

ION TRAPPING STUDIES AND MITIGATION STRATEGIES FOR THE EIC ERL-BASED STRONG HADRON COOLER

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Abstract

An Energy Recovery Linac based strong hadron cooler was previously considered for the Electron-Ion Collider. The required electron beam parameters for variable-energy strong hadron cooling place significant constraints on ion trapping and collective effects. This paper presents initial studies of these constraints through a combination of analytical modelling and numerical simulations of ion production, trapping behaviour, and mitigation strategies. A multi-bunch tracking framework based on ELEGANT with the `ionEffects` module is used to simulate machine operation over millisecond time scales, corresponding to more than 3×10^5 electron bunches. The simulations include modelling of ionisation processes together with transverse electron-ion dynamics, allowing the evolution and accumulation of ions to be investigated. Analytical expressions based on Gaussian beam distributions are used to estimate ion trapping conditions and benchmark the simulation results. A bi-periodic bunch spacing scheme is also investigated as a possible mitigation method by detuning the ion oscillation frequency. These studies provide an initial assessment of ion trapping in the strong hadron cooler and demonstrate possible approaches for reducing beam-ion effects.

INTRODUCTION

The Electron-Ion Collider (EIC) requires efficient beam cooling to achieve high luminosity. An Energy Recovery Linac (ERL)-based strong hadron cooler is a promising option because it can sustain high average current and continuous operation. However, the high repetition rate and bunch charge also introduce significant beam-ion collective effects. Residual-gas ionisation produces ions that can accumulate and become trapped in the electron beam potential, resulting in emittance growth and particle loss.

This is particularly important in ERL systems, where millisecond-scale operation corresponds to hundreds of thousands of bunch passages, enabling a cumulative build-up of ions within the beam potential. As a result, beam-ion interactions can progressively intensify, leading to significant ion accumulation and eventual particle loss if no mitigation is applied. These considerations motivate a detailed study of ion trapping and its mitigation in ERL-based coolers.

ION TRAPPING CRITERION

Ion trapping is analysed using a linear kick-drift model, in which each bunch passage provides a transverse focusing

kick followed by a drift over the bunch spacing S . The corresponding kick and drift transfer matrices are

$$K(a) = \begin{pmatrix} 1 & 0 \\ -a & 1 \end{pmatrix}, \quad D(S) = \begin{pmatrix} 1 & S \\ 0 & 1 \end{pmatrix}, \quad (1)$$

where $K(a)$ represents the transverse focusing kick with effective focusing strength a , and $D(S)$ represents the drift over the bunch spacing S . The analysis applies independently to the horizontal and vertical planes, with focusing strengths

$$a_{x,y} = \frac{2N_e r_p Q}{A_{\text{ion}} \sigma_{x,y} (\sigma_x + \sigma_y)}, \quad (2)$$

as given in [1], where N_e is the bunch population, r_p the classical proton radius, σ_x and σ_y the transverse beam sizes, Q the ion charge state, and A_{ion} the ion mass number.

For a uniformly spaced bunch train, the one-period transfer matrix becomes

$$M = K(a)D(S) = \begin{pmatrix} 1 & S \\ -a & 1 - aS \end{pmatrix}. \quad (3)$$

Stable ion motion requires $|\text{Tr}(M)| \leq 2$ [2], leading to

$$0 \leq aS \leq 4. \quad (4)$$

Ions are trapped when this condition is satisfied, allowing stable confinement within the beam potential over many bunch passages. Since ion accumulation is undesirable, the unstable regime

$$aS > 4, \quad (5)$$

is preferred for ion clearing. The corresponding critical ion mass can be written as [1, 3]

$$A_{x,y} = \frac{N_e r_p S Q}{2 \sigma_{x,y} (\sigma_x + \sigma_y)}, \quad (6)$$

with the instability condition

$$A < A_{\text{crit}} = \min(A_x, A_y), \quad (7)$$

indicating that lighter ions are more likely to escape the beam potential.

Figure 1 shows the transverse RMS beam sizes along the ERL beamline obtained from the BMAD lattice model. The beam sizes vary significantly along the lattice and directly affect the local trapping condition. The resulting critical mass A_{crit} is shown in Fig. 2. It can be seen that A_{crit} remains below the mass of H_2 over most of the lattice, indicating that even the lightest ions are trapped over a large fraction of the beamline. Only a short region of approximately 0.17 m exhibits $A_{\text{crit}} > A_{\text{H}_2}$, where H_2^+ ions are not trapped.

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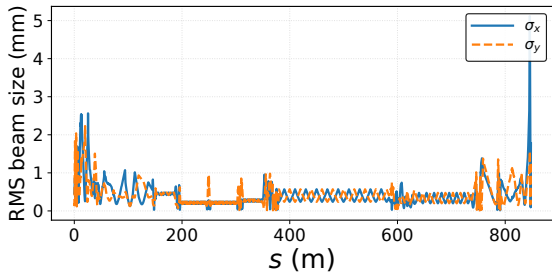


Figure 1: Transverse RMS beam sizes σ_x and σ_y along the ERL beamline obtained from the BMAD lattice model [4].

