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QUADRATED DIELECTRIC-FILLED REENTRANT CAVITY RESONATOR AS A PROTON BEAM POSITION DIAGNOSTIC*

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Abstract

Low proton beam intensities (0.1-40 nA) are used for medical treatment of tumours at the PROSCAN facility in Paul Scherrer Institut (PSI). A cavity resonator using four quadrants operating in a dipole mode resonance has been developed to measure beam positions at these low intensities. The TM110 resonance frequency of 145.7 MHz is matched to the second harmonic of the beam pulse repetition rate (i.e.72.85 MHz). HFSS (High Frequency Structural Simulator) provides the BPM geometry and important parameters such as pickup position; dielectric dimensions etc. Comparison of test bench measurement and simulation provides good agreement. The measured position and signal sensitivity are limited by the noise, so that a position signal can be derived at beam intensities of at least 10 nA . We will discuss potential methods to increase the sensitivity. The dipole cavity resonator can be a promising candidate as a non-invasive position diagnostic at the low proton beam intensities used in proton therapy.

INTRODUCTION

In proton radiation therapy at PSI, we use proton beams of low intensities (0.1-40 nA). Currently monitoring such low intensities with sufficient accuracy and reliability, is performed with ionization chambers [1].We face a strict regulation of their use due to scattering issues. We vanquish it with a non-invasive beam current monitor, working on the fundamental mode of resonance [2, 3]. To gain similar advantage for beam position information, we built a reentrant four-quadrant cavity resonator, which works on the dipole mode of resonance.

TM110 CAVITY BPM

Dipole mode (TM110) cavity resonators [4, 5], find its use for beam position measurements where beam signals are weak as they provide large signal/displacement. The directly retrievable TM110 mode is a position-dependent mode, which exists only for offset positions and is zero for a centered beam. The amplitude of this mode (combination of horizontal and vertical polarization) is proportional to the bunch charge (=beam intensity) and its position offset. For PROSCAN, we chose the resonance frequency at 145.7 MHz, which is the second harmonic of the beam pulse repetition rate of 72.85 MHz. The bunch length of the beam pulses is 2ns. However, in addition, we need a reference monopole mode (TM010) cavity at 145.7 MHz to determine the sign of displacement and common-mode elimination. Figure 1 shows a schematic layout of the device.

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The beam excited TM110 signals can be evaluated as a cylindrical cavity of a given radius and gap length:

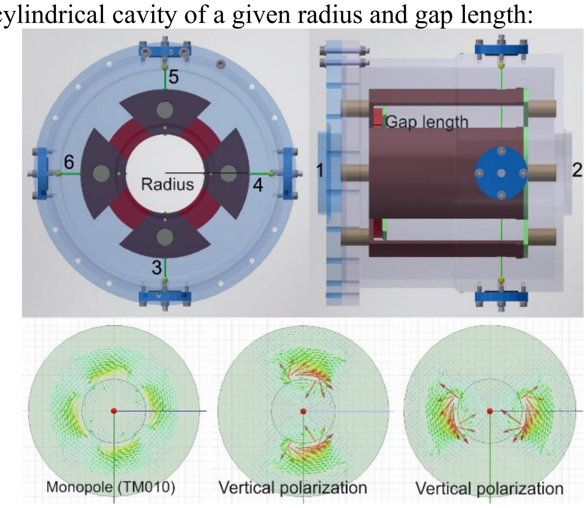

Figure 1: Schematic layout showing the 4 quadrants of the position monitor, as indicating the major parameters. 1 and 2 beam entrance and exit ports. 3-6 pickup ports.

$$V_{110}^{out}(\Delta x) = \left(\frac{R}{Q}\right)_{110} .\omega.q.\sqrt{\frac{50\Omega}{Q_L}}B_c\frac{\beta}{1+\beta} \qquad (1)$$

where, (R/Q)110, is the normalized shunt impedance of the TM110 mode for an unloaded quality factor, Q; ω is the angular resonance frequency; q is the bunch charge, QL is the loaded quality factor, Bc is the beam-coupling coefficient, β is the pickup coupling coefficient [4]. Below we will describe how these parameters can be optimized.

ANSYS HFSS SIMULATION

We use ANSYS HFSS (High Frequency Structural Simulator) to calculate H and E field distributions in different design layouts and to find the optimal geometrical parameters [6].

As shown in Fig. 1, the prototype comprises of four suspended Alumina ceramic [7] filled reentrant cavities within a common grounded cylinder and supported by PEEK[8]. The four cavities, occupy each quadrant of the grounded aluminum cylinder (two for X and two for Y) and are insulated with respect to each other.

Analysis Setup: Boundaries and Excitations

We have developed a parametric model of the prototype with the help of the inbuilt modeller.. We have designed a transmission-line-like structure with a Perfect Electric Conductor (PEC) as a centre conductor, which simulates the proton beam. We have performed a network analysis [9] to evaluate the transmission coefficients (S_{ij}) between the waveport excitations of the simulated beam and the pickup ports at the cavities.

