

SLC – THE END GAME

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Abstract

The design of the Stanford Linear Collider (SLC) called for a beam intensity far beyond what was practically achievable. This was due to intrinsic limitations in many subsystems and to a lack of understanding of the new physics of linear colliders. Real progress in improving the SLC performance came from precision, non-invasive diagnostics to measure and monitor the beams and from new techniques to control the emittance dilution and optimize the beams. A major contribution to the success of the last 1997-98 SLC run came from several innovative ideas for improving the performance of the Final Focus (FF). This paper describes some of the problems encountered and techniques used to overcome them. Building on the SLC experience, we will also present a new approach to the FF design for future high energy linear colliders.

1 INTRODUCTION

The SLC machine has been the first of his kind and most of the problems encountered to reach the design performances are related to the new physics of this collider. Through the years of operation there has been a continuous increasing of the beam intensities and an improving of the beam qualities. The limits to this process are mainly due to three reasons:

- 1) Intrinsic design limitation of many subsystems in handling higher beam powers, like the gun, the Damping-Rings RF, the Linac RF, the positron target etc. In addition high radiation levels and damage have limited the total peak and integrated beam charge through the machine even more.
- 2) Intrinsic design limitation in the emittance dilution of many subsystems like the Ring-To-Linac transport lines, the main Linac, the Arcs, the FF.
- 3) Lack of understanding the new physics of the Linear Colliders. In particular the emittance optimization in the whole machine and the FF optimization.

All the points have been heavily attacked through the years. In particular solving point 3) proved to be the key to overcome the other problems. Tab.1 summarizes the design and achieved beam parameters. We can see that despite the lower beam currents, the achieved luminosity is just a factor two less than design, thanks to smaller emittances and IP spot sizes. In the following some of the

improvements obtained in the last SLC run (1997-98) will be described.

Table 1: Design and achieved SLC beam parameters

	Design	Achieved	Units
Beam charge	7.2e10	4.2e10	e [±] /bunch
Rep. rate	180	120	Hz
DR ϵ_x	3.0e-5	3.0e-5	m rad
DR ϵ_y	3.0e-5	3.0e-6	m rad
FF ϵ_x	4.2e-5	5.5e-5	m rad
FF ϵ_y	4.2e-5	1.0e-5	m rad
IP σ_x	1.65	1.4	μ m
IP σ_y	1.65	0.7	μ m
Pinch factor	220%	220%	Hd
Luminosity	6e30	3e30	cm ⁻² sec ⁻¹

2 EMITTANCE DILUTION IN SLC

2.1 Ring to Linac transport lines

This line it also used to compress the bunch length out from the damping ring from 6.5mm down to about 1mm. Due to the high beam energy spread and big lattice dispersion required for the compression, emittance dilution arises from chromatic aberrations, wakefields, and possibly coherent synchrotron radiation. Thanks to several improvements in the hardware and in the tuning from the runs apart the last, the dilutions had been already contained within relatively small values (~10-20%).

2.2 Linac

The main source of emittance growth was due to chromatic aberrations and wakefields. One of the sources of chromatic aberrations is the energy mismatch of the lattice and the beam due to klystron RF-phase errors. In the last run we developed a method to measure such phases in a fast and reliable way. Fig.1 shows a typical measure obtained by measuring the beam energy varying a group of eight klystron phases, such measure takes about two seconds and can be repeated as often as needed. Another chromatic aberration comes from unwanted residual dispersion in the line due to magnet misalignments and not optimal orbits. We developed a new steering algorithm to establish identical orbits for electron and positrons in the Linac. Such solution minimizes the beam dispersions since the method is equivalent to force two electron beams with 200% energy difference to have the same orbit, hence no dispersion. In addition SVD algorithms has been employed to obtain the

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best corrector setting for a given orbit. Such method has been also successfully applied at LEP [2] with similar results.

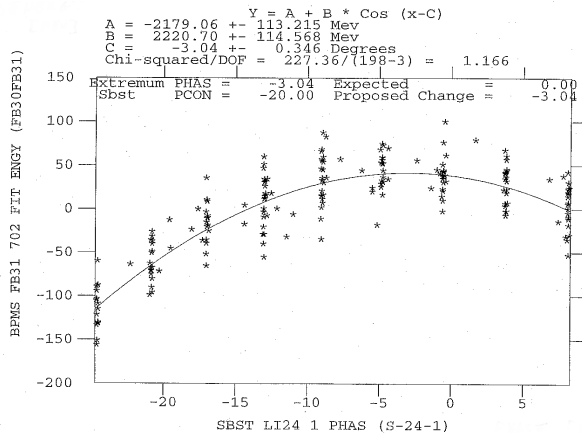


Fig. 1: Beam energy versus a group of eight klystron phases, simultaneously varied.

