Plamsa Diagnostics: Probes

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Outline

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Overview

Probe: Diagnostic tool that is literally inserted into a plasma

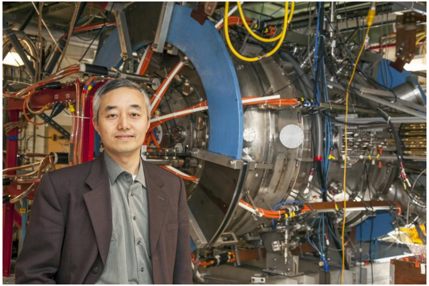
Advantages

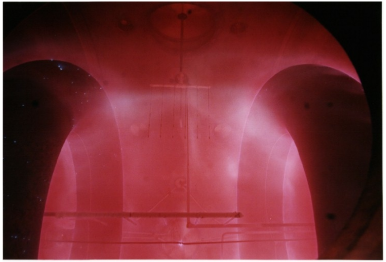
- Give very localized measurements.
- Variety of probe types for different measurements.

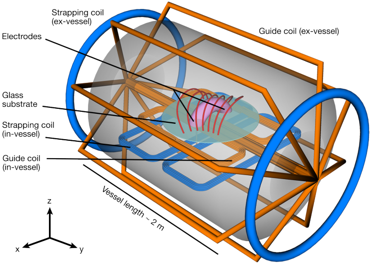
Limitations

- Only available to low temperature plasmas. (Several eV at most)
- Can easily perturb the plasma.
- Results complicated to decipher.

Example plasma: Magnetic Reconnection Experiment (MRX)







Experimental Parameters	
Electron density	$\sim 1 \times 10^{14}\,\mathrm{cm}^{-3}$
Electron Temperature	$5 - 10\,\mathrm{eV}$
Ion Temperature	$\sim 5\,\mathrm{eV}$
Magnetic Field	$\sim 200\,\mathrm{G}$
Pulse Length	$\sim 200\,\mu\mathrm{s}$
Plasma Size	$R \sim 40\,\mathrm{cm},\, a \sim 15\,\mathrm{cm}$

Example plasma: Tokamak scrape off layer

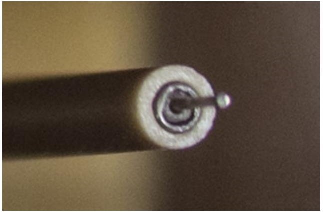
NSXT-U

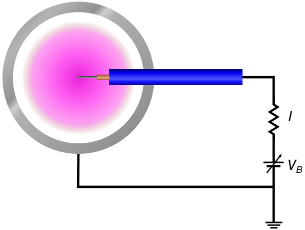
Experimental Parameters	
Electron density	$\sim 1 \times 10^{13}\,\mathrm{cm}^{-3}$
Electron Temperature	$10 - 50\,\mathrm{eV}$
Ion Temperature	$\sim 100\,\mathrm{eV}$
Magnetic Field	$\sim 2\,\mathrm{T}$
Pulse Length	$\sim 5\,\mathrm{s}$
Plasma Size	$R \sim 1.7\,\mathrm{m}, a \sim 0.7\,\mathrm{m}$

Outline

Langmuir Probes

- Simplest plasma diagnostic.
  - Just a biased wire in a plasma.
  - Measures: T_e, n_e, and V_{P}.
  - Everything is a Langmuir probe!
- Vary the bias (V_{B}) and measure the current to make an “I-V trace."
- A particle is captured by the probe if:
  - It is incident on the probe.
  - It has enough energy to overcome the potential difference.





Active + Fields → Particles

Electron current to a Langmuir probe

- An electron is captured if it has enough energy to overcome the bias.

