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Electron Lenses for Modern and Future Accelerators

Design of high-performance guns for the HL-LHC HEL

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Abstract: The High Luminosity LHC project (HL-LHC) foresees the construction and installation of important new equipment to increase the performance of the LHC machine. The Hollow Electron Lens (HEL) is a promising system to control the beam halo. It improves the beam collimation system of the HL-LHC and mitigates possible equipment damage in case of failure scenarios from halo losses. The halo can store up to 30 MJ energy. The specifications for this new device are quite demanding. The source, an electron gun with an annular shaped cathode, must deliver a current up to 5 A. This is five times higher than the current in the existing electron lenses in Fermi and Brookhaven national laboratories. This note describes the programme carried out to design and test high-perveance guns equipped with two types of high-performance scandate cathodes. The size of the final gun for the HL-LHC lenses is now considerably smaller than the one of the first prototype, allowing a reduction of diameter and cost of the superconducting magnet system used to steer the electron beam. The tests carried out at FNAL, BVERI and BJUT demonstrated that the developed cathodes fulfil the specifications and can supply a 5 A fully Space Charge Limited (SCL) current.

Keywords: Accelerator Applications; Accelerator Subsystems and Technologies; Beam dynamics

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1 Introduction

The Large Hadron Collider (LHC) at CERN, is the largest and most powerful accelerator for high-energy physics [1]. This machine upgrade, the High Luminosity LHC (HL-LHC), will operate with extremely high beam power. The nominal stored beam energy will be 675 MJ, almost double with respect to the LHC design (nominal 362 MJ) [2].

In a particle accelerator, such as the LHC, several processes may lead to beam losses. The manipulations needed to prepare the beams for collision and the collisions for physics entail unavoidable beam losses, which generally become greater as the beam current and the luminosity are increased. In addition, the LHC's superconducting environment demands a 99.99% efficient beam-loss cleaning to avoid magnet quenches from uncontrolled losses. The protection of the accelerator equipment from the consequences of uncontrolled release of energy is therefore essential.

The circulating proton beams are made of 25-ns-spaced proton bunches. The cross section of a bunch has a highly populated central part called core and a periphery part named halo. Since the beam losses directly depend on the beam-halo behaviour, great attention must be paid to its formation, growth, and interaction with the beam core.

The collimation system has the primary role to clean away the beam halo and to maintain losses at sensitive locations below safe limits. Collimators are also used to minimize background in the experiments.

Hollow electron lenses (HEL) are a promising method to improve the beam collimation system. HEL are expected to boost the performance of the LHC and of its High-Luminosity upgrade through active control of halo particles, diffusion speed, and tail population [3]. Figure 1 shows the layout of the HL-LHC HEL. In the HEL a low-energy, high-current hollow electron beam runs co-axially with the circulating hadron beam, over about three meters [4]. The electron beam acts on the halo particles at large transverse amplitudes from 3.6σ to 7.2σ (σ = 0.31 mm) without perturbing the beam core thanks to the central zero field given by the hollow axially symmetric charge.

