High accuracy beam current monitor system for CEBAF's experimental Hall A

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HIGH ACCURACY BEAM CURRENT MONITOR SYSTEM FOR CEBAF'S EXPERIMENTAL HALL A *

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Abstract

CEBAF accelerator delivers continuous wave (CW) electron beams to three experimental Halls. In Hall A, all experiments require continuous, non-invasive current measurements and a few experiments require an absolute accuracy of 0.2 % in the current range from 1 to 180 µA. A Parametric Current Transformer (PCT), manufactured by Bergoz, has an accurate and stable sensitivity of 4 µA/V, but its offset drifts at the µA level over time preclude its direct use for continuous measurements. Two cavity monitors are calibrated against the PCT with at least 50 µA of beam current. The calibration procedure suppresses the error due to PCT's offset drifts by turning the beam on and off, which is invasive to the experiment. One of the goals of the system is to minimize the calibration time without compromising the measurement's accuracy. The linearity of the cavity monitors is a critical parameter for transferring the accurate calibration done at high currents over the whole dynamic range. The method for measuring accurately the linearity is described.

1 INTRODUCTION

The CEBAF accelerator delivers continuous wave (CW) electron beams to three experimental halls. Most of the experiments need to measure the beam current with an absolute accuracy of about 1%. A few experiments in Hall A require an improved accuracy of 0.2% in the 1 to 180 µA dynamic range. Two cavity monitors equipped with linear, stable and low noise detection electronics require periodic calibrations against a parametric current transformer (PCT) manufactured by Bergoz (Crozet, France). The PCT is an absolute measuring device. However, its excessive offset drifts preclude its direct use for accurate current measurements. It is possible to calibrate the cavity monitors against the PCT with 50 µA or more beam current in a reasonable time (~1/2 hour). The good linearity of the cavity electronics allows accurate extrapolation of the result obtained at one current measurement to the whole dynamic range. The next sections describe the detailed design of the monitor, the errors contributing to the system performance, the high accuracy method used for measuring the linearity of the electronics and the results of the past few years of operation. In addition to beam current, the experiments require measurement of the beam charge. This necessitates additional circuitry with better timing precision than that of the current monitor.

2 SYSTEM DESCRIPTION

2.1 PCT related components

Figure 1 shows the beam line components, which consist of the toroidal PCT sensor, a cavity on its upstream side and a cavity on its downstream side. The PCT toroid is sensitive to the DC component of the magnetic field generated by the beam current around the beam pipe [1].

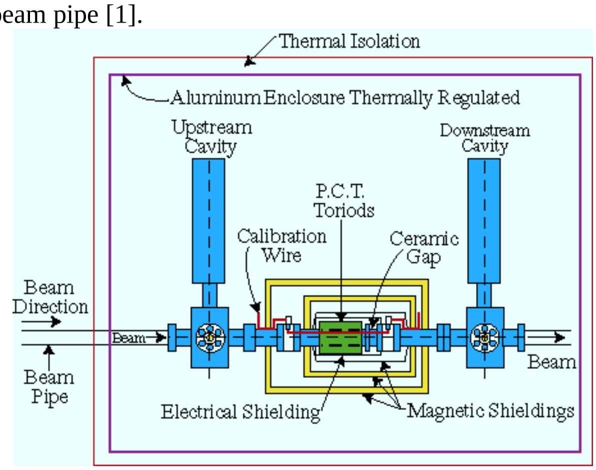

Figure 1. Current Monitor components on the beam line

A ceramic gap interrupts the beam pipe's conductivity and prevents any parasitic currents from flowing inside the toroid. Three magnetic shields, two of iron and the innermost one of µ metal, suppress the offset drifts due to external varying magnetic fields. A thermoregulated enclosure, surrounding the entire assembly, reduces further the PCT offset drifts. An electric shielding prevents the high frequencies of the beam spectrum from propagating outside the monitor from the ceramic gap. Absorbing materials prevent RF noise from reaching the sensor.

The PCT front end, which is two meters from the sensor, sends the signal to a remote unit located 50 m away in the counting house. The remote unit delivers to an HP34401A multimeter, used as a voltmeter, a DC voltage consistently equal to 4.000 mV per µA of beam.

