

Energy recovery proton linear accelerator

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High-power proton linear accelerators have important applications in both scientific research and industry. However, the operation of such accelerators with megawatt-level beam power is expensive and limits the broad availability of these facilities. In this Letter, we propose a novel energy recovery proton linear accelerator in which the final GeV-level proton beam is reinjected into the linear accelerator from the accelerator exit and is decelerated in the same accelerator down to about 2 MeV, close to the initial beam energy. This substantially reduces the power consumption of the proton linear accelerator and also avoids the need for a high-power beam dump. We demonstrate this concept through self-consistent simulations and show that the beam-beam effect between the forward-accelerating beam and the backward-decelerating beam would not be a limiting factor for the proposed concept. A potential application of this concept to an electron-ion collider based on energy recovery electron and ion accelerators is discussed.

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Introduction. High-power proton linear accelerators (linacs) provide an important tool for scientific discoveries in high-energy physics, material science, chemistry, biology, and other fields. These accelerators can be used as drivers to produce muons, neutrinos, neutrons, and radioactive elements. They can also be used to drive subcritical nuclear reactors for power generation and nuclear waste transmutation. A number of these facilities have been built or are under construction around the world [1–6]. However, the operation of a high-power proton linear accelerator is expensive. A megawatt-level proton accelerator requires more than a megawatt electric power supply for the rf accelerating cavities. Furthermore, a beam dump that can handle high-power megawatt-level spent beam is needed. In this Letter, we propose an energy recovery proton linear accelerator in which a portion of the proton beam, after the beam-target interaction, is sent back into the linear accelerator. This portion of the proton beam will be decelerated through the linear accelerator and give its energy back to the rf cavity. This significantly reduces the radio frequency (rf) power usage in the superconducting cavity and the operational cost of the entire accelerator. The final low-energy proton beam will be removed from the accelerator and sent to a low-power beam dump.

Since it was first proposed in 1960s [7], the electron energy recovery linac has been extensively studied for several decades. A series of workshops have been dedicated

to this topic since 2005 [8–17]. A number of electron energy recovery linacs have been built around the world [18–24]. So far, no proton energy recovery linac has been studied or developed. The key difference between a proton beam and an electron beam is that the proton has a much larger mass (approximately 1800 times that of the electron). Consequently, it has a much lower velocity than the electron given the same kinetic energy. In a proton linear accelerator, during the acceleration from MeV to GeV, the proton velocity changes significantly. For efficient acceleration through rf fields, this requires the use of different types of rf cavities with different geometric lengths or frequencies. In an electron linear accelerator, after a few MeV, the velocity of the electron is close to the speed of light. There is little variation in electron velocity during the process of acceleration, allowing the use of only one type of rf cavity structure in the electron linac. This makes energy recovery easier without losing deceleration efficiency by passing different energy electron beams through the same rf cavity. As a result, the conventional electron energy recovery linac typically has a racetrack shape, with the rf accelerator on one side and the application target (e.g., undulator) on the other side. The high-energy electron beam exiting from the linear accelerator passes through the undulator to generate radiation and is then brought back to the entrance of the accelerator with an appropriate phase for deceleration through the linac. There is no collision between the accelerated electron beam and the decelerated electron beam. However, this type of accelerator footprint will not work for a proton beam since the high-energy proton beam from the exit of the accelerator cannot be brought back to the entrance of the accelerator for deceleration. The rf cavity designed for a low-energy proton beam will not effectively accelerate or decelerate a high-energy proton beam. In this Letter, we propose a novel

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accelerator design so that the high-energy proton beam can be effectively decelerated in the accelerator for energy recovery.

Energy recovery proton accelerator. Figure 1 shows a schematic plot of the proposed energy recovery proton linear accelerator. The accelerator consists of a low-energy proton source and a radio frequency quadrupole (RFQ) to accelerate the proton beam to about 2 MeV. Then, this beam is further accelerated through a number of sections of the superconducting linear accelerator to several GeV before exiting the accelerator. Each section consists of one type of superconducting rf cavity. After interacting with the target material, the portion of the proton beam that does not undergo large deflection or nuclear reaction is brought back to the exit of the accelerator through a return loop. This proton beam is sent backward from the end of the linear accelerator to the entrance of the superconducting linear accelerator. The backward-moving proton beam is decelerated through each rf cavity and yields its energy to the rf fields inside the cavity. Hence, inside each cavity, the proton beam has the correct energy and velocity corresponding to that cavity structure for effective deceleration. At the entrance of the superconducting linac, the backward proton beam attains an energy of about 2 MeV before being sent to the beam dump. The proton beam power into the beam dump will be much lower than the original beam and can be easily handled. To attain the design energy of the proton beam, the rf amplitudes and phases inside the rf cavities have to be appropriately set. Once they are set, the rf electromagnetic field amplitudes and phases stay the same for all bunches. To decelerate the backward-moving proton beam using the same rf setting, the linear accelerator has to be carefully designed as discussed in the following.

