

Charge-exchange cooling of multicharge-state heavy-ion beams

Hiroshi Imao 

RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan



(Received 10 December 2025; accepted 4 March 2026; published 14 April 2026)

A novel cooling mechanism for heavy-ion beams, termed charge-exchange cooling (CEC), is proposed. Phase-space-dependent zoned charge exchange combined with charge-state-dependent closed-orbit distortions (CODs) enables rapid, autonomous, turn-by-turn contraction of the phase-space distribution for continuous-wave heavy-ion beams. The resulting dynamics forms a stochastic affine-map system with state-dependent switching and a net negative drift. CEC is implemented in the charge stripper ring 1 (CSR1), under development at the RIKEN RI Beam Factory, where zoned charge exchange and charge-state-specific CODs are readily incorporated. Proof-of-principle studies based on two- and multicharge-state models, together with realistic CSR1 simulations, demonstrate fast turn-by-turn cooling under practical machine conditions and establish CEC as a new beam-cooling principle with potential implications for future accelerator design and applications.

DOI: [10.1103/PhysRevAccelBeams.29.L044001](https://doi.org/10.1103/PhysRevAccelBeams.29.L044001)

In medium- to high-energy heavy-ion beams, emittance growth caused by charge-state multiplication at ion sources and strippers is unavoidable. Because of the small charge-to-mass ratio q/m , acceleration is slow, adiabatic damping is weak, and space-charge effects in the early acceleration stage remain significant. For the same reason, existing cooling techniques, including electron cooling [1–3], stochastic cooling [4,5], and ionization cooling [6,7], do not show a strong cooling effect on a turn-by-turn basis for heavy ions. As a result, the generation, accumulation, and application of high-brightness heavy-ion beams remain a major challenge.

In conventional cooling schemes for fixed-charge-state beams, the strong interactions required to achieve sufficient cooling inevitably induce charge exchange and cause beam loss, which is regarded as an undesirable side effect. In this Letter, we challenge this conventional view and propose a new cooling principle, charge-exchange cooling (CEC), in which the charge exchange is treated as an active resource for cooling design.

CEC comprises a three-stage process. First, a particle ensemble is probabilistically divided into multiple charge states q according to its phase-space coordinate $\mathbf{z}$. Each charge component then undergoes its own independently designed beam transport based on volume-preserving operations. Finally, the components are merged into a single beam.

The key element that enables this initial splitting is the multizone stripper (MZS). By segmenting the stripper spatially and phase-synchronously if necessary, a coordinate-dependent charge-transition probability $P(q|\mathbf{z})$ is implemented so that particles located in different regions of phase space are statistically converted into different charge states. In this scheme, the charge state q acts as a dynamic “tag” that statistically reflects the particle’s phase-space coordinate at the moment of stripping and determines the subsequent charge-dependent transport. Consequently, particles in different phase-space regions undergo systematically different optical actions.

After applying the designed charge-tag-dependent optical actions, the subsequent merging of the branched phase-space distributions results in a reduced phase-space width compared with the initial distribution. Although each individual transport map is volume-preserving, stochastic alternation through charge exchange produces an effective phase-space contraction that is fully consistent with Liouville’s theorem. Cooling proceeds through the recursive repetition of this split-transport-merge cycle.

CEC operates autonomously on a turn-by-turn timescale using only charge exchange and beam transport, without beam detection or feedback, and hence, is intrinsically applicable to continuous-wave (cw) beams as a fast-cooling mechanism.

A powerful platform for CEC is the charge stripper ring 1 (CSR1 [8–11]) under development at the RIKEN RI Beam Factory (RIBF [12]). As shown in Fig. 1, the injected $^{238}\text{U}^{35+}$ ions are first stripped by an upstream N_2 stripper that resets the charge distribution of the circulating beam, and then by a main He stripper that converts them to high charge states [13,14]. From the generated charge states 59^+ through 66^+ , seven components excluding $q = 64$ circulate

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

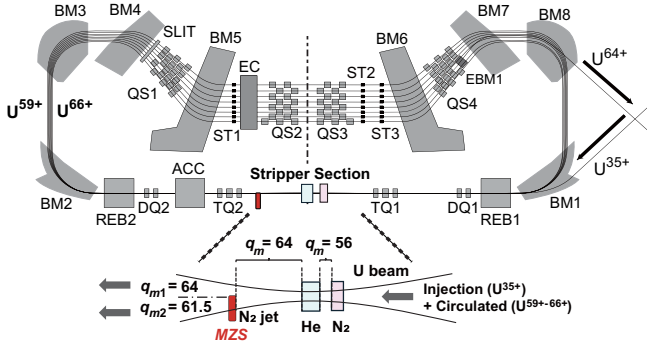


FIG. 1. Schematic layout of CSR1 (circumference $\simeq 44.6$ m, revolution time $\simeq 1$ μ s). Injected $^{238}\text{U}^{35+}$ ions at 10.8 MeV/u are stripped by an upstream N_2 stripper and a main He stripper to form the circulating charge states $59^+ - 66^+$. All charge states except $q = 64$ circulate with a common circumference, while $q = 64$ is extracted by a kicker (EBM1). Quadrupoles (QS), rf cavities (ACC, EC, REB), steerers (ST), and slits (SLIT) provide multicharge-state transport, COD control, and loss localization. The lower panel shows the stripper section. The upstream N_2 stripper resets the charge distribution of the circulating beam, and an ultrathin downstream N_2 jet is introduced in this work as a multizone stripper (MZS) that splits the mean charge into $q_{m1} \simeq 61.5$ and $q_{m2} \simeq 64.0$.

