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HIGH-YIELD POSITRON SYSTEMS FOR LINEAR COLLIDERS

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ABSTRACT

Linear colliders, such as the SLC, are among those accelerators for which a high-yield positron source operating at the repetition rate of the accelerator is desired. The SLC, having electron energies up to 50 GeV, presents the possibility of generating positron bunches with useful charge even exceeding that of the initial electron bunch. The exact positron yield to be obtained depends on the particular capture, transport and damping system employed. Using 31 GeV electrons impinging on a W-type converter target, and with adequate matching of the positron beam phase-space at the target to the acceptance of the capture RF section, the SLC source is capable of producing, for every electron, up to two positrons within the acceptance of the positron damping ring. The design of this source and the performance of the positron system as built are described. Also, future prospects and limitations for high-yield positron systems are discussed.

1. INTRODUCTION

To achieve high luminosity at the interaction region of a linear collider, both the positron and the electron beams must have high intensity and low emittance. The emittance considered here includes the full six-dimensional phase-space volume ($x, x', y, y', dP/P$, and dz). RF linacs for high-energy acceleration operate with pulse repetition rates in the range of hundreds of Hz. It is possible to accelerate many more than one microbunch of particles in a single RF pulse, but for colliders, the disruption of the initial colliding pair of bunches at the interaction point presently precludes any usefulness of closely following pairs. Thus the luminosity is proportional to the intensity of a single microbunch. In conventional RF accelerating structures, the useful intensity is limited by the beam-induced fields interacting back on the beam in the form of wakefields. Since these intensity limitations apply equally to the acceleration of positrons and electrons, the positron source system must be able to deliver at least as many positrons to the linac as the electron source and at the same pulse rate. This requirement is the primary difference between positron source systems designed for linear colliders and those designed for other types of accelerators. One might note in particular that storage rings do not require a high-intensity positron source in any critical sense.

For the SLC, which is designed to operate at a maximum of 120 Hz, the flux required per beam is 6×10^{12} particles sec^{-1}.

2. METHODS OF PRODUCING POSITRONS

Two methods have been used to produce positrons for accelerators. The principle method, pair-production, will be discussed below. The second method, incorporating various forms of nuclear β-decay, has been utilized until now only in small, low energy accelerators, but may prove useful for future generations of colliders. Several (np) reactions have been proposed as a source of very high positron flux.[1] In particular, the $^{58}Ni(np)^{58}Co$ reaction has been singled out because the neutron-activated material can be transported and enriched outside a fission reactor. The maximum expected flux from this reaction, 10^{15} e^+ sec^{-1}, could be improved upon by use of the $^{63}Cu(n\gamma)^{64}Cu$ reaction, but present radiation handling techniques would require in-reactor post-activation enrichment. Although the technical means to produce positron fluxes of these magnitudes exist, the subsequent formation of high-brightness pulsed beams is not well defined.

Bombardment of positron emitters with energetic protons generated in the plasma of a fusion reaction has also been suggested as a route to high positron flux.[2]

High-flux nuclear β-decay positron sources may prove more useful in the foreseeable future for high-duty-factor accelerators than for linear colliders.

At present, all positron sources for high-energy accelerators generate positrons in a converter target by pair-production. The basic mechanism for the production of electron–positron pairs by photons is well described in the literature. When traversing material, photons of sufficient energy will initiate a cascade shower involving pair-production, Compton scattering and bremsstrahlung. For photons above 10 MeV, pair-production dominates over Compton scattering.

Accelerator positron sources in use or proposed for the near future differ in the method of obtaining photons for initiating the cascade shower. The initial photons can be produced external to the material, or with impinging electrons they can be produced within the material itself by bremsstrahlung.

Although bombardment of a converter target by high energy electrons is the conventional technique, there are some inviting features to using photons to initiate the cascade shower. The proposal for the VLEPP collider includes a positron source in which the high energy post-collision bunch is transported through a helical undulator to produce very high energy circularly-polarized photons.[3] The electrons are then bent out of the way and the photons are allowed to continue straight ahead and impinge on a positron converter target. The positrons exiting the target are then collected and transported to the beginning of the positron linac. For unity yield, the electrons must have an energy $\geq$100 GeV and a long, very strong undulator is required. The unique feature of the proposed VLEPP positron source proposal is the production of polarized positrons.

