

Characterizing and Optimizing Polaris Plasma

Report reasearch internship at the Swiss Plasma Center

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Contents

1	Introduction	2
2	Physical background	2
2.1	Fusion	2
2.2	Plasma	2
2.3	Polaris: Our Stellarator	3
3	Global plasma characterization	3
3.1	Method and physical background of probes	3
3.2	Measurement setup	3
3.3	Results and discussion	4
4	Exploring reproducibility	5
4.1	Procedure and results	6
4.2	Discussion and Conclusion	7
5	Plasma generation optimization	8
5.1	Reduce plasma blob around antenna with teflon tube	8
5.2	Isolate antenna foot with less risk of coating	8
5.3	Impact of glass and metal window on plasma density	9
6	Estimation of power coupling efficiency	9
6.1	Physical background	9
6.2	Construction process and calibration	11
6.3	Why it did not work	12
7	Visualization of magnetic field lines	13
7.1	Method	13
7.2	Results	13
8	Acknowledgments	14

1 Introduction

In my 8 weeks summer internship I worked in the Swiss Plasma Center, a domain that is driven by the goal of one day make fusion as an energy supply possible. Nuclear fusion is the process that powers the sun: light atomic nuclei combine, releasing enormous amounts of energy. If this process can be harnessed and controlled on Earth, it could provide a nearly limitless source of electricity with very little greenhouse gas emissions. However, fusion can only occur at extremely high temperatures, where the electrons start leaving their atoms: this state of matter, sometimes called "the fourth state of matter", is plasma. The temperatures are so high, that the plasma must be carefully contained without touching any physical walls, since every material would melt immediately. This is done using strong magnetic fields, an approach known as magnetic confinement. The heating of the plasma, cooling of the machinery and magnetic confinement, require a lot of energy [1]. Although significant progress has been made in achieving fusion energy gain, a fusion power plant capable of producing net electricity has yet to be demonstrated.

In the laboratory of low-temperature plasmas I worked with Polaris, a newly built small scale stellarator[2]. This is a device that confines the plasma in an untypical way. My task was to explore and characterize the plasma by doing radial profiles of its density in different conditions and to optimize the plasma generation.

2 Physical background

2.1 Fusion

The aim of plasma research is to generate energy efficiently from the fusion process. Fusion is the phenomenon that occurs when two light ions collide at a sufficiently high speed and fuse together. As the atomic nuclei thereby enter a more stable state, energy is released. In most fusion reactors, the plan is to use deuterium and tritium ions, which combine to form a helium atom, a neutron and energy [3]. Deuterium is an isotope of hydrogen that occurs in water in small but measurable concentrations.

As water is available worldwide, its extraction is not dependent on geographical location. Tritium is also an isotope of hydrogen, but due to its radioactivity (half-life of around 12.3 years), it occurs almost never naturally on Earth. It must therefore be bred within fusion reactors themselves: the fast neutrons produced during the fusion reaction strike a lithium-containing breeding blanket surrounding the reactor core. This process produces new tritium, which can be fed back into the reactor as fuel [4].

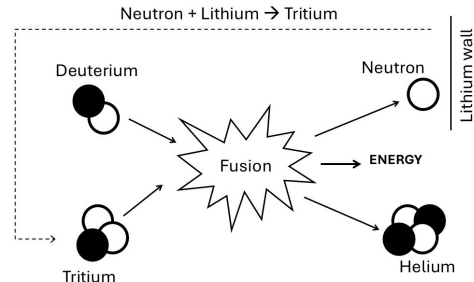


Figure 1: Fusion reaction.

2.2 Plasma

For two ions to fuse, they must be traveling at a very high speed in order to overcome the electrical repulsive force between them. The temperature needs to be so high that the matter transitions into the fourth state of matter: plasma. In plasma, electrons are separated from their atomic nuclei, resulting in an ionized gas. As plasma consists of electrically charged particles, it can be confined by electromagnetic forces. Depending on the magnetic field, the plasma moves in a specific shape following the magnetic field lines [5]. There are many different heating mechanisms for creating plasma. In Polaris a RF antenna with a single turn coil is used. An alternating current flows at radio frequency through the coil, creating a magnetic field that changes in time, and according to Faraday's law, a changing magnetic field induces an electric

field. This electric field accelerates the free electrons in the gas, and when they collide with gas atoms, they knock out further electrons, which ionizes the gas and sustains the plasma.

2.3 Polaris: Our Stellarator

Polaris is a newly built small-scale stellarator. A stellarator is a device in which the plasma is shaped by the coils that generate the magnetic field. In contrast to conventional, well-researched tokamaks, where the plasma takes the form of a doughnut, the plasma in stellarators has a complex shape resembling a twisted doughnut. Their three-dimensional magnetic geometry introduces substantial design and optimization challenges. However, they appear to offer promising advantages over tokamaks as they don't require a large plasma current for confinement, which offers the potential for steady-state operation [6]. The aim of Polaris is to draw more attention to this type of plasma confinement and to explore the plasma within a stellarator. [2]

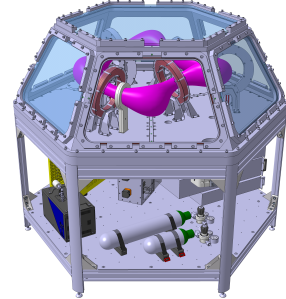


Figure 2: Model of Polaris [2].

3 Global plasma characterization

The aim of this series of measurements is to investigate how the radial profile of the plasma density and of the floating potential V_{float} changes in response to magnetic fields of varying strength and different RF antenna power levels.

