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REENTRANT CAVITY RESONATOR FOR LOW INTENSITIES PROTON BEAM MEASUREMENTS*

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Abstract

A non-interceptive beam current monitor has been developed to investigate the measurement possibilities of low-intensity beams down to 1 nA for proton therapy machines without the drawback of interceptive monitors. This works on the principle of a reentrant cavity resonator such that its fundamental mode resonance frequency of 145.7 MHz matches the second harmonic of the pulse repetition rate of the cyclotron beam, i.e., 72.85 MHz. The Driven Modal analysis from the simulation tool ANSYS HFSS was used for parametric model development and to optimize design parameters such as e.g. the position of the inductively coupled pick-ups. A ceramic plate has been inserted in the resonator gap to relax the precision required during manufacturing. A test bench has been designed and constructed for the characterization tests of the prototype. Comparison of the simulated and the experimental scattering parameter from the test bench shows a good agreement.

INTRODUCTION

For proton therapy at PSI, monitoring low intensity proton beam (1-800 nA) is a necessity. This is traditionally performed using an ionization chamber [1]. However, this degrades the quality of the beam due to scattering issues. Therefore, this implies a strict regulation of the use of these devices during therapy. To mitigate this issue, a non-interceptive beam current monitor has been developed which is also advantageous for on-line control. This monitor works on the principle of a reentrant cavity resonator.

REENTRANT CAVITY RESONATOR

The reentrant cavity resonator designed at PSI based on Ref. [2] is a coaxial resonator tuned at 145.7 MHz, matched to the 2nd harmonic of the beam pulse repetition rate of 72.85 MHz. The resonator is a combination of a capacitor and a cavity acting as an inductor. Its functioning principle is illustrated in Fig. 1 [3]. It shows the induced E field and H field concentrated in the capacitive region and inductive region respectively. The resonant frequency could be evaluated by considering the resonator as a coaxial transmission line [4].

The inductance and capacitance can be approximated as

$$L = \frac{\mu_o}{2\pi} \ln \frac{b}{a} \tag{1}$$

$$C_{coax} = 2\pi\varepsilon_o / \ln \frac{b}{a} \tag{2}$$

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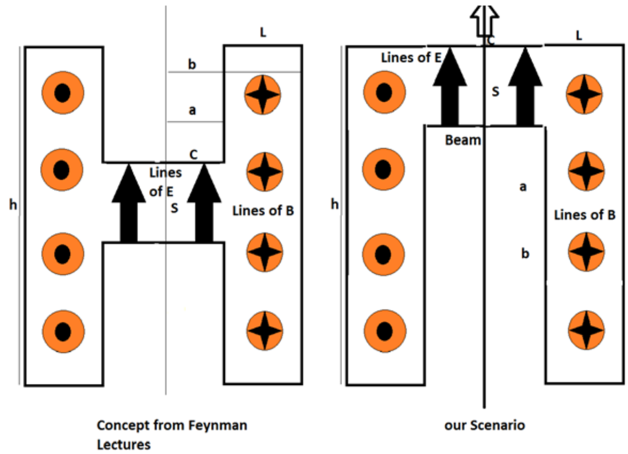

Figure 1: Resonators of progressively higher resonant frequencies [3]. Adaptation to PSI scenario.

The central gap capacitance will be of the form

$$C_{gap} = \varepsilon_o \frac{\pi a^2}{s} \tag{3}$$

The corrected resonance frequency can then be expressed as

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{[L(C_{coax} + C_{gap})]}} \tag{4}$$

The dimensions of the resonator could be determined as given by [5].

ANSYS HFSS SIMULATION

ANSYS HFSS (High Frequency Structural Simulator); a high frequency electromagnetic field simulation solution is used to investigate the reentrant cavity resonator [6].

The prototype design consists of a one capactive region filled with a dielectric as shown in Fig. 2. The material for the dielectric is Macor ceramic [7]. This makes the capacitive gap larger. It then relaxes the machining precision requirements and simplifies tuning if required.

Parametric Model Creation

The ANSYS HFSS 3D modeller is used to create fully parametric design without editing complex macros/model history [8]. The model is created as a coaxial transmission line with a reentrant zone filled with the Macor. The model is created as a vacuum volume with necessary boundary conditions, i.e., Aluminium as ground cylinder.

