NEW ON-LINE GAIN DRIFT COMPENSATION FOR RESONANT CURRENT MONITOR UNDER HEAVY HEAT LOAD

P.-A. Duperrex*, M. Gandel, D. Kiselev, Y. Lee, U. Müller, PSI, Villigen, Switzerland

Abstract

For high intensity beam operation (3mA, 1.8MW) in the PSI cyclotron, a new current monitor for proton beams has been installed during the 2009 maintenance period. This current monitor is an actively cooled re-entrant cavity with its resonance tuned to the 2nd RF harmonic (101 MHz). The resonator is behind a graphite target and the heavy heat load due to the energy deposition of the scattered particles induces some large gain drifts.

An innovative scheme to measure on-line the actual resonator gain and to correct the current was developed. This compensation method is based on the measurement of two side-band pilot signals 52 kHz off the RF frequency.

This paper will present the measurement scheme and the achieved performances during beam operation.

INTRODUCTION

The newly installed proton beam current monitor called “MHC5” is located approximately 8 m behind a 4 cm thick graphite target used for muon and pion production. The resulting heat load from the target scattered particles is the main concern for this monitor. This problem will be even acuter for future high intensity beam operation (3 mA, 1.8 MW). For that reason, the new monitor has an active water cooling system, its surface was blackened to improve the radiation cooling and its mechanical structure was improved for better heat conduction.

Even with these improved cooling features, the MHC5 exhibited some anomalous gain drifts over ±10% during operation at high current (>1mA). For this reason, it was necessary to implement a drift compensation that could account for these dynamic changes.

RESONATOR AND HEAT LOAD

Measurement Principle

The current monitor consists of a re-entrant resonant system symmetric to the round proton beam pipe. The open-end gap in the beam pipe couples some of the wall current into the resonator. The resonator is tuned at 101.26 MHz, the 2nd harmonic of the proton beam bunch frequency. This harmonic is used because of the better signal-to-noise ratio, the RF noise components from the generator being mainly at the odd harmonics. No significant shape dependency of the 2nd harmonic amplitude for relative small beam pulses is expected [1]. The oscillating magnetic field in the resonator is measured using a magnetic pick-up loop, the signal being proportional to the beam current.

The resonance condition is given by:

$$\tan\left(\frac{2\pi L}{\lambda_m}\right) = \frac{\lambda_m}{2\pi\, c\, C\, Z_o}$$

with L the resonator length, c the speed of light, C the capacitor shunt, Z_o the characteristic impedance of the transmission line, and λ_m the resonant wavelength. Any change of the capacitor gap or resonator length will induce a drift of the resonance frequency

Mechanical Design

The monitor is made of aluminium (anticorodal 110), with a 10µm coating layer of silver to improve the electrical conductivity. It has an active water cooling system. The monitor itself being in vacuum, the external surfaces were chemically blackened to increase the emissivity of the monitor to provide an additional cooling.

Advantages of such devices are its relative construction simplicity and its ruggedness with respect to radiation. Disadvantages are its sensitivity to temperature and that it is not an absolute measurement; the signal has to be calibrated using another current monitor.

Heat Load Effects

The predicted heat load on the MHC5 due to the shower particles is about 230W for a 2mA [2]. Without water cooling, the monitor would easily reach 200^o C. Such heat load and high temperature change the resonance conditions of the monitor by modifying the shunt capacitor value and the resonator length.

For that reason, temperature bench tests have been performed before the installation of the monitor on the beam line. External resonant circuits have been added to compensate the temperature drifts. Gain drifts smaller than 0.3dB were measured for the expected temperature variations during beam operation (30 to 70 ^{o}C).

However, the observed gain drifts during operations are larger than those simulated on the test bench. These larger drifts are actually induced by the non-homogeneity of the power deposition, resulting in a non-uniform temperature distribution, deforming the resonator, shifting the resonance frequency and modifying the gain around the resonance frequency.

It was thus necessary to implement a drift compensation method that could account for these dynamic changes during beam operation.

---

*pierre-andre.duperrex@psi.ch

ON-LINE DRIFT COMPENSATION

Compensation Principle

A drift compensation scheme using a pilot signal 600 kHz off the designed resonator frequency was previously tested to investigate the potential of such a method [2].

The basic idea of this new on-line drift compensation scheme is to use 2 pilot signals ±52kHz from the RF 2nd harmonic (101.26MHz) to get an estimate of the resonator gain at the RF 2nd harmonic. The 2 pilot signals are feed into the resonator and measured using a second magnetic pick-up loop identical to the one used for the current measurement (see Fig.1). The frequency difference (52kHz) between the pilot signals and the beam signal is large enough to avoid interference with the standard current monitor electronics but small enough so that the average of the 2 pilot signals can provide a good estimate of the gain at the RF 2nd harmonic frequency.