In the energy recovery proton linac design, the initial beamline element layout and rf cavity amplitude and phase settings are chosen according to the forward-accelerating proton beam. For rf cavity i , the initial rf input phase for the forward-moving proton beam at this cavity is ϕ_i . Now, for a backward-moving proton beam with the same energy as the forward-moving proton beam at the exit of rf cavity i , its initial phase has to be appropriately chosen so that the backward-moving proton beam will be decelerated to the same energy as the forward-moving proton beam at the entrance of the cavity. This initial phase for the backward-moving proton beam is denoted as φ_i . The actual phase of that backward-moving proton beam at the exit of rf cavity i

from the end of the entire linear accelerator is θ_i . Normally, $\varphi_i \neq \theta_i$, the difference is given as $\delta_i = \varphi_i - \theta_i$. In order to attain the correct deceleration through rf cavity i for the backward-moving proton beam, this difference should be a multiple integer of 2π . This can be achieved by adjusting the distance between rf cavities i and $i + 1$. Assuming the velocity of the proton beam after cavity i is v_i , the change of phase $\delta\theta_i$ due to the change of the distance δl_i between cavities i and $i + 1$ is given as

$$\delta\theta_i = \omega \frac{\delta l_i}{v_i}, \quad (1)$$

where ω is the reference angular frequency. Given the initial phase difference δ_i for the backward-moving proton beam, in order to attain the correct deceleration, the change of phase should satisfy:

$$2\delta\theta_i - \delta_i = 2n\pi, \quad (2)$$

where n is an integer. The resultant distance change δl_i will be:

$$\delta l_i = \frac{(\delta_i + 2n\pi)v_i}{2\omega}. \quad (3)$$

After the change of separation distance between rf cavities i and $i + 1$, the new input phase for cavity $i + 1$ with angular frequency ω_{i+1} should be reset to $\phi_{i+1} - \frac{\omega_{i+1}}{\omega} \delta\theta_i$ so that the forward-moving proton beam will gain the same amount of energy through the cavity $i + 1$ as in the original setting. The initial phase of the backward-moving proton beam at the exit of rf cavity $i + 1$ will be reset to $\varphi_{i+1} + \delta\theta_i$. This process starts from the first rf cavity and repeats until the last rf cavity in the energy recovery proton linear accelerator. The initial phase θ_i for the backward-moving proton beam at the exit of rf cavity i is attained by choosing the initial phase φ_N for the last rf cavity for a given deceleration energy and running the backward proton beam through the accelerator with the original settings, i.e., initial rf cavity separation distance and rf field amplitudes and input phases.

Beam-beam effect in an illustrative example. As an illustration, we present an energy recovery proton linac using three types of superconducting rf cavities. This linac accelerates a proton beam from about 2 MeV to about 0.5 GeV and then decelerates it back to the initial 2 MeV. The choice of 0.5 GeV as the final kinetic energy is due to its optimal suitability for certain muon production applications [25]. The three types of rf cavities are derived from the PIP-II proton linear accelerator design [2].

The first type of rf cavity is a 162.5 MHz half-wave resonator with a geometric beta of 0.09. This section of the accelerator increases the proton beam energy from 2.1 MeV to about 31 MeV. The maximum longitudinal electric field on axis in this section is 20 MV/m, corresponding to a maximum

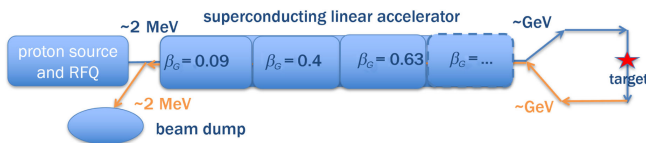


FIG. 1. Schematic layout of an energy recovery proton linear accelerator.

energy gain of about 1.6 MeV per cavity. There are a total of 31 such cavities in this section. The rf design phase is set to -30° for the first cavity. To simplify the design, the rest of the rf cavities in this section use the same input phase as the first cavity.

