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BEAM LOSS AND AVERAGE BEAM CURRENT MEASUREMENTS USING A CWCT

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Abstract

The CWCT is a novel instrument adapted to an accurate average current determination of bunched CW beams or macro pulses. By combining a high-droop current transformer with novel electronics for signal analysis, an output signal bandwidth of DC to about 500 kHz and a current resolution down to the micro-ampere level are achieved. Beam current fluctuations are followed within microseconds, permitting fast detection of beam loss. These characteristics render the CWCT an ideal instrument for HPPAs, for example ADS linacs, and other proton or ion accelerators. We present the CWCT principle and the CWCT performance achieved in beam experiments at UNILAC, GSI.

INTRODUCTION

New trends in accelerators are driven by the society to better and faster serve its needs in medicine, energy and materials studies:

- Accelerators for proton-hadron therapy and medical isotopes production,
- High-power proton accelerators (HPPA) for accelerator driven systems (ADS), e.g. nuclear waste transmutation or subcritical reactors, and spallation neutron sources (SNS),
- Accelerators for materials studies.

Additional background information can be found in [1].

These accelerators, initially developed to produce macropulses at low repetition rate, began to evolve towards CW beam accelerators, which hinders the use of ACCTs and introduces beam instrumentation challenges interfering with the use of DCCTs:

- Beam power damages equipment, rendering fast loss detection mandatory.
- Temperature variations are large.
- In low to medium energy sections, magnetic strayfields are high due to compact designs.
- Space for instrumentation is scarce.

Moreover, longitudinal bunch profiles vary during the energy ramp further complicating average current measurements and accurate beam loss detection.

In response, Bergoz Instrumentation developed a novel system for average beam current measurements. It consists of a current transformer (CWCT) and analog electronics (BCM-CW-E) to process the CWCT's output signal. CWCT and BCM-CW-E are an alternative to ACCTs and DCCTs, well suited in many cases where those cannot be used.

Their characteristics were optimized for CW proton and ion accelerators, e.g. the injectors of the China ADS project [2] or the MYRRHA ADS project [3]. Though they can be used for macropulse measurements and in other types of accelerators. Table 1 summarizes CWCT and BCM-CW-E design specifications. Fig. 1 shows photographs.

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

Bunch repetition rate	50 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	

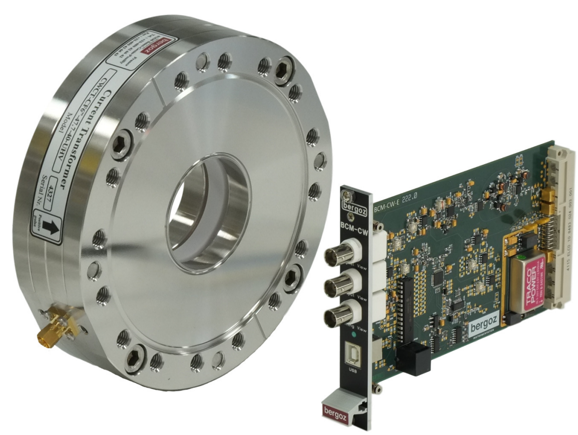

Figure 1: CWCT and BCM-CW-E.

CWCT and BCM-CW-E electronics were installed at UNILAC, GSI [4] for beam measurements. UNILAC can accelerate a wide variety of ions at different charge states up to several MeV/u kinetic energy. It is capable of fast switching between two different ion sources and sets of accelerator parameters. Like this, changing the macropulse current and its position as well as changing length and width of the individual pulses could be done with little impact on other beam users.

CWCT / BCM-CW-E PRINCIPLE

Passive current transformers (CT) are only capable of measuring AC currents down to a certain minimum

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frequency $f_{\mathrm{CT,min}}$, depending on CT characteristics like number of turns and relative permeability of the transformer core. In time-domain, the loss of low frequency spectral contributions manifests itself by the droop $D_{\mathrm{CT}} = 2\pi f_{\mathrm{CT,min}}$, which describes the CT signal's tendency towards zero for long input signals.

