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A New Scheme for Measuring the Length of Very Short Bunches at CEBAF

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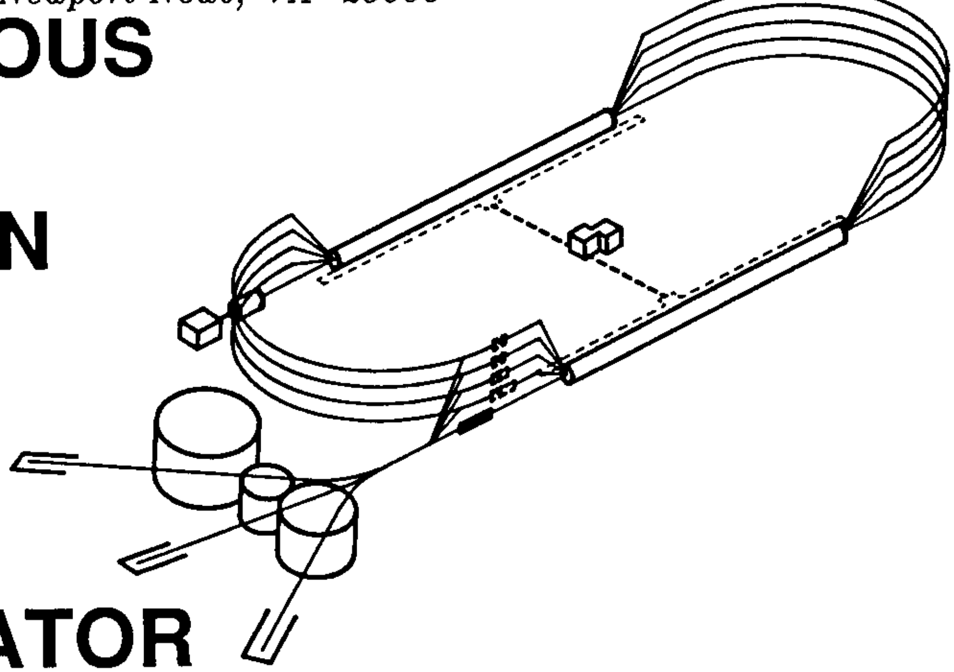

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Newport News, Virginia

A NEW SCHEME FOR MEASURING THE LENGTH OF VERY SHORT BUNCHES AT CEBAF*

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ABSTRACT

The CEBAF injector is designed to bunch a 100 keV beam chopped to 60° to a very short bunch of less than 1° at 5 MeV energy. Presented are a new scheme[1] for measuring the phase distribution in the bunch that gives information about bunch length, and preliminary experimental results that show a resolution of better than 0.1° in phase at 1.5 GHz (or 0.2 ps in time). The advantages of the scheme compared with existing methods for bunch phase width measurement, such as using streak cameras, measuring the transverse spot size of the bunch by deflecting the beam[2], measuring the energy spread by bunch traversing a section of accelerating structure at zero cross phase, or observing transition radiation[3], are: high resolution is obtained; it is suitable for any level of energy; and it is inexpensive. The scheme is not easy to apply to an intense beam where the space charge effect has an important impact on bunching.

INTRODUCTION

A superconducting accelerator at CEBAF will provide a high quality CW beam of energy from 0.5 GeV to 4.0 GeV. The relative energy spread (95% of particles) of the machine will be about 1×10^{-4}. This requires that the injector must supply a well-bunched beam to the main accelerator of phase width less than 1° at 1.5 GHz. Obviously, a method to measure the length of the very short bunch is of importance. There are several different methods available for measuring bunch length, including 1) a streak camera, 2) measuring the transverse spot size of the bunches after traversing a deflecting structure, 3) measuring the energy spread with a spectrometer after beam passage through a section of accelerating structure at zero phase, and 4) measuring the transition radiation emitted by the beam. After careful investigation we conclude that these methods are expensive and that the resolution of these methods is not good enough to measure the bunch length of the well bunched beam from the CEBAF injector (PARMELA shows that the anticipated phase width of a 5 MeV bunch could be as small as 0.5° at the entrance to the first full cryogenic unit if all parameters are set optimally). Also, some of these methods do not work well in the lower energy regions of the injector. The method proposed here is

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to measure the phase distribution within the bunch by detecting a phase shift of fields induced by a series of sub-bunches in a cavity while sweeping the phase of the chopper system with respect to the rest of the injector. The sub-bunches are obtained by having a narrow slit at the chopping aperture.

