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A 3 GHz WALL CURRENT TRANSFORMER FOR VERY HIGH BANDWIDTH BEAM CURRENT MEASUREMENTS

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Abstract

Non-destructive beam current measurements are a crucial aspect of beam instrumentation in any particle accelerator. Often, these measurements must be capable of distinguishing individual beam pulses. In an increasing number of accelerators, pulse repetition rates reach the GHz range. Consequently, beam current measurement bandwidth must exceed a few GHz.

To meet this requirement, a wall current transformer was developed with a bandwidth exceeding 3 GHz. It was tested using a vector network analyser and with an electron beam at CERN's CLEAR facility. Both measurements showed excellent agreement. We introduce the wall current transformer principle and discuss the measurement results. Additionally, we highlight some challenges that must be addressed when measuring high-frequency signals.

INTRODUCTION

In particle accelerators, beam current measurements are used to evaluate long-term stability, transport efficiency, bunch-to-bunch variations or even bunch length. Each of these applications demands different measurement characteristics, notably bandwidths. To allow the separation of individual bunch signals, current measurement bandwidth must surpass the bunch repetition rate, which can be in the GHz range.

Previous attempts to push bandwidth limits above several GHz showed that Wall Current Monitors (WCM) and Wall Current Transformers (WCT) are principally capable of achieving such a goal [1-3]. However, no device evolved out of these efforts that is as versatile and generally available as a normal current transformer.

At Bergoz Instrumentation a development was carried out aiming to achieve 3 GHz bandwidth with a device that resembles closely a normal UHV-compatible current transformer of 40 mm length.

Very Fast Current Transformer

The Very Fast Current Transformer (VFCT) (Fig. 1) is based on the WCT measurement principle [3-5]. That means, instead of measuring the beam current with a single current transformer that surrounds the entire beam, the vacuum chamber wall is cut into several segments, and small transformers measure the beam-induced currents flowing across each of these segments. Since these transformers are considerably smaller, detrimental resonances are pushed to higher frequencies. Individual transformer signals are combined inside the VFCT.

Figure 1: Very Fast Current Transformer.

As a particularity, the VFCT was designed to provide a differential output signal using two SMA connectors. The difference of these signals gives the measurement result proportional to beam current. Creating a differential output signal was preferred because it reduces signal perturbations inside the VFCT. Using two SMA output connectors allows signal transmission over low-loss coaxial cables.

The VFCT has a bandwidth from below 200 kHz to above 3 GHz and a sensitivity of about 1 V/A. It is intended to measure short single pulses or high-repetition rate pulse trains.

CLEAR Facility

The CERN Linear Electron Accelerator for Research (CLEAR) is a user facility providing electron beams for a varied and large range of experiments [6]. The electron beam is produced by sending a pulsed UV laser to a Cs_2Te photocathode and is then accelerated to 200 MeV with three 3 GHz accelerating structures in a 20 m long linear accelerator. The accelerated beam is then transported to several experimental beamlines, both in air and in vacuum.

A pulse made of 1 to 150 bunches can be sent to all these experimental beamlines. The bunch length is typically around 3 ps and the bunch separation can be either 333 ps (3 GHz bunch repetition rate) or 667 ps (1.5 GHz bunch repetition rate). The pulse repetition rate can range from 0.833 Hz to 10 Hz.

Being able to produce bunches at 3 GHz repetition rate, CLEAR requires high frequency beam instrumentation for successful accelerator tuning and, consequently, high quality beam delivery to the experiments. However, sufficiently fast beam current diagnostics was previously not available for standard operation.

For the measurements performed at CLEAR, the VFCT was installed in air at the end of the CLEAR beamline just in front of the beam dump.

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MEASUREMENTS

Before installation at CLEAR, the VFCT was tested using a calibrated Agilent E5071 4-port vector network analyser (VNA). Only when these measurements gave satisfying results, beam measurements at CLEAR were performed with the aim to confirm VNA measurements in a realistic installation environment. It is important to recognize that these two measurement situations are very different. Results are not directly comparable.

To excite the VFCT with the VNA via coaxial cables, it must be put into a coaxial measurement contraption, which geometrically matches the cables to the VFCT aperture and allows signal continuity but also introduces a high frequency impedance mismatch. To account for this, the obtained VFCT transmission coefficients (S21 and S31) are normalized by the excitation signal fraction passing through the contraption (S41). This yields good estimations of the mismatch-free transmission coefficients only if the mismatch is small.

At CLEAR, signals were recorded using a LeCroy SDA11000 oscilloscope. VFCT and oscilloscope were connected by 10 m Times Microwave LMR400UF with 1 m Belden H155 on each end. Signal deformations due to frequency dependent coaxial cable attenuation and dephasing need to be considered as well as the response characteristics of the oscilloscope itself.

While above mentioned systematic differences can be measured and mathematically corrected, the beam itself introduces some unknown contributions.

Single Pulse Measurements

VFCT single bunch responses are shown in Fig. 2. Measurements taken at CLEAR correspond very well to the response calculated from VNA S-parameter measurements assuming a single very short pulse.

