BUNCH SHORTENING SIMULATIONS BY RF MODULATION IN THE EIC BEAM ACCUMULATOR RING

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Abstract

The Beam Accumulator Ring (BAR) of the Electron–Ion Collider (EIC) injector chain accumulates polarized electron bunches of up to 32 nC before extraction into the Rapid Cycling Synchrotron (RCS). The large momentum compaction of the compact BAR lattice, combined with impedance-driven bunch lengthening, yields an equilibrium rms bunch length that lies at or above the upper edge of the RCS injection specifications. Using a geometric and resistive-wall impedance model together with multi-particle tracking in ELEGANT, we study bunch shortening by RF voltage modulation, in which an abrupt reduction of the RF amplitude induces a quarter-synchrotron-period rotation in longitudinal phase space so that the beam is extracted at its shortest projection. The simulations show that, for both 49 MHz and 98 MHz RF options under consideration, RF voltage modulation compresses the bunch into the required length and energy-spread window with operational margin.

INTRODUCTION

The Electron–Ion Collider (EIC) is under construction at Brookhaven National Laboratory to explore the fundamental structure of matter [1]. The Beam Accumulator Ring (BAR) is a 36.5 m circumference electron accumulator in the EIC polarized-electron injector chain, located between the 750 MeV linac and the 5 GeV to 18 GeV Rapid Cycling Synchrotron (RCS). The main beam specifications at injection and extraction are summarized in Table 1.

Table 1: BAR beam specifications at injection and extraction

Parameter	Injected beam	Extracted beam
Energy	750 MeV	750 MeV
Charge	1.1 nC	28 nC*
Geometric emitt.	hor: 45 nm rad ver: 30 nm rad	hor: < 170 nm rad rms ver: < 65 nm rad rms
Energy spread	0.45 %	0.05 % to 0.5 %
Bunch length	0.7 mm	20 mm to 70 mm
Repetition rate	30 Hz	1 Hz

*Maximum charge of 32 nC in the BAR is assumed to provide margin for possible particle loss.

The functional role of the BAR is to accumulate, over approximately 30 linac pulses at 30 Hz, a single polarized electron bunch for injection into the RCS. The nominal extracted bunch charge is 28 nC, while accumulation up to 32 nC provides margin for losses during extraction and transfer. The design is derived from the NSLS VUV ring lattice and vacuum chamber concept [2], modified to meet EIC injector requirements of high bunch charge, polarization preservation, and matching to the injection and extraction transport lines.

The high single-bunch charge places demanding constraints on the longitudinal dynamics. The rms bunch length at extraction must lie in the 20 mm to 70 mm window set by the RCS RF bucket and downstream machine protection. With the nominal accumulator RF voltage of 100 kV, the equilibrium bunch length is close to the upper edge of this window, and impedance-driven potential-well distortion can push it outside specification. In this study, we summarize the impedance-limited bunch length of the latest BAR lattice, present the RF voltage modulation scheme proposed for bunch shortening before extraction, and show ELEGANT [3] tracking results including the full impedance budget.

BAR Parameters

Key parameters of the current BAR lattice are listed in Table 2. Two RF options are being considered: the baseline 49 MHz system ($h = 6$) inherited from the NSLS VUV RF design [4], and a candidate 98 MHz system ($h = 12$) that offers a shorter natural bunch and eases synchronization with the 591 MHz RCS [5]. Both options use the same 100 kV nominal RF voltage.

The large momentum compaction ($\alpha_c = 0.084$) inherited from the compact VUV-class lattice, combined with the modest RF voltage available in an accumulator, results in a long natural bunch even at zero current. For the 49 MHz option the natural bunch length already exceeds the 70 mm upper limit of the extraction specification; for the 98 MHz option the natural bunch sits just inside the window with negligible margin.

Table 2: BAR Lattice and RF Parameters

Parameter	Value	
Energy	0.75 GeV	
Circumference	36.52 m	
Horizontal emittance	114 nm	
Momentum compaction α_c	0.0843	
Natural energy spread	5.8×10^{-4}	
Energy loss per turn	14.66 keV	
Long. damping time	9.6 ms	
Accumulated single-bunch charge	32 nC	
RF option	49 MHz	98 MHz
Harmonic number h	6	12
RF voltage (nominal)	100 kV	100 kV
Synchrotron tune ν_s	0.0033	0.0046
Natural rms bunch length	87 mm	61.5 mm

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IMPEDANCE-DRIVEN BUNCH LENGTHENING

A longitudinal impedance model of the BAR has been developed by combining 3D electromagnetic simulations (GdfidL) of the main vacuum components with an analytical resistive-wall contribution for the rectangular 80 mm × 40 mm aluminium chamber [6]. The geometric budget includes RF-shielded bellows, flanges with RF contact springs, BPM button assemblies, gate valves, pumping ports, clearing electrodes, and the ceramic kicker chambers with tapered transitions and a 3 μm titanium inner coating. The resulting total impedance at the design bunch length of 61.5 mm gives a loss factor $k_{\mathrm{loss}} = 14.37\,\mathrm{mV/pC}$ and a normalized impedance $|Z/n| \approx 0.25\,\Omega$, with no strong narrowband features.

