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PROGRESS ON THE ELECTRON ION COLLIDER'S RCS RF RAMP DEVELOPMENT

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Abstract

We report on progress developing the Energy and RF ramp for the EIC's Rapid Cycling Synchrotron (RCS). The development of the RF voltage and phase ramp from injection energy at 400 MeV to 5, 10 and 18 GeV extraction energy requires control of the bunch's longitudinal aspect ratio to avoid both collective instabilities, RF bucket height and width as well as lattice dynamic aperture limits. Further the ramp profile must meet the technical limits for the current super conducting cavity design.

INTRODUCTION

The EIC's Rapid Cycling Synchrotron (RCS) is a proposed full energy polarized electron injector for the EIC's Electron Storage Ring (ESR). It is designed to deliver two 28nC bunches at 5 and 10 GeV and two 11nC bunches at 18 GeV every second. It is fed by a polarized 7nC source and 400 MeV LINAC which will generate two bunches separated by about 2 microseconds every shot. For the 5 and 10 GeV modes it will deliver four shots of two 7nC bunches. For the 18 GeV mode it will deliver two shots of two 5.5nC bunches. The bunch length at the exit of the pre-injector will be 40ps RMS (τ) with a relative momentum spread of 0.25% RMS (δ). Each train of 4 (in the case of 5 and 10 GeV mode) or 2 (in the case of 18 GeV mode) will be merged into a single bunch, yielding two bunches to be extracted to the ESR.

The merge itself was previously to occur right after injection [1]. However more recently it has been preliminarily decided to move it to 1 GeV. This was to minimize the time the beam spent at injection energies where it is thought that the field quality of the magnets might be poorer. Simulations of the merge at 1 GeV including wakefields give a final bunch with an RMS bunch length of 162 ps and dp/p of 1.9e-3. This bunch aspect ratio along with radiative losses set the initial voltage and phase for the main 591 MHz SRF accelerating cavities.

ENERGY RAMP

In the past we considered using a ramp function modeled using a hyperbolic-like tanh function [1]. However we found it necessary to be able to control the peak ramp rate early on and at the end of the ramp more tightly. Thus we have chosen to use a piecewise continuous to the second degree polynomial function shown in Eq. 1.

$$E(t) = \begin{cases} E_0 + b_1 t^3 + c_1 t^4 & t < T_1 \\ E_1 + mt & T_1 \leq t \leq T_2 \\ E_3 + b_2 (dT_3 - t)^3 + c_2 (dT_3 - t)^4 & T_2 < t \leq T_3 \end{cases} \quad (1)$$

Here we define T_1 as the time to accelerate to the top ramp rate, E_0 the initial energy, E_1 the energy at the beginning of the linear ramp, E_3 the top energy, m the linear ramp rate, T_2 the time to the end of the linear ramp and T_3 the time to the end of the acceleration ramp. Here we choose the end of the linear ramp to occur at and energy E_2 right after the last intrinsic spin resonance which sets the value for T_2. To ensure continuity and smoothness in both the first and second derivative we set the coefficients and other parameters as follows:

$$\begin{gathered} b_1 = m/T_1^2 \quad c_1 = -m/(2T_1^3) \\ E_1 = E_0 + b_1 T_1^3 + c_1 T_1^4 \\ b_2 = -m/dT_3^2 \quad c_2 = m/(2dT_3^3) \end{gathered} \quad (2)$$

Here dT_3 sets the length of the final parabola ramp.

Since the bunch is the longest right after the merge, accelerating with such a long bunch requires some care managing the limited area of the RF bucket. In this article we focus on the portion of the ramp after the merge from 1 GeV to 18 GeV, and using a linear ramp rate given by an ideal acceleration from 400 MeV to 18 GeV in 100 msecs or $m = 0.176$ GeV/msec and $T_1 = 4000$ turns or 51.32 msecs and $dT_3 = 3.5$ msecs. Fig. 1 shows a plot of the Energy ramp.

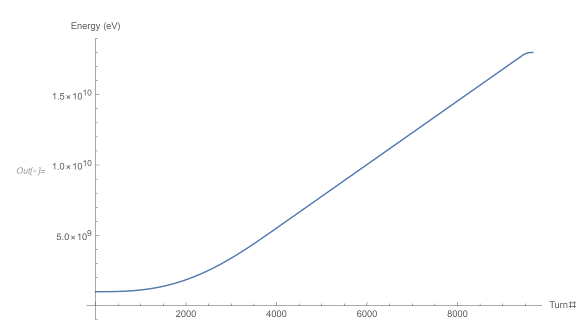

Figure 1: Turn-by-turn Energy Ramp parameterized by Eq. 1

With the Energy ramp defined we can also derive the energy gain per turn given as the derivative with respect to turn of the energy ramp function. The energy gain per turn is shown in Fig. 2

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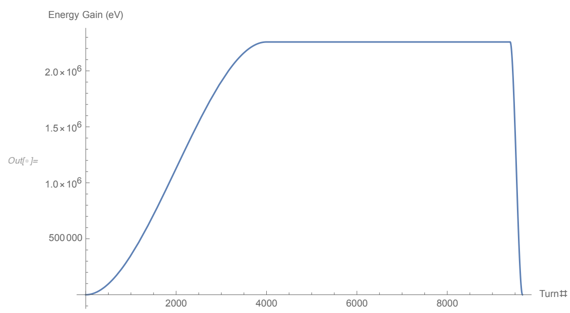

Figure 2: Turn-by-turn Energy gain per turn.

