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HOM frequency control of SRF cavity in high current ERLs

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Abstract

The acceleration of high-current beam in Superconducting Radio Frequency (SRF) cavities is a challenging but essential for a variety of advanced accelerators. SRF cavities should be carefully designed to minimize the High Order Modes (HOM) power generated in the cavities by the beam current. The reduction of HOM power we demonstrate in a particular case can be quite large. This paper presents a method to systematically control the HOM resonance frequencies in the initial design phase to minimize the HOM power generation. This method is expected to be beneficial for the design of high SRF cavities addressing a variety of Energy Recovery Linac (ERL) applications.

1. Introduction

We present a cost-effective method for the reduction of HOM power, which is particularly significant for high-current ERLs [1,2]. High current applications are in the focus of accelerators science, being relevant for numerous applications including high luminosity colliders for nuclear physics with a complex bunch structure and, high flux Free Electron Laser accelerator. A key consideration of high current operation is the beam-cavity interaction. The residual electromagnetic field deposited by the beam excites the eigenmodes in the resonant cavities, known as higher order modes [3]. The HOM may lead to beam instabilities and induce excessive

RF loss on the cavities' surfaces. The basic method to address this problem is the addition of load-terminated RF couplers that damp the HOMs. However, removing a large power from the cavity through these HOM dampers is a technological challenge and it is also expensive. We describe below a novel technique to reduce the amount of the HOM power that has to be damped by a particular approach to the design of the cavity's structure [4,5]. Since multi-cell cavities minimize the cost of the accelerator and at the same time generate more HOM power than single cell cavities, we focus our discussion on multi-cell cavities, in particular 5-cell and above which are ubiquitous.

A sample impedance spectrum of a typical multi-cell cavity is plotted in Fig. 1. Our approach to the reduction of the HOM power introduces targeted modifications to the RF cavity structure that manipulates the impedance spectrum to reduce the overlap of peaks in the impedance spectrum with peaks in the beam Power Spectral Density (PSD), and thus minimize the HOM power generation [6,7].

Figure 1. A typical impedance spectrum of a multi-cell SRF cavity, in this case a 5-cell cavity at 650 MHz. Note that the impedance spectrum exhibits sharp peaks that are orders of magnitude larger than the background.

HOM power is generated mostly by the overlap of peaks in the current PSD and peaks in the cavity's impedance in the frequency domain. Examples of time domain bunch train and its corresponding frequency domain spectrum are illustrated in Fig. 2. Given a particular bunch pattern in time domain, the current spectrum comprises a set of delta functions modulated by a

Sinc function. The center-frequencies of main lobes of the Sinc function are at the harmonics of $1/T$ where T is the bunch repetition rate. In an ERL operation, the decelerating bunches are offset by an odd multiple of half the period of the RF frequency f . Therefore, the lowest frequency center lobe of the Sinc function is at twice the linac RF frequency. The center lobe bin's width is $2/\tau$, where τ is the beam-current pulse width, and the side lobes bin width is $1/\tau$ [8,9,10].

Figure 2. The power spectral density of the current in time and frequency domains. The side lobes are the separate bins whose amplitudes are smaller on both sides of the center lobe. The center lobe frequency bandwidth is $2/\tau$ where τ is the pulse width, while the side lobes have a width of $1/\tau$. The main frequency is defined by the bunch frequency, while the fine structure is characterized by the period as $1/T$. This pattern repeats at the harmonics of the linac RF frequency in general, but for an ERL, it repeats at even harmonics of this frequency.

Clearly the cavity's impedance spectrum and the beam current PSD are rich in details, and that makes the task of reducing the HOM power challenging. However, once the accelerator design establishes the features of the beam structure that enable the calculation of the PSD, it should be possible to design the acceleration cavities to accommodate the beam current features. In this paper, we provide a detailed methodology to engineer the SRF cavity such that the HOM frequencies impedance spectrum avoids deliberately a given current PSD peaks to minimize the HOM power generation and maximize the Beam Breakup (BBU) threshold.

