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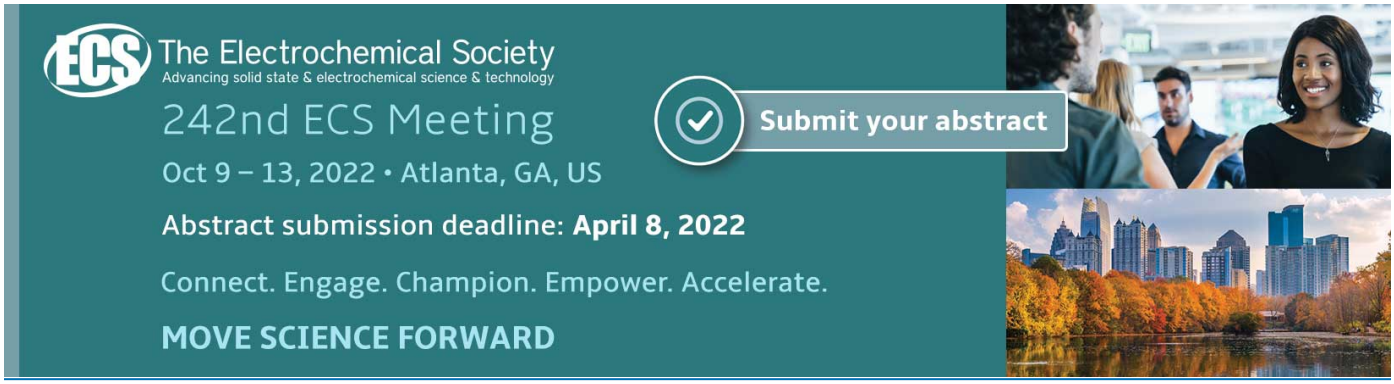

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Performance comparison of LaB6 and C12A7:e- emitters for space electric propulsion cathodes

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Abstract. This work, based on an EU-funded project, NEMESIS, is aiming at developing electride-based cathode technology which is compatible with all kinds of electric propulsion systems requiring neutralization. Its target is to demonstrate and validate the performance of a novel C12A7:e- electride material as electron emitter instead of traditional thermionic emitters such as lanthanum hexaboride, LaB_6, or barium oxide, BaO. In this study, a fair comparison between LaB_6 and C12A7:e- samples was performed both addressing pure material characterization parameters as well as comparing performance as cathodes under different architectures and operational conditions. In this case, a current/cathode power ratio around 3 mA/W was obtained when using the C12A7:e- sample in a plasma environment with Ar, which is approximately one order of magnitude higher compared to the LaB_6 sample.

1. Introduction

Electric propulsion (EP) is an increasingly adopted technology for spacecraft propulsion in station keeping, orbit raising, or primary propulsion applications. EP systems use electrical and magnetic fields to change the velocity of a spacecraft. Most of these kinds of spacecraft propulsion systems work by electrically expelling propellant, reaction mass, at high speed. A common need for most of the EP thruster technologies is to operate a device for electron emission either for plasma generation or for charge neutralization of impellent positive ions [1–3]. Permanent research on new materials and architectures is mandatory to optimize efficiency of such devices in the extreme operation conditions and limited resources in space.

Traditional electron emitters used for EP in the space industry are lanthanum hexaboride, LaB_6, and barium oxide, BaO, both requiring very high temperatures for operation, thus consuming large amounts of energy and producing huge thermal stress to EP thrusters and neutralizers and all surrounding subsystems, which drives to deterioration and reduction in components lifetime even when using expensive high thermally resistant materials.

