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STATUS OF BEAM INSTRUMENTATION AT THE ELECTRON BEAM TEST STAND AT CERN

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Abstract

The Electron Beam Test Stand (EBTS), a collaborative effort at CERN with the Accelerator Research and Innovation for European Science and Society (ARIES) project, has been purpose-built within the High Luminosity Large Hadron Collider (HL-LHC) initiative. This comprehensive test facility features a high-perveance electron gun producing a hollow electron beam, supported by a magnetic system comprising normal conducting solenoid magnets with horizontal and vertical correctors. The EBTS boasts an array of advanced beam instrumentation, including YAG:Ce screens, a multi-channel Pin-Hole Faraday cup, a Beam Position Monitor (BPM), and a Beam Gas Curtain (BGC) profile monitor integrated with an optical transition radiation (OTR) screen. Additionally, it includes an electron collector.

This paper offers an overview of the EBTS, emphasizing the design and capabilities of its various beam instruments. It further provides insights into some prototype test results with pulsed electron beams, and upcoming tests with DC beams. The EBTS holds great potential as a valuable tool for advancing electron beam technologies, particularly in the realm of sources and instrumentation for electron cooling devices.

INTRODUCTION

The EBTS at CERN has been designed and constructed to address the objectives outlined in ARIES WP16 (Intense, RF Modulated, E-Beams (IRME)) [1–3], as well as HL-LHC WP5 (Collimation) and WP13 (Beam Instrumentation) [4]. The key objectives include:

- Designing and building a test stand capable of evaluating an electron gun, equipped with instrumentation for measuring both transverse and longitudinal profiles of the RF-modulated electron beam.
- Conducting measurements to characterize the properties of the RF-modulated electron beam generated by the gun within this test stand.
- Prototyping components, such as the electron gun, collector, and BPM, to potentially implement hollow electron lenses (HEL) for active beam-halo control in the HL-LHC.
- Developing a gas curtain monitor to precisely align the electron and proton beams within the hollow electron lens.

Although the ARIES project concluded in 2022, the R&D part of the HL-LHC project remains ongoing. This section will delve into specific aspects of the HEL and their implications on the design of the EBTS. The EBTS will be described in subsequent sections along with an update on the current status of beam instrumentation at this facility.

High Luminosity LHC Hollow Electron Lens

The purpose of HEL is to enhance the transverse beam halo diffusion and provide controlled halo depletion for HL-LHC proton beams [5]. By superimposing a low-energy (about 10 keV), high-current (5 A) counter-propagating hollow electron beam with the proton beam, halo particles in the proton beam experience non-linear transverse kicks, while the particles in the beam core remain unaffected. Over time, these kicks accumulate, diffusing and eventually removing halo particles through downstream collimation. The electron beam must be concentric with the proton beam (within 100 µm) over a three-meter interaction region to achieve 90 % halo depletion in five minutes [6, 7].

The key components for HEL, as depicted in Figure 1, include the electron gun and pulse modulator for generating the pulsed hollow electron beam. Two beam position monitors are employed to precisely locate the proton and electron beams in the interaction region. The minimally invasive beam profile monitor, known as the BGC (for Beam Gas Curtain monitor) [8–14], acts as an overlap monitor for both beams. Additionally, a collector serves as an electron beam dump. The setup also features superconducting solenoids, compensation magnets, and steering coils to guide and control the beams within their designated orbits.

The HEL prototype components to be tested at the EBTS include the electron gun, BPM, BGC, and electron collector.