The second type of rf cavity is a 325 MHz single-spoke resonator with a geometric beta of 0.4. This section contains 34 such cavities, accelerating the proton beam energy from about 31 to about 173 MeV. The maximum longitudinal electric field on axis in this section is 25 MV/m, corresponding to a maximum energy gain of about 5 MeV per cavity. The rf design phase is set to -40° for the first four cavities and -30° for the fifth cavity. The remaining cavities in this section use the same input phase as the fifth cavity.

The third type of superconducting rf cavity is a 650 MHz elliptical five-cell cavity with a geometric beta of 0.63. This section contains 33 cavities, accelerating the proton beam energy from 173 to about 505 MeV. The maximum longitudinal field on axis is 30 MV/m, corresponding to a maximum energy gain of about 12 MeV per cavity. The rf design phase is set to -30° for the first cavity, with the remaining cavities in this section using the same input phase.

To simplify the design of the accelerator, we set the separation distance between two rf cavities within each section to be $\beta\lambda$. This allows the same rf input phase to be used within that section, effectively treating each section as a single large rf cavity. The separation distances between accelerator type sections 1 and 2, and between sections 2 and 3, are adjusted following Eq. (3). This ensures that the same rf cavity phase settings can be used for both acceleration and deceleration.

Figure 2 shows the proton beam kinetic energy evolution as it accelerates from 2.1 MeV to about 0.5 GeV and then decelerates from 0.5 GeV back to 2.1 MeV through the same superconducting linear accelerator with identical rf settings. The figure demonstrates that with appropriate design, the same rf settings can be used for both

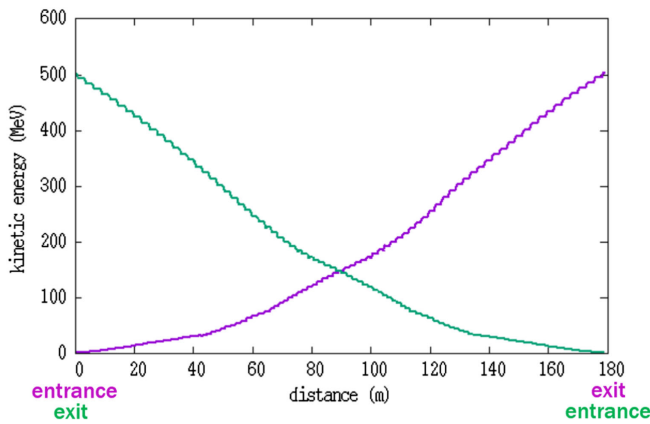


FIG. 2. Proton beam kinetic energy evolution from the superconducting accelerator entrance to the exit for acceleration (magenta) and from the exit to the entrance for deceleration (green).

acceleration and deceleration of the proton beam through the linear accelerator. During the deceleration stage, the proton beam returns its energy to the rf fields inside the superconducting cavities, significantly reducing the rf power needed to operate the linear accelerator.

In this example, we use solenoids for transverse focusing in the first two sections of the superconducting linac since the proton beam energy is relatively low in these sections and solenoid focusing is more effective. In the third section, a quadrupole focusing-drift-defocusing-drift (FODO) lattice is used to provide transverse focusing.

Figure 3 shows the transverse root mean square (rms) size and longitudinal rms bunch length evolution for the forward-accelerating proton beam through the accelerator. Both horizontal and vertical beam sizes stay within several millimeters. The longitudinal bunch length becomes shorter toward higher energy due to acceleration damping and strong focusing. The initial proton beam distribution is assumed to be Gaussian with an initial 0.2 mm mrad transverse emittance and 0.064 deg-MeV longitudinal emittance, similar to the proton beam emittance out of the PIP-II RFQ injector design [2]. Here, the reference frequency