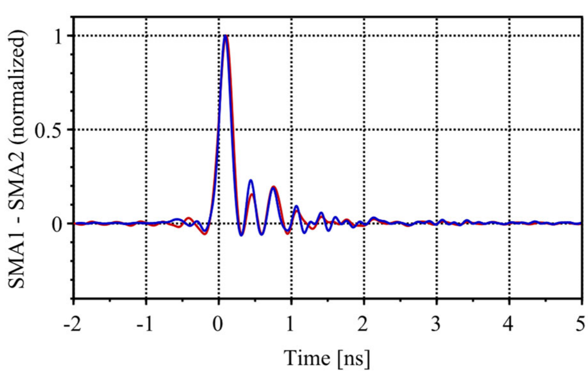

Figure 2: Single pulse measured at CLEAR (blue, 39 pulse average) and calculated from VNA S-parameter measurements (red).

For this figure, VNA S-parameter measurements include transmission characteristics of the coaxial cables used to connect the VFCT and the oscilloscope at CLEAR. Since these cables have slightly different lengths, data recorded by the oscilloscope and the VNA had to be corrected for the induced electrical delay to achieve exact phasing before calculating signal differences. A few picoseconds delay between the two signals have a visible impact on the reconstructed pulse shape.

Figures 3 and 4 show the individual signals of the two VFCT outputs. Again, beam signals and VNA signals are very similar. But their correspondence is not as good as in Figure 2. That means, the beam excited a stronger common mode. In Figs. 3 and 4, the frequency of the common mode resonance following the main pulse is between 5 GHz and 6 GHz. This indeed corresponds to the high-frequency behaviour visible in the VFCT frequency response (Fig. 5).

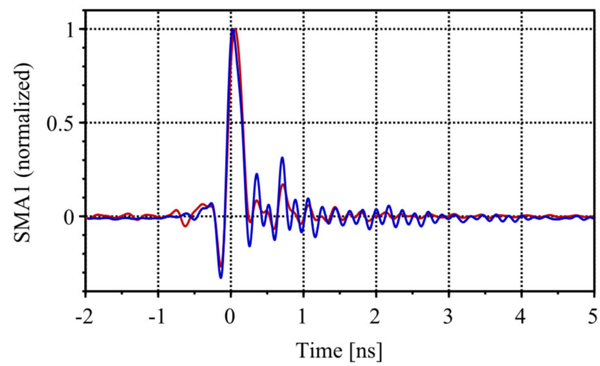

Figure 3: First VFCT output measured at CLEAR (blue, 39 pulse average) and calculated from VNA S-parameter measurements (red).

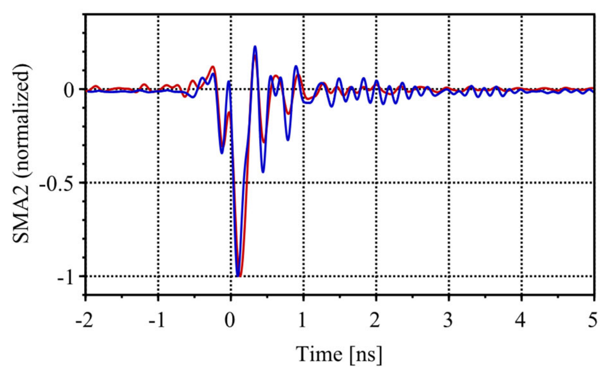

Figure 4: Second VFCT output measured at CLEAR (blue, 39 pulse average) and calculated from VNA S-parameter measurements (red).

Frequency Response

Frequency-domain transmission coefficients (difference of outputs) are plotted in Fig. 5. To get the frequency response of the VFCT only, coaxial cables and oscilloscope response were mathematically removed from CLEAR single pulse beam measurements.

To match the VNA and the beam measurements further, transmission coefficients were also deduced assuming that during these measurements the beam at CLEAR consisted of a main bunch with 93% of the total charge and a secondary bunch carrying only 7% of the total charge. The two bunches were separated by 0.667 ns, i.e. 1.5 GHz repetition rate. Under this assumption, also the VFCT response as deduced from the beam measurements reaches 3.3 GHz bandwidth, which is the same as for the VNA measurements.

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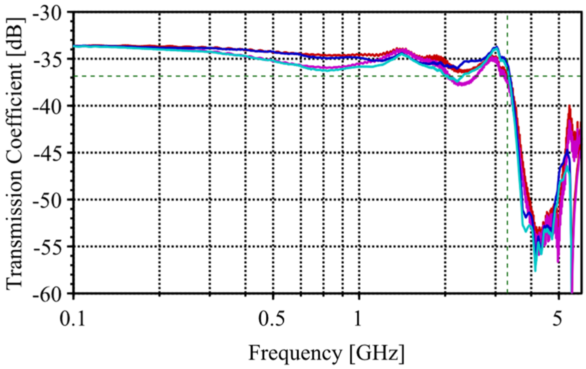

Figure 5: Transmission coefficients measured by VNA (red), VNA measurements multiplied by assumed beam spectrum (pink), deduced from beam measurements (cyan) and beam measurements corrected for assumed beam spectrum (blue).

