DESIGN OF BPM PU FOR LOW-BETA PROTON BEAM USING MAGIC CODE

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Abstract

We have designed the BPM PU based on capacitive buttons for use in the KOMAC (Korea Multi-purpose Accelerator Complex), the high-intensity proton linac that are under development at the KAERI (Korea Atomic Research Institute), Korea. The KOMAC is aiming to produce CW 20-mA beam current at the 100-MeV energy. We have chosen the button-type PU since it is easier to fabricate than other type PUs including the stripline, and it could provide enough signal power because of the high beam current. The PU sensitivity was calculated by the MAGIC that is a kind of the Particle-In-Cell code that originates from the plasma science community. The utilization of the MAGIC code is especially useful for BPM PUs in the low-beta sections of the accelerator, because it is difficult to obtain the PU sensitivity experimentally due to the difficulties in simulating the low-beta beams by the electromagnetic waves in a test bench. In this presentation, we report on the design of the BPM PU based on the MAGIC calculation.

1 INTRODUCTION

Front-ends of modern HPPAs (High-Power Proton Accelerators), such as RFQs and DTLs are generally complex and have tight installation spaces. This is especially true for diagnostic devices, and their design and installation often become designer's "nightmare." Meanwhile, diagnostics including BPMs and CTs are very important for successful commissioning and operation of the accelerators. Hence, their implementation should be considered from the early stage of the accelerator design. Successful compromise between the two conflicting side is possible when the diagnostic devices can be made compact without sacrificing their performances. Compact devices are easy to handle, economical, and generally have better high-frequency characteristics. Modern beam diagnostic devices are far more compact than their ancestors. For example, some CTs from the Bergoz Instrumentations are now integrated with CF flanges and their total length (axial) can be made as small as 30 mm. Majority of BPM PUs (Pick-Ups) for proton accelerators are still striplines that yield well defined response even for low-intensity beams. But their sizes are still too big to be installed in the narrow front-ends the accelerator. For example, the axial length of the striplines for the SNS (Spallation Neutron Source, USA) linac exceeds 100 mm, even if they are installed in the vacuum. Button-type capacitive PUs have been simple and reliable, but their application to the proton machines has been limited because of their insufficient response to low-intensity beams. Modern HPPAs (High-Power Proton Accelerators) such as the KOMAC are designed to have very high beam intensities, so that even the buttons could generate enough signals for precision beam position measurements. Refer to Table 1 for the major beam parameters of the KOMAC accelerator.

Table 1: Beam parameters of KOMAC accelerator

	Operation Mode		note
	CW	Pulse	
Beam Energy	3 - 20 - 100 MeV		BPM operation region
β	0.08 - 0.20 - 0.43		
V	1.003 - 1.021 - 1.107		
Average Beam Current (Iav)	Max 20 mA	Peak 20 mA	
Pulse Width	-	Few ms	
Bunch Length	160ps		PARMILA simulation result
Bunching Frequency	350 MHz		

In this context, we have chosen the button-type PU for use in the KOMAC accelerator. One of the disadvantages of the buttons is that, it is difficult to predict the PU sensitivity using analytic formulas. In fact, the PU sensitivity for low-beta beams can not be practically determined even by experimental methods, due to the difficulty of simulating electromagnetic fields from the low-beta beams. In this regard, we have decided to utilize the computer code for determining the sensitivity of the button-type PU. We have chosen the MAGIC code which is a kind of the PIC (Particle-In-Cell) code and can treat the particle and electromagnetic system in the full three dimensional manner.

2 THEORETICAL CONSIDERATIONS

The theoretical estimation of the sensitivity of stripline PU was established by R. E. Shafer.[1] He found the sensitivity of the stripline PU as the dB ratio of the wall currents induced at two opposite electrodes that are parts of a cylindrical beam pipe and extend infinitely in the axial direction. Here we only quote the result. The dB ratio is given by,

$$\left(\frac{I_{WR}}{I_{WL}}\right)_{dB} = \frac{160}{Ln(10)}(1+G)\frac{\sin(\varphi/2)}{\varphi}\frac{x}{b}+O(x^2) \qquad (1)$$

where, the G is approximately,

$$G = 0.319\left(\frac{\omega b}{\beta\gamma c}\right)^2 - 0.0145\left(\frac{\omega b}{\beta\gamma c}\right)^3 \qquad (2)$$

and, φ = electrode width,
b = radius of beam pipe,
x = beam position,
ω = angular frequency,
β = particle velocity (v/c),
γ = the beam energy,
c = velocity of light.

