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The Concept and Applications of a Dual Energy Storage Ring

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ABSTRACT

A dual energy electron storage ring configuration is initially proposed as an electron cooler to cool the ion beam in a collider. It consists of two energy loops, the electron beam in the high energy loop undergoes the synchrotron radiation damping to obtain the desired beam property and the beam in the low energy loop is for cooling of the ion beam. The two different energy loops are connected by an energy recovery linac. A lattice design of such a dual energy storage ring has been completed and beam stability conditions are established. We performed numerical simulations to demonstrate the beam qualities and evaluated the cooling performance. In this paper, we present the study results and discuss possible applications of such a concept in many physics research and medical fields.

KEYWORDS
Dual energy, energy recovery, damping, cooling

1. INTRODUCTION

The concept of an accelerator with different energies was initiated in the ref [1], as shown in Fig. 1. Such a design consists of two loops with significantly different energies: the low energy loop and the high energy loop. As the common beamline, an Energy Recovery Linac (ERL) accelerates the beam from the low energy E_L to the high energy E_H and then decelerates the beam from E_H to E_L in the subsequent pass [1]. Hence, this is a new type of accelerator configuration called an energy recovered loop accelerator where an ERL structure is a sandwich between two loops.

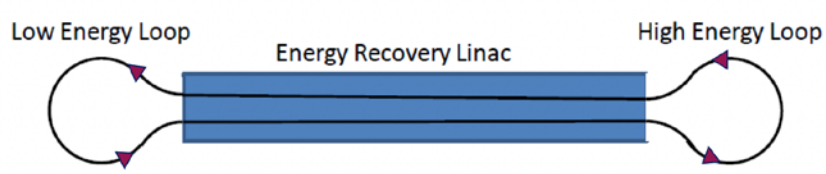

Figure 1. The configuration of an energy recovered loop accelerators.

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2. A Dual Energy Storage Ring and its Possible Applications

We propose a dual energy storage ring, schematically shown in Fig. 2. Unlike the energy recovered loop accelerator where two beams propagate in opposite directions in the ERL, the beams in the dual energy storage ring move along the same direction in the ERL. Such a configuration has various applications in physics and medical sciences. We have thoroughly studied its cooling application where electron beams undergoing the natural synchrotron radiation damping at the high energy can be utilized to cool the ion beams at the low energy [2]. In addition, such a concept may have other potential applications that needs to be explored. Here, our study mainly focuses on a dual energy storage ring electron cooler for hadron beam cooling in a collider. The details on the design concept, beam dynamics study along with the cooling performance has been carried out in such a dual energy storage ring cooler. In the last two sections, we briefly discuss two possible applications to produce a dual-color Compton light source and detect electric dipole moments based on this dual energy storage ring concept.

2.1. Dual Energy Storage Ring Electron Cooler

The emittance growth in hadron beams due to intra-beam scattering (IBS) and all heating effects would deteriorate the luminosity in a collider. A strong hadron beam cooling is required to preserve, and reduce if applicable, the beam emittance. We propose a dual energy storage-ring-based electron cooler that uses electron beam to extract heat away from hadron beam in the low energy cooling section while electron beam to be cooled by the synchrotron radiation in the high energy damping section [3]. The cooling and damping sections are connected by the Superconducting Radio-Frequency (SRF) structure. The schematic drawing and a preliminary optics design of such a cooler is shown in Fig. 2.

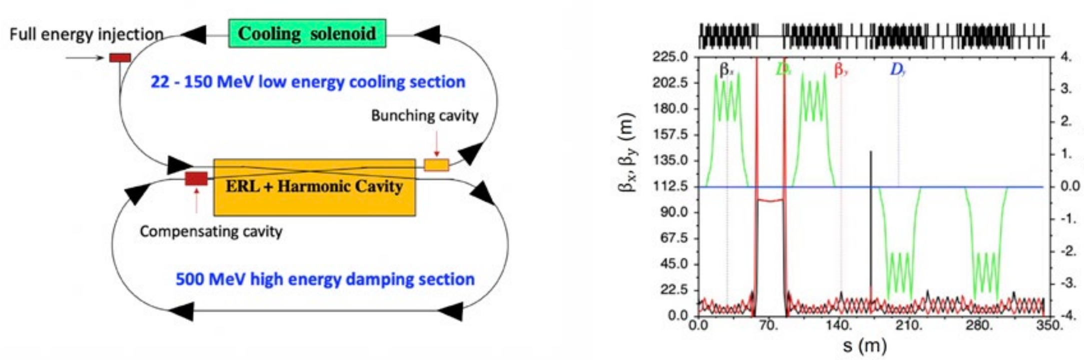

Figure 2. Schematic Drawing (Left) and Preliminary Optics Design (Right) of a Dual Energy Storage Ring Cooler.

