HARMONICALLY RESONANT CAVITY AS A BUNCH LENGTH MONITOR

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Abstract

A compact, harmonically-resonant cavity with a fundamental resonant frequency of 1497 MHz was used to evaluate the temporal characteristics of electron bunches produced by a 130 kV dc high voltage spin-polarized photoelectron source at the Continuous Electron Beam Accelerator Facility (CEBAF) photoinjector, delivered at 249.5 and 499 MHz repetition rates and ranging in width from 45 to 150 picoseconds (FWHM). The cavity's antenna was attached directly to a sampling oscilloscope that detected the electron bunches as they passed through the cavity bore with a sensitivity of ~ 1 mV/µA. The oscilloscope waveforms are a superposition of the harmonic modes excited by the beam, with each cavity mode representing a term of the Fourier series of the electron bunch train. Relatively straightforward post-processing of the waveforms provided a near-real time representation of the electron bunches revealing bunchlength and the relative phasing of interleaved beams. The non-invasive measurements from the harmonically-resonant cavity were compared to measurements obtained using an invasive rf-deflector-cavity technique and to predictions from particle tracking simulations [1].

THE HARMONIC CAVITY

The Harmonic cavity was designed to resonate at many harmonic TM_{0N0} modes, and to suppress or displace TE and non-axially symmetric TM modes within or beyond its operational bandwidth. The shallow saucer-shaped cavity (Fig 1) has a mode spectrum free of TE modes for several tens of GHz because TE modes resonate at frequencies greater than $c/2h$ where c is the speed of light and h is the cavity length along the beam's direction of motion. Radial slits cut into the cavity walls do not affect the TM_{0N0} modes which have purely radial wall currents while the TM_{MNP} modes with azimuthal mode numbers, M, less than the number of discontinuities are suppressed. Finally, the shape of the cavity was tuned to yield harmonic TM0N0 modes. This was accomplished in the design phase by iteratively modifying the cavity geometry and solving for the TM_{0N0} mode frequencies with the field solver POISSON/Superfish [2]. The TM_{0N0} cavity modes are axially symmetric and have a field maximum on the cavity axis, i.e., along the direction of the electron beam motion.

Electron bunches at a pulse repetition rate w_0 can be described using a Fourier series expansion:

$$i_{beam}(t) = a_1 \cos(w_o t + \theta_1) + a_2 \cos(2w_o t + \theta_2)\ldots + a_n \cos(nw_o t + \theta_n) \quad (1)$$

where a_n and θ_n describe the relative amplitudes and phases of each contributing harmonic term. The non-invasive bunchlength monitor cavity was designed to measure each term of the Fourier series expansion:

$$v_{detected}(t) = a_{TM_{010}} \cos(w_0 t + \theta_{010}) + a_{TM_{020}} \cos(2w_0 t + \theta_{020}) \ldots + a_{TM_{0n0}} \cos(nw_0 t + \theta_{0n0}) \quad (2)$$

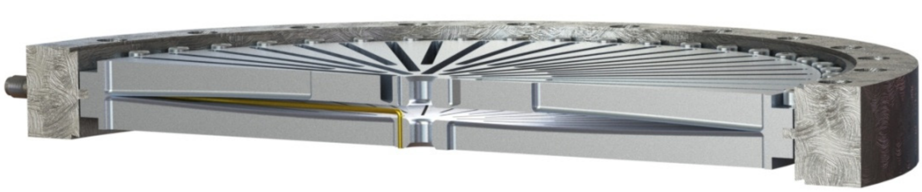

Figure 1: (top) A cut-away drawing of the harmonically-resonant cavity showing the antenna and the curvature of the cavity surfaces. (bottom) A photograph of the cavity nested inside the bore of a 10" double-sided knife edge Conflat flange. Two additional 10" Conflat flanges attach to either side to form the UHV-compatible vacuum vessel.

