MEASUREMENT OF SPEED OF LIGHT EMITTED BY ULTRARELATIVISTIC SOURCE*

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Abstract

The paper focuses on the results of experiments on direct measurement of speed of the light emitted by an ultrarelativistic source. The source of synchrotron radiation (SR), electron storage ring Siberia-1 at the Kurchatov Institute, was used as a pulsed source of light. Experiments were made on the visible part of the SR emitted by ultrarelativistic electron bunch moving along a curved trajectory in the magnetic field of the bending magnet.

The measured velocity is within 0.3 % of the standard speed of light in a vacuum.

INTRODUCTION

The statement that "the speed of light is independent of the velocity of the source" was put forward by Einstein as the second postulate of special relativity [1]. In the last century, many astronomical observations and experimental studies have been devoted to accrediting this postulate, see, e.g., recent review [2]. During this time, the validity of this postulate was questioned many times with regard to the insufficient accuracy of the measurements, which was usually due to the low velocity of the source v compared to the speed of light *c*. In this work, we directly measured the speed of the light emitted by a source moving with an ultrarelativistic velocity and found that this speed does not differ from the standard speed of light in a vacuum, which is in agreement with Einstein's postulate.

SETUP AND THE IDEA OF THE EXPERIMENT

The experiment was based on the use of synchrotron radiation from a bunch of relativistic electrons moving at a velocity very close to the speed of light *c* along a curved trajectory in the magnetic field of the bending magnet of the electron storage ring. Under these conditions, it is easy to measure the speed of the emitted light in a very high laboratory vacuum.

According to the Newton–Ritz corpuscular ballistic hypothesis [3–5], which is most popular among opponents of special relativity, the speed of the light emitted by an electron bunch in the forward direction at a tangent to the trajectory should be twice as high as the speed of the light emitted by a source at rest. If this very large effect existed, it could easily be detected without special tricks in view of a high intensity of the synