SETUP FOR DETERMINATION OF THE LONGITUDINAL PROFILE AND DURATION OF ULTRASHORT ELECTRON BUNCHES[1,2]

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Abstract

The Setup for determination of the longitudinal profile and duration of ultrashort electron bunches is proposed. The key idea is based on the connection between charge distribution along the bunch and time-shape of Optical Transition Radiation (OTR) burst. The OTR pulse is stretched by a special linear device after which it is intensified by a linear amplifier and further is processed by a corresponding algorithm. As a result the initial OTR pulse is reconstructed. An experimental device for registration of a single ultrashort light pulse is developed and now is operating. Using this device the shape of the laser pulse of duration $1 \leq \tau \leq 15$ *ps* was reconstructed. While doing this, time resolution of pulse structure of about *50 fs* was achieved.

Introduction

The determination of the electron bunch distribution function (especially of the longitudinal profile and bunch duration) is the object for intensive study of many authors [1–4].

We proposed and now realize the method which is based on unambiguous dependence of the time profile of OTR burst on the longitudinal charge distribution function along a bunch [5].

In the optical frequency band the determination of time profile (waveform) of single nonreproducible ultra-short pulses (USP) of picosecond and subpicosecond duration is a matter of independent scientific interest.

The existent methods of USP measurement can be divided into two groups: direct and indirect.

Most of studies devoted to indirect methods of USP measurement refer to the measurement of spectral-time characteristics of laser USP with energy no less than 10^{-5} J.

As for the measurements of time characteristics of incoherent USP with energy up to 10^{-10} J, the methods available are based largely on direct streak-camera measurements.

At present we are unaware of the methods of measurement of the time profile (waveform) of single nonreproducible USP with the energy lower than 10^{-11} J and duration about 1 ps.

We propose a method of measurement of a time profile of a single nonreproducible incoherent OTR USP with energy lower than 10^{-1} J, duration from 1 to 10 ps in a band $\lambda=(530+5)$ nm.

1. Work performed for the Lawrence Berkeley Laboratory.
2. Work supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the US Department of Energy under Contract No DEAC03-76SF00098.

OTR Burst Time Profile

What will be seen by the observer when a uniformly moving charged bunch at a velocity **v** crosses the boundary interface of two media? Let the bunch charge distribution have a form

$$\rho(z,r,\Phi) = qZ\left(\frac{z}{d}\right)R(r,\Phi); \; 0 \leq r \leq a; \; 0 \leq \Phi \leq 2\pi \qquad (1)$$

where q is the bunch charge, a - a quantity that defines the bunch transverse dimensions, d - defines its longitudinal dimension, $Z(z/d)$ is the charge distribution along the bunch and $R(r,\Phi)$ - the same for the bunch cross-section.

We refer to the case of oblique entrance of the bunch

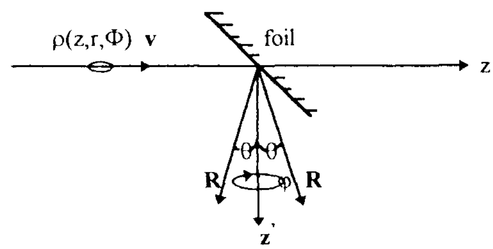

Fig.1. The Oblique Entrance.

From theoretical considerations [5] it follows that the dependence of TR intensity contains information on the function of charge distribution in the bunch. Indeed, the TR arises precisely at the moment when the bunch passes through the boundary and the number of emitted quanta is proportional to the square of the charge passing through the boundary at the given instant of time. The number of emitted photons per unit solid angle can be written in the form

$$\frac{dN_{ph}}{dt\,d\theta\,d\varphi} = \frac{1}{137}N_e^2\frac{c\lambda}{8\pi^3}\frac{\sin^3\theta}{1-\beta^2\cos^2\theta}S(\tilde{\theta})\hat{Z}(L)\hat{Z}^*(L) \qquad (2)$$

where N_e is the total number of particles in the bunch, $L=\beta R-vt$ and $\hat{Z}(L)$ is determined as

$$\hat{Z}(L) = \int_{-\infty}^{\infty} Z\left(\frac{z}{d}\right)\frac{\sin\frac{\Omega}{v}(L-z)}{L-z}\exp\left(-i\frac{\omega_0 z}{v}\right)dz, \qquad (3)$$

