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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.

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 significantly 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 $1\mu\text{s}$ 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 $12.7\mu\text{s}$ 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.

(a)

(b)

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.

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 500mA, achieved with 10 total re-circulations (5 accelerating + 5 decelerating). In the Nominal operation mode, the maximum total current is 340mA 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.

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

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

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.

142

2. eRHIC cavity impedance

143

2.1 Single bunch loss factor.

144

145 The cavity impedance R is an intrinsic
146 property related to the cavity, independent of
147 the bunch pattern. The real part of the
148 impedance (at resonance) of each mode is a
149 product of the normalized impedance R/Q
150 and the loaded quality factor Q_{load} . Usually,
151 Q_{load} is dominated by the external Q ,
152 designated Q_e . HOM couplers are adapted to
153 reduce Q_e for damping the HOM power to a
154 safe level and also reduce the HOM field
155 level in the steady state. In this study, we will
156 evaluate the HOM power generation for
157 bunch trains with various structure in the time

158 domain, using for example the eRHIC case
159 and a 5-cell cavity.

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

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

172

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

176

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

191 resolve the all modes whose Q is less than
192 2×10^5 .

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

200 The beam pipe radius is 5.3cm, thus the
201 cutoff frequencies are 2.152GHz, 4.940GHz
202 for the first two circular monopole modes.
203 We use the eigenvalue impedances up to
204 5GHz which is 7.7 times for the fundamental

205 TM010 mode. In the Tesla type 9 cell cavity
 206 simulation, the high Q trapped mode
 207 frequency could be 5 times of the
 208 fundamental frequency. [7,8]

209 The comparison between the real part of
 210 the longitudinal impedances from time
 211 domain and eigenvalue simulations is given
 212 in Fig 3. The high frequency impedances
 213 (above 3GHz) agree well because the Q_e are
 214 fairly low. For the low frequency region, the
 215 impedance values from the time domain
 216 solver are smaller than those from the
 217 eigenvalue solution, and that is because the
 218 simulated wake length is not long enough to
 219 resolve them. Thus, the impedance from
 220 truncated time domain simulation is
 221 inaccurate. Thus we do not use the low
 222 frequency impedance obtained from time

223 domain simulation for HOM power
 224 estimation, we use the low frequency
 225 impedance from eigenvalue simulation
 226 instead. However, the eigenvalue simulation
 227 is not computationally efficient at high
 228 frequencies. Fortunately, the time domain
 229 simulation provides a good agreement with
 230 the eigenvalue impedance spectrum at the
 231 high frequency range, as can be seen in Fig.
 232 3. Thus, in order to obtain the correct
 233 impedance over the full spectrum and avoid a
 234 costly simulation, we combine the impedance
 235 spectrum from eigenvalue and time domain
 236 simulation. The impedance spectrum that we
 237 use to estimate our HOM generation under
 238 5GHz comes from the eigenvalue solver, and
 239 above 5GHz from the time domain solver.

Fig 3: The impedance spectrum of the cavity below 5GHz. We compare the impedance from eigenvalue simulation (a) and time domain simulation (b). c: Extending the frequency range to 18GHz. Impedence from frequency domain (blue dots) and time domain (red solid) are combined.

The numerically calculated single bunch loss factor is 3.06V/pC, using a short-range wake potential and a Gaussian bunch charge distribution. The loss factors obtained from the frequency domain and time domain differ by less than 1% for a single bunch.

2.2 HOM generation by a bunch train.

The average HOM power is typically given by the product of the loss factor, the

bunch charge and the average current. However, for a bunch train, successive bunches can absorb or enhance the HOM energy left behind by the previous bunches, [9,10,11,12,13,14] leading to HOM power that depends on the bunch pattern. In this study, we estimate this effect for different bunch patterns, using as an example potential eRHIC operating modes

3. Bunch patterns and HOM generation

3.1 The Bunch Pattern

The ERL mode of the eRHIC linac presents the linac cavities with a particular time-domain pattern of accelerating and decelerating bunches. While this pattern includes bunches with different energies the HOM power generation is independent of the bunch energy. Therefore, we take the accelerating/decelerating bunches with multiple energies as a single particular pattern in time, as shown in Fig 1.

Within the accelerating and decelerating trains, the bunch separation time is an integer multiple of the period of the ERL frequency of 647.2MHz. The accelerator design allows us to choose a phase shift between the accelerating and decelerating trains by an integer of the ERL period. Thus for the ERL mode, the head of the accelerating and decelerating bunches are separated by $N+0.5$ times the period of the fundamental ERL RF frequency, where N is an integer. While the average current remains the same for the

various patterns, the bunch frequency spectrum does change. A few selected bunch patterns are shown in Fig 4 for different values of N.