The SRF system in common beamline consists of ERL and harmonic cavity. ERL is the main cavity running on the crest that accelerates the electron beam from low energy E_L to high energy E_H. During the decelerating pass going from E_H to E_L, the main cavity runs 180^0 from the crest. When the main cavity runs at crest during the beam acceleration, the harmonic cavity next to the main cavity runs with a decelerating phase. And when the main cavity runs 180^0 from the crest during beam deceleration, the harmonic cavity runs with an accelerating phase. Hence, the total voltage gain during the acceleration is exactly cancelled by the total voltage loss during the deceleration. To provide the longitudinal focusing on the system, a bunching cavity running at a zero-crossing phase outside the common beamline is used that provides the necessary longitudinal focusing for the system. Harmonic cavity among the main cavity extends the RMS bunch length up to the several centimeters to provide enough cooling of the ion beam. A compensating cavity is used to compensate the energy loss due to the synchrotron radiation [4,5]. All these cavities are superconducting elliptical shape cavities which run at low temperature environment. ERL may have numbers of similar elliptical cavities to form a single cryomodule. Each cavity in this cryomodule is supplied with the proper rf phase and voltage to accelerate or decelerate the electron beam. Twiss parameters and the dispersion functions of the preliminary optics are plotted along the beam line, shown in Fig. 2. The cooling channel length in this preliminary optics is about 40.0 m but it can be extended if needed. Beam dynamics studies have been carried out both analytically and in simulations. Single and many particles tracking simulations are performed using the code ELEGANT [6]. They verify the beam stability in a dual energy storage ring system.

2.1.1. Dynamic aperture, momentum aperture and Touschek lifetime

We have studied the Dynamic Aperture (DA) and Momentum Aperture (MA) in a dual energy storage ring using numerically intensive procedures in ELEGANT. The dynamic or physical aperture is defined as the largest betatron oscillation amplitude which is still stable in the presence of non-linear fields in a storage ring [7]. The top side of Fig. 3 shows the maximum DA possible which is $\pm 10\sigma_x$ in the horizontal plane and $40\sigma_y$ in the vertical plane. Here σ_x and σ_y are the root mean square beam sizes in two planes, respectively.

