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ABSOLUTE BUNCH LENGTH MEASUREMENTS OF LOW ENERGY BEAMS USING ACCELERATING RF CAVITY

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Abstract

The experimental technique has been proposed and demonstrated by authors for measuring the temporal distribution and absolute bunch length of picosecond-level low-energy electron bunch generated by an electron gun using radial electric and azimuthal magnetic fields of an accelerating (TM_{01} mode) radio frequency cavity. In this scheme, an accelerating RF cavity provides a phase-dependent transverse kick to the electrons, resulting in the linear coupling of the trajectory angle with the longitudinal position inside the bunch like a transverse deflecting cavity. In this paper, we show a detailed estimation of various aspects of the temporal resolution of this method with feasible parameters and deconvolution of the Gaussian distribution for accurate reconstruction of the temporal distribution.

INTRODUCTION

Energy Recovery Linac (ERL) demonstrators [1–3] are established to demonstrate physical challenges and key technologies of the generation, acceleration, transport, and energy recovery of high brilliance and high average current beams in superconducting cavities. The beam quality assurance in those high-brightness and high-current injectors is crucial. Therefore, a diagnostics beamline is mostly installed at the end of the injector to gauge beam quality in six-dimensional phase spaces [4, 5]. A transverse deflecting cavity that has a dipole mode to imprint the temporal information into transverse momentum is widely adopted [6–8] to measure a temporal distribution as well as absolute bunch length. This is a space-charge-free method but it has a technical difficulty to transport low-energy beams without the deterioration of beam qualities to the cavity where is typically located far downstream of the injector due to the limited space in low-energy injectors. As a complementary way to measure longitudinal beam properties near the electron gun, the zero-phase method [9] is also used. This method yields a linear RF chirp in the longitudinal phase space by using an accelerating cavity with a zero-crossing phase and transforms the longitudinal phase-space distribution to the transverse direction by dispersion function originated by a dipole magnet. However, it is not suitable for high current beams because the longitudinal phase space is strongly distorted at higher bunch charge by longitudinal space charge forces [10] while the beam is transported to the dipole magnet located far downstream of the gun. We have been proposed and demonstrated [11, 12] a new method that uses radial EM fields of an accelerating cavity to measure the temporal distribution and absolute bunch length using existing instruments in the beamline such as a corrector magnet and a screen monitor.

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RESOLUTION OF THE METHOD

To utilize the method, it demands a corrector magnet for adjusting the initial beam offset and angle, an accelerating cavity (TM_{01} mode), and a screen monitor located downstream of the cavity. The schematic layout is shown in Fig. 1.

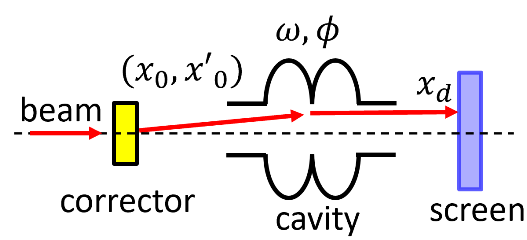

Figure 1: Schematic layout for the proposed method.

The initial beam offset x_0 and angle x'_0 are defined at the position of the corrector magnet. The beam passes the center of the cavity when the offset is vanished at the corrector position, i.e. $x_0 = 0$. With an on-axis beam, the temporal resolution R_t of the method is given by [12]

$$R_t = \frac{\sqrt{\sigma_c^2 + 2\sigma_{x0}\sigma_c}}{\left|d_{12}x'_0\right| \omega}, \tag{1}$$

where σ_c is the spatial resolution of the screen monitor, σ_{x0} is the initial beam size at the screen monitor without the offset and angle, d_{12} is the deflection coefficient associated with an initial angle, and $\omega = 360$ deg $\times f$, where f is the frequency of the cavity. With a state-of-the-art technique for the screen monitor [13] that has been proven measurements of a beam size of 1.44 μm using a 200 μm thick LYSO:Ce scintillator, the temporal resolution of our method can be improved enormously. Assuming that the initial beam angle is 16 mrad which is equivalent to 1/3 of the cavity radius for a 1.3 GHz superconducting cavity and d_{12} of -0.0324 mm/deg/mrad measured at a beam energy of 390 keV, the temporal resolution is calculated as a function of the spatial resolution of the screen monitor at various initial beam sizes.

