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NON-INVASIVE BUNCH LENGTH DIAGNOSTICS FOR HIGH INTENSITY BEAMS*

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Abstract

Modern particle accelerators utilize photoinjectors and compression schemes to produce short high peak current electron bunches for various applications like x-ray free electron lasers, high gradient beam driven acceleration and others. At present there is no non-invasive and fast diagnostic of short sub-picosecond bunch lengths.

Euclid Techlabs LLC proposes a non-invasive, real-time detector which can be retrofitted into an existing beamline and measure the bunch length in real time using interferometric methods. Diffraction radiation is the mechanism to be used to produce a measurable signal without intercepting the beam. This became possible as sensitivity of pyrodetectors continued to improve, while peak beam power grows. For high peak current beams there is a possibility of a single shot measurement. This can be done with a pair of closely placed vacuum breaks that create a spatial correlation of the generated signals which can be measured by a pyro-detector array or a THz camera. The bunch length is determined from the correlation data using an iterative beam profile recovery algorithm.

NON-INVASIVE BUNCH LENGTH DIAGNOSTICS

Bunch length measurement is one of the most difficult measurements that are an essential part of the beam diagnostic suite at accelerator facilities. At modern electron accelerator facilities, a bunch compression is performed to obtain an intense, ~ ps-long beam. Traditional methods for short bunch length measurements include the deflecting cavity-based approach (Fig. 1) [1], radiation-based spectral methods [2], and electro-optic detection methods [3].

There are two facts that, in Euclid's view, will lead to a practical solution for robust, non-invasive bunch length measurements. First, the sensitivity and spectral characteristics of commercially available power diodes and pyro detectors continue to improve. A number of vendors offer mm-wave and THz cameras – arrays of such detectors with integrated electronics, etc. And second, the average power and repetition rate of beams for nuclear applications continue to grow. Such powerful beams are capable of producing measurable signals in the "non-invasive" regime.

The non-invasive bunch length measurement proposed here picks off coherent radiation from the beam and measures portions of the autocorrelation function to infer the bunch length. In this sense, this method is an adaptation of the coherent radiation-based bunch length measurement methods described above. Figure 1 shows the evolution of coherent radiation-based methods that led to the measurement technique proposed here [4-6]. Coherent transition radiation (a) intercepts the beam to produce a large signal. However, if there is enough average power, diffraction radiation can be used, which technically does not intercept the beam (b), and can be made less invasive (c) if there is high enough detector sensitivity, finally arriving at RF beam pickups / vacuum pipe breaks.

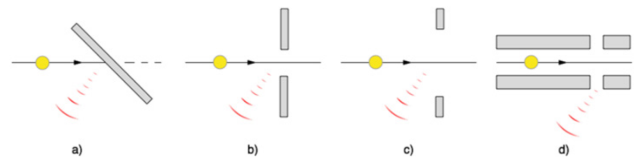

Figure 1: Evolution of coherent radiation-based bunch length measurements.

The pioneering work in single-shot bunch length measurement was done at the A0 photoinjector at Fermilab [7, 8]. A spatial autocorrelation of two transition radiation signals generated by the electron beam is measured by a detector array. A conceptual scheme is presented on Fig. 2 [7]. The bunch length is inferred from the autocorrelation function [9].

In the experiment at Fermilab [8], bunch length variations (FWHM) between 0.8ps and 1.5ps were measured. To cover a broad spectral range (>1 THz), pyrodetectors were used. Experiments at A0 demonstrated the viability of the concept.

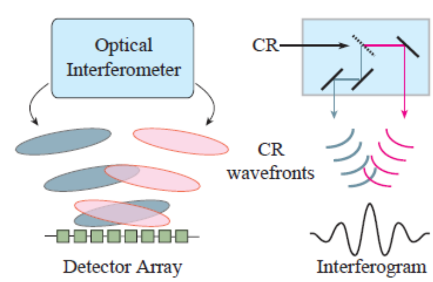

Figure 2: From [7]. Conceptual scheme of the real-time interferometer (RTI) which autocorrelates the phase fronts of a beam-based coherent radiation source to determine bunch length information.

In this proposal, we take it one step further towards a commercial unit. We propose two separate diffraction radiation sources packaged with the detector array, virtually without any optics. This potentially complicates the design process. However, when that is resolved, the detector is much simpler and has higher sensitivity due to proximity of the detector array to the radiation source. The conceptual design of the bunch length detection setup

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is depicted in Fig. 3. As the beam passes the small gap, its field radiates from the gap and travels towards the array of detectors. Due to the microstrip configuration, there is no cut off for the excited mode, making the structure broadband for short pulse measurements. Depending on the detector location, the pulses from the first and second break will arrive with some relative time delay. Spatial interference scaled by $1/r$ in intensity will again correspond to an autocorrelation function. This method is similar to the single shot autocorrelator developed by Andonian et al. [7].

