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# Simulation of the RF system with reversed phasing

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In this paper we report on the ELEGANT simulation for the Electron Storage Ring (ESR) RF system with reversed phasing using the lattice version of 5.3 at 5 GeV energy. The full beam dynamics results, including energy spread, bunch length and centroid offset as a function of bunch number in the train are presented. Some of the RF system related parameters, required as the input for particle tracking simulations, have been calculated analytically using the RF system related equations. The obtained results has been compared with the results simulated by Tianmu Xin, Michael Blaskiewicz and Gabriele Bassi using C++ and the SPACE codes.

## INTRODUCTION

The electron ion collider (EIC) is under development, including design and R&D, at Brookhaven National laboratory [1]. The EIC will provide collision of high-energy polarized electron and hadron beams at center of mass of 20-140 GeV. The new electron injection scheme of the EIC consists of the electron polarized source, 400 MeV LINAC, the rapid cycling synchrotron (RCS) with a possible energy ramp from 400 MeV to 18 GeV and the electron storage ring (ESR), where the beam can be accelerated at 5 GeV, 10 GeV and 18 GeV energy. While the ion injection scheme is based on the present RHIC facility [2], which includes the proton polarized source, the 200 MeV LINAC, the booster, the Alternating Gradient Synchrotron (AGS) and the Hadron Storage Ring (HSR). A ∼10 MW power is required to compensate losses due to synchrotron radiation and beam induced wakefields in ESR at 2.5 A average current within $M = 1160$ bunches [1]. With the RF voltage of $V_{RF}$=12 MV at 5 GeV and $V_{RF}$=24 MV at 10 GeV, the required detuning frequency becomes so large that the beam can be Robinson unstable [3]. To reduce the detuning frequency range, the reversed phasing RF system is considered for the EIC project as an option for the stable beam operation. It is a well known concept, when two groups of cavities are set up with the same RF cavity voltage and different synchronus phases. Experimentally, the RF system with the reversed phasing was tested with a beam in KEK B-Factory [4] and no issues during operation were found.

To simulate the beam dynamics with the reversed phasing RF system concept for the EIC project, Tianmu Xin has developed C++ code and the results were compared with the SPACE code [5] data simulated by Gabriele Bassi. As the results, Michael Blaskiewicz and Tianmu Xin have presented and discussed the obtained data in the EIC CDR 2021, in the collective effects section.

In this note, we cross-check the EIC CDR results and discuss particle tracking simulations for the reversed phasing RF concept using the ELEGANT code [6]. First, we compare the results with the EIC CDR data at 5 GeV energy applying the relevant beam parameters from the EIC CDR. Second, we perform the numerical simulations for the updated lattice parameters and different RF system configuration.

## RF SYSTEM RELATED EQUATIONS

Focusing ($\pi/2 \le \varphi_f \le \pi$):

$$N_{c,f}V_f \sin\varphi_s + N_{c,d}V_d \sin\varphi_s = V_{RF}\sin\varphi_s \tag{1}$$

Defocusing ($0 \le \varphi_d \le \pi/2$):

$$N_{c,f}V_f \cos\varphi_s - N_{c,d}V_d \cos\varphi_s = V_{RF}\cos\varphi_s, \tag{2}$$

where $N_{c,tot} = N_{c,f} + N_{c,d}$ and $V_c = V_f = V_d$.

The synchronous phase is

$$\sin\varphi_s = \frac{U_0}{N_{c,tot}V_c}, \tag{3}$$

where $U_0$ is the energy loss per turn, $N_{c,tot}$ is the total number of the RF cavities. After solving the system with two equations, the voltage per cavity $V_c$ is

$$V_c = \sqrt{\frac{V_{RF}^2 - U_0^2}{(N_{c,f} - N_{c,d})^2} + \frac{U_0^2}{N_{c,tot}^2}} \tag{4}$$

The detuning frequency $\Delta f$ can be found as

$$\Delta f = -f_{RF} \frac{R/Q \cdot I_{av}}{V_c} \sqrt{1 - \frac{U_0^2}{V_{RF}^2}}, \tag{5}$$

where $f_{RF}$ is the RF frequency, $I_{av}$ is the average current.

