ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP33

BEAM CURRENT MEASUREMENTS AT THE NANO-AMPERE LEVEL USING A CURRENT TRANSFORMER

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Abstract

In conventional proton therapy (PT) typical beam currents are of the order of 0.1 nA. At these currents dose monitoring is reliably achieved with an ionization chamber. However, at the very high dose rates used in FLASH irradiations (employing beam currents >100 nA) ionization chambers will exhibit large intensity dependent recombination effects and cannot be used. A possible solution is a current transformer. Here we report on the performance of the LC-CWCT (Bergoz Instrumentation, France) which has been developed to push noise floor of such non-destructive current measurement systems into the nano-ampere range. We present first beam current measurements at the PARTREC cyclotron (Netherlands). Beam currents measured by the LC-CWCT and a Faraday Cup were shown to linearly correlate up to the maximum intensity of 400 nA used in the measurements. For pulsed beams, charge measured by the LC-CWCT linearly correlated with pulse length over the measurement range from 50 to 1000 µs. Measurement noise as low as 2.8 nA was achieved. The results confirm that the LC-CWCT has the potential to be applied in FLASH PT for accurate determination of beam current and macro pulse charge.

INTRODUCTION

FLASH PT aims to use ultra-high dose rate (>40 Gy/s) beams for cancer treatment, which has been proven in preclinical studies to spare doses for healthy tissues while maintaining the treatment effects on some specific tumour models [1-3] compared to conventional PT. The beam current extracted for FLASH PT is around 1000 times higher than for clinical PT (~0.1 nA), which leads to a challenge for beam extraction in clinical cyclotrons.

Some studies also show that the beam time structure causes a variation of the FLASH effect [4]. Further studies need to be done to examine conditions and beam parameters, i.e. current, pulse width, energy, frequency, triggering the FLASH effect in clinical practices. Thus, it is of great significance to have a flexible test bench capable of providing varying beam parameters for FLASH PT studies.

The PARTREC cyclotron is expected to provide ultra-high dose rates for FLASH pre-clinical studies over the next few years. Because the PARTREC facility is not in clinical use it is more flexible and modifications to beam intensity and time structure can be implemented more easily than at a clinical facility.

However, the beam monitor and control system designed for use at clinical dose rates, which is based on ionization chambers (ICs), faces a challenge in delivering precise doses at beam currents used to achieve FLASH beam dose rates. Specifically, the response of plane-parallel ICs [5-7] shows a dependence on dose rate which can become unacceptably large at ultra-high beam currents due to volume recombination effects; an effect which can be neglected in clinical settings. For FLASH PT studies, it is essential to improve the beam monitoring system for high currents (i.e. a few 100 nA to µA). Tests have shown that the ion collection efficiency of a plane-parallel IC designed at PARTREC is around 83% with a peak current of 543 nA (at 150 MeV beam energy).

A Faraday cup was applied in previous experiments to control the delivered proton fluence and to deduce IC efficiency, assuming the Faraday cup is dose rate independent. For FLASH dose rates, a current transformer, which is non-destructive to the beam, can provide the necessary redundancy in dose delivery by measuring beam currents for both CW and pulsed beams.

For the present study we tested a specially developed current transformer, the LC-CWCT, with a 150 MeV proton beam at the PARTREC cyclotron. Macro-pulse length and average current were varied during the measurements. A Faraday cup was installed at the end of the beamline to give a reference value for the input beam current. The aim of this work was to verify the noise levels of the LC-CWCT output signals of different bandwidths (100 Hz, 10 kHz and 350 kHz) in a real beam environment, and the potential of using an LC-CWCT in FLASH PT for real-time beam monitoring and control under complicate beam conditions.

LC-CWCT AND BCM-CW-E

The CWCT and the corresponding BCM-CW-E electronics [8] have been successfully used to measure microampere beam currents with sub-microampere resolution [9]. By applying a fast sample-and-hold measurement the BCM-CW-E deduces level of the CWCT output signal between any two consecutive beam pulses. From these signal levels average input currents can be deduced. The only necessary condition is that input beam bunches are well separated. For convenience the output signal is provided with three different bandwidths: 350 kHz, 10 kHz and 100 Hz.