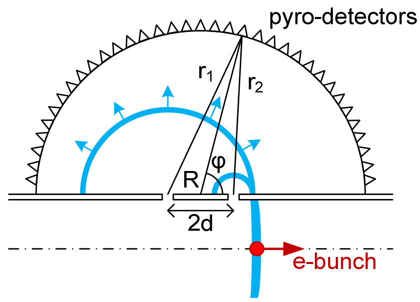

Figure 3: Non-invasive bunch length measurement setup.

The wakefield simulation with a 1 ps beam and a set of two 200-micron wide beam pipe breaks, separated by 0.5 mm, was done using CST Particle Studio. Figure 4 shows the signal evolution with time. As the beam propagates, a strong signal is generated at each break. These signals proceed to interfere and we measure them with an array of integrating pyro detectors, bolometer arrays, or a THz camera.

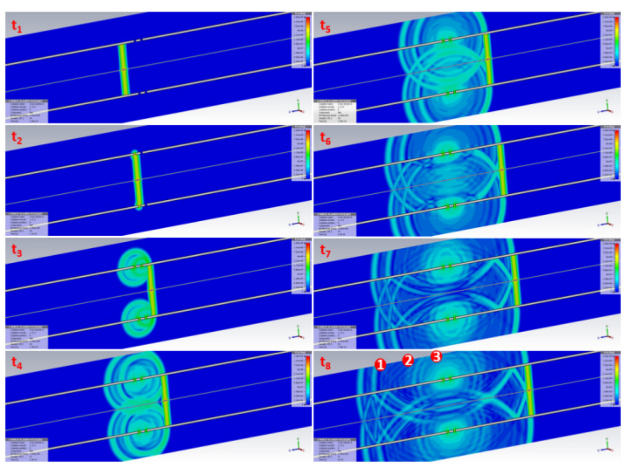

Figure 4: CST simulation of a 1 ps beam passing by two 200-micron beam-pipe breaks separated by 0.5 mm. Consequent shots at times t_1, t_2, … t_8 are presented. There is interference between the excited pulses that can be measured with a detector array. The detector array location is shown on the t_8 plot with red circles.

Taking the measurements from this array of 11 detectors placed 2.5 mm away from the vacuum break wall and spaced along the direction of beam propagation at 1 mm, we obtain an autocorrelation function (Fig. 5). The autocorrelation function characteristic width corresponds to the bunch length. In the simulation we used x-ray FEL parameters: 1 kA peak current beam (σ_z = 1 ps) produced 1 kW peak power. With ~1 kHz repetition rate, the duty cycle is low – 10^{-6}, leading to 1 μW average power. This is well within the sensitivity level of pyro detectors.

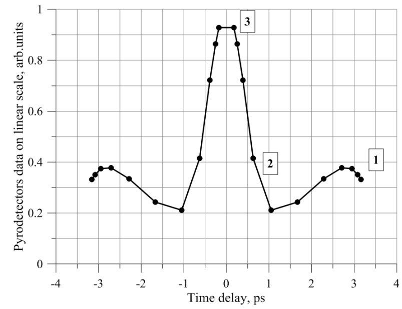

Figure 5: Pyro-detector's output for various time delay pairs, i.e. autocorrelation function.

BUNCH SHAPE RETRIEVAL ITERATION PROCEDURE

Most methods of bunch length measurement result in a bunch's autocorrelation function. However, it is impossible to reconstruct the bunch shape from the frequency spectrum without further assumption about the signal. In [10], Kramers-Kroenig relations are used, along with the minimal phase retrieval method. In [11], an iterative procedure used for phase retrieval of quasioptical wave packets [12] has been proposed for electron beams. In this proposal, we will develop this idea further into practical use.

Here, we present an example of an iterative process for bunch shape retrieval for the geometry presented in Fig.3. We have a distributed array of pyro detectors, which measures the integrated intensity ε(φ) as a function of the angle φ. We assume $u^{(0)}(t)$, an initial approximation to the real bunch time distribution $u_0(t)$. The Fourier spectrum of this function is:

$$A_{in}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} u^{(0)}(t)\cdot \exp(i\omega t)dt. \quad (1)$$

The field at the second slit corresponds to the field at the first slit, $u^{(0)}(t)$, delayed by $\tau = 2d/c$. The spectrum of the second slit source differs from the spectrum of the first slit by a multiplier $\exp(i\omega t)$. The spectrum of the combined signal from two slits can be found from

$$A_{out}(\omega,\varphi) = A_{in}(\omega)\cdot G(\omega,\varphi), \quad (2)$$

where G is the Green's function of two point-like sources separated by $2d$ written in terms of Hankel functions:

$$G(\omega,\varphi) = H_0^{(1)}\left(\frac{\omega}{c}r_1(\varphi)\right) + \exp(i\omega\tau)\cdot H_0^{(1)}\left(\frac{\omega}{c}r_2(\varphi)\right). \quad (3)$$