## 12&6 RF SYSTEM (CDR)

The main electron beam and the RF system parameters are presented in Table I and Table II for a case of 12 focusing and 6 defocusing cavities. The average current is $I_{av}$=1.9 A within 580 bunches. The results of the particle tracking simulations are presented in Figs. 1, 2, 3, 4. The obtained results agree well with the CDR's data. The $\sigma_s(M_i)$ dependence has a parabolic shape with different bunch length along the bunch train. The minimum bunch length is $\sigma_s$=6.8 mm in the middle of the bunch train.

To perform the numerical simulations, the ELEGANT input file has been set up as a combination of the RFCA and the RFMODE elements, where in RFCA we specified the voltage per cavity, RF frequency, and phase, while in RFMODE the beam loading parameters as the shunt impedance, the quality factor and the detuning frequency. The simulated energy spread of the unperturbed bunch is a little bit higher than the predicted one with the RF cavities in one location. To obtain the reliable results, the RF cavities have been redistributed throughout the lattice. The energy spread of the unperturbed bunch is converged with 6 locations of the RF cavities distributed throughout the lattice. It needs to be further understood. It should be also noted that modeling of the reversed phasing RF system with the RFMODE element only was not successful. The beam is unstable with the low-level RF feedback "ON". Further analysis is required.

| | | |
|---|---|---|
| Energy, $E_0$ | 5 | GeV |
| Average Current, $I_0$ | 1.9 | A |
| Momentum Compaction, $\alpha_c$ | 1.03e-3 | |
| Number of Bunches, $M$ | 580 | |
| Energy Loss per turn, $U_0$ | 1.316 | MeV |
| RF Voltage, $V_{RF}$ | 14.66 | MV |
| Bunch Length, $\sigma_s$ | 7.1 | mm |
| Energy Spread, $\sigma_\delta$ | 6.8e-4 | |

TABLE I: Main electron beam parameters (CDR).

## 10&7 RF SYSTEM

The lattice parameters has been changed, since the CDR was published, especially the momentum compaction $\alpha_c$. It has been increased up to $\alpha_c = 1.33 \cdot 10^{-3}$. The average current is $I_{av} = 2.5A$ within $M = 1160$ bunches. The main electron beam and the RF system parameters are listed in Table III and Table IV. The beam parameters are related to the 5.3 lattice version. With the updated parameters, the RF system with 10 focusing and 7 defocusing cavities has been simulated. The detune frequencies are much lower than the revolution frequency $f_0 = 78.194kHz$ with counter phasing scheme. The total number of macroparticles used in ELEGANT is 5k. The results of the particle tracking simulations are presented in Figs. 5, 6, and 7. The bunch length dependence has a parabolic shape (Fig. 5), similar as in a previous case with 12 and 6 cavities. The bunches at the end of the train have a significantly larger

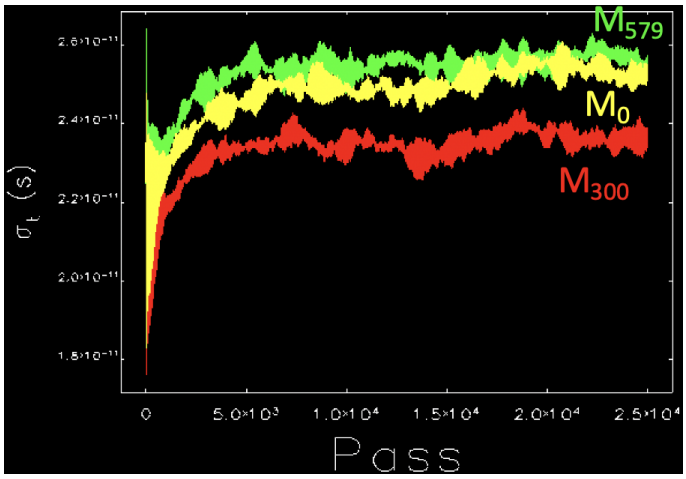



FIG. 1: Particle tracking simulations of the bunch length vs. number of turns for bunch number $M_0$, $M_{300}$, and $M_{579}$.