3.1 Method and physical background of probes

Langmuir probes were used to measure the density. These usually consist of two electrodes placed within the plasma, a bias sweep is applied relative to the earth, and the response current collected at the tip surface is measured. Knowing the current as a function of the voltage allows one to compute the electron temperature and the density. [7, chap. 2.1.1] Here, a simplified version of this probe was used, which requires only a single electrode. We make use of the fact that, when the polarization is sufficiently low, the current tends towards a minimum value, known as I_{sat} . If the electrode is polarized very deeply, to -60 V, the measured current corresponds to I_{sat} . The density can be calculated using the following formula:

$$|I_{sat}| = e\alpha_0 n u_B A_{sh}.$$

Where n is the density in particles per m^3 , e is the charge of an electron, $a_0 = 0.61$ is a constant [7, chap. 2.1.1], $u_B = \sqrt{k_B T_e / m_i}$, where k_B is the Boltzmann constant and m_i is the ion mass. With this simplified form of the Langmuir probe, no information is obtained regarding the temperature. It has been set at $T_e = 3eV$. A_{sh} is the area of the electrode which is exposed to the plasma, here this corresponds to 10.55 mm^2 . The other tip of the Langmuir probe was used to measure the floating potential V_{float} . The floating potential is the voltage that an object left alone in a plasma settles at: the light, fast electrons hit it more often than the heavy ions, so it charges up negatively until it repels enough electrons that equal amounts of positive and negative charge arrive and no net current flows.[9]

3.2 Measurement setup

The measurements were taken using a two-tip Langmuir probe. However, one tip was used to measure V_{float} and the other to measure I_{sat} , as described before. For measuring I_{sat} a -60 V

source and a $50\ \Omega$ resistance were used. The voltage over this resistance and V_{float} were directed to an oscilloscope.

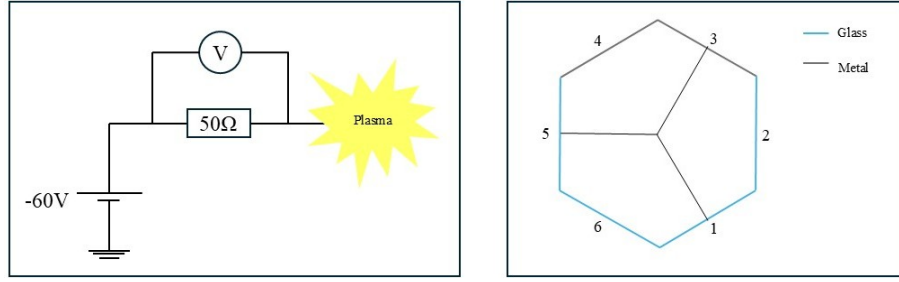


Figure 3: Left: electrical scheme for measuring I_{sat} , right: position of glass and metal windows.

3.3 Results and discussion

In Figure 4 I_{sat} is represented accordingly to the coil current and the radio-frequency (RF) antenna. The graph shows that, the higher the antenna power and the stronger the magnetic field, the greater the plasma density. Within a given magnetic field strength, the overall shape of the curve hardly changes. It is also noticeable that the stronger the magnetic field, the higher the density near the main axis and the lower it is on the edges, the plasma therefore appears to be more concentrated in the center. With 50 A, the radial profile does not correspond to the typical profile with a bulge in the middle.

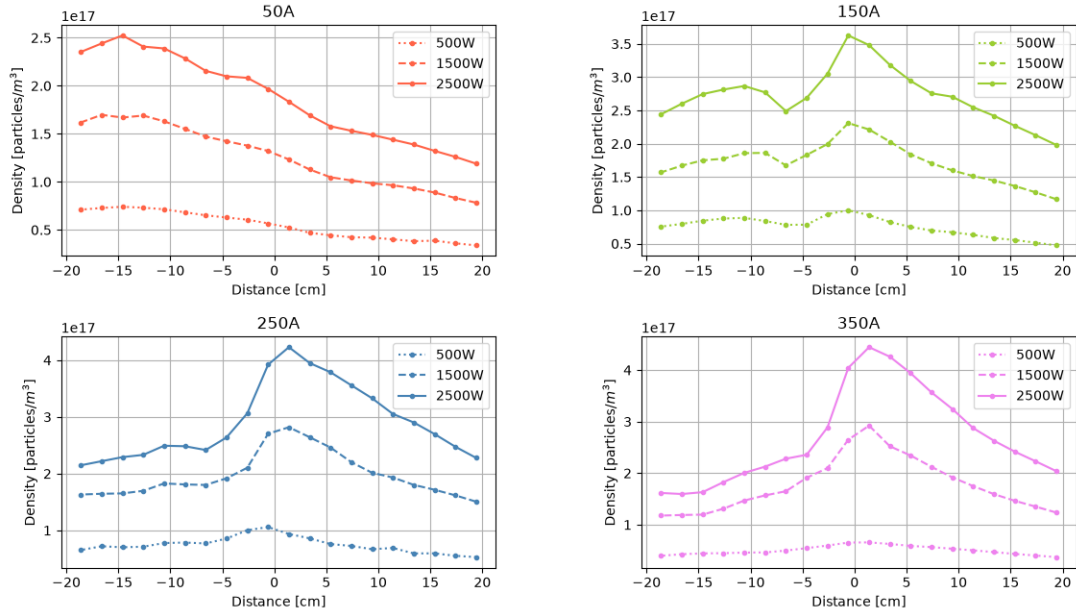


Figure 4: I_{sat} according to four different magnetic field strength with different RF antenna powers.

Figure 5 shows the floating potential with different coil currents and antenna powers. Similarly as with the density, V_{float} also increases as the antennas power and the magnetic field strength increase. However, the shapes of the curves appear more arbitrary and do not seem to correlate directly with the strength of the magnetic field. Also here, no typical radial profile is yet discernible with 50 A.

