DEVELOPMENT OF A LOW-BETA BPM FOR MYRTE PROJECT*

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Abstract

MYRTE (MYRRHA Research Transmutation Endeavour) performs research to support the development of the MYRRHA (Multi-Purpose Hybrid Research Reactor for High-Tech Applications) research facility, which aims to demonstrate the feasibility of high-level nuclear waste transmutation at industrial scale. MYRRHA Facility aims to accelerate 4mA proton beam up to 100 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. MYRTE aims to qualify beam operation at 1.5MeV. Two BPMs were realized for MYRTE operation. This paper addresses the design, realization, and calibration of these two BPMs and their associated electronics. The characterization of the beam shape is performed by means of a test bench allowing a position mapping with a resolution of 0.02mm.

GENERAL DESCRIPTION OF MYRTE

The MYRTE project was launched in 2015 to perform the necessary research to support the development of the MYRRHA (Multi-Purpose Hybrid Research Reactor for High-Tech Applications) facility, which aims to demonstrate the feasibility of high-level waste transmutation at industrial scale.

MYRRHA LINAC is accelerating a beam with characteristics sketched in Table 1.

Table 1: Beam Specifications

Particle	Current (mA)	Energy (MeV/u)
Proton	0.1-5	1.5-600

MYRTE 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.

The characterization is performed at the injector.

The injector is constituted by an ECR proton source, a low energy beam transfer line followed by a Radiofrequency Quadrupole (RFQ) which accelerates beam up to 1.5MeV/u. RFQ frequency is set to f_{acc}=176.1 MHz

Beam Position Monitors (BPM) measures beam position, phase shift regarding the accelerating signal and an indication on the beam transverse shape. This paper details the steps of design, fabrication and qualification of these two BPMs.

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 BPMs are used. Each BPM is equipped with 4 probes formed by a sealed 50Ohm 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.
- Beam phase shift with respect to the main reference signal. Beam velocity and energy are processed from this measurement.
- Beam quadrupole moment figuring in the second order moment of the beam transverse distribution.

BPM SPECIFICATIONS

- In the scope of MYRRHA project, IPN is in charge of the realization of BPMs for the 17MeV-100MeV section. In the scope of MYRTE project, two BPMs partially characterize the beam emerging of the RFQ.
- The specifications are similar for both MYRRHA and MYRTE. The precision on the position should be less than 100µm on both axes. The beam phase shift relative to the accelerating signal should be measured with a precision less than 1 degree. The beam quadrupole moment should be less than 1.6mm² for circular beam or within 20% precision for elliptical beams.

Table 2 summarizes the BPM specifications.

Table 2: BPM Specifications

Parameter	Range	Precision
Position	±5 mm	100µm
Phase	360degrees	1degree
Quadrupole moment	±5mm	Max(1.6mm²;20%)

BPM DESIGN

The way both projects were held was to focus on the design of the BPM for the 17-100MeV/u section and to simulate the said design at beam energy equal to 1.5MeV.

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This process has the advantage of gaining a considerable time in the scope of MYRRHA schedule; it does offer an acceptable solution for MYRTE but not the best solution.

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.

The BPM probe is considered as a capacitor that is charged by the beam and discharged through the resistor connected to ground. The probe has a high-pass-filter characteristic with cut-off 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. Moreover, it is 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 MYRTE scope (beam energy =1.5MeV/u), the electric field in the electrode is an electrostatic field, the 2nd and upper harmonics of the beam image current are close to nil. Readout electronics must therefore operate at f_{acc} with the interference risk from the RF power.

In the MYRRHA scope (beam energies between 17 and 100MeV/u), the 2nd and upper harmonics of the beam image current are important. Readout electronics must therefore operate at f_{acc} and upper harmonics. Readout electronics processing tones above 0.5GHz are expensive and cumbersome; therefore, only f_{acc} and $2f_{acc}$ tones of the BPM received signals are processed: this solution is a good trade off as the associated electronics is affordable and the interference risk from the RF power is minimal.

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 MYRTE and MYRRHA projects:

- A strong output signal at each electrode (strong signal to noise ratio) particularly at the two first harmonics (f_{acc} and $2f_{acc}$). 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 …)
- The feed through resistance should be equal to 50Ohm 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 were calculated using the method described by Shafer [2].

BPM diameter is set to D=56mm.

Only four parameters are optimized in this BPM design

- Electrode angular width α: it is advised to be less than 70deg to reduce the inter coupling between adjacent electrodes. The wider α is the stronger the electrode output signal is however, the sensitivity to beam displacement is slightly reduced.
- 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 gap h and the relative permittivity ε_r: they are chosen in order to operate the BPM below or around its cut-off frequency.

Simulations with python model and optimizations run with CST deliver a BPM length equal to 62mm. Each electrode has an angular coverage of 60 degrees.

BPM model is depicted in Figure 1.