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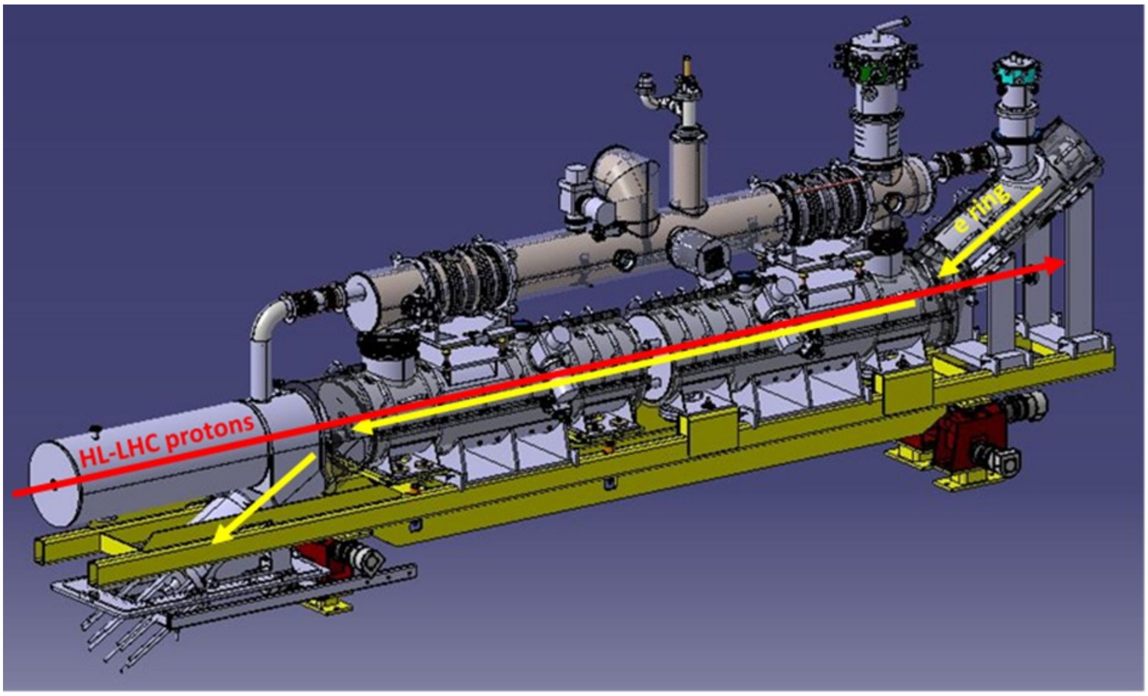

Figure 1. HEL layout. In yellow the electron ring path, in red the HL-LHC hadrons path.

The main advantages in employing an electron beam cloud around the proton beam, instead of a bulk scraper, are a closer positioning to the high-energy proton beam centre without damage risk in accidental operation conditions and no impact on impedance.

2 Electron gun and cathode development programme

In the HEL an annular thermionic cathode emits the electron beam, which is accelerated and then confined, compressed and steered by a magnetic field generated by a set of superconducting solenoids. The electrons finally dissipate their energy on a collector. The size of the cathode and the level of the magnetic field in different points define the size of the electron beam along its path. According to HL-LHC requirements, the cathode must deliver a Space-Charge-Limited current up to 5 A at 10 kV cathode-anode differential voltage. This current is about five times higher than the previously designed and operated electron lenses [5, 6] in high energy colliders. The cathode external diameter is in the present design 16.1 ± 0.02 mm. The cathode lifetime in operation must be longer than one year to avoid a replacement during an LHC data taking run.

To assess the possibility of reaching such a high current, a programme to design and test different cathodes and electron guns was launched about four years ago.

The programme consisted of three phases. The initial phase targeted a current of 5 A using a tungsten dispenser cathode, with BaO:Cao:Al_2O_3 impregnant, available on the market. This cathode was larger than the nominal size, with an emitting surface 2.44 times wider than the one foreseen for the HL-LHC HEL. The electron gun was not optimized in size but derived from an existing prototype, previously developed and tested at FNAL [7].

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Scope of the second phase was to demonstrate that the required 5 A can be delivered by a cathode having a smaller size (16.1 mm external diameter), the right one for HL-LHC lenses. We tested an impregnated scandate cathode provided by BVERI (Beijing Vacuum Electronics Research Institute). The electron gun had a hybrid structure with anode and electrodes scaled according to the cathode dimensions and assembled on the support designed for the first-phase electron gun.

The third phase foresees the construction and test of an optimized gun with reduced size support elements and cathode, anode and electrodes equal to those of the phase two. Reduced dimensions of the electron gun imply smaller size of the surrounding superconducting solenoid with considerable savings in cost.

The electron emission in function of the shape and position of the cathode and other electrodes was computed for the HL-LHC gun with the code Warp particle-in-cell. The nominal perveance of the 16.1 mm external diameter cathode electron gun is 6.91 μperv. The figures below give an example at 10 kV cathode-anode voltage, 0.4 T field and 6.91 A total current.

