ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-MOPP07

BEAM POSITION MONITOR FOR MYRRHA 17-100 MeV SECTION*

M. Ben Abdillah†, F. Fournier, University Paris-Saclay, CNRS/IN2P3, IJClab, France

Abstract

MYRRHA (Multi-Purpose Hybrid Research Reactor for High-Tech Applications) aims to demonstrate the feasibility of high-level nuclear waste transmutation at industrial scale. MYRRHA Facility aims to accelerate 4 mA proton beam up to 600 MeV. The accurate tuning of LINAC is essential for the operation of MYRRHA and requires measurement of the beam transverse position and shape, the phase of the beam with respect to the radiofrequency voltage with the help of Beam Position Monitor (BPM) system. MINERVA is the first phase of MYRRHA. It includes several sections allowing beam acceleration up to 100 MeV. A BPM prototype was realized for the single spoke section (17 MeV-100 MeV). This paper addresses the design, realization, and calibration of this BPMs and its associated electronics. The characterization of the beam shape is performed by means of a test bench allowing a position mapping with a resolution of 0.02 mm.

GENERAL DESCRIPTION OF MYRRHA

MYRRHA is a high power proton accelerator with strongly enhanced reliability performances. The conceptual design is on-going for more than 15 years. The adopted LINAC scheme to fulfil the reliability goal is based on 2 distinct sections, as illustrated in Fig. 1

The first phase (MINERVA) currently ongoing until 2026 aims at demonstrating the fault compensation strategy for the 600 MeV linac on a 100 MeV linac. The MYRRHA phase 1 accelerator will deliver a 100 MeV, 4 mA CW proton beam. The accelerated beam will be sent to a PTF (Proton Target Facility) for various applications including fusion research and isotope production.

MINERVA addresses the topics that have been identified as priority ones to successfully pursue the research, design and development of the MYRRHA accelerator and prepare for its actual construction. Among the topics, beam characterization would deliver data of fundamental importance in all beam dynamics simulation tools.

Beam Position Monitor (BPM) is a non-destructive beam diagnostic system, it measures beam position, phase shift regarding the accelerating signal and also gives an indication on the beam transverse shape. IJClab is in charge of the realization of a BPM prototype in order to contribute to the characterization of the beam along 17-100 MeV section that accelerates the beam from 17 MeV to 100 MeV. This document details the steps of design, fabrication and qualification of this prototype.

GENERAL DESCRIPTION OF BPM

BPMs allow measuring the vertical and horizontal coordinates of the center of gravity of the beam position and assessing the transverse size of the beam. Capacitive BPM is used. Each BPM is equipped with 4 probes formed by a sealed 50 Ohm feedthroughs attached to an electrode. The probes (feedthrough + electrode) should be as identical as possible and they should be symmetrical regarding the center of the BPM.

BPM must meet a set of constraints (vacuum, magnetism, positioning, steaming, resistance to ionizing radiation) in order to ensure its integration into the machine.

The beam induces electrical signal on each electrode, beam position, transverse shape and energy are induced from these electrical signals. The electronic module provides the following information by processing the electrical signals delivered by the electrodes:

- The horizontal and vertical position of the center of gravity of the beam.
- The phase of the beam with respect to the main Radio Frequency reference signal. Beam velocity and energy are processed from this measurement.
- Beam Ellipticity figuring in the second order moment of the beam transverse distribution.

BPM SPECIFICATIONS

Table 1 summarizes beam properties and BPM specifications for 17-100 MeV section of the MINERVA project.

- The precision on the position should be less than 100 µm on both axes. The phase shift relative to the accelerating signal should be measured with a precision less than 1degree. The beam ellipticity should be less than 1.6 mm² for circular beam while it should be measured within 20% precision for elliptical beams.

Table 1: Beam Parameters and BPM Specifications

Parameter	Range	Precision
Energy E	17 MeV- 100 MeV	
Current I	0.1 mA-4 mA	
Duty cycle	2.10^{-4} to 0.125	
Bunch length @17 MeV	15°; 230 ps	
Bunch length @100 MeV	5°; 80 ps	
F_{acc}	176.1 MHz	
Beam pipe	28 mm	
Measured Position	±5 mm	100µm
Measured Phase	360degrees	1degree
Measured Ellipticity	±5 mm	Max (1.6mm²;20%)