Fig.4. The charge distribution is shown inside the period of 9.38MHz. Inside the accelerating (red dots) and decelerating (green circles) trains, the bunch separation time is the period of 647.2MHz. The heads of the accelerating and decelerating trains are separated by $N+0.5$ times the period, where: (a) $N=0$. (b) $N=5$. (c) $N=12$. (d) $N=16$.

To simplify the discussion, we start with the $N=0$ case. Fig 5 shows the Power Spectral Density (PSD) of the current with a bunch pattern from Fig 4(a). The PSD is composed of a set of very narrow width spikes with spacing of 78.2kHz, which is not resolved in the figure.

Fig.5: The PSD of the bunch pattern of Fig 4(a). (a). The full frequency ranges up to 30GHz, showing the envelope of the Gaussian distribution, with fine details showing a strong enhancement at a multiple of twice the linac frequency. (b). A detailed segment around the linac's fundamental frequency, where the odd harmonics of the linac's frequency are depressed. Due to

the high occupancy of bunches in the 9.38MHz frequency, the effect of the gap (repeating at 78.2kHz) is negligible. Additional modulation is related to the number of bunches in the 9.38MHz linac bunch train, in the shape of the Sinc function.

The observed PSD spectrum has two envelopes, a Gaussian, resulting from the Gaussian bunch charge modulation, and a Sinc function, resulting from the square current modulation due to the macro-bunch. The center frequencies of main lobe of the Sinc function are at the harmonics of the bunch repetition rate. Since the decelerating bunches are offset by half the period of the 647.2MHz, they generate the main lobe spacing of 1294.4MHz. The width of the main lobe of the Sinc function is twice the width of the side lobe, which is determined by the bunch occupation time. At the even harmonics of fundamental frequency, the amplitudes of the bunch spectrum are enhanced. The current spectrum should be

zero at the odd harmonics of fundamental frequency due to the ERL mode.

Next we estimate the HOM power generation due to the bunch patterns of the nominal and ultimate operation modes of the eRHIC machine.

3.2 Nominal design example

In the Nominal design, the average current through the Linac is 340mA with 7 accelerating turns. The heads of the accelerating and decelerating trains are shifted by a multiple (N+0.5) of the period of the fundamental frequency. Fig 6 shows the pattern in the case of N=3. The next macro bunch arrives 106ns later, which is the period of 9.38MHz.

352 Fig.6: The bunch pattern for the nominal operation mode of eRHIC for $N=3$. The energy of the
 353 electron bunches ranges from 50MeV to 11.7GeV. The heads of accelerating (green circles) and
 354 decelerating (red dots) trains separation time is a $(N+0.5)$ time 1.54ns, which is the period of
 355 647.2MHz.

356 By varying the delay integer N (the shift 366 than the prediction from the single bunch loss
 357 parameter), the bunch spectrum changes. 367 factor.
 358 Therefore, the HOM power generation 368 By integrating the current PSD with the
 359 depends on N , even though the impedance of 369 cavity impedance, we obtain the effective
 360 the cavity remains the same. Each bunch 370 loss factor of the bunch trains. The effective
 361 encounters different wake potentials and 371 loss factors are plotted as a function of shift
 362 generates HOM energy at different RF 372 number N in Fig. 7. Note that the maximum
 363 phases, which are related to each bunch's 373 shift is bounded by the availability of RF
 364 arrival timing of a cavity. The time averaged 374 buckets within the macro bunches.
 365 HOM power generation is quite different

375

376

377 Fig.7. The effective loss factor of the multi-bunch patterns for various values of the shift parameter
 378 N in the nominal design of eRHIC.

379 From Fig. 7, we can see that the loss 383 mode contribution, the effective loss factor at
 380 factor, and thus HOM power generation, is 384 $N=4$ is reduced by 11.6%. For the charge
 381 minimal at $N=4$. Compared with the single 385 2.6nC and the average beam current of
 382 bunch loss factor without the fundamental 386 340mA, the average HOM power is 1.95 kW

387 instead of the 2.21kW estimated by the single
 388 bunch wake field.
 389 The loss factor discussed above is
 390 integrated over the full frequency range. Now
 391 we consider the frequency distribution of the

392 HOM power. Fig. 8 illustrates the loss factor
 393 integrated up to a given frequency. The multi
 394 bunch case with $N=4$ is compared with the
 395 single bunch loss factor.

396

397 *Fig. 8. The integrated loss factors of a single bunch (red solid) and multi-bunch pattern when*
 398 *$N=4$ (blue dots) for the nominal eRHIC design. The loss factor of the fundamental mode is not*
 399 *included. The light blue vertical line marks 5GHz.*

400 Below 5GHz, the single bunch loss
 401 factor is ~ 1.78 V/pC, while the multiple
 402 bunch (at a shift parameter $N=4$) has loss
 403 factor of ~ 1.55 V/pC. This means that in
 404 addition to the reduction of the fully
 405 integrated loss factor in the multi-bunch case,
 406 the fraction at the low frequency part is also
 407 reduced. This feature must be given
 408 consideration in the design of the HOM
 409 damping scheme.