A different proposal for producing the initiating photons is to use channeling. Channeling is a thoroughly studied technique in which high energy particles are passed through a crystal that acts as an atomic wiggler. Chehab and colleagues at ORSAY have proposed directing a multi-GeV e^- beam along the <110> axis of a Ge or Si crystal to produce photons for initiating a cascade shower in a converter target.[4] They conclude that with an SLC-type positron collection system, a yield $\geq$ 1 could be achieved for 20 GeV incident electrons. The advantage of this method over the conventional one with electrons incident on the converter is that the heating of the converter itself, which is a serious limitation for collider sources, is expected to be less severe. However, the resistance of the crystal to radiation damage is yet to be tested.

As stated above, all high energy accelerators with positron sources now initiate a cascade shower by using high energy electrons impinging on a converter to produce radiation by bremsstrahlung. To optimize the yield, a high-Z material with a thickness equal to shower maximum is chosen for the converter. The incident e^- beam must have a multi-GeV energy to give a yield on the order of unity.

The positron yield at any point in a conventional positron system depends on the details of at least three factors. The yield is here defined as the ratio of positrons at a given point in the system to the number of electrons impinging on the converter target. Defined this way, the properties of the electron beam—the beam cross section and bunch length at the converter as well as the energy—are important. The second factor is the positron collection efficiency downstream of the converter. Finally, the phase-space properties required of the final positron beam must be taken into account. Each of these three factors will be elucidated below by using the example of the SLC positron source.

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3. PROPERTIES OF INCIDENT e^- BEAM

The SLC is the first linear electron–positron collider to be built. It has the only operating high-yield positron source. The SLC source is used here to illustrate the factors that determine the yield. A schematic representation of the collider is shown in Fig. 1. The SLC has a single 50 GeV 3-km RF linac. To produce positrons, an electron bunch is damped after initially being accelerated to 1.2 GeV, then accelerated to approximately 31 GeV at the two-thirds point, where it is deflected onto a converter target. Positrons from the converter are collected, accelerated immediately to 220 MeV, transported 2 km back to the beginning of the linac, reinjected into the linac and accelerated to 1.2 GeV. The positrons then have their transverse emittance damped in a separate damping ring (DR) and finally are accelerated to 46 GeV along with a companion electron bunch. With the aid of the two arcs, the e^-/e^+ bunch pair is finally brought to collision at the final focus. The present e^- beam parameters at the converter are given in Table 1.

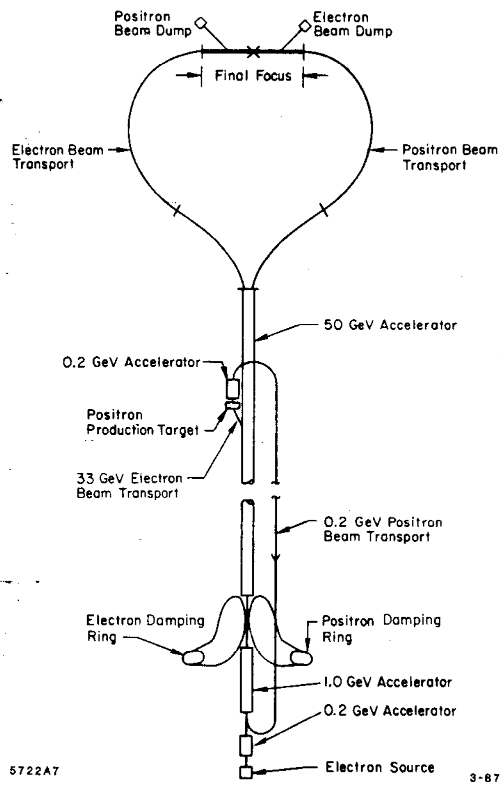

Fig. 1: Overall layout of the SLC.[5]

Table 1: Properties of incident electron beam.