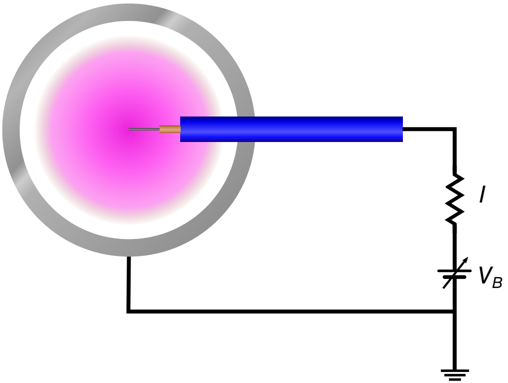
The electron current that is collected by a planar probe is given by

$$J_{e,z} = e\int_{v_{\min}}^{\infty} v_z f(\boldsymbol{v}) d^3 v$$

where

$$\frac{1}{2} m v_{\min}^2 = e(V_{\mathrm{P}} - V_{\mathrm{B}})$$

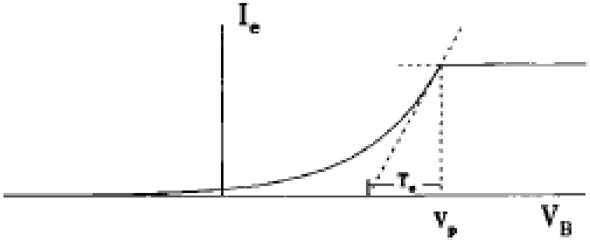
is the minimum velocity needed to reach the probe.



Electron current in a Maxwellian plasma

$$I_e(V_B) = \begin{cases} I_{e,\text{sat}} & V_B > V_P \\ I_{e,\text{sat}} e^{\frac{-e(V_P - V_B)}{T_e}} & V_B < V_P \end{cases}$$

$$I_{e,\text{sat}} = Ane\langle v \rangle = Ane\sqrt{\frac{T_e}{2\pi m_e}}$$

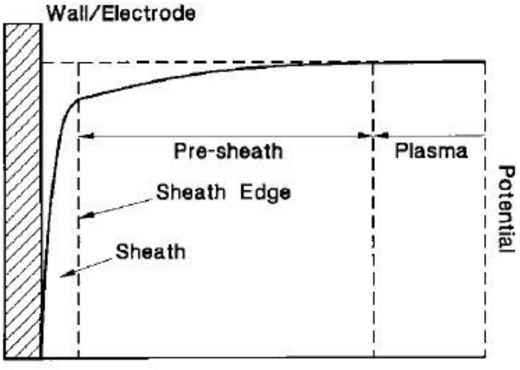


N. Hershkowitz,*How Langmuir Probes Work* (Academic, New York, 1989), pp. 113–183.

- When $V_B = V_P$, electrons are collected as if the probe isn't there.
- Flat portion only for truly ideal probe.
- Usually I_e will continue to increase with increased V_B.

Sheath formation

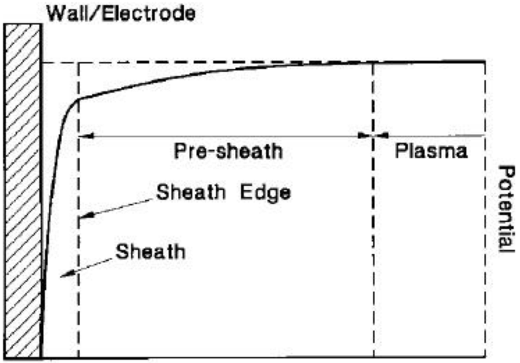
- The sheath is the region around the probe where the space potential changes from V_{B} to V_{P}.
    - Quasi-neutrality breaks down.
- Sheath size is limited to several $\lambda_{\mathrm{D}e}$.
- Potential in the sheath must be concave down $\implies n_i > n_e$.
- Electrons able to overcome V drop are collected.



Ion Contribution

- Tempting to handle ions exactly the same as electrons.
- Only valid if $T_e = T_i$.
- Often not the case for low temperature plasmas.

If $T_i << T_e$ the ion current must be handled differently than for the electrons leading to the “pre-sheath."



Particle densities in the sheath region

Assume Boltzmann electrons, and ion conservation

$$n_e(V) = n_0 e^{\frac{e(V-V_P)}{T_e}}, \quad n_i v_i(V) = n_s v_s = \text{Const.}$$

