

# A PRECISE PULSED CURRENT SOURCE FOR ABSOLUTE CALIBRATION OF CURRENT MEASUREMENT SYSTEMS WITH NO DC RESPONSE

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## Abstract

Absolute calibration of systems with no DC response requires pulsed calibration circuits. This paper presents a precise pulsed current source designed primarily for remote calibration of a beam intensity measurement system. However, due to its simple and flexible design, it might also prove interesting for other applications. The circuit was designed to drive a load of 10 Ω with current pulses lasting a few hundred microseconds with an amplitude of 1 A and precision in the order of 0.01 %. The circuit is equipped with a half-bridge for precise determination of the absolute output current using the 0 V method. This paper presents the circuit topology and discusses in detail the choice of the critical components along with their influence on the final achieved accuracy. The performance of the built prototype of the current source is presented with laboratory measurements.

## INTRODUCTION

Many modern measurement systems have no low-frequency response so that their calibration cannot be achieved with DC signals. One of the available possibilities to calibrate such systems is to use a circuit generating long pulses with a well-defined and stable amplitude.

The pulsed current calibration unit described in this paper consists of two main circuits: a current source generating the calibration current and a half-bridge circuit for measuring the current with high accuracy. Similar circuitry was developed in the past for the inductive beam position monitors of the CERN CLIC Test Facility (CTF3) [1].

This paper describes the principle of operation and discusses the choice of the most critical components. A brief description of additional features, extending the field of potential applications, is also given.

All measurements shown in this paper were obtained with a prototype circuit built and optimised for calibrating the new bunch-by-bunch intensity measurement system of the Large Hadron Collider (LHC) [2, 3]. The source was designed to deliver a current pulse of 1 A into 10 Ω load for a few hundred microseconds. However, the system can easily be adapted for other values of the current and a wide range of loads by simply adjusting the values of a handful of components.

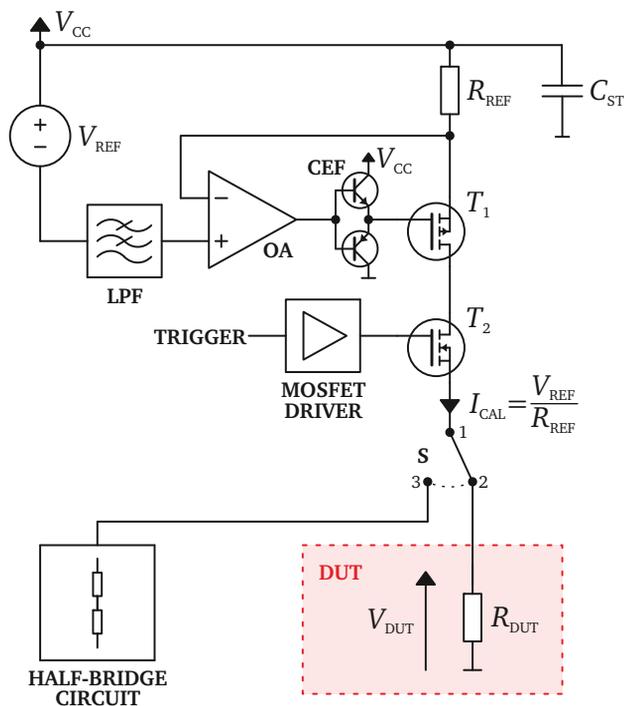


Figure 1: A simplified circuit diagram of the current source. LPF - Low-Pass Filter; OA - Operational Amplifier; CEF - Complementary Emitter Follower; DUT - device being calibrated

## CURRENT SOURCE

The principle of operation of the current source can be explained using the circuit diagram shown in Fig. 1. During normal operation the switch S is in position 1-2 to send the calibration current  $I_{CAL}$  to the grounded load  $R_{DUT}$  of the device to be calibrated.

