BNL-223339-2022-TECH

EIC-ADD-TN-32

The feasibility of electron beam slip stacking in EIC Rapid Cycling Synchrotron

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August 2022

Electron-Ion Collider

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

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The feasibility of electron beam slip stacking in EIC Rapid Cycling Synchrotron

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(Dated: August 26, 2022)

Announced in 2020, the Electron Ion Collider will be constructed at Brookhaven National Lab (BNL) by modifying the existing Relativistic Heavy Ion Collider (RHIC) facility. Among the alterations include the installation of an electron storage ring (ESR) and a Rapid Cycling Synchrotron (RCS) in the existing RHIC tunnel. The RCS will accelerate polarized electrons from 400MeV to 5GeV,10GeV and 18 GeV and transfer it to the ESR. The LINAC source produces 7nC per shot meanwhile the RCS requires 28nC per bunch of charge. Currently, it is planned to inject 4 bunches into adjacent RF buckets and then merge them into a single RF bucket using fields from several RF cavities. However, this requires a kicker with an exceptionally fast rise and fall time to inject into adjacent RF bucket without disturbing the existing circulating bunch and this requires harmonic RF kickers. Our study focuses on determining the feasibility of an alternate particle injection method that will utilize slip stacking, a method that accommodates the circulation of multiple beams with different momentum in the same azimuthal space of the beampipe, thus permitting the accumulation of charge from several shots into a single RF bucket. We find the momentum aperture required for slip stacking using current RCS beam parameters exceeds the RCS's momentum deviation limit, dp/p = 1.5%. We determine the appropriate dimensions the beam must have to enable slip stacking and conduct a literature review of slip stacking schemes in other facilities. The literature review tentatively indicates that slip stacking has not been attempted on electron beams at a major accelerator facility.. The slip stacking approach has the potential to save the cost of the harmonic RF kicker and bunch merging cavities.

I. INTRODUCTION

The current transfer and injection of polarized electron beams from the initial acceleration stage in the 400 Mev LINAC to the RCS is a multi step process that involves bunch merging and the use harmonic RF kickers. It would prove difficult for the gun and injector LINAC to produce 28nC bunches as required by the RCS. Instead, two bunch trains consisting of four 7nc bunches with 1.6ns spacing will be injected into adjacent bucket. The bunch train will have a spacing of $\sim 2\ \mu s$.The bunch train schematic is shown in Figure 1. Each bunch train will be merged into a single RF bucket pairwise using 295.5MHz and 147.8MHz RF cavities.

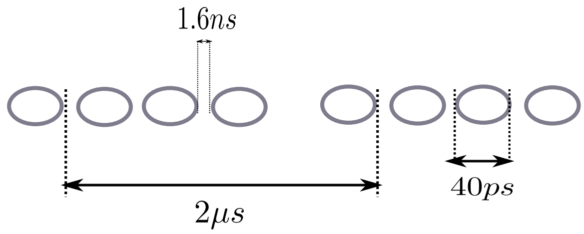


FIG. 1: Two trains of 4 bunches with $2\mu s$ spacing between the trains. Within the train, bunches are spaced $1.6ns$ apart RMS bunch length, $\hat{\tau}= 40ps$

A. Current RCS injection design

Single pulse kickers are insufficient to inject electron bunches from the LINAC to the RCS since a remarkably short 1.6ns rise/fall time is needed. Instead, a RF harmonic kicker is proposed. It will combine a few harmonics with fundamental frequency of 148 MHz (1/4 of 591 MHz) to achieve a 1.6 ns rise/fall time in the micro pulse. [1]

B. Slip stacking

In this technical note, we explore the feasibility of using slip stacking to avoid the use of the harmonic RF kickers. Slip stacking is a configuration where

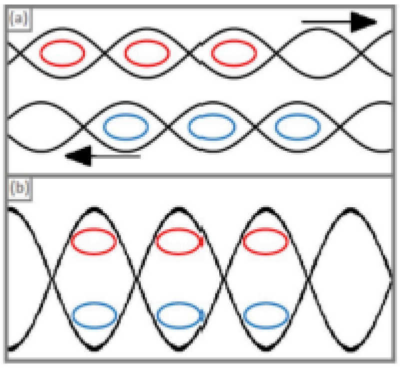


FIG. 2: Two sets of bunches slipping in opposite directions then combined in the same RF bucket once azimuthally overlapping [2].

multiple beams of different momentum occupy the same azimuthal space of the beam line. In Figure 2, this is depicted schematically. In Figure 5, we show how slip stacking could be used to inject bunch train into the RCS.