* Work supported by SCK-CEN
† sidi-mohammed.ben-abdillah@ijclab.in2p3.fr

ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-MOPP07

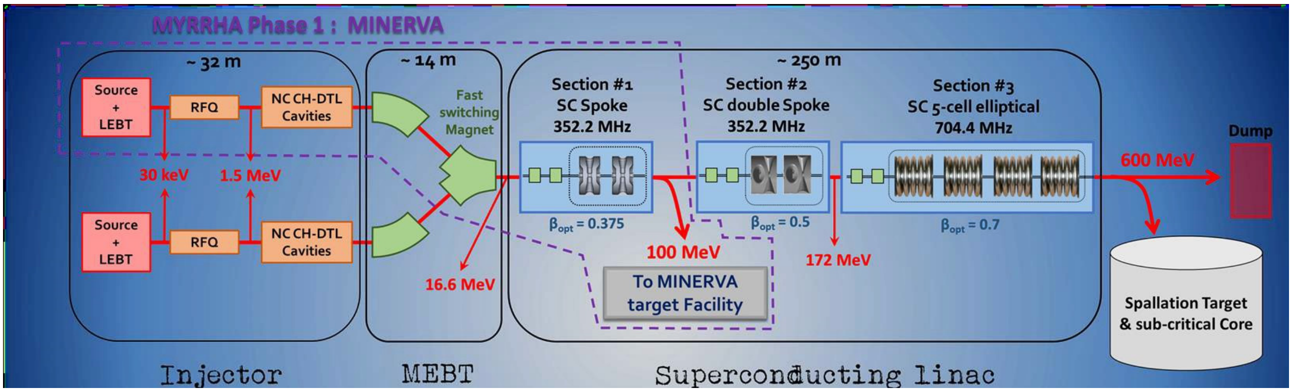

Figure 1: Conceptual design of MYRRHA with MINERVA outlined.

BPM DESIGN

Experience with SPIRAL2 BPMs [1] was of a great help. The relatively similar properties between the beams of MYRRHA and SPIRAL2 led us naturally to match the design of SPIRAL2 BPMs to MYRRHA and also improve this design.

The BPM probe is considered as a capacitance that is charged by the beam and discharged through a resistance connected to ground. The probe has a high-pass-filter characteristic with cutoff frequency $F_c=1/2\pi RC$.

High frequency information from the BPM is sometimes required to estimate bunch length or shape characteristics, or for the monitoring of the beam phase/time-of-flight. However, there are irregularities and resonant effects at very high frequencies due to mismatching between beam pipe and BPM, it is also difficult to match four electronics channels in gain and high impedance. Therefore, it is advised to operate the BPM at low frequencies ($F_{acc} < F_c$).

In the MYRRHA scope (beam energies between 17 and 100 MeV/u), the 2nd and upper harmonics of the beam image current are important. Consequently, Readout electronics must operate at f_{acc} and upper harmonics. Readout electronics processing high tones (above 0.5 GHz) are expensive and cumbersome; therefore, only 1st and 2nd harmonic tones of the BPM received signals are processed.

Regarding BPM design, emphasis is then put on 1st and 2nd harmonic tones of the BPM received signals.

The BPM design should succeed the following criteria for 17-100 MeV section of MYRRHA project:

- A strong output signal at each electrode (strong signal to noise ratio) particularly at the two first harmonics (f_{acc} and 2 f_{acc}). This would limit complications in the design of acquisition electronics.
- A strong sensitivity to the beam displacement
- Robust design: the BPM will be subject to numerous manipulations (tests, calibrations …)
- Simple design: at least 30 BPMs might be fabricated for 17-100 MeV section, therefore the fabrication should be made as simple as possible.
- The feed through resistance should be equal to 50 Ohm in order to match the impedance if the cables routing the received signal to the readout electronics.

BPM SIMULATIONS

The influence of the electrode dimensions on the signal level and harmonic content for different beams was calculated.

BPM diameter is set to D=56 mm

BPM model is depicted in Fig. 2.

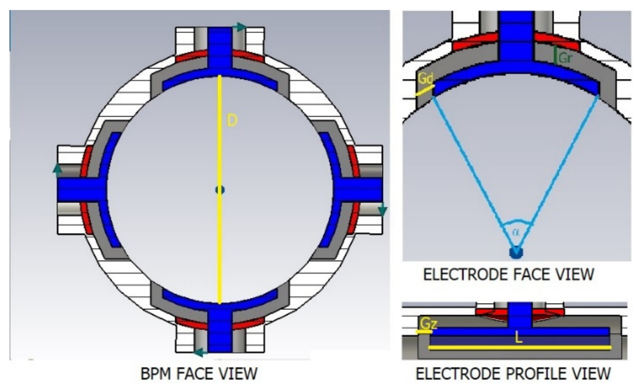

Figure 2: Design parameters.

The following parameters are optimized in BPM design

- Electrode angular width α: The wider α is the stronger the electrode output signal is however the sensitivity to beam displacement is slightly reduced. However, it is advisable to respect α<70° to reduce mutual impedance between electrodes.
- Electrode length L: the longer the electrode is, the stronger is the electrode output signal is. The sensitivity to beam displacement remains unchanged. However, long electrode is not that rigid only with soldering in its center.
- The gaps Gr, Gd, Gz and the relative permittivity ε_r are chosen in order to operate the BPM below or around its cutoff frequency.

