MEASURING CHARGE AND AVERAGE BEAM CURRENT USING TURBO-ICT AND BCM-RF-E IN TRACK-CONTINUOUS MODE

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Abstract

Turbo-ICT and BCM-RF-E provide two different modes of operation for two different kinds of measurements: sample-and-hold (S&H) mode for single pulse charge measurements and track-continuous (T-C) mode for average current measurements of CW beams. However, under certain circumstances it is also possible to use T-C mode for single pulse charge measurements or average current measurements of complex beam patterns.

INTRODUCTION

For a general discussion of Turbo-ICT and BCM-RF-E please refer to [1,2]. The focus of this note is on the BCM-RF-E output signal when T-C mode is used for single pulse charge measurements or average current measurements of complex beam patterns.

When excited by a beam, the Turbo-ICT with its front-end band-pass filter and amplifier (FEFA) creates a resonance signal. This resonance is transmitted to the BCM-RF-E via a coaxial cable. Here it is further band-pass filtered and then transformed by a logarithmic amplifier to a corresponding resonance envelope (Figure 1).

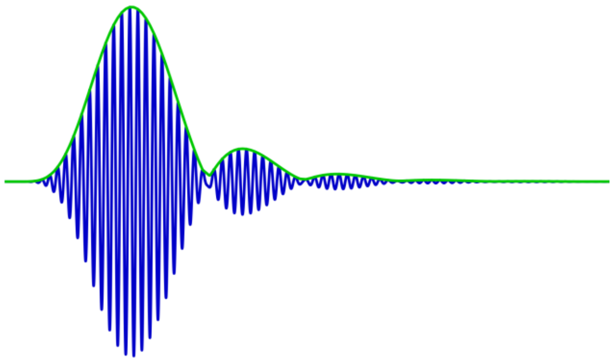

Figure 1: Sketch of a resonance excited by a single beam pulse (blue) and the corresponding envelope (green).

Envelope shape depends on the input beam pattern, Turbo-ICT transformer gain, FEFA characteristics, coaxial cable attenuation, BCM-RF-E input filter and logarithmic amplifier characteristics.

Further gain, offset and filtering are applied to the envelop signal before being available at the BCM-RF-E output. Additionally, some noise may be added by the electronics. Since gain, offset, filter and noise are applied to a logarithmic signal, their impact must be carefully considered to avoid unwanted side-effects on the measurement results.

Mathematically speaking, the challenge is that all these operations need to be inverted to deduce the average input current from the measured output voltage.

By design, Turbo-ICT and BCM-RF-E avoid some of the possible problems. Their calibration is adequate for the discussed use case. But the user himself must be careful, too, when performing measurements and during data analysis.

SIGNAL ENVELOPE

An important point that needs to be discussed is how well the measured resonance envelope represents the average input signal. Figure 2 compares a resonance and its envelope to the output signal of a low-pass filter. This low-pass filter was tuned to have same filter-type and filter-order as the band-pass filter which creates the resonance, but only half the bandwidth.

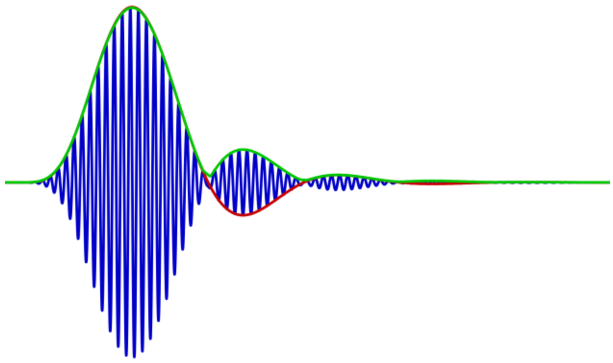

Figure 2: Sketch of resonance (blue), envelope (green) and corresponding low-pass filter signal (red, partially hidden behind envelope).

During the main resonance, envelope and low-pass filter signal agree, but then start to differ. This has consequences for the deduction of average current and charge.

A low-pass filter is the frequency-domain equivalent to time-domain averaging. That means, the output signal of a low-pass filter is by definition a correct representation of the average input signal, i.e. average beam current. As such, it also preserves the integral, i.e. beam charge. Since the envelope differs from the low-pass filter signal, it cannot be an exact representation of the average input signal and it cannot yield an exact integral.

The problem is that the ringing after the main resonance alternates between being out-of-phase and in-phase. Every second bump of the envelope should be negative. Such a signal correction could be achieved by post-processing the measured envelope and would yield a signal which is an accurate representation of the average input signal (Figure 3).