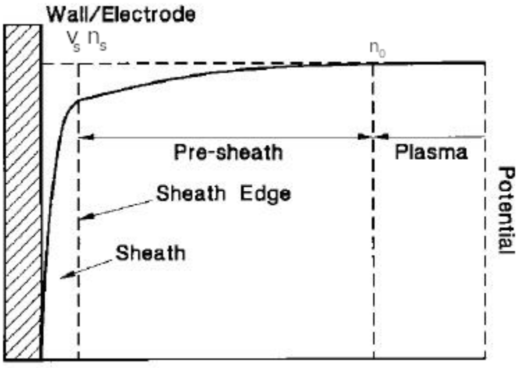
Energy conservation for ions,

$$\frac{1}{2} m_i \left[v_i(V)\right]^2 + q_i V = \text{Const.}$$

Yields

$$n_i(V) = \frac{n_s}{\sqrt{1 + \frac{2q_i(V_s - V)}{T_e}\left(\frac{c_s}{v_s}\right)^2}}$$

with $c_s^2 \equiv T_e/m_i$



Ion Contribution for $T_i << T_e$

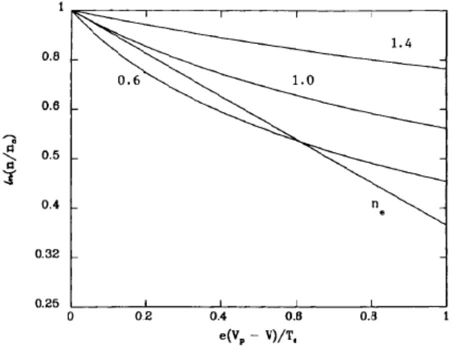
$$n_i(V) = \frac{n_s}{\sqrt{1 + \frac{2q_i(V_s - V)}{T_e}\left(\frac{c_s}{v_s}\right)^2}}$$

$n_i > n_e$ requires $v_s > \sqrt{\frac{T_e}{m_i}} \equiv c_s$ and that the sheath edge is $\sim \frac{1}{2}T_e$ below V_P making,

$$I_{i,\text{sat}} = Aen_s v_s = \exp\left(-\frac{1}{2}\right)Ane\sqrt{\frac{T_e}{m_i}} \approx 0.6Ane\sqrt{\frac{T_e}{m_i}}$$

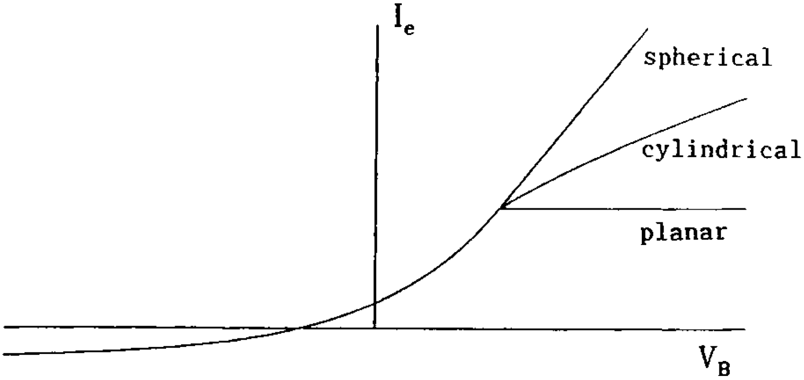
- At very negative biases, this current is very flat making it a reliable measure of n_e.
- $I_{i,\text{sat}}$ is collected by the probe for all biases below V_P.

$n_i(V)$ & $n_e(V)$ for values of v_s/c_s



N. Hershkowitz, *How Langmuir Probes Work* (Academic, New York, 1989), pp. 113–183.

Total I-V trace



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Floating potential

V_f: The bias where no net current is measured, i.e. electron and ion currents balance.

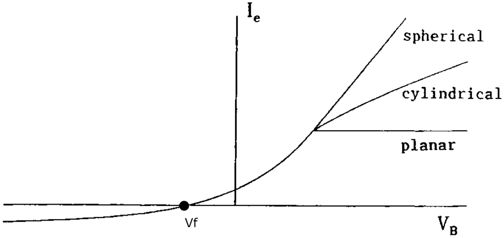
$$I_i = I_e$$

$$0.6Ane\sqrt{\frac{T_e}{m_i}} = I_{e,\mathrm{sat}}\mathrm{e}^{-e(V_\mathrm{P}-V_\mathrm{f})/T_e}$$

