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Beam Size Measurement at High Radiation Levels

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Abstract

At the end of the Stanford Linear Accelerator the high energy electron and positron beams are quite small. Beam sizes below $100\,\mu m$ (σ) as well as the transverse distribution, especially tails, have to be determined. Fluorescent screens observed by TV cameras provide a quick two-dimensional picture, which can be analyzed by digitization. For running the SLAC Linear Collider (SLC) with low backgrounds at the interaction point, collimators are installed at the end of the linac. This causes a high radiation level so that the nearby cameras die within two weeks and so-called "radiation hard" cameras within two months. Therefore an optical system has been built, which guides a 5 mm wide picture with a resolution of about $30\,\mu m$ over a distance of 12 m to an accessible region. The overall resolution is limited by the screen thickness, optical diffraction and the line resolution of the camera. Vibration, chromatic effects or air fluctuations play a much less important role. The pictures are colored to get fast information about the beam current, size and tails. Beside the emittance, more information about the tail size and betatron phase is obtained by using four screens. This will help to develop tail compensation schemes to decrease the emittance growth in the linac at high currents.

1 Introduction

The production rate for high energy physics events, called luminosity $\mathcal{L}$, of an accelerator is given by the simplified formula:

$$\mathcal{L} = \frac{N^2 f}{2\pi\sigma_*^2}, \tag{1}$$

where N is the number of particles in one of the colliding bunches, f the repetition frequency and σ_* the small spot size at the interaction point (IP). The size σ is given by

$$\sigma = \sqrt{\beta\varepsilon}, \tag{2}$$

with β is the betatron function at that location and ε is the emittance of the beam, in principle a constant. Different conditions like beta-mismatch and filamentation, bad steering or alignment and transverse wakefield effects can cause a significant emittance blow-up. For a matched beam (beam-β is equal lattice-β) equation 2 shows that only the beam size has to be determined. For any case at least three sizes at different betatron phase Φ locations (or at different quadrupole settings) are necessary to calculate the beam parameters α, β, ε, where $\alpha = -1/2 \cdot d\beta/d\Phi$ [1]. Therefore the measurement of beam sizes is an important part of controlling emittance blow-up. The small beam sizes below $100\,\mu m$ at the end of the SLAC-linac require a good resolution of the measuring system. This is investigated in the first sections. A high radiation level, which is produced by nearby collimators, forces the cameras to be moved to a remote location. A radiation hard system using only first surface mirrors in that area is shown next. At the end some first results are presented.

2 Resolution

The desired resolution is determined by the expected beam sizes and the allowable errors; while the achievable resolution depends on the screen thickness and granularity, the optical and the camera resolution.

2.1 Desired Resolution

The expected beam sizes at the end of the SLC linac are given by equation 2. With $\gamma\varepsilon = 3 \cdot 10^{-5}$ m rad, $\beta_{min(max)} = 25\,(50)$ m and a relativistic gamma-factor of $\gamma = 92\,000$ corresponding to 47 GeV, the beam sizes will be $\sigma = 90\,(130)\,\mu m$. So the resolution of the measurement should be below this. With about $50\,\mu m$ resolution (see below) the measured beam size will be up to 15 % more ($\sigma_{meas} = \sqrt{90^2 + 50^2}/90 \cdot \sigma_0 = 1.15\,\sigma_0$) or the measured emittance 30 % more. By knowing the resolution to 20 % ($50\pm10\,\mu m$) the measurement accuracy increases to about 7 % in size or 15 % in emittance at the low beta points. With half these values at the high beta points, this system provides besides the visual information a good absolute emittance value down to $0.2 \cdot 10^{-5}$ m rad.

2.2 Achievable Resolution

Different elements between the screen and the observer can degrade the resolution of a small beam size. The thickness and its granularity of the screen, the diffraction limit of the light path and the line resolution of the camera contribute to about $\sigma = 30\,\mu m$ each [2]. In the following the resolution values are given as sigma (σ) of a gaussian corresponding to the beam size (magnification factor), sometimes calculated from the full-width half-maximum of a distribution by $\sigma \approx$ FWHM/2.35.

2.2.1 Screens

The screens are made out of Al_2O_3:Cr and emit light at 695 nm (Ruby). The self-supporting material is about

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120 μm thick (t) and has a granularity of the order of 5–10 μm (up to 30 μm) in corn diameters.

