

# SIMULATION BASED ANALYSIS OF THE ANOMALOUS RF DRIFTS OF A CURRENT MONITOR AT PSI PROTON ACCELERATOR FACILITIES

Y. Lee\*, P.-A. Duperrex, M. Gandel, D. Kiselev, U. Mueller  
Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

## Abstract

A new current monitor (MHC5) based on a re-entrant cavity tuned at the 2nd RF harmonic (101.26 MHz) has been in operation since April 2009 at PSI. It monitors the current of the high intensity 590 MeV proton beam at 8 m downstream of the graphite meson production target (TgE). The scattered particles and their secondaries from TgE introduce a heavy thermal load approximately of 230 W on MHC5 at 2 mA beam intensity, which is carried away by active water cooling. The inhomogeneous temperature profile in MHC5 results in thermomechanical deformations which leads to a change in its HF electromagnetic characteristics. Indeed, anomalous RF drifts were observed during initial operations, which had to be compensated for, to obtain correct beam current monitoring. In this paper, the physics of the observed RF drift is analyzed by using advanced multiphysics simulation technologies.

## INTRODUCTION

A new current monitor (MHC5) has been in operation at the PSI high intensity proton accelerator since April 2009. The 3D model of the MHC5 system is shown in Fig. 1. However, the initial measurements of the beam current

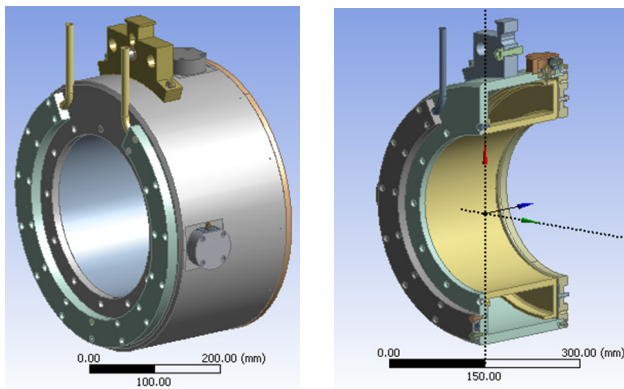


Figure 1: The 3D drawings of MHC5 with active water cooling (left). The cavity structure of the MHC5 is shown in the half-cut geometry (right). The proton beam comes from the left.

showed anomalous RF drifts, before it was electronically compensated for [1, 2]. In this paper, we investigate and analyze the cause of the observed anomalous RF drifts of the MHC5, using multiphysics simulation technologies.

\* yong-joong.lee@psi.ch

## MHC5 AS A RESONATING SYSTEM

### MHC5 as a resonating wave transmission system

The MHC5 is a resonating system which is tuned at the 2nd RF harmonic (101.26 MHz) of the proton beam at PSI. The intended RF is obtained by a short circuited coaxial waveguide system with an external shunt reactance connected to the transmission line.

The cavity volume of the MHC5 system is schematically illustrated in Fig. 2, in axis-symmetric view. The

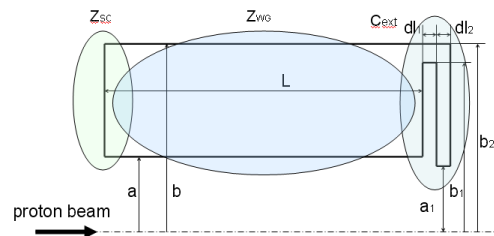


Figure 2: The sketch of the cavity volume of MHC5.

resonating transmission line model corresponding to Fig. 2 is shown in Fig. 3. The resonance occurs when

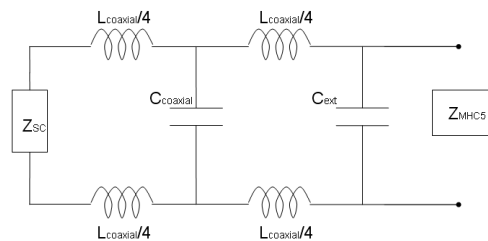


Figure 3: The resonating circuit concept MHC5. For short circuited coaxial waveguide,  $Z_{SC} = 0$ .

