Emitting Probes

J. P. Sheehan[1], Yevgeny Raitses[2], and Noah Hershkowitz[3]

1. University of Michigan
2. Princeton Plasma Physics Laboratory
3. University of Wisconsin

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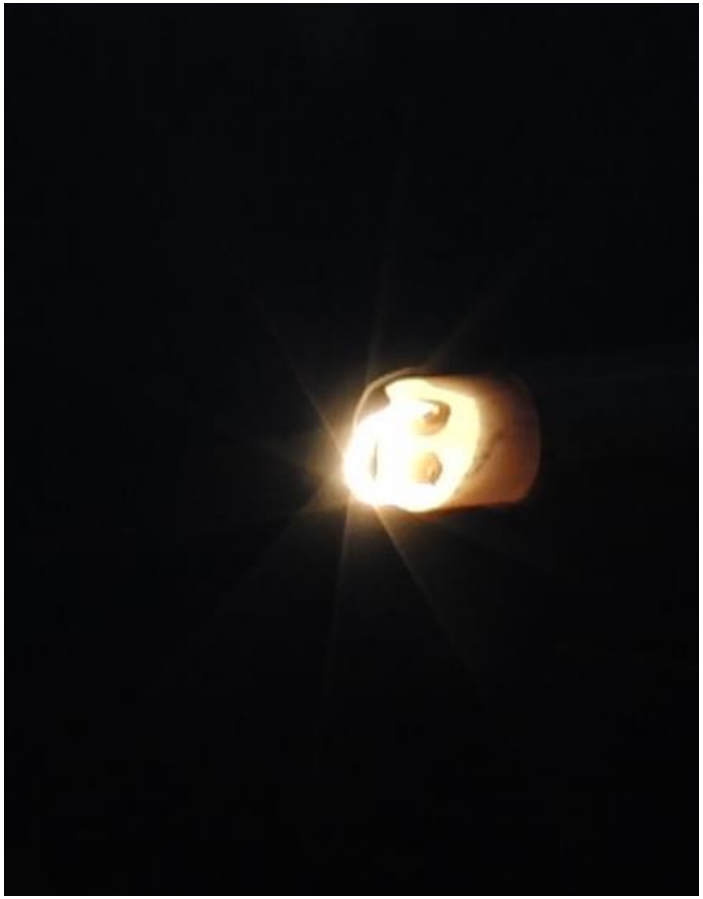
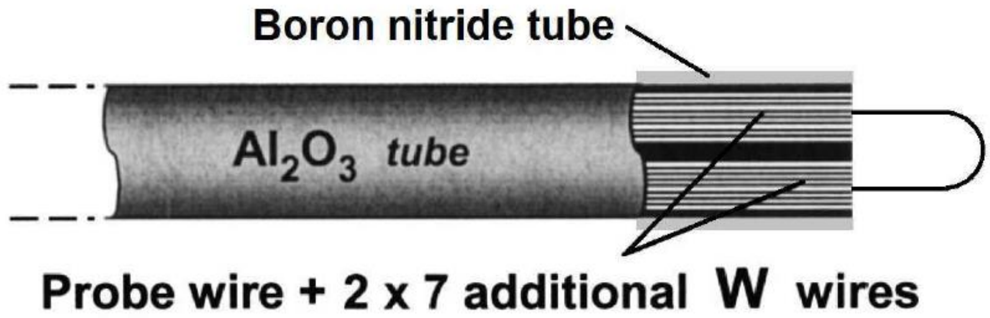
Summary of Topics

- Methods for measuring plasma potential
- Emissive sheath theory
- Heating schemes
- Probe construction
- Special case considerations
- Choosing an emissive probe



Why use an emissive probe?

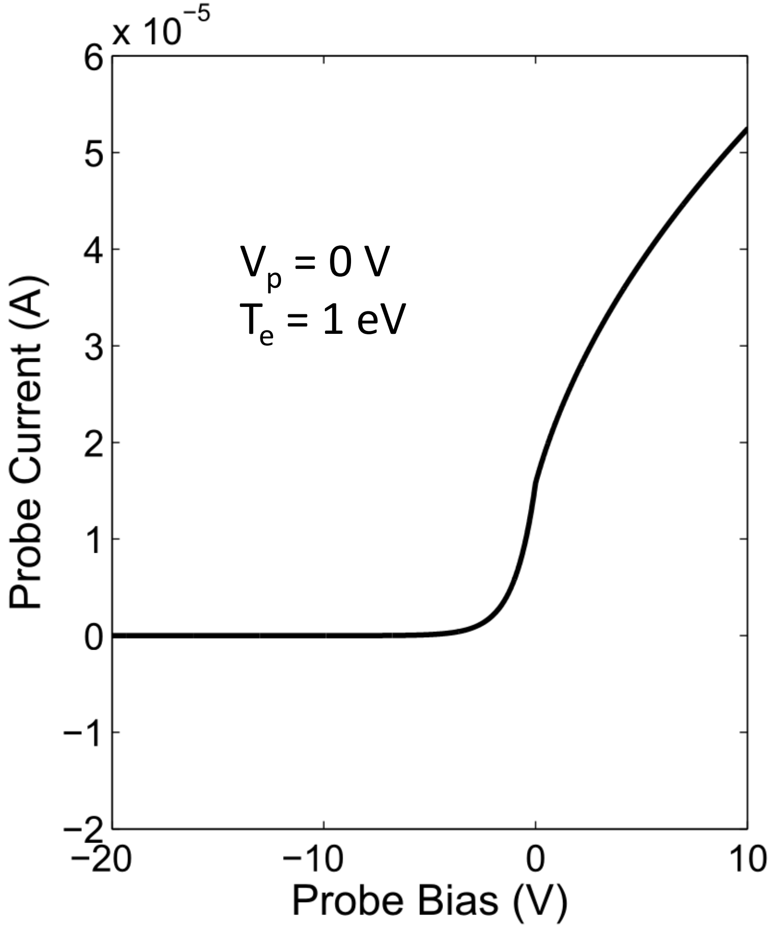
- Measure the electrostatic potential
- Can be used to infer electric fields and particle flows
- Versatile
- Robust
- Proven and established



J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich and N. J. Fisch, Physics of Plasmas **18** (7), 073501 (2011).

Start from Langmuir probe I-V trace

- Ions contribute negative current, electrons positive current
- In Maxwellian plasma, electron current exponential below plasma potential
- Above plasma potential current limited only be geometry



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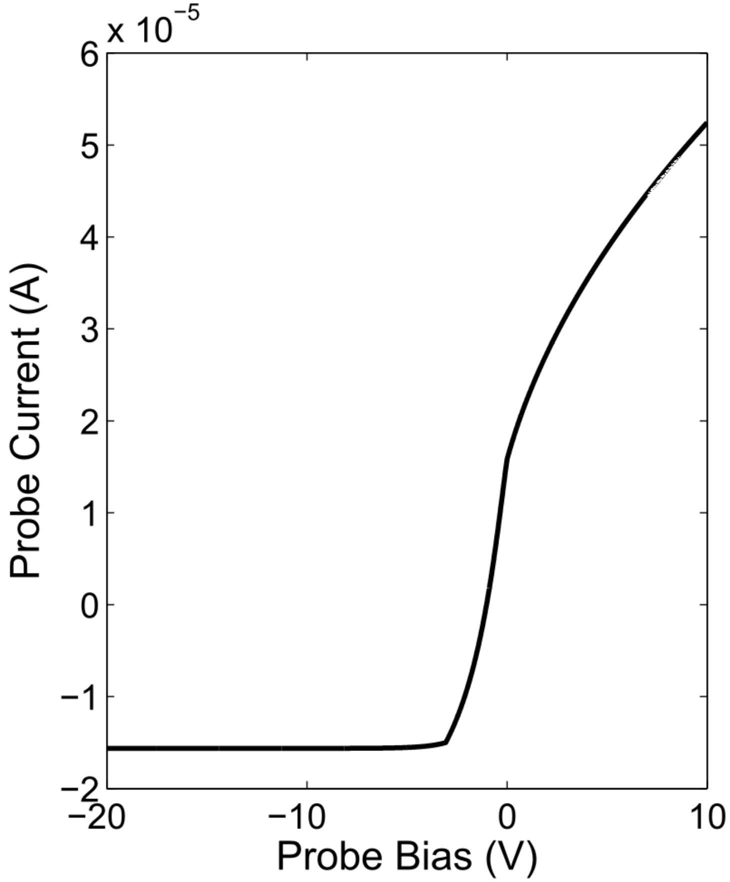
Emission current modifies I-V trace below plasma potential

- Electrons can only be emitted when probe biased below plasma potential
- Emission current limited by temperature of probe

$$j_{ee,t} = A_G T_w^2 \exp\left(-\frac{e\phi_w}{T_w}\right)$$

- Below plasma potential I-V trace modified by emission, above it stays the same



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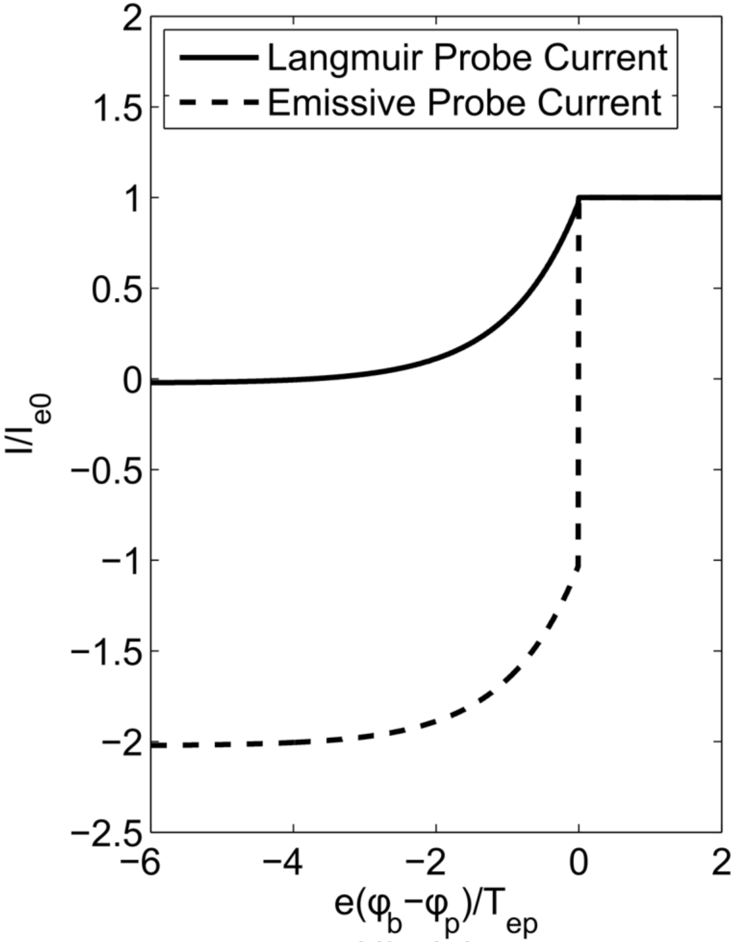
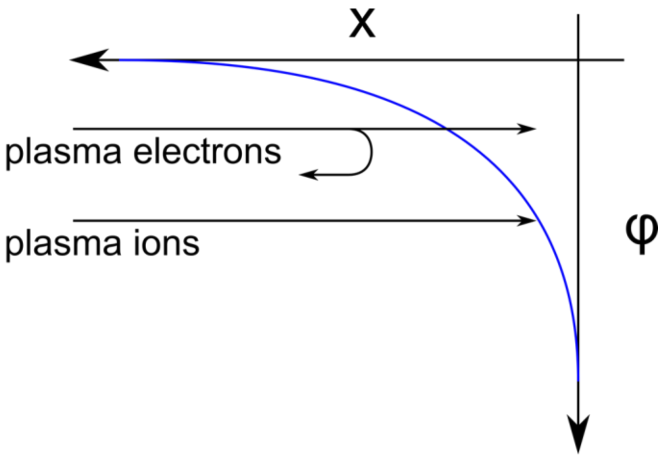
Separation point technique

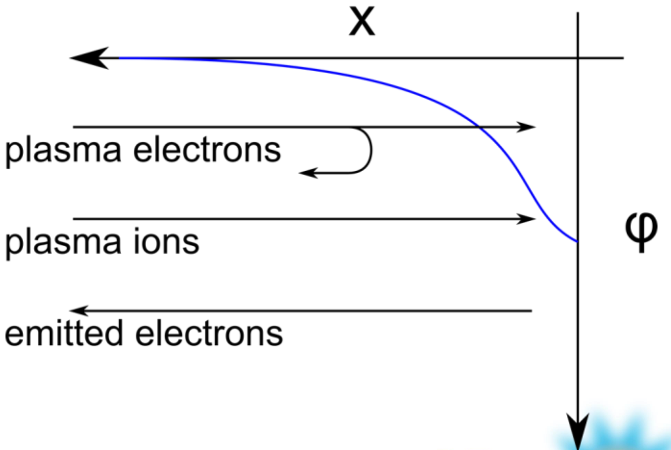


- Earliest method, formulated by Langmuir
- Assumes emitted electrons are cold
- Plasma potential is the point where Langmuir I-V and emissive I-V traces separate
- Very time consuming before computer automation

Electron emission reduces the sheath potential and electric field

- In collecting sheath, net positive space-charge
- Emitted electrons reduce net space charge
- Reduce sheath potential
- Reduce electric field at emitter surface
- Increased plasma electron current compensated by emitted electron current