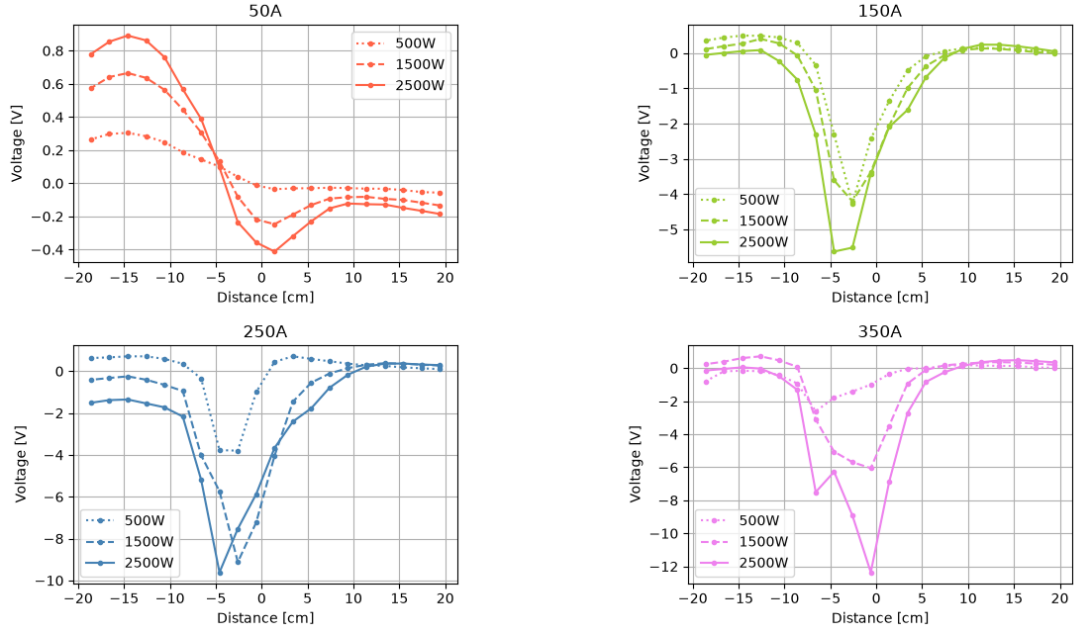


Figure 5: V_{float} according to four different magnetic field strength with different RF antenna powers.

The graph on Figure 8 shows that the plasma density is linear with respect to the power of the RF antenna.

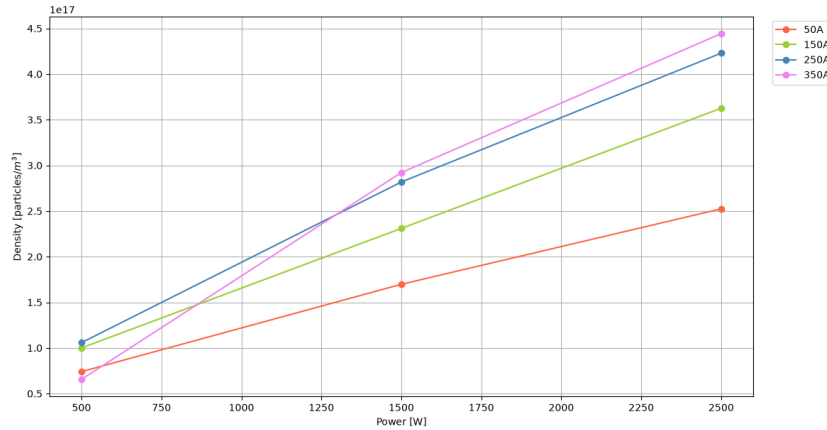


Figure 6: Maximum of the density over the radial profile according to the power of the RF antenna.

4 Exploring reproducibility

Sometimes the vacuum has to be broken and Polaris opened, for example to replace probes or clean the windows. The vacuum then has to be re-established and it takes several hours for the pressure to stabilize. The aim of this series of measurements was to determine how much time it takes, after switching on the pumps, until the plasma is stable and reproducible measurements can be taken. To this end, radial density and V_{float} profiles were taken at regular time intervals over a period of up to 30 hours. There were three different experiments: a radial profile every 30 minutes, a radial profile every 2 hours, three radial profiles with several hours in between. This

allows to compare the saturation time and how the presence of plasma influences the pressure drop.

4.1 Procedure and results

Radial profiles of I_{sat} and V_{float} were obtained using Langmuir probe with the same setup as in Chapter 3. Argon was used, with 150 A in the coils and 2500 W in the RF antenna. The turbomolecular pump was switched on 10 minutes after the primary pump was started. After a further 20 minutes, the series of measurements was started.

A lot of plasma: a radial profile every 30min.

By taking a radial profile every 30 minutes, a fine distribution of measurements was obtained, making it possible to track the stabilization process precisely. The plasma was maintained for 10 minutes each time to analyze whether the presence of a large amount of plasma accelerates the process.