Then,

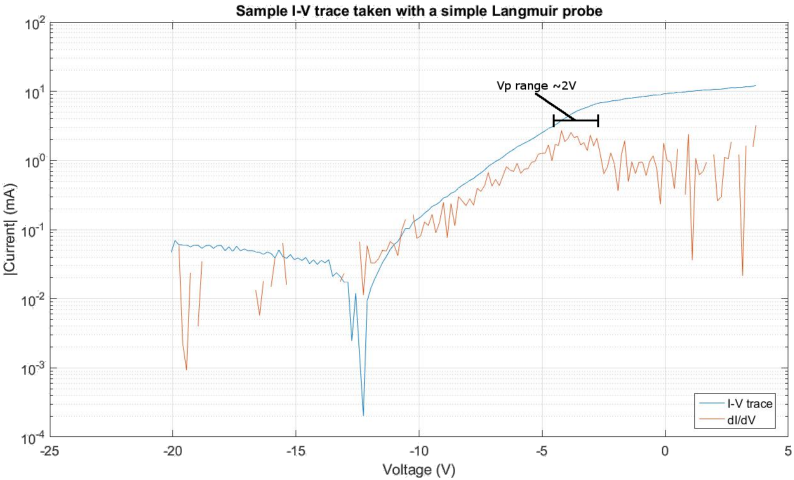
$$V_\mathrm{P} - V_\mathrm{f} = \frac{T_e}{e}\ln\left(\frac{1}{0.6\sqrt{2\pi}}\sqrt{\frac{m_i}{m_e}}\right)$$

$$= \frac{T_e}{e}\ln\left(\frac{I_{e,\mathrm{sat}}}{I_{i,\mathrm{sat}}}\right) = 5.24\frac{T_e}{e} \quad \text{for Xe}$$



V_f is very easy to measure and can give a reasonable estimate for V_P.

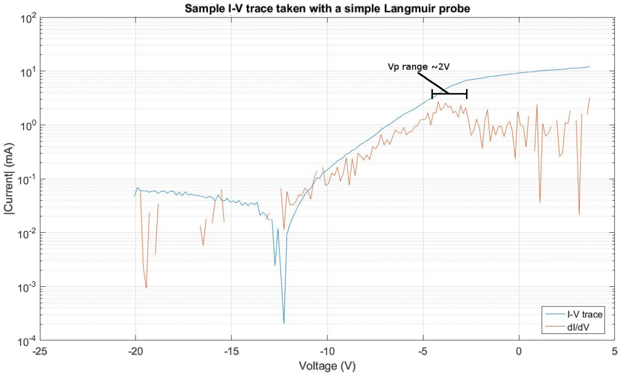
A More Realistic Example



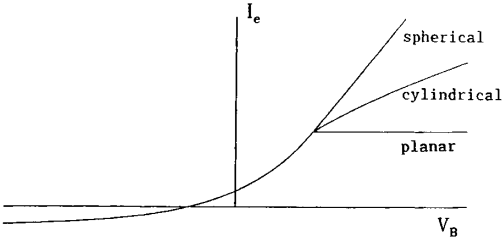
Langmuir probe data from a xenon plasma with $B = 20$ G, $V_B = -55$ V, and $I = 1.21$ A.

Measurements from Langmuir probes

- Electron temperature, T_e
  - Measured from sweeping the bias and the slope of $\ln(I(V))$.
- Electron density, n_e
  - Bias probe very negative, $(V_\mathrm{P} - V_\mathrm{B})/(eT_e) \gg 1$, and measure $I_{i,\mathrm{sat}}$.
  - Requires knowledge of T_e, but not very sensitive to actual value.
- Plasma potential, V_P
  - Located at the "kink" in the I-V trace.
  - Roughly estimated by V_f with knowledge of T_e.



Non-ideal effects: Sheath expansion



- The sheath is several λ_{De} long in order to shield the plasma from V_B.
- As the bias is increased, the sheath size increases $\implies$ effective area increases.
- If the probe size is much larger than the sheath, this can be greatly mitigated, at least for $I_{i,\mathrm{sat}}$.
- When the sheath is larger than the probe, can get orbit limited effects where particles enter the sheath but miss the probe.

Non-ideal effects: Field-line draining

- Drawing the full $I_{e,\text{sat}}$ can be very disruptive to a plasma.
- In magnetized plasmas, drawing too much current from a field line can “drain" the density faster than it can be replenished.
- $I_{e,\text{sat}}$ is rarely used as a diagnostic tool but can be useful for cleaning probes.

