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BEAM CURRENT MEASUREMENTS WITH SUB-MICROAMPERE RESOLUTION USING CWCT AND BCM-CW-E

F. Stulle*, L. Dupuy, E. Touzain, Bergoz Instrumentation, Saint Genis Pouilly, France
W. Barth[1], P. Forck, M. Miski-Oglu[1], T. Sieber, GSI, Darmstadt, Germany
[1]also at Helmholtz Institute Mainz, Mainz, Germany

Abstract

The CWCT current transformer and its accompanying BCM-CW-E electronics allow accurate, high-resolution beam current measurements. This is achieved by combining a high-droop current transformer with low-noise sample-and-hold electronics. Thanks to a fast response time on the microseconds level the system can be applied not only to CW beams but also macropulses. Pulse repetition rates may range from 10 MHz to 500 MHz, rendering CWCT and BCM-CW-E suitable for a wide variety of accelerators. We report on test bench measurements achieving sub-microampere resolution. And we discuss results of beam measurements performed at the cw-LINAC, GSI.

INTRODUCTION

A growing number of particle accelerators is used worldwide for a growing variety of applications. Each of the applications has its own peculiarities which the particle beam, e.g. the particle species and energy, needs to be adapted to. This leads to a diversified accelerator landscape with a large variety of particle beam characteristics.

While beam instrumentation has been developed for most of these particle beams, in some cases existing solutions are either not optimum or not at all applicable due to the particle beam characteristics or the accelerator environment. Consequently, the development of improved beam instrumentation remains important for new and existing accelerators.

One recurring topic for new developments is the measurement of average beam currents. Especially average current measurements of CW beams, i.e. long streams of particle pulses, are challenging, because these are (quasi) DC currents.

Passive beam instrumentation coupling either capacitively, e.g. the pick-up electrodes of beam position monitors, or inductively, e.g. current transformers, to the electromagnetic fields of the particle beam cannot detect DC fields.

Only when using active sensors, e.g. DCCTs based on the fluxgate principle [1], DC beam currents can be measured non-invasively. Unfortunately, such sensors tend to be highly sensitive to the accelerator environment and too slow for some applications.

However, if a CW beam consists of well separated pulses using a passive current transformer and appropriate signal analysis can be sufficient to deduce the average current from the detected AC signal. The idea is to detect in between consecutive pulses the baseline of the transformer's output signal, e.g. with a fast sample-and-hold circuit. This results a signal proportional to the average input current.

Such a measurement system has been developed by Bergoz Instrumentation and first results have been reported in [2]. It consists of a passive current transformer (CWCT) and analog electronics (BCM-CW-E) to process the CWCT's output signal. Due to its fast response time on the microsecond level, it can be used for CW beams and long macropulses. Table 1 summarizes CWCT and BCM-CW-E design specifications. Figure 1 shows photographs.

Table 1: CWCT and BCM-CW-E Design Specifications

Bunch repetition rate	10 MHz — 500 MHz
Current measurement range	10 µA — 200 mA
Response time (full bandwidth)	1 µs (10% — 90%)
Output noise (10 kHz bandwidth)	1 μA_{rms}
Output noise (100 Hz bandwidth)	0.5 μA_{rms}
Output voltage (in 1 MΩ)	−4 V — +4 V
Controlled via TTL or USB	

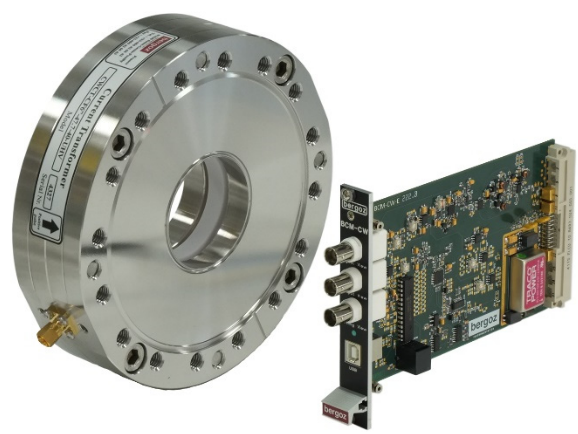

Figure 1: CWCT and BCM-CW-E.

