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BPM FOR THE HIGH ENERGY BEAM TRANSPORT LINE OF MINERVA PROJECT AT SCK-CEN*

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Abstract

MYRRHA will be a research infrastructure highlighted by the first prototype of a sub-critical nuclear reactor driven by a 600 MeV particle accelerator (ADS). This project aims to explore the transmutation of long-lived nuclear wastes. A first phase is planned to validate the reliability of a 100 MeV-4 mA Protons LINAC carrying the beam toward an ISOL facility, prefiguring the real MYRRHA demonstrator at 600 MeV [1]. This project is called MINERVA [2]. The conception of the high energy beam transport lines (HEBT) at 100 MeV has been studied [3]. This paper presents the status of the studies on a new analytical model BPMOK allowing Beam Position Monitor (BPM) optimizations. The model has been validated by experimental measurements in the installations IPHI at CEA at Saclay and SPIRAL2 at GANIL at Caen. BPMOK is applied to optimize the HEBT's BPM based on the BPM developed for the MINERVA LINAC.

Our objective is to optimize the BPM for the HEBT in order to keep the same acquisition electronics as the BPM for the LINAC.

INTRODUCTION

The high-energy beam transport (HEBT) of MINERVA needs non-interceptive diagnostics to measure beam characteristics. The beam orbit correction will use Beam Position Monitor (BPM). The BPM selected is a button type electrostatic pick-up. This detector measure the charges induced by the electric field of the beam particles on an insulated metal plate [4]. For this purpose, four pick-up plates are mounted crosswise at the beam pipe wall. The beam position (centre-of-mass) is deduced with the difference signals of opposite plates for both transverse planes.

Beyond the beam position, these BPM devices allow us to measure beam energy, beam ellipticity and the beam current. This work describes the studies on the BPM selected for the HEBT of MINERVA, aiming to realise parametric studies and to optimize the BPM sensitivity for a 100 MeV Proton beam.

Usual analytical model for BPM button type simulation use multiple strong hypothesis as considering only the first order in calculations, a pencil beam or relativistic beam ($\beta \approx 1$) [4]. In low beam speed ($\beta < 1$ and $\beta < 2\omega a/\gamma c$), relativistic correction are required [5], with ω the frequency component used, a the BPM radius aperture, c the light velocity in the vacuum and γ the Lorentz factor.

Existing software as CST Wakefield solver [6] allows realizing BPM design. CST can calculate the output voltage of BPM's electrodes. The Wakefield solver of CST does not take into account the transverse size of the beam. Also, needed meshcell refinement may increase the calculation time. CST can be time consuming in the range of hours or days depending on the geometry of the problem, mesh cells, needed accuracy and the available hardware.

We present a new analytical approach called BPMOK (Beam Position Monitor Optimization Kraft). This model doesn't need the usual strong hypothesis to calculate the output voltage of the electrodes of a BPM button type. BPMOK is faster than CST by a factor from 10 to 1000 depending the configuration in the CST calculations. Our model takes into account all the important parameters: the geometry of the BPM and the beam characteristics. BPMOK calculates the frequency components of the electrodes's output voltage of button types BPMs.

We were able to compare BPMOK calculations with our experimental results carried out at IPHI at CEA Saclay and at GANIL/SPIRAL2 in Caen. This allowed us to propose an optimized design of such BPM for the HEBT of the MINERVA project.

THE MODEL BPMOK

The main principle of BPMOK is evaluating the electric field map generated by a Gaussian beam (cf. eq. 1), superposed for a train of bunch repeated at the frequency F_{acc}, going through the BPM. The field is calculated at each point M(x,y,z) to the electrode surface (cf. Fig.1).

