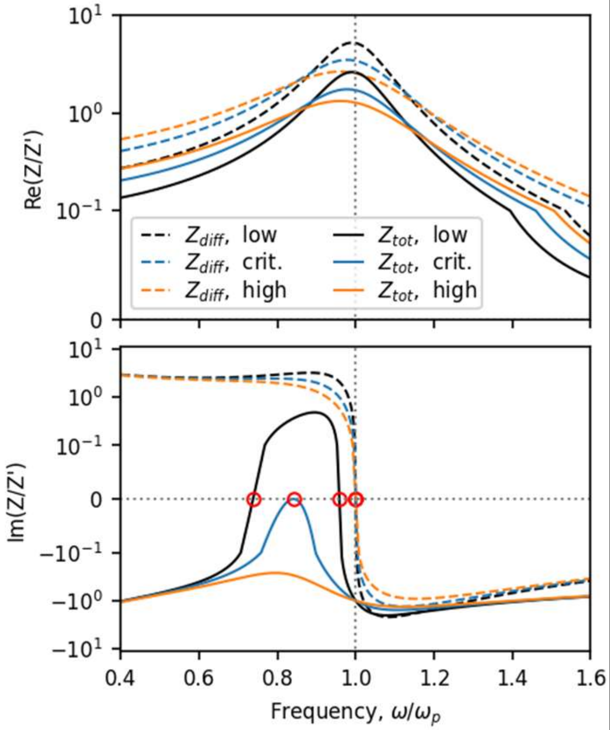
PIP Monopole

Electrical model



Plasma model





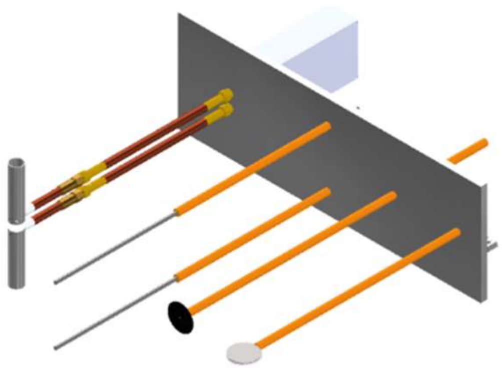
Other findings: (too small for this margin to contain)

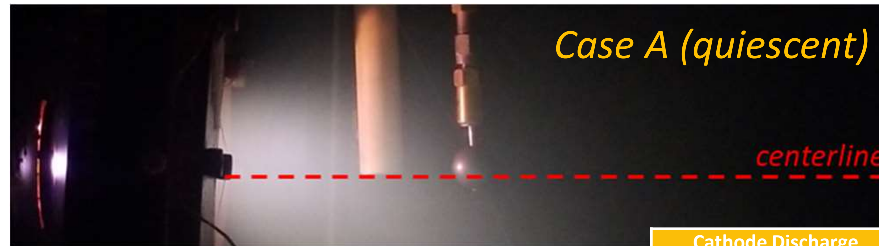
- Best to let $r_p > \lambda_D$
- "Effective" probe size ~3X real size

[1] D. D. Blackwell, et. al, *Rev. Sci. Inst.*, 2005, 10.1063/1.1847608.
[2] E. D. Gillman, E. Tejero, et. al., *Rev. Sci. Inst.*, 2018, doi: 10.1063/1.5033329

