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THE DEVELOPMENT PROGRAMME OF CATHODES AND ELECTRON GUNS FOR THE HOLLOW ELECTRON LENSES OF THE HIGH LUMINOSITY LHC PROJECT*

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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, has to 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 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.

INTRODUCTION: HOLLOW ELECTRON LENSES FOR HL-LHC

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, as the LHC, a number of 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 an 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.

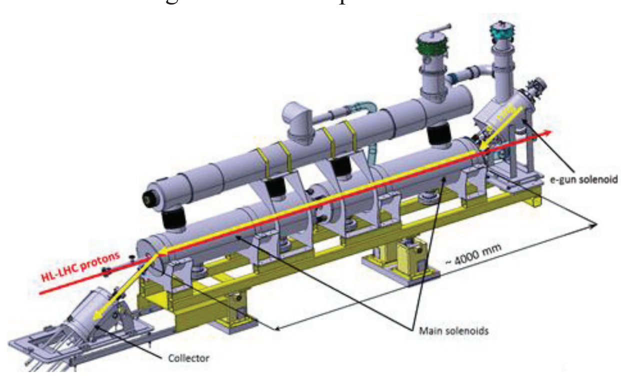

Figure 1: HEL layout. In yellow the electron ring path, in red the HL-LHC protons path.

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 3σ to 6σ (σ = 0.27 mm) without

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perturbing the beam core thanks to the hollow axially symmetric charge.

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.

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 has to deliver a Space-Charge-Limited current up to 5 A at 10 kV cathode - anode differential voltage. This is about five times higher than the previously designed and operated electron lenses [5], [6]. The cathode external diameter is 16.1±0.02 mm and its lifetime in operation must be longer than one year.

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

The programme consisted in 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].

The second phase tested an impregnated scandate cathode provided by BVERI, with dimensions matching the HL-LHC HEL requirements. 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 included 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.

During the test programme, it was decided to implement a fourth phase still ongoing in BJUT: the development 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. 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 and increases the cathode lifetime. The first production tests were carried out with a cathode having a smaller size with respect to 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 four phases.

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

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

RESULTS

The electron guns of phase 1 and 2 were tested at FNAL in pulsed current mode with a 4 µs pulse width 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 2 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.

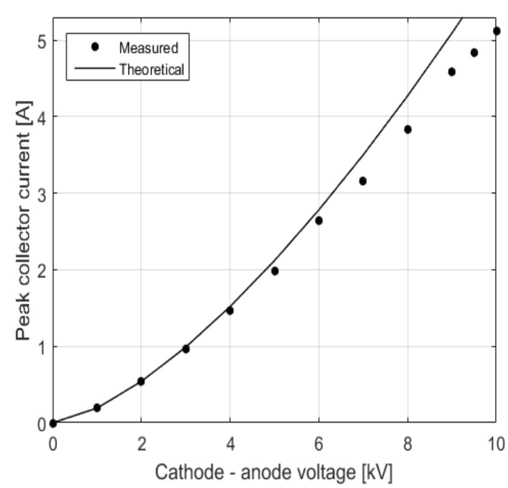

Figure 2: Current delivered by the phase 2 cathode and electron gun, as a function of the cathode - anode voltage.

This result is particularly important and encouraging. It confirms that it is possible to obtain more than 5 A with a

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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.

OPTIMIZED ELECTRON GUN

Figure 3 shows a 3D representation of the electron gun optimized for the HEL application (phase 3).

Cathode, anode and other electrodes are assembled on a common support made of aluminium nitride ceramic Shapal™. This material has excellent electrical insulation and mechanical strength properties as well as good thermal conductivity. These characteristics minimize the risk of cracks or failures during the use of the electron gun. 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.

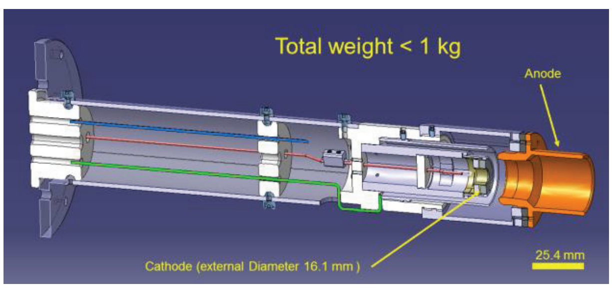

Figure 3: Longitudinal section of the optimized electron gun.

PHASE FOUR CATHODES

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. The tests carried out in BJTU demonstrated that a scandium oxide content of 5% in weight in the tungsten matrix minimizes the working temperature [8].

For practical reasons it has been decided to start 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. Pulse emission with a pulse width of 5 µs and a repetition rate of 50 Hz was measured. The *I-V* plots were recorded and are shown in Figure 4 [8].

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.

Life test of a cathode were carried out at 850 °C with a DC load of 0.2 A. The cathode, until now, lasted 10000 hours and the tests are still ongoing. As shown in Figure 5, knee temperatures is 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.

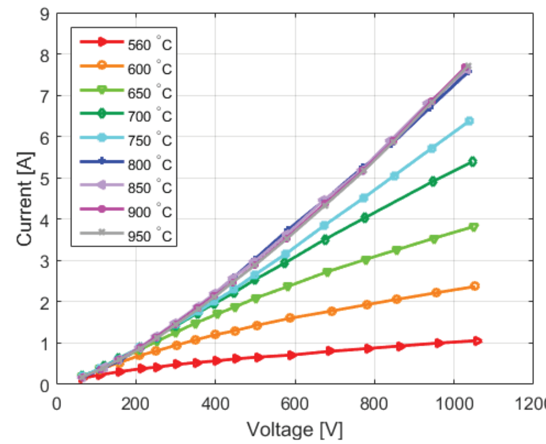

Figure 4: Current-voltage plot as a function of the different temperatures of phase 4 cathode.

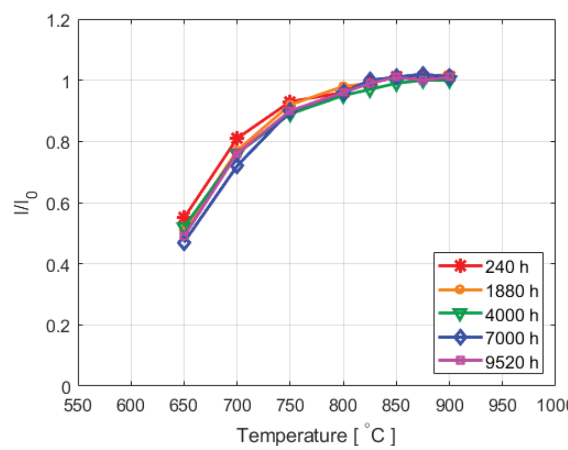

Figure 5: Normalized Roll-Off curves during life test (I_0 = 5 A/cm^2).

CONCLUSIONS

The cathode used for HL-LHC Hollow Electron Lenses has 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. Thanks to the scandia-doped dispenser cathode, the electron gun operating temperature decreases of about 250 °C and the generated current density increases by 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.

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