Following successful first beam measurements at UNILAC, GSI [2], the BCM-CW-E electronics was further improved. Using a newly developed test bench at Bergoz Instrumentation enhanced stability and resolution are observed. Test bench measurements are discussed in the next section.

To demonstrate the improved performance with beam, CWCT and BCM-CW-E electronics were installed at the cw-LINAC [3], which is currently under development at GSI and HIM. This linac will provide CW ion beams mainly dedicated to GSI's super heavy elements (SHE) program. Consequently, in the future a measurement system for average currents of CW beams will become mandatory. Existing ACCTs could only be used for macropulse studies.

* stulle@bergoz.com

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So far, a single 216.8 MHz superconducting prototype cavity was installed, allowing the acceleration of ion beams to energies ranging from 1.4 MeV/u to 2.2 MeV/u. The ions are provided by the already existing high charge state injector (HLI) at 108.4 MHz repetition rate and 1.4 MeV/u beam energy.

The beam measurements were performed using macro-pulses of Ar^{9+} ions at a nominal energy of 1.86 MeV/u. Results of those beam measurements are discussed further below.

TEST BENCH MEASUREMENTS

A test bench is being developed at Bergoz Instrumentation which will allow calibration and performance verification of CWCT and BCM-CW-E.

To mimic a particle beam, the test bench uses an Agilent 8133A pulse generator. This generator can either produce CW streams of pulses or macro pulses (when equipped with option 002) at up to 3.3 GHz repetition rate. Pulses are rectangular and can be as short as 150 ps. Maximum pulse amplitude is 3 V. At a duty cycle of 50% the maximum average signal current is 30 mA.

For enhanced accuracy and dynamic range, a fixed 3 V signal amplitude is generated and the signal current is accurately measured using a calibrated ACCT. Prior to passing the CWCT, signal amplitude variations are achieved using Agilent 8494H/8496H programmable attenuators. Their attenuation steps were determined using a calibrated Agilent E5071C vector network analyzer before setting up the test bench. A schematic of the test bench is shown in Fig. 2.

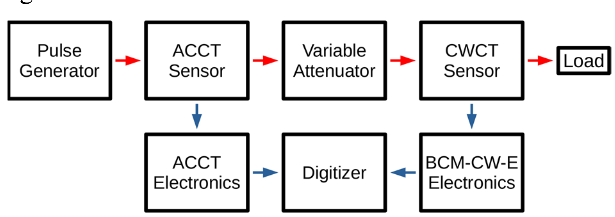

Figure 2: Schematic of the CWCT test bench.

For the test bench measurements, the same CWCT was used as for the beam measurements at GSI. CWCT sensitivity was 5V/A. The BCM-CW-E electronics was slightly modified compared to the one used at GSI. BCM-CW-E gain was set to 40dB. The pulse generator was set to 108 MHz repetition rate.

First results were obtained by observing ACCT-E and BCM-CW-E output signals on an oscilloscope (LeCroy SDA11000). A full-bandwidth BCM-CW-E output port was measured and filtering was done mathematically. During these measurements the pulse generator created 1 ms long macropulses.

Figure 3 shows the CWCT measuring a 22 µA macropulse using full output bandwidth (~600 kHz) as well as 100 kHz and 10 kHz bandwidth filtering. The achieved measurement noise was:

$$\sigma_{CWCT} = 1.59\ \mu A \text{ (full BW)}$$
$$\sigma_{CWCT} = 0.89\ \mu A \text{ (100 kHz BW)}$$
$$\sigma_{CWCT} = 0.25\ \mu A \text{ (10 kHz BW)}$$

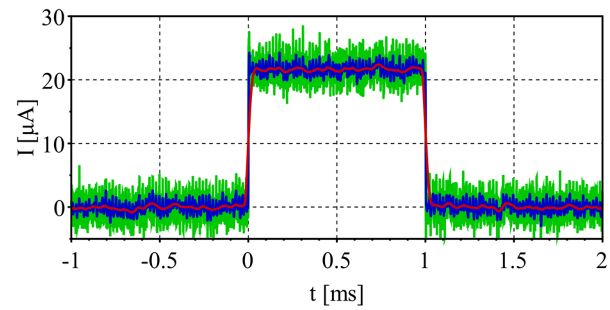

Figure 3: CWCT measuring a macropulse using full BW (green), 100 kHz BW (blue) and 10 kHz BW (red).