As shown in Fig. 2, the method with a spatial resolution of the screen monitor of 1.44 μm yields temporal resolutions of 32 fs, 50 fs, and 70 fs for initial beam sizes of 20 μm, 50 μm,

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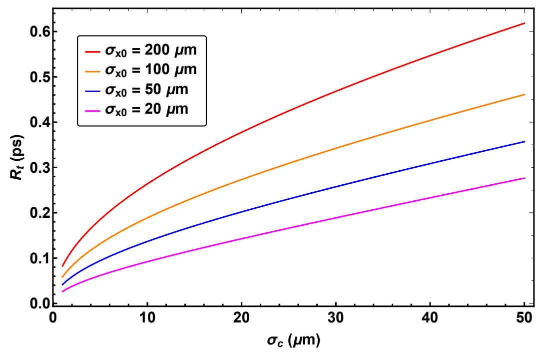

Figure 2: Temporal resolution as a function of the spatial resolution of the screen monitor at various initial beam sizes. The calculation is performed with an initial angle of 16 mrad and d_{12} = -0.0324 mm/deg/mrad measured at a beam energy of 390 keV.

and 100 μm. From Eq. (1), the temporal resolution depends not only on the spatial resolution of the screen monitor and the initial beam size but also on the deflection coefficient d_{12} which is determined by a peak on-axis accelerating field, a distance between the cavity and the screen monitor, and the beam energy. By numerical simulations using General Particle Tracer code [14], the d_{12} is investigated as a function of the initial beam energy at a peak on-axis accelerating field of 7.21 MV/m. The coefficient is rescaled with the experimentally measured value of -0.0324 mm/deg/mrad at a beam energy of 390 keV. The d_{12} as a function of the beam energy is fitted by the formula of

$$d_{12}(x) = a_1 \left(\frac{1}{1 + e^{a_2 (x^{a_3} + a_4)}} - 1 \right), \tag{2}$$

where a_1, a_2, a_3, and a_4 are fitting parameters. The fitted parameters are given in Tab. 1 and the result is shown in Fig. 3.

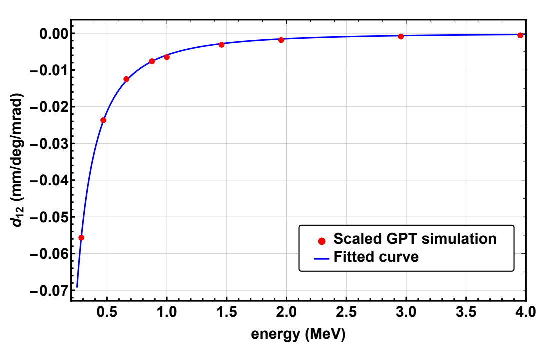

Figure 3: Rescaled d_{12} value as a function of the initial energy. This is simulated using General Particle Tracer and rescaled by the measured value.

The resolution as a function of the initial beam energy can be estimated by substituting the fitting coefficients and Eq. (2) into Eq. (1). With a fixed initial angle of 16 mrad and a spatial resolution of the monitor of 1.44 μm, the temporal resolution as a function of the initial beam energy is shown in Fig. 4.

Table 1: Fitting Parameters for the Estimation of d_{12} Value at the Specific Beam Energy

Coefficient	Value	Coefficient	Value
a_1	2.77	a_2	-17.1
a_3	0.11	a_4	-0.64

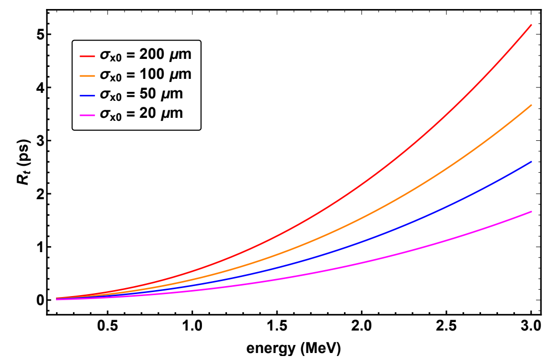

Figure 4: Temporal resolution of the method as a function of the initial beam energy with various initial beam sizes.

The temporal resolution is 76 fs, 272 fs, and 1.1 ps for beam energies of 0.5, 1, and 2 MeV with an initial beam size of 50 μm. This indicates that the method can measure about 100 fs bunch for photo-cathode DC guns that has a beam energy of about 0.5 MeV and about 1 ps bunch for photo-cathode SRF guns which has the initial energy of about 2 MeV.