Parameter	Typical Value	SLC Specification
$\sigma_x = \sigma_y$	0.6 mm	0.6–0.8 mm
σ_E	0.5%	0.5%
σ_z	0.5 mm	0.5 mm
E	31 GeV	30–35 GeV
Intensity	2×10^{10} e^- pulse^{-1}	7×10^{10} e^- pulse^{-1}
Rate	10–30 Hz	120 Hz

The positron yield is fairly insensitive to the electron beam energy spread and bunch length. The beam size at the converter is established by a spoiler located just upstream. Under normal conditions the positron yield depends strongly on the position of the beam at the target. A feedback loop corrects the target position to within 100 μm every six minutes. A history plot of the command variable for this feedback loop indicates that the position rarely strays more than 300 μm before correction. (In part, this is because the extraction line transporting the e^- beam from the linac to the converter is not only designed to be achromatic, but also because its magnets are scaled in energy every six minutes by a second feedback loop.)

4. COLLECTION OF POSITRONS

A sketch of the SLC positron system[6] between the converter target and the beginning of the 220 MeV transport line returning the positrons to the beginning of the linac is shown in Fig. 2. The target is closely followed by RF-accelerating sections to minimize any increase in phase-lag, and to boost the energy to 220 MeV. Solenoidal fields surround the target and the first portion of the accelerator, followed by a F0D0 array that continues for the remainder of the return line. The two 180° bending systems—a vertical bend shown in Fig. 2 after the booster linac and a horizontal bend not shown near the 1.0 GeV linac reinjection point—are both achromatic and isochronous. The transport system is designed to have an acceptance of $\gamma\epsilon = 10^{-2}$ m.

The converter target itself is shown in Fig. 3. It consists of a cylinder of W–26 Re that is 6 mm in radius and six radiation lengths long (about 20 mm). The target cylinder is encased in cast sterling silver embedded with stainless-steel tubes for water cooling. This target has operated for about one year with incident e^- pulse rates of 10–30 Hz and an intensity of generally 2×10^{10} e^- pulse^{-1}. No target deterioration can be detected after the estimated total of 2×10^8 pulses. Computer-modeled simulations of the heat stresses induced in the target material by the incident e^- beam indicate that the maximum power capability of this target is about 7.5 kW at 60 Hz. A higher-power target, which is scheduled for installation in Fall 1989, is described later.

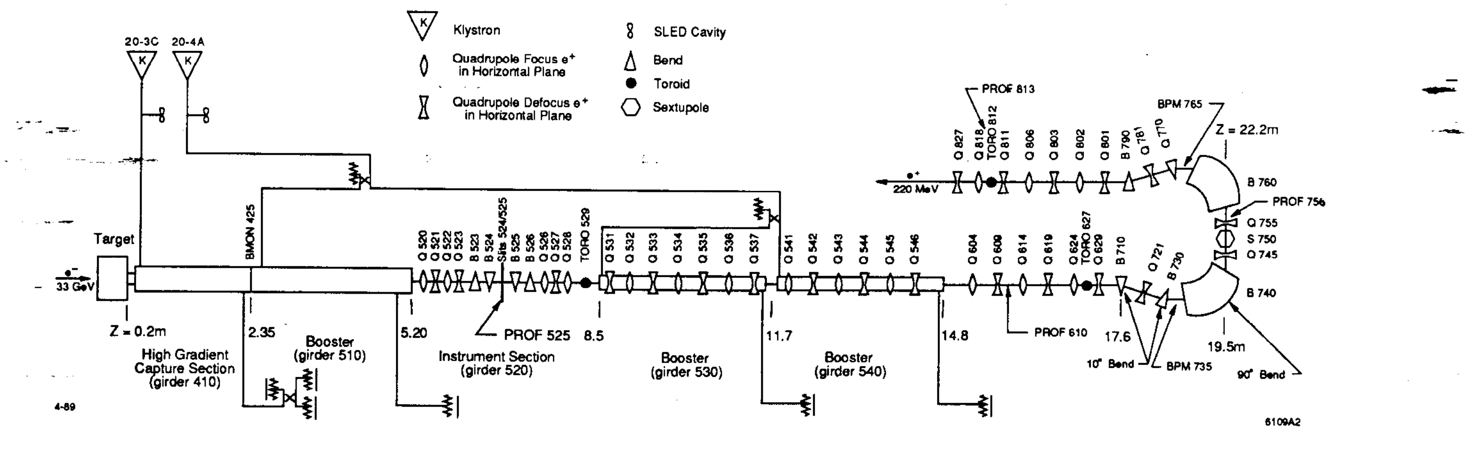

Fig. 2: Positron-dedicated linac and initial transport system.

