Proc. 13th International Beam Instrumentation Conference,Beijing JACoW Publishing
ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-THP08

USING TRANSIMPEDANCE AMPLIFIERS FOR CURRENT MEASUREMENTS OF LONG BEAM PULSES

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Abstract

CERN H^- Linac 4 (L4) and ion Linac 3 (L3) operate with millisecond beam pulses, which pose a challenge for beam current measurements based on Fast Beam Current Transformers (FBCTs). In the past the low cut-off frequencies of the FBCTs were actively lowered using a combination of transimpedance (TI) amplifiers and integrating amplifiers. Unfortunately, in many locations such amplifiers were sensitive to interference from neighbouring power systems. The situation was particularly difficult in L3, where in addition to long beam pulses, the challenge was also small beam currents. The interference problems had been addressed for years with limited success and finally it was decided that the whole FBCT front-end electronics should be renovated, with the main objective being to improve the immunity to interference. This paper describes the evolution of the FBCT front-end electronics and installations, which has finally allowed reliable beam current measurements, whose examples are provided. The key improvement was the use of small TI amplifiers directly connected to the FBCTs, which in addition simplified installations in both linacs. The TI amplifiers provide an active low impedance load to the FBCTs, extending their time constants by some two orders of magnitude, as compared to operation with a 50 Ω load. Challenges of the TI amplifier implementation are described, along with particularities of their beam commissioning.

[1] Please note that schematics in [1] and [2] do not take into account subsequent hardware modifications to include an integrating amplifier stage present in all L3 and L4 FBCT amplifiers before the renovation described in this paper.

INTRODUCTION

As illustrated in the left photograph of Fig. 1, in the past each L3 and L4 FBCT (T) was connected to its head amplifier (A) by a twisted-pair cable [1, 2][1]. Its resistance limited the smallest value of the FBCT load seen by the amplifier and therefore the lowest achievable droop of the beam signal. The cable resistance can also give rise to interference voltages induced by ground loop currents caused by nearby power equipment.

The first limitation was overcome in the past by using an integrating amplifier, which compensated the signal droop achieved by the input TI amplifier. As FBCTs even of the same type can have inductances differing by more than 100 %, each FBCT thus required a dedicated amplifier with the compensation adjusted to its inductance. With about 30 FBCTs operational in the linacs [3], this requirement heavily complicated the installations, their maintenance and spares management.

Laborious maintenance and many interference problems, which had not been properly solved for years, finally led to an upgrade programme of the linac FBCT amplifiers, along with their installations. The new scheme, shown in the right photograph of Fig. 1, is based on small amplifiers (A) installed directly on the FBCT output connectors. All three cables of the installation, namely the beam signal, the calibration signal for one-turn FBCT calibration winding and the power supply, are equipped with simple balun transformers (B) built with a few turns of cable wound on high-permeability toroids. The baluns increase the impedance of potential ground loops and therefore reduce the corresponding currents.

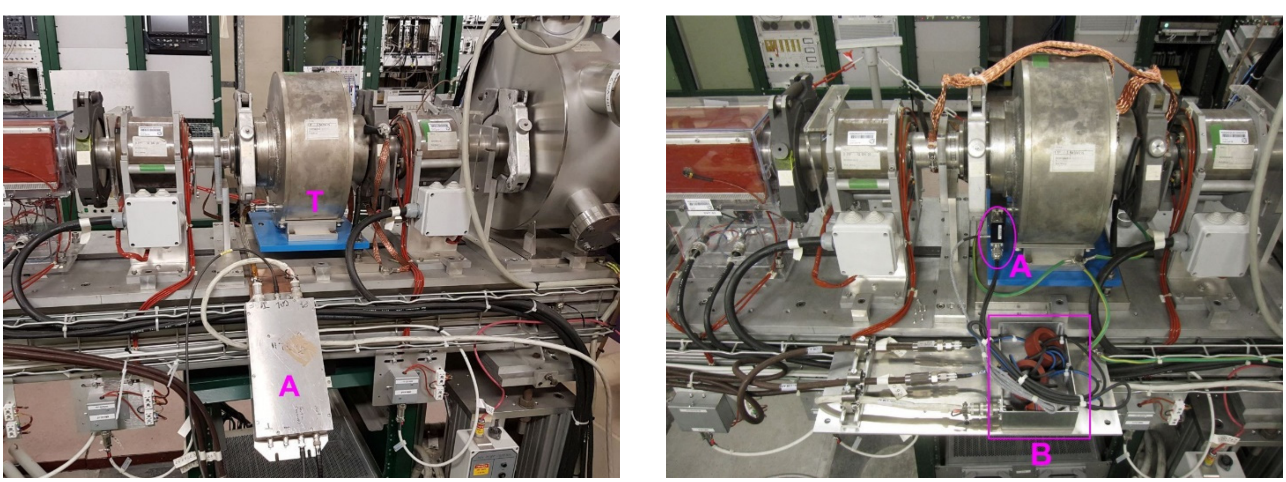

Figure 1: Photographs of the old Linac 3 FBCT installation (left) and the new (right) on the example of ITL.BCT15.