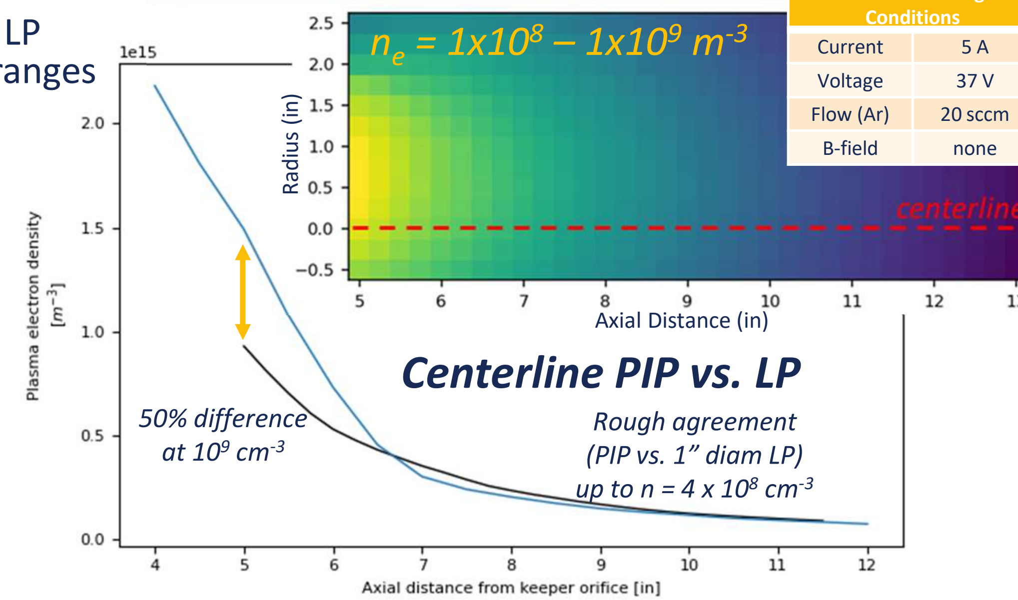
Another Quick Data Look at PIP vs. LP

- Cathode comparisons:
  - Decent agreement from low 10^6 – mid 10^8 cm^{-3}
  - Hard to get good comparison against a single LP over this large range!
- Future work: comparison against multiple LP types in situ across larger plasma density ranges





Cathode Discharge Conditions	
Current	5 A
Voltage	37 V
Flow (Ar)	20 sccm
B-field	none



PIP Rules of Thumb: Static, Single-Point Measurements

- Size monopole with sufficiently large radius to capture desired lower density limit ($r_p > \lambda_D$)
- Move calibration plane as close to PIP as possible (short coaxial stem) and de-embed remaining stem
- Potentially subtract off PIP vacuum impedance as a shortcut to nonlinear impedance modeling

What about Time Resolution? 100 kHz Straightforward; >1 MHz Perhaps?

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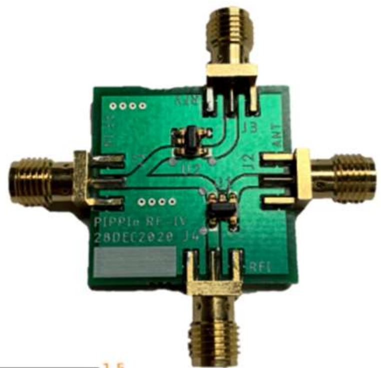
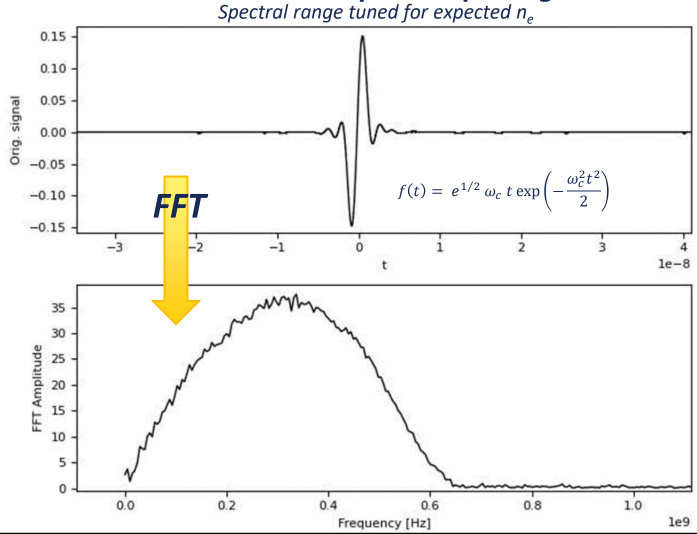
- There are two ways to get Z = Z(f)
  - VNA method: Measure Z carefully at each individual frequency (slow)
  - Pulsed RFIV method: Send in a pulse with broadband frequency content, and use FFT
    - *DuBois et al, Rev. Sci. Instrum. 92, 015118 (2021)*

