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SIGNAL ANALYSIS AND DETECTION FOR THE BPMs OF THE LHC HOLLOW ELECTRON LENS

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Abstract

The Large Hadron Collider (LHC) at CERN will be equipped with two hollow electron lenses (HEL) for the high luminosity upgrade, which allow for scraping of the LHC proton or ion beams transverse tails by overlapping a coaxial hollow electron beam over a 3 m length. A precise alignment of the two beams is essential for the HEL functionality, the bunched LHC hadron beam of up to 7 TeV beam energy, and the non-relativistic, DC-like electron hollow beam of 10 keV energy. The absolute and relative transverse positions of both beams will be monitored by two stripline beam position monitors (BPM), located in the HEL, and the pickup signal processed by a narrowband signal detection system. This paper summarizes the analysis of the expected proton and electron beam signals, including laboratory measurements, with aim of a narrowband diode-detection read-out electronics as BPM signal processor.

INTRODUCTION

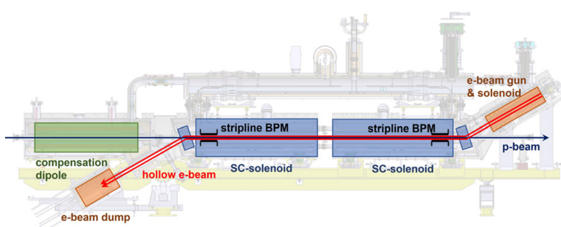
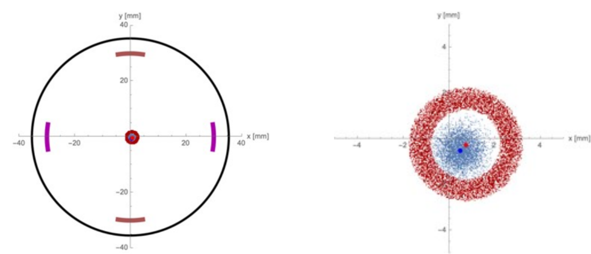


Figure 1: Sketch of the HL-LHC hollow electron lens (HEL).

A high-luminosity LHC upgrade project (HL-LHC) is in progress at CERN [1], with the goal to boost the yearly integrated luminosity from presently 50−65 fb^{-1} to > 250 fb^{-1} at the two collision experiments ATLAS and CMS. Among the many changes and improvements required, a new particle collimation strategy was developed to enhance the transverse beam halo depletion, which includes the use of a hollow electron lens (HEL) for each of the two circulating hadron beams [2]. It utilizes a "non-material" hollow electron beam scraper, placed coaxially around the proton beam, to increase the diffusion rate of protons or ions with large emittance. Figure 1 shows the schematic of the approximately 6-meter-long HEL system in a sectional view, which consists of a thermionic electron beam gun, accelerating a hollow electron beam of up to 5 A current to approximately 12 keV beam energy, before being bent onto the LHC proton beam orbit. The beam is controlled by two main superconducting solenoid magnets and a set of auxiliary solenoids and steering magnets, before being bent downwards to a beam dump. Inside the 120 mm warm bore of each superconducting solenoid, a beam position monitor (BPM) pickup with four symmetrically arranged electrodes is located. The horizontal and the vertical pairs of stripline electrodes of 400 mm length are used to monitor the beam position of both beams, i.e.the hollow electron beam and the counter-propagating proton beam, each detected separately at the upstream ends of the electrodes by a high-resolution BPM signal processor, enabling a precise relative alignment of both beams.



(a) (b)

Figure 2: Hollow electron beam position measurement with a BPM pickup (left), proton and hollow electron beam close-up (right).

Figure 2 (left) gives an idea of the BPM pickup of 60 mm diameter aperture in a cross-section view, indicating the beam pipe and the stripline electrodes, as well as both beams near the center. Figure 2 (right) illustrates a close-up cross-section view of the proton and the hollow electron beam in a non-optimized beam position, both beams should be perfectly centered to each other. Also indicated are their center-of-charges, by a blue dot (for the proton beam) and a red dot (for the hollow electron beam), as they would be monitored by the proposed BPM system. The proton and hollow electron beams to be detected have very different beam formats, see Table 1.