An example of a steady-state CT response, i.e. after several time constants $\tau_{\mathrm{CT}} = 1/D_{\mathrm{CT}}$, to a CW stream of pulses is shown in Fig. 2. The average of such a signal is zero.

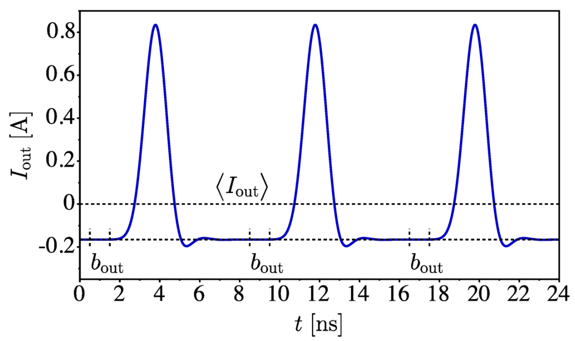

Figure 2: Drooped CT output signal for a CW input beam.

In between consecutive pulses, the CT output signal I_{out} drops to a certain value b_{out}, which is its baseline value. The following constraints must be fulfilled to allow its use for the determination of the average input current:

- The beam pulses including tails must be shorter than the pulse repetition period t_{rep}.
- For non-relativistic beams, the electromagnetic field lines detected by the CT are longitudinally deformed [5]. On the vacuum chamber wall, the EM field pulses must remain shorter than t_{rep}. In other words, the CT input signal I_{in} must drop to zero after each pulse.
- The CT pulse response must be sufficiently well behaving to allow I_{out} falling to a constant baseline after each pulse. That means, the CT output pulses must be shorter than t_{rep} and all ringing must have vanished.
- τ_{CT} must be considerably longer than t_{rep} to avoid a notable impact of the CT droop on I_{out} in between two pulses.

Under these assumptions, b_{out} is a direct measure of the average input current:

$$\langle I_{\mathrm{in}} \rangle = -b_{\mathrm{out}}/g_{\mathrm{CT}},$$

where g_{CT} is the CT gain.

This can be understood by considering that the CT droop induces a DC offset but does not noticeably deform the output signal if $\tau_{\mathrm{CT}} \gg t_{\mathrm{rep}}$, thus preserving the distance between average signal and baseline. The CT's high-frequency response may deform the signal but has no impact on average signal or baseline.

Already in [6] it had been recognized that the baseline of some beam diagnostics signals could be directly used to determine a beam's average current. Interestingly, it seems this idea has not been widely adopted.

The baseline can be accurately reconstructed from I_{out} by applying fast sample-and-hold techniques. After each pulse I_{out} is sampled over short time intervals and the value is held until the next sample is taken, leading to a piecewise constant signal I_{base}.

Since the CT's reaction time to pulse-to-pulse charge fluctuations, i.e. average beam current fluctuations, is limited to τ_{CT}, any beam induced variation of I_{base} must be equal to or longer than τ_{CT}. Hence, I_{base} is a good measure of the baseline at any point in time if $\tau_{\mathrm{CT}} \gg t_{\mathrm{rep}}$.

Prior to sampling, low-frequency noise is removed from I_{out} by high-pass filtering at a frequency $f_{\mathrm{in,max}} \geq f_{\mathrm{CT,min}}$. After sampling, high-frequency noise and the possible sampling steps are removed from I_{base} by low-pass filtering a little above $f_{\mathrm{in,max}}$. Almost no beam information is lost due to such a low-pass filter. This is possible because the sampling is a non-linear transformation. The high-pass filter prior to sampling acts on a different spectrum than the low-pass filter after sampling.

An additional low-pass filter prior to sampling is added to avoid that contributions at unnecessarily high frequencies deteriorate the sampling accuracy. It reduces noise and avoids that strong but short signal spikes drive the electronics into saturation.

The CWCT and BCM-RF-E working principle is outlined in Fig. 3.

