Enhancement of ECRIS performances by means of carbon nanotubes based electron guns

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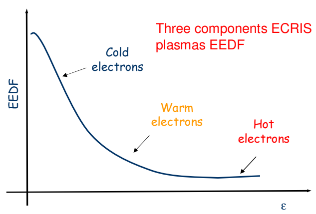
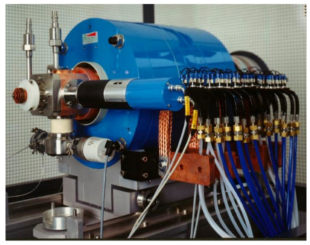
Experimental set-up and electron gun assembly

The main goal of our experiment is the characterization of either extracted current and X-rays under different plasma conditions and in presence of a source of auxiliary electrons. The effect on the quality factor of the additional electrons on the EEDF of the plasma has been particularly studied. **We present an electron gun based on CNTs and working as an active electron donor for the CAESAR ECRIS operating at LNS.**

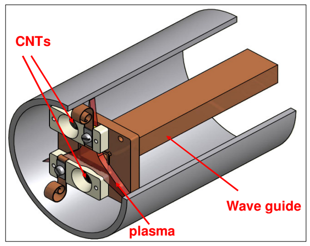


Cold electrons contribute to plasma stability, warm electrons are of primary importance for ionization up to high charge states, moderate amounts of hot electrons contribute to ion confinement, but very high energy particles (E>300 keV) are detrimental for ECRIS (liquid He boil-off).

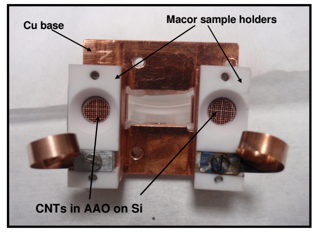
Maximization of the warm component is mandatory to ensure high ionization rates and safe operations. Several techniques have been investigated in the last decade in order to increase the electron density: Addition of auxiliary electrons can be done by means of active or passive methods (like alumina tubes and other techniques).

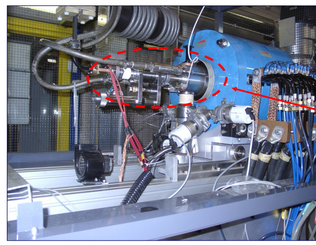


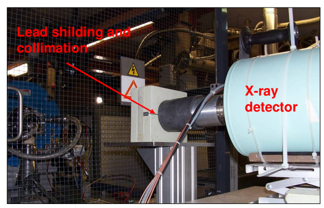
The ECR ion source CAESAR, which operates at INFN-LNS laboratories as injector of the K-800 Superconducting Cyclotron since 2000.

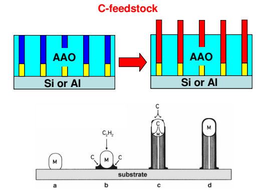


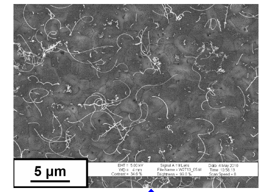
The CNTs electron gun is essentially made of three elements: a CNTs cathode obtained on a 300 mm thick silicon substrate, a 150 mm thick mica spacer and an anodic copper grid with quad cells of 350 mm side. CNTs eject electrons because of the field emission effect, i.e. quantum tunneling, which is obtained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





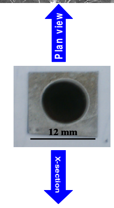


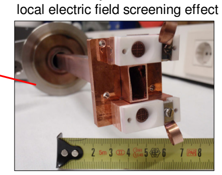


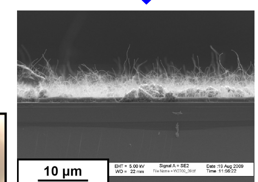


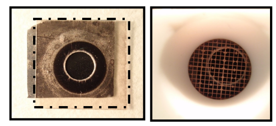
CNTs array synthesized by Catalyst Assisted-CVD:

- Porous alumina grown on silicon substrate
- Cobalt nanoparticles, as catalyst, electro-deposited within alumina pores
- Multy-walls CNTs grown @ 620 C (height 3-20 μm,∅ ~ 80 μm)
- Emitter density ~ 1/1000 pores to avoid local electric field screening effect



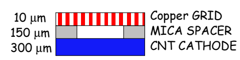






150 μm thick MICA spacer with central hole (∅ 4 mm)

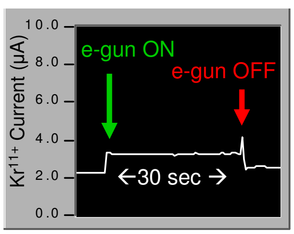
Cu grid (80% transparency)



The substrate for CNT syntesis:
sylicon chip (12x 12 mm; 280 μm thick)
porous alumina layer (2-3 μm) with catalyst electrodeposited in the pores bottom

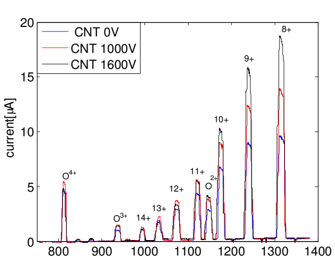
High robustness → easy to integrate

EFFECTS OF CNT BASED E-GUN ON CSD



Trend of the Kr11+ current (in mA) 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.