Table 1: Proton and Hollow Electron Beam Specifications

	Time structure	Beam charge /current	Relativistic factor β	Transverse size
Proton beam	2760 bunches ~ 1 ns (4σ)	$1 - 2.3e^{11}$ p/b	1	$\sigma_x \approx \sigma_y$ ≈ 0.3 – 1.2 mm
Hollow electron beam	"DC-like" 1.2 – 86 µs pulse duration	0.1 – 5 A	0.2 – 0.24	Inner diameter ≈ 2 – 8 mm Outer diameter ≈ 4 – 16 mm

Figure 3 illustrates the situation of the two beams at the location of the HEL stripline BPM in a longitudinal section view. Let's name the two symmetric stripline electrodes "A" and "B", either the horizontal, or the vertical pair of electrodes. With the help of a signal pre-processing scheme,

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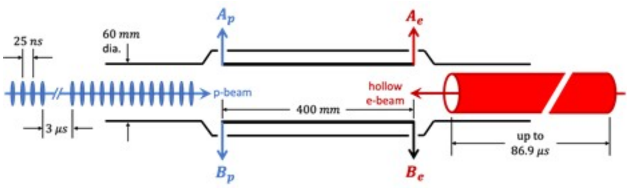


Figure 3: HEL beam position monitor.

it will be always the upstream electrode pair which senses the relevant beam type, indicated by the index "p" for the proton or ion beam and "e" for the hollow electron beam.

THE HEL STRIPLINE BPM PICKUP

While the final HEL BPM requires a 60 mm diameter beam pipe aperture, we use an existing larger model of 81 mm aperture for our test bench measurement, and for the initial beam test at the HEL test stand as well. This stripline type BPM pickup is equipped with four electrodes of 400 mm length, two per plane, each precisely tuned to a 50 Ω characteristic impedance. Each stripline covers a 0.307 rad azimuthal width, corresponding to a 17^0 covering angle.

For the RF characterization of the BPM a coaxial test setup was manufactured, which enables RF measurements over a wide range of frequencies. The particle beam is "replaced" by a tapered, coaxial center conductor of constant 50 Ω characteristic impedance, see Fig. 4. This bench setup will provide a TEM field configuration, similar to that of a particle beam travelling at a relativistic velocity near c.

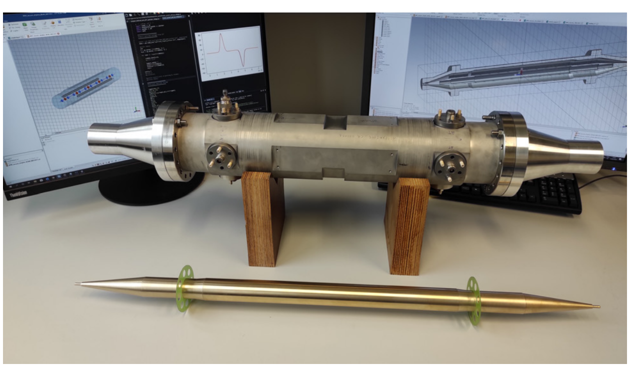
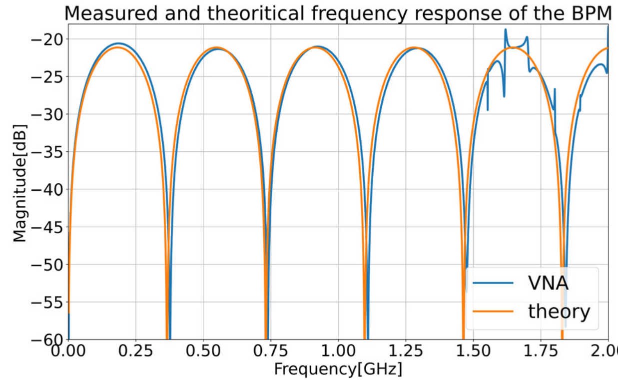
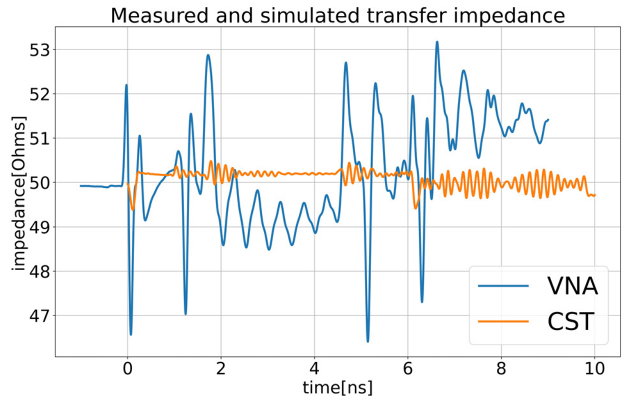


Figure 4: The stripline BPM between a tapered coaxial test bench structure with the inner and outer conductor.

