

DUAL-RF PHASE CONTROL FOR ADIABATIC ENERGY RAMPING IN THE EIC RAPID CYCLING SYNCHROTRON*

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Abstract

The Electron-Ion Collider (EIC) Rapid Cycling Synchrotron (RCS) accelerates electrons from 750 MeV to 10 GeV over approximately 64.7 ms. The baseline design ramps both the RF voltage and phase simultaneously to maintain the synchronous phase and synchrotron tune throughout the ramp. This paper presents an alternative approach in which the RF cavities are divided into two groups, each operating at a fixed voltage of 6.5 MV, with the effective voltage synthesised entirely through phase control. Two implementations are studied: a symmetric scheme (Option A) in which both groups vary symmetrically about the synchronous phase, providing exact matching of both the energy gain and synchrotron tune; and an asymmetric scheme (Option B) in which one group is pinned at the final operating phase while the other varies to supply the required energy gain. The adiabaticity of the resulting synchrotron tune evolution is used as the acceptance criterion for Option B. Ramp profiles, phase trajectories, and adiabaticity metrics are presented for both schemes.

INTRODUCTION

The EIC RCS is a key component of the EIC accelerator complex at Brookhaven National Laboratory [1] with on-axis injection into ESR up to 28 nC. During each injection cycle, electrons injected at 750 MeV from the linac are accelerated to a top energy between 5 GeV and 18 GeV, with the nominal operating point at 10 GeV [2]. The RF system consists of eight 591 MHz SRF cavities [3]. The ring operates above the transition energy throughout ($\eta > 0$, $\beta \approx 1$), with a circumference of 1507.015 m, harmonic number $h = 2970$, and momentum compaction factor $\alpha_c = 6.458 \times 10^{-4}$.

The baseline RF ramp simultaneously adjusts the cavity voltage $V_{\text{rf}}(t)$ from 1.12 MV to 13.0 MV and the synchronous phase $\phi_s(t)$ from $\approx 180^\circ$ to $\approx 131^\circ$ to maintain synchronism as synchrotron radiation losses increase with energy [4]. While this approach is well understood, it requires full dynamic range voltage control of all eight cavities throughout the ramp.

A natural question is whether the voltage ramping requirement can be eliminated entirely, replacing it with pure phase control. This paper investigates such a scheme, in which the cavities are split into two independently phased groups, each held at a constant voltage equal to half the peak design

voltage. The phasor combination approach used here is analogous to azimuthal combination techniques used in proton synchrotrons [4, 5].

SINGLE-RF BASELINE

In the baseline single-RF system all eight cavities operate at the same phase and voltage. The synchronous phase above transition satisfies

$$\phi_s(t) = \pi - \arcsin\left(\frac{U_0(t)}{V_{\text{rf}}(t)}\right), \quad (1)$$

where $U_0(t) \propto E(t)^4$ is the synchrotron radiation energy loss per turn. The energy gain per turn is $\Delta E = V_{\text{rf}} \sin \phi_s$, and the small-oscillation synchrotron tune is

$$Q_s = \sqrt{\frac{h \alpha_c V_{\text{rf}} |\cos \phi_s|}{2\pi E}}. \quad (2)$$

The adiabaticity of the ramp is characterised by the fractional change in Q_s per synchrotron period [6, 7],

$$\mathcal{A}(t) = \frac{1}{Q_s^2 f_0} \left| \frac{dQ_s}{dt} \right| \times 100 \%. \quad (3)$$

Key parameters at injection and top energy are summarised in Table 1.

