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OPERATION OF THE PHOENIX V3 ECRIS APPLYING DOUBLE FREQUENCY HEATING

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Abstract

PHOENIX V3 is an upgraded version of the V2 ECRIS to be installed at the heavy ion injector at SPIRAL2. The source is under commissioning at LPSC since 2016. One of the main upgrades of the V3 concerns the new microwave injection system including two WR62 waveguide apertures. This new plug having two waveguide ports allows running the ECRIS with the double frequency heating mode by connecting two different high power microwave sources. For the investigation of this plasma feeding method a klystron generator at 18 GHz proving up to 2 kW microwave power was used together with a traveling wave tube amplifier with a 12.75-14.5 GHz bandwidth and 650 W maximum output power. Several experiments were carried out in order to verify the performance with respect to the single frequency operation. Different ion source configurations were investigated and different frequencies and power combinations were analyzed with the aim to maximize the high charge state ion production and to reduce the ion beam instability. The results are reported here.

INTRODUCTION

At LPSC the room temperature PHOENIX V3 ECRIS is under commissioning since 2016. This upgraded version of the PHOENIX V2 ECRIS features a larger plasma chamber, a new hexapole and a reduced vacuum pressure under operation [1]. So far high current of highly charged ions of gaseous and metallic elements has been extracted from this ion source. [2-4].

In order to enhance the high charge state production to fulfil the requirements of SPIRAL2 (i.e. ion beams with intensities of several pµA up to ion mass M~60) high microwave power and other techniques must be applied.

An operation mode successfully used to enhance the beam current of highly charged ions is the “double frequency heating” which consists of the injection of two electromagnetic waves at different frequencies into the ion source. [5]

For this purpose the PHOENIX V3 is equipped with a new microwave injection system including two separate WR62 waveguide apertures where two different high power microwave sources can be connected. The ion source performance has been tested with double frequency heating and has been compared with the single frequency operation. Different ion source parameters were investigated and different frequencies and power combinations were analysed with the aim to maximize the high charge state ion production and to reduce the ion beam instabilities. The results are reported here.

EXPERIMENTAL SET-UP

The PHOENIX V3 ECRIS is designed to operate at 18 GHz and a klystron generator proving up to 2 kW microwave power is used for the ion source commissioning.

The double frequency heating has been performed by connecting a Traveling Wave Tube Amplifier (TWTA) with a 12.75-14.5 GHz bandwidth and 650 W maximum output power to the second waveguide port of the injection plug. In order to properly perform the measurements, following components have been used:

- A WR62 high power wideband 20 dB isolator in order to prevent the reflected and cross coupled power to the TWTA;
- Waveguide vacuum windows covering the TWTA´s bandwidth and the klystron frequency;
- A specially designed 60 kV DC-Break for the TWTA connection with low insertion loss.

Concerning the DC-Break, full wave simulations were performed at LPSC in order to find the best geometrical configuration and the proper dielectric material to achieve a flat insertion within the bandwidth of the amplifier.

The prototype measurements done with a Network Analyser confirmed that the requirement of a flat insertion loss higher than 0.4 dB in the 12.75-14.5 GHz frequency range is fulfilled.

Two WR62 directional couplers are inserted between the isolator and the ion source. Microwave power probes are connected to each directional coupler to measure the forward and the cross-coupled power from the ECRIS. Once the microwave sources have been connected, safety tests were performed to check the power levels crossing between the two waveguides in order to prevent any damage of the microwave sources.

The measurement campaign was carried out with Argon as main gas and Oxygen as support gas and the main focus was the optimization of the intensity of the extracted Ar^{14+} charge state. A 20 kV extraction voltage and a -2 kV voltage were applied to the ECRIS and to the electron repeller electrode, respectively.

One should note that the second waveguide was used for the first time in the source for this experiment and that the second RF vacuum window was installed 2 days

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before starting the experiment. The presented results were achieved within one week and outgassing of the second waveguide was observed during the whole experiment.

The magnetic field configuration was tuned during the measurements, however, already observed during the preliminary investigations, the best performance was measured when the magnetic field is optimized for 18 GHz single frequency operation.

EXPERIMENTAL RESULTS

Preliminary measurements were carried out with the single microwave frequency provided by the 18 GHz klystron in order to study the performances enhancement of PHOENIX V3 when the double frequency heating is applied. The Argon charge state distribution when the ion source settings are tuned to optimize the intensity of Ar^{14+} is shown in Fig. 1. This spectrum was obtained shortly after venting the source to install the second RF window and the Ar^{14+} intensity obtained is lower than the usual reference intensity of 120 µA.

