

## DAMPING RINGS TOWARDS ULTRA-LOW EMITTANCES\*

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### Abstract

Damping Rings (DR) designs to achieve ultra-low emittance beams in Linear Colliders (ILC and CLIC) will be reviewed pointing out the major issues both from the beam dynamics and the technological point of view and comparing the required performances with the one achieved at SLC. The design, beam simulations, benchmarking and performances already achieved in test facilities, especially the KEK-ATF1 facility, will be presented. Finally, future R&D plans and schedule in terms of beam performances, beam stability and technological development as well as the world-wide organization to achieve them will be discussed.

### INTRODUCTION

Parameters of ILC and CLIC Damping Rings (DR) are listed in Table 1 compared with those for SLC DR. DR parameters for high energy colliders ILC and CLIC are quite different from SLC ones in terms of lower emittance, higher current, higher number of bunches and shorter bunch distance. SLC has been operated between 1986 and 1998, since then progress has been achieved both in storing high currents ( $\Phi$  and B-Factories), very low emittances (ATF, 3rd generation synchrotron light sources), and in stabilizing the beams. The main difference in the present DR designs is that they all are wigglers dominated rings, to increase radiation damping and reduce emittance.

Table 1: SLC, ILC and CLIC DR Parameters

	SLC	ILC	CLIC
Energy (GeV)	1.19	5	2.4
C (m)	35	6695	360
N bunches	1	2767	1554
N part./bunch	$4 \times 10^{10}$	$2 \times 10^{10}$	$2 \times 10^9$
$\tau_{x,y}$ (ms)	3.5	25	2.8
$\gamma \epsilon_x$ (nm)	$3 \times 10^4$	5600	550
$\gamma \epsilon_y$ (nm)	$1.7 \times 10^4$	20	3.3
Mom. comp.	$1.5 \times 10^{-2}$	$4.1 \times 10^{-4}$	$0.81 \times 10^{-4}$
$U_0$ (MeV)	0.080	8.7	2.1
Energy spread	$0.77 \times 10^{-3}$	$1.29 \times 10^{-3}$	$1.26 \times 10^{-3}$
$\sigma_i$ (mm)	5	6.0	1.55
RF volt.(MV)	0.8	46.6	2.4
RFfreq.(MHz)	714	650	1875

### SLC EXPERIENCE

SLC experience has demonstrated the importance of the DR in order to achieve the proper beam sizes and beam stability at the IP [1].

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The Final Focus Test Beam (FFTB) at SLAC demonstrated the possibility of focused beam sizes in the nanometer ranges, achieving 50nm vertical beam size.

Soon after SLC commissioning it was realized that the longitudinal microwave instability threshold current (single bunch) was very low in the DR [2]. Above threshold there was small pulse-to-pulse variation in bunch length and longitudinal phase of the extracted beam, that was amplified in the linac, and that made it almost impossible to operate the collider. When the microwave instability was recognized as a limiting performance (in the late 1980's), the bellows were sleeved; in 1994 the entire chamber in both rings was removed, and a new, low impedance vacuum chamber was installed.

When the "new" DRs were turned on, it was found that bunch lengthening was indeed reduced; the threshold, however, also went down. This was due to a new "weak" instability, which triggered theoretical work, and was, in the end, rather well understood. It was then possible to routinely run the Drs at more than twice the threshold, increasing the number of particles per bunch by a factor  $\sim 1.5$  with respect to the old ring.

### CLIC DAMPING RING

The emittance requirements for the CLIC DR are very demanding due to the extremely small beam sizes at the IP needed to get high luminosity at the multi-TeV energies. The bunch structure and damping time are given by the time pulse structure of the CLIC linac [30]. A very short bunch distance and high RF frequency, unusual in storage rings, are needed and the ring circumference remains comparatively small.

The CLIC DRs aim at unprecedented small normalized equilibrium emittances of 3.3 nm vertical and 550 nm horizontal, for a bunch charge of  $2.6 \cdot 10^9$  particles at 2.4 GeV [4]. In this parameter regime the dominant emittance growth mechanism is Intra-Beam Scattering (IBS).

