A LASER-HETERODYNE BUNCH-LENGTH MONITOR FOR THE SLC INTERACTION POINT*

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Abstract

Since 1996, the transverse beam sizes at the SLC interaction point (IP) can be determined with a 'laser wire', by detecting the rate of Compton-scattered photons as a function of the beam-laser separation in space. Nominal laser parameters are: 350 nm wavelength, 2 mJ energy per pulse, 40 Hz repetition rate, and 150 ps FWHM pulse length. The laser system is presently being modified to enable measurements of the longitudinal beam profile. For this purpose, two laser pulses of slightly different frequency are superimposed, which creates a travelling fringe pattern and, thereby, introduces a bunch-to-bunch variation of the Compton rate. The magnitude of this variation depends on the beat wavelength and on the Fourier transform of the longitudinal distribution. This laser heterodyne technique is implemented by adding a 1-km long optical fibre at the laser oscillator output, which produces a linearly chirped laser pulse with 4.5-A linewidth and 60-ps FWHM pulse length. Also, the pulse is amplified in a regenerative amplifier and tripled with two nonlinear crystals. Then a Michelson interferometer spatially overlaps two split chirped pulses, which are temporally shifted with respect to each other, generating a quasi-sinusoidal adjustable fringe pattern. This laser pulse is then transported to the Interaction Point.

1 INTRODUCTION

At the interaction-point (IP) of the Stanford Linear Collider (SLC), the bunch length has long been one of the least controlled beam parameters. Due to a variety of effects, the IP bunch length can easily vary between about 0.4 and 1.5 mm rms. For example, the bunch length is sensitive to changes of the linac rf phase due to bunch compression (or anticompression) in the collider arcs (the transport lines connecting linac and IP), to steering in the bunch compressor (RTL) and to longitudinal instabilities in the damping rings [3]. A diagnostic for monitoring the IP bunch length is desirable, since there is circumstantial evidence for a correlation of bunch length and luminosity, and since the predicted luminosity enhancement due to disruption [2] and the effect of longitudinal wake fields are both strongly bunch-length dependent.

One promising scheme to measure the bunch length utilizes the IP 'laser wire' [1]. So far the laser wire is being used only to determine the transverse single-beam sizes, which are inferred from the variation of the Compton-scattering rate as the electron or positron beams are moved across the laser beam. In this paper, we describe a modification of the laser system which will allow us to also measure the (average) longitudinal beam profile.

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2 MEASUREMENT PRINCIPLE

The method of choice was first proposed in Ref. [4]: Two collinear laser pulses of slightly different frequency are superimposed to generate a non-stationary fringe pattern. For a sufficiently small beat frequency, the spacing between fringe maxima and minima is comparable to, or larger than, the bunch length. Assuming the phase between fringe pattern and beam is random, the Compton rate will vary from pulse to pulse. The depth of this variation, M, is proportional to the Fourier transform of the longitudinal profile $f(t)$ [4]:

$$M \equiv \frac{N_{\gamma,\max} - N_{\gamma,\min}}{N_{\gamma,\max} + N_{\gamma,\min}} = \frac{F_\omega}{F_0} \tag{1}$$

where $F_0 = \int_{-\infty}^{\infty} f(t)\ dt$, $N_{\gamma,\max\ (\min)}$ the maximum (minimum) Compton signal, and

$$F_\omega^2 = \left(\int f(t) \cos \omega_b t\ dt \right)^2 + \left(\int f(t) \sin \omega_b t\ dt \right)^2 \tag{2}$$

and $\omega_b = \omega_1 - \omega_2 = \omega/\lambda\ (\Delta\lambda)$. Here ω_1, ω_2 are the frequencies of the two overlaping laser pulses, while λ the average wavelength and $(\Delta\lambda)$ the difference in wavelength between the two pulses. By measuring the variation depth M at different beat frequencies ω_b, the entire Fourier transform of the bunch spectrum can be obtained. Ref. [4] also introduces a dilution factor caused by the finite transverse sizes of electron and laser beams. Due to the smallness of the SLC IP beam sizes, this factor is not relevant for our application here.

3 LASER SYSTEM

The first stage of the existing laser is a mode-locked Nd:YLF oscillator, that produces 150 ps pulses, with 2 nJ of energy at 119 MHz repetition rate and is phase locked to the accelerator rf frequency. Subsequently, some of these laser pulses are amplified in a Nd:YLF regenerative amplifier (RA), where in approximately 10 roundtrips they reach an energy of 9 mJ, each at a repetition rate of 40 Hz. In order to achieve the smaller possible laser spot size in the IP, the laser pulse frequency is tripled using a doubling CD^*A and a tripling KD^*P crystal. Laser parameters are: $\lambda = 350$ nm, 150 ps FWHM, 2 mJ pulse energy,

