TUNABLE Q-FACTOR GAS-FILLED RF CAVITY

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Abstract

Fermilab is the main institution to produce the most powerful and wide-spectrum neutrino beam. From that respective, a radiation robust beam diagnostic system is a critical element in order to maintain the quality of the neutrino beam. Within this context, a novel radiation-resistive beam profile monitor based on a gas-filled RF cavity has been proposed. The goal of this measurement is to study a tunable Q-factor RF cavity to determine the accuracy of the RF signal as a function of the quality factor. Specifically, the measurement error of the Q-factor in the RF calibration is investigated. Then, the RF system will be improved to minimize signal error.

INTRODUCTION

A neutrino beam is a unique probe for researching beyond the standard model. Within this context, the hadron beam utilized in the production of a high-quality and wide-spectrum neutrino beam at Fermilab requires a radiation robust beam profile diagnostic system. To this end, a novel radiation-resistive beam profile monitor based on a gas-filled RF cavity has been proposed to fulfill this purpose.

The incident energetic hadronic particles ionize those in the gas of the cavity. The amount of beam-induced plasma is then proportional to the number of incident particles. The interaction of the ionized particles with the radiofrequency field inside the cavity can then be considered as plasma loading. This phenomenon is interpreted as a plasma resistance which induces the RF power dissipation in the plasma. The beam profile is reconstructed by observing the amount of plasma loading from an individual cell in a multi-RF cavity which forms a hodoscope structure.

The proposed research and development timeline for this monitoring system consists of a series of beam tests with different intensities and cavity designs. First, the apropriate quality factor (Q-factor) of the cavity will be studied by performing a table-top test with a novel tunable Q-factor RF cavity. Following this measurement the cavity will be exposed to a beam test from which the accuracy of the signal will be analyzed. A final intense beam test will be performed to evaluate the radiation robustness of the RF cavity for hadron beam profile monitoring applications.

CONCEPTUAL DESIGN

The use of a Radio-Frequency cavity as a hadron monitoring system has the potential to provide a radiation robustness

technique for reconstructing the beam profile [1]. The gas-filled RF cavity hadron monitor works by correlating the RF power loss inside the cavity (from gas ionization) to the incident beam energy. Thus, the plasma loading will be proportional to the beam intensity [2], [3]. Within this context, the quality factor of the cavity (Q-factor) is a key parameter to obtain the ratio between the power supplied to cavity to the power lost due to plasma loading.

High Q-factor RF cavities are commonly desired in accelerator applications since a low power supply can be used to gradually increase the energy inside the cavity without loosing power. However, the nature of high-Q cavities also prevents to quickly feed energy back into the cavity due to its large impedance. On the other hand, low Q-factor RF cavities allow to more rapidly feed power back into the cavity to compensate for energy loss. Nevertheless, low Q-factor cavities require larger supplies of power to mantain energy inside the cavity. The opposite behavior between high-Q and low-Q cavities require the development of a hadron monitoring system with a RF cavity at an "intermediate" quality factor. The Q-factor of the RF cavity hadron monitor needs to be high enough to guarantee the containment of RF power inside the cavity, while low enough so that power can be supplied back quickly after the beam ionization.
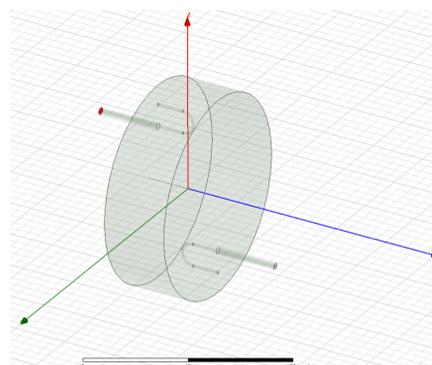
Figure 1: Conceptual design of tunable Q-factor pillbox RF cavity.