CST is used for BPM simulations, it estimates the levels of the induced electrode voltage at frequency harmonics (first and second). BPM simulations are run with a beam current equal to 4 mA. Electrode length and angular width are kept low in order to maintain a feasible electrode stability and concentricity. The optimization on the parameters mentioned above led to the following result: L=45 mm, α=45deg, Gr=Gz=Gd=4 mm.

ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-MOPP07

- For a beam current I=4 mA, the expected BPM output signal amplitude and BPM position and ellipticity sensitivities are mentioned in Tables 2 and 3.

Table 2: Expected Parameters at F_{acc}

Energy	Parameter	Value
Section start	Output amplitude (centered beam)	24 mV
	Position sensitivity	1.25 dB/mm
	Ellipticity sensitivity	0.19 dB/mm²
Section end	Output amplitude (centered beam)	11 mV
	Position sensitivity	1.22 dB/mm
	Ellipticity sensitivity	0.11 dB/mm²

Table 3: Expected Parameters at $2F_{acc}$

Energy	Parameter	Value
Section start	Output amplitude (Centered beam)	27 mV
	Position sensitivity	1.38 dB/mm
	Ellipticity sensitivity	0.13 dB/mm²
Section end	Output amplitude (Centered beam)	16 mV
	Position sensitivity	1.24 dB/mm
	Ellipticity sensitivity	0.11 dB/mm²

With a beam intensity of 100 µA, the level is 34dB lower; the cables bringing the BPM signals to electronics rack (about 30 m long) would bring an extra 3dB lost. The signals strengths at the electronics inputs are close -60 dBm.

BPM FABRICATION

The feedthrough pin is fragile and brazing it to a large electrode is subject to errors in electrodes positioning and concentricity over the 4 electrodes of the BPM. It would be even more difficult to repeat this operation properly over more than 100 electrodes.

SOLCERA*, which already provided BPMs for SPIRAL 2 LINAC, suggests reinforcing the feedthrough pin with a molybdenum spacer around it assuring though a better positioning and concentricity of the electrodes.

MYRTE BPM [2] realization steps were repeated for MYRRHA 17-100 MeV section BPM. The following issues were noticed during this realization.

Feedthrough Realization

10 feedthroughs were tested. Due to brazing, the external diameter of feedthroughs is higher than expected. However, it doesn’t affect the BPM operation as all the feedthroughs suffer from the same default. The length of the connector before the joint is not the same over the 10 feedthroughs. Though, 2 samples were not accepted. Four feedthrough are chosen as the difference between their capacitances is less than 0.01 pF and their TDR responses are close to identical.

BPM Block Realization

Once the needed feed-through matched, the BPM block was fabricated and delivered, the controls had shown a deviation over reference faces higher than the precision requested. This has a direct effect on the alignment of the BPM inside the LINAC: the offset between the BPM and the beam pipe revolution axes is increased. However, this offset could be measured with precision at IJClab test bench and taken into account in BPM operation.

BPM CHARACTERIZATION

BPM Position Parameters

The BPM position coordinates are related to the electrodes received signals through the following equations:

$$\left(\frac{R}{L}\right)_{dB} = \big(1 + G(\beta, f)\big)S_x(f) * \big(X - \Delta_x(\omega)\big)$$

$$\left(\frac{T}{B}\right)_{dB} = \big(1 + G(\beta, f)\big)S_y(f) * \big(Y - \Delta_y(\omega)\big)$$

(X, Y) are the beam position coordinates. β the beam relative velocity; f the electrodes output signal acquisition frequency. S_x and S_y the position sensitivity at β=1.

Δ_x and Δ_y the position offsets at β=1.

G(β,f) is a correction factor set by Shafer [3] depending on β and f. G (1, f) =0.

The equations above operate properly for beam positions close to beam pipe central axis.

Position sensitivity changes with the beam position. Full interest is put on positions close to the beam pipe central axis. The goal is to measure beam position offset and sensitivity.

- The approach used for MYRTE BPM [2] is repeated. The results of the measurements of BPM electrical offsets and position sensitivity (with relative velocity β≈1) are summarized in Table 4.

Table 4: BPM Position Parameters

Frequency	Position offset	Position sensitivity
F_{acc}	(76 µm; -162 µm)	1.19 dB/mm
$2F_{acc}$	(71 µm; 98 µm)	1. 2dB/mm

The measured position sensitivity is applied at any position in the beam pipe. Therefore, the error between the measured position and the beam position is increased away from the beam axis. This error is measured for positions covering a 20 mm*20 mm square centered at the BPM electrical center. The results are mentioned in Fig. 3.

ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-MOPP07

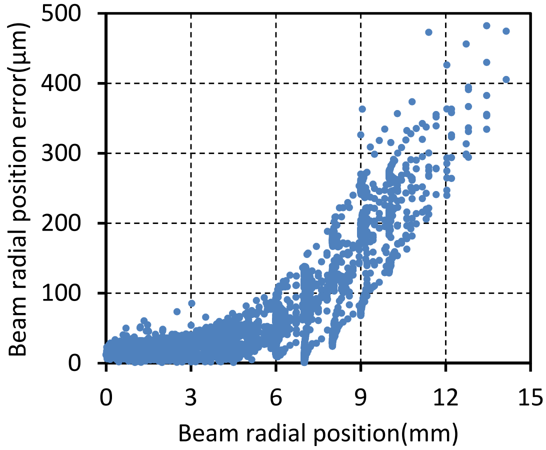

Figure 3: Position error.

The error is within 100 µm for radial position up to 6 mm, which satisfies the BPM specifications.

BPM Ellipticity Parameters

The ellipticity offsets emphasizes the case of centered beam with an elliptical transverse shape; the said beam induced equal signals on opposite electrodes but not the same signal on the 4 electrodes of the BPM.

For a beam with a circular transverse shape, the BPM ellipticity is related to the electrodes received signals through the following equation:

$$\left(\frac{R*L}{T*B}\right)_{dB} = \left(1 + G_E(\beta, f)\right) S_E(f) * \left(X^2 - Y^2\right) - \Delta_E(f)$$

(X, Y) are the beam position coordinates. S_E is the ellipticity sensitivity at β=1. Δ_E is the ellipticity offset at β=1 at the BPM electrical center. $G_E(\beta,f)$ is a correction factor mentioned in [4].

An experiment was run using the test bench in IJClab. A sweep over the Y axis (from -1 mm to 1 mm with a 50 µm step) is performed. The wire transverse shape is circular. The experiment results are sketched in Table 5.

Table 5: BPM Ellipticity Parameters

Frequency	Ellipticity offset	Ellipticity sensitivity
F_{acc}	0.2dB	0.033dB/mm²
$2F_{acc}$	0.1dB	0.033dB/mm²

Regarding the ellipticity offset, the ellipticity error is 0.01dB which corresponds to 0.3 mm².

The ellipticity sensitivity is measured close to the center. It is though applied at any position in the beam pipe. Therefore, the error between the measured ellipticity and the beam ellipticity is increased away from the beam axis. The said error is measured for positions covering a 5 mm*5 mm square centered at the BPM electrical center. The results are mentioned in Fig. 4.

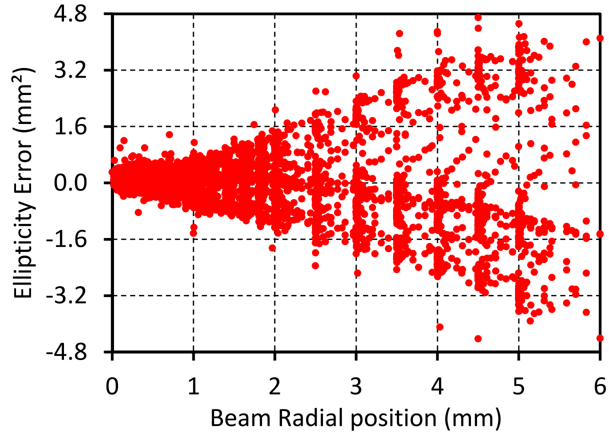

Figure 4: Ellipticity error.

The error is within 1.6 mm² for radial position up to 2 mm, which is quite less than desired in specifications.

CONCLUSION

MYRRHA 17-100 MeV section BPM prototype is presented in this paper. The mechanical fabrication is offering stable and reproducible BPM. BPM Characterization shows that beam position measurement is satisfied within specifications. Beam ellipticity is measured properly for a limited range of beam positions, a better mapping of ellipticity sensitivity is needed to match specifications on that point.

REFERENCES

[1] M. Ben Abdillah *et al.*, "Development of the beam position monitors for the SPIRAL2 Linac", in *Proc. 1st Int. Beam Instrumentation Conf. (IBIC'12)*, Tsukuba, Japan, October 2012, TUPA18, pp.374-377.

[2] M. Ben Abdillah, P. Blache, F. Fournier, and H. Kraft, "Development of a Low-beta BPM for MYRTE Project", in *Proc. IBIC'19*, Malmö, Sweden, Sep. 2019, WEPP002, pp. 504-507.

[3] R.E. Shafer, "Beam position monitor sensitivity for low beta beams", in *Proc. 1994 Int. Linac Conf.*, Tsukuba, Japan, 1994, pp. 905-907.

[4] M. Ben Abdillah, "Novel electrostatic beam position monitors with enhanced sensitivity", in *Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16), Barcelona, Spain, September* 2016, TUPG09, pp. 335-337.