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MEASUREMENT OF THE TRIPS SOURCE PLASMA PARAMETERS BY MEANS OF A LANGMUIR PROBE

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Abstract

The intense proton source TRIPS, designed for the TRASCO project and now under installation at the Laboratori Nazionali di Legnaro, has been operational for 4 years at INFN-LNS and now all the macroscopic parameters are well defined, as for beam current, beam emittance, neutralization factor and reliability.

No information has been available up to now about the plasma parameters for such a type of microwave discharge ion source, except for theoretical estimations. This report will describe the measurements of electron and ion density, temperature, plasma potential for typical operational conditions, along with the description of the experimental set-up used for the measurements, based on a Langmuir Probe.

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1. INTRODUCTION

TRIPS (Trasco Intense Proton Source) is a high intensity proton source originarily designed for the nuclear waste transmutation TRASCO project, based on a powerful 2.45 GHz microwave source (2 KW maximum). The goal of this project is the production of 30 mA cw proton beam with a normalized emittance below 0.2π mm rad for an operating voltage of 80 KV. The source has achieved all the major requirements and a full description is given in [1, 2, 3].

For this ion source, extensive diagnostics are available at the beam extraction end to characterize the ion beam in terms of current, intensity and charge state etc. Furthermore an optimization as regards to the operational source parameters like microwave power, feed gas pressure etc. and to the desired beam parameters has been achieved. However, the microscopic plasma parameters like plasma density, electron temperatures and plasma potential, which are expected to play a critical role in determining the microwave discharge ion source [4] efficiency and the quality of the ion beam, are not yet known. Hence, a control on the plasma parameters will help to tailor the plasma and to obtain even better beam characteristics, which may be relevant for future applications in the frame of NTA-HPPA project of INFN, devoted to the design of high power proton accelerator.

2. DESCRIPTION OF THE LANGMUIR PROBE (LP)

The LP measurement system consists of a probe, of its electronic instrumentation for biasing and of the control system for its positioning and for the data acquisition; a graphic software package for analyzing the data is also used. The scheme of the LP used at LNS to perform the measurements is shown in figure 1.

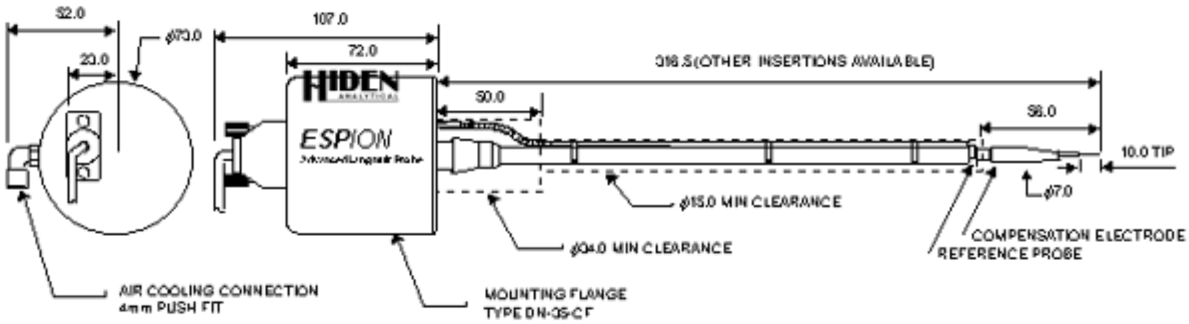

Figure 1: A scheme of Langmuir Probe used at INFN-LNS for plasma measurements on TRIPS.

The active part of a LP is a cylindrical probe of tungsten wire (length ≈1.5 mm, radius ≈ 0.15 mm in our case) inserted into the plasma chamber radially or axially through the apposite ports. This tungsten wire is spot welded to a semi-rigid coaxial cable and connected to a BNC connector. The probe can be biased with a sweeping voltage ranging from −200 Volt to +100 Volt (the range of the sweeping potential can be varied via software within this range, according to the experimental conditions). The main advantage of the Langmuir probe, along with the moderate cost and simple construction, is the determination of the most important plasma parameters in one single measurement [5, 6, 7, 8]. Analyzing the *I-V* curve, it is possible to extrapolate the floating potential V_f, the plasma potential Vp, the Electron Energy Distribution (EED), the electron temperature end density, the ion temperature and density. Figure 2 shows a typical curve for the TRIPS plasma.

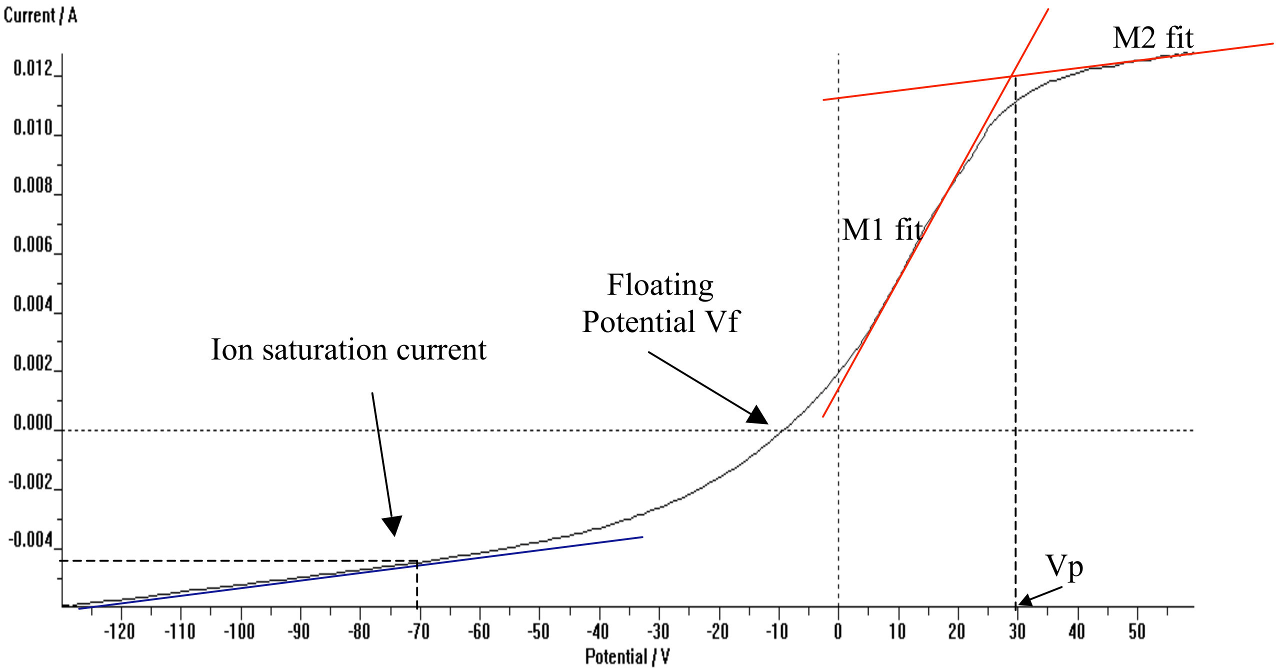

Figure 2: Characteristic curve obtained by Langmuir Probe measurement of plasma parameters.

