

## NON-INVASIVE BUNCH LENGTH DIAGNOSTICS OF SUB-PICOSECOND BEAMS\*

S.V. Kuzikov<sup>†,1,2</sup>, A.A. Vikharev, Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia

S. Antipov, Euclid Techlabs LLC, Bolingbrook, IL, USA  
also at <sup>1</sup>Euclid Techlabs LLC, Bolingbrook, IL, USA

also at <sup>2</sup>Lobachevsky University of Nizhny Novgorod, Nizhny Novgorod, Russia

### Abstract

We propose a non-invasive bunch length measurement system based on RF pickup interferometry. A device performs interferometry between two broadband wake signals generated by a single short particle bunch. The mentioned wakes are excited by two sequent small gaps in beam channel. A field pattern formed by interference of the mentioned two coherent wake signals is registered by means of detector's arrays placed at outer side of beam channel. The detectors are assumed to be low cost integrating detectors (pyro-detectors or bolometers) so that integration time is assumed to be much bigger than bunch length. Because rf signals come from gaps to any detector with different time delays which depends on particular detector coordinate, the array allows to substitute measurements in time by measurements in space. Simulations with a 1 ps beam and a set of two 200 micron wide vacuum breaks separated by 0.5 mm were done using CST Particle Studio. These simulations show good accuracy. One can recover the detailed temporal structure of the measured pulse using a new developed synthesis procedure.

### RF PICK-UP INTERFEROMETRY FOR BUNCH LENGTH MEASUREMENTS

We propose to design a device that will effectively perform interferometry between two broadband wake signals generated by the beam. At high repetition rates, interferometer scans at accelerators can be performed quickly. In a matter of seconds, the data can be averaged to improve the signal to noise ratio and allow the use of inexpensive pyro-detectors as opposed to bolometers. As a result one get spatial autocorrelation function for single shot measurement.

#### Measurements of ~10 ps Bunch Length

In the case of relatively long beams (10 ps) we propose to utilize power diodes with coaxial RF pickups arranged in pairs. A beam pickup intercepts a small fraction of the image current flowing along the beam pipe (Fig. 1). Two signals are combined with a time delay in a coaxial combiner.

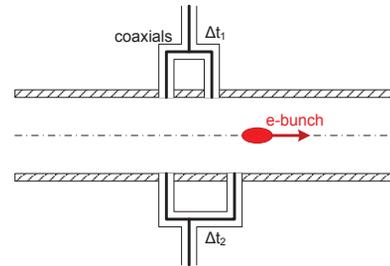


Figure 1: 10 ps resolution non-invasive bunch length measurement setup based on coaxial pairs placed along the z-direction.

Depending on the time delay between the RF pickups, the combined power varies as a function of time. The figure 2 shows the results of a simulation that involves a 10 ps beam passing by two RF pickup probes combined with variable delays. By using several pairs with different delays an autocorrelation function can be produced (Fig. 3).

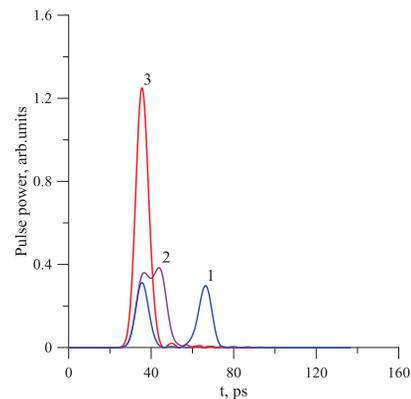


Figure 2: Power time dependence for various time delays.

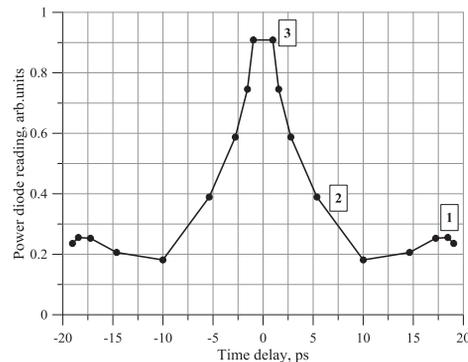


Figure 3: Pyro-detector's output for various time delay pairs.

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<sup>†</sup>email address: sergeykuzikov@gmail.com

Measurements of Sub-picosecond Bunches

For this case the bunch length detection setup is depicted in Fig 4. 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 so that signals of >1 THz spectrum width can be accurately measured. Depending on 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. A commercial mm-wave - THz camera can be used as detector array [1].

The simulation with a 1 ps beam and a set of two 200 micron wide vacuum breaks separated by 0.5 mm was done using CST particle studio. The Fig. 5 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 (red circles indicated on Fig. 5).

