CEBAF PR-90-014
September 1990

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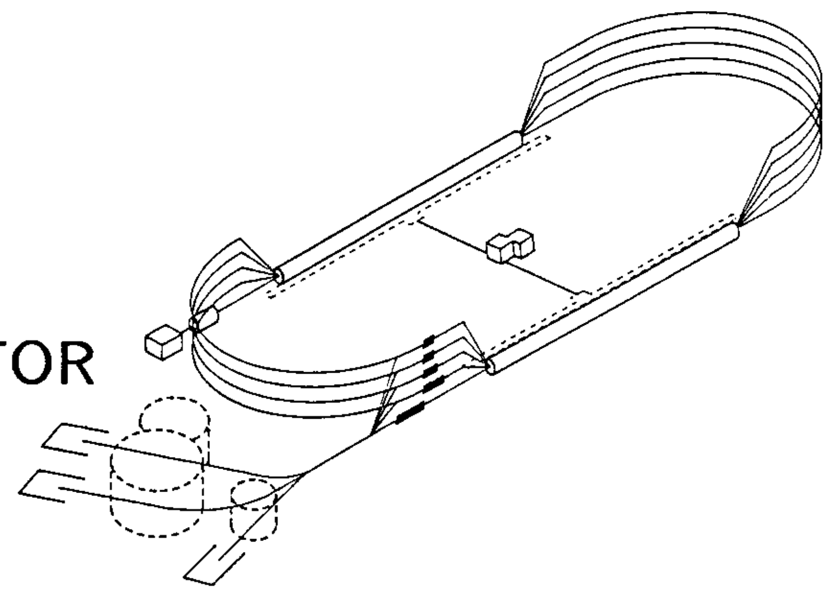

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Newport News, Virginia

TECHNIQUE OF MEASURING BUNCH LENGTH BY PHASING AN RF CAVITY*

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Introduction

The bunch length in the CEBAF electron beam, less than 1° in phase or 2 ps when fully relativistic, is too short to be measured by direct timing techniques. An indirect measurement that has been proposed is the well-known method of changing the phase of an accelerating cavity and observing the energy spread in the beam. The bunch usually rides at the crest of the rf wave in order to maximize the acceleration and to minimize the energy spread. By altering the phase of one or several cavities, the energy spread can be increased by an amount that is proportional to the bunch length. By measuring the energy spread for several phases, the bunch length can be determined.

The method has been applied in tests at the CEBAF injector. The aims of the trial were to see the limitations of the technique, and to understand how it could be improved to the point that it could be used as a regular diagnostic tool. Then the backphasing method can provide a rapid and inexpensive, if rather imprecise, measurement of the bunch length.

The cavities in the injector, shown in Figure 1, are driven by two klystrons. The first cavity raises the beam energy to about 2.7 MeV, which is nearly fully relativistic ($\beta = 0.98$). The phase of the second cavity can then be altered to increase the energy spread. Calculations have indicated that the phase length of the bunch at the entrance of the second cavity can be measured with 10% precision; this figure represents the limit of validity of the computation, and is further degraded by spectrometer errors.

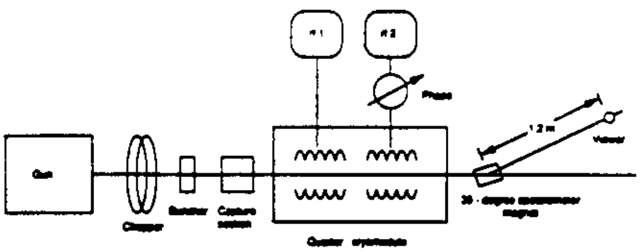

Figure 1. Schematic layout of CEBAF Injector

Energy Spread in the Beam

To a first approximation, the energy spread produced in the beam by the second rf cavity because of phase spread is given by

$$\delta E = E_0 \sin \phi \, \delta\phi, \tag{1}$$

where E_0 is the energy an electron would gain in traversing the cavity at optimum phase, ϕ is the phase difference of the bunch centroid from optimum, and $\delta\phi$ is the phase spread in the bunch. The bunch length l is related to the phase spread by

$$l = \lambda \beta \, \delta\phi/(2\pi), \tag{2}$$

where λ is the rf wavelength, and $\beta (= v/c)$ is very nearly equal to 1. A closer approximation for δE can be gained by using the beam transport code PARMELA, which includes the effects of phase drift that is present because β is not quite equal to 1. A PARMELA subroutine has been prepared by Geoffrey Krafft explicitly to model the CEBAF cavity.[1]

We can characterize the beam by its energy spread δE and its phase spread $\delta\phi$. Their values at the output of a cavity can be connected to their values at the input. Let the subscript i denote input, and o denote output. For small dispersions, we have the following linear relations:

$$\begin{aligned} \delta E_o &= \left(\frac{\partial E_o}{\partial E_i}\right) \delta E_i + \left(\frac{\partial E_o}{\partial \phi_i}\right) \delta\phi_i \\ \delta\phi_o &= \left(\frac{\partial \phi_o}{\partial E_i}\right) \delta E_i + \left(\frac{\partial \phi_o}{\partial \phi_i}\right) \delta\phi_i. \end{aligned} \tag{3}$$

The transfer coefficients $\partial E_o/\partial E_i$, $\partial E_o/\partial \phi_i$ are computed by PARMELA.