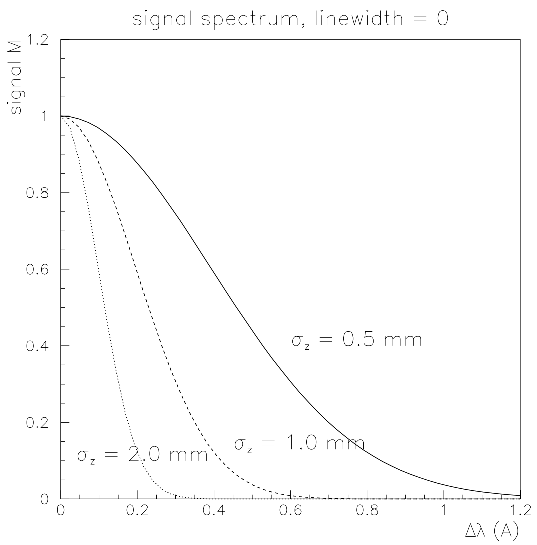

Figure 1: Modulation depth for Gaussian bunches of different rms bunch lengths versus wavelength difference $\Delta\lambda$.

and 40 Hz repetition rate [1]. The system is converted into a bunch-length monitor by adding a 1-km long optical fiber between oscillator and RA, and a Michelson interferometer after the harmonic generation, while also taking into account the effect of gain narrowing in the RA and of the nonlinear crystals on the bandwidth of the laser pulse [5]. A rough schematic of the original and upgraded laser systems is shown in Fig. 2

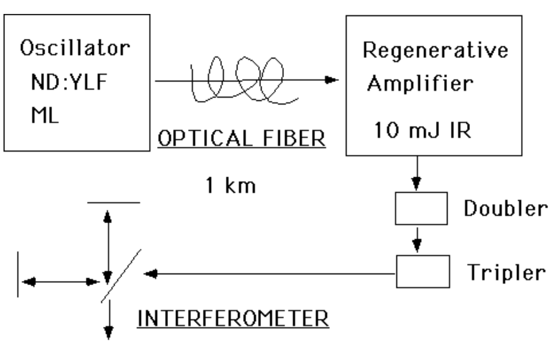

Figure 2: Schematic of the SLC IP laser system; elements added for the heterodyne bunch-length monitor are shown underlined.

The initial laser pulse produced by the mode-locked oscillator is 150 ps long and has a linewidth of 0.1 A. Self-phase modulation (SPM) in the optical fiber increases the linewidth to about 4.5 A and group-velocity dispersion (GVD) lengthens the pulse to 210 ps. The intensity of the input and output pulses in the fiber and the chirping introduced on the output pulse is shown in Fig. 3.

In the RA, the length of this 'chirped' pulse is reduced to 60 ps and the linewidth is decreased to about 3.5 A, due to 'gain-narrowing' as shown in Fig. 4.

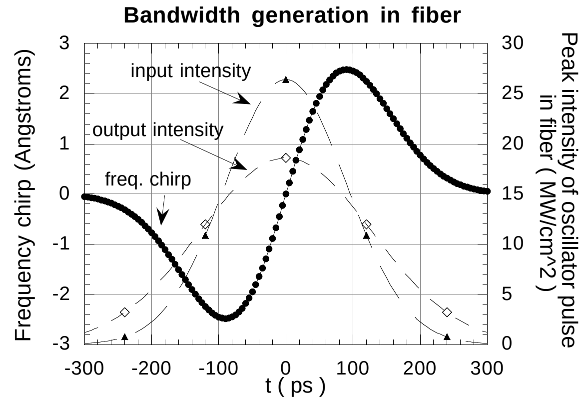

Figure 3: Intensity of input and output laser pulse and chirping introduced on the output pulse due to SPM and GVD from the fiber.

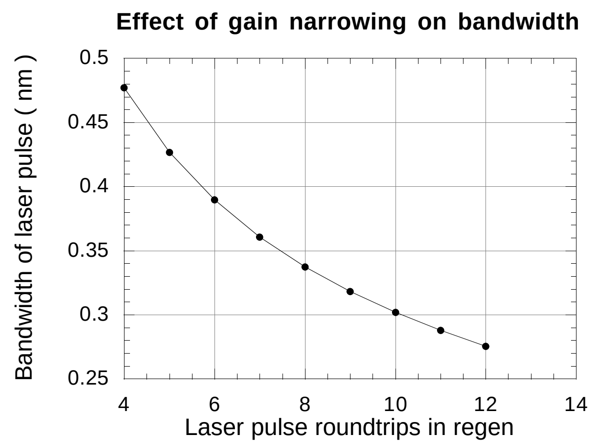

Figure 4: Effect of the amplification process in the regenerative amplifier (RA) on the bandwidth of the oscillator laser pulse as a function of the number of roundtrips in the RA.

