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SLC ENERGY SPECTRUM MONITOR USING SYNCHROTRON RADIATION*

J. SEEMAN, W. BRUNK, R. EARLY, M. ROSS, E. TILLMANN and D. WALZ

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Summary

The SLAC Linac is being upgraded for the use in the SLAC Linear Collider (SLC). The improved Linac must accelerate electron and positron bunches from 1.2 GeV to 50 GeV while producing output energy spectra of about 0.2%. The energy spectra must be maintained during operation to provide for good beam transmission and to minimize chromatic effects in the SLC ARCs and Final Focus. The energy spectra of these beams are determined by the bunch length and intensity, the RF phase and waveform and the intra-bunch longitudinal wakefields. A non-destructive energy spectrum monitor has been designed using a vertical wiggler magnet located downstream of the horizontal beam splitter at the end of the SLC Linac. It produces synchrotron radiation which is viewed in an off-axis x-ray position sensitive detector. The expected resolution is 0.08%. The design considerations of this monitor are presented in this paper. A pair of these monitors is under construction with an installation date set for late summer 1986.

1. Energy Spectrum

The energy spectrum of an SLC beam is determined by the length and intensity of the bunch and RF parameters. The bunch length produced by the Damping Ring-Compressor complex is in the range of 1 to 1.5 mm. The beam is accelerated over 2946 m of linac powered by 229 klystrons (2856 MHz) with a gradient of about 18 MV/m. The high bunch intensity (5×10^{10}) generates strong longitudinal wakefields. The integrated wakefields are position dependent within the bunch causing the longitudinal head to be decelerated only slightly but the tail to be decelerated by about 2 GeV over the length of the linac. To compensate, the RF phase is adjusted so that the bunch is centered ahead of the voltage crest where the RF gradient nearly cancels the wakefield induced gradient.

Two simulated energy spectra representing high and low bunch intensities are shown in Fig. 1. Both spectra have widths less than 0.2% RMS when 1% energy cuts are made. The shape difference between the two plots is striking and an energy spectrum monitor must be capable of detecting both. The far-off energy particles are due to the nonlinear nature

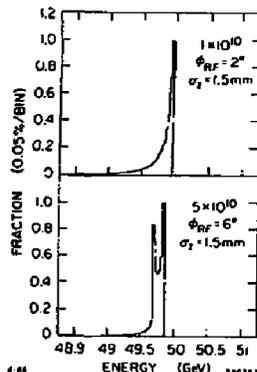


Fig. 1. Expected energy spectra for SLC beams at the end of the linac.

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of the RF and wakefield forces and are removed from the beam early in the ARCs by momentum defining slits. Finally, synchrotron radiation generated in the ARC bending magnets will further smear the spectra in Fig. 1 by about 0.08%³ before the bunch arrives at the Final Focus.

2. Optics and Layout

One of the best locations in the SLC for a measurement of the energy spectrum is immediately downstream of the beam splitter magnet at the end of the Linac. In this region near quadrupole Q2 the horizontal dispersion η remains large but the horizontal betatron function β becomes quite small. This small betatron function is very important because occasionally a large transverse tail will appear on the beam due to transverse wakefields and it should not contaminate the spectrum measurement. For the same reason the momentum defining slits are located nearby. A general layout of the spectrum monitor is shown in Fig. 2. A horizontally dispersed e^+ or e^- beam passes through a half wavelength vertical wiggler and emits synchrotron radiation which diverges from the beam trajectory. The synchrotron radiation is filtered to produce x-rays which strike an off-axis fluorescent screen. A high resolution TV system views and processes the screen image. The particle and x-ray beam trajectories are shown in Fig. 3. Table 1 gives the parameters of the beams in the wiggler region.

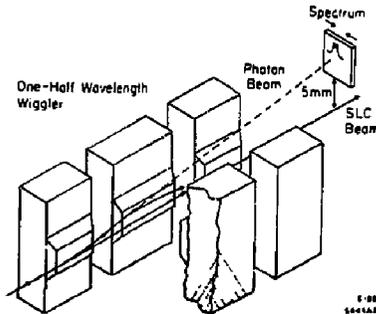


Fig. 2. SLC energy spectrum monitor using a vertical wiggler magnet and an off-axis x-ray detector.

