SLAC-PUB-6177
April 1993
(A)

Beam Size Measurements with Noninterceptive Off-Axis Screens

F.-J. DECKER, R. BROWN, J.T. SEEMAN

Stanford Linear Accelerator Center[*], *Stanford, California 94309*

Abstract

At the end of the Stanford Linear Accelerator the transverse distributions of small electron and positron beams ($\sigma \approx 100\,\mu$m) are measured by profile screens. To avoid constant interception and emittance blow-up of the production beams, the beams are deflected with fast magnets on to off-axis screens. One in a 1000 pulses is deflected. The required and achievable resolutions are described in another paper [1]. Here we concentrate more on the magnets, the screen set-up, the readout, and signal processing of the video data. Together with the kicker magnet, two PCs, one for electrons, one for positrons, are triggered recording the next frame of the camera. Hardware and software process this information quickly producing a color-enhanced picture which is displayed in the controlroom. With the resulting visual and digital information, the wakefield tails of the beam can be compensated using orbit oscillations. Minute by minute variations and slow drifts of the beam are recognizable.

1 Introduction

The transverse density distribution of a beam can be obtained from an image of a beam which hits a fluorescent screen. Normally a screen is moved into the beam line for observation disrupting the beam for the downstream use. Here we present a set up which routinely obtains the beam distribution without effectively disturbing the downstream operation of the accelerator. This is achieved by kicking one out of many beam pulses on to an off-axis screen.

2 Set Up of the Off-Axis Screens

The set up consists of kicker magnets, off-axis screens and the optical system to the remote cameras.

2.1 Kicker Magnets

At the end of the SLC-linac four "kicker" magnets are installed at betatron phase advances of 0°, 22.5°, 90° and 112.5°. A pulse with a peak current of 600 A and a rise and fall time of 1 ms each provides a beam offset of 6 mm at the downstream fluorescent screens which are about 2 to 3 mm off axis (Fig. 1).

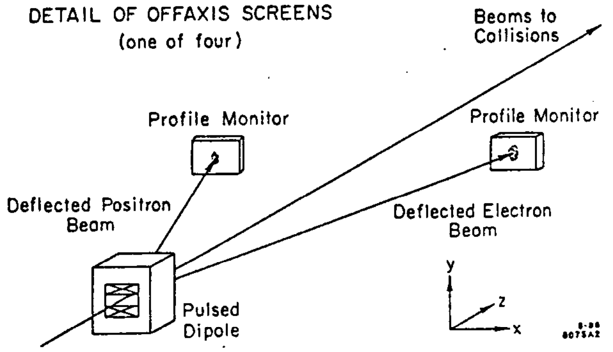

Figure 1: Principle Set Up of the Off-Axis Screens.

A pulsed dipole (kicker) magnet deflects one out of many beam pulses, going to interaction point for collision. This one pulse (electron and positron bunch) hits the nearby off-axis screens.

For one out of 960 pulses, this is every eight seconds at 120 Hz, one of the kickers bends the beams (electrons and positrons) onto two screens. Eight seconds later the next kicker fires and so on, till the beams have hit all eight screens. With the measured sizes the emittance ellipse in phase space can be calculated.

2.2 Screens

The self-supporting screens are $120\,\mu$m thick and made out of Al_2O_3:Cr which emits light at 695 nm. They are tilted by an angle of 60° with respect to the beam so that the beam size is magnified by a factor of two. The tilt angle is either in x or y to enlarge the spot dimension with the smaller β-function. Holes of $340\,\mu$m diameter are drilled into the screens in a pattern of 3 by 2 mm for calibration purposes.

The resolution of the 12 m long optical system is discussed in another paper [1], here we will give only a summary of the different sources contributing to the resolution (Tab. 1). The resolution of $50\,\mu$m is subtracted in quadrature. In the 60° case the beam showed that a $25\,\mu$m resolution is more reasonable. This indicates that the material is not as transparent under beam conditions as in the laboratory tests. This might come from high radiation damage.

For flat beams used in the current operation the expected vertical beam sizes are $\sigma_z = \sqrt{\varepsilon_z \beta} = 30\,(45)\,\mu$m, with $\gamma\varepsilon_z = 0.3 \cdot 10^{-5}$ m-rad and $\beta_{min,(max)} = 25\,(50)$ m. This is comparable with the resolution of the system.

---

[*] Work supported by the Department of Energy contract DE-AC03-76SF00515.

Presented at the Particle Accelerator Conference (PAC 93), Washington, DC, May 17–20, 1993

	σ_c	σ_t	σ_o	σ_g	σ_Σ
0°	30	0	30	30	52
60°	15	45	15	15	52

Table 1: Resolution Contributions in μm.

