

Energy Vernier System for CEBAF*

G. A. Krafft, J. J. Bisognano, M. T. Crofford, J. C. Hovater, L. Merminga, S. N. Simrock, and S. D. Witherspoon
CEBAF

12000 Jefferson Avenue, Newport News, VA 23606

and

K. Kubo

KEK

Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

The beam energy of CEBAF must be accurately controlled for precise physics experiments. In order to achieve a relative energy spread better than $\sigma_E/E = 2.5 \times 10^{-5}$, a feedback system is needed to stabilize the energy against phase and amplitude fluctuations in the individual cavities. In the energy vernier system, the energy deviation of the beam is measured at a location with high dispersion. The error signal controls the accelerating gradient of selected vernier cavities. The methods used to correct the energy will be discussed, as well as the noise sources in the system. The results of beam tests at the CEBAF north linac will also be reported.

I. INTRODUCTION

The functions of the energy vernier are to stabilize the average energy of the emerging beam and to set the RF phases in the cavities in a way that minimizes the energy spread. In this paper it is proposed that the first function is accomplished by a dedicated fast spectrometer-based feedback system. The second problem is solved using a low-noise phase shifter between the master oscillator and the phase reference line to optimize the overall linac phase.

A. Requirements of the Energy Vernier

Ideally, the RF system is timed so the bunches arrive synchronized with the RF; the bunch centroid (in phase) should coincide with the RF crest. Mathematically, the requirement is

$$\bar{\theta}_n = \int \theta f_n(E, \theta) dE d\theta = 0$$

where $f_n(E, \theta)$ is the single-particle longitudinal distribution function of the beam electrons as they enter the n th cavity, E is the kinetic energy, and θ is the phase with respect to the RF in the n th cavity. Performing the proper statistical average to obtain the rms relative energy spread at the end of the machine yields

$$T_{\text{rms}}^2/T^2 = E_{\text{rms}}^2/T^2 + \sigma_\theta^2/2$$

where T is the total energy, E_{rms} is the rms energy spread at injection and σ_θ is the rms phase spread. The beam

emerging from the ideal system has a finite energy spread because of the finite energy spread at injection and because of the finite bunch length. For CEBAF at full energy, the first term in the sum is negligible compared to the second term.

When errors derived from the RF system are included [1], and when it is assumed that the vernier operates perfectly, the relative energy spread is

$$T_{\text{rms}}^2/T^2 = E_{\text{rms}}^2/T^2 + \sigma_I^2/2 + \sigma_\delta^2 \sum_{n=1}^N (\phi_n - \Phi)^2/N^2 + \sigma_\delta^2(\sigma_\delta^2/2 + \sigma_I^2)/N + (\sigma_A/A)^2/N \quad (1)$$

assuming the fast errors in different cavities are statistically independent and

$$T_{\text{rms}}/T = \sqrt{E_{\text{rms}}^2/T^2 + (\sigma_I^2 + \sigma_\delta^2)^2/2 + (\sigma_A/A)^2} \quad (2)$$

assuming the fast errors are completely correlated. In these equations, σ_I denotes the rms phase spread emerging from the injector, σ_δ denotes the rms fast phase error in the field of the accelerating cavities (e. g., those in the RF controls), ϕ_n is the slow phase error of the n th cavity (e. g., those from thermal drift in the phase line), Φ is the phase introduced by the vernier to minimize the energy spread (usually $\Phi \approx \sum_{n=1}^N \phi_n/N$), σ_A/A is the rms relative amplitude fluctuation in the cavities, and N is the number of cavities.

To achieve the requisite energy spread, the following specifications were used in the CEBAF RF system design:

Table 1 RF Tolerances Yielding
 2.5×10^{-5} rms Relative Energy Spread [2]

σ_I	0.27°
UNCORRELATED ERRORS	
σ_A/A	2.0×10^{-4}
σ_f	0.25°
σ_s	2.6°
CORRELATED ERRORS	
σ_A/A	1.1×10^{-5}
σ_f	0.13°

Because a gradient error in the vernier is directly an energy error on the beam, the requirement on the gradient

*Supported by U. S. DOE contract DE-AC05-84ER40150.

vernier system is that the corrected energy error be less than the expected energy spread; choosing an rms error less than 1.0×10^{-5} gives less than 15% energy spread growth.

Because vernier phase errors appear like any other correlated phase error, the vernier must correct the average phase to under a bunch length; 0.05° is the design requirement chosen.

B. Basic Description the Energy Vernier

A schematic of the vernier scheme appears in Fig. (1). The gradient portion of the vernier system is based on a "spectrometer" that exists in the first CEBAF arc [3,4]. The beam produces a BPM signal at a location of high dispersion in the lattice. The signal is converted to base-band and compared to a BPM set voltage that is obtained from the computer control system. The difference signal is sent to the gradient set in the RF controls of two vernier cavities that have opposite coupler kicks.

