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RECIRCULATION OF THE SLAC BEAM*

W. B. Herrmannsfeldt, M. A. Allen, R. H. Helm, G. A. Loew, R. B. Neal and P. B. Wilson

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Abstract

The intent of this proposal is to boost the energy of the SLAC beam into the 40 GeV range by recycling the electrons through the accelerator for a second pass. In order to use the normal klystron repetition rate (360 pps), the beam must be stored for the entire interpulse period (2.8 ms). Storage would be achieved in a 6.9 km-long path extending over the entire length of the accelerator housing. The direction of the beam would be reversed in magnet loops located at the ends of the accelerator. Beam energy losses due to synchrotron radiation would be made up by a room temperature linac operating at the accelerator frequency (2856 MHz). At the end of the storage interval, corresponding to about 122 revolutions, the beam would be reinjected into the accelerator to be accelerated for a second time. The final energy would equal the sum of the energy during storage plus the energy gained on the second pass. The recirculator could also be used for high duty cycle (up to 7%) experiments at the recirculating energy by simply storing the beam and extracting about 1% of the electrons per revolution.

1. Introduction

The present SLAC accelerator has the capability of producing electrons in the 20 GeV range at the rate of 360 pps. The duty cycle is 0.06%. The purpose of the Recirculating Linear Accelerator (RLA) described in this paper, is twofold. First, it will boost the energy of the two-mile machine into the 40 GeV range. This energy increase will be achieved by storing the present beam in a recirculator and then reinserting it into the accelerator for a second pass. Second, it will increase the beam duty cycle at the present energy by a factor of 100 by using the recirculator as a beam stretcher. Both of these improvements will greatly expand the physics opportunities of the existing accelerator.

The RLA is the third method proposed in the last two years to upgrade the energy and duty cycle of the SLAC accelerator.[1-4] The first consisted of simply adding more RF power to the existing machine. This method is costly and may only be carried out gradually. The second was the proposed conversion of the two-mile machine to a 100 GeV, long duty cycle, superconducting accelerator. Implementation of this conversion, while very challenging, would be premature at this time because many problems in RF superconducting technology remain to be solved; moreover, it may not become feasible early enough to make the machine competitive from the physics point of view.

The RLA appears to present many of the advantages of the above approaches while avoiding the disadvantages of great expense and long lead time; the present estimated cost is $13.7 million and the time for completion is 3 years after date of authorization.

2. General Description of Project

The principle of the RLA is illustrated in Fig. 1. The beam, after having been accelerated once through the

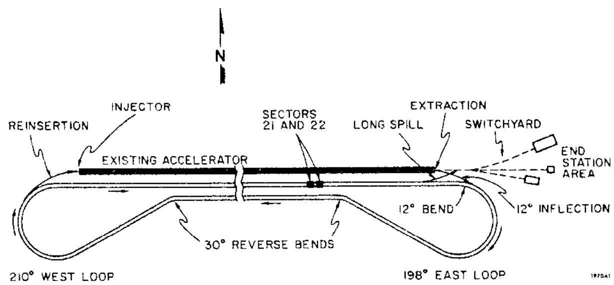

FIG. 1--Schematic layout of recirculation system.

existing accelerator, is extracted and stored in a recirculator by means of a 12° inflection system. The recirculator consists of two 95 m radius loops joined by two ~3 km long straight sections. In the loops, the beam is bent by a system of alternating-gradient magnets. Two 30° reverse bends will be used to connect the loops to these straight sections. The entire recirculator will be 6.9 km long. After 122 revolutions corresponding tc one machine interpulse period (2.8 ms or 1/360 s), the beam is reinserted into the accelerator for a second pass. Alternately it will be possible to use the recirculator as a "beam stretcher"; every time the 1.6 μs train of electron bunches approaches the downstream or east loop, a fraction of the beam is "peeled off" and "spilled" into the beam switchyard (BSY) and the experimental areas. Since the recirculating period is 23 μs and the beam pulse is 1.6 μs long, the resulting duty cycle is 7%.