simultaneously in a multicharge-state lattice designed to provide a common circumference, while the target charge state $q = 64$ is extracted by a kicker (EBM1). The beam energy loss of approximately 2% at the stripper is fully compensated for by the accelerating cavity (ACC) in each turn.

In CSR1, the stripper is located at the mirror-symmetry point, where the Twiss parameters of all charge-state lattices are matched with a common β , $\alpha = 0$, and zero dispersion $D = D' = 0$ using the quadrupole stations (QS) and rebuncher cavities (REB1–2), whereas the phase advance μ_q differs among the charge states. Consequently, long-term coherence among the charge components is lost, which suppresses resonances and damps coherent motion. From the perspective of CEC, CSR1 inherently provides probabilistic charge branching and charge-specific transport. With the introduction of an MZS, the split-transport-merge cycle of CEC is executed recursively on a turn-by-turn basis, where independent operation is achieved through charge-dependent closed-orbit distortions (CODs). This enables fully autonomous CEC on the revolution timescale (~ 1 μ s/turn).

In the following, we formulate CEC with CODs as a stochastic affine-map system and derive the cooling condition under which the expected change of the normalized phase-space norm becomes negative, referred to as the negative-drift condition. Through both simplified design models and linear multicharge-state simulations based on the CSR1 design, we demonstrate that the combination of an MZS and charge-dependent COD can achieve fast and autonomous cooling under realistic machine conditions.

To this end, we consider an idealized ring model in which each charge state q has its own Twiss-matched lattice, and introduce the corresponding Twiss-normalized phase-space coordinates $\mathbf{z}$ for the one-turn map M_q of each charge state. In the absence of COD, the one-turn map is given by $\mathbf{z}_{n+1} = R(\mu_q)\mathbf{z}_n$, where $R(\mu_q)$ is the rotation matrix with phase advance μ_q that is symplectic and conserves $|\mathbf{z}|$.

In recursive CEC, a charge-dependent COD shifts the rotation center to $\mathbf{O}_q$, and the one-turn map becomes an affine transformation, $\mathbf{z}_{n+1} = \mathbf{O}_q + R(\mu_q)(\mathbf{z}_n - \mathbf{O}_q) = R(\mu_q)\mathbf{z}_n + \mathbf{d}_q$, with $\mathbf{d}_q = \mathbf{O}_q - R(\mu_q)\mathbf{O}_q$. Including the coordinate-dependent charge-transition probability $P(q'|q, \mathbf{z})$, the turn-by-turn evolution of the phase-space distribution is given by $f_{n+1}(\mathbf{z}', q') = \sum_q \int d\mathbf{z} \delta(\mathbf{z}' - [R(\mu_q)\mathbf{z} + \mathbf{d}_q])P(q'|q, \mathbf{z})f_n(\mathbf{z}, q)$. This defines a stochastic affine-map system where the maps $\mathbf{z} \mapsto R(\mu_q)\mathbf{z} + \mathbf{d}_q$ are selected according to the coordinate-dependent probability $P(q'|q, \mathbf{z})$.

We used the normalized phase-space norm as a measure of the beam size, $V(\mathbf{z}) = |\mathbf{z}|^2$. The one-turn change is expressed as $V(\mathbf{z}_{n+1}) - V(\mathbf{z}_n) = 2R(\mu_q)\mathbf{z}_n \cdot \mathbf{d}_q + |\mathbf{d}_q|^2$. The conditional expectation at $\mathbf{z}_n = \mathbf{z}$, which governs the average cooling or heating behavior, is given by the drift function

$$D(\mathbf{z}) = \sum_q P(q|\mathbf{z})(2R(\mu_q)\mathbf{z} \cdot \mathbf{d}_q + |\mathbf{d}_q|^2). \quad (1)$$

If $P(q|\mathbf{z})$ and the COD vectors $\mathbf{d}_q$ are designed so that $D(\mathbf{z}) < 0$ holds in the large-amplitude region $|\mathbf{z}| > R$, a cooling regime is obtained where the average phase-space amplitude contracts. When the linear term $2R(\mu_q)\mathbf{z} \cdot \mathbf{d}_q$ dominates at large amplitudes, the sign of $D(\mathbf{z})$ is governed by the probability-weighted sum of inner products $\sum_q P(q|\mathbf{z})R(\mu_q)\mathbf{z} \cdot \mathbf{d}_q$. Cooling is obtained when the zone-selective charge switching, the charge-dependent transport $R(\mu_q)$, and the COD orientations are arranged such that the probability-weighted inner product becomes negative in the outer region. As cooling proceeds, $|\mathbf{z}|$ equilibrates at a scale comparable to $|\mathbf{d}_q|$, indicating that the size of the equilibrium distribution is set by the COD amplitude.

