

**APPLICATION OF FERROELECTRIC CATHODES  
TO ENHANCE THE ION YIELD IN THE CAESAR SOURCE AT LNS**

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With increasing RF power the electron concentration in the plasma of ECR ion sources is decreasing in comparison to the ion concentration, so that the plasma is charging up positively. Direct injection of electrons into the ECR plasma can increase the electron charge density and the ion current yield. We have used ferroelectric cathodes to inject electrons into the Argon plasma of the CAESAR ion source at INFN-LNS (Catania, Italy). The cathode was placed at about 10 cm from the hot plasma and a bipolar high voltage pulse of 1.6 kV was used to trigger the electron emission. No additional acceleration has been provided. The use of the ferroelectric cathode leads to an increase of about 30% of the Ar<sup>8+</sup> intensity, which has been monitored during the test. In addition, magneto-hydrodynamic instabilities in the ECR source were damped during and after electron injection.

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# APPLICATION OF FERROELECTRIC CATHODES TO ENHANCE THE ION YIELD IN THE CAESAR SOURCE AT LNS

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## Abstract

With increasing RF power the electron concentration in the plasma of ECR ion sources is decreasing in comparison to the ion concentration, so that the plasma is charging up positively. Direct injection of electrons into the ECR plasma can increase the electron charge density and the ion current yield. We have used ferroelectric cathodes to inject electrons into the Argon plasma of the CAESAR ion source at INFN-LNS (Catania, Italy). The cathode was placed at about 10 cm from the hot plasma and a bipolar high voltage pulse of 1.6 kV was used to trigger the electron emission. No additional acceleration has been provided. The use of the ferroelectric cathode leads to an increase of about 30% of the  $\text{Ar}^{8+}$  intensity, which has been monitored during the test. In addition, magneto-hydrodynamic instabilities in the ECR source were damped during and after electron injection.

## 1 INTRODUCTION

Although the performance of Electron Cyclotron Resonance Ion Sources (ECRIS) in terms of ion beam intensity, energy spread, emittance and ionisation capability up to very high charge states is constantly improving, ECRIS plasmas always suffer a deficit in the electron population, because the electrons escape along the loss cone with a rate largely higher than that of the ions [1, 2, 3]. The electron deficit generates a positive potential in the plasma, which shortens the ion lifetime and consequently the ionisation rate. The use of elements, which act as electron donors and lower the plasma potential, can extend the ion lifetime in the plasma or the plasma density and increase significantly the ionisation probability and the yield of multiply charged ions [3].

Different systems have been used throughout the years: electron injection by a dedicated electron gun, use of special plasma chamber wall coatings, use of biased disks or use of Al plasma chambers. In this paper we present the result of electron injection from ferroelectric cathodes into the Argon plasma of the ECRIS CAESAR of LNS, Catania, Italy [4]. We have chosen ferroelectric cathodes for their robustness and for their capability of producing high emission yields of energetic electrons in virtually

any environments and without accelerating field. The resulting installation is much simpler than that of a conventional electron gun, which requires a diode gap of a few tens of kV and whose cathodes are easily poisoned.

## 2 FERROELECTRIC CATHODES

Electron emission from disk-shaped ferroelectric ceramics can be triggered by a high voltage pulse (a few kV) applied to electrodes deposited directly on the cathode surfaces<sup>1</sup>. The applied electric field triggers polarisation switching which causes the emission of the electrons located in the emitting surface layer. Due to the non-linearity of the ferroelectric ceramics, energetic electrons are emitted [5].

Tests performed at University of Milano indicated that fast bipolar excitation pulses (first positive, then negative) are to be preferred to monopolar ones as they lead to higher electron emission yield and cathode lifetime [6]. The higher yield is a consequence of the larger polarisation change produced by a bipolar pulse. The leading positive pulse induces a positive polarisation charge on the ferroelectric emitting surface, which attracts screening charges (i.e. electrons). The subsequent negative pulse, by switching the polarisation, causes their ejection into the vacuum. In addition, tests performed at the University of Milano, indicate that the alternate excitation prevents the ferroelectric domains to freeze in a preferred orientation. As a consequence, the ferroelectric domains maintain their sensitivity to an external electric field and electron emission occurs up to the damage threshold of the cathode electrodes.

A new kind of ferroelectric ceramic (lead-barium-zirconium-titanate (PBZT) doped with 2% of  $\text{Bi}_2\text{O}_3$ ) [7] was used for the experiments described in this paper. This material has a ferroelectric-paraelectric phase transition temperature very close to room temperature (about 60 °C), thus a low electric field is required to trigger the polarisation switching.

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<sup>1</sup> In our case, for convenience, the excitation pulse is applied to the rear surface of the cathode, while the front surface is kept at ground potential.