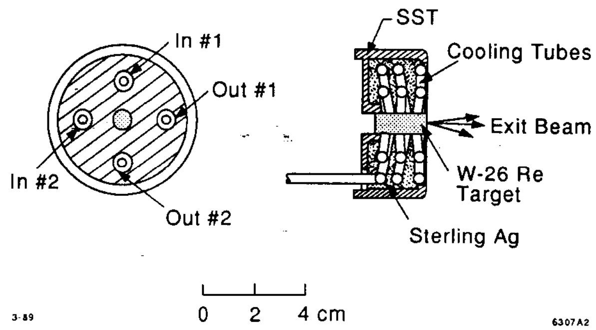

Fig. 3: Cross section of the present SLC converter target.

The time structure of positrons exiting the target is similar to that of the incident e^- beam. The energy distribution of the usable positrons peaks at about 10 MeV, with a significant number of lower-energy particles. To avoid debunching, as well as to minimize the transverse emittance, it is desirable to accelerate the positrons to ultrarelativistic energies as soon as possible. However, the positrons, which emerge from the target in a phase space with small radial extent but large angular dispersion, must first be matched to the acceptance of the capture section with its relatively large radial extent but small angular acceptance.

For this phase-space transformation, most accelerator positron sources use a quarter wave transformer (QWT).[7] Although a QWT makes a significant improvement in yield over a simple solenoid, it does have a fairly narrow energy bandpass. For the original SLAC positron source, Helm proposed an adiabatic matching field that would have a large energy acceptance.[8] Other possible focusing techniques include a *Li* lens, or even a pulsed current through the target material itself.

A pulsed magnetic field provided by a flux concentrator (FC) added to a tapered DC field provides a pseudo-adiabatic phase-space transformation for the SLC source. The FC, which is placed as close to the target as possible (3 mm), consists of 12 turns with a conical internal cross section. To maintain the efficiency of the device, the turns are cut from a solid block of *Cu* by EDM (electric discharge machining) using a 50 μm wire. After cleaning and work hardening, the spacing between turns is 100–150 μm, which is still less than the skin depth at 100 kHz. No insulating materials are used in the FC except for ceramic supports at the low voltage end.

The FC in relation to the target and the following accelerator section is shown in Fig. 4. The target and FC are surrounded by a DC tapered-field solenoid while a DC uniform-field solenoid surrounds the accelerator. The DC field profile calculated by POISSON is shown in Fig. 4, along with the measured field of the FC. The values of the relevant parameters are given in Table 2.

Table 2: Magnetic field properties.

Flux Concentrator	
Number of turns	12
Spacing	0.15 mm
B_{peak}	5.8 T at 16 kA
Pulse	100 kHz, half-sinewave
Tapered Field Solenoid	
B_{peak}	1.2 T
Uniform Field Solenoid	
B	0.5 T

For an adiabatic device, the field should be as high as possible at the target, then slowly taper to a lower uniform value.

