Probes for direct determination of the plasma potential


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Why is it important to measure $\Phi_{pl}$ and how can we do it?
Can we make $V_{fl}$ equal to $\Phi_{pl}$?
Plasma potential measurements with cold probes.
Conventional emissive probes.
Laser-heated emissive probes.
The ball-pen probe.
Plug probe and baffled probe.
A few results.
Conclusion
Why is it important to measure the plasma potential $\Phi_{pl}(x,t)$, and thereby the electric field $E(x,t)$?

- The plasma potential controls the general particle transport in a plasma.
- Electric field fluctuations control the radial loss of plasma particles across the magnetic field and are therefore essential for the confinement of the plasma.
- Theories and numerical simulations of the edge region deliver the electric field or the plasma potential as most important parameter.
- Therefore it would be essential to measure $\Phi_{pl}$ and its fluctuations as fast as possible and with a sufficient spatial resolution on as many positions as possible simultaneously.
How can the plasma potential be measured?

- In contrast to the measurement of other plasma parameters the determination of the plasma potential $\Phi_{pl}$ is more difficult.
- $\Phi_{pl}$ can be measured by electron or ion beams, however, these methods are not only intricate but also expensive and do not have a good temporal or spatial resolution.
- The simplest, least expensive and most straightforward method with good temporal and spatial resolution is the plasma probe.
- However, although in principle we can derive $\Phi_{pl}$ from the current-voltage characteristic of a cold probe through the maximum of the first derivative, this process either takes time and/or is also not free of errors in a non-Maxwellian plasma.
I-V characteristics of various probes in a magnetized plasma which in principle allow a direct determination of $\Phi_{pl}$

For simplicity, $\Phi_{pl}$ is assumed to be zero.

Why is the floating potential of a cold probe not simply the plasma potential?
This is due to the strong imbalance of the masses of the negative and the positive charge carriers in a conventional plasma. Therefore electrons have a much higher mobility, which leads to a negative charging of all floating electrodes in touch with a plasma.
What can we do to make the floating potential of a probe identical with the plasma potential?

In principle there are two possibilities:

• Either we compensate the plasma electron saturation current by an equally strong current on the negative side of the characteristic; this is the principle of the emissive probe.
• Or we reduce the plasma electron saturation current, until its magnitude becomes equal to that one of the ion saturation current; this is the principle of the ball-pen, plug and baffled probe.
Plasma potential measurements with cold probes

The simplest way – from ideal probe theory:

\[
\Phi_{pl} = V_{fl} + T_e \ln \left( \frac{I_{es}}{I_{ls}} \right) = V_{fl} + \Delta T_e
\]

So we have to know the electron temperature.

**But:**

The electron temperature can fluctuate during the measurement and there can be temperature gradients in the region of investigation (which is always the case in the edge region of a hot magnetized plasma).

**In addition:**

A cold probe will deliver erroneous results for the plasma potential whenever there is a stronger deviation of the electron velocity distribution function from a Maxwellian, for instance when there is an electron drift or an electron beam or runaway electrons.
Basic equation for floating potential of a cold probe in a Maxwellian plasma

Total current of the probe:

\[ I_p(V_p) = I_i(V_p) - I_e(V_p) \]  \hspace{1cm} (1)

Electron and ion currents for \( V_p \leq \Phi_{pl} \):

\[ I_e = I_{es} \exp \left( \frac{V_p - \Phi_{pl}}{T_e} \right) \]

\[ I_i = I_{is} \]  \hspace{1cm} (2)

Floating potential

\[ I_p = 0 \Rightarrow V_p = V_{fl} \]

from which we get the equation mentioned above:

\[ \Phi_{pl} = V_{fl} + T_e \ln \left( \frac{I_{es}}{I_{is}} \right) = V_{fl} + \Delta T_e \]  \hspace{1cm} (3)
In this case equations (3) becomes:

$$\Phi_{pl} = V_{fl,em} + T_e \ln \left( \frac{I_{es}}{I_{is} + I_{em}} \right) = V_{fl,em} + \Delta_{em} T_e$$

(4)

Normalized difference $\Delta_{em}$ between plasma potential and floating potential with and without electron emission:

$$\Delta_{em} = \frac{\Phi_{pl} - V_{fl,em}}{T_e} = \ln \left( \frac{I_{es}}{I_{is} + I_{em}} \right)$$

(5)

For a magnetized hydrogen plasma $\Delta = 2.5$
Difference between unheated and heated floating probe potential

(a) versus emission current, normalized to electron saturation current

(b) versus temperature of the probe wire, assuming tungsten as wire material

\[ n_e = 10^{17} \text{ m}^{-3}, \quad T_e = 10 \text{ eV}, \]
hydrogen plasma
Emissive probe construction of the IEPPG
(Innsbruck Experimental Plasma Physics Group)

The probe holder is a ceramic tube (Al$_2$O$_3$) of oval cross section (1.4/2.3 mm outer diameters) and a length of 8 cm. The tube has two bores of 0.7 mm diameter each.

Inside the bores the tungsten wire is spliced with thin copper threads to increase the conductivity. This guarantees that only the probe loop is glowing when a current is passed through.
A typical small tokamak for fusion experiments as e.g. ISTTOK (Instituto Superior Técnico Tokamak), Lisbon or CASTOR (Czech Academy of Science Torus, Prague)

Major radius $R \approx 0.40 \text{ m}$, minor radius $r \approx 80 \text{ mm}$, magnetic field $B = 0.5 - 1 \text{ T}$, toroidal current $I_t \approx 10 \text{ kA}$, hydrogen plasma

Typical core plasma electron density and electron temperature:

$n_e \approx 10^{19} \text{ m}^{-3}$
$T_e \approx 180 \text{ eV}$

Typical edge plasma electron density and electron temperature:

$n_e \approx 10^{18} \text{ m}^{-3}$
$T_e \approx 10 \text{ eV}$
Typical probe characteristics from the CASTOR tokamak, Prague, Czech Republic

Current-voltage characteristic with increasing wire heating

Floating potential with increasing wire heating

We observe that $V_f$ becomes more positive for increasing probe heating, and it approaches the true value of $\Phi_f$.

