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PRECISION ENERGY MEASUREMENT TECHNIQUE*

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Introduction

For some electron scattering experiments it is not necessary to have a very narrow electron energy spectrum, but is necessary to know the energy centroid of each beam pulse with great precision. In the past such experiments at SLAC have been run with the momentum defining slit set to a very small opening (perhaps $\Delta p/p \approx \pm 0.05$), in order to know the energy precisely. As a result they have suffered reduced beam intensity, significantly reduced duty factor, and greater operational difficulties. For a particular experiment to be performed next winter, a better system is necessary. This experiment is "A Test of Parity Violation in the Inelastic Scattering of Polarized Electrons."[1] For this experiment it is necessary to measure any correlation between the energy and the polarization of the electron beam with a precision in $\Delta E/E$ of 0.001%. The beam polarization will be reversed randomly on a pulse-to-pulse basis. Since each data point will consist of thousands of polarization reversals, a system which measures the energy change from each pulse to the next to an accuracy of $E/E \lesssim .01\%$ will permit determination of the correlation between energy and polarization to the required accuracy. With a technique that was recently successfully tested at SLAC, it is possible to open the slits to $\Delta p/p = \pm 0.5\%$ and measure the energy centroid of each beam pulse with a precision of ±0.01%. With ±0.5% slits, nearly 100% of the beam is transmitted from the linear accelerator to the target. The technique depends on the fact that the path length through bending magnets in the beam switchyard (BSY) depends on energy. The electrons from SLAC are so highly relativistic that the velocity can be considered to be independent of energy: $1-\beta \lesssim 10^{-9}$. The higher energy electrons travel a longer path through the bending magnets and hence have a longer time of flight. This may be expressed in terms of the derivative

$$\frac{1}{E}\frac{dE}{dt} = \frac{0.06\%}{\text{picosecond}} .$$

Since the beam is bunched with a 2856 MHz structure, it is possible to measure the time of flight by measuring the phase difference between two 2856 MHz signals induced in microwave cavities located before and after the bending magnets, as in Fig. 1.

Estimate of Resolution

Using electronics described below, it is possible to measure differential phase to $.0013^\circ$. At 2856 MHz, 1° of phase is 0.97 picoseconds. So this phase measurement precision corresponds to an energy measurement precision of $8 \times 10^{-5}\%$. Before we can conclude that we can measure energy shifts to this precision, we must consider the other contributions to variations in the measured time of flight. Horizontal displacements of the

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beam entering the switchyard change the time of flight by .03 picoseconds/mm, which corresponds to $\Delta E/E \approx .002\%$. Short term beam displacements as large as 1 mm are rare and easily observed on the position monitors. So .002% is a conservative estimate of the error in the energy measurement due to this source. The change in time of flight caused by a change in the horizontal angle θ of the beam entering the switchyard is .01 picosecond/mrad. The upper limit on angular motion of the SLAC beams is about 0.1 mrad; so this contribution is $\Delta E/E = .00006\%$. The contributions due to vertical displacement and angular motion are much smaller. Transverse motion of the beam produces another source of error. The electrical center of the gap for each cavity is a surface which is surely not precisely a plane normal to the beam axis. Thus the longitudinal position of each cavity is a function of the transverse position of the beam. If we rather arbitrarily estimate this variation to be 25 microns, we get a variation in t of .08 picosecond. Multiplying this by $\sqrt{2}$ because these are two cavities required for the measurement, we find an error of $\Delta E/E$ caused by cavity asymmetries (or misalignments) of .007%. Finally, mechanical vibrations can change the distance between the two cavities as well as can the phase shift through the transmission lines to the phase bridge. Possible causes for mechanical vibration are the mechanical fore pumps on the vacuum system, and turbulence in the water cooling flow through the microwave cavities. We have not studied this effect, so, again basing our estimate on ignorance, we estimate the equivalent longitudinal motion to be 10 microns for each cavity. Combining the effect of both cavities by multiplying by $\sqrt{2}$ we get an error $\Delta E/E = .003\%$. These estimated errors are summarized in Table 1.