In light of this problem, an innovative approach was taken to determine the adequate quality factor of the hadron monitor RF cavity. Specifically, a tunable Q-factor RF cavity was develop to study this precise problem. Figure 1 shows the conceptual design of the tunable Q-factor RF test cavity. A main frame is a 2.45 GHz pillbox stainless steel RF cavity and two loading loops installed on the top plate to adjust the Q-factor. The Q-factor can be tuned from approximately 1,000 to 100 by rotating the loading loops and thus changing

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the coupling strength of the signal to the cavity. Figure 2 shows a block diagram of the RF electronic system. Since the peak power of the cavity is 1 - 10 mW, a standard RF source (HP8341A + a solid-state RF amplifier) is used. In order to measure RF envelope precisely, a fast RF peak power detector (Boonton, RTP5000) will be used. The power meter has good sensitivity in the range of -50 to 20 dBm. A spectrum analyzer (E4445A) and/or network analyzer are used to measure the coupling strength of each loop and the quality factor of cavity.
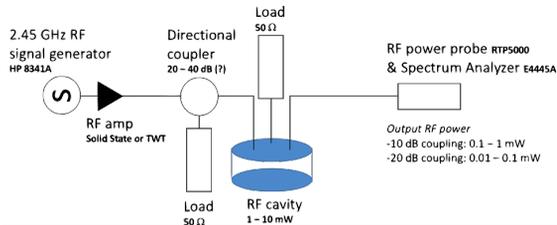
Figure 2: Electronic configuration of calibration measurements of tunable Q-factor RF cavity.

Numerical simulation for the pillbox cavity were performed on HFSS software as shown in Figure 3 and Figure 4. During these analysis it was observed that by rotating the coupling loops inside the cavity a greater load impedance was obtained and thus the RF power decreased. The critical coupling and decoupling of the the loading loops then shows the possibility of increasing and decreasing the excitation of the TM010 resonant mode of the cavity. In essence, *power bleeding* through magnetic coupling loops is the main mechanism behind the tunability of the Q-factor inside the cavity. The images below show captures of the HFSS simulation.
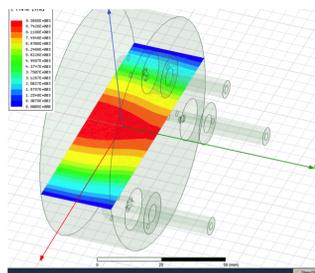
Figure 3: HFSS software simulation of tunable Q-factor RF cavity (1).

The tunable Q-factor RF cavity design was fabricated, calibrated, and tested by rotating the magnetic coupling loops. The determination of the corresponding quality factor was done with a spectrum/network analyzer by measuring bandwidth and resonant frequency.

BENCHTOP MEASUREMENTS

The goal of these measurements is to use the tunable Q-factor RF pillbox cavity described in the previous section to study the accuracy of the RF signal as a function of the Q-factor. Measurement error in the RF calibration is particularly investigated in order to improve the RF cavity design.
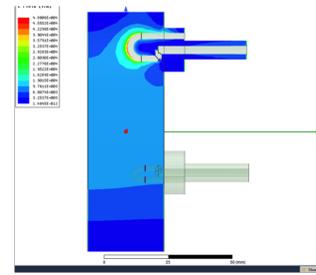
Figure 4: HFSS software simulation of tunable Q-factor RF cavity (2).

The tunable Q-factor cavity will also be used in future beam tests in which the electron capture time will be measured as functions of Q-factor and concentration of electronegative dopant. Figure 5 shows a physical image of the tunable Q-factor RF cavity used in the benchtop measurements.

Figure 5: Tunable Q-factor Radio-Frequency cavity.

The experimental test bench utilizes a network analyzer in order to study the variation of the bandwidth around the resonant frequency of the RF cavity. The loading loops are rotated in order to apply more coupling strength and tune the quality factor of the cavity. The measurement is performed systematically in 10 degrees rotation increments while recording the matching impedances, loaded Q-factor, and computing the resultant resonant Q-factor. The network analyzer is capable of performing a loaded quality factor calculation that in turn allows to estimate the Q of the cavity. Currently, multiple different coupling loops have been studied which couple with the TM resonant mode in a greater or lesser way. The critical coupling of the loops span a quality factor that ranges from $\approx 150 - \approx 850$.

Based on the theoretical behavior of the cavity, when the coupling loops are positioned at 0° radially with respect to the center, the coupling with the magnetic field is maximum. The flux area through the loops is completely open and power should be dissipated at the loops impedances. When the loops are rotated at 90°, however, the coupling was expected to be minimum, as the flux area is not facing the magnetic field and thus there is no power dissipation at the loads. Nevertheless, the results presented in Figure 6 shows a completely opposite, yet interesting, behavior.

