ON THE FREQUENCY CHOICE FOR THE eRHIC SRF LINAC*

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Abstract

eRHIC, a future electron-hadron collider proposed at BNL, will collide high-intensity hadron beams from one of the existing rings of RHIC with an electron beam from a multi-pass 21.2 GeV superconducting RF (SRF) Energy Recovery Linac (ERL). A novel approach to the multi-pass ERL, utilizing a non-scaling FFAG, was recently proposed [1]. It has many advantages over the previous designs including significant cost savings. The current design has up to 16 passes in two FFAG rings. To mitigate various beam dynamics effects, it was proposed to lower RF frequency of the SRF linac from 704 MHz used in the previous design. In this paper we consider different effects driving the frequency choice of the SRF ERL and present our arguments for choosing a lower RF frequency.

INTRODUCTION

An electron-ion collider eRHIC will collide high-intensity hadron beams from RHIC with an electron beam delivered by a multi-pass ERL. An FFAG-based ERL will accelerate an electron beam to 15.9 GeV (50 mA) after 12 passes through an SRF linac or to 21.2 GeV (18.5 mA) after 16 passes [1]. In both cases, the linac energy is 1.322 GeV. A 704 MHz superconducting cavity has been developed at BNL for high-current applications [2,3,4]. The cavity, named BNL3, has an optimized geometry that supports strong damping of higher order modes (HOMs) while maintaining good properties of the fundamental mode. The damping is accomplished via six antenna-type couplers attached to the large diameter beam pipes [5]. The simulations showed that this HOM damping scheme provides sufficient suppression of the parasitic HOM impedance to satisfy requirements of the previous version of eRHIC. However, with up to 16 passes in the FFAG version the requirements to the HOM impedance becomes more stringent, To mitigate various beam dynamics effects, it was proposed to lower the RF frequency. In this paper we consider different effects driving the SRF frequency choice, present arguments for choosing a lower frequency and finally describe the main SRF linac.

CONSIDERATIONS AFFECTING THE FREQUENCY CHOICE

There are several considerations affecting the frequency choice for a high current multi-pass ERL: a bunched beam structure, bunch length, energy spread, beam breakup (BBU) instability threshold, SRF losses, RF power efficiency, cost and complexity considerations. In the eRHIC case, most of these considerations point toward a lower frequency [6]. Below we briefly consider some of the effects.

A continuous train of electron bunches can lead to accumulation of ions and the fast ion instability [7]. To clear the accumulated ions, a gap of about 0.95 ms (of the same duration as an abort gap for the RHIC beams) is introduced in eRHIC [8]. Such a gap in the electron beam induces a transient voltage on the ERL cavities:

$$\frac{\Delta V_c}{V_c} = \frac{I_b T_{gap}}{2\pi c E_{acc} N_{cell}} \omega^2 , \quad (1)$$

where V_c is the cavity accelerating voltage, ΔV_c is the transient due to the abort gap of duration T_{gap}, I_b is the beam current, E_{acc} is the accelerating gradient, N_{cell} is the number of cells per cavity, ω is the RF frequency, and c is the speed of light. As the transient voltage fraction is proportional to the frequency square (for the same accelerating gradient and number of cells per cavity), there is a clear advantage of using lower frequency cavities.

One of the salient features of eRHIC is the ability to use polarized electrons in collisions. Preserving polarization of the electron beam throughout an acceleration cycle is a difficult task and the dominant depolarizing effect is caused by an energy spread induced by the RF wave curvature [1]. While this can be alleviated with energy spread compensation linac [9], in the end it limits the bunch length. Lower frequency allows us to proportionally increase the bunch length, which, in turn, reduces various wake field effects. For example, the linac loss factor is approximately proportional to the cavity frequency square.

A transverse beam break up is the dominant effect limiting beam current in ERLs. The instability threshold current is inversely proportional to the frequencies of higher order modes. Also, the number of HOMs is reduced proportionally to the cavity frequency, as fewer low-frequency cavities are required to build the linac. If one can lengthen the bunch (as in the case of eRHIC) with lowering the frequency, the total number of HOMs per cavity within the bunch spectrum stays constant. Thus the overall improvement of the BBU threshold scales inversely to the frequency square. This consideration is of special importance for a multi-pass ERL.

During the last few years, new advances in the SRF technology demonstrated possibility of preparing cavities with a very low residual resistance of just a few nanoOhm, see for example reference [10]. This is

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especially beneficial at low frequencies, where SRF losses are dominated by residual losses as the BCS component becomes very small. As it was discussed elsewhere [11], improving the residual resistance shifts optimal cryogenic performance of SRF linacs to lower frequencies.

Additional considerations include better RF power generation efficiency at lower frequencies; possible lower sensitivity to an environmental (microphonic) noise; some cost advantages related to the reduced complexity of the system and smaller number of components in the linac.

As at very low frequencies (~300 MHz and below) the size of the cavities becomes inconveniently large, we have chosen a frequency of 422 MHz for eRHIC, which is the 45th harmonic of the RHIC bunch repetition frequency of 9.38 MHz.