Analysis Setup

Driven Modal solution type is used for investigating the resonator. With Macor as dielectric, the conducting surface of the model was assigned as Aluminium. A pair of long and short inductive pickups is used for measuring the beam induced magnetic field in the resonator.

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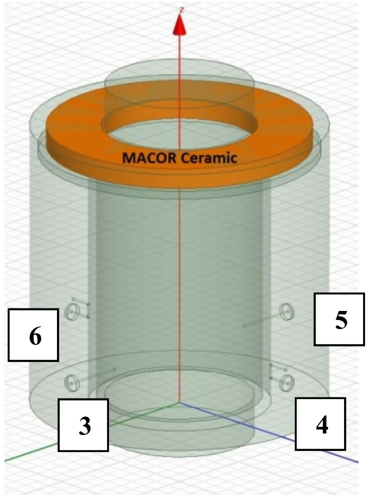

Figure 2: Parametric model of the reentrant cavity resonator designed using the HFSS 3D modeller. (3, 4, 5 and 6 represent waveport excitations with 50 Ohms port impedance). 3 and 5 are long pickups. 4 and 6 are short pickups.

Waveport excitation is assigned with port impedance of 50 Ohms. The scattering parameters, as simulation output results, provide a complete description of the RF behaviour of the resonator.

Simulation Results

Figure 3 represents the induced field distribution from the simulation model. The field distribution confirms the working principle of the resonator prototype as described in the theory above. The scattering parameter coupling between one long inductive pickup marked 3 and a short inductive pickup marked 4 is calculated from the simulation and is represented in Fig. 4.

Similarly for all combination of pickups, the resonance frequency and corresponding Q factor is evaluated and is represented in Table 1.

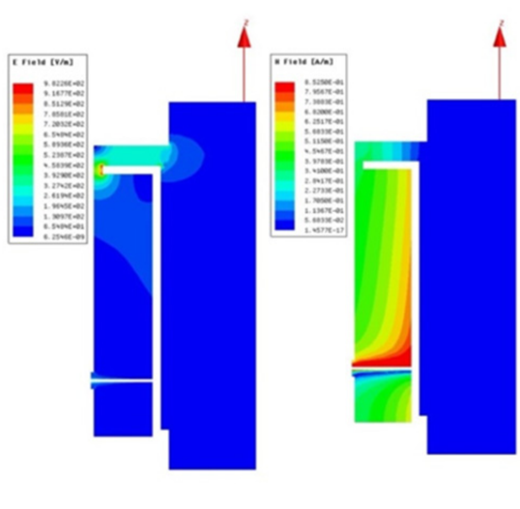

Figure 3: Induced E and H field within the resonator. The image is derived from the HFSS simulation.

EXPERIMENTAL MEASUREMENT

Mechanical Model

From the simulation parametric investigation, the mechanical dimensions of the cavity resonator have been deduced and a prototype has been built based on it as shown in Fig. 5.

Test Bench Characterization

A standalone test bench has been built to perform characterization tests, i.e., network analysis to evaluate the scattering parameter between pickup combinations. The working components of the test bench include the prototype, FCL100 linear drives from Newport, and a ZNB8 network analyser from Rohde-Schwarz. The 2-port network analysis is performed on the resonator with the other two pickup ports terminated with 50 Ohms. This ensures that the test bench and the simulation environment are identical.

Test Bench Results

2-port network analysis measurements have been performed for all pickup combinations. Figure 4 represents the measured S34, i.e., scattering parameter between a long and a short pickup.

The measured resonance frequency is 148.64 MHz; the Q factor is 40.87 with a corresponding transmission loss of 21.88 dB. For other possible combinations of pickups, the measured resonance frequency, its corresponding peak value and Q factor is summarised in Table 1. Note that the resonance frequency slightly varies depending on the pick-ups for the measurements. This 50 kHz variation illustrates how closely simulations can describe an experimental set-up with its inherent imperfections.

DISCUSSION AND FUTURE WORK

For non-interceptive monitoring of low intensities proton beam, a reentrant cavity resonator was designed to match the 2nd harmonic of the beam pulse repetition rate (72.85 MHz), i.e., 145.7 MHz. The resonator has the induced E field and H field concentrated mostly in the capacitive and inductive regions respectively. A prototype was built based on the simulation results and could be characterized on a test bench. Simulations and test bench measurements are compared in Table 2.