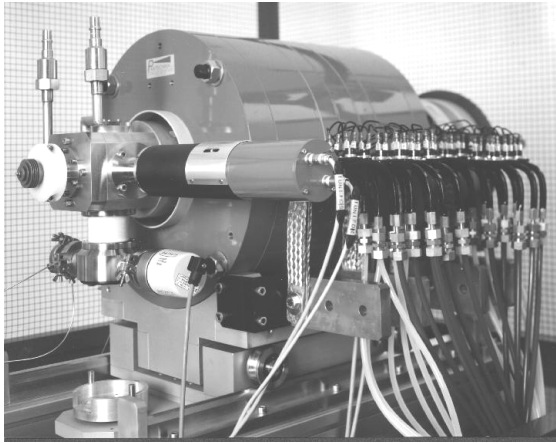


Figure 1: The source CAESAR at INFN-LNS.

The cathodes have been prepared at University of Milano from ceramics produced at the University of Katowice [7]. The disk-shaped cathodes have a diameter of 8 mm and a thickness of 0.6 mm. The emitting surface electrode consists of a 200  $\mu\text{m}$  period grid and the rear surface electrode of a solid disk. The emitting area is about 12  $\text{mm}^2$ . The cathodes were switched with bipolar voltage pulses of  $\pm 1.6$  kV amplitude applied to the rear electrode of the cathode, corresponding to about 25 kV/cm across the cathode.

### 3 ION YIELD ENHANCEMENT TESTS

#### 3.1 The ECRIS

The ECR ion source CAESAR is described in [4]. The source can operate at an ECR frequency of up to 18 GHz with one of the highest confining fields yet achieved in conventional ECR ion sources. The plasma chamber is aluminum made and a biased disk is used to enhance the

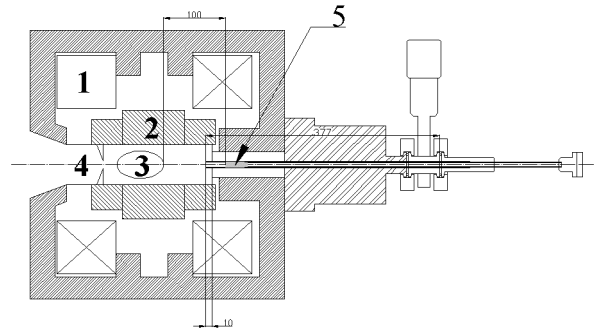


Figure 2: Basic test setup with ECR ion source chamber: (1) coils, (2) hexapole, (3) ECR plasma surface, (4) extractor, (5) ferroelectric cathode.

electron density. A photograph of the source is shown in Figure 1. We have decided to perform our test on the CAESAR source rather than on the super-conducting SERSE ion source, which is also available at LNS for two reasons: (1) the smaller size and the simpler layout of CAESAR simplify any kind of test, if not extremely high values of charge state are needed, (2) the worse magnetic confinement of CAESAR is expected to enhance the effect of the ECR plasma electron deficit.

#### 3.2 Experimental Set-up

The ferroelectric cathode was inserted into the injection channel of the ion source as shown in Figure 2. The emitting grid electrode was connected to the ground potential of the plasma chamber wall. The high voltage power supplies and control electronics were included into a Faraday cage placed on top of the CAESAR. No additional acceleration has been provided. As the electron current could not be measured during the tests, it has to be extrapolated from off-line measurements performed at the University of Milano with the same cathode

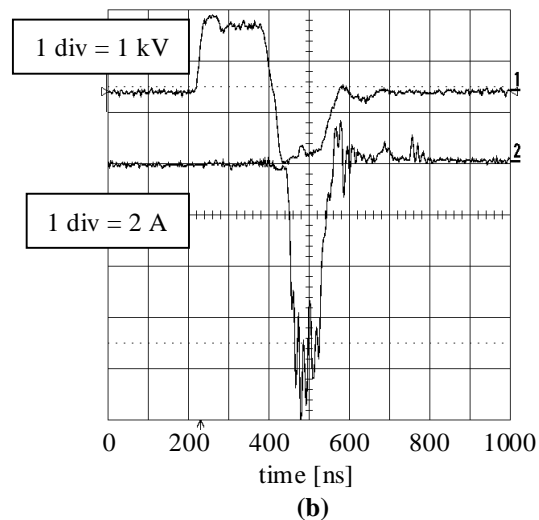
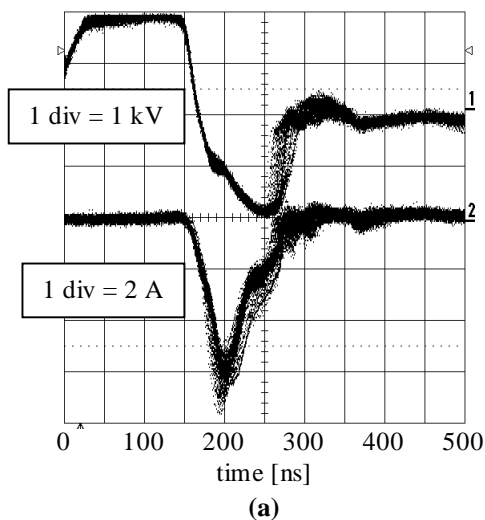