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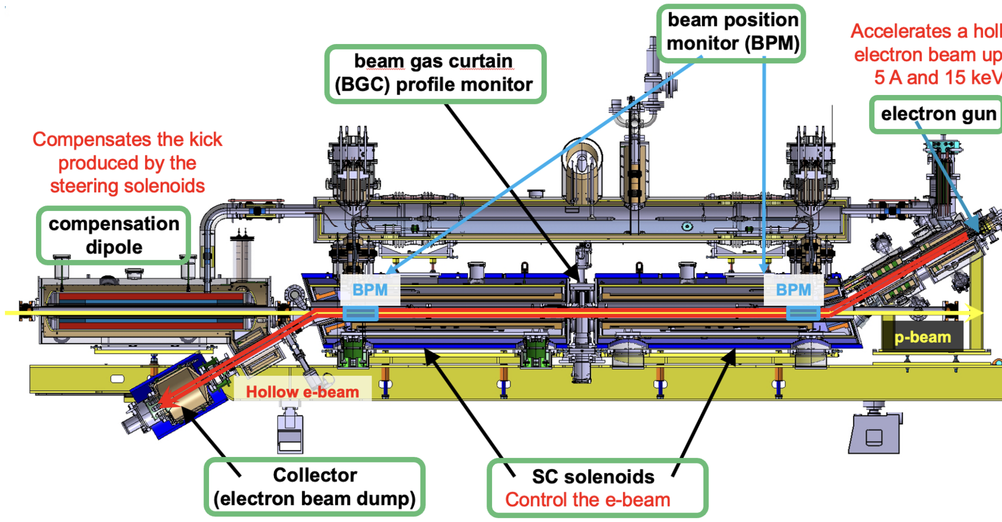

Figure 1: 3D model of a preliminary design of the HEL for HL-LHC.

ELECTRON BEAM TEST STAND (EBTS)

The EBTS layout, shown in Figure 2, emphasizes HEL components outlined in green. Resistive solenoids, capable of producing a maximum axial magnetic field of 0.4 Tesla, guide the electron beam, each featuring horizontal and vertical correctors for precise beam control. A sector valve divides the EBTS into two independent volumes, allowing separate interventions. The upstream volume houses the Beam Diagnostic Box (BDB), providing electron beam assessment even when downstream instruments are unavailable.

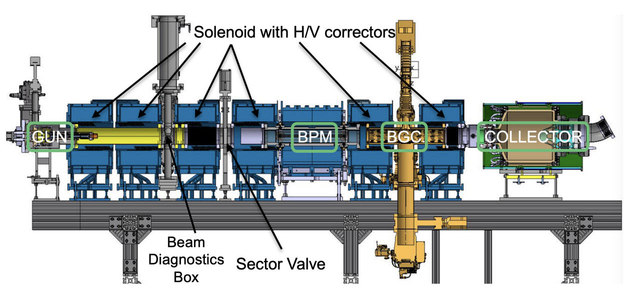

Figure 2: 3D model of the EBTS.

The EBTS supports modular installations, offering versatility for testing electron guns, collectors, beam profile monitors, beam position monitors, pulse modulators, power converters (including high voltage ones), and control and interlock systems.

In the remainder of this section, we will provide a concise overview of the electron gun and the parameters of the generated electron beam, followed by descriptions of the various beam instruments currently operational within the EBTS in the next section.

Electron Gun

The EBTS currently employs the HEL Gun v3, as depicted in Figure 3. This gun features a hollow cathode with a 16.10 mm outer diameter and 8.05 mm inner diameter, capable of providing a current density of 3.33 A/cm^2 at an operating temperature of 950 °C. Within the EBTS, the electron gun delivers a beam current of up to 5 A and a beam energy of up to 15 keV.

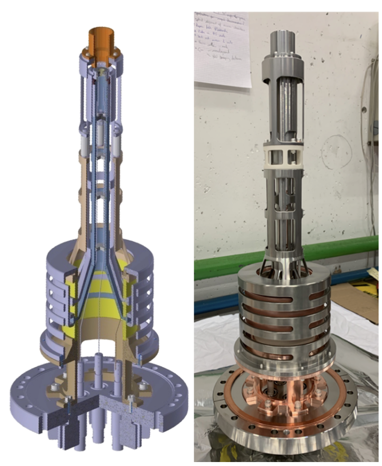

Figure 3: HEL electron gun 3D model (left) and image of the assembled gun (right).