Regarding the symmetry of this coaxial BPM test bench setup, we characterized the transfer impedance of 1-of-4 striplines w.r.t. the coaxial "beam" input, with the help of a vector network analyzer (VNA). Figure 5 (a) shows the magnitude response of the beam-to-electrode transfer function of the upstream (port 2: |S21(f)|) and of the downstream (port 3: |S31(f)|) stripline electrode w.r.t. the stimulus signal connected to the coaxial "beam" port, i.e. port 1. All unused ports of the setup have been terminated in their characteristic impedance. The S21 measurement depicted in Fig. 5 (a) matches the analytical analysis very well.



(a)



(b)

Figure 5: (a) The frequency response of the BPM stripline electrode, upstream port (S21) from measurement (VNA) and theory, and downstream port (S31). (b) Measured / simulated TDR of the BPM test bench setup.

We also verified the characteristic impedance of the coaxial setup using the time-domain reflectometry (TDR) option of the VNA. Figure 5 (b) compares the VNA-based TDR measurement with a numerical analysis performed with the commercial *CST Studio Suite software* [3]. While the agreement is not perfect, the 50 Ω characteristic impedance is still well-matched within ±5 % over the entire length of the coaxial line.

BPM SIGNAL ANALYSIS

The hollow electron lens BPM should measure the center of charge of both beams, separately for the proton and for the electron beam, and independently of their individual beam formats. As a first step, we analyse the expected beam signal from the BPM pickup electrodes:

Proton Signal Analysis

Up to 2760 proton beam bunches are circulating in the LHC at a relativistic velocity $\beta = v/c \approx 1$, with a spacing of ~ 7.5 m ≡ 25 ns between them, see also Table 1. The up to 2.3×10^{11} protons (≡ 36.8 nC) within each bunch have an approximate Gaussian longitudinal distribution, with $\sigma_t \approx 250$ ps. In case of lead-ion beams, the bunch intensity

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is much lower, $\sim 5 \times 10^{10}\ Pb^{82+}$, also the ion bunches tend to be a little longer. For the measurements in the laboratory those values had to be limited to a bunch length equivalent of $\sigma_t \approx 420$ ps, and a maximum bunch intensity of 0.084 nC, by the maximum ratings of our available pulse signal source generator, see also Fig. 6 (a). This Gaussian-like, proton bunch equivalent pulse signal is fed into the coaxial BPM test bench setup, while the response signals produced at the upstream and downstream ports of one of the BPM stripline electrodes are measured with a broadband oscilloscope. Figure 6 summarizes the proton signal analysis, (a) shows the proton bunch equivalent voltage input signal, terminated with 50 Ω, (b) the time-domain voltage output signal at the upstream and downstream ports of the stripline electrode and (c) the simulated transfer-function frequency domain characterization |S21(f)| for both, the upstream and the downstream port. The time-domain measurements Fig. 6(a) and (b) have been compared with analytical estimations (theory), and with numerical simulations (CST), demonstrating a good agreement. Please note, for $\beta \approx 1$ the stripline electrode acts as a TEM directional coupler, and therefore any remaining signal at the downstream port is an unwanted error signal due to non-TEM field effects. From the measurements we can estimate the directivity as $v_{up}/v_{down} \approx 15 \equiv 24$ dB, which is also observed in the frequency-domain VNA analysis, Fig. 6(c).

Electron Signal Analysis

The electron gun of the hollow electron lens will produce a circular electron beam of approximately 10 keV energy, which corresponds to a relativistic velocity of $\beta = 0.2$, see also Table 1 [2]. The longitudinal distribution of the electrons is assumed to be uniform and correspond to a constant DC beam current with 5 A maximum. The extraction voltage between cathode and anode in the gun can be varied, with rise and fall times of ~ 200 ns, which allows to switch on-off the hollow electron beam during the 3 µs abort gap of the LHC hadron beam (see Fig. 3), or in the kicker-gap between batches. Therefore, the maximum duration of the hollow electron beam is 86.9 µs, while the repetition rate is equivalent to the LHC revolution time of 88.9 µs. Like for the proton signal analysis, the laboratory equipment limits the electron beam intensity to equivalent 0.1 A maximum (DC). Figure 7 (a) shows the inverted time-domain signal with 200 ns rise/fall times. Figure 7 (b) shows the corresponding output signal at the upstream stripline port w.r.t. the electron beam, which is basically a differentiated waveform of the input signal, Fig. 7 (a), as the stripline acts as capacitive coupled RC high-pass filter for these low frequencies (with $R = 50\ \Omega$).

