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 Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany,
[1]also at Helmholtz Institute Mainz, Mainz, Germany
*stulle@bergoz.com

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. 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.

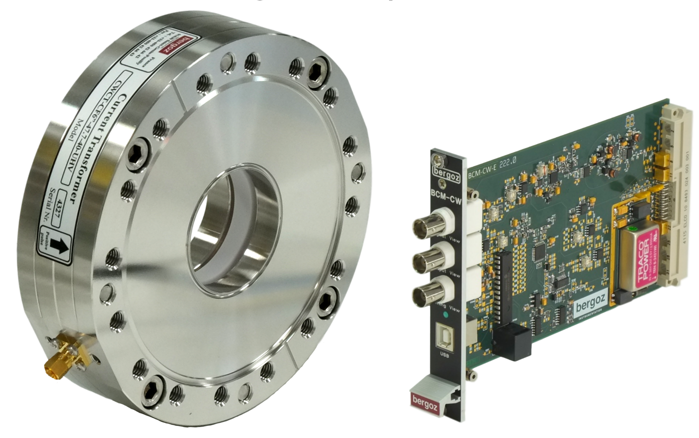
Passive beam instrumentation coupling either capacitively, e.g. pick-up electrodes of beam position monitors, or inductively, e.g. current transformers, to the electromagnetic fields of the particle beam cannot detect DC fields.

Only when using active sensors, e.g. DCCTs based on the fluxgate principle, 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 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 at LINAC2018. 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, the system can be used for CW beams and long macropulses.

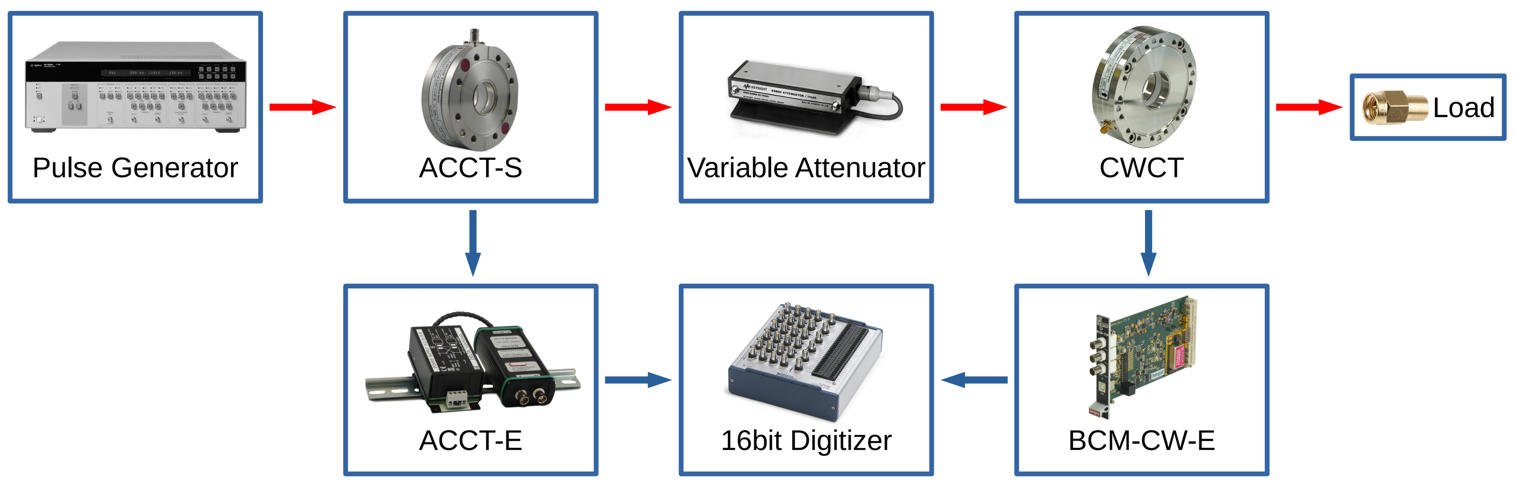
CWCT and BCM-CW-E design specifications

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



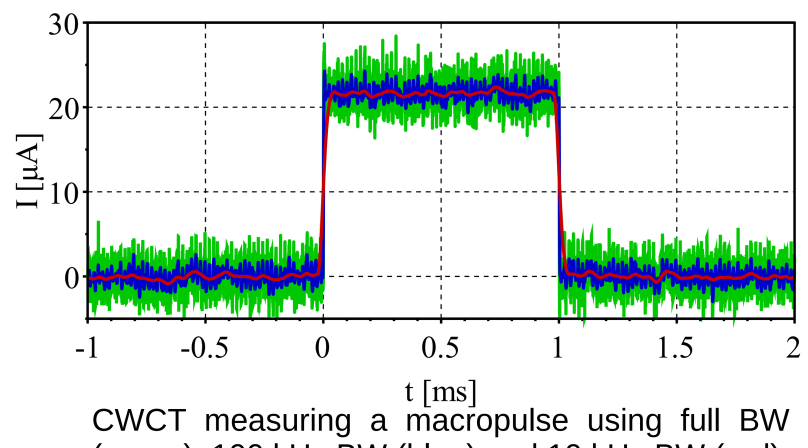
Test Bench Measurements

- 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 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 an ACCT. Prior to passing the CWCT, signal amplitude variations are achieved using Agilent 8494H/8496H programmable attenuators.