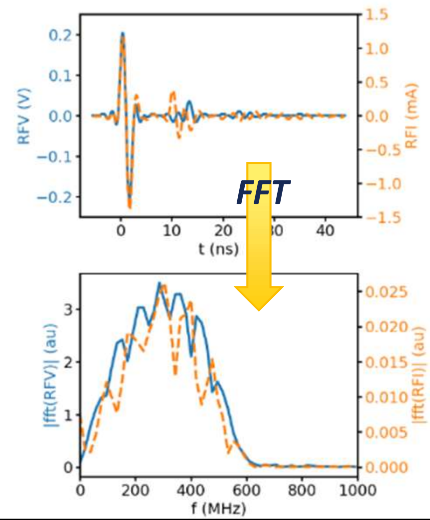


The RFIV board picks off the PIP antenna current and voltage for data acquisition

Gaussian Monopulse Input Signal

Spectral range tuned for expected n_e

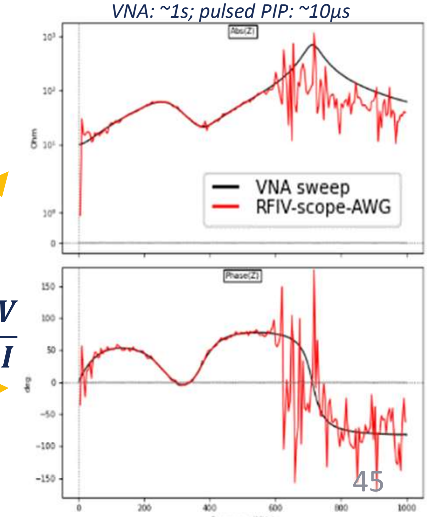




$$Z = \frac{RFV}{RFI}$$

RFIV Board vs. VNA Output

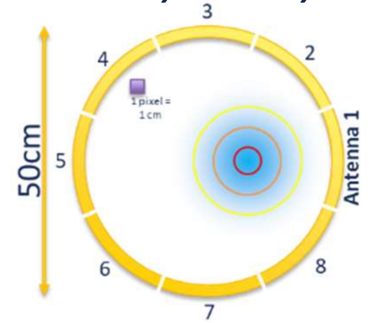
VNA: ~1s; pulsed PIP: ~10µs



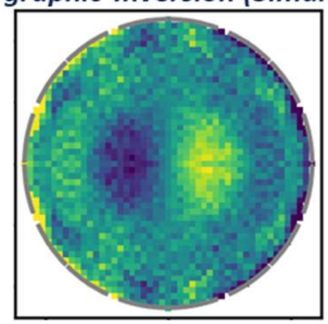
What if You Used Your Antenna to Transmit *and* Receive? Or, PIP Tomography

- So far we've only talked about sending signals from an antenna into a plasma, and measuring the antenna's self-impedance
  - What if we have more than one antenna?
  - Can we get anything from the mutual impedance?
- Technique:
  - Use antenna array's mutual impedances $|Z_{mn}|$ to detect plasma presence
  - Sweep through frequency to capture Z=Z(f)
  - Start with a 2D geometry
- That's a beautiful dream. Where are we in reality?
  - Derived theory of mutual impedance probes in a plasma
  - Conducted some 2-D simulations of N_{array}= 8 circular dipole array
  - Developed reconstruction algorithms
    - Pseudo-inverse problem
    - Incorporates multi-frequency data
    - Builds on sensitivity map "basis functions"
  - Attempting inversion of some simple plasma shapes

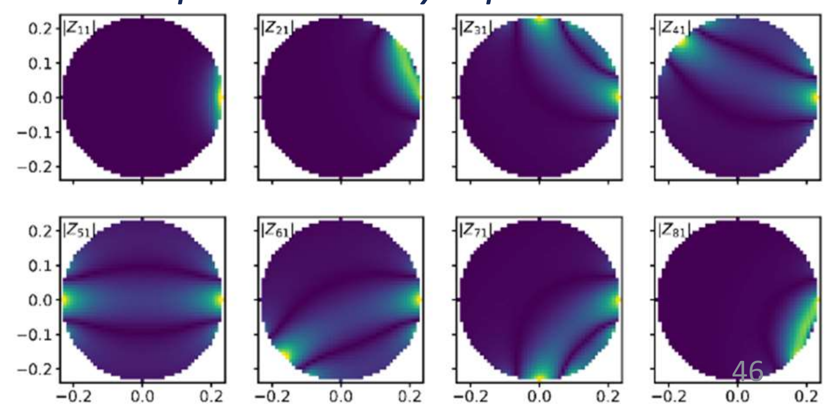
PIP Tomography Array Geometry



Example Time-Resolved Tomographic Inversion (Simulated!)