2. Methodology

The numerical calculations used in this work have been carried out using the ABCI and ACE3P codes [11,12].

Our objective is to tune a number of HOM frequency bands independently through a specific design of the accelerating cavity, in order to place them at regions on low power spectral density of the beam current. To achieve this objective, we choose a number of parameters that control the frequencies of the various modes through variations of the shape of the cavity. Ideally, we would like to tune each selected HOM band predominantly with one parameter, but clearly there is coupling to other modes. Thus, our objective is to select parameters that are as orthogonal as possible and yet are sufficiently responsive.

We observe that the first 3 harmonics of the PSD are responsible for most of the HOM power because the shunt impedance of the HOMs in this frequency region is significantly bigger than at the higher frequencies, as can be seen in Fig. 1. In addition, the bunch spectrum has an envelope of a Gaussian function determined by the bunch length, which adds to the reduction of the HOM power generation at higher frequencies. Thus, we can reduce the magnitude of the task by aiming

at steering the HOMs away from these three harmonics. While we use a specific example, the method can be generalized to other cavities and beam characteristics.

To ease the task, we would like to tune a minimal set of HOMs. We observe that in the ERL, the first three harmonics of the beam current PSD, which account for most of the HOM power generation in the cavity, are even harmonics of the ERL's accelerating cavity frequency. We find that there are eight pass bands of HOMs with non-negligible R/Q that lie in the neighborhood of these harmonics. These modes are as follows: Near the 2nd harmonic, we find the TM_{011} and TM_{020} pass bands, and the TM_{032} and TM_{013} pass bands are observed near the 4th harmonic. Near the 6th harmonic, we find pass bands that may be identified as TM_{045} , TM_{055} , TM_{054} and TM_{043} . These eigenmodes bear resemblance to the modes of a pillbox cavity, which are available in a closed analytic form, but differ mostly because of the beam pipe opening. We will design the cavity geometry to tune the eigenfrequencies of those pass bands in this report.

The tools we have in our hands are modifying the center cells' design, the end cell design and fine surface tuning, as will be detailed in the following sections.

A multi-cell elliptical cavity comprises of a few center cells and two end cells. The electromagnetic modes in the central cells are coupled and therefore form a pass-band with split modes. Each pass-band contains resonances corresponding to the number of cells in the cavity. A dispersion curve is used to describe the resonant frequencies of the electromagnetic modes as a function of the cell-to-cell phase delay. The group and phase velocity of each EM modes can be determined.

The cavity cell shape can be described by two ellipses and one tangential straight part, as shown in Fig. 3. The end cells usually require a somewhat different design to adjust the coupling of the

beam pipe to the cavity modes. We will now proceed to describe the parameters that control the mode-frequency and discuss specifics of their effectiveness.

2.1. Center cell design:

We use the design of the center cells to tune two HOM pass bands: the TM_{011} and the TM_{020} pass bands while keeping the fundamental frequency of the TM_{010} π mode constant. The frequencies of those modes should be adjusted to a minimum of the current PSD. In the ERL scenario that we use for a practical demonstration of the method, the nearest low values of the current PSD occur at exactly ± 130 MHz off the even harmonic. This adjustment requires at least three independent tuning parameters. In reality, we use more than three parameters since we also have goals of increasing the R/Q of the fundamental mode, reducing the R/Q of the HOMs and reducing the peak surface fields.

For modes with the azimuthal mode index $m=0$, following a pillbox cavity approximation, the resonant frequencies are determined by the n 'th root of Bessel functions of the first kind and its derivative as well as the cavity length.

An important geometrical parameter (independent of the surface resistance) for cavity modes is the shunt resistance divided by the quality factor of the mode, R/Q .

