

## The North Arc of the SLC as a Spin Rotator\*

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### ABSTRACT

The 1992 running cycle of the Stanford Linear Collider (SLC) showed that the orientation of the electron polarization vector at the interaction point was very sensitive to the vertical orbit in the north collider arc. We point out the reason for this sensitivity—the spin tune is equal to the vertical betatron tune. We devise a scheme of closed vertical orbit bumps which provide arbitrary manipulations of the polarization vector at the IP. We have developed an analytical model for the tuning of this ‘arc spin rotator’ and have performed a detailed numerical analysis to show its effectiveness. We present experimental results.

### I. INTRODUCTION

The SLC arcs bend the beams from the end of the linac into the Final Focus area where the beams collide. They are about a mile long and densely stacked with combined function magnets. The quadrupole field of these magnets is very strong—their focal length is 1 meter.

The spin motion, more precisely, the motion of the spin expectation value of the beam, is given by the BMT equation [1],

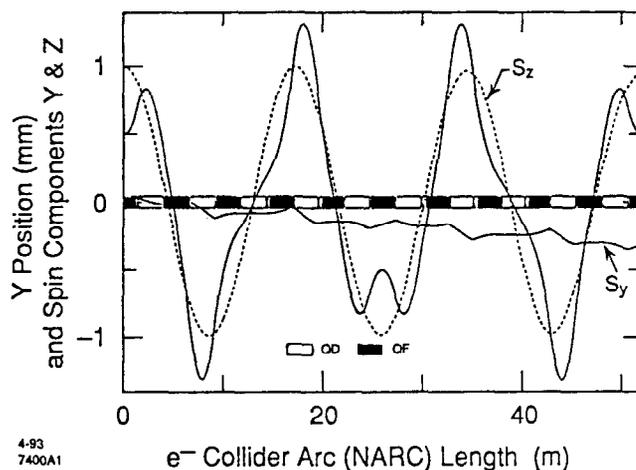
$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}. \quad (1)$$

The spin  $\vec{S}$  rotates around the magnetic field  $\vec{\Omega}$  in the rest system of the electron. If an electron is deflected in a transverse magnetic field by an angle  $\phi$ , the spin is rotated around the field axis by

$$\phi = a\gamma \cdot \phi, \quad (2)$$

where  $a$  is the anomalous momentum of the electron and  $\gamma$  the Lorentz factor.

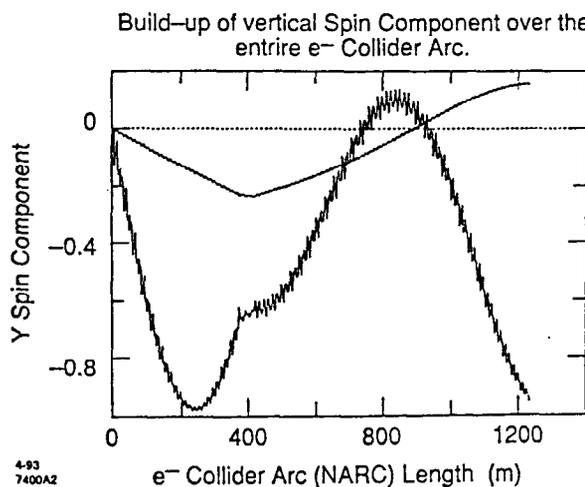
At the beam energy corresponding to the peak rate of Z particle production (45.6 GeV) the spin phase advance,  $\Delta\phi$ , and the vertical betatron phase advance are equal ( $108^\circ$  per cell). The additional spin rotations experienced by a particle performing vertical oscillations therefore add in resonance. This resonant build-up is shown in Fig. 1. The vertical component of the spin is steadily increasing as the betatron motion of the particle and the spin tune (indicated by the longitudinal component) are in phase.



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Fig 1. Vertical orbit and the vertical and longitudinal spin components over the first of twenty-three achromatic sections of the arc. The particle is launched with a vertical offset of 0.5 mm, the spin with longitudinal orientation.

To illustrate how drastically vertical orbit changes in the arc can alter the arc spin transport, Fig. 2 shows the vertical spin component of two particles with 0.5 and 0.05 mm vertical launch offset over the entire arc. The spin at arc entrance points again in the longitudinal direction. At the reverse bend section (400 m), a phase slip occurs between spin and betatron phase advance.



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Fig 2. Vertical spin component over the entire arc for particles of 0.5 and 0.05 mm vertical launch offset.

