PRELIMINARY DESIGN OF A FEMTOSECOND OSCILLOSCOPE*

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Abstract

The calculations on motion of electrons in a finite length electromagnetic field of linearly and circularly polarized laser beams have shown that one can use the transversal deflection of electrons on a screen at a certain distance after the interaction region for the measurement of the length and longitudinal particle distribution of femtosecond electron bunches. In this work the construction and preliminary parameters of various parts of a device that may be called femtosecond oscilloscope are considered. The influence of various factors are taken into account. For CO_2 laser intensity 10^{16} W/cm^2 and field free drift length 1m the deflection is 5.3 and 0.06 cm, while the few centimeters long interaction length between 2 mirrors requires assembling accuracy 6 mm and 1.3 micron for 20 MeV and 50 keV, respectively.

INTRODUCTION

At present optical laser pulses with femtosecond length [1] find wide application for generation of X-ray photon attosecond bunches [2], and there is a proposal for the possible production of zeptosecond electromagnetic bursts [3]. Using recent accelerator technology intense electron and photon bunches with 30-100 fs length are obtained [4, 5]. As the calculations show with the help of femtosecond laser beams one can produce [6] attosecond electron bunches. In the works [7,8] it is proposed a method for obtaining femtosecond electron and photon bunches at fourth generation synchrotron sources LCLS and TESLA X-FEL, while in the works (see [9]) it is already a few year a method is under development for production of cw femtosecond X-ray beams from storage rings.

The existing main methods for the measurement of the length, particle density distribution and in some cases of some other parameters of ultrashort bunches of electrons and photons belong to time domain and frequency domain (see [10,11] and references therein). In the case of the time domain methods (streak camera, RF deflection in cavities, spectrometers) the time information on the bunches is transformed into measurable transversal space deflection as in usual oscilloscopes which work for processes as short as part of nanoseconds. The best-achieved resolution of complicated streak camera is a few tens of femtoseconds [12]. The inverse transformation of the space information into time for these types of devices is relatively simple.

In the case of frequency domain methods (coherent Cherenkov, transition, diffraction and synchrotron radiation, microwave spectroscopy) the time information is converted into spectral-frequency information. These methods use either spectral or autocorrelation measurements. The achieved best resolution is few hundreds femtoseconds, though theoretically some methods will work better at shorter times. The inverse transformation of the obtained results into time for these types of devices is connected with the use of certain retrieval algorithms.

The rapid advance of the ultra short bunch measurement methods resulted in the development of new methods that operate in the combined time-frequency domain. For instance, the frequency resolved optical gating (FROG) method [13] and the simplest its realization [14], which are widely used for the diagnostics of optical femtosecond laser pulses. A combined domain method for determination of the structure of ultra short relativistic electron bunches has been proposed recently in [15].

Following [16] in [17,18] it has been shown that if the 0,05-50 MeV electrons of a femtosecond bunch pass a free field region after the interaction with electromagnetic field of circularly polarized laser photons in a finite length interaction region, they will be circularly swept with the laser photon frequency on a screen. This allows to measure electron bunch lengths less than laser photon period by measuring the length of the arc by position sensitive detectors. The principles of construction of a femtosecond oscilloscope working as time domain device have been discussed in [16, 17]. In this work we optimize the parameters of the proposed femtosecond oscilloscope and estimate the expected accuracy of the measurement of the length of the electron bunches.

CONSTRUCTION OF THE LASER OSCILLOSCOPE AND ANALYTICAL AND NUMERICAL RESULTS

Fig. 1 shows schematically the construction of the oscilloscope, which in the principle differs from the time

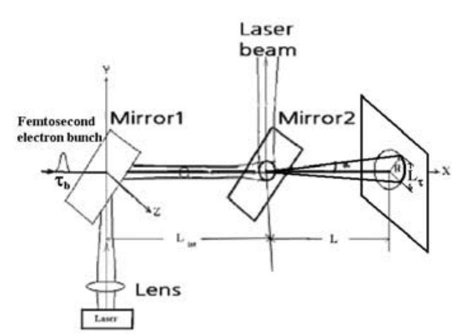

Figure 1: The scheme of the laser oscilloscope.

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domain RF methods (see, for instance, [19]) only by the fact that the electron beam sweeping is done with the help of laser higher frequency electromagnetic field instead of RF fields in cavities. Let a femtosecond electron bunch the length of which will be measured passes the thin mirror1 and up to second mirror2 interacts with the electromagnetic field of circularly polarized seed laser photon bunch which has much longer (say, picosecond) length and larger cross section. As the results of calculations [17,18] show in the interaction region with length L_{int} the electrons move along helices with very small radius less than the laser photon wavelength and negligible radial drift. Coming out from this region the electrons continue to move along the tangent to their trajectory at the mirror2 and after a field free region L they are swept with frequency ω along a circle on the screen with radius

$$R = \frac{2ceE_0}{\omega^2} \times \sqrt{B^2\Delta\eta^2 + \left(4B^2 + \frac{L^2k^2}{p_{x2}^2} + \frac{2LB\Delta\eta}{p_{x2}}\right)\sin^2\frac{\Delta\eta}{2} - 2B^2\Delta\eta\sin\Delta\eta} \quad (1)$$

where

$$p_{x2} = p_{x0} + \frac{2Be^2E_0^2}{\omega^2}\left(1-\cos\Delta\eta\right), \quad (2)$$

$$B = \frac{p_{x0} + \sqrt{m^2c^2 + p_{x0}^2}}{2m^2c^2}, \quad (3)$$

$E_0(V/cm) \approx 20\left[I\left(W/cm^2\right)\right]^{1/2}$ is the amplitude of the laser field with intensity I, p_{x2}, p_{x0} are the x-projections of the electron initial and final momenta and

$$\Delta\eta = \omega\frac{L_{\text{int}}}{v} - \frac{\omega}{c}L_{\text{int}} = \frac{2\pi L_{\text{int}}}{\lambda\gamma^2\beta(\beta+1)} \approx \frac{\pi L_{\text{int}}}{\lambda\gamma^2} \quad (4)$$

Thus the chosen L_{int} determines $\Delta\eta$ and R.