The CWCT can be considered a noise free current source. All noise is either coming from the signal processing on the BCM-CW-E electronics, or from environmental noise, for example, captured by the coaxial cables connecting CWCT and BCM-CW-E.

In such a situation a very effective way of boosting the signal-to-noise ratio is to amplify the signal directly at the source. That means, by adding a low noise amplifier directly at the CWCT output the measurement range can be

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11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP33

shifted to lower currents. The low current limit is given only by the noise introduced by this amplifier. To distinguish from the normal CWCT, the combination of CWCT and low noise amplifier is called LC-CWCT.

Performance of the LC-CWCT was first measured on a test bench. The noise floor was determined to $\sigma_{350\mathrm{kHz}} = 300$ nA, $\sigma_{10\mathrm{kHz}} = 36$ nA, $\sigma_{100\mathrm{Hz}} = 7$ nA for the three available output signals of different bandwidth. Such low noise levels render the LC-CWCT interesting for many ion accelerators which produce beam currents <1 µA, thus requiring non-destructive beam instrumentation with nanoampere resolution.

However, these values were determined in a rather low noise electronics lab. Since particle accelerators tend to be an environment with plenty of electromagnetic noise, it was decided to verify LC-CWCT performance in a particle accelerator.

MEASUREMENT SETUP

A proton beam was accelerated to 150 MeV with a bunch repetition frequency of 55 MHz. During the experiments, the average beam current could be varied up to 400 - 500 nA. Time structure of the proton beam could be controlled to have macro-pulse lengths varying from 50 µs to 1000 µs, i.e. from short pulse mode to near CW mode. The beam spot size of around 3.5 mm (FWHM) passed entirely though the LC-CWCT aperture of 96 mm.

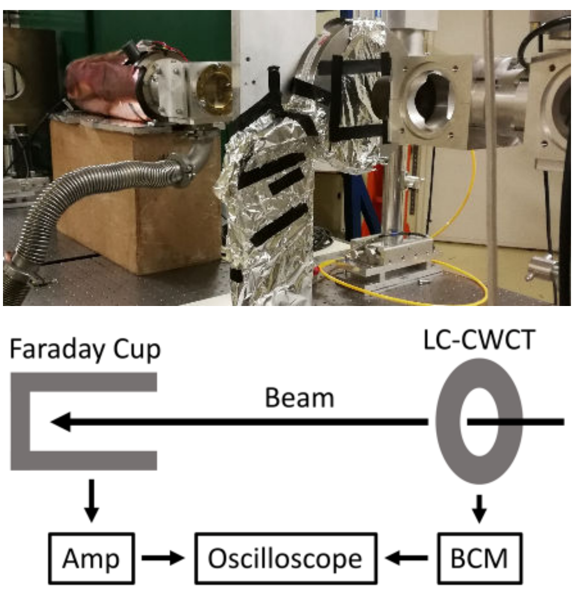

Figure 1: Photograph of the experimental setup with LC-CWCT (wrapped in aluminium foil to reduce noise) and Fcup (top). Schematic drawing of experimental setup and electronics readout system (bottom).

Figure 1 (top) shows a photograph of the experimental setup with the LC-CWCT and the Faraday cup (Fcup). The LC-CWCT was installed behind a beam window close to the end of an experimental beamline of the PARTREC cyclotron. About 1 m further the beam was collected by a Fcup. First tests with beam showed that indeed some non-negligible noise was picked up. Completely wrapping the LC-CWCT in aluminium foil resolved this issue. Note that the proton beam passed the aluminium foil without noticeable degradation.

A schematic drawing of the experimental setup is shown in Fig. 1 (bottom), including the electronics readout system. The LC-CWCT output signal was processed by the BCM-CW-E electronics module. The current signal from the Fcup was converted to a voltage signal by an amplifier (FEMTO, DLPCA-200). All output signals were recorded by an oscilloscope (Rohde&Schwarz RTH1004). The digitized data was stored for off-line analysis.