We shall study the case of two beams, b_1 and b_2 in the RCS. The beams are longitudinally focused by 2 RF cavities with frequencies f_1 and f_2 respectively and each beam is perturbed by the other RF cavity. In this study, a particle synchronized with upper RF is our frame of reference and the influence of the lower RF cavity is added. We define the phase slipping frequency, $\Delta\omega$ below.

$$\Delta\omega = 2\pi\Delta f \tag{1}$$

where $\Delta f = f_1 - f_2$. The motion of a particle under the influence of two main RF cavities are governed by the equations below [3]:

$$\dot{\phi} = 2\pi\omega_0 h\eta\delta \tag{2}$$

$$\dot{\delta} = \frac{e\omega_0 V}{\beta^2 E}[\sin(\phi) + \sin(\phi - \Delta\omega t)] \tag{3}$$

where ω_0 is the revolution frequency, h is the RCS harmonic number, η is the phase slip factor, e is the particle charge, V is the effective RF voltage and E is particle's total energy $\beta = \frac{v}{c}$, the velocity fraction of the speed of light. The dynamics of a slip stacked beam can be uniquely defined by the slip stacking parameter, α_s, defined below.

$$\alpha_s = \frac{\Delta\omega}{\omega_s} \tag{4}$$

where ω_s, the synchrotron frequency is given by

$$\omega_s = \omega_0\sqrt{\frac{hV_0|\eta\cos\phi_s|}{2\pi E\beta^2}} \tag{5}$$

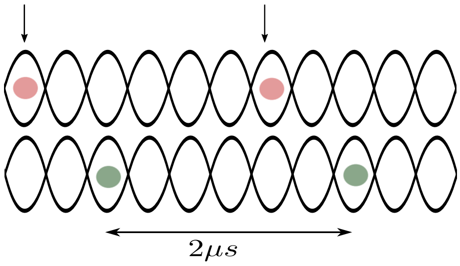
. Equivalently, α_s describes the extent to which the two buckets, determined by f_1 and f_2 overlap. In particular, we are concerned about the momentum aperture limit, $\frac{dp}{p}$ defined as the the maximum momentum deviation a particle can have from ideal on-energy particle. In section III, we calculate the required $\frac{dp}{p}$ for slip stacking using the current dimensions the beam would have upon bunch rotation in the transfer line between the LINAC and the RCS [1]. In section II, a review is made of slip stacking schemes in other facilities. We note that all the studies referenced in this paper study slip stacking with hadron beams while ours is unique in that it focuses on electron beams.

II. REVIEW OF SLIP STACKING SCHEMES

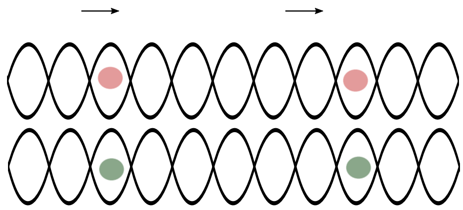
Slip stacking was first demonstrated at CPS and SPS to improve local line density in the proton- antiproton project at CERN. Despite which slip stacking scheme used they found that bunch distortion increases quickly with bunch size (Boussard and Mizumachi [4]).

1. *Constant frequency bunch combination*

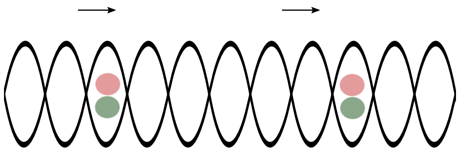
For 800MeV CPS injection, bunch b_1 was produced in a CPS booster ring with RF frequency f_1. A total of 5 CPS cavities driven at f_1 trapped b_1. The bunch b_2 came from another booster ring was trapped in an identical manner. The separation of bunch b_1 and b_2 was set at a minimum of one RF period. Superimpositon of the bunches occurred after they had drifted by 5 RF periods. Combination is triggered by a pulse which is produced after an integer number of periods of is counted. At this trigger, all 10 RF cavities connected to a the normal phase loop system. Additionally, their voltages were set to the maximum of 20kV to give maximum acceptance. With f_1 and f_2 constant, the beams combine as a result of rising magnetic fields. The optimum frequency separation was found at $\alpha_s = 5$. The scheme worked for the highest injected intensities of $\approx 10^{13}$ppp, but unexplained beam losses occurred above $\sim 6 \times 10^{12}$ppp. This scheme's unique



(a) Two 7nC bunches (red) are injected in an off momentum orbit with maximum momentum aperture limit dp/p =1.5%.