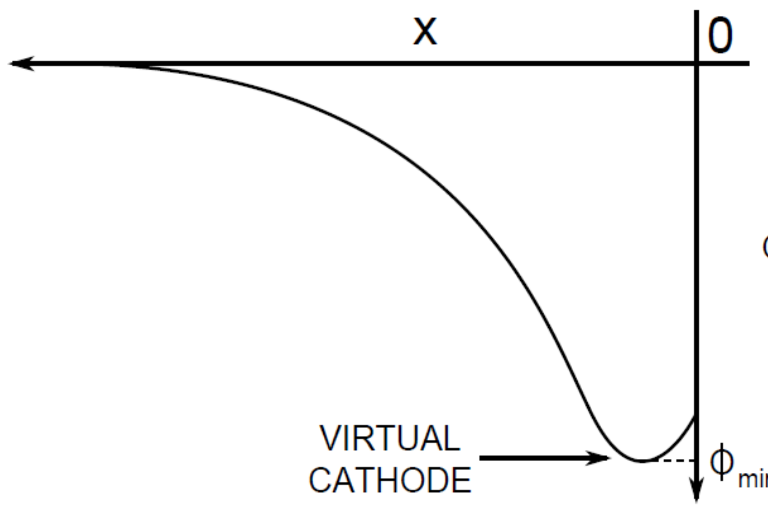


A SCL emitting surface floats T_{ep}/e below the plasma potential

- At large enough emission current, net negative space-charge near surface
- Virtual cathode forms, limiting further reduction of sheath potential
- At Space-Charge Limit (SCL) emissive sheath potential is T_{ep}/e
- SCL sheath much smaller potential than collecting sheath

<u>Space-Charge Limited Solution</u>

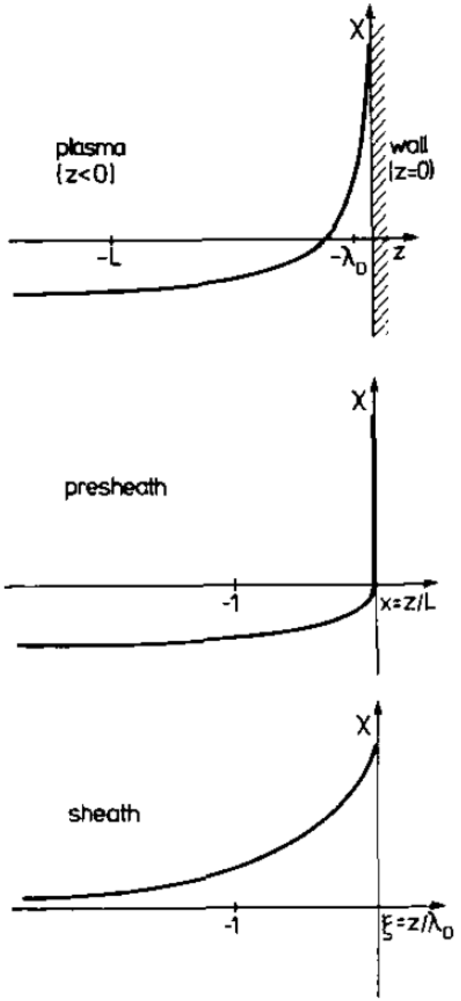
$$\Phi_w = -\frac{e\phi_w}{T_{ep}} = 1.02$$



G. D. Hobbs and J. A. Wesson, Plasma Physics 9 (1), 85 (1967).

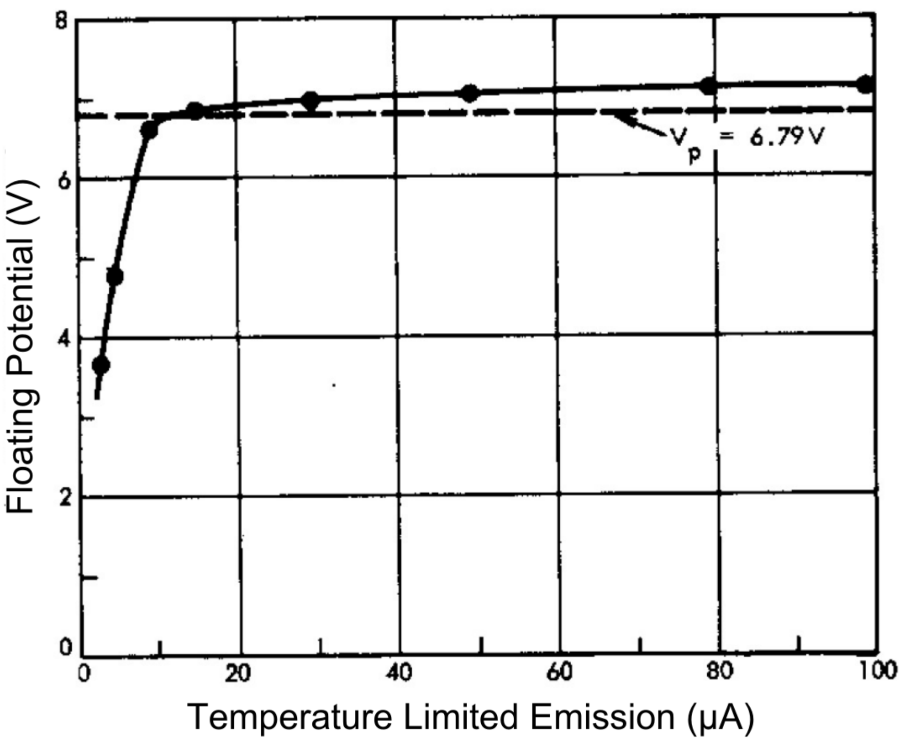
Emissive sheaths require a presheath

- Needed to accelerate ions
- Slightly modified by emitted electrons
- Adds additional ~0.5 – 1.0 T_e/e
- Length scale determined by
  - Charge-exchange collisions
  - Ionization
  - Geometry



K. U. Riemann, Journal of Physics D-Applied Physics **24** (4), 493-518 (1991).

Floating point technique



R. F. Kemp and J. M. Sellen, Review of Scientific Instruments **37** (4), 455 (1966).

- Plasma potential is floating potential of highly emissive probe
- Error of ~$1.5T_{ep}/e$
- Most popular method
- Robust
- Easy to execute

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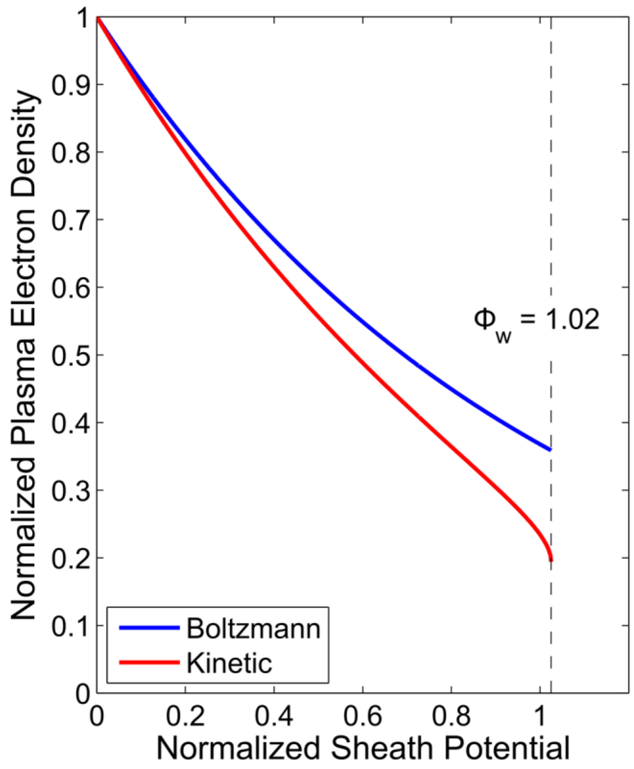
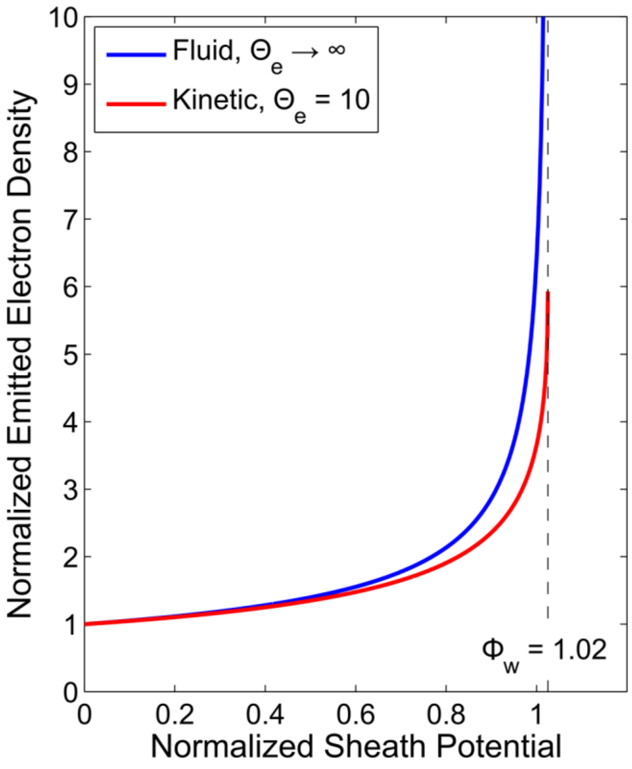
Kinetic effects reduce the electron density near the surface

Plasma electrons lost to surface



Emitted electron temperature



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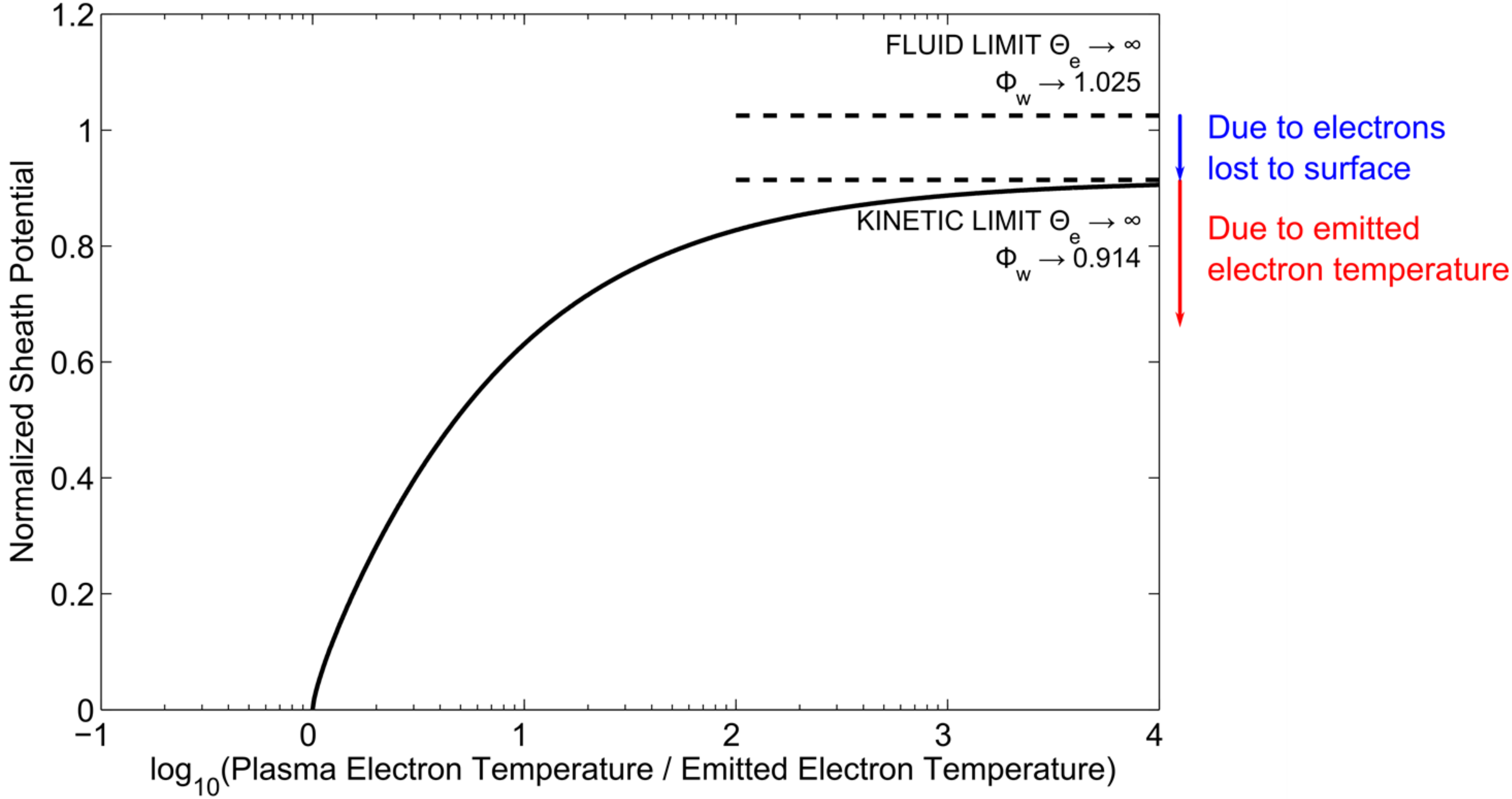
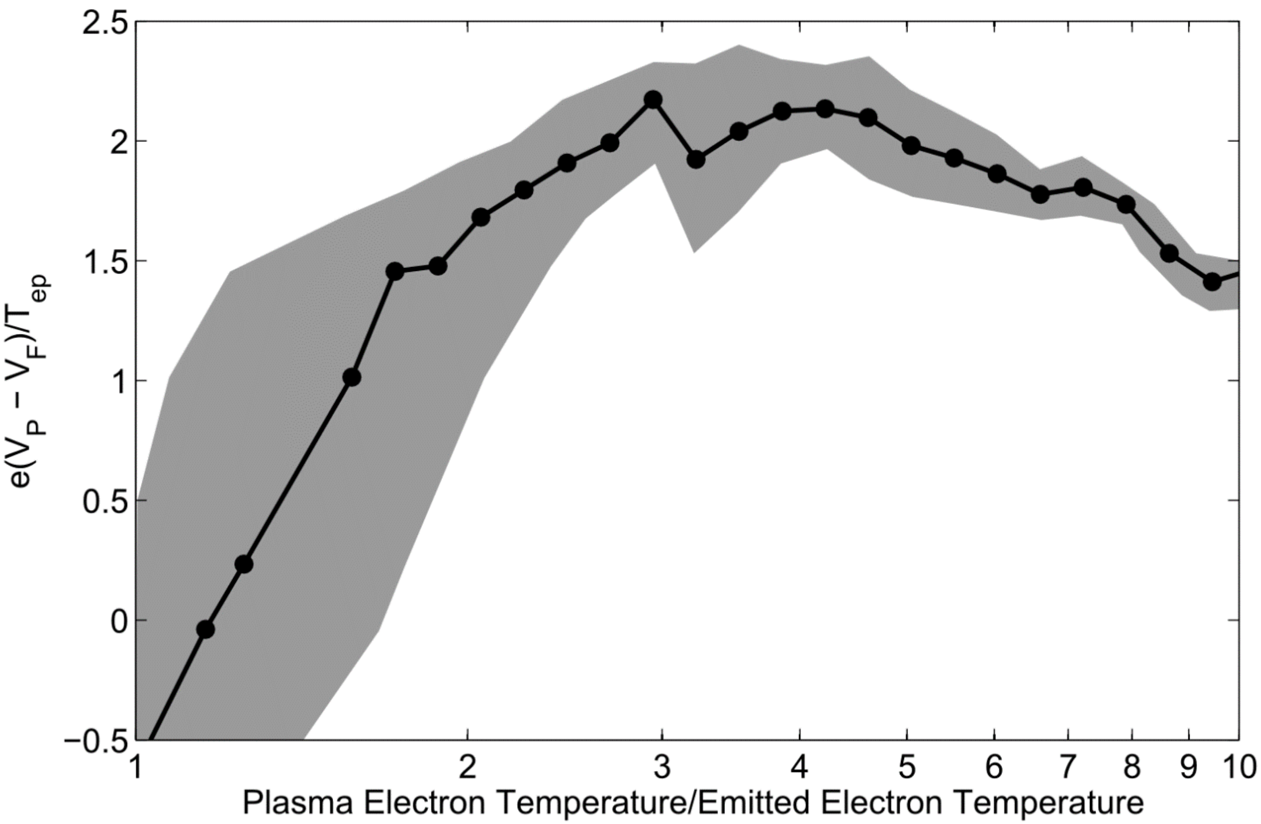
Emissive sheath potential is reduced by the emitted electron temperature