The measured resonance frequency of the reentrant cavity resonator is approximately 2% higher than the simulated resonance frequency. The corresponding S-peak value of the measurement is better than the simulated values for all possible combinations of pickup. The measured Q value is as well in very good agreement with the simulated value.

The difference in the measured resonance frequency of the resonator from the simulation can be mainly attributed to manufacturing tolerance of the Macor ceramic, as the dielectric constant plays an influential role.

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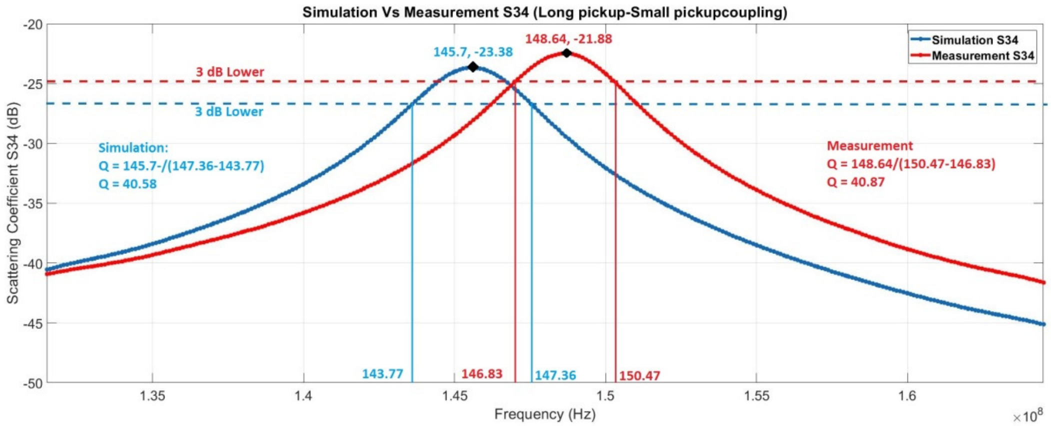

Figure 4: S34 coupling for the cavity resonator model from the simulation. The peak frequency corresponds to the resonance frequency of the resonator. The simulated Q value of the resonator is 40.58.

Table 1: Simulated and Measured S34 (Scattering Parameter) for all Pickup Coupling and their Corresponding Q Value

S parameter	Simulated Resonance Frequency (MHz)	Measured Resonance Frequency (MHz)	Simulated S-peak (dB)	Measured S-Peak (dB)	Simulated Q-Value	Measured Q-Value
S34	145.7	148.64	-23.38	-21.88	40.58	40.87
S35	145.7	148.68	-1.53	-1.34	40.58	40.77
S36	145.7	148.64	-23.38	-21.22	40.58	40.75
S45	145.7	148.64	-23.38	-21.89	40.58	40.58
S46	145.7	148.69	-45.22	-41.78	40.58	40.73
S56	145.7	148.64	-23.38	-21.23	40.58	40.64

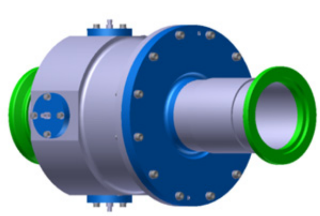

Figure 5: Mechanical model of the reentrant cavity resonator prototype. The dimensions are taken from the ANSYS simulation model.

Table 2: Simulation vs Measurement for the Scattering Parameter and its Corresponding Peak and Q Values

Deviation of the measurement from the simulation			
S-Parameter	**Resonance Frequency**	**S-peak (dB)**	**Q-Value**
S34	2.01%	1.5	0.7%
S35	2.04%	0.19	0.46%
S36	2.01%	2.16	0.42%
S45	2.01%	1.49	0%
S46	2.04%	3.44	0.37%
S56	2.01%	2.15	0.15%

Moreover, the dielectric constant of the Macor ceramic is frequency dependent [9]. Hence, the value used in the simulation could be different from the dielectric constant of the Macor that is used in the construction of the prototype.

The advantage of using Macor is its machining flexibility and this could be used to tune the resonator to 145.7 MHZ. This will be investigated with the help of the ANSYS HFSS simulation by parametrizing the dielectric constant and performing a parametric sweep analysis to understand the influence of the dielectric constant.

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