Thus, in the first set of benchtop measurements two important conclusions can be drawn: 1) The rotation of magnetic
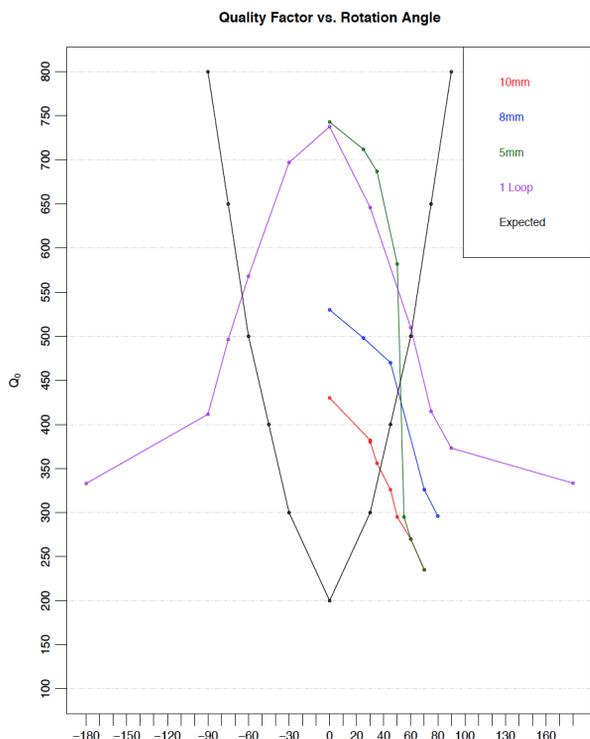
Figure 6: Results plot of measurements of quality factor vs. rotation degree of loading loop.

coupling loops is capable of changing the Q-factor of the cavity throughout the predicted range. 2) The Q-factor of the cavity changes with an opposite behavior than the one initially predicted. Multiple explanations were proposed for this phenomenon, including coupling with undesired modes of the electric field, or disturbances of the magnetic field near the loop due to symmetry breaking.

In an attempt to study the behavior of this cavity further, the field distribution inside the cavity was analyzed using a bead-pull procedure. Based on this measurement it was possible to confirm that the field distribution inside the cavity greatly agrees with that simulated in HFSS software. Alternatively, the geometry effect near the pickup loop was more carefully studied using HFSS. In this simulation it was observed that the strength of the local field excited near the pickup loop is sufficiently relevant to disturb the fundamental TM010 mode inside the cavity as shown in Figure 7 and Figure 8.
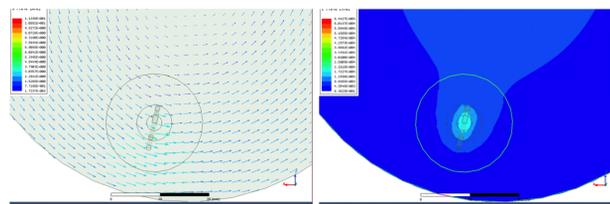
Figure 7: HFSS simulation of magnetic field (left) and electric field (right) before rotation.
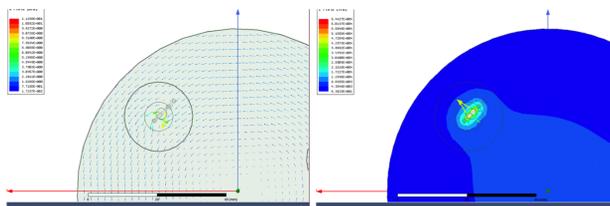
Figure 8: HFSS simulation of magnetic field (left) and electric field (right) after rotation.

Throughout the realization of the benchtop measurements for the tunable Q-factor RF cavity, the fundamental concept behind the tunability of the quality factor was proven. Independently from the rotation angle, pickup loops can couple with the magnetic field inside the cavity and bleed power through loads. The initial design of the RF cavity used the rotation of loops to adjust the variability of magnetic flux area. Nevertheless, the opposite behavior observed in the experimental benchtop measurements asked for a theoretical explanation. Propsed hypotheses include the excitation of undesired modes by rotation of the loops as well as local field disturbances due to near-field excitations.

ACKNOWLEDGEMENTS

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