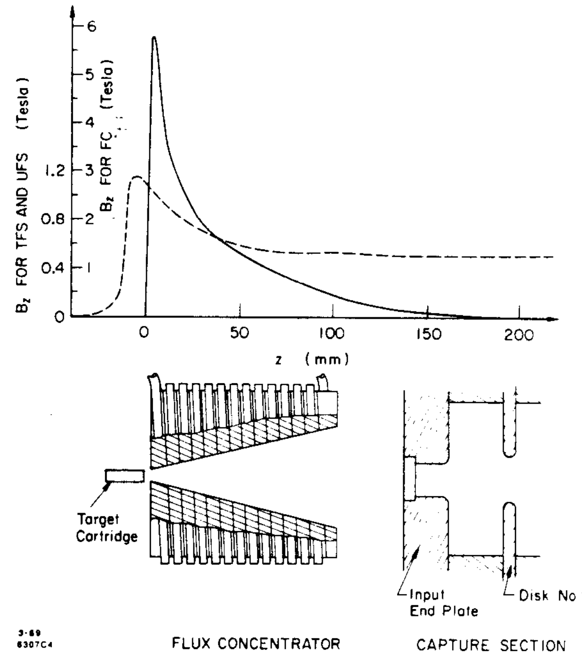

Fig. 4: The SLC pseudo-adiabatic phase-space transformation system. The units shown in cross section at bottom are to scale. The computed DC solenoidal fields and measured FC pulsed field are shown above with the same z-scale.

The condition shown by Helm to be sufficient for an adiabatic transformation is

$$\epsilon \equiv \left| \frac{P \, dB/dz}{e \, B^2} \right| \ll 1 \quad ,$$

where P is in units of mc and B in mc/e per meter. Although the combined solenoidal field of the SLC source is only pseudo-adiabatic ($\epsilon \sim 0.3$), the bandpass is in fact slightly larger than the ± 10 MeV acceptance of the two 180° bend systems.

5. ACCELERATION AND TRANSPORT

RF acceleration begins immediately following the FC. The capture section is a 1.5 m, travelling wave, disk-loaded waveguide operating at the standard SLC linac frequency of 2856 MHz. A constant-impedance structure with an iris of 9 mm radius was chosen to maximize the radial acceptance. The section is powered with a dedicated SLAC 5045-klystron operating with a 3.5 μsec RF pulse into a SLED cavity. The section has been partially processed to an accelerating gradient of 50 MeV/m without beam, and now operates routinely with high-intensity beams at 40 MeV/m.[9]

The high-gradient capture section is followed by the first of three standard SLAC 3-m accelerating sections powered by a second 5045-klystron with a SLED cavity, as shown in Fig. 2. Again, to achieve rapid acceleration, the first section receives half the RF power. The uniform field solenoid ends with the first booster section, after which the quadrupole F0D0 lattice begins.

6. COMPUTER SIMULATIONS

The shower cascade in the converter target can be calculated in detail with a Monte Carlo program called EGS.[10] This program is used to establish a matrix of positrons at the exit of the target, each particle being tagged for position, momentum and time. To track these particles through the solenoidal and accelerating fields of the source region, a relatively simple ray-tracing program, ETRANS, by H. Lynch, has been written at SLAC to facilitate setup and variation of parameters. ETRANS ignores the effects of space charge and wakefields. The effect of the F0D0 lattice must be separately studied using a more complete program such as TURTLE. Fig. 5 shows some positron