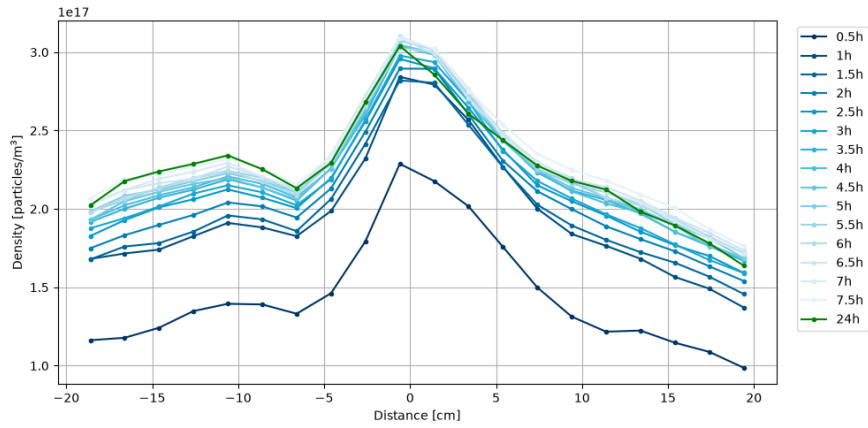


Figure 7: Evolution of the density radial profile, going from dark blue to light blue and in green the last profile.

Less plasma: a radial profile every 2h.

A radial profile was taken every 2 hours, the plasma lasted approximately 5 minutes each time (the time it takes to do the measurement).

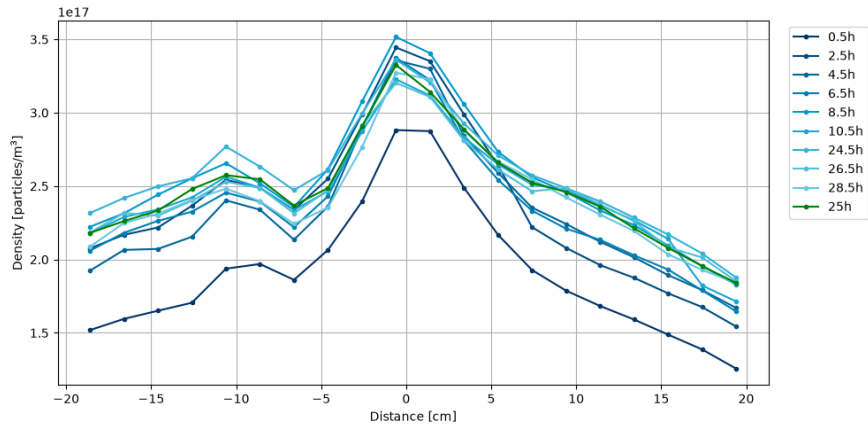


Figure 8: Evolution of the density radial profile, going from dark blue to light blue and in green the last profile.

Very little plasma: 3 radial profiles over 22h.

Three radial profiles were taken: one at the start, one after 5 hours, as the previous measurements suggested that saturation was reached after 5 hours, and one after 22 hours, when saturation had definitely been reached. Here the stabilization happened with very few plasmas.

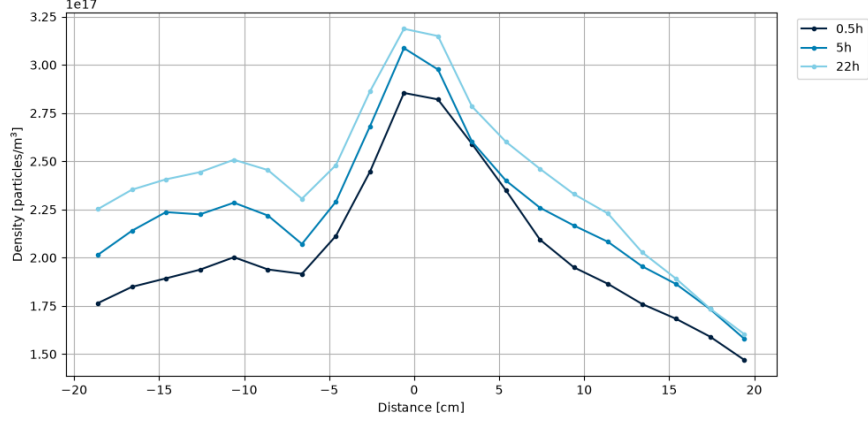


Figure 9: Evolution of the density radial profile, going from dark blue to light blue.

4.2 Discussion and Conclusion

The plasma density changes very rapidly during the first 5 hours, after which the curve flattens out. The orange curve (measurements taken every 2 hours) is rather irregular, particularly in the region near the main magnetic field axis ($r=1.4$). In contrast, the green curve (measurements taken every 30 minutes) is fairly continuous. The first data points in the three curves are widely spaced. This may be because the pressure varies very rapidly at the beginning, that even a timing inaccuracy of a few minutes causes significant differences in plasma density. Both the orange and green lines stabilize after approximately 10 hours, meaning that the rate at which maximum density is reached does not appear to depend on the amount of plasma generated during the process. It is curious, however, that the green line does not reach the same level as the orange one. One hypothesis is that the pumping mechanism is not powerful enough to reduce the pressure sufficiently within 20 minutes, the time interval between two plasmas. This would mean that the pressure in the orange measurement series was always slightly higher than in the blue one. The blue data points fit quite well between the orange and green curves.

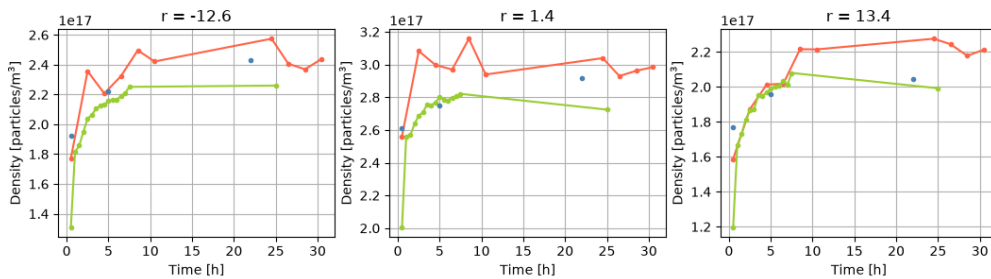


Figure 10: Stabilization of density over time at three different places: $r = -12.6$ cm in the inner edge, $r = 1.4$ cm in the center of the plasma, $r = 13.4$ cm at the outer edge.