The Fcup works as an absolute dosimeter in this experiment controlling the total delivered proton fluence, since it is dose rate independent. Its inhouse design allows to reduce vacuum pressure to around 10^{-3} to 10^{-4} mbar. The Fcup setup also has an electron suppression electrode that prevents secondary electrons from escaping the Fcup It was previously calibrated with a current generator connected to the same amplifier (gain = 10^7, bandwidth = 50 kHz), so that the output voltage signal shows a linear response as a function of the input current.

Noise and Accuracy Evaluation

To evaluate the noise and accuracy of the LC-CWCT, we applied a low beam current (around 24 nA) with a macro-pulse length of 900 µs and a repetition frequency of 1 kHz. The beam was kept on for 1.5 s, corresponding to a total of 1500 input pulses. BCM-CW-E 100 Hz output signal was recorded on the oscilloscope. Other ports of the oscilloscope were connected to the Fcup and the input pulse timing trigger.

For a second test, beam current was increased stepwise to around 500 nA with a macro-pulse length of 1000 µs and a macro-pulse repetition frequency of 10 Hz. This time 10 kHz and 350 kHz BCM-CW-E output signals were recorded. The above two cases were repeated 25 times for each beam setup. The digitized data was saved with the oscilloscope for off-line analysis.

Linearity Evaluation

The other critical functionality we were interested in was proportionality with beam current, which was expected to be linear over a wide current range.

The input beam pulse length was 900 µs with a beam current ranging from around 20 nA to 400 nA. BCM-CW-E 10 kHz output was recorded on the oscilloscope. The electronics connection of other channels (i.e. Fcup and timing trigger) was the same as for the noise and accuracy evaluation. For the linearity test, average signals of 128 macro-pulses were digitized and saved by the oscilloscope.

For a second test, beam current remained unchanged. Macro-pulse length was varied from 50 µs to 1000 µs. Oscilloscope connections were as before, averaging was set to one. By integrating on the oscilloscope macro-pulse charges were obtained and saved. For each macro-pulse length setting 25 values were saved.

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RESULTS AND DISCUSSIONS

Noise Evaluation

The main objective of the noise measurements was to determine whether measurement noise in the accelerator is comparable to the noise obtained during lab measurements. A typical macro-pulse measurement is shown in Fig. 2 (top). Noise of the 350 kHz bandwidth output is about 210 nA and noise of the 10 kHz filtered output is around 28 nA. The noise obtained from a series of datasets is plotted in Fig. 2 (bottom). All of the values measured in the accelerator are below the noise obtained in test bench measurements (i.e. σ_{350kHz} = 300 nA, σ_{10kHz} = 36 nA). The lower noise is due to a shorter measurement time which does not permit to capture low frequency noise.

For much lower beam currents, these high bandwidth BCM-CW-E outputs are still too noisy to obtain useful current information. Figure 3 shows the measured current (~24 nA) from the 100 Hz bandwidth output for 1500 macro-pulses of 900 µs length repeated at 1 kHz. The obtained noise level is around 2.8 nA, which is lower than that tested in the lab (i.e. σ_{100Hz} = 7 nA).

High bandwidth outputs work well for high beam currents, but their noise level is unacceptable when the beam current is below a few 10 nA. On the contrary, the 100 Hz bandwidth output works well for lower beam currents with long macro-pulse lengths (i.e. nearly CW beams). However, this output will be too slow to process short, pulsed beams (i.e. a few 10 µs), in which case the 10 kHz (or higher) bandwidth output may be preferable.