Thickness The thickness ($t = 120\,\mu$m) contributes in two ways to the resolution. First, assume that the camera is looking straight at the beam (e.g. by a mirror with a hole) and is focused on the middle of the screen. A thin beam produces a line within the screen which is seen as a small disc with

$$\sigma_d = \frac{1}{2.35}\frac{t}{2F}. \tag{3}$$

With an F-number of the optical system of $F = 1.4$, the disc is as big as 18 μm. On the other hand for $F = 15$ and a resolution of 30 μm the focus can be ± 1 mm away from the screen.

Tilt Tilting a thin screen e.g. by 60° increases the resolution of the beam in one dimension and makes it easier to get access to the picture on the screen. A thick 60° tilted screen [3] gives the main contribution of the screen (44 μm):

$$\sigma_{sc} = \frac{\sqrt{3}\cdot t}{2\cdot 2.35}. \tag{4}$$

Granularity The different corn sizes around 10 μm of the screen material scatter the light and therefore contribute to the resolution. Not knowing the distribution of the corn sizes and the right mathematics (give me a hint) for calculating the effect, it has been measured in the lab. A resolution target has been imaged into the middle of the screen and the resolution measured to be 56 μm from the other side. The light produced by a beam traverses on average half the thickness, so the resolution due to granularity is $\sigma_g = 28\,\mu$m.

2.2.2 Optical System

The optical system should provide the imaging from the screen to the camera sitting in a low radiation environment without a significant degradation (see Fig. 1). Starting with a certain field of view (e.g. 3 × 4 mm), the desired resolution ($\approx 30\,\mu$m) and the distance to the camera ($\approx 12\,m$), the system can be designed.

Diffraction Limit Diffraction limits the principle resolution of an optical system. A lens of diameter D and a focal length f produces a spot diameter d (ring of the first diffraction minimum) of

$$d = 2.44\frac{f}{D}\lambda, \tag{5}$$

where λ is the wavelength of the light (695 nm). So an F-number of $F = f/D$ of 12–15 provides that $d =$ 20–25 μm. A non-obvious fact (reason: tails in distribution) should be mentioned: The resolution σ_o of the optical system is about d: $\sigma_o \approx d$, which can be checked by looking at MTFs (modulation transfer functions, e.g. [4]).

Light Path Distance The manageable distance over which light can be easily and inexpensively transported (no large diameter optics, no vacuum pipes) depends on the optical design, air fluctuation and the vibration levels.

Optical Design To keep the light diameter within the diameter D of a lens (e.g. 50 mm) the magnification can be $M = D/v = 10$, where $v = 5$ mm is the diameter of the field of view. With $F = 12$ or a corresponding focal length $f = 0.6$ m the picture would be $s = 6$ m away:

$$s = f\cdot M = D_1F_1\cdot D_2/v. \tag{6}$$

To achieve the necessary distance one bigger lens of $D_2 = 100$ mm is used at a distance of about 10 m, acting as a field lens, which concentrates the light of the nearby image to the camera 2 m away.

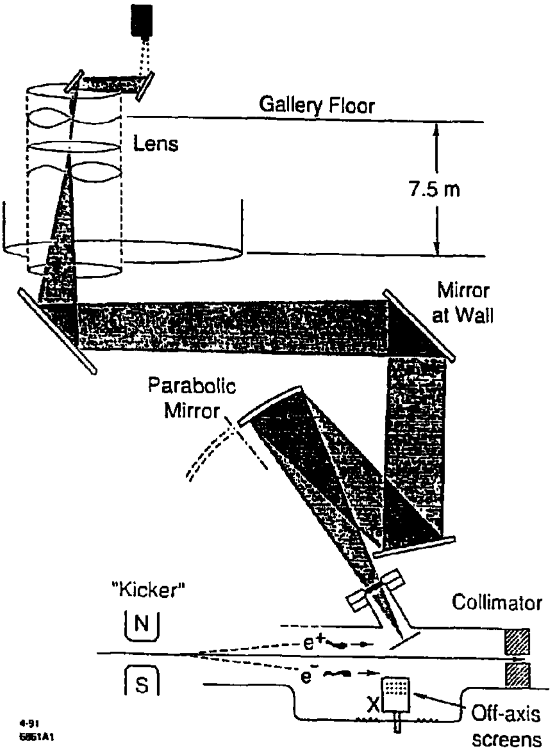

Figure 1: **Light Path of the Off-Axis Screens.**

Every two seconds the e^+ and e^--bunches are kicked onto the off-axis screens at the end of the SLC-linac. The radiation from the collimators near the screens forced the cameras to be moved to a low radiation area 12 m away. The first parabolic mirror provides a diffraction limited resolution below 30 μm and helps to achieve a small diameter of the light path and a low sensitivity to air fluctuations and vibration levels by enlarging the picture for the long distance.