By sending a DC current into a wire passing through the toroid (figure 1), one can periodically calibrate the PCT sensitivity. A Keithley current source sends a known

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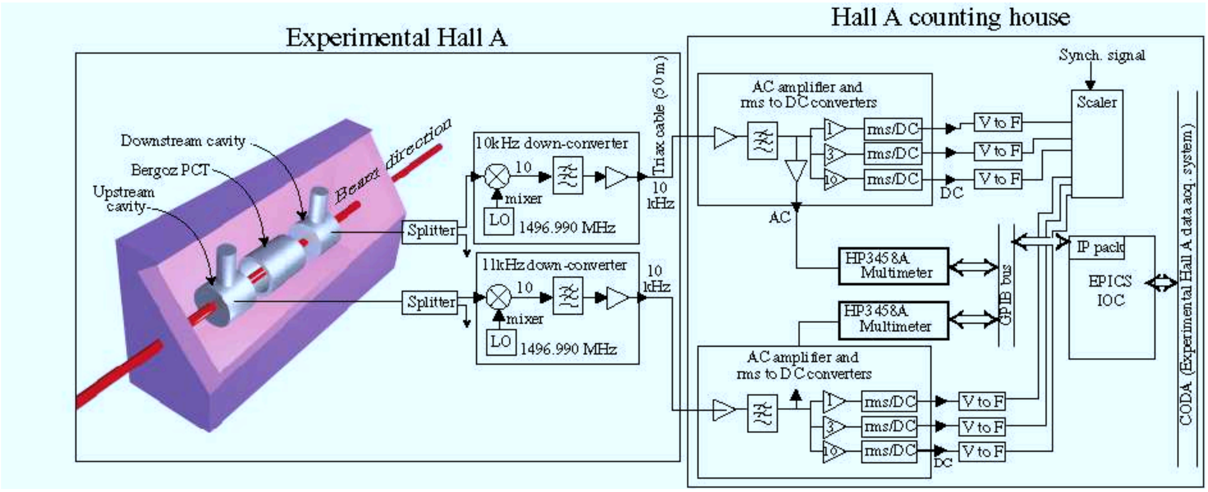

Figure 2: Cavity monitor block diagram.

intensity into the wire through a 50 m long triaxial cable. A HP3458A multimeter, whose accuracy is traced to NIST intensity standard, measures the current. The excellent linearity of the PCT allows calibrations at 2 mA. It is higher than the actual beam current, but improves the precision.

2.2 Cavity monitors

The two cavities are of pill box type, tuned on the 1497 MHz component of the beam current spectrum corresponding to the TE010 mode. This component does not depend on either the bunch length (< 1 ps) or the beam position (6 ppm error for a 5 mm off centered beam [2]). The cavities, made of stainless steel and critically coupled have a relatively low quality coefficient (Q ≈ 1500). The temperature stability of the system is ± 0.2˚C. Work related to the beam line vacuum may move the cavities out of tune, requiring tuning by means of a network analyzer.

Figure 2 shows the cavity monitor block diagram. 7/8" Heliax cables carry the cavity signals to their respective downconverters. The latter bring the signal frequency down to 10 kHz for accurate amplitude measurements. The downconverters and their Local Oscillators (LOs) have thermal stabilization. Belden 9222 triaxial cables connect the downconverters to the 10 kHz electronics located 50 m away in the counting house. The Heliax and triaxial cables were selected for their low attenuation resulting in negligible temperature effects. The 10 kHz electronics comprises an amplifier and a filter designed for a very flat response in the 9-to-11 kHz range in order to accommodate possible frequency drifts of the local oscillator (LO) and employs operational amplifiers and high stability resistors for gain stability.

The signal from each cavity monitor splits into two separate paths. The first leads the 10 kHz signal measured every 1.2 s to a high precision AC voltmeter (HP3458A multimeter) configured in "synchronous mode". Each measurement represents the current averaged during most of the 1.2 s. The other path comprises three sets of amplifiers of different gains, each followed by an rms-to-DC converter. These DC outputs cover the low, middle and high parts of the dynamic range and feed into Voltage-to-Frequency converters (V-to-F) and then, to scalers. The scalers (frequency counters) are fast; they provide a 20 µs timing accuracy. The scaler count is directly proportional to the number of periods between the start and the end triggers of a data run and ideally is proportional to the charge delivered during that time.

The accelerator's controls system (EPICS) asynchronously gathers data from the cavity monitors (two AC voltmeters) and the PCT (DC voltmeter) over GPIB bus. The Hall A experiment's data acquisition system, called CODA, reads the scalers as well as the EPICS cavity monitor and PCT signals. They are part of the experiment's data stream stored for off-line analysis.

