Nonlinear Effects in the SLC e^+ Transport Line*

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Abstract

The target area of the SLC positron system, 2 km down the LINAC, is connected back to the front end of the machine by a 2 km long transport line, consisting of 75 FODO cells, with a quadrupole aperture of 10 cm. The beam in the return line experiences a loss larger than predicted. Taking into account the relatively high dodecapole component in the FODO lattice quadrupoles of 2.5 % of the quadrupole component at a radius of 4.65 cm, it is found through particle tracking that nonlinear resonances occur for certain values of the phase advance per FODO cell, particularly at 90°, the standard value previously used. These resonances lead to particle loss in the outer layers of phase space due to the particles with a large amplitude being more affected by the dodecapole moment. These resonances are very similar to the ones found in circular machines. The influence of random variations of the quadrupole strength and position is also analysed. Initial measurements of the positron transmission as a function of the quadrupole focusing strength in the positron return line show a perceptible improvement for the values in phase advance favored by the tracking results.

Introduction

The positrons for SLC are produced by 33 GeV electrons extracted from the 3 km long main linear accelerator after two thirds of its total length. After acceleration to 220 MeV in a dedicated Linac the positrons are transported back to the front end of the main Linac in a 2 km long transport line called positron return line (PRL), mounted above the main Linac [1,2].

This transport line has, apart from bending and matching regions at both ends, a regular FODO structure with a period length of 25.42 m. Each F quadrupole is preceded by a horizontal beam position monitor and followed by a horizontal steering magnet. D quadrupoles are equipped with the corresponding vertical elements. The aperture radius of the PRL is 5 cm. The phase advance per FODO cell was chosen to 90°, to allow an easy beam steering. The whole system is designed to accept an energy spread of ±5%.

Since the linear acceptance of the PRL is higher than the calculated output emittance of 22 $\pi\, mm\, mrad$ of the 220 MeV accelerator a 100% transmission is expected. However, during the SLC runs in 1989 and 1990 particle losses of the order of 15% distributed along this line were observed. These losses vanished when the beam were collimated at the upstream end of the return line. Thus effects due to beam interaction with the residual gas could be excluded. Wake field effects can be excluded as well, since no dependence of the relative losses on beam intensity could be observed.

Therefore nonlinear components of the PRL quadrupoles were taken into consideration as a possible source of the losses. The strongest nonlinear contribution in a quadrupole with four-fold symmetry is the dodecapole component [3]. This component has been measured with a rotating coil to be about 2.5% of the quadrupole component at a radius of 4.65 cm. The effects of this dodecapole component are studied with the methods of particle tracking.

The Tracking Code

The main goal of the tracking program was to estimate the reduction of the transport line acceptance due to nonlinear field components of the quadrupoles. At first a sample of particle coordinates in 4-dimensional phase space is generated, uniformly distributed in a 4-dim. hypersphere. The volume of this hypersphere V_i is chosen considerably larger than the expected linear acceptance. If N_i is the initial number of test particles and N_f the number of particles which passed the transport line, the 4-dim acceptance volume V_a is given by

$$V_a = \frac{N_f}{N_i} V_i$$

The tracking is done by the common method of representing linear elements with matrices and nonlinear elements with kicks, neglecting the finite length of the nonlinear elements. The aperture is represented by circular diaphragms in the middle of each quadrupole. A specific complication in the modelling of the PRL is the presence of the earth field, since no shielding is installed. The effect of the earth field can readily be observed by inspection of the horizontal PRL correctors settings. Therefore the effect of a drift space has to be modified to

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix} + \begin{pmatrix} \frac{1}{2}\vartheta L^2 \\ \vartheta L \end{pmatrix}$$

where ϑ is the deflection angle due to the earth field per m. The value of ϑ in the case of the PRL is 0.095 mrad/m. It is

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interesting to mention that a beam steered to zero displacement in all horizontal beam position monitors will have a systematic horizontal displacement in the D-quadrupoles of about 4.6 mm due to this effect.

The tracking program is also able to simulate random misalignments and coil excitation errors. The orbit errors due to the misalignments and earth field influence are compensated by appropriate changes of the steering magnets settings.

Tracking Results

The 4-dimensional acceptance of the PRL is calculated as a function of the phase advance per FODO cell. Fig. 1 shows the results for pure quadrupoles and for quadrupoles with the measured dodecapole component. In the first case one has