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The impact on the SLC operation was originally observed as a very sensitive dependence of the longitudinal polarization at the IP on the vertical orbit launch into the arc. The main effect, however, is not caused by depolarization but by a mere rotation of the polarization axis, since the vertical beam size is only 40  $\mu\text{m}$  (20  $\mu\text{m}$  for flat beams). However, the precision of instrumentation and orbit correction in the arcs proved sufficient to provide stable polarization orientation at the IP. The solenoid spin rotator magnets in the damping ring area could be used to compensate for the arc spin rotation and orient the spin at the IP into the longitudinal direction [2].

Colliding flat beams to increase the luminosity of the SLC [3] would have increased the difficulty of optical matching through the solenoid rotators. Beam rotations would have to be compensated and emittance preserved, requiring additional hardware (at least eight skew quadrupole magnets) and new tuning techniques. Therefore, we investigated the possibility of using controlled manipulations of the vertical orbit in the arc to orient the spin at the IP.

## II. CONCEPT FOR AN ARC SPIN ROTATOR

A spin rotator is a sequence of magnets which provide control of spin orientation of the beam while leaving the outgoing orbit unaffected. The spin rotators in the damping ring area of the SLC provide an example (Fig. 3).

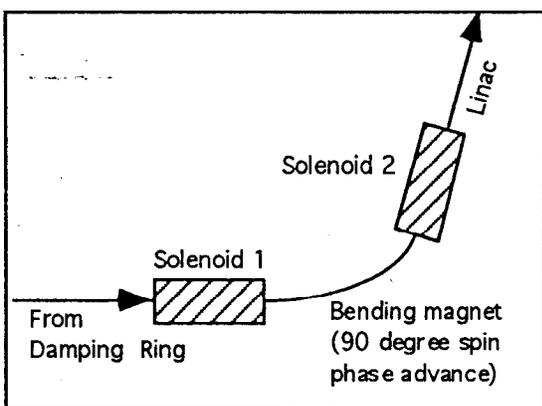


Fig 3. Spin rotator with solenoid magnets in the SLC damping ring area (NRTL - Linac Sector 2)

Two solenoid magnets capable of rotating the spin around the longitudinal axis by up to 90 degrees are separated by horizontal bending magnets which rotate the spin 90 degrees around the vertical axis. Different settings of the solenoid magnets can rotate the spin to any point of a half sphere at the launch into the linac without changing the launch itself.

In the arcs we know that vertical oscillations cause additional rotations around an axis in the horizontal/longitudinal plane. So in principle two adjustable closed vertical orbit bumps separated by a fixed spin rotation around the vertical axis (two arc magnets provide 108 degrees) work as a spin rotator. The length of the bumps should be a multiple of  $6\pi$  (one achromat) to minimize the optics perturbations. In practice, we use two interleaved bumps. They each span  $42\pi$  in betatron and spin phase and overlap for all but two arc magnets (see Fig. 4).

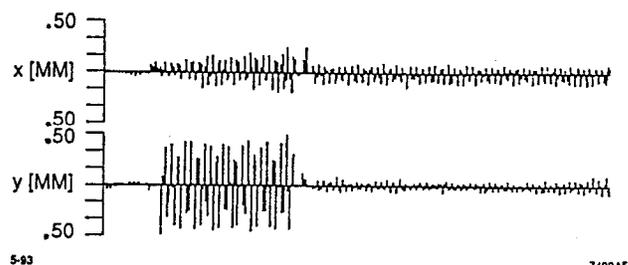


Fig 4. Difference orbit in the North Arc showing typical spin bump. This bump rotates the spin by 60 degrees. Note the x-y coupling due to arc rolls.

## III. TUNING CONSIDERATIONS

There is a principle difference between rotating the spin in the arcs and rotating it at linac injection with the solenoid magnets. The absolute orbit in the arcs is only known to about one millimeter. Therefore the absolute spin rotation in the arcs is entirely unknown. The polarization measurement at the Interaction Point (IP) is restricted to longitudinal polarization[4]. Even so, measuring the IP polarization for three different settings of the solenoid magnets, which produce three transverse states of the spin at the launch into the arc, gains enough knowledge about the arc spin rotation to calculate the correct setting of the solenoids for longitudinal spin direction at the IP[5].