Figure 2 shows the phase-space geometry produced by a horizontal zone stripper combined with a one-turn map with charge-dependent CODs. The q_1 - and q_2 -zones (blue and red) are mapped by $R(\mu_1)$ and $R(\mu_2)$ about their respective CODs (crosses). For illustrative purposes, the phase advance μ is folded into the interval $[-\pi, \pi]$ rather than using the conventional definition ($\mu > 0$), and a special symmetric case with $\mu_1 = -\mu_2$ is chosen to visualize the contraction mechanism more intuitively. When a particle crosses the zone boundary, the active rotation center switches, and the alternating action of multiple

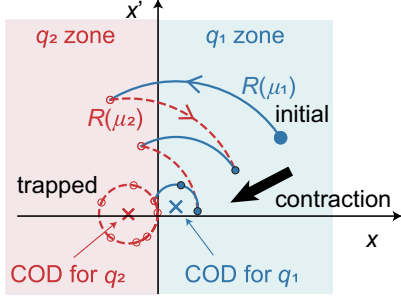


FIG. 2. Idealized multizone stripper (MZS) that fully separates the beam into two charge states, q_1 (blue) and q_2 (red), based on the horizontal coordinate. Each charge state follows a one-turn map $R(\mu_1)$ or $R(\mu_2)$ about its charge-dependent COD (crosses). For illustrative purposes, the phase advance μ is folded into the interval $[-\pi, \pi]$ rather than using the conventional definition ($\mu > 0$), and a special symmetric condition with $\mu_1 = -\mu_2$ is chosen. A negative phase advance is represented as a counter-clockwise rotation. Switching of the active center at the zone boundary can generate contracting phase-space dynamics. Although particles appear trapped near the CODs in this fully separated case, a realistic MZS produces distributed transitions and an equilibrium motion between the CODs.

centers generates, on average, a contracting dynamics in the large-amplitude region. Scattering by the MZS enters the drift function $D(\mathbf{z})$ only as an additive constant and does not alter the essential CEC structure.

From a mathematical viewpoint, under the conditions realized in the present system, the charge transitions are sufficiently mixed within the set of circulating charge states, and the negative-drift condition is satisfied in the large-amplitude region. Therefore, the dynamics obey the Foster-Lyapunov condition, and the Meyn-Tweedie theory [15] supports ergodic convergence to a unique equilibrium distribution with a finite second moment. As the emittance of this equilibrium distribution is smaller than that of the injected beam, CEC functions as a robust cooling mechanism that is insensitive to the detailed initial conditions.

To verify that the stochastic affine-map dynamics and the associated drift function produce phase-space contraction, we performed numerical tests using a two-charge-state model and an eight-charge-state model that mimics CSR1. In both cases, normalized horizontal coordinates $\mathbf{X} = (x, x')$ were used, and the initial distribution was assumed to be uniform within a unit disk. When Twiss matching is satisfied, the particles undergo rotational motion in circles of constant radius.

Using the minimal model in which only the two charge states q_1 and q_2 circulate, we examined the optical conditions under which CEC was realized. As a specific example of position-dependent charge switching by an MZS, we adopted a probability model in which the probabilities are inverted according to the sign of the horizontal coordinate x , namely $P(q_1|\mathbf{X}) = p$ for $x \geq 0$ and $P(q_1|\mathbf{X}) = 1 - p$ for $x < 0$, with $P(q_2|\mathbf{X}) = 1 - P(q_1|\mathbf{X})$. In the following,