The energy lost due to synchrotron radiation in the bending loops will be restored by an RF system located in Sectors 21 and 22, as shown in Fig. 1. Because the energy lost varies as the fourth power of the stored energy, economy dictates that beam storage be initially limited to 17.5 GeV. This 17.5 GeV added to the 25 GeV obtained from the second acceleration will yield a total of 42.5 GeV. The increase to 25 GeV from the present 22 GeV maximum is being achieved by replacing the 20 MW klystrons by 30 MW tubes. At the 17.5 GeV level, the synchrotron radiation loss is ~ 125 MeV per turn.

The RF system will consist of two conventional 333 ft. accelerator sectors. Spare accelerator sections of the SLAC type will be used. Since the recirculating period is 23 μs, the klystrons will have to run at 43,500 pps, i.e., a duty cycle of ~10%. A system of sixteen tubes, each providing 220 kW of peak power, is being proposed. The resulting gradient will be sufficiently high to produce a peak voltage of 150 MV. Assuming peak beam currents of the order of 10 mA (10^{11} electrons/pulse), average beam powers of the order of 250 kW will be obtained at 42.5 GeV.

At a later date, it may be possible to gradually increase the RLA storage energy to 21 or 25 GeV. This may be achieved by adding conventional RF power or preferably by means of a short superconducting accelerator section. The present two-mile accelerator may also be

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upgraded by replacement of present klystrons with new 60 MW tubes. The single pass energy would then be increased to a maximum of 35 GeV, taking the total energy up to 60 GeV. In all the above descriptions, it is of course understood that the accelerator will continue to be operable in the present single pass mode.

The magnet lattice for the recirculator will consist of approximately 300 bending and focusing magnets. The east loop will be in the horizontal plane but the west loop will be tilted down towards the south at 4% grade to conform to the local terrain. This will produce some coupling between vertical and horizontal electron motion which is briefly discussed later in this paper. Housing for the loops will be 8 ft. I. D. cylindrical pipes (precast concrete storm drains).

The vacuum system for the recirculator will be independent from the existing accelerator. An average pressure of 5×10^{-7} torr during beam storage is planned. The long drift line and the two new accelerator sectors will be supported above the existing machine as shown in Fig. 2.

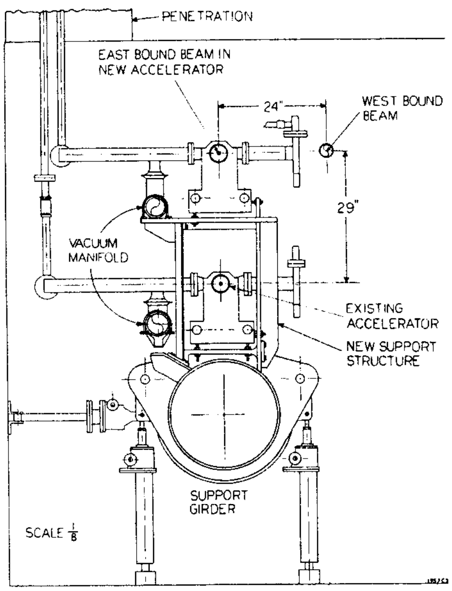

FIG. 2--Schematic of Accelerator Housing showing cross sections of present accelerator, 666 ft. new accelerator (east-bound beam) and return loop (west-bound beam).

Electrical power requirements for the RLA will add a load of 6.3 MW which is within the capacity of the existing SLAC substation. Beam guidance instrumentation and control will be installed and centralized in the existing control room.

A special off-axis injector will be provided as a source for the 17.5 GeV beam and modifications will be made in the beam switchyard to handle the new higher energy beams. The housing for the loops will be covered with 15 ft. of earth shielding, and protection systems will be incorporated to make radiation levels entirely negligible.