$$\begin{cases} E_r(M) = \frac{\gamma q e}{4\pi\varepsilon_0}\sum_k \iiint f_k \frac{x(x-x_0)+y(y-y_0)}{a} dx_p dy_p dz_p \\ f_k = \frac{N\,(2\pi)^{-3/2}}{\sigma_x\sigma_y\sigma_z}\frac{\exp\left[-\frac{1}{2}\left(\left(\frac{x_p-x_0}{\sigma_x}\right)^2+\left(\frac{y_p-y_0}{\sigma_y}\right)^2+\left(\frac{z_p-z_0}{\sigma_z}\right)^2\right)\right]}{\left[(x-x_p)^2+(y-y_p)^2+(\gamma z-z_p+k\gamma L_{acc})^2\right]^{3/2}} \end{cases} \tag{1}$$

With γ the Lorentz factor, qe the charge of the particle, (x_0, y_0) the position of the beam in the transversal plane, a the aperture radius of the BPM. k the index representing the number of the bunch around the central bunch $k \in [-N_{bunchs};\ +N_{bunchs}]$. f_k is a contribution function of partition for a Gaussian beam at the point M. N is the number of particles in the bunch. σ_x, σ_y and σ_z are respectively the beam RMS size on each plane. x_p, y_p, and z_p are the coordinates of the particles in the bunch. $L_{acc} = \beta c/F_{acc}$ is the distance between 2 successive bunch along the beam axis.

The electric field map is translated with the beam velocity and integrated on the electrodes surfaces (cf. Fig. 1). The limit condition is a field normal to the surface. This integration gives the amount of induced charges in function of the time and so the output of induced charges in function of the time and finally the output voltage of the electrodes. Once the temporal signal is generated, BPMOK calculate the frequency components of the signal using a Discrete Fourier Transform (DFT). BPMOK has a modular structure and can be easily modified. The signal transmission in

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coaxial cables and attenuation or amplification systems can also be included [7].

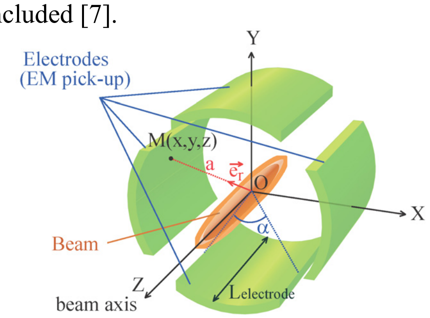

Figure 1: Scheme of the BPM and the position of the point M on the electrode's surface where the field induced by the beam is integrated.

MEASUREMENTS AT IPHI

IPHI is a prototype of high intensity RFQ at CEA Saclay. It accelerates a Proton beam at 3 MeV up to 100 mA with a bunch repetition frequency F_{acc} = 352.21 MHz. After its RFQ, the beam is transported by a direct line toward a beam dump or by a deviated line toward an experimental use. The measurements has been done with the BPM situated in the direct line at 450 mm before its Wire Scanner [8]. The BPM of IPHI is installed transversally pivoted by 45°. The coaxial cables has been characterised on site with a VNA to evaluate the transmission signal from the BPM to our oscilloscope. The output signal has been recorded with a 4 ps time step. A DFT of the signal gives the first harmonic component. For a single pulse (set of data), the beam presented sight transverse instability which leads to measurement uncertainties.

For each set of data, the beam has been off-centered by using two upstream steerers and has been modified in transverse sizes using an upstream quadrupole (cf. Fig. 2).

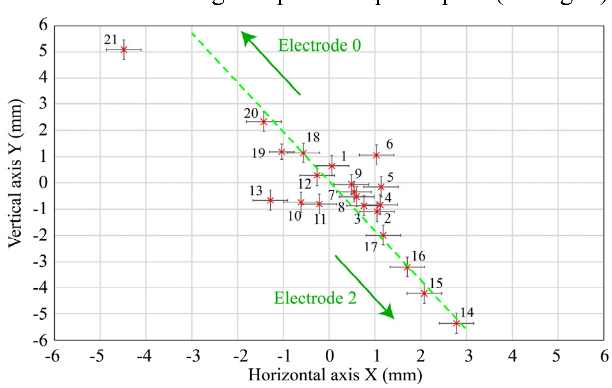

Figure 2: Compilation of measured positions by the BPM for the set of data used in our experiments. The beam is steered between the electrode 0 and the electrode 2.