3.3 Ultimate design example

410 Next we study the high current operation
 411 mode of the ultimate eRHIC Linac-ring
 412 design. We apply the same method we used
 413 above for the nominal operation mode.
 414 Similarly, the loss factors for multi bunch
 415 pattern are plotted as a function of shift N in
 416 Fig 9.

Fig. 9. The effective loss factor of the multi-bunch patterns for various values of the shift parameter N in the eRHIC ultimate design.

The integrated loss factor reaches minimum when $N=5$. In this case, the heads of accelerating and decelerating trains are separated by 7.72ns which is 5.5 times the period of 647.2MHz. The HOM power calculated for the multi-bunch pattern with $N=5$ is 18% smaller than what might be

expected from the single bunch method. The average current is 500mA from Table 1, thus the generated HOM power is 5.48kW instead of 6.63kW from single bunch estimation

In Fig.10, we show the breakdown of the integrated loss factor by frequency for $N=5$.

Fig. 10: The integrated loss factors of a single bunch (red solid) and multi-bunch pattern when $N=5$ (blue dots) for the nominal eRHIC design. The loss factor of the fundamental mode is not included. The light blue vertical line marks 5GHz.

Below 5GHz, single bunch loss factor is $\sim 1.78\text{V/pC}$, while the multiple bunch ($N=5$) has loss factor of $\sim 1.28\text{V/pC}$. The HOM power below 5 GHz is $\sim 3.39\text{ kW}$. The high frequency ($>5\text{ GHz}$) HOM power is 1.88 kW .

Lastly we consider the high-energy case of the ultimate operating mode. We use 12

accelerating turns to reach 20 GeV . The linac average current is limited to 145 mA to restrict the synchrotron radiation power. The effective loss factor as a function of N is shown in Fig. 11.

Fig. 11. The effective loss factor of the multi-bunch patterns for various values of the shift parameter N in the high-energy mode of the ultimate design of eRHIC.

After breaking down the contribution by examining the integration loss factor in Fig. 12, we find that the HOM contribution beyond 5GHz remains ~28.8%. The maximum HOM power generation per cavity

Fig. 12. The integrated loss factors of a single bunch (red solid) and multi-bunch pattern when $N=3$ (blue dots) for the nominal eRHIC design. The loss factor of the fundamental mode is not included. The light blue vertical line marks 5GHz.

3.4 Spectral study

Mathematically, the Fourier transform of a bunch train with a phase shift relative to the origin is a product of the Fourier transform of the un-shifted train by a function that depends on the phase shift.

The spectrum of an ERL bunch train is a linear combination of the spectra of accelerating and decelerating bunch trains. Thus the combination spectrum and its PSD will exhibit a dependence on the phase shift. This dependence can manifest itself as enhancement or reduction at different frequencies.

It would be instructive to compare the PSD of bunch patterns with different shift

parameters N . In the ultimate high-energy case, we chose two bunch patterns: $N=3$ (where we obtain the minimal effective loss factor) and $N=14$ (where the effective loss factor is more than that of single bunch). We compare their PSD in Fig 13. Note that the PSD axis is normalized. Both bunch patterns have the same average current. In Fig 13, it is clear that the shift N does not change the frequencies where the spikes occur, but changes the amplitude distribution among different spikes. The amplitude reduction of odd harmonics component of $N=3$ is larger than that of $N=14$. The odd harmonic components in the spectrum are greatly reduced when the shift RF cycle is 3 but enhanced when the shift RF cycle is 14.

Fig. 13. (a) The current PSD for two cases: 3 RF periods shift (red dots) and (b) 14 RF periods shift (blue solid). The frequency ranges up to 30GHz. Fig 13 (c) illustrates a zoomed-in envelope of the PSD up to 1.5GHz. The envelopes show a clear difference of the two cases. The PSD (vertical) axis is in arbitrary units.

4. Additional Considerations

4.1 Transient Cavity voltage change

In the ERL mode, the net beam loading for the fundamental mode is zero. Therefore, the cavity fundamental mode voltage remains the same when a macro bunch passes through it. However, the transient beam loading within this macro bunch varies, depending on the bunch pattern. Thus, it would be useful to estimate the fundamental mode power evolution and evaluate the bunch energy variation caused by the beam loading. In our ultimate design eRHIC example where the bunch charge is the largest, the energy gain of each cavity is 21.16MV, the stored energy is 218J and the bunch charge is 5.3nC. Thus the 7 accelerating (or 7 decelerating) bunches remove (or add) 0.112J (a fraction of 5.14×10^{-4}) of the stored energy, and change the fundamental mode voltage by 5.43kV. We find that for the shift parameter $N=5$ the maximum fundamental voltage swing is 5 times this number, or 27.15kV, which is acceptable.