Table 1. Estimate of Pulse-to-Pulse Resolution

Source of Error	ΔL (microns)	Δt (picoseconds)	$\Delta E/E$ (%)
Phase measurement		.0013	.00008
Horizontal motion of beam		.03	.002
Angular motion of beam		.001	.00006
Cavity asymmetries	$25\sqrt{2}$	.12	.007
Mechanical vibrations	$10\sqrt{2}$	.05	.003
$\left[\sum_i \left(\frac{\Delta E}{E}\right)_i^2\right]^{1/2}$			.008

Long Term Stability

The long term stability of the energy measurement system is at least two orders of magnitude worse than its short term resolution. Long term drifts are caused by the phase shifts due to temperature changes in the long cable from the first cavity to the phase bridge. The phase bridge is located near the second cavity because the beam induced pulses from both cavities must arrive at the phase bridge at the same time. It is possible to build a line with a feedback system which maintains a constant phase shift through the line, but such a system is quite expensive. For the present application, only good pulse-to-pulse resolution is required.

Phase Measurement Electronics

A homodyne system for measuring the phase between the output of the two transducers is shown in Fig. 1.

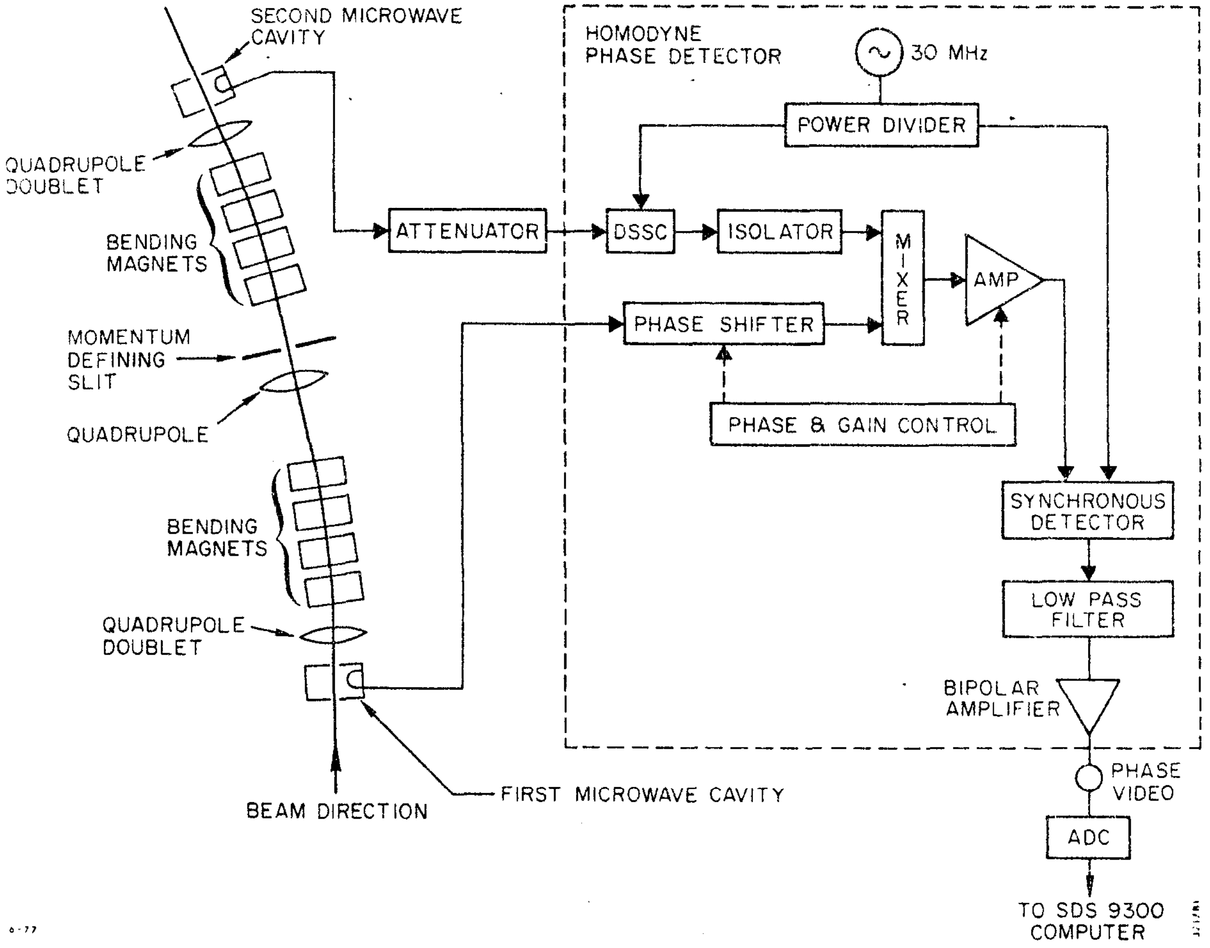

Fig. 1. Precision energy measurement system.