PROPOSED SCHEME

A layout of the CEBAF injector and the scheme for measuring bunch length in this system is shown in figure 1. The injector is comprised of a 100 keV gun, two identical square pillbox chopper cavities, a buncher, a side-coupled capture section, two superconducting five cell cavities (at this point beam energy is 5 MeV), and two full cryogenic units (each of them consists of eight cavities). The output energy is expected to be 45 MeV. Two identical dipole modes polarized perpendicular to each other are excited in the chopper cavities. A CW beam passing by the first chopper cavity, where the two modes have equal amplitudes and 90° phase difference, will project onto a circle with a diameter of ≈ 1 cm on a slit plane which is about 0.5 m downstream from the first chopper cavity. A 60° radial slit allows 60° out of every 360° to pass the chopper system. There are lenses on both sides of the slit. The second chopper cavity deflects the beam back to the axis if its RF phase is correct with respect to the first cavity. In the experiment a cavity which is used for picking up beam fourth harmonic signal is located in the 5 MeV region (wherever the bunch length is to be measured) about two meters downstream from the output of the second superconducting cavity.

The CEBAF accelerator operates at 1.5 GHz. The cavity is a simple cylindrical one without nose cones, operating in a TM_{020} mode at 6 GHz to detect the fourth harmonic of the beam induced fields for higher sensitivity. It is made of stainless steel, and has a radius of ≈ 4.51 cm and a length of 2.5 cm. Its loaded Q value is about 1000. The radius of the beam pipe is 1.2 cm. The R/Q of the cavity is 24.6 Ω. It is expected that for a 10 μA average current of the sub-bunches, the output signal from the cavity is about -26 dB.

The slit system consists of two slits, one of them has 60° radial open angle for normal beam operation, and the other has about 10° open angle for measuring the bunch length. During normal operation the 60° slit is used. The injector is tuned by minimizing the energy spectrum of the output beam with help of a spectrometer. Then the 10° slit is moved to the position where the 60° slit used to be. A sawtooth waveform signal is applied to the **x** terminal of the oscilloscope and to an electronic phase shifter, which sweeps the phase of both chopping cavities around the set point, i.e., with respect to the rest of the injector. The signal from the double balanced mixer is connected to the **y** terminal of the oscilloscope. As a result, the phase of the centroid of the sub-bunch with respect to initial phase is shown on the screen of the oscilloscope. The bunch length is determined by measuring the vertical width of the curve after calibration.