The coaxial, air-transmission-line BPM test bench (Fig. 4) will always excite a Transverse Electro-Magnetic (TEM) field pattern with a signal velocity $\beta = 1$, also for the hollow electron beam equivalent current signal shown in Fig. 7 (a). However, the effects of the non-relativistic beam velocity of $\beta = 0.2$ on the output signals of the stripline was investigated through simulations with the "Particle-In-Cell" solver

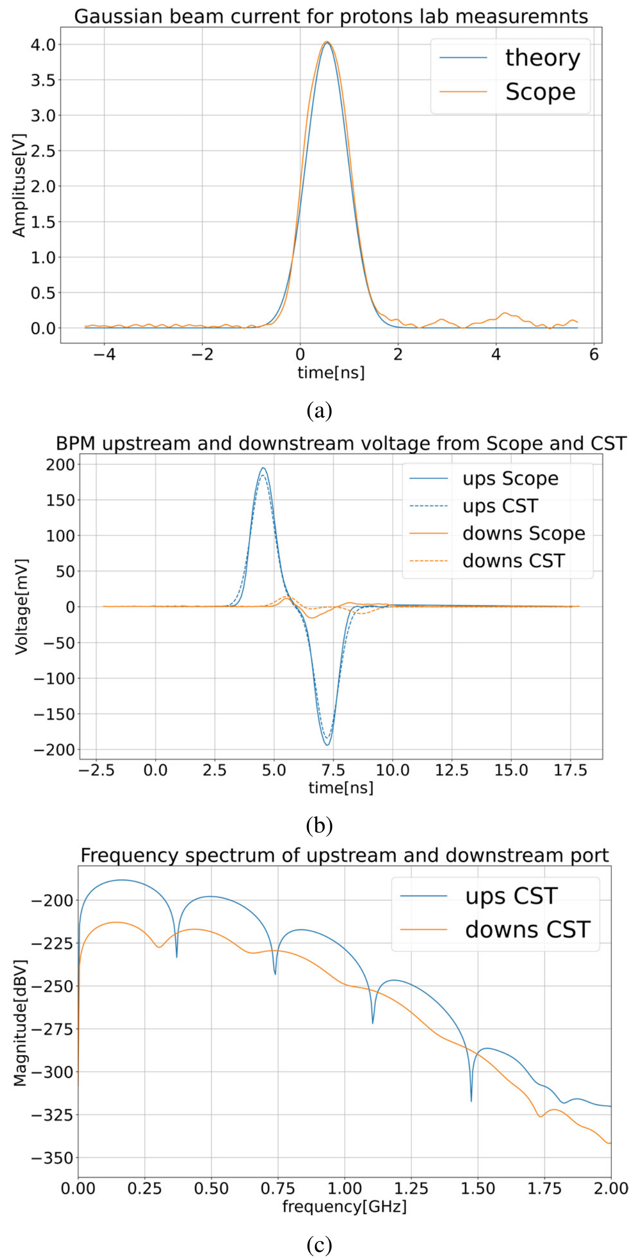

Figure 6: (a) Proton bunch signal, time-domain. (b) Stripline BPM response, TD, upstream and downstream ports (c) Stripline BPM response, FD, upstream and downstream ports.

of CST. Figure 8 shows the result as magnitude spectrum in the frequency-domain of the stripline electrode output signal, which is the upstream port for the low-beta electron beam. Also shown in Fig. 8 is the residual error signal from the proton bunches (downstream proton port) due to the limited directivity of the striplines, see also Fig. 6 (c) (orange trace). To resolve this interference a frequency discrimination around ~ 15 MHz seems to be a viable option.

