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DC AND PULSED ELECTRON BEAM TEST FACILITY AT CERN

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Abstract

An electron beam test stand was designed and constructed at CERN, under the umbrella of the High-Luminosity LHC project, to test components for the Hollow Electron Lens (HEL), and in collaboration with the ARIES project for testing the Space Charge Compensation electron gun. The test facility features normal conducting magnets providing solenoid fields of the order of fractions of Tesla, beam diagnostics including screens (YAG, Chromox and OTR) for the full electron beam characterisation, a Faraday Cup collector to measure the total electron current, and a high voltage power supply up to 40 kV (with the possibility of biasing both gun and collector). It offers the possibility of testing high current and high perveance guns, specific beam instrumentation, electron collectors, and beam pulse modulators. In this paper the facility is described and the first results validating the design of the HEL gun are presented.

INTRODUCTION

Hollow Electron Lenses (HEL) [1] were proposed for active halo depletion at the CERN High Luminosity Large Hadron Collider (HL-LHC). They require high intensity and high charge density hollow electron beams of up to 5 A, confined in the region of overlap with the circulating LHC beam, into a ring of 1.2 mm inner and 2.4 mm outer diameter, accelerated to 15 keV to guarantee transport up to the collector [2], and aligned with an accuracy ~100 µm around the hadron beams. In parallel, the upgrade of the SIS18 machine at GSI, with an increased ion beam intensity, foresees space charge compensation utilizing electron beams [3, 4] at high intensity (average 10 A at several tens of keV) and RF modulation to match the longitudinal ion beam profile. Both projects require a test facility capable of characterizing electron gun current emission yields and measuring the transverse profile with and without current modulation. In addition, for the HEL, validation of the design of a collector capable of withstanding up to 25 kW beam power and qualification of the performance of the foreseen beam instrumentation, namely strip-line Beam Position Monitors (BPM) [5] to measure both absolute and relative beam positions, and a Beam Gas Curtain monitor (BGC) [6, 7] to guarantee that the beams overlap, are also required.

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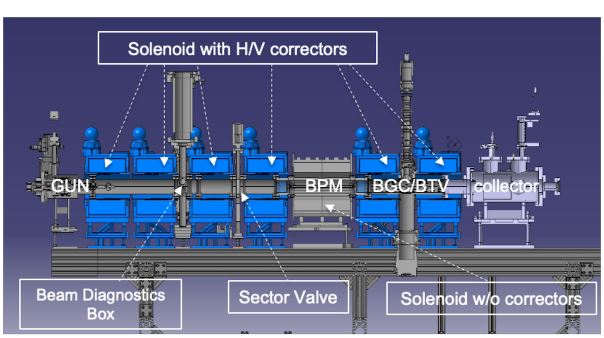

Figure 1: Schematic of the CERN electron beam test facility.

ELECTRON BEAM TEST FACILITY DESCRIPTION

A schematic of the Electron Beam Test Facility is shown in Fig. 1. The magnetic system was designed to ensure the confinement of the electron beam and its transport to the collector. It is composed of ambient temperature (water cooled) solenoid magnets, depicted in blue. Each magnet is provided with horizontal and vertical dipoles to steer the electron beam to either compensate for mechanical misalignment or displace it to characterize the BPM. The modularity allows to install different magnet configurations, depending on need and number of components present at the facility. At the gun side, a pair of magnets provide an extended region of constant field. The vacuum system is divided into two sectors by an all-metal automatic gate valve. One sector is reserved for the electron gun and a diagnostic box, the other for any equipment to be tested. Each volume is equipped with a pumping system capable of keeping a pressure in the range of 10^{-8} mbar during electron beam operation.

The diagnostic box consists of a 6-arm chamber (pictured on the left side in Fig. 2), where a movable YAG:Ce scintillator screen and a multi-hole Faraday Cup (FC) can be inserted to measure the electron beam profile and intensity. The other arms are used for gas injection (for venting the vacuum system with nitrogen), pressure measurement, support of the structure, and one spare arm. The light produced at the YAG screen is collected by a camera positioned behind a viewport at the back of the collector (see right side in Fig. 2). A retractable plate at the collector can be inserted to avoid irradiation of the viewport when the YAG screen or the multi-hole FC are not inserted. Since we typically operate electron beams at 10 keV energy, which are fully absorbed by the YAG screen, beam measurements have been limited to currents of a few hundred mA and a pulse duration of few µs. A full characterisation of the linearity of the YAG screen with power deposition is still to be done. The multi-hole FC is still under commissioning, and will be discussed in a later publication.

