Multiturn circulation of an energy-recovery linac beam in a storage ring

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A light source based on the combination of an energy-recovery linac (ERL) and a storage ring is a feasible scheme for next generation light sources. We propose a system with which a beam of an ERL circulates through two or four turns in a storage ring. The system consists of several deflecting cavities and static deflecting magnets. With this system, the average current of the ring can be two or four times higher than that of the ERL, thus easing the burden on the ERL. Resultant low bunch current can lead to a high quality ERL beam and low average current of the ERL can lead to a multipass scheme.

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I. INTRODUCTION

Light sources based on energy-recovery linacs (ERLs) [1–9] are the likely candidates for next generation light sources and a GeV-scale energy-recovery experiment was successfully carried out at CEBAF [3]. The circulation of a beam of an ERL in an existing storage ring [5–7] provides a feasible approach for this purpose, due to the sustainability of its conventional ring operation, and because it requires minimal modification of the existing ring. We propose a two- and a four-turn circulation system for an ERL beam in a storage ring, which increases the average current of the storage ring two or four times more than the average current of an ERL which is limited by beam breakup instabilities [10–13] or by the performance of electron sources. [14–17]. Also resultant lower bunch current can lead to a beam of higher quality and low average current of ERLs can lead to multipass schemes. The multiturn system also increases the bunch rate by a factor of the increase of the average current. The multiturn circulation system consists of transverse deflection cavities and static magnets, and produces the time dependent transverse deflection required for injection, extraction, and pass through of bunches. Such a deflection cavity has been developed and installed as a crab cavity in the high energy collider, KEKB [18].

Multiturn circulation schemes with fast pulsed kickers are proposed for the ILC damping ring [19,20] or ERL based electron-ion colliders [21–25]. The injection/extraction schemes with such kickers have more freedom of the choice of the number of turns. For the ILC damping ring, the shorter rise/fall time of the kick can lead to more bunch rate in the ring and consequently to less size of the ring and fast kickers are intensively being developed with parameters: a few nanoseconds rise/fall time with corresponding 30 cm kicker length, 3–6 MHz repetition rate with 1 ms duration and less than 1% duty [26–30]. For the multiturn circulation of the ERL beam, the bunch spacing in the ring is subnanoseconds and the required rise/fall time of the kick is also very short. The corresponding kicker length is a few cm, which significantly reduces the kicker efficiency and requires a large number of kickers and/or much high power kicker drive sources. The required duty is 100% with a few tens MHz repetition rate. Such parameters are much more challenging than that for the ILC damping ring. The reduction of the bunch rate in the ring is a way to ease these requirements. However, more bunch current is required to keep average current in the ring and this leads to the degradation of the beam quality in an electron source. On the other hand, our scheme is in the scope of current technologies of rf deflection.

Also several systems manipulate the trajectories in rings bunch-by-bunch and turn-by-turn with deflection cavities. At CTF3 at CERN, deflection cavities with frequency multiplication rings are used to increase bunch rates [31–36], and, at the ILC damping ring, deflection cavities are proposed for devices to manipulate bunch-by-bunch trajectories for injection and extraction [36,37]. However, such systems cannot be applied for the multiturn circulation systems proposed in this paper.

II. TWO-TURN CIRCULATION

First, we discuss the system for two-turn circulation (two-turn system). The required deflection for a two-turn system is

$$\theta(t) = \theta_0 \tfrac{1}{2}(\cos \omega_D t + 1) \tag{1}$$

and is shown in Fig. 1, where θ_0 is the required deflection angle for injection into and extraction from a ring, $\omega_D = 2\pi f_D$ is the angular frequency of a deflection cavity, and f_D is the bunch rate from an ERL. The period of the cavity $T_D = 1/f_D$ and the period of the ring T_0 are adjusted to fulfill the following condition:

$$T_0 = (h \pm \tfrac{1}{2}) T_D, \tag{2}$$

where h is a positive integer. A possible configuration for a two-turn system is shown in Fig. 2, which consists of one deflection cavity with frequency of f_D and two DC magnets. The trajectories of a bunch within the system for different timings of time step $T_D/2$ are shown in Fig. 3.

