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The mapping & avoidance of high order cavity modes

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The mapping & avoidance of high order cavity modes

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***Abstract* — In this paper a technique developed in 2016 [1] is presented for mapping the multidimensional, multi-mode high order mode landscape of a beam driven super conducting RF cavity. The initial use case for this technique was intended to allow longitudinal gradient control of a beam driven super conducting cavity while simultaneously avoiding many dangerous high order modes and excessive component stresses. This paper will focus on the stability and component stress considerations of the 56MHz superconducting cavity, located in the 4 o'clock sector interaction region of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The 56MHz cavity is intended to work in conjunction with the Stochastic Cooling system to improve the longitudinal confinement in the central 197MHz RF bucket and thus increase the integrated luminosity during heavy ion beam runs at RHIC [2][3].**

Keywords— 56MHz, HOM, HOMD, RHIC, FMD, Mode Mapping

I. Introduction

Superconducting radio frequency (SRF) cavities are essential components of many particle accelerators, providing high acceleration gradients at high power efficiency. While extremely power efficient, these cavities are susceptible to the excitation of high order modes (HOMs) [4][9], which can lead to beam instability and reduced performance due to localized component heating, multipacting [5], and in the worst case a cavity quench.

To mitigate these effects, it is essential to employ effective HOM damping techniques. In this paper, the challenges of high order mode damping will be discussed, and a proposed solution that eliminates the need and expense of dedicated HOM dampers in the 56MHz superconducting cavity at RHIC is presented.

One of the most significant challenges in HOM damping is the broad frequency range in which many dangerous high Q resonances may reside. Unlike the fundamental mode, which has a well-defined resonant frequency, HOMs can occur at a multitude of frequencies above the primary cavity design frequency and will be swept (often to a larger extent) with the cavity tuner sweep.

Traditional HOM damping techniques are designed to damp these high frequency resonant modes simultaneously to ensure the broadband cavity impedance remains below an acceptable level. Specifically, it is of great importance to sufficiently damp the monopole modes which are the most likely modes to be driven by, and to kick, the beam longitudinally.

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It is often the case that electrical, mechanical, and thermal stresses become limiting factors in the usefulness of most HOM damper designs thus requiring n dampers to achieve the required Ql@HOMtot or Ql@HOM/n. One of the primary challenges to overcome in HOM damper design is to achieve fundamental field isolation while maintaining a high degree of coupling to the HOMs. This is especially challenging when magnetic field coupling is used. This is because even if the desired load isolation is achieved (reducing the extracted fundamental current to zero), the HOM damper coupling loop is emersed in high fundamental magnetic fields which gives way to eddy current excitation and thus localized heating in the loop structure itself.

The high order mode dampers designed for use in the 56MHz super conducting cavity at RHIC suffered from many of the challenges stated above and thus were removed from the cavity completely. In their place resides a new method for avoiding beam induced energy accumulation at high Q, high order mode cavity resonant frequencies.

II. Design Concept

This technique is based on the dynamic mapping of all longitudinal HOMs where the beam spectrum is expected to be of sufficient magnitude to excite one or more high order cavity resonances. This can ultimately lead to an uncontrolled high frequency gradient buildup and beam instability.

In the original implementation, the dynamics of the mapping were defined by three parameters which included the cavity tuner deflection (T_{POS}), and the depth of penetration of both the fundamental damper (Dp_{FMD}) and the fundamental power coupler (Dp_{FPC}). After a preliminary review, a static value was selected for the Dp_{FPC} based on the coupling factor required for proper microphonic compensation with careful attention paid to various subsystem stresses and constraints.

With a discrete sampling of the operational space, a map can be created at each high order mode that has been selected for analysis. At each point of the parametric sweep, the resonant frequency ($fres$), and Q external ($Qext$), are recorded and used in conjunction with the simulated (R/Q) for each of the relevant eigenmodes. The properties of each resonance are then used to calculate the elemental equivalent parameters needed to properly describe the evolution of each resonance for all combinations of T_{POS} and Dp_{FMD}. Example expressions for the operational space sampling can be observed below.