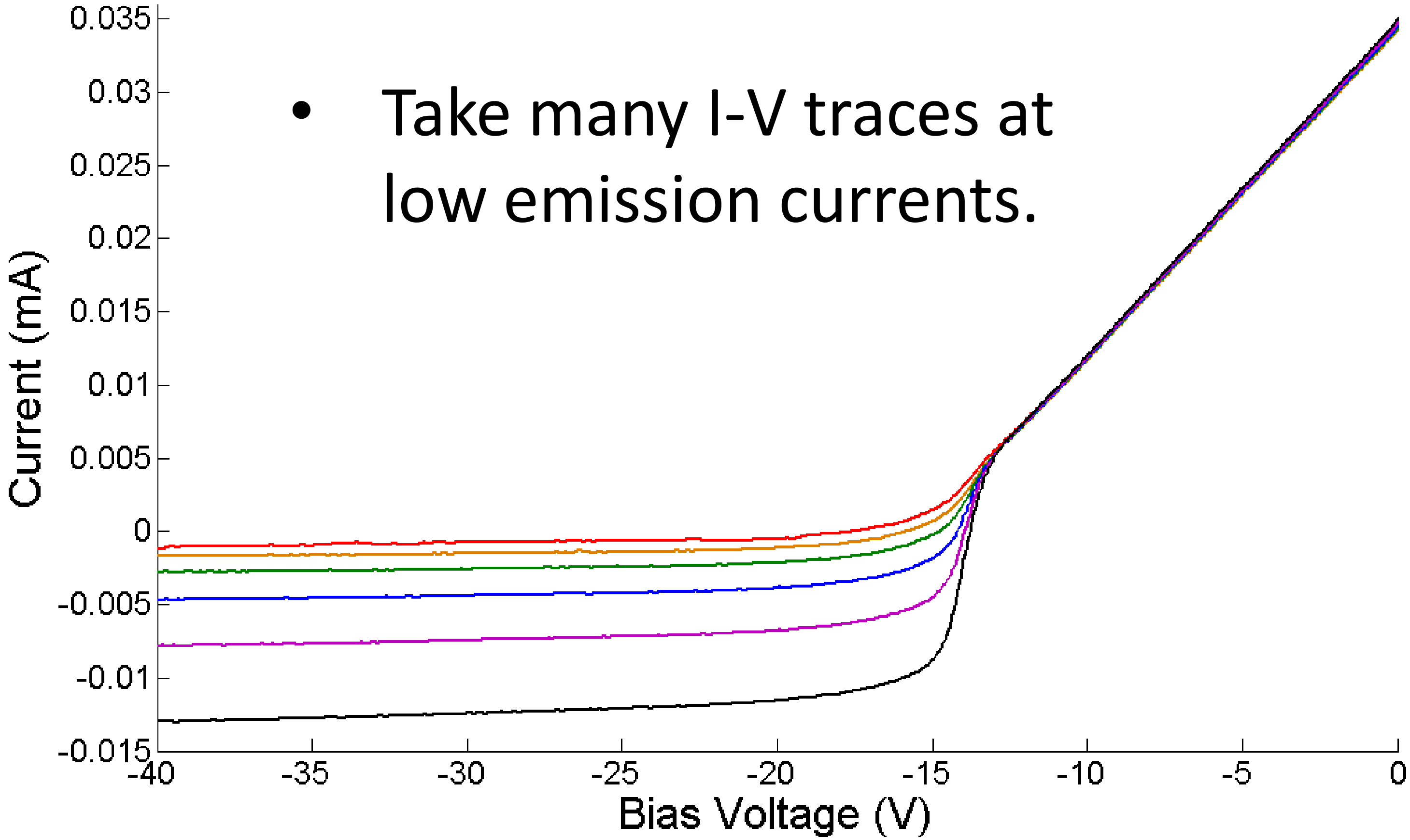
J. P. Sheehan, N. Hershkowitz, I. D. Kaganovich, H. Wang, Y. Raitses, E. V. Barnat, B. R. Weatherford and D. Sydorenko, Physical Review Letters **111** (7), 075002 (2013).

Kinetic theory predictions were confirmed by experiments



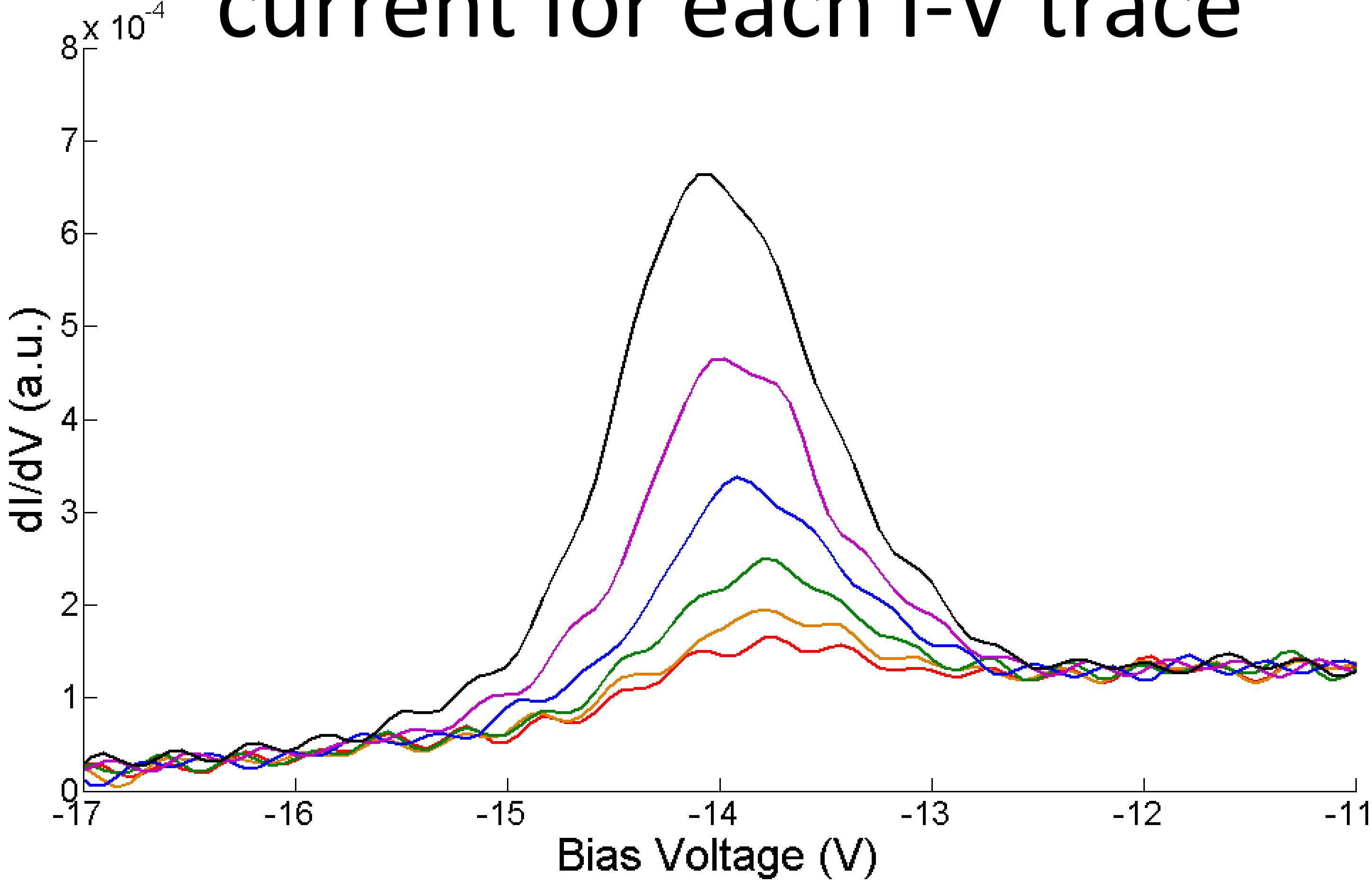
J. P. Sheehan, N. Hershkowitz, I. D. Kaganovich, H. Wang, Y. Raitses, E. V. Barnat, B. R. Weatherford and D. Sydorenko, Physical Review Letters **111** (7), 075002 (2013).

Inflection point technique: developed to reduce space-charge effects



- Take many I-V traces at low emission currents.

Find the inflection point and temperature limited emission current for each I-V trace



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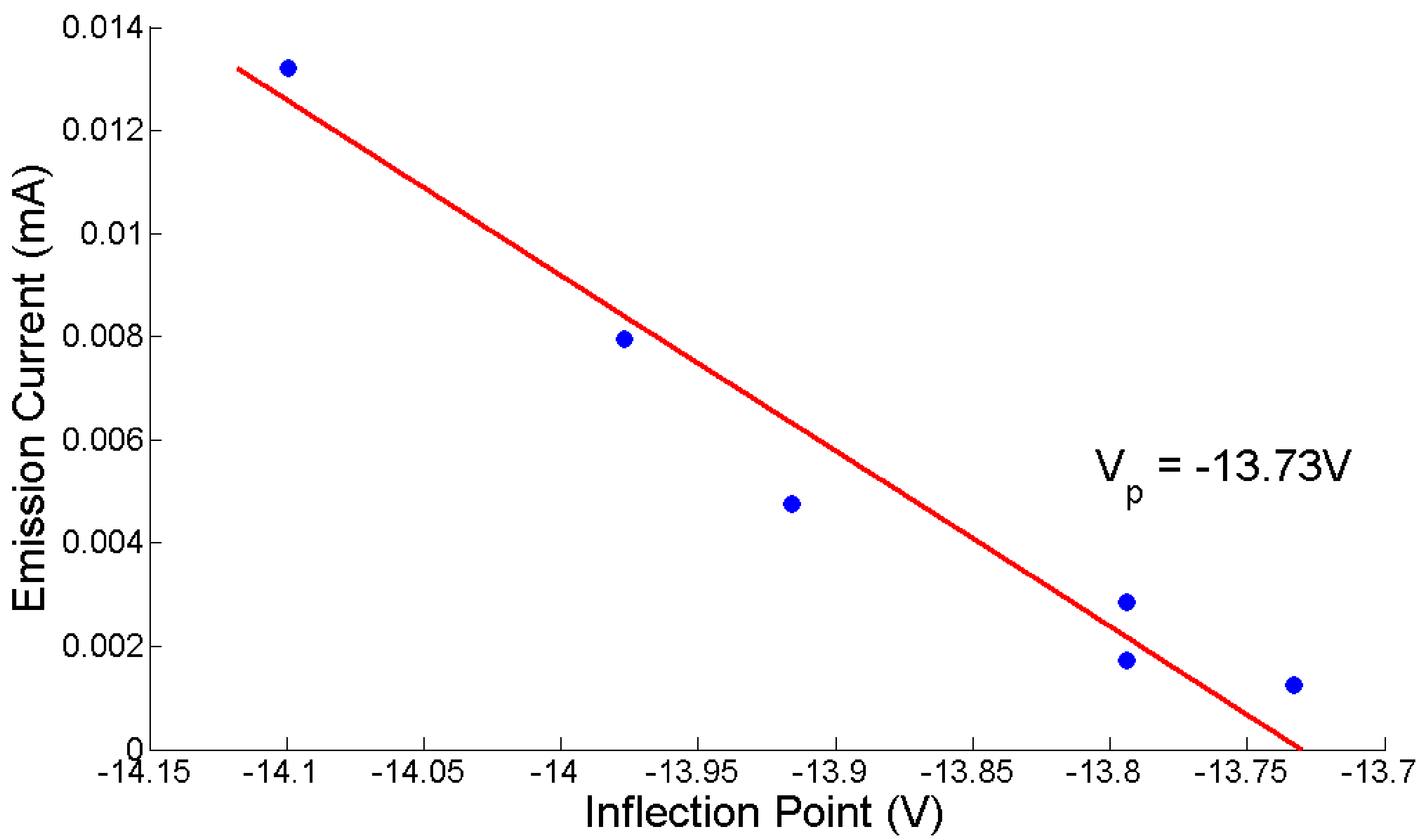
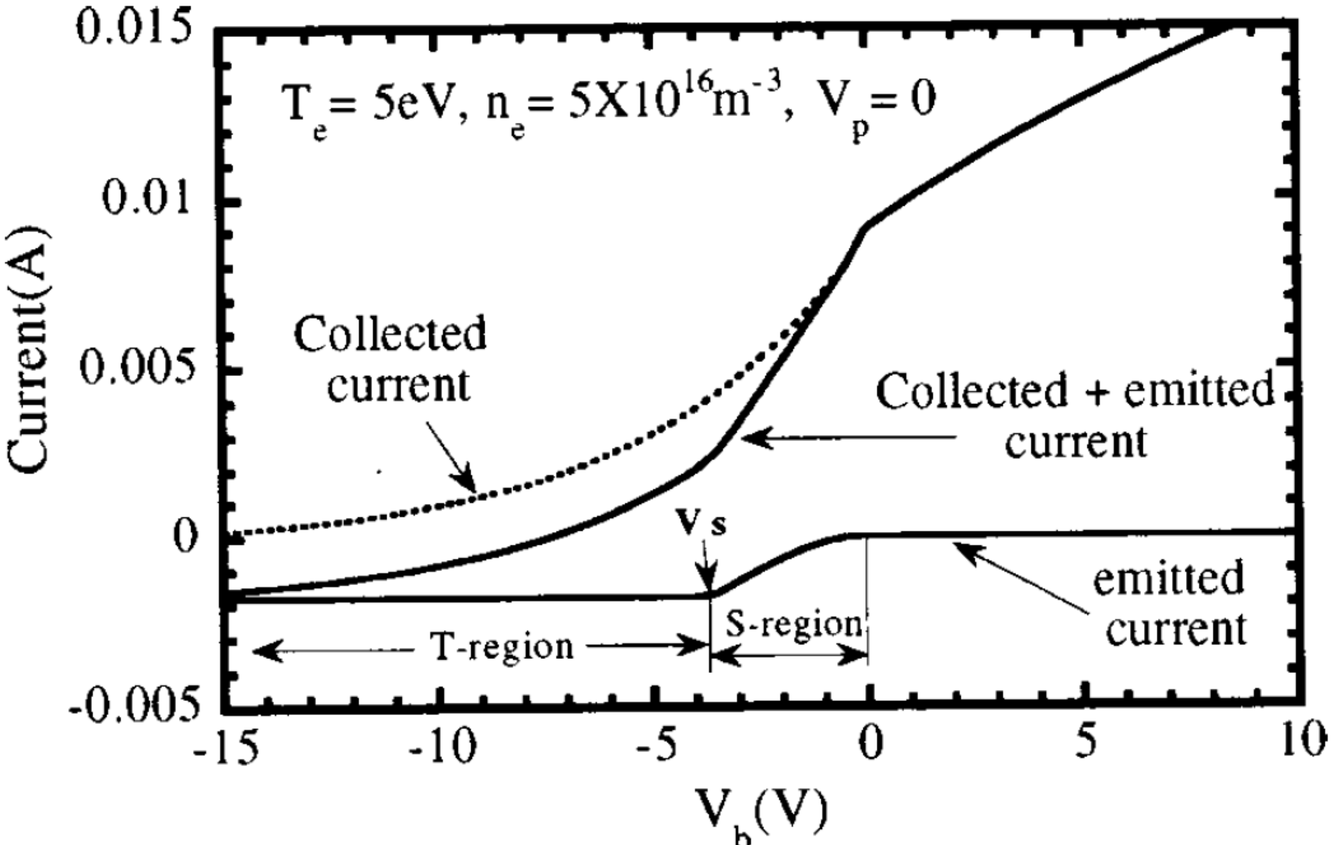
Extrapolate inflection point to zero emission current