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LINAC 4 AMPLIFIERS

The first amplifier prototype of the new design, installed in L4 in 2022, was an integrating amplifier, whose block diagram is shown in Fig. 2. It had a standard 50 Ω input impedance, allowing the use of a non-reflective Low-Pass Filter (LPF) at the input [4]. The filter was very important to deal with the strong 352 MHz interference picked up from the L4 RF cavities, which some of the FBCTs are installed between. However, the 50 Ω amplifier inputs combined with the FBCT inductances resulted in very short time constants. In the most difficult cases, the time constants were about five times shorter than the beam pulse and the end of the pulse had to be amplified by some two orders of magnitude more than the beginning, to achieve beam pulse droops of a percent level. This was achieved in the first stage with an operational amplifier (op-amp) A_1, whose low frequency gain ($\approx R_I/R_G$) was some two orders of magnitude higher than the gain ($\approx R_F/R_G$) for high frequencies ($R_I \approx 100\, R_F$). The two following stages provided the necessary gain to bring the beam current signal to a level adequate to send over the long coaxial cables to the acquisition system [5].

The installed integrating amplifier prototype yielded good quality signals. However, the accuracy to which its response had to be matched to a particular FBCT exceeded by far the initial expectations. This made such a scheme impractical to be used for larger installations. Moreover, it was discovered that the droop compensation given by the integrating amplifier depends on the signal amplitude. Figure 3 presents the output signals of the L4 integrating amplifier for two signal amplitudes differing by a factor 10 when operated on a laboratory FBCT model with a simulated rectangular beam pulse injected into the calibration winding. The measured effect was confirmed with simulations to be a fundamental limitation of this configuration and is related to the integration of the op-amp bias current and its input offset voltage.

The presented measurements also reveal two other drawbacks of integrating amplifiers, namely the distorted top of the pulse and the fact that the droop can be overcompensated. These heavily complicate and limit the droop compensation implemented in the system software.

Finally, the L4 amplifiers were built in the transimpedance configuration shown in Fig. 4, with the first prototype installed in 2023. In this scheme the amplifier small input resistance $R_{IN} = R_{IN1} + R_{IN2}$ is the load of the FBCT, allowing large time constants and, therefore, small beam pulse droops to be achieved. The conversion of the FBCT secondary winding current into a voltage is performed by the feedback resistor R_F, which is much larger than R_{IN}, allowing convenient voltages after the first stage to be achieved and assuring a good signal-to-noise ratio (SNR). The low-pass filter is put after the TI stage, where its characteristic impedance can be freely chosen. The following two stages amplify the beam current signal to a level adequate for a transmission over the long coaxial cables to the acquisition system [5].

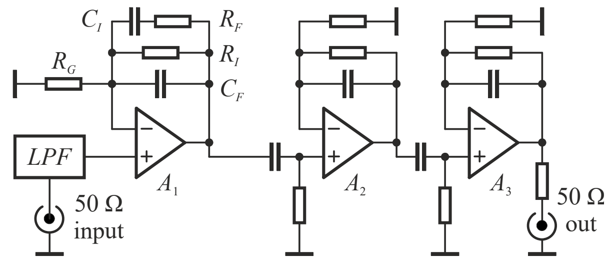

Figure 2: Block diagram of the L4 integrating amplifier.

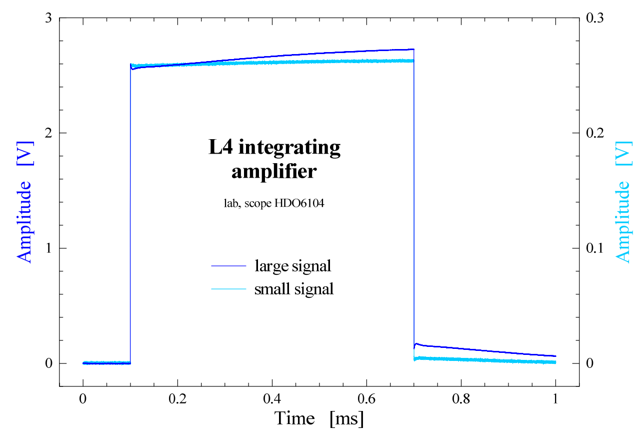

Figure 3: Output signals of the L4 integrating amplifier for two signal amplitudes differing by a factor 10 when operated on a lab FBCT model with a simulated rectangular beam pulse injected into the calibration winding.