Intense synchrotron radiation damping from wigglers is required to counteract IBS effect. The ring is based on a racetrack shape with two  $180^\circ$  arcs made from 48 TME cells each and long straight sections to accommodate a total wiggler length of 152 m. Although dynamic aperture and tolerances of this design remain challenging, benefits are obtained from the strong damping.

Most of the beam dynamics issues related to high currents are similar to that for the ILC DR, in fact the charge per bunch is 10 times lower but the bunch spacing is  $\sim 10$  times shorter and the total current is nearly the same. The most challenging technical issues are related to the wiggler design and to problems of wiggler radiation absorption.

## ILC DAMPING RING

The Baseline Configuration (BC) for the ILC DR was chosen in November 2005 by a working group of nearly 50 researchers that have performed comparative studies of different options based on seven different lattices with circumferences ranging from 17 to 3 km. A description of the process and of the principle considerations leading to the choices of the baseline DR configuration is given in [5] and the supporting studies are documented in [6].

Here we summarize the recommendation for the choice of the circumference and layout. The positron damping ring should consist of two (roughly circular) rings of approximately 6 km circumference in a single tunnel. For the electrons the configuration consists of a single 6 km ring. The main issues for the circumference choice were acceptance, collective effects and kickers. Achieving the required acceptance is easier in a large, nearly periodic, 6 km ring than in a “dogbone ring”, like the TESLA one, or in a compact 3 km ring. Some of the beam dynamics issues, in particular fast-ion instability and electron cloud, favor a larger circumference, while others as space-charge favor a smaller circumference.

The choice of having two rings for positrons is mainly due to electron-cloud effects that make a single ring of circumference 6 km or lower unattractive, unless significant progress can be made with mitigation techniques. Space-charge effects will be less problematic in a 6 km than in a 17 km ring. The injection/extraction kickers are more difficult in a shorter ring; at present the kickers for a 6 km ring are considered feasible even though more R&D is required to fulfil all the specifications.

The parameters in Table 1 refer to the BC that will be used for the Reference Design Report and the cost estimate to be completed by the end of this year. All the specifications should be satisfied also for the “low charge” parameter set, which foresees twice the number of bunches with half the charge.

The ring (OCS) has a 10-fold symmetry and incorporates 10 straight sections, of which 4 dedicated to RF and wigglers and 2 for injection/extraction lines and tune adjustment [7]. Each of the 10 arcs is made of 7 TME cells plus dispersion suppressor. A lattice design based on FODO cells is also under study to compare the performances [8, 9].

## BEAM DYNAMICS ISSUES

### Acceptance

A large acceptance is needed to inject the high emittance positron beam with high efficiency.

Extensive dynamic aperture studies on reference lattices proposed for the BC have been performed applying different techniques [6]. For comparison the calculations have been performed with different wiggler models and different codes, finding a good agreement. In Fig.1 is shown dynamic aperture in the OCS lattice with a realistic wiggler model, based on the CESRc wiggler, and with multipole errors included. The aperture required for

injection is  $3\sigma_x$  and the dynamic aperture is greater than  $5\sigma_x$  even for 1% energy deviation.

The injection efficiency of the reference lattices has been estimated using a simulated distribution of injected positrons: the OCS lattice achieves 100% injection efficiency with a good safety margin.

Finally, tracking studies were done to determine the effects of the physical aperture in the wiggler, which is expected to be the limiting aperture [10].

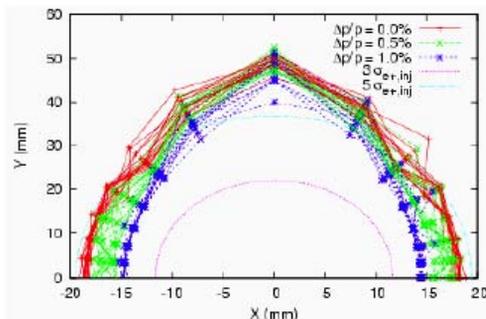


Figure 1: Dynamic aperture in the OCS lattice with modified CESRc wiggler model and multipole errors.