3. Beam Dynamics

3.1 General Characteristics

The beam dynamics of the RLA generally resemble the dynamics of the Cornell Electron Synchrotron[5] with a few outstanding differences:

1. Since the energy and all the magnetic fields are held constant, the problem of moving the beam through the transition energy does not exist. The electron bunches will normally be located on the falling side of the RF wave.

2. Because the recirculator contains about 6000 m of straight drift length with fairly closely spaced quadrupole lenses, it is possible to make adjustments in the betatron tune without affecting the bending system.

3. The reverse bends provide a continuous adjustment on the momentum compaction, $\alpha = (\delta\ell/\ell)(E_0/\epsilon)$. Here $\delta\ell/\ell$ is the fractional change in path length due to the fractional change in energy ϵ/E_0; E_0 is the nominal energy of the stored beam. Normally α would be small, i.e., $10^{-5} < \alpha < 2\times10^{-4}$. The low value for α is necessary to keep the short bunch length which must be preserved if the beam is to have a reasonable energy spectrum after the second acceleration.

4. The long drift length reduces the RF power required by reducing the relative time the beam spends in the bending magnetic field. Since the storage period is only 2.8 ms, the effect of the long path is to reduce the number of revolutions to the relatively small value of about 122.

3.2 Recirculating Lattice

The main bend lattice is expected to consist of alternating gradient cells. In order to reduce the driving of radial phase space blow-up by synchrotron quantum fluctuations, it is desirable to reduce the rms value of the η-function. The η-function defines the off-momentum equilibrium orbit. This reduction is achieved by using a short betatron wavelength, resulting in short cells, each containing only two high gradient magnets.

Numerous alternative cells have been investigated by means of the TRANSPORT[6] and SYNCH[7] computer programs. The properties of a promising looking main bend lattice are summarized in Table I. Each cell contains

TABLE I

MAGNET LATTICE PARAMETERS

Number of Betatron Wavelengths (rounded to nearest integer):			
	Main Bends	Straight Sections	Total (including misc.)
Horizontal	11 each	6 total	31
Vertical	5 each	6 total	19

Beam Path Lengths (6900 m total including miscellaneous):		
Main Bends	Reverse Bends	Main Tunnel
2 × 375 m	2 × 154 m	3090 m east 2230 m west

Recirculator Period	Recirculator Frequency	Harmonic Number
23 μsec	43.5 kHz	6.6×10^4

Estimated beam size: ± 0.7 cm maximum radial and vertical.
Path length dispersion per 210° bend: $\langle \delta\ell | \epsilon/E_0 \rangle = 1.125$ m.
Damping factor: D = 1.56

two 3^o bending magnets. The mean field is 6.58 kG at 17.5 GeV. Figure 3 shows the resulting function η, and the betatron functions β_x and β_y.

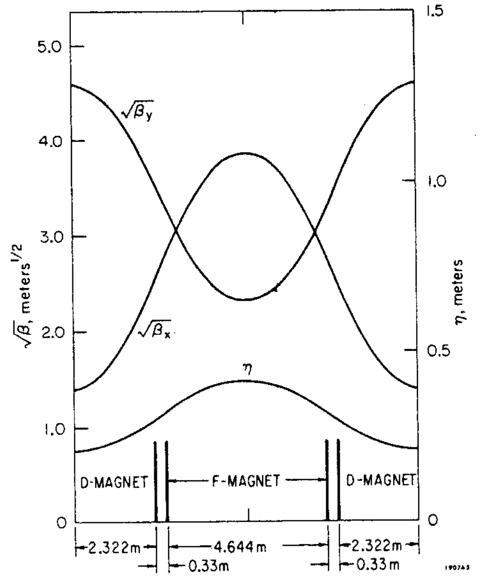

FIG. 3--η, β_x and β_y functions.