3 ACCURACY AND CALIBRATION

3.1 Current measurements

Several sources of error, when added quadratically contribute to an uncertainty of ~ 3 10^{-4} to the PCT's measurements with respect to NIST intensity standard. The combined errors to the cavity monitor system's sensitivity drifts between calibrations (performed once or twice a month,) reach about 4 10^{-4}. The largest component comes from a combination of tuning uncertainty, cavity temperature variations, and barometric pressure changes. It amounts to a 12 kHz detuning uncertainty, corresponding to 3 10^{-4} error. These errors, as well as the non-linearity effects, are small compared to the reproducibility of the cavity monitor's calibrations. Calibration of the cavity monitors requires turning off and turning on the beam several times at one-minute intervals. The process is invasive to beam delivery to all experimental halls. It takes about ½ hour with a beam of at least 50 µA to reach better than 0.2% accuracy. The accuracy improves linearly with the current. The distribution of the calibration coefficients over the last few years indicates a global calibration accuracy of about 0.2%. Since the other sources of error, including the linearity effects, are negligible, this number is representative of the absolute accuracy of the cavity monitors from 1 to 180 µA.

3.2 Charge measurements

The total beam charge delivered during a physics run is the product of the sum of the beam current measurements and the measurement period. A standard physics run lasts between 0.5 and 1 hour. One or more beam delivery interruptions may happen during that time. When the beam goes off or comes on, the CODA's computer sees the interruption with a random delay that can amount to several seconds. This timing uncertainty translates into a charge error greater than the total error budget of 0.2%. Attempts at bringing down this error required three sets of rms-to-DC converters, V-to-F converters, and scalers. (see fig. 2.) The two latter components meet the required specifications but the rms-to-DC converter does not. Its linearity does not match that of the HP3458A voltmeter. Linearity measurements of the scaler outputs with respect to a faraday cup in the injector 5 MeV region have shown 0.5% error in the 1-to-120 µA current range. Another problem of the rms-to-DC converters is that their frequency response is not flat in the ±1 kHz range of LO drifts. A potential solution to this problem is to replace the LO with a synthesizer locked to the machine's master oscillator.

In reality, the continuous recording of the scalers, the cavity AC voltmeters and PCT voltmeter provides all the necessary information to achieve the desired accuracy. The naturally occurring beam interruptions provide the appropriate beam-on-to-off calibration steps for cavity and charge monitors (scalers). Low current experiments (< 50 µA) require an invasive calibration cycle at high current once or twice a month. Those experiments, using the scalers and voltmeters recordings, can make off-line corrections to the small rms-to-DC converter errors and slow drifts in order to bring the accuracy to 0.2%.

4 LINEARITY MEASUREMENT METHOD

Accurate non-linearity measurements at high frequencies are difficult. The usual method of switching an attenuator from input to output does not work in a system without physical output port. It would not be valid either for devices with different input and output frequencies, like downconverters. Instead, a 6 dB attenuator, whose attenuation does not need to be exactly known, is used. Its attenuation needs only to be constant during the measurement period. A measurement at a defined input level is done by switching the attenuator in and out of the input circuit; then one can compute the output level ratio for the two attenuator configurations. Performing the same operation at input levels 6 dB apart over the whole dynamic range produces a series of ratios. A perfectly linear system yields constant output ratios; it is usually the case for actual systems in the middle of their dynamic range. The method actually shows deviations from a response of the form $\log Vout = a * \log Vin$ equivalent to $Vout = Vin^{a}$. Thus for the method to be valid, the device under test must be intrinsically linear (a = 1) in its mid range. It is the case of the downconverter and amplifiers that constitute the cavity electronics. Figure 3 shows the linearity of one of the cavity electronics systems.

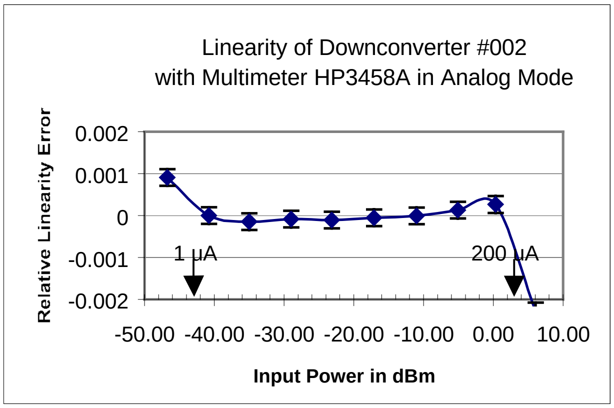

Figure 3: Linearity of one of the cavity current monitors

5 SUMMARY

A current monitor with 0.2% absolute accuracy has been in regular use in Hall A since February 1999. It includes two cavity monitors that are calibrated about twice a month with beam against a commercial reference (PCT current monitor). Additional circuits measuring the charge over 0.5 to 1 hour of beam delivery are accurate to 0.5%. Recording all the relevant signals as part of the experiment data stream allows retrieving the charge to the required accuracy of 0.2 %.

6 ACKNOWLEDGEMENTS

We thank Charlie Sinclair who initiated this project with his team [3].

7 REFERENCES

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