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A 1.2 GeV DAMPING RING COMPLEX FOR THE STANFORD LINEAR COLLIDER*

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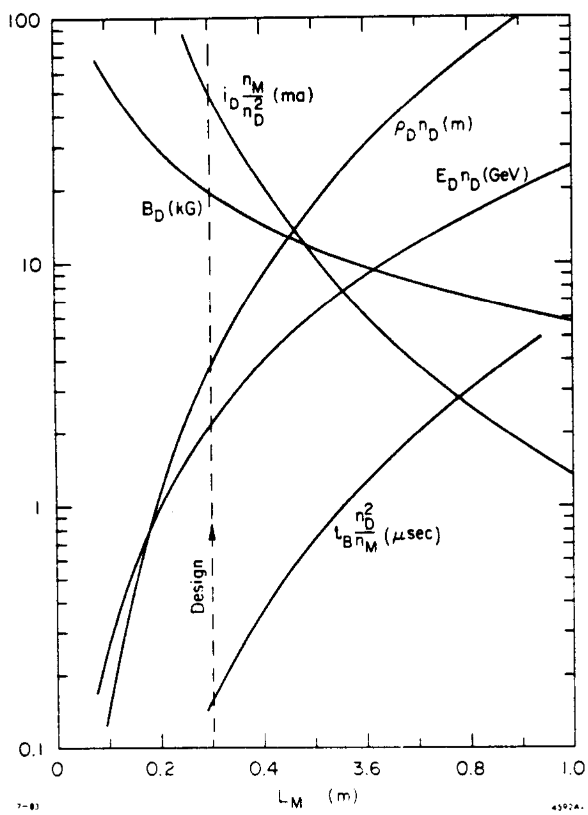
Summary The choice of parameters, the design, a 2-1/2 year construction program and the early operation of a high field, high tune research and development damping ring complex for one of the two linear collider[1] beams are described.

Introduction The primary purpose of damping rings is to reduce the transverse phase spaces of e^+ and e^- beams to suitably small values at the injection end of a linear collider such that their bunches, when accelerated to high energies, can be made to collide with high luminosity. Further, longitudinal bunch length control must be provided to minimize wake field effects in the accelerator. Finally, it is desirable to provide a means of preserving and manipulating the spin polarization of the electron beam.

Choice of Ring Parameters Taking as given that positrons are created at the converter with an invariant emittance of about $\epsilon_c = 5\pi(MeV/c)mm$, and that the design luminosity requires (before certain emittance growths are accounted for) an invariant emittance of $0.015\pi(MeV/c)mm$ radian meters, a transverse phase space reduction of about 300 is needed. The damping time must be in the millisecond region, since the Collider will operate at 180 Hz. The interplay between damping ring energy E_D, bending radius ρ_D, field B_D, the number of bunches per ring n_B, the number of rings n_M, the time between bunches in a ring τ_B, the total beam current i_D (assuming 5×10^{10} particles/bunch) has been parameterized[2] as a function of bending magnet length for a separated function lattice and is shown in Fig. 1.



Combining this parameterization with the physically realizeable values of magnetic fields, gradients and practical rise and fall times for injection and extraction kickers leads to the ring parameters shown in Table 1. Two bunches circulate in each ring in opposing buckets. For the e^+ case, the opposing buckets are filled and emptied on alternating accelerator pulses. Hence, the e^+ spend 11.1 milliseconds or 3.6 damping times in the ring. For the e^- case, less damping is required, so two bunches are simultaneously injected and extracted each 5.5 ms, the second bunch being used to subsequently generate positrons for refilling the emptied e^+ bucket.

Table 1. Design Parameters for the Damping Rings

Energy	1.210	GeV
Circumference	35.270	m
Revolution Frequency	8500.400	kHz
RF Frequency	714.000	MHz
Harmonic Number	84	
Transverse Damping time	3.059	msec
Equilibrium Emittance		
(with full coupling)	$9.1 \cdot 10^{-9}\pi$	rad m
Equilibrium Related		
Energy Spread	$7.3 \cdot 10^{-4}$	
Momentum Comp. Factor	.01814	
Energy Loss/Turn	93.1	keV
Bending Radius	2.0372	m
Bending Field	19.812	k Gauss
CELL — Structure	1/2 FODO 1/2 F	
ν_x	~ 7.25	
ν_y	~ 3.25	
Acceptance		
in phase space	$\leq 4.13 \cdot 10^{-6}\pi$	rad m
in energy	$\leq \pm 1\%$	
RF System and Related Parameters		
RF — voltage	800	kV
Phase	6.7°	
Synchrotron Frequency	107.3	kHz
Tune	.0126	
Equilibrium Bunch Length	5.9	mm
ϵ_c (critical energy)	1.9283	keV
I (2 bunches)	136.2	ma
P (synchrotron radiation)	12.68	kW