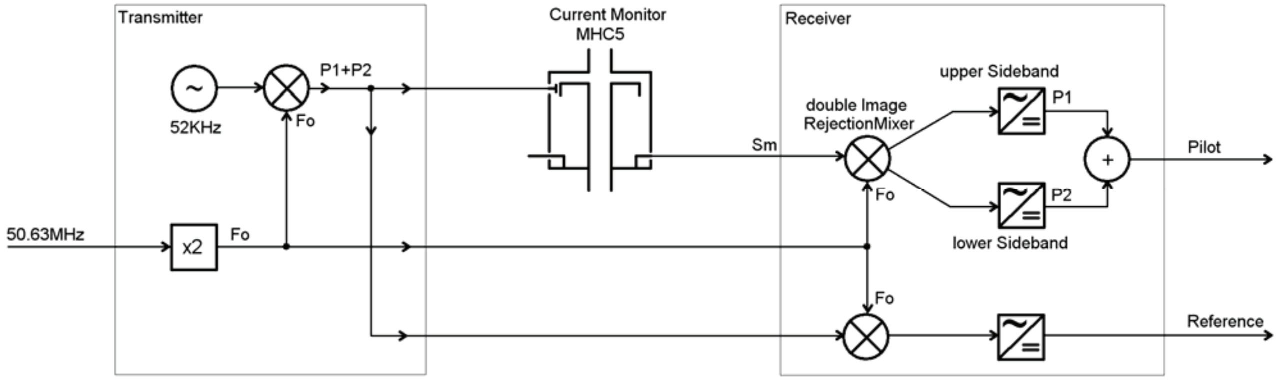

Figure 1: Schematic of signal measurements for the on-line drift compensation. A 52 kHz signal is mixed with the second RF harmonic and feed into the current monitor resonator. The signals are then measured using a double image rejection mixer. The ratio Pilot/Reference provides an estimate of the resonator gain.

Electronics and Signal Processing

A 52 kHz signal is mixed with the second RF harmonic generating two pilot signals 52kHz off the 101.26MHz frequency. The resulting signal is feed into the current monitor resonator (Fig.1). The pick-up signal is then measured using a double image rejection mixer, shown in Fig.2).

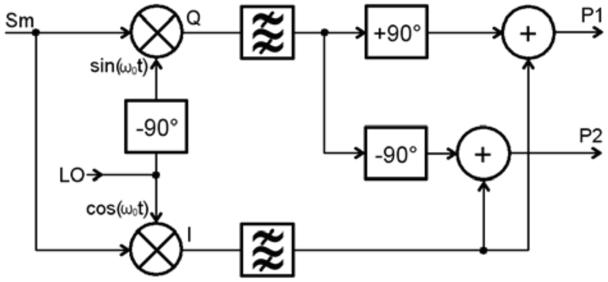

Figure 2: Details of the double image rejection scheme. The Q demodulated component is phase shifted and the resulting signals are recombined with the in-phase signal.

The pick-up signal S_m coming from the loop in cavity can be expressed as:

$$S_m = P_{10}.\cos(\omega_1.t+\phi_1)+P_{20}.\cos(\omega_2.t+\phi_2)+S_{beam}.\cos(\omega_0.t)$$

Where ω_o the angular frequency of the RF 2nd harmonic, $\omega_1=\omega_o-\Delta\omega$ and $\omega_2=\omega_o+\Delta\omega$ the angular frequency of the pilot signals, with $\Delta\omega$=52 kHz, P_{10} (resp. P_{20}) the amplitude of the first (resp. second) pilot signal and S_{beam} the amplitude of the beam signal.

After mixing down the signals with the image rejection, a 52kHz band-pass filter eliminates the undesired high frequency components and the beam signal contribution (DC component).

The resulting base-band in-phase (I) and quadrature phase (Q) signals are then:

$$S_I(t)=\frac{1}{2}P_{10}.\cos\left(\Delta\omega.t-\phi_1\right)+\frac{1}{2}P_{20}.\cos\left(\Delta\omega.t+\phi_2\right)$$

$$S_Q(t)=\frac{1}{2}P_{10}.\sin\left(\Delta\omega.t-\phi_1\right)-\frac{1}{2}P_{20}.\sin\left(\Delta\omega.t+\phi_2\right)$$

By introducing 90deg. phase shifts on the Q output:

$$S_{Q+90\deg}(t)=\frac{1}{2}P_{10}.\cos\left(\Delta\omega.t-\phi_1\right)-\frac{1}{2}P_{20}.\cos\left(\Delta\omega.t+\phi_2\right)$$

$$S_{Q-90\deg}(t)=-\frac{1}{2}P_{10}.\cos\left(\Delta\omega.t-\phi_1\right)+\frac{1}{2}P_{20}.\cos\left(\Delta\omega.t+\phi_2\right)$$

The two pilot signals can then be extracted:

$$S_I(t)+S_{Q+90\deg}(t)=P_{10}.\cos\left(\Delta\omega.t-\phi_1\right)$$

$$S_I(t)+S_{Q-90\deg}(t)=P_{20}.\cos\left(\Delta\omega.t+\phi_2\right)$$

That way, the upper-side and lower side part of the signal are separated. An average is then performed to estimate the level of a pilot signal at the RF frequency. The ratio Pilot/Reference provides an estimate of the effective calibration factor that can take into account the drifts due to the dynamic resonator gain changes.

