Non-Invasive Bunch Length Diagnostics of Sub-Picosecond Beams

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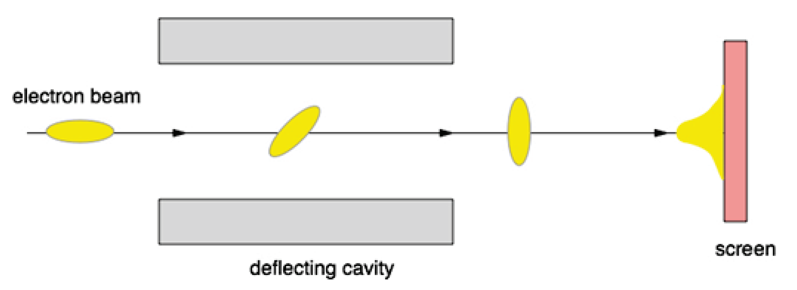
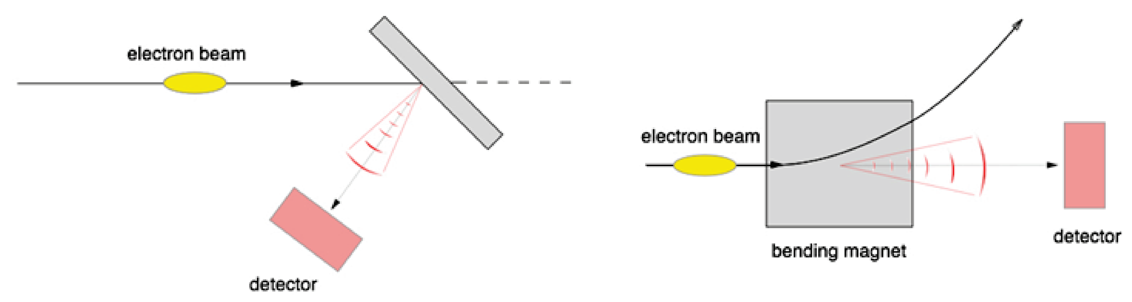
Abstract

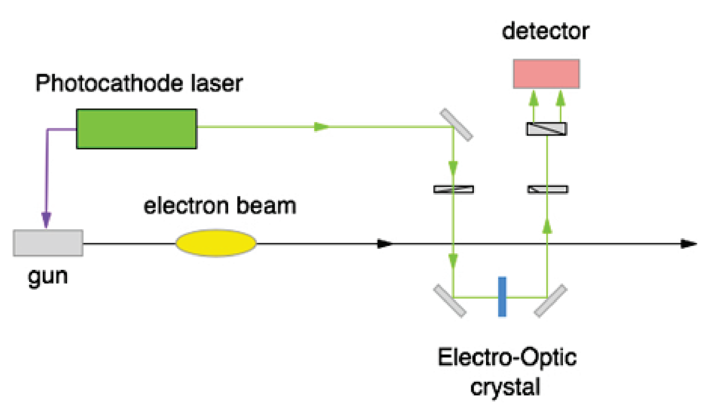
We propose a non-invasive bunch length measurement system based on RF pickup interferometry. A device performs interferometry between two broadband wake signals generated by a single short particle bunch. The mentioned wakes are excited by two sequent small gaps in beam channel. A field pattern formed by interference of the mentioned two coherent wake signals is registered by means of detecror'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. Moreover, one can recover the detailed temporal structure of the measured pulse using a new developed synthesis procedure.



