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CHARACTERIZATION OF AN PROTON ECR ION SOURCE FOR LOW BEAM CURRENT*

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Abstract

In this paper we analyze the behavior of a low beam current proton ECR ion source for linac. During the operation of the source, as a function of the operating parameters we have observed a complex behavior. The state of the plasma is highly dependent on the input parameters, and in some cases even bi-stable conditions can be achieved showing abrupt changes in the state. To try to understand this behavior we carried out a series of experiments varying the input parameters both sequentially and randomly to avoid following the same path every time. Thanks to these experiments we have been able to observe the change in the luminosity of the plasma, which is an indirect measure of the degree of ionization in the plasma, along with the changes in reflected and transmitted RF power delivered to the source. We also characterized the relation between the outer temperature of the ion source chamber walls and the plasma. In addition to this we have analyzed the resulting extracted ion beam using a pepperpot and a faraday cup. We have observed that our beam does not have one dominant species and has three species that are found in comparable quantities.

INTRODUCTION

The LINAC 7 project is a research project that aims to create a compact low intensity proton accelerator with an energy of 7 MeV. As detailed in Ref. [1], while some accelerator stages are still in design, this work focuses on characterizing the Ion Source where positively charged particles are generated, the beam extraction to create the particle beam, and the Low Energy Beam Transport (LEBT) stage, which focuses the beam to go onto the next accelerating stage. A good understanding and control of the first stages of a LINAC is essential, because this is where many of the most important properties of the beam are determined. Among them, the most important are the current of the beam, which mostly depends on the performance of the Ion Source and the beam extraction [2], and the emittance of the beam, which once the beam is generated keeps constant through all the path of the accelerator [3].

To better understand the Ion Source and the extracted beam, various experiments have been conducted, exciting different behaviors in the plasma and beam and measuring relevant parameters. By analyzing the results of the experiments, it is possible to better understand the behavior of the first stages of the LINAC 7 accelerator.

Between the instruments used to manage and measure the parameters of the accelerator, many are of common use, like gas flow control, pressure measurement, a pepperpot and a Faraday cup to measure the characteristics of the beam, and luminosity measurements to determine the ignition degree of the plasma on the Ion Source. In addition to those, there is a specialized instrument developed for the LINAC 7 project that allows to measure the amplitude and phase of the incident and reflected RF signals used to excite the Ion Source, allowing calculation of the reflection coefficient, which varies with plasma state [4].

Some of those experiments deal with the effects of the temperature on the inner walls of the Ion Source, which increases during its operation, affecting the plasma [5]. The rest of the experiments are about better understanding different states on the plasma, which are believed to be linked with the chemical reactions on the ionized plasma, where different states belong to different predominant chemical species generated inside [6]. By better understanding this phenomena, it is intended to prioritize a state on the plasma where H^+ is the main generated element, and to maximize the amount of generated H^+.

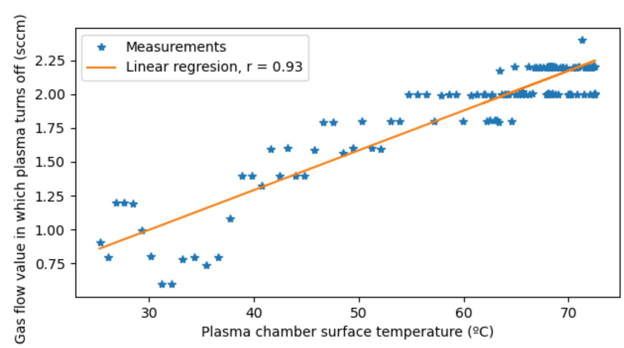

Figure 1: The relation between the temperature on the surface of the Ion Source, and the value of gas flow in which the plasma turns off.

PLASMA EXTINCTION AND TEMPERATURE RELATION

Since during the operation of the ion source a considerable amount of energy is used to generate the plasma, the temperature of the resonant cavity increases over time. This