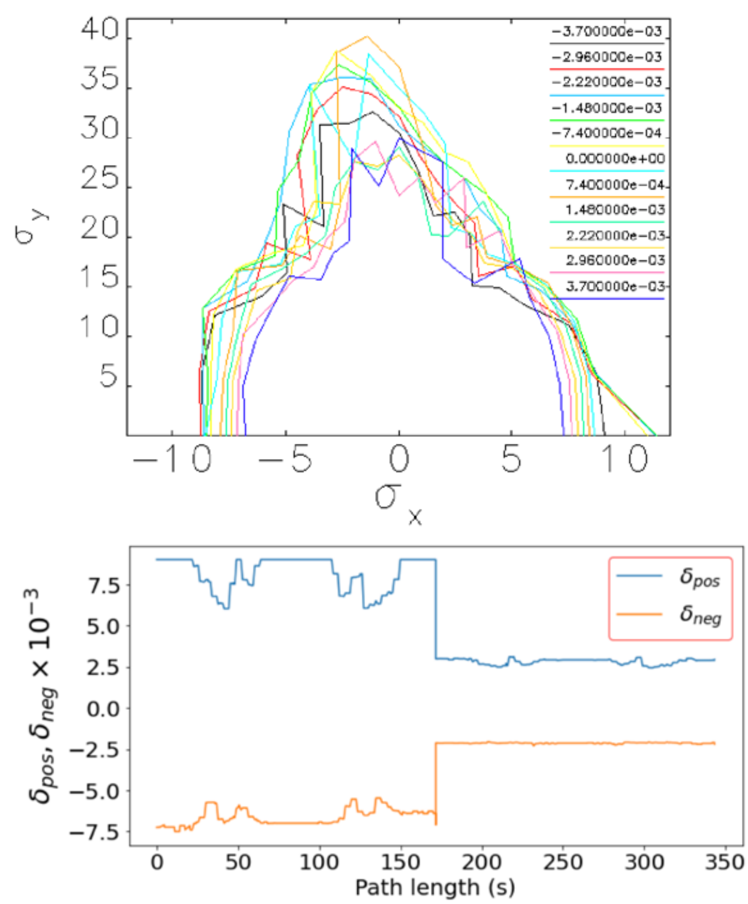

Figure 3. Dynamic Aperture (Top) and Momentum Aperture (Bottom) in a Dual Energy Storage Ring Cooler.

The momentum aperture is defined as the maximum momentum deviation that a particle can have without becoming unstable and being lost by colliding with the vacuum chamber of the storage ring [8]. The MA search using ELEGANT is carried out starting at the beginning of the low energy loop and going to the end of the high energy loop, shown on the right plot of Fig. 3. We can see that the momentum acceptance in the low energy loop is larger than that in the high energy loop. The reduction of MA in the high energy loop is due to the adiabatic damping of beam phase-space through the RF acceleration from the low energy loop [9], with the ratio of two energies [10].

Touschek scattering is a phenomenon describing the collision of two electrons in a bunch with transferring a small momentum in the transverse direction into a large momentum in the longitudinal direction, leading the loss of particles. Based on the MA of the ring, Touschek lifetime is calculated both analytically and in simulations using ELEGANT. The results are presented in Table I. Details on the analytical calculation of the Touschek lifetime in a dual energy storage ring is discussed in the ref [5].

Table I. Touschek lifetime in a dual energy storage ring

Method	Touschek lifetime τ (h)		
	τ (Low Energy at 150 MeV)	τ (High Energy at 500 MeV)	τ (Total)
ELEGANT	0.67	0.43	0.42
Formula	0.68	0.34	0.34

Table I shows Touschek lifetimes in a dual energy storage ring for the low energy loop at 150 MeV and the high energy loop at 500 MeV. The lifetime values, obtained from the analytical calculations and simulations, agree well. Further exploration on increasing the momentum acceptance to extend the Touschek lifetime is in progress.

2.1.2. Damped equilibrium emittance and energy spread

Synchrotron radiation in an electron storage ring damps the electron beam towards an equilibrium in all three degrees of freedom. The equilibrium emittance and energy spread in a dual energy electron storage ring are simply a balance between radiation damping and quantum excitation. Calculations show that these equilibrium parameters tend to be dominated by the radiation in the high energy loop. The analytical formulas to calculate the damped equilibrium emittance in a dual energy storage ring is given by

$$\epsilon_x = \frac{C_q}{\hat{\gamma}} \frac{\left(\gamma_H^6 \left\langle \frac{\mathcal{H}_x^H}{\rho_H^3} \right\rangle + \gamma_L^6 \left\langle \frac{\mathcal{H}_x^L}{\rho_L^3} \right\rangle\right)}{\left[\left((1-\xi_x^H)\gamma_H^3 \left\langle \frac{1}{\rho_H^2} \right\rangle + (1-\xi_x^L)\gamma_L^3 \left\langle \frac{1}{\rho_L^2} \right\rangle\right)\right]} \tag{1}$$

In the same way, the damped equilibrium energy spread is calculated using the formula given by

$$\frac{\sigma_E^2}{E^2} = \frac{\left(\gamma_H^7 \left\langle \frac{1}{\rho_H^3} \right\rangle + \gamma_L^7 \left\langle \frac{1}{\rho_L^3} \right\rangle\right)}{\left[\left((2+\xi_H)\gamma_H^3 \left\langle \frac{1}{\rho_H^2} \right\rangle + (2+\xi_L)\gamma_L^3 \left\langle \frac{1}{\rho_L^2} \right\rangle\right)\right]} \tag{2}$$

Here, damped equilibrium parameters have the contribution from both the low energy and the high energy loops. Details in the derivation of Eq. (1) and Eq. (2) are discussed in the ref [5]. Damped equilibrium parameters obtained from analytical calculations and tracking simulations are summarized in Table II.