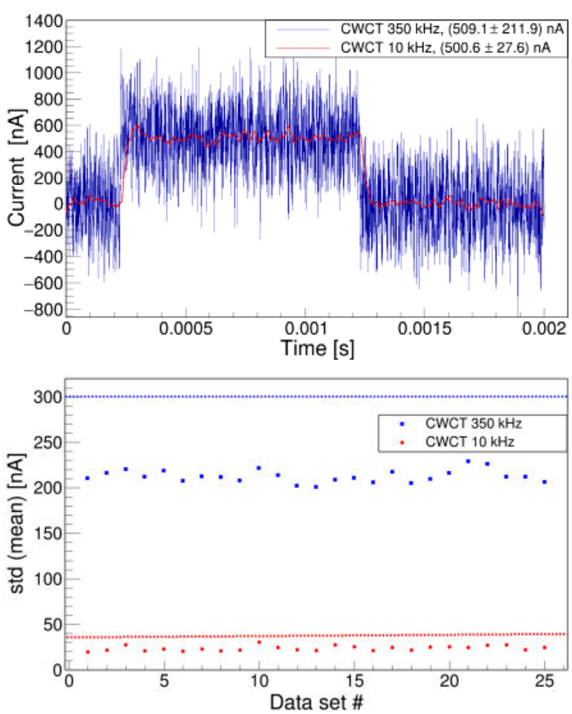

Figure 2: Measured beam currents for macro-pulses of 1000 µs, 10 kHz and 350 kHz BCM-CW-E outputs (top). Noise levels from the two outputs for 25 sequential input macro-pulses, dashed lines indicate noise levels obtained by bench measurements (bottom).

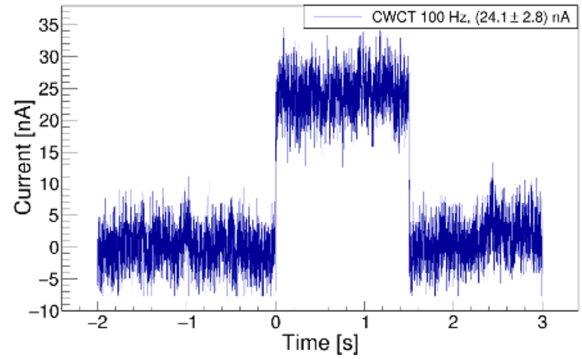

Figure 3: Measured beam current with a low output bandwidth (100 Hz) and long input beam. The beam was kept for 1.5 s with a total of 1500 macro-pulses (900 µs length, 1 kHz repetition rate).

Linearity Evaluation

A range of beam currents was applied to LC-CWCT and Fcup to evaluate linearity of the current transformer. Assuming the Fcup is dose-rate independent, the current measured by the LC-CWCT is linearly proportional to the current collected by the Fcup from 24 to around 400 nA average beam current, as shown in Fig. 4. The error bars are small since averages of 128 macro-pulses were used for these measurements. Noise of the 10 kHz output is around 30 nA, which is unacceptable for a few 10 nA input beam. However, averaging of 128 macro-pulses reduces noise level to just a few nA.

The current measured by the LC-CWCT is almost 25% higher than that collected by the Fcup, as shown in the linear fit equation. There might have been some beam losses in the beamline in between LC-CWCT and Fcup. That means, not all particles which passed through the LC-CWCT were collected by the Fcup. This is a systematic error due to the experimental setup, which does not affect the linearity test of the device. However, due to these experimental conditions a comparison of the absolute measurement accuracy was not possible.

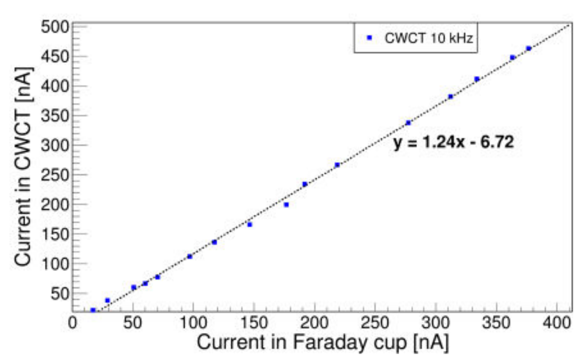

Figure 4: Beam current measured by LC-CWCT (10 kHz output) as a function of current collected by the Fcup. The input macro-pulse length was 900 µs and the output signals (i.e. both LC-CWCT and Fcup) were averaged for a total of 128 pulses (error bars are smaller than the markers).