In this paper are discussed the physical properties of the dodecacalcium hepta-aluminate (mayenite, $12CaO{\cdot}7Al_2O_3$, $Ca_{12}Al_{14}O_{33}$ or C12A7) based electride, hereinafter referred to as C12A7:e- material. This novel material has excellent materials properties for thermionic devices for EP applications such as hollow cathodes or thermionic emitters [4]. Its properties are superior to those of conventional

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ceramics currently employed in EP neutralizer technology. It is anticipated that C12A7:e- neutralizer technology is a potential game changer widening the applicability of EP immensely by enabling new mission scenarios due to higher reliability, compatibility with alternative propellants, lower power consumption on satellite and less thermal load at low costs.

One objective of this work, based on the EU-funded project Novel Electride Material for Enhanced electrical propulSIon Solutions (NEMESIS) [5], is to demonstrate and validate for the first time the application of a C12A7:e- electride material as electron emitter instead of traditional thermionic emitters such as LaB_6 or BaO. As it is demonstrated, the performance of the electride material is superior to any other electron emitter due to its unique properties such as its chemical inertness, its low work function, a much lower operational temperature, and an improved lifetime. Due to the novel application and the low knowledge about the behavior of the material in a plasma environment, several devices with different cathode architectures were designed and tested before obtaining an optimize prototype able to operate with a LaB_6 and a C12A7:e- sample.

In this work, we will first compare the results of C12A7:e- and LaB_6 materials, in terms of thermionic emission, and then we will move to a real operation environment of both thermionic materials placed inside a cold cathode neutralizer prototype within a plasma environment.

2. C12A7:e- and LaB_6 material thermionic emission parameter characterization

2.1. C12A7:e- and LaB_6 comparison of thermionic emission in vacuum

As previously commented, the pure thermionic emission of a C12A7:e- sample and a LaB_6 sample will be first compared in terms of the extracted current density as function of temperature and acceleration voltage.

In a first experiment, run by *Justus-Liebig-University of Giessen*, the setup is an anode-cathode configuration where the distance between them is 2 mm. The sample was heated by a heater underneath the cathode, and the cathode is negatively biased to accelerate the emitted electrons towards the anode. In addition, the sample temperature is measured by a thermal imaging camera. During the initial tests performed using medium electron concentration samples of C12A7:e- ($N_D \approx 10^{20}$ cm^{-3}), the extracted current density was similar for both emitters at medium temperatures, around 600 °C, when biasing with 1000 V (see Table 1).

Table 1. Comparison of C12A7:e- and LaB6 current densities at 1000 V extraction voltage

Emitter	Temperature (ºC)	Current density (nA/cm^2)
C12A7:e-	607	106
LaB_6	603	104

To verify the current emission values, further tests were performed at *Exotrail* premises with a different setup and prototype. The experimental setup includes the use of a vacuum chamber, a test hardware in which a sample is placed, a power supply and sourcemeter for voltage and current control, thermocouples and software for data acquisition. The vacuum chamber is equipped with a rough pump and a turbopump with a pressure during test in the range of $1 \cdot 10^{-6}$ to $8 \cdot 10^{-6}$ mbar. Regarding the setup, it includes a pyrolytic boron nitride heater, a boron nitride insulator and a tantalum foil as cathode and anode terminal. The distance between cathode and anode is 4.1 mm, similar value compared to the first experiment. In this prototype, the temperature is monitored by two thermocouples.

To assure a correct measurement of the current, a procedure was developed in order to allow the proper outgassing at different temperatures before acquiring the data. In addition, the leak current of the system, without samples, was measured and subtracted from the current-voltage curves recorded at different sample temperatures.