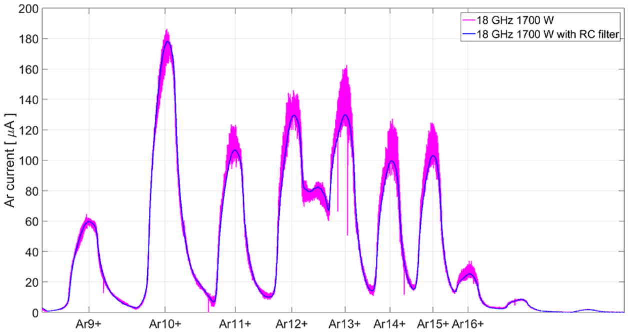

Figure 1: Argon charge state distribution for the single frequency operation.

The maximum current intensities of around 100 µA of Ar^{14+} and around 20 µA of Ar^{16+} have been achieved with single frequency operation at a maximum power level of 1700 W. Because of the low resolution of the spectrometer dipole the highest measured charge state, i.e. Ar^{17+}, cannot be properly separated from the O^{7+}. To overcome this drawback, the commissioning of a new bending dipole is ongoing. For this reason the charge states distribution analysis is restricted to the Argon charge states from 9+ to 16+ while the charge states 10+ and 15+ are superimposed to O^{4+} and O^{6+}, respectively.

It was observed that the measured current presented a periodical oscillation, with repetition frequency around 300 Hz, which could be related to plasma instabilities or to electrical noise. The superposition of a second pumping wave reduced such an instability as shown in Fig. 2 where the Ar^{14+} current evolution, recorded for 5 seconds and 20.000 samples/sec, is plotted. By calculating the standard deviation σ and the mean µ of the measured currents, it is possible to calculate the Probability Density Function:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \qquad (1)$$

This function, calculated for the single frequency operation and for the double frequency heating confirms that this latter technique is useful to reduce the plasma instabilities, as already observed in [6].

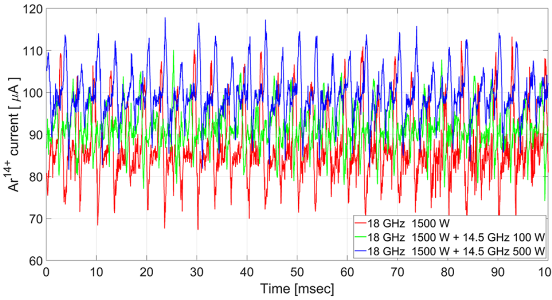

Figure 2: Argon current evolution (20000 samples/sec) for the single frequency operation and for different power combinations of the two frequencies.

In Fig. 3 the normalized Eq. (1) is plotted by using the analysed Ar^{14+} current data for the single frequency operation and when a second microwave source at 14.5 GHz provides additional power levels. This figure confirms that an additional power of 100 W at a second microwave frequency is enough to reduce the current oscillations and to enhance the extracted current of highly charged ions. This enhancement is also a function of selected frequencies as already measured at GSI [7].

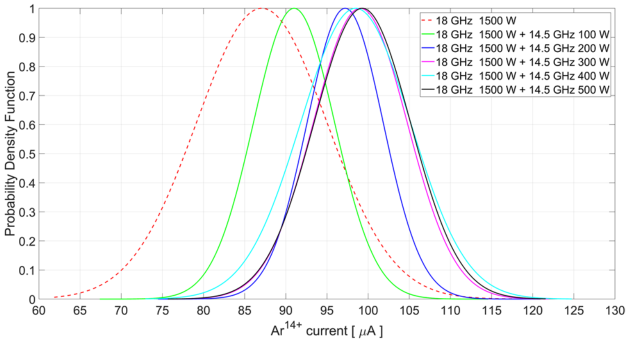

Figure 3: Probability Density Function of the measured Ar^{14+} current for the single frequency operation and for different power combinations of the two frequencies.

In order to find the second frequency where the Ar^{14+} current is optimized, a microwave sweeping generator is used to drive the TWTA with frequency ramps between 12.75 and 14.5 GHz in steps of 200 kHz.

Because of the measured oscillating current a RC low-pass filter, with a cut-off frequency < 300 Hz, is used to limit the periodical instability during the frequency sweep. The overall effect of the filter on the analysed current is shown in Fig. 1 (blue vs purple curve). Then the Ar^{14+} current has been measured while the frequency ramps between 13.8 and 14.5 GHz were performed. The starting frequency was increased since no intensity enhancement was found between 12.75 and 13.8 GHz.

In Fig. 4 is shown the Ar^{14+} intensity for different power combinations distributed between the 18 GHz generator

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and the frequency tuned TWTA. The highest intensity measured with the single operation at 18 GHz is included in the figure. By comparing the Ar^{14+} currents when a total input power level of 1700 W is sent to the ECRIS at 18 GHz with the case when it is the sum of powers (1400W+300W) delivered from two generators at different frequency (cyan line) it is worth noting a current enhancement, with respect to single frequency operation, independent on the choice of the second frequency.