The beams characteristics used as input of BPMOK has been evaluated using profiles measurements with the Wire Scanner and TraceWin beam dynamics simulations [9]. Figure 3 presents the comparison of the first harmonic predicted by BPMOK for each electrodes and the associated measurements the nominal beam dynamic of IPHI with a 15 mA beam. Uncertainties concern the intensity, energy, geometry of the BPM, the beam position and the bunch length. The model BPMOK has been validated for all sets of data (beam misalignment, size and intensity).

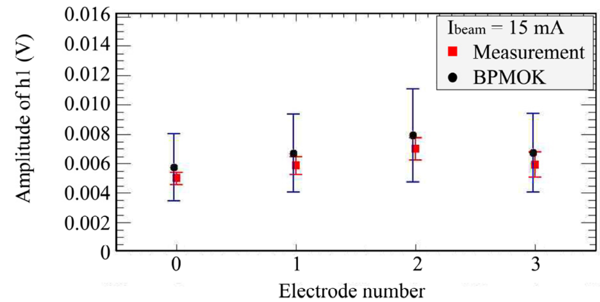

Figure 3: Comparison of predicted first harmonics from BPMOK and the measurement for each electrodes of the BPM. The error bars represent uncertainties at 2 RMS.

MEASUREMENTS AT SPIRAL2

The SPIRAL2 installation at GANIL in Caen is dedicated to nuclear physics and pluridisciplinary researches. The accelerator aims to deliver heavy and light ions up to 5 mA with a bunch repetition frequency F_{acc} = 88.05 MHz. The commissioning of the LINAC was achieved at the end of 2019 with a 33 MeV Proton beam.

During our experiments, the beam intensity was set to 160 µA. Each accelerating lattice of the LINAC has two quadrupoles. The BPM used for our measurements are inserted in the first quadrupole of each lattice of the LINAC [10]. Twenty BPM are installed along the LINAC and their measurements are associated with a beam energy from 0.75 MeV to 33 MeV.

The associated acquisition electronics measured the first and second output harmonics h1 and h2 of each electrodes of all the BPM simultaneously. Their digital part calculates the beam position using h1 or h2. Figure 4 presents the measured horizontal position with h1 and h2 in the nominal beam dynamic in the LINAC.

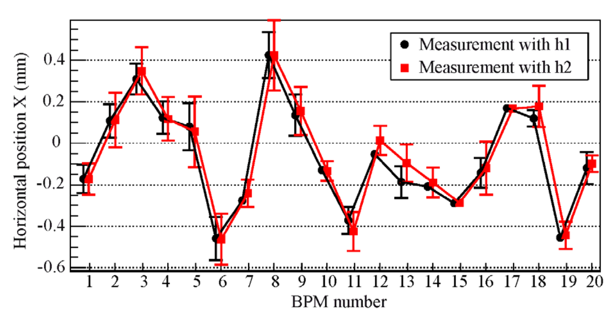

Figure 4: Measured horizontal position of the beam in the LINAC of SPIRAL2 as a function of the BPM number.

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The beams characteristics used as input of BPMOK has been fixed using TraceWin calculations. The beam dynamics has been cross-checked with 3 profilers in the MEBT before the LINAC. Figure 5 presents the comparison of the harmonics h1 predicted by BPMOK for each electrodes with the associated measurements. This measurements concerned a centred beam in the LINAC. Such measurements has been took for horizontally off-centred beam on the BPM N°2 from -8 mm to +8 mm. Uncertainties concern the intensity, energy, geometry of the BPM, the beam position and the bunch length. The model BPMOK has been validated for all sets of data for h1 and h2.