Another misleading effect of the dispersion was the apparent emittance dilution in the middle of the linac, where four wire scanners are available for emittance measurements. In this location the energy spread is very large because the BNS damping [2], so few millimeters of dispersion were causing apparent emittance growths in excess of 100%. In the past this dilution was attributed to wakefields, so large orbit bumps were used to minimize them, effectively creating wakefields to cancel dispersion. In the last run such optimization was abandoned.

Another problem in minimizing the Linac wakefields was the lack of emittance measurements at the end of the Linac. In fact the last possible emittance measurement occurs some 300m before the end, simulations showed that up to 100% blow up could occur in this last region. A big effort was then put in developing an on line emittance measurement in the FF. Since the additional background in the SLD detector caused by wire-scans in the FF, very thin and light Z-material wires had to be developed to allow a continuous measuring and tuning of the emittances. Fig.2 shows an example of a particular wire scan when the beam was optimized on the Linac wires only, or directly in the FF.

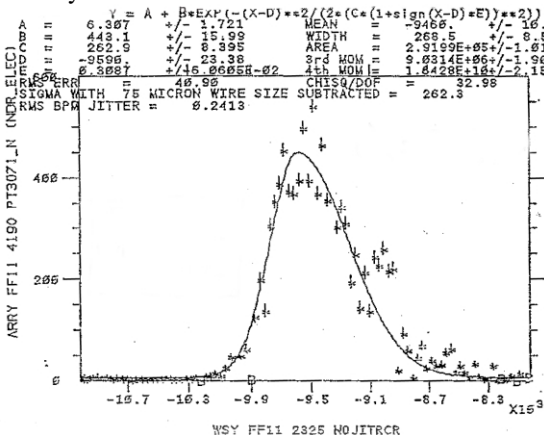


Fig.2a: Typical FF wire scan after optimizing the Linac emittances

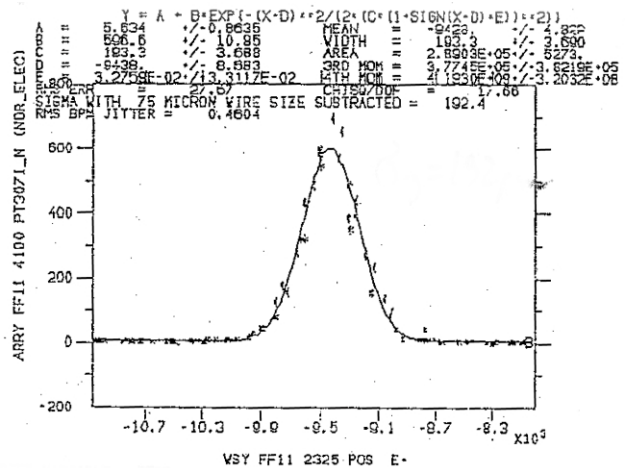


Fig.2b: Same FF wire, after optimizing the emittances directly in the FF

Moreover, in order to improve the quality of the measurement, the resolution of some of the FF Beam-Position-Monitors was upgraded to $2\mu\text{m}$, allowing for a beam-jitter correction of the scans. Fig.3 shows an example of the improved scan quality.