Note that for highly relativistic beams, G = 0, and the PU sensitivity depend only on the PU geometry. One of the main features of Eq. (1) and (2) is that the PU sensitivity depends on the beam energy and the processing frequency.

Shafer's theory is useful for estimating the PU sensitivity as the function of the beam energy, the frequency, and other parameters. One of major limitations of the theory is that it can not be applicable to general three dimensional geometries, such as the button-type PU. There are commercial electromagnetic codes that can simulate 3D geometries, including the MAFIA T3. The MAFIA T3 can handle only ultra-relativistic particles and can not be applied to low-beta beams. (The port boundary of the MAFIA T3 can accept only TEM mode whose phase velocity is equal to that of the light. And low-beta beams generate fields that are not in the simple TEM mode.)

3 MAGIC SIMULATIONS

The limitations of the Shafer's theory and the MAFIA code have led us to consider on using the MAGIC code. It is versatile and can handle arbitrary combinations of particle beams and electromagnetic structures. Like the MAFIA T3, the MAGIC also can not match the wide-band beam fields to its port boundaries. Without the proper matching of the wave fields at the port boundaries, we get many oscillations in the simulation output that will deteriorate the reliability of the simulation results. In order to circumvent this difficulty, we have utilized lossy medium placed close to the ports that absorbs incident waves. The position of the lossy objects and the ports can be made far from the region of major interests in the simulation without distorting the physical reality.

Fig. 1 shows the 3D model of the button PU for the MAGIC simulation and its cross-sectional view in the transverse plane. In the left figure of Fig. 1, proton bunches travel left-to-right direction. Beam signals are coupled to the four buttons that are installed around the circumference of the beam pipe. Buttons are connected to 50-ohm coaxial lines whose dimensions are different from those of usual fabrication. This simplified the simulation geometry without sacrificing reliability of the simulation.

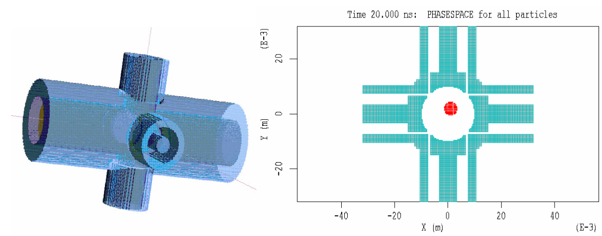

Figure 1: Modelling of button-type PU for MAGIC simulation. Left figure: 3D model, Right figure: Cross-sectional view. Dot inside beam pipe in right figure indicates proton beam. Diameter of beam pipe is 20 mm.

Default beam parameters used in the simulation are shown in Table 2. The left figure of Fig. 2 is the voltage waveform developed between the inner and outer conductors of the coaxial line. As expected, they are considerably longer than the beam bunch length, which is due to the axial extension of fields from the low-beta beams. (β = 0.08 for E = 3 MeV) With increasing the beam energy, beam fields concentrate in the transverse plane, and the pulse widths of signals coupled to buttons are shortened approaching that of charge distribution in the beam. This is shown in Fig. 4 which is the signal waveform for the beam energy of 100 MeV. Compare this with Fig 2.

Table 2: Default beam parameters used in MAGIC simulation.

Beam Energy	3 MeV
Average (Peak) Beam Current	20 (570) mA
Bunching Frequency	350 MHz
Bunch Length	43 ps rms

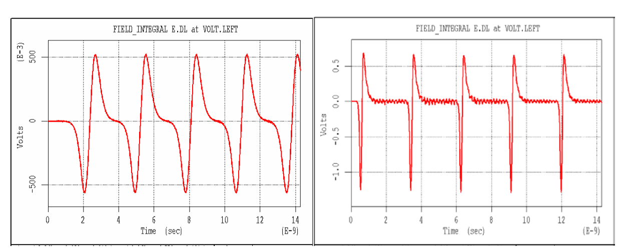

Figure 2: Waveforms of voltage signal developed at the end of one of coaxial lines for beam energies of 3 MeV (left) and 100 MeV (rght).

The contour plot of longitudinal electric field (Ez) and the vector plot of (Ex, Ez) are shown in Fig. 3. They clearly show the longitudinal extension of the field due to the low-beta beam.