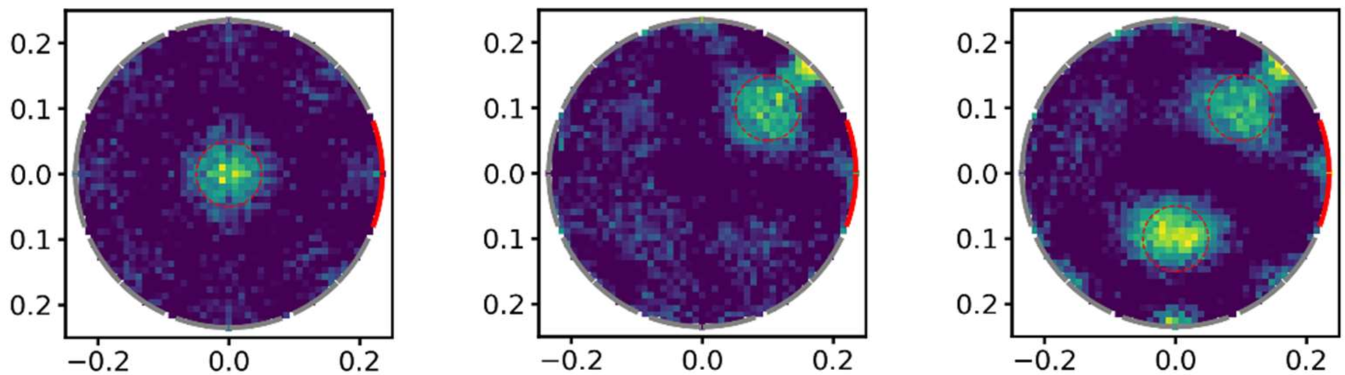
Mutual Impedance Sensitivity Maps to Plasma Perturbation



Initial PIT Reconstruction Using Moore-Penrose Pseudoinverse

We generate the tomographic inverse for three distributions:

- Using Jacobian constructed as indicated in the previous slide
- The pseudoinverse is calculated once and can be used to quickly produce reconstructions
- Conducted 3 numerical simulations
  - Centered 10 cm top-hat
  - Offset 10 cm top-hat
  - Two offset 10 cm top-hats
- Red dashed circles indicate the size of the perturbation

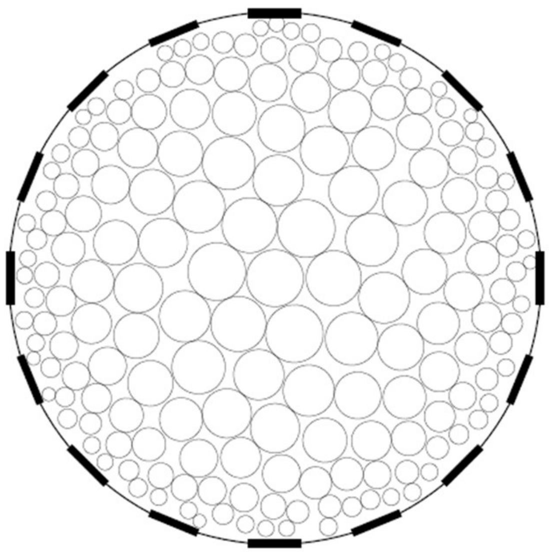


Some brief words about image resolution, because that's all anyone ever wants to know…

Resolution is Difficult to Quantify

- Typically for Electric Impedance Tomography
  - Uniform pixel sizes are taken
  - An arbitrary number of pixels are chosen
  - Numerical modeling allows for reconstructions
  - Resulting reconstructions are qualitatively compared with input dielectric maps
- System response dependent on
  - Contrast of perturbation
  - Size of perturbation
  - Location of perturbation
  - Assumed background
  - Number of antennas
  - Type of stimulus

