PERFORMENCE OF THE TIME RESOLVED SPECTROMETER FOR THE 5 MeV PHOTO-INJECTOR PHIN

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Abstract

The PHIN photo-injector test facility is being commissioned at CERN to demonstrate the capability to produce the required beam for the 3rd CLIC Test Facility (CTF3), which includes the production of a 3.5 A stable beam, bunched at 1.5 GHz with a relative energy spread of less than 1%. A 90° spectrometer is instrumented with an OTR screen coupled to a gated intensified camera, followed by a segmented beam dump for time resolved energy measurements. The following paper describes the transverse and temporal resolution of the instrumentation with an outlook towards single-bunch energy measurements.

INTRODUCTION

The CTF3 drive beam is currently generated with a thermionic gun and subharmonic bunchers inducing high losses (30%) and producing 8% satellites [1]. A photo-injector is a valuable alternative capable of overcoming the inefficiency of the RF system since the bunch train's temporal structure follows the laser's one [2]. Such a photo-injector, named PHIN, is under commissioning at CERN in collaboration with LAL and CCLRC. It should produce a 1.2 μs long train of bunches spaced by 667 ps (8 ps bunch length and 2.33 nC bunch charge) with an energy stability below 0.1% and a relative energy spread smaller than 1%. PHIN features several diagnostic tools to address these issues [3]; beam energy and energy spread are measured using a 90° spectrometer designed in 2009 and tested during the first commissioning of PHIN [4]. The spectrometer consists of an Optical Transition Radiation (OTR) screen for precise energy spread measurements. Time resolved measurements are obtained via a segmented beam dump which is a key device for identifying energy variations along the pulse train due to beam loading and RF power fluctuations. This paper describes the performance of the instrumentation with a focus on the time resolution of the detectors.

THE PHIN SPECTROMETER

The non-movable OTR screen, tilted by 45° with respect to the beam axis and imaged by an intensified gated camera with a minimum gate duration of 5 ns [5], is placed 580 mm downstream of the dipole, see Fig. 1. The segmented beam dump, made out of 20 stainless steel plates (2 mm thick and spaced by 1 mm) parallel to the beam direction and working as Faraday Cups, sits at the end of the spectrometer line, outside of the vacuum chamber, at a distance of 739 mm from the dipole. The dispersion in the line is equal to 820.2 mm and 1067 mm for the OTR screen and the segmented dump respectively. The fast read-out of the 20 segments gives a time resolved horizontal beam profile, corresponding to the beam energy spread along the pulse. A typical time resolved spectrum is shown in Fig. 2.

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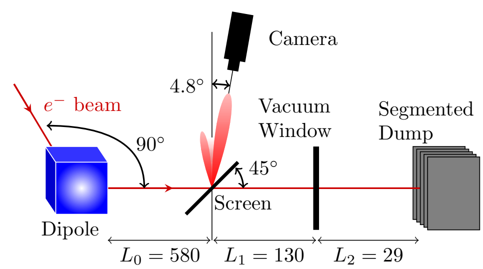

Figure 1: Layout (in mm) of the PHIN spectrometer.

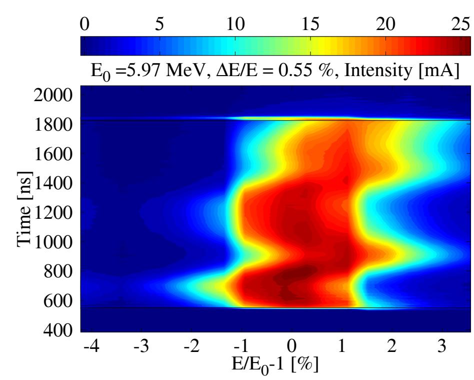

Figure 2: Time resolved energy spread; the energy fluctuations along the pulse are due to RF variations [6].

ENERGY RESOLUTION AND ERRORS

At 5.5 MeV multiple scattering of the beam in the OTR screen and vacuum window increases the 1σ beam profile at the segmented dump by: $L_1 \tan(\sigma'_s) + L_2 \tan(\sigma'_{vac})$. Where σ'_s and σ'_{vac} are the increase in beam divergence due to the OTR screen and vacuum window respectively. Correcting for this and the beam's intrinsic size (σ_b) the horizontal profile, encoding the energy spread, is:

$$\sigma_{E,d} = \sqrt{(\sigma_d - L_1 \tan(\sigma'_s) - L_2 \tan(\sigma'_{vac}))^2 - \sigma_b^2}$$

This is converted to the relative energy spread through:

$$\frac{\Delta E}{E} \simeq \frac{2}{\pi}\frac{\sigma_{E,d}}{L_0+L_1+L_2} \pm \frac{2}{\pi}\frac{\Delta\sigma_{E,d}}{L_0+L_1+L_2}$$