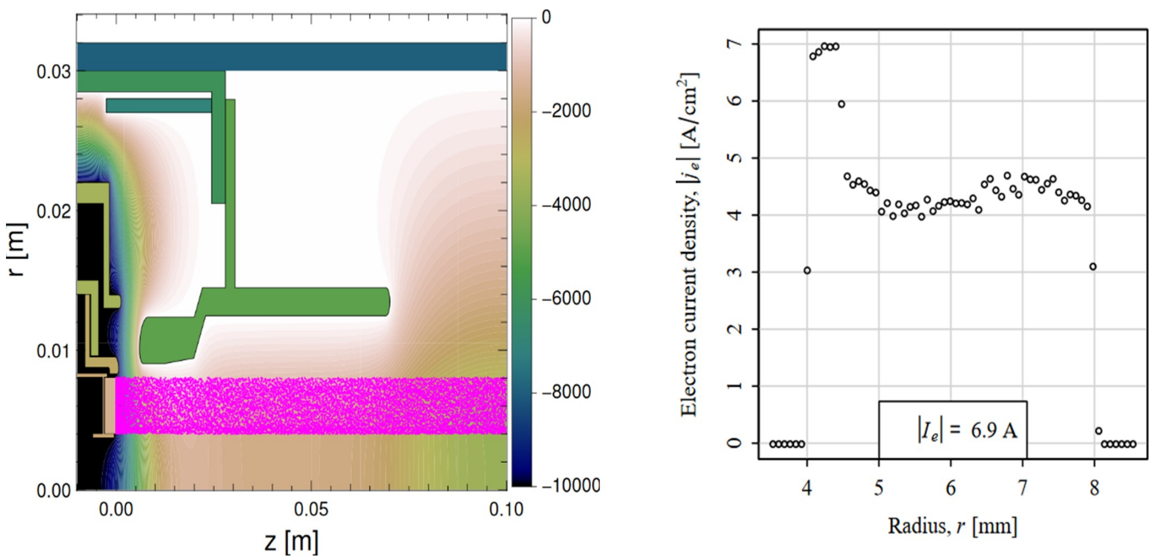

Figure 2. Electron emission (on the left) and radial distribution of the current density (on the right) simulated for the 16.1 mm external diameter cathode.

During the test programme, it was decided to try a further cathode development still ongoing in BJUT (Beijing University of Technology): the design of a high performance scandia doped dispenser cathode able to deliver the nominal current of 5 A, while working at lower temperature than those previously tested. This development is not a must for the HL-LHC lenses, but a lower working temperature is a simplification and a great advantage. It reduces the heat load affecting the electron gun zone in the vacuum system of the HEL (which is connected to the LHC primary vacuum) and increases the cathode lifetime. The first production tests were carried out with a cathode having a smaller size than the nominal one for the HEL (half diameters). The work will then continue with a full HEL size test.

Table 1 reports the main dimensions and parameters of the electron guns and cathodes of the three phases and the ones of the possible further development.

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Table 1. Summary of cathode and electron guns main parameter. The composition of scandium oxide, or scandia, is Sc_2O_3.

		Phase 1	Phase 2	Phase 3	Future dev.
Cathode type		Ba-W impregrated	impregrated scandate		scandia doped dispenser
Cathode	$Ø_{inner}$	12.5 mm	8.05 mm	8.05 mm	4 mm
	$Ø_{outer}$	25 mm	16.1 mm	16.1 mm	8 mm
	$A_{surface}$	3.68 cm^2	1.5 cm^2	1.5 cm^2	0.38 cm^2
	$T_{working}$	1100 °C	950 °C	950 °C	850 °C
Gun	$Ø_{external}$	200 mm	200 mm	50 mm	50 mm
	weight	25 kg	24 kg	10 kg	10 kg

3 Results of phase 1 and phase 2 electron guns

The electron guns of phase 1 and 2 were tested at FNAL in pulsed current mode with a 4 µs pulse length and a 4 Hz pulse frequency. The phase 1 electron gun delivered a current of 6.25 A at 10 kV cathode-anode differential voltage. This represents a peak current density of 1.7 A/cm^2.

Figure 3 presents the current versus the cathode-anode differential voltage for the second phase electron gun. The obtained maximum current is 5.2 A at 10 kV, equivalent to a peak current density of 3.5 A/cm^2. This result is particularly important and encouraging. It demonstrated that it is possible to obtain more than 5 A with a 10 kV cathode-anode differential voltage in an electron gun with cathode, anode and other electrodes at the size required for the HL-LHC HEL.

Figure 4 shows the cathode on its support during the assembly of the gun.