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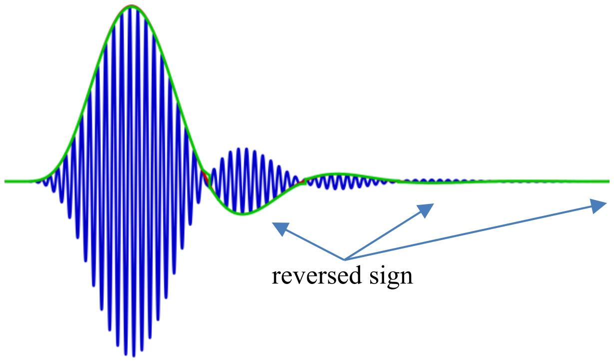

Figure 3: Sketch of resonance (blue), envelope after post-processing (green) and corresponding low-pass filter signal (red, almost completely hidden behind envelope).

T-C MODE MEASUREMENTS

During measurements and data analysis, one must keep in mind that the BCM-RF-E output signal is the resonance envelope on a logarithmic scale. This fact adds special constraints on the data acquisition system which are usually considered of minor or even no importance when measuring a signal on a linear scale.

Data acquisition hardware must be able to follow the BCM-RF-E output signal without inducing any deformations, for example signal bandwidth must be preserved. Even very small signal variations must be properly resolved, i.e. voltage resolution must be very good.

First, to avoid signal deformations analogue bandwidth of the data acquisition system must surpass BCM-RF-E output signal bandwidth of 10 MHz considerably, at least by a factor 2.

Second, for a good temporal resolution of the envelope a sampling rate of at least 50 MS/s is required. Higher sampling rates are preferable.

Third, to achieve <1% accuracy on a linear scale the logarithmic envelope must be measured with an accuracy <2 mV. An effective vertical resolution of 12 bits is required, i.e. the nominal resolution of the data acquisition system must be better than 12 bits. Voltage range must span -1 V to +5 V. While the envelope itself cannot be negative, noise may be slightly negative.

Digitizers fulfilling these specifications are available. Even some high-resolution oscilloscopes may be sufficient. But normal 8 bit oscilloscopes do not resolve small voltage differences which are important since the envelope is on a logarithmic scale.

Fifth, for data analysis every sampled value must be transferred to a linear scale by applying the T-C mode transfer function mentioned in the calibration report. Digital filtering or averaging of the samples prior to this operation is allowed only if the signal bandwidth is conserved. This may serve to reduce noise induced by the digitizer or oscilloscope as well as the noise induced by the BCM-RF-E signal path after the log-amp, but not the noise already present in the signal entering the BCM-RF-E.

Sixth, if the measured envelope signal has some additional bumps, their correct sign should be re-established. As discussed in the previous section, sign of every second bump must be reversed. Sampling rate must be high enough to resolve minima between the bumps, i.e. probably higher than the 50 MS/s mentioned above.

Finally, a low-pass filter can be applied to remove noise or even to reduce signal bandwidth. The resulting signal should be an accurate measurement of the average input current.

T-C MODE AND SINGLE PULSE CHARGE

It is obvious that T-C mode must be used to measure average currents of complex beam patterns. On the other hand, S&H mode is usually considered superior for single pulse charge measurements. And it is not obvious why it could be beneficial to perform such measurements in T-C mode.

One advantage is that no precise trigger signal needs to be provided. This may be of interest in accelerators with strong pulse-to-pulse charge jitter because precisely finding the envelope apex, i.e. a precise trigger timing setup, is difficult under such conditions. If bunch arrival time jitter surpasses a few nanoseconds using T-C mode may be the only option.

Measurement accuracy may benefit, too, if T-C mode is used. The advantage is that the whole envelope is available, not just a single point on its apex as in S&H mode. For example, digital filtering, integration, or curve-fitting algorithms could be applied. Statistical data analysis may even allow to separate noise contributions induced before and after the log-amp. This could be of interest in laser plasma accelerators where strong EMI can spoil the signal entering the BCM-RF-E (before log-amp), but also the signal leaving the BCM-RF-E (after log-amp).

CONCLUSION

Track-continuous (T-C) mode of Turbo-ICT and BCM-RF-E can be used for more measurements than just average currents of CW beams. It is applicable to complex beam patterns or single pulses.

However, to achieve good accuracy independent of the beam pattern some prerequisites need to be fulfilled. During measurements, sampling rate and vertical resolution need to be high enough to properly resolve the signal (≥50 MS/s, ≥12 bits). And for data analysis, it must be kept in mind that some operations are not permitted before transforming data from logarithmic scale to linear scale and re-establishing the correct sign of some parts of the measured signal envelope.

REFERENCES

[1] F. Stulle, J. Bergoz, “Turbo-ICT pico-coulomb calibration to percent-level accuracy”, Proc. of Free Electron Laser Conference (FEL’15), Daejeon, South Korea, 2015, paper MOP041

[2] Turbo-ICT & BCM-RF-E User's Manual