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Multiple bunch HOM evaluation for ERL cavities

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ABSTRACT

In this work we investigate the effect of the bunch pattern in a linac on the Higher Order Mode (HOM) power generation. The future ERL-based electron–ion collider eRHIC at BNL is used as an illustrative example. This ERL has multiple high current Superconducting Radiofrequency (SRF) 5-cell cavities. The HOM power generated when a single bunch traverses the cavity is estimated by the corresponding loss factor. Multiple re-circulations through the Energy Recovery Linac (ERL) create a specific bunch pattern. In this case the loss factor can be different than the single bunch loss factor. HOM power can vary dramatically when the ERL bunch pattern changes. The HOM power generation can be surveyed in the time and frequency domains. We estimate the average HOM power in a 5-cell cavity with different ERL bunch patterns.

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1. Introduction

High current linear accelerators may encounter significant design challenges due to the generation of very high Higher Order Mode (HOM) power. The amount of HOM power depends on the degree of overlap of the driving term in the beam with the response term of the cavity. Very high HOM power will be generated when there is coincidence of a peak in the Power Spectral Density (PSD) of the beam current with a peak in the impedance spectrum of the cavity. Therefore, it stands to reason that changing the timing pattern of the beam can change the beam PSD and thus the HOM power.

In this paper we introduce a couple of parameters that modify the PSD of certain accelerators. In a machine that has a bunch train structure that includes a gap (including pulsed machines) we can stretch the bunch train to some extent. We will introduce the "Stretch Parameter" later on. In an Energy Recovery Linac (ERL) we can control the timing of the decelerating bunches relative to the accelerating bunches, introducing what we will call the "Shift Parameter". We will show that the shift parameter and stretch parameter modify the PSD and thus significant affect the amount of HOM power generated by the beam in a particular cavity. The exact response of the HOM power to these parameters depends not only on the PSD, but also on the cavity HOM spectrum. Thus we will present the case by using a particular example, taken from the eRHIC design.

The eRHIC accelerator is proposed at BNL to collide electrons with protons and ions in order to explore the internal structure of nucleons and nuclei and, especially, the role that gluons play in nucleon processes [1]. We plan to add an electron accelerator in the present tunnel of the RHIC ion ring. One of the proposed options (Linac-ring design) is to utilize ERL technologies [2]. eRHIC circulates the electron bunches for multiple turns through the Superconducting Radiofrequency (SRF) Linac. The ERL technique recovers the energy of particles after collision and reduces the operational cost of this machine. The accelerating and decelerating electrons will see the RF field of cavities at different phases defining whether they acquire energy from or deposit to the RF structures.

In the eRHIC ERL, the proton and electron bunches will collide at a rate of 9.38 MHz which is the repetition rate of the protons. The electrons are accelerated by a SRF Linac whose fundamental frequency is 647.2 MHz. In order to reach the final collision energy, electrons will be accelerated by multiple recirculation passes, up to 12, through the SRF Linac. The electrons gain 1.665 GeV energy from each pass through the Linac. The resulting bunch pattern also contains a gap, about 1μs duration, for ion clearing purpose. The gap repeats at a rate of 78.2 kHz, which is the proton's revolution frequency. Therefore, both proton and electron bunch patterns at the collision point are defined by two frequencies, 78.2 kHz and 9.38 MHz. Within the 12.7 μs period corresponding to the 78.2 kHz revolution frequency, there will be 110 bunches with repetition rate of 9.38 MHz and the gap. The bunch patterns from multiple recirculation overlap in the Linac. An example of an electron bunch pattern observed at a fixed location in the Linac is given in Fig. 1.

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Table 1
The electron beam parameter for different eRHIC operation modes and stages.

	Nominal design	Ultimate design	
	Low energy mode	Max current mode	Max energy mode
Number of recirculations	14	10	24
Collision energy, GeV	11.7	8.3	20
Source current, mA	24	50	6
Bunch charge, nC	2.6	5.3	0.6
Total current, mA	340	500	145