If we integrate the A_{out} spectrum, we will reproduce the φ – dependence of the integrated intensity produced by a pulse with $u^{(0)}(t)$ distribution:

$$\varepsilon(\varphi) = \int_{-\infty}^{\infty}|u(t,\varphi)|^2 dt \equiv \int_{-\infty}^{\infty}|A_0(\omega,\varphi)|^2 d\omega, \quad (4)$$

This will, however, differ from the measured distribution, ε(φ). If we adjust A_{out} in the following way

$$A_{out}^{(n+1)}(\omega,\varphi) = \frac{A_{out}^{(n)}}{\left|A_{out}^{(n)}\right|}\cdot\frac{\sqrt{\varepsilon(\varphi)\cdot s(\varphi)}}{W}, \quad (5)$$

this distribution will correspond to the measured ε(φ). Here $s(\omega) = \int_{-\infty}^{\infty}\left|A_{out}^{(n)}(\omega,\varphi)\right|^2 d\varphi$ is the frequency-dependent power flux integrated over all angles, and $W =$

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$\int_0^{\pi}\varepsilon(\varphi)d\varphi \equiv \int_{-\infty}^{\infty}|s(\omega)|^2 d\omega$ is the full radiated energy. The A_{out} term corresponds to another A_{in}, which in turn defines a corresponding $u(t, \varphi)$. This distribution, however, is not necessarily produced by two neighboring slits. To satisfy this restriction, we trim $u(t, \varphi)$ to produce a new iteration, the $u^{(1)}(t)$ distribution on two slits. This distribution produces a new A_{in} with corresponding A_{out}, etc. Algorithmically, it is easier to go straight to A_{in} from A_{out} in the following way:

$$A_{in}^{(n+1)}(\omega) = \frac{\int_0^{\pi} A_{in}^{(n+1)}(\omega,\varphi)\cdot G^*(\omega,\varphi)d\varphi}{\int_0^{\pi}|G(\omega,\varphi)|^2 d\varphi}, \quad (6)$$

We tested this procedure on a double Gaussian distribution reconstruction (Fig. 6, red curve), with

$$u_0(t) = \exp(-t^2/2\tau^2) + 0.2\cdot\exp(-t^2/7\tau^2). \quad (7)$$

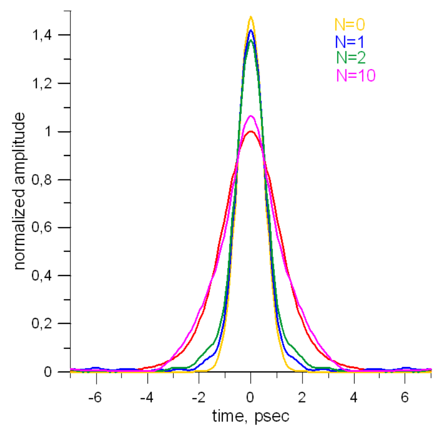

Figure 6: Original bunch distribution (red), first iteration (yellow) and 10th iteration (pink).

We started with $u^{(0)}(t) = \exp(-2t^2/\tau^2)$, the yellow curve on Fig. 6. Following 10 iterations, the mutual power coefficient between the 10th iteration of the bunch time distribution and the original function reached 99.5%.

We also attempted reconstruction of a triangular bunch as an example of a nonsymmetrical bunch shape. The initial guess was chosen to be nonsymmetrical, and after 40 iterations, the bunch shape had been reconstructed (Fig. 7).

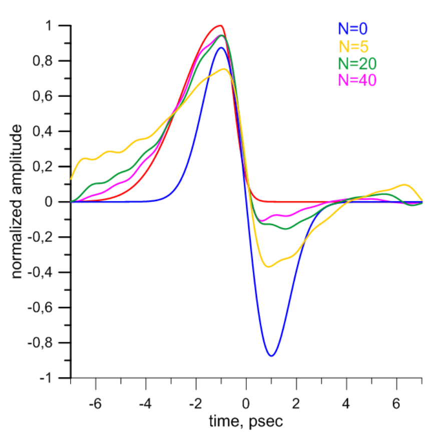

Figure 7: Reconstruction of non-symmetrical pulse shape (triangle – red). After 40 iterations, a shape close to a triangle is reconstructed (pink).

CONCLUSION

The carried out simulations show that picosecond as well as sub-picosecond bunch lengths can non-destructively be measured for a single shot using interferometry between two broad-band signals produced by bunch itself. An iterative synthesis procedure allows also recovering a particular longitudinal bunch shape.

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