ENHANCEMENT OF ECR PERFORMANCES BY MEANS OF CARBON NANOTUBES BASED ELECTRON GUNS*

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Abstract

The CANTES experiment at INFN-LNS tested the use of carbon nanotubes (CNTs) to emit electrons by field emission effect, in order to provide additional electrons to the plasma core of an ECR ion source. This technique was used with the Caesar source, demonstrating that the total extracted ion current is increased and that a relevant reduction of the number of "high energy" electrons (above 100 keV) may be observed. The injection of additional electrons inside the plasma increases the amount of cold and warm electrons, and then the number of ionizing collisions. Details of the construction of CNTs based electron gun and of the improvement of performances of the Caesar ECR ion source will be presented.

EXPERIMENTAL SET-UP

The ECR ion source CAESAR, operating at INFN-LNS laboratories as injector of the K-800 Superconducting Cyclotron since 2000, has been used as testbench for the CANTES technique,.

In the past, several passive techniques for the injection of secondary electrons were tested [1], with the purpose to increase the electron density and to prolong the ion lifetime in the plasma, enhancing the ionization probability. For example alumina was tested as source of secondary electrons [2].

Active materials, like ferroelectric cathodes, such as PBZT doped with 2 % of Bi_2O_3, have been employed because of their capability of producing high emission yields of energetic electrons [3]. However, their robustness is not sufficient for stable applications into ECRIS. In fact, they showed not only a lack of reliability, but also a limited resistance in plasma environment, and they failed after short time.

During this experiment, we tested a new active technique which makes use of CNTs-based electron guns. In our set-up, two electron guns are placed on a copper plate connected to the RF waveguide, that is usually employed as bias disk in the CAESAR source. A potential in the range 0-2.5 kV, is then applied between the chamber and the waveguide, and the same potential is used to produce the emission field (i.e. the extraction field) between CNTs and the anodic grid.

At an earlier stage, CNTs samples of the same type as used for CAESAR have been tested in microwave discharge plasma (MDIS), in order to preliminary verify if electron and ion collisions can damage them. The adopted MDIS apparatus operates at 2.45 GHz and generates, in presence of an off-resonance magnetic field, a weakly ionized and strongly collisional plasma because of the low electron temperature (T_e<10 eV) and high pressure (0.4 mbar). Tests were made both for air plasma and nitrogen plasma. Results were collected in fall of 2008 and they have shown that CNTs exposed to intense plasma milling (up to 4 mA/cm^2 current density and 300 C/cm^2 of integral dose) have been damaged in presence of oxygen (air plasma) but were perfectly resistant to nitrogen plasma. After the response of this preliminary test-bench, CNTs cathodes have been used for tests in ECR ion sources.

The CNTs electron gun used for the test is made of three elements: a CNTs cathode obtained on a 300 μm thick silicon substrate, a 150 μm thick mica spacer and an anodic copper grid with quad cells of 350 μm side. CNTs eject electrons because of the field emission effect, i.e. quantum tunneling, which is obtained by applying an electric field higher than 3-4 V/μm.

The gun elements are kept together by a MACOR holder, on which the electrical connection is obtained by an evaporated gold track. The MACOR holder is then fixed on a copper plate, i.e. the bias disk of the source, connected to the waveguide of the plasma chamber. The anodic grids are linked to the ground potential of the plasma chamber wall by means of copper creeping contacts. Two of such electron guns were mounted on the same bias disk during the experimental tests. A picture of a CNTs sample and the assembled guns is shown in Figure 1. The CNT e-gun scheme inside the plasma chamber is shown in figure 2 and the CAESAR source during the experiment is shown in figure 3. Prior to the plasma test, each CNTs sample was tested in terms of field emission, by means of a custom-designed apparatus [4]. The field emission properties of similar samples (i.e. CNTs arrays in free-standing porous alumina foils) were already tested [5] and found to be able to produce current densities up to 10-40 mA/cm^2. Emission measurements for the samples tested in CAESAR (i.e. CNTs arrays in porous alumina on silicon), gave even better results, with

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*Work supported by 5th Nat. Comm. of INFN (CANTES experiment).
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current densities up to 50-100 mA/cm^2. The emission surface in our samples was set to about 0.1 cm^2, by using a mica spacer with a 3 mm diameter central hole (Fig. 1). The measurements of X-rays emitted by the CAESAR's central plasma region have been carried out by using an HPGe detector (High Purity Germanium), collimated through lead shielding blocks, in order to suppress secondary X-rays coming from electrons impinging on the lateral walls of the plasma chamber. The detector was surrounded by additional lead in order to minimize the leakage of the X-ray radiation around the main collimator. The collimation hole was 1 mm^2 .