The value of  $I_{CAL}$  is determined by the ratio of the reference voltage  $V_{REF}$  and the reference resistance  $R_{REF}$ , both being part of the regulation loop. The non-inverting input of the operational amplifier (OA) is set to  $V_{CC} - V_{REF}$  and additionally filtered by a low-pass filter (LPF). OA regulates its output voltage such that its inverting input virtually matches the voltage of the non-inverting input. Hence, the voltage at the inverting input of OA also equals  $V_{CC} - V_{REF}$  which in turns yields a voltage drop of  $V_{REF}$  across the reference resistor  $R_{REF}$ . The complementary emitter-follower (CEF) buffers the output of OA to drive the large gate capacitance of the top p-channel MOSFET  $T_1$  to improve the response time

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of the loop. The capacitor  $C_{ST}$  provides a low-impedance storage for the charge necessary to generate the current pulse.

The regulation loop can operate only when the bottom n-channel MOSFET  $T_2$  is switched on. Hence,  $T_2$  is used to gate the output current and produce pulses of the required length. When  $T_2$  is switched off, the OA output reaches its negative rail making  $T_1$  switch on. The gate of  $T_2$  is connected to a dedicated MOSFET driver designed for the fast driving of large gate capacitance. The length of the TRIGGER input pulse defines the length of the generated current pulse.

In its other position 1-3, the switch S directs the output current to the half-bridge circuit used for the precise measurements of the output current.

The maximum allowed value of  $R_{DUT}$  is limited by the compliance voltage of the current source i.e. the maximum output voltage  $V_{DUT}$  for which the source can deliver constant current  $I_{CAL}$ . For the designed source  $V_{CAL,max} \approx V_{CC} - V_{REF}$ , hence:

$$R_{DUT} < \frac{V_{CC} - V_{REF}}{I_{CAL}} \quad (1)$$

The quality of the generated current is directly linked to the quality of the voltage reference  $V_{REF}$  and therefore the reference should be exceptionally stable and clean. Due to the topology of the current source, a two-pin voltage reference was used to refer it directly to the positive power supply rail. A number of such integrated circuits are available on the market. The precision voltage reference used in the prototype has an initial voltage accuracy of 0.05 %, temperature coefficient of 4 ppm/°C and low-frequency noise in the order of 7 ppm<sub>pp</sub>. Nevertheless, additional filtering by the LPF with a cut-off frequency of 2 Hz was required to further reduce the low-frequency fluctuations. The LPF was built with a precision operational amplifier in a follower configuration in which the output voltage is independent of the value of the resistors used. For the prototype a  $V_{REF}$  of 5 V was used to set the inputs of OA far enough from the power supply rails to ensure its proper operation.

The other critical component of the source is the reference resistor  $R_{REF}$ . Once  $V_{REF}$  is set, the value of  $R_{REF}$  directly determines the value of  $I_{CAL}$ . There are a number of high-precision 4-terminal current-sensing resistors available commercially and two identical resistors were used in parallel to achieve the desired  $R_{REF}$  of 5  $\Omega$ . Each of the resistors has a tolerance of 0.01 %, thermal coefficient of 0.05 ppm/°C and power coefficient of 4 ppm/W.

An important feature of the design is that the tolerances on the absolute value of  $V_{REF}$  and  $R_{REF}$  are not as critical as their stability and drifts, as  $I_{CAL}$  can be precisely measured with the half-bridge circuit.

The operational amplifier used has a very small input bias current of 0.5 pA to minimise the error introduced by the inverting input bias current flowing through  $R_{REF}$ . A precision, low-noise, JFET-input operational amplifier with 120  $\mu$ V input offset voltage, 250 nV<sub>pp</sub> low-frequency noise and slew rate of 20 V  $\mu$ s<sup>-1</sup> was used.

Due to the limited output impedance of the power supply, most of the output current must come from the local storage capacitor  $C_{ST}$  when the current source is turned on. It can be assumed that the supply voltage  $V_{CC}$  decreases at the same rate as the voltage across  $C_{ST}$ . For the designed source  $C_{ST}$  of 5 mF was chosen to limit the drop of  $V_{CC}$  to 100 mV for the nominal current of 1 A and the maximum pulse length of 500  $\mu$ s as calculated from:

$$\Delta V_{CC} = \frac{I_{ST} \cdot t}{C_{ST}} \quad (2)$$

The output current pulse of the prototype is shown in Fig. 2 with a zoom on the initial 5  $\mu$ s shown in Fig. 3. The source was triggered with pulses of 250  $\mu$ s every 100 ms.