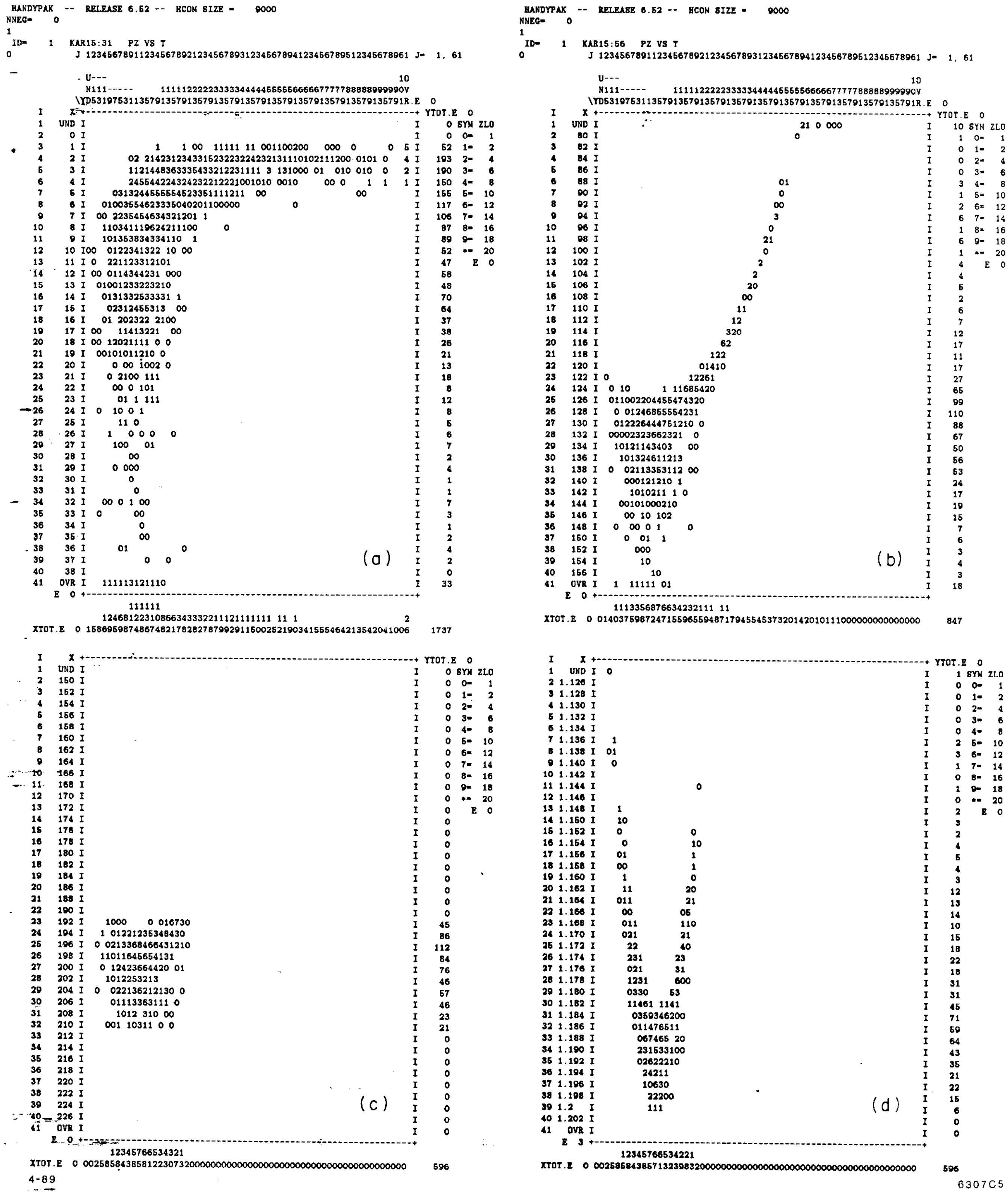

Fig. 5: Energy (ordinate in MeV) and time-lag (abscissa from −15 to +101 psec) distributions generated using ETRANS for 200 incident e^- particles. The total number of positrons is shown in the lower righthand corner. The final acceptance at the LTR is $\Delta t = \pm 18$ ps. The four distributions correspond to: (a) Positrons immediately after the flux concentrator; (b) Positrons after first booster section, including the angular cut of the F0D0 lattice and with the RF phase adjusted for prompt acceleration; (c) Positrons after the energy cut of the first 180° turn; and (d) Positrons at 1.2 GeV, before the phase cut of the bend to LTR.

energy and time-lag distributions generated from ETRANS by Kulikov. The initial EGS matrix used here is based on 200 electrons hitting the target. Fig. 5(a) shows the positrons exiting the FC. These 1737 positrons are reduced to 847 by the time they emerge from the first booster section at about 120 MeV, when the simulation results can be compared with measured values. The energy-phase correlation seen in Fig. 5(b) is a typical result of RF acceleration. The distribution of Fig. 5(b) includes the effect of the quadrupole lattice (a 4.6 mrad cut) between the first booster section and the measuring toroid (TORO 529). In the simulations, the energy is boosted to 200 GeV. The distribution of Fig. 5(c) includes the ±5% energy cut of the first 180° bend. The remaining 596 positrons are expected to make it to the end of the 1.0 GeV linac, as shown in Fig. 5(d).