a) Measured Data

$$fres_{(T_{POS},Dp_{FMD})n} = \begin{pmatrix} fres11 & fres12 \\ fres21 & fres22 \end{pmatrix}_n \quad Qext_{(T_{POS},Dp_{FMD})n} = \begin{pmatrix} q_{ext11} & q_{ext12} \\ q_{ext21} & q_{ext22} \end{pmatrix}_n$$

n = Cavity Odd Harmonic Numbers

b) Characteristic Shunt Impedance (Eigenmode Solution Result)

$$\left(\frac{r}{q}\right)_n$$

c) Resulting Component Model Synthesis

$$r_{11} = \left(\frac{r}{q}\right)_n q_{ext11} \qquad l_{11} = \left(\frac{\left(\frac{r}{q}\right)_n}{2\pi f_{res11}}\right) \qquad c_{11} = \frac{1}{2\pi f_{res11}\left(\frac{r}{q}\right)_n}$$

$$R_n = \begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix}_n \quad L_n = \begin{pmatrix} l_{11} & l_{12} \\ l_{21} & l_{22} \end{pmatrix}_n \quad C_n = \begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix}_n$$

It should be noted that with the recent upgrades to the cavity and subsystems, there are now two fundamental power couplers and so theoretically the mapping can be created in a four-dimensional space. Any attempt at a first pass mapping should be limited to a small subset of the coupler ranges. It's likely however, that given the desired performance parameters, static values can be selected for the two FPCs. If the HOM mapping data does not change much compared to the original scan performed in 2016 this will likely be sufficient. In particular, the comprehensive FMD upgrades presented in [6] will likely be enough to avoid additional mapping complexity. It is important to note however, if the mapping changes in a way that makes a clean program path more difficult, there remains a possibility that one or both FPCs may also need to be dynamically manipulated which could result in the requirement for a three or four-dimensional mapping. This will ultimately depend on the changes in the effective cavity geometry and relative field distributions given the FPC and FMD upgrades.

III. Analysis

The above defined measured data (a), simulated characteristic shunt impedance (b), were imported into MATLAB® to generate the component model synthesis matrix (c), for each of the FMD and Tuner locations.

The code then generates a two-beam (post re-bucket) time domain bunch train as it would appear at the gap of the 56MHz cavity. This is shown below in Figure $1_{(Top)}$.

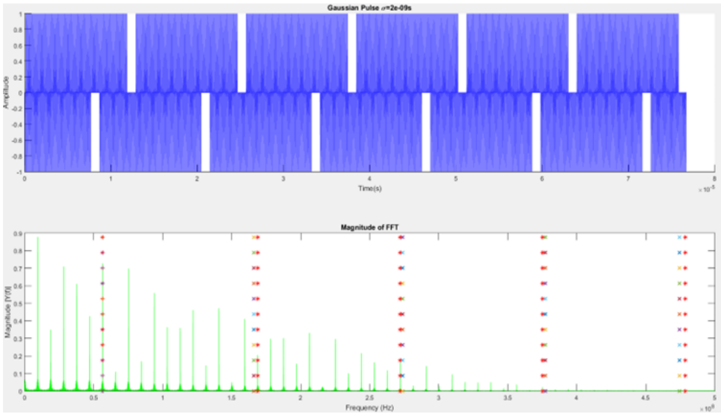


Figure 1

A closer look at the dual-beam bunch structure used can be observed below in Figure 2.

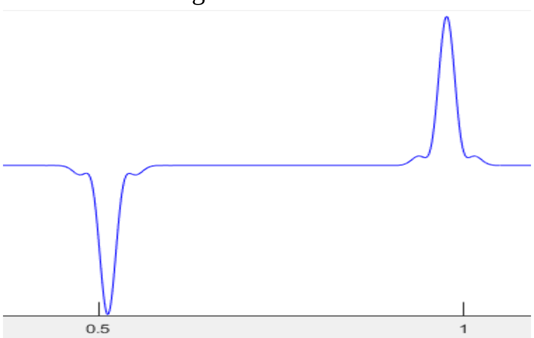


Figure 2

The FFT of the bunch train is then calculated and shown in Figure $1_{(Bottom)}$. The beam current magnitude is taken at each revolution line within each HOMs operational space and evaluated as a sinusoidal driving current. The vertical points tracing from bottom to top indicate the frequency bounds of each HOMs operational space. An example of this can be observed more readily in the selective n=3 FFT result shown in Figure 3.