The energy spread is measured by the 5-MeV spectrometer, consisting of a rectangular magnet to bend the beam 30°, 1.20 m of drift space, and a viewer. The diameter of the working region of the viewer is 2.2 cm. The line after the cryomodule has no focusing magnets. The diameter of the observed spot is equal to the sum of $\sqrt{\beta\epsilon}$ and the dispersion. Since only the dispersion is interesting, the 'native' spot size represents an offset that must be subtracted away. We find δE_o for several different phases of the second rf cavity, holding everything upstream of the cavity fixed. The spot diameter is measured for several phases of the second cavity relative to optimum. The angular divergence $\delta\psi$ of the beam is then related to the momentum spread.

$$\delta\psi = 2 \tan \left(\frac{\psi}{2}\right) \frac{\delta p}{p} + C, \tag{4}$$

where $\psi = 30°$ is the bend angle, p is the momentum, and C is a constant (equal to $\sqrt{\beta\epsilon}/L$). We set $\delta p/p = \delta E/E$ and combine Equations 3 and 4 to give

$$\delta\psi = 2 \tan \left(\frac{\psi}{2}\right) \left[\left(\frac{\partial E_o}{\partial E_i}\right) \frac{\delta E_i}{E_o} + \left(\frac{\partial E_o}{\partial \phi_i}\right) \frac{\delta \phi_i}{E_o} \right] + C. \tag{5}$$

* This work was supported by the U.S. Department of Energy under contract DE-AC05-84ER40150.

Results

The results for the measurements are given in Table 1. The constant C, the input energy spread δE_i, and the input phase spread $\delta\phi_i$ can be found by least squares, yielding as the best fit the following values:

$$\begin{aligned} \delta E_i &= 0.0386 \text{ MeV}, \\ \delta\phi_i &= 0.247^\circ, \\ C &= 3.34 \times 10^{-3}. \end{aligned} \tag{6}$$

Bounds for the systematic error can be established by assuming extreme values for the constant C. It can be no less than 0, for an arbitrarily precise spectrometer, and it can be no larger than the smallest observed value of $\delta\psi$, 7.5 mrad. With these values for C, the corresponding values of $\delta\psi$ are 0 and 0.53°. Thus,

$$\delta\phi_i = 0.25^\circ \begin{pmatrix} +0.28^\circ \\ -0.25^\circ \end{pmatrix}. \tag{7}$$

TABLE 1
Results of Bunch Length Measurements

Phase	Final Energy (E_o)	Diameter	($\partial E_o/\partial E_i$) (from PARMELA)	($\partial E_o/\partial \phi_i$)
°	MeV	radians		MeV/°
0.0	5.106	0.00796	1.0	0.0*
20.0	4.560	0.00749	1.0	0.0156
40.0	4.536	0.00870	1.0	0.0281
60.0	3.873	0.01022	1.0	0.0375
70.0	3.483	0.01088	1.0	0.0406

* ΔE_o is of second order in $\Delta\phi_i$ near optimum phase.

The diameter is shown as a function of phase in Figure 2, which also plots the function for the best-fit values of Equation 6.

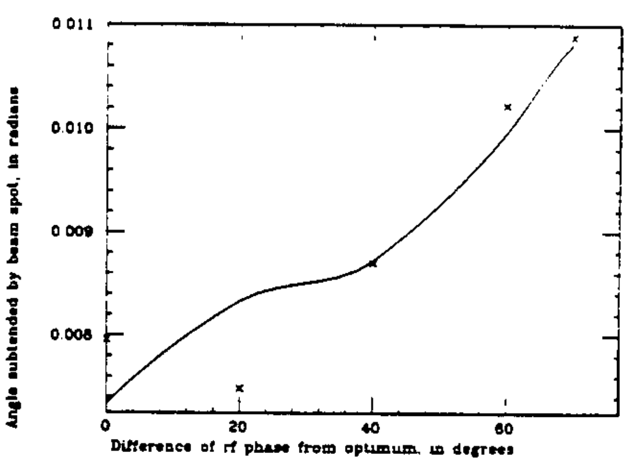

Figure 2. Spot size as a function of phase shift

Summary

In summary, we conclude that the method has proven to be practical for a quick measurement of the bunch length, suitable for preliminary beam setups. Further improvement can be achieved by installing a profile monitor in place of or in addition to the viewer, and by using more sophisticated optics in the spectrometer. With a profile monitor and with spectrometer resolution of 10^3, we will be able not only to find the bunch length but also to observe its structure.

Acknowledgements

Many persons have helped in obtaining the results reported here. We wish to express particular thanks to George Neil and Charlie Sinclair for their operation of the injector, and to Kelly Mahoney for running the rf controls.

Reference

1. Geoffrey Krafft, CEBAF-TN-0051.