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We employ driven modal solver from HFSS for the network analyser simulation. For all of the four floating cavities, we couple the signal out inductively with long antenna loops at the pickup ports. Beam entrance and exit ports are terminated by the characteristic impedance of a coaxial line equivalent. For the pickup ports, we have assumed a 50Ω port impedance.

Optimized Model

Following Eq. (1), for a given bunch charge and resonance frequency, we can maximize the signal output by maximizing either (R/Q)110, Bc or β.

(R/Q)110 can be maximized by lowering the cavity radius and increasing the cavity gap length. Similarly, Bc can be maximized by lowering the cavity radius. The coupled out signal amplitude is hugely influenced by β as it is indirectly proportional to QL, loaded quality factor. This is directly influenced by the antenna loop. Having a loss-free dielectric like the alumina ceramic in our model, helps to optimize the resonator. Compared to a pillbox cavity we have relatively smaller cavity radius and a larger gap length.

Simulation Results

Figure 2 (a) shows the Sij-transmission plots (between i=pickup port (3-6) and j=1=beam entrance) for both X plane and Y plane cavities, for 2mm offset in Y plane. Figure 2 (b) shows the H-field plots at the cross-sectional plane halfway the pickup height. From Fig. 2 (a) we observe for a positive beam offset in one plane (S31 (red)), that the dipole mode configuration in the orthogonal plane is not changing (S41 and S61 (pink)). For the in-plane cavities, we observe S-transmission (S31 as peak and S51 (blue) as valley) indicative of the vertical beam offset. The frequencies corresponding to S31 and S51 differ by only 100 kHz. It is due to the presence of a unipolar monopole mode at 127.1 MHz, affecting the polarity of the dipole mode and shifts only the valley but not the peak coefficient. This shows that the mode contamination does not influence a near-by cavity for a given offset. An optimized HFSS model (with beam pipe extensions) matched to 145.7 MHz provides us with the geometry and its dimensions. The coupling parameters are as in Table 1.

TEST BENCH CHARACTERIZATION

We characterized the BPM on a stand-alone test bench [3] as 2-port network analyser measurements between entrance and measurement ports identical to the simulation.

Test Bench Results

Halfway the measurements we have inspected the BPM to verify the mechanical positioning of the cavities and the ceramic.

Before Inspection We measured S-transmission between the 2 cavities of each plane without beam analog as shown in Fig. 3. This provides information on modes that exist in the resonator within a given frequency span and is in good agreement with simulation bar the 3 dB lower coefficients.

After Inspection We summarize the S- measurement for all pickup ports with respect to the beam entrance (with beam analog) in Table 1.The dipole frequencies for both X and Y plane is different without a beam analog as seen in Fig. 3 compared with beam analog measurements. As can be seen in Fig. 3, slight mechanical offset (±0.1 mm and ±0.1°) due to the inspection have an effect of resonance frequencies (2 MHz) as well as on the sensitivity (3dB).

The pickup sensitivity of individual cavities are listed in Table 1, relative to the input signal power (in dB) and in nV for a beam current of 1 nA at their respective resonance frequencies. The sensitivities of the cavities are not the same, as shown in Fig. 4. The deviations between the individual cavities indicates the sensitivity to cavity symmetry for dipole mode configuration.

DISCUSSION

In the absence of a beam analog, the measured X and Y dipole mode frequencies after inspection, differ by 500 kHz and 2.4 MHz from the design demands. In addition, the monopole mode frequency and the Higher Order Modes (HOM) differs by 2 MHz (without beam). With 16.7 MHz between the monopole mode and the dipole mode, mode contamination affects the performance.