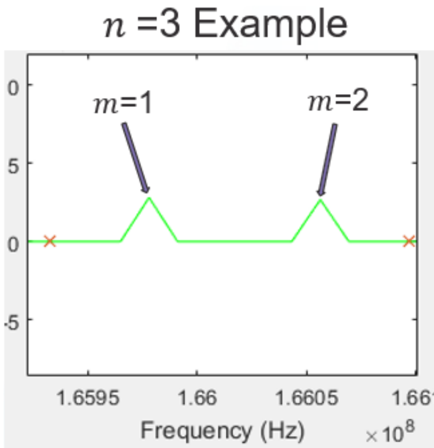


Figure 3

With the driving terms resolved, each beam revolution line within a given HOM tuning range is evaluated independently and the cumulative sum of the resulting voltages are calculated. The formulas derived for this are shown below.

$$Z_{nm} = \frac{1}{\frac{1}{R_n} + \frac{1}{j2\pi frev_m L_n} + j2\pi frev_m C_n}$$

$$Vp_{mode\ n} = \sum_{m=1}^{m} \sqrt{2} * Ibm * |Z_{nm}|$$

$$where\ m = Revolution\ Line\ Number$$

A plot of the resulting voltages obtained when applying the above calculations for the n=7 case is shown below in Figure 4.

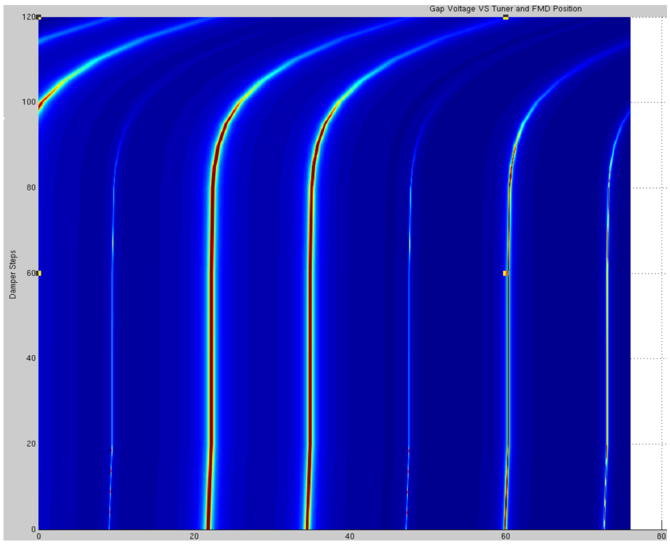


Figure 4 (n=7)

It can clearly be observed that there are many revolution lines contained in the operational space of the higher cavity harmonics. By observing the peak voltage magnitudes in the plot shown above, the fundamental dampers effect on the external Q and resonant frequency become clear. This is particularly true for damper step positions between 80 and 120. This was an important finding in formulating a safe path of navigation which allowed the cavity to tune into the desired drive harmonic while maintaining stability.

The final expression used to construct the complete HOM map can be observed below.

$$Vptot=\sum_{n=3}^{9}\sum_{m=1}^{m}\sqrt{2}*Ibm*|Znm|$$

The resulting HOM map created by applying the above expression can be observed below in Figure 5.

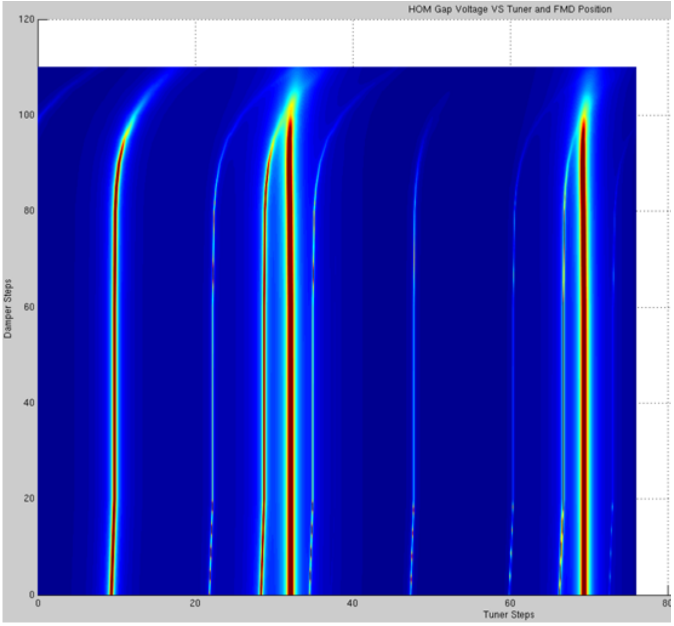


Figure 5

The peak cavity voltage at the fundamental harmonic (n=1) mapped onto the operational space can be observed below in Figure 6.