For pulse modulation, a Marx generator [15] is used, offering a rapid 200 ns rise/fall time and an adjustable pulse duration ranging from 1 to 100 microseconds. The system supports a repetition frequency between 1 Hz and 1 kHz.

Both the cathode and electron gun's performance have undergone validation, with testing conducted at FNAL (using HEL Gun v1) and CERN (using HEL Gun v3) [16, 17]. Figure 4 showcases the results of this characterization and provides a comparison of the experimental data with the outcomes from three distinct simulation programs.

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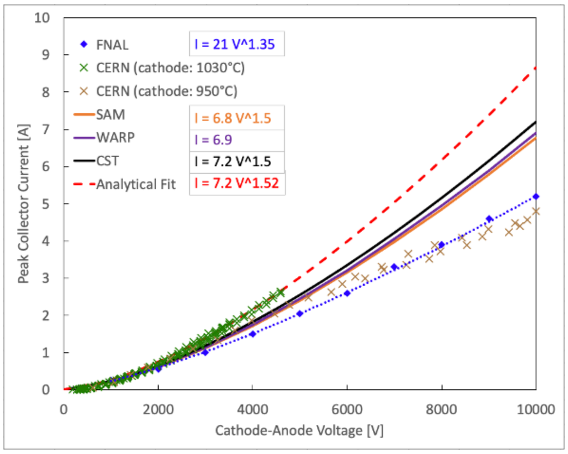

Figure 4: Characterization of the HEL electron gun.

BEAM INSTRUMENTATION

The beam instrumentation at the EBTS consists of beam profile monitors, a beam position monitor (BPM), and an electron collector.

Beam Profile Monitors

The EBTS is equipped with four beam profile monitors, each serving specific functions:

1. YAG:Ce screens
2. Pin-Hole Faraday cup
3. BTV screen
4. BGC

The YAG:Ce screens and Pin-Hole Faraday cup are positioned at the BDB location, while the BTV screen and BGC are located at the position labelled BGC in Figure 2.

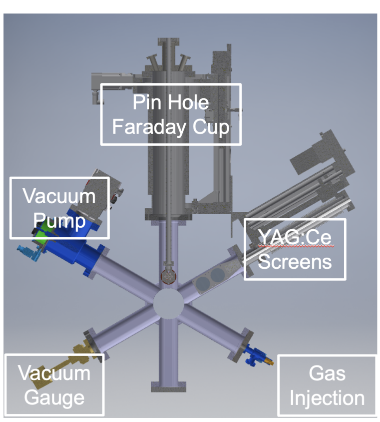

Figure 5: 3D model of the BDB.

YAG:Ce Screens The BDB, depicted in Figure 5, includes a pair of 50 mm diameter, 0.1 mm thick YAG:Ce screens mounted on the diagonal linear translator. One screen is coated with a 100 nm thick aluminum layer which reflects photons generated normal to the screen surface, increasing the signal intensity by a factor of 2. This works well when the signal intensity is low. The second screen is coated with a 20 nm thick indium tin oxide (ITO) layer which is transparent and minimizes smearing of the beam profile. This works well when the signal intensity is high. Both aluminum and ITO are conductive layers that prevent charge buildup on the YAG:Ce screens.

A YAG:Ce screen, when inserted into the beamline, is perpendicular to the electron beam direction of motion. The photons generated at the screen travel downstream and pass through an optical viewport before they are collected by a scientific camera (Manufacturer: Thorlabs, Model: CS135MU).

YAG:Ce screens offer benefits such as high photon yield, rapid decay time, and exceptional image resolution. However, they can encounter challenges like image saturation and screen damage when exposed to high-intensity or prolonged electron beam operation.

In this paper, only measurements with the aluminum coated YAG:Ce screen are shown. The beam profile acquisition and analysis procedures for these screens have been entirely automated. Figure 6 illustrates an example of the acquired image and the subsequent beam profile analysis.