Using this impedance model, the equilibrium bunch length and energy spread at 32 nC were computed by ELEGANT multi-particle tracking inlcuding longitudinal impedance. Results at zero and nominal charge are summarized in Table 3. In both RF cases, potential-well distortion and the onset of the microwave instability produce a mild additional lengthening of a few mm and a correspondingly small increase in energy spread. For the 49 MHz option, the equilibrium bunch length at 32 nC is 89.1 mm, exceeding the RCS upper limit of 70 mm by 19 mm. For the 98 MHz option, the bunch length is 63.5 mm, within specification but with no operational margin. The energy spread remains at $\sim 0.58 \times 10^{-3}$ in both cases, well within the 0.5×10^{-3} to 5×10^{-3} RCS acceptance.

Table 3: Equilibrium rms Bunch Length σ_s (mm) and Energy Spread σ_δ ($\times 10^{-3}$) at Zero and Nominal Charge from ELEGANT.

	49 MHz		98 MHz	
	0 nC	32 nC	0 nC	32 nC
σ_s (mm)	87.0	89.1	61.5	63.5
σ_δ ($\times 10^{-3}$)	0.577	0.583	0.575	0.584

A bunch-shortening manipulation prior to extraction is therefore required for the 49 MHz option and is desirable for the 98 MHz option to build robustness against impedance-budget uncertainties and jitter in the accumulated charge.

RF VOLTAGE MODULATION

The principle of RF modulation [7] is to let a bunch that is initially elongated in phase rotate in a mismatched, maximum-height RF bucket, and to extract it when the phase-space ellipse lies along the energy axis, i.e. at the shortest time projection. For a stationary bucket in an accumulator, three variants are commonly used to force the mismatch:

- *Adiabatic voltage reduction*: the bunch length scales as $V^{-1/4}$, but full adiabaticity requires many synchrotron periods and a large dynamic range in voltage.
- *Abrupt (non-adiabatic) voltage reduction*: after a quarter synchrotron period, a bunch rotation provides compression proportional to $V^{-1/2}$. The manipulation is fast, limited only by the transient response of the RF cavity and its servo loops.
- *Phase jump* of π radians on the unstable fixed point: the bunch stretches along the separatrix and is extracted at its shortest dimension.

The last option was studied in earlier BAR designs [8], while effective, it tilts the bunch in phase space and makes it more sensitive to RF non-linearities during the compression quarter-period. For the present design the *abrupt voltage reduction* scheme is preferred to mimimize the power. Beam dynamics are described by the standard discrete longitudinal map [7]

$$\delta_{n+1} = \delta_n + \frac{V_{\mathrm{RF}}(n)}{E/e}\left[\sin\varphi_n - \sin\varphi_s\right], \tag{1}$$

$$t_{n+1} = t_n + \delta_{n+1}\,\alpha_c T_0, \qquad \varphi_n = \omega_{\mathrm{RF}} t_n + \varphi_s, \tag{2}$$

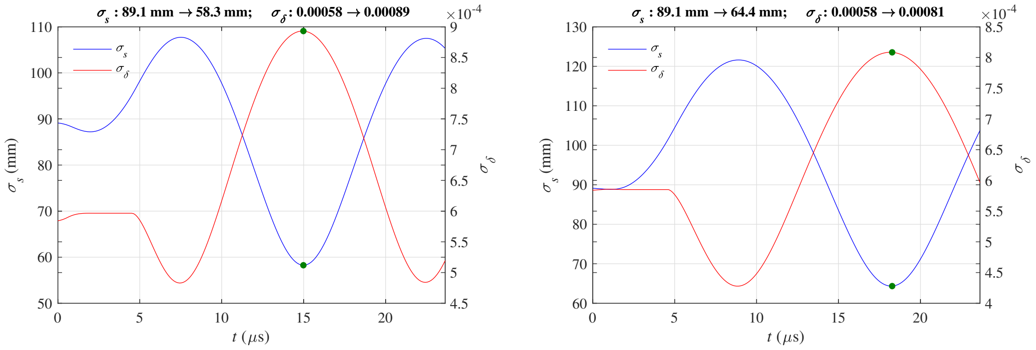
where $V_{\mathrm{RF}}(n)$ is the programmed turn-by-turn RF amplitude. Under an abrupt reduction from V_0 to $V_1 < V_0$, the bunch finds itself mismatched inside the smaller bucket; the outer phase-space ellipse rotates at the local synchrotron frequency $\omega_{s,1} \propto \sqrt{V_1}$, and after a quarter-period the bunch reaches its minimum time extent at the cost of an increase in energy spread by the same factor. Extraction is timed to this instant.

The scheme imposes three practical requirements on the RF system: a fast voltage step (short compared to $1/\nu_s f_0$, i.e. a few tens of μs); accurate servo control of the cavity field during the transient; and synchronization of the extraction kicker trigger to the phase-space-rotation minimum. All three are compatible with the EIC Common Platform LLRF architecture [8].