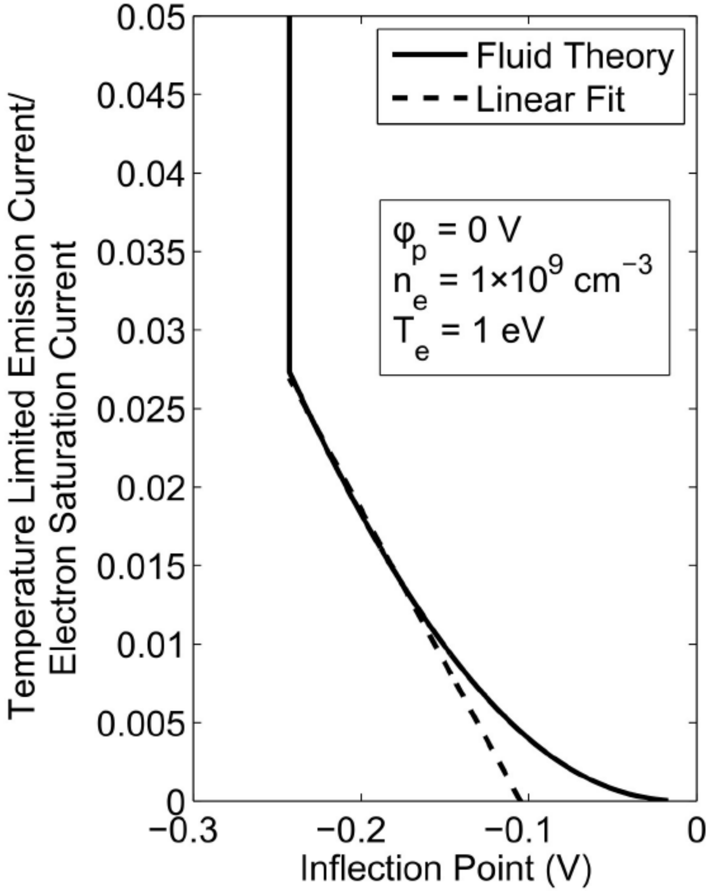


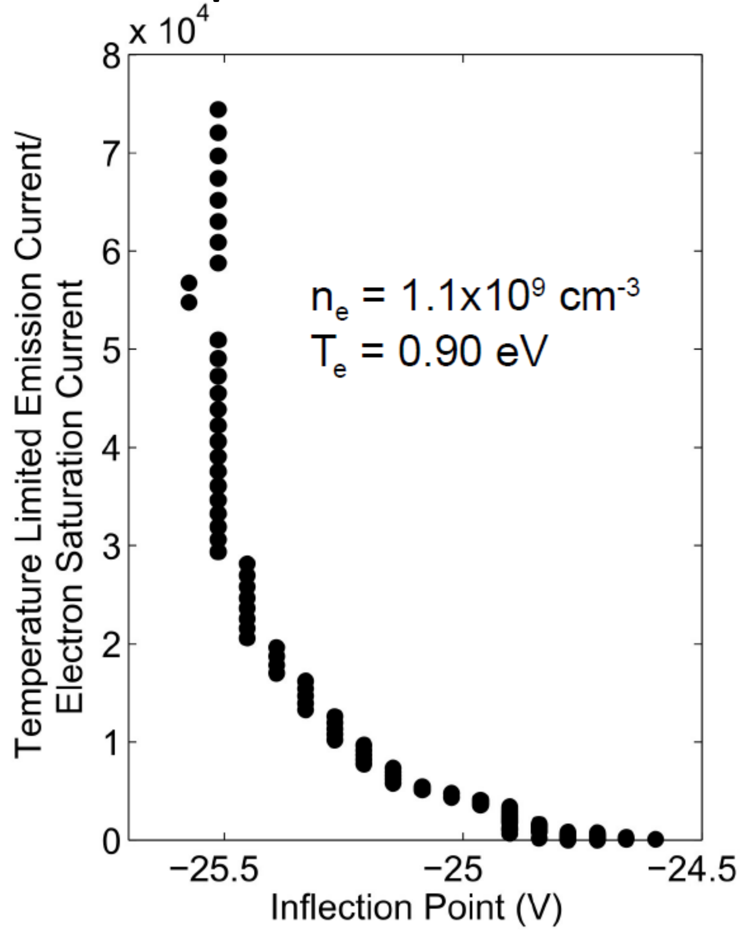
Fluid theory can provide justification for inflection point technique



M. Y. Ye and S. Takamura, Physics of Plasmas **7** (8), 3457-3463 (2000).

Inflection point technique accurate to within $T_{ep}/10e$

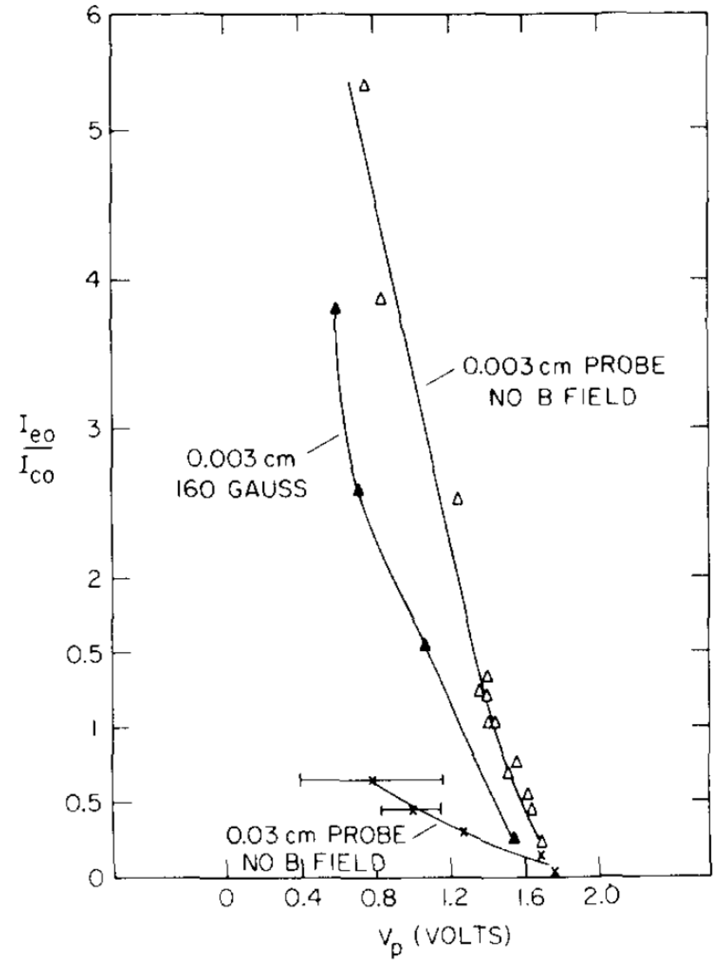




J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich and N. J. Fisch, Physics of Plasmas **18** (7), 073501 (2011).

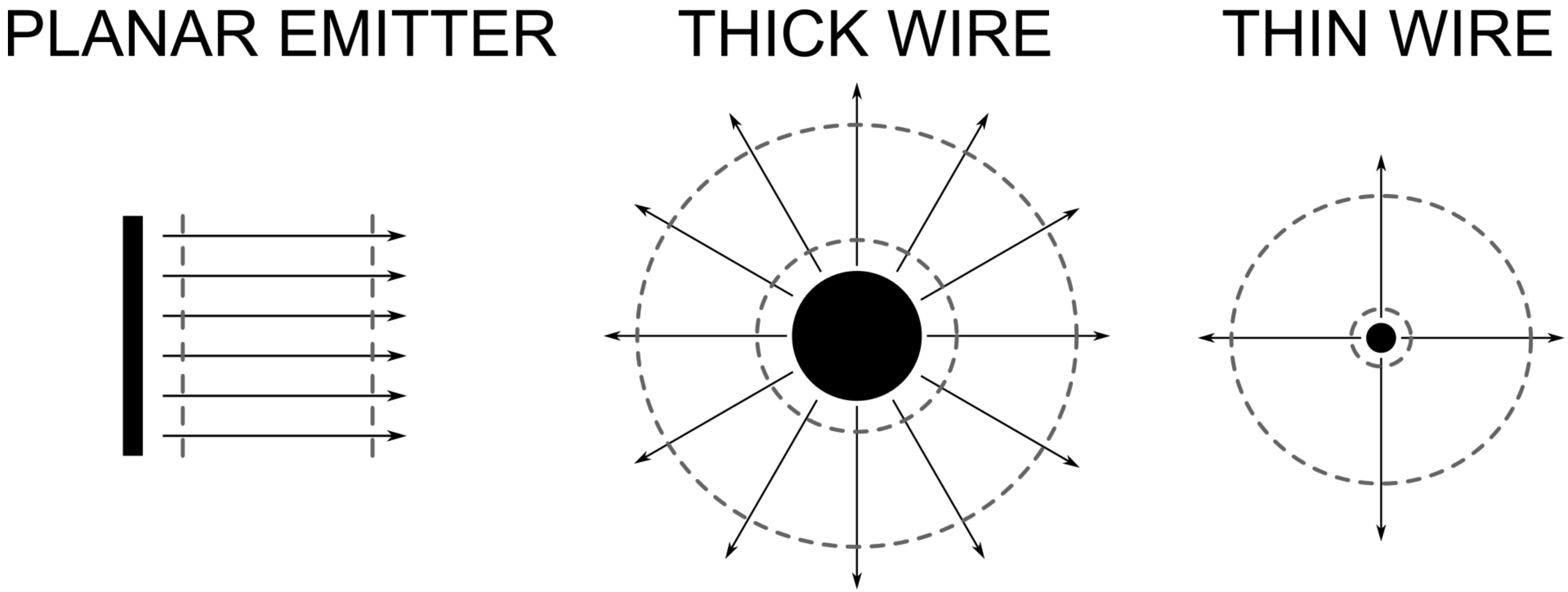
Geometric effects demonstrate limitations to planar theories

- Slope of inflection point vs. emission current dependent on probe diameter
- Smaller probe
  - More accurate measurements
  - Smaller emission current
  - More fragile