RECONSTRUCTION OF TEMPORAL DISTRIBUTION

The method enables single-shot measurements of the temporal distribution of the beam that is imprinted into the horizontal direction through coupling generated by the cavity. However, the horizontal profile at the screen monitor not directly reveals the temporal distribution since the horizontal distribution at the screen monitor $H(x)$ can be interpreted by a convolution of the initial temporal distribution $f(\tau)$ and horizontal distribution with the deflecting term $g(x)$. This is given by [12]

$$H(x) = \int f(\tau) g\left(x - d_{12} x'_0 \omega \tau\right) d\tau. \tag{3}$$

Therefore, a deconvolution of the initial profile measured with $x' = 0$ is necessary. Assuming a Gaussian distribution in both horizontal $Ae^{-x^2/(2\sigma_x^2)}$ and longitudinal $Be^{-\tau^2/(2\sigma_t^2)}$ planes, the beam distribution at the screen monitor can be represented by performing the integration in Eq. (3). This is given by

$$H(x) = AB \frac{\sqrt{2\pi}\sigma_t \sigma_x}{\sqrt{\sigma_x^2 + k^2 \sigma_t^2}} \; e^{-\frac{x^2}{2(\sigma_x^2 + k^2\sigma_t^2)}}, \tag{4}$$

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where $k = d_{12}x'_0\omega$. The convoluted profile is also Gaussian distribution with a standard deviation of $\sqrt{\sigma_x^2 + k^2\sigma_t^2}$ since the Gaussian profiles have been taken into account. For the deconvolution of the initial horizontal beam size, this can be achieved by performing renormalization of the measured profile with several parameters defined in the beam experiment as

$$T(x) = e^{-\left(\frac{x^2}{2k^2\sigma_t^2}\right)} = H(x)/H\left(\frac{\sigma_x}{k\sigma_t}x\right). \quad (5)$$

With the horizontal beam size estimated from an image measured with $x' = 0$, bunch length and machine parameters such as frequency and deflecting coefficient, the Gaussian deconvolution is applied. In addition to the Gaussian deconvolution (Eq. (5)), the Wiener filter and the Richardson-Lucy algorithm are also tested. The Wiener filter is the most popular deconvolution algorithm and it uses a closed analytic formula for estimating the object function. The Richardson-Lucy algorithm, also known as the expectation maximization method, is an iterative scheme that computes successive improved images from the starting point [15]. For both filters, a Gaussian Point Spread Function (PSF) with the width determined by fitting on the initial profile measured with $x' = 0$ is applied. The results are shown in Fig. 5.

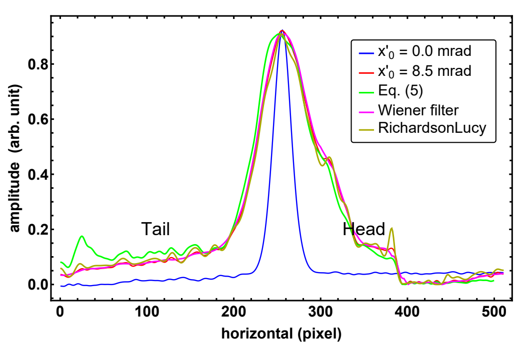

Figure 5: Deconvolution of temporal distribution using analytical formula (Eq. (5) for Gaussian beams and various algorithms.

Since the beam size measured with an angle of 7.3 mrad is a noticeably larger than the initial profile, the modification of the distribution by the deconvolution using two algorithms is negligible. Further studies on the deconvolution algorithm with non-Gaussian filters are necessary.

SUMMARY

We proposed a new method for measuring a temporal profile and absolute bunch length at contemporary high brightness injectors without special instruments. This opens a new possibility of the precise tuning of longitudinal beam properties at low-energy photo-cathode guns. A state-of-the-art screen monitor enables the bunch length measurement in the range of tens of femtoseconds at 0.5 MeV and one picosecond at 2 MeV with a peak on-axis accelerating field of about 7 MV/m. For the precise reconstruction of the temporal distribution, several methods for the deconvolution of the initial beam distribution, also well known as PSF, are tested. The result shows that the deconvolution is not crucial when the beam enlargement by the cavity field is large enough.

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