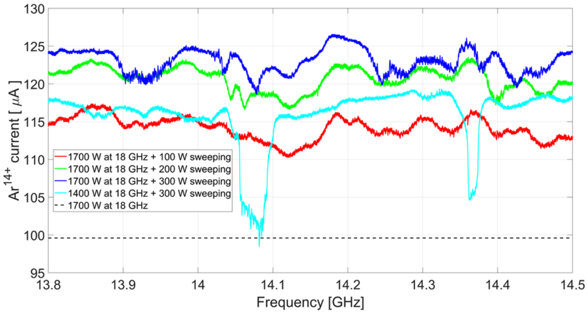

Figure 4: Ar^{14+} intensity comparison between single frequency (dashed line) and double frequency injection.

This enhancement is measured for several higher charge states as shown in the charge states distributions of Fig. 5. The spectra, measured for different frequencies with the highest Ar^{14+} current enhancement, confirm the current gain (up to 15% for Ar^{14+} and up to 34% for Ar^{16+}) obtained with the double frequency system providing the same input power.

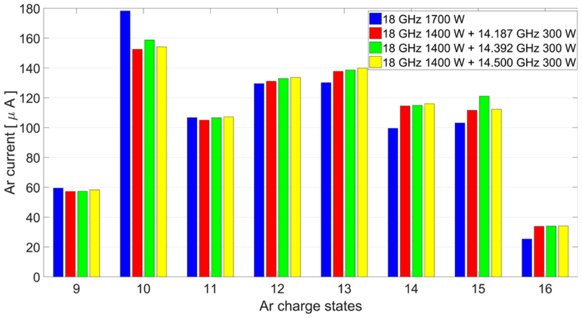

Figure 5: Argon spectra comparison between single frequency injection at 18 GHz and double frequency heating (same input power)

It is also observed that the higher the total forward power and the lesser is the effect of the second frequency on the extracted current. When the maximum power level provided by the klystron, 1700 W, is combined with 100, 200, 300 W coming from the TWTA (see the red, green and blue lines of Fig. 4) the dependence of the extracted current on the second frequency is less than 10 µA. A part of this limitation may be caused by the second wave guide outgassing increasing the neutral pressure in the source and thus reducing the high charge state ion population. Several weeks of operation would be necessary to get rid of the bias outgassing and to investigate further the relation between second RF power and high charge state current improvement. Nevertheless for the maximum input power configuration, 1700 W at 18 GHz + 300 W at a variable frequency, it is possible to identify the frequencies where the Ar^{14+} current is optimized (the highest peaks of the blue line of Fig. 4): 14.187, 14.366 and 14.5 GHz. The charge states distributions of Argon when 300 W power at these three frequencies is combined with the maximum power of 1700 W at 18 GHz are shown in figure 6. For this configuration up to a 24% Ar^{14+} current gain and up to a 54% Ar^{16+} current gain are obtained with respect to single frequency operation, when the second microwave frequency is set to 14.187 GHz.

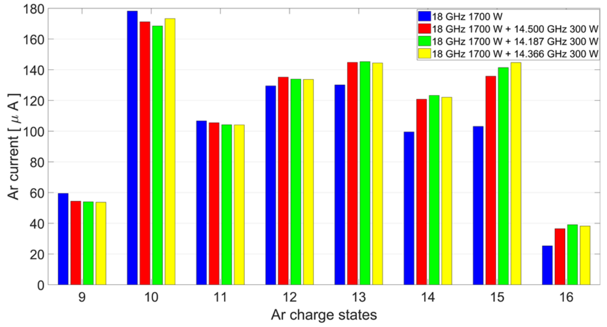

Figure 6: Argon spectra for single frequency injection at 18 GHz and for double frequency heating.

CONCLUSIONS

For the first time the PHOENIX V3 ECRIS has been operated in double frequency mode and an improved stability is measured. The experiment was performed during one week, right after venting the source and installing new second vacuum window and WR62 waveguide, generating transient outgassing. The measurement results were nevertheless quite promising since the maximum extracted Ar^{14+} current is enhanced from ~100 µA to ~125 µA and the Ar^{16+} current increased from ~25 µA to ~39 µA. A high outgassing effect was experienced for higher power levels of the TWTA, thus limiting the capabilities of the ECRIS to produce still higher intensities in double frequency mode. A longer experiment would be necessary to get rid of outgassing and to check the real gain of double frequency at high TWTA power. This result was achieved with a microwave frequency tuning system which allowed to identify the frequencies where the extracted current of higher charge states was optimized.

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