J. R. Smith, N. Hershkowitz and P. Coakley, Review of Scientific Instruments **50** (2), 210-218 (1979).

Higher curvature allows emitted electrons to quickly disperse



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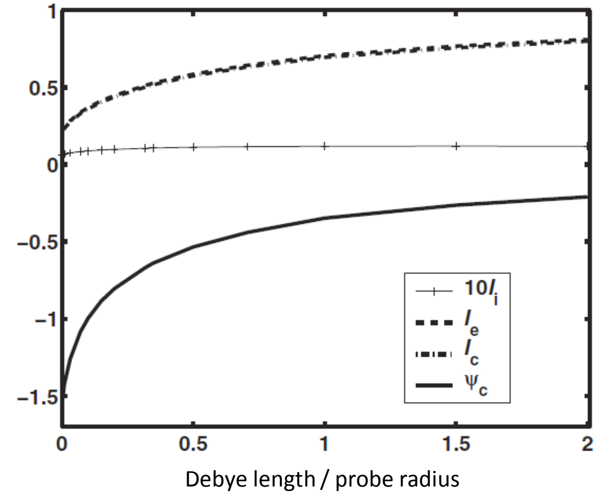
Cylindrical effects further complicate emissive probe floating potential

- Smaller probe radius
  - Ion convergence reduces net space-charge
  - Smaller sheath potential
- Orbital motion effects
  - Preliminary results
  - May increase emitted electron density
  - Increase sheath potential



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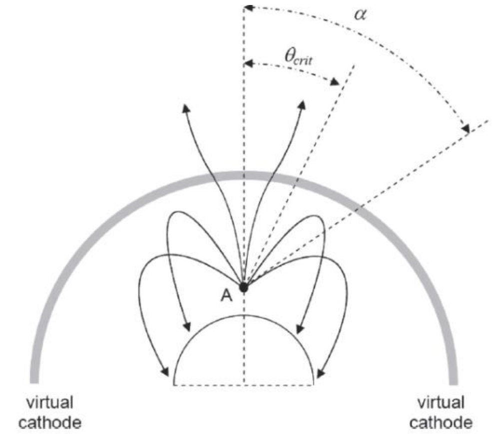

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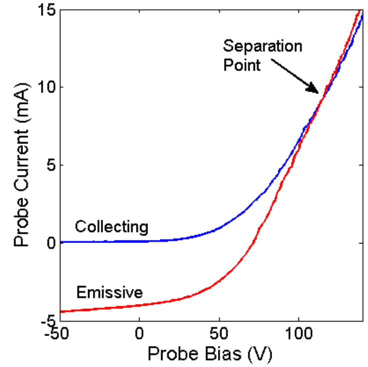
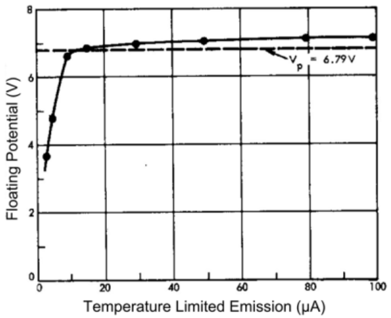
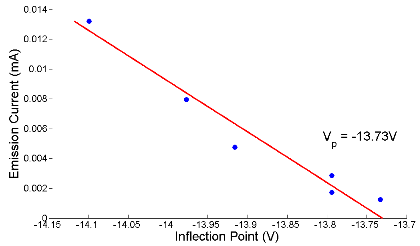
1. A. Fruchtman, D. Zoler and G. Makrinich, Physical review. E, Statistical, nonlinear, and soft matter physics **84** (2), 025402 (2011).
2. S. Robertson, IEEE Transactions on Plasma Science **40** (10), 2678-2685 (2012).

Summary of techniques

- Separation point: where collecting I-V and emitting I-V intersect
- Floating point: floating potential at space-charge limit
- Inflection point: in the limit of zero emission for low emission currents







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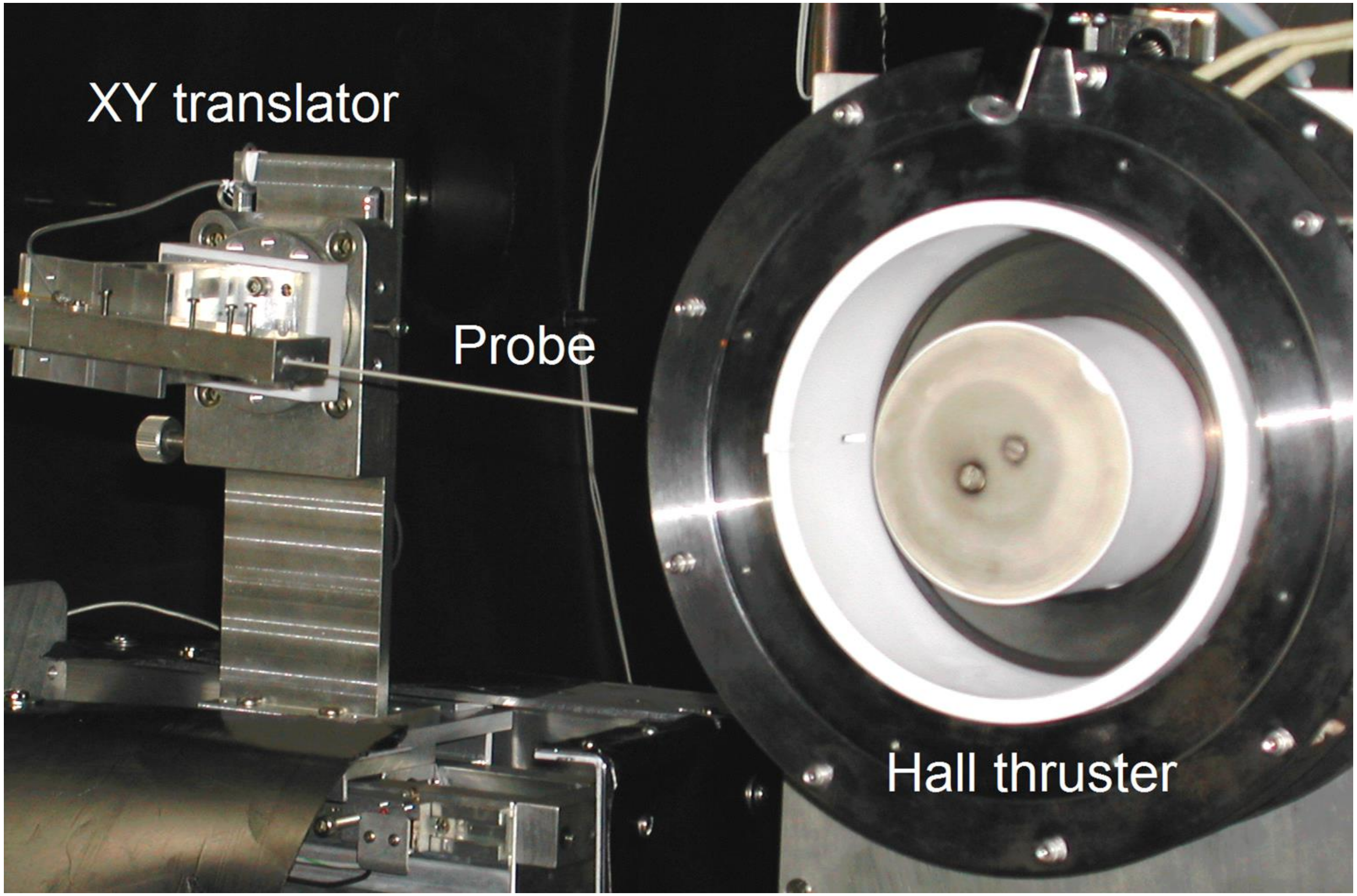
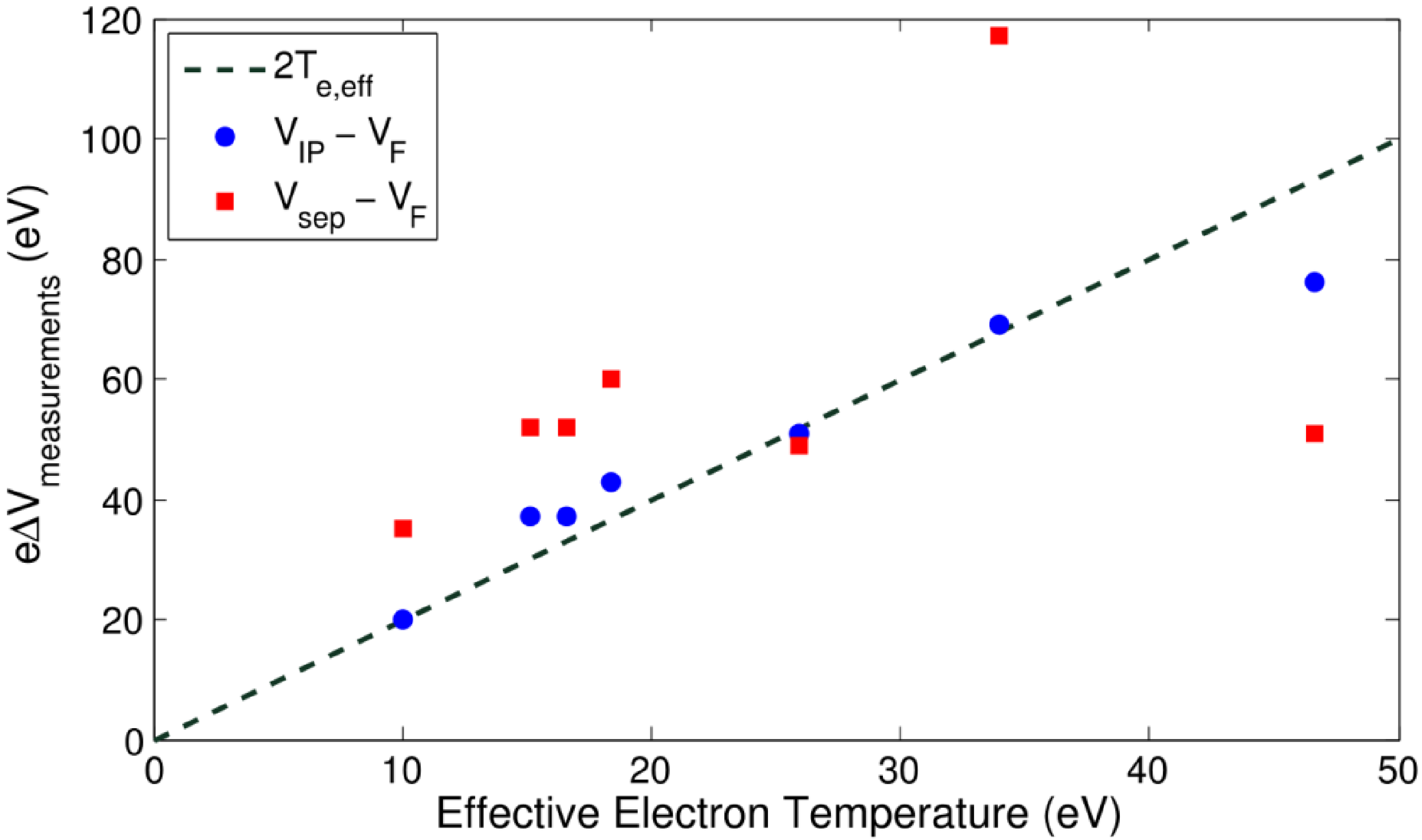
Emissive probe techniques were compared in Hall thruster plume



J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich and N. J. Fisch, Physics of Plasmas **18** (7), 073501 (2011).

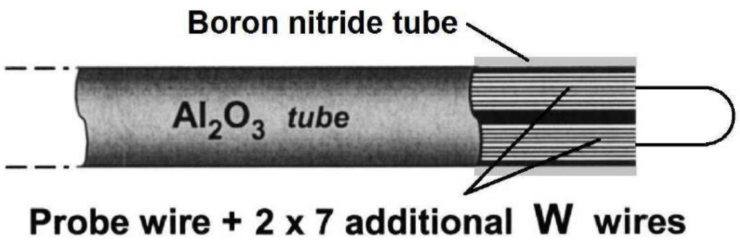
Floating potential of highly emissive probe ~2T_e/e below plasma potential

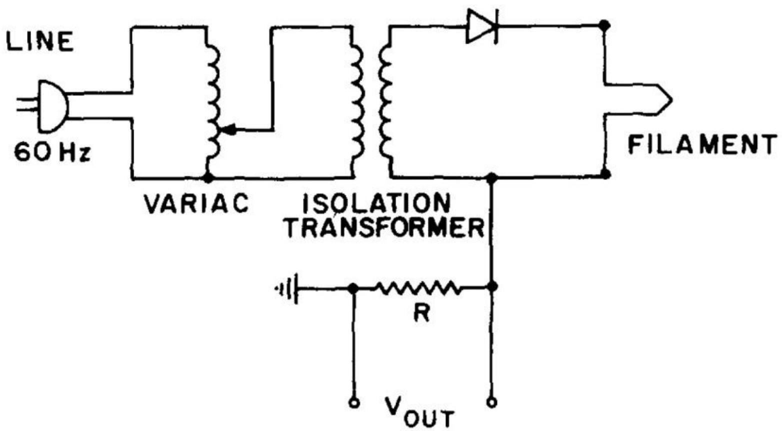


J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich and N. J. Fisch, Physics of Plasmas **18** (7), 073501 (2011).