Layout The geometry of the first complex is shown in Fig. 2. It is planned to locate the center lines of the second ring and transport lines about .7 meters above the first. The insert in the figure depicts how particles of opposite sign are extracted and reinjected into the accelerator in the limited space between linac sectors. The scheme employs vertical deflection of the beams into a double Lambertson septum magnet in which the upper channel has its magnetic field of opposite polarity to the lower channel. This septum directs both outgoing and returning beams. For stability during collider operation this system will operate DC, but for ring tests the first vertical magnet is pulsed to provide interlacing with beams for the other linac programs.

A bunch length compression scheme[3] is employed in the return line which serves to transform the longitudinal phase space in the ring from ($\sigma_z \sim 6$ mm, $\sigma_E/E \sim .07\%$) to ($\sigma_z \sim 0.5$ mm, $\sigma_E/E \sim 0.8\%$) suitable for reinjection into the linac.

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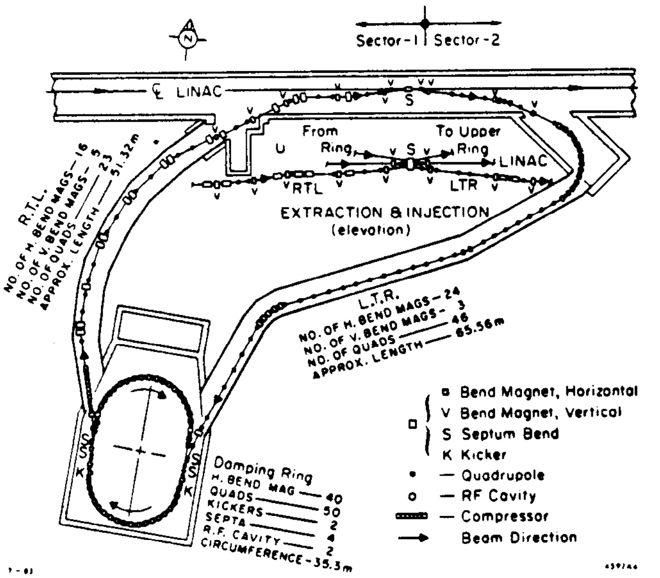
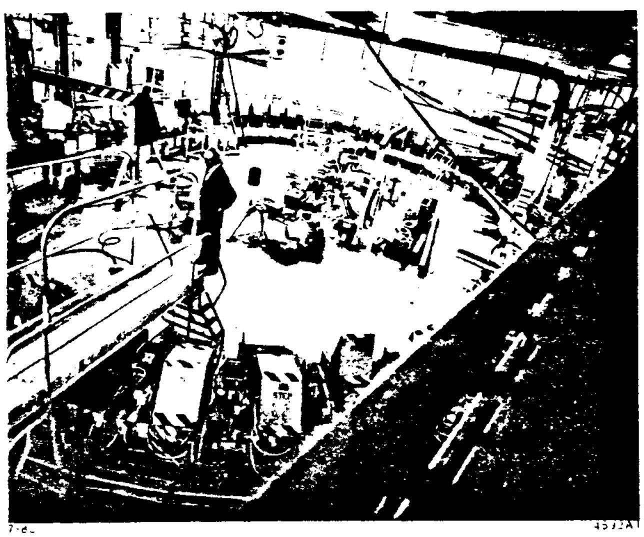
The compressor accelerating section is located at the entrance of the return line.