Table 1: Single-RF Ramp Parameters at Injection and Top Energy

Quantity	Injection	Top energy
Energy	750 MeV	10 GeV
V_{rf}	1.12 MV	13.0 MV
ϕ_s	179.98°	130.87°
Q_s	0.01741	0.03310
U_0	0.30 keV	18.5 keV

DUAL-RF PHASE CONTROL CONCEPT

The dual-RF scheme divides the eight cavities into two groups of four. Each group operates at a fixed voltage

$$V_{\text{fixed}} = \frac{V_{\text{rf,max}}}{2} = 6.5 \text{ MV}, \quad (4)$$

which is the minimum value that keeps the scheme feasible at all times (see Option B). The combined kick seen by the beam is

$$F = V_{\text{fixed}} \sin \phi_a + V_{\text{fixed}} \sin \phi_b, \quad (5)$$

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which using the sum-to-product identity gives

$$F = 2 V_{\text{fixed}} \cos(\delta) \sin(\bar{\phi}), \quad (6)$$

where $\bar{\phi} = (\phi_a + \phi_b)/2$ is the mean phase and $\delta = (\phi_a - \phi_b)/2$ is the half-gap between the two groups. This is equivalent to a single cavity with effective voltage $V_{\text{eff}} = 2 V_{\text{fixed}} \cos \delta$ at phase $\bar{\phi}$. Setting $V_{\text{eff}}(t) = V_{\text{rf}}(t)$ and $\bar{\phi}(t) = \phi_s(t)$ simultaneously determines the two group phases.

Option A: Symmetric Scheme

In Option A both groups are placed symmetrically about $\phi_s(t)$ at each time step:

$$\phi_a(t) = \phi_s(t) + \delta(t), \quad (7)$$

$$\phi_b(t) = \phi_s(t) - \delta(t), \quad (8)$$

where the phase half-gap is

$$\delta(t) = \arccos\left(\frac{V_{\text{rf}}(t)}{2 V_{\text{fixed}}}\right). \quad (9)$$

By construction, $V_{\text{eff}}(t) = V_{\text{rf}}(t)$ and $\bar{\phi}(t) = \phi_s(t)$ are matched exactly at every step. Since $Q_s \propto \sqrt{V_{\text{eff}}} \cos \phi_s$, the synchrotron tune is also reproduced exactly. At injection $\delta \approx 85^\circ$, reflecting the large phase spread needed to synthesise a small effective voltage from two large fixed-voltage sources. At top energy $\delta = 0^\circ$ and both groups are in phase.

The feasibility constraint $V_{\text{rf}}(t)/(2 V_{\text{fixed}}) \leq 1$ is satisfied by construction for all t when $V_{\text{fixed}} = V_{\text{rf,max}}/2$.

Option B: Asymmetric Scheme

Option B fixes Group A at the final steady-state synchronous phase for the entire ramp:

$$\phi_a = \phi_{s,\text{final}} = 132.25^\circ \quad (\text{constant}), \quad (10)$$

providing a constant energy contribution $\Delta E_A = V_{\text{fixed}} \sin \phi_{s,\text{final}} = 4.81 \text{ MV}\cdot\text{e}$. Group B supplies the remaining energy gain at each step via the supplementary branch of the arcsine:

$$\phi_b(t) = \pi - \arcsin\left(\frac{\Delta E(t) - \Delta E_A}{V_{\text{fixed}}}\right), \quad (11)$$

where $\Delta E(t) = V_{\text{rf}}(t) \sin \phi_s(t)$ is the total required energy gain per turn. The supplementary branch ensures $\phi_b \rightarrow \phi_{s,\text{final}}$ as $t \rightarrow t_{\text{final}}$, so both groups arrive at the same phase at the end of the ramp. The feasibility condition requires

$$\left|\frac{\Delta E(t) - \Delta E_A}{V_{\text{fixed}}}\right| \leq 1, \quad (12)$$

which is satisfied with margin $[-0.74, +0.77]$ for the nominal ramp parameters.

Because only ϕ_b is free, the energy gain ΔE is matched exactly but V_{eff} and Q_s are not independently controlled. The relevant acceptance criterion is therefore the adiabaticity $\mathcal{A}(t)$ of Option B's own Q_s profile, evaluated using Eq. (3).