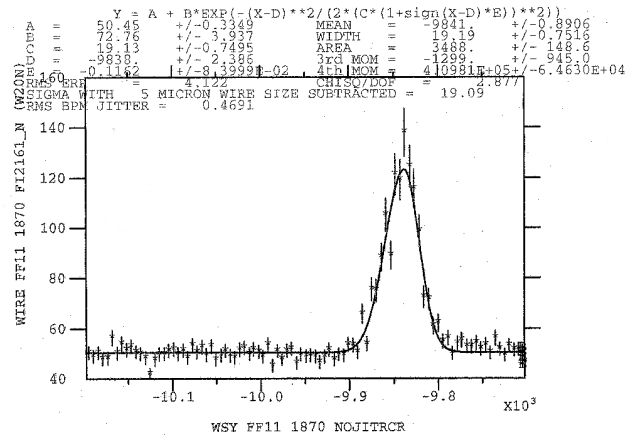


Fig 3a: FF wire scan, without beam jitter correction

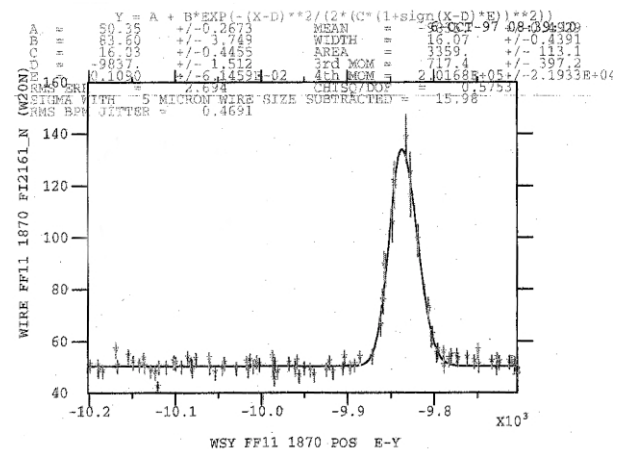


Fig.3b: Same scan as fig 3a, but with beam jitter correction

2.3 Arcs

Some of the emittance dilution in the Arcs comes from the intrinsic design contribution from synchrotron radiation. This is about $11 \cdot 10^{-6} \text{m} \cdot \text{rad}$ in the horizontal plane and $1.2 \cdot 10^{-6}$ in the vertical. Spurious contributions, mainly in the vertical plane, come from residual coupling and dispersion. In the past runs a very robust technique had been developed [3] to minimize such aberrations. In the last run, thanks to the FF-wires, was possible to precisely measure its effectiveness in terms of emittance minimization and closely monitor the Arcs performances during the run. Fig.4 shows a typical example.

As a result of the improved diagnostic and emittance tuning the spurious emittance growth in the last run through the whole machine was reduced to about 20% in the horizontal plane and 50% in the vertical, about 2-3 times better than in the past.

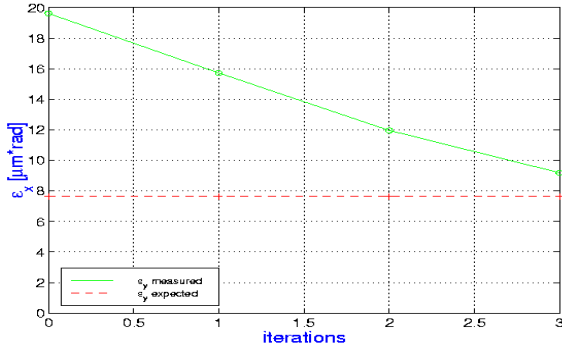


Fig.4: FF vertical emittance as function of Arc-tuning iterations. The expected value comes from the measurement at the end of the Linac plus the contribution from the synchrotron radiation in the Arc

3 NEW FF OPTICS

3.1 Smaller β_x^*

The theoretical FF performances are limited by spot size dilution due to synchrotron radiation from the bends in the Chromatic Correction Section (CCS) and high order chromo-geometric aberrations. The effect of the latest was greatly overestimated since they mainly increase the “rms” of the Interaction Point (IP) distribution, but do not so greatly affect the luminosity. To better understand the true FF theoretical potential, a new definition of beam size “Luminosity Equivalent Sigma” has been employed, directly from the luminosity definition:

$$\sigma_y (les) = \frac{1}{2\sqrt{\pi} \int_{-\infty}^{\infty} \rho^2(y) dy}; \quad \int_{-\infty}^{\infty} \rho(y) dy = 1$$

being $\rho(y)$ the vertical relative beam charge density. This definition should be compared with the standard:

$$\sigma_y (rms) = \sqrt{\int_{-\infty}^{\infty} \rho(y) y^2 dy}$$

Fig.5 shows the horizontal and vertical spot sizes versus the horizontal beam divergence, showing that much larger divergences are needed to increase the luminosity. Moreover a better optic was found to minimize the spot size dilution from synchrotron radiation. As a side effect the disruption enhancement greatly benefit from this optic since it is directly related to the horizontal beam size.