AC Joule Heating

- Resistive heating
- Typical probe resistance: ~3Ω
- Half-wave rectified heating current
- Period must be shorter than cooling time (10s of ms)
- Data collected during nonheating half-cycle
- Inflection point and floating point may shift due to cooling

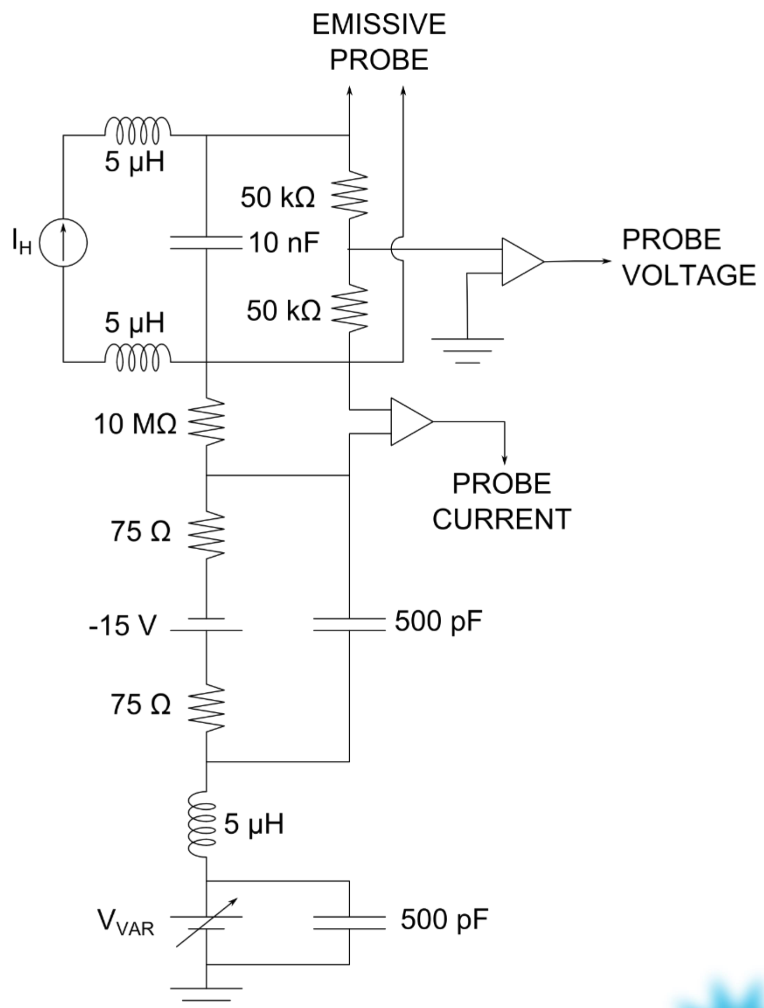




M. A. Makowski and G. A. Emmert, Review of Scientific Instruments **54** (7), 830-836 (1983).

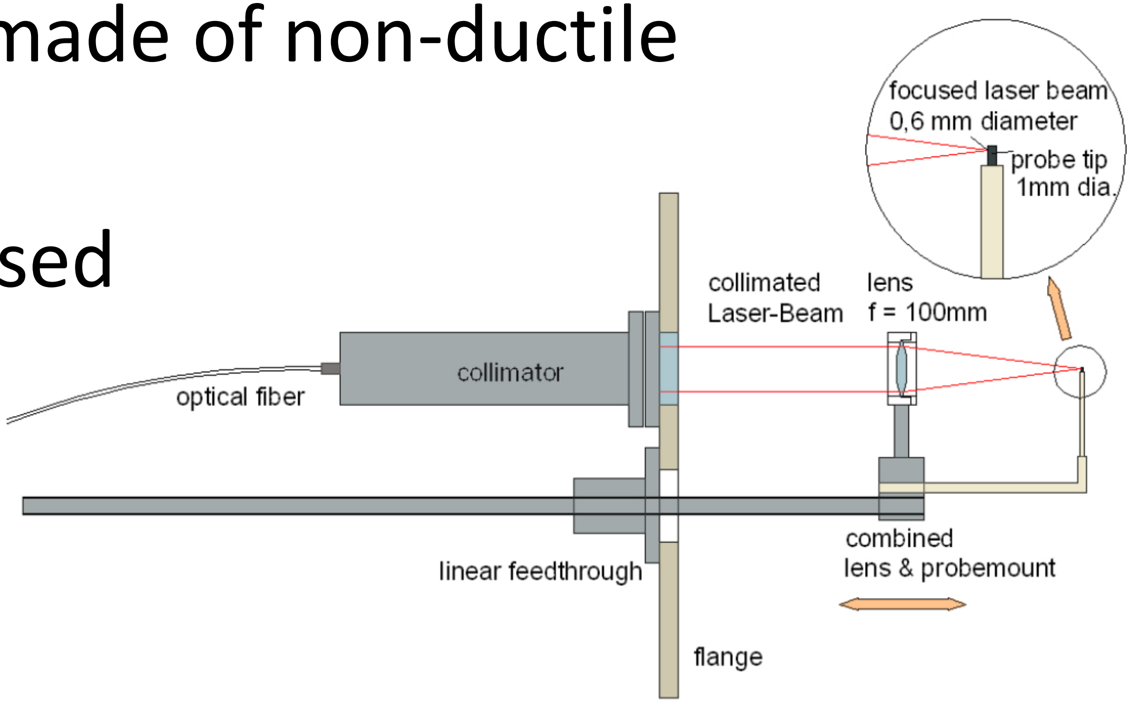
DC Joule Heating

- Heating current: 100s of mA to 1s of A
  - Depends on probe thickness
- Added circuit elements can reduce noise
- Data taken while probe is heated
  - Must account for heating potential
- Large shunt resistor (10s – 100s of MΩ) for accurate measurements



Laser Heating

- CO_2 laser (10 – 20 W)
- Probe can be made of non-ductile material
- Infrequently used



R. W. Schrittwieser, R. Stärz, C. Ionita, R. Gstrein, T. Windisch, O. Grulke and T. Klinger, Journal of Plasma Fusion Research **8**, 632-636 (2009).

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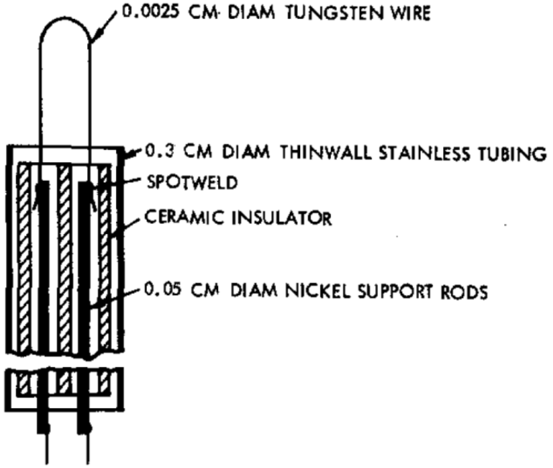
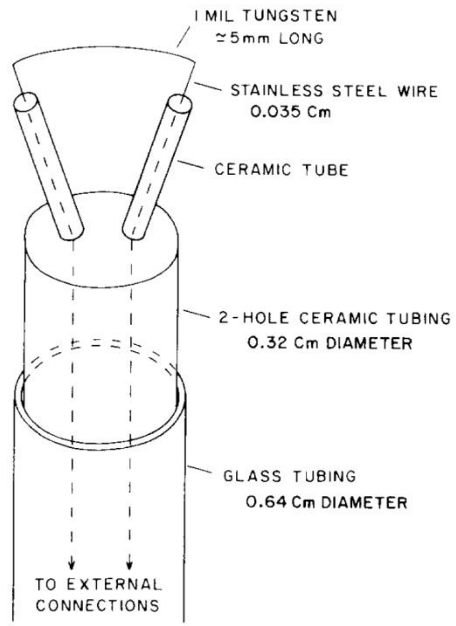
Emissive filament shape

Hairpin



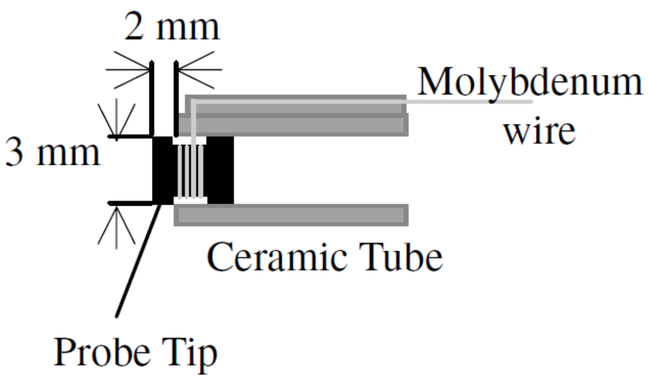
R. F. Kemp and J. M. Sellen, Review of Scientific Instruments **37** (4), 455 (1966).

Linear



J. R. Smith, N. Hershkowitz and P. Coakley, Review of Scientific Instruments **50** (2), 210-218 (1979).

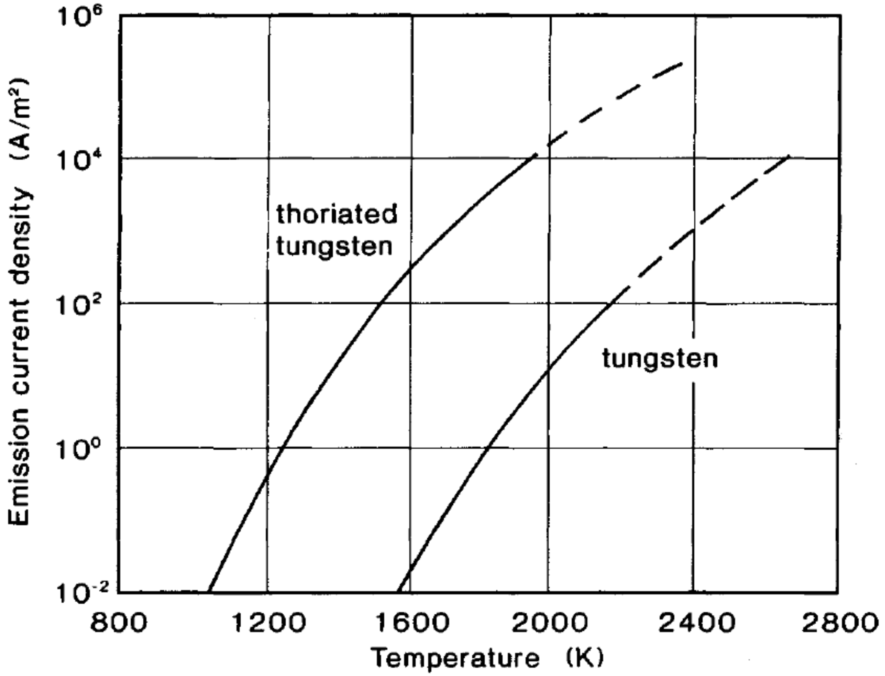
Loop-Free



R. Schrittwieser, A. Sarma, G. Amarandei, C. Ionita, T. Klinger, O. Grulke, A. Vogelsang and T. Windisch, 2006.

Low work function materials are necessary for high emission

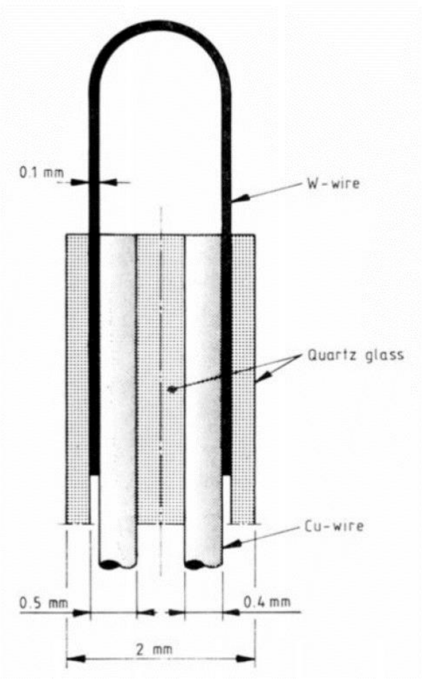
- Thoriated tungsten wire is typical
  - 2% doped
  - $10^3 - 10^4$ more emissive than undoped
- Loop-free
  - Graphite
  - LaB_6
- For oxygen plasmas
  - Rhenium
  - Iridium



E. Lassner and W.-D. Schubert, (Kluwer Academic/Plenum Publishers, New York, 1999), pp. 422.

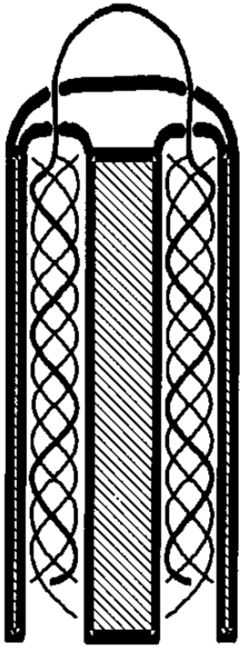
Connecting electrical leads

Mechanical



S. Iizuka, P. Michelsen, J. J. Rasmussen, R. Schrittwieser, R. Hatakeyama, K. Saeki and N. Sato, Journal of Physics E-Scientific Instruments **14** (11), 1291-1295 (1981).

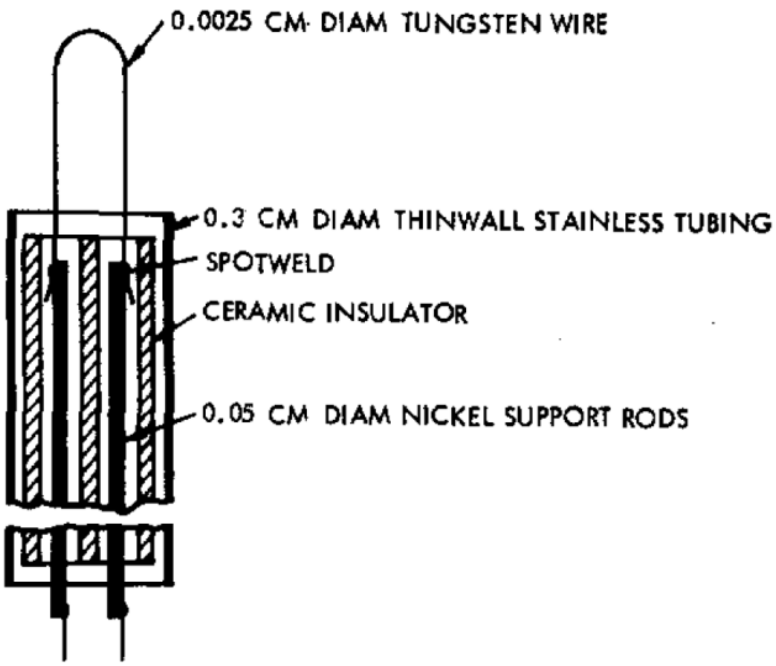
Braid



A. Siebenforcher and R. Schrittwieser, Review of Scientific Instruments **67** (3), 849-850 (1996).

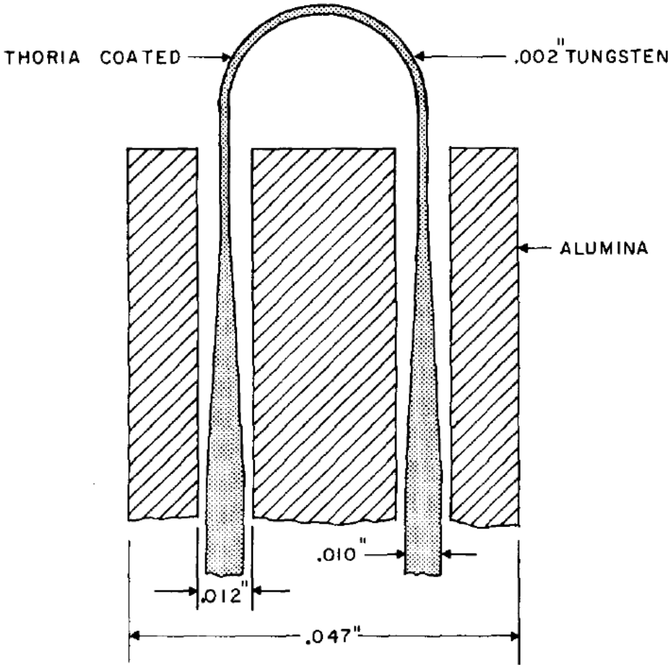
Connecting electrical leads (cont.)