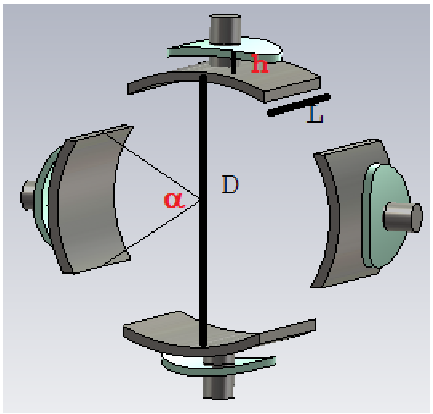

Figure 1: BPM model in CST.

With a beam current equal to 5mA, the expected BPM probe output voltage and BPM position sensitivity, at injector start, are mentioned in Table 3.

Table 3: BPM Expected Specifications

Parameter	Precision
Output voltage	-13dBm
Position sensitivity	1.59dB/mm
Quadrupole moment sensitivity	0.05dB/mm

With a beam current of 100µA, the level is 34dB lower; the cables bringing the BPM signals to electronics rack (about 30m long) would bring an extra 3dB lost. The signals strengths at the electronics inputs would be close to -50dBm.

Readout electronics should offer 100µm precision in position measurement for input signals down to -50dBm.

BPM FABRICATION

Using ceramic barrettes in BPM fabrication [3] eases electrodes positioning and offers a robust and reproducible BPM.

MYRTE BPM realization followed the same process used in SPIRAL2 BPM fabrication [1]:

- Feedthrough realization: 20 reverse polarity feedthroughs that were tested. The testing first verifies feed-through isolation then measures its capacitance and TDR* response and finally matches four feedthrough to form a single BPM block. Feedthroughs had capacitances measuring 1.4pF with a margin of ±0.03pF.

- BPM realization: the selected feedthroughs were sent for BPM blocks realization. Two BPM blocks were delivered, their isolation was verified, and their capacitance were measured and verified to be within ±0.05pF per block. Electrodes TDR responses show differences at high frequencies.

  The BPM block is then soldered to stainless steel tubes then to CF100 flanges.

MYRTE BPM is depicted in Figure 2.

Three drawbacks were noticed during BPM realization:

- BPM Electrodes capacitances values are higher than expected; this is mainly due to stray capacitances. The BPM cut-off frequency is around 250MHz, therefore, the BPM operates in derivative mode at 176.1MHz (better sensitivity) and in image mode at 352.2MHz (better output signal).
- Difference between BPM electrodes capacitances.
- Ringing effects in the TDR responses, these effects are harmful at very high frequencies.

BPM CHARACTERIZATION

Frequency Response

The frequency response of the electrodes was measured over the band 10MHz - 1GHz. A coaxial wire is positioned close and parallel to the central axis of the BPM (inside the BPM). A VNA* is used: port 1 is transmitting signal to the coaxial wire whether ports 2 and 3 are receiving signals from opposite electrodes (top/bottom or right/left). S21 and S31 correspond to the transmission attenuation for the opposite electrodes.

The high pass filter feature is confirmed and the electrode responses are similar.

BPM position parameters

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

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

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

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

Δ_x and Δ_y are the position offsets at β=1.

G(β, f) is a correction factor set by Shafer [4] and depending on β and f. G(1, f)=0.

The precedent formulas are only available for beam positions close to the BPM electrical center.

In order to enhance the quality of measurement of BPM position parameters, SPIRAL2 BPMs test bench [1] is used.

The test bench is upgraded over two aspects:

- Measurement repeatability: the test bench reference point (0, 0) is verified with a pin/hole system giving a precision under 10µm. The test bench is placed in temperature controlled room.
- Measurement precision: BPM displacements on both axes are measured with a dedicated laser probes system giving a precision under 10µm.

The BPM is positioned so that right/left electrodes are aligned with the linear precision stage moving the wire over the X axis.

The BPM mechanical center is measured using a triangulation method.

The BPM electrical center corresponds to the position where the amplitudes of opposite electrodes received signals are equal.

The BPM position offset coordinates are the algebraic differences between BPM mechanical center and electrical center.

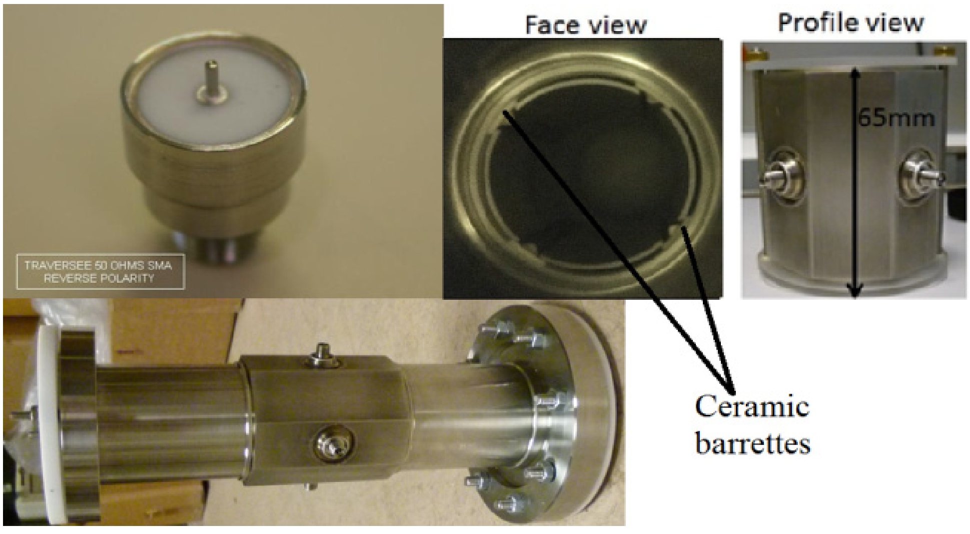

Figure 2: Top: feedthrough and BPM Block views, bottom: entire BPM.