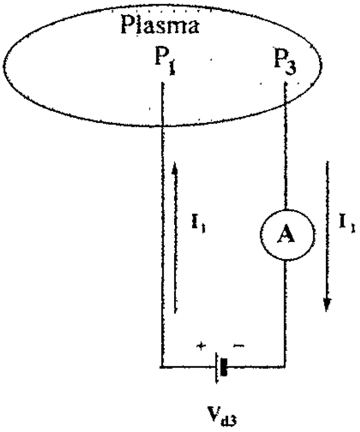
Outline

Double Langmuir probe setup

Issue: Biasing a probe relative to ground can be problematic if V_P varies rapidly in time.
Solution: What if we bias relative to the plasma?

- Two identical Langmuir probes are placed in the plasma and float relative to ground.
- A bias voltage, V_B, is applied between them.
- The resulting current flowing between them is measured.
- The total current is limited to $I_{i,\mathrm{sat}}$.
- Can measure T_e and n_e. Less useful for V_P.

$$I(V_\mathrm{B}) = I_{i,\mathrm{sat}} \tanh\left(\frac{eV_\mathrm{B}}{T_e}\right)$$



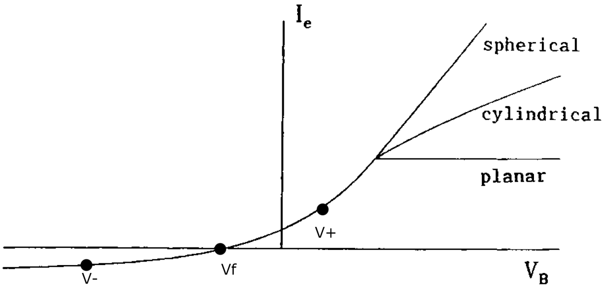
H.Ji, et. al Rev. Sci. Instrum. **62**, 2326–2337 (1991)

Triple Langmuir probe setup

Issue: Sweeping the bias voltage of a probe limits your time resolution.
Solution: What if we could simultaneously measure enough points of the I-V curve to get the info we want?

It turns out that we only need 3

- One tip is a simple floating probe.
- The other two are in a double probe configuration with a fixed bias.



Triple Langmuir probe analysis

The currents

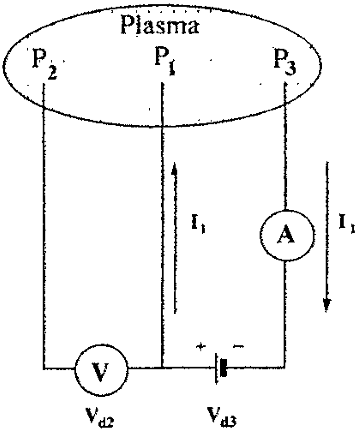
$$I_+ = -I_{e,\text{sat}} e^{-e(V_P - V_+)/T_e} + I_{i,\text{sat}}$$
$$I_- = -I_{e,\text{sat}} e^{-e(V_P - V_-)/T_e} + I_{i,\text{sat}} = -I_+$$
$$I_f = -I_{e,\text{sat}} e^{-e(V_P - V_f)/T_e} + I_{i,\text{sat}} = 0$$

Combining them,

$$1/2 = (I_+ - I_f)/(I_+ - I_-)$$
$$1/2 = \left(1 - e^{-e(V_+ - V_f)/T_e}\right) / \left(1 - e^{-e(V_+ - V_-)/T_e}\right)$$

If $V_B \gg T_e/e$,

$$e(V_+ - V_f) \approx T_e \ln 2$$



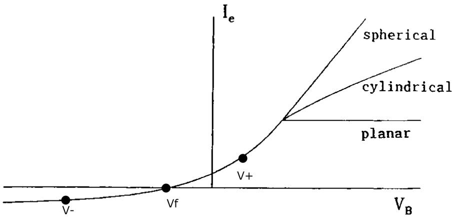
H.Ji, et. al Rev. Sci. Instrum. **62**, 2326–2337 (1991)

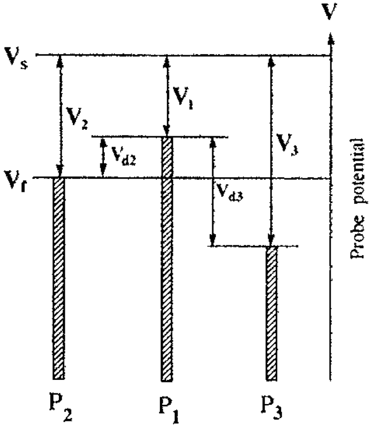
Triple probe usage

$$e(V_+ - V_\mathrm{f}) \approx T_e \ln 2$$

$$I_- \approx I_{i,\mathrm{sat}} = 0.6Ane\sqrt{\frac{T_e}{m_i}}$$

- Only need to measure 2 voltages and 1 current.
- Fast measurement of both T_e and n_e.