RESULTS

Off-line Analysis

Before implementing the on-line drift compensation scheme in the accelerator control system, some off-line analyses were performed.

Figure 3 is an example of such analysis. The MHC5 new calibration method (red line) is compared with the one deduced from the MHC6 (blue line), another current monitor further down the beam. The MHC6 is not subject to such heat load and is very stable as far as the resonator is concerned. So, there was no need to implement such an on-line calibration scheme for the MHC6. By assuming that MHC5 and MHC6 are measuring the same current (the beam losses between them are considered to be small enough to be neglected), the MHC5 calibration factor can also be estimated and thus both estimate can be compared. At the time t=2.5days, the MHC5 cooling was switched off, the MHC5 temperature raised from 40 to 90^{o} C and the calibration changed by 30%. Even during this phase, the new scheme estimate matches the effective calibration changes.

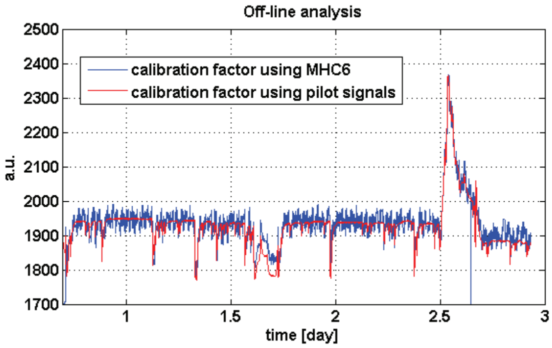

Figure 3: Off-line calibration. Even for a 30% variation, the calibration factor deduced from the pilot signals (red line) matches the one using MHC6, a second current monitor (blue line) further down the beam line.

On-line Results

Figure 4 shows the performance of the system as the calibration scheme was switched. Changes in the calibration parameter values for the MHV5 can be observed. These are due to cooling effects after a beam loss or smaller beam currents. The comparison between MHC5 and MHC6 measurements confirm that even for these condition changes (see the plotted ratio MHC5/MHC6) the current measurement shows improved stability.

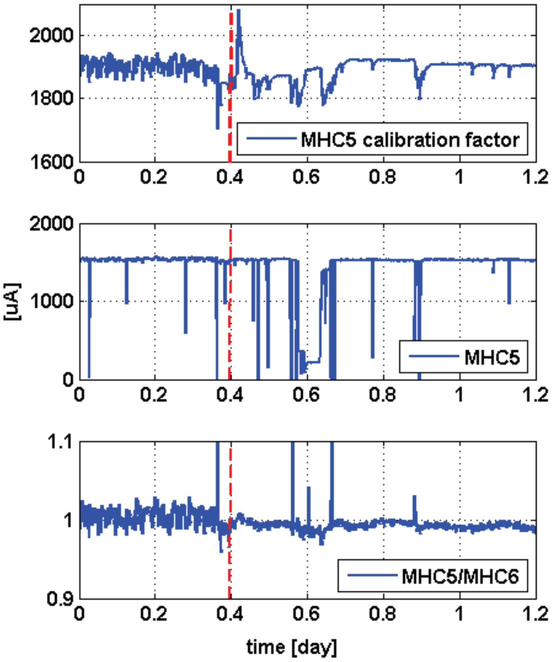

Figure 4: Transient behaviour of the new drift compensation scheme. At t=0.4day the on-line calibration is switched on. The ratio MHC5/MHC6 exhibits an improved stability.

CONCLUSION

Heavy heat load on the newly installed MHC5 monitor was a challenge for beam current measurements. The new on-line drift compensation using two pilot signals very close to the 2nd harmonic frequency provides accurate beam current measurement for different load conditions and transient beam conditions that could lead up to 30% changes in the resonator gain.

This innovative scheme may have wider applications where resonant systems are subject to uncontrolled drifts.

REFERENCES

[1] R. Reimann, M. Rüede, “Strommonitor für die Messung eines gepulsten Ionenstrahls”, Nucl. Instr. Meth. 129 (1975) 53.

[2] P.A. Duperrex, P. Baumann, S. Joray, D. Kiselev, Y. Lee, U. Müller, „Design and operation of a current monitor under heavy heat load” DIPAC’2009, May 2009, TUPD20, p.336 (2009).

[3] Y. Lee "Simulation based Analysis of the anomalous RF drifts of a Current Monitor at the PSI Proton Accelerator Facilities", MOPEC072 this conference.