The ion saturation current is obtained by the tangent to the I-V curve in high negative probe voltage range as shown in figure 2. By removing this part, the I-V curve is related only to the electron current; ion and electron saturation currents are strictly connected to the density of each species. We can determine the plasma potential in two different ways: the first one by calculating the first derivative of the I-V curve and by taking the voltage at which it has the maximum; the second one by calculating the interception point between the two linear fits M1 and M2 as shown in figure 2. M1 is the linear fit of the transition region between the floating potential Vf and the plasma potential Vp estimate, Vf being the potential for which electron and ion current contributions are equal; the slope of M1 line is used to determine the electron temperature. As the positive voltage attracts the electrons M2 represents the linear fit of the electron saturation current. This value can be affected by the presence of H^- ions in the plasma, but the amount of H^- is negligible in the experimental conditions here reported. Finally, the Electron Energy Distribution Function (EEDF) can also be obtained; in fact EEDF is proportional to the second derivative of the I-V curve.

3. EXPERIMENTAL SET-UP

The measurements have been performed both axially and radially with respect to the plasma chamber of the TRIPS source. A motor allows to move the probe in different positions inside the plasma chamber without venting, in order to determine the variation of the plasma parameters along the radial and axial direction.

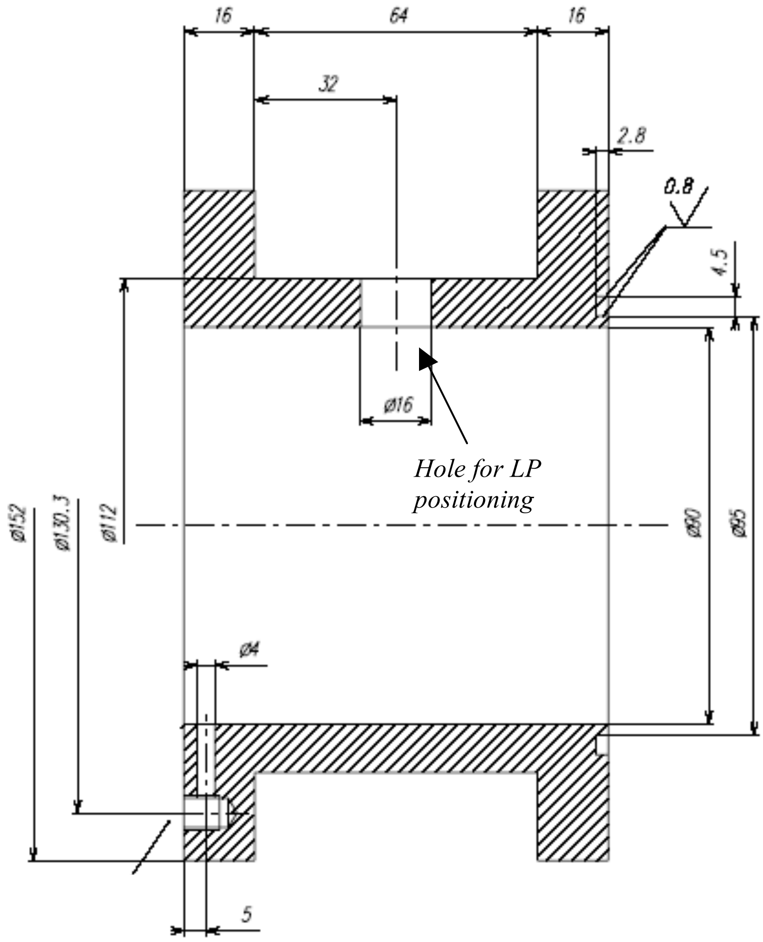

Figure 3: Cross section of the TRIPS plasma chamber with the hole for LP allocation.

In order to permit the LP positioning in both directions, the plasma chamber has been modified. Figure 3 shows the design of the section of the plasma chamber; the hole for the LP insertion is shown in the upper part and it is placed exactly in the middle of the chamber; the plasma chamber dimensions are also shown in figure 3. Figure 4 shows the photo of TRIPS.

The system for coils motion and (on the right) a part of the waveguide that sustains the plasma by means of microwaves of 2.45 GHz can be seen.

A new design has been carried out also for the extraction electrode, with a slight modification with respect to the usual one, as shown in figure 5. In such a way the axial measurements have been performed by placing the LP inside the extraction hole.

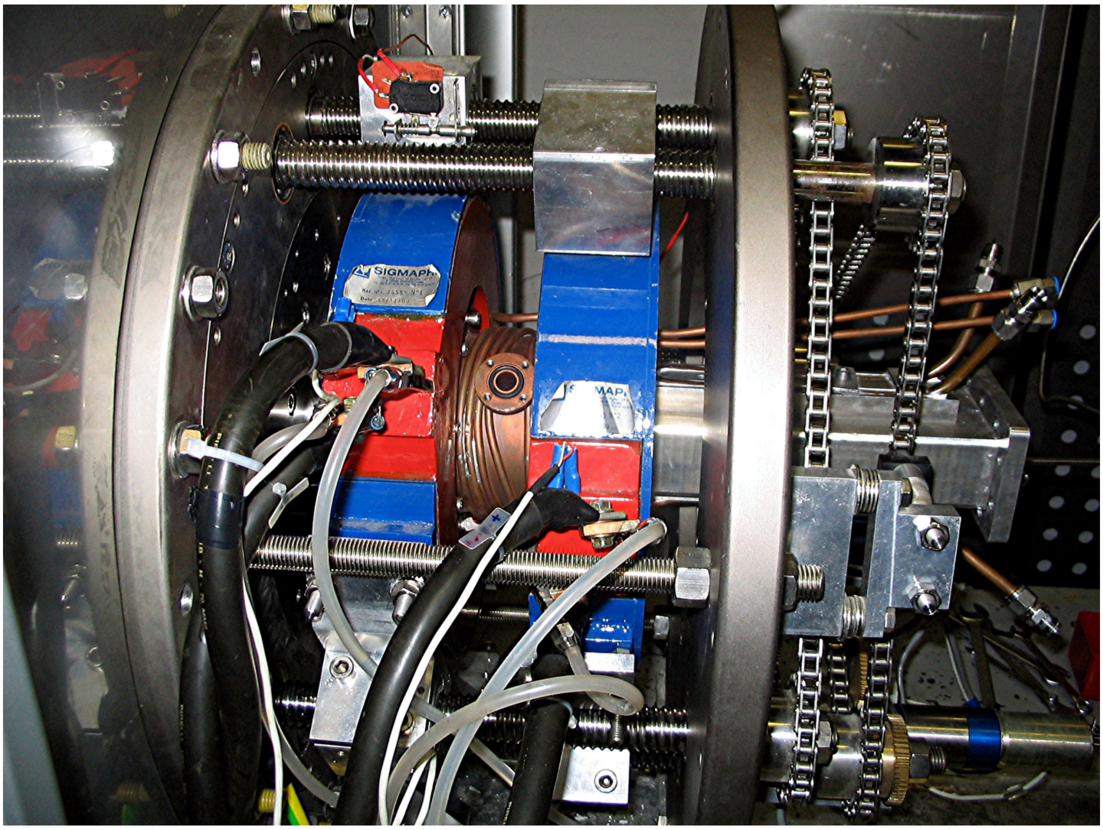

Figure 4: Side view of TRIPS at INFN-LNS. The hole in the copper plasma chamber for the radial positioning of LP is clearly visible in the middle of the two coils.