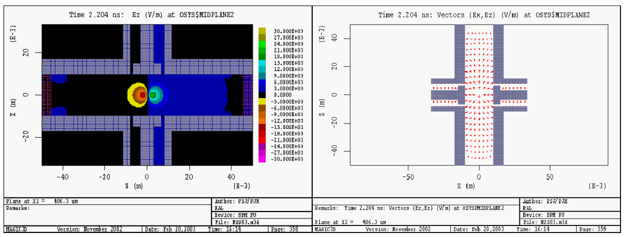

Figure 3: Contour (left) and vector (right) plots of electric fields showing their longitudinal extension. Right figure is rotated by 90 degrees with respect to left one.

The dependence of the PU sensitivity on the beam energy was simulated with result shown in Fig. 4. As expected from the Shafer's theory, the sensitivity increases dramatically with decreasing the beam energy. It also increases with increasing frequency at low energies but converge to the same value at high energies.

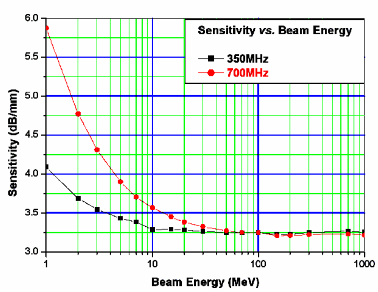

Figure 4: Dependence of PU sensitivity on beam energy.

Sensitivity of the PU to beam position change was simulated by moving the beam in the transverse plane in the step of 1 mm. The sensitivity map was obtained by plotting the delta-over-sum values of band-pass filtered voltage signals appearing at the ends of the coaxial lines. The center frequencies and bandwidth of the band-pass filter were 350 or 700 MHz and 20 MHz respectively. See Fig. 5 for the sensitivity maps for the frequencies of 350 and 700 MHz.

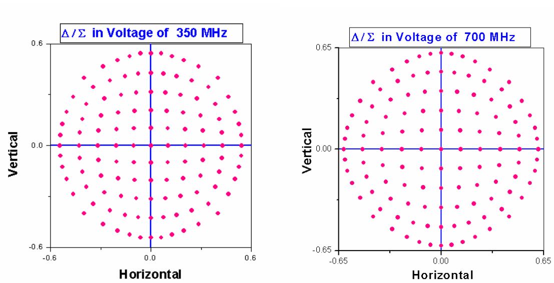

Figure 5: Sensitivity map of button PU at the frequencies of 350 and 700 MHz. Beam pipe diameter = 20 mm. Button diameter = 12 mm. Beam energy and beta are 3 MeV and 0.08 respectively.

Note that the sensitivity for 700 MHz was about 7.5% larger than that of the 350 MHz.

In order to confirm the validity of the MAGIC simulation, we have simulated the BPM PU of the PLS (Pohang Light Source). The PU consists of four buttons with 9.5-mm diameter installed in vacuum chamber that has diamond-like cross section. Table 3 compares some of simulation results with experimental measurements. Beam parameters used in the simulation are; Beam energy = 2.5 GeV, Average (Peak) current = 200 (1600) mA, Bunching frequency = 500 MHz, Bunch length = 26 ps. The measured signal amplitude may contain substantial errors due to our rough estimation of the cable attenuation for the wide-band pulses. Simulated sensitivity values needs further refinement with finer meshes.

Table 3: Comparison between MAGIC simulation and experimental measurement results of PLS BPM PU.

		Simulation	Measurement
Signal Amplitude (V)		5.5	3
On-center Sensitivity (%/mm)	X	6.6	6.15
On-center Sensitivity (%/mm)	Y	7.7	6.13

4 CONCULSION

We conclude this article with the following summarizing remarks:

1. A button-type PU for use in the KOMAC (Korea Multi-purpose Accelerator Complex) accelerator was designed.
2. Electrical performance of the PU was simulated by the MAGIC code.
3. Dependence of the PU sensitivity on the beam energy and the frequency well corresponded to the theoretical predictions.
4. Simulation results of the PLS (Pohang Light Source) electron BPM PU reasonably agreed to the experimental measurements.
5. The MAGIC code is versatile and useful for designing and simulating delicate aspects of BPM PUs.

6 REFERENCES

[1] R. E. Shafer, "Sensitivity of PUs for low beta beams," Proc. of the BIW93.