### Low Emittance

The achievement of ultra low vertical emittance is one of the challenges of DR. This requires very good alignment tolerances, lattices with low sensitivity to alignment errors, beam based alignment techniques, efficient coupling and dispersion correction algorithms, and high resolution beam position monitors [11].

Simulations show that, assuming the alignment errors of the KEK ATF ring, the design vertical emittance of 2 pm could be achieved in the OCS ring. Anyway an experimental demonstration of such a low emittance is still expected.

Intensive studies on the feasibility of an even smaller vertical emittance are performed for the CLIC DR [12].

### E-cloud

Electron cloud effects were one of the crucial issues in the choice of the circumference for the ILC baseline configuration. Studies to benchmark the simulation codes against experimental data are ongoing at the CERN SPS, DAΦNE, the PSR, PEP-II and KEKB; so far, the results of the simulation codes are generally supported by experimental data.

The build-up of the electron cloud is strongly dependent on the bunch separation, which decreases with the damping ring circumference; therefore reducing the circumference can make electron cloud effects more severe. Electron cloud can be difficult to suppress in the dipole and wiggler regions where it is expected to be most severe. Careful estimates were made of the secondary electron yield threshold for electron cloud build-up, and the related single- and coupled-bunch instabilities, as a function of beam current and surface properties for a variety of optics designs [13]. On the basis of this work, the baseline configuration currently specifies a pair of

6 km damping rings for the positron beam. It would be highly desirable to find possible solutions to mitigate the effects of the electron cloud in order to achieve the nominal design parameters in a single 6 km ring.

### Fast Ion Instabilities

Due to high bunch density and short bunch spacing fast ion instabilities could be a serious problem for electron DR. Gaps in the bunch fill pattern can reduce the ion density by a factor 100 and even more. Feedback system can suppress the instability in the ILC DR, even for 3ns bunch spacing, if there is sufficient gap between the trains. This argument is treated in many papers at this conference [14, 15, 16, 17, 18].

### Other Collective Instabilities

In the absence of a detailed design of the vacuum components, a preliminary estimate of the ILC DR broadband impedance has been performed scaling from PEP-II-LER. To mitigate the risk of operating above the microwave instability threshold the present version of the OCS lattice has a higher momentum compaction and therefore a high RF voltage, which drives a cost increase. Possible solutions have been considered: first of all the design of a low impedance vacuum chamber; as an alternative the use of a high harmonic RF cavity to shorten the bunch or a negative momentum compaction lattice that could allow a shorter bunch length, as shown by recent measurements at DAFNE, and could allow to operate with negative chromaticity at reduced sextupole strengths [19].

Other collective effects are Intrabeam Scattering (IBS) [20] and space charge effect [21]. The first is extremely important for the CLIC DR [4], the second is important only for very long DR, as the TESLA DR, but should not be a concern for the OCS ring.

## TECHNOLOGICAL ISSUES

### Fast Kickers

The injection and extraction kickers are one of the most critical issues since the bunch distance in the ring, and therefore the choice of the ring circumference, are related to the kicker pulse duration; moreover the stability of the beam position at the IP depends also on the kicker pulse stability. R&D programs are in progress in different laboratories at a global level both on the fast pulsers and on the stripline electrodes.

The injection and extraction kickers for the positron should satisfy the following requirements: ultra short rise and fall time (total pulse duration  $< 12.4$  ns for  $e^+$ ,  $< 6.2$  ns for  $e^-$ ); good uniformity; low impedance; 3 Mhz for  $e^+$  (6 Mhz for  $e^-$ ) repetition rate.