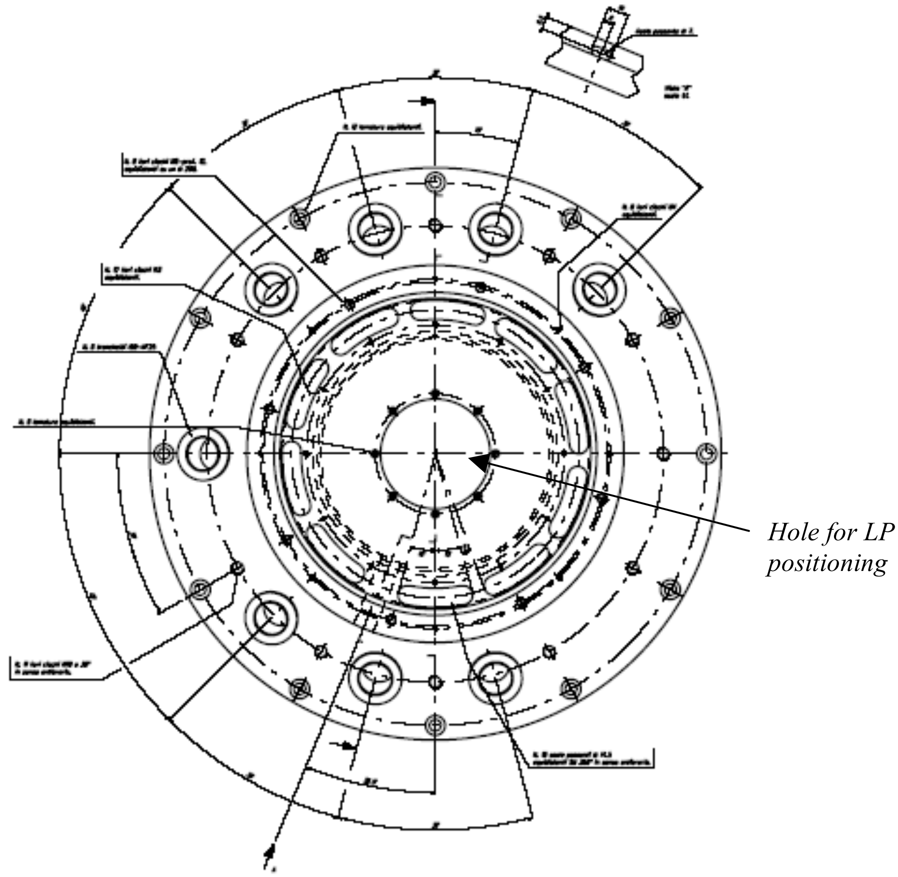

Figure 5: Scheme of the TRIPS plasma chamber with the hole for LP allocation (cut view).

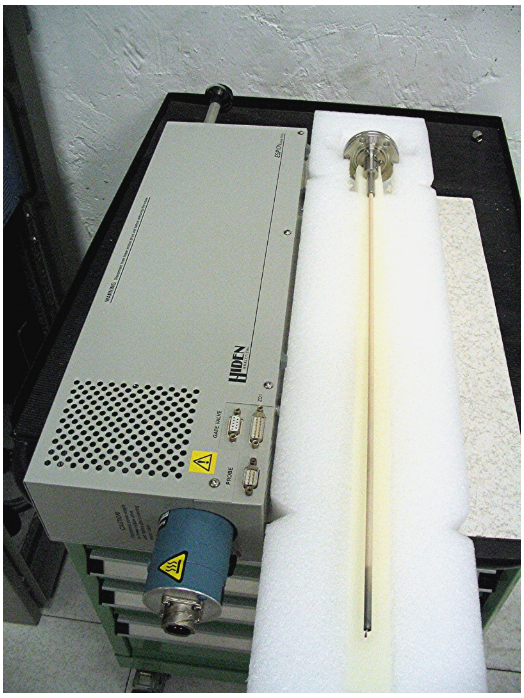

Figure 6: The ESPion Langmuir Probe used for the measurements here reported and the linear motion system.

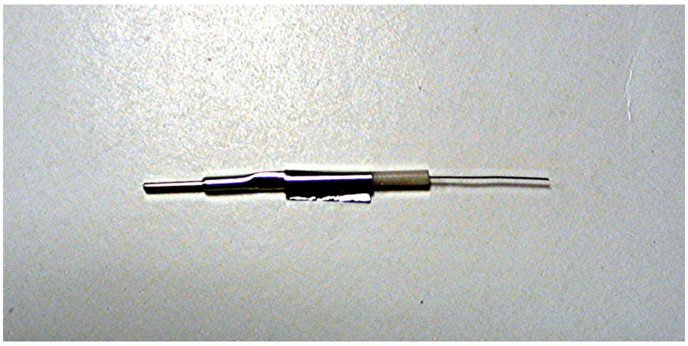

Figure 7: The probe tip.

Figures 6 and 7 show respectively the Langmuir Probe used for measuremens with its motion system, and a detail of the probe tip.

4. AXIAL MEASUREMENTS

The axial measurements have been performed by positioning the LP along the axis of the plasma chamber and acquiring the data for each position inside the chamber, for several microwaves powers and by keeping approximately the same value of gas pressure. Hence it is possible to show the trend of the most important parameters with respect to the distance, as it can be seen in figure 8 for the electron temperature. A step of 5 mm was chosen for the probe positioning.