The transducers are TM_{010} cavities whose output is 20 dB m/mA^2. The output from the second cavity is fed into a double sideband suppressed carrier (DSSC) modulator. The modulation is produced by a relatively high-level (10 dBm) 30 MHz CW signal. The DSSC modulation can be considered as 180^o phase-modulation at a 30 MHz rate (with sinusoidal amplitude modulation which does not significantly affect the detection mechanism). The 30 MHz DSSC 2856 MHz signal passes through an isolator (to avoid reflections which can be modulated and retransmitted as spurious energy error signals) to a mixer which is used as a phase-detector. Here it is mixed with a coherent 2856 MHz reference signal derived from the first cavity. The output of the mixer is a 30 MHz signal. The phase shifter is adjusted so that the mixer amplifier output is zero at a given energy, which occurs when the two inputs are in quadrature. A perturbation in energy will cause a change in phase and hence a change in output. If the input to the homodyne phase detector from the second cavity is less than the input from the first cavity, then the mixer output voltage amplitude $V_m = k_i I k_m \phi/57.3 \equiv \phi k I$, where

k_i = cavity voltage into a 50 ohm input at the phase bridge per unit current through it,

I = pulse current through the second cavity,

k_m = conversion gain of DSSC-mixer, and

ϕ = change in phase shift in degrees.

The minimum measurable phase shift ϕ_m is given by $\phi_m = V_n/k$, where V_n is the noise equivalent amplifier input voltage. If $k_i = 3.16$ V/mA, $k_m = .1$, and $V_n = 7\ \mu V$, then $k = 5.5$ mV/mA-degree and $\phi_m = 1.3 \times 10^{-3}$ degrees at one mA. The mixer output is amplified and fed into a synchronous detector, where it is phase-compared with part of the original 30 MHz signal. It is necessary to adjust the phase of one 30 MHz signal to maximize the video output from the synchronous detector. A low-pass filter removes the residual 30 MHz signal, and the video passes through a bipolar video amplifier to an analog-to-digital converter and then to the SDS 9300 computer, where it is normalized and processed.

It might appear desirable to use means such as limiter amplifiers to obtain a signal that is proportional to phase shift only, and is independent of current. However that is not the case, because the current transmitted through the energy defining slits varies in amplitude with time, and we desire

$$\frac{\int E(t)\, I(t)\, dt}{\int I(t)\, dt}$$

rather than $\int E(t)\, dt$, i.e., the energy averaged over the total charge rather than time averaged over a pulse width.

Experimental Tests

In February, a test of this energy measurement technique was performed using microwave cavities that are part of the original beam switchyard instrumentation. The results of the test are shown in Figs. 2, 3, and 4. In order to calibrate the energy monitor a beam was set up which switched between two energies that were 0.3% apart on alternate pulses. The phase bridge video output was integrated within the pulse, digitized, and fed to the online SDS 9300 computer. The computer recorded the data. It then calculated the change in voltage between each pulse and the following pulse, sorted these changes into bins and plotted a histogram of the number in each bin. This method of analysis minimizes the effect of slow drifts in energy on the measurement. The histogram is shown in Fig. 2. There are two peaks in the distribution, one at +0.3% for low to high energy transition, and another at -0.3% for the downward transition. Therefore, the separation between peaks, 145 channels, represents 0.6%. It follows that 242 channels equals 1% in energy. In Fig. 3 the same pulse-to-pulse energy change histogram is plotted for a single energy beam. The distribution has a standard deviation $\sigma = 2.3$