Uniform Response Discretization



Winkler and Rieder (2014)

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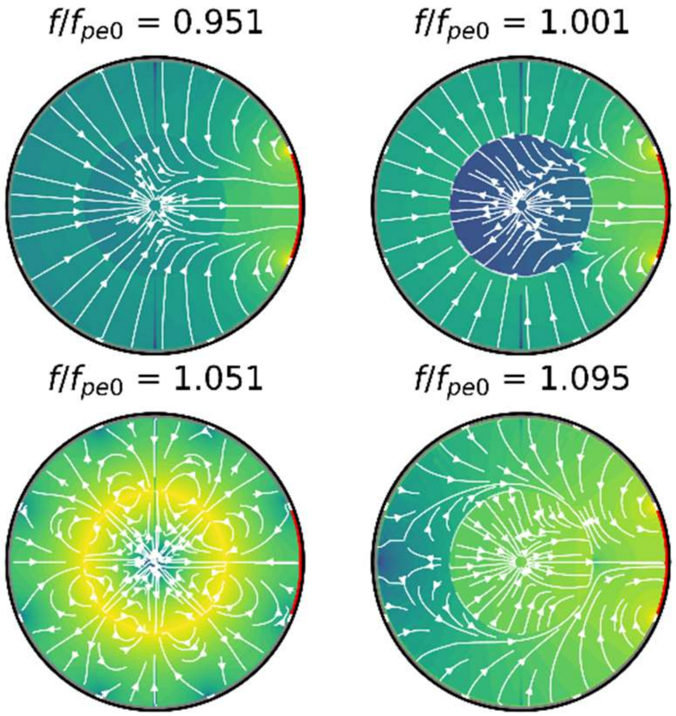
Multi-spectral Measurements Provide More Information for Reconstructions

Multi-frequency Reconstruction

- Radical changes to currents paths for different frequencies indicates spatial information available
- Multiplicative factor on information available for each frequency used
- Should increase "resolution" for fixed number of antennas

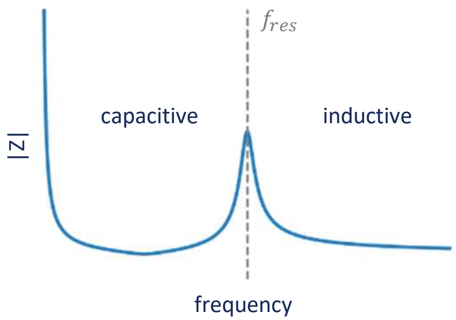
- Tailored inversion incorporating known plasma physics will also improve reconstruction

Current Paths for Various Frequencies

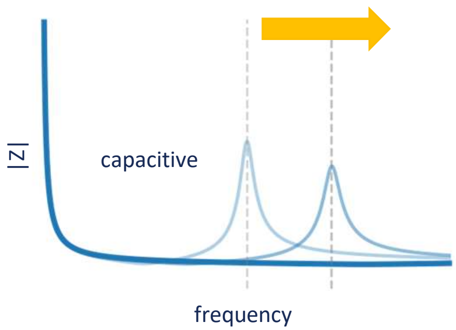


Background for Accuracy Validation: PIPs Really Measure Permittivity, Not Density

Resonant Dipole Impedance in Vacuum



Transition to Short Dipole Regime



- Our PIPs are very short dipoles, hardly antennas at all, so Z is capacitive:

$$Z_{dipole} = \frac{1}{i\omega C}$$

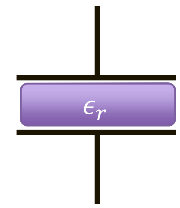
- We measure Z first in vacuum, then in a plasma where Z becomes:

$$Z_{dipole} = \frac{1}{i\omega \epsilon_p C}$$

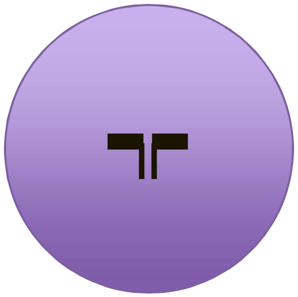
- The plasma density comes out of a complex dielectric permittivity, we get a plasma density as:

$$\epsilon_p = 1 - \frac{e^2 n}{\epsilon_0 m_e} \frac{1}{(\omega^2 + \nu^2)} + i \frac{e^2 n}{\epsilon_0 m_e} \frac{\nu}{(\omega^2 + \nu^2)}$$

$$\omega_p{}^2 = \frac{e^2 n}{\epsilon_0 m_e}$$



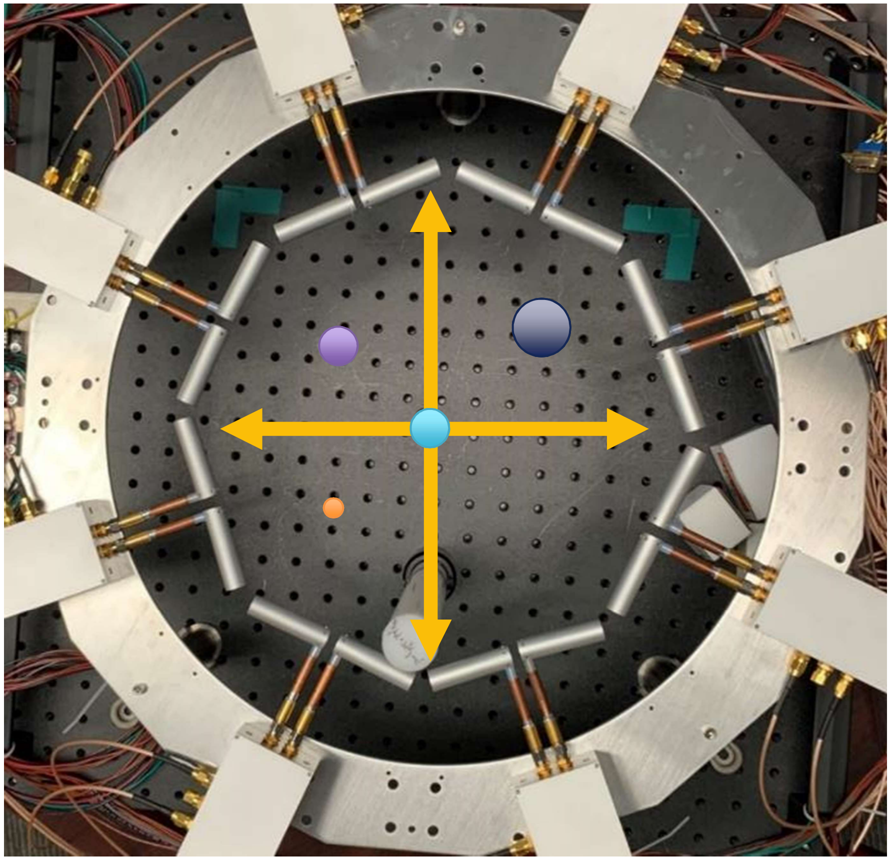
$$Z = \frac{1}{i\omega C} \rightarrow Z = \frac{1}{i\omega \epsilon_r C}$$



Insight for accuracy validation: We can get materials of known ε easily!