Different components of an optical system contribute to the overall performance. Here the σ-resolution in beam sizes are shown for no angle and a 60° angle to the beam making most of the resolutions twice as good. The camera (c) has a line resolution. If the screen is transparent, the thickness (t) of the screen has a big effect. The diffraction limit of the optical system (o) and the granularity (g) of the screen gives further limitation. The overall resolution (Σ) is about 50 μm in both cases.

3 Cameras, Electronics and Computer

The images from the screens are processed with cameras, cables, combining boxes and readout computers.

3.1 Initial Set Up

The initial set up had eight RCA TC 2521U (Ultracon) cameras and two signal switching boxes each combining the four camera signals of one beam (e.g. electrons). The video signal was sent over two RG 59 cables to two PCs in the control room. In this system three problems occurred which could be localized to the switch box: (1) Non-linear signal behavior, (2) a non-synchronization to the beam arrival resulting in half the beam spot bright the other half dimmer in the vertical, and (3) a loss of half the video lines and therefore resolution.

This set up was changed to newer CCD cameras (COHU 4810), eight 1/2' solid shield aluminum CATV transfer cables and a multiplexed readout card in the computer. This system will be described further.

3.2 Cameras

The cameras should have sufficient spatial resolution, and a good linear or square root of amplitude (Gamma = 0.5) response over a wide dynamic range. One sigma of a Gaussian distribution corresponds to a modulation transfer function (MTF) value of about 60 %. With 250 TV lines at that value and an image area of 8.8 $*$ 6.6 mm a resolution of about 30 μm (6.6 mm/250) is achieved (similar to the old camera). The dynamic range or signal-to-noise ratio of 55 dB (compared to 44 dB) should give some improvements. Fig. 2 shows the response of an LED spot with linear and Gamma = 0.5 setting showing that the full dynamic range is achieved for the 0.5 value. Recent measurements have shown that for Gamma = 0.5 the response curve is not exactly the predicted one, giving different size for different intensities.

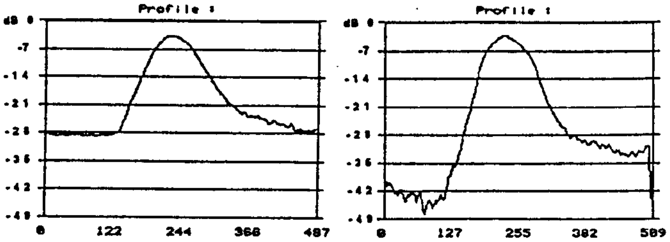

Figure 2: Signal Response for Gamma = 1 and 0.5.

An LED spot (asymmetric) on the camera was read out with a Gamma setting of 1 (linear) and 0.5 ($\sqrt{intensity}$). The intensity over the spot is plotted in logarthmic scale versus the pixel number. For a Gaussian spot this should give a quadratic behavior (or x^4 for Gamma = 0.5) down to the noise level.

3.3 Computers and Cards

The new cables to the computers reduced a frequency dependent loss of 7 dB down to less that 1 dB at higher frequency (10 MHz). The 8-channel video multiplexer (DT2859) from Data Translation [2] switches from one screen to the next one corresponding to a bit pattern from the kickers fed into the parallel input/output (printer) port of the 486 PC. The frame grabber (DT2861) in the PC is triggered externally to acquire a picture (or several consecutive) from the camera. An array processor card allows "hardware" calculations, for example averaging over the surrounding pixels (7 $*$ 7 convolution) in 1.7 s. (This took 30 (3) min on a 386 PC without (with) a co-processor.)

3.4 Program

The program was written in C with DT-IRIS subroutines [2]. Since this package doesn't support printout from a stored picture another program, Image-Pro, is used. The initial program had many features to handle the hardware status: It had to decide which screen was hit, adjust the gain (varying combining box signal), judge from the size pattern whether it is an electron or a positron beam (this is still used), resynchronize if the beam went away (1 Hz suppresses the kicker trigger) and averaged over five video frames. Additionally, there are different test bits possible which generate design beam spots, take old saved raw data for processing or generate a movie like sequence were wakefield tails are developing in phase space.

The main design criteria for the program were the following features: It should provide a color enhanced video signal of four spots per beam which should show low intensity parts of the beam tails. It should also provide the sizes and emittances of the beams and display them.

Colored Display. The display consists of a color table with 16 colors and black lines in between. These lines have two advantages: They help visual acuity and also provide contour lines for a black and white printout like for this paper. With this table and a linear camera response the smallest recognizable level would be 6 % of the peak value. Therefore the input table, which transforms the camera signal heights into 255 numbers, was changed to square root of intensity (not necessary if Gamma = 0.5 at the camera). This should make tails and beam halos down to 0.5 % visible. A further enhancement makes background noise like stripes and waves on the picture visible.

To suppress backgrounds one picture frame is acquired and a few frames later a background frame, which is subtracted from the first one. The result is scaled and convoluted over $6*6$ pixels which reduces pixel noise and washes out the difference between the two interlaced fields of one frame (beam spot decays or camera changes gain). Additionally, the spots are centered in their respective quadrants of the video image and projections in x and y plotted, indicating also the center and the symmetric one sigma points.

