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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].

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 $1/\tau$ [8–10].

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.

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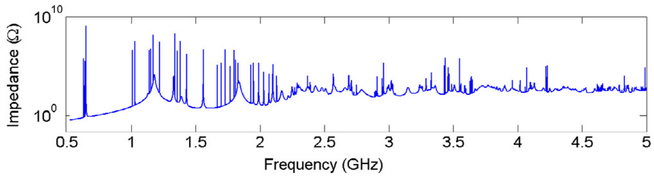

Fig. 1. A typical impedance spectrum of a multi-cell SRF cavity, in this case a 5-cell cavity at 650 MHz. Note that the impedance spectrum exhibits sharp peaks that are orders of magnitude larger than the background.

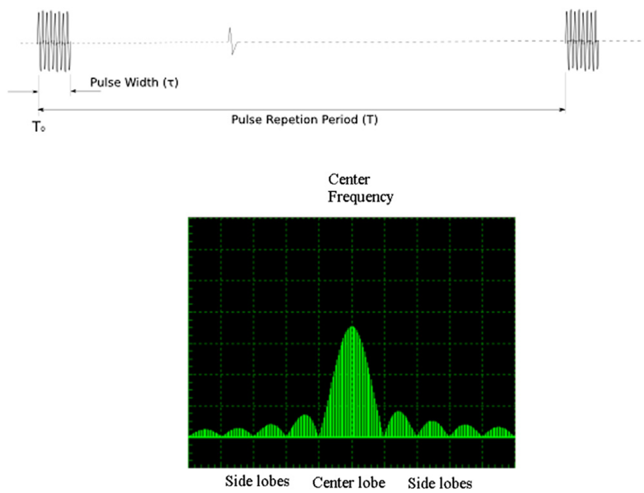

Fig. 2. The power spectral density of the current in time and frequency domains. The side lobes are the separate bins whose amplitudes are smaller on both sides of the center lobe. The center lobe frequency bandwidth is $2/\tau$ where τ is the pulse width, while the side lobes have a width of $1/\tau$. 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.

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 nth 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.

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.