(b) Over time, the bunches slip with respect to one another.



(c) Once the bunches overlap azimuthally, they are captured into single RF bucket with frequency $\frac{f_1+f_2}{2}$. This process is repeated 3 additional time to create two 28nC bunches.

FIG. 3: Proposed slip stacking RCS injection scheme. In this proposal, there would no longer be concern that the injection of the second bunch train would kick the already circulating beam because it would be injected at an off-momentum orbit. Thus, eliminating the need of harmonic RF kickers that achieve a 1.6ns rise/fall time.

feature is that RF frequency of the beam is held constant in the recombination process and thus the beams combine due to the increase in RF voltage.

2. Average frequency bucket capture combination

In this scheme, 12 equispaced bunches were injected into the SPS and then combined by pairs at the 270 GeV storage energy to achieve design luminosity. First, adjacent bunches are separated in momentum as described later in section 3 of that paper. To minimize final beam emittance, their energy difference is reduced shortly before they superimpose azimuthally. To combine the bunch pairs they are combined into a single large bucket at frequency $\frac{f_1+f_2}{2}$. To achieve this, f_1 and f_2 are ramped down linearly i.e. $\frac{df}{dt}$, the rate at which each of the frequencies were changed was constant. The approaching time was 25 ms. Computer simulations were used to optimize values such as α, V_{RF} and $\frac{df}{dt}$ for minimum bunch area after combination. Figure 4 show this slip stacking scheme with the optimal parameters.

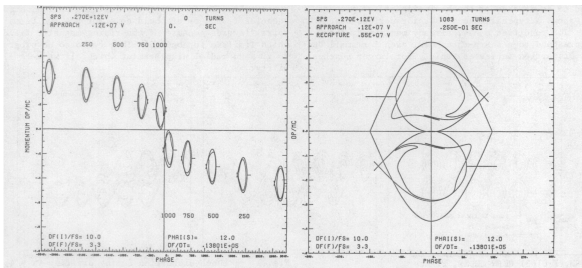


FIG. 4: SPS 270 GeV bunch approach and combination. $\frac{df}{dt} = 13.8$kHz/s [4]

3. Bunch interleafing at average frequency.

More recently, a slip stacking study was carried out by Argyropoulos et al. for the SPS. Two superbatches, sb_1 and sb_2 spaced by 100 ns are injected. Then, they are captured by 2 independent pairs of 200 MHz cavities. The RF frequency will be varied to accelerate sb_1 meanwhile the decelerating sb_2. The batches slip by one another and then are brought back together by decelerating sb_1 and accelerating sb_2. Once the bunches are interleaved as shown in Figure 5 , they are recaptured at average frequency. This differs from the schemes shown in Figures 4 and 5 where the beams overlap at the exact same phase when recombined.

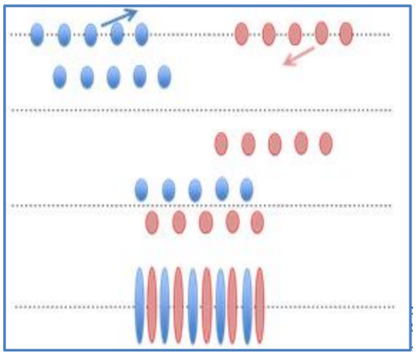


FIG. 5: Bunch interleafing. Once they are interleafed, they are captured into same azimuthal space by setting both RF cavities to $\frac{f_1+f_2}{2}$. [5]

III. CURRENT RCS SYNCHROTRON FREQUENCY CONSTRAINTS

The synchrotron frequency ω_s is limited by the maximum amplitude off-momentum deviation, $\hat{\delta}$, the maximum bunch length, $\hat{\tau}$ and the phase slip factor, η as shown below

$$\frac{\hat{\delta}}{\hat{\tau}} = \frac{\omega_s}{\eta} \tag{6}$$

The current maximum amplitude off-momentum deviation, $\hat{\delta}$, maximum RMS bunch length, $\hat{\tau}$, relativistic gamma, γ, RCS transition gamma, γ_t and the phase slip factor, η are displayed in Table I.

