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POSITRON AND DAMPING RING REQUIREMENTS FOR FUTURE e^+e^- COLLIDERS*

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Abstract

Future e^+e^- colliders will need positron sources that stretch present technical capabilities. The project teams for these proposed colliders are working to extend these capabilities. A positron source encompasses many elements: an electron driver, production target, lattice optics, capture section, damping ring(s), injection/extraction short-pulse kickers, an emittance preserving complex delivery system, specific injection specifications, and (perhaps) polarization. The required technical parameters need to accommodate many beam aspects including bunch intensities, final emittances, spacings, train lengths, and desired damping times. For this note, the technical requirements for positrons related to bunch charges, number of bunches, damping ring (DR) lengths and damping times for the various positron sources for the presently proposed colliders are compared, concentrating on their DR specifications.

INTRODUCTION

An Implementation Task Force (ITF) [1] was started as a part of the Snowmass-2022 exercise that looked at the proposed future colliders. As a part of the ITF studies, positron production, accumulation, storage, and damping were briefly investigated as an important aspect of the design of the various colliders. Although positrons were not a specific part of the charge of the ITF, positron production issues entered many of the designs in a major manner. In this note some positron aspects and parameters are discussed for producing and delivering trains of positron bunches for future colliders relative to the damping rings.

ELECTRON-POSITRON COLLIDERS

The positron damping rings (DR) for fifteen e^+e^- colliders are reviewed. Four of these for past or present colliders are discussed first and, then, eleven are discussed from proposed future colliders ranging from rings to linear colliders. A brief description is given for each collider and then the technical parameters of their positron DR systems are discussed.

Over the course of the two-year Snowmass-2022 process, many of the proposed colliders changed parameters such as repetition rates, bunch charges, number of bunches, and machine lengths. The well-established proposed colliders changed only a little (e.g. ILC, FCCee, and CEPC) but some of the lesser developed changed greatly (e.g. plasma wakes, structure wakes, energy recovery proposals). Below are brief collider descriptions

The SLC [2] was a collider at SLAC operating at the Z using the SLAC copper “two mile” linac colliding single e^+ and e^- bunches.

The LEP ring collider [3] at CERN operated at the Z and higher while colliding 4 to 8 bunches.

The PEP-II ring collider [4] at SLAC operated with two rings of different energies at the Upsilon energy colliding 1732 bunches in each ring.

The present SuperKEKB collider [5] at KEK operates with two rings of different energies at the Upsilon energy colliding 2151 bunches in each ring.

The proposed FCCee ring collider [6] would use a new tunnel near CERN with two rings with energies up to ttbar colliding about 10,000 bunches in each ring.

The proposed CEPC ring collider [7] would use a new tunnel in China with two rings with energies upgradable to ttbar colliding up to 12,000 bunches in each ring.

The proposed ILC collider [8] would be a pulsed SC linac in Japan that would collide trains up to 1312 bunches per pulse initially at the Higgs energy.

The proposed CLIC collider [9] would be a pulsed, two-beam copper linac near CERN colliding trains of up to 352 bunches per pulse.

The proposed cold copper collider C3 [10] would be a pulsed cold copper linac colliding bunch trains up to 133 bunches per pulse.

The proposed circular energy recovery collider CERC [11] would use a 100 km circular tunnel to ramp up and down the two beams in energy over several turns recovering the beam energy in SC RF linacs and collision particles in damping rings with top-up injection.

The proposed energy recovery linear collider ERLC [12] would be two CW SC linacs with energy and particle recovery while operating with continuous bunches with top-up injection.

The proposed recycling linear collider ReLiC [13] would be a CW SC linac energy recovery linac operating with nearly continuous bunch trains with beam energy recovery in the linacs and particles recovery in damping rings.

The proposed plasma wake PWFA-LC [14] would be a pulsed beam-driven plasma linac, colliding single e^+ and e^- bunches up to 10,000 Hz.

The proposed laser-driven plasma wake LWFA-LC [15] would be a pulsed linac, colliding single e^+ and e^- bunches up to 50,000 Hz.

The proposed structure wake SWFA-LC [16] would be a pulsed two-beam-driven linac colliding trains of e^+ and e^- bunches.

POSITRON DAMPING RINGS

The colliders described above all need damping rings to reduce the emittances of the positron bunches either generated from scratch or being recycled after collisions and to accommodate the needed bunch spacing and trains. In Table 1 are listed the colliders, the respective DR energies, and required modes of operation. The DR energies were

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chosen to fulfil the requirements of low beam emittances for collisions and the requisite number of bunches in each bunch train. In the ITF studies some of the above proposed pulsed colliders did not specify a DR system, neither its energy nor length. In those cases a DR energy of 3 GeV was chosen to complete our studies matching closely those of the CLIC DR parameters which was determined to technically work for them.