Spot Weld



R. F. Kemp and J. M. Sellen, Review of Scientific Instruments **37** (4), 455 (1966).

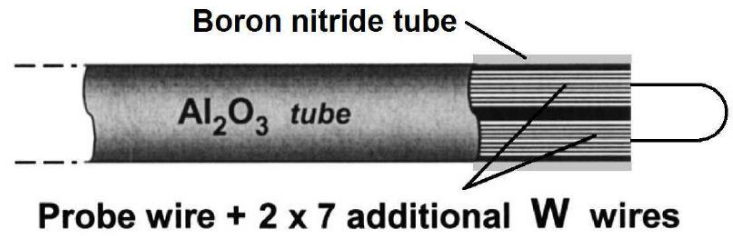
Electrolytic Etching



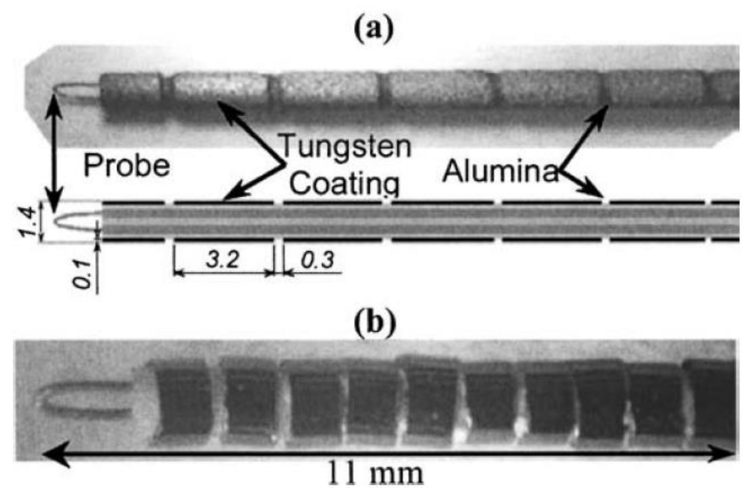
R. W. Motley, Journal of Applied Physics **43** (9), 3711 (1972).

Probe shaft may perturb plasma

- Dual bore alumina tube
- Telescoping probe
- Electrical shielding for temporal resolution
- SEE in high energy density plasmas
- Segmented conductive probe shaft
  - Tungsten or graphite
  - Greatly reduces plasma perturbations



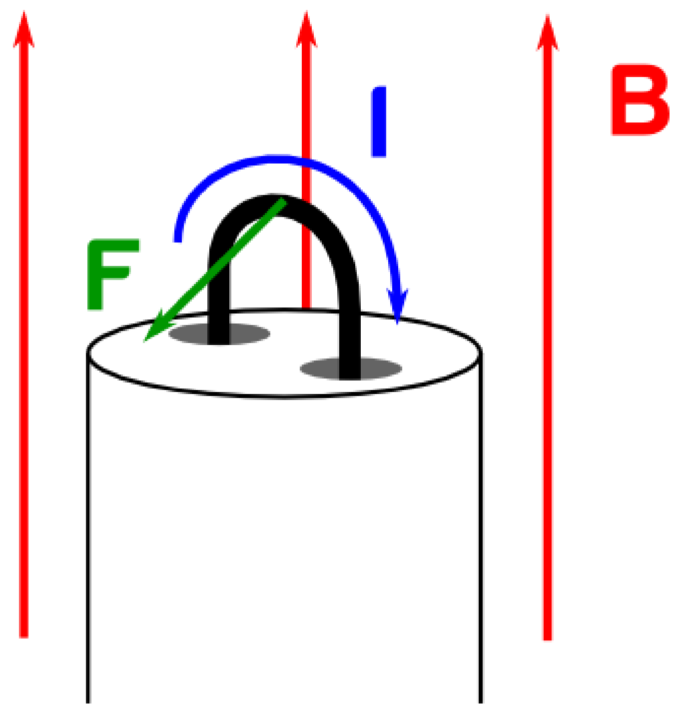
J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich and N. J. Fisch, Physics of Plasmas **18** (7), 073501 (2011).



D. Staack, Y. Raitses and N. J. Fisch, Review of Scientific Instruments **75** (2), 393-399 (2004).

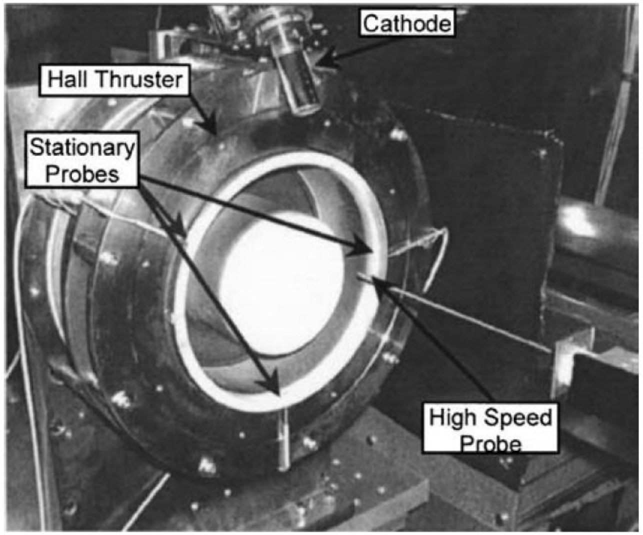
Magnetic Fields

- Changes effective probe area
  - Orient probe perpendicular to magnetic field
- Deformation of Joule heated probe
  - Avoidable with laser heating
- Anisotropic EVDF



Temperature, density gradients

- Hall thrusters, for instance
- Temperature and density decrease away from thruster
- $V_p - V_f \approx T_e$
- λ_d / r_p
- Errors in electric field measurements



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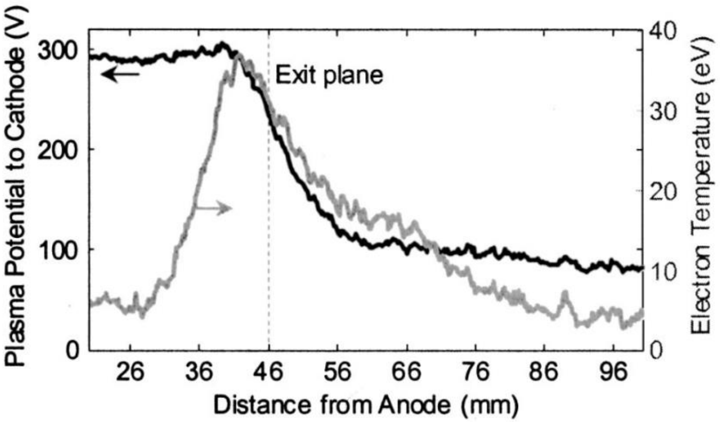

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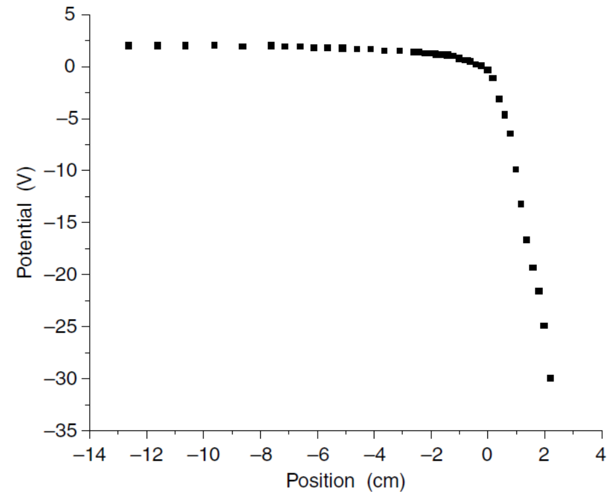
1. D. Staack, Y. Raitses and N. J. Fisch, Review of Scientific Instruments **75** (2), 393-399 (2004).
2. D. Staack, Y. Raitses and N. J. Fisch, Applied Physics Letters **84** (16), 3028-3030 (2004).

Sheaths

- Langmuir probes cannot be used in sheaths
- Floating potential method more difficult as density decreases
- Inflection point method preferred
- Direction of slope can identify sheath edge



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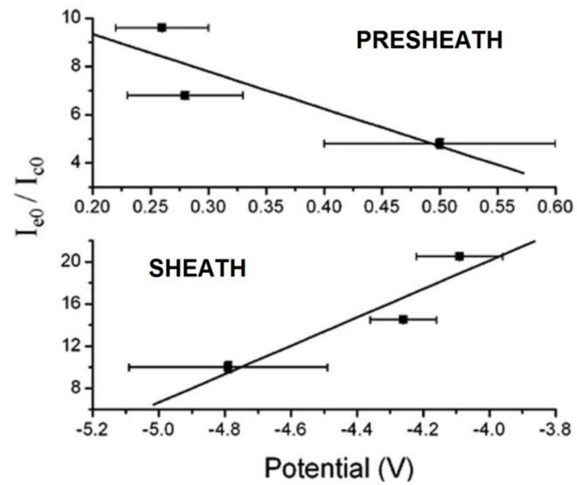

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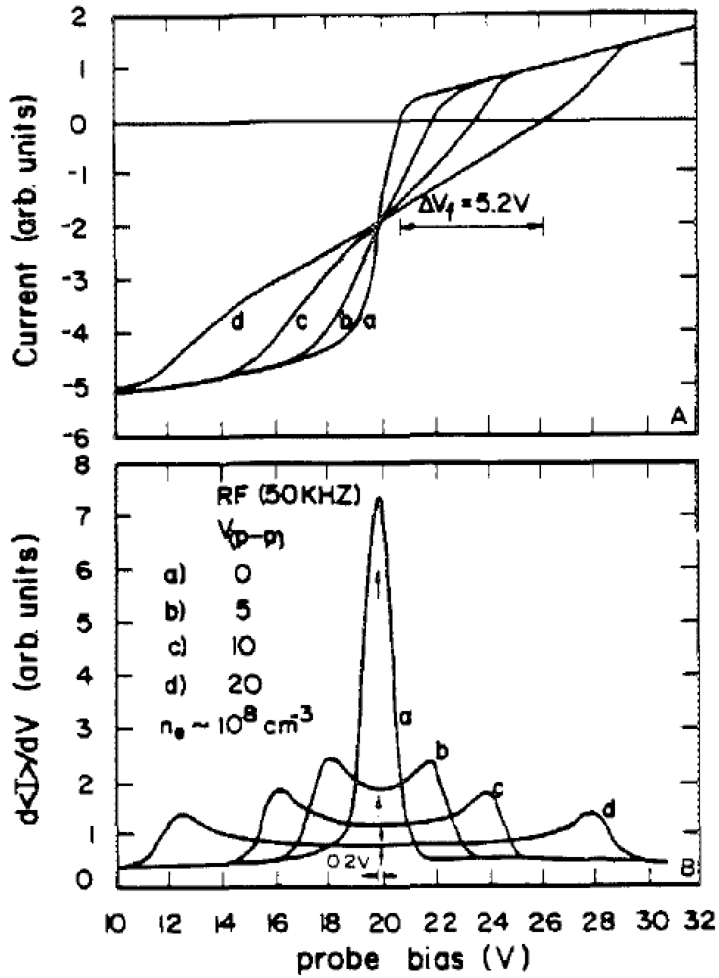
1. L. Oksuz and N. Hershkowitz, Plasma Sources Science and Technology **14** (1), 201-208 (2005).
2. X. Wang and N. Hershkowitz, Review of Scientific Instruments **77** (4), 043507 (2006).