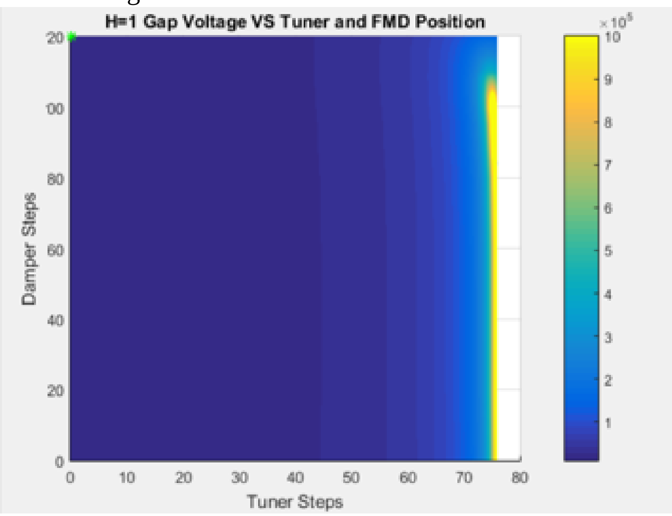


Figure 6

Another consideration involved with selecting a safe path to traverse through the operational space is the fundamental dampers extracted power as shown in Figure 7. In the original cavity design, the fundamental damper was not intended to extract power for an extended period and was only designed with a 20kW load [7][8]. As a result, it was required that careful attention be paid to the amount of average power extracted and dissipated by the fundamental damper subassembly and load.

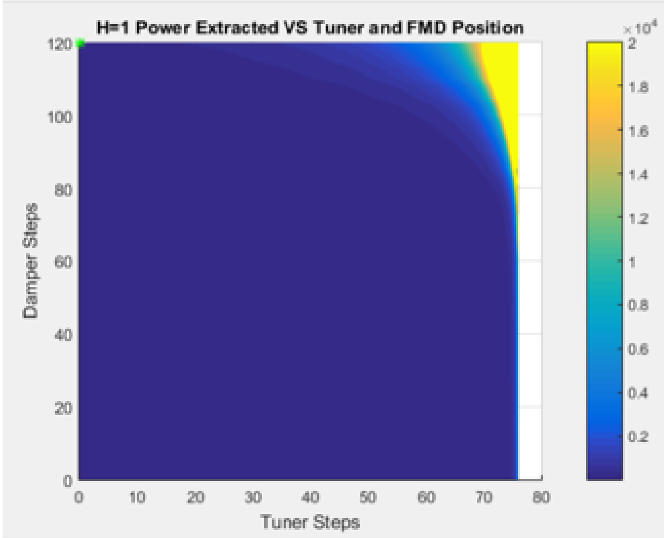


Figure 7

Putting it all together, a safe path like the one shown below in Figure 8 can be mapped onto the operational space.