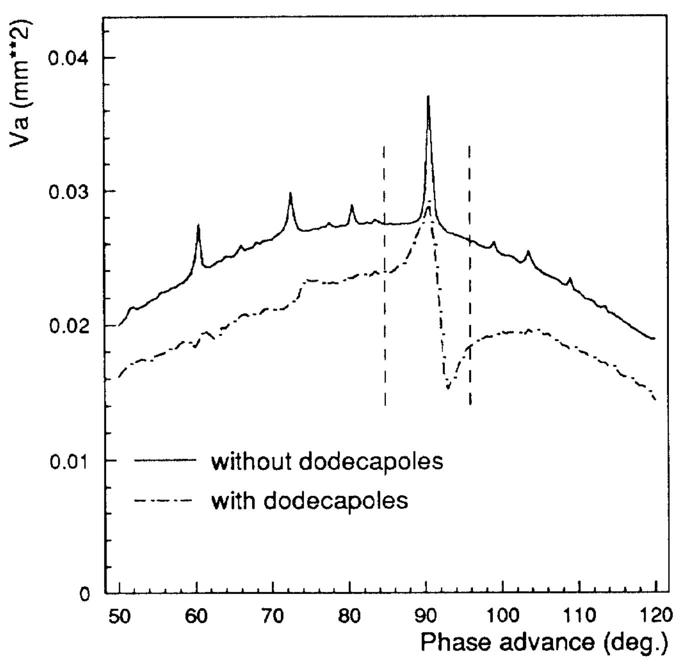

Figure 1: PRL acceptance as a function of phase advance per FODO cell

a smooth curve with a couple of sharp peaks superimposed. The sharp peaks correspond to phase advance values which give rational numbers when 360° is divided by them. They are particularly pronounced in the case of integer ratios. The peaks are explained by the fact that a diaphragm at the position of the β function maximum defines an acceptance area bounded by a polygon in the case of rational ratios, rather than an ellipse in the case of non rational ratios. In the case of integer ratios this polygon is regular. The width of these peaks will decrease with increasing number of FODO cells.

The smooth part of the curve has it is maximum close to the 76.5° value known from analytical calculations [4]. This is not obvious, since these calculations only deal with one plane in phase space, thus implying a rectangular aperture.

The acceptance curve calculated with dodecapole components shows a general depression of about 20% compared to the other curve plus a resonant acceptance reduction with minimum value at 93° phase advance, due to a fourth order resonance. The nature and characteristic of this resonance is well known from synchrotron theory, but its astonishing that it can become effective within only 75 FODO cells.

The strong effect of the fourth order resonance is particular important for the PRL since 90° was the previous setting of this line. With this setting the phase advance covers a range indicated by the dashed vertical lines in fig. 1 due to the large energy spread of the positrons.

Introducing random misalignments of $\pm 2\,mm$ and quadrupolstrength errors of $\pm 1\%$ gives a reduction of acceptance of about 20% without changing the shape of the curves. The resonant behaviour is maintained. Disabling the earth field effects described in the preceding section gives an acceptance increase of about 7%. The shape of the curves is not much affected.

Due to a suggestion of K.L. Brown the calculations were redone with slightly different settings of F and D quadrupoles, each one 3% below respective beyond the value used for the calculation with equal quadrupole strengths. The results are

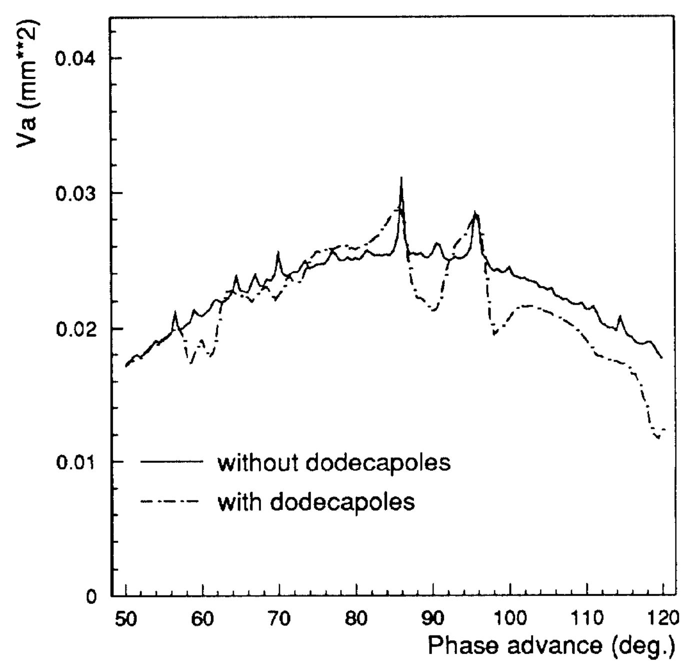

Figure 2: PRL acceptance, with 3% FD imbalance

shown in fig. 2. The abscissa gives the phase advance values which one would obtain for equal quadrupole strengths. The overall acceptance without dodecapoles is a little less than in the case with equal quadrupoles and no dodecapoles, but apart from regions with resonances there is no reduction of acceptance due to the dodecapoles for phase advance values lower than 90°. However the third and sixth order resonance become effective and due to the different phase advances in the horizontal and vertical plane a splitting of the resonances occurs.

It has to be mentioned that the calculated acceptance, even in the region of the fourth order resonance, is still 2.3 times larger than the positron emittance defined by the aperture of the positron capture accelerating section and the solenoid field strength in this section [2]. However, to obtain estimates for possible particle losses one has to take into account phase space filamentation due to nonlinearities and chromatic errors in the upstream systems, which was not done yet.