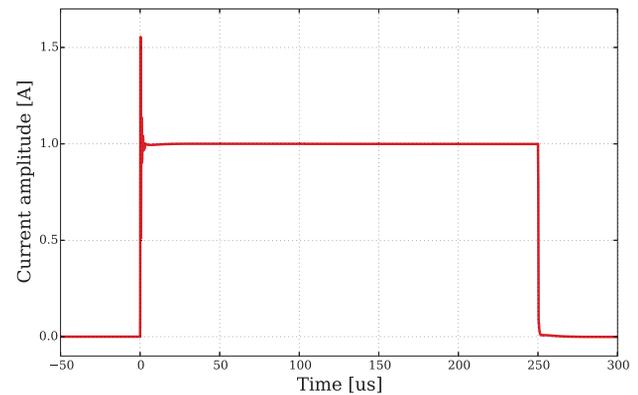


Figure 2: Output current of the current source.

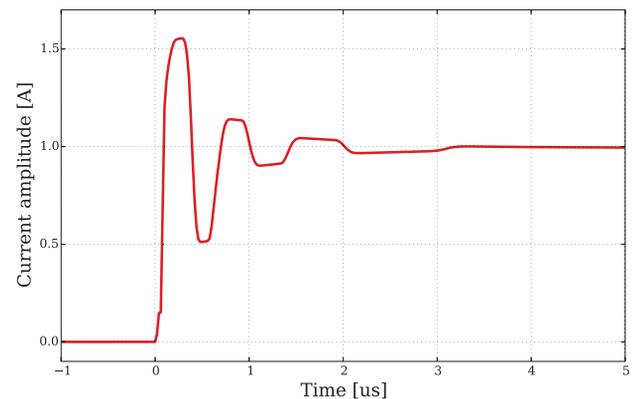


Figure 3: The first 5  $\mu$ s of the pulse shown in Fig. 2.

The output current oscillates for approximately 3.5  $\mu$ s before reaching its nominal value of 1 A within 0.1 % accuracy. After an additional 30  $\mu$ s it attains an accuracy of  $\pm 0.01$  %.

The initial oscillation of the output current illustrates the operation of the regulation loop of the current source. When the current source output is switched off by  $T_2$ , the operational amplifier OA is saturated at its negative rail. At the beginning of the pulse the output current reaches the maximum possible value as  $T_2$  can be turned on much faster than the regulation loop starts working. The regulation then kicks in to stabilise the output current at the nominal value.

### HALF-BRIDGE CIRCUIT

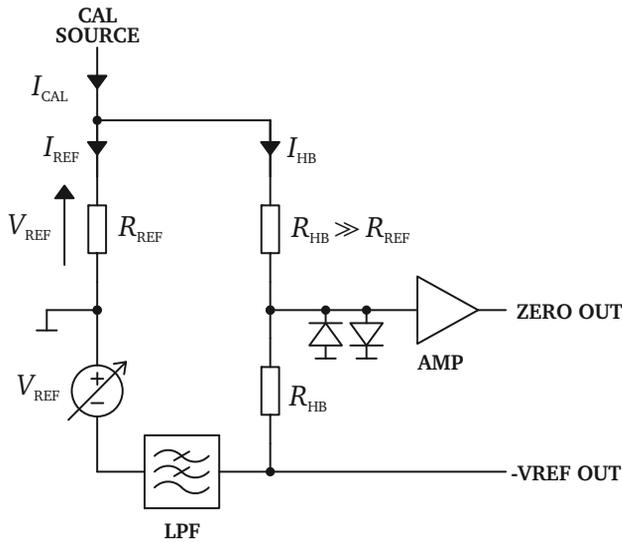


Figure 4: A simplified circuit diagram of the internal half-bridge.

When the switch S of the circuit diagram in Fig. 1 is in position 1-3, the pulsed current  $I_{CAL}$  is sent to the half-bridge circuit shown schematically in Fig. 4. The pulsed calibration current  $I_{CAL}$  is converted into a voltage which is compared to a DC voltage of the opposite sign. Hence, the value of the pulsed  $I_{CAL}$  can be accurately determined with DC measurements.

The calibration current  $I_{CAL}$  is converted into voltage across the reference resistor  $R_{REF}$ . If the adjustable  $V_{REF}$  is set such that  $V_{REF} = I_{REF} \cdot R_{REF}$  then the potential at the common node between the two half-bridge resistors  $R_{HB}$  is 0 V.

