DESIGN OF A NEW BEAM CURRENT MONITOR UNDER HEAVY HEAT LOAD*

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Abstract

At the Paul Scherrer Institute (PSI), a 590 MeV 50 MHz High Intensity Proton Accelerator (HIPA) has been operated for many years at 2.2 mA / 1.3 MW and it will be in future upgraded to 3 mA / 1.8 MW. Downstream from a target for pion and muon production is a beam current monitor, called MHC5. The thermal load in MHC5 induced by the scattered particles from the target causes its resonance to drift. Even with an active cooling system, the drift remains a problem.

A new beam current monitor has been designed to overcome this shortcoming. The mechanical design of the new monitor has been completed and manufactured. Different improvements have been implemented compared to the monitor in operation. For instance, graphite has been used as material for the resonator instead of aluminium to minimize the thermal expansion, a thermal self-compensation scheme has been implemented to counteract the frequency drift, its structural stability has been improved and the thermal load has been reduced. The design and the preliminary lab test results are presented in this paper.

INTRODUCTION

A proton beam current monitor called "MHC5" has been installed in the PSI 590 MeV proton cyclotron for several years. The MHC5 is a coaxial resonator tuned at 101.26 MHz, the 2nd harmonic of the proton beam pulse frequency. The magnetic field in the resonator is directly proportional to the beam current. It is located approximately 8 m behind a 4 cm thick graphite target used for muon and pion production. As a consequence, the monitor is exposed to scattered particles and their secondaries from this target and the resulting thermal load causes the resonance frequency to drift. For the current system, the variations of the system gain caused by the frequency drift are too large (10-20%) even with an active cooling system [1]. These drifts should be minimized. A new beam current monitor should be designed and aimed to future high intensity beam operation (3 mA, 1.8 MW).

PRELIMINARY SIMULATION

In order to have a good understanding of the performance of MHC5 in the beam tunnel, preliminary simulation about the monitor in operation was carried out by ANSYS.

The MHC5 in operation is made of aluminium (anticorodal 110), with a 10 μm coating layer of silver to improve the electrical conductivity. The monitor itself is in vacuum and the active water cooling keeps the resonator at an average temperature of about 50°C. Four thermocouples monitor the resonator temperature [2], as shown in Figure 1.

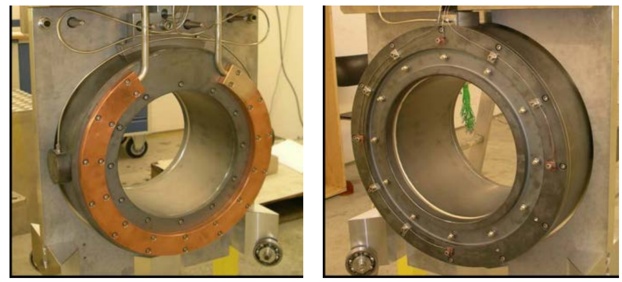

Figure 1: The MHC5 in operation, the pipe for water cooling at the beam entry side (left), the thermocouples installed on the beam exit side (right).

The energy deposition on MHC5 in operation under 3 mA proton beams is about 345 W, calculated by MARS [3]. The velocity and temperature of the cooling water is 1.91 m/s and 48°C, by which the convection coefficient can be calculated out, which is about 10500 W/(m^2·K). The ambient temperature in the tunnel is 50°C. The thermal distribution and deformation of MHC5 in operation as shown in Figure 2. The frequency drift of this case is 730 kHz.

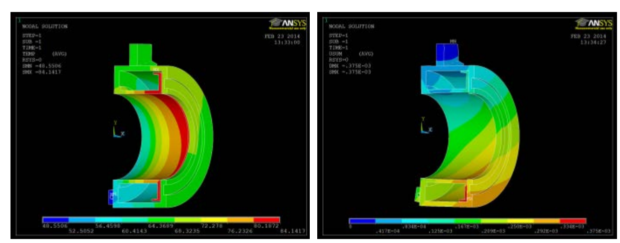

Figure 2: Thermal distribution (left) and thermal expansion (right) of MHC5 in operation with water cooling.

Causes of the Frequency Drift

In addition to the frequency drift due to the thermal expansion of the resonator, the thermal gradient due to the active cooling is making the shift larger. From simulation calculations (Figure 2), the peak temperature and the maximum expansion part are located at the inner part of the monitor. Inner parts have larger deformations than the outer parts because of the thermal gradient, which decreases the capacity gap and lead to additional resonance frequency drifts.

To reduce the frequency drift, it is therefore essential to minimize the deformations of the monitor. Thus the

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power deposition, the thermal expansion and the thermal gradient on the monitor have to be minimized.