Radio frequency plasmas

- Time averaged floating potential ambiguous
- Derivative of I-V trace reveals time averaged potential oscillations
- Mostly insensitive to emission current as long as $I_{e0} \sim 1 – 10\ I_{c0}$

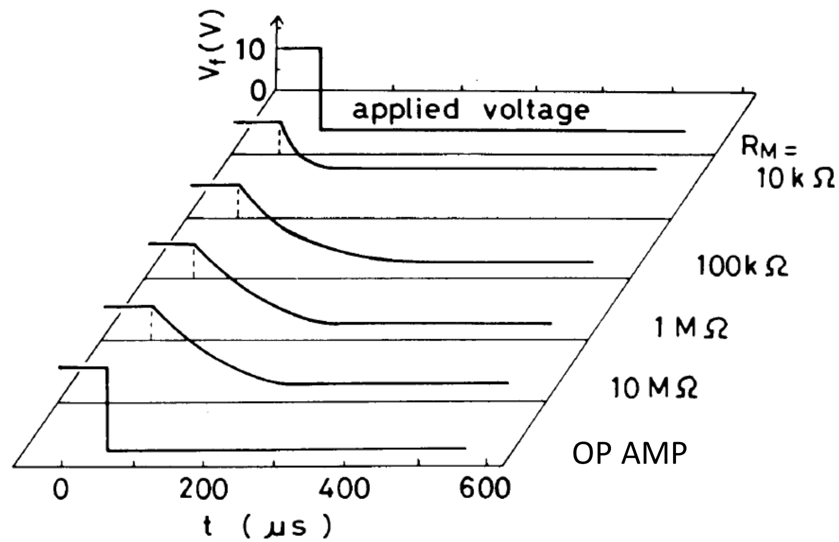


E. Y. Wang, N. Hershkowitz, T. Intrator and C. Forest, Review of Scientific Instruments **57** (10), 2425-2431 (1986).

Temporal Resolution

- Probe acts as RC circuit
  - C_0: stray capacitance
  - R_0: sheath resistance
  - R_M: measurement resistor
- High speed op amp greatly improves response time (< 1 μs)
- Laser heated probes have faster response times
- Time resolved rf potentials

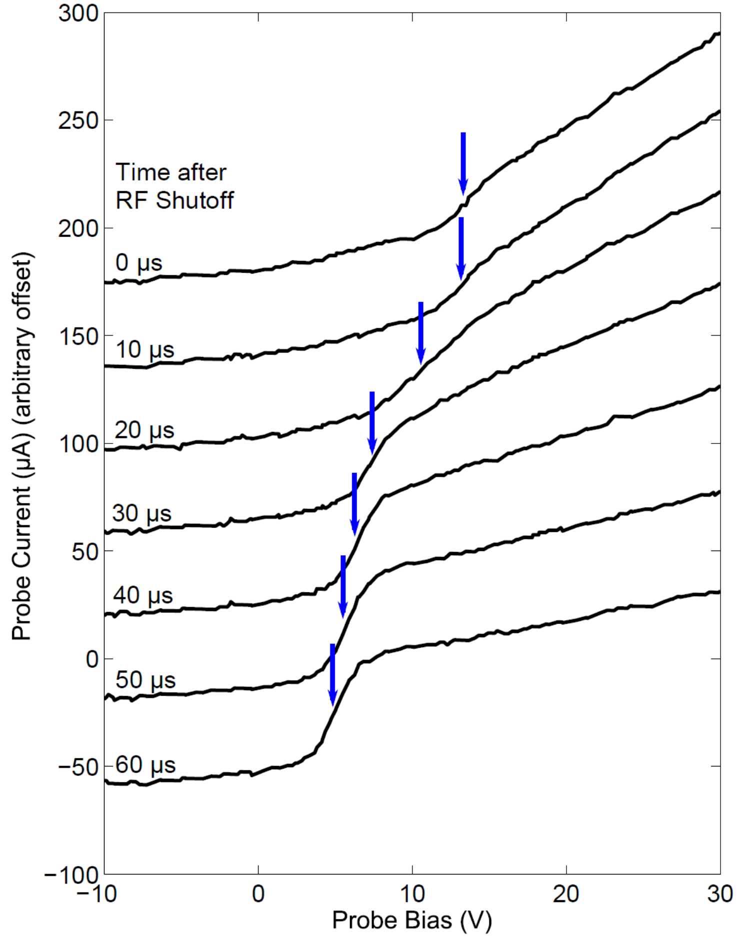
$$\tau_M = \frac{C_0 R_0 R_M}{R_0 + R_M}$$



H. Fujita and S. Yagura, Japanese Journal of Applied Physics Part 1-Regular Papers Short Notes and Review Papers **22** (1), 148-151 (1983).

Slow-Sweep

- Measure current vs time at many probe biases
- Transpose to determine I-V trace vs time
- Allows time resolved inflection point method
- Easy, inexpensive to execute
- Same temporal resolution as floating probe
- Only for regular, period oscillations



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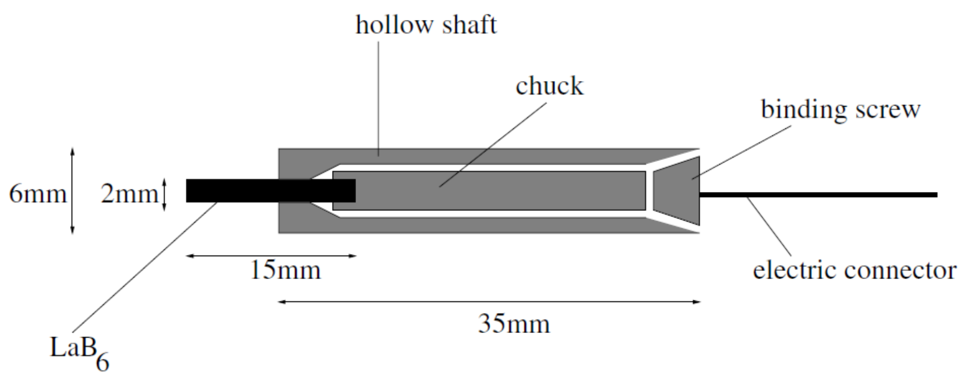
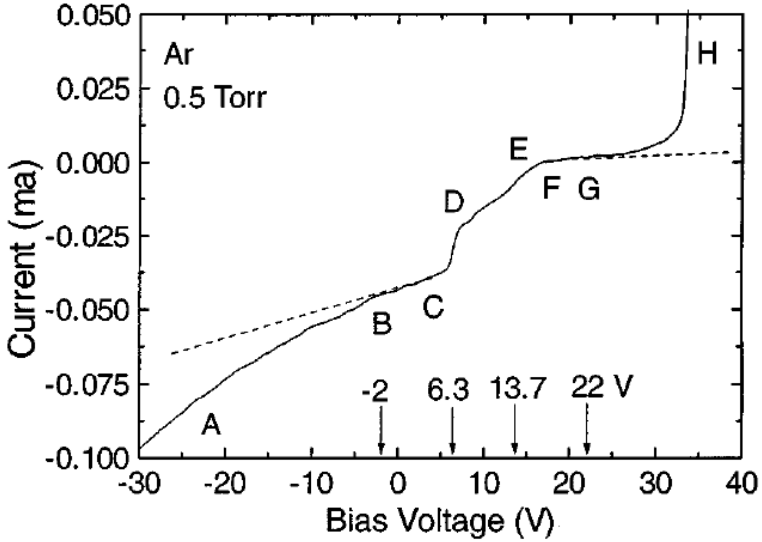
High Energy Density

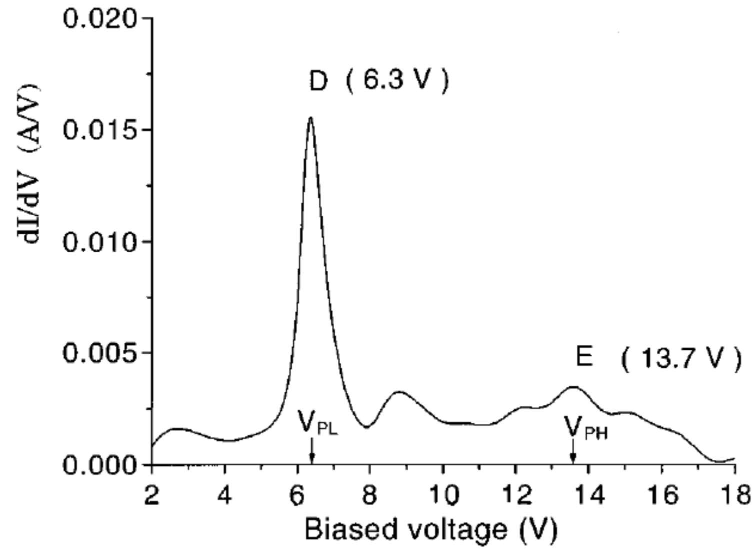
- High heat flux can melt probe
- For I-V trace, electron saturation current can contribute to Joule heating
- Self emissive probe uses plasma for heating
- Fast (1 m/s) actuator removes probe before it melts



M. A. Fink, M. Endler and T. Klinger, 2004.

High Pressure ($\gtrsim$1 Torr)



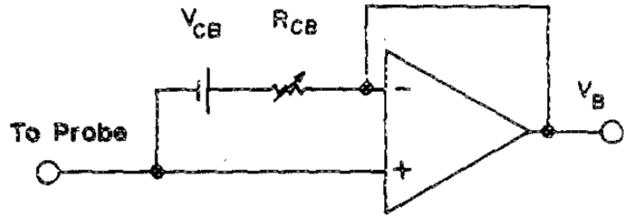


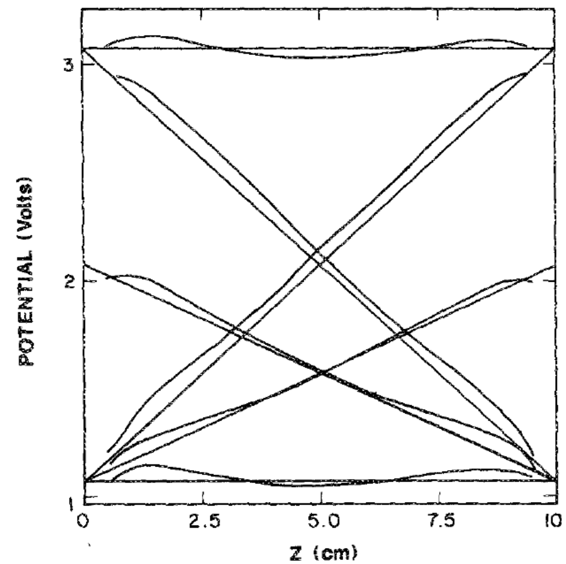
- Electrons accelerating to/from probe can cause additional ionization
- Measurements have not yet be attempted in atmospheric pressure plasma

S. L. Yan, H. Kamal, J. Amundson and N. Hershkowitz, Review of Scientific Instruments **67** (12), 4130-4137 (1996).

Vacuum potential measurements

- Emissive probes can make vacuum potential measurements
- Useful for plasma/vacuum interface
- Circuit forces probe potential to draw set current
- Graph shows measurements between capacitive plates

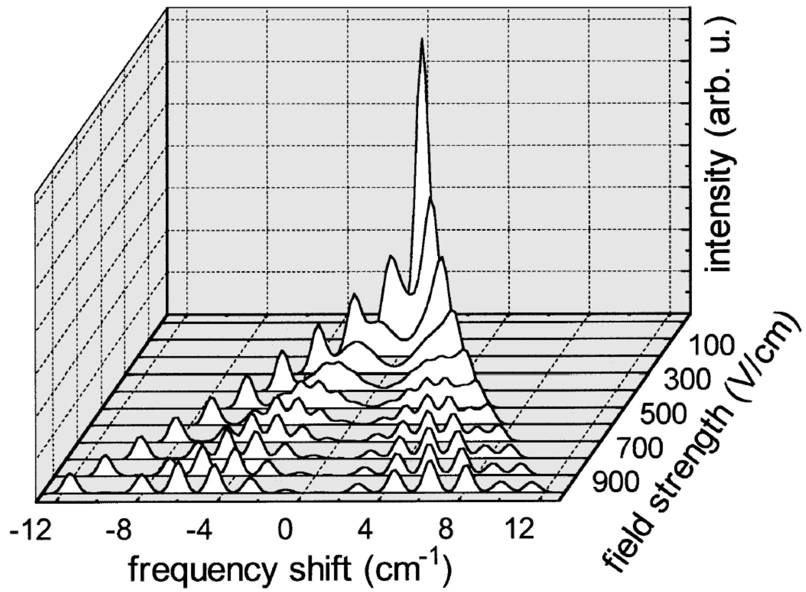




D. Diebold, N. Hershkowitz, A. D. Bailey, M. H. Cho and T. Intrator, Review of Scientific Instruments **59** (2), 270-275 (1988).

Probes vs. Optics

- Stark broadening
  - Measures electric field (> 30 V/cm)
  - Resolution of 0.1 mm
  - Limited by ion electric microscopic fields
- Probes
  - No minimum electric field
  - Resolution of 1 mm



U. Czarnetzki, D. Luggenhölscher and H. F. Döbele, Physical Review Letters **81** (21), 4592-4595 (1998).

Recommendations: Density

n_e (cm^{-3})	Technique
$n_e \leq 10^5$	Vacuum current bias Inflection point in the limit of zero emission
$10^5 \leq n_e \leq 10^{12}$	Inflection point in the limit of zero emission Floating point in the limit of large emission
$10^{12} < n_e \leq \frac{1.8 \times 10^{14}}{\sqrt{T_e}}$	Secondary electron emissive probe Floating point with self-emissive probe
$n_e > \frac{1.8 \times 10^{14}}{\sqrt{T_e}}$	Optical techniques

J. P. Sheehan and N. Hershkowitz, Plasma Sources Science and Technology **20** (6), 063001 (2011).

Recommendation: System

Plasma system	Heating method	Technique
Vacuum	Joule heating	Vacuum current bias
Highly magnetized plasma	Laser heating	Inflection point Floating point
Radio frequency Double plasma device or beams Non-neutral	Joule heating	Inflection point
Fusion plasma: bulk	Optical techniques	
Fusion plasma: edge	Laser heating Self-emission	Floating point

J. P. Sheehan and N. Hershkowitz, Plasma Sources Science and Technology **20** (6), 063001 (2011).

Recommendation: Applications

Applications	Technique
Steady state potential **Potential in a sheath**	Inflection point in the limit of zero emission
Real time monitoring **Spatial scans** **Temporal development** **Fluctuations**	Floating point in the limit of large emission

J. P. Sheehan and N. Hershkowitz, Plasma Sources Science and Technology **20** (6), 063001 (2011).

Conclusions

- Very useful tool for plasma potential measurements
  - Robust for a wide variety of plasmas
  - Good range for many low temperature plasma experiments
- Don't ignore the uncertainties of each technique
  - Electron temperature
  - Parameter gradients
  - Geometry

Acknowledgments

This work was supported by the US Department of Energy Grants No DE-FG02-97ER54437 and No 3001346357 and the Fusion Energy Science Fellowship Program administered by Oak Ridge Institute for Science and Education under a contract between the US department of Energy and the Oak Ridge Associated Universities.

1. J. P. Sheehan and N. Hershkowitz, Plasma Sources Science and Technology **20** (6), 063001 (2011).
2. J. P. Sheehan, R. Raitses, N. Hershkowitz, and M. McDonald, NASA Standard (2013), submitted.

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