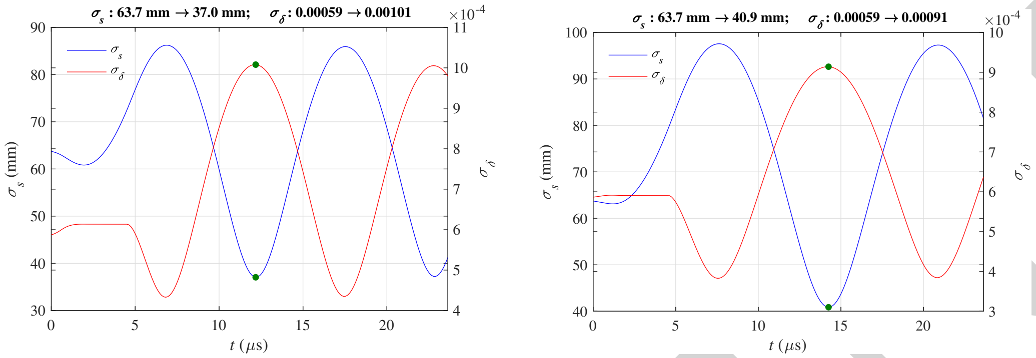
SIMULATION RESULTS

The RF voltage modulation was simulated with ELEGANT using 5×10^4 macroparticles per bunch including the longitudinal impedance discussed in above section. A realistic RF voltage ramp provided by the RF group was applied instead of an idealized step to account for the finite rise time of the transmitter and cavity filling, while minimizing the RF power. For the voltage reduction, the minimum voltage was limited to 20 kV, since excessively low RF voltage can lead to multipacting in the cavity.

Figure 1 shows the evolution of the rms bunch length σ_s and rms relative energy spread σ_δ during the voltage modulation, for both RF frequency options and both modulated voltages. Starting from the equilibrium distribution of Table 3, the abrupt voltage reduction drives a coherent quadrupole oscillation: the bunch shears in the mismatched bucket, σ_s reaches its minimum approximately one quarter of a synchrotron period after the voltage step, and σ_δ grows by the inverse factor. Extraction is timed to this minimum, marked by green dots in each panel.



(a) 49 MHz, $V_1 = 155$ kV (b) 49 MHz, $V_1 = 100$ kV



(c) 98 MHz, $V_1 = 155$ kV (d) 98 MHz, $V_1 = 100$ kV

Figure 1: Evolution of the rms bunch length σ_s (blue, left axis) and energy spread σ_δ (red, right axis) during RF voltage modulation at 32 nC, for both RF options and both modulated voltages. Green dots mark the extraction instant.

Table 4 summarizes the bunch length and energy spread at the extraction instant. For the 49 MHz option, the bunch is reduced from 89.1 mm to 64.4 mm at 100 kV and to 58.3 mm at 155 kV. For the 98 MHz option, the bunch is reduced from 63.5 mm to 40.9 mm at 100 kV and to 37.0 mm at 155 kV. In every case, the resulting energy spread remains within the 0.5×10^{-3} to 5×10^{-3} RCS acceptance.

Several remarks follow. First, for the 49 MHz option, 100 kV modulation is sufficient to bring the bunch inside the specification, with a small but non-zero margin; the 155 kV case relaxes operational tolerances. Second, the 98 MHz option reaches the RCS window with decent margin already at 100 kV, making it the more robust choice against impedance uncertainties and RF amplitude jitter. Third, the factor-of-two trade-off between bunch length reduction and energy spread increase is consistent with the $V^{-1/2}$ scaling expected from the non-adiabatic compression.

Table 4: Bunch Length σ_s (mm) and Energy Spread σ_δ ($\times 10^{-3}$) at 32 nC at the Extraction Instant. Specifications: $\sigma_s \in [20, 70]$ mm, $\sigma_\delta \in [0.5, 5.0] \times 10^{-3}$.

	49 MHz		98 MHz	
Configuration	σ_s	σ_δ	σ_s	σ_δ
No modulation	89.1	0.58	63.5	0.58
Modulation, $V_1 = 100$ kV	64.4	0.81	40.9	0.91
Modulation, $V_1 = 155$ kV	58.3	0.89	37.0	1.01

CONCLUSION

We have shown that RF voltage modulation is a viable bunch-shortening scheme for the EIC BAR. The compact high-α_c BAR lattice, combined with the impedance gives an equilibrium bunch length at 32 nC that exceeds the 70 mm RCS upper limit in the 49 MHz configuration and sits at the edge of the window in the 98 MHz configuration. ELEGANT tracking with the full longitudinal impedance demonstrates that an abrupt reduction of the RF amplitude to 100 kV or 155 kV, followed by a quarter-synchrotron-period rotation, compresses the extracted bunch well inside the 20 mm to 70 mm and 0.5×10^{-3} to 5×10^{-3} RCS acceptance in both RF options. The 98 MHz option provides the largest operational margin and is therefore preferred from a longitudinal-dynamics standpoint. Work in progress includes the integration of beam loading and cavity transient response in the RF model, optimization of the voltage-ramp waveform together with the extraction kicker timing, and verification of the required transient voltage response on a prototype cavity.

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