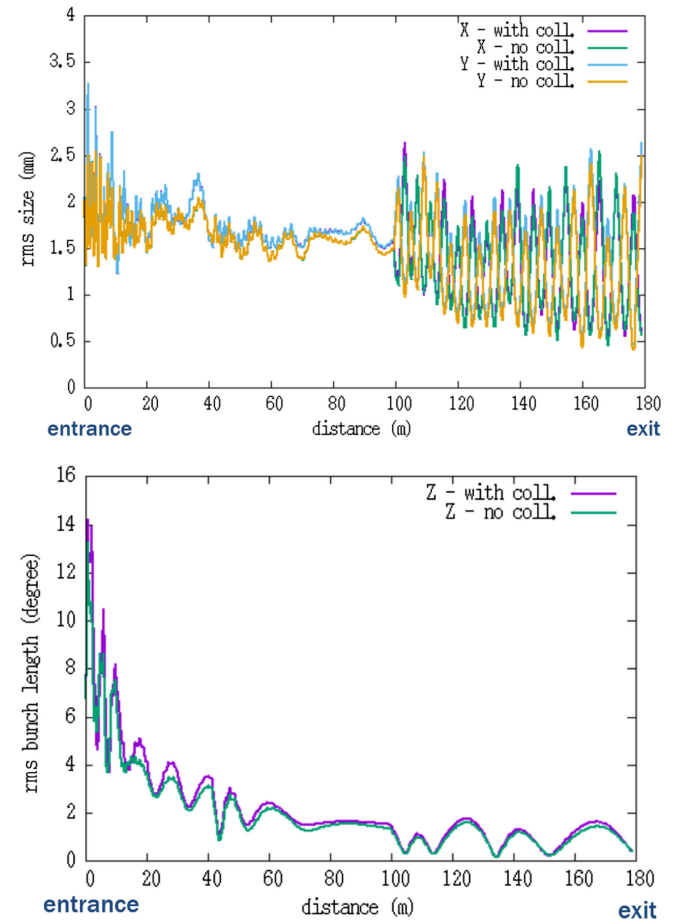


FIG. 3. Proton beam transverse rms size (top) and longitudinal rms bunch length (bottom) evolution during the forward acceleration through the accelerator.

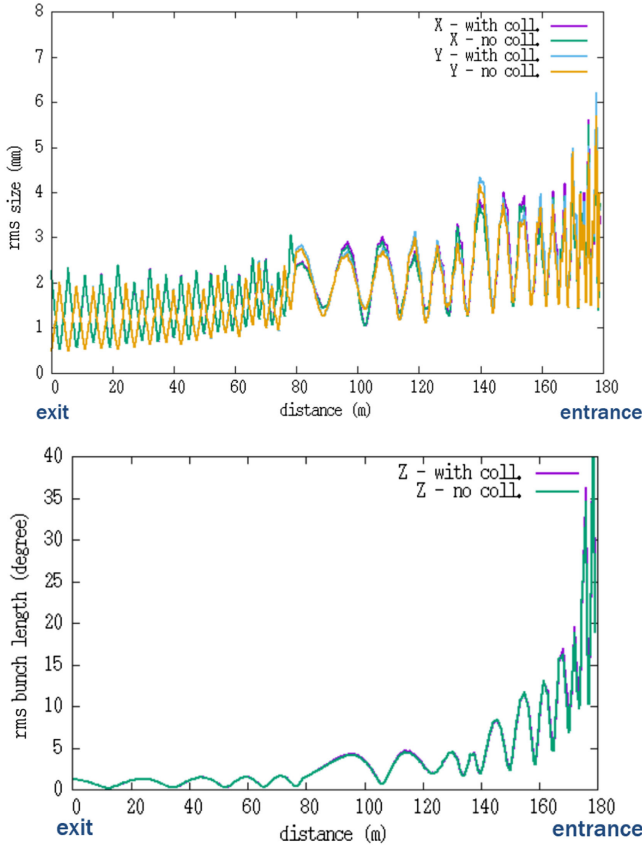


FIG. 4. Proton beam transverse rms size (top) and longitudinal rms bunch length (bottom) evolution during the backward deceleration through the accelerator.

used in the longitudinal emittance and bunch length is 162.5 MHz. The simulation was done using the IMPACT-Z code, a three-dimensional position-dependent parallel particle-in-cell code including self-consistent space-charge effect [26].

Figure 4 shows the transverse rms beam size and longitudinal rms bunch length of the backward-moving proton beam as a function of distance starting from the exit of the accelerator. The backward-moving proton beam maintains reasonable transverse beam size and bunch length except near the entrance of the accelerator where the proton beam energy is low. This issue can be mitigated with collimators or by reoptimizing the focusing lattice around that region.