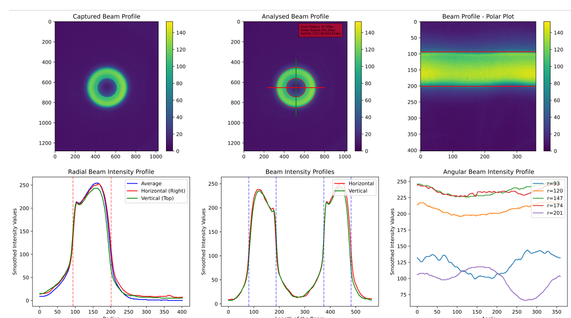

Figure 6: Transverse profile of a 4 keV, 25 mA, 25 µs long hollow electron beam as measured with a YAG:Ce screen.

Pin-Hole Faraday Cup The Pin-Hole Faraday cup, located on the vertical linear translator on the BDB (Figure 5), consists of seven pins with a 10 mm pitch in a hexagonal arrangement, each pin featuring a 0.2 mm aperture. The entire Faraday cup assembly is adjustable in XYZ directions within a range of ±20 mm.

This type of Faraday cup offers the advantage of withstanding very high electron beam intensities. Furthermore, acquiring the beam profile only necessitates an electrical feedthrough, eliminating the need for a camera or viewport. However, one notable challenge is the time required for profile acquisition; for an image with 900 data points on a grid, this process can take up to 30 minutes. On the other hand, a fast acquisition is possible if one wants to only check the uniformity of emission over few points.

The current status of the Pin-Hole Faraday cup is as follows: individual testing of each pinhole with nominal electron beam parameters has been successfully conducted. Additionally, the automation of beam profile acquisition and analysis has been implemented. Unfortunately, a setback occurred just before the first fully automated acquisition,

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when the PXI scope card experienced a malfunction. The card has been repaired and is scheduled for reinstallation at the EBTS by the end of 2023.

BTV Screens The BTV (or Beam TV [18]) consists of a screen positioned at an angle (between 45 and 60 degrees depending on the light emission pattern) w.r.t. the electron beam direction of motion, and a camera (Manufacturer: Basler, Model: acA1920-40gm) collecting the light through a viewport perpendicular to the beam direction. A high speed gated intensifier (Manufacturer: Hamamatsu, Model: C9547-01) is optionally used.

At the EBTS, two distinct types of BTV screens have been tested [19]. The first type is Chromox (scintillating screen), known for its high photon yield but long decay times [20]. One challenge associated with Chromox screens is the accumulation of charge which may blur or completely distort the profile image as evident in Figure 7.

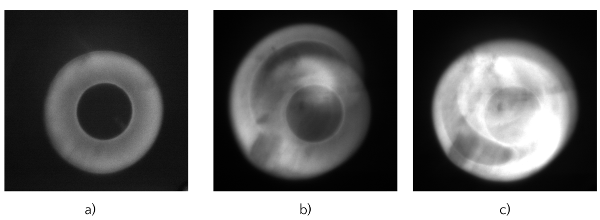

Figure 7: Transverse profile of a 7 keV, 3 µs long hollow electron beam as measured with a Chromox screen. The beam current is a) 2 mA b) 44 mA c) 87 mA. The image distortion is visible in b) and c).

The second type of screen tested at the EBTS is glassy carbon (OTR screen). These screens offer a low photon yield but boast an exceptionally short decay time [20]. This characteristic makes them suitable for examining longitudinal beam slices (when used with a gated intensifier) and evaluating the electron beam's uniformity in the longitudinal direction as depicted in Figure 8. Glassy carbon screens at the EBTS do not encounter saturation issues. Generally, BTV screens are capable of withstanding high beam intensities and extended pulse durations, exhibiting good radiation resistance and response linearity.

However, it is important to note that the image resolution, especially with glassy carbon screens, is inferior to that of YAG:Ce screens. Additionally, longer acquisition times may be necessary for beam intensities that are not significantly high.