λ is radiated wavelength corresponding to the frequency ω_0, $(\omega_0-\Omega)<\omega<(\omega_0+\Omega)$ are real measurements in a sufficiently narrow frequency band $(\Omega/\omega_0<<1)$. If the Fourier spectrum lies in the interval 2Ω then,

$$\hat{Z}(L)\hat{Z}(L)^* \cong [Z(L)]^2 \qquad (4)$$

and the instantaneous distribution density of the number of photons turns out to be proportional to the square of bunch distribution function.

At $\beta \to 1$ and $\theta << 1$, $S(\tilde{\theta}) = 2(\ln\gamma + \ln\tilde{\theta} - 1/2)$.

The detected narrow-band signal in terms of the communication theory is a picture or image of the initial object, in our case - the longitudinal bunch distribution function [5].

For determinition of the longitudinal profile of the bunch, it is expedient to detect its TR energy that comes on the spherical surface segment which is symmetric about z' axis. $2\tilde{\theta}$ is the apex angle of the cone supported on the segment perimeter.

As shown by calculations, at the number of electrons in a bunch 10^{10} in the wavelength band $\lambda=(530\pm5)nm$ the number of radiated photons for different charge distributions is $\geq 10^{8}$ per radian.

Setup Block Diagram and Prototype Experimental Realization

The essence of the method is as follows. The USP OTR is preliminary converted in a special linear device with frequency dispersion which executes time broadening of the USP in the preset way. Then the converted pulse is amplified by an optical linear amplifier and is detected by a time-analyzing streak-camera as a photochronogram (PCG). The PCG by means of a video-camera and corresponding interface is entered into the computer where the initial OTR USP time profile (waveform) is restored in accordance with the developed algorithm.

The realization of the proposed method in the form of a block diagram is presented in Fig. 2.

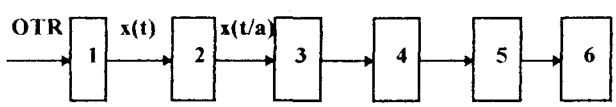

Fig. 2. The Setup Block-diagram: 1-Optical Filter, 2 - Expander-Converter, 3 - Optical Linear Amplifier, 4 - Streak-camera, 5 - TV-camera, 6 - PC.

Calibration of the setup consists in the measurement of the OTR simulator standard light pulse whose shape is preliminary measured with the resolution of 50 fs[].

The technical realization of the proposed method includes three stages:

- development and experimental check of the setup prototype enabling to determine the time profile (waveform) of an incoherent USP with duration about 15ps using the OTR burst simulator (1994) ;
- development and experimental check of the setup prototype enabling to determine the time profile of an incoherent USP with duration ≥1ps, using the OTR burst simulator (1994-95);
- construction of the setup and its experimental testing on the beam (1995).

In operation it is necessary to solve the following main problems:

- construction of OTR burst simulator;
- construction of an expander for pulses from 1 to 10ps;
- usage of a streak-camera with high resolution (≤1ps);

Setup prototype

Simulation of the OTR USP representing incoherent superposition of still shorter wave trains can be realized as follows.

It is generally known that the propagation of laser USP in condensed media is accompanied by the display of such nonlinear effects as self-focusing, stimulated Raman scattering (SRS) self-modulation, etc.

Competition of these effects as well as their interaction results in essential change of spectral composition and time envelope of the USP without change of its duration. It should be noted that the first two of the above-cited effects display more intensely at operation with picosecond pulses. Of particular importance is the circumstance that nonstationary nature of nonlinear response of the refractive index leads to the fact that the addition to the refractive index does not reproduce the pulse shape because the relaxation time of nonlinear polarizability is comparable with the pulse duration.