In Table 1 past, present, and proposed e^+e^- colliders are listed, showing the DR energy for the respective (most demanding) cases and the mode of operation [top-up (TU) or single use (SU, i.e. using the positrons once)], from low to high DR energies. From the Table is clear there is a strong trade-off between shorter damping times at higher energies but at the cost of higher equilibrium emittances.

Table 1: Past, Present, and Proposed e^+e^- Colliders

Collider	**Collider Energy CM [GeV]**	**DR Energy [GeV]**	**Operation mode**
SLC	98	1.21	SU
LEP	209	0.6	TU
PEP-II	3.5x9	1.21	TU
SuperKEKB	4x7	1.1	TU
Proposed:			
FCCee	91	1.54	TU
CEPC	91	1.1	TU
ILC	250	5	SU
CLIC	250	2.86	SU
C3	250	3	SU
CERC	240	8	TU
ERLC	250	5	TU
ReLiC	250	3	TU
PWFA-LC	1000	3	SU
LWFA-LC	1000	3	SU
SWFA-LC	1000	3	SU

POSITRON DAMPING RINGS

For a given collider the positron generation system must produce the needed number of positrons and bunches each second. The damping rings system must provide adequate damping to reduce the emittances. The DR length and lattice provide the needed space for the bunches and damping/storage time.

In Table 2 the designed DR bunch spacing, the damping time, and the number of damping time needed are listed for the DRs of past, present, and proposed e^+e^- Colliders.

The damping times for top-up injection colliders tend to be much longer than single use colliders as the injection rates are reduced. Furthermore, the particle recycling colliders have damping rings that need shorter storage times to allow the recycled bunches to be collided more often.

Table 2: DR properties for Past, Present, and Proposed e^+e^- Colliders

Collider Damping Ring for	**DR Bunch spacing (m)**	**Damping time (msec)**	**N. damping times stored**
SLC	17.6	3.1	5.5
LEP	15.7	34	330
PEP-II	17.6	3.1	5.5
SuperKEKB	28.8	10.9	3.7
Proposed:			
FCCee	15	11.6	3.8
CEPC	18.4	11.4	3.6
ILC	1.85	23.9	8.3
CLIC	0.5	2.0	10
C3	1.6	2	10
CERC	2.6	2	2
ERLC	~2	2	2
ReLiC	1.0	4	2
PWFA-LC	1.6	2	10
LWFA-LC	1.6	2	10
SWFA-LC	1.6	2	10

STORED BUNCHES AND TRAINS

Some of the future colliders need single injected positron bunches and some need trains of bunches. In Table 3 are listed DR requirements for bunch trains and number of bunches per train for the past, present and future colliders, showing the number of stored bunch trains, number of bunches per train, and the total number of bunches stored at any instant.

The requirements for the DRs are many: short damping times, number of damping times needed, number of bunch trains stored, bunches per train, and the appropriate beam energy. The cost of a DR include power components and length components. The cost components include the pulse rate, drive energy, drive beam particles, radiation losses per turn, and cooling systems. The length components include the usual elements: magnets, vacuum systems, RF cavities, tunnel, controls, and alignment. Each collider therefore has a unique set of requirements.

The plasma colliders need single bunches but many each second leading to large circumference damping rings. The pulsed SC linacs (e.g. ILC) need a few bunch trains per second but many bunches in one bunch train leading to lengthy damping rings. Top-up injection rings (e.g. FCCee and CEPC) need a steady source of positrons but at a relatively low charge per bunch so the DRs can be smaller. The particle recycling colliders (e.g. CERC, ReLiC) need a large DR circumference to store many bunches needing to be damped briefly for a few damping times before reuse.

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Table 3: DR Stored Bunch Properties for Past, Present, and Proposed e^+e^- Colliders

Collider Damping Ring for	N. stored bunch trains	N. bunches per train	Total n. stored bunches at once
SLC	2	1	2
LEP	8	1	8
PEP-II	2	1	2
SuperKEKB	2	2	4
Proposed:			
FCCee	8	2	16
CEPC	4	2	8
ILC	1	1312	1312
CLIC	1	312	312
C3	3	133	133
CERC	1	264	264
ERLC	100	1	100
ReLiC	600	20	12000
PWFA-LC	300	1	300
LWFA-LC	940	1	940
SWFA-LC	20	231	4620