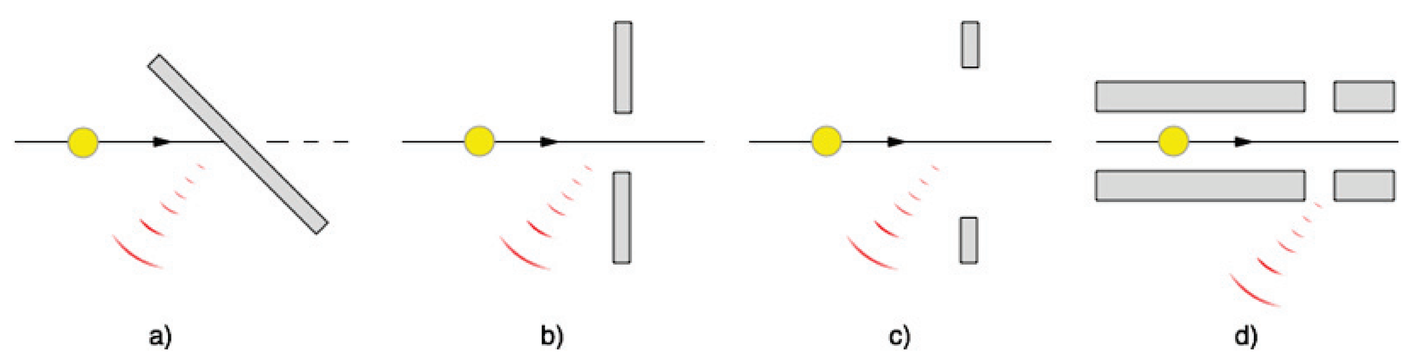
Schematic of a deflecting cavity detector.



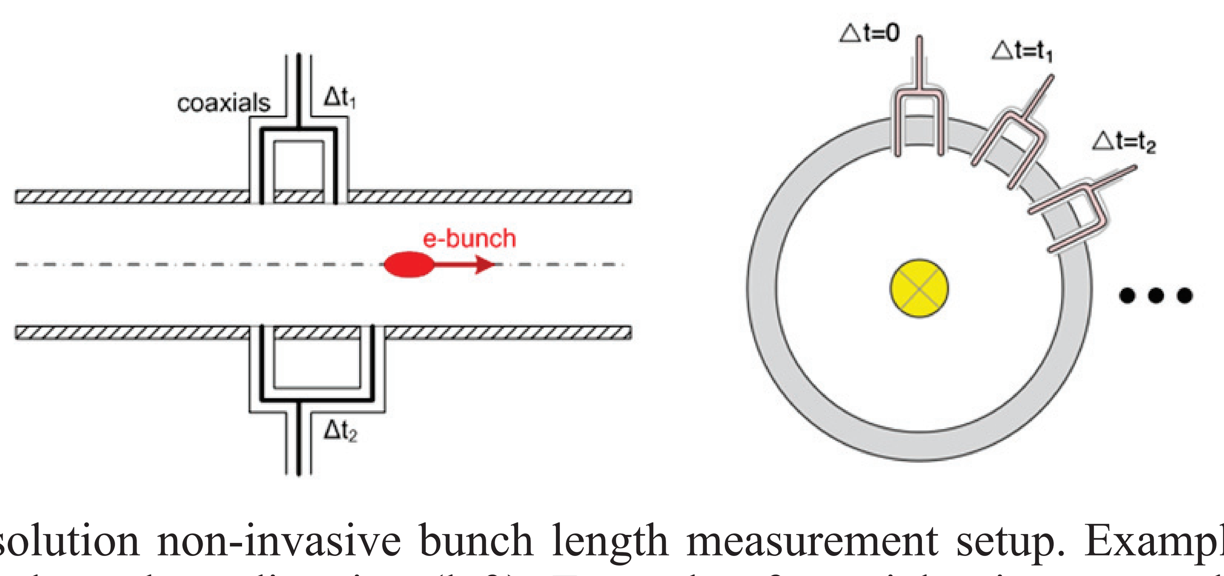
Transition radiation (left) and synchrotron radiation (right) as a source of information for the reconstruction of the beam length and shape.



