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EXPERIMENTS WITH A QUADRATED DIELECTRIC-FILLED REENTRANT CAVITY RESONATOR AS A BEAM POSITION MONITOR (BPM) FOR A MEDICAL CYCLOTRON FACILITY*

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Abstract

Low beam currents (0.1-10 nA) are used for tumour treatment in the proton radiation therapy facility at PSI. The facility houses a superconducting cyclotron with an extraction energy of 250 MeV pulsed at 72.85 MHz. Online measurement of the beam position is traditionally performed with the help of ionisation chambers (ICs), however, at the expense of reduced beam quality and scattering issues. There is a strong demand to have this measurement performed with minimal beam disturbance, since the beam position is directly associated with the dose-rate applied. A cavity resonator, working on the principle of an electric dipole mode resonance, whose frequency is coupled to the second harmonic of the pulse rate, has been built to measure beam position in a purely non-invasive manner. Followed by a reasonable agreement between the test-bench and the simulation results, the cavity is installed in one of the beamlines. Here, we report on the measurement of the cavity BPM as a function of beam current and position and its shortcomings. When measured with a spectrum analyser, the cavity BPM can deliver position information within the accuracy and resolution demands of 0.50 mm.

INTRODUCTION

Proton beams of low beam currents (0.1-10 nA) are used for radiation therapy at PSI, and its position is traditionally measured with multi-strip ionisation chambers (ICs) [1]. Due to a strict demand for minimal disturbance of the beam, a non-invasive BPM, modelled as four LC cavities within a ground cylinder with a common dielectric is described in [2] as a potential replacement to ICs. It is designed to work on the dipole mode (TM_{110}) of resonance at 145.7 MHz for off-centered beams. The BPM prototype is characterised on a test-bench and its position dependence is in good agreement with the simulation expectation as seen in [2]. The TM_{110} mode frequencies of the horizontal and the vertical polarisations, localised in horizontal and vertical cavities, are at 146.0 MHz and 148.1 MHz due to cavity asymmetries from reassembling to correct for sensitivities as described in [2]. Hence, for validation of the BPM prototype with beam measurements, only horizontal plane cavities are studied due to its proximity to the design TM_{110} mode frequency demand.

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BEAMLINE MEASUREMENTS

The BPM, as shown in Figure 1 [3] , is installed in the temperature-controlled (28.5±0.5 °C) proton therapy facility, PROSCAN, at six meters from the degrader exit (Figure 2).

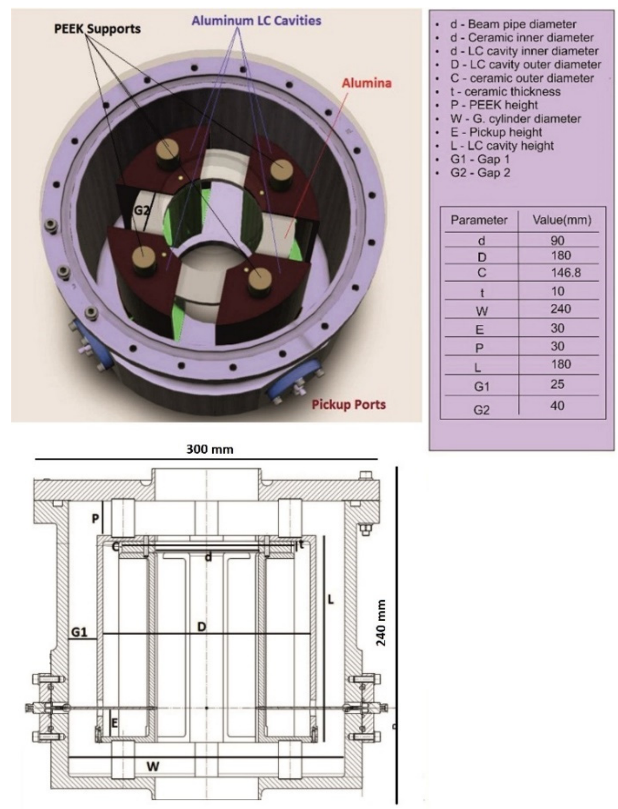

Figure 1: Geometry of the four-quadrant reentrant cavity BPM with its design TM_{110} mode frequency at 145.7 MHz and its design monopole mode frequency (TM_{010}) at 127.1 MHz.