5 Plasma generation optimization

5.1 Reduce plasma blob around antenna with teflon tube

The distribution of the plasma is not uniform. A large plasma blob forms in the immediate vicinity of the antenna. The idea was to use a teflon tube wrapped around the antenna to force the plasma to go in the direction of the magnetic field lines and preventing it approaching the windows. The plate next to the antenna should heat up less and, and that the plasma density should be distributed more evenly around the entire circumference. Teflon is very easy to work with, but it is not a long-term solution as it slowly melts at plasma temperatures. However, it is easy to test out different configurations, which could then be implemented in a permanent form, for example using a metal tube. Radial profiles of I_{sat} and V_{float} were done to analyze the impact of the tube.

First, a 15 cm long one-sided tube was tested. Less plasma did indeed form between the antenna and the window, although the overall density was lower. The straight tube does not align exactly with the direction of the magnetic field lines and is therefore likely to obstruct the plasma. For this reason, a 5 cm long tube was used next. On the inner side of the plasma, the smaller local maximum is weaker with the teflon tube. This suggests that less plasma is in fact generated outside the RF antenna ring. The teflon tube seems to have a big impact on V_{float} , especially the little tube with 2500 W reduces the absolute value.



Figure 11: Top: big teflon tube, bottom: small teflon tube.

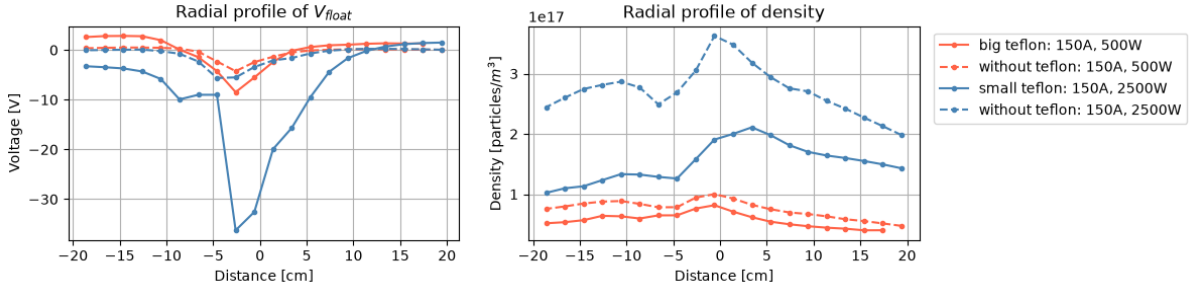


Figure 12: Impact big and small teflon tubes on density and V_{float} .

5.2 Isolate antenna foot with less risk of coating

To prevent plasma from forming at the base of the antenna, the lower part of the antenna must be isolated. So far, this has been done with copper tape. A thin layer of coating used to form after several plasmas, which was probably partly caused by the copper tape. As a replacement, a small frame made of aluminum plates was constructed, which, given the purity of the material, is unlikely to lead to any deposits. A lot of measurements were done after this change, and indeed less coating formed.



Figure 13: Aluminium foot.

5.3 Impact of glass and metal window on plasma density

Each window on Polaris can be made of either glass or metal. Probes must be attached to metal windows, which is why there may be different configurations of glass and metal windows depending on the measurement location. However, the metal windows may influence the plasma, as they are electrical conductors. Radial profiles of I_{sat} with different window configurations were compared (Figure 15). There indeed is a difference: a glass window next to the antenna reduced the plasma density. For V_{float} , the difference in magnitude is less pronounced, although the shape of the profile differs slightly. The blue and green lines represent the same situation; their measurements were carried out under the same conditions but on another day. However, it can be seen that they do not coincide - particularly for I_{sat} - as they should theoretically. This indicates measurement inaccuracy.

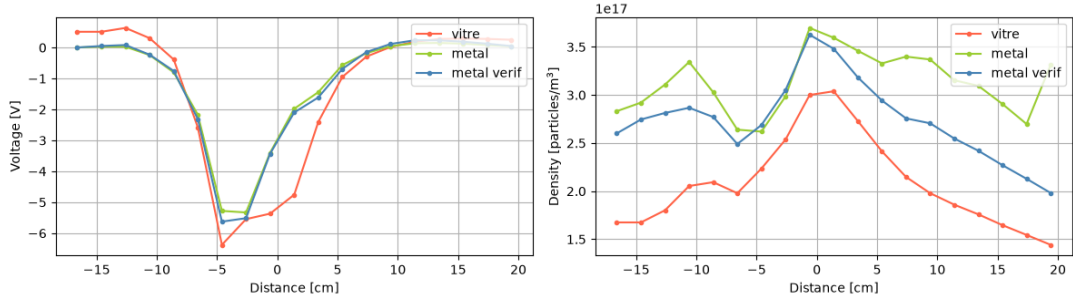


Figure 14: Comparison radial profiles with metal and glass plate next to antenna.

6 Estimation of power coupling efficiency

The objective of this project was to find out how efficiently RF power is transferred from the Polaris antenna to the plasma and how much dissipates in another way. This would therefore allow us to compare the conditions under which the power is used most efficiently. When plasma is ignited, it acts as an electrical load and modifies the antenna impedance. Measuring both the antenna current and voltage allows the complex impedance to be determined. By comparison of the impedance with and without plasma, the power coupled to the plasma can be estimated.