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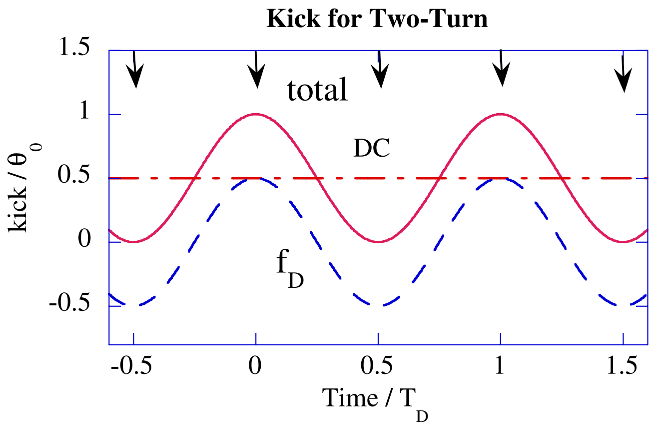

FIG. 1. (Color) Required deflection for two-turn system. Deflection of the system (solid), cavity with frequency of f_D (dashed), and two DC magnets (dot-dashed) are shown. Timing of bunch passages into the system is at every $T_D/2$, indicated by arrows.

The two-turn system works as follows. At the injection of a bunch into the storage ring, the deflection directions of the cavity and the DC magnets are the same and the injected bunch from an ERL is deflected by an angle θ_0 and set on the axis of the storage ring. After the bunch circulates through the first turn of the ring, the phase of the cavity is advanced by 180 degrees and the cavity deflection direction is inverted. The strength of the DC magnets is adjusted to cancel the cavity deflection and the trajectory of the bunch in the system is a chicane. After the second turn, the phase of the cavity returns to that at the injection, and the bunch is extracted from the ring to the ERL. A new bunch from the ERL is simultaneously injected into the ring. This occurs for every bunch from the ERL. Therefore, the bunch rate in the ring is $2f_D$, twice that of the ERL, and the circulating current in the ring is double the current from

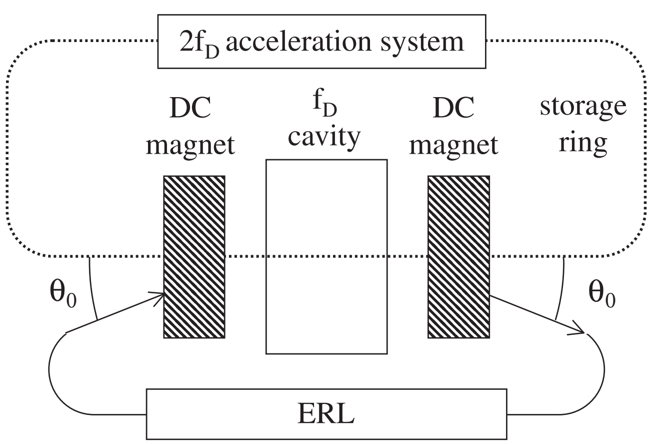

FIG. 2. Possible configuration of two-turn system. Two DC magnets are placed one on either side of deflection cavity (frequency of f_D). Acceleration system (frequency of $2f_D$) in ring compensates radiation loss of beam.