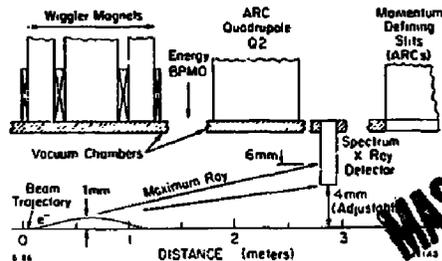


Fig. 3. Elevation view of the spectrum monitor region.

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Table 1. Beam Parameters for the Spectrum Monitor.

For the Particle Beam at the Source Point:	
Energy (E)	50 GeV
$\gamma = E/m_0c^2 $	97847
γ_{rms}	3.0×10^{-5} rad-m
$\Delta E/E$	0.002
$\beta x(\beta y)$	10 (25) m
η_x	80 mm
η_y	-0.008
σ_{x0}	55 μ
σ_{y0}	88 μ
σ_{z0}	160 μ
For the Photon Beam at the X-Ray Detector:	
Distance from source point l	2.38 m
σ_{xE}	120 μ
σ_{yE}	31 μ
$2l/\gamma$	48 μ
σ_{xTOT}	133 μ

3. Magnet Design

Two wiggler monitors are required; one each for the two SLC beams. Each wiggler magnet consists of three dipoles with the center magnet about twice as long as the end magnets. The nominal operating field is about 17 Kg. The length of the first pole was chosen such that a 50 GeV beam would be bent 2.5 mrad so that the x-rays produced would be about 5 mm off-axis 2.4 m downstream. The second two poles were designed so that the wiggler would be symmetric and would return the SLC beam to its nominal trajectory.

There were two choices for the magnet design. One choice was three classical H magnets in series. This design was ultimately chosen for its ease of construction and magnetic trimming ($\int Bd\ell = 0$). Figure 4 shows an end view of the magnet and its parameters are listed in Table 2.

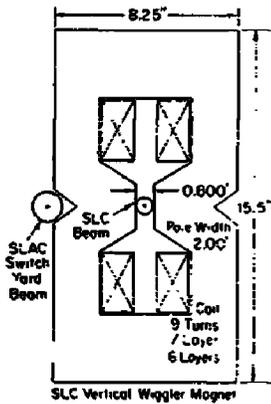


Fig. 4. End view of the wiggler dipole magnet.

Table 2. Wiggler Magnet Parameters

Magnets per wiggler	3
Core lengths (inches)	8.8, 18.0, 8.8
Overall length (inches)	53.2
Gap field (maximum) (Kg)	18.7
Current (maximum) (Amps)	300.
Voltage (maximum) (in series)	55.
Size of trim on center pole (%)	4.

The second choice was to return the magnetic flux from the poles not through backlegs as in the H magnet design but from the central pole to the end poles through connecting iron plates. At first it appeared that the magnet could be powered from a single coil on the central pole. However, three dimensional calculations using TOSCA showed that too much of the flux from the central pole was not returning through the end poles but away from the beam in the third dimension. A cure for this problem was to place coils on each pole. Furthermore field trimming of this magnet to make the field integral zero required forcing flux from magnet-half to magnet-half off the beam line. A workable wiggler using this design was obtained but the other simpler solution was chosen.

4. Synchrotron Radiation Spectrum

The usable portion of the synchrotron radiation spectrum from the wiggler is the range of x-rays above about 100 to 300 KeV. These x-rays have sufficiently small divergence angles so that the transverse beam size of interest (150 μ) is not obscured. The x-rays collected by the detector come from the downstream end of the first pole and the upstream end of the second pole in about 22 cm of 17 Kg field. The critical energy of the synchrotron radiation is 3.0 MeV. The expected photon spectrum for 5×10^{10} particles per pulse at 120 Hz is shown in Fig. 5. The total power is about 2.2 Watts. A tungsten filter (5 mm) is used to cut off the spectrum below about 100 KeV. Tungsten was chosen because it attenuates high energy photons less for a given attenuation at 100 KeV than a lower Z material. The filtered spectrum is also shown in Fig. 5. The remaining x-rays interact with a phosphor layer 150 μ thick settled on an aluminum substrate. The spectrum of the x-rays which interact with this screen is plotted in Fig. 5. The total power interacting with the phosphor is about 3.5 milliwatts. The filter absorbs about 0.6 Watts.