TABLE I: Initial RCS beam parameters

$\hat{\delta}$	0.25%
$\hat{\tau}$	40ps
γ	783
γ_t	68
η	-2.14E-04

Using the parameters shown in Table I, it is found that ω_s= 13.6kHz. We assume α_s =4 as the minimum stability limit [3] [4]. Using (4), the required angular frequency separation $\Delta\omega$ is 54.3kHz. The difference in harmonic number between the two RF cavities, $\Delta h = h_1 - h_2$ can be expressed as:

$$\Delta h = \frac{\Delta\omega}{2\pi\omega_0} \tag{7}$$

For the RCS revolution frequency is found via the equation below

$$\omega_0 = \frac{2\pi}{T_0} = \frac{2\pi c}{c_{RCS}} \tag{8}$$
$$= 489.7kHz \tag{9}$$

where T_0 is the revolution period, c_{RCS} is the circumference of the RCS. With this result, we find Δh = 0.11.

This scenario was simulated in Figure 6below.

The difference in the angular frequency of the two RF cavities $\Delta\omega$ is related to the momentum aperture, $\frac{dp}{p}$, taken up by the two beams[3].

$$\frac{dp}{p} = \frac{\Delta\omega}{2\pi\omega_0 h\eta} \tag{10}$$

The resulting $\Delta\delta$ is found to be 6.75%, which exceeds the RCS momentum aperture limit.

IV. RCS MOMENTUM APERTURE CONSTRAINT

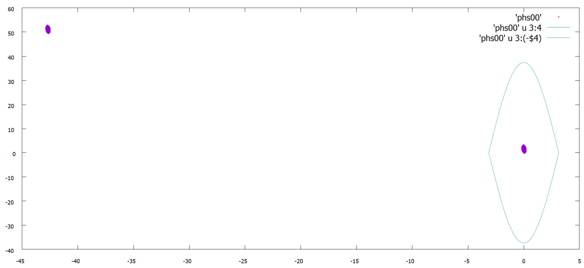
We repeat the calculations of section III, but instead we start by imposing the RCS momentum aperture limit of 1.5% in (10) and end by finding a suitable beam energy spread and bunch length.

Requiring $\Delta\delta$ = 1.5% yields $\Delta\omega$ = 12.1kHz. Assuming a α_s = 4, the synchrotron frequency to be $\omega_s = 12.1kHz/4$ = 3.02kHz using (4). Using the phase slippage factor as in Table I, the ratio of maximum energy spread to bunch length must be

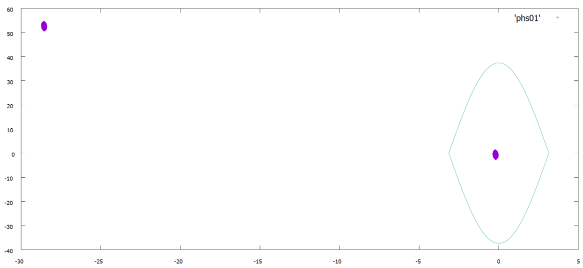
$$\frac{\hat{\delta}}{\hat{\tau}} = 13.9E06 \tag{11}$$

For example, to maintain the current $\hat{\delta} = 0.25\%$, then $\hat{\tau}$ must be 180ps. Conversely, to keep the current $\hat{\tau} = 40ps$, $\hat{\delta}$ must be 0.06%. Finally, we find Δh = 0.025 using (7)

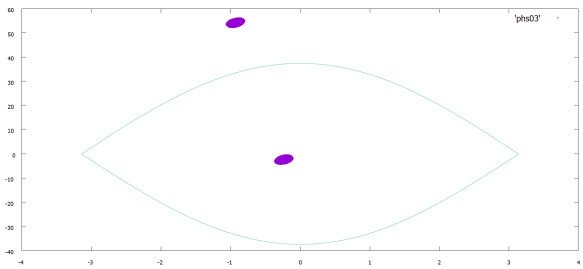
Equation 6 is rearranged to find the RF cavity voltage appropriate for the given bunch scheme. As-



(a)



(b)



(c)

FIG. 6: Simulation of particle slip stacking using current RCS synchrotron constraints.

suming $\phi_s = 0$, Equation 6 reduces to

$$V = \frac{2\pi E \omega_s^2}{(c/R)^2 h |\eta_0|} \tag{12}$$

V. CONCLUSION

In this paper, we studied the feasability of slip stacking in the RCS as a means to avoid the costly use of harmonic RF kickers. The literature review conducted tentatively suggests that slip stacking has not been attempted for electron beams at a major accelerator facility. The current beam parameters in the RCS ($\hat{\tau} = 40ps$ and $\hat{\delta} = 0.25\%$) are not conducive to slip stacking because the momentum aperture taken up by the two beam exceeds the RCS momentum aperture limit of 1.5%. The beam parameters that would satisfy the RCS momentum aperture limit are suggested.

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