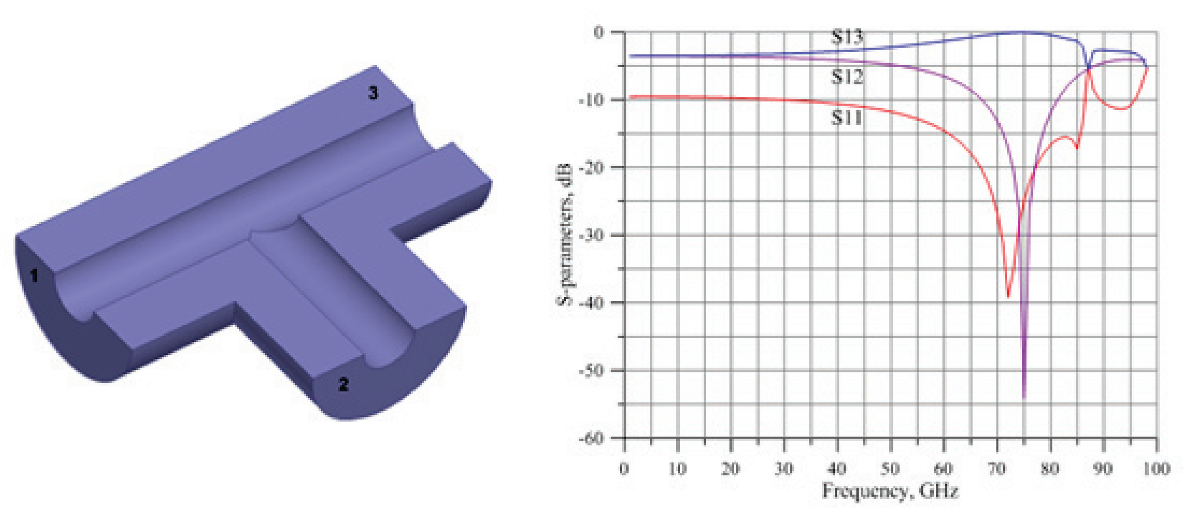
Electro-optic sampling of electric fields carried by the charge distribution by picosecond laser pulses.



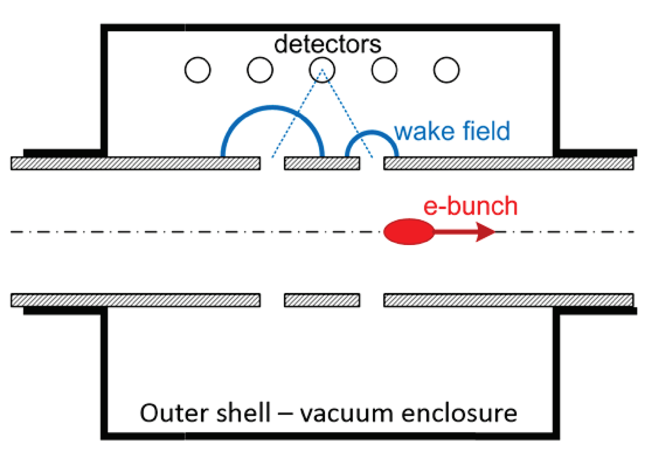
Evolution of coherent radiation based bunch length measurements.



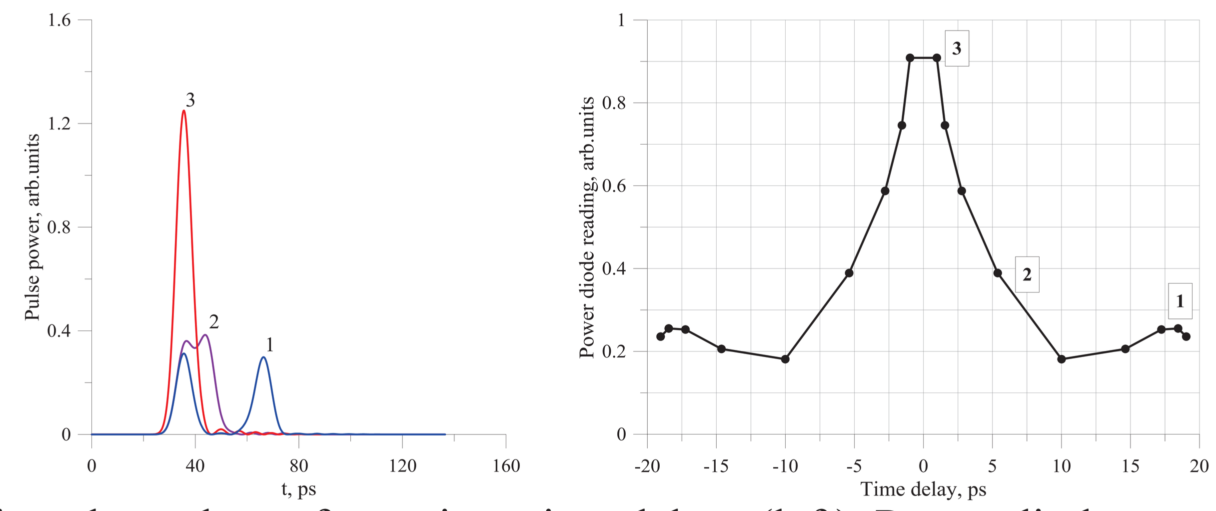
~10 ps resolution non-invasive bunch length measurement setup. Example of coaxial pairs placed along the z-direction (left). Example of coaxial pairs mounted on a flange (right). The delay time between the coaxial pickups in a pair is controlled by the positioning of the combiner.