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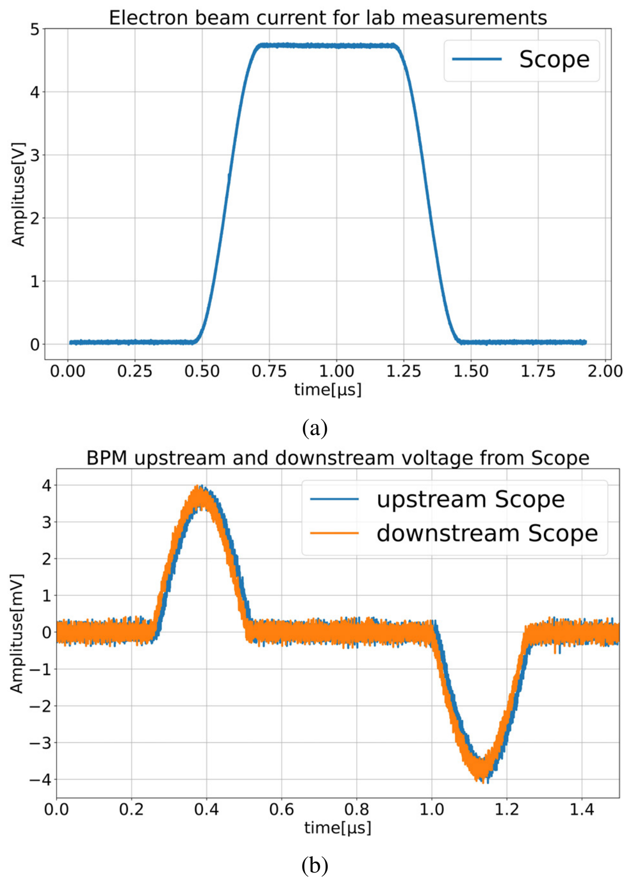

Figure 7: (a) Electron beam current for lab measurements and (b) measured output voltage at the upstream BPM port.

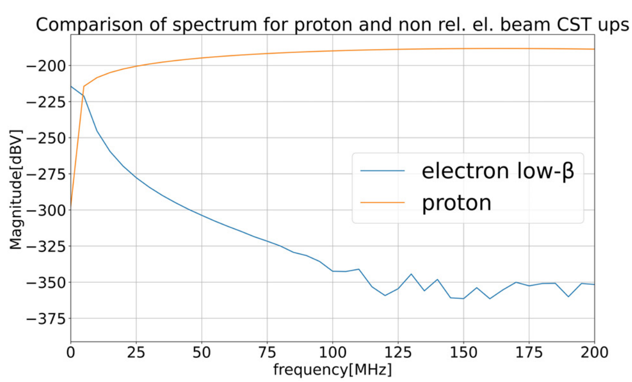

Figure 8: Frequency-domain magnitude spectrum for the low-beta electron beam signal, and the residual proton beam error signal.

Signal Detection and Frequency Discrimination

The proposed BPM signal processing for both beam signals is based on a time-domain signal peak detection scheme. This requires the time domain signals for the stripline electron ports A_e to be error free of the convoluted residual proton signal content, and vice versa the time domain signal on the proton ports A_p to ensure a pure proton signal without electron signal content. On the proton port A_p the residual electron signal, even with the maximum electron beam intensity of 5 A (DC), will have a peak value < 1 V calculated from simulations. In the same port the proton or ion signal with the minimum bunch charge of 5×10^{10} cpb will have a peak value of~ 15 V that is adequate to ensure a correct proton / ion signal measurement by the peak detection scheme. On the electron port A_e the maximum peak value of electron signal will be the same <1 V while the maximum residual proton signal on this port can reach ~ 6 V indicating the necessity of an additional signal pre-processing scheme that will suppress the higher proton peak value. Thus, a third order low pass non reflective filter with a cut-off frequency of 13.3 MHz (see Figure 8) was designed, which rejects the high frequency proton signal content and allows our peak detection scheme to detect the pure electron beam peak values.

BPM MEASUREMENT RESULTS

The proposed architecture of the read-out front-end electronics for the BPM signals is sketched in Fig. 9. For our test in the laboratory, we used the stripline BPM test bench as shown in Fig. 4 and applied the electron and proton beam signals discussed in the previous section - simultaneously on both inputs, in counter-propagating manner, delivered by two synchronized pulse generators, however, with approximately 250× (protons) / 50× (electrons) lower intensity compared to the nominal proton / electron beam intensity. The BPM pickup signals from the upstream ports (w.r.t. the protons) are fed to 4 (out of 8) channels of the narrowband diode-detection read-out electronics system called DOROS[4]. The