The sensitivity of the BPM is expected to be nearly constant for different energies since the influence of energy spread from the degrader on bunch length elongation at the BPM location will be minimal unlike for the BCM location as described in [4].

The measurement reference is an IC located within a meter behind the BPM. The measurement chain, as shown in Figure 2, consists of a single stage amplification of 36 dB each for the horizontal plane cavities and a spectrum analyser. The pickups of the vertical plane cavities of the BPM are terminated with 50 Ω. The beam position response of the BPM prototype is verified at different beam currents and energies.

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The beam current response is measured at two different beam positions: 2.4 mm and 4.8 mm for a 200 MeV beam. The beam energy dependency is tested for 200 MeV and 138 MeV at 4.8 mm. The beam position response is measured at two beam currents: 2.6 nA and 12.2 nA for a 138 MeV beam. Also, the horizontal cavity response for a vertical offset is investigated. The IC used as reference monitor has a beam current and position uncertainty of 1% and 5%.

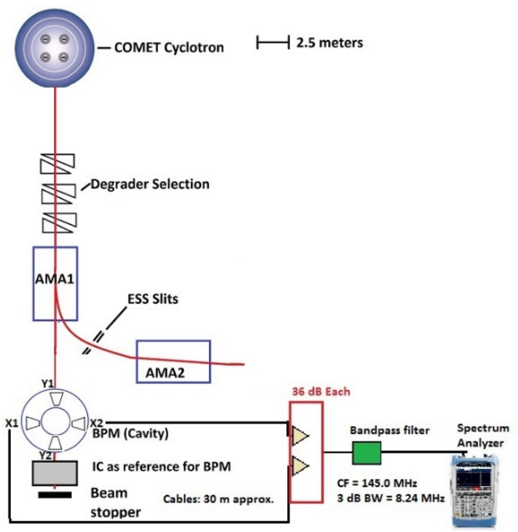

Figure 2: BPM located at six meters from the degrader exit. The measurement chain consists of two low noise-amplifier with 36 dB gain each, followed by a bandpass filter. A spectrum analyser provides amplitude measurement of the BPM for beam position offsets.

Beam Current and Energy Response

The BPM signal is proportional to beam current and beam position. For a given position offset, the BPM's beam current response is linear and the beam current sensitivity is higher for larger position offsets as expected and as seen in Figure 3.

The beam current sensitivity of the X1 cavity, shown in Figure 4, is only 3% lower at 138 MeV compared to 200 MeV, which is in close agreement with the 4% difference in bunch length for the two energies at the BPM location.

Beam Position Response

The 30% higher position sensitivity of the X2 cavity compared to the X1 cavity could be due to the induced cavity asymmetries as discussed in [2]. Consequently, the beam-pickup coupling coefficients of the cavities are affected as indicated by different saturation of the different cavities (encircled in red and purple in Figure 5). As a result, the linear response of the X2 cavity is existent over a position range of - 10.0 mm to +10.0 mm, but for the X1 cavity, it exists over a smaller range from -10.0 mm to +3.0 mm. Similarly, relative to measurements with 2.6 nA beam current, the position sensitivity of the X1 and X2 cavities is improved by approximately 14% and 11% when using 12.2 nA.