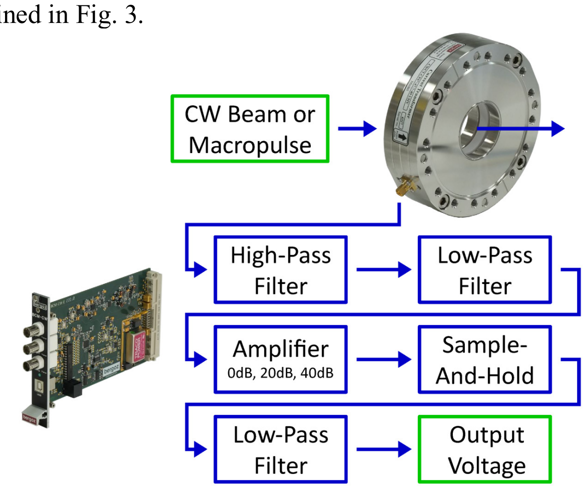

Figure 3: CWCT and BCM-CW-E principle.

In general, I_{base} can be considered the signal of a low-pass filter of upper cut-off frequency $f_{\mathrm{base,max}} = f_{\mathrm{CT,min}}$. The corresponding response time $t_{\mathrm{r,base}}$ (10% - 90%) is:

$$t_{\mathrm{r,base}} \approx 0.35/f_{\mathrm{CT,min}}.$$

MEASUREMENTS

CWCT and BCM-CW-E were installed at the end of UNILAC's X2 beamline at GSI, Darmstadt. Their performance was tested with 100 µs long macropulses of Argon ions. The pulse repetition rate within a macropulse was 36 MHz as given by UNILAC's first acceleration stage. The second acceleration stage is operated at 108 MHz, fixing the pulse length to the nanosecond level. The rather low pulse repetition rate combined with short pulses render the UNILAC beam well-adapted for first tests. The previously mentioned constraints on beam and CWCT / BCM-RF-E characteristics are fulfilled.

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A further advantage was that the beam current could also be measured using a close-by ACCT manufactured by GSI [7]. The ACCT accuracy was about 1% of the full-scale value as determined by a test pulse from a current source. This allowed a comparison of the CWCT to a well-established reference. CWCT and ACCT signals were recorded using a 12bit oscilloscope. The trace data was saved for offline analysis.

Since the ACCT signal had a lower bandwidth than the CWCT signal, the CWCT data was mathematically low-pass filtered at 90 kHz to achieve a similar rise-time. Still, ACCT and CWCT signals remained slightly different.

Current Scan

The average current was varied from 10 µA up to 4500 µA. In some data sets strong current fluctuations were observed along the macropulses. Rapidly changing parts of the output signals were not considered for ACCT and CWCT comparison because of above-mentioned bandwidth differences. An example for the macropulse current measured by the two systems is shown in Fig. 4.

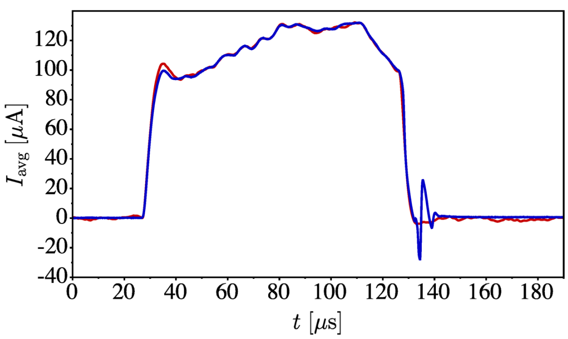

Figure 4: Currents measured by ACCT (blue) and CWCT filtered at 90 kHz (red). The trailing wiggle in the ACCT data is an irrelevant artefact of signal clamping.