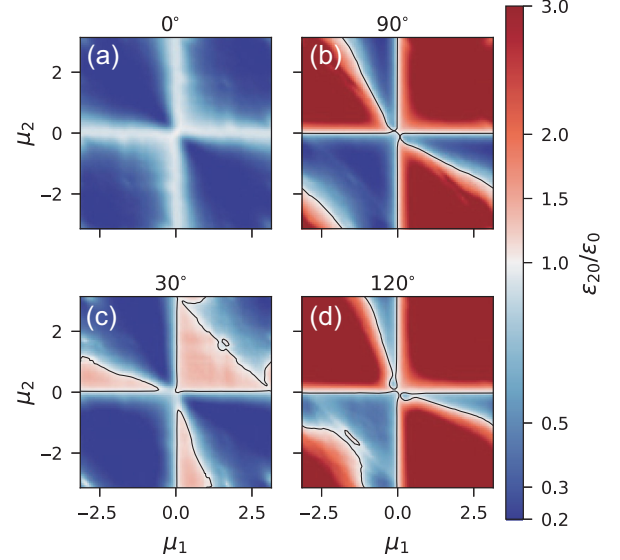


FIG. 3. Cooling-heating map of CEC based on the two-charge-state stochastic affine model. The charge state is selected probabilistically by the sign of x ($p = 0.8$), and each map acts with phase advances μ_1, μ_2 about its own COD ($|\mathbf{O}_1| = |\mathbf{O}_2| = 0.10$, $\mathbf{O}_1 = -\mathbf{O}_2$). Colors show the emittance ratio after 20 turns, $\varepsilon_{20}/\varepsilon_0$, in the (μ_1, μ_2) plane (blue indicates cooling, red indicates heating, black indicates the boundary). The labels 0° , 30° , 90° , and 120° indicate the orientation of the COD difference vector $\mathbf{O}_1 - \mathbf{O}_2$, obtained by rigidly rotating the two COD vectors $\mathbf{O}_1$ and $\mathbf{O}_2$ in the x - x' phase space by the same angle while preserving both their magnitudes and their antiparallel relationship. This orientation strongly governs the cooling pattern through its geometric relation to the zone-switching condition.

we use $p = 0.8$, where $p = 0.5$ corresponds to the normal stripper. The one-turn map for each charge state is given by the affine map, $\mathbf{z} \mapsto R(\mu_q)\mathbf{z} + \mathbf{d}_q$, and the magnitude of the COD vector $\mathbf{O}_q$ is fixed at $|\mathbf{O}_q| = 0.10$ with only its direction varied. Figure 3 shows the normalized emittance ratio after 20 turns, $\varepsilon_{20}/\varepsilon_0$, in the (μ_1, μ_2) plane for the four COD orientations. Blue indicates cooling (< 1), and red indicates heating (> 1). For the horizontal configuration (0°), $\varepsilon_{20}/\varepsilon_0 \leq 1$ over the entire plane, taking the equality only on the integer-tune lines. As the COD direction is rotated to 30° and 90° , the cooling regions progressively shrink. For 120° , heating becomes dominant, and at 180° the pattern is inverted relative to 0° , resulting in heating over the entire plane. This asymmetric dependence does not originate from the orientation of the CODs themselves, but rather from the relative geometry between the zone-switching boundary and the COD difference vector $\mathbf{O}_1 - \mathbf{O}_2$. When a particle crosses the zone boundary, if the effective COD switches to the same side as the particle displacement in phase space, the relative displacement is reduced, resulting in cooling. In contrast, if the COD switches to the opposite side, the relative displacement increases, leading to a heatinglike behavior.

The broad cooling region observed for the horizontal COD configuration can be understood analytically using

the drift formalism. For particles uniformly distributed on a circle of radius r , the one-turn averaged drift is defined as $I \equiv \int_0^{2\pi} D(\theta) d\theta$. For $\mathbf{O}_1 = (+O_x, 0)$ and $\mathbf{O}_2 = (-O_x, 0)$, and for a zone stripper yielding $q_1 : q_2 = p : (1-p)$ in the right-half plane and $(1-p) : p$ in the left half plane, angular averaging gives $I(r) = 4O_x S(\pi O_x - (2p-1)r)$, where $S \equiv \sin^2(\mu_1/2) + \sin^2(\mu_2/2)$.

For $O_x > 0$, the cooling condition $I(r) < 0$ reduces to $\pi O_x - (2p-1)r < 0$, and the equilibrium radius follows from $I(r_{\text{eq}}) = 0$ as $r_{\text{eq}} = \pi O_x / (2p-1)$, showing that the final equilibrium scale is proportional to COD amplitude, $r_{\text{eq}} \propto |\mathbf{O}|$. In the large-amplitude region $r \gg r_{\text{eq}}$, the drift behaves as $I(r) \simeq -4S(2p-1)O_x r$, demonstrating that the cooling force is proportional to O_x . Accordingly, $|\mathbf{O}|$ serves as the primary control parameter that simultaneously sets the cooling rate and the final equilibrium emittance.

The emittance change per turn follows from the conditional expectation of the normalized phase-space norm $V(\mathbf{z}) = r^2$ as $\langle V_{n+1} \rangle = r^2 + I(r)/(2\pi)$. Since the emittance scales as $\varepsilon \propto \langle r^2 \rangle$ for the present isotropic distribution, one finds $\langle \varepsilon_{n+1} \rangle / \varepsilon_n \simeq 1 - (2/\pi)S(2p-1)O_x/r$. Thus, a finite fraction of the emittance is reduced on every turn, typically at the percent level in the representative cooling region of Fig. 3(a). Comparable few-percent-per-turn cooling rates are also obtained in the eight-charge-state model and in the realistic CSR1-based simulations discussed below, indicating that this behavior is not an artifact of the two-charge-state idealization. This turn-by-turn finite contraction sharply contrasts with conventional electron and stochastic cooling, where heavy-ion cooling time constants are typically in the 0.1–10 s range [2,3,5].