- First results were obtained by observing ACCT-E and BCM-CW-E output signals on an oscilloscope. 1 ms long macropulses were created by the pulse generator. The macropulse current was determined from the ACCT signal.
- The achieved measurement noise was:

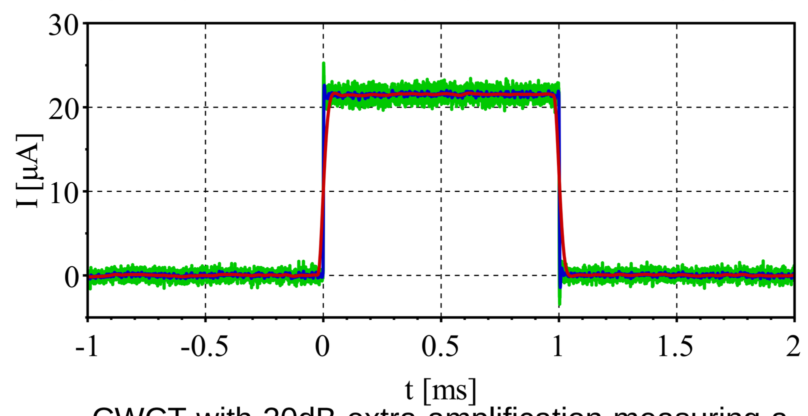
$$\sigma_{CWCT} = 1.59\,\mu A \text{ (full BW)}$$
$$\sigma_{CWCT} = 0.89\,\mu A \text{ (100 kHz BW)}$$
$$\sigma_{CWCT} = 0.25\,\mu A \text{ (10 kHz BW)}$$



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

- To boost the signal entering the BCM-CW-E a 20dB amplifier was added at its input.
- For this configuration, the achieved measurement noise was:

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



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

- Similar performance was achieved when using the complete test bench, i.e. the 16bit digitizer and proper statistics over many macropulses and CW signals.
- Without extra amplification:

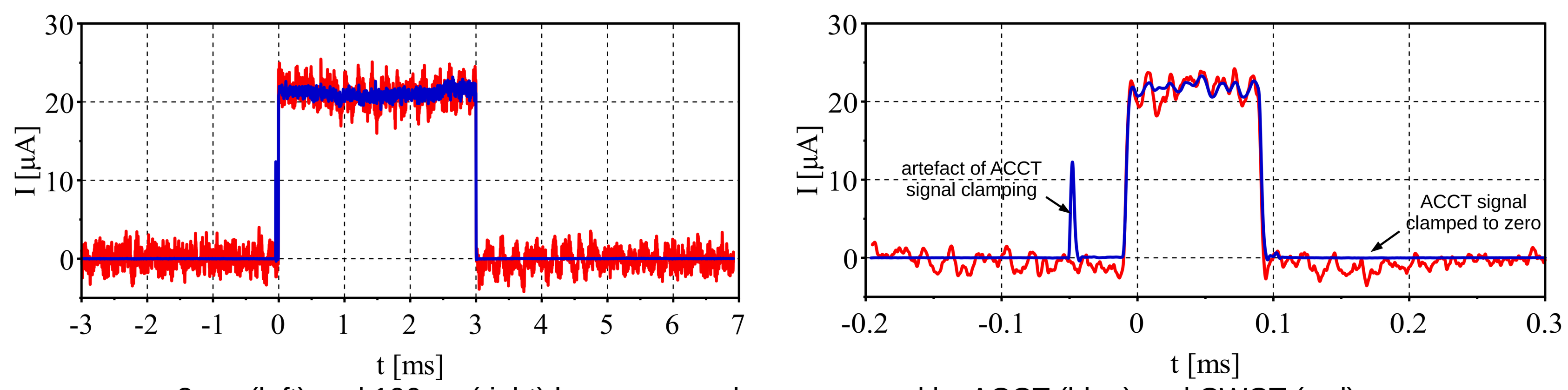
$$\sigma_{BCM\ Output} = 1.74\,\mu A \text{ (full BW)}$$
$$\sigma_{Output\ View} = 1.67\,\mu A \text{ (full BW)}$$
$$\sigma_{10kHz} = 0.51\,\mu A \text{ (10 kHz BW)}$$
$$\sigma_{100Hz} = 0.32\,\mu A \text{ (0.1 kHz BW)}$$

- With 20dB extra amplification:

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

cw-LINAC Measurements

- For beam measurements, CWCT and BCM-CW-E were installed at GSI's new cw-LINAC.
- Macropulses of Ar^{9+} ions at 1.4 MeV/u were provided by the high charge state injector (HLI).
- Pulse repetition rate within the macropulses was 108.4 MHz.
- The beam was accelerated in a superconducting prototype cavity to 1.86 MeV/u.
- Macropulse current was determined by a calibrate ACCT with 100 kHz bandwidth.
- During analysis the CWCT signal ("BCM Output" = full BW into 50Ω) was mathematically filtered at 100 kHz to match the ACCT bandwidth.