Figure 1 shows the outcome of the comparison tests on thermionic current emission measured with C12A7:e- and with LaB_6 emitter materials at different temperatures and acceleration voltages. As seen in Figure 1, the emission current extracted from the C12A7:e- sample is higher than that of the LaB_6 one. For example, at about 900°C, the extracted electron currents of the C12A7:e- and the LaB_6 samples are 0.1 mA and 0.01 mA, respectively

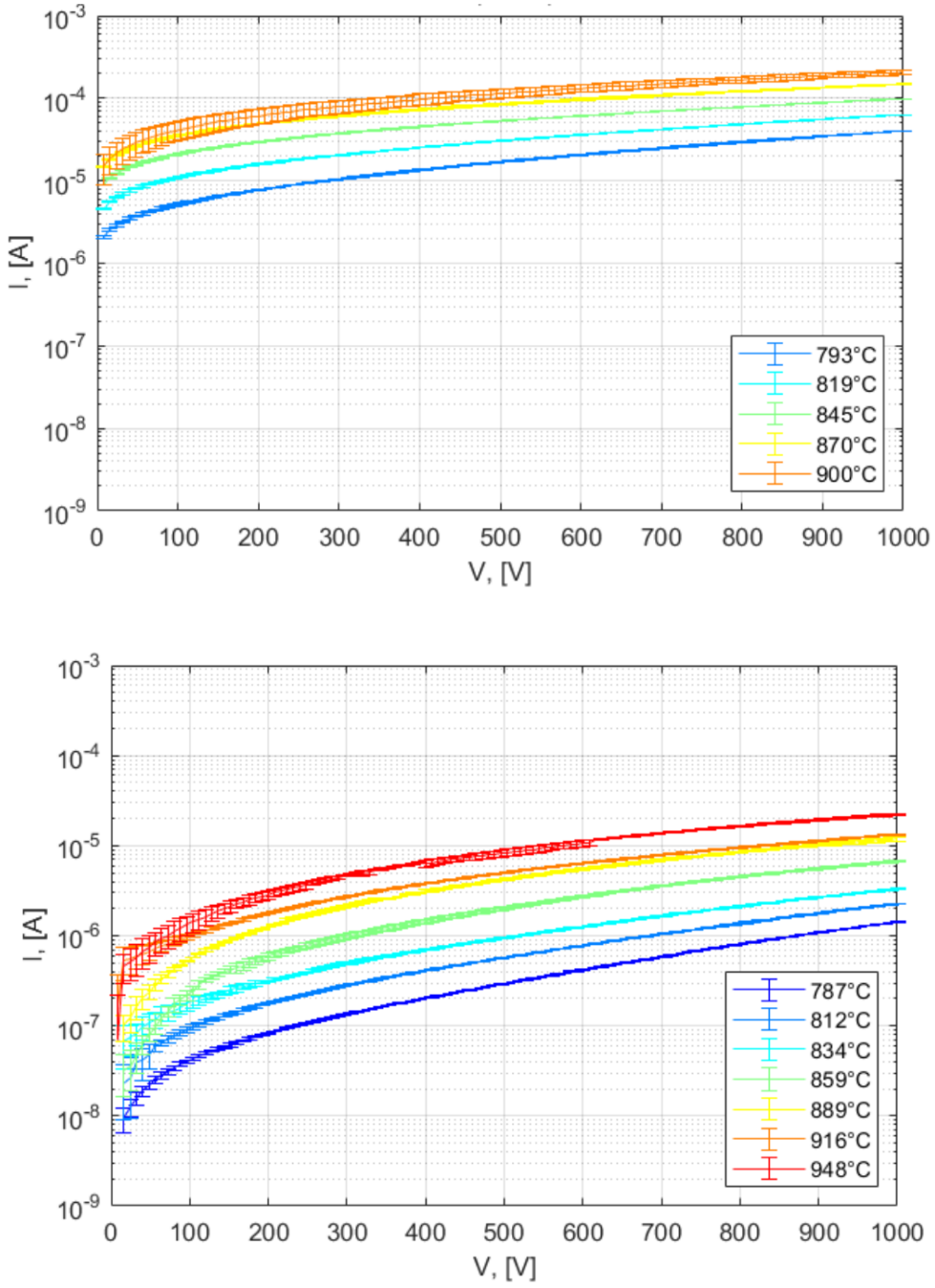

Figure 1. Emission current extracted from C12A7:e- (top) and LaB6 (bottom) 8 mm diameter disc samples