Such rapid contraction arises because CEC is based on a principle fundamentally different from cooling mechanisms that rely on dissipative processes acting directly on particle motion. In CEC, charge-state switching induces a phase-correlated switching of the effective rotation center (COD), leading to a reduction of the oscillation amplitude as a turn-by-turn mapping; cooling therefore proceeds as a sequence of discrete operations on the revolution-time scale.

This mechanism is analogous to crane antisway control, in which oscillations are suppressed not by direct damping but by moving the support point (COD) in synchrony with the motion. In CEC, this synchronization is realized in a stochastic and statistical manner through charge-state switching. In other words, cooling in CEC arises from dynamic switching of the reference point of motion rather than from direct energy dissipation.

Next, we carried out a similar analysis for an eight-charge-state system with $q = 59^+ - 66^+$ based on the CSR1 design conditions. For each charge state, the designed phase advance μ_q of CSR1 was used to construct the corresponding one-turn rotation matrix. The multizone stripper (MZS) was modeled using a coordinate-dependent mean charge $q_m(x) = [1 - s(x; a)]q_{m1} + s(x; a)q_{m2}$, with $s(x; a) = 1/[1 + \exp(x/a)]$, and the actual charge state

was sampled from a discrete Gaussian distribution with width $\sigma_q \simeq 1.7$. In this analysis, $q_{m1} = 61.5$ and $q_{m2} = 64.0$ were chosen to represent the two main peaks achievable with the CSR1 internal stripper, and the parameter a characterizes the blurring length of the zone boundary.

The charge-dependent COD was determined, guided by the two-charge-state results, using a horizontal linear slope $\mathbf{O}_q = (k(q - q_{\text{mid}}), 0)$, where $q_{\text{mid}} = (q_{m1} + q_{m2})/2$, and k is the principal design parameter. A systematic parameter scan confirms that, as in the two-charge-state case, a smaller magnitude of k yields a smaller equilibrium 4 rms emittance at the expense of a larger number of turns required for cooling, whereas reversing the sign of k converts cooling to heating (in the present work, a negative k corresponds to the cooling condition).

As a representative cooling point, we chose $k = -0.03$ and $a = 0.10$ and performed multiparticle tracking for the eight-charge-state system. Figure 4 shows the phase-space distributions at 0, 5, 20, and 80 turns and the contours of the drift function $D(\mathbf{z})$. An initially uniform disk is transported into the negative-drift region within a few turns and converges to a finite-radius stationary core. After 80 turns, the horizontal 4 rms emittance ratio is reduced to $\varepsilon_{x,80}/\varepsilon_{x,0} \simeq 0.09$, demonstrating a clear CEC effect under eight-charge-state conditions.

To assess the practical feasibility of CEC, we performed linear multicharge-state simulations based on the CSR1

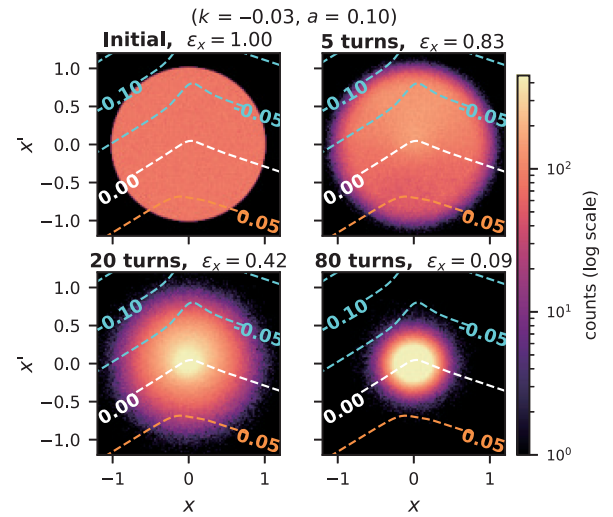


FIG. 4. Phase-space contraction under the multicharge-state map constructed from the position-dependent charge distribution $P(q|\mathbf{z})$ and the charge-dependent closed orbits $\mathbf{O}_q = k(q - q_{\text{mid}})$ ($k = -0.03$, $a = 0.10$). The dots denote the particle distribution, and dashed curves are contours of the drift function $D(\mathbf{z})$ (cyan: cooling, $D < 0$; orange: heating, $D > 0$; white: $D = 0$). Distributions after 0, 5, 20, and 80 turns are shown. An initially uniform disk is transported along the negative-drift region toward the center and converges to a finite-radius stationary core. The 4 rms emittance ε_x in the Twiss-normalized phase space decreases monotonically with turn number.

design parameters at the RIBF. Particles that leave a circulating charge range $59^+ - 66^+$ are lost, and charge-exchange losses of approximately 5%/turn intrinsically limit the effective number of turns. Under this realistic constraint, we examined whether CEC could overcome emittance growth due to straggling.