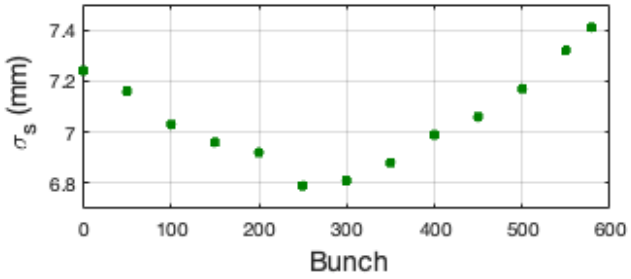



FIG. 2: The bunch length $\sigma_s$ dependence on the bunch number $M$, $\sigma_s(M_i)$.

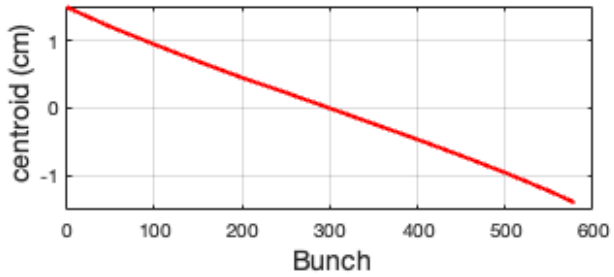



FIG. 3: Bunch centroid offset vs. the bunch number.

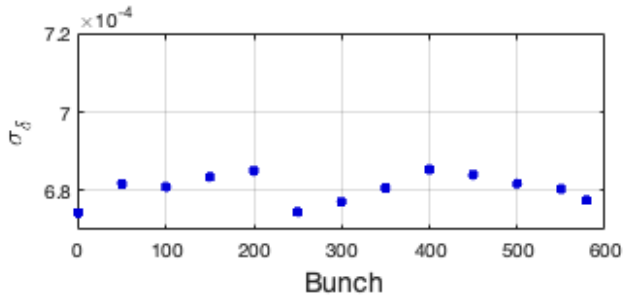



FIG. 4: The energy spread dependence on the bunch number, $\sigma_\delta(M_i)$.

| | | |
|---|---|---|
| Number of foc. & def. cavities | 12 & 6 | |
| RF Frequency, $f_r$ | 591.150 | MHz |
| Quality Factor, $Q$ | 576290 | |
| R/Q | 37 | |
| Voltage per Cavity, $V_c$ | 2.434 | MV |
| Synchronous Phase, $\varphi_s$ | 178.3&1.7 | deg |
| Detune Frequency (focusing) | -17176 | Hz |
| Detune Frequency (defocusing) | 16960 | Hz |
| Total Cavity Voltage of foc. & def. cavities, $V_{c,tot,foc}$ & $V_{c,tot,def}$ | 29.2 & 14.6 | MV |
| Total Generator Voltage of foc. & def. cavities, $V_{g,tot,foc}$ & $V_{g,tot,def}$ | 18.4 & 0.92 | MV |
| Generator Phase of foc. & def. cavities, $\varphi_g$ | 109 & 71 | |

TABLE II: RF system parameters (CDR).

length than the bunches early in the train. The time evolution of the bunch centroids shows something close to a cotangent behavior along the train (Fig. 6) with their zero offset in the middle of the train. The energy spread $\sigma_\delta(M_i)$ dependence looks a bit noise (Fig. 7) due to a less number of macroparticles used during the simulations, but we don't observe an explicit parabolic dependence as in the case of the bunch length. The present simulations have been performed with the RF system only, including the RF cavity impedance. Since the bunch length is varied along the train, it may effect the Robinson threshold with presence of the beam-induced wakefields and impedances (leading to a tune shift). The minimum bunch length in the middle of the train is $\sigma_s \approx 6mm$. The bunch length spread in the train is $\sim 1mm$.