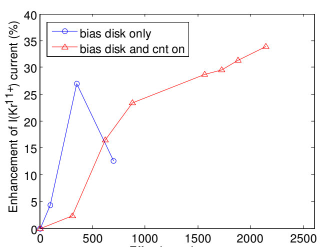
Current improvements obtained with the CNTs-based electron gun can be compared with those observed when using the bias-disk alone. To the latter we applied potentials ranging from 35 to 720 V, but at bias voltages larger than 350 V the extracted current drastically decreases. Conversely, the current is boosted by CNTs for voltages higher than 750 V and then it increases monotonically, slowly approaching to saturation above 1000 V.



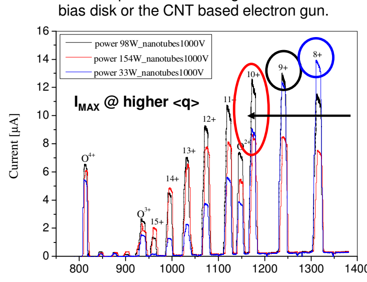
Changes in the CSD when three different biasing voltages are applied on the CNT extraction grid, at 30 W of RF power. This low power level limits the most evident increase of the extracted current to the lower charge states.

It is also interesting to note the afterglow-like peak when the electron gun is going to switch off. The gain of current is almost 60 % and reaches 100 % during the afterglow peak, at an RF power of 35 W.

CNTs applied voltage [V]	CNTs effective voltage [V]	Kr^{11+} currents [μA]	
		Bias disk + CNTs	Bias disk only
0	0	11.5	11.5
100	80	---	11.8
350	310	11.8	14.6
700	620	13.4	13.4
1000	880	14.2	---
1800	1560	14.8	---
2000	1720	14.9	---
2200	1880	15.1	---
2500	2140	15.4	---



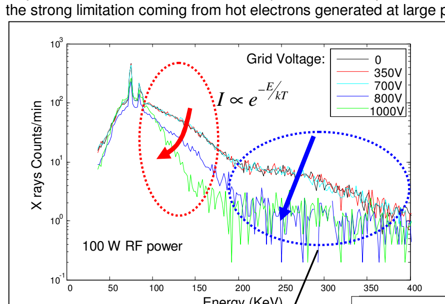
Comparison of the enhancement factor in the production of the kr^{11+} chrge state at 100 W of RF power when using the conventional bias disk or the CNT based electron gun.



Increasing the power, the number of warm electrons increases as well, so that the CSD shifts to higher charge states (because of the larger warm component temperature). However, it can be observed in the X-ray spectra that the hot electrons are still damped by the auxiliary electrons.

INVESTIGATIONS ABOUT THE DAMPING OF THE HOT ELECTRONS

CNTs provide additional and even more important benefits to ECR plasmas: the total suppression of the hot electrons component is evident above 1000 V. The same effect is not evident when using a conventional biased disk, which in addition deteriorates the performances above 350 V. This result is even more important than benefits provided to CSD, because the usage of CNTs-based electron guns may be an effective and reliable technique to further improve the modern ECRIS performances without the strong limitation coming from hot electrons generated at large power and high frequencies.



Pile-up effect (due to hot electrons Impinging chamber walls)

Injecting additional cold electrons

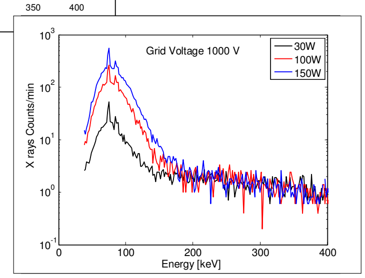
Hot electron component is reduced

Bremsstrahlung peak narrower

High Energy X-rays decrease

Hot electron generation mechanism results damped

The suppression of the hot electron component does not depend on the applied RF power. The hot electron tail completely disappears at 1000 V of CNT grid biasing voltage, and it is not affected by the increase of the microwave power, at least up to the maximum level employed in our experiment.



Long time operation and CNT electron gun reliability

The last part of the experiment was devoted to the verification of the CNT based electron gun reliability over long time operations. At the given pressure and power the Kr^{11+} current extracted when the electron gun was on was 40% larger than the current coming out in usual operations. A slowly decaying trend was however evident during the first 8 hours, featuring a weak degradation of the nanotubes. The interruption of output current occurred after 24 hours of cw operations, due to a blackout of the laboratory electrical network.