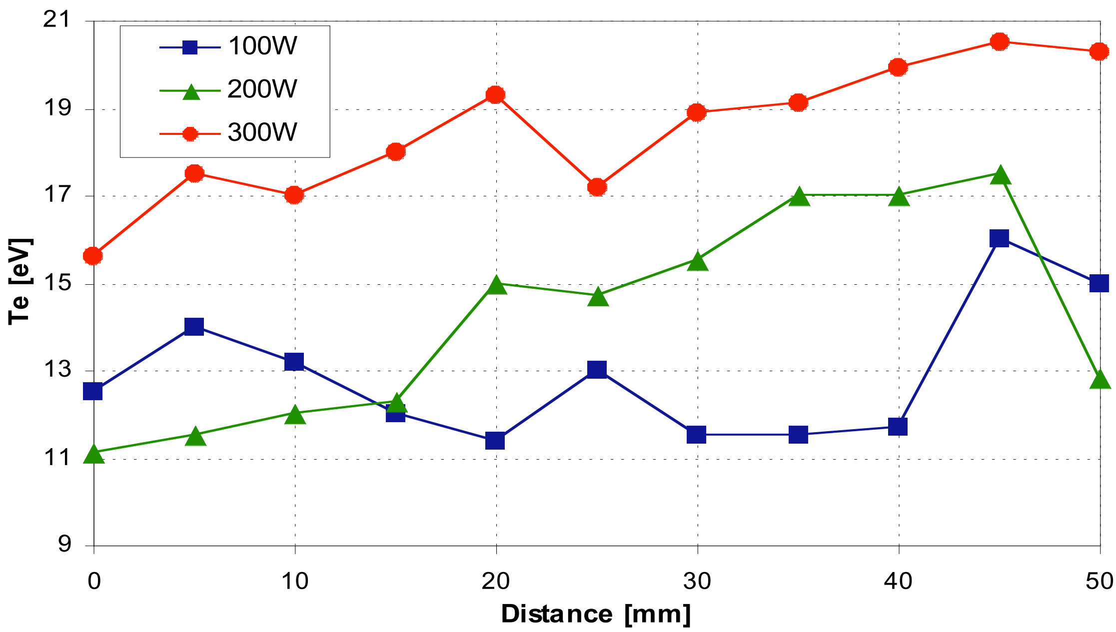

Figure 8: Trend of the electron temperature along the plasma chamber axis; z=0 corresponds to the extraction end of the plasma chamber.

In order to have a good statistics for each point reported in the figures, a minimum number of aquisition of 700 was chosen and then the software averaged the data, thus recostructing a characteristic curve like in figure 2. In such a way the plasma oscillations are smoothed.

The electron temperature T_e related to 100, 200 and 300 W is in reasonable agreement with the theoretical forecasts. In fact, in order to obtain protons by any source it is necessary that the electrons' energy is of the same order of the ionization potential for Hydrogen (i.e. 13.6 eV). As it can be seen from figure 8 the electron temperature varies between 12 and 20 eV and it increases slightly from one end (0 mm) towards the center of the plasma chamber (48 mm) for each microwave power.

The increase of the rf power does not affect the electron temperature proportionally, as the loss mechanisms are dominant in a microwave discharge ion source and high energy electrons are immediately lost because of the lack of radial confinement .

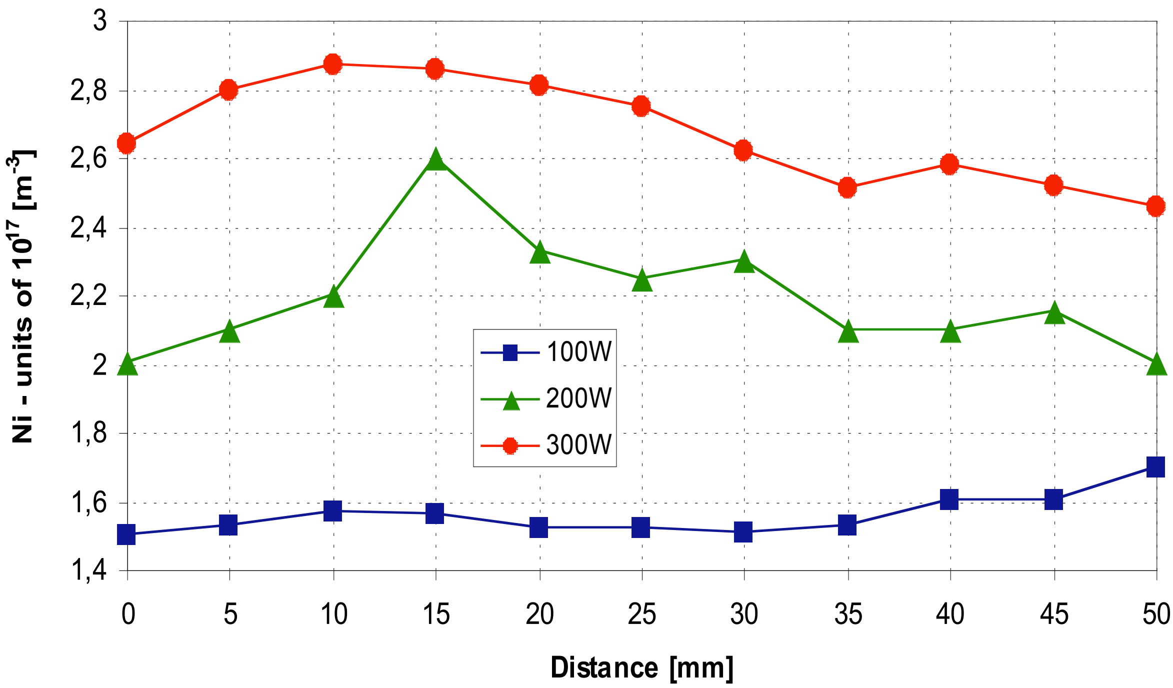

Figure 9: Ion density for different positions along the plasma chamber axis.

Figure 9 shows the trend for the ion density. The ion density is almost constant along the axis of the chamber (fluctuations of ±10% are related to the RF ripple and to the beam ripple) and it increases approximately 30% for each 100 W step. In this case the results are close to the theoretical estimations, even if the damage of the probe tip can explain the decrease for $Z \geq 35\ mm$ at 200 and

300 W. Anyway the distribution of the microwave field inside the plasma chamber was optimized to have a maximum close to the extraction end (*Z=0 mm*).