The error on $\sigma_{E,d}$ is:

$$\Delta\sigma_{E,d} = \sqrt{\sum_{ij} \left(\partial_{x_i}\sigma_{E,d}\right)^T M_{ij}\partial_{x_j}\sigma_{E,d}}$$

Where $\boldsymbol{x} = (\sigma_d, \sigma'_s, \sigma'_{vac}, \sigma_b, L_1, L_2)$ and $\partial_{x_i}\sigma_{E,d}$ is the derivative vector. The error matrix is assumed to be $M_{ij} = \Delta x_i \Delta x_j$. For a typical beam with $\sigma_d = 12$ mm and $\Delta\sigma_d = 1$ mm it is found that the absolute error on $\Delta E/E$, measured by the segmented dump, is $\pm 0.06\%$, making this detector accurate to within 7.4%. The largest contribution comes from the error on the measured profile at the segmented dump, i.e. σ_d.

For an ideal beam, the minimum resolvable energy spread is 0.25%, corresponding to the case where all the beam enters one segment.

BEAM MEASUREMENTS

The nominal PHIN design parameters were achieved in 2009 [7], however as presented here lower quality beams were used to test the spectrometer's performance.

Electrical CrossTalk in the Segmented Dump

Aside from beam dynamics and the effect of beam line elements, the measured energy spread is increased by the dump's intrinsic electrical crosstalk between neighbouring channels. Using a network analyser this effect was measured to be a maximum of 10 dB in the 96 MHz sampling frequency range of the ADCs, see Fig. 3. Assuming only nearest neighbour crosstalk, this effect is modelled by:

$$C\mathbf{S_{in}} = \mathbf{S_{out}} \text{ with } C_{i,i} = 1, C_{i,i+1} = C_{i,i-1} = \eta_{XT}$$

η_{XT} is the crosstalk between nearest neighbours and the index i runs over the segments in the dump. Assuming a Gaussian distribution as input signal $\vec{S}_{in}$ the broadened signal $\vec{S}_{out}$ is computed and fitted to a Gaussian. With $\eta_{XT} = 10$ dB the relative broadening of σ_d is only 1.8% for a typical PHIN beam, see Fig. 4.

Segmented Dump Time Resolution

The stopping time of 5.5 MeV electrons in stainless steel, simulated in Geant4 [8], shows that the intrinsic time resolution is 17 ps which corresponds to a working regime of $0 - 58$ GHz, see Fig. 5. In routine operations, the segmented dump channels are connected to the 96 MHz ADCs via 55 m long BNC cables, which give already a 3 dB attenuation at 12 MHz. Any fluctuations in the signals occurring at higher frequencies would be slightly distorted. To minimise the bandwidth limitations due to cabling and the ADCs, one channel of the segmented dump was connected via a 100 m N-type cable to an oscilloscope with an 18 GHz analogue bandwidth. For N-type cables the 3 dB/100 m attenuation threshold is rejected at 115 MHz. The measured raw signal and its FFT, Fig. 6, show that the segmented dump is capable of resolving the beam's 1.5 GHz bunching structure. However the bunch profile cannot be resolved; with this setup the segmented dump's temporal resolution is considered to be the FWHM of the measured individual bunches, i.e. 520 ps. This limit is due to cable length and impedance mismatches between the stainless steel segments and the connectors. This was confirmed by connecting an impedance-matched single-channel Faraday Cup, sketched in Fig. 7, to the oscilloscope with the same N-type cable. As can be seen in Fig. 6 the beam current goes almost to zero in between bunches and the temporal resolution improves to 250 ps.

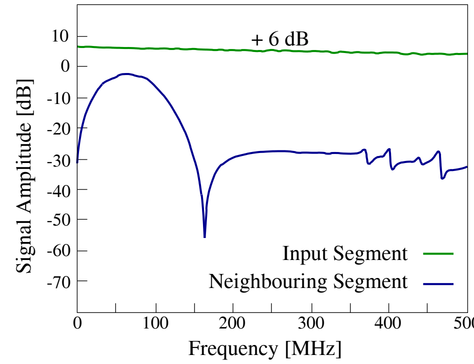

Figure 3: Crosstalk measured with a network analyser.

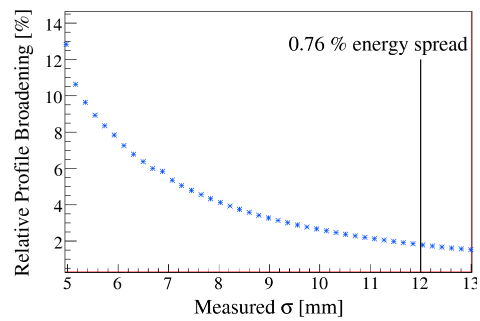

Figure 4: Effect of crosstalk on the measured profile.