MATERIAL SELECTION

A reduction of the thermal expansion can be achieved by selecting a material for the resonator that has a lower thermal expansion coefficient than the one of the existing resonator (anticorodal 110).

Graphite has been selected for this reason. It has a lower thermal expansion coefficient (see Table 1). Furthermore, it has a very high emissivity. As a result, the active cooling is no more required and the thermal gradient can also be strongly reduced.

Consider all the requirements graphite is selected to make the new MHC5. Table 1 compares the main properties of graphite and anticorodal 110. Compare to anticorodal 110 graphite has much higher emissivity, lower resistivity and lower thermal expansion coefficient.

Table 1: Main Properties of Graphite and Anticorodal 110

	Graphite	**Anticorodal 110**
Thermal expansion coefficient (K^{-1})	2.9e-6	23.4e-6
Emissivity	0.95	0.05
Electrical resistivity (Ω·m)	9.8e-6	3.5e-8
Thermal conductivity (W/(m·K))	129	162

The lower electrical conductivity might have been an issue if a high Q factor was required. In fact, it is not needed or even not desired. Since a high Q factor requires a high temperature stability. A mismatch between the resonance frequency and the beam harmonic frequency has a stronger impact on the resonator gain at the beam frequency. For instance, to achieve a gain variation lower than 2%, the shift range must be lower than 200 kHz if the resonator Q value is 100 whereas for a Q of 1000, the maximal shift is 20 kHz (see Figure 3).

Our goal is to reach a gain variation lower than 1% for a Q of ~150, which requires a maximum frequency shift of 100kHz.

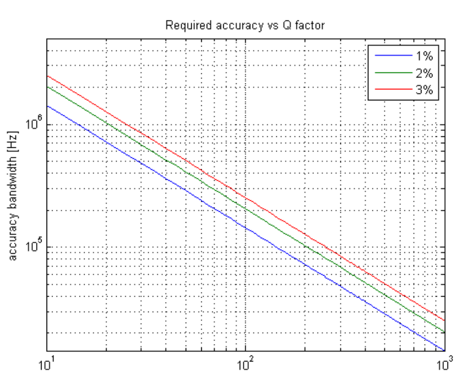

Figure 3: Required accuracy VS. Q factor.

DESIGN OPTIMIZATION

By simply replacing the aluminium by graphite and keeping otherwise the same design, the expected total power deposition on the graphite monitor is around 400 W. The calculated frequency drift in this case for a 3 mA proton beam is ~400 kHz, which is too large compared to a 100 kHz maximum limit. The thermal distribution of this case shows in Figure 4.

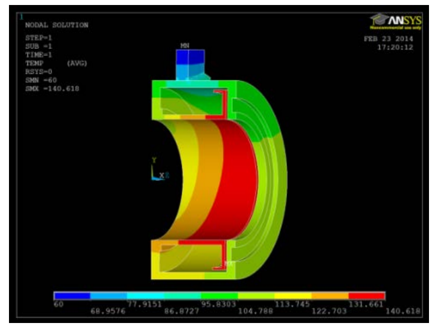

Figure 4: Thermal distribution of the graphite MHC5 with same dimension as the operation one (minimum Temperature: 60℃, maximum temperature: 140℃).

Power Load Reduction

The power load deposition has been reduced by increasing the inner diameter of the resonator. Indeed, the distribution of the scattered particles is Gaussian in transverse plane; that is, the number of scattered particles decreases with the radius. Therefore, increasing the inner diameter leads to a reduction of the power load. When the inner diameter of the MHC5 is increased from 255 mm to 280 mm, the corresponding power deposition is decreased from 400 W down to 169 W.

One thing should be pointed out, that the capacity gap of this case needed to decrease from 4.5mm down to 2.5mm to keep the same resonance frequency. This will make the manufacture more difficult, since the resonance frequency is very sensitive to the size of the capacity gap.

Self-compensation Scheme

The frequency shift is mainly caused by the thermal expansion of the resonator itself, a higher temperature leading to a low resonance frequency. One possible way to counteract this effect is to use a second material with much larger expansion coefficient in such a way to increase the capacitor gap (e.g. increases the resonance frequency) while keeping the other characteristics unchanged. This has been done by inserting a thin aluminium shim as shown in Figure 5.

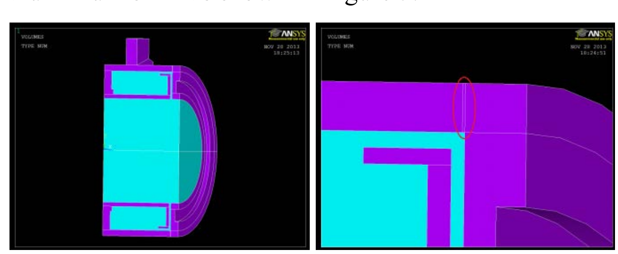

Figure 5: Position of the aluminium shim (red elliptical).