Notably, at the EBTS, the Chromox screen displayed limited effectiveness for beam currents exceeding 5 mA or pulse durations extending beyond 3 µs. This limitation primarily stems from the aforementioned charge accumulation issue. In contrast, the glassy carbon screen has been thoroughly tested, commissioned, and operates effectively.

Beam Gas Curtain (BGC) The EBTS incorporates a minimally invasive beam profile monitor known as the

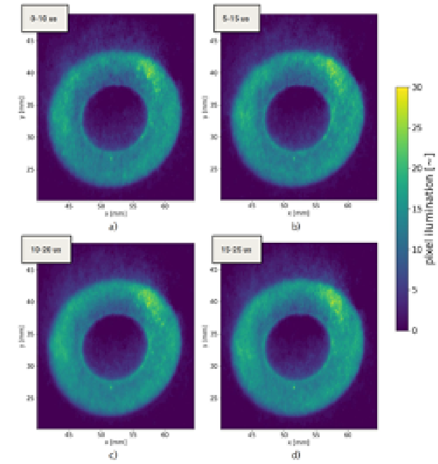

Figure 8: Transverse profile of a 7 keV, 1.2 A, 25 µs long hollow electron beam as measured with a glassy carbon screen. Each distribution corresponds to a longitudinal slice: a) 0-10 µs i.e. first slice (head) of the beam b) 5-15 µs i.e. second slice of the beam c) 10-20 µs i.e. third slice of the beam and d) 15-25 µs i.e. final slice (tail) of the beam.

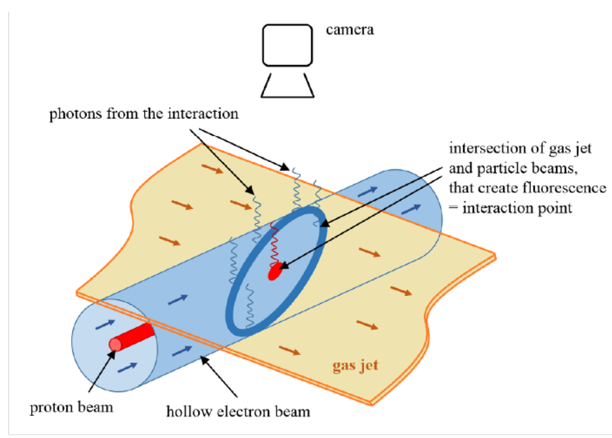

Figure 9: Working principle of the BGC.

BGC [8–14]. This monitor generates a thin and dense supersonic gas sheet by directing high-pressure gas through a series of skimmers. The particle beam interacts with this gas sheet to produce beam-induced fluorescence photons that can be captured by a camera to produce a transverse beam profile (Figure 9). The gas sheet (or curtain) dimensions depend by the apertures of the skimmers installed. The intensity of the signal vary with the gas type injected.

The advantages of the BGC include its minimally invasive approach to beam profile measurement and bidirectionality, enabling the examination of reflected and secondary electrons at the EBTS or the counter-propagating proton beam at the HEL.

However, the BGC does present challenges, such as prolonged acquisition times and the need for active gas pumping in vacuum. Additionally, its intricate setup, considerable footprint, and high manufacturing costs are notable drawbacks.

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The BGC, originally designed for HEL as an overlap monitor for the electron and proton beams, was successfully tested and commissioned at the EBTS by the end of 2022. A BTV screen was used to validate its performance. Figure 10 shows the electron beam transverse profiles acquired by the BGC using different working gases. Preliminary analysis suggests that the BGC can achieve the required 100 µm resolution for HEL [21].