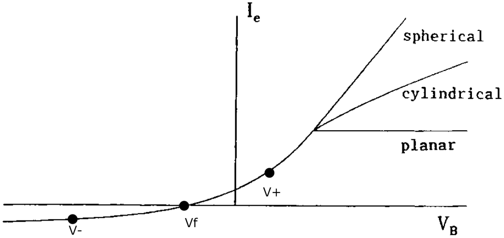




H.Ji, et. al Rev. Sci. Instrum. **62**, 2326–2337 (1991)

Double and triple probe limitations

- Cannot measure an arbitrary $f(v)$, Rely on the assumption of a Maxwellian.
- Need low spatial variation of plasma.
  - Plasma must be identical at each tip.
  - Spatial variation is solved by placing the tips very close together.
  - If they are placed too close, they will perturb each other's plasma or even arc if sheaths overlap.
- More complex and perturbative than a single Langmuir probe.



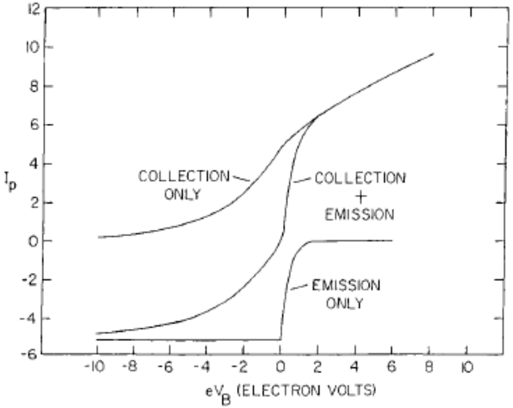
Outline

Motivation for Emissive Probes

Issue: V_P measurements are very challenging.

$$V_P - V_f = \frac{T_e}{e} \ln\left(\frac{I_{e,\text{sat}}}{I_{i,\text{sat}}}\right)$$

- What if we could make $I_{i,\text{sat}} \sim I_{e,\text{sat}}$?
- Then $V_f = V_P$.
- A probe emitting an electron is equivalent to collecting an ion.
- Can effectively make $I_{i,\text{sat}}$ larger.
- A hot filament can be used to emit electrons into the plasma.

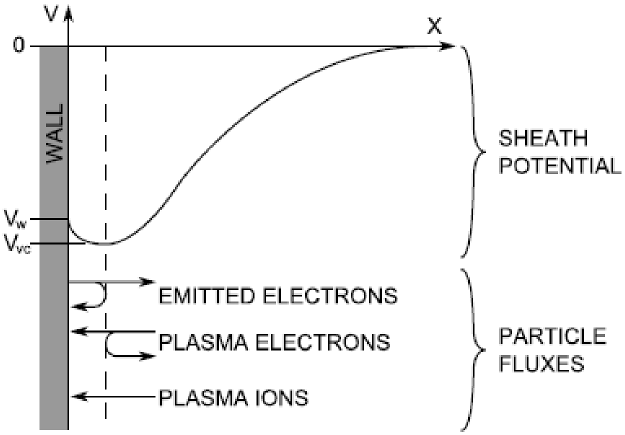


N. Hershkowitz, *How Langmuir Probes Work* (Academic, New York, 1989), pp. 113–183.

Space Charge Issues

- As the emission current grows, the sheath is affected.
- Emitted electrons mean that less incoming ones need to be stopped.
- After a critical emission level, V_{f} stops rising and a virtual cathode appears.