6.1 Physical background

The aim is to determine, qualitatively, the power entering the plasma, P_p . The power is given by

$$P_p = r_p I_p^2,$$

with r_p the resistance of the plasma and I_p the current. The impedance without the plasma Z_0 of the antenna is given by $Z_0 = r_0 + jL_0\omega$, where r_0 is the resistance and L_0 the inductance of the antenna. With the plasma, the impedance will become $Z_1 = r_0 + \delta r + j(L_0 + \delta L)\omega$. δr and δL depend on the Plasma parameters [8]. By knowing δr and δL and with the help of some simulations, it is possible to make conclusions about the strength of the coupling between the plasma and the antenna and thereby determine qualitatively how P_p varies.

With $I = I_0 e^{j\omega t}$, we have $V_1 = r_0 I$, $V_2 = L_0 \frac{dI}{dt} = L_0 j\omega I$. So,

$$V = V_1 + V_2 = (r_0 + j\omega L_0)I,$$

and by using $V = ZI$,

$$Z = |Z|e^{j\phi} = r_0 + j\omega L_0.$$

This relation will only be used to measure the order of magnitude.

The relation that will be used to find the impedance experimentally is given by

$$V_0 = ZI_0 = |Z|e^{j\phi}I_0 \Leftrightarrow |Z|(\cos \phi + j \sin \phi) = \frac{V_0}{I_0}.$$

So by knowing the antenna voltage V_0 , the antenna current I_0 and the phase shift ϕ between both, Z is

$$Z = \frac{V_0}{I_0}(\cos \phi + j \sin \phi)$$

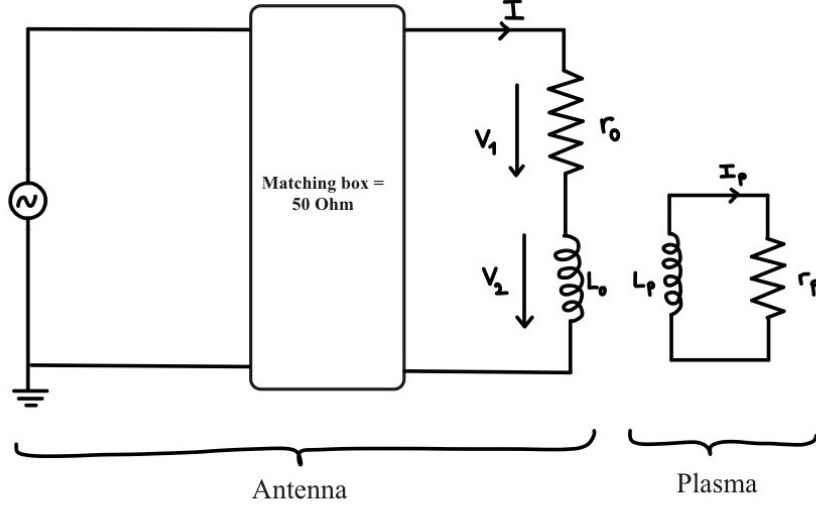


Figure 15: Scheme of the antenna and the plasma

Current sensor

The current sensor is based on electromagnetic induction. An RF current flowing through the antenna generates a time-varying magnetic field. A small pickup coil placed close to the antenna intercepts part of this magnetic flux. Since the magnetic field is proportional to the antenna current, the induced voltage is proportional to the current amplitude.

The current going through the antenna is $I = I_0 \sin(\omega t)$ and the therefore created magnetic field is $B = B_0 \sin(\omega t)$. The induced voltage in the coil is given by

$$V_{ind} = -\frac{d\phi_B}{dt},$$

where ϕ_B is the magnetic flux through the surface enclosed by the coil. As the magnetic field varies only weakly over the area of the coil and is perpendicular to its area, the flux can be approximated by

$$\phi_B = n \int \vec{B} \cdot d\vec{s} \approx nBS = nB_0 \sin(\omega t)S.$$

Where n is the amount of turns of the coil and S the coil area. B_0 can be obtained using the fourth maxwell equation,

$$B_0 = \frac{\mu_0 I_0}{2\pi d},$$

where d is the distance between the antenna and the coil. So we get

$$V(t) = n\omega B_0 S \cos(\omega t) \Rightarrow V_0 = n\omega B_0 S = \underbrace{\frac{n\omega\mu_0 S}{2\pi d}}_{A_{eff}} I_0.$$

A_{eff} will be determined with the calibration.

Numerical application to know how many turns the coil needs so that $I_0 = 1$ A corresponds to approx. $V_0 = 1$ V : $\omega = 2\pi f$ with $f = 13.56$ MHz the antenna frequency, the radius of the coil is 4 mm, so $S = 16\pi mm^2$, $d \approx 9mm$, and $I_0 = 1$ A, $V_0 = 1$ V. So we get,

$$n = \frac{V_0 d}{f \mu_0 I_0 S} \approx 10.$$

Voltage sensor

The antenna voltage was measured using a capacitor. A small copper plate mounted inside a 3D-printed housing is placed close to the antenna conductor. Together with the antenna, the plate forms a small capacitor. The output voltage of the probe is proportional to the antenna voltage.

6.2 Construction process and calibration

A 30 x 30 x 40 mm housing was printed which can be clipped directly onto the antenna.

The coil itself consists of thin copper wire wound into ten turns. The number of turns was chosen so that an antenna current of approximately 1 A induces a voltage of around 1 V in the coil. To establish electrical contact, the coating was removed from both ends of the coil and they were soldered to prepared connecting cables. The solder joint was then covered with insulating tape to prevent short circuits, and subsequently wrapped with copper tape. Once the coil had been pressed into place with the lid, the entire assembly was wrapped with copper tape on the outside, creating a Faraday cage and thus providing electromagnetic shielding.