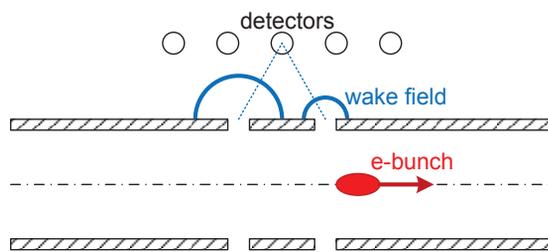


Figure 4: 1 ps non-invasive bunch length measurement setup.

The Fig. 6 shows autocorrelation function measured with probes placed parallel to the beam trajectory at the edge of the outer shell. Taking the measurements from this array of 11 detectors placed 2.5 mm away from the vacuum break wall, we obtained an autocorrelation function. Again we see that autocorrelation function characteristic width corresponds to the bunch length. In the simulation we used x-ray FEL parameters: 1 kA peak current beam ( $\sigma_z = 1$  ps) produced 1 kW peak power. With ~1 kHz repetition rate the duty cycle is low –  $1e-6$  leading to 1  $\mu$ W average power. This is well within the sensitivity level of pyro-detectors [1]. A cryo-cooled bolometer is even more sensitive.

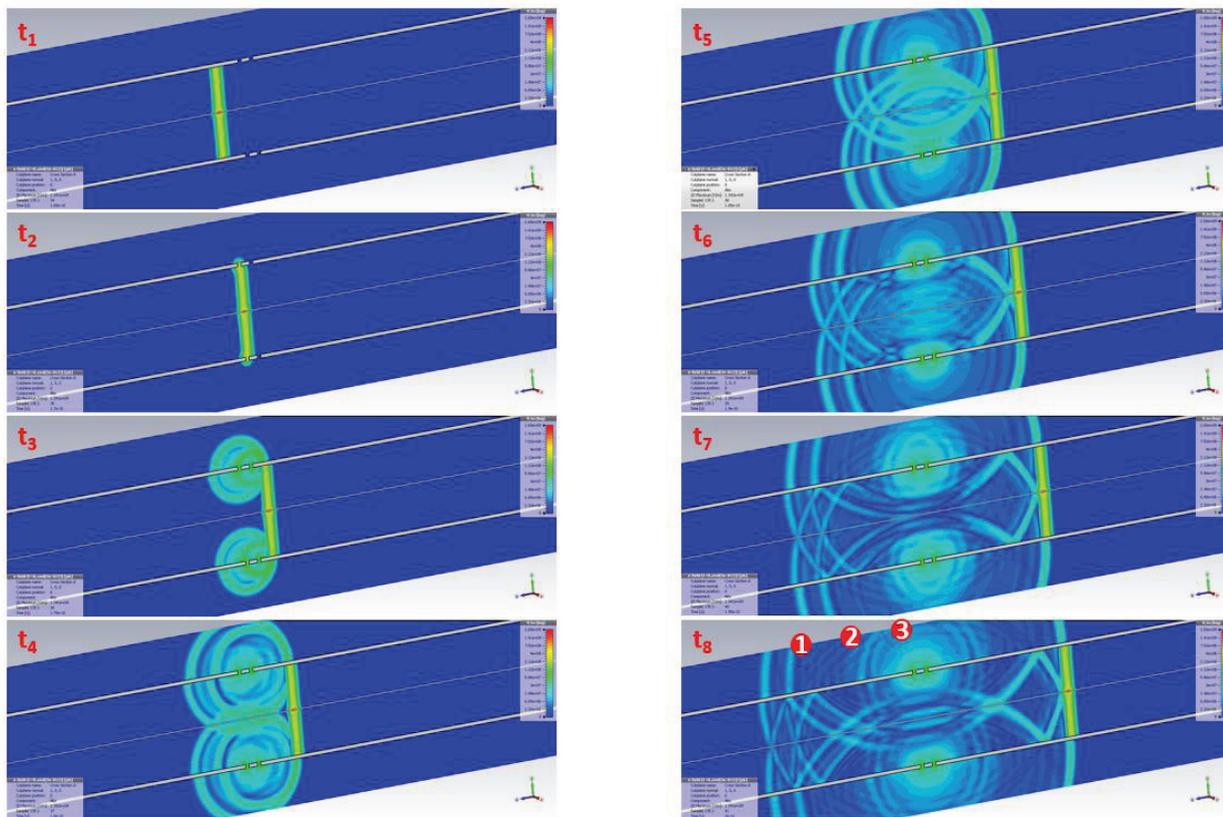


Figure 5: CST simulation of a 1 ps beam passing by two 200 micron vacuum breaks separated by 0.5 mm. Consequent shots at times  $t_1, t_2, \dots, t_8$  are presented. There is an interference between excited pulses which can be measured with a detector array. The detector array location is shown on  $t_8$  with red circles.