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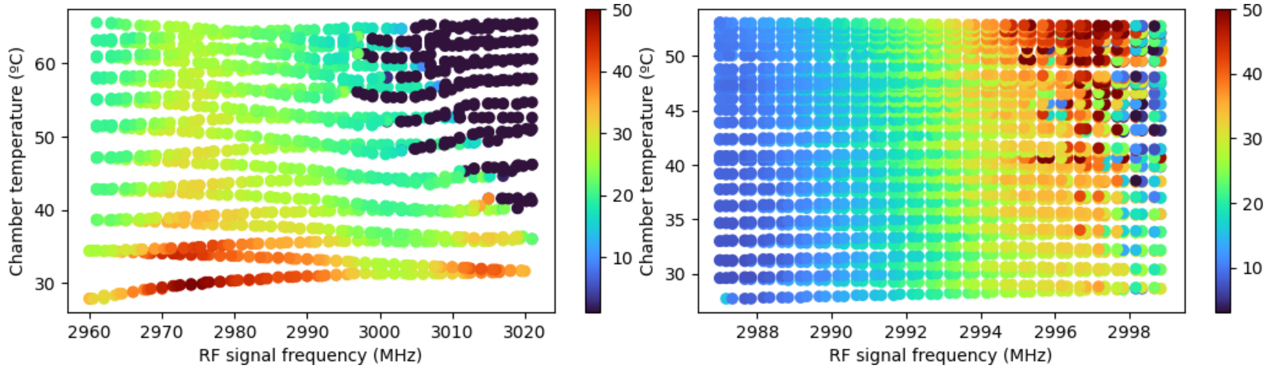

Figure 2: Up, the relative luminosity of the plasma depending on the frequency of the incident RF signal, and the temperature on the surface of the Ion Source. The dark zone on the high frequency high temperature area corresponds to measurements where the plasma was off. Down, the same experiment, with the effect of the temperature compensated. Note that the measurement of the luminosity is done in a. u., and that the different measurements are scaled differently along different experiments.

temperature has an effect on the behavior of the plasma, which can be measured on the moment the plasma turns off. By keeping a constant RF power incident onto the Ion Source, and decreasing the gas flow so that the plasma turns off, it is possible to measure at which gas flow value turns off the plasma. By comparing these measurements with the temperature of the surface of the Ion Source at each moment, it is possible to obtain the graphic shown in Fig. 1. It can be seen that there is a clear relation between the two values, one that appears to be linear.

The higher the temperature on the Ion Source, the higher the amount of gas flow required to keep the plasma on. There are many possible explanations for this phenomenon, and two hypothesis have been raised on our team:

On the one hand, it is possible that the temperature increase is affecting the permanent magnets that create the magnetic field for our Ion Source. With the increase in the temperature, it is possible that they generate a different magnetic field, and that this changes the ECR resonant frequency of the cavity. By changing the resonant frequency, it is possible that the frequency of the RF signal is closer to it on low temperatures than in high ones, and therefore the effect would be due to the generally lower stability of the plasma at high temperatures.

On the other hand, this effect can also be linked to gas expansion inside the Ion Source. If the gas inside the cavity behaves like an ideal gas, and its temperature is linked to the temperature on the surface of the Ion Source, at higher temperatures it would expand, reducing the density of H_2. If the relevant magnitude for the plasma generation is the H_2 density inside the cavity, and not the incident gas flow, the observed effect would be again explained.

FREQUENCY CYCLES WITH TEMPERATURE INCREASE

To see if the first of the previous hypothesis holds, a simple experiment has been performed. The frequency of the incident RF signal has been changed, and how the relative luminosity varies with the frequency and temperature changes have been measured. The results of the experiment can be seen in Fig. 2.

It can be seen that the luminosity for the same frequency generally decreases with the increase in the temperature, but that the frequency with highest luminosity always stays the same, around 2975 MHz. Hence, the ECR resonant frequency does not highly change with the increase of the temperature on the surface of the Ion Source.

DENSITY MODEL WITH IDEAL GAS EQUATION

Discarding the first hypothesis, let us analyze the second one, according to which the density of the gas inside the ion source changes with the temperature of the chamber. In order to try to test this approach, a model of the density has been created, and it has been used to try to compensate for the effect of the temperature on the gas density inside the ion source.

For the model, some assumptions have been done. First of all, let us assume that the gas inside the ion source behaves like an ideal gas. Also, let us assume that the temperature of the gas inside the cavity is proportional to the temperature on the surface of it, so that $(T_{surface} - T_{amb}) = K_1(T_{gas} - T_{amb})$ is fulfilled. Finally, it is assumed that the plasma shutdown shown in Fig. 1 always happens at a constant density. With these assumptions, the density of the gas on the ion source can be calculated as:

$$\rho \propto \frac{P}{K_1(T_{gas} - T_{amb}) + T_{amb}} . \quad (1)$$

Given that the volume is constant. ρ is the density of gas, P is the pressure, T_{gas} and T_{amb} are the temperature of the gas and of the ambient and K_1 is a constant.