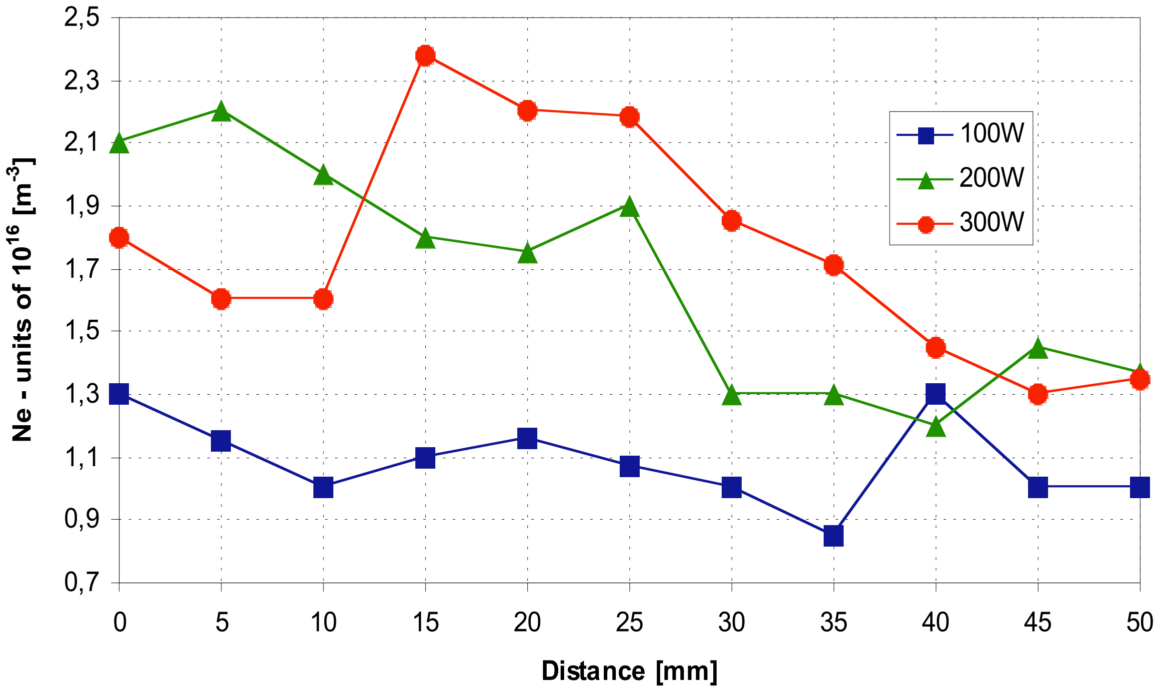

Figure 10: Electron density for different positions along the plasma chamber axis.

Electron density behaviour is more complicated and it is shown in figure 10, featuring a density about an order of magnitude smaller than for the ions; this is explained by the higher mobility of the electrons and by the absence of the radial confinement so that the electrons move away from the axis soon and protons still remain. We can try to evaluate theoretically the difference between ion and electron density; it is possible to prove that the ratio between ion and electron density depends on the square root of the ratio between ion and electron mass, i.e [9, 10]:

$$\frac{n_e}{n_i} \propto \frac{I_e}{I_i}\left(\frac{m_e}{m_i}\right)^{1/2} \qquad (1)$$

where I_e and I_i are respectively the electron and ion saturation current. The relation (1) is valid only when the ratio between the probe radius r_p and the Debye length λ_D is much higher than one. For the TRIPS plasma this condition is not satisfied and so the relationship between densities ratio and masses ratio is similar but more complicated; the electron density is lower in general than the ion one, taking into account that the ratio between saturation currents is not higher than 10 in our case. If we carefully analyze figure 9 and 10 it can be noticed that the difference between n_e and n_i is about one order of magnitude for each power, in agreement with the theoretical forecasts.

Additionally, our estimation does not take into account Coulombian effects and plasma dynamics, but it is just based on two-body collisions, so a high precision cannot be reached.

5. RADIAL MEASUREMENTS

The radial measurements shown in this section were carried out with different magnetic field profiles. The magnetic field is generated by means of the two coils shown in figure 4. The magnetic field profile can be varied by moving the coils and by varying the current that flows in each one. Measurements have been performed with four different profiles named *TRIPS*, *CEA design*, *PM-TRIPS tentative model*, *PM-TRIPS ideal design* and figures 11, 12, 13, 14 show them.

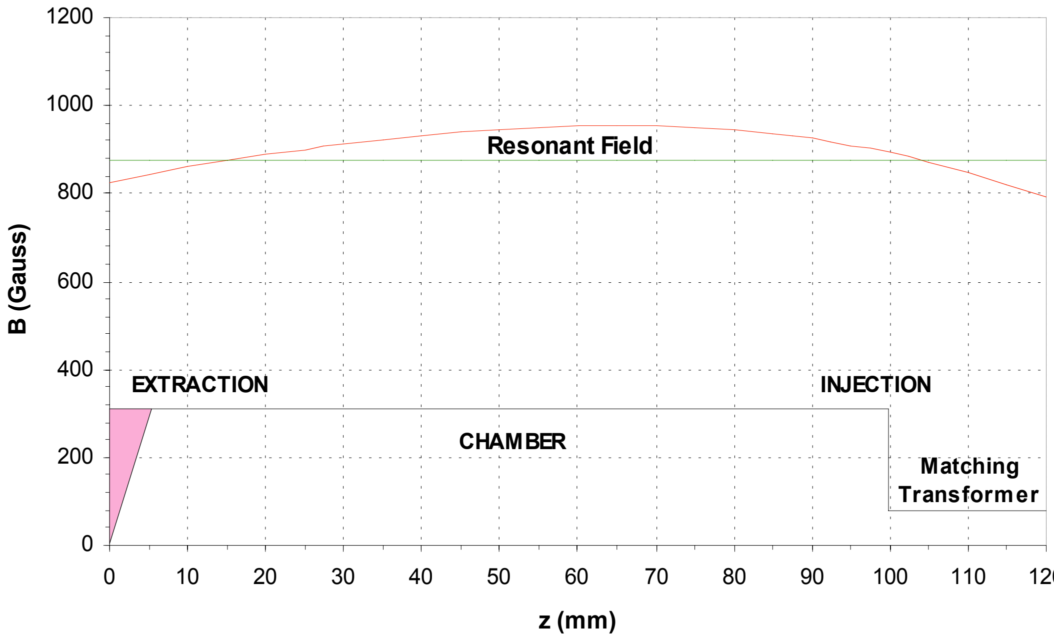

Figure 11: TRIPS magnetic field profile.

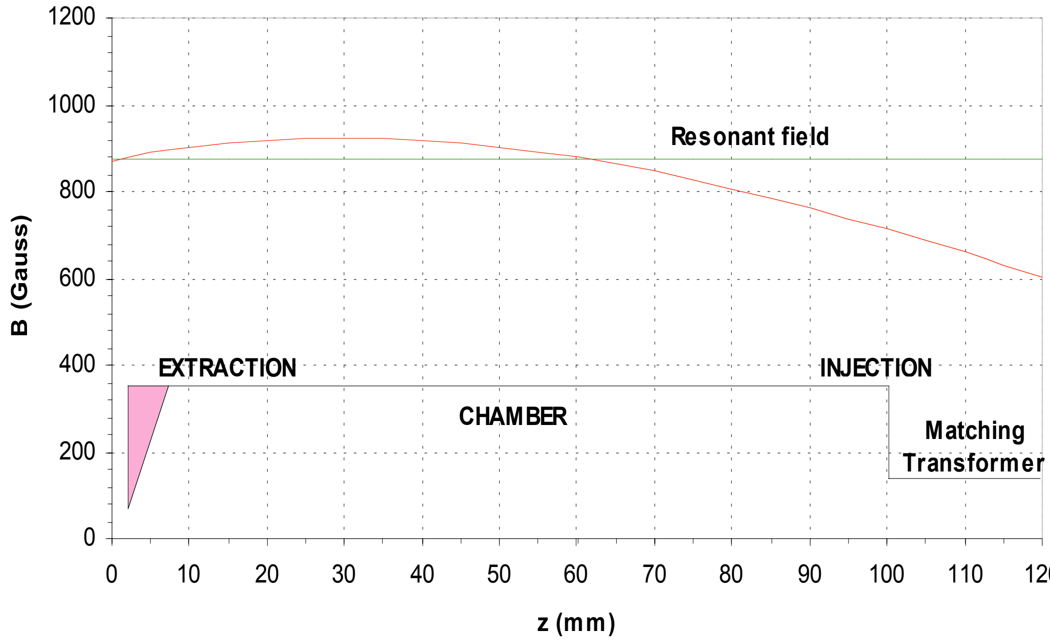

Figure 12: CEA design magnetic field profile.