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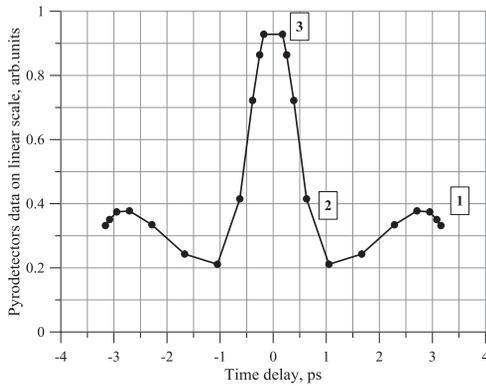


Figure 6: Pyro-detector’s output for various time delay pairs, i.e. autocorrelation function.

### SYNTHESIS PROCEDURE TO RECOVER PULSE SHAPE

A pyro-detector integrates (over time) the intensity of a sum of two identical pulses separated by a time delay  $\tau$ , -  $E(t)$  and  $E(t + \tau)$ :

$$\int_{-\infty}^{+\infty} |E(t) + E(t - \tau)|^2 dt = 2W + 2C(\tau), \quad (1)$$

$W$  is the energy in the pulse and  $C(\tau)$  is the autocorrelation function. This is measured in the experiment for various values of  $\tau$  either by moving the mirror in an interferometer [2] or by combining signals in separate RF pickup pairs with various delays  $\tau$ , as proposed here or by measuring at different positions for spatial correlation as proposed and implemented for CTR interferometry [3].

Note that Fourier transform of the autocorrelation function equals to the square of the absolute value of the Fourier transform,  $F(\omega)$ , of the original signal:

$$\int_{-\infty}^{+\infty} C(\tau) \cdot \exp(i\omega\tau) d\tau = \left| \int_{-\infty}^{+\infty} E(t) \cdot \exp(i\omega t) dt \right|^2 = |F(\omega)|^2 \quad (2)$$

The Eqs. (1) and (2) allow to describe the problem of pulse shape recovery. One knows the absolute value of Fourier transform, one also knows that function describing pulse shape  $u(t)$  is the real function, the phase of  $u(t)$  is flat (or it is flat with finite number of jumps on  $\pi$  in general case). Using this information one needs to find the unknown phase of spectrum and pulse shape  $u(t)$  as well. As a rule there is also an additional information that  $u(t)$  is defined at some time interval  $T$ ,  $u(t)$  equals to zero everywhere out of the mentioned interval.

In order to solve this incorrect mathematical problem an iteration procedure can be implemented. One chooses an initial approach for the unknown function  $u_0(t)$  (for example, a rectangular shape can be used), then the Fourier transform  $F_0(\omega)$  has to be calculated. The absolute value of the obtained  $F_0(\omega)$  does not generally coincide with the square root of Fourier’s transform for the meas-

ured autocorrelation function. That is why, for the next iteration one can hide the obtained  $|F_0(\omega)|$ , but to keep the obtained phase. So a new Fourier function is to be:

$$F_1(\omega) = |F(\omega)| \cdot \exp(j \arg[F_0(\omega)]). \quad (3)$$

Knowing a new approach of Fourier transform, one calculates a new approach  $u_1(t)$ . For a next step, one produces  $u_2(t)$ , saving the absolute value of  $u_1(t)$  within time interval  $T$  and inserting the flat phase. The flat phase corresponds to the particular case, when frequency dispersion is negligibly small so that pulse shape does not degrade at distance to measuring detectors. In a general case the phase, as it was mentioned, can include as big jumps as  $\pi$ . In this case the obtained phase should be processed using a filter which has in output 0 or  $\pi$  in dependence on to that value  $\arg[u_n(t)]$  is closer.

According to the described procedure one can calculate  $F_n(t)$  and  $u_n(t)$  respectively. From iteration to iteration these functions approach to the given  $|F(\omega)|$  and to the true  $u(t)$  correspondingly.

The proposed procedure belongs to methods studied in the papers [4-7]. In particular, a similar procedure was used for recovering of amplitude and phase distributions of quasi-optical wavebeams [6]. In these papers it was noted that multiple solutions can arise. The procedure is not necessary going to a true distribution. The only statement is that from iteration to iteration the mutual content of a function at current iteration and true function does not reduce. A quality of the procedure depends on many factors. Nevertheless, in most cases the procedure provides good accuracy better than 1%.

### 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.

### REFERENCES

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