DAMPING RING LENGTH

The needed minimum length L of a DR involves many technical factors and is given by:

$$L = Sb * Nsb = Sb * Nbt * Nbpt \tag{1}$$

Sb is the bunch-to-bunch separation in the DR. Nsb is the number of stored bunches. Nbt is the number of stored bunch trains. Nbpt is the number of bunches per train. The variables in play are the damping time without wigglers (e.g. SLC), wiggler based DRs (e.g. ILC, CLIC), and tunnel costs. The calculated minimum DR length does not include needed space for other functions including gaps for injection, abort kickers, ion reduction, or electron-cloud dissipation. In Table 4 are listed the positrons per bunch, needed bunch trains per second, and the derived (or actual) required DR circumference for the future colliders.

In Table 4, the positron DR of past, present, and proposed e^+e^- colliders are listed showing the number of positron per bunch, number of trains per second, and the required positron DR circumference. The resulting DRs have very difference sizes. The SLC DR is the shortest at 35 m as it stores only 2 bunches and provides a very short damping time. Long train DRs (e.g. ILC) have long lengths due to storing many bunches in a train and supporting multiple trains. Single bunch colliders with very high rates (e.g. LWFA-LC, SWFA-LC, and PWFA-LC) need large damping rings to allow many bunches to damp simultaneously.

Table 4: Number of Positron per Bunch, Number of Trains per Second, Required Positron DR Circumference

Collider DR for	DR n. positrons per bunch ($\times10^{10}$)	Bunch trains per second	DR length (m)
SLC	5	120	35.3
LEP	2.5	0.09	126
PEP-II	0.9	30	35.3
SuperKEKB	4.1	50	135.5
Proposed:			
FCCee	2.2	200	242
CEPC	4.4	200	147
ILC	2	5	3200
CLIC	0.43	50	428
C3	0.63	120	650
CERC	8.1	800	1000
ERLC	0.1	5300	300
ReLiC	1.0	2200	4000
PWFA-LC	1.0	15000	500
LWFA-LC	0.12	47000	1550
SWFA-LC	0.31	5	7500

POSITRON PRODUCTION RATES

The number of positrons that need to be produced each second is a very important number since the hardware production cost is strongly correlated with this rate.

Given Tables 1 through 4, the number of positrons that need to be produced per second can be calculated. In Table 5 are listed the number of colliding bunches that need filling, the proposed injection rate, and the total number of positrons that must be produced per second.

From Table 5 several conclusions can be seen. The SLC had the highest production rate of positrons to date. Top-up injection into storage ring colliders (e.g. FCCee, CEPC, CERC, ReLiC) is the easiest from the rate perspective. The single-use high-rate colliders (e.g. ILC, CLIC, C3, LWFA-LC, PWFA-LC SWFA-LC) have production needs that are 10 to 20 times that of the SLC and are represented well by the CLIC positron system.

There are several special cases:

1) The ERLC is a CW SC collider that needs to have a cycle time of 2 seconds on and 4 seconds off for SC cavity He cooling needs. The positrons will need to be stored during the off time for the ERLC or else the positron production rate will much higher that shown in Table 5.

2) As shown in its schematic drawings, the ERLC does not have a direct DR but a single-pass-wiggler emittance-reduction system for the colliding bunches which means that the emittance disruption during collision must be quite small.

3) The CLIC based positron DR system is relatively compact compared to others and includes a pre-damping

ring and bunch stacking. This system will likely need further investigation if it becomes the baseline for other single pass future colliders.

Table 5: Injection Requirements for Past, Present and Future Colliders.

Collider Damping Ring for	**N. colliding bunches to fill**	**Injected bunch rate (Hz)**	**Total e$^+$ injection rate per second (x10^{12})**
SLC	120	120	6.0
LEP	8	100	0.12
PEP-II	1732	30	0.15
SuperKEKB	2151	100	0.2
Proposed:			
FCCee	10000	200	6.0
CEPC	12000	100	3.8
ILC	6560	6560	131
CLIC	17600	17600	100
C3	16000	16000	100
CERC	1600	160	0.16
ERLC	53000	5300	0.05
ReLiC	22000	2200	0.03
PWFA-LC	10000	10000	100
LWFA-LC	47000	47000	56
SWFA-LC	23100	23100	72

CONCLUSIONS

The various proposed future e^+e^- colliders will put additional constraints on the positron production and damping ring systems. Several of the proposed colliders require large increases in the capabilities of the positron production and damping rings compared to past systems, reaching over an order of magnitude in some cases. For those colliders, a sustained programmatic effort will be needed to reach solutions for these requirements.

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