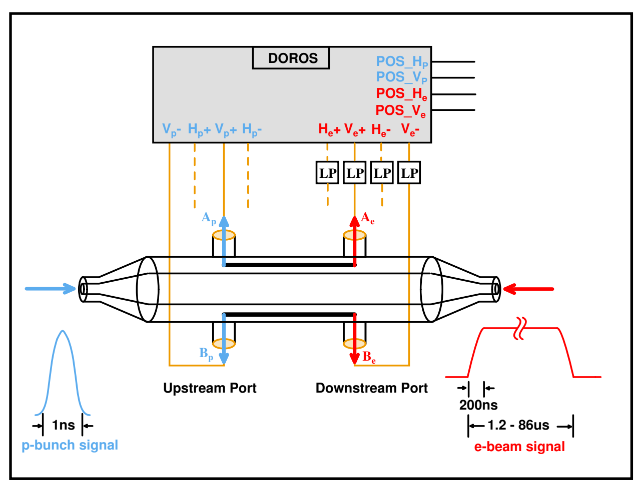

Figure 9: BPM measurement setup schematic.

DOROS BPM signal processor detects the four peak signal levels and calculates the position of the bunched beam for the horizontal and vertical plane w.r.t. the center of the BPM. The four downstream BPM ports w.r.t. the protons, i.e., the electron signal upstream ports, are passed through a 3rd order, non-reflective low-pass filter with 13.3 MHz cut-off frequency, and then fed to the other four read-out channels of the same DOROS system. Figure 10 (a) and (b) summarizes the position measurement results for two different, 12-hour

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long laboratory measurement runs using our BPM test bench setup, performing one measurement per second. The mean value has been deducted from the original measurements for better visualization and comparison of the long-term drift effects. Both, the mean value and the variance of the measured data are displayed in the plots of Fig. 10 (a) and (b). The lower peak values of the electron signals result in a lower resolution, which is still < 0.15 µm. The long-term drift effects of the non-temperature stabilized BPM read-out electronics are ~ 1.5 µm, and fulfill the requirements of the HEL beam alignment during typical LHC luminosity runs.

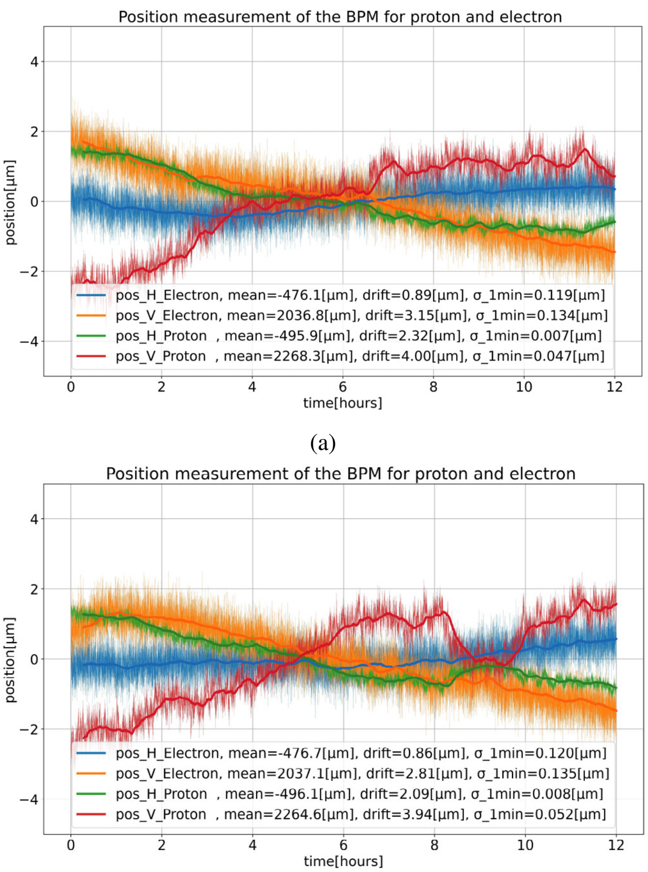

Figure 10: 12-hour long HEL BPM laboratory measurements with simulated beam signals.

CONCLUSION

A BPM measurement setup, developed to simultaneously measure the center of charge position of both, a quasi-DC, low-beta hollow electron beam and bunched hadron beam travelling at a relativistic velocity is presented. Numerical simulations and laboratory measurements demonstrate the feasibility of the system composed out of well-known components, a stripline-BPM pickup, low-pass filters, and a peak-detector signal processing system to fulfil the requirements for the beam alignment in the hollow electron lens of the HL-LHC.

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