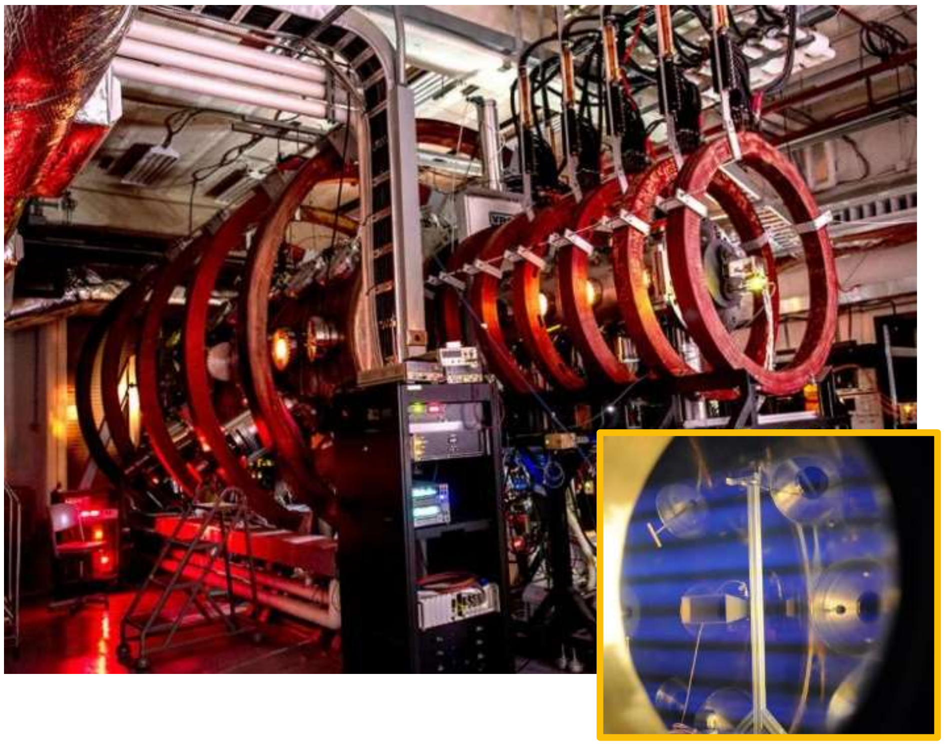
Could You Use a Plasma Density “Standard Candle” That Isn’t Plasma At All?

- What if you just used… a candle?
  - Or any other hunk of wax, plastic, or suitable dielectric?
- We know the dielectric constants of materials well (and they’re cheap!)
  - PTFE, quartz, polystyrene, etc.;
  - Easy to find bulk materials with ε=1-10
  - Lossy materials could provide complex ε too
- Could this be the way to make an absolute calibration of a PIP density measurement?

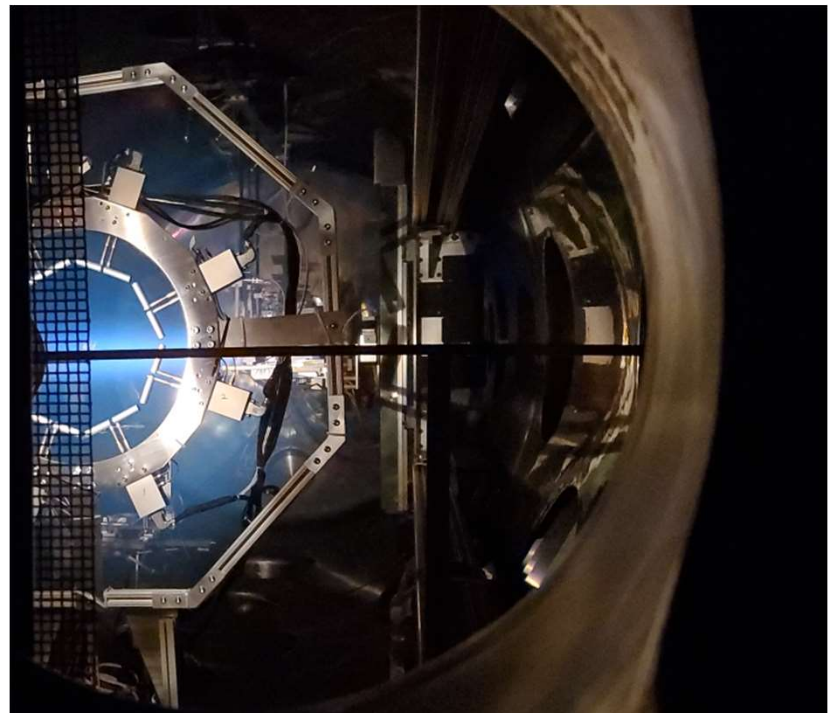


What About a Nice Textbook Plasma for Tomography?