| | | |
|---|---|---|
| Energy, $E_0$ | 5 | GeV |
| Average Current, $I_0$ | 2.5 | A |
| Momentum Compaction, $\alpha_c$ | 1.33e-3 | |
| Number of Bunches, $M$ | 1160 | |
| Energy Loss per turn, $U_0$ | 0.95 | MeV |
| RF Voltage, $V_{RF}$ | 10.1 | MV |
| Bunch Length, $\sigma_s$ | 6.8 | mm |
| Energy Spread, $\sigma_\delta$ | 5.16e-4 | |

TABLE III: Main electron beam parameters (lattice v5.3).

| | | |
|---|---|---|
| Number of focusing & defocusing cavities | 10 & 7 | |
| RF Frequency, $f_r$ | 591.150 | MHz |
| Quality Factor, $Q$ | 334364 | |
| R/Q | 37 | |
| Voltage per Cavity, $V_c$ | 3.35 | MV |
| Synchronous Phase, $\varphi_s$ | 179.05&0.95 | deg |
| Detune Frequency (foc.) | -16240 | Hz |
| Detune Frequency (def.) | 16240 | Hz |
| Total Cavity Voltage of foc. & def. cavities, $V_{c,tot,foc}$ / $V_{c,tot,def}$ | 33.52 & 23.47 | MV |
| Total Generator Voltage of foc. & def. cavities, $V_{g,tot,foc}$ / $V_{g,tot,def}$ | 6.39 & 4.47 | MV |
| Generator Phase of foc. & def. cavities, $\varphi_g$ | 158.1 & 21.9 | |

TABLE IV: RF system parameters.

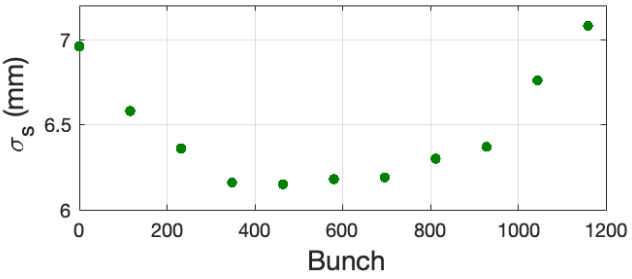



FIG. 5: The bunch length $\sigma_s$ dependence on the bunch number $M_i$, $\sigma_s(M_i)$.

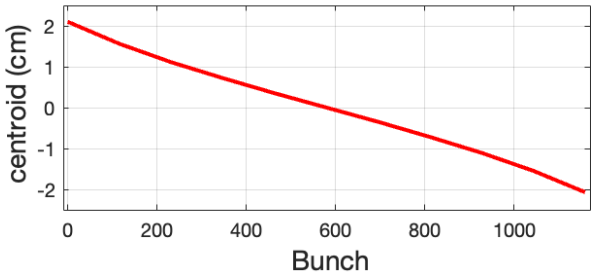



FIG. 6: Bunch centroid offset vs. the bunch number.

## SUMMARY

Using the ELEGANT code, we were able to reproduce the counter phasing simulated data discussed by Tianmu Xin and Gabriele Bassi and to perform the simulations with updated lattice parameters for a different set of focusing and defocusing cavities. The next step is to check if the synchrotron tune spread can lead to instabilities including the EIC impedance budget and taking into account the bunch lengthening due to potential well distortion. We need further to investigate the RFMODE element in the ELEGANT code for application of the low-level RF feed-back to the EIC RF system.

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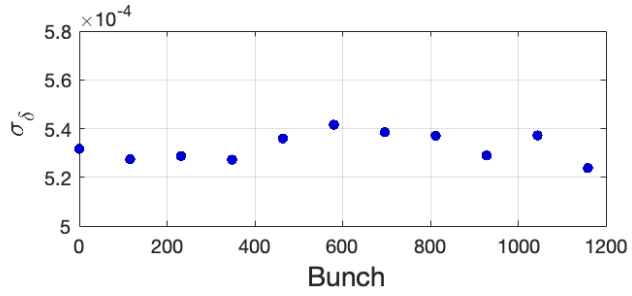



FIG. 7: The energy spread dependence on the bunch number $M_i$, $\sigma_\delta(M_i)$.