The matching of the η-function between the main bends and the adjacent straight sections is accomplished by a system consisting of a bending magnet which disperses the beam and a quadrupole which focuses the dispersed off-momentum rays.[8] With proper choice of spacing of the elements and quadrupole strength, the proper values of η and η' in the bending ring are matched to the condition $\eta = \eta' = 0$ in the straight sections. The overall transformation through the main bend is then achromatic, and $\langle\eta^2\rangle$ is minimized within the bending lattice. The proposed system is shown in Fig. 4. The

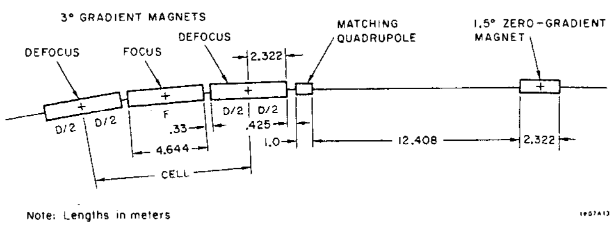

FIG. 4--Section of main ring showing η-matching section and one complete cell.

main bend terminates in a full-length D-magnet (radially defocusing) at each end. The 1.5° bending of each η-matching magnet then makes the total bend an integral multiple of 6°.

The reverse bends, in addition to bending the beam into and out of the main accelerator housing, serve the additional purpose of providing a continuous adjustment of the momentum compaction. The reverse bend layout is shown in Fig. 5. The four 7.5° bends each consist three 2.5° magnets. The off-momentum ray is focused by the doublet and passes through the central bend with negative dispersion — i.e., inside the mean ray. The symmetry quad symmetrizes the off-momentum ray thus making the overall system achromatic. By varying the horizontal focal length of the doublet, the total path length difference may be varied over a finite range.

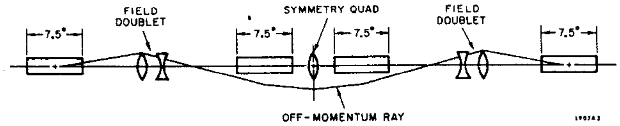

FIG. 5--Dispersion-ray diagram for reverse-bend system. Each 7.5° bend consists of three 2.5° magnets.

Each of the main bends contributes about 1.1 m to this matrix element. Thus, for a design value of $\langle\delta\ell|\epsilon/E_0\rangle \approx 0.7$ m for the entire recirculator, the matrix element for each reverse bend should be $\langle\delta\ell|\epsilon/E_0\rangle \approx -0.75$ m. This corresponds to a momentum compaction of $\alpha = \langle\delta\ell|\epsilon/E_0\rangle/L \approx 1\times10^{-4}$ (where $L \approx 6900$ m is the total path length). Solutions have been found which are variable over a range of -0.75 ± 0.25 m, giving a net momentum compaction which may be varied within the range $3\times10^{-5} < \alpha < 17\times10^{-5}$. The vertical focal strength of the doublets may be varied to keep the vertical transport properties of the system nearly constant.

The calculation of damping rates employs the damping factor D, defined by Sands[9] as

$$D = \frac{\oint \eta(s)\, G(s) \left[G(s)^2 + 2K_1(s)\right] ds}{\oint G(s)^2\, ds}$$

which becomes $D = 1.56$ for the complete loop of the RLA. The function G(s) is the bending term defined by $G(s) = 1/r(s)$ and the function $K_1(s)$ is the focusing term $K_1(s) = (ec/E_0)(dB(s)/dx)_0$ evaluated on the design orbit, $x=0$. The function $\eta(s)$ is the equilibrium orbit for an off-momentum particle defined by $x(s) = \eta(s)\,\epsilon/E_0$.

The damping rates are given by $\alpha_i = J_i(fU/2E)$ where f is the circulating frequency and U is the energy lost per turn to synchrotron radiation. The coefficients J_i are the damping partition numbers given by $J_s = 2+D$ for synchrotron phase oscillations and $J_x + J_y = 2-D$ for the horizontal and vertical oscillations. As long as the J_i's are positive, the motion is damped. In the absence of x-y coupling, $J_y=1$ and $J_x=1-D$. The recirculator will, however, have x-y coupling because of the tilted plane of the west loop. Thus, the damping partition number J_x will become less negative due to the x-y coupling. However, for the small values of J_x that are anticipated, the antidamping rate is so slow as to be negligible during the 2.8 ms storage period for the energy range being considered. If the energy range of the RLA is increased in the future, it is possible to modify D by introducing special magnetic elements.