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* TDR: Time Domain Reflectometer.

* VNA: Vectorial Network Analyzer

A circular wire is positioned inside the BPM. A sinusoidal signal is transmitted to the wire. The BPM probes received signals are transmitted through custom RF coaxial cables (attenuation within 0.01dB and phase shift within 0.2deg at f_{acc}) and measured using power sensors.

The input power is set so that the electrodes received signal amplitudes are about -20dBm when the wire is positioned at (0, 0).

In order to measure position sensitivity S_x, the wire is swept over the X axis (sweep step= 100µm). The difference between opposite electrode received magnitudes (R/L) dB is measured. For example, the results at the operating frequency H1 are depicted in Figure 3.

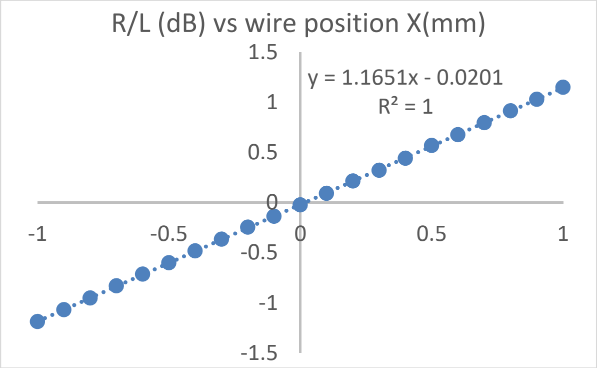

Figure 3: Position Sensitivity Measurement at H1.

The BPM position offset and sensitivity at β=1 are gathered in Table 4:

Table 4: BPM Position Parameters Measurements

BPM	Sensitivity(dB/mm)	Offset(µm)
1	1.165	(36;166)
2	1.163	(-49;123)

BPM Quadrupole Moment Parameters

The BPM quadrupole moment E is related to the electrodes received signals and the beam position coordinates through the following equation:

$$\left(\frac{R*L}{T*B}\right)_{dB} = G_Q(\beta,f)\,S_Q(f)\left(Q+X^2-Y^2-\Delta_Q(f)\right)$$

S_Q and Δ_Q are respectively the quadrupole moment offset and sensitivity at β=1. $G_Q(\beta, f)$ is a correction factor mentioned in [5] and depending on β and f. $G_Q(1, f)=1$.

The wire transverse shape is circular; therefore, Q=0. A sweep over the X axis (from –4mm to 4mm with a 0.1mm step) is performed.

The results at the operating frequency H1 are depicted in Figure 4. The parabolic shape in Figure 4 confirms the equation above. Analog behavior is verified on the Y axis. With the wire placed at the BPM electrical center, the amplitudes at the electrodes outputs at F_{acc} are measured and the quadrupole moment offset is calculated.

The BPM quadrupole moment offset and sensitivities at β=1 are gathered in Table 5.

The weak quadrupole moment sensitivity makes it difficult to measure precisely beam transverse shape. Threshold for circular transverse beams (1.6mm²) corresponds to a change of 0.05dB is the BPM received signal amplitude.

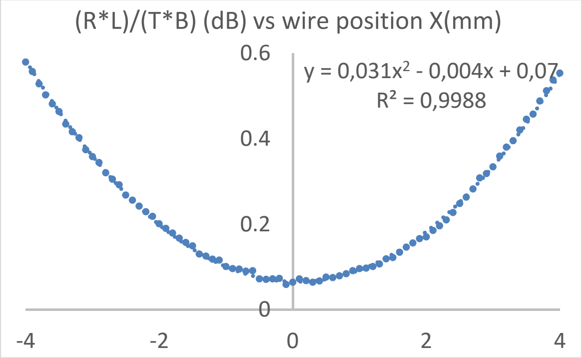

Figure 4: Quadrupole moment measurement at H.

Table 5: BPM Quadrupole Moment Parameters Measurements

BPM	Sensitivity(dB/mm)	Offset(mm^2)
1	1.165	4.09
2	1.163	-3.97

CONCLUSION

MYRTE BPMs are presented in this paper. The mechanical fabrication is offering stable and reproducible BPMs. BPM Characterization shows a good agreement to expected position and quadrupole moment parameters.

For low-level beam, BPM electrodes outputs could be processed by LIBERA single pass H acquisition module. however, limitations occur for beam quadrupole moment measurement at these levels.

ACKNOWLEDGEMENTS

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