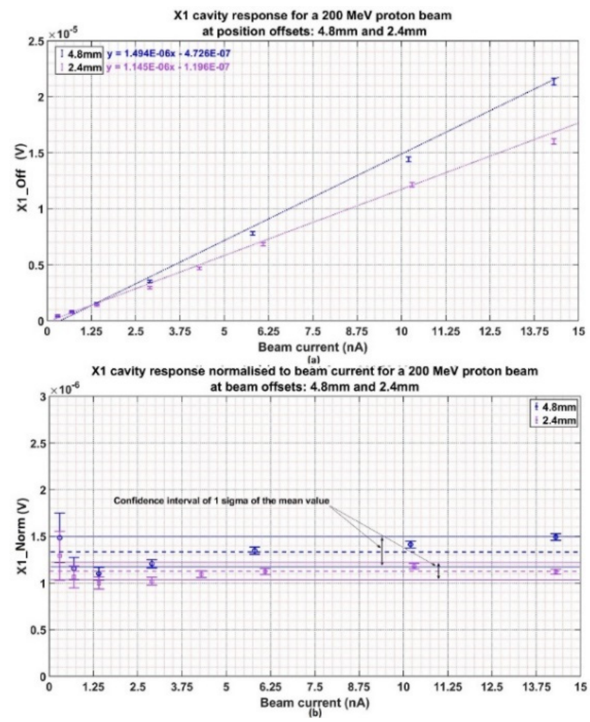

Figure 3: (a) X1 cavity response after measurement-offset correction. (b) After beam current normalisation. The error bars constitute two σ measurement uncertainty.

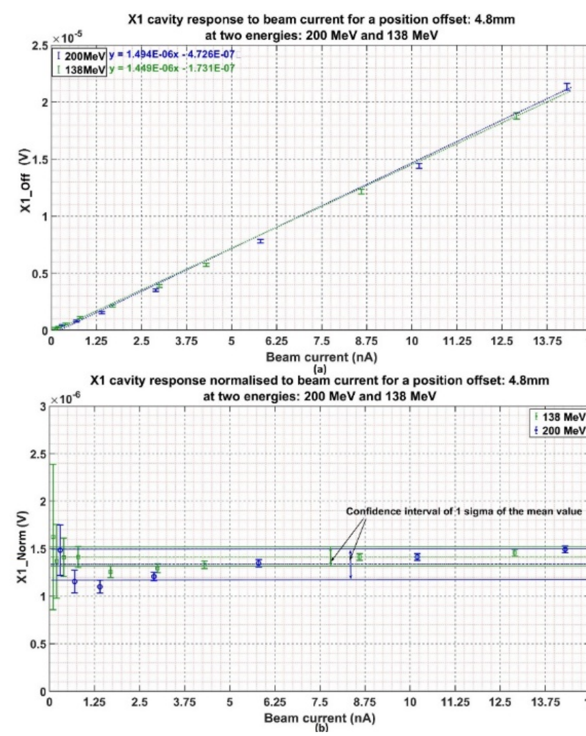

Figure 4: (a) X1 cavity response with measurement-offset correction for a 200 MeV and 138 MeV proton beam at 4.8mm towards X1. (b) After beam current normalisation. The error constitute two σ measurement uncertainty.

For a beam shift along the Y-axis, the TM_{110} mode's horizontal polarisation is unexcited and the signals from the horizontal cavities remain constant as expected (Figure 6).

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The measurement plots represented are after measurement-offset correction and beam current normalisation. The measurement-offset for the beam current and the beam energy studies represent RF interferences and for the beam position study, is the zero position information. The measurement-offset is assumed invariant in time and in phase with positive polarisation of the induced dipole mode.