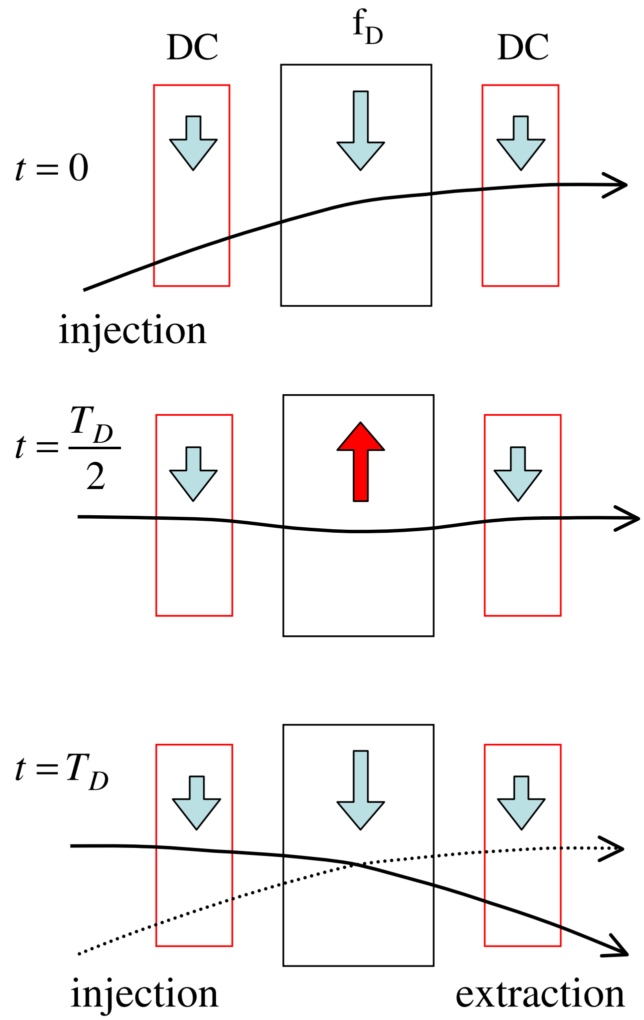

FIG. 3. (Color) Deflection of two-turn system in Fig. 2 at various timings of bunch passages. Arrows indicate deflection directions. At $t = 0$, deflection directions of cavity and DC magnets are the same and bunch from ERL is injected on axis of ring. At $t = T_D/2$ when bunch circulates through the first turn in ring, deflection directions of cavity is opposite to that of DC magnets, and trajectory of bunch is a chicane. At $t = T_D$ as bunch circulates through second turn, deflection is same as $t = 0$ and bunch is extracted from ring to ERL. New bunch is simultaneously injected into ring.

the ERL. The energy lost by the synchrotron radiation during the circulation in the ring is compensated by an rf acceleration system with frequency of $2f_D$.

The time dependence of the cavity deflection increases the angular spread of the bunch. We will estimate this effect. We define τ and τ_0 as the timing shift of the electron from the bunch center and the shift of the bunch center from the maximum or the minimum of the rf deflection force, respectively. If $\omega_D\tau \ll 1$ and $\omega_D\tau_0 \ll 1$, the shift of the deflection is

$$\Delta\theta = \theta_0 \tfrac{1}{2}\omega_D^2(\tau^2 + 2\tau\tau_0). \tag{3}$$

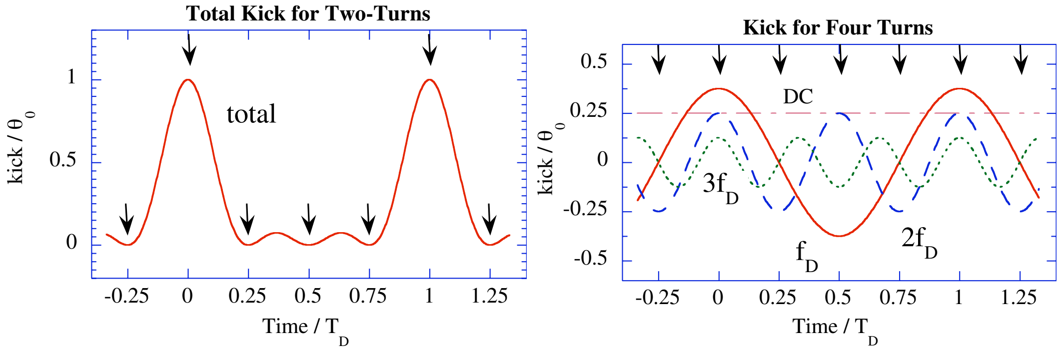

FIG. 4. (Color) Required deflection for four-turn system. Deflection by the system is shown in the left figure. In the right figure, the deflections by cavities of f_D (solid), $2f_D$ (dashed), and $3f_D$ (dotted), and by four DC magnets (dot-dashed), are shown. The timing of bunch passages is at every $T_D/4$, indicated by arrows.