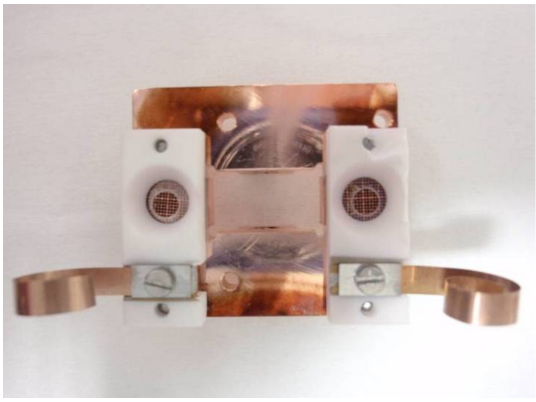

Figure 1: The CAESAR waveguide, holding two CNTs electron guns. The copper creeping contacts are used to put the extraction grid at the same potential of the chamber, while the CNTs are put to negative potential with respect to the chamber.

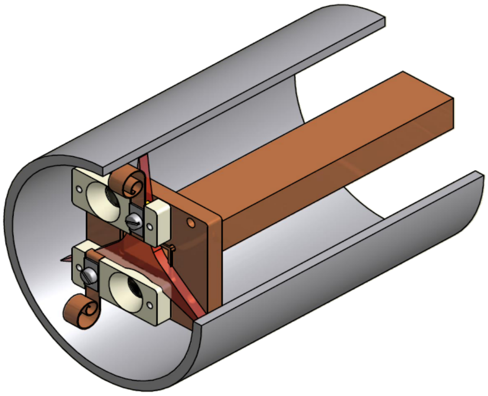

Figure 2: The scheme of the CNTs electron gun.

RESULTS AND DISCUSSIONS

The charge state distribution has been measured at different RF power and voltages applied to the CNTs electron gun for the Kr, working at fixed pressure. The Kr^{11+} extracted current has been taken as reference, for comparison of results. The extracted currents can be compared with those obtained when the CNTs electron gun was switched off. The beam current exceeded the one obtained with the biased disk already at 1 kV, as it can be observed in fig. 4. In spite of the small emission area, an increase of 30-70% was obtained in any case. (about 40% for Kr^{11+}).

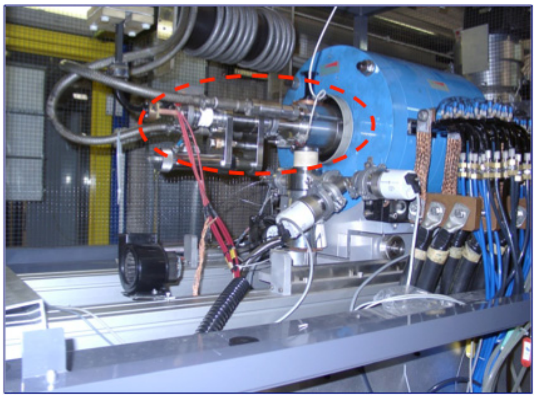

Figure 3: The CAESAR source injection section.

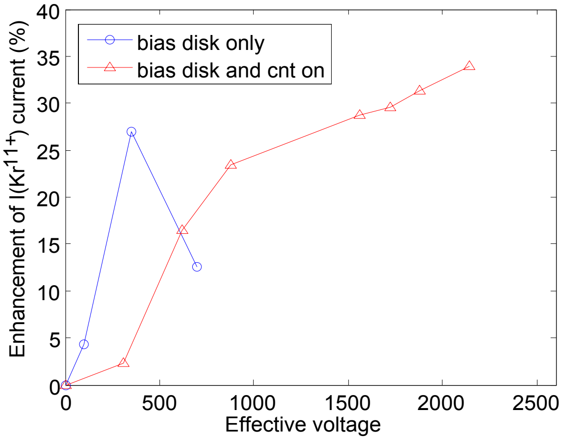

Figure 4: Comparison of produced Kr^{11+} current when using conventional biased disk or emitting CNTs.

Figure 5 shows the extracted current for Kr^{11+} when the CNTs emission is switched on and off, in a time window of 30 seconds and with a RF power of 35 W. The "jump", which takes place immediately after the electron emission from CNTs, was obtained with 2500 V applied to the CNTs extraction grid. It is also interesting to note the afterglow-like peak when the electron gun is switched off, which is similar to the one observed in pulsed operations. The limited time allotted for this experiment did not permit to check if the CNT's afterglow peak and the RF afterglow may be combined to obtain further enhancement of the current peak values.