For each CWCT gain setting, the measured CWCT output voltages U_{CWCT} were fitted to the corresponding currents I_{ACCT} as measured by the ACCT. Using the obtained scaling factors and offsets, the CWCT voltages were transformed into currents I_{CWCT}. The resulting transfer functions were:

$$I_{\mathrm{CWCT,0dB}} = 48547.3\,\frac{\mu\mathrm{A}}{\mathrm{V}}\,(U_{\mathrm{CWCT}} - 0.0373\,\mathrm{V})$$

$$I_{\mathrm{CWCT,20dB}} = 4469.7\,\frac{\mu\mathrm{A}}{\mathrm{V}}\,(U_{\mathrm{CWCT}} - 0.0435\,\mathrm{V})$$

$$I_{\mathrm{CWCT,40dB}} = 390.7\,\frac{\mu\mathrm{A}}{\mathrm{V}}\,(U_{\mathrm{CWCT}} - 0.0498\,\mathrm{V})$$

The resulting I_{CWCT} is compared to I_{ACCT} in Fig. 5. The relative deviation of I_{CWCT} from I_{ACCT} is shown in Fig. 6.

Very good linear correlation of CWCT and ACCT was achieved for all three CWCT gain settings. At 0 dB gain, some CWCT noise was present. However, all CWCT values stayed within ±7% of the ACCT values. At 20 dB gain, the CWCT values stayed within ±1% for currents above 1 mA. At 40 dB gain, from 90 µA to 250 µA the CWCT values remained within ±2%. Above 250 µA, amplifier saturation started to become important.

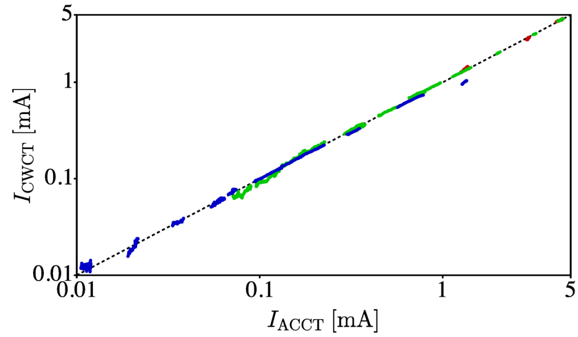

Figure 5: I_{CWCT} versus I_{ACCT}. CWCT 0 dB gain (red), CWCT 20 dB gain (green) and CWCT 40 dB gain (blue). The black dotted line marks equal currents.

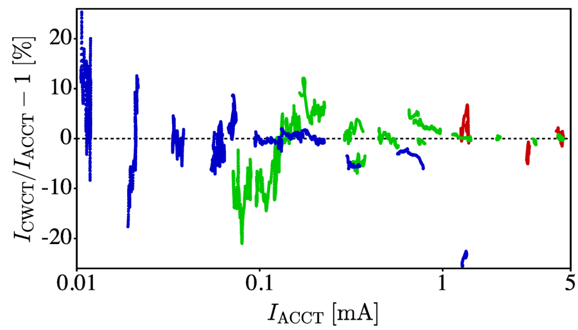

Figure 6: Relative deviation of I_{CWCT} from I_{ACCT}. CWCT 0 dB gain (red), CWCT 20 dB gain (green) and CWCT 40 dB gain (blue). For 40 dB gain, amplifier saturation is visible above 250 µA.

The observed variations may be partially caused by systematic effects, e.g. oscilloscope vertical scale switching.

Nevertheless, by choosing an appropriate CWCT gain an agreement between ACCT and CWCT better than ±5% could be achieved for currents of 90 µA and above.

Pulse Length, Width and Position Scans

Further to the current scan also the length of the pulses, their width and position were changed to determine possible dependences on these parameters. During these tests, ACCT and CWCT showed both no signs of measurement quality degradation until beam loss started.

CONCLUSION

The CWCT and BCM-CW-E were developed for average current measurements of CW beams and macropulses. Their properties are ideal for proton and ion accelerators.

Performance was examined with beam at UNILAC, GSI. Very good agreement was found with a close-by ACCT.

The macropulse current was varied from 10 µA to 4500 µA. ACCT and CWCT showed a linear correlation for all three CWCT gain settings. The CWCT noise floor was at a few microamperes.

Tests varying pulse length, pulse width and pulse position revealed no dependencies on such beam properties.

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