The R/Q of the fundamental accelerating mode should be kept as high as possible for efficient acceleration of the beam. At the same time, the shunt impedance of the HOMs should be as low as possible to minimize the HOM power generation. The cavity design has to consider also other key performance parameters of the cavity, such as the peak surface electric and magnetic fields. These various performance criteria dominate the choice of the shape of elliptical multi-cell cavities. The parameterization of the shape of such a cavity is illustrated by Fig. 3. The key parameters are the radii (a_j, b_j , $j=1,3$) and centers (X_j, Y_j , $J=1,3$) of the upper and bottom ellipses,

the two angles of connecting straight lines (α_1, α_2) and the iris diameter. Of these parameters, only six variables are necessary for the optimization process. There are various ways to choose these, and our choice is: 1. Iris radius, 2. Top ellipse height, 3. Top ellipse long radius, 4. Top ellipse short radius, 5. Bottom ellipse long radius, 6. Bottom ellipse short radius. The angles α_1, α_2 of the cavity wall are determined by the above chosen parameters. Since we keep a bilateral symmetry of the center cells, $\alpha_1 = \alpha_2$. The frequencies of the HOMs are sensitive to these angles and the iris radius. However, we are constrained to small, even negative angles by the R/Q of the fundamental mode, depends on them.

Figure 3. The key parameters of the cavity cell. The cell is made by a figure of revolution of the shown outline. The labels X, Y, a, b represent the center coordinates and radii of each ellipse. There are 12 parameters for these 3 ellipses, however only six are independent parameters due to design constraints, such as the beam velocity, the TM_{010} pi-mode frequency, and the choice of bilateral symmetry for ease of manufacturing.

As mentioned earlier, as we tune the HOM frequencies we maintain the fundamental frequency constant, by slightly scaling the entire cavity transverse geometry. This change has a small effect on the HOM frequencies, which can converge rapidly in a few iterations.

We have investigated the effectiveness of various cavity geometry parameters in tuning the HOM pass-bands. We fortunately found that the choice of a re-entrant cavity shape tunes the critical HOM frequencies to optimal values and at the same time increase the R/Q of the fundamental accelerating mode. This is demonstrated by the dispersion curves shown in Fig. 4 as a function of the changes in the cell geometry. The results show that the frequencies of the HOMs respond well to the geometry changes, allowing us to control the HOM frequencies over a range of about ± 100 MHz off the second harmonics frequency. Also, we found the R/Q of the TM_{020} modes are greatly reduced. One might argue that the loss factor for single bunch shall be higher, but the loss from a multi-bunch pattern does not depend on the loss factor. Thus, reentrant cavity shape is preferable for our objectives: Frequency control of the HOM pass-bands, high R/Q of the fundamental mode and lower R/Q for the HOMs.

Figure 4. The center cell shape variations and the effect on the dispersion curves. The cell shapes all have the same frequency of TM_{010} mode, but the cell length changes. The different color curves represent the different HOM families in the first Brillouin zone. Red is the TM_{010} , black is the TM_{011} , green is the TM_{020} , magenta is the TE_{012} and light blue is the TM_{021} mode. The dotted lines represent the curve whose phase velocity is the speed of light.

2.2. End cell design

We use the design of the end cells to tune two HOM pass bands: the TM_{032} and the TM_{013} as well as maintaining the fundamental frequency of the TM_{010} π mode constant. As discussed in Section 2.1, the nearest low values of the current PSD occur at exactly ± 130 MHz off the 4th harmonic, which is at 2.6 GHz. This adjustment requires at least three independent tuning parameters. In reality, we use more than three parameters since we also have goals of increasing the R/Q of the fundamental mode, reducing the R/Q of the HOMs and reducing the peak surface fields.

The end cell connects to the beam pipe on one side and the center cells on its other side. The end cell breaks the periodic boundary conditions that lead to the dispersion curves and thus affects the previously tuned frequencies. The direction and magnitude of this tuning may be different for each mode, and it depends on the field distribution details in the beam pipe. Leakage of electric field into the beam pipe increases the mode frequency and leakage of magnetic field will reduce it. TM_{0nl} will be coupled out as TM_{0m} waveguide modes. The end cell geometry may convert blocked higher order TM modes into lower order TM modes and couple them out of the cavity. The first three iris cut-off frequencies of the TX_{0x} are: TM_{01} at 1.602 GHz, TE_{01} at 2.553 GHz and TM_{02} at 3.677 GHz. The variables available for tuning the end cell are illustrated in Fig. 5.