For L4 the lowest value of R_{IN} is 0.3 Ω, resulting in a high gain of the TI stage ($-R_F/R_{IN}$), in the order of a thousand. This requires that A_1 has a low offset voltage, to avoid spoiling its dynamic range at the output. The following stages also have important gains, thus the stages are AC-coupled. The input and the output of the amplifier must be DC-coupled, in order to achieve an overall low frequency cut-off of below 1 Hz with the low resistance values present.

The main disadvantage of the TI amplifier is that it cannot have a classic input low-pass filter and this is the reason why it was not the first scheme tried. The only protection of the input from the strong L4 RF interference is capacitor C_{IN}, which together with R_{IN1} and the FBCT output impedance forms a simple RC low-pass filter. As experience proved, this simple filter is what made it possible to use TI amplifiers in L4, as without it the A_1 input stage was saturated by RF content to the extent that A_1 worked as an envelope detector, whose signal was added to the beam current output signal.

Both sides of the TI amplifier circuit are shown in Fig. 5. An important part, not shown in the diagram of Fig. 4, is the ± 11 V power supply, with two low-noise, low dropout linear regulators and extensive passive filtering (bottom photograph).

Figure 6 presents the output signals of the L4 TI amplifier for two signal amplitudes differing by a factor 10

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when operated on a laboratory FBCT model with a simulated rectangular beam pulse injected to the calibration winding. The TI amplifier does not suffer from any of the disadvantages seen in the corresponding measurements for the L4 integrating amplifier shown in Fig. 3.

An example of a measurement from the first L4 FBCT (50 turns, inductance 79 mH) equipped with a TI amplifier is shown in Fig. 7. The beam current signal does not suffer from any interference and the droop on the 1.6 ms beam pulse is only about 2 %.

A shorter beam pulse, from the first FBCT (20 turns, inductance 8.2 mH) after the beam chopper, equipped with a TI amplifier is shown in Fig. 8. In this case the 6 MHz bandwidth of the TI amplifier allows the fine time structure of the pulse to be resolved.

LINAC 3 TI AMPLIFIERS

After very good results were obtained with TI amplifiers in L4 a similar solution was attempted in L3. However, due to almost three orders of magnitude lower beam currents and smaller FBCT inductances with similar beam pulse lengths, measurements in L3 are by far more challenging.

The L3 TI amplifier prototype was installed on the first FBCT (10 turns, 3.3 mH) after the ion source. This FBCT works with the longest beam pulse and therefore requires the lowest load resistance. The TI design was pushed to the limit and R_{IN} consisted only of the resistance of the FBCT winding and the input connections. R_{IN} was estimated from the signal droop to be about 0.2 Ω, resulting in a DC gain of the first stage of well beyond a thousand. The total low frequency gain of the amplifier was about a quarter of a million. With modern low-noise, precision and fast op-amps such an extreme gain could be achieved while still conserving a good SNR and about 800 kHz of bandwidth.

The achieved results and the difficulty of L3 beam current measurements are illustrated in Fig. 9, showing the beam current as measured with the FBCT system (in red) and the FBCT output signal measured with a 12-bit oscilloscope (in blue). The oscilloscope signal consists mostly of 200 MHz interference from the nearby RF system, and the beam signal is seen only as short, about 0.7 mV pulses resulting from a differentiation of the beam signal by the LR circuit formed by the FBCT inductance and the 50 Ω load of the oscilloscope input.

After a year of successful operation of the TI amplifier on the first L3 FBCT similar amplifiers were installed on the following two FBCTs. It was a large surprise to discover that the inputs of both amplifiers were saturated by 200 MHz RF interference, resulting in signals with excessive amplitudes related to the interference envelope. This was explained by oscilloscope measurements of the FBCT output signals, revealing a few hundred mV of 200 MHz RF content, which overwhelmed the beam signal by more than two orders of magnitude and for which the simple TI input filter was not sufficient.

After extensive investigations in the L3 hall some 95 % of the RF interference at the FBCT output was removed by installing “interference bypasses” made of thick copper braids, connected to the vacuum chamber on either side of the FBCT. A prototype of such a bypass is visible in the right photograph of Fig. 1.