Figure 3: Waveforms of excitation voltage (top trace) and emitted current (bottom trace) as recorded during offline test of electron emission from ferroelectric cathodes, (a) superposition of 100 shots taken before the test in the ECRIS, (b) bets-of-class shot taken after the test in the ECRIS.

before and after the test in the ECRIS (see Figure 3). Figure 3.a shows the typical result of superposition of 100 consecutive shots taken before the test. Figure 3.b shows the highest emission shot after the test (about 8 A). As the average emitted current before and after the test was 6 and 4.5 A, respectively, we conclude that a current of about 5 A ( $40 \text{ A/cm}^2$ ) in 100 ns pulses, was injected into the plasma.

The effects of the presence of the hot plasma instead of the cold laboratory vacuum and of the positive plasma potential (+50 to +100 V) are not precisely quantifiable, but lead to higher emission in the ECRIS tests than in the off-line tests.

The extracted ions with a kinetic energy equal to 20 keV per charge state are focused by a solenoid and deflected by a  $90^\circ$  dipole magnet, to be analyzed with a Faraday cup located at its image point. The intensity of the  $\text{Ar}^{8+}$  species has been monitored during the experiment.

### 3.3 Experimental Results

During the test, the plasma was run in dc mode and the ferroelectric cathode was pulsed at a repetition rate from 1 to 500 Hz. Also the cathode-plasma distance was varied from 4 to 20 cm. The highest enhancement of the ion current yield was obtained at a repetition rate of 250 Hz and at a cathode-plasma distance of 10 cm.

Figure 4 shows the  $\text{Ar}^{8+}$  current as a function of the RF heating power. Without electron injection, the ion current increases with the RF power but tends to saturate. The injection of electrons seems to avoid such saturation and 30% higher ion currents are produced at the RF power of 400 W (which is the optimum and maximum RF power for  $\text{Ar}^{8+}$ ). The electron injection from the ferroelectric cathode proves to be increasingly effective with increasing RF power heating. Such behaviour is physically reasonable: the higher is the RF power level, the higher are the velocities to which the electrons are accelerated by the RF field and the more electrons are lost from the outer plasma shell to the walls of the plasma chamber. Restoring the charge equilibrium of the plasma must inevitably increase the ion current yield. At low power levels the electron loss from the plasma seems to be negligible and the amount of injected electrons is too small to significantly increase the ECR yield.

In all experiments contributing to Figure 4 the ferroelectric cathode was pulsed at a repetition rate of 250 Hz. The time between emission pulses is 4 ms, which is comparable to the build-up time of the  $\text{Ar}^{8+}$  ions in an argon plasma of density of about  $10^{12}/\text{cm}^3$ . The electron injection also improved the magneto-hydrodynamic stability of the ECR source; as observed on the oscilloscope signal of the Faraday cup, the beam ripple decreased by a factor two or three.

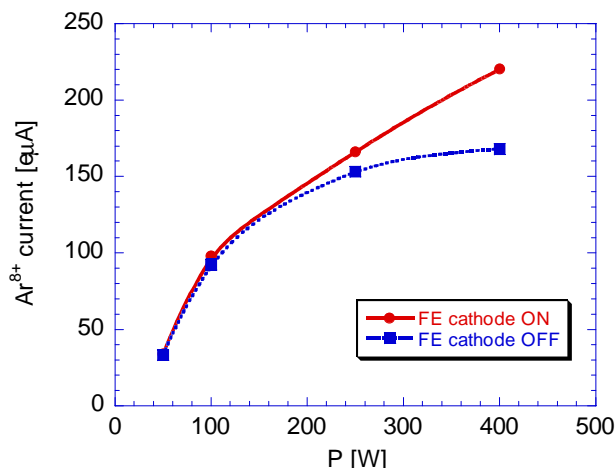


Figure 4:  $\text{Ar}^{8+}$  ion current as a function of RF heating power with and without electron injection from the ferroelectric cathode.

## 4 CONCLUSION

The preliminary tests with electron injection from ferroelectric cathodes into an ECR Ar ion plasma have produced an increase of the yield of ion output current of 30%. The electron injection proved to be increasingly effective with increasing RF power heating. In addition, the controlled injection of electrons along the axis increased the ion current stability.

A new ferroelectric material with a ferroelectric-paraelectric phase transition near to room temperature has been used in the tests. The cathode was operated without an external extraction voltage and with the emitting grid electrode of the cathode connected to ground.

In principle, a large enhancement of the electron density inside the plasma may change the sign of the plasma potential. In this case, not only the ion yield could increase, but also the average charge state, because of the enhanced confinement and of the higher ion lifetime.

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