A NOVEL INSTRUMENT FOR AVERAGE CURRENT MEASUREMENTS OF CW BEAMS

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Abstract

The CWCT is a novel instrument developed for the accurate determination of the CW beam average current. It measures average beam currents down to the micro-ampere level with noise contributions below 1 µA. Its output signal follows beam current fluctuations within ≤1 µs, permitting fast detection of beam loss. These characteristics render the CWCT an ideal instrument for proton and ion accelerators. We present the CWCT principle and laboratory measurements using various input signals.

INTRODUCTION

After two decades domination of the accelerator world by synchrotron light sources, new accelerator trends emerge which require new types of beam diagnostics.

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

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

More background information can be found, for example, in reference [1].

These accelerators, initially developed to produce macropulses at low repetition rate, began to evolve towards CW beam accelerators; introducing new beam instrumentation challenges.

The challenges connected with those new proton CW beam accelerators are the following:

- In the low to medium energy sections, magnetic stray fields are high due to compact designs.
- The longitudinal bunch profile changes during the energy ramp.
- Temperature variations may be large in HPPAs.
- Space for instrumentation is scarce.
- The CW proton beam power can damage equipment.

Bergoz Instrumentation company mission is to develop beam diagnostics fulfilling new needs. Based on above described challenges, a novel system for average current measurements was developed. It consists of a current transformer (CWCT) and analog electronics (BCM-CW-E) to process the CWCT's output signal. The characteristics were optimized for CW proton and ion accelerators, though the system can be used in other accelerators, too.

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The design specifications are summarized in Table 1.

Table 1: CWCT and BCM-RF-E 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	

CWCT / BCM-CW-E PRINCIPLE

A passive current transformer (CT) is only capable of measuring AC currents. That means, a DC component and other low frequency contributions in the input signal's spectrum will always be lost during transfer through the CT. In time-domain, the loss of these spectral contributions manifests itself by creating the so-called droop D_{CT}, 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 CT time constants $\tau = 1/D_{\mathrm{CT}}$, to a CW stream of equal pulses is shown in Fig. 1. In such a case, the average output current is zero. In between consecutive pulses the CT output signal falls to a certain value b_{out} which is the baseline value, i.e. the CT output value after the input signal has fallen to zero.

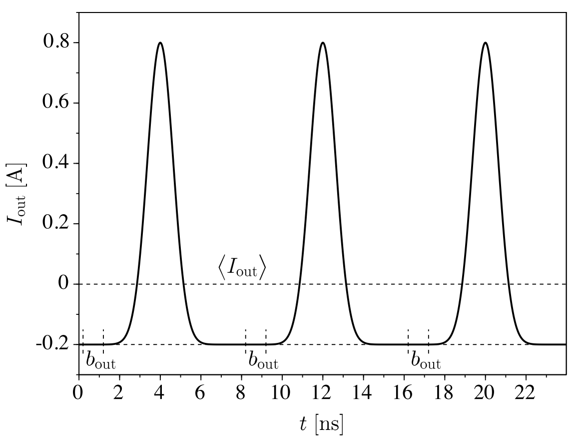

Figure 1: Sketch of a drooped CT output signal for a CW input beam.

If I_{in} falls to zero between any two consecutive pulses and if the CT output pulses are shorter than t_{rep}, b_{out} is a direct measure of the average input current $\langle I_{\mathrm{in}} \rangle = -\langle b_{\mathrm{out}} \rangle / g_{\mathrm{CT}}$, where g_{CT} is the CT gain. This can be understood by considering that a CT preserves the distance between average signal and baseline, because the CT droop induces a DC offset but does not deform the output signal. The shape of CT output signal I_{out} is defined by the input current I_{in} and the CT's high-frequency response, which has no impact on the average current or the baseline.

That the baseline of a current transformer's output signal could be directly used for average current measurements had been recognized before, e.g. in [2]. Interestingly, it seems this idea has not been widely adopted.

A particle beam in an accelerator exhibits pulse-to-pulse charge fluctuations. That means, the average beam current fluctuates. The CT signal's baseline b_{out} follows any input current variations with a time constant limited by the CT's lower cut-off frequency.

The baseline can be accurately reconstructed from $I_{out}(t)$ by applying fast sample-and-hold techniques. I_{out} is sampled over short intervals $t_a \leq t \leq t_b$ after each pulse (Fig. 1) and each value is held until the next sample is taken. This leads to a piecewise constant signal $I_{base}(t)$ varying at the bunch repetition frequency $f_{rep} = 1/t_{rep}$. Due to the CT's time constant τ, any beam induced variation of the baseline must be equal to or slower than τ. That means, even though $I_{out}(t)$ is sampled only over short intervals, $I_{base}(t)$ is a good measure of the baseline at any point in time.