If we assume that the timing distribution of the bunch has a Gaussian shape with a root mean square of σ_τ, we have the root mean square of the spread of the angle, σ_θ, as

$$\sigma_\theta = \theta_0 \omega_D^2 \sigma_\tau^2 \sqrt{\frac{3}{4} + \frac{\tau_0^2}{\sigma_\tau^2}}. \tag{4}$$

III. FOUR-TURN CIRCULATION

This concept can be extended to the system for four-turn circulation (four-turn system). The required deflection for a four-turn system is

$$\theta(\tau) = \theta_0 \tfrac{1}{8}(3\cos\omega_D t + 2\cos 2\omega_D t + \cos 3\omega_D t + 2) \tag{5}$$

and is shown in Fig. 4. The period of the ring is adjusted to

$$T_0 = (h \pm \tfrac{1}{4})T_D. \tag{6}$$

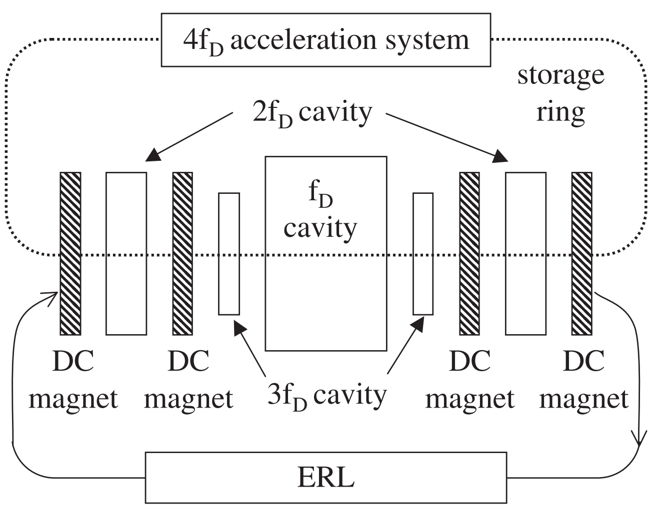

FIG. 5. Possible configuration of four-turn system. System consists of deflection cavities with frequency f_D, $2f_D$, and $3f_D$, and DC magnets.

A possible configuration for a four-turn system is shown in Fig. 5. This consists of one deflection cavity with the frequency of f_D, two second-harmonic deflection cavities of $2f_D$, two third-harmonic deflection cavities of $3f_D$, and four DC magnets. The trajectories of the bunch within the system for different timings of time step $T_D/4$ are shown in Fig. 6.

The four-turn system works as follows. At the injection of a bunch into the storage ring, the deflection directions of the cavities and the magnets are the same, and the bunch is injected on the axis of the storage ring. At the end of the first, second, and third turns, the total deflection is zero, and the trajectories of the bunch in the system are chicanes. After the fourth turn, the phase of the cavities is the same as at the injection, and the bunch is extracted from the ring to the ERL. A new bunch is simultaneously injected into the ring. The energy lost by the synchrotron radiation during the circulation is compensated by an rf acceleration system with frequency of $4f_D$. The third-harmonic deflection is added to cancel the crab motion of bunches induced by $d\theta(t)/dt$ of the deflection of the frequency f_D at $t = (1/4)T_D$ and $(3/4)T_D$. With the third-harmonic deflections, the crab motion of a bunch is also like a chicane as shown in Fig. 7. Note that, without the second-harmonic deflection cavities, the system can operate as a second two-turn system with opposite injection and extraction directions.

As in the two-turn system, the time dependence of the transverse deflection produces the angular spread of the bunch. A comparison between Eq. (1) and Eq. (5) shows that the spread by the four-turn system is several times greater than that by the two-turn system in Eq. (4). Also in this four-turn system, precise timing adjustment between the f_D cavity and the $3f_D$ cavities at $t = (1/4)T_D$ and $(3/4)T_D$ is required to cancel the deflection of the center of the bunch. If the shift of this timing is τ_c, the deflection of the bunch center can be obtained from Eq. (5) as