If the electron bunch length τ_b is less than the period of the laser light T then a part of the circle with length L_τ will be obtained on the screen (see Fig. 1). Measuring the length of this arc one can determine

$$\tau_b = \frac{L_\tau T}{2\pi R} \quad (4)$$

with $\Delta\tau_b/\tau_b = \sqrt{\left(\Delta L_\tau/L_\tau\right)^2 + (\Delta R/R)^2}$ (The contribution of other errors is small).

In [17,18] it has been described these principles of time measurements. In Fig. 2 It is shown the dependence of R upon L_{int} for $\omega = 10^{15}$ rad/s, $E_0 = 2.10^9 V/cm$ $L = 100$ cm. In Fig.3 it is given the dependence of R and of the period DL of the helix motion in the interaction region upon R.

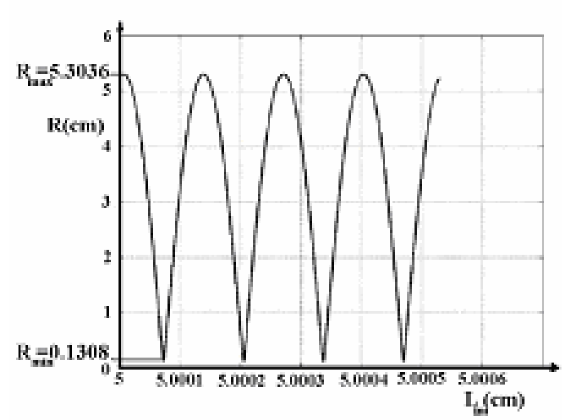

Figure 2: The dependence of R upon L_{int}.

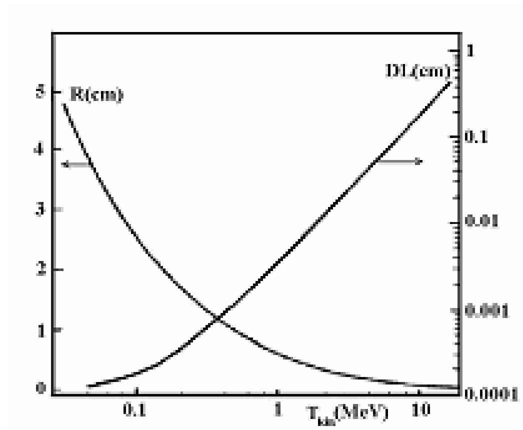

Figure 3: The dependence of R (left oordinates) and DL (right oordinates) on kinetic energy of the beam T_{kin}.

The assembly accuracy ΔL_{int} of the mirrors must be less than DL. Taking into account these results, the parameters of possible detectors and of electron beams one can performed a preliminary design of the oscilloscope and estimate the expected errors.

We shall assume that the sizes of the electron beam on the screen with or without seed laser are measured with the help of position sensitive detectors with overall error ~ 50 μm such as the micro channel plate (MCP) with charge coupled devices (CCD) [19]. On the other hand R must be sufficiently large of the order of tens or hundreds of CCD sizes to have reasonable $\Delta\tau_b/\tau_b$. Let us assume R = 1 cm which is reasonable for MCP/CCD detector and electron beam cross section ~100 μ [19]. Since R decreases with the increase of T_{kin} it is necessary to increase the intensity I with the increase of T_{kin}. On the other hand DL, therefore, ΔL_{int}, the assembly accuracy ΔL_{int} of the mirrors, increase with the increase of electron energy .

Some values of $R_{max}[cm]$ for: $E_0 = 2 \cdot 10^7 \frac{V}{cm}$, $\nu = 3 \cdot 10^{13}(CO_2 \ \ laser)$ and different values of γ are listed in table1.

Table 1.

T_{kin}	50keV	100keV	1MeV	10MeV	20MeV
γ	1.1	1.2	3	21	41
R_{max}	2.712	1.874	0.4397	0.06	0.03
L_{opt}	37	53	227	1667	3333

To have the preferable R_{max} about $1cm$ one may vary L_{opt} in cm, as it is shown in table 1.

CONCLUSION

As it follows from the results moderate laser intensities can serve for the length measurement in a wide electron energy region. The parameters of the femtosecond CO_2 laser oscilloscope for electron energy 50 MeV and R = 1 cm are $E_0 = 2.10^8 V/cm \, (W = 10^{14} W/cm^2)$, $L = 100cm$ and L_{int} = 5 cm. Using Nd:YAG lasers with T =3 fs and almost the same parameters one can measure the parameters of τ_b =1 fs bunches.

Of course, for optimal measurements of bunches one can vary various geometrical and detector parameters. Using Fig. 4 for this purpose one can vary only laser intensity.

Measuring the density distribution of the charges on CCD pixels one can measure the longitudinal distribution of the particles in the bunch. Unfortunately the proposed method is useless for bunches consisting of particles other than electrons and positrons using the processes of secondary electron emission and further acceleration because the processes have time resolutions of the order of picoseconds [20].

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