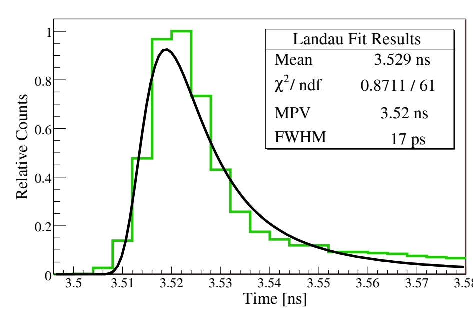

Figure 5: Time distribution of a 0 ps long bunch of electrons once stopped in stainless steel.

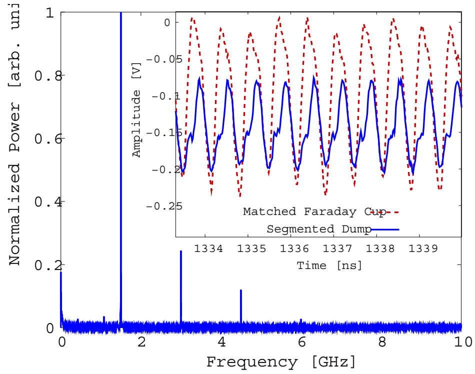

Figure 6: Individual bunches measured by the segmented dump and the FFT of the pulse.

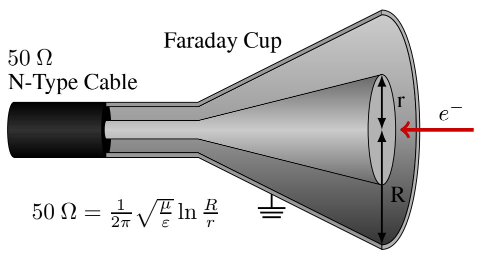

Figure 7: Impedance matched Faraday Cup.

OTR Screen Time Resolution

The OTR screen's time resolution was tested using a low charge $0.1\ \mathrm{nC}$ beam with the camera's minimum $5\ \mathrm{ns}$ gate. Due to the little amount of light collected the camera was set to a high gain (76%), increasing the amount of shot noise. A measurement of the beam's transverse profile, see Fig. 8, shows that measurements under such conditions are still feasible. Given that the PHIN nominal bunch charge is 23 times higher ($2.3\ \mathrm{nC}$), it can be expected that single bunch measurements could be achieved with faster cameras.

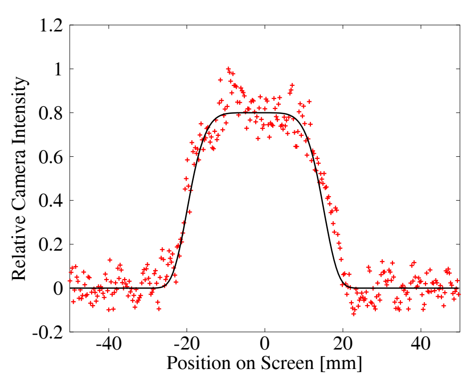

Figure 8: Transverse profile measured with a $5\ \mathrm{ns}$ gate.

Segmented Dump and OTR Screen Agreement

The segmented dump and OTR energy spread measurements were compared over time intervals of $200\ \mathrm{ns}$ along the pulse train. The result of the scan is shown in Fig. 9. Each interval was measured several times; giving a mean relative energy spread. The standard deviation is referring to shot to shot fluctuations. The scan shows that the two detectors measure the same relative energy spread up to $7.8 \pm 4.6\%$.

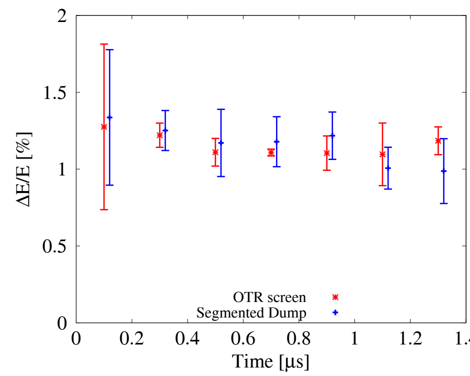

Figure 9: Gated OTR scan measurements, compared with the segmented dump.

CONCLUSION AND OUTLOOK

The tests presented here show that the instrumentation is well adapted for PHIN's needs: the energy spread measured with the segmented dump and the OTR screen has been shown to agree within $7.8 \pm 4.6\%$ over $200\ \mathrm{ns}$ time intervals. Extrapolating from the OTR data, single bunch measurement should be possible. The time response of segmented dump detectors can be improved by carefully designing the cabling and connections. SMA type connectors could directly be soldered to the segments to minimize the number of connectors and to allow a higher bandwidth.

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