2.2. C12A7:e- and LaB6 performance comparison in a plasma discharge cathode

In this section, we will describe the comparison tests of both materials as emitter in a plasma discharge cathode neutralizer. For this purpose, we will use one-inch diameter discs with 2 mm thickness of each material as emitter, placed within a prototype heater less neutralizer described hereafter. In this case, the cathode is based on a heater less neutralizer working at low temperatures, approximately below 300ºC, and therefore reducing the power consumption compared with the previous prototype setups described in section 2.1. A conceptual scheme and a description of the main characteristics of the cathode are represented in Figure 2, and the results of performance test under different operation conditions are presented below.

As a brief description, it is necessary to use a negatively bias power supply for the cathode (V_c) while the keeper is grounded. As it can be seen in Figure 2, the noble gas is introduced in the gap space between the keeper structure and the cathode, being the keeper totally isolated from the cathode. In addition, a positively bias power supply, hereinafter named as V_a (anode), is also necessary. This metallic anode, located at approximately 40 mm, will collect the electron current emission from the cathode.

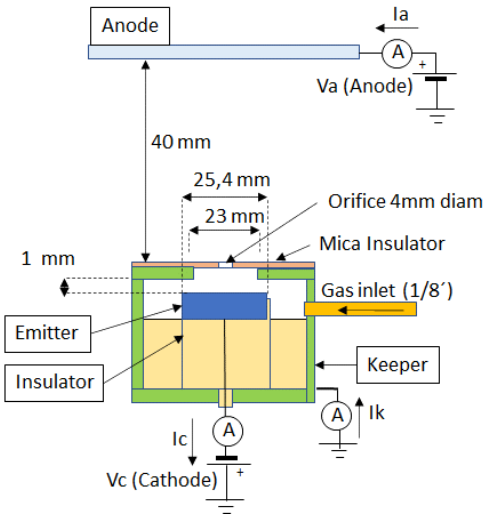

Figure 2. Scheme of the heater less neutralizer used for performance tests

Table 2. Vacuum chamber and control equipment characteristics

Vacuum chamber	300x300x350 mm size Turbo molecular pump Edwards EXT255H Vacuum pump Alcatel Vacuum level up to 10^{-7} Torr Connectivity of up to 9 thermocouples
Control equipment	Pico-amperemeter (Keithley DDM 6500) DB9 connector for 9 analog signals Two current sources (100 A, 22.3 A) High voltage power supply 300 V

Table 3. Performance test conditions

Size sample	25.4 mm diameter and 2 mm thickness
Cathode voltage (V_c)	150-300 V
Gas	Ar and Xe: from 1 to 50 sccm mass gas flow
Thermocouple	Type K connected at the base of the sample

The performance measurement tests presented hereafter were obtained with the same vacuum chamber, and test set-up cathode prototype configuration, described in Tables 2 and 3. As it will be presented in the following figures, the anode current (I_a) was obtained as a function of the anode voltage (V_a), gas flow and cathode power (P_c) parameters.

It was observed that cold start ignitions present instabilities for both materials before reaching 200 ºC. To solve this issue a warmup procedure was applied from room temperature till reaching close to 250 ºC. This process was initially carried out by means of a heater, but finally it was replaced by an Ar bombardment with a mass flow of 50 sccm for 5 min. Once the system is ignited and thermal stabilized, we obtained a stable operation mode of the cathode without instabilities using a mass flow of 0.9 sccm Xe and 1.5 sccm of Ar.

In Figure 3 we can observe that anode currents and performance ratios are significantly higher for C12A7:e- electride than for LaB_6 when using 1.5 and 10 sccm of Ar. For example, when applying 30 W and using 1.5 sccm of Ar for C12A7:e-, we obtained around 20 mA anode current with the anode grounded, and a current of around 100 mA when applying an anode voltage of 20 V. A similar performance was observed with a mass flow of 10 sccm of Ar where the current obtained for the electride sample achieved a value of 150 mA at 30 V of anode voltage.