4.2 Bunch stretch patterns

There is an additional way in which we can change the bunch train pattern and affect the PSD. In the example of the eRHIC high-

energy operation case, there are 12 accelerating and 12 decelerating bunches placed within the period of 9.38 MHz. 9.38MHz is 69th harmonics of 647.2MHz, allowing us to stretch the duration of the bunch train. Let us introduce the “stretch parameter” M (integer). We set the separation time between each bunch in the accelerating (and decelerating) train to be M times the RF period of 647.2MHz. Thus the previous discussion corresponds to the case of $M=1$. Fig 14 shows examples of the bunch patterns where $M=1,2,3,4$. While stretching the bunch separation inside of both trains, the cavities continue to operate in ERL mode where the energy of fundamental mode is transferred from decelerating to accelerating bunches. However, the bunch PSD spectrum will change. In time domain, the wake fields seen by successive bunches are quite different due to the longer delay in the arrival time. The stretching in time domain allows more time for damping the wake field between the successive bunches. Thus we can expect that the effective loss factor would be further reduced. In the following simulation, we study the effective loss factor as a function of M .

Fig.14. The bunch patterns within 9.38 MHz period (110ns) and 12 acceleration turns. (a). $M=1$, (b). $M=2$, (c). $M=3$, and (d). $M=4$. The shift parameter N is set at 1 for all four cases. Inside the accelerating (green circles) and decelerating (red dots) trains, bunch separation times are 1.54 ns, 3.08 ns and 4.62 ns respectively where 1.52 ns is the period of 647.2 MHz.

The effective loss factors of these four cases are given in Fig 15 when the numbers of the stretch parameter M are varied between 1 and 4. The generated HOM power from a cavity can be obtained accordingly. When the stretch parameter M is 4 and the shift parameter N is 1, the effective loss factor is 1.7V/pC, and that is the minimal HOM power/cavity for the ultimate design. The minimal loss factors occur at different shift parameters as we vary the stretch parameters M . The integrated loss factors from different frequencies of these cases will be discussed later.

Fig.15. The integrated loss factors of multi-bunch for various values of the stretch parameter $M=1$ (blue squares), $M=2$ (green diamonds), $M=3$ (pink circles) and $M=4$ (black stars). The numbers of accelerating and decelerating bunches in the trains are 12.

Now we study the PSD when the stretch parameter M is varied. The PSD is given in Fig. 16 when $M=1, 2, 3, 4$. The amplitude component at 647.2MHz vanishes due to the ERL mode, regardless of the value of M . Different M cases have different Sinc

function envelopes, and the larger stretch parameter has smallest lobe bin bandwidth and denser population in PSD. HOM power generation will be different because the impedance spectrum will be the same.

Fig. 16. The current PSD for stretch parameters: $M=1$ (a:blue), $M=2$ (b:green), $M=3$ (c:pink) and $M=4$ (d:black) and comparison with the single bunch spectrum (red solid). Frequency span of 0~30GHz. The bunch patterns in time domain are shown in Fig. 14. The frequency ranges up to 30GHz. The PSD axis is normalized and in arbitrary units.

Choosing accelerating-decelerating train shift parameter $N=1$ for different stretch factors M in Fig 17, we can plot effective loss factors for different cases. The effective loss factors are 2.0264V/pC, 2.1589V/pC, 1.999V/pC, 1.6750V/pC, respectively. The integrated loss factors for different cases are

plotted in Fig 17. In Fig 17, for M values of 1, 2, 3 and 4, the HOM power contributions below 5GHz are 71.6%, 76.4%, 62.5% and 65.7%, respectively. These power levels and frequency contributions allow a well-informed design of the HOM damping system.

Fig 17. The integrated loss factor without fundamental mode of single bunch (red) and four cases with different values of stretch parameter M and $N=1$. The integrated loss factors are chosen and plotted based on the minimal HOM power generation for different M . Single bunch (red solid), $M=1$ (blue Dashed line), $M=2$ (green Dash-dot line), $M=3$ (pink Dotted line), and $M=4$ (black stars Dotted line).

5. Conclusion

We have shown that different bunch patterns affect the average HOM power generation. For this purpose, we introduced two parameters that modify the bunch pattern, the shift and stretch parameters. We demonstrated that a significant variation of the HOM power results when these parameters are changed. It also follows that

the ERL HOM power cannot be accurately calculated from the single bunch loss factor. When designing an energy-recovery linac, selecting a certain bunch pattern can help minimize the average HOM power generation. This study estimates the effective loss factor of different bunch patterns by using a particular example, the eRHIC ERL.

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