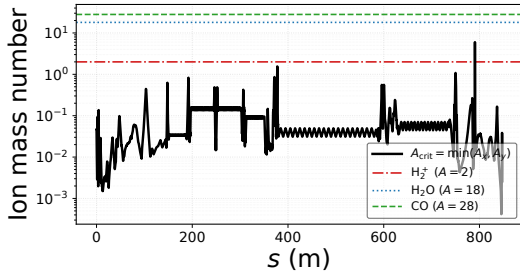


Figure 2: Critical ion mass $A_{\text{crit}} = \min(A_x, A_y)$ along the ERL beamline. The atomic masses of representative residual gases are overlaid for comparison.

SIMULATION OF ION DYNAMICS

Beam-ion simulations were performed using ELEGANT [5] with the ionEffects module [6]. A train of 353,772 bunches was tracked at 98.5 MHz, corresponding to 3.59 ms of operation. Each bunch carries 1 nC and is represented by 1000 macro-particles.

Ion production was modelled using a residual-gas composition of H_2 , CO , CH_4 , and CO_2 , based on APS studies [1]. The corresponding partial pressures are listed in Table 1. The baseline ERL cooler lattice produces strongly varying beam sizes and focusing strengths along the beamline.

Figure 3 shows the final trapped ion population together with the lattice beta functions. Ion accumulation is strongly localised, with the largest populations in segments S2–S4. In S6 and S7, beam loss is dominated by large beta functions associated with incomplete energy recovery, therefore the present analysis focuses mainly on S1–S4.

The evolution of trapped ions and cumulative electron loss is shown in Fig. 4. Segments S3 and S4 exhibit the fastest initial ion accumulation, followed by saturation and gradual reduction as ions become unstable and escape the beam potential. The electron loss increases progressively throughout the bunch train, reaching a total loss fraction of 2.44%, corresponding to 8.62×10^{-6} C of lost charge.

Table 1: Residual Gas Composition Used in the Simulation

Gas	CO_2	CO	CH_4	H_2
Pressure (nTorr)	0.16	0.32	0.22	1.3

These results show that ion accumulation develops over millisecond time scales and leads to both progressive beam loss and strong spatial non-uniformity.

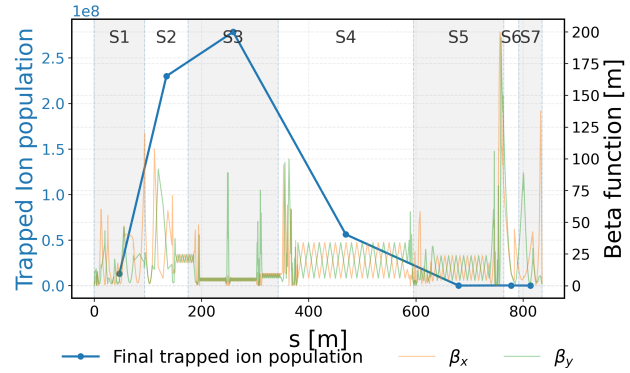
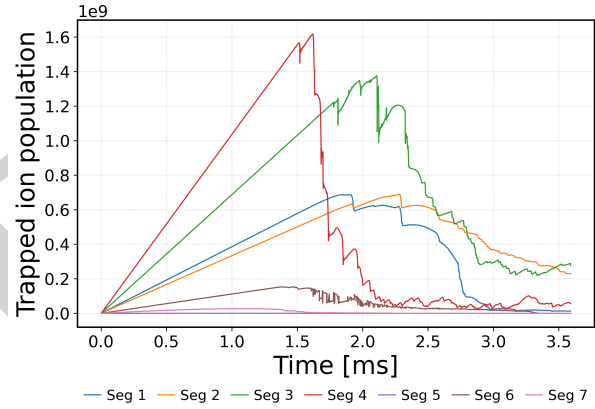
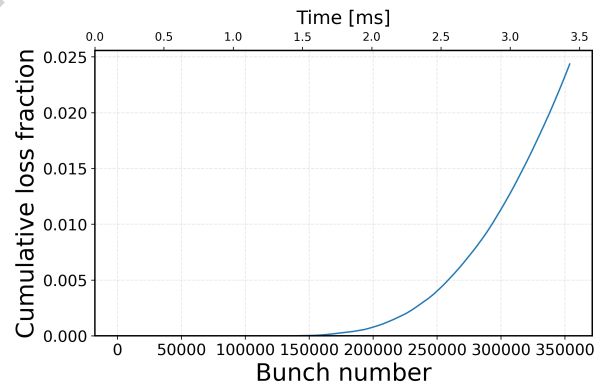


Figure 3: Final trapped ion population in each interaction segment along the ERL beamline, overlaid with the horizontal and vertical beta functions.



(a) Evolution of trapped ion population for different beamline segments.



(b) Cumulative electron loss fraction as a function of bunch number.