Low-frequency noise can be removed from $I_{out}(t)$ prior to sampling by high-pass filtering close to $f_{CT,low}$. High-frequency sampling noise can be removed from $I_{base}(t)$ by low-pass filtering close to $f_{CT,low}$. No beam information will be lost due to these two filters, even though both filters cut the spectrum at the same frequency. This is possible because the sampling is a non-linear transformation. The low-pass filter, which is in front of the sampling, acts on a different spectrum than the high-pass filter, which is after the sampling.

The working principle is outlined in Fig. 2.

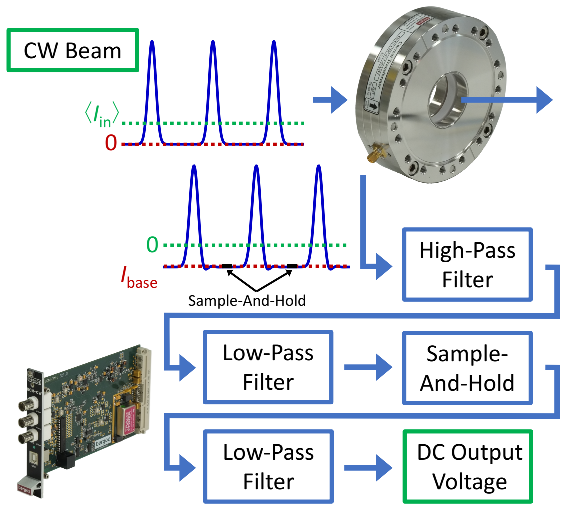

Figure 2: CWCT and BCM-CW-E principle.

In general, $I_{base}(t)$ can be considered the signal of a low-pass filter of upper cut-off frequency $f_{base,high} = f_{CT,low}$ and time constant $\tau_{base} = 1/(2\pi\, f_{CT,low})$. The response time $t_{r,base}$ of $I_{base}(t)$ is the rise-time (10% - 90%) of a low-pass filtered step function:

$$t_{r,base} \approx \frac{0.35}{f_{CT,low}}.$$

Constraints of Application

The following three constraints must be fulfilled for a successful measurement of the baseline and its use for the determination of the average input current:

- The input pulses including any tails must be shorter than t_{rep}. In other words, I_{in} must fall to zero after each individual pulse.
- The CT pulse response must be sufficiently well behaving to allow I_{out} falling to its baseline after each pulse, e.g. all pulse-induced ringing must have vanished.
- The CT time constant τ must be considerably longer than t_{rep} to avoid a measurable impact of the CT droop on I_{out} in-between two input pulses.

MEASUREMENTS

A current transformer, CWCT, has been developed whose characteristics are well-adapted to the needs of above-mentioned method of average current measurements, mainly lower and upper cut-off frequencies. Additionally, an analog electronics card, BCM-CW-E, was developed which performs the required sample-and-hold signal detection as well as signal filtering and amplification (Fig. 3).

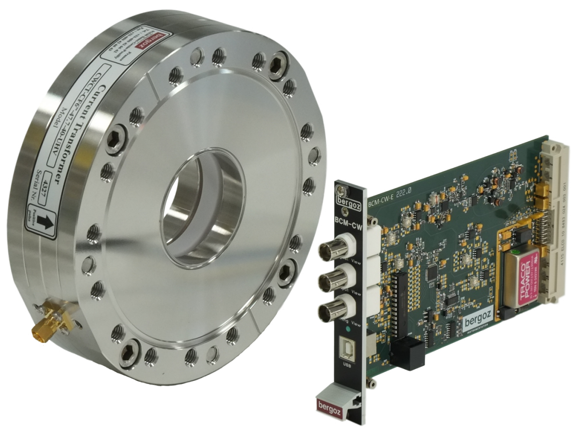

Figure 3: CWCT and BCM-CW-E.

Setup

The input signal is generated by an Agilent 8133A pulse generator and a 1 GHz low-pass filter. The signal passing through the CWCT aperture is measured using a 50 Ω feed-through termination, a low-pass filter and a voltmeter measuring directly the CWCT input signal's average voltage. Dividing this voltage by 50 Ω results the average input current.

Using an RF splitter, the CWCT output signal is observed on an oscilloscope and simultaneously detected by the BCM-CW-E. The BCM-CW-E output voltage is measured using another voltmeter.

At the BCM-CW-E input, the maximum achievable signal corresponds to an average input current of about 5.7 mA. Using variable step attenuators, the input current is varied between this maximum and a minimum of about 2 µA. BCM-CW-E on-board gain settings of +20 dB and +40 dB are used to span the measurement range.

Figure 4 shows the input signal and the CWCT output signal measured by an oscilloscope. Pulse repetition frequency is 200 MHz. After the pulse, the input signal remains close to zero, showing only minor wiggles. The CWCT output signal is a good representation of the input signal, scaled by the CWCT gain of 1/20. The CWCT shows a small resonance which vanishes quickly and is thus not important. It shall be noted that this resonance is a feature of this particular CWCT. Such resonances could be avoided or at least reduced by further tuning.