Figure 5. The tuning parameters of the outer half of the end cell in the cavity design. The inner half is identical to the design of the center cells of the cavity. The independent parameters are the center Y_4 and radius a_4 of the top ellipse, radii a_5 and b_5 of the bottom ellipse, cell length and the beam pipe radius. The angles α_3 of the cavity wall is determined by the above chosen parameters.

Besides the adjustments for the HOM pass band tuning, we must consider a few other issues. The fundamental frequency of the end cells must be kept constant for maintaining the field flatness of the complete cavity. In addition, we keep the shape of the inner half of the end cell identical with the shape of the center cells to simplify fabrication. Thus, we use just the shape of the outer half of the end cell for tuning the HOM pass bands. That leaves us with three key geometrical variables - the beam pipe diameter, the re-entrance angle, and the end cell length. We use the end-cell length to maintain the frequency of the fundamental mode, so we are left with two parameters to control the two HOM pass bands, the TM_{032} and the TM_{013} .

We scanned the beam pipe diameter and the reentrant angle. The changes in shape and their effect on the mode frequency are shown in Fig. 6.

Figure 6. The effect of small perturbations of the shape of the end-cell, aimed at detuning HOM modes near the 4th harmonic of the beam frequency at 2.6 GHz. The figures on the left depict the cavity shape changes, while the figures on the right show the effect of these changes on the different modes frequency and unloaded Q change correspondingly. The end cell shape variations maintain the frequency of TM_{010} mode invariant. The arrows represent the direction of the changes.

2.3. Fine surface perturbation.

Given the above design of the whole cavity, our last task is to tune several HOM pass bands that are in the vicinity (± 260 MHz) of the 6th harmonic of the fundamental frequency. As we have seen in Sections 2.1 and 2.2, the nearest low values of the current PSD occur at exactly ± 130 MHz off the 6th harmonic at 3.9 GHz. We deal only with modes whose shunt impedance is higher than $1 \times 10^5 \Omega$, which are tentatively identified as the TM_{045} , TM_{055} , TM_{054} and TM_{043} pass bands. This procedure requires a perturbation that has a negligible effect on the previously tuned, lower

frequency pass bands. We do this by introducing four shallow depressions in selected locations on the inner surface of the cavity. Such a schematic small feature is represented in Fig. 7. These depressions are smooth and continuously differentiable Gaussian shapes, and thus produce a negligible electric or magnetic field enhancement. The depressions vary in width, height and location on the cavity's surface.

Figure 7. A Gaussian shape depression for fine-tuning is depicted at a possible location on the cavity wall. The depression is oriented to conform to the cavity surface. On the left we show the cavity surface with this barely noticeable depression marked by a circle. The zoom-in to this depression is shown on the right.

From the Slater perturbation method [13], the change of the mode frequency is determined by the radiation pressure of the mode, as given in equation 1.

$$\frac{\Delta f}{f} = \frac{1}{U} (\oint \mu_0 H^2 dV - \oint \epsilon_0 E^2 dV) \approx \frac{1}{U} (\mu_0 H^2 - \epsilon_0 E^2) \Delta V \quad (1)$$

Where the integration is carried over the volume of the perturbation of the cavity.

The radiation pressure curves, $\mu_0 H^2 - \epsilon_0 E^2$, of the four selected HOM modes are plotted along the surface of the cavity in Fig. 8. Thus Fig. 8 provides guidance for the selection of these depressions, by looking for frequency-specific, high-sensitivity locations for a particular mode, while reducing the response for the other modes.