3.3 RF System

Phase stability in the RLA is achieved by placing the bunches of electrons on the falling side of the RF wave just as in a conventional synchrotron operating above the transition energy. The farther the beam is phased off crest, the stronger the phase focusing becomes, but also the more peak RF voltage must be supplied. The synchrotron phase oscillations which result from quantum fluctuations in electron energy tend to be smaller in amplitude and more rapid as the bunches are phased farther off crest. However, the phase oscillations also depend on the momentum compaction parameter; the lower values of α result in smaller amplitude phase oscillations for the same energy excursion, but at a lower synchrotron oscillation frequency. These interrelations are shown in Table II[10] for the case of 17.5 GeV. Since the initial spread in phase and energy ($\epsilon_0/E_0 \approx 0.3\%$, $\delta\phi_0 \approx 4°$) will likely be less than the damped values shown, and since the storage time is comparable to the synchrotron damping period, it is probable that the resultant phase and energy amplitudes will be less than those shown in Table II.

TABLE II

SYNCHROTRON OSCILLATION PARAMETERS FOR 17.5 GeV

U = 125 MeV/turn μ_c = 134 keV

α_0 = 157 sec^{-1} α_s = 550 sec^{-1}

Synchrotron damping period = 1.8 msec

Momentum spread (at damped equilibrium) = 0.12%

V_{RF} (MV)	ϕ_s (degrees)	T_s (turns)	ϵ_m/E_0 (%)	σ_ϕ (degrees)	$T_{quantum}$ (msec)	i_p (mA)
			Momentum Compaction $\alpha = 0.5 \times 10^{-4}$			
130	16	30	.33	6.8	1.1×10^1	8.8
135	22	26	.54	5.7	3.0×10^3	6.9
140	27	23	.73	5.1	6.6×10^6	4.7
			Momentum Compaction $\alpha = 1 \times 10^{-4}$			
135	22	18	.39	8.0	3.1×10^1	6.9
140	27	16	.52	7.2	1.1×10^3	4.7
145	31	15	.63	6.7	8.7×10^4	2.1
			Momentum Compaction $\alpha = 1.5 \times 10^{-4}$			
140	27	13	.42	8.9	7.4×10^1	4.7
145	31	12	.52	8.2	1.2×10^3	2.1
150	34	11.5	.61	7.7	2.9×10^7	0.0

In this table, U is the energy lost per turn by synchrotron radiation and μ_c is the critical energy of the synchrotron radiation. The damping rates are given by $\alpha_0 = fU/2E_0$, where f is the recirculator frequency, and $\alpha_s = (2+D)\alpha_0$. V_{RF} is the peak value of the RF voltage, ϕ_s is the synchronous phase angle and σ_ϕ is the standard deviation of phase angle. T_s is the synchrotron oscillation period and ϵ_m/E_0 is the momentum acceptance of the system. The quantum lifetime $T_{quantum}$ is the expected lifetime of an electron due to the possibility that a quantum fluctuation will excite phase (energy) oscillations out of the RF bucket. For negligible losses during the storage period, the quantum lifetime should be $T_{quantum} \gg 100\ T_s$, i.e., several hundred milliseconds. It can be seen that this condition is amply fulfilled for the higher peak voltages. The last column shows the peak pulsed current that can be recirculated assuming that the maximum unloaded RF voltage is 150 MV.

The steady-state beam loading voltage induced in the SLAC accelerator is found to be 0.037 MV/mA per section or 2.37 MV/mA for 2 sectors (64 sections). This steady-state value is attained after the 0.8 μs transient, i.e., the structure filling time. It is possible to compensate for this transient by delaying the RF pulse of some of the klystrons during the filling time. This method is similar to the technique used regularly on the two-mile accelerator. If compensation for transient beam loading is done imperfectly, the bunch centroids will execute phase oscillations whose amplitudes must be added to the amplitudes of the phase oscillations within the bunches to determine the effective bunching of the stored beam.