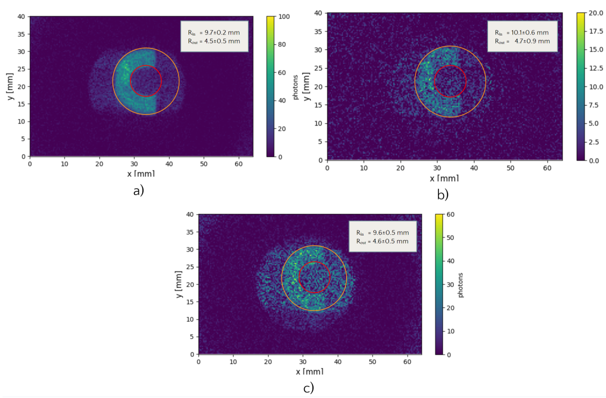

Figure 10: Transverse profile of a 7 keV, 1.5 A, 25 µs long hollow electron beam as measured with the BGC. The working gas is a) nitrogen, b) neon, and c) argon.

The BGC is currently installed in the LHC and has been used to measure both proton and ion beam profiles. An improved version of the BGC is scheduled for installation at the EBTS in the future.

Beam Position Monitor (BPM)

At the HEL, the BPM serves to independently measure the transverse positions of the proton and electron beams using vertical and horizontal stripline electrodes [22]. Located between the sector valve and the BGC, the HEL BPM prototype at the EBTS has an outer diameter of 100 mm and inner diameter of 80 mm, with a stripline length of 400 mm and a width of 12.4 mm (Figure 11). The BPM has been designed to work with a 200 ns rise/fall time which is set by the requirements of the electron beam at the HEL.

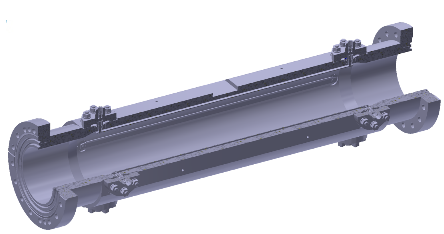

Figure 11: 3D model of the HEL BPM prototype.

Simulations and laboratory tests have shown that the BPM can achieve a position resolution of 0.2 µm, despite a long-term drift of approximately 4 µm. The BPM was installed at the EBTS in September 2023 and conducted its first measurements with a hollow electron beam in early October. The collected data is currently under analysis.

Electron Collector

The most downstream component of the EBTS is the electron collector, depicted in Figure 12. This HEL collector prototype features an 80 mm entrance aperture and can be biased up to +5 kV relative to the cathode potential. Designed to absorb continuous beam power of up to 25 kW, it is operable in both DC and pulsed mode.

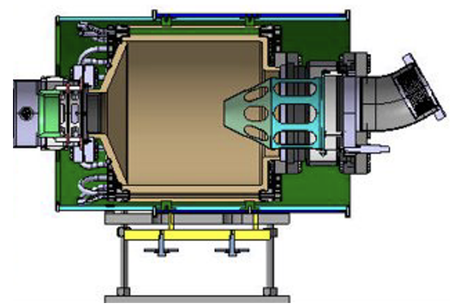

Figure 12: 3D model of the HEL collector prototype.

Utilizing this collector poses challenges due to stringent vacuum requirements and the need to minimize secondary electron emission. Its operation demands a high-voltage platform and demineralized cooling water, both of which are currently unavailable at the EBTS. Efforts are underway to provide these essential facilities.

The collector's design and simulations have been finalized, with raw materials ordered, and fabrication and assembly currently in progress. Installation of the collector at the EBTS is scheduled for 2024.

CONCLUSION

The EBTS has served as a critical testbed for prototype components essential for the HL-LHC HEL, including the electron gun, the BGC and the BPM. The collector prototype is slated for installation and testing in 2024. The EBTS is equipped with an electron gun, collector, BPM, and multiple beam profile monitors, rendering it a versatile facility for comprehensive characterization of electron guns, collectors, beam pulse modulators, and various beam instrumentation. Furthermore, its compatibility with DN-100 installation makes it an appealing resource for collaborators seeking to validate equipment for electron coolers and related applications.

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