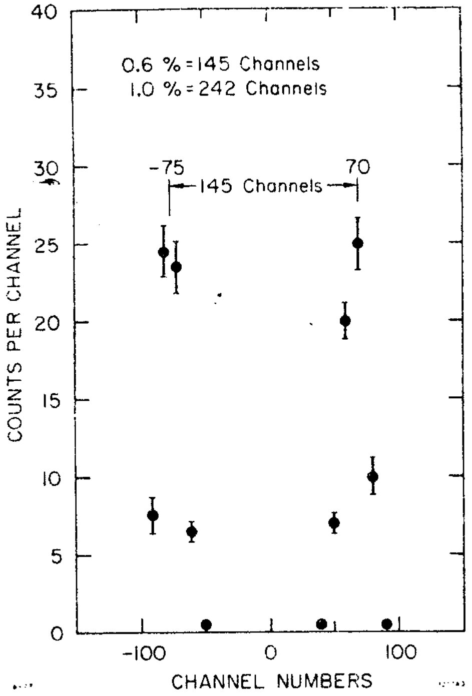

Fig. 2. Calibration of energy monitor by energy wobbling.

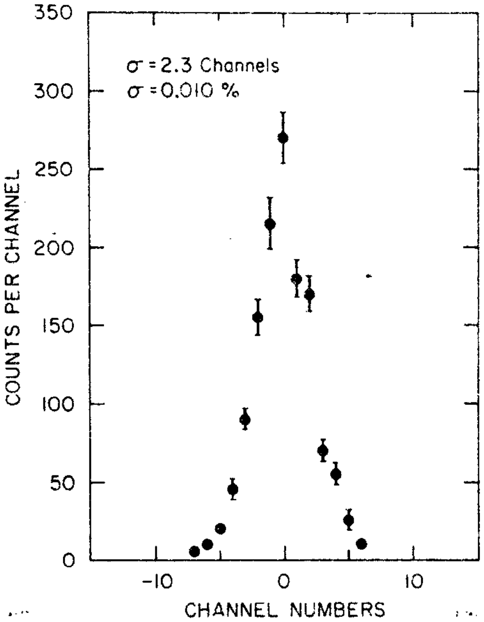

Fig. 3. Pulse-to-pulse energy jitter during stable run.

channels; i.e., $\sigma = 0.010\%$. From this we can conclude that the pulse-to-pulse energy jitter of the beam is $\Delta E/E \leq \pm.01\%$. We can also conclude that the pulse-to-pulse energy resolution of the time of flight energy measurement system is $\leq 0.01\%$. We do not know the relative contribution of the measurement system and actual energy jitter to the distribution.

During the time while we were setting up this test, we noticed that one particular klystron caused a rythmic wobble of phase bridge output video whenever it was put on the beam. The data with this unstable klystron on the beam is plotted in Fig. 4. The standard deviation has increased to 8.7 channels, or .036%.

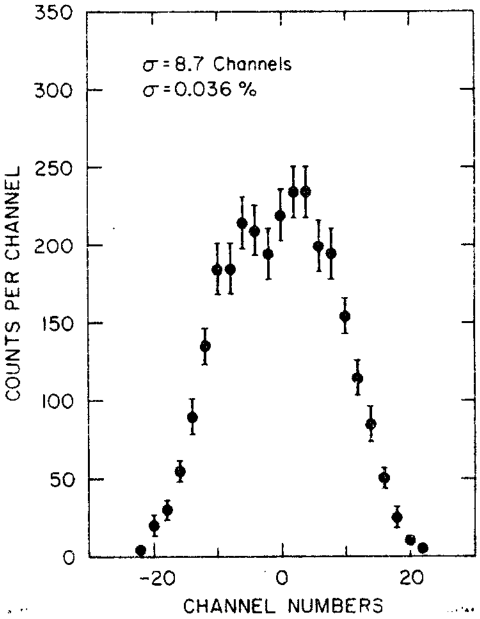

Fig. 4. Pulse-to-pulse energy jitter with unstable klystron on beam.

Acknowledgments

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Reference

1. W. Ash *et al.*, "A Test of Parity Violation in the Inelastic Scattering of Polarized Electrons at the Level of the Weak Interaction," Stanford Linear Accelerator Center. Proposal No. E-122 (May 19, 1975).