A further reduction of the RF interference was achieved by installing magnetic toroids directly on the FBCT winding ends, creating low resistance series inductances and thus increasing the order of the TI input filter.

The result of the improvements to the second L3 FBCT (10 turns, 3.6 mH) is presented in Fig. 10, showing the

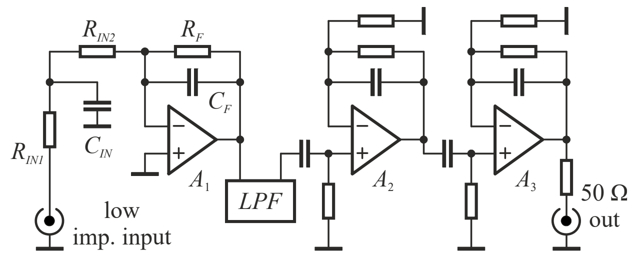

Figure 4: Block diagram of the L4 and L3 transimpedance amplifier.

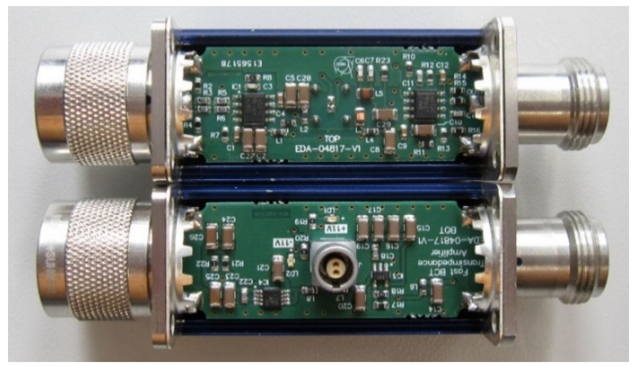

Figure 5: A photograph of both sides of the transimpedance amplifier circuitry.

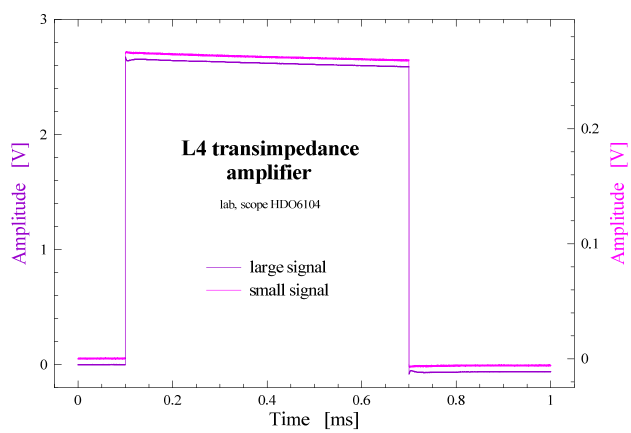

Figure 6: Output signals of the L4 transimpedance amplifier for two signal amplitudes differing by a factor 10 when operated on a lab FBCT model with a simulated rectangular beam pulse injected to the calibration winding.

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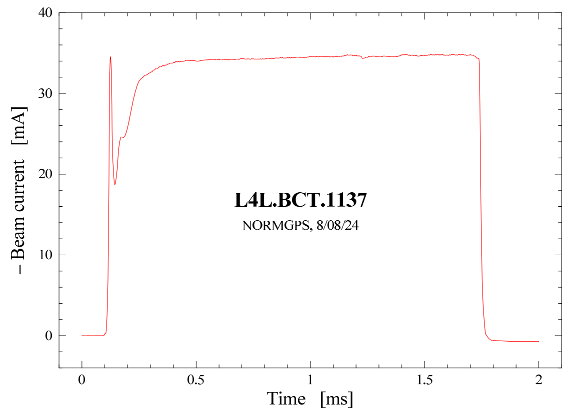

Figure 7: Beam current on the first L4 FBCT, as measured by the FBCT system. Please note the very low droop on 1.6 ms beam pulse.

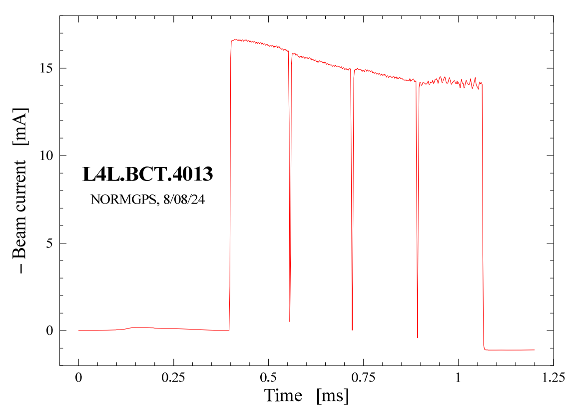

Figure 8: Beam current on the third L4 FBCT, the first after the beam chopper, as measured by the FBCT system. Please note high frequency content present.