NRL's Space Chamber in the Plasma Physics Division; inset, a typical electron-beam generated plasma



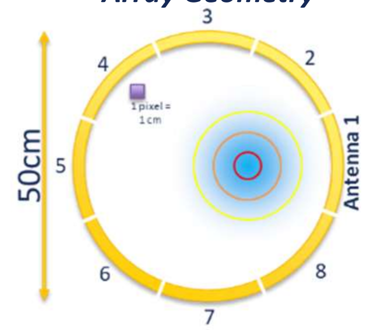
An axisymmetric plasma column in the Space Chamber for validation of PIP tomography



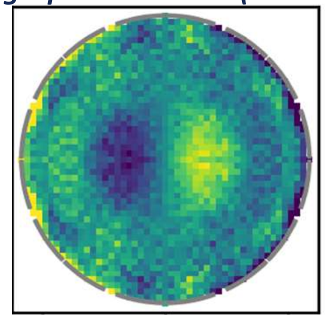
Some Closing Thoughts

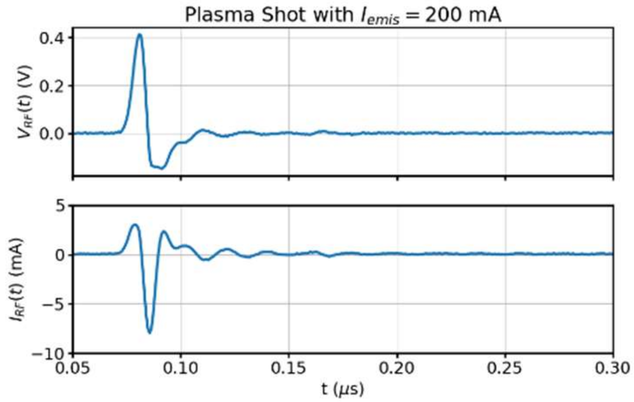
- If you can do static tomography, could you do time resolved pictures too?
  - Simulation suggests yes… but theory isn't practice
- When we watch a pulsed PIP shot "ring down", what is the damping mechanism?
  - How does the ringdown "collision" frequency to fit ε compare to an effective anomalous collision frequency?
  - Could we use this technique as another way to infer this quantity in plasma?

PIP Tomography Array Geometry



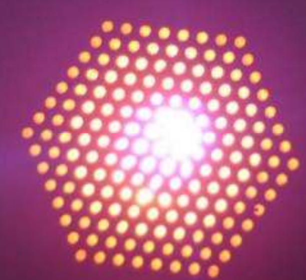
Example Time-Resolved Tomographic Inversion (Simulated!)

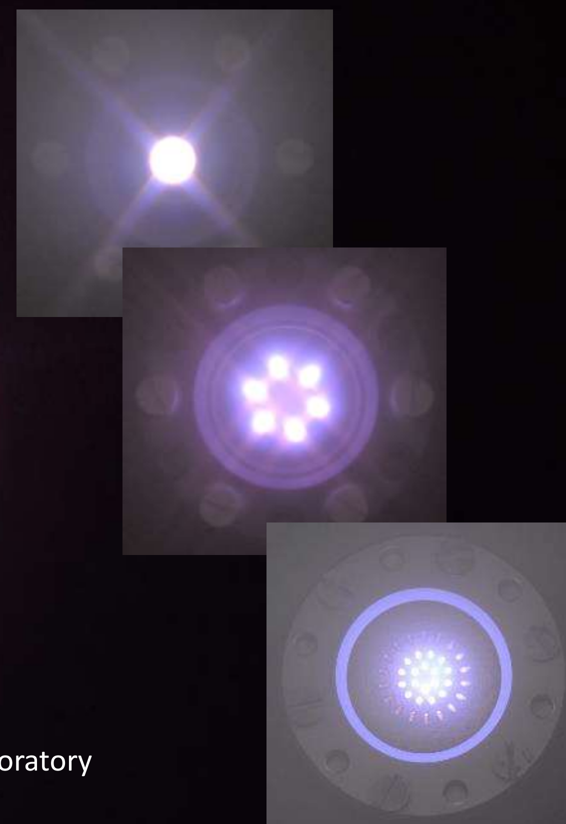




Questions?

We are recruiting!
Interns, Co-ops, and Post-docs for Cathodes, Diagnostics, and More!





Summer 2022 internship application (Nov. 1): https://nreip.asee.org/labs/naval_research_laboratory
Post-doc opportunities (quarterly): http://sites.nationalacademies.org/pga/rap/
Summer faculty positions ONR (Dec. 14): http://onroutreach-summer-faculty-research-sabbatical.com/