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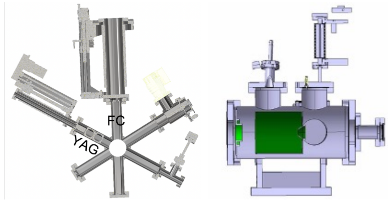

Figure 2: Diagnostics Box and Collector at the test facility.

The hollow electron beam will diverge inside the collector following the lines of the magnetic fringe field, and hit the collector surface (in green in Fig. 2) for current measurements. The pulse modulator (EPULSUS®-FPM1-12), connected to the gun anode (details below), was especially developed for our purpose by *EnergyPulse Systems*. It is a Marx generator [8] based modulator with a rise time of 200 ns, the equivalent time duration between two consecutive injections in the Super Proton Synchrotron (injector to the LHC). As the voltage is increased from zero to 10 kV, the extracted current changes from zero to 5 A at the designed gun perveance. The generator has pulse duration ranging from1 µs to 100 µs, and the possibility of varying the extraction voltage continuously. The weakness of this pulse modulator has been its lacking protection against return currents, which has caused it to fail on several occasions due to the overloading of the transistors. The system is currently being modified.

ELECTRON GUN MEASUREMENTS

First Campaign and Gun Characterisation

For the first measurement campaign, the Electron Beam Test Facility consisted of the HEL electron gun [9] to be tested, the diagnostic box, the gate valve and the collector, together with the necessary magnetic system, as shown on the left hand side in Fig. 3. The gun has a cathode that can be biased to the chosen electron beam energy, namely 15 kV for the HEL [2], while the extraction voltage, and thereby also the electron beam current, is set by biasing the anode with respect to the cathode via a pulse modulator. As mentioned above, the extraction voltage necessary to obtain a beam of 5 A equals about 10 kV. The gun is mounted inside a dedicated chamber with a viewport, allowing to measure the temperature along the gun support structure, a residual gas analyser to monitor the gas species during electron emission and verify the vacuum compatibility of the gun, and a pump to limit the pressure at the cathode. As mentioned in [9], the measurements allowed to identify problems of the first version of the gun design, where heat evacuation was not sufficient, leading to high temperatures at the ceramics, which became conductive and caused arcs. The design was subsequently modified, as shown in Fig. 4, and the gun was partially characterised with the sequence of measurements described below. It should be noted that the cathode emission itself had previously been validated by measurements both at the producer, Beijing University of Technology (BJUT), and with a larger body gun, measured at Fermilab [10].

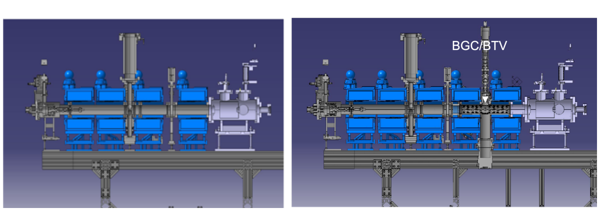

Figure 3: Schematics of the test facility as for the first (left) and second (right) measurement campaigns.


Figure 4: HEL electron gun [9] 3D model (left) and prototype (right). The hollowed cathode has an inner and outer diameter of ∼8.05 mm and ∼16.10 mm respectively, and can be seen in the enlargement inside the anode.

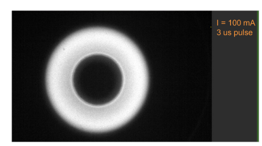

Figure 5: Electron beam from the HEL gun, with 100 mA and 3 µs pulse. The round and uniform structure of the beam is clearly visible.

Fig. 5 shows one of the first measurements of the hollow electron beam at the YAG screen at the CERN Electron Beam Test Facility. The beam intensity – measured at the collector – was about 100 mA. In these conditions, the electron beam is very stable and the shape and uniformity of the beam look perfectly annular. Fig. 6 shows tests of compression of the beam at the YAG screen. The maximum extracted current measured with this gun at the test stand was 4.5 A, with an extraction voltage of 9.5 kV. The gun seems to follow well the *Child-Langmuir* law, that gives the maximum space-

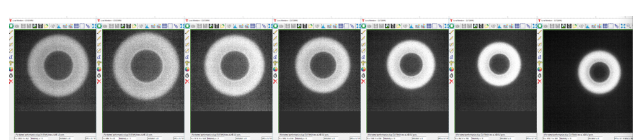
Figure 6: HEL gun electron beam, imaged at the YAG screen, during magnetic compression with 20 mA and 3 µs pulses. The outer beam diameter (in mm) is, from left to right, 24, 26.5, 24.4, 21.6, 19, 17.1 and 13.2. The beam moves during compression indicating a slight misalignment of the gun with respect to the axis of the magnetic field lines. The misalignment was corrected for later measurements.