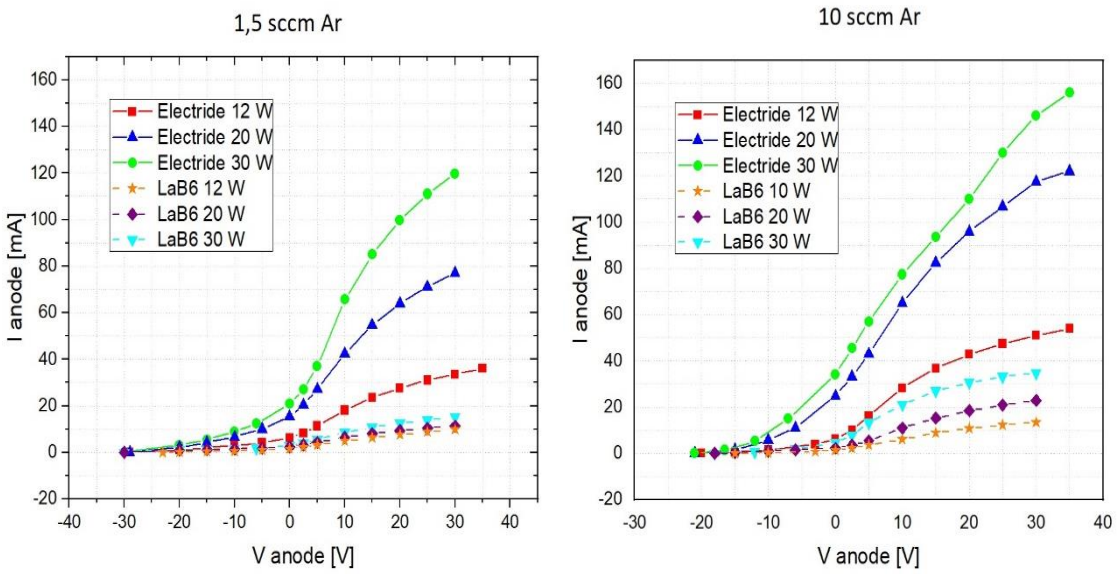

Figure 3. I/V characterization curves of C12A7:e- and LaB_6 samples in a cold cathode at 1.5 and 10 sccm Ar mass flow for different cathode powers

In Figure 4 we can see the results of the anode I/V characterization curves for 10, 20, and 30 W cathode power levels, for 0.9 and 5 sccm mass flow of Xe. The LaB_6 sample was not characterized when using 0.9 sccm mass flow of Xe since it was not possible to reach a stable operation of the cold cathode below 5 sccm, being this another advantage of the C12A7:e- sample.