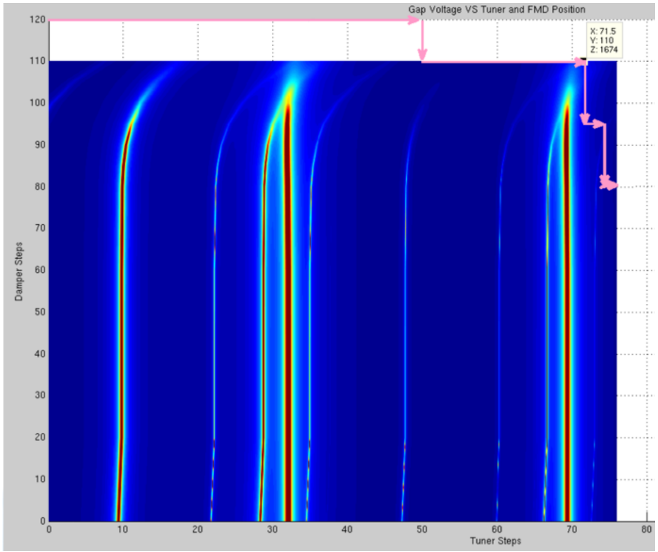
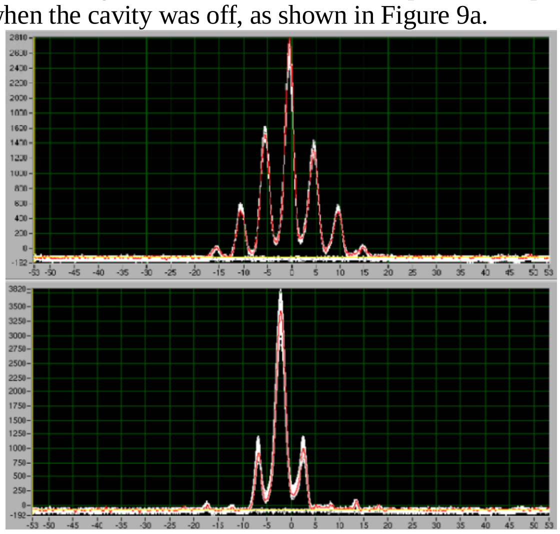


Figure 8

IV. Implementation & Results

In practice the above mapping was used to execute a safe and stable turn on of the 56MHz cavity in May of 2016. Figure 9b shows the effect of approximately 900kV of 56MHz voltage on the stored beam bunch profile compared to when the cavity was off, as shown in Figure 9a.



(a)

(b)

Figure 9

If the mapped beam revolution lines are not avoided the beam can go unstable very quickly as can be observed in Figure 10 below.

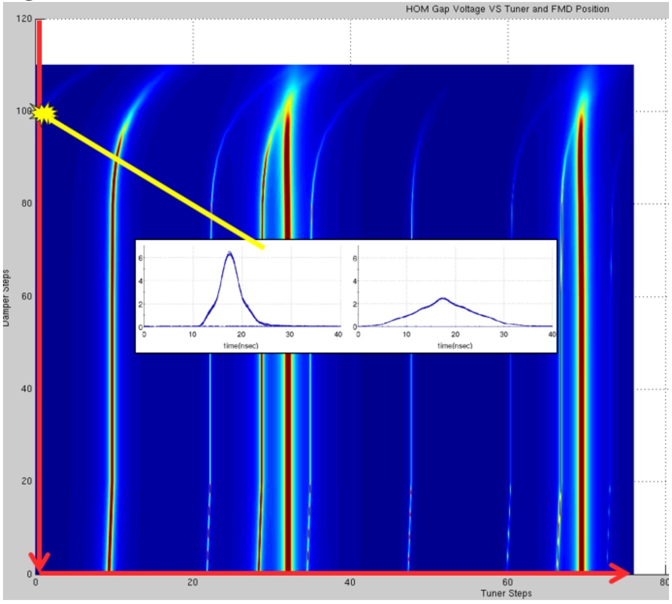


Figure 10

The above illustration shows an instance where the original damper extraction procedure was followed. In this example the beam became unstable just below the damper position of 100. The inset plot in Figure 10 shows the beam profile before (left), and after (right), as the n=7 mode crosses a beam revolution line. Figure 4 indicates the existence of this dangerous crossing with more clarity as the voltage magnitude is not scaled against the much higher intensity of the lower frequency modes.

V. CONCLUSION

The multidimensional, multi-mode landscape construction technique presented was originally developed as a solution to a specific problem. It is conceivable however, that this technique may find future application where a precise operational space mapping of fundamental and high order mode locations, and stresses, can be of logistical benefit.

In application, a concept and feasibility study of operating a beam driven superconducting cavity without HOM dampers has been presented, first to the RHIC Machine Advisory Committee in 2016 [1], and now in this paper. With the HOMD couplers removed the method described here has allowed the cavity to achieve 1MV CW during operations. Operation beyond this voltage was not achievable due to what is presumed to be various damaging events during commissioning. The cavity and various critical components have undergone an extensive failure analysis and a comprehensive set of upgrades have been performed [6]. Commissioning of the 56MHz cavity in RHIC is currently underway.

VI. REFERENCES

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