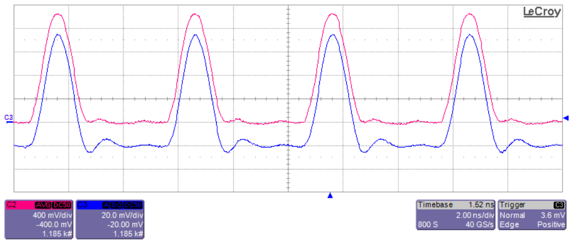

Figure 4: Input signal (red), CWCT output signal (blue).

Results

The measurement results are shown in Fig. 5 (20 dB gain) and Fig. 6 (40 dB gain).

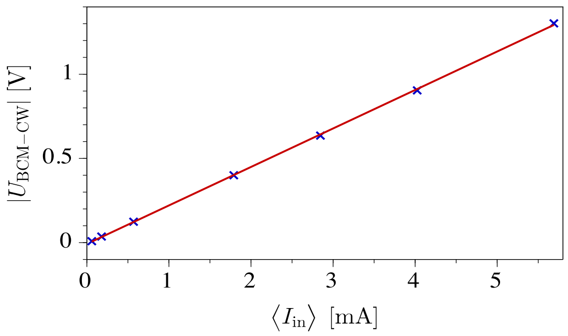

Figure 5: For a BCM-CW-E gain setting of 20 dB, output voltage versus average input current (blue marks) and a linear fit to the data (red line).

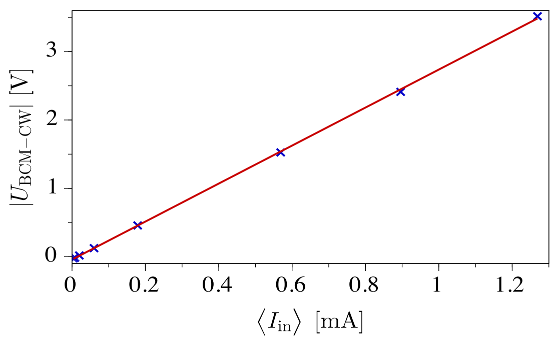

Figure 6: For a BCM-CW-E gain setting of 40 dB, output voltage versus average input current (blue marks) and a linear fit to the data (red line).

The measurement linearity remains within 1% for input currents above 600 µA (20 dB gain) and 60 µA (40 dB gain). For lower input currents, the resolution of the measurement setup limits the measurement precision.

The reaction time of the BCM-CW-E is measured using an input signal corresponding to 50% full scale resulting in –2 V output voltage. When disabling the input signal, the output voltage follows within 700 ns (Fig. 7). This value is due to the slew rate limit of amplifiers used on the BCM-CW-E. Thus, it can be considered the fastest possible reaction time. The impact of the CWCT droop was not visible in this particular measurement, because the signal's lower cut-off frequency was intentionally increased by a high-pass filter.

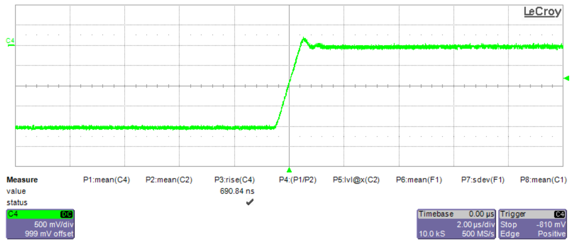

Figure 7: BCM-CW-E reaction time for a signal step from 50% full-scale down to zero.

The output noise is measured using a spectrum analyzer. Within 100 kHz bandwidth, 600 µVrms (20 dB gain) and 4400 µVrms (40 dB gain) total output voltage noise is observed. These values correspond to input current noises of 2.6 µArms and 1.6 µArms, respectively. Both values are compatible with the design specifications (compare Table 1).

CONCLUSION

Novel devices, CWCT and BCM-CW-E, for average current measurements of CW beams were developed. Their characteristics are ideal for proton and ion accelerators.

The CWCT and BCM-CW-E performance was tested in the laboratory using a pulse generator as a signal source. The measurements prove a very good linearity down to the microampere level. The reaction time is better than 1 µs. Noise is close to the 1 µArms level (100 kHz bandwidth).

To examine better the low charge limit, further tests are planned with an improved measurement setup. Beam tests will follow as soon as possible.

REFERENCES

[1] Accelerators for Society initiative of the TIARA project, http://www.accelerators-for-society.org, http://www.eu-tiara.eu/

[2] H. Koziol, "Beam Diagnostics", in Proc. of Cern Accelerator School Third General Accelerator Physics Course, Salamanca, Spain, 1988