The amount of current that can be recirculated is maximized if, after the transient effects have died out, all the klystrons are identically phase. Referring to Fig. 6, it

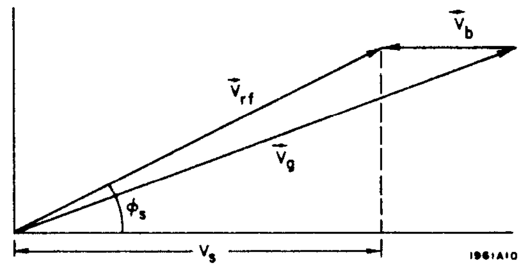

FIG. 6--Vector diagram showing the addition of the generator voltage V_g and the beam induced voltage V_b to result in the final RF voltage V_{RF} where ϕ_s is measured from the wave crest.

can be seen that the effective RF voltage is the vector sum $\vec{V}_{RF} = \vec{V}_g + \vec{V}_b$ where V_g is the amplitude of the unloaded voltage produced by the klystrons and V_b is the amplitude of the beam induced voltage. The voltage V_s required to replace synchrotron radiation losses is then given by $V_s = V_{RF} \cos\phi_s$. The values of V_{RF} and ϕ_s given in Table II can be used to calculate the maximum value of V_b, using the simple relation $V_b = [V_g^2 - V_{RF}^2 \sin^2\phi_s]^{1/2} - V_{RF}\cos\phi_s$. From these, one obtains the peak recirculating current given in the last column, assuming V_g = 150 MV. It is seen that for a reasonable quantum lifetime of ~1 second, about 7 mA can be recirculated at $\alpha = 0.5 \times 10^{-4}$. At a lower recirculating energy, using the full 150 MV of RF voltage, it is possible to recirculate considerably more current up to the point where loading in the main accelerator becomes the limitation. Thus, for example, at 17.0 GeV, over 10 mA can be recirculated and at 15.0 GeV, over 30 mA can be recirculated.

3.4 Instabilities and Tolerances

The following instabilities and special beam problems were the subject of a summer study[12] at SLAC and are still being studies:

1. x-y coupling due to the tilted plane of the westloop.
2. Betatron tune shift due to chromaticity.
3. Head-tail effect.
4. Betatron tune shift due to ion neutralization.
5. Synchrotron tune shift due to space charge.
6. Synchrotron phase spread due to RF jitter.
7. Beam breakup due to transverse RF mode excitation.
8. Alignment tolerances.

A detailed discussion of these effects is too long for this paper and will eventually be presented in subsequent papers on the RLA. The preliminary estimates that have been made for these effects have pinpointed some areas (such as for example, RF jitter) where some special care will be necessary. However, none of the instabilities studied so far such as head-tail or beam breakup appear to be significant or uncontrollable at the currents proposed for the RLA.

Acknowledgements

The authors wish to acknowledge the contributions of a large number of SLAC colleagues who are participating in the RLA study. Special thanks are due R. J. Gould and J. R. Rees. In addition, they are indebted to the members of the RLA Summer Study held at SLAC, June 7th - 18th, 1971 which included E. D. Courant (BNL), E. Freytag (DESY), K. Halbach (LBL H. A. Hogg (SLAC), C. J. Kruse (SLAC, R. H. Miller (SLAC), P. L. Morton (SLAC), D. Mohl (LBL-CERN), W.K.H. Panofsky (SLAC), C. Pellegrini (Frascati), J. R. Rees (SLAC), B. Richter (SLAC), M. Sands (U.C. Santa Cruz), A. Sessler (LBL), L. Smith (LBL), and L. Teng (NAL). Separate, more comprehensive notes produced during this study will be published at a later date.

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