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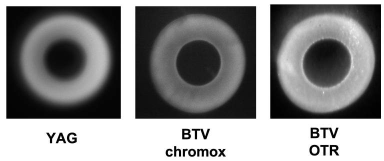

Figure 7: YAG, Chromox and OTR screen images. The shots parameters were respectively: 364 mA, 4.6 keV, 5 µs; 2 mA, 7 keV, 5 µs; and 1.2 A, 7 keV, 25 µs.

charge-limited current in a planar diode of infinite radius as: $I = K/d^2 \cdot V_d^{\frac{3}{2}}$, where d is the distance between cathode and anode, and K/d^2 is the gun perveance. Fitting our measurements we obtain a perveance of $5.8 \times 10^{-6}\ \mathrm{AV}^{-\frac{2}{3}}$, that compares well with the $5.9 \times 10^{-6}\ \mathrm{AV}^{-\frac{2}{3}}$ found at FNAL with the same cathode/anode geometry (but different gun design) [9, 10].

Second Campaign and BGC Measurements

The second measurement campaign focused on testing the imaging screens, capable to withstand higher beam intensities, that are installed just upstream of the collector. Those measurements were a first step to characterise the beam at the location where the BGC [6] is foreseen. The BGC was designed to measure the spatial overlap between the HEL and the LHC beams. It is a complex, non-invasive beam profile monitor that images the fluorescence produced by a particle beam interacting with a gas curtain. The gas curtain produced at the BGC is about 2 mm thick and has an angle of 45° with respect to the beam direction of motion. More details about the BGC can be found here [11].

The imaging measurements were carried out with two different types of screens, a fluorescent aluminium oxide screen (Chromox) and an Optical Transition Radiation (OTR) screen made out of glassy carbon, both installed at the location labelled BGC/BTV in Fig.3.

Some examples of those measurements are shown in Fig. 7. In this paper we do not go into great details about the comparison of the screen measurements with BGC, since this is part of a PhD thesis that is being prepared. We would like, nevertheless, to make some observations:

YAG : The YAG screen is used for beam measurements at low current or short pulse. We have not yet investigated saturation effects, but this will be part of a future study.

BTV : The image of the BTV-Chromox is shown for 2 mA beam intensity and 7 keV. As the beam intensity was increased, the images show some blurring. Similar effects were also observed in [12], and will also be part of a future, more systematic study. Images from the OTR have been obtained for the maximum beam current and always provide a high quality for the measurements [13].

BGC : The first images using the BGC are shown in Fig. 8. The compression and beam position with respect to the gas curtain – of which one can see the edges when the beam is larger than 12 mm – is different in the three images. Those images show a 'second' beam, overlapping

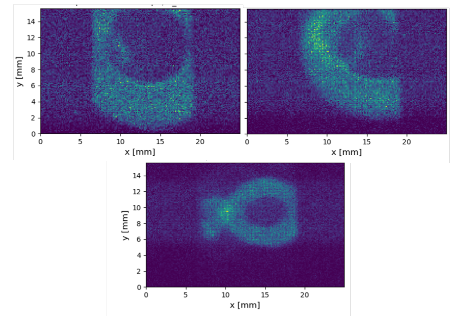

Figure 8: HEL gun electron beam measurements at the BGC.

with the hollow electron beam, more clearly visible on the third image in Fig. 8. This was interpreted as part of the electron beam being reflected from the collector, since it is not visible with BTV measurements, where the screens used are thick enough to fully intercept the incoming beam, while the BGC gas curtain is non-invasive and produces photons with beam particles from any direction. In order to remove this effect, it was necessary to tune the magnetic fields and correct for beam misalignment. The beam sizes and distributions measured by the BTV and the BGC were comparable, and confirmed that the sensitivity of the BGC is well adapted to measure the HEL electron beam when operating at high current and in DC mode. Discussions on the measurement accuracy and image resolution will be given in future publications.

CONCLUSIONS AND OUTLOOK

In this paper we presented the status and first results of the Electron Beam Test Facility at CERN, and described its various components, such as gun, pulse modulator, diagnostic box, collector, and BTV. The HEL electron gun was successfully characterised using a suite of beam instruments developed to measure the transverse beam properties at high current using either an OTR screen or a Beam Gas Curtain monitor. A new measurement campaign is being prepared to validate the performance of a strip-line BPM, which has to be compatible with the 200 ns rise time foreseen for the HEL electron beam on / off switching. For this purpose, a BPM prototype will be added in 2023 between the sector valve and the BGC/BTV location, as shown in Fig. 1. A new HEL collector will be tested later in 2023 or in 2024. More investigations will also be performed using the BGC to understand if it can be used to measure the electron capture efficiency of the collector. In the medium term future, the facility is expected to become a test-stand at CERN for high current and high perveance guns, beam instruments, pulse modulators and collectors.

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