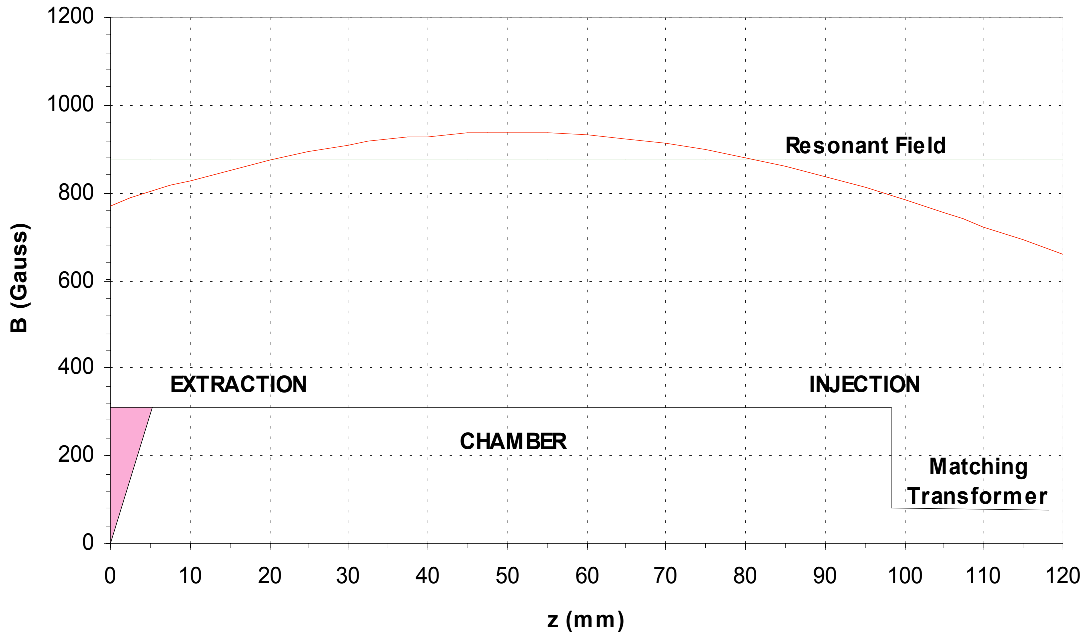

Figure 13: PM-TRIPS ideal design magnetic field profile.

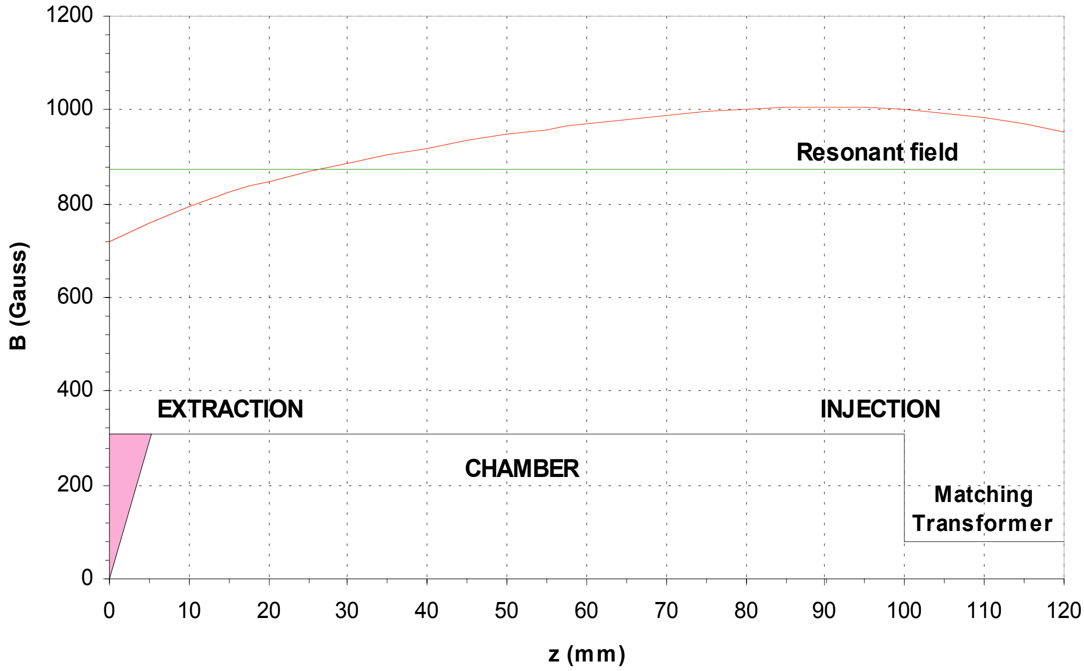

Figure 14: PM-TRIPS tentative magnetic field profile.

Table 1 summarize the main characteristics of the profiles.

	I_1 [A]	I_2 [A]	Pos. 1 [mm]	Pos. 2 [mm]
TRIPS	124	128	24	26
CEA design	71	161	30	30
PM-TRIPS ideal design	133	90	43	35
PM-TRIPS tentative design	124	128	45	6

Table 1: Summary of the coils' currents and positions for each magnetic field profile.