$\text{Im}[Z_{MHC5}] = 0$ , and the resonance condition for the RF  $f_{res}$  is given by

$$\tan\left[\frac{2\pi f_{res} L}{c}\right] = \frac{1}{2\pi f_{res} C_{ext} Z_{WG}}. \quad (1)$$

Here, the external capacitor  $C_{ext}$  is defined by the gap  $dl_2$  at the proton beam exit region and the  $Z_{WG}$  is the impedance of the loss free coaxial line of length  $L$  with its end short circuited [3],

$$Z_{WG} = j \frac{\sqrt{\mu_0/\epsilon_0}}{2\pi} \ln(b/a) \tan\left[\frac{2\pi f L}{c}\right]. \quad (2)$$

The resonance frequency  $f_{\text{res}}$  drifts to  $(1 + \beta_f)f_{\text{res}}$  when the geometric and circuit parameters are changed by

$$\begin{aligned} L &\rightarrow (1 + \beta_L)L, C_{\text{ext}} \rightarrow (1 + \beta_C)C_{\text{ext}}, \\ a &\rightarrow (1 + \beta_a)a, b \rightarrow (1 + \beta_b)b, \end{aligned} \quad (3)$$

for infinitesimally small fractional changes of  $\beta$  parameters. Up to the first order accuracy, one can deduce from Eqs. (1) and (3) the fractional drift of  $f_{\text{res}}$  given by

$$\beta_f = -\frac{2x\beta_L + \sin 2x\beta_C}{2x + \sin 2x} - \frac{\sin 2x \left( C_{\text{ext}}(\beta_b - \beta_a)\sqrt{\mu_0/\epsilon_0}f_{\text{res}} \tan x \right)}{2x + \sin 2x}, \quad (4)$$

where  $x$  is defined by  $x \equiv 2\pi f_{\text{res}}L/c$ .

### MHC5 as a resonating RF cavity

The HF modal simulation takes MHC5 as a resonating cavity with a small gap opening at the external capacitor side. Figure 4 shows a electric field configuration of the resonating MHC5 cavity volume, using ANSYS.

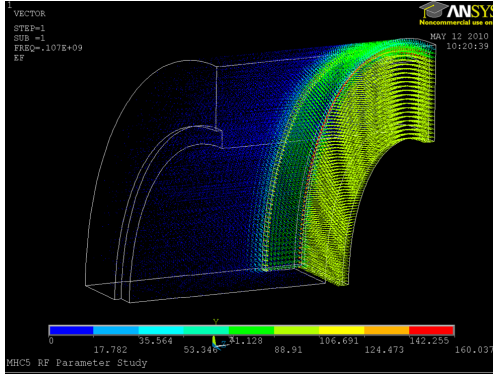


Figure 4: The calculated electric field vectors at RF. Different from conventional RF-cavities, the electric field energy density is concentrated in the  $C_{\text{ext}}$  gap zone.

The calculated RF at the reference room temperature 24 C is 107.02 MHz which is slightly higher than the target RF 101.26 MHz. The difference can be adjusted by fine tuning the gap  $dl_2$  only. Using Eq. (4) for  $\beta_L = \beta_a = \beta_b = 0$  and the relation  $\beta_C = -\delta dl_2/dl_2$ , one deduces that the intended fine tuning can be done by reducing  $dl_2 = 4.6$  mm by  $\delta dl_2 \simeq -0.6$  mm. This observation is qualitatively confirmed by HF electromagnetic simulations for different  $C_{\text{ext}}$  gap sizes  $dl_2$ , as shown in Fig. 5.

## UNIFORM THERMAL EXPANSION AND RF DRIFT

### Preliminary analysis

We consider small perturbations to electromagnetic and geometric parameters from the RF condition, as given by

**04 Hadron Accelerators**

**A15 High Intensity Accelerators**

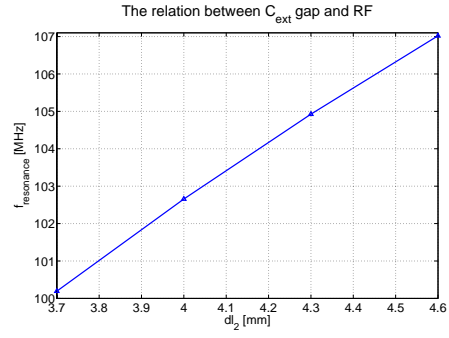


Figure 5: The calculated relation between RF and  $C_{\text{ext}}$  gap fine tuning. The intended RF of 101.26 MHz is obtained for  $\delta dl_2 = -0.8$  mm.