A similarly elegant way to set the arc bumps cannot be found because their additional spin rotations (which we assume as known) are interleaved with unknown rotations due to the unknown absolute arc orbit. To tune the arc polarization bumps, we step through a nine-point grid of bump settings for which the measured longitudinal polarization is fitted to the under constrained function

$$\frac{P_z}{|P|} = (a_1 + a_2 \cos \theta_1 + a_3 \sin \theta_1) \cdot (b_1 + b_2 \cos \theta_2 + b_3 \sin \theta_2) \quad (3)$$

which reflects that two bump amplitudes (or rotation angles)  $\theta_1$  and  $\theta_2$  together with unknown rotation parameters shape the outcome of this scan.

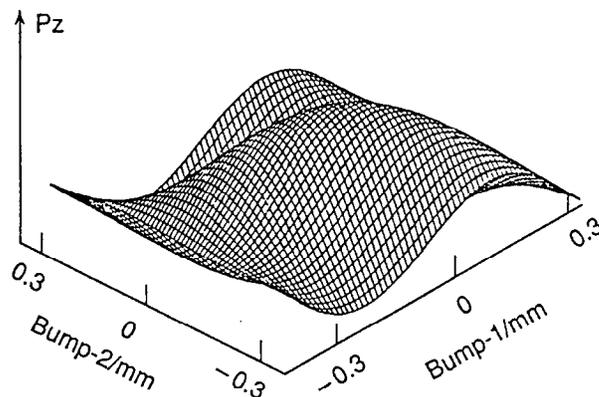


Fig 5. Fit for a 9-point grid scan with the arc polarization bumps. The fit form is given in eqn. 3.

#### IV. SIMULATION CALCULATIONS

Extensive tests with simulation calculations had been done before the first machine studies. A simulation code was written which tracks single particles and their spin through the arc. The optics are linear, the spin rotations are calculated to all orders, and rolls are included (the SLC arcs have rolls of up to 10 degrees). The code was cross-checked against existing spin tracking codes [6].

First calculations showed that the axis of the additional spin rotation caused by a vertical orbit bump is sufficiently independent of the rotation angle (bump amplitude) as long as the orbit amplitude is confined to 1.0 mm (which is beyond the limits for optical considerations).

Then the complete polarization optimization with vertical arc bumps was simulated. Different initial arc orbits were generated and 9-point grid scans were simulated for each of these. The calculated results of the grid scans was fitted with eqn. 3 and the predicted result verified with a final calculation. In all cases the spin vector could be rotated into the longitudinal direction at the IP within a few degrees.

#### V. MACHINE STUDIES

To initiate a vertically closed orbit bump in the north arc, one magnet is displaced vertically (the arc is steered by physically moving the main combined function magnets). For design optics, a magnet with a phase difference of  $6\pi$  downstream-closes the bump with the same move in the opposite direction. In practice, a few additional small corrections are applied to achieve bump closure of less than  $20\mu\text{m}$  rms downstream oscillation amplitude (see Fig.4). The same combinations of magnet displacements are then reproducibly scaled to scan the grid.

Optimization with the grid scan was immediately successful. Table 1 shows data for one of the first grid scans taken. It compares the data to the fit values using eqn.3. The peak value predicted by the fit was found within 2% at the specified bump configuration.

Table 1: IP Polarization 9 Point 'Grid-Scan'

Point #	Measured $P_z$ [%]	Error on $P_z$ [%]	Fitted $P_z$ [%]
1	+6.8	1.3	+3.1
2	+16.0	0.8	+17.9
3	-32.0	1.0	-27.9
4	-12.2	0.7	-12.2
5	+8.0	0.9	+8.0
6	+24.0	0.6	+24.0
7	-18.8	0.7	-18.7
8	-33.5	0.6	-33.5
9	+9.0	0.9	+9.0

Fit Results ==>

Set Bump-1 = -298  $\mu\text{m}$   
 Set Bump-2 = +21  $\mu\text{m}$   
 $P_z = -41.2\%$  (measured = -39.0%)

#### VI. CONCLUSION AND OUTLOOK

Rotating the spin at the IP with arc spin bumps proved to be from the first machine experiments an effective and reliable tool. The solenoid spin rotators have remain switched off for the entire 1993 run cycle. Bump optimization requires only a few hours and has been stable for months under normal SLC operating conditions.

The SLC is presently operating with >60% electron polarization. The polarization degree at the beginning of the arc is thought to be around 80%[7]. Spin diffusion due to energy spread (0.3% rms) accounts for 10% relative polarization loss. Studies are under way to recover the additional polarization loss due to diffusion by means of further arc orbit tuning.

#### VII. ACKNOWLEDGMENTS

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