With this, the relation between the temperature and the plasma shutdown density derived from the values on Fig. 1 can be calculated, and K_1 can be fitted until the relation is null. The optimum value for K_1 has been estimated at 6.308, so that the normal range of temperatures for the gas inside the chamber would be between 22 °C (ambient temperature)

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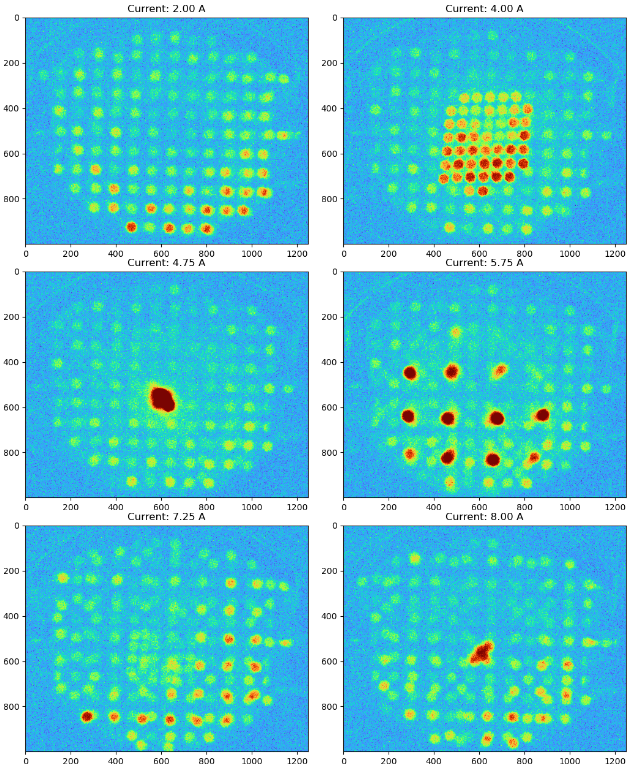

Figure 3: Images taken from the pepperpot camera with different currents on the focusing solenoid. The color represents the intensity of each pixel, in arbitrary units.

and 440 °C. This range is reasonable, because the steel of the chamber has suffered no damage, but in a previous experiment a piece that was soldered with tin came off, due to the tin melting (about 232 °C).

With this model, a simple controller has been created to maintain a constant density inside the ion source varying the gas flow depending on the temperature. With this controller, the experiment of the frequency cycles has been repeated, obtaining the results shown in Fig. 2 down. It can be seen how the effect of the temperature is largely compensated.

ANALYSIS OF ELECTRICAL PROPERTIES OF THE PLASMA

Continuing with the analysis of the behavior of the ion source of the LINAC 7 accelerator, there are a couple of experiments that appear to show different states on the plasma of the ion source. It is believed that those states can be linked with the generation of different species on the ion source plasma, which have been studied on previous works on the team [6]. Thanks to the new instrument that can measure the reflection coefficient of the ion source at the frequency of the incident RF signal, it has been possible to perform the experiment shown in Fig. 4.

In this experiment, it can be seen how the luminosity of the ion source changes abruptly with smooth changes on the gas flow. These changes happen between states where it is hard to distinguish the plasma from one that is off (blue and dark blue) and states where the luminosity appears to change more smoothly with the gas flow at high luminosity values (red).

DIFFERENT SPECIES ON THE PEPPERPOT

As have been mentioned before, there are multiple species being generated on the ion source and extracted on the beam to the LEBT. It is believed that those species are H^+, H_2^+ and H_3^+. Due to their different mass-charge relationships, each species responds differently to electric and magnetic field applications. Those which have more mass will reach smaller velocity when electrostatically accelerated on the beam extraction, and they will be curbed less when under a magnetic field, like on the solenoids that focus the beam.

This effect is measurable using the pepperpot in the LEBT. An experiment was designed where the beam extracted from the ion source is focused using solenoids. By changing the current that goes through the solenoids, it is possible to apply more or less curvature to the beam, focusing it more or less. Thus, an experiment was conducted where solenoid current was varied, and a photo was taken of the pepperpot for each current setting.

In Fig. 3 some of the resulting images of the experiment can be seen. With low currents, it is not possible to distinguish the different species, and none of them is focused. With the increase of the current to 4.75 A, one of the species gets focused on the pepperpot, and the rest stays at the same place. If the current is further increased, it can be seen that the beam becomes divergent for one of the species, and when getting close to 7-8 A another species starts to focus too. In the final image at least three species can be seen, one diverging, the other focused, and the rest not focused at all.

FARADAY CUP CURRENT MEASUREMENTS

The Faraday cup in the LEBT has a limited radius, so it only measures the current of particles near the center of the beam. As a result, different focusing conditions yield different current measurements. In the previous experiment it has been seen that by varying the current on the LEBT solenoids it is possible to focus certain species, while keeping unfocused others. Hence, using appropriate parameters on the different stages, it should be possible to measure the current of each different species separately on the Faraday cup. This way, by knowing how each species reacts against the parameters on the accelerator (specially the Ion Source), it would be possible to favor the generation of the desired species for the LINAC 7, the H^+.