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For a case where the power load is 169 W the simulations with a 5 mm thick shim shows a frequency shift of 10 kHz compared to 200 kHz in the case without aluminium shim.

Capacity Gap Improvement

High permittivity material such as Ceramic (99.5% Al_2O_3) [4] can be used to fill in the capacity gap to increase the gap's size and while keeping the same resonance. This relaxes the mechanical tolerance as well as providing more rigidity to the capacitor plates.

Simulations with a ceramic ring and a resulting 6.1 mm capacitor gap indicate the frequency drift can be reduced to 8 kHz. The simulated thermal distribution is shown in Figure 6.

An advantage of using a ceramic plate between the capacitor plates is that the ceramic acts as a thermal bridge. It balances the thermal distribution between the inner and the outer parts, diminishing its gradient, thus proving a further stabilization effect as far the frequency shift is concerned.

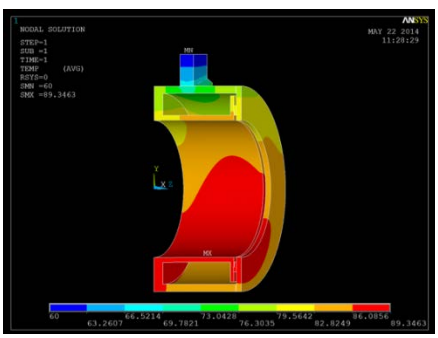

Figure 6: Thermal distribution of the final design.

FINAL DESIGN

Figure 7 shows the final model for the simulations, the capacity gap is set to 6.1 mm filled with a ceramic cirque (the red part) and the thickness of aluminium shim (the blue part) is 2 mm and with inner diameter 280 mm.

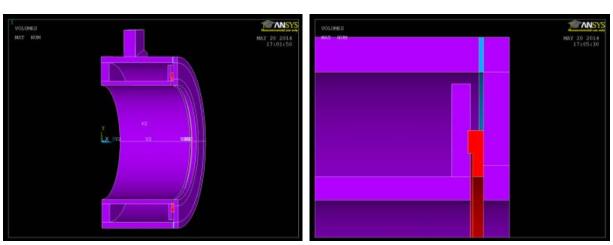

Figure 7: Half model over view (left) and details (right) of the new design of MHC5.

Combination of BCM and BPM

Beside the beam current measurements, 4 pickups have been mounted on the inside wall to measure the beam position, as shown in Figure 8(left). On the both side of the MHC5, 6 thermocouples in total are mounted to monitor the temperature of the MHC5. 8 tuning screws are used to do the fine tuning work, as shown in Figure 8 (right).

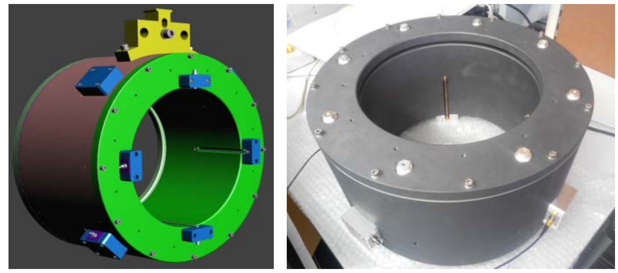

Figure 8: New MHC5 after mechanical drawing (left) and the new monitor lying in the lab (right).

FIRST LAB TEST

After the new monitor delivered to PSI, first lab test is carried out immediately. For the resonance frequency, the new MHC5 can be easily tuned to 101.26 MHz with 8 tuning screws (Figure 9). The Q factor in room temperature is 130 when a pair of small pickup loop (1 cm^2) are used and 92 when a pair of big pickup loop (13.5 cm^2) are used.

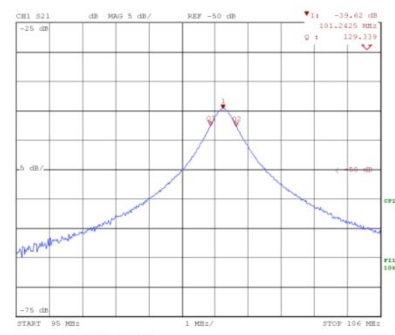

Figure 9: Result of the first lab test.

CONCLUSION

From our first lab test, the new beam current monitor made of graphite does have less frequency drift than the aluminium one. Further test is still going on and the new monitor will be mounted on the beam line next February, its performance will be checked then.

ACKNOWLEDGMENT

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