The measured yield is compared with the simulation results in Table 3. The conditions for this comparison are given in Table 1 (except the simulation here uses E = 33 GeV and σ_z = 2 mm for electrons) and in the first part of Table 3. The results agree well until the positron beam is injected into the linac-to-ring (LTR) transport line to the damping ring. The LTR energy acceptance is ±2.5%, which should accommodate the energy spread in the beam generated in accelerating to 1.2 GeV by the rather large bunch length. At present, about 30% of the charge in the LTR is apparently lost because of a very long, low energy tail, the origin of which is not yet understood. Another loss of approximately 20% occurs in the 1.0 GeV linac itself, possibly due to a beta mismatch. The measured and predicted beam parameters are compared in Table 3.

Table 3: Comparison of design and measured results.

	Design or Simulated	Measured or Operational
Conditions		
Flux concentrator	5.8 T	5.0 T
Tapered field solenoid	1.2 T	1.1 T
Uniform field solenoid	0.5 T	0.5 T
Return line energy	200 MeV	220 MeV
Magnets	All at model values	All but 1 at model values
Yield (e^+/e^-)		
End of first booster section	4.2	4.4
Injection into 1.0 GeV linac	3.0	2.7
After injection into LTR	3.0	1.4
Positron beam parameters in LTR		
σ_Z	2.0 mm	2.9 ± 1.0 mm
σ_E	1.0%	0.8 ± 0.1 %
γ^ϵ	250 × 10^{-5} m	(150 ± 50)× 10^{-5} m

7. NEW DEVELOPMENTS AT SLC

The positron LTR was originally designed for an energy acceptance of ±1.6%, or, correspondingly, a bunch length (or phase) acceptance of ±15 psec. The acceptance of the damping ring turned out to be about ±1.0% and some losses were experienced between the LTR and the DR. Since an energy-phase correlation already existed in the LTR bunch, it was decided to better match to the DR energy acceptance by installing an energy compressor in the LTR. The technique is to pass the beam through the zero-crossing of the RF of a 3-m accelerating section newly installed in the high-dispersion region of the LTR. With the correct RF phase and amplitude, the beam energy dispersion should be significantly reduced. To realize the full potential of the compressor, the aperture of the upstream portion of the LTR has been opened to ±2.5%. The LTR now shows no loss, but the DR parameters still have to be properly set to eliminate a loss of about 25%, which is now seen in the first five turns. (A final loss of about 25% while the beam is stored and extracted is also expected to be eliminated.) The present yield at the final focus is about 0.7 positrons for every electron at the converter target.

To accomodate the 40 kW of beam power expected at the converter target when the SLC is fully operational, a new moving target module is being prepared. This will be a W–26 Re target in a cast sterling silver cooling jacket, similar in design to the present target described above, except that it will have a much larger radius of 32 mm. The target will be trolled from the side through a long-life hydro-formed bellows (lifetime ~ 10^8 cycles) at a rotational frequency of 1.7 Hz for a 120 Hz SLC beam rate. Computer-simulated heat-stress studies indicate this target can accomodate up to $7{\times}10^{10}$ e^- pulse^{-1} at 120 Hz if the beam width is $\sigma \geq 0.8$ mm.

8. FUTURE POSITRON SOURCES FOR COLLIDERS

Several possibilities for positron sources for future colliders were indicated earlier. An effort is now underway to find a very high power positron source for the multiple microbunch beams desired for a future B-factory. Sievers is developing a conceptual design for a 1.5 MW rotating target with high tangential speed.[11] To somewhat overcome the effect of the expected breakup of the high-Z target material, he proposes placing many small targets inside individual graphite containers around the periphery of a large wheel. The individual targets must be water-cooled from the inside radius of the wheel, as well as from the outside. Studies of the intense radiation and heat problems, as well as unique focusing techniques, continue.

ACKNOWLEDGMENTS

A large number of physicists, engineers and technicians from SLAC and elsewhere have worked diligently over the past few years to design, build and commission the SLC positron source. In particular, the design work proceeded principally under the direction of Stan Ecklund. In addition to important contributions in all areas, Artem Kulikov is recognized for his seminal work in developing the present SLC flux concentrator.

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