To improve the measurement sensitivity a 20dB amplifier was used to boost the signal coming from the CWCT. For this configuration, Fig. 4 shows the CWCT measuring a 22 µA macropulse using full output bandwidth (~600 kHz) as well as 100 kHz and 10 kHz bandwidth filtering. The achieved measurement noise was:

$$\sigma_{CWCT} = 0.56\ \mu A \text{ (full BW)}$$
$$\sigma_{CWCT} = 0.18\ \mu A \text{ (100 kHz BW)}$$
$$\sigma_{CWCT} = 0.06\ \mu A \text{ (10 kHz BW)}$$

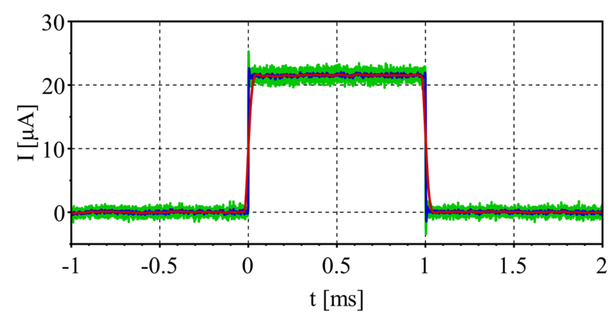

Figure 4: CWCT with 20dB extra amplification measuring a macropulse using full BW (green), 100 kHz BW (blue) and 10 kHz BW (red).

Above results are based only on single macropulses, which were recorded on an oscilloscope. Thus, low frequency signal drift is not visible. And oscilloscope noise may have had some impact. During the macropulse, BCM-CW-E output voltages were about 10 mV without the extra amplification and 100 mV with extra amplification.

The test bench allows to perform complete signal amplitude scans and proper statistics using many macropulses and CW signals. A 16bit digitizer allows higher resolution sampling. Thus, avoiding the addition of spurious noise.

Without the extra amplification, the achieved measurement noise was for the four BCM-CW-E output ports:

$$\sigma_{\text{BCM Output}} = 1.74\ \mu A \text{ (full BW)}$$
$$\sigma_{\text{Output View}} = 1.67\ \mu A \text{ (full BW)}$$
$$\sigma_{10kHz} = 0.51\ \mu A \text{ (10 kHz BW)}$$
$$\sigma_{100Hz} = 0.32\ \mu A \text{ (0.1 kHz BW)}$$

and with 20dB extra amplification:

$$\sigma_{\text{BCM Output}} = 0.36\ \mu A \text{ (full BW)}$$
$$\sigma_{\text{Output View}} = 0.34\ \mu A \text{ (full BW)}$$
$$\sigma_{10kHz} = 0.07\ \mu A \text{ (10 kHz BW)}$$
$$\sigma_{100Hz} = 0.03\ \mu A \text{ (0.1 kHz BW)}$$

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All those values are similar to the ones obtained before using single macropulses. Differences are within expectation due to the very different measurement setups and the resulting data sets used for noise calculation.

The measurement results indicate that CWCT and BCM-CW-E are capable of very high resolution measurements especially when using extra amplification. Original specifications (see Table 1) were surpassed considerably. Though it must be acknowledged that performance was achieved under certain circumstances which may not always be fulfilled in a particle accelerator.

When measuring macropulses low frequency noise could be mitigated by considering that before and after a macropulse the signal must drop to zero. Such a correction is not possible when measuring CW beams. Consequently, measurement noise will effectively be higher.

It is still being investigate whether the current test bench setup and measurement parameters are sufficient to properly quantify CWCT and BCM-CW-E noise. CW signal measurements over several minutes revealed very low frequency output voltage fluctuations on the millivolt level. Though, the corresponding current noise remained close to above-stated values.

BEAM MEASUREMENTS

Due to previous beam tests at UNILAC [2], the CWCT current transformer was already available at GSI. And it was decided to test this sensor also with the improved BCM-CW-E electronics at GSI. This time CWCT and BCM-CW-E were installed at the newly developed cw-LINAC [3]. For comparison an ACCT manufactured by GSI was available [4]. Voltages were recorded for off-line analysis using a LeCroy HDO6104A 10bit oscilloscope (Fig. 5).