Saturation occurs here for $\Delta_w - \Delta = 1.35$ instead of 2.5 according to the simplest theory.
The VINETA Experiment, IPP Greifswald

Magnetic field $B$ [mT] \hspace{1cm} 100
Plasma density [$10^{19}$ m$^{-3}$] \hspace{1cm} \leq 2
Electron temperature $T_e$ [eV] \hspace{1cm} 3
Ion temperature $T_i$ [eV] \hspace{1cm} 0.2
A cylindrical piece of LaB$_6$ or graphite irradiated from above by infrared light of 808 nm from a diode laser (JenLas HDL50F from JenOptik, Jena, Germany) with up to 50 W.

A laser-heated probe has several advantages as compared to a conventional emissive wire probe:

- Graphite or LaB$_6$ are heatable to much higher temperatures, therefore **higher electron emission and longer lifetime**.
- No current flows through the probe, therefore **no danger of deformation in a magnetic field**.
- Lower capacity of the probe system, therefore **better time response**.
- Surface of the **probe is an equipotential area**.
Laser-heated probe in the VINETA machine II

VINETA vacuum vessel
Plasma column
Lens head
Glass fibre cable
Electric connection
Graphite probe pins
Ceramic tubes
Recent results of the laser-heated probe in the VINETA plasma

Current-voltage characteristic with increasing laser heating

Floating potential with increasing laser heating

$p = 0.23 \text{ Pa, Ar, helicon discharge}$

$r = 0 \text{ mm} = \text{center of the plasma column}$

$\Phi_{pl,\text{em}} = 11.4 \text{ V}$

$\Phi_{pl,\text{cold}} = 13.7 \text{ V},$ determined from the 1st derivative of the cold probe characteristic
The ball-pen probe

\[ \Phi_{pl} = V_{fl} + T_e \ln \left( \frac{j_{es} A_c(h)}{j_{is} A(h)} \right) \]

This equation states that the potential \( \Phi_{pl} \) at the plasma spray is equal to the potential \( V_{fl} \) plus the electron temperature \( T_e \) times the natural logarithm of the ratio of the electron density current \( j_{es} \) over the ion density current \( j_{is} \), multiplied by the cross-sectional area ratio \( A_c(h)/A(h) \). The equation concludes that the potential at the plasma spray is equal to the potential at the collector, as indicated by the arrow in the diagram:

\[ \Rightarrow V_{fl} = \Phi_{pl} \]
Some measurements with the ball-pen probe in CASTOR

I-V characteristics for various collector positions; $h$ is negative when the collector is inside the shielding tube;

Floating potential (blue squares) and $\ln(I_{es}/I_{is})$ (black dots) with respect to $h$. The radial position of the probe head is at $r = 75$ mm inside the edge region of CASTOR.
XOOPIC simulations of the \( IV \)-characteristic of the ball-pen probe

With the depth \( h \) of the collector as parameter

Ball-pen I-V characteristics - PIC simulations

- \( h = 0.3 \text{ mm} \)
- \( h = 0.2 \text{ mm} \)
- \( h = 0.1 \text{ mm} \)
- \( h = 0.05 \text{ mm} \)
- \( h = 0.03 \text{ mm} \)
- \( h = 0 \text{ mm} \)

- \( R=1.0; V_i=?? \text{ V}; T_e=?? \text{ eV} \)
- \( R=1.7; V_i=-37 \text{ V}; T_e=17 \text{ eV} \)
- \( R=3.8; V_i=-45 \text{ V}; T_e=20 \text{ eV} \)
- \( R=8.1; V_i=-53 \text{ V}; T_e=20 \text{ eV} \)
- \( R=9.8; V_i=-56 \text{ V}; T_e=23 \text{ eV} \)
Other probes based on this principle

1) The baffled probe:*}

FIG. 1. Sketch of the baffled probe. (1) Tungsten wire tip; (2) ceramic baffles; (3) ceramic tube.

FIG. 3. Probe current to the open (upper curve) and closed (lower curve) baffled probe. Dots correspond to floating potentials. For potentials less than \(-5.5\) V both curves practically coincide. \(B = 0.3\) T.

Other probes based on this principle

2) The plug probe:*)

![Diagram of plug probe system](image)

**FIG. 1.** Sketch of the plug probe system for $E$ field measurements.

![Graph of current vs. probe voltage](image)

**FIG. 3.** Typical plug probe characteristics (dots). Calculated characteristics (full line). The plasma conditions are the following: helium pressure $p = 0.35$ Pa, $B = 0.154$ T, $n = 2 \times 10^{17}$ $m^{-3}$, $T_e = 2.45$ eV, and $T_i = 0.22$ eV. The probe sizes are $R = 0.125$ mm and $L = 18$ mm.

By the way: Emissive probes were even used on space crafts!

Conclusion

• We have discussed various plasma probes, by which a direct determination of the plasma potential is possible.
• These probes are constructed in such a way that their floating potential yields an acceptable measure of the plasma potential.
• Therefore also the temporal and spatial resolution for the determination of $\Phi_{pl}$ with these probes is relatively good; the latter in particular of the laser-heated emissive probe.
• A certain perturbation of the plasma by such a probe can unfortunately not be avoided.
• There is still an open question concerning the formation of a space charge around the probe even in the floating case.
Thank you very much for your attention!

Hechenberg as seen from our office