Sizes and Emittance Values. The sizes are extracted out of the projections in x and y. Since the background subtraction is not perfect and the convolution produces non-zero values near the boundary, a simple rms calculation wasn't correct. A non-linear fit with a Gaussian (or asymmetric) function would have been the right thing if there were no constrains in speed. Therefore the following method is used. The peak center is defined as the average of all values 90 % of the maximum and higher. From this center the right and left sigma is achieved by averaging all values between 48 and 72 % on one side of the maximum (linear scale). This was checked with some generated distributions. It is very fast and also very robust to strange beam-distributions. The σ of the beam is the average of the left and right sigmas minus the resolution of 50 (25) μm in quadrature. The results are displayed in the corners of the TV image in μm (SX=σ_x,... see Fig. 3). The asymmetry or tails of the beam is given by:

$$T = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \tag{1}$$

for one spot. The numbers TX, TY give the average of the two top or two bottom spots. Positive numbers represent a tail to the top and right on the left screens (left on the right screens, mirror image).

The normalized "emittance" $\gamma\epsilon$ at each screen is calculated by

$$\gamma\epsilon = \gamma\frac{\sigma^2}{\beta}, \tag{2}$$

where β is the β-function at the screen and $\gamma = 90\,000$ the relativistic Lorentz factor. The results are shown in the middle of the left and right side in mm-mrad. This information indicates a mismatch of the beam or problems with the calibration of each camera. The arithmetic average of all four numbers will give Bmag*emittance since there are two pairs of two screens being 90° apart [3]. Bmag is a factor indicating the emittance blow-up of a mismatch after filamentation. These emittance numbers (EX, EY in mm-rad) are in the center of the display. Above them is an averaged number for x and y of 20 good measurements. These numbers, together with size and tail values, go to the VAX control computer via a DAC card in the PC. There they are put into history buffers.

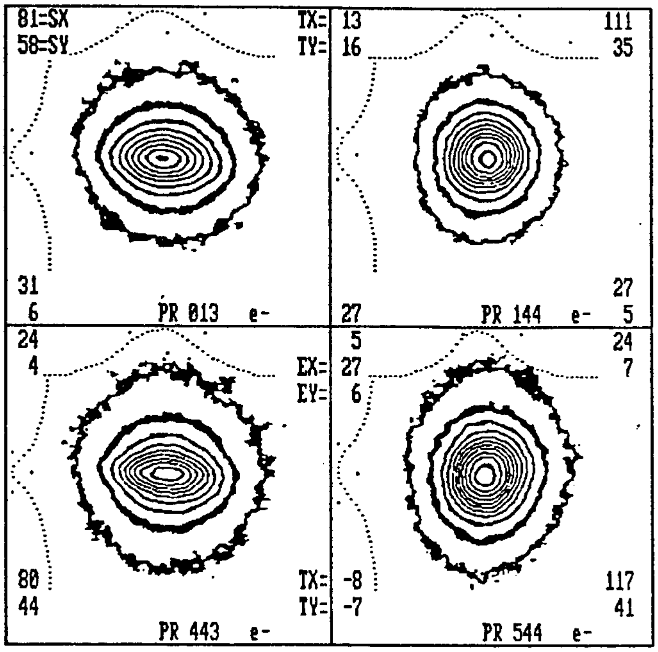

Figure 3: Flat Beam Spots.

The normally colored pictures show the transverse distribution of the electron beam at the end of the SLC-linac. The flat beam set up resulted in emittances of $\gamma\epsilon_{x(y)} =$ 27(6) *mm-mrad (see center of picture).*

4 Measurements

Fig. 3 shows an example for flat beams. The emittance ratio is about 5:1 at the end of the linac. This measurement was done with low currents ($\leq 2 \cdot 10^{10}$ particles) and a longer store time in the damping ring. This example is near the resolution limit for y.

Often one-sided asymmetries (wakefield tails) occur which can easily be seen on these screens. Control of the tail is made by introducing betatron oscillations with a certain phase and amplitude, so that no tails are visible [4].

5 Conclusion

Non-interceptive off-axis screens give a continuous information of the beam distribution, size and emittance at the end of the SLC-linac.

References

[1] F.-J. Decker, *Beam Size Measurement at High Radiation Levels*, PAC, San Francisco, May 1992, p. 1192.

[2] DATA TRANSLATION (R), *Product Handbook: Image Processing, Data Acquisition*, 1991, Tel. (508) 481-3700.

[3] W.L. Spence, *Private communication.*

[4] J.T. Seeman et al., *Introduction of Trajectory Oscillations to Reduce Emittance Growth in the SLC Linac*, HEACC'93, Hamburg, July 1993, p. 879.