$$\theta = \theta_0 \tfrac{3}{8} \omega_D \tau_c. \tag{7}$$

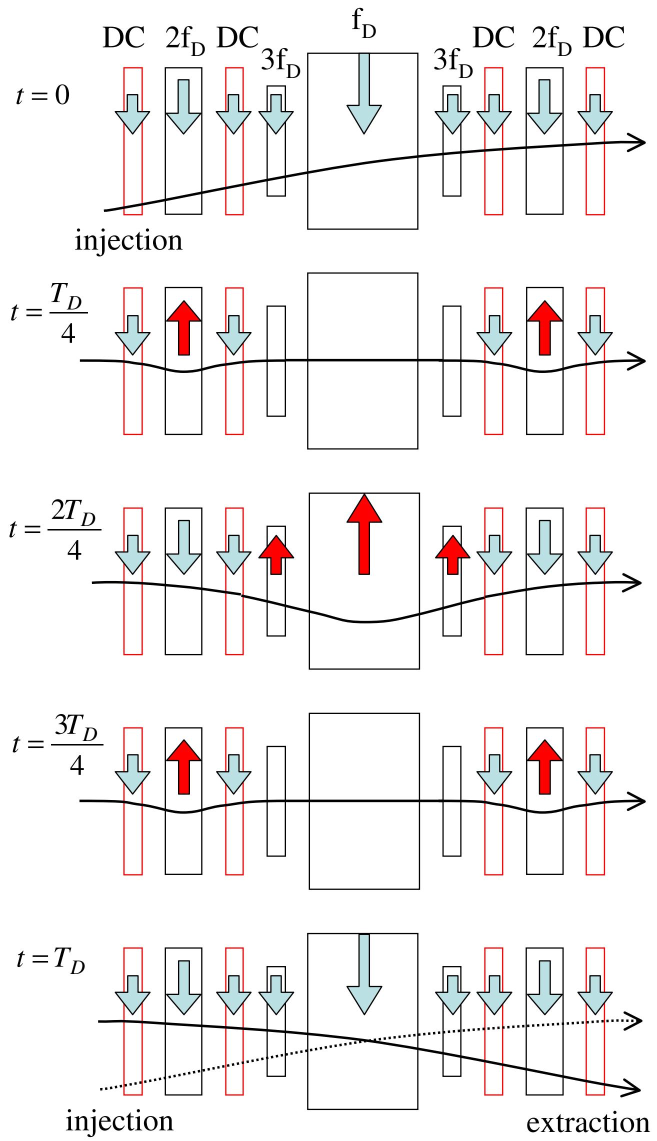

FIG. 6. (Color) Deflection of four-turn system in Fig. 5 at various timings of bunch passages. Arrows indicate direction of deflections. At $t = 0$, the deflection directions of cavities and DC magnets are the same and bunch from ERL is injected into ring. At $t = (1/4)T_D$, $(2/4)T_D$, and $(3/4)T_D$, when bunch circulates through the first, second, and third turns in ring, respectively, total kicks are zero and trajectories of bunch are chicanes. At $t = T_D$, when bunch circulates through the fourth turn, deflection is the same as $t = 0$ and bunch is extracted from ring to ERL. New bunch is simultaneously injected into ring.