In the frequency doubler and tripler, the linewidth increases again, by about a factor $\sqrt{2}$. Finally, the electric field of the pulse that enters the Michelson interferometer is

$$E(t) \approx \hat{E}_0 \, e^{-\alpha_0 t^2} e^{i(\omega_0 t + b t^2)} \tag{3}$$

with $\alpha_0 \approx 3.85 \times 10^{20}$ s^{-1}, $\omega_0 \approx 5.39 \times 10^{15}$ s^{-1}, and $b_0 \approx 5.8 \times 10^{22}$ s^{-1}. If the path length in the two interferometer arms is different, there is a time delay $\Delta t = 2\Delta x/c$ between the two split light pulses ($2\Delta x$ is the pathlength difference, controlled by a movable mirror), and the intensity of the final recombined pulse is

$$\begin{aligned} I(t) &= I_0 \left(e^{-2\alpha_0 t^2} + e^{-2\alpha_0 (t+\Delta t)^2} + \right. \\ &+ \left. 2 e^{-2\alpha_0 (t+\Delta t) t} \cos(b_0 2 t \Delta t) \right) /4 \end{aligned} \tag{4}$$

which represents a quasi-sinusoidal fringe pattern with an effective wavelength difference of $\Delta\lambda = \lambda^2 2 b_0 (\Delta x)/(\pi c^2)$; I_0 is the peak intensity of the original pulse. As an example, $\Delta x = 0.9$ mm corresponds to $\Delta\lambda = 0.5$ A. Figure 5 shows an exemplary fringe pattern according to Eq. (4).

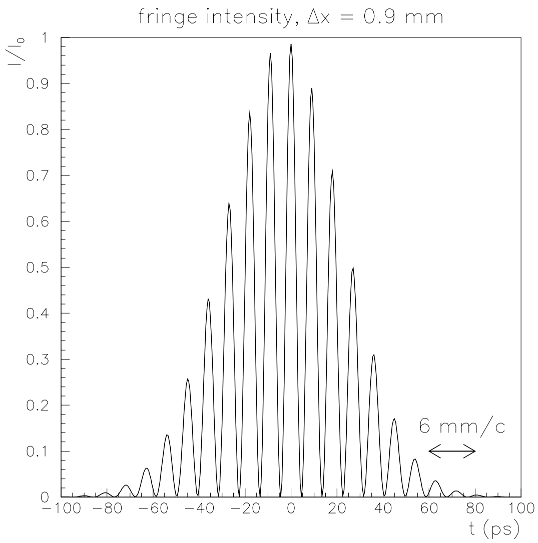

Figure 5: Intensity fringe pattern for a mirror displacement Δx ~0.9 mm.

The fringe pattern will be monitored by converting the laser beat wave into infrared (IR) radiation using a photoconducting GaAs antenna. This radiation in turn is characterized with a (second) Michelson interferometer operating in the IR, that is followed by a Si-based bolometer [6, 7].

4 RESOLUTION

For SLC bunch lengths, highest sensitivity is achieved when the wavelength difference $\Delta\lambda$ is chosen as about 0.3 A (see Fig. 1). For this value of $\Delta\lambda$ and assuming $\sigma_z \approx 1$ mm, the relative change of the signal M is approximately equal to that of the bunch length: $\Delta M/M \approx \Delta\sigma_z/\sigma_z$.

Several effects determine the achievable bunch-length resolution.

- Beam-orbit jitter: the horizontal beam orbit varies randomly by about $0.3\sigma_x$, from pulse to pulse. For a horizontal collision offset of Δx, the signal M decreases roughly as $\exp(-(\Delta x)^2/(4\sigma_x)^2)$, if the laser-beam diameter approximately equals that of the particle beam. Hence, a $0.3\sigma_x$ orbit variation changes the signal by about 2%.

- Laser-intensity imbalance: denoting the intensity ratio of the two split pulses by x, the maximum signal M is given by $2x/(x^2 + 1)$. If the imbalance $(1 - x)$ is smaller than 10%, the resulting error of the measurement will be less than 1%.

- Laser-intensity variation: pulse-to-pulse variation of the laser intensity, which should be smaller than 5%, introduces a measurement error of similar magnitude.

During the last SLC run, a larger IP beam-orbit variation than that quoted above was observed over a time period of a few minutes. The reason was that the IP beam-orbit feedback is not active when one of the colliding beams is dumped while measuring the size of the other. This problem can be avoided by intermittently reestablishing the collisions, between laser-wire scans.

In conclusion, we expect to measure the bunch length and bunch profile with a relative accuracy better than 10%.

5 OUTLOOK

The laser-heterodyne bunch-length monitor at the SLC interaction point will be commissioned in the summer of 1997. The monitor is expected to prove a valuable diagnostic tool for SLC operation. Specifically, it should facilitate linac RF phasing and RTL tuning, support studies of final-focus wakefields and disruption luminosity enhancement, and be used as a calibration for a multi-channel RF bunch-length monitor which has recently been installed in the SLC South Final Focus [8].

6 REFERENCES

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