Figure 4: Long-time evolution of ion accumulation and electron beam loss in the ERL simulation.

MITIGATION USING BI-PERIODIC BUNCH SPACING

Ion trapping can be mitigated by modifying the bunch spacing, thereby altering the periodic focusing experienced by ions. For a bi-periodic filling pattern with alternating spacings S_1 and S_2 , where $S_1 > S_2$, the transverse ion motion is described by a kick–drift–kick–drift sequence. The corresponding one-period transfer matrix is

$$M = D(S_2)K(a)D(S_1)K(a), \quad (8)$$

with the stability condition obtained from the trace criterion $|\text{Tr}(M)| \leq 2$,

$$0 \leq (aS_1 - 2)(aS_2 - 2) \leq 4. \quad (9)$$

Defining the focusing strength

$$C_{x,y} = \frac{2N_e r_p Q}{\sigma_{x,y}(\sigma_x + \sigma_y)}, \quad (10)$$

and imposing $S_1 + S_2 = 2S$ to preserve the average bunch spacing, the stability condition can be rewritten in terms of ion mass using $a \propto 1/A_{x,y}$ as

$$\begin{cases} \frac{S_1 S_2}{2(S_1 + S_2)} C_{x,y} \leq A_{x,y} \leq \frac{S_2}{2} C_{x,y}, & \text{or} \\ A_{x,y} \geq \frac{S_1}{2} C_{x,y}. \end{cases} \quad (11)$$

An ion is considered trapped if stable motion exists in at least one transverse plane over repeated bunch passages. For a given ion species, the local trapping condition is evaluated along the lattice using the position-dependent beam sizes $\sigma_x(s)$ and $\sigma_y(s)$, shown in Figure 1. Regions where the stability condition is not satisfied in both transverse planes are defined as untrapped regions.

The total untrapped region length is obtained by summing all lattice intervals where the ion motion is unstable. Figure 5 shows the resulting untrapped length for H_2^+ ions as a function of the spacing ratio S_2/S_1 .

Compared with the uniform-spacing case, the bi-periodic pattern produces substantially larger untrapped regions over most of the scanned range. Increasing asymmetry between S_1 and S_2 further enlarges the unstable regions, indicating reduced long-term ion confinement.

These results show that non-uniform bunch spacing can effectively suppress ion trapping by breaking the periodic focusing condition required for stable ion motion. Bi-periodic bunch spacing therefore provides a simple and robust mitigation method for ion accumulation in ERL-based coolers.

Further studies will be required to evaluate the impact of non-uniform bunch patterns on electron cooling performance and to verify that the required cooling rate can still be achieved. Extension to multi-periodic and more general non-uniform filling patterns will be investigated in future work.

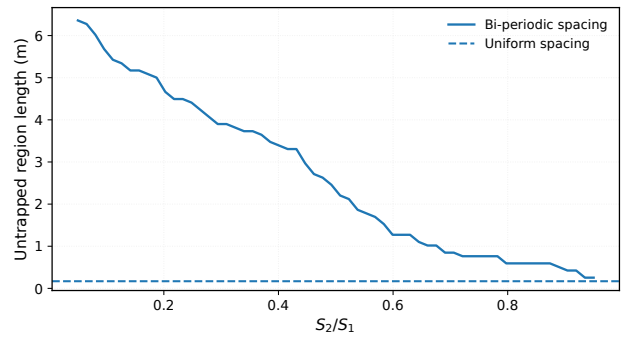


Figure 5: Total untrapped region length for H_2^+ ions as a function of the spacing ratio S_2/S_1 , compared with the uniform-spacing case.

CONCLUSION

Ion trapping in an ERL-based strong hadron cooler has been investigated using a combination of analytical modelling and long-time multi-bunch simulations. The analytical kick–drift model provides a clear criterion for ion stability and shows that, under uniform bunch spacing, even light ions such as H_2^+ can be trapped over a large fraction of the lattice due to the strong variation of beam sizes.

Self-consistent simulations performed with ELEGANT confirm that ion accumulation develops on millisecond time scales and exhibits pronounced spatial non-uniformity along the beamline. The accumulation leads to a progressive increase in beam loss, demonstrating that beam–ion effects can significantly impact the performance of the ERL cooler if left unmitigated.

A bi-periodic bunch spacing scheme has been analysed as a mitigation strategy. The modified spacing breaks the periodicity of ion oscillations, splitting the stability region and substantially increasing the fraction of the lattice where ions become unstable. The results show that stronger asymmetry in the bunch spacing leads to a larger untrapped region, highlighting the effectiveness of non-uniform bunch patterns in suppressing long-term ion trapping.

ACKNOWLEDGEMENTS

This work was supported by the Cockcroft Institute Core Grant under UKRI grant number UKRI1887. The authors at Jefferson Lab are supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contract No. DE-AC05-06OR23177. The authors would also like to thank Joe Calvey and Michael Borland of the APS for valuable discussions and advice regarding the implementation and use of the `ionEffects` elements in ELEGANT.

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