An experiment has been done to try to measure this, in which the same parameters of the previous experiment have been used, setting the solenoids current to 4.75 A. This way, the first of the species (which is believed to be H^+) is focused while the rest are unfocused, and the current on the Faraday cup should be mainly proportional to this species. Then, the power of the RF signal going to the Ion Source has been

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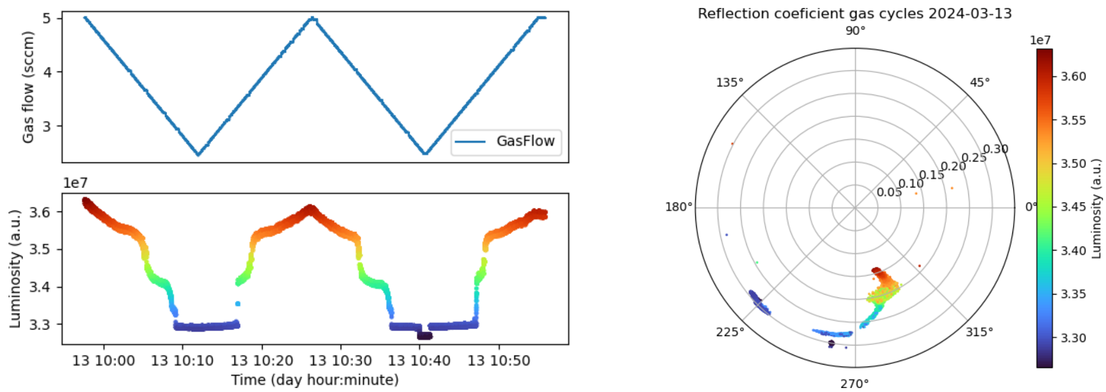

Figure 4: On the left, gas flow cycles and measured luminosity at each moment. On the right, the polar plot of the reflection coefficient of the ion source.

changed on cycles, increasing and decreasing it. In the Fig. 5 the results of this experiment can be seen.

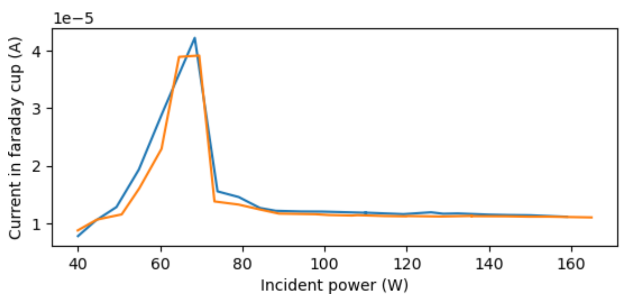

Figure 5: The current measured on the Faraday cup with 4.75 A on the focusing solenoid in function of the power going through the Ion Source. The blue is the result of increasing the power, and the orange of decreasing it.

While in previous experiments it has been seen that the luminosity of the Ion Source always increases with both the gas flow and the power of the RF signal that goes to the Ion Source, it can be seen how in the current of the beam the same is not true. We found that there is a certain RF power where the current of the species selected by the focusing is optimum, and further increasing the RF signal power rather than increasing it decreases its intensity.

Currently, this experiment has not been repeated using different focusing currents on the solenoids so that other species can be analyzed. But when those experiments have been done, it can be possible to determine the composition of the plasma for different parameters on the Ion Source, and how each of its components affects to the luminosity of the Ion Source, to see if the measurements on the Faraday cup can be somehow correlated to those of the luminosity.

CONCLUSIONS AND FUTURE WORK

Thanks to the experiments shown in this work, the team now has a much better understanding about the behavior of the Ion Source of the LINAC 7 accelerator, and it is hence more prepared to optimize its performance and the overall performance of the accelerator. It also provides some clear points where future work have to be put in:

- The temperature of the Ion Source is an important factor on the charged particles generation. It has to be included in the control of the system, by taking into account the changes in the temperature, or by introducing a cooling system to keep it constant after a thermal conditioning step.
- Thanks to the analysis of the photos on the pepperpot scanner, we have experimental proof of different species being formed on the Ion Source and accelerated. How each of those species behaves and how the generation of H^+ can be maximized has to be further explored, in order to get the maximum current on the particle beam, and to apply the correct magnetic fields on the LEBT to focus the desired species only.
- Regarding this, the next experiments can be to perform more measurements using the Faraday cup and different focusing currents on the solenoids, so that how the current of different species answer to the parameters on the Ion Source can be explored.

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