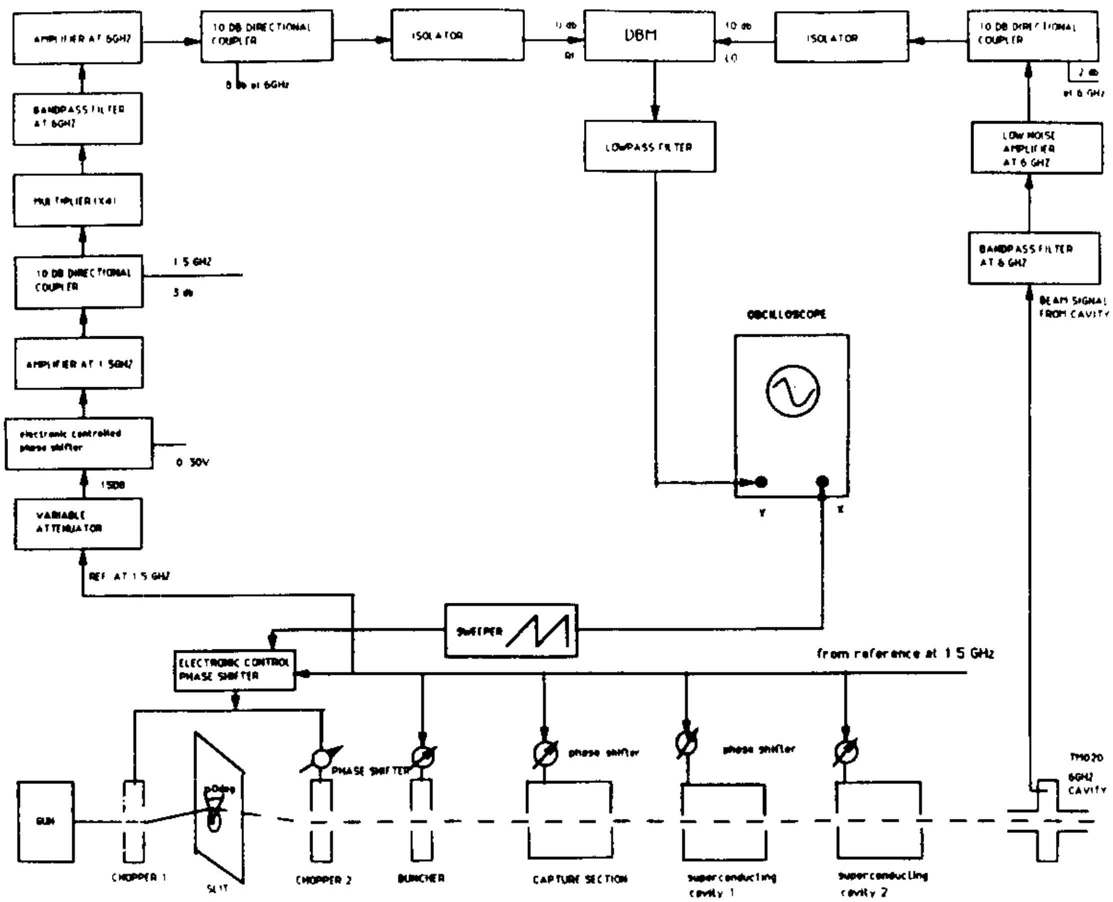

Figure 1. Bunch length measurement.

SEVERAL CONSIDERATIONS

First, the scheme is not easily applied to cases where space charge effects play an important role. Basically, this scheme is good for CW accelerators and, perhaps, for high duty factor accelerators also.

Second, because the beam current is constant for each sub-bunch series, the beam loading effect during phase sweeping is ignorable to the first order, as long as sweep phase ranges within the phase capture region of the injector. The beam loading is very small in the room temperature components of the CEBAF injector. By contrast, the superconducting cavities are highly beam loaded. The filling time for the room temperature devices is of order a microsecond and for the superconducting cavities is of order a millisecond. If the sweeping speed is slow enough, the feedback system that stabilizes the RF amplitude and phase in each device will eliminate the second order beam loading effect that is caused by the slightly different energy gain of each sub-bunch in the device during the measurement. In the experiments the phase sweeping frequency is 2 Hz.

Though the initial phase width of each sub-bunch is a constant and determined by the narrowed slit open angle, the final phase width of each sub-bunch varies during phase sweeping. By Fourier analyses, the amplitude of the fourth harmonic of beam-induced field is

$$a_4 = 2a_0 \frac{\sin 2\phi}{2\phi} \tag{1}$$

where a_0 is the average current which is constant, and ϕ is the final sub-bunch phase width. It is seen from eq. (1) that even if the final phase width of the sub-bunch varies from 0.1° to 2°, the relative variation in the amplitude of the fourth harmonic is under 0.1%.

INITIAL EXPERIMENTAL RESULTS

Figure 2 shows a signal of beam-induced field from the fourth harmonic cavity. Figure 3 gives experimental results with different phase sweeping ranges. The horizontal axis shows the time in units of 100 ms per division. As mentioned above, the sweeping frequency is 2 Hz. The vertical axis shows the detected phase of the centroid of the 10° sub-bunch. The sensitivity is calibrated to 1.7 mV per degree at 6 GHz. Figure 3(a) is a case without phase sweeping. It shows the bunch phase jitter. The peak to peak is $\approx$ 1.7 mV, or 1° at 6 GHz, yielding 0.25° bunch phase jitter at 1.5 GHz. This result is consistent with what we expect from the specifications on variations in RF amplitude and phase in each of the upstream components. Averaging gives a straight line parallel to the x axis. Figure 3(b) shows a case with 25° phase sweeping. The peak to peak is 2.1 mV, or 0.31° at 1.5 GHz, and the variation on average is 1.2 mV, or 0.18° at 1.5 GHz. Figures 3(c) and 3(d) show results when the phase is swept through 50° and 100°, respectively. The peak to peak phase fluctuations are 0.78° and 1.6°, and on average the phase variations are 0.5° and 1.5° at 1.5 GHz, respectively. The measurements are summarized in figure 4. Curve 1 shows the intrinsic bunching performance of the injector. Curve 2 shows the bunch length including time-dependent errors. It is possible that time-independent phase error, for example from energy spread caused by the buncher or chopper cavities, sets a limitation to the performance of the injector. The measurements may not be sensitive to the effects of time-independent errors. However, such effects should not normally have an obvious impact on the bunching characteristic of the injector. The measurements show that the phase jitter is 0.2°, and they are consistent with a total bunch length of 0.9° at 1.5 GHz.