Figure 8. The four HOM radiation pressure curves on the cavity's wall are plotted along the surface of the cavity. The electromagnetic fields are symmetric because the cavity has longitudinal symmetry. The radiation pressure amplitudes are normalized to stored cavity energy of 1 Joule. The plots, from top to bottom, are for the mode at 3.71 GHz, identified as a TM045 mode, 3.85 GHz (TM055), 3.96 GHz (TM054) and 4.05 GHz (TM043). The selected locations for the tuning depressions are marked by arrows.

Our objective is to solve for the volumes, V_1 through V_4 , of the depressions chosen at the selected locations such that we change the modes' frequencies by Δf_1 through Δf_4 as desired. Using Equation 1 four times, we can generate the following linear equations in a matrix form:

$$\begin{pmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta f_4 \end{pmatrix} = B \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix} \quad (2)$$

The elements B_{ij} of the 4 by 4 matrix B are evaluated by choosing volumes V_j with $V_{i \neq j} = 0$, then we get $B_{ij} = \Delta f_i / V_j$. The values for the volumes of the four depressions are then obtained by inverting the matrix B and substituting for Δf_i the desired values.

$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix} = B^{-1} \begin{pmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta f_4 \end{pmatrix} \quad (3)$$

By selecting the locations of the depressions as indicated in Fig. 8, we obtain the B matrix numerically in equation 4. The units of the elements are in kHz/mm³.

$$B = \begin{pmatrix} -0.1458 & -0.0186 & 0.0002 & 0.0131 \\ 0.0007 & -0.3338 & 0.0001 & -0.0174 \\ -0.0398 & 0.0684 & 1.0227 & 0.0067 \\ -0.0094 & 0.0125 & 0.0003 & 1.2057 \end{pmatrix} \quad (4)$$

The locations of the depressions and their volumes are provided in Table 1, next section.

These locations are at a position along the surface where the radiation pressure of the desired mode, shown in one of the four plots of Fig. 8, is high, but the radiation pressure of the other three modes is low. This selection is carried out by a simple program, and the quality of the selection can be examined by observing the B matrix of Equation 4. we note that the diagonal elements are large whereas the off-diagonal elements are small.

The resulting volume of the depressions is quite small and allows various methods to introduce them following the forming of the 'dumbbells' of the cavity cells. The depressions can be precision-machined on the dumbbells using an end-mill with a custom-made tool. In practice, we will determine the finer surface tuner size and location empirically.

2.4. The cavity assembly

We connected the end group from Fig. 6 with center cells from Fig. 4 to make 5-cell cavity, and calculated the HOM frequencies and other specifications. We plotted the cavity design and the on-axis E field amplitude of the fundamental TM_{010} mode in the Fig. 9. The accelerator electric field flatness is achieved. Table 1 provides the geometry of a fully optimized 650 MHz cavity as done through the various steps outlined in this paper.

Figure 9. The 5-cell cavity design from Table 1 is shown in a 2D figure. The on-axis electric field has identical amplitudes in all cells.

Table 1: Design parameters of the new low HOM power cavity.

Center Cell Parameters	Bottom ellipse a	Bottom ellipse b	Bottom ellipse Y	Top ellipse a	Top ellipse b	Top ellipse y
Values (cm)	4.000	2.389	9.557	9.000	2.966	15.649
End group Parameters	Top ellipse y	Top ellipse a	Bottom ellipse a	Bottom ellipse b	Beam pipe radius	Half-cell length
Values (cm)	15.421	9.263	4.371	3.022	5.9	6.000
Surface tuners Parameters	Depression 1	Depression 2	Depression 3	Depression 4		
Size (cm ³)	12.6076	12.1437	3.9070	1.6744		
Longitude location (m)	0.73	0.43	0.89	0.98		

In the comparison with other multi-cell cavities designs, most of the figures of merit are independent of the frequency (such as the R/Q , geometry factor and the surface field ratios). The frequencies of the cavities in this comparison ranges from 647 MHz to 750 MHz. We normalize

the loss factors to the fundamental mode frequency of 650 MHz and bunch length of 3 mm RMS. The comparison is given in Table 2.