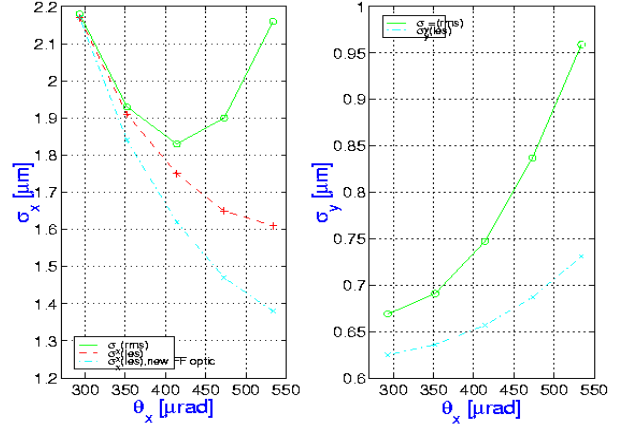


Fig.5: Horizontal and vertical “rms” and “les” spot sizes versus horizontal angular divergence

3.2 Additional sextupoles

Unfortunately smaller β_x^* yields to larger detector background, so big efforts went into its minimization. One of the breakthroughs was the discovery that big contributions to the background were originated in the Arcs and FF itself, because of higher order chromo-geometric aberrations, specifically T_{266} and T_{226} , causing off-energy particles to cross the IP at very large angles. The addition of more sextupoles in the systems greatly reduced these effects. Fig.6 shows an example of the detector background as a function of the T_{226} “knob” created with such additional elements.

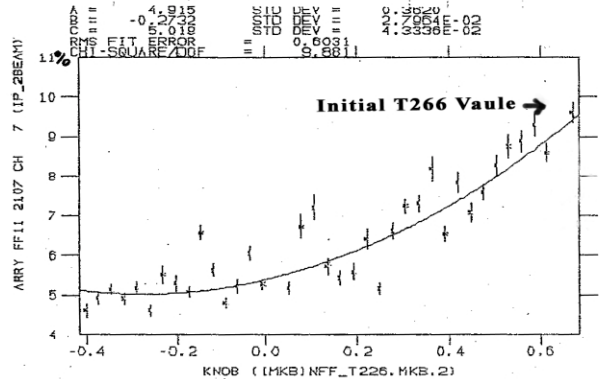


Fig.6: Drift chamber occupancy (in %) versus the second order chromatic aberration T226

3.3 Less synchrotron radiation

About 30% luminosity dilution in the FF was due to emittance dilution from synchrotron radiation originated by the bends in the CCS. In order to decrease this contribution, the bends were weakened and close by correctors, together with horizontally misaligned quadrupoles, were used to generate the total bend angle. The luminosity increase was estimated to be about 8%.

3.4 Octupoles

Another FF upgrade was the insertion of octupoles in the CCS in order to decrease the third order aberrations. To minimize cost and engineering very small and powerful permanent magnets were used. Remote movers were necessary, in order to precisely align them with the beam. Indeed, a misaligned octupole generates additional aberrations according to:

$$\begin{aligned}\Delta y_{IP} &= R_{34} K_{oct} [3(x - x_{off})^2 (y - y_{off}) - (y - y_{off})^3] \\ \Delta y_{IP} (octupole) &= R_{34} K_{oct} (3x^2 y - y^3) \\ \Delta y_{IP} (sextupole) &= -2R_{34} K_{oct} (3xyx_{off} - y^2 y_{off}) \\ \Delta y_{IP} (waist) &= 3R_{34} K_{oct} (x_{off}^2 - y_{off}^2) y \\ \Delta y_{IP} (coupling) &= 6R_{34} K_{oct} x x_{off} y_{off} \\ \Delta y_{IP} (offset) &= -R_{34} K_{oct} (3x_{off}^2 y_{off} - y_{off}^3)\end{aligned}$$

From the equations above we can see that the IP vertical waist shift is a quadratic function of the misalignments. So the simplest and most effective method to center the octupoles was found to measure the waist position versus the octupoles position and place them at the point relative to the peak of the parabola. Fig.7 shows a typical scan. The typical resolution in the alignment was better than 20 μ m.

The measured vertical spot size reduction due to the octupoles has been of about 15%, very close to the expected value.