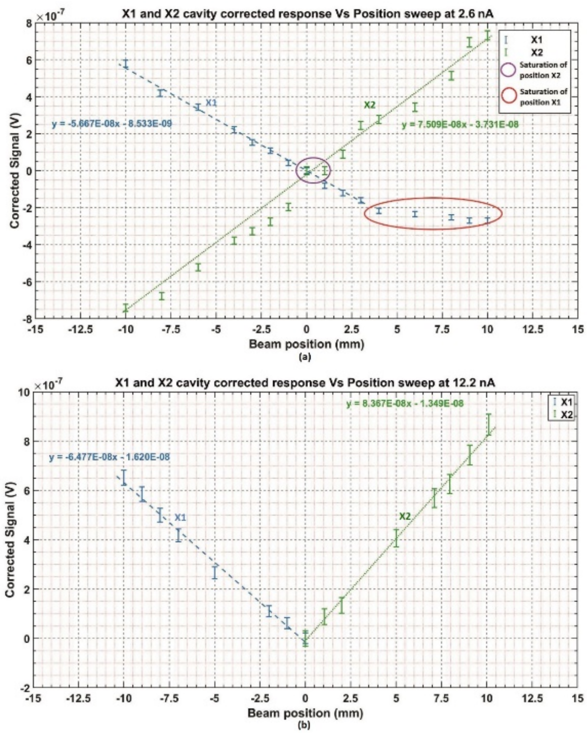

Figure 5: Beam current normalised response of both the horizontal cavities with two σ measurement uncertainty. (a) 2.6 nA beam current. (b) 12.2 nA beam current.

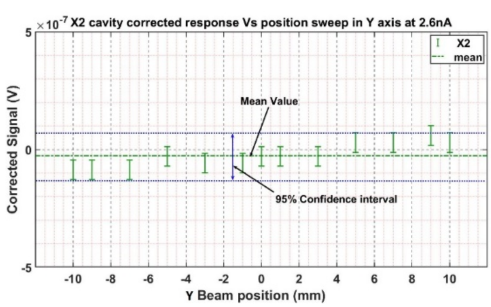

Figure 6: Beam current normalised response of the X2 cavity for position sweep in Y axis in the range -10.0 mm to +10.0 mm. The error bars constitute two σ measurement uncertainty.

The position sensitivity, the position error and the position resolution from the measurement for both the horizontal plane cavities are summarised in Table 1. The slope of the linear-fit equations in Figure 5 gives the position sensitivity of the horizontal plane cavities. The absolute difference between the calculated position and the reference position from the IC gives the position error. This total position error includes systematic error due to alignment, measurement-offset, and the random error of the measurement, which represents the position resolution and is given by the σ of the calculated position.

Table 1: Measurement Summary of X1 and X2 Cavities

Position Parameters	**2.6 nA**		**12.2 nA**	
	X1	**X2**	**X1**	**X2**
Sensitivity, nV/mm	56.7	75.1	64.8	83.7
Error, mm	0.21	0.54	0.27	0.18
Resolution, mm	0.17	0.26	0.18	0.14

DISCUSSIONS

In both the beam current and beam energy dependence study, Figure 3 (b) and Figure 4 (b), we observe a deviation in the normalised response of the X1 cavity in the range 0.5 nA ≤ Beam current ≤ 2.5 nA. This is probably due to amplitude and phase variation of the measurement-offset during measurement. Since the measurement was performed with a spectrum analyser, only the amplitude was measured and assumed as time-invariant. For beam currents higher than 2.5 nA, the BPM response (both amplitude and phase) is sufficiently large to be not affected by such fluctuations in the measurement-offset.

Similarly, in the beam position response study, for smaller product of beam current and position (i.e. beam current × position ≤ 2.5 nA mm), the measurement-offset fluctuation is dominating the amplitude measured by the spectrum analyser. When the product of beam current and position is larger than 2.5 nA mm, the BPM response is not influenced to a greater extent by the measurement-offset.

This is an important observation that will be considered while designing a dedicated measurement chain for the BPM. This dedicated measurement chain will have I/Q demodulation [5] of the BPM signal with respect to the cyclotron RF.

With this dedicated measurement chain having a signal integration time of one-second, a better isolation from RF interference and a stronger amplification, beam position measurement can be performed with this cavity BPM for beam currents in the range (0.1-10) nA.

CONCLUSION AND FUTURE WORK

In this work, we have demonstrated non-interceptive beam position measurement, for beam currents in the range 2.5-10 nA, using a four-quadrant dielectric-filled reentrant cavity monitor, with a spectrum analyser. To our knowledge, this is the first non-interceptive device for beam position measurements at a proton therapy facility.

Following these successful measurements with the BPM prototype, a new cavity BPM has been developed that is expected to deliver at least a factor two better position sensitivity than of the prototype. Initial test-bench measurements are in good agreement with the expectations. Beamline measurements of the new BPM will be performed in the near future.

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