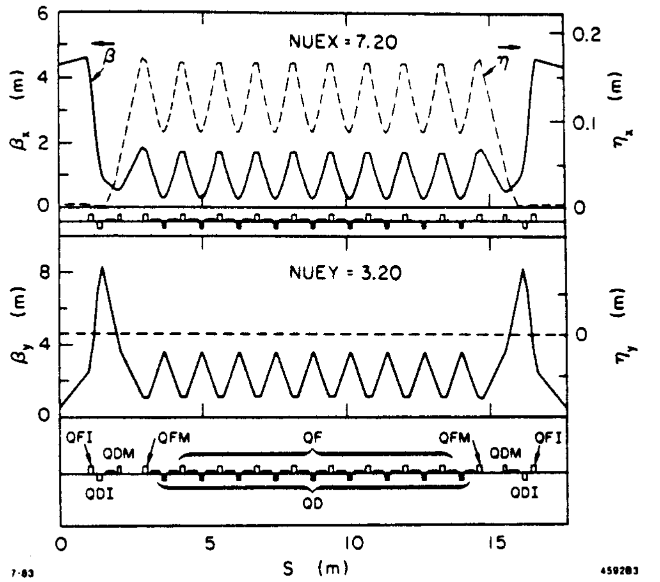


To preserve and manipulate the spin polarization of the electron beam, the geometry of the transport lines is so chosen that solenoidal spin rotators ($\int B_z dz \simeq 6.3$ Tm) can be inserted in regions of zero dispersion at odd $\pi/2$ multiples of precession angle.[4] At 1.21 GeV this occurs at bend angles of $n \times 32.8°$.

The ring resides in a concrete vault (Fig. 3) some 35 feet below grade. The connecting transport lines are housed in eight-foot diameter tunnels.



Optics (a) Ring: The nominal design betatron and dispersion functions of the ring are shown in Fig. 4. Quadrupoles which bear a common name are bussed in six families so that their strengths can be varied to change tunes and the optical properties of the insertion. It is intended to run the machine on the coupling resonance $\nu_x - \nu_y = 4$ to minimize the beam emittance. Sextupoles are introduced at the ends of each bending magnet by pole face shaping to correct the natural chromaticities from ~ -9 to $\sim +0.5$. The theoretical aperture required in the cells to accept the positron emittance is only about ± 4 mm.



(b) LTR: The components of the linac to ring transport are very similar to those of the ring with the exception that all quadrupoles are run from a common bus with their lengths adjusted for proper strength. To fine tune or correct matches at the linac and ring ends, the first eight and last ten quads contain separately adjustable trim coils.

(c) RTL: Since the longitudinal phase compressor reintroduces a large momentum spread, $2\sigma_p/p \sim \pm 1.6\%$, it has been found necessary to correct this optical train to second order in both planes. This is accomplished by means of a non-isochronous, 2-stage, nested second-order achromat.[5]

Components Only some of the more unusual features of the complex can be pointed out in this brief report.

(a) Ring and LTR Magnets:

- Bending magents: gap-2 cm, field = 19.8 kG, length = 32 cm, sextupoles $S_F \simeq S_D \approx 25$ m^{-2}
- Quadrupoles: Bore 2.5 to 5 cm, gradients up to 7 kG/cm, length 10.6 to 23 cm.

Most components are indeed miniature by normal standards.

(b) Septa: The ring injection and extraction septa are of the current sheet type and operate, since there are no vacuum windows, in the UHV environment of the ring. The pre-septum is 3 mm thick and carries 2400 A to produce 3 kG in a 1 cm gap. The post septa are of two-turn construction to produce 8 kG. Total deflection is $\sim 10°$.

(c) Kickers: The injection and extraction kickers are 33 cm long, 2.2 cm gap, ferrite loaded (Ferrox-cube 4C4) transmission lines of characteristic impedance 16.6 Ω. They transmit their field through ceramic vacuum tubes, the inside of which have been coated with a conducting layer (1.2 Ω/□ of Kovar) to carry the high image currents of the beam. The time to establish peak fields of 1 kG is about 45 nsec, short enough to not disturb the second, circulating bunch. This time is a combination of the natural rise time of the pulser, the filling time of the ferrite and the shift introduced by eddy currents in the coating of the vacuum chamber. The 40 kV pulser consists of a resonantly charged Blumlein discharged by means of a thyratron firing at rates up to 180 pps. Since the launch angle and position into the linac, which controls wake field effects, is related to the angle of the extraction kick, the pulse-to-pulse amplitude jitter must be held to better than .03%. This tolerance has been met!