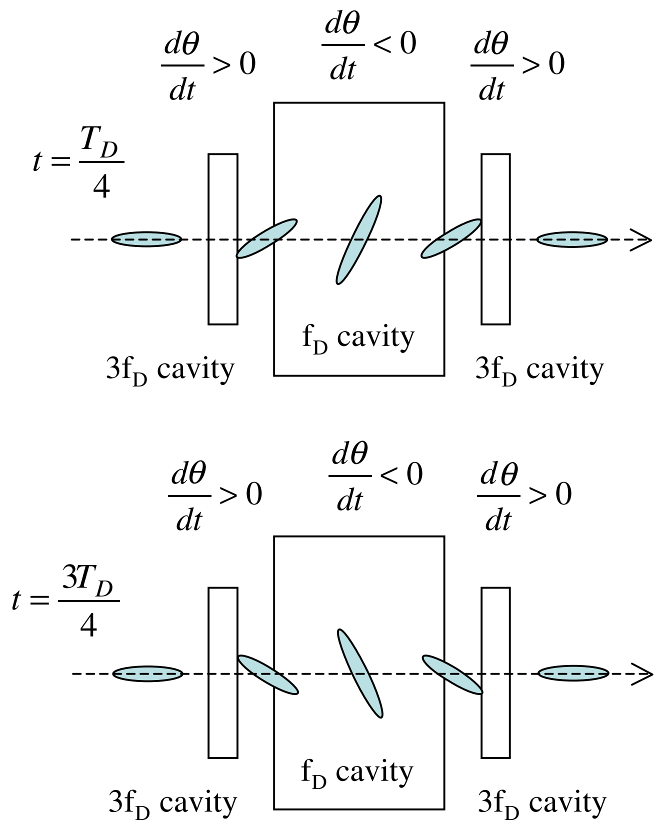

FIG. 7. (Color) Crab motion at cavity with frequency f_D and cavities with $3f_D$ at $t = (1/4)T_D$ and $(3/4)T_D$ in four-turn system shown in Fig. 5. Motion of head and tail of bunch is also like a chicane.

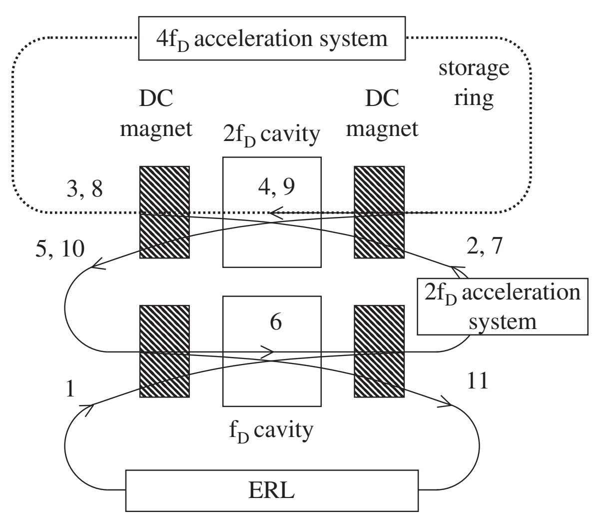

FIG. 8. Four-turn system with the cascading of two two-turn systems with a ring-shaped beam transport. Bunch from ERL is injected to the beam transport (1). Next, bunch is injected to ring (2), circulates twice (3,4), and is extracted from ring to transport (5). Bunch passes through two-turn system in transport without deflection (6) and is injected back into ring (7). Bunch circulates twice through ring (8,9), is extracted to transport (10), and further to ERL (11).

Another four-turn system is a cascading of the two-turn system, as shown in Fig. 8. This system does not use the zero crossing of the rf deflection, thus, does not require a precise timing adjustment between cavities.

The cascaded system works as follows. A two-turn system A with a $2f_D$ cavity is installed in a storage ring. A ring-shaped beam transport with another two-turn system B with a f_D cavity is placed between the storage ring and an ERL. The two-turn system B injects a bunch from the ERL into the beam transport. The injected bunch passes through the transport and is injected into the storage ring by the two-turn system A. After the bunch circulates through the ring twice, it is extracted from the ring to the transport. The extracted bunch passes through the two-turn system B in the transport without the deflection and is again injected into the ring. The bunch circulates through the ring twice and is extracted from the ring to the transport and sent to the ERL. Then each bunch circulates the ring 4 times and the bunch rate in the ring is $4f_D$.

A $4f_D$ rf acceleration system in the storage ring and a $2f_D$ rf acceleration system in the transport compensate the radiation loss. In principle, this cascaded system can extend more stages to obtain more average current.

IV. EXAMPLE IN SPRING-8 STORAGE RING

As an example, we will discuss an application of the system to the 25 m-long straight section of the SPring-8 storage ring [38].

The beam parameters listed in Table I are based on the typical ERL parameters for light sources in low emittance mode operation (high coherence mode) [4–7]. The definitions of the dimensional parameters are shown in Fig. 9.