RF RAMP

After the merge, the final bunch will have a long aspect ratio which requires some careful handling in order to accelerate with minimal loss of particles out of the RF bucket as the bucket shape changes and the bunch damps adiabatically. We also needed to keep the voltage generally monotonically increasing during the acceleration. We accomplished this by ramping the synchrotron tune between its initial and final values using a function $g(n)$ which used the energy ramp function normalized between 0 and 1 taken to the fourth root as shown in Eq. 3,

$$\begin{aligned} g(n) &= (E(n) - E0)/(E_3 - E_0) \\ Q_s(n) &= g(n)^{1/4}(Q_s(T_3) - Q_s(0)) + Q_s(0). \end{aligned} \quad (3)$$

This appeared to maximize the RF bucket area to bunch ratio. For these ramps we use the following relationships for the phase ϕ_s and voltage V accounting for radiative losses U_0.

$$\begin{aligned} V &= \sqrt{(\frac{Q_s^2 E 2\pi}{h\eta})^2 + (E' + U_0)^2} \\ \phi_s &= \arccos(\frac{Q_s^2 2\pi E}{\eta h V}) \\ U_0 &= C_\gamma \frac{E^4}{\rho}. \end{aligned} \quad (4)$$

In Fig. 3 and 4 the resultant phase and voltage ramp are shown.

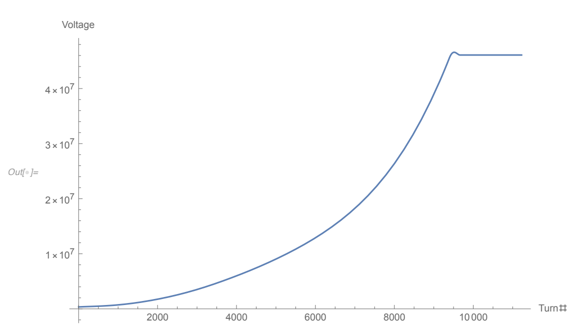

Figure 3: Voltage Ramp turn-by-turn

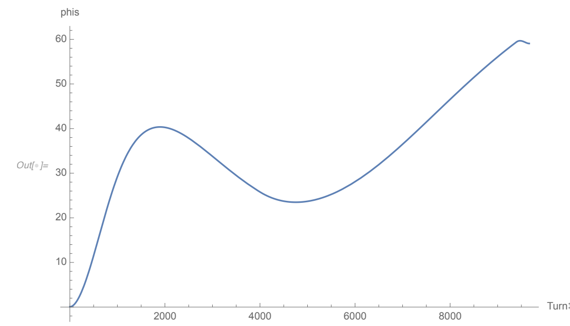

Figure 4: Phase ramp turn-by-turn

MICROWAVE INSTABILITIES

The collective instabilities can be checked for this ramp using the approximate formula for the microwave instability,

$$\frac{Z}{n} \approx \frac{2\pi^3 E\alpha\hat{\tau}\hat{\delta}^2}{3Q} \quad (5)$$

Where Q is the bunch charge (28nC for 5 and 10 GeV extraction and 11 nC for 18 GeV) and α is momentum compaction factor for the RCS lattice. While $\hat{\tau}$ and $\hat{\delta}$ represent the RMS bunch length in time and relative energy deviation respectively. Estimates of the Impedance for the RCS place is at about $\frac{Z}{n} \approx 0.1$. As can be seen from Fig. 5 we are above this threshold through the whole 18 GeV ramp. However for the 5 and 10 GeV ramp with 28nC bunch charge we would exceed it right before 5 GeV. This probably will require adjusting the extracted longitudinal emittances to stay above this threshold or controlling the impedance more.

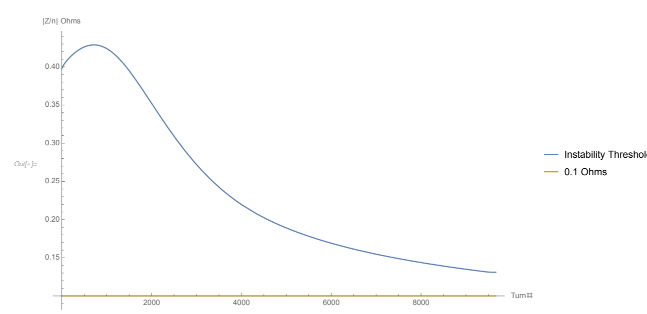

Figure 5: RCS microwave threshold versus energy for 11nC bunch.

We will need to study the effect of collective instabilities early on during the ramp in more detail in the future.

TRACKING

Using the RF and energy ramp derived, we tracked a 100 particle up the ramp using the particle tracking code Zgoubi [2]. The particle distribution relative to the RF bucket's separatrix are plotted for turn 1000 in Fig. 6. We observed losses of about 6 particles between turn 600 to 2000 out of 10000 turns. This simulation included synchrotron radiative effects but not collective wake-field effects.

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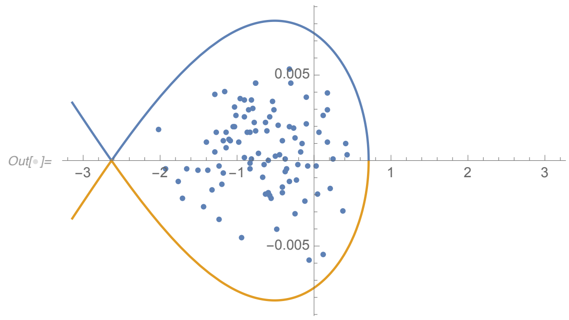

Figure 6: Turn 1000 for 100 particle tracking using Zgoubi

CONCLUSION

We have developed a piecewise Energy and RF function for the ramp from 1 GeV to 18 GeV. Tracking results show that this ramp function still has losses of about 6% during first several 100 turns. More study of how to ramp the RF phase and voltage and the rate of the energy ramp is required to bring these losses to zero.

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