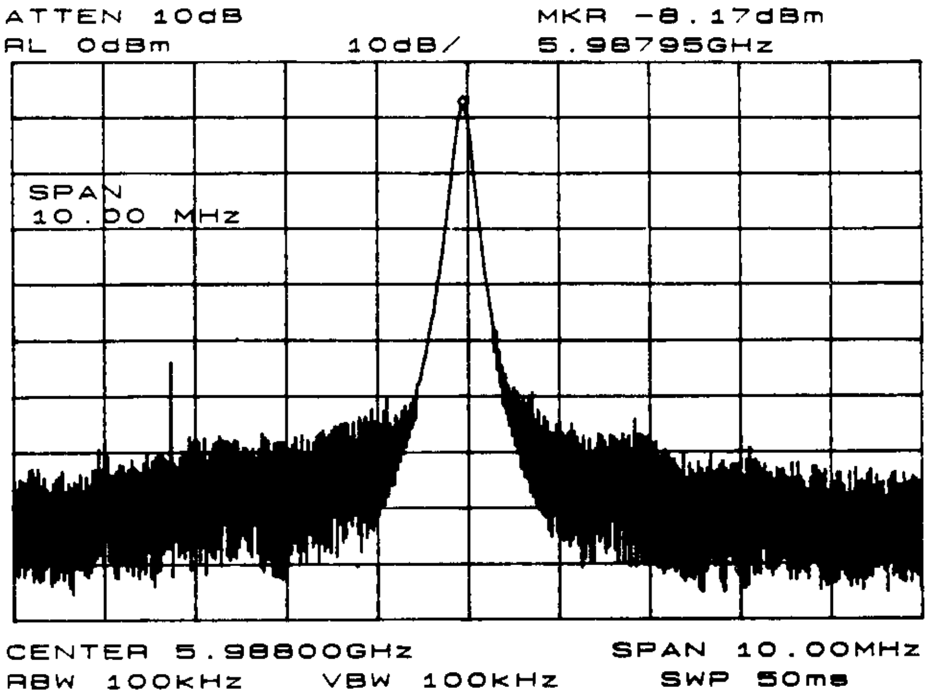

Figure 2. Signal of beam-induced fourth harmonic from the cavity.