For the voltage sensor a 10 x 10 mm copper plate has been soldered to a cable and then attached to a 3D printed box, which can be stuck on the antenna in the same way as the current sensor.

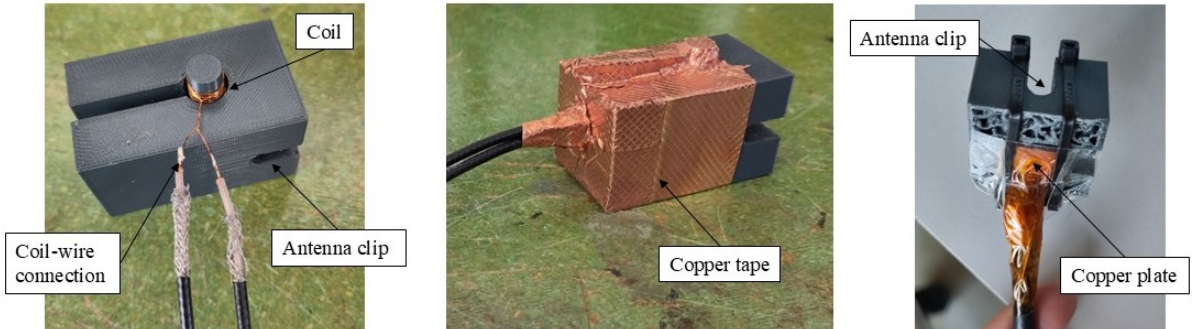


Figure 16: Left and middle: current sensor, right: voltage sensor.

For the calibration a power tube, a big 50 Ω resistance, a power generator and a hybrid combiner were used.

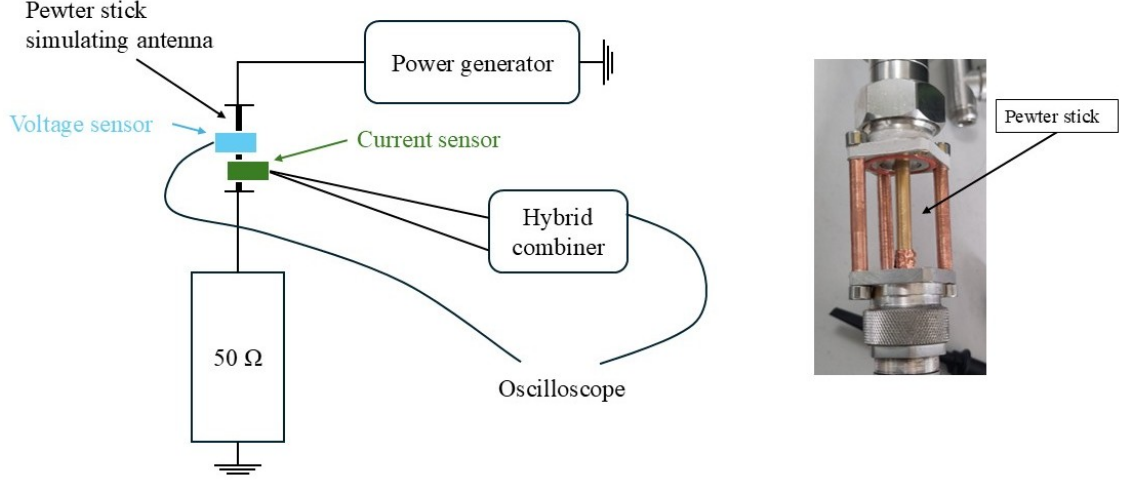


Figure 17: Left: electrical scheme of the calibration, right: power stick simulating the antenna

Some measurements on the calibration setup have been taken and analysed. By knowing the phase shift between the voltage and current, the real and imaginary part of the impedance can be known.

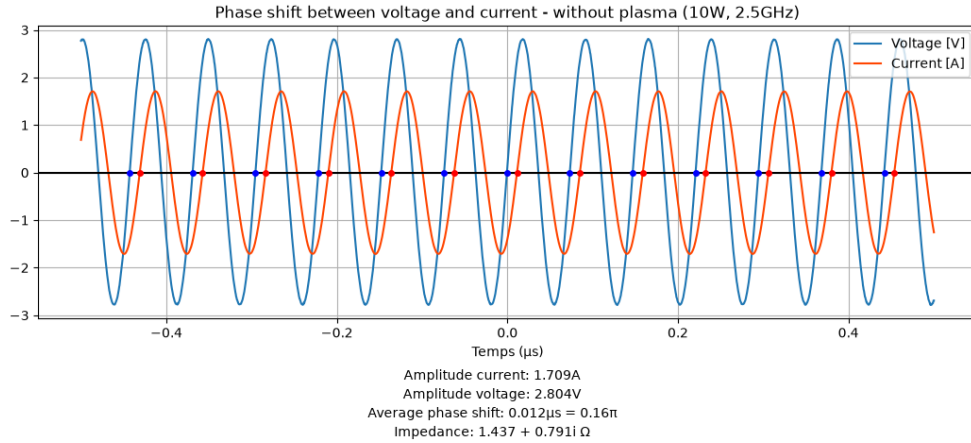


Figure 18: First calibration measurements

6.3 Why it did not work

By doing a short calculation of the order of magnitude, it was realized, that the phase shift that would be measured, would be so small, that it's impossible for the oscilloscope to perceive it. By previous measurements it is known that the resistance of the antenna without plasma is $r_0 = 0.06\Omega$ and the inductance is $L_0 = 0.4 \cdot 10^{-6}H$. With the plasma it can be estimated that the impedance changes very weakly so that it can be neglected and the resistance increases almost by a factor of 100. Therefore $L_0 + \delta L \approx L_0$ and $r_0 + \delta r = 1\Omega$. With the antenna frequency equal to 13.56 MHz, the impedance without plasma is

$$Z_0 = 0.06 + 34j\Omega \quad \text{and with plasma} \quad Z_1 = 1 + 34j\Omega.$$

So the difference of the phase shift is

$$\delta\phi \approx \frac{\pi}{2} - \arctan\left(\frac{0.06}{34}\right) - \frac{\pi}{2} + \arctan\left(\frac{1}{34}\right) = 1.58^\circ \approx 0.0003\mu s$$

The sampling frequency of the oscilloscope is 2.5 GHz, so the intervals between the measurement points are $\Delta t = \frac{1}{2.5 \cdot 10^9} = 0.0004 \mu s$. Sadly this is not precise enough to draw any conclusions.