Table II: Equilibrium emittance and energy spread in a dual energy storage ring

Parameter	Low Energy Section		High Energy Section	
	Analytical	Tracking	Analytical	Tracking
ϵ_x (μm)	18.20	19.90	2.73	2.55
Difference (%)	9.83		6.59	
$\frac{\sigma_E}{E}$ (10^{-3})	3.03	3.28	0.454	0.509
Difference (%)	8.25		12.11	

Calculations and simulations are done with the beam energies of 150 MeV in the low energy section and 1000 MeV in the high energy section. Overall, the results show a good agreement with 100 particles being used to extract the damped parameters. The discrepancy between the analytical calculation and tracking simulation is expected to be further reduced with more particles. Electron beam energy of 1000 MeV in the high energy section is used to save the simulation time for a fast-damping effect. These estimated parameters are in the absence of all the effects besides quantum excitation that would increase the electron beam emittance.

2.1.3. Cooling performance

Electron cooling [11] is a powerful method to preserve and/or reduce the transverse size and momentum spread of the stored hadron beams in a collider. We estimate the cooling performance using the code JSPEC [12]. In these simulation, electron beam energy of 150 MeV is used to cool the proton beam at 275 GeV. The proton beam parameters are taken from [13]. Table III shows the cooling electron beam and cooled ion beam parameters. Cooling times in all three dimensions are shorter than the proton intra-beam scattering (IBS) times. This promising result suggests that the dual energy storage ring cooler may be one of the possible cooler designs to cool the relativistic ion beam.

Table III: Cooling electron beam and cooled proton beam parameters

Parameter	Unit	Electron	Proton
Energy	MeV	150	275,000
Bunch intensity	10^{10}	6.9	6.9
Bunch charge	nC	11.1	11.1
RMS bunch length	cm	2.5	6.0
Normalized emittance h/v	µm	670/108	2.8/0.45
Energy spread	10^{-4}	6.9	6.8
IBS times h/v/l	s	5/12328/0.44	-
Damping times h/v/l	s	3.2/0.69/0.25	-

Cooler channel length	m	120.0	
Cooler channel magnetic field	T	2.0	
IBS times h/v/l	h	-	2.3/283/4.0
Cooling times h/v/l	h	-	2.2/26/0.4

*h/v/l stands for horizontal, vertical, and longitudinal dimensions.

Table III shows the cooling performance with the given proton and electron beam parameters. The cooling channel length is taken to be 120.0 m in simulation. Cooling times in all three dimensions are shorter than the proton IBS times. It means, 275 GeV proton beam can be cooled using 150 MeV electron beam within the given cooling time presented in Table III. This promising result suggests that the dual energy storage ring cooler may be one of the possible cooler designs to cool the relativistic ion beam.

2.2. Dual-Color Compton Light Source

When a relativistic electron beam interacts with a high-field laser beam, intense and highly collimated electromagnetic radiation will be generated through Compton scattering. This results a highly energetic polarized photons along the electron beam motion [14]. Because of such an intense radiation produced with desirable properties, there are many Compton light source facilities around the world.

We propose a new design concept of Compton light source based on a dual energy storage ring. The schematic drawing of a dual-color Compton light source is shown in Fig 4. In this design concept, ERL is used to accelerate and decelerate the beam at two different energies: E_L for the low energy loop and E_H for the high energy loop respectively. Fixed Field Alternating gradient (FFA) optics is used to design the arc since FFA has some advantages over simple arc design [15]. Due to different beam rigidity, low energy electron beam bends more and moves along the path indicated by blue solid line whereas high energy electron beam bends less and moves along the path indicated by black solid line.

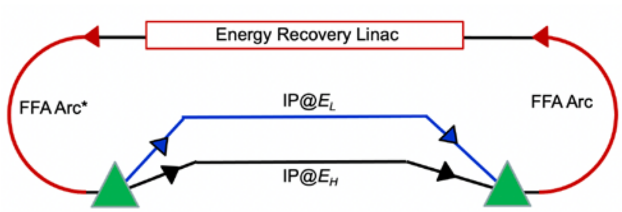

Figure 4. Schematic Drawing of a Dual-Color Compton Light Source

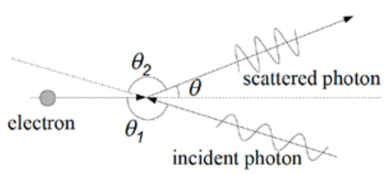

Figure 5. Schematic Drawing of a Dual-Color Compton Light Source [16].