The simulations were performed using an in-house linear multicharge-state tracking code (CSRS) developed for CSR1 studies. For each charge state, the code includes one-turn transport matrices, bending-magnet matrices based on three-dimensional magnetic-field calculations, charge exchange at the stripper, outer halo scraping by slits, and correction steerers that provide charge-dependent CODs. A pure accumulation mode without beam extraction was assumed in order to isolate the intrinsic convergence properties of CEC. The one-turn transport matrix has a block-diagonal structure in which the horizontal $X-X'$, vertical $Y-Y'$, and longitudinal (phase-momentum) degrees of freedom are mutually independent [11].

The initial beam at the stripper center was considered as a 4 rms Gaussian distribution with $1 \text{ mm} \times 3 \text{ mrad}$. For all charge states, Twiss matching was performed with $\beta_{x,y} = 0.333 \text{ m}$, $\beta_z = 2.4 \text{ m}$, and $\alpha = 0$, together with dispersion matching $D = 0$ and $D' = 0$. Angular straggling was set to 0.4 mrad (1σ) per turn [16].

As shown in Fig. 1, in the standard configuration, the reset N_2 stripper, with an areal density of approximately 0.1 mg/cm^2 , produces a mean charge of $q_m \simeq 56$ [17], and the subsequent main He stripper, with an areal density of approximately 0.3 mg/cm^2 , raises it to $q_m \simeq 64$ [14], thereby forming a multicharge-state circulation band of $59^+ - 66^+$.

For the CEC demonstration in simulation, an ultrathin N_2 gas jet with an areal density of 0.01 mg/cm^2 was assumed downstream of the main He stripper to form a practical multizone stripper (MZS), selectively splitting the mean charge into $q_{m1} \simeq 61.5$ and $q_{m2} \simeq 64.0$. Although the partial irradiation of the beam is nonstandard, producing such an ultrathin jet is well within the capability of existing gas-jet stripper technology [18–20], and the associated energy loss is negligible. In the simulation, the charge-state width was set to $\sigma_q \simeq 1.7$, and the zone-boundary blurring parameter to $a = 0.10$. An approximately 1.5 m drift was included upstream of the stripper to expand the beam to the $\sim 10 \text{ mm}$ scale at the gas-jet location. Under this condition, the steering angles of the charge-dependent steerers (ST3) were scanned over the range $\pm 0.2 \text{ mrad}$ for each charge state to numerically optimize the CEC condition.

Figure 5(a) shows the turn-by-turn evolution of the horizontal 4 rms emittance ϵ_x (initially $\sim 3 \text{ mm} \times \text{mrad}$). In the baseline configuration (reset + main stripper), the emittance increases monotonically because of the angular straggling and exceeds 3 times the initial value after 60 turns. With COD alone, the growth is further enhanced by an optical mismatch. With the slit only, the emittance

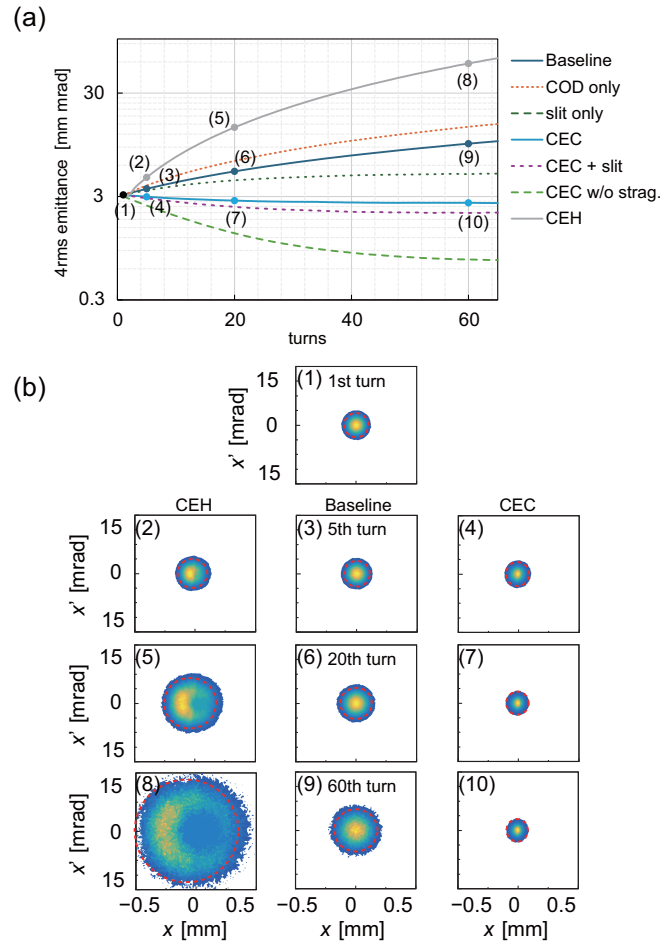


FIG. 5. (a) Turn-by-turn evolution of the horizontal 4 rms emittance ϵ_x for various conditions. (b) Evolution of the $X-X'$ phase-space distribution at 1, 5, 20, and 60 turns. The red dashed circle indicates the corresponding 4 rms emittance radius. CEC produces contraction to a finite-radius core, while CEH generates a hollow distribution.