The two precision resistors  $R_{HB}$  have equal values, much larger than  $R_{REF}$ , to make the half-bridge current  $I_{HB}$  negligibly small with respect to  $I_{REF}$ .

Assuming that the value of  $R_{REF}$  is known, the value of  $I_{REF} \approx I_{CAL}$  can be indirectly measured as  $V_{REF}/R_{REF}$  after adjusting  $V_{REF}$  such that the potential at the common node of the half-bridge is 0 V. To improve the stability of the circuit,  $V_{REF}$  can be low-pass filtered.

For the prototype  $V_{REF}$  can be adjusted by two means: a precision trimming potentiometer and a remotely controlled Digital to Analogue Converter (DAC). Each of these can independently regulate  $V_{REF}$  by  $\pm 0.2\%$ .

In nominal conditions the potential at the common node of the half-bridge is very close to 0 V. To increase the resolution of the measurement this signal is amplified with a relatively large gain. This also decreases the influence on the measurement accuracy of the offset voltage of the digitiser used to determine the 0 V conditions.

For the developed prototype, the amplification factor was chosen such that 1 mV at the output translates to 1 ppm of deviation from the nominal current. Clamping diodes are

used to keep the amplifier out of saturation when there is no  $I_{CAL}$  sent to the half-bridge.

If required, the half-bridge current  $I_{HB}$  can be taken into account for a more precise determination of  $I_{CAL}$ :

$$I_{CAL} = I_{REF} \cdot \frac{R_{REF} + R_{HB}}{R_{HB}} = V_{REF} \cdot \frac{R_{REF} + R_{HB}}{R_{REF} \cdot R_{HB}} \quad (3)$$

Similarly to the current source,  $R_{REF}$  and  $V_{REF}$  should be very stable. However, contrary to the current source circuit, the absolute accuracy of the components used in the half-bridge circuit is critical. The 5 V voltage reference used in the half-bridge circuit was the same as the one used in the current source.  $R_{REF} = 10\ \Omega$  consisted of a single resistor of the same type as the  $R_{REF}$  used in the current source. Since the value of  $R_{REF}$  was twice as high as in the current source,  $V_{REF}$  also had to be increased by a factor of two. A  $V_{REF} = -10\text{ V}$  was achieved by amplifying the output of the voltage reference with an operational amplifier and implementing low-pass filtering with a cut-off frequency of 2 Hz. This apparent complication has, in reality, a few advantages. The same types of resistor and voltage reference are shared by the current source and the half-bridge circuit which simplifies selection of components and makes potential drifts more coherent. Moreover, the  $R_{REF}$  of the half-bridge is exactly the same as the  $R_{DUT}$  of the device being calibrated so the current source operates at the same output voltage, minimising the impact of the output impedance of the source on the calibration quality.

The set value of  $V_{REF}$  can be directly monitored with 50 ppm accuracy using a precision multimeter. The value of  $R_{REF}$  can be known with a tolerance of 100 ppm. Hence, using the half-bridge circuit built with the components described and accounting for  $I_{HB}$ , the absolute accuracy for determining  $I_{CAL}$  is at the level of 150 ppm.

The output signal of the half-bridge circuit of the prototype is shown in Fig. 5 with a zoom to the area of interest around 0 V shown in Fig. 6. The source was triggered with 250  $\mu\text{s}$  pulses every 100 ms.

The measurements indicate that the output current of the source is within 200 ppm of its nominal value 22  $\mu\text{s}$  after triggering and within 100 ppm after additional 10  $\mu\text{s}$  and attains its nominal value after approximately 130  $\mu\text{s}$  with some subsequent decay.

### PROTOTYPE

A picture of the prototype calibration circuit is shown in Fig. 7. The source can be seen in the lower left-hand side with the half-bridge in the upper left-hand side.