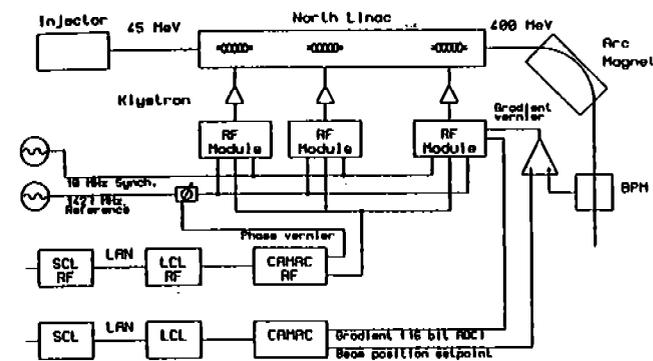


Figure 1 Schematic of Energy Vernier

The phase portion of the vernier system is based on a computer controlled electronic phase shifter. The low noise phase shifter shifts the phase of the phase line going to the individual linac sections. This has the effect of shifting the phases of all the cavities in the linac section with respect to the beam. Then, using the procedure outlined below, the correct offset phase is computed and updated through the computer control system.

II. VERNIER SYSTEM

A. Gradient Control

More detail on the feedback system is given in Fig. (2). The open-loop gain of the feedback system, G_{ol} , is

$$G_{ol} = N \alpha G_a G_d S D / E_0,$$

where N is the number of vernier cavities, α is the RF control module amplitude conversion ratio in MeV/V, G_a is any amplifier gain inside the loop, G_d is the differential gain of the position set amplifier, S is the sensitivity of the BPM in V/m offset, D is the dispersion at the BPM location in m, and E_0 is the total energy at the vernier. Numerical values consistent with the current CEBAF designs are $\alpha = 0.5$ MeV/V, $D = 10$ m, and $S = 140$ mV/mm.

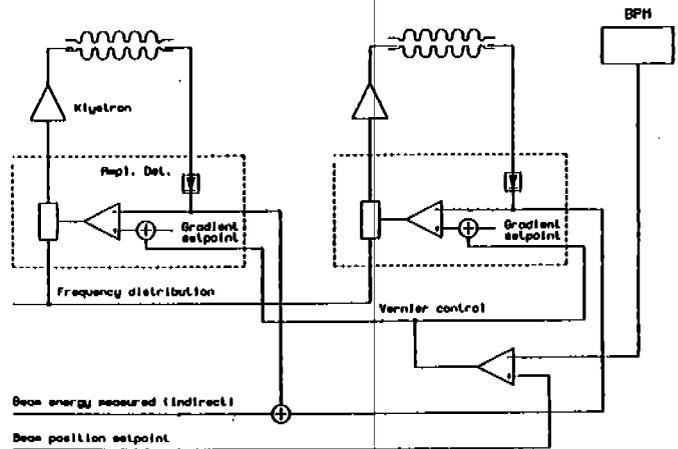


Figure 2 Detail on Gradient Vernier

The main noise source for this system is the energy error from the slow phase errors in the RF system, denoted by ΔE . As usual, the regulated energy gain error, δE , is suppressed relative to the noise by the closed-loop gain of the system,

$$\delta E = \frac{\Delta E}{(1 + G_{ol})}$$

The largest slow phase error that is expected is around 1.5° . To suppress the energy error generated by such a phase error to 1×10^{-5} requires an open-loop gain of 100. Such a gain is achieved with $G_a \cdot G_d \approx 40$ with two vernier cavities.

Two problems in this scheme might be anticipated. The first is that tilt misalignment of the vernier cavities would invalidate the approach. A tilt misalignment has the effect of mimicking the dispersion in measurements at a given BPM. A simple calculation gives

$$D_{\text{eff}} = D + M_{12}^1 \sin(\alpha_1) + M_{12}^2 \sin(\alpha_2)$$

where the M_{12} s are transfer matrix elements between the vernier cavities and the BPM and the α s are tilt misalignment angles [3]. However, if the dispersion is different, this has an effect only on the closed-loop gain of the feedback loop, which can always be increased as needed.

A more substantial problem is beam missteering which causes position errors in the BPM unrelated to the energy fluctuations. One way to solve this problem is to have an orbit lock before the spectrometer to guarantee that steering errors are corrected before entering the spectrometer. The high regulation of the arc dipole power supplies ensures that negligible error is introduced by the bend.

B. Phase Control

In more detail, the software phase control procedure is outlined in the flow chart in Fig. 3. After tuned beam is placed on the vernier BPM, the BPM reading is saved and used as an offset for subsequent calculations. The hardware and software control is activated. If the gradient control is activated, the beam remains fixed in the BPM.