RESULTS

Figure 1 shows the plots of parameters for Option A. The effective voltage panel confirms exact reconstruction of $V_{\text{rf}}(t)$, and the Q_s error is identically zero throughout the ramp. The phase half-gap $\delta(t)$ sweeps smoothly from 85.1° at injection to 0° at top energy. The adiabaticity remains below the 2% threshold throughout.

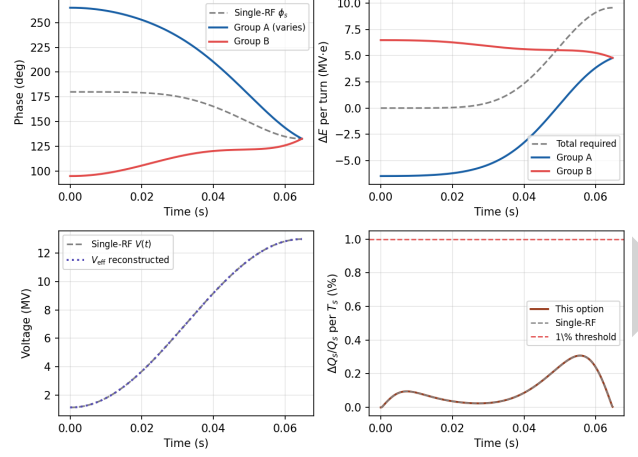


Figure 1: Option A (symmetric). Top left: Group A (blue) and Group B (red) RF phases versus time, with the single-RF $\phi_s(t)$ as reference (dashed). Top right: energy gain per turn per group and total required (dashed). Bottom left: reconstructed V_{eff} versus single-RF $V(t)$. Bottom right: adiabaticity $\mathcal{A}(t)$ with 1% threshold.

Figure 2 shows the corresponding plots for Option B. The energy gain is matched exactly, but the effective voltage diverges from $V_{\text{rf}}(t)$ during the ramp, resulting in a modified Q_s profile. The key question is whether this modified profile satisfies the adiabaticity criterion. The adiabaticity panel (bottom left) shows the result alongside the single-RF reference and the 2% threshold line. The phase separation between the two groups $\phi_b - \phi_a$ converges monotonically from its injection value to zero at top energy as both groups meet at $\phi_{s,\text{final}}$.

A comparison of key quantities for the two options is given in Table 2.

Table 2: Comparison of Single-RF Baseline and Dual-RF Options

Property	Single-RF	Opt. A	Opt. B
$V_{\text{fixed}}/\text{group}$	—	6.5 MV	6.5 MV
Voltage ramped?	Yes	No	No
Group A phase	Single	Varies	Fixed
Group B phase	Single	Varies	Varies
ΔE match	—	Exact	Exact
Q_s match	—	Exact	Approx.
V_{eff} match	—	Exact	Approx.
Adiabatic (<2%)?	Yes	Yes	Yes

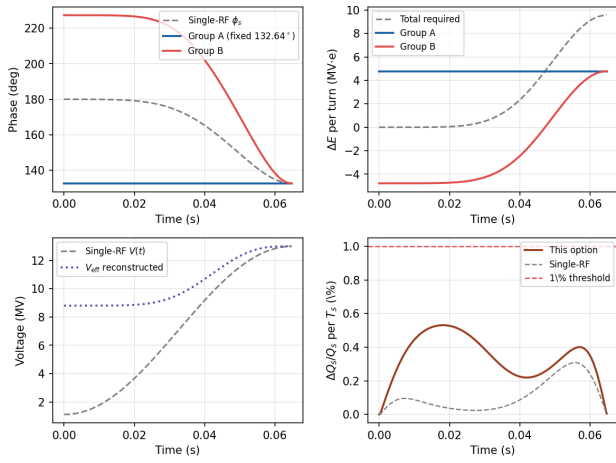


Figure 2: Option B (asymmetric) parameters. Same panel layout as Fig. 1. Group A (blue) is fixed at $\phi_{s,final}$ throughout; Group B (red) varies to supply the remaining energy gain. V_{eff} deviates from $V(t)$ during the ramp and converges at top energy.