In order to avoid bunches from different ERL passes from piling on top of each other in the linac and to avoid uneven voltage transients, the circumference of the FFAG should be chosen appropriately. For eRHIC we have chosen it to be one RF wavelength longer than the circumference of RHIC. In this case all bunches travel in groups of *N* (*N* is the number of ERL passes) accelerating bunches separated by one RF period, followed by *N* decelerating bunches with the same bunch separation. This bunch pattern, shown in Figure 1, will produce a regular voltage transient and will ensure that the accelerating and decelerating bunches at the same pass have the same energy. At 422 MHz the transient is small, of the order of 10^{-3} in magnitude.

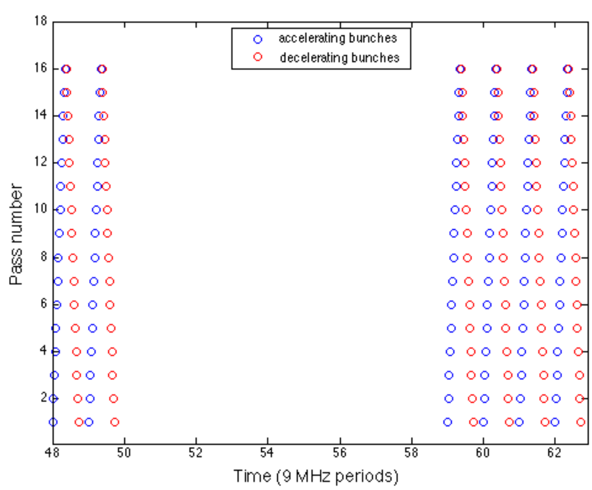

Figure 1: Bunch pattern in the eRHIC FFAG ERL with 16 passes, showing the ion-clearing gap.

As we mentioned above, the dominant effect, which limits the beam current in ERLs, is the transverse BBU. To evaluate this effect for eRHIC, we have scaled the previously developed BNL3 cavity shape to 422 MHz and calculated parameters of several lowest dipole HOM pass bands. The results are shown in Figure 2. This data set was used for BBU simulations, which predicted the threshold beam current higher than 50 mA even with no HOM frequency spread [1].

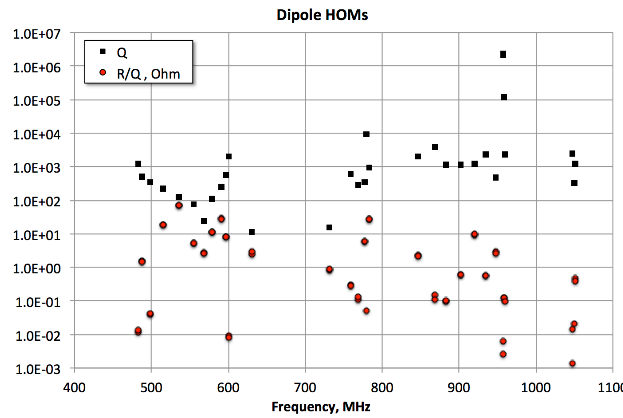

Figure 2: Quality factors and *R/Q*'s of the dipole HOMs.

MAIN SRF LINAC

The ERL SRF systems will have to provide only power necessary to maintain stable amplitude and phase of the electromagnetic field inside SRF cavities and to compensate for any parasitic energy losses incurred by the beam (due to synchrotron radiation, resistive wall and higher order modes). The maximum amount of the parasitic beam power loss is set to 12 MW, which in turn limits the beam current at 21.2 GeV to 18.5 mA. The main SRF linac only accelerates and decelerates the electron beam. It will be installed in the 200-meter long IR2 straight section of the RHIC tunnel. Parameters of the main SRF linac are listed in Table 1. The beam loss power will be compensated by a separate linac, located at the same IR and operating at the second harmonic of the main linac. An energy spread caused by the curvature RF waveform causes depolarization of spins of electrons. To minimize this effect, an energy spread compensation linac is required. This SRF linac will operate at the fifth harmonic of the main linac frequency.

Table 1: Parameters of the Main SRF Linac

Energy gain	1.32 GeV
Bunch length	4 mm rms
Bunch repetition frequency	9.38 MHz
Number of RF buckets per RHIC revolution	120
Number of RF buckets filled	111
RF frequency	422 MHz
Number of 5-cell SRF cavities	42
Linac fill factor	0.60
Accelerating gradient	18.4 MV/m
Operating temperature	1.9 K

The main SRF linac will utilize five-cell 422-MHz cavities, scaled versions of the BNL3 704-MHz cavity developed for high current linac applications [2,3,4]. Each cavity will be housed in an individual cryounit, a series of

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which will form one long cryomodule [9]. The cavities will operate at an accelerating gradient of 18.4 MV/m. The cavities will be powered from individual high power RF amplifiers. At 6 Hz peak detuning due to microphonic noise, the required peak RF power will be approximately 32 kW per cavity. A high beam current and multi-turn operation of the ERL imposes stringent requirements on damping of higher order modes (HOMs) in the cavities to avoid beam breakup (BBU) instabilities. The HOM power is reaching 11.7 kW per cavity at a beam current of 50 mA and 12 ERL passes.

CONCLUSION

In this paper we considered several issues driving the frequency choice of a high current multi-pass superconducting RF ERL for eRHIC. All beam dynamics effects point toward a lower RF frequency. Considering this and technology limitations, we have proposed to lower the eRHIC main linac frequency from 704 MHz to 422 MHz.

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