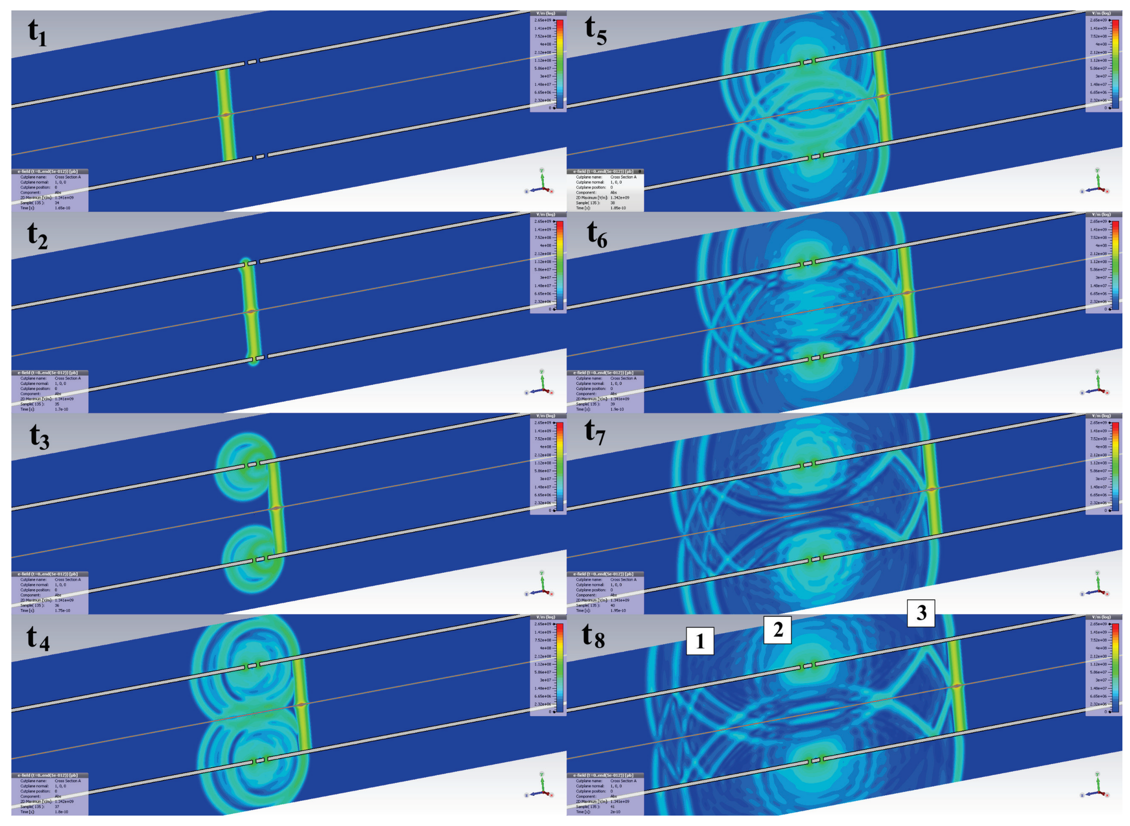
Coaxial combiner and its RF properties.