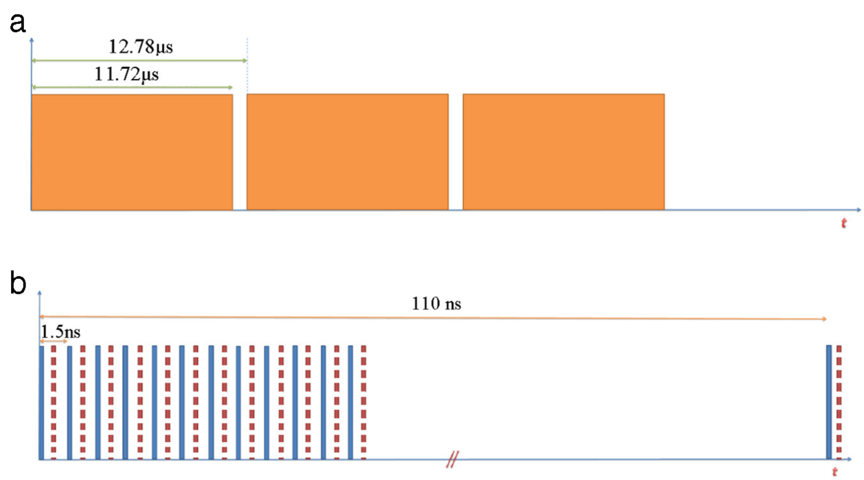

Fig. 1. The pattern of electrons bunches in the eRHIC main Linac. Blue and red bars represent the de-accelerating (blue) and accelerating bunches (red dots) within the 9.38 MHz period of 106 ns. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

There are two operation modes proposed in this machine, nominal and ultimate. In the ultimate operation mode, we have a high-current version and high-energy version. The high-energy version has 24 passes in the linac (12 accelerating and 12 decelerating), however the bunch charge is quite small to limit the synchrotron radiation losses. In the high-current mode, the maximum total current through the Linac is 500 mA, achieved with 10 total re-circulations (5 accelerating + 5 decelerating). In the Nominal operation mode, the maximum total current is 340 mA with 14 total re-circulations. Table 1 lists the relevant parameters for eRHIC's operating modes of interest. The number of re-circulations and the bunch charge affect the power generated in the HOMs. We will evaluate the HOM power generation for both design versions.

It is well known that the HOM power is proportional to the product of average current and bunch charge [3]. In this study, we will estimate the HOM generation by multiple bunch patterns and calculate the loss factor for multiple bunch patterns. We find that the bunch pattern has a significant effect on the HOM power. We structure this paper as follows: The impedance is obtained in Section 2. We vary the bunch pattern and obtain the HOM power generation in Section 3. In Section 4 we verify this study through a simulation in time domain, discuss some other possible bunch train patterns and practical considerations.

2. eRHIC cavity impedance

2.1. Single bunch loss factor

The cavity impedance R is an intrinsic property related to the cavity, independent of the bunch pattern. The real part of the impedance (at resonance) of each mode is a product of the normalized impedance R/Q and the loaded quality factor Q_{load}. Usually, Q_{load} is dominated by the external Q, designated Q_e. HOM couplers are adapted to reduce Q_e for damping the HOM power to a safe level and also reduce the HOM field level in the steady state. In this study, we will evaluate the HOM power generation for bunch trains with various structure in the time domain, using for example the eRHIC case and a 5-cell cavity.

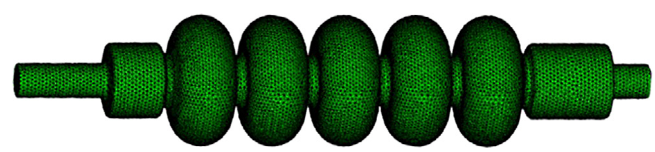

Fig. 2. 5-cell SRF Cavity without HOM couplers. The effective accelerating length is 1.15 m and the physical length is 1.68 m. The packing factor of this design is 0.684. For estimates in this paper we approximate the HOM dampers by perfectly absorbing boundaries.

The 5-cell cavity, shown in Fig. 2, is designed to minimize the HOM generation for high current application [4]. This cavity is one of the candidate cavities considered for the eRHIC ERL and it is used as an example in this study. The final cavity design is still under development.

In this study, we add a long beam pipe on both ends with perfect absorbing boundary conditions. This is a good approximation to two beam pipe absorbers placed on both ends in the current design.

The loss factor for single bunch operation is obtained and benchmarked by simulations with the computer codes ABCI and T3P at a bunch RMS length of 3 mm [5,6]. The integrated loss factor and the cavity impedance up to 39 GHz is 3.06 V/pC. The longitudinal impedance can be given by a Fourier transform of the wake potential. Extending the span in time domain produces a higher resolution in frequency domain, necessary to resolve modes with high quality factors. In this study, we obtained the wake potential over 300 m, which is a time span of approximately 1×10^{-6} s. We can confidently resolve the all modes whose Q is less than 2×10^5.

For trapped modes whose loaded quality factor Q_{load} is higher than 2×10^5, the impedance may not be fully resolved by a Fourier transform from the truncated time domain wake field. We conduct an independent eigenvalue simulation to obtain their mode information.

The beam pipe radius is 5.3 cm, thus the cutoff frequencies are 2.152 GHz, 4.940 GHz for the first two circular monopole modes. We use the eigenvalue impedances up to 5 GHz which is 7.7 times for the fundamental TM010 mode. In the Tesla type 9 cell cavity simulation,