5. X-ray Detector and Digitization

A schematic of the x-ray detector is shown in Fig. 6. The tungsten filter and phosphor screen are mounted in a housing movable relative to the SLC beam line via bellows. The screen is tilted about a horizontal axis so that the television camera viewing the screen will not have depth of field problems. The screen and camera move together and the focus is always maintained. The horizontal spot size is about 0.5 mm and represents the energy spectrum of the SLC beam. The vertical spot size is about 3 mm but contains no information because it is in the plane of the bend. The high resolution camera system uses an Ultricon video tube chosen for its linearity, good sensitivity, and low blooming. The camera is used

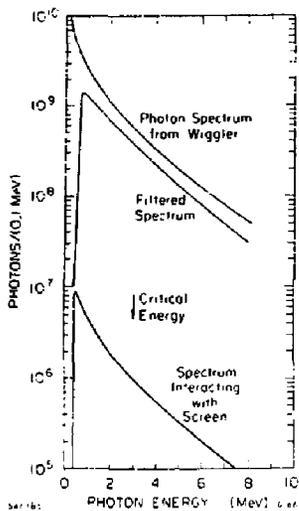


Fig. 5. Synchrotron radiation spectra at 5×10^{10} electrons per pulse (120 Hz) emitted by the wiggler, passed through the filter and interacting with the screen.

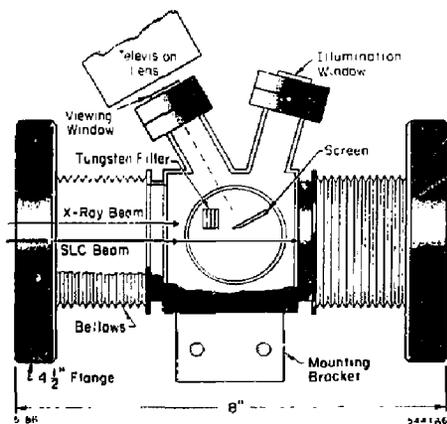


Fig. 6. Schematic of the off-axis x-ray detector.

with an 85 mm lens and a 15 mm extension tube to produce a magnification of 2.0. The field of view is 4×5 mm. The bench measured resolution of this system is about 50 μ on the screen. This corresponds to a resolution of the energy spectrum of an SLC beam of 0.08 %.

The intensity of the spot may be adjusted in several ways. The lens has a remotely adjustable iris, the thickness of the tungsten filter is variable, the detector may be remotely moved closer to the beam where more light is available, and finally, the phosphor may be changed. The intensity of light was estimated by comparing it to that produced by an electron beam striking the screen directly which has been tested often at SLAC.

The comparison shows that with care the x-ray produced spot should be visible down to intensities of 2×10^9 electrons per pulse at 20 Hz.

The video output of the camera will be used in three ways. One signal will be sent to the main control center for direct observation by the SLC operators. Another signal will be processed using a transient waveform digitizer which allows careful study of the spectrum. The third signal will be used in the fast energy spectrum feedback system. A single horizontal TV scan line will be processed by an analog circuit designed to produce peak and width signals easily used in a fast algorithm. Plans for using a CCD line scan camera are being made which allows spectrum measurements to be taken on every pulse.

6. Resolution and Backgrounds

The natural divergence angle of the x-rays produced by the wiggler is given by $[\lambda/\lambda_c]^{1/3}/\gamma$ where λ_c is the critical x-ray wavelength. This angle multiplied by the distance to the detector (2.4 m) gives a size of 48 μ at the screen averaged over the filtered spectrum. The betatron beam size mapped to the detector is about 31 μ . When these sizes are added to the expected energy-related size of 120 μ in quadrature, the total size is 133 μ . The energy spectrum should be well resolved.

The hard radiation from upstream bending magnets will pass below the detector. Soft radiation can hit the detector but care was taken in the design to allow very little scattered light into the lens.

Photoelectrons from the back surface of the filter have an angular distribution which is zero at low angles but peaks at 10 to 30° for MeV photons. The one centimeter distance to the screen allows these electrons to be uniformly distributed over a large area.

Compton electrons from the filter and the aluminum screen support can strike the phosphor. The Compton electrons are peaked in the forward direction but have a rather large spread over 5 to 10°. The electrons from the filter will be uniformly distributed after traveling 1 cm. The only direction from which the electrons from the screen support can enter the phosphor is vertically upward. Those vertical electrons will not cause problems for horizontal spot measurements.

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