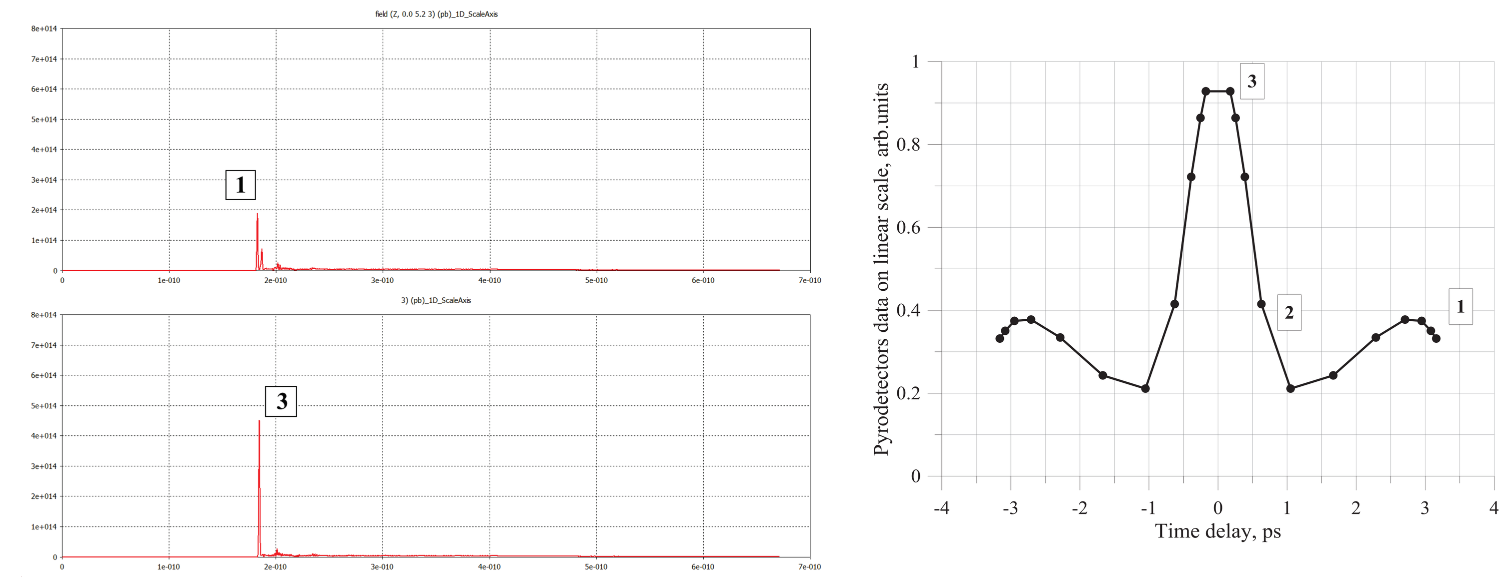
~1 ps non-invasive bunch length measurement setup.



Power time dependence for various time delays (left). Power diode output for various time delay pairs: autocorrelation function (right).



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, … 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 white boxes.



Time domain signal measured in two different locations of the detector array. The top plot is an example of signals from vacuum breaks arriving simultaneously (probe 3 on figure 10 – t_8) and adding up to produce a high peak power. The bottom plot is an example of sizeable time delay: the first signal had a short travel distance to the field probe, while the second one had a longer travel distance and was attenuated (probe 1 on figure 10 – t_8).

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 τ, - $E(t)$ and $E(t+\tau)$:

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

W is the energy in the pulse and $C(\tau)$ is the autocorrelation function. 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:

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

The equations above 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 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 choose 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 measured 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:

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

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 π. In this case the obtained phase should be processed using a filter which has in output 0 or π 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.