In the proposed energy recovery proton linear accelerator, the backward-moving proton beam is decelerated and returns its energy to the rf fields inside the superconducting cavity. Meanwhile, a forward-moving proton beam is simultaneously accelerated through the accelerator. The two beams will collide inside the accelerator at a number of locations. The total number of collisions is approximately twice the total time of a single proton bunch passing through the linear accelerator divided by the bunch separation time in a bunch train. The locations of these

collisions can be computed numerically using the reference particle trajectory information of the forward-moving bunch and the backward-moving bunch.

The beam-beam interaction effect between the forward-moving proton beam and the backward-moving proton beam should be checked to ensure that this effect does not substantially blow up either beam. To evaluate this effect, we carried out a self-consistent simulation of two colliding bunches using a parallel time-dependent three-dimensional particle-in-cell code, IMPACT-T [27].

At each collision location, the forward-moving proton bunch and the backward-moving proton bunch are converted from the distribution at a given position into a distribution at a given time. They then drift back to the position so that the heads of both bunches are close to each other. The collision process is then simulated by following the two beams as they cross each other self-consistently. The space-charge forces within the bunch itself and the beam-beam forces from the oppositely moving bunch are computed at each time step using the particle-in-cell method. After the two bunches pass through each other, each bunch drifts back to the collision location and is converted back into the position-dependent particle distribution. Each bunch then continues its acceleration or deceleration inside the accelerator until the next collision occurs, and the simulation of the collision process is repeated.

In the above example, we did not treat the forward-moving proton beam and the backward-moving proton beam simultaneously. Instead, we assumed that one proton beam is already present at the collision locations by simulating that beam through the linear accelerator and storing the beam phase space distribution at those precalculated collision locations. This distribution is then used to evaluate the beam-beam effect on the other proton bunch (either forward moving or backward moving) when the collision occurs.

Figure 3 shows the transverse rms size and longitudinal rms bunch length evolution of the forward-moving proton bunch subject to the beam-beam effect from the backward-moving bunches stored at the collision locations. For comparison, we also plotted these results in the same figure as the rms size and bunch length evolution without the beam-beam effect.

Figure 4 also shows the transverse rms size and longitudinal rms bunch length evolution of the backward-moving proton bunch subject to the beam-beam effect from the forward-moving proton bunches stored at the collision locations. It is seen that the effect from the beam-beam interaction of colliding beams on the rms size and bunch length is small. Compared with the space-charge effect, the interaction time of the two colliding beams is much shorter. This results in smaller effect on proton beam size evolution.

Potential applications. In this study, we propose a novel proton/ion energy recovery linear accelerator concept that

could significantly reduce operational costs in multiple applications. The efficiency of this concept increases with the fraction of the high-energy proton beam that can be sent back to the linear accelerator for energy recovery. For example, in some muon production applications, more than 96% of the high-energy proton beam transmits through the target material [25]. An energy recovery proton linear accelerator would substantially reduce the rf power required during operation, along with its associated costs.

The proton beam energy exiting from the target depends on the thickness of the target material. Protons experiencing large energy loss due to strong interactions with target nuclei will undergo larger deflection and can be collimated through the return loop. However, protons interacting with target material primarily through soft interactions with electrons will not suffer significant energy loss. This portion of the proton beam will be transported back to the linear accelerator for energy recovery.

Conventional electron energy recovery linacs have been proposed for high-energy collider applications [28,29]. Another potential application of the novel proton energy recovery linac is an electron-proton/ion collider or a proton-proton collider, where the consumption of the high-energy proton/ion beam during each collision is minimal. Nearly the entire high-energy proton/ion beam can be sent back to the linear accelerator for energy recovery, drastically reducing the operational costs of such colliders.

Figure 5 shows a schematic plot of a potential electron-ion collider based on the energy recovery electron and proton/ion accelerators. The middle section contains a superconducting proton/ion linear accelerator that consists of multiple types of rf cavity structures for different speeds of ions, an ion source, and a radio frequency quadrupole (RFQ). This accelerator accelerates the proton beam to 20 GeV to attain relativistic speed.

The proton beam exiting from this accelerator is sent upward and passes through a 180° right arc before entering a lower side superconducting linac that consists of a single type of rf cavity. The proton beam gains another 20 GeV kinetic energy after this linac and passes through a 180° left arc, now with 40 GeV proton beam energy.