Measurements

During August 1990 some initial measurements were performed on the PRL, looking for effects of the phase advance on the transmission. In particular lattices with 75° and 55° phase advance per regular FODO cell and appropriate adjustment of the matching cells at both ends of the PRL were calculated and loaded. The transmission is also sensitive to the condition of

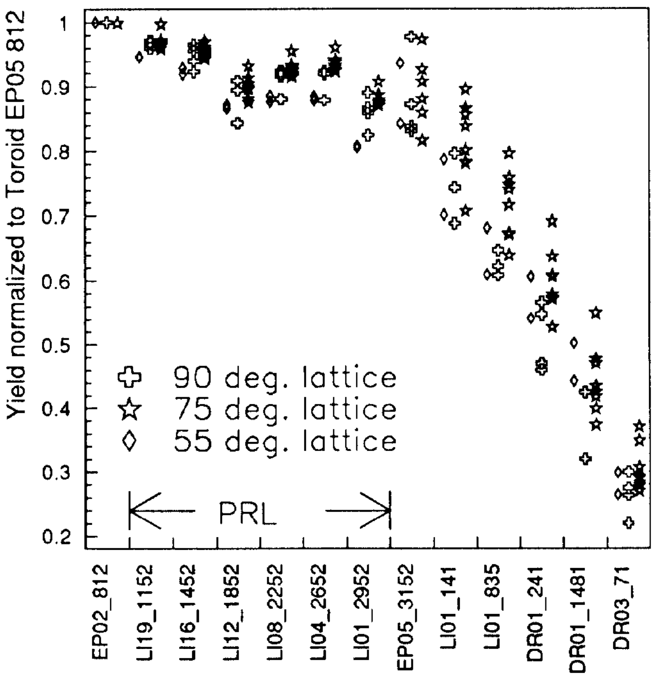

Figure 3: Toroid readouts in PRL and downstream systems. Values are normalized to the last toroid upstream of the PRL

the primary electron beam. To exclude effects due to variations of the primary electron beam, the new configurations were exchanged with the old one several times, each time recording the readouts of the beam current monitors. The raw results of these measurements are shown in fig. 3. In fig. 4 the average ratio of the toroid readouts for the 75° lattice to the 90° lattice is plotted. Apparently the 75° lattice gives on average the better transmission. The average gain in transmission at the injection of the SLC positron damping ring is 14%.

Most of the improvement in transmission with the 75° lattice is obtained in parts of the machine downstream of the PRL, namely during reinjection of the positrons into the SLC main Linac, while the reduction of losses in the PRL itself is only marginal (see fig. 4). A possible explanation for the larger losses with the 90° lattice in the systems downstream of the

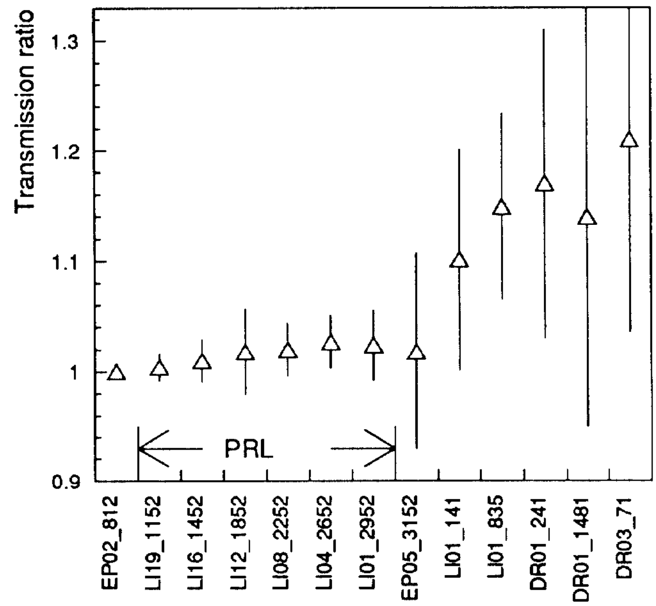

Figure 4: Transmission of the 75° lattice normalized to the transmission of the 90° lattice

PRL could be phase space filamentation due to the fourth order resonance.

Further measurements are needed to investigate the effect of a FD imbalance and to determine the real acceptance volume by measuring the transmission of a collimated beam as a function of upstream steering magnet strengths.

Conclusions

The tracking results show that resonance effects, well known from circular machines, can also become important in periodic transport lines, especially when large emittance beams have to be transported. To obtain a maximum acceptance in a transport line with a FODO structure phase advances per FODO cell between 70° and 80° should be chosen, with a slight difference between horizontal and vertical phase advance.

First measurements at the SLC positron return line indicate that the transmission can be improved by choosing phase advance values in this region. However further measurements are needed to get a more complete understanding.

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