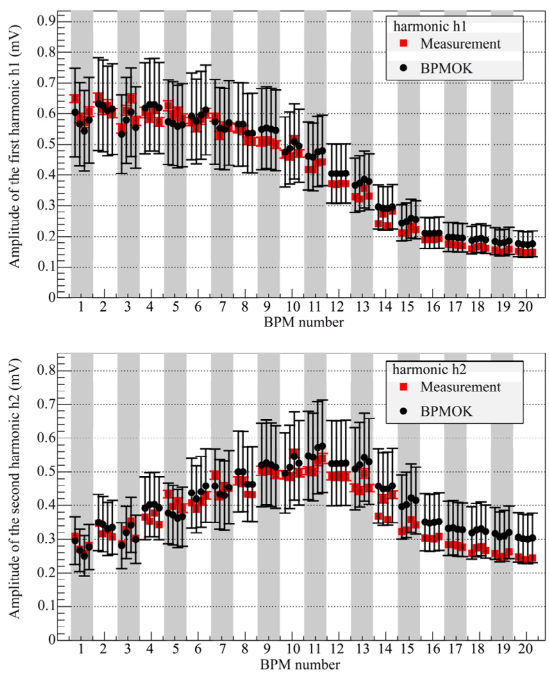

Figure 5: Variation of h1 and h2 amplitudes along the LINAC as a function of the BPM number. The measurements and the predictions of the model BPMOK are compared. The error bars represent uncertainties at 2 RMS.

OPTIMIZATION OF THE BPM FOR THE HEBT OF MINERVA

The specifications for the BPM of the LINAC of MINERVA is fixed for a 4 mA nominal beam. A prototype was built in order to test the BPM accuracy on a test bench at IJCLAB [11, 12]. The associated acquisition cards is a LIBERA LSPH by Instrumentation Technologies allows to answer to the BPM accuracy specifications for input power from -47 dBm up to +9 dBm. The project will use the amplitudes of the first and second harmonics h1 and h2.

The objectives are to optimize the BPM of the LINAC for the HEBT using the same acquisition electronics. The radius of the BPM needs to be adapted from 28 mm to 50 mm. BPMOK allows us to make a parametrical study based on the starting geometry of the BPM of the LINAC with a 50 mm radius and beam parameters. This starting geometry has been simulated with CST and is in good agreement with the model BPMOK (cf. Fig. 6).

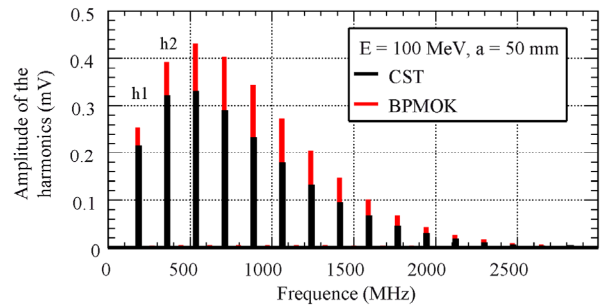

Figure 6: BPMOK vs CST: DFT of typical output signal from the BPM with a 50 mm radius for a centred beam.

A parametrical study using BPMOK based on the starting geometry allows us to determine the final geometry of the BPM for the HEBT of MINERVA (cf. Fig. 7) [7].

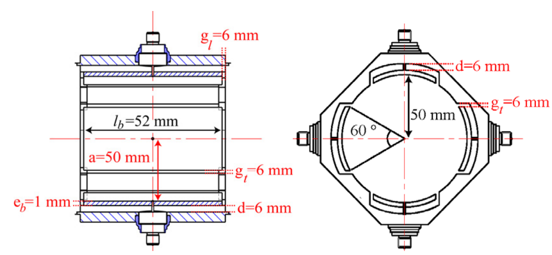

Figure 7: Principle scheme of the geometry of the BPM for the HEBT of the MINERVA

CONCLUSION

The new analytical model BPMOK has been presented. BPM measurements on real beam at IPHI and SPIRAL2 facility has validated the model. BPMOK is in good agreement with CST simulations. BPMOK has been used to make a parametrical study in order to find a BPM geometry for the HEBT in order to use the same electronics as the BPM of the LINAC of MINERVA. Further studies with BPMOK will try to determine the possibility to measure the bunch length with the BPM using the ratio h1/h2.

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