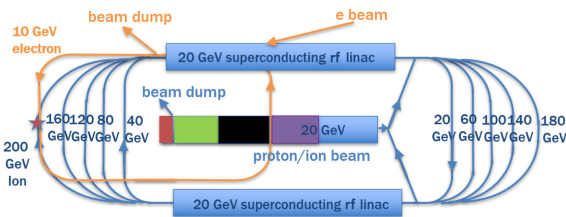


FIG. 5. Schematic plot of a potential electron-ion collider based on energy recovery electron and ion accelerators. Here, different colors in the middle of plot represent multiple rf cavity structures for different speed of proton/ion.

This proton beam is then accelerated in the upper side superconducting linac, which also consists of a single type of rf cavity and attains another 20 GeV gain. After this linac, the proton beam passes through another right arc for 60 GeV beam energy. This process is repeated several times until the proton beam attains 200 GeV energy and is transported to the left arc for collision at the interaction point (IP) with a 10 GeV electron beam from the upper side superconducting linac.

After the collision, the proton beam is sent back to the upper side linac for deceleration to 180 GeV. This proton beam passes through the right arc of 180 GeV and is decelerated by the lower side linac to 160 GeV before entering the left arc of 160 GeV. This process is repeated several times until the proton beam is decelerated to 20 GeV. This beam passes through the 20 GeV right arc and is sent back to the middle energy recovery superconducting linac proposed in this study. The beam is further decelerated in this linac until its kinetic energy is reduced to about 2 MeV before being kicked out to a beam dump.

The 10 GeV electron beam, after collision, is sent back to the upper side linac for deceleration to 2 MeV before being sent to the beam dump. If we assume that both proton beam and electron beam have 1.6 nC charges and 162.5 MHz repetition rate, this results in about 1 MW rf power consumption for the proposed electron-ion collider. This is an order of magnitude less than the rf power usage of the present electron-ion collider under design [30].

The peak luminosity for this energy recovery electron-ion collider can be estimated using a round Gaussian approximation as

$$L = \frac{N_e N_p f}{4\pi\sigma^2}, \quad (4)$$

where N_e and N_p are electron and proton bunch intensities, respectively, f is the repetition rate, and σ is beam rms size. Assuming a final 2 μm normalized emittance for the proton beam at 200 GeV and 10 μm normalized emittance for the electron beam, and 1 mm and 2 cm Twiss beta function values at IP, respectively, this results in a peak luminosity higher than $1.4 \times 10^{34}/\text{cm}^2/\text{s}$.

Using energy recovery electron and ion accelerators for an electron-ion collider avoids the beam-beam limits and other resonances in conventional ring-based colliders. Furthermore, it substantially reduces the consumption of rf power and the resultant operational cost.

Conclusions. In this study, we proposed a new energy recovery proton/ion linear accelerator that extends the energy recovery concept from the electron beam to the proton beam regime.

Due to the special properties of proton linear accelerators, which require multitype rf accelerating cavity structures for different energy acceleration (before attaining

relativistic speed), this proton energy recovery linac requires a different design from the conventional electron energy recovery linac. By appropriately designing the distance between the rf cavities in this accelerator, the same rf input phases can be used for both the forward-accelerating beam and the backward-decelerating beam. The backward-moving proton beam attains the appropriate energy in front of each rf cavity for efficient deceleration and returns its energy back to the rf cavity.

Furthermore, a critical effect in the proton energy recovery linac (not present in conventional electron energy recovery linacs) is the beam-beam interaction between the forward-moving accelerating beam and the backward-moving decelerating beam. In this study, we evaluated this effect through self-consistent simulations in both directions. The simulation results showed that the beam-beam effect will not cause beam blow-up and is relatively small compared with the space-charge effect. The backward-moving proton beam's initial distribution (with similar emittances to those of the exiting forward-moving beam) used in our analysis provides a baseline for assessing the beam-beam effect, even though it does not fully account for interactions with target material. In practice, realistic beam distribution after target interaction may have larger emittance, potentially resulting in weaker beam-beam effects.

In this study, we also presented two potential applications in which energy recovery techniques can enable more cost-effective and sustainable high-energy proton/ion accelerator facilities in the future. Detailed simulation studies including beam-target interactions and machine tolerance for specific applications will be reported in future work.

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Data availability. The data that support the findings of this article are openly available [31].

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