CNTs provide additional and even more important benefits to ECR plasmas, as they contribute to the total suppression of the hot electrons component, that is evident above 1000 V. The same effect is not evident when using a conventional biased disk. Although the not perfect collimation of the detector cannot permit to extrapolate quantitative estimations on electron spectral temperature, it is however evident in fig. 6 that the number of the hottest electrons decreases.

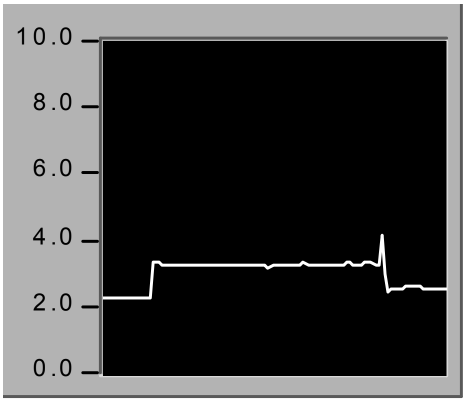

Figure 5: Trend of the Kr^{11+} current (in µA) during the switching on-off of CNTs emission, in a time window of 30 seconds. The CNTs applied voltage was 2500 V, at 35 W RF power.

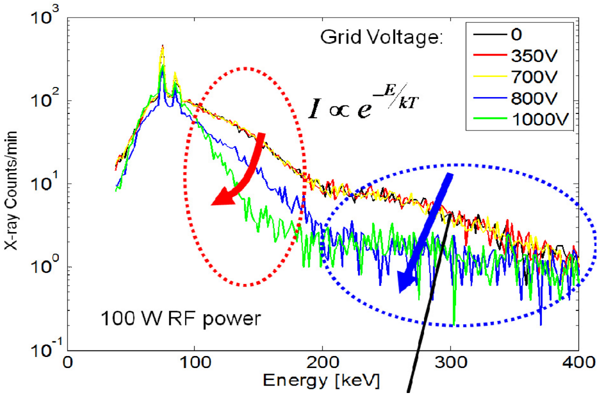

Figure 6: Axially emitted X-ray spectra for different voltage values and RF power of 30 W.

By providing additional cold electrons to the plasma, the average energy decreases as a larger number of electrons will share the same amount of energy injected into the plasma chamber by means of the microwave (the RF power is kept constant).

Measurements at low power shown in figure 6 are similar to the ones collected at 100 W and 150 W, demonstrating that the contribution of CNTs is effective in all cases (either for the current increase and for the damping of hot electron generation), and that the optimal CNTs' voltage increases with the power. Confirmations of these results came also by measurements at different values of the pressure in the chamber, even if some fluctuations in the maximum enhancement factor were evident. In all cases the counting rate of the X-rays above 100 keV was strongly damped. Long run measurements were also done. In fig. 7 the current plot during a 24 hours tests is shown, with all parameters fixed (gas input, power, magnetic field).

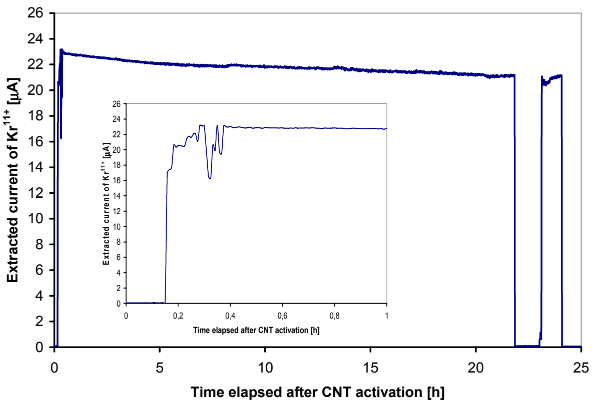

Figure 7: Current plot during a 24 hours test.

The small decrease is correlated to plasma chamber outgassing, which changed the pressure conditions inside.

CONCLUSIONS

We have observed a relevant reduction of the number of higher energy electrons after the injection of the electrons emitted by the CNTs-based electron gun. The current gain was between 30 and 70%. Once that a full comprehension of the phenomenon will be gained, this last result may be applied to modern ECRIS which performances are strongly limited by the occurrence of such hot electrons, especially when large power and frequencies above 18 GHz are used.

The use of CNTs-based emitters has solved robustness problem which emerged when ferroelectric cathodes were used. For the presented tests, their period of operation was limited to some tens of hours. Future experiments on ECRIS will focus on reliability tests, for one week or more.

ACKNOWLEDGEMENTS

The support of the 5th National Committee of INFN (CANTES experiment) is gratefully acknowledged.

The authors wish to thank Salvo Marletta, Maurizio Castro, Luciano Allegra, Salvo Vinciguerra, at INFN-LNS, and Michele Furini at INFN Bologna, for their help in supporting the experiment during its preparation and data taking.

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