TRACKING RESULTS

Particle tracking was performed with ELEGANT [8] for all three ramping schemes using the combined ramp parameter files described above. An ensemble of macro-particles representative of the injected longitudinal distribution was tracked through the full 64.7 ms ramp from 750 MeV to 10 GeV. The final longitudinal phase space distributions — energy deviation $\delta = \Delta p/p$ versus arrival time τ — at the end of the ramp are shown in Fig. 3.

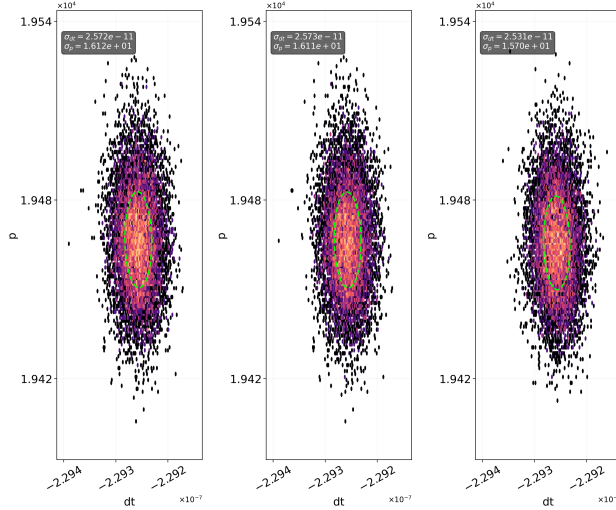


Figure 3: Final longitudinal phase space distributions at 10 GeV from ELEGANT tracking. Left: single-RF baseline. Centre: dual-RF Option A (symmetric). Right: dual-RF Option B (asymmetric). All three schemes produce comparable final distributions, confirming that both dual-RF options preserve beam quality relative to the single-RF baseline where the voltage is ramped along with the phase.

The final distributions for all three schemes are in close agreement. The emittance, energy spread, and bunch length

at the end of the ramp are comparable across the three cases, confirming that the phase-only control approach does not introduce significant emittance growth or particle loss relative to the single-RF baseline. Minor differences in the distribution tails between Option B and the other two schemes are consistent with the modified Q_s profile during the early part of the ramp, and are within acceptable tolerances for injection into the ESR.

DISCUSSION

Option A provides an exact equivalent of the single-RF ramp in terms of both energy gain and synchrotron tune, at the cost of requiring both cavity groups to move throughout the ramp. The symmetric structure means the two groups always straddle the synchronous phase by equal amounts, which may simplify low-level RF control implementation. The tracking results confirm that beam quality is fully preserved.

Option B offers a simpler hardware arrangement — Group A never moves after the initial set-point is established — at the cost of a modified synchrotron tune profile during the ramp. The tracking results demonstrate that, despite the Q_s deviation from the single-RF profile, the ramp remains sufficiently adiabatic to preserve beam quality to within the tolerances required for ESR injection.

Both options eliminate the need for dynamic voltage control of the cavity amplitude, potentially simplifying the RF power system requirements. The combined ELEGANT parameter files produced by the ramp calculator described here are compatible with the `modulate_elements` command in ELEGANT and were used directly for the tracking studies presented above.

FUTURE WORK AND CONCLUSION

Two dual-RF phase-control schemes have been developed and validated for the EIC RCS energy ramp from 750 MeV to 10 GeV. In the symmetric Option A, both cavity groups vary symmetrically about the synchronous phase, exactly reproducing the baseline single-RF ramp dynamics with no voltage ramping. In the asymmetric Option B, one group is held fixed at the final operating phase while the other varies to match the energy gain, with adiabaticity of the resulting tune evolution as the acceptance criterion. ELEGANT tracking confirms that all three schemes produce comparable final longitudinal phase space distributions, demonstrating that phase-only RF control is a viable alternative to the conventional voltage ramp for the EIC RCS. While the data shown in this paper is for 10 GeV, the method is applicable to other operational energies (5 GeV to 18 GeV). Future work involves adding beam-loading effects to the simulation.

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