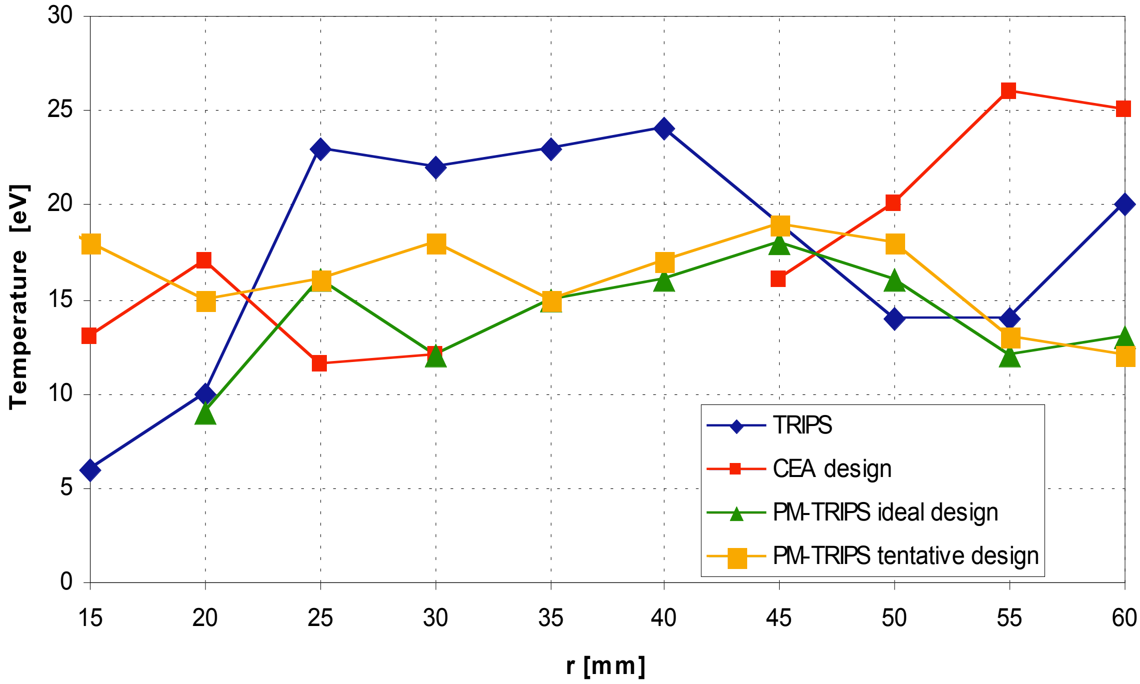

Figure 15: Electron Temperature along the plasma chamber radius (r=45 mm is the center of the chamber).

The series of measurements along the radial direction at *Z=48 mm* were carried out to verify that the microwave and plasma distribution was exactly the designed one, as it appears in section 4. In this case even different magnetic field profiles have been also tested. It is very interesting to show in particular the results obtained with different profiles, because of their importance to determine future developments of TRIPS, in particular for the permanent magnets version.

In this case we focused our attention on the higher power (300-500 W) that is the operational condition (*r=0* is set at the plasma chamber wall, which diameter is 90 mm).

Figure 15 shows the electron temperature along the radial direction for four different magnetic field profiles, and for 300 Watt of microwave power.

Plasma instabilities and probe pollution have affected the radial measurements more than the axial ones. Then the fluctuations of data during acquisition is higher than the previous case. In spite of these fluctuations the results concerning the electron temperature are in reasonable agreement with the axial measurements. In particular for the two “PM-TRIPS designs” (ideal and tentative) the temperature trend is quite constant along the entire plasma chamber, with a mean temperature of about 15 or 16 eV (axially the measured mean temperature for the “TRIPS” profile was about 16 to 20 eV). For “TRIPS” profile the temperature is higher (between 14 eV and 24 eV) with the maximum not exactly in the central region of the plasma chamber (about 45 mm), and after it falls

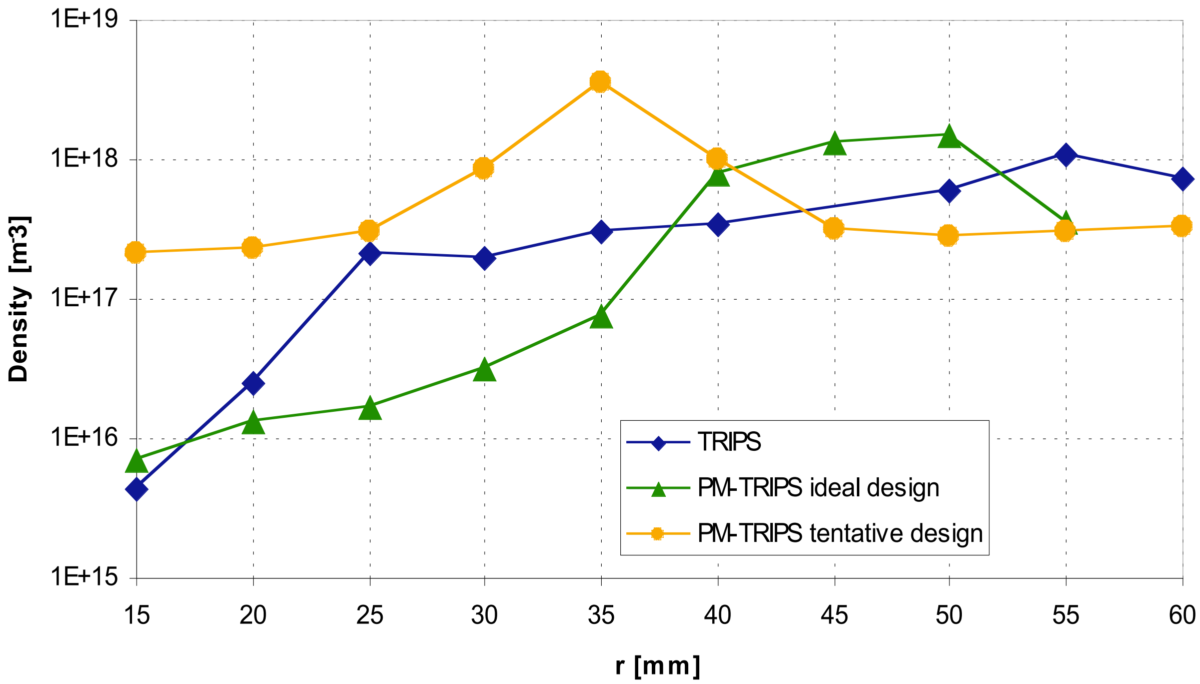

Figure 16: Ion density along the plasma chamber radius. Microwave Power=300 W.

down around 50 mm. For the "CEA" profile the measurements were much complicated, because of a high plasma instability; in fact between 30 and 45 mm there are no data, as the characteristic curve cannot be drawn.

Figure 16 shows the behaviour of the ion density. The profile "CEA" has been omitted because of the bad plasma conditions, that cannot allow an appropriate data processing.

The ion density for the "PM-TRIPS tentative design" is almost constant except for distances around 35 mm, while for the other two profiles the ion density grows up towards the center of the plasma chamber. It is interesting to notice that the plots are in logarithmic scale, i.e. radially the variation of n_i with the distance is much stronger than axially. This is the effect of the microwave injection scheme, that uses a 4-step matching transformer to enhance the microwave field close to the axis. In addition, considering that the emittance of the TRIPS beam is better than the design value, we can consider to have a much larger extraction hole for some applications, if an off-axis high density plasma is present and this will be the aim of a next session of tests in 2006. The profiles "TRIPS" and "PM-TRIPS ideal design" feature a typical density profile with a maximum close to the center of the plasma chamber.

Figure 17 shows the electron density. Equation (1) can be used again to evaluate the ratio n_e/n_i and we notice that the experimental results are in reasonable agreement with calculations, as it is for the axial case.