For very short macro-pulses, the output signal from the 10 kHz bandwidth output cannot reach a plateau as shown in Fig. 5 (top). Its bandwidth corresponds to a rise time of

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about 35 µs. This is the reason why for previously discussed current measurements macro-pulses >500 µs were used.

However, it is possible to estimate the charge of short macro-pulses (<100 µs) by performing an integration of the output signals. Figure 5 (bottom) shows the average measured charge for 25 input macro-pulses as a function of the macro-pulse length. Measured charge and macro-pulse length correlate linearly. Thus, even if macro-pulse length is too short for direct current measurements, macro-pulse charge can still be accurately determined by integration of the LC-CWCT output signal.

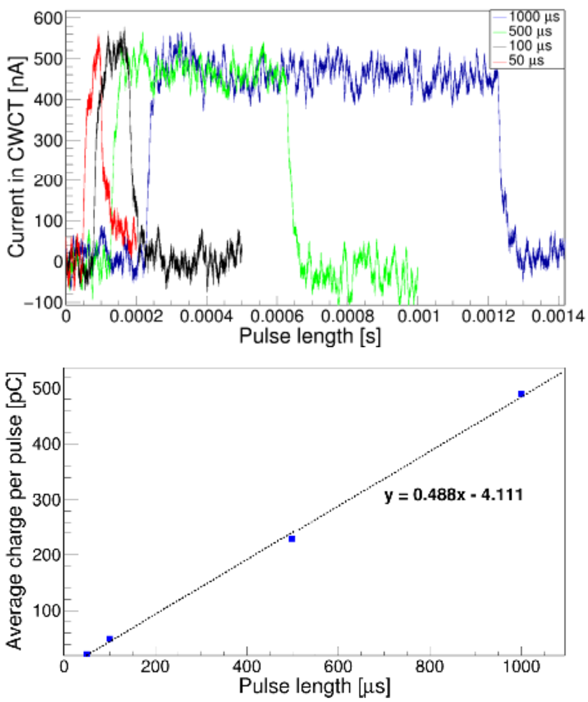

Figure 5: Macro-pulse current measured by LC-CWCT (10 kHz output) depending on macro-pulse length ranging from 50 to 1000 µs (top). Macro-pulse charge obtained by integration of LC-CWCT output signal as a function of macro-pulse length, averages of 25 input macro-pulses (bottom). Error bars are smaller than the marker.

CONCLUSION

In this experiment, we evaluated the performance of a newly developed current transformer LC-CWCT in terms of noise level and linearity in a proton beam environment. The results show that the noise level measured with beam is as low as measured on a test bench. With a noise level of 2.8 nA (100 Hz measurement bandwidth) even beam currents as low as 24 nA could be well resolved.

However, the 100 Hz output bandwidth is too slow for short, pulsed beams. Higher bandwidth outputs with 10 kHz and 350 kHz bandwidth were also tested with a much higher beam current up to around 500 nA. Measured noise levels were around 28 nA and 210 nA, respectively. Also these values showed good reproducibility over time and agreed with results measured on a test bench.

The LC-CWCT 10 kHz output was compared to a Faraday cup. Good linearity over a wide current range up to the maximum measured current of around 460 nA was observed. The measured macro-pulse charge was also found to be linear with pulse lengths ranging from 50 to 1000 µs, at the above current level.

The LC-CWCT provides signals with three bandwidths (100 Hz, 10 kHz, 350 kHz) which allows measuring either low currents with low noise levels or short macro-pulses with fast response time. Since the LC-CWCT is a non-destructive device, it can be installed anywhere along the beamline for online dose monitoring. Our measurements show that it has the potential to be used in FLASH PT studies with varying beam characteristics. Furthermore, LC-CWCT characteristics may be applicable for current and charge measurements in other low-current particle accelerators.

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