For a two-turn system, these parameters require a cavity deflection voltage of 4 MV, which is comparable to the current parameters of the crab cavity installed in KEKB (2 MV) [18]. The KEKB crab cavity is 3 m long including a long rf damping port attached longitudinally to the cavity which is required for the high current operation of KEKB. Hence, it should be possible to shorten the length of the cavity for an ERL that has a much lower current than KEKB. The angular spread produced by the two- and four-turn systems with parameters in Table I and with Eq. (4) are listed in Table II with setting $\tau_0 \ll \sigma_\tau$. The spread produced by the two-turn system is sufficiently small compared to the intrinsic angular spread of the ERL beam. However, the four-turn system produces an angular spread comparable to the spread of the ERL beam. From Eq. (4), the angular spread produced by the system can be reduced to an acceptable level by the reduction of the length of the bunch or the bunch rate of the ERL by a factor two as listed also in Table II.

TABLE I. Sample parameters of SPring-8 storage ring based ERL light source with a multiturn circulation system at a long straight section (LSS). The definition of the dimensional parameters is shown in Fig. 9.

Energy	8 GeV
Normalized emittance	0.1 mm rad
Beta function at LSS	25 m
Angular spread of beam at LSS ($\sigma_{x'}$)	0.5 μrad
Bunch length (σ_τ)	2 ps
Length of LSS ($= L_s + 2L_f$)	25 m
Length of the system (L_s)	5 m
Length for injection/extraction (L_f)	10 m
Beam separation for injection/extraction	10 mm
Total kick by system (θ_0)	1 mrad

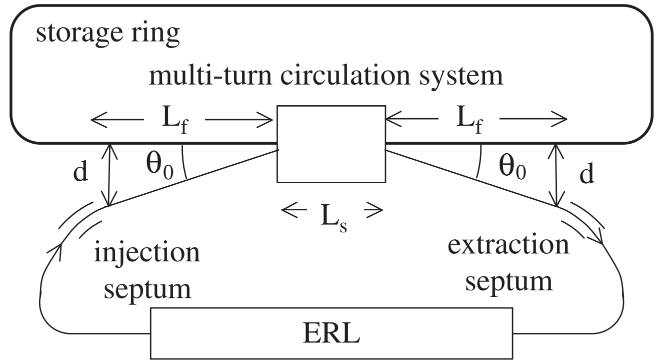

FIG. 9. Configuration of multiturn circulation system in 25 m-long straight section of SPring-8 storage ring. The dimensional parameters in the figure are listed in Table I.

The timing shift between the f_D cavity and the $3f_D$ cavities, τ_c, should be less than 30 fs to suppress the total deflection of the bunch center to the allowable value of 0.1 μrad. This adjustment of the timing shift is very challenging, given the current technologies. For the stability of the amplitude of the cavity deflections or DC magnets, the level of 10^{-4} is required for the orbit stability within the spread of the ERL beam. In the systems, the trajectories of the bunch in the cavities are not the same turn-by-turn, and the effect of this should be analyzed in future work for the practical application of the system. The path length differences of the turn-by-turn trajectories in the systems are the order of $(\frac{\theta_0}{2})^2 L_s \sim 2$ μm and are small enough. Both in the two-turn system or the four-turn system, the injected bunch and extracted bunch collide in the system. However, beam-beam effects is expected to be small because the beam is at high energy and the collision is not head-on and the collision angle is less than one milliradians.

In conclusion, we proposed a system for an ERL beam to circulate two or four turns in a storage ring to increase the average current in the ring. Resultant low bunch current can lead to higher quality ERL beams and low average

TABLE II. Angular spread σ_θ by multiturn circulation system for bunch rates 1.3 and 0.65 GHz and for bunch lengths 2 and 1 ps with parameters in Table I

Bunch rate, length (f_D, σ_τ)	1.3 GHz, 2 ps	0.65 GHz, 2 ps 1.3 GHz, 1 ps
Two-turn system		
First and second turn	0.12 μrad	0.029 μrad
Four-turn system		
First turn	0.58 μrad	0.14 μrad
Second and fourth turn	0.23 μrad	0.058 μrad
Third turn	0.12 μrad	0.029 μrad

current of ERLs can lead to multipass schemes. The effect of the rf deflection on the beam quality is analyzed and, for a sample of the SPring-8 case, the degradation of the beam emittance from the rf deflection of the four-turn system is rather big. However, this can be reduced to the acceptable level by the reduction of the bunch rate of 1.3 GHz or the bunch length of 2 ps by a factor two.

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