Eq. (3). Note that the geometric parameters  $L$ ,  $a$  and  $b$  have the dimension of the length, while the capacitor  $C_{\text{ext}}$  also has the dimension which is proportional to length. Therefore, if MHC5 expands uniformly due to homogeneous increase in equilibrium temperature by  $\Delta T$ , it is reasonable to take  $\beta_L = \beta_a = \beta_b = \beta_C = \alpha_{\text{MHC5}}\Delta T$ , where  $\alpha_{\text{MHC5}} = 2.34 \cdot 10^{-5} \text{ K}^{-1}$  is the thermal expansion coefficient of Anticorodal 110 which is the building material of MHC5. From Eq. (4), one then obtains the fractional change of the RF given by  $\beta_f = -\alpha_{\text{MHC5}}\Delta T$ . For  $f_{\text{res}} = 101.26$  MHz, this leads to

$$\frac{\Delta f_{\text{res}}}{\Delta T} = -2.37 \text{ kHz/K}. \quad (5)$$

### Measurements and numerical simulations

In a climate chamber, the MHC5 has been uniformly heated up to the equilibrium temperatures of 34, 44, 54 and 64 degrees [C] from the room temperature 24 C, and the corresponding RF drifts have been measured for three different fine tunings of the RF settings. The equivalent laboratory condition has been then set up for the thermal and stress simulations, in ANSYS. The calculated thermal deformations are then used for HF electromagnetic simulations, in order to calculate the associated RF drifts. For tested temperatures, the measured and the simulated differential RF drifts  $\Delta f_{\text{res}}/\Delta T$  are compared in Table 1, in the unit of [kHz/C]. In calculating thermal deformations, two

Table 1: The differential RF drifts  $\Delta f_{\text{res}}/\Delta T$  obtained from climate chamber tests and numerical simulations.

$T_{\text{eq}}$	test #1	test #2	test #3	sim #1	sim #2
34	-8.3	-8.5	-8.3	-3.0	-8.7
44	-7.5	-10.3	-8.8	-2.5	-7.4
54	-6.0	-8.0	-8.0	-2.6	-8.3
64	-6.8	-8.5	-7.0	-1.9	-8.0
Avg.	-7.1	-8.8	-8.0	-2.5	-8.1

boundary conditions (BC) are used, the first with freely expanding MHC5 boundaries (**sim #1**) and the second with

the flat surface at the beam entry side fixed (**sim #2**). The BC setting **sim #2** agrees with the measured differential RF drifts well, whereas the setting **sim #1** confirms the theoretical estimation given by Eq. (5).

## NONUNIFORM THERMAL EXPANSION AND ANOMALOUS RF DRIFT

Based on the particle power deposition calculated from MARS [4], thermal simulations have been performed for MHC5, using ANSYS and CFX. The thermal simulations underestimate the temperatures at the thermocouple locations by approximately 1 C; for details see Ref. [4]. The calculated temperature configurations are then used for mechanical simulations. Figure 6 shows the calculated temperature and the horizontal deformations of MHC5 at 1.32 mA proton beam intensity, where the reference temperature is taken to be 22 C.

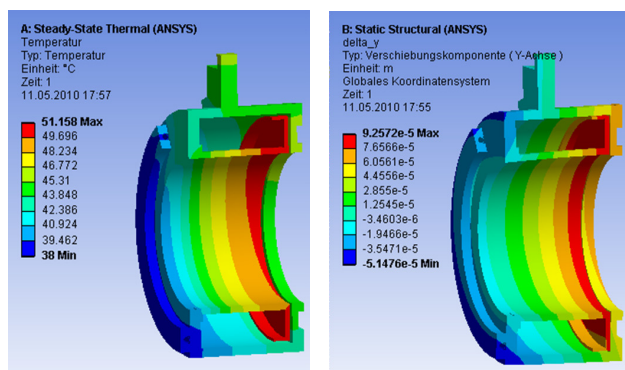


Figure 6: The calculated temperature (left) and the horizontal deformation (right) of MHC5 at 1.32 mA.