Stripline kickers studied for the ILC positron DR can be used for an upgrade of the DAΦNE injection system (see Fig. 2). This will allow to test with beam measurements the achievement of the kicker performances and

possibly to test new fast pulsers. High voltage test on a prototype have been successfully made [22].

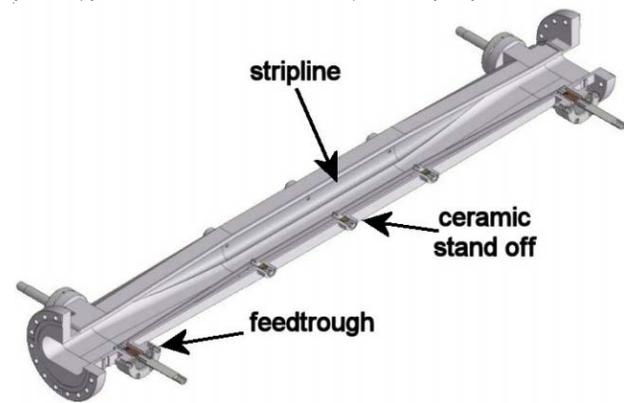


Figure 2: Mechanical drawing of the kicker.

The striplines, 327 mm long, producing beam deflection of 0.1 mrad with 7 kV voltage pulses at 1.28 GeV installed at the KEK-ATF were used to test pulsers with beam. A total width of the main pulse around 5 ns has been achieved, with a small pulse ahead of the main pulse, and a tail of more than 5 ns. Tests to correct these effects have been done connecting two pulsers with opposite polarity and achieving a sharp edge with 2.2 ns rise time [23].

Although results so far indicate the feasibility of kickers with rise/fall times sufficient to allow bunch separations as short as 3 ns, the full specifications have not yet been achieved. Pulse repetition rates of 3 Mhz have been demonstrated, but the specifications for the pulse amplitude stability look still to be very challenging.

There is a fruitful collaboration between many laboratories on the kickers and pulsers R&D [24, 25], and the performances achieved are rapidly improving.

### Wigglers

A high quality field is needed to achieve the dynamic aperture necessary for good injection efficiency. A large gap is needed to achieve the necessary acceptance for the large injected positron beam: a full aperture of at least 32 mm is highly desirable for injection efficiency.

Wiggler technology Baseline: The CESR-c SC wigglers have demonstrated the basic requirements for the ILC damping ring wigglers and have been chosen as baseline, since they allow for a very good field uniformity in a large aperture [26].

Alternatives are Hybrid PM wigglers [27] that have the advantage of not requiring power supplies, cabling, cooling and cryogenics. A design with acceptable costs for hybrid wigglers, meeting specifications for aperture and field quality, steel needs to be developed.

New wigglers for CLIC based both on SC and PM technology have been proposed. In this case the challenges are in the achievement of the highest field with the lowest period length and the handling of the heating due to the synchrotron radiation [4].

## Feedbacks

A digital feedback system of the type used at DAΦNE, PEP-II and KEKB is certainly recommended for the DR: in a digital system the feedback gain can be increased without increasing the noise. A stripline electrode can be used as kicker in the transverse plane and an overdamped cavity (DAΦNE type) in the longitudinal plane. The minimum feedback damping time measured at DAΦNE is 6 ms, corresponding to 20 turns with a 500 W power amplifier.

Tests of an FPGA based feedback system were recently made by an international collaboration at KEKB and ATF [28].

## TEST FACILITIES

### Accelerator Test Facility ATF

The KEK Accelerator Test Facility (ATF) is a 1.3GeV storage ring capable of producing ultra-low emittance electron beams and has a beam extraction line for ILC R&D [29]. The ATF has proven to be an ideal place for researches with small, stable beams:  $2 \times 10^{10}$  single bunch and low current 20 bunch-train with 2.8nsec bunch spacing have been extracted.

The DR is used by an international collaboration for beam dynamics studies, as fast ion instability, microwave instability, damping wigglers, and for developing specific DR instrumentation, as pulsed laser wire monitor, X-ray SR monitor, very fast kicker with about 1nsec rise/fall time.