A high-power laser incident at Interaction Point (IP) interacts with an electron beam and undergoes Compton scattering. As a results, high energy X-rays radiation is produced. The theory of Compton scattering of a laser photon by a relativistic electron is discussed in [16]. The great advantage of this type of dual-color Compton light source design is it can provide two lasers with different photon energies for one experiment. For 500 MeV electron beam energy and 800 nm incident photon beam wavelength, the expected energy of the scattered photon beams is about few MeV. The total number of photons can be obtained by computing the area under the spectra curve as explained in the ref [17]. The tentative number of photons per collision is about 10^4 and the number of photons per second is obtained by multiplying this number by the frequency of collision. Then roughly the number of photons per second becomes 10^{14}.

2.3. Dual Energy Storage Ring for Electric Dipole Moment (EDM) Search

A two-energy storage ring design can be used to perform experiments to measure the permanent Electric Dipole Moment (EDM) of the electron relevant to CP violation and matter-antimatter asymmetry in the universe, and to search for dark energy and ultra-light dark matter. The simplest layout design of a ring for measuring the electron EDM is presented in Fig. 6 [18].

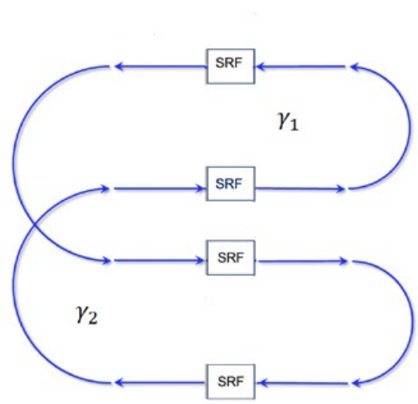

Figure 6. Layout of a Dual Energy Storage Ring for Measuring the Electron Electric Dipole Moment.

A dual energy storage ring in Fig. 6 is configured in the figure-8 spin transparency mode such that the net bend at each of the energies is zero. This eliminates the spin presession due to the Magnetic Dipole Moment (MDM). SRF cavities are used to accelerate and decelerate the electron beam going from the low energy ring to the high energy ring and vice-versa. The beam directions in the two arcs of each energy are opposite to one another, making the net bending angle zero. This principle is equally applicable to hadron beams. However, while for electrons electrostatic acceleration and deceleration may be sufficient, hadron beams require larger energy difference that cannot be provided by an electrostatic field. Such a large energy difference may be achieved using Energy Recovering Linacs (ERLs).

The optics design of such a ring system to measure the EDM must provide a high efficiency in terms of the EDM spin rotation rate, a long spin coherence time, adequate momentum acceptance and dynamic aperture, low emittance growth rates due to Intra-Beam Scattering (IBS), and an acceptable stored beam size. Since there is a change in the bending direction between the adjacent arcs, each arc must be achromatic.

The dispersion can be suppressed in each arc by varying the bending direction within the arc while keeping its net bend fixed at 180^0. This allows for achromatic weak-focusing arc design with constant horizontal and vertical focusing strengths [19]. A conventional Mott polarimeter can be used to measure the electron beam polarization in the energy range from a few keV to a few MeV. The principle of Mott polarimetry and the experimental procedure to measure the electron EDM are discussed in [20]. The SRF structure in this design have time-varying magnetic fields accompanying the oscillating electric fields. The effect of these magnetic fields on the spin requires further study.

3. CONCLUSIONS

In this paper, we present a feasibility and applicability of a dual energy storage ring cooler to cool the hadron beams in future colliders. The linear optics has been designed, and a stability study is carried out analytically and in simulation. The electron beam parameters in such a cooler are calculated and based on calculated electron beam parameters, the cooling performance on the proton beam at 275 GeV is simulated using JSPEC simulation code. The cooling performance shows that this type of ring-based electron cooler provides a feasible path for cooling of ion beams in a collider, for example Electron-Ion Collider (EIC). We also briefly discussed two applications, namely, dual-color Compton light source and facility for detecting electric dipole moment based on a dual energy storage ring. These applications are very interesting and carry a huge potential in physics and medical research.

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