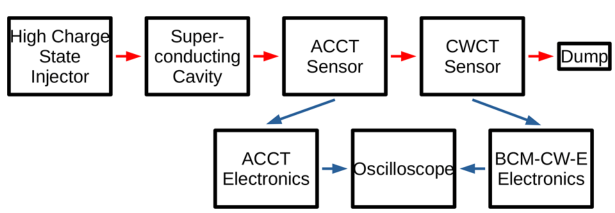

Figure 5: Schematic of the cw-LINAC setup.

BCM-CW-E gain was kept at 40dB during all beam measurements. For some tests an additional 20dB amplifier was used to boost the signal entering the BCM-CW-E. In front of the BCM-CW-E a low-pass filter was used to remove high frequency noise above 300 MHz. A high-pass filter removed signals below 300 kHz, which effectively improved BCM-CW-E response times (see [2] for details). However, the ACCT had a bandwidth of about 100 kHz. Thus, during analysis also the CWCT output signal was mathematically filtered at this frequency.

Since CWCT and BCM-CW-E were not calibrated prior to the beam measurements, comparison to the calibrated ACCT could only be done in terms of signal shape and noise. Since the ACCT signal was clamped before and after the macropulse, a comparison was possible only during the macropulse.

During the measurements, the beam consisted of macropulses of variable length, while the beam current mostly remained close to 20 µA. Several macropulses were recorded under varying conditions. Throughout the measurements, operators continued tuning the accelerator.

Figure 6 shows the measured signals for a 3 ms macropulse of 21 µA average current. Figure 7 shows the measured signals for a 100 µs macropulse of 22 µA. ACCT and CWCT follow the same waveforms. But the CWCT signal contains about twice the noise as the ACCT:

$$\sigma_{\mathrm{ACCT}} = 0.5\ \mu\mathrm{A}$$
$$\sigma_{\mathrm{CWCT}} = 1.2\ \mu\mathrm{A}$$

For the calculation of these and the following standard deviations, ACCT and CWCT signals were decorrelated to correct for beam current fluctuations. The plots show untreated data, i.e. the signals were not decorrelated.

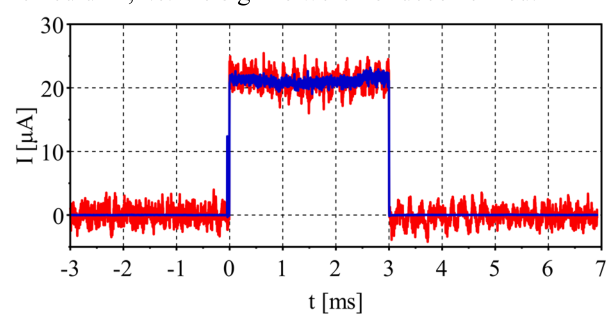

Figure 6: 3 ms macropulse of 21 µA measured by ACCT (blue) and CWCT (red); 100 kHz measurement bandwidth.

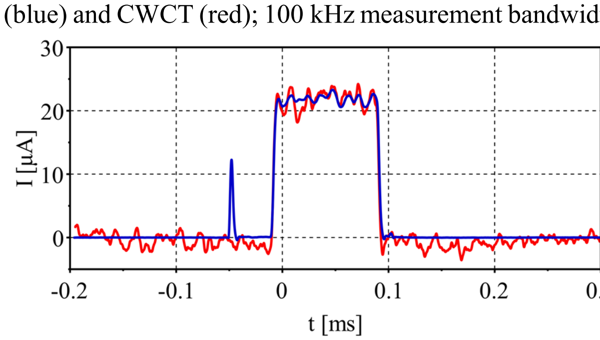

Figure 7: 100 µs macropulse of 22µA measured by ACCT (blue) and CWCT (red); 100 kHz measurement bandwidth. The spike in the ACCT signal is an artefact of clamping.