Above 4 GHz, transmission coefficients rise again. This is probably a remainder of a common mode which is well suppressed but not perfectly cancelled by signal combination. Such a behaviour can also be observed in the time-domain measurements shown in Figs. 2–4.

The VNA and beam measurements deviate by up to 1 dB for frequencies below about 3.5 GHz. There may be several reasons for such a deviation. The real beam spectrum is not known. Errors might be introduced when correcting for the impact of oscilloscope response and coaxial cables. The VFCT itself may behave differently when tested with a VNA in a 50 Ω loaded coaxial measurement contraption compared to being placed isolated in air at CLEAR.

Macropulse Response

Further to the single pulse measurements, macropulse measurements were performed at CLEAR. Figure 6 compares VFCT measurements to measurements of the cathode laser intensity. Bandwidth of the laser measurement system is similar to the VFCT bandwidth. It also produces some ringing. Real laser pulse length is considerably shorter. However, apex variations correspond to bunch charge variations along the macropulse created by the cathode. Since both measurements agree well, it can be deduced that the five pulses were well transported from the source (location of laser measurement) to the dump (location of the VFCT).

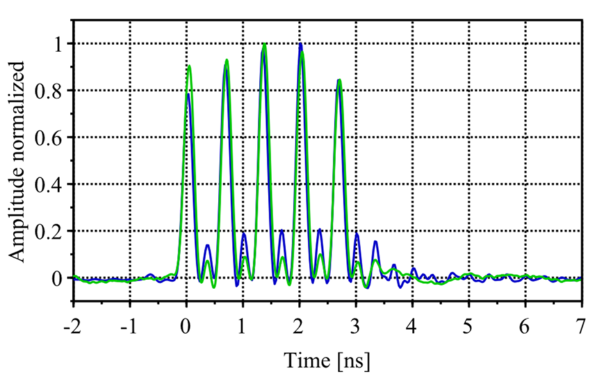

Figure 6: Short 1.5 GHz macropulse measured by VFCT (blue) and cathode laser intensity (green).

However, when switching to 0.333 ps bunch separation (3 GHz), the laser intensity and the VFCT signal would deviate considerably as seen in Fig. 7. Transmission seemed worse and every second pulse would be particularly badly transported. The beam transport was considerably improved by tuning the position of the laser on the cathode and the effect was visible instantly with the VFCT as shown in Fig. 8. These measurements highlight the importance of having a faithful beam current measurement system for improving accelerator performance.

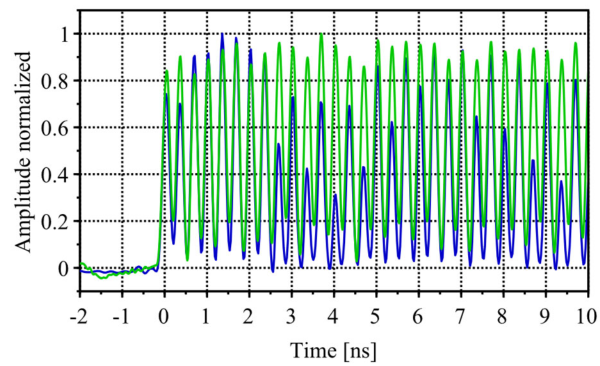

Figure 7: Start of a long 3 GHz macropulse measured by VFCT (blue) and cathode laser intensity (green).

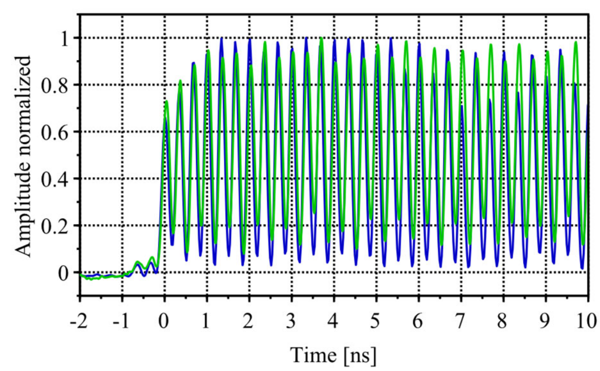

Figure 8: Start of a long 3 GHz macropulse measured by VFCT (blue) and cathode laser intensity (green) after laser position tuning.

CONCLUSION

A very fast current transformer was developed based on the wall current transformer principle. Its measurement bandwidth surpasses 3 GHz, which allows distinguishing individual pulses in accelerators with several GHz beam pulse repetition rates.

The size and the sensitivity are comparable to standard current transformers, which makes the VFCT a valid alternative in cases where a higher bandwidth is required.

The VFCT performance was evaluated in the laboratory using a vector network analyser. And it was tested with beam at CERN's CLEAR facility. Both measurements show excellent agreement. The VFCT's applicability to high-repetition rate beams was confirmed.

The VFCT fills a gap in the CLEAR beam diagnostics and can contribute to improving beam quality. It is now installed and used at CLEAR for standard operation.

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