The stability of the prototype was measured with the half-bridge circuit over a 24-hour period with the source triggered by 250  $\mu\text{s}$  pulses every 100 ms. A histogram of the results is presented in Fig. 8 showing the average deviation from the nominal current for a 10  $\mu\text{s}$  period of the half-bridge output measured 120  $\mu\text{s}$  after triggering the source. The measurements follow a Gaussian distribution with a standard

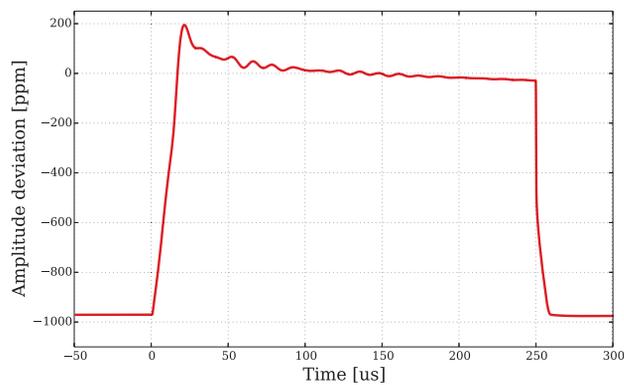


Figure 5: Full output of the half-bridge circuit.

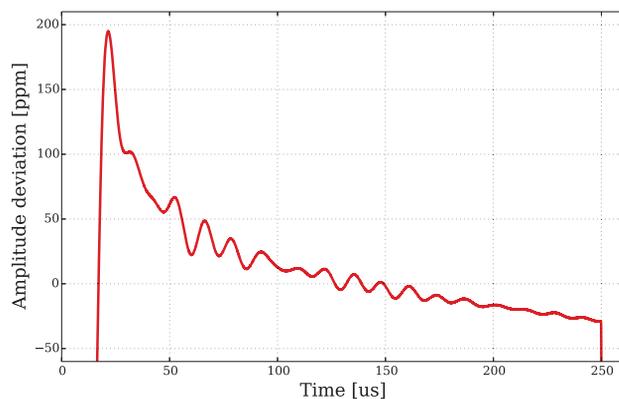


Figure 6: Output of the half-bridge circuit as the source current stabilises.



Figure 7: A photograph of the prototype.

deviation of 4.7 ppm. The largest measured deviation from the nominal current was 18.5 ppm

The prototype also includes additional features to accommodate the needs of the LHC bunch-by-bunch intensity measurement system. There are eight selectable output relays to allow a single source to calibrate multiple devices. The source can be triggered using one of the eight available trigger inputs, some of which have timings predefined on the hardware level. In order to protect the devices being calibrated from excessive power sent to their calibration inputs, each of the trigger signals passes through a hardware duty-cycle protection circuit which limits the average output current to 0.1 % of the nominal current. To allow the calibra-

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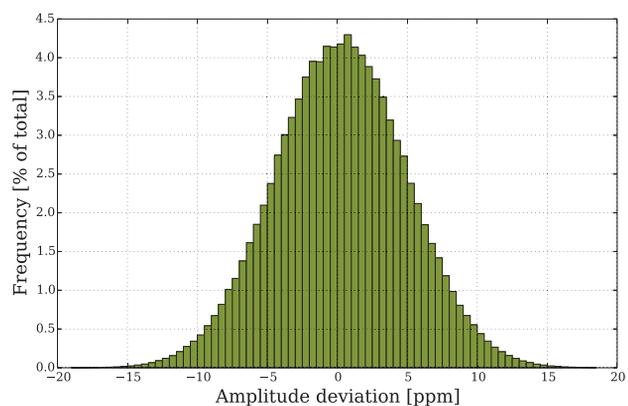


Figure 8: Current source stability measured with the half-bridge over a 24-hour period.

tion of different sensitivity ranges of the acquisition system, the prototype also includes an input for an external source and supports daisy-chaining multiple current sources.

## CONCLUSIONS

The pulsed current calibration circuitry described in this paper was originally optimised for calibrating the new bunch current measurement system in the LHC.

Laboratory measurements of a prototype show that the achieved absolute accuracy is limited to approximately 200 ppm (0.02 %) by tolerances of the components used and the decay of the output current, but is nevertheless exceptionally stable. The shot-to-shot stability has a standard deviation of only 4.7 ppm and the output current within 100 ppm of the nominal current after 32  $\mu$ s.

The current source and half-bridge circuits were optimised to be simple, stable and precise yet flexible enough so that the calibration current can be easily adjusted by replacing a few components. The number of performance-critical components was minimised making it an interesting choice for applications requiring a precise pulsed current generator.

## ACKNOWLEDGEMENTS

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