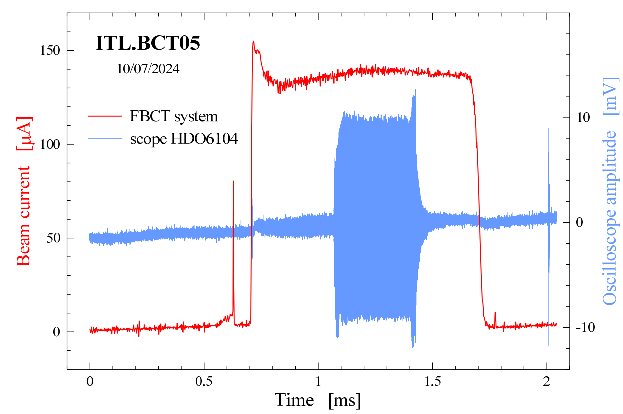

Figure 9: Beam current on the first L3 FBCT as measured by the FBCT system (in red) and a corresponding scope measurement of the FBCT output voltage (in blue) .

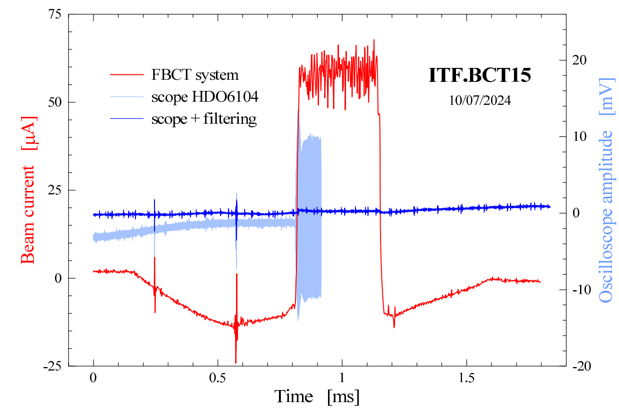

Figure 10: Beam current on the second L3 FBCT as measured by the FBCT system (in red) and corresponding FBCT output voltages measured with a scope in full bandwidth (light blue) and in high resolution (dark blue).

beam current measured by the FBCT system (in red) and corresponding FBCT output voltages measured with a 12-bit oscilloscope in the full bandwidth (light blue) and in a high resolution mode (dark blue), which features a digital filter removing the RF interference in an attempt to reveal the beam signal. Even with such strong filtering the differentiated beam signal is barely visible on the oscilloscope, as its amplitude is only about 0.35 mV and the interference surpasses it by a factor of about 30.

A TI amplifier was also installed on the third L3 FBCT. However, there the copper bypass could not be installed in an effective way as it was not possible to attach it to the vacuum chamber due to space constrains. This limitation could be a reason why this particular FBCT suffers from perturbations induced by nearby pulsed magnets. The issue is being investigated and potential remedies are being studied.

SUMMARY AND OUTLOOK

During last two years small TI amplifiers were designed, prototyped and installed on most of the L4 FBCTs and three L3 FBCTs. These new amplifiers simplified the FBCT installations and their maintenance, while improving the measured signal quality. In particular, the new system requires only four types of the amplifier for all linac FBCTs, while in the past, in most cases, each of the 30 FBCTs had its own dedicated amplifier configuration.

In the near future, all linac FBCTs operated with long beam pulses will be equipped with the TI amplifiers presented in this paper. In the case of one L3 FBCT further studies are required to reduce interference induced by nearby magnets. If simple means, as improved grounding, better shielding or a differential input to the amplifier are not sufficient, this particular FBCT could be envisaged to be the first to be renovated, as the current design does not have good magnetic shielding and is based on enamelled flanges without an RF bypass for the beam current. Interference levels present in the L3 hall are very high and, without renovating the FBCTs themselves, improving the signal quality further seems to be very challenging.

The present FBCT acquisition system [5] is more than twenty years old and its replacement is currently being designed. The new system will be able to operate with

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larger signal droops than the current one, as more advanced droop compensation can be implemented in the digital domain. This will allow the TI input resistances to be increased by a few times and the low frequency amplifier gains to be reduced by the same factor. This should in turn bring a similar reduction of the susceptibility to the low frequency interference pick-up.

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