Some improvement could be achieved by mathematically filtering the measured signals to 10 kHz bandwidth:

$$\sigma_{\mathrm{ACCT}} = 0.4\ \mu\mathrm{A}$$
$$\sigma_{\mathrm{CWCT}} = 0.9\ \mu\mathrm{A}$$

To further improve the CWCT resolution, an additional 20dB amplifier was added in front of the BCM-CW-E. The measurement noise dropped to:

$$\sigma_{\mathrm{ACCT}} = 0.5\ \mu\mathrm{A}$$
$$\sigma_{\mathrm{CWCT}} = 0.9\ \mu\mathrm{A}$$

for 100 kHz bandwidth (Fig. 8) and

$$\sigma_{\mathrm{ACCT}} = 0.1\ \mu\mathrm{A}$$
$$\sigma_{\mathrm{CWCT}} = 0.1\ \mu\mathrm{A}$$

for 10 kHz bandwidth (Fig. 9).

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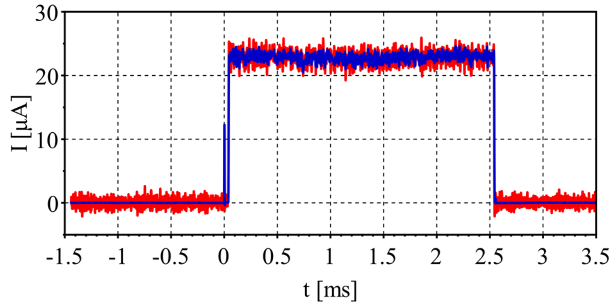

Figure 8: 2.5 ms macropulse of 23 µA measured by ACCT (blue) and CWCT with 20dB extra amplification (red); 100 kHz measurement bandwidth.

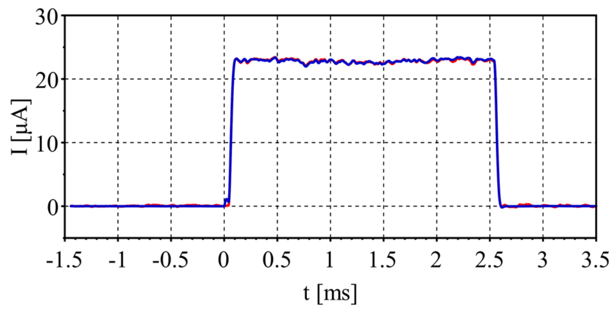

Figure 9: 2.5 ms macropulse of 23 µA measured by ACCT (blue) and CWCT with 20dB extra amplification (red); 10 kHz measurement bandwidth. The CWCT signal is almost entirely hidden behind the ACCT signal.

In this last case, beam current fluctuations became more important than the noise added by the measurement systems. Thus, decorrelation became considerably more effective than before. Which explains why also the calculated ACCT noise was reduced.

But decorrelation and noise calculation were done only for a 2.5 ms macropulse. As discussed in the last section, low frequency noise contributions are not visible in such data and thus cannot be taken into account. For longer macropulses and CW beams, CWCT resolution is presumably worse than the 100 nA stated above.

Nevertheless, very good beam current resolution could be achieved with rather moderate signal filtering. That means, CWCT and BCM-CW-E can indeed detect beam current fluctuations well below a microampere while keeping a good response time of the order of 10 µs.

CONCLUSION

CWCT and BCM-CW-E allow high resolution average current measurements of macropulses and CW beams. They can be adapted to a wide variety of accelerators and beam parameters.

A test bench for calibration and performance evaluation is being developed at Bergoz Instrumentation. Measurements on this test bench show sub-microampere resolution. In some cases, even the 100 nA level could be reached. A similar resolution could be achieved using ion beams at GSI's cw-LINAC.

Extra amplification of the signal entering the BCM-CW-E proved to be an effective way to improve CWCT and BCM-CW-E resolution on the test bench and during beam measurements in the accelerator.

Further test bench improvements are planned. Especially, absolute current calibration of CWCT and BCM-CW-E will become possible. The impact of very low frequency voltage fluctuations will be studied. Most notably, the limits of extra amplification in front of the BCM-CW-E will be determined. Results indicate that still the BCM-CW-E noise limits current resolution; noise of the 20dB amplifier is measurable but not yet limiting performance.

ACKNOWLEDGEMENTS

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