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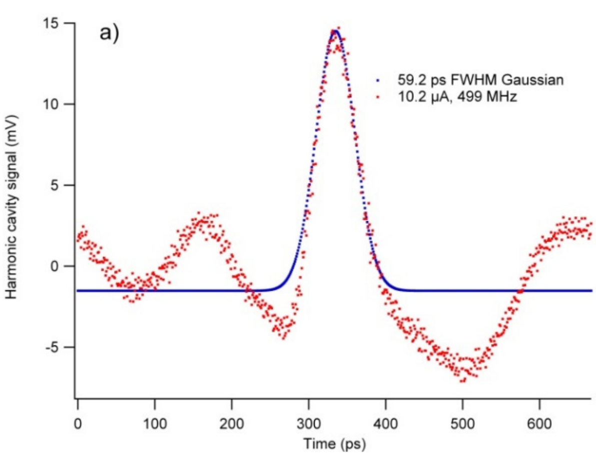
where a_{TM0N0} and θ_{0N0} describe the relative amplitudes and phases of each detected cavity mode. If the harmonically-resonant cavity were perfect, with infinite bandwidth and with all modes perfectly harmonic and equally coupled to the antenna, the amplitude coefficients and phase terms of both equations would be identical (barring a scale factor). However, the cavity and antenna do not have infinite bandwidth and manufacturing imperfections result in some modes being slightly displaced from the intended resonant frequencies. Similarly, the cavity antenna does not couple identically to all modes. In sections below, we describe how these imperfections can be corrected with a post process that multiplies the individual terms of the detected waveform's Fourier series expansion with the cavity's transfer function. In principle, the cavity transfer function can be calculated by dividing equation 1 by equation 2, but this requires that the electron bunch profile be precisely known. In this work, the cavity transfer function was determined empirically via blind deconvolution [3, 4].

Bunchlength Measurements Using the Harmonically-Resonant Cavity

After making invasive bunchlength measurements using the rf-deflector technique, non-invasive measurements were made using the harmonically resonant cavity at a location upstream of the rf-deflecting cavity using the photogun's "laser 1" operating at 499 MHz and with 45 ps optical pulsewidth. A Tektronix SD-30, 40 GHz sampling head was directly attached to the sma-vacuum feedthrough of the harmonically resonant cavity and connected to a 11801B digital sampling oscilloscope with an extender cable. Figure 2 (a) shows an oscilloscope measurement of a 10 μA beam, (red) and an estimate of the true shape of the electron bunches that induced the measurement (blue). The "distortions" seen in the detected waveform stem from small imperfections in the cavity geometry, and imperfect antenna coupling to all cavity modes. Slightly off-resonant cavity modes, combined with non-uniform antenna coupling, result in phase and amplitude differences between the measured response of each cavity mode and the Fourier series of the beam that induced it. The amplitude differences in the harmonic spectrum of both waveforms are shown in Fig.2 (b).

If the resonant frequency of an individual cavity mode is slightly off design, the beam can still excite this mode provided the beam's Fourier term is not outside the mode's resonance curve. But driving a cavity mode off the resonance peak causes a decrease in detected amplitude, and it introduces a phase shift between the beam and the excited mode. The error associated with this mode can be corrected using a single complex multiplier that "un-shifts" the phase offset and scales the detected amplitude. A series of complex multipliers - one for each cavity mode - can be created. This series expansion has a functional form similar to equation 1 and it is called the cavity transfer function. The beam's true Fourier series representation can be obtained by multiplying each term of the Fourier series of the detected signal by each term of the cavity transfer function.

The challenge associated with this approach relates to the fact that the cavity transfer function is not explicitly known, rather it must be deduced in a sensible manner. However, once the transfer function is known, it can then be used to correct the cavity systematic errors for all subsequent data, independent of new bunch shapes.



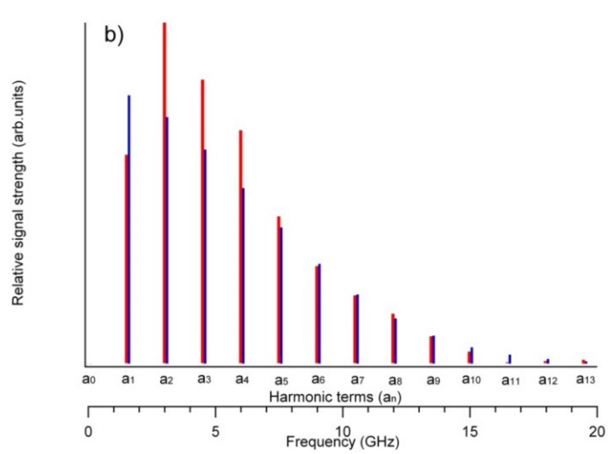


Figure 2: (a) A raw oscilloscope trace of a 10 μA beam made using laser 1 as it passed through the harmonically-resonant cavity (red), and an estimate of the bunch profile that induced it (blue). These waveforms were used to create a transfer function that transformed measurements of higher current beams with the minimum signal outside the central bunch. (b) The signal strength of each resonant mode of the harmonically-resonant cavity as measured (red), and the response of an ideal harmonic cavity (blue).