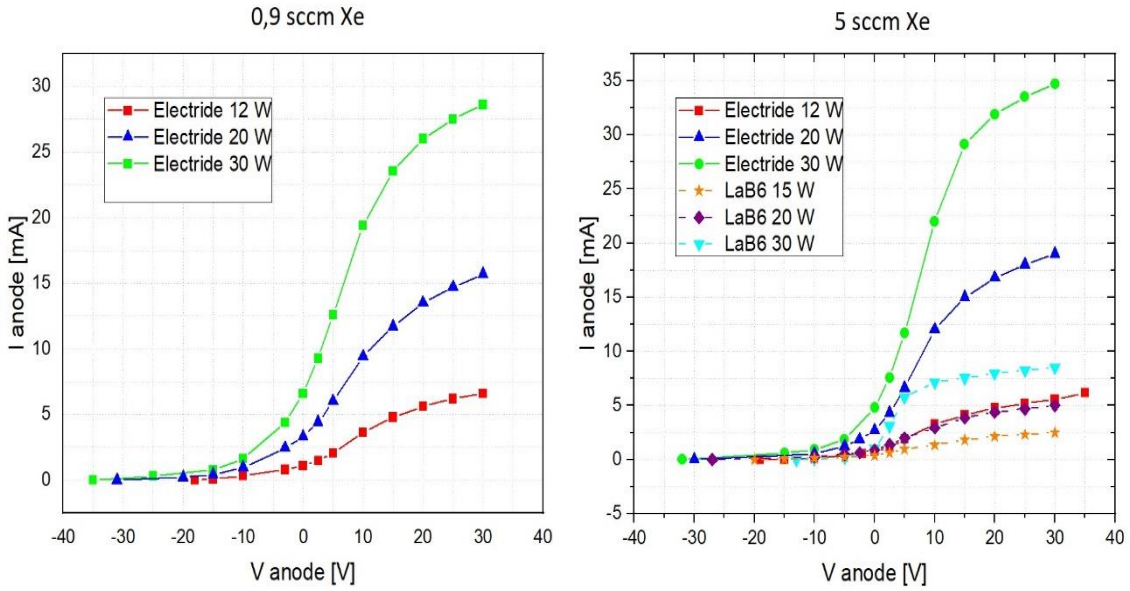

Figure 4. I/V characterization curves of C12A7:e- and LaB_6 in a cold cathode at 0.9 (left) and 5 sccm (right) Xe mass flow for different cathode powers.

As it can be observed in Figure 4, the LaB_6 needs a minimum of 15 W cathode power while the C12A7:e- electride sample is able to operate using 12 W of cathode power. It can also be seen that, both for 20 and for 30 W, the anode current is clearly higher with electride sample. We can also observe a current saturation at low anode voltages, 10 to 15 V, in the case of the LaB_6 curves.

In addition, Table 4 is showing a summary of the performance of the heater less neutralizer, with a C12A7:e- and a LaB_6 sample, working at different Xe and Ar mass flow with 30 W cathode power (P_c) and 20 V of anode voltage. As it can be observed, C12A7:e- shows a clear superiority with both Ar and Xe and, above all, a better stability of the anode current was observed with lower mass flows and power cathode (P_c).

Table 4. Performance comparison test results in a cold cathode neutralizer working at low temperature

		I_a (mA)	**I_a/P_c (mA/W)**
C12A7:e-	Ar 1.5 sccm	99.6	3.32
	Ar 10 sccm	110.0	3.36
LaB_6	Ar 1.5 sccm	5.4	0.18
	Ar 10 sccm	20.5	0.68
C12A7:e-	Xe 0.9 sccm	26.0	0.86
	Xe 5 sccm	31.9	1.06
LaB_6	Xe 0.9 sccm	N.A.	N.A.
	Xe 5 sccm	5.8	0.19

As the results indicate the I_a/P_c ratio obtained for the C12A7:e- sample are around 3.3 mA/W with Ar and 1 mA/W with Xe, confirming the great possibilities of C12A7:e- material for designing cold cathodes in neutralizers operating at temperatures below 250 °C.

3. Conclusions

One of the conclusions of this work is that LaB_6 will perform similar to C12A7:e- in devices working purely based on temperature induced electron emission. C12A7:e- starts thermionic current emission at lower temperatures than LaB_6. However, current intensity emission from C12A7:e- is similar due to the low A constant in Richardson-Dushman equation.

Regarding the operation in a plasma environment with low temperatures, around 250 ºC, a higher performance of the C12A7:e- sample was observed. In this case, a performance ratio of 3.3 mA/W was measured when using Ar and 30 W of power cathode for the C12A7:e- sample. Further performance improvements under test could even improve these performance ratios.

Additional performance comparisons are expected on other neutralizer devices under development, like the hollow cathode neutralizer designed at *JLU Giessen*. A higher C12A7:e- performance observed in the here described cold cathode neutralizer is also expected in these hollow cathode neutralizers presently under tests.

Acknowledgements

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