4 Phase 3 electron guns. Final small size for the HL-LHC lenses.

To minimize the gun dimensions, we designed an extremely compact option. Cathode, anode and other electrodes were assembled on a common support made of aluminium nitride ceramic Shapal^{TM}. The introduction of a single common insulating support for all elements working at different voltage allows a significant reduction in the number and size of the structural components. On the other hand, the distance between the cathode 'hot temperature spot' and the ceramic support was too short, causing its overheating and the loss of its insulating properties [8]. For this reason, we could not test this configuration at high voltage difference between cathode and anode.

To avoid these problems, we designed a longer structure with the goal of maximizing the distance between the hot cathode and the ceramic parts and increasing the heat conduction towards the gun end plate. This new structure is shown in figure 5.

We plan to complete this gun and test it within the first half of year 2021.

5 Future developments

The goal of this part of the programme is to produce and test a nano-sized scandia doped dispenser cathode, able to provide high emission at lower working temperature than in the previous designs.

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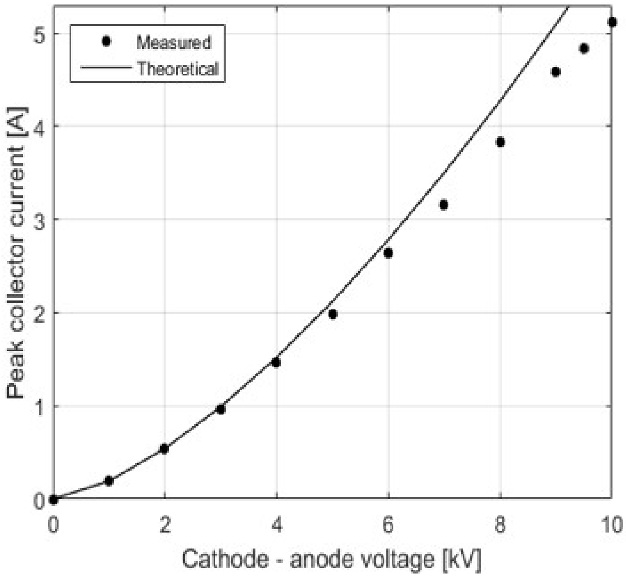

Figure 3. Current delivered by the phase 2 cathode and electron gun, as a function of the cathode-anode voltage.

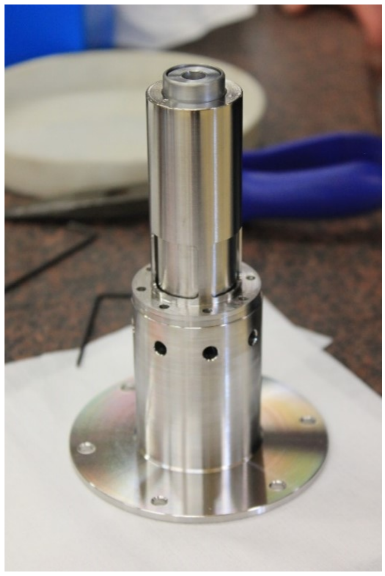

Figure 4. The 16.1 mm external diameter cathode assembled on the support before being integrated in the electron gun.