Another important factor is the beam transverse instability which induces its splitting into multiple filaments each manifesting nonlinear effects. So in fluids the SRS process proceeds on several frequencies in each filament irrespective of others, and the superposition of beats of various components of SRS filaments ultimately yields a highly irregular structure of the pulse envelope. An essential contribution is also made by stimulated four-photon parametric scattering leading to broadening of pulse spectrum and amplification of individual spectral components. As a result the USP at output represents incoherent superposition of large number of pulses with modulated phases and different mean frequencies, and the time envelope, accordingly, will contain a great number of irregular spikes of various duration and intensity. The time structure scale is determined by a distance between different components of SRS and is in the limits 0.01 - 1.0 ps.

The choice of a medium is determined by the following requirements: a rich spectrum (multi-frequency) of natural (own) frequencies of the medium and amply high nonlinear susceptibility. These requirements are met by organic fluids: nitrobenzene, ethanol as well as definite dye solutions which we used in experiments.

The prototype of the setup intended for determination of the time profile (waveform) of incoherent USP includes the following principal units:

- a picosecond JAG:Nd laser with a passive shutter and USP extraction from the central part of a train by electrooptical shutter, radiation wavelength $\lambda=1.064mm$, duration $\tau=15$-18 ps, spectral width $\Delta\lambda=0.4nm$;
- OTR simulator, dye-operating, where occurs conversionof coherent laser radiation into incoherent one;

- expander unit which represents a system of linear dispersive media;
- streak-camera "Agat-SF-3";
- detection unit that comprises a video-camera on CCD-matrix and a PC with a software.

The prototype operates as follows. The laser-emitted USP arrives at the simulator on the output of which, according to above-stated considerations we have an incoherent pulse with a wavelength $\lambda=530nm$ and spectral width $\Delta\lambda=5nm$. Then the simulator-converted pulse which simulates the OTR USP arrives at the input of the expander which executes USP linear broadening in the preset way. Broadened to 48 ps pulse is then lens-imaged on the input of a streak-camera. On the screen of the latter we have a photochronogram of the broadened pulse. The photochronogram image with the use of the video-camera is entered into the PC and by the developed software the shape of the broadened pulse is determined and the initial pulse is restored.

The block diagram of the prototype is presented in Fig. 3.

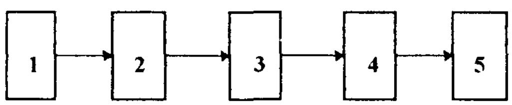

Fig. 3. Block-Diagram of Setup Prototype. 1- Laser, 2- Picoross, 3- Expander, 4 - Streak-camera, 5 - Register.

The determination of the shape of laser-emitted USP was performed by a measuring device whose operation is based on the cross-correlation method. Simultaneously the pulse shape was measured by a streak-camera "Agat-SF-3" with resolution 2 ps. With account of the fact that the cross-correlation measuring device resolution ≅ 0.05 ps [6] there was made correction of the laser USP photochronogram results as well as adjustment of the streak-camera.

The pulse obtained on the simulator's output was detected by the streak-camera. The measurement results show that USP duration on the OTR simulator is unchanged, however some torsion of the forward front with simultaneous spectrum broadening takes place.

The measurement of the shape of the broadened pulse on the output of the expander was performed using the streak-camera.

Conclusion

In conclusion we would like to note that the first stage we had obtained experimental corroboration of the possibilities of the method proposed. The laser pulse of 15-18 ps duration was exposed to time broadening in a linear disperse media. After that, according to the suggested scheme, that pulse's shape recovered with a time resolution of about 2 ps. To control the adequacy of the recovered time shape of the laser pulse, we used the method based on the determination of the shape by the cross-correlation function with a time resolution of 50 fs.

Now we are completing the development of the detection system for a time shape of the OTR pulse of 1 to 10 ps duration. For that we will use in appropriate laser with a pulse length about 1 ps. This will enable us to optimize the system of linear time broadening as well as other units for the detection and recovery of OTR pulse shape.

We note once again that our available streak-camera has a time resolution about 2 ps. Since the pulse time broadening in the expander is limited ($\leq$ 10) [5], then to analyze the OTR pulses of $\leq$ 1 ps a streak-camera with a better resolution is needed.

The authors are thankful to LBL Directorate and to Prof. A.M. Sesslerr as well as to DESY Directorium and to Coordinator DESY-YerPhI Collaboration Dr. G. Sohngen for solidarity and great support.

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