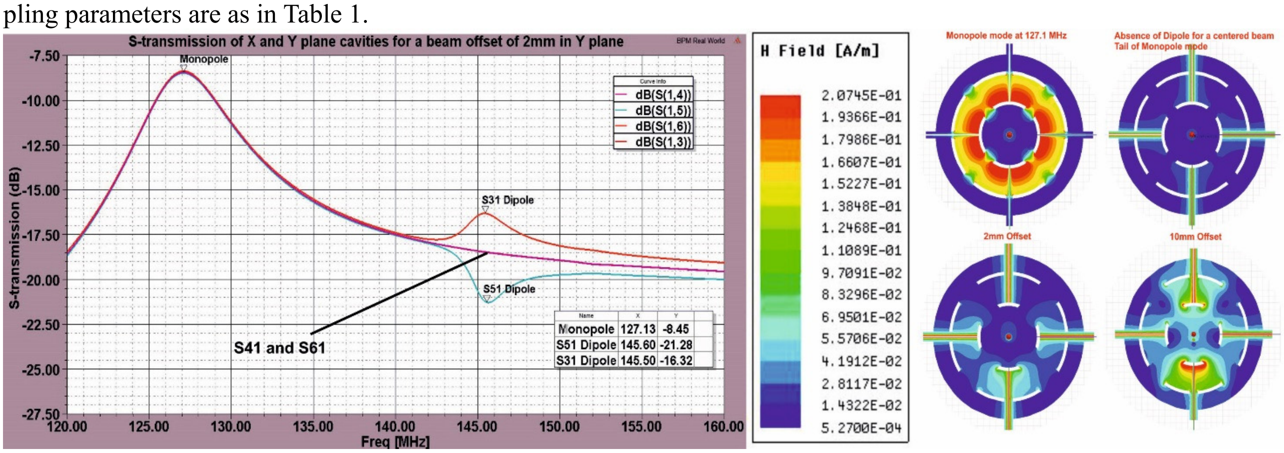

Figure 2: (a) S-transmission plots for both X and Y plane cavities for 2mm offset in Y plane. (b) Field configuration of monopole and dipole modes.

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Table 1: Comparison of S-Transmission for Individual Cavities Corresponding to Positive Displacements Between HFSS Results and Measurements

Offset	(dB)	at 146.0 MHz (dB) Y plane		at 148.1 MHz (dB) X plane		nV for 1nA equivalent				
(mm)	HFSS	S31	S51	S41	S61	HFSS	S31	S51	S41	S61
0	-18.37	-17.5	-17.95	-20.11	-19.3	16.19	17.89	16.99	13.25	14.46
2	-16.32	-16.18	-16.66	-18.36	-17.7	20.49	20.83	19.71	16.20	17.48
5	-13.78	-14.25	-14.78	-16.27	15.36	27.46	26.01	24.47	20.61	22.89
10	-10.8	-11.59	-12.22	-13.38	12.2	38.69	35.33	32.86	28.75	32.93
15	-8.63	-9.55	-10.2	-11.2	-10.01	49.67	44.68	41.46	36.95	42.38

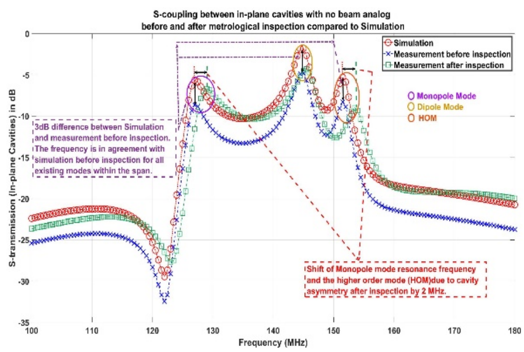

Figure 3: S-coupling for in-plane cavities before and after inspection compared with simulation. Marked in circles are the modes in the structure between 100-180 MHz.

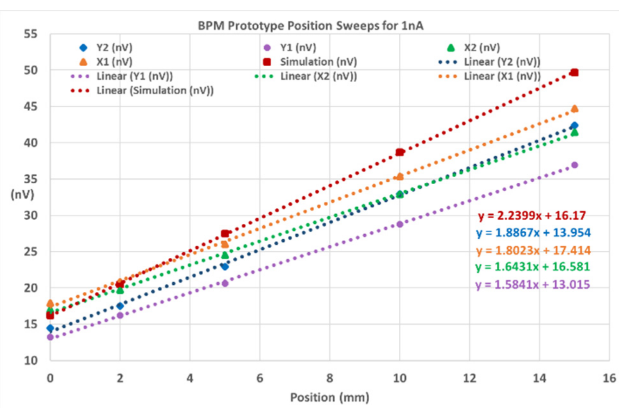

Figure 4: Position sensitivity comparison between simulation and test bench for positive displacements.

This can be prevented by using a monopole mode cavity designed at 145.7 MHz and use it to remove the charge dependency from the dipole mode configuration [10, 11]. The 3 dB difference is due to a 15% smaller antenna loop compared to the design as this directly contributes to QL.

The validity of the prototype is confirmed by comparing the signal sensitivity for a given beam offset of 2 mm, between theory (Eq. (1)), simulation and measurement. For a bunch charge of 1.36E-17 C, the output voltage reads as 25 nV (theory), 20.5 nV (simulation) and (20.83 nV measured S31).

For a beam with a nominal bunch length of 2ns and a repetition rate of 72.85 MHz, the 2nd harmonic component is approximately 25% of the beam current. This provides a signal of 5 nV for 1 nA at 72.85 MHz (- 153 dBm) with a SNR of 17, assuming 4 dB noise factor for an integration time of 1sec (- 174.0+4.0 = -170.0 dBm). This places a stringent condition on the use of the BPM for ultra-low signals. To measure signals with a SNR of 35-40, we thus need a beam intensity of minimum 8-15 nA.

CONCLUSION AND FUTURE WORK

After careful evaluation and characterization studies, the BPM prototype is promising for beam currents of at least 10 nA. We are investigating possibilities to decrease this limit.

Prior to beamline testing, the prototype must be reassembled preserving symmetry with the highest precision (better than ±0.1 mm and ≤±0.1°). We must also evaluate crosstalk between the cavities and beam-angle corrections as they limit the resolution.

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