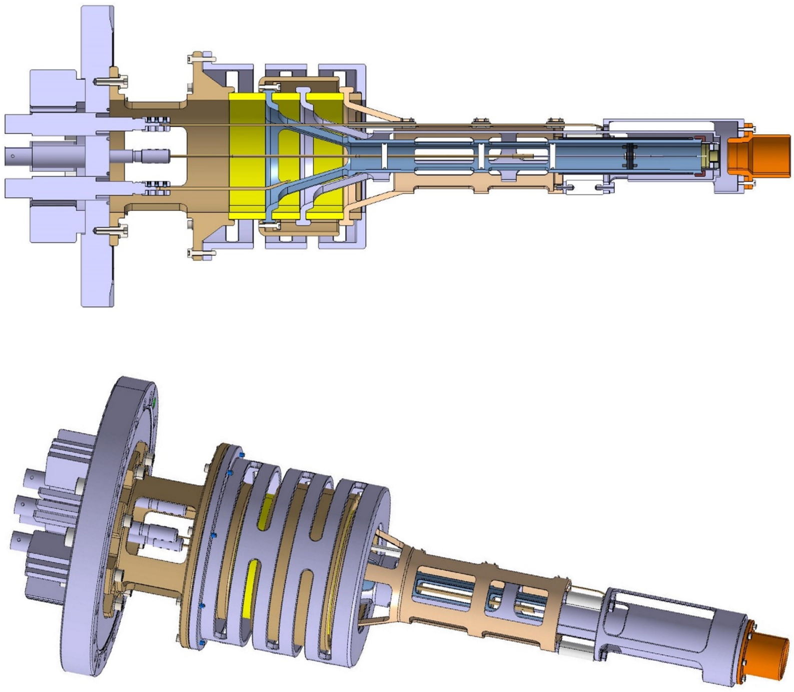

Figure 5. Longitudinal section and 3D view of the electron gun optimized for the HL-LHC HEL. The supports of the cathode and of each electrode are insulated among them by ceramic (in yellow) rings. The rings and the supports are kept together by the pressure given by the external spring element (the grey cylinder with slots).

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The tests carried out in BJTU demonstrated that a scandium oxide content of 5% in weight in the tungsten matrix minimizes the working temperature [9].

For practical reasons it has been decided to start the prototype construction with smaller cathode dimensions and then increase them to reach the HEL requirements. Therefore, the inner and outer diameters of the first test cathode are half of those foreseen for the HL-LHC HEL.

This annular cathode has been tested at BJUT in a dedicated emission measurement system in a closely spaced diode configuration. Pulsed emission with a pulse duration of 5 μs and a repetition rate of 50 Hz was measured. The *I*-*V* plots were recorded and are shown in figure 6 [9].

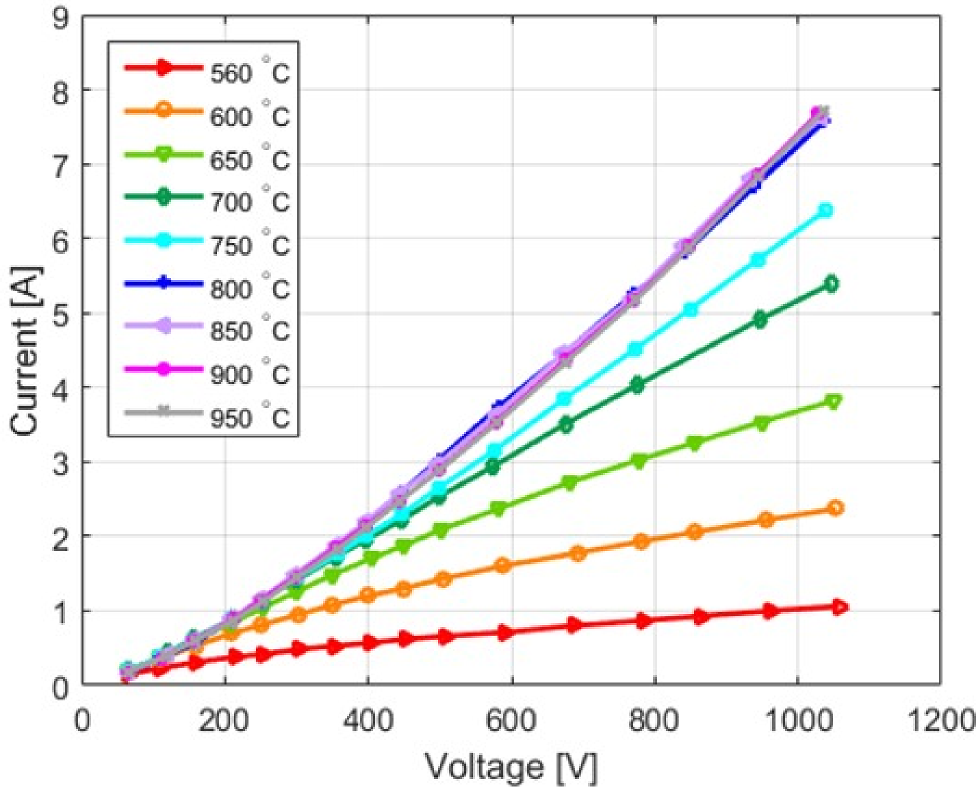

Figure 6. Current-voltage plot as a function of the different temperatures of a nano-sized scandia doped dispenser cathode.

A fully space-charge limited total current of 5 A (current density 13.6 A/cm^2) could be reached at operation temperatures of 800 °C, measured with a micro-optical pyrometer as for all the other temperatures mentioned from here on in the manuscript. The operating temperature is more than 250 °C lower with respect to the first cathode tested during phase 1 and the observed current density is almost an order of magnitude larger.