Table 2: *Comparison between the new low HOM power design and other cavity designs.*

Specifications	BNL3[14]	BNL4[15]	Ampere Class[16,17]	New Cavity
R/Q (Ohm)	506	502.509	506.5	659.7
Geometry factor (Ohm)	283	272.499	291.1	221.807
Loss factor of fundamental (V/pC)	0.51	0.5123	0.51	0.6643
Bmax/Eacc (mT/MV/m)	4.27	4.42	4.27	3.76
E _{max} /E _{acc}	2.46	2.27	2.5	2.29

The loss factor values provided in Table 2 are calculated in time domain for a single bunch operation (using an RMS length of 3 mm). From time domain simulation, we found that the HOM loss contribution above 4.2 GHz comprises less than 50% of the total loss factor. We will calculate the HOM power of those cavities in the next section for a particular ERL application.

3. HOM power evaluation for a specific ERL application

Now we can apply our computational tools to the new optimized cavity in order to obtain a detailed calculation of HOM power for a particular ERL scenario. We conducted a frequency domain simulation to obtain the precise longitudinal impedance of the optimized cavity. The boundary condition on the beam pipe are set up as perfect absorber, which is a good approximation to the real practical case. We evaluated the HOM spectrum up to 4.2 GHz, since the third harmonic frequency of the ERL is 3.9 GHz. Using the frequency domain solver, we obtained and plotted the R/Q and external Q in the frequency domain up to 4.2 GHz in Fig. 10.

Figure 10. The longitude components of the HOM modes in our low HOM power cavity design.

We will use this impedance spectrum in the next section to calculate the HOM power generation for different applications.

Now we are in a position to calculate the monopole HOM power generation up to 4.2 GHz for a particular beam current structure which is characteristic to an electron-ion collider. The bunch pattern we use corresponds to an ERL, with a train of 10 accelerating and decelerating bunches. Each bunch has a charge of 4.26 nC. The ERL RF frequency is 647.2 MHz, and the macro bunch repetition frequency is 9.38 MHz. That totals to an average ERL current of 0.4 A [1]. We plot the impedance and the bunch pattern spectrum in Fig. 11. In our optimized design, near the second harmonic frequency of the fundamental mode, the high impedance modes are tuned to the local minima of the SINC function. By doing so, these HOM pass bands develop very little power.

Figure 11. The impedance spectrum of the optimized cavity and the pulsed operating bunch spectrum, demonstrating the clear reduction of overlap of HOM pass bands with the beam current PSD.

The HOM power developed by the optimized cavity can be compared to one of the current designs of BNL4 [15] and Ampere class [16] cavities. The integrated HOM power of these cavities, up to 4.2 GHz, are plotted in Fig. 12. The integrated power curves are calculated without any intentional HOM and bunch spectrum frequency alignment.

Figure 12. The integrated HOM power up to 5 GHz with three HOM frequency alignment scenarios: BNL4 [15], Ampere Class [16] and the current new design.

With this particular ERL bunch spectrum, the HOM power from this new cavity is ~ 1.3 kW, while BNL4 and Ampere class cavities are 5.8 kW and 2.4 kW, respectively with the same bunch spectrum. The HOM power reduction is at least 40% or over a factor of four, depending to which cavity we compare our results.

4. Conclusions

In this report, we propose a new method to minimize HOM power generation in an ERL by targeted modifications of the cavity's shape. This method can be applied to various bunch patterns for different high current Energy Recovery Linac projects. Given the bunch pattern of the beam in the ERL, we derive guidance on how to shift the frequencies of a set of HOM pass-bands. We then outlined modifications of the center cells of the cavity, the end cells of the cavity and finally added small perturbations of the cells to tune the remaining HOM pass-bands. While this method has general applicability, we use a particular cavity design to illustrate the particular steps and the

actual performance of the resulting cavity. In particular, we demonstrated that in a bunch pattern used in an ERL for an electron ion collider we reduce the HOM power by a very significant factor.

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