3 ms (left) and 100 µs (right) long macropulses measured by ACCT (blue) and CWCT (red).

- To correct for beam current fluctuations, ACCT and CWCT signals were decorrelated before calculating the noise (standard deviation of measured currents during a macropulse).
- The resulting values are (for full ACCT BW and after filtering):

$$\sigma_{ACCT} = 0.5\,\mu A \text{ (100 kHz BW)} \qquad \sigma_{ACCT} = 0.4\,\mu A \text{ (10 kHz BW)}$$
$$\sigma_{CWCT} = 1.2\,\mu A \text{ (100 kHz BW)} \qquad \sigma_{CWCT} = 0.9\,\mu A \text{ (10 kHz BW)}$$

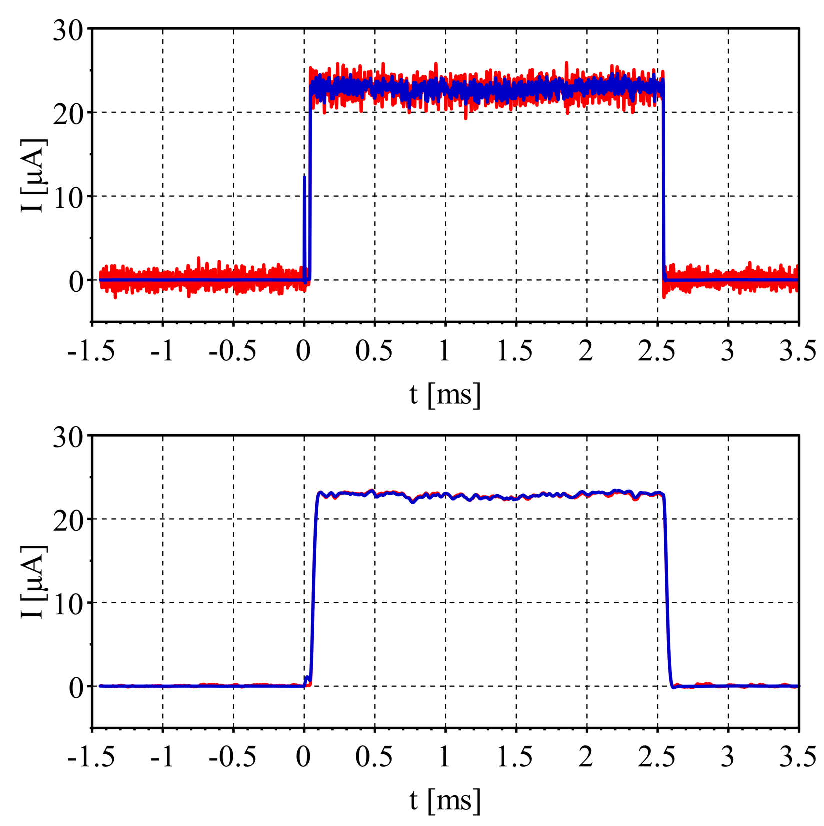
- To further improve the CWCT resolution, an additional 20dB amplifier was added in front of the BCM-CW-E.
- The measurement noise dropped to:

$$\sigma_{ACCT} = 0.5\,\mu A \text{ (100 kHz BW)}$$
$$\sigma_{CWCT} = 0.9\,\mu A \text{ (100 kHz BW)}$$

and when filtering to 10 kHz bandwidth:

$$\sigma_{ACCT} = 0.1\,\mu A \text{ (10 kHz BW)}$$
$$\sigma_{CWCT} = 0.1\,\mu A \text{ (10 kHz BW)}$$

- Beam current fluctuations became more important than noise added by the measurement systems. Thus decorrelation became more effective. Which explains why also the calculated ACCT noise was reduced.
- When measuring short macropulses, low frequency fluctuations manifest themselves as offsets. They add to the calculated noise only for long macropulses or CW beams. For such cases, resolution will presumably be worse than the 100 nA stated above.



2.5 ms long macropulses measured by ACCT (blue) and CWCT with 20dB extra amplification (red); 100 kHz BW (top), 10 kHz BW (bottom).

Conclusions

- 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.
- Following first test with beam at GSI's UNILAC, the BCM-CW-E was further improved.
- Test bench measurements show sub-microampere resolution, surpassing original specifications.
- The results could be confirmed with beam at GSI's cw-LINAC.
- 20dB amplification of the signal entering the BCM-CW-E proved to be an effective way to improve resolution on the test bench and in the accelerator.
- A resolution on the 100 nA level could be achieved.
- Results indicate that still the BCM-CW-E noise limits measurement resolution; noise of the 20dB amplifier is measurable but not yet limiting performance.