A life test of a cathode was carried out at 850 °C with a DC load of 0.2 A. The cathode lasted more than 10000 hours, which is well above the operational hours in a year of use of HL-LHC. As shown in figure 7, the knee temperatures are about 725 °C, 100 °C less than the operational point. The overlapping of the Roll-Off curves measured during the testing period confirms the operational stability of the cathode.

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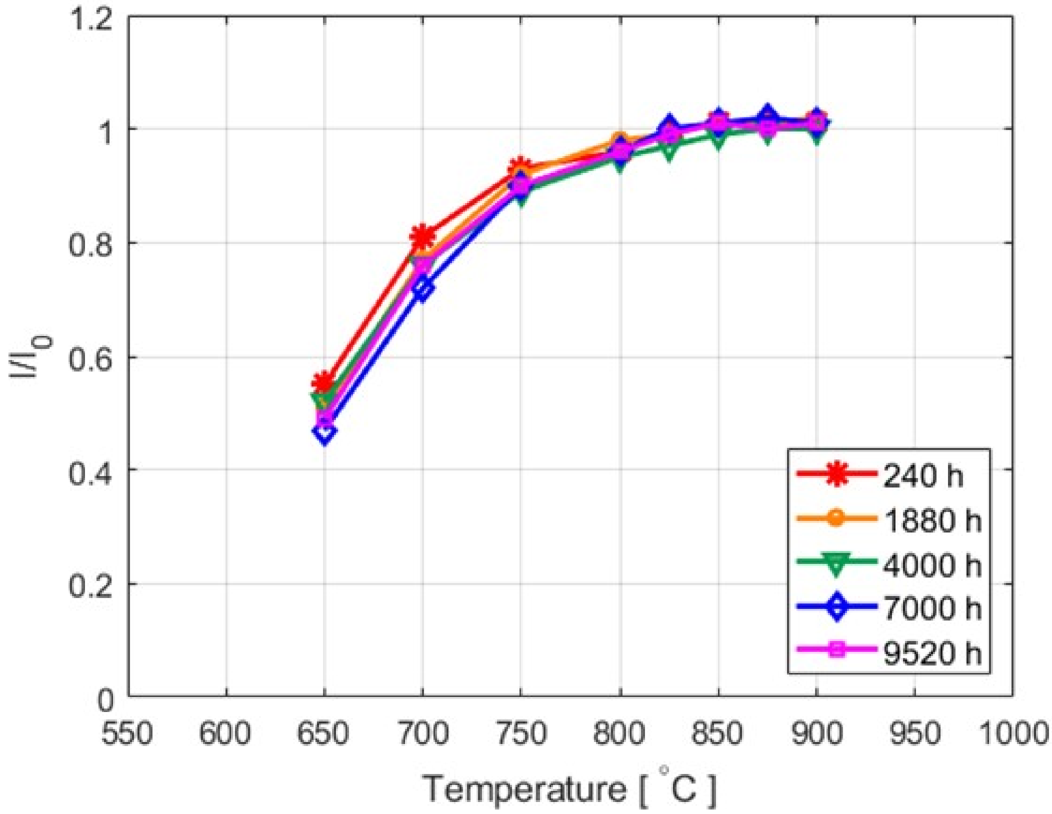

Figure 7. Normalized Roll-Off curves during life test (I_0 = 5 A/cm^2).

6 Conclusions

The electron guns of HL-LHC Hollow Electron Lenses have to deliver a total current much higher than those installed in similar devices previously designed for other accelerators. After a few years of successful R&D, a highly optimized electron gun with a cathode that satisfies the nominal requirements of HL-LHC HEL was designed, built and tested.

The final configuration of the electron gun, with improved thermal insulation of the ceramic parts, and compatible size with the available space in HL-LHC HEL, is under manufacturing and will be tested in the next months.

Finally, if the scandia-doped dispenser cathode will be successfully produced, the electron gun operating temperature could be decreased by about 250 °C and the generated current density could be increased up to almost one order of magnitude with respect to the commercial cathodes. The lifetime of this new cathode was proved to be higher than one year. This new cathode can be very useful not only for the HL-LHC HEL, but for other applications as well.

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