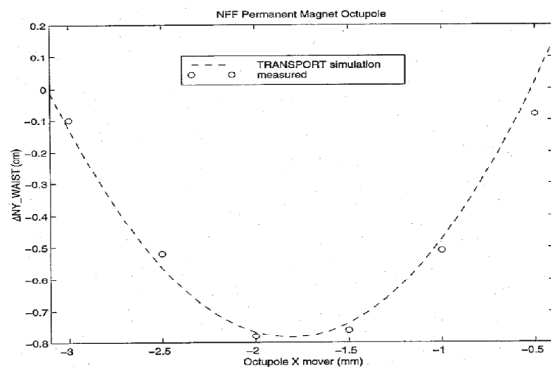


Fig.7: Measured and simulated vertical waist shift versus the octupole horizontal position

3.5 Triplet boost

The last FF hardware upgrade concerned the triplets. The FF final demagnification is performed by a superconducting triplet powered by a single power supply. However we were able to independently boost the closest quadrupole to the IP in order to reduce the peak betas across the triplet. This both reduces background and chromaticity resulting in a measured horizontal spot size reduction of about 7% and a relative increase of about 14% in luminosity (thanks to a larger disruption enhancement).

4 LUMINOSITY OPTIMIZATION

The main software upgrade in the FF regarded the minimization of the first order IP aberrations, namely X/Y waists and dispersions and X'Y coupling. Previously the beam spot sizes as measured by beam-beam scans were minimized as function of the relative "knobs". Such method proved to be slow and inaccurate, resulting in a luminosity dilution of about 30%. A much more accurate method was developed, consisting in subliminally moving such knobs up and down optimizing some luminosity monitor signals [4]. The accuracy of the method in minimizing these aberrations was measured to be about 10 times better than the old one. Similar algorithms are currently used at the SLAC B-factory.

With this method any small change in the first order aberrations could be detected much faster and more precisely. Hence it was possible to use it to also minimize also all the residual FF second order aberrations, that in the past had always been very difficult to measure. For instance residual chromaticity in the FF could be precisely measured from the waist shift as function of the beam energy:

$$T_{346} = \frac{\Delta waist_y}{\frac{\Delta E}{E}}$$

The aberration could then be minimized by adjusting the y-sextupoles strength in the CCS.

Similarly second order FF geometric aberrations could be measured, by determining the waist shift as function of an incoming betatron oscillation:

$$T_{344} = \frac{\Delta waist_y}{\Delta y'_{IP}}; \quad T_{324} = \frac{\Delta waist_y}{\Delta x'_{IP}}$$

These aberrations were canceled by using a sextupole just upstream the triplet and the sextupole components of the octupoles, misaligned now on purpose, to compensate for the measured aberration.

5 NEW FF OPTICS: BEYOND SLC

Looking at the SLC-FF evolution we can conclude that does not exist a unique FF optic. Based on the SLC experience and FF limitation, we should develop different systems, for the much more demanding future linear colliders, to simultaneously minimize all the problems encountered. A big effort should be devoted to reduce the number of components in general, to ease the comprehension and tuning of the system.

The background in the detector, as the main limitation to the luminosity, was highly underestimated, as well as the luminosity dilution from synchrotron radiation.

An example of a FF optic, extensively described in [5], which tries to meet all these requirements is shown in Fig.8. The optical properties at the IP phase are equivalent to the traditional schemes, but all the other just mentioned problems are greatly reduced.

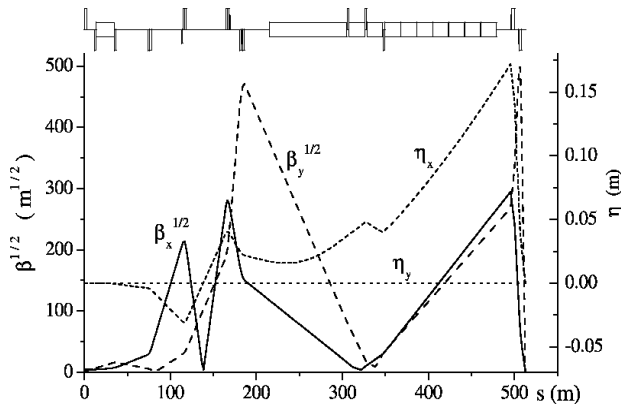


Fig.8: Possible FF optic for a 1TeV/CM collider. Focusing and defocusing quadrupoles are indicated as up and down bars, while the bends are centered. Sextupoles are interleaved with the final doublet and the two quadrupoles just upstream the bend.

6 CONCLUSIONS

SLC has been a very useful machine for the physics community. Almost all the aspects of the accelerator physics have been explored during SLC operation. Several new phenomena have been observed, one of the most striking one is the disruption enhancement, due to the strong beam-beam focusing at the IP, in excess of 100% [6]. Many other systems around the world did benefit somewhat from the SLC know-how and, most important of all, the linear colliders now seem the logic next step for the high energy physics.

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