(d) Vacuum: Ion effects, if not dealt with, can be expected to affect the phase space of beams in the electron ring.[6] A two-step attack is employed. Distributed ion pumps (150 ℓ/sec) are located in each of the 40 bending magnets[7] to reduce presure (after cleanup) into the 10^{-8} torr range. Further, the partitioned vacuum chamber is designed to let the electric field of the pump electrodes leak into the beam region to cause the ions to migrate and be cleared. Clearing in the remaining circumference is provided by clearing electrodes and by biasing the beam position monitor strips with voltages up to ± 1 kV.

(e) R.F. System: This system has been recently described in detail.[8] Since the ring does not accumulate, notable is the problem of transient beam loading which occurs when substantial current (5×10^{10} particles/bunch) is injected. The solution, which is to anticipate this current and introduce an appropriate pulsed phase jump, has been calculated to be adequate and has been implemented.

(f) Phase Compressor Section: As mentioned earlier, it is essential to control the bunch length of the beams reinjected into the linac. A standard SLAC 10-foot S band acceleration section is used to accelerate/decelerate the early/late particles in the bunch. Since bunch length is thus transformed to energy spread, the amount of compression is controlled by the peak accelerating voltage ($\sim$ 31 MeV) and will be monitored by means of an energy spectrum monitor.

(g) Instrumentation and Control: The damping ring complex is computer-controlled through the new SLC distributed net.[9] On-line calculation of machine models and control of elements[10,11] can be performed from any terminal on the site. The transport lines are equipped with nine $A\ell_2 0_3(Cr)$ profile monitors, seven current measuring toroids, six gap monitors and two multifoil spectrum monitors. Provision is made in the ring for measuring beam size with moveable scrapers and a synchrotron light monitor. In the whole complex, over 100 steering coils can be selected. There are essentially four beam position monitors[12] per betatron wavelength throughout (67 BPM), the outputs of which are sampled sequentially, digitized and finally displayed on-line in either numerical or graphical form by means of an Apple-II computer. Betatron tunes are measured by very lightly exciting the beam. The resulting signals are highly amplified with a low noise amplifier, demodulated from the revolution frequency and observed on a swept frequency analyzer with a typical resolution of .003 in tune.

Some Project Milestones

Authorization to start construction	October 1, 1980
Conventional facilities notice to proceed	May 6, 1981
Beneficial occupancy of housing	December 21, 1981
Completion of LTR installation	October 1, 1982
Beam transported to entrance of ring	December 12, 1982
Completion of ring installation	December 28, 1982
Beam stored in ring	February 27, 1983
Completion of RTL installation	July 30, 1983

To date, the cost of construction and installation of the complex described above is about 5M\$. Of this amount, 1.3 M\$ is associated with the housing and utilities. The total power consumption for operation at 1.21 GeV is $\sim$ 1.7 MVA.

Commissioning and Operation Commissioning runs have taken place on the average of 3-1/2 days per week. This schedule was dictated by the ongoing installation of RTL components and the availability of beams and manpower. All studies have taken place at .957 GeV, so that linac Sector-1 did not need to be run in the SLED-I mode. Since April, tests have been conducted using the single bunch e^- collider gun[13] which has produced up to $1.3 \times 10^{10} e/S$ band bunch at the end of Sector-1 in an energy band of 1%. Transmission through the LTR transport, which now needs some realignment, has been greater than 80%. Ring capture efficiencies have ranged up to 50% so that maximum storage has been $5 \times 10^9 e$/bunch. The base pressure in the ring without beam is typically 2×10^{-9} torr or lower, rising to 5×10^{-8} torr at the largest stored currents. The chamber is expected to clean up with time. Beam lifetimes are typically $\sim$ 40 minutes. The performance of the RF system bears out its design in every way. The initial alignment of the ring was such that beam could be stored with only about five correcters active. Beam position monitor readings are repeatable to 0.1 mm, better than expected.

Most of the studies concentrated on understanding the ring lattice. Recently reasonable mathematical fits to measured tunes, beta and eta functions have been achieved taking into account that pole face rotations were inadvertently introduced into the steel of the bending magnets twice instead of once. This corrected model has been used successfully to adjust parameters to approach those of the design. Chromaticities are now appropriately positive. Prior to this understanding, a vertical instability was observed, but it is not known whether this was of a head tail type or due to some other mechanism. The horizontal coherent damping time is $\sim$ 1 msec. It remains to accurately measure the incoherent damping times and equilibrium beam sizes.

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