The smallest vertical emittance has been achieved in single-bunch-mode operation at ATF. The emittances were measured with a laser-wire beam-profile monitor installed in the DR. The bunch length and the momentum spread of the beam were also recorded under the same conditions. The smallest vertical rms emittance measured is 4 pm in the limit of zero current. It increases by a factor of 1.5 for a bunch intensity of  $10^{10}$  electrons. There are no discrepancies between the measured data and the calculations of intra-beam scattering.

The ATF2 proposal aims to create a final focus test facility that, using a low emittance ILC-like bunch train extracted from ATF1 and compact final focus optics, would be capable of achieving 37 nm beam size with a beam centroid stability within a few nm.

### New Proposals

CESR-c as DR test facility. In 2008 it will be possible to reconfigure CESR as a damping ring test facility, CEsRrTF, for the ILC project. With its complement of 12 damping wigglers that meet or exceed all ILC damping ring requirements, CEsRrTF will offer horizontal emittances in the few nanometer range and the ability to operate with positrons or electrons [30].

The HERA electron ring, which ends operation mid 2007, matches almost perfectly the major DR design parameters; therefore it has been proposed to use it for the ILC DR [31].

## R&D PLANS

R&D plans are in progress at a worldwide level. The ILC activity is leaded by GDE, which has a dedicated R&D board to coordinate the activity for the whole project. For the damping ring an international working group on voluntary base has been set-up. The activity of this group is coordinated by the 4 DR Area Leaders and is focused on tasks, with a task coordinator, dedicated to the major issues. Regional organizations and funding, as EUROTeV in Europe, are present. There is a strict collaboration with the CLIC DR activity in the tasks dedicated to common issues, the most important are e-cloud and fast ion instabilities.

The ongoing activity is well represented by the many papers presented at this conference on DR issues. Based on the proposal of the research groups a list of R&D activities for the DR has been compiled and will be discussed at the next GDE meeting at Vancouver.

### Beam Dynamics Single Particle

Lattice design activities will continue in order to optimize the performance, improving dynamic aperture, reducing sensitivities to errors and misalignments and to different instabilities and at the same time setting the specifications for the technical systems.

### Beam Dynamics Multi Particle

R&D efforts are in progress worldwide to improve simulation codes benchmarking at existing facilities in order to fully characterize e-cloud instability and to find cures to mitigate it.

Between the possible solutions vacuum chamber coatings with low SEY materials, and grooves in the chamber have been proposed. At present a very promising solution is the use of clearing electrodes [32], which, should strongly reduce the electron density in the beam region. Further study and experimental demonstration are needed.

Characterize the fast ion instability and define the requirements for vacuum chamber pressure, gaps in the fill pattern and feedback systems in the electron DR.

Develop impedance models, and calculate short and long-range wakefields and single-bunch instability thresholds to characterize single and multi-bunch instabilities.

Characterize space-charge effects, estimate emittance growth from IBS, estimate the impact from coherent synchrotron radiation (CSR), injection and extraction transients, Touschek lifetime.

### Technical Subsystems

Optimize designs of vacuum system components in order to minimize single and multi bunch instabilities, handle the high synchrotron radiation power in the wiggler sections and mitigate effects of e-cloud and fast ion instability.

Develop design of wigglers satisfying DR requirements for aperture and field quality, peak field and period length

and synchrotron radiation power handling and e-cloud mitigation.

Develop stripline electrode design and high power pulser for fast injection/extraction kickers.

Develop dedicated diagnostics as high resolution bpm's, precision bunch-by-bunch beam size monitor, instrumentation for monitoring emittance damping, fast dispersion measurements.

Design low noise, fast damping time transverse and longitudinal feedback systems.

### Tests

The most important tests to demonstrate DR performance are the measurement of a vertical emittance lower than 2 pm, the effectiveness of cures for e-cloud instability and the beam tests of fast injection/extraction kickers.

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