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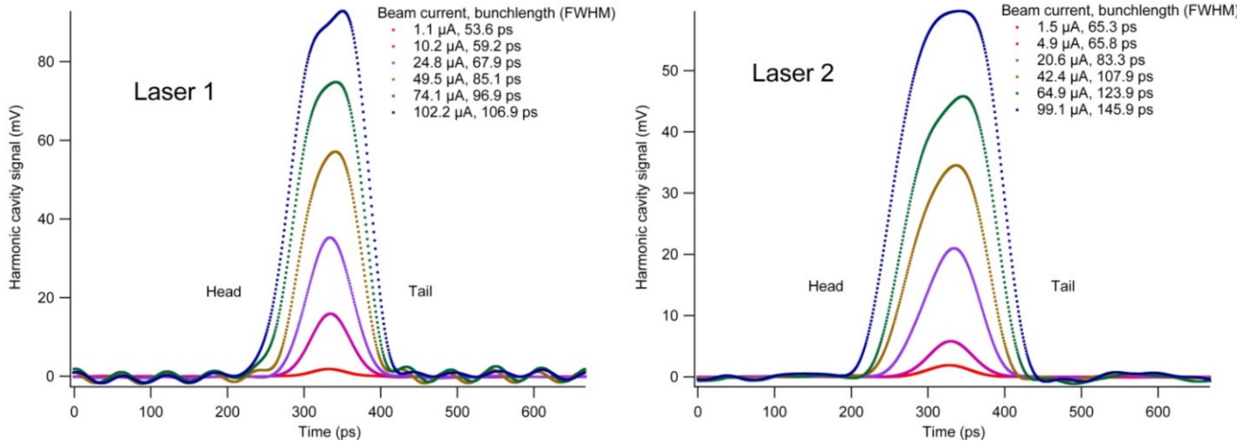

Figure 3: Bunchlength measurements made with the harmonically-resonant cavity of 499 MHz electron beams using “laser 1” with 45 ps optical pulsewidth FWHM (top), and 249.5 MHz beams using “laser 2” with 60 ps optical pulsewidth FWHM (bottom), for different extracted beam currents. These plots were obtained by transforming the raw oscilloscope waveforms using an estimate of the harmonic cavities transfer function.

To generate a sensible cavity transfer function, the method of blind deconvolution [3, 4] was employed. A low-current waveform obtained using “laser 1” operating at 499 MHz and with 45 ps optical pulsewidth was selected because space charge forces were less likely to influence the shape of the bunch. Fourier series were created for “guessed” Gaussian bunchlengths ranging from 40 to 60 ps, in 2 ps increments. Candidate transfer functions were then calculated by dividing the Fourier series of the guessed profiles by the Fourier series of the actual measured waveform. Each of these candidate transfer functions was then used to correct the waveforms of measurements of longer bunches arriving at the harmonically resonant cavity. Most of these transfer functions did a poor job of correcting waveform distortions, particularly at higher currents. The transfer function deemed most accurate was one that generated the least amount of signal outside the central bunch. It produced the corrected waveforms shown in Figure 3 (a), where distortions and oscillations outside the central bunch were effectively minimized. The same methodology was employed for measurements obtained using “laser 2” shown in Fig. 3 (b).

CONCLUSION

A novel non-invasive bunchlength measurement technique was validated against a traditional invasive rf-deflector cavity technique, and particle tracking simulations. The compact harmonically-resonant cavity provided near-real time evaluation of electron bunches as short as 35 ps and phase information of interleaved beams. Future plans include making design and manufacturing improvements to increase the harmonic cavities bandwidth and antenna coupling uniformity, and developing an algorithm to more accurately determine the harmonically resonant cavities transfer function. It was shown that the harmonic cavity provides very practical information on the relative phasing of interleaved pulse trains, a feature that will reduce the setup time of the CEBAF photoinjector. It is possible this feature could be exploited at other locations at CEBAF, for example, where beams at higher energy are combined for recirculation through the linac.

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