It has turned out that this design has a lot of advantages: Beside smaller optical parts (not $D = s/F = 0.8$ m), the quick (after 0.6 m) and big ($M \approx 16$) magnification provides less sensitivity to air motion. A motion of 200 μm over 12 m, observed by alignment crews, are decreased down to the 10 μm level. The one large lens, mounted near the top of a vertical penetration in a protection pipe, can be used for two light paths of two nearby screens (electrons and positrons).

A mirror flatness of about $\lambda/8$ and vibration levels of 0.1 μm over the diameter produce a disturbance or offsets of about $\Delta x = 40\,\mu$m in 10 m distance. Taking the magnification into account this is small compared to the diffraction limit (in design),

$$\Delta x \approx 2 \cdot \frac{f}{D}\frac{\lambda}{8} \ll d. \tag{7}$$

On the other hand vibrations of up to 40 μm on the screen were observed in the first test setup, where one mirror was mounted on top of the water cooled accelerator. The resolution can be checked by looking at the smallest visible corn size over the whole imaging system. Shiny corns had two coma-like tails of about 25 μm, which decreased the resolution in the worst case to 50 μm (see below).

Abberations Geometric and chromatic abberations have been investigated. Achromatic and radiation hard lenses can be made in principle by a combination of silica (SiO_2) and MgF_2 (probably also CaF_2, LiF) lenses. Due to high costs and the lack of proof of real radiation hardness, lenses are avoided in the accelerator area and instead curved first surface mirrors are used.

Focusing parallel light, a spherical mirror has a geometric abberation of

$$\Delta x = \frac{1}{4}\frac{x^3}{(2f)^2}, \tag{8}$$

where Δx is the minimum disc diameter and x the offset from the axis of the light (in this case the diameter $D = 2x$). In a one-to-one imaging situation with a tilted mirror astigmatism occurs:

$$\Delta x = \frac{D\,x^2}{(2f)^2}. \tag{9}$$

An off-axis parabolic mirror avoids all of these above abberations and has been chosen for this reason. It has been observed, that these mirrors have to be aligned carefully to avoid coma:

$$\Delta x = \frac{2\,D^2\,x}{(2f)^2}. \tag{10}$$

Here x is the offset of the focus point from the axis.

3 Experimental Results

The first experimental results with a beam on the screens have shown their usefulness in getting a visual colored picture of the beam. Fig. 2 shows, for instance, a beam with a huge wakefield tail. Steering the beam flat to the axis of the linac decreases the tail by a large amount. But at high currents, even with a well steered linac, tails are present. These can be decreased by introducing betatron oscillations with a certain phase and amplitude, so that no tails are visible on the screens.

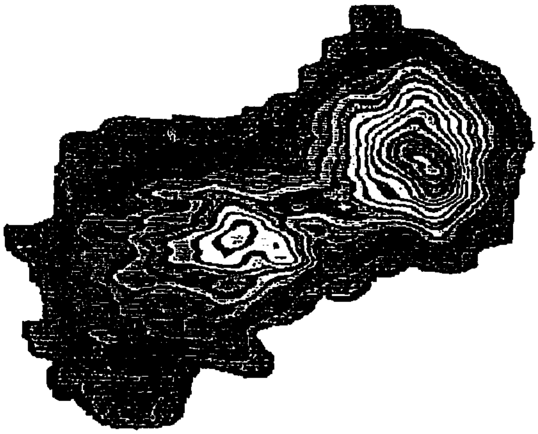

Figure 2: Beam with a Wakefield Tail.

The (normally colored) picture gives a two-dimensional projection of the beam distribution. Contour lines help the black and white visibility.

4 Conclusion

A real radiation hard system has been achieved by moving the cameras far away and carefully designing the light path to get the desired resolution. The overall resolution is further limited by the screen thickness and the camera resolution to about 50 μm.

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