reaches an apparent equilibrium near $5 \text{ mm} \times \text{mrad}$, not by cooling, but because the slit continuously scrapes the halo generated by emittance growth. In contrast, with CEC the emittance decreases after a short transient and converges to $\sim 2.7 \text{ mm} \times \text{mrad}$ within approximately 20 turns. With CEC + slit, the equilibrium value is further reduced. Under the idealized condition without straggling (CEC w/o strag.), the emittance decreases to $0.74 \text{ mm} \times \text{mrad}$ after 60 turns. Reversing the COD sign (charge-exchange heating, CEH) leads to rapid divergence.

The corresponding $X-X'$ phase-space distributions in Fig. 5(b) show a monotonic expansion for the baseline case, whereas CEC leads to a contraction into a compact stationary distribution with a finite radius. In contrast, CEH produces a hollow distribution with a depleted core around its origin.

These results demonstrate that, by adding an ultrathin N_2 gas jet to the standard CSR1 stripper configuration and

optimizing the charge-dependent CODs with steerers, CEC remains effective under realistic machine conditions. Even in the presence of the angular straggling and the charge-exchange losses, an efficient phase-space contraction is achieved within a few to several tens of turns.

In conclusion, we propose CEC, a new cooling mechanism that exploits the charge-state degrees of freedom intrinsic to multicharge-state heavy-ion beams. By combining coordinate-dependent charge transitions $P(q|\mathbf{z})$ with charge-dependent CODs, phase-space contraction is achieved without violating Liouville's theorem. The one-turn dynamics form a stochastic family of affine maps, and a negative drift at large amplitudes ensures convergence to a finite-radius equilibrium state whose scale is quantitatively set by the COD amplitude.

Two-charge-state and eight-charge-state studies demonstrate not only the existence of cooling but also a finite per-turn cooling rate, and realistic CSR1-based simulations confirm that CEC can be realized under practical machine conditions. This turn-by-turn contraction, which contrasts sharply with the long time constants of conventional electron and stochastic cooling, establishes CEC as an intrinsically fast and autonomous cooling mechanism for heavy-ion beams. Additional effects such as space-charge affect the cooling rate but not the validity of the CEC principle.

Beyond the present implementation using an ultrathin N_2 gas jet, other stripper concepts, such as liquid [21] and rotating solid [22] strippers, may provide sharper charge-zone separation. The cooling action can also be extended beyond the horizontal plane through appropriate zone design and time-dependent charge control. Longitudinal CEC is feasible using finite dispersion at the stripper together with a charge-state-selective energy-correction cavity (EC [10]).

Although CSR1 is not a dedicated cooling ring, the present results indicate that further improvements in CEC performance can be expected with increased charge-state multiplicity, which naturally motivates the development of a dedicated multicharge-state system, such as the internal-target ring Chreostron [11]. A dedicated ring with CEC can open new application domains, including high-brightness radioactive-ion production, long-duration internal-target nuclear-reaction studies, and extreme rare-event experiments.

On the other hand, the ring geometry itself is not essential for the realization of CEC. The same principle can also be implemented in beamline configurations in which the optical structure of the CSR is unfolded into a linear layout and multiple stages are compactly connected using several MZSs as nodes. In such configurations, constraints associated with circular circulation are relaxed, providing greater flexibility in branching, transport (or acceleration), and merging operations, although achieving a sufficient number of effective repetitions may require a larger overall system scale.

More broadly, this study shows that stochastic charge-state processes can be embedded directly into circular beam dynamics to generate forms of stability beyond those available in conventional deterministic accelerator optics.

The author expresses gratitude to Osamu Kamigaito for discussion. This study was supported by JSPS KAKENHI Grant No. JP25H00656.