The software can correct on the gradient control signal. The accuracy of the control is equal to the permitted range in the software loop. The response time of the system, at present limited by BPM acquisition time, is of order 5 sec.

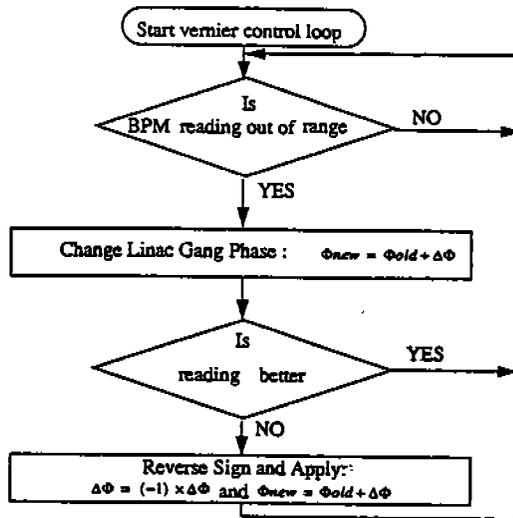


Figure 3 Software Phase Control Procedure for the Vernier

III. RESULTS

Initial tests were performed on both the hardware and software portions of the vernier system. Both tests were based on the BPM in the first spreader of the CEBAF accelerator. The test BPM was at a location where the dispersion is about 1.4 m.

In the hardware test, an energy modulation was introduced into the beam at cavity NL18-8. The square wave energy modulation had a frequency from 1 Hz up to 30 Hz. Cavities NL13-7 and NL13-8 were used as the vernier cavities. At 1 Hz modulation frequency, when the loop was closed the modulation was corrected by 20%. Saturation of a preamp in the feedback chain prevented higher loop gains from being achieved.

Two simple modifications of the hardware should yield substantial improvements on this result. First is to increase the amplitude conversion ratio in the RF control module. A factor of ten increase has been implemented in the vernier controls but not tested with beam. Secondly, when the arc is run in a high dispersion mode where $D \approx 10$, there should be another factor of seven improvement in gain, with no additional electronic noise.

A final factor of five should be possible by going to more sophisticated BPM front end electronics. Such electronics are being developed for this purpose, for fast orbit lock purposes, and also for fast time plots from the BPMs.

The software vernier was tested successfully. With the hardware system off, the software algorithm was used to correct the linac phase using the BPM output from the

same spreader BPM. The result was that the beam was held stably to under 0.5 mm by adjustments of the overall linac phase alone for periods of several minutes. With a dispersion of 1.4 m, this means the energy error was held to under 2.5×10^{-4} . The stability of the algorithm was also investigated by forcing the loop to go unstable by input parameter adjustment, and by restoring the correct input parameters. Energy errors up to 2.5×10^{-3} were induced and reproducibly corrected by the algorithm.

When the software is used to do energy corrections with the 10 m dispersion of the final system, the energy error will be under 2.5×10^{-5} , about a factor of two from the ultimate goal. It is thought that suitable optimization of the feedback loop algorithm will allow us to achieve the final goal.

IV. CONCLUSIONS

A feedback system control scheme has been used for the energy vernier. The amplitudes of the vernier cavities are adjusted to produce a constant position in a BPM at a high dispersion point. To set the phase for minimum energy spread, a correlated phase shift is introduced into the section of linac to be phased, and the gradient signal in the vernier cavities responds with enough sensitivity to unambiguously determine the correct phase shift.

Prototype designs of the electronics for the energy vernier system have been completed. The resulting electronics have been tested with beam during the recent CEBAF run. The results were not entirely satisfactory because the dispersion at the BPM used in the studies was not as large as in the final system. Additionally, amplifier saturation limited the performance of the closed-loop system, but this problem should be solved during the next iteration, where the amplitude conversion constant of the RF controls is increased. After these improvements, achieving the energy specification will be possible.

The software phase correction algorithm was successfully implemented and tested on a low-dispersion BPM. The energy error was corrected to under 2.5×10^{-4} for drift times longer than a few seconds. When the experiment is repeated with a BPM at a higher dispersion location, the energy error will be under 2.5×10^{-5} .

More work needs to be done on orbit locking hardware and software to ensure that position offsets at the BPM are totally correlated with energy offsets.

V. REFERENCES

- [1] G. Krafft, J. Bisognano, and R. Miller, CEBAF-TN-0050 (1987).
- [2] G. A. Krafft, CEBAF-TN-90-0269 (1990).
- [3] G. A. Krafft and S. N. Simrock, CEBAF-TN-90-0280 (1990).
- [4] Y. Chao *et al.*, these proceedings.