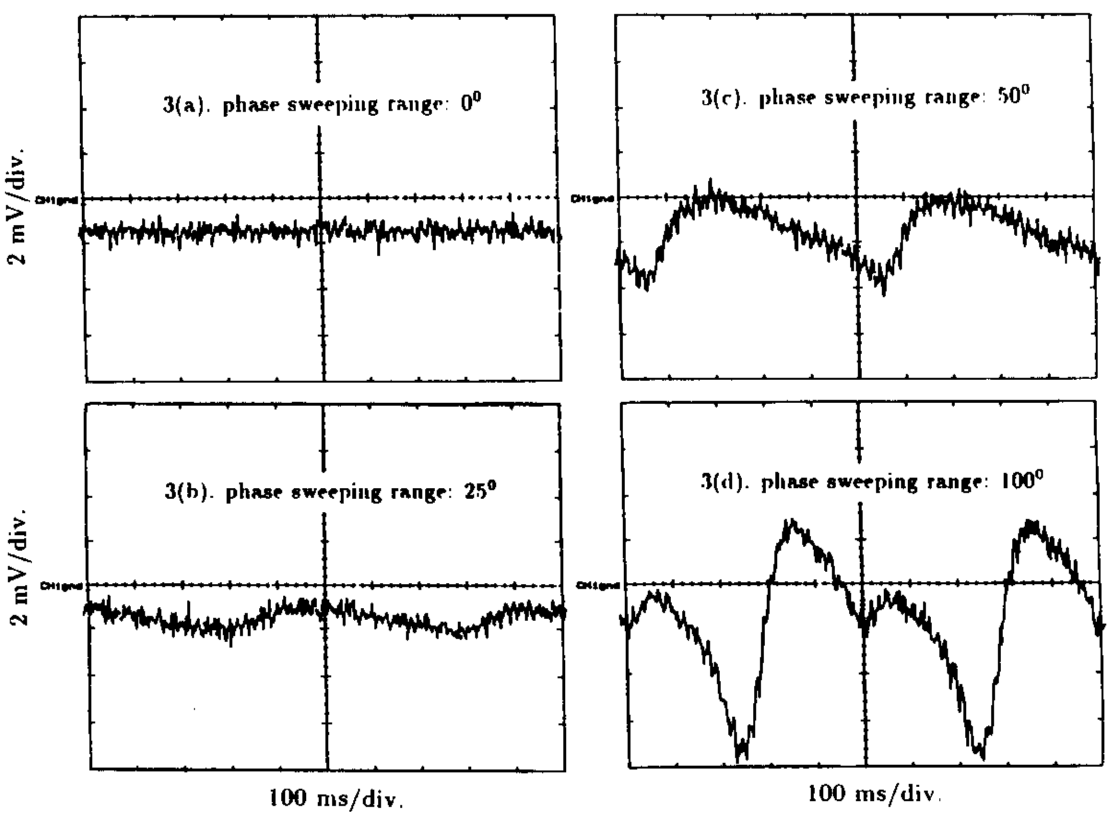

Figure 3. Preliminary experimental results of bunch length measurements.

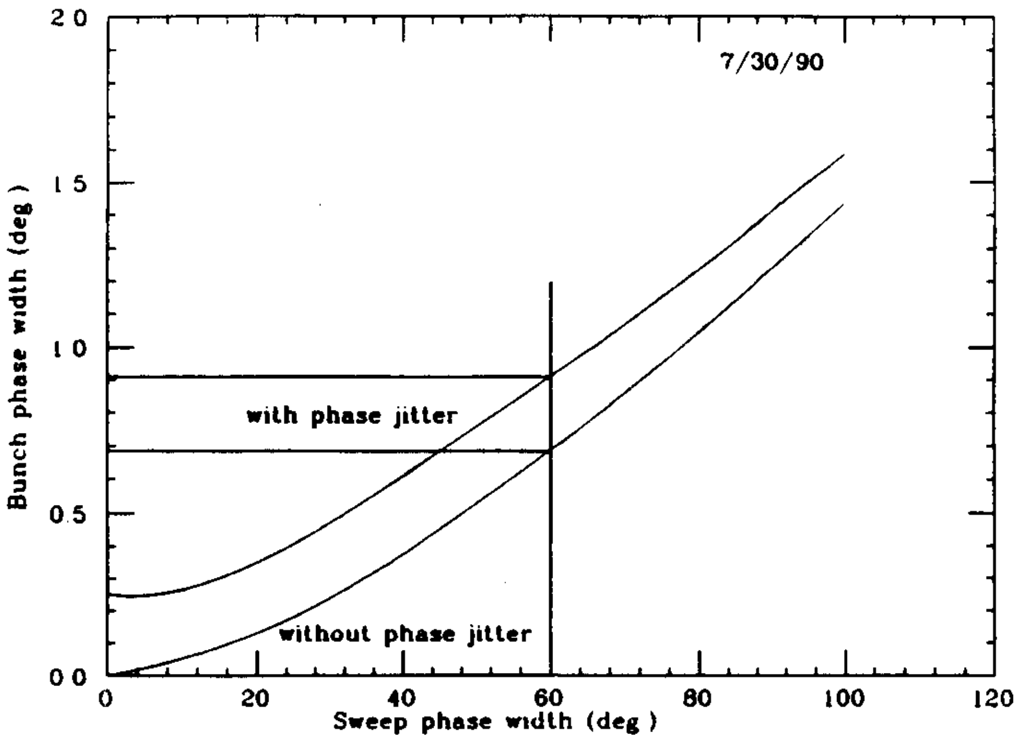

Figure 4. Final bunch width vs. initial phase width.

ACKNOWLEDGMENTS

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