Data Availability The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

-
- [1] G. I. Budker, An effective method of damping particle oscillations in proton and antiproton storage rings, *Sov. At. Energy* **22**, 438 (1967).
 - [2] V. Parkhomchuk, New insights in the theory of electron cooling, *Nucl. Instrum. Methods Phys. Res., Sect. A* **441**, 9 (2000).
 - [3] M. Steck, P. Beller, K. Beckert, B. Franzke, and F. Nolden, Electron cooling experiments at the ESR, *Nucl. Instrum. Methods Phys. Res., Sect. A* **532**, 357 (2004), International Workshop on Beam Cooling and Related Topics.
 - [4] S. van der Meer, Stochastic damping of betatron oscillations in the ISR, Technical Report No. CERN/ISR-PO/72-31, European Organization for Nuclear Research (CERN), Geneva, 1972.
 - [5] D. Möhl, G. Petrucci, L. Thorndahl, and S. van der Meer, Physics and technique of stochastic cooling, *Phys. Rep.* **58**, 73 (1980).
 - [6] D. Neuffer, Principles and applications of muon cooling, *Part. Accel.* **14**, 75 (1983).
 - [7] M. Bogomilov *et al.*, Demonstration of cooling by the muon ionization cooling experiment, *Nature (London)* **578**, 53 (2020).
 - [8] H. Imao, Charge stripper ring for RIKEN RI Beam Factory, *J. Instrum.* **15**, P12036 (2020).
 - [9] H. Imao, Status update of the charge stripper rings project, *J. Instrum.* **18**, P03028 (2023).
 - [10] RIKEN Nishina Center, RIBF facility upgrade project, Technical Report, RIKEN, 2023, https://www.nishina.riken.jp/researcher/RIBFupgrade/RIBF_Upgrade_NCAC.pdf.
 - [11] H. Imao, A charge stripper ring for RIKEN RI beam factory, in *Proceedings of the HIAT2025, East Lansing, MI (JACoW, Geneva, Switzerland, 2025)*, pp. 298–303, FRX01, 10.18429/JACoW-HIAT2025-FRX01.
 - [12] Y. Yano, The RIKEN RI Beam Factory project: A status report, *Nucl. Instrum. Methods Phys. Res., Sect. A* **261**, 1009 (2007), The Application of Accelerators in Research and Industry.
 - [13] H. Okuno, N. Fukunishi, A. Goto, H. Hasebe, H. Imao, O. Kamigaito, M. Kase, H. Kuboki, Y. Yano, S. Yokouchi, and A. Hershcovitch, Low-Z gas stripper as an alternative to

- carbon foils for the acceleration of high-power uranium beams, *Phys. Rev. ST Accel. Beams* **14**, 033503 (2011).
- [14] H. Imao, H. Okuno, H. Kuboki, S. Yokouchi, N. Fukunishi, O. Kamigaito, H. Hasebe, T. Watanabe, Y. Watanabe, M. Kase, and Y. Yano, Charge stripping of ^{238}U ion beam by helium gas stripper, *Phys. Rev. ST Accel. Beams* **15**, 123501 (2012).
- [15] S. P. Meyn and R. L. Tweedie, *Markov Chains and Stochastic Stability*, Communications and Control Engineering (Springer-Verlag, London, England, 1993), Vol. 37.
- [16] R. Anne, J. Herault, R. Bimbot, H. Gauvin, G. Bastin, and F. Hubert, Multiple angular scattering of heavy ions ($^{16,17}\text{O}$, ^{40}Ar , ^{86}Kr , and ^{100}Mo) at intermediate energies (20–90 MeV/u), *Nucl. Instrum. Methods Phys. Res., Sect. B* **34**, 295 (1988).
- [17] H. Kuboki, H. Okuno, H. Hasebe, S. Yokouchi, N. Fukunishi, Y. Higurashi, J. Ohnishi, T. Nakagawa, H. Imao, O. Kamigaito, A. Goto, M. Kase, and Y. Yano, Charge-state distribution of ^{238}U in nitrogen gas and carbon foil at 14 and 15 MeV/nucleon, *Phys. Rev. ST Accel. Beams* **14**, 053502 (2011).
- [18] W. Barth, A. Adonin, C. E. Düllmann, M. Heilmann, R. Hollinger, E. Jäger, J. Khuyagbaatar, J. Krier, P. Scharrer, H. Vormann, and A. Yakushev, U^{28+} -intensity record applying a H_2 -gas stripper cell, *Phys. Rev. ST Accel. Beams* **18**, 040101 (2015).
- [19] P. Scharrer, C. E. Düllmann, W. Barth, J. Khuyagbaatar, A. Yakushev, M. Bevcic, P. Gerhard, L. Groening, K. P. Horn, E. Jäger, J. Krier, and H. Vormann, Measurements of charge state distributions of 0.74 and 1.4 MeV/u heavy ions passing through dilute gases, *Phys. Rev. Accel. Beams* **20**, 043503 (2017).
- [20] H. Imao *et al.*, Design and operation of a helium gas stripper for high-intensity uranium beams at the RIKEN Radioactive Isotope Beam Factory, *Rev. Sci. Instrum.* **97**, 033301 (2026).
- [21] T. Kanemura, M. LaVere, R. Madendorp, F. Marti, T. Maruta, Y. Momozaki, P. N. Ostroumov, A. S. Plastun, J. Wei, and Q. Zhao, Experimental demonstration of the thin-film liquid-metal jet as a charge stripper, *Phys. Rev. Lett.* **128**, 212301 (2022).
- [22] H. Hasebe, H. Okuno, A. Tatami, M. Tachibana, M. Murakami, H. Kuboki, H. Imao, N. Fukunishi, M. Kase, and O. Kamigaito, Development of a rotating graphite carbon disk stripper, *AIP Conf. Proc.* **1962**, 030004 (2018).