It is seen from Fig. 6 that the temperature at the inner cylinder is higher than that at the outer disk. This is mainly due to the fact that this region is exposed to higher particle energy deposition. Active water cooling also contributes to the inhomogeneous temperature distribution.

The deformed geometries for different beam loads are used for HF electromagnetic modal calculations. Table 2 presents the calculated RF drifts of MHC5 for different proton beam currents, where the  $T_{TC}$  represents the temperature at the thermocouple site. For the temperatures 22

Table 2: The calculated differential resonance frequencies  $\Delta f_{res}/\Delta T$  of MHC5, for different proton currents  $I_p$ .

$I_p$ [ $\mu$ A]	$T_{TC}$ [C]	$T_{min}$ [C]	$T_{max}$ [C]	$f_{res}$ [MHz]	$\Delta f_{res}/\Delta T_{TC}$ [kHz/C]
0	22.0	22.0	22.0	107.02	-
0	38.0	38.0	38.0	106.89	-8.44
440	39.9	38.0	42.3	106.78	-53.7
880	42.1	38.0	46.8	106.70	-38.6
1320	44.3	38.0	51.2	106.59	-50.0
1760	46.5	38.0	55.5	106.49	-43.2

C and 38 C, uniform temperature distribution is taken. The  $\Delta f_{res}/\Delta T_{TC}$  obeys the calculated value **sim #2** in Table 1. Once the beam is switched on, the MHC5 temperature begins to rise above the cooling water temperature 38 C, and the inhomogeneous temperature fields are developed. This results in about factor 5 larger values of  $\Delta f_{res}/\Delta T_{TC}$  than the ones measured from the climate chamber tests summarized in Table 1.

The calculated anomalous RF drifts can be understood as follows. Assume that the temperature drift at the outer and inner cylinders are given by  $\Delta T_{TC}$  and  $\Delta T_{max}$ , respectively. From the relation between  $T_{max}$  and  $T_{TC}$  listed in Table 2, it is reasonable to set  $\Delta T_{max} = 2\Delta T_{TC}$ . Under such unequal temperature drifts, one can deduce that the  $C_{ext}$  gap  $dl_2$  undergoes the thermal deformation  $\Delta dl_2$  which is approximately given by  $\Delta dl_2 \simeq -\alpha_{MHC5}\Delta T_{TC}L$ . At 2 mA, a rough estimation gives  $\Delta dl_2 \simeq -3.6 \cdot 10^{-5}$  m. Using the relation between  $dl_2$  and  $f_{res}$  shown in Fig. 5, this corresponds to  $\Delta f_{res}/\Delta T_{TC} \simeq -28$  kHz/C. This agrees with the results presented in Table 2, qualitatively.

## CONCLUSIONS AND OUTLOOK

The anomalous RF drifts of the new current monitor MHC5 at PSI high intensity proton accelerator has been analyzed. A number of CFD, thermal, stress and HF electromagnetic simulations has been performed, using ANSYS. The calculated RF drifts from the HF modal simulations are consistent with the bench tests and the circuit analysis of the coaxial waveguide with external shunt capacitance. The observed anomalous RF drifts monitored during beam operations are due to the non-uniform thermal expansions in MHC5, which is caused by non-uniform particle energy deposition and active water cooling.

As further steps, the topics on the impact of the RF drifts on the signal amplitudes and the effect of the q-factor on the signal stability will be investigated. Also, the dynamic characteristics of the thermomechanically induced RF drifts will be analyzed.

## REFERENCES

- [1] P.-A. Duperrex, P. Baumann, S. Joray, D. Kiselev, Y. Lee, U. Mueller, "Design & Operation of a Current Monitor under Heavy Heat Load," Proc. DIPAC 2009, Basel, Switzerland, p. 336 (2009).
- [2] P.-A. Duperrex, M. Gandel, D. Kiselev, Y. Lee, U. Mueller, "New on-line gain drift compensation for resonant current monitor under heavy heat load," Proc. IPAC 2010, Kyoto, Japan, MOPE063 (2010).
- [3] F. R. Connor, "Wave Transmission," Edward Arnold Ltd., London (1972)
- [4] Y. Lee, P.-A. Duperrex, D. Kiselev, U. Mueller, "A Simulation based thermal Design of a New Current Monitor at PSI Proton Accelerator," Proc. PAC 2009, Vancouver, Canada, p. 1272 (2009).