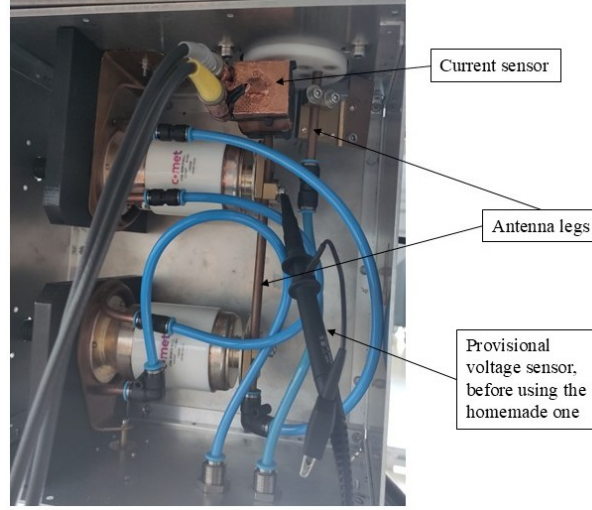


Figure 19: Experimental setup in the matching box

7 Visualization of magnetic field lines

To visualize the magnetic field lines, a probe that generates a localized plasma was used. The charged particles of the little plasma follow the magnetic field lines creating a thin beam.

7.1 Method

The probe consists of a thin tungsten filament, 0.1 mm wide, through which an electric current of approximately 2 A flows. This causes the filament to heat up significantly, begin to glow and generate a small plasma by releasing electrons. These move along the magnetic field lines, which thus become visible.

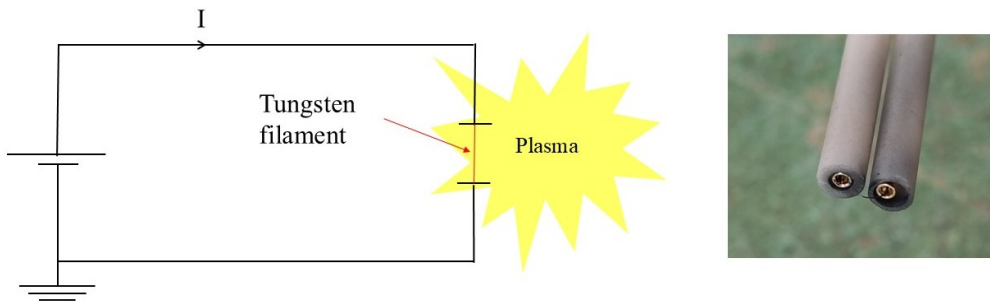


Figure 20: Left: electrical scheme for electron beam probe, right: tungsten filament

7.2 Results

The best results were obtained with neon. The magnetic field lines were beautifully visible.

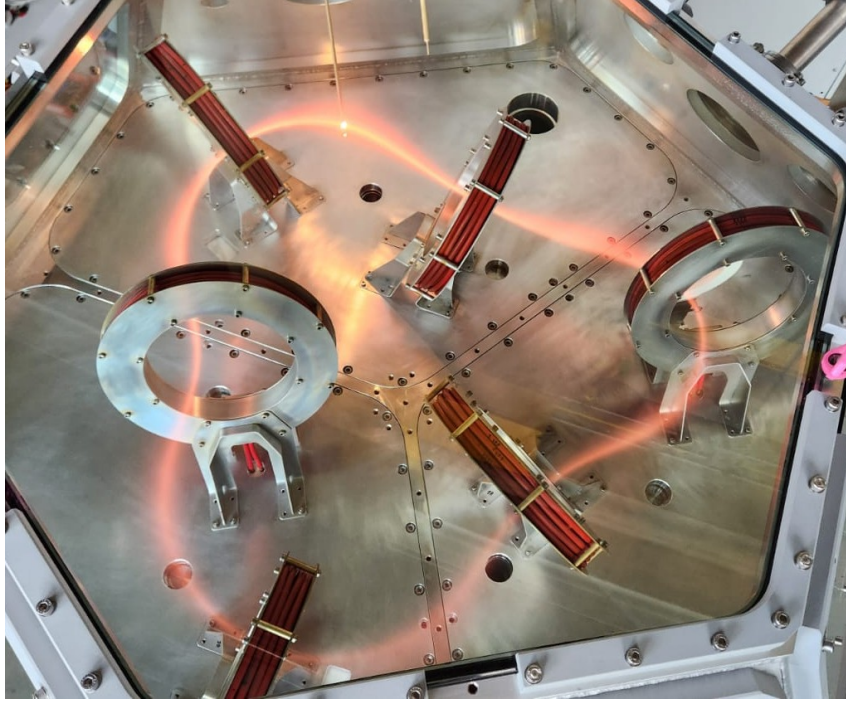


Figure 21: Plasma following the magnetic field line

8 Acknowledgments

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