For a highly emitting probe:
$V_{\mathrm{f}} \approx V_{\mathrm{P}} - T_e/e$



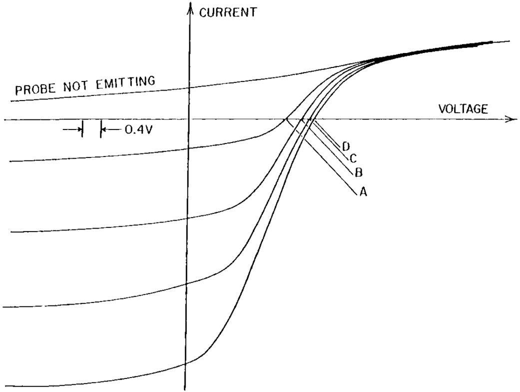
J. P. Sheehan and N. Hershkowitz, Plasma Sources Sci. Technol. **20**,063001 (2011).

Emissive Probe Issues

$$V_f \approx V_P - T_e/e$$

- Floating potential still coupled to the electron temperature.
- Filament lifetime very limited.
- Extra circuitry needed to heat a filament.
- Strong limit on plasma density since need $I_{\text{emit}} \sim I_{e,\text{sat}}$.

Emissive probe I-V traces at different emission temperatures



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Bdot probe operation

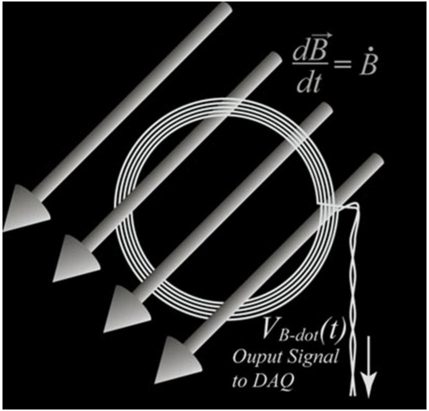
Bdot probe: (AKA Mirnov coil) used to measure the magnetic field in a low temperature plasma.

Work via Faraday's Law

$$V_{\text{coil}} = -NA\frac{\mathrm{d}B_{\perp}}{\mathrm{d}t}$$

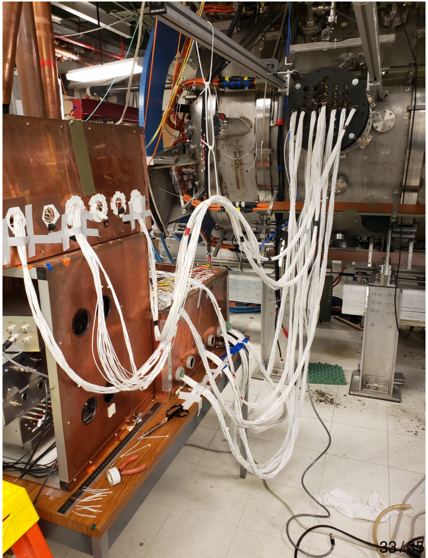
- Signal can be passed through a passive integrator to get $B_{\perp}(t)$.
- Using a triplet of probes get 3-D measurement at one point.
- Need to be shielded from the plasma.

Passive + Fields

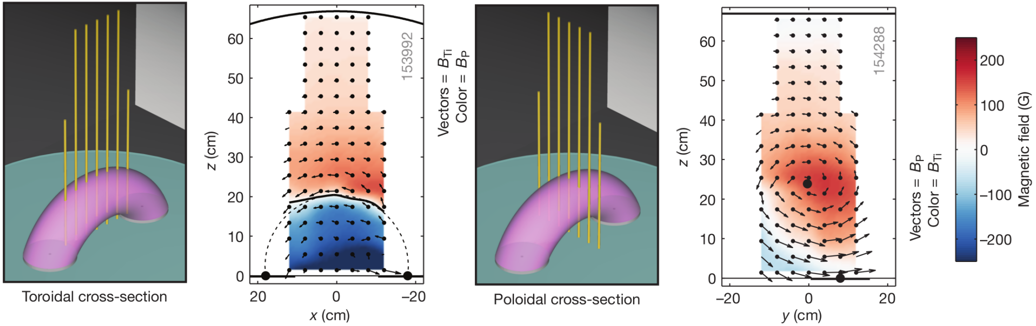


Bdot probes in MRX

C. Myers, *Laboratory study of the equilibrium and eruption of line-tied magnetic flux ropes in the solar corona*, Ph. D. Thesis (2015).



Example Bdot data from MRX



Myers *et al.*, Nature **528**, 526 (2015)

Questions?

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A good reference:

N. Hershkowitz, *How Langmuir Probes Work* (Academic, New York, 1989), pp. 113–183.