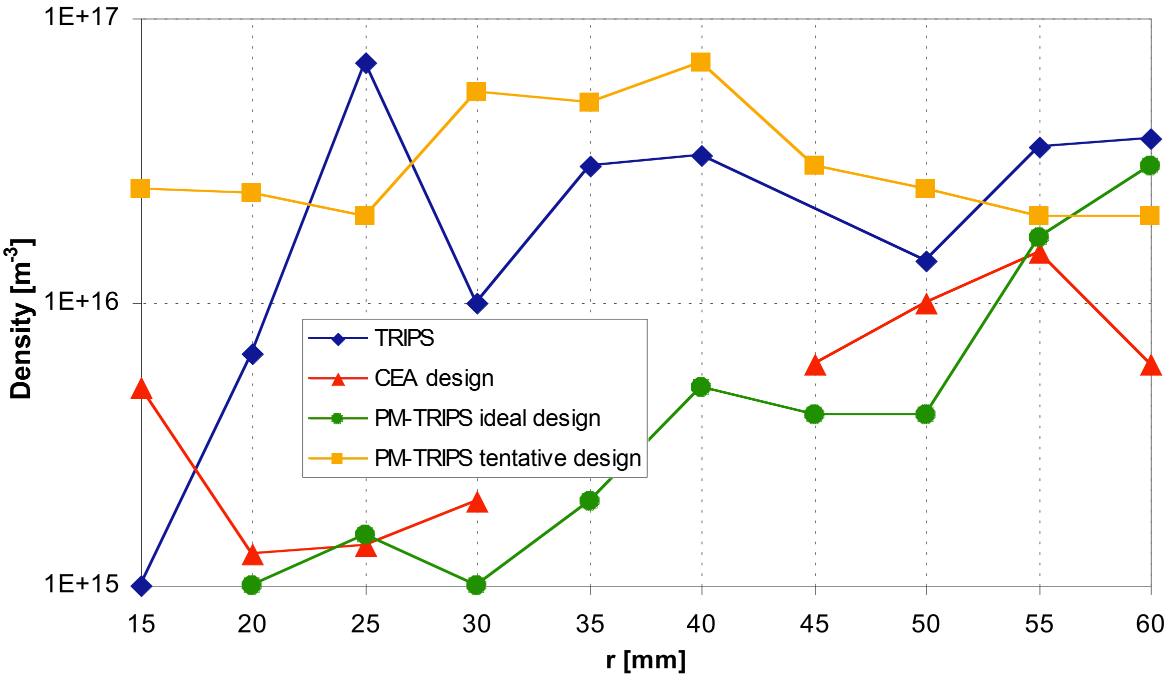

Figure 17: Electron density along the plasma chamber radius. Microwave Power=300 W.

For the electron density we can evaluate the "PM-TRIPS ideal design" that features a set of values (whereas they are stable) close to the "CEA design" and much lower than the profiles "TRIPS" and "PM-TRIPS tentative design". Once again for the "PM-TRIPS tentative design" there is a maximum between 30 and 45 mm, while for the "TRIPS" profile there is a strange fluctuation of data, related probably to the deterioration of the probe tip. It comes out from the figures that the "TRIPS" profile and "PM-TRIPS tentative design" have the best plasma parameters.

A final measurement was done to evaluate the increase of ion density with the power and the results are given in figure 18.

The enhancement of ion density for a power of 500 W is less than one order of magnitude but the interesting fact is that a steady behavior is presented which is the result of a very stable plasma behavior. Unfortunately measurements at power rate above 500 W were not possible because of the probe tip deterioration.

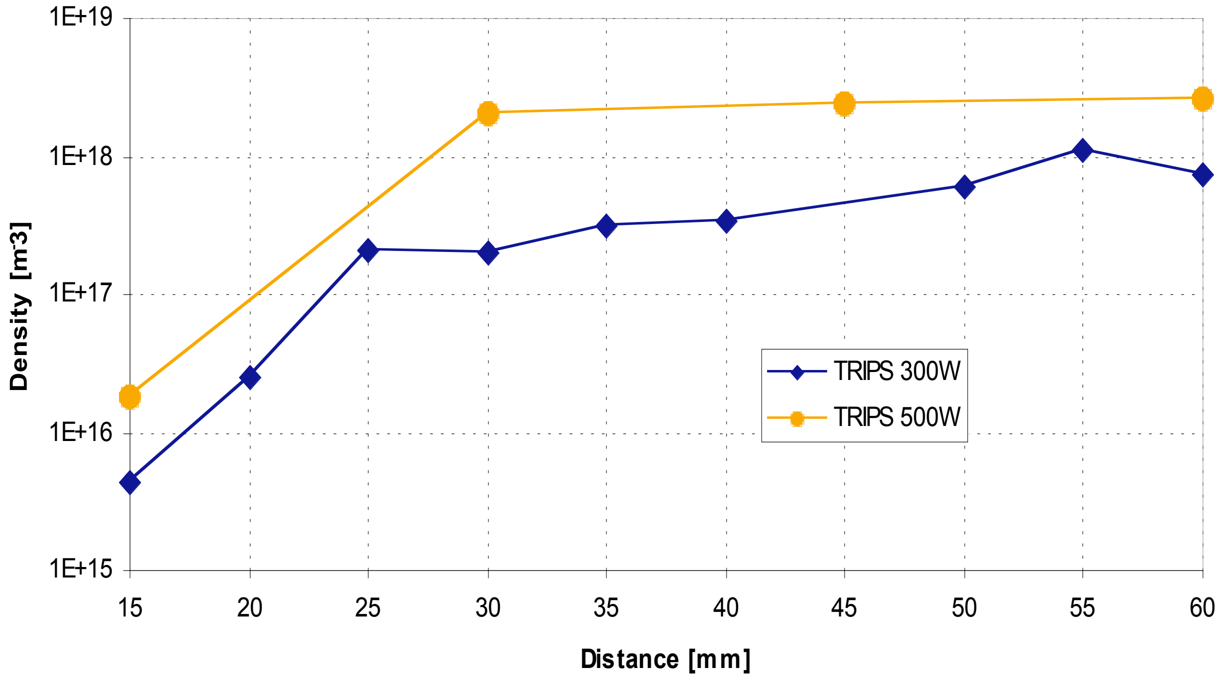

Figure 18: Ion density along the plasma chamber radius at microwave power of 300 and 500 W for TRIPS profile.

6. CONCLUSIONS

An important series of measurements have been performed for the plasma of TRIPS source in order to evaluate the principal plasma characteristics. A special attention has been devoted to the characterization of the different magnetic field profiles, because of the plan to build a new source based on the same working principles of TRIPS, but with permanent magnets, named PM-TRIPS. The informations obtained with the Langmuir Probe have permitted to improve the design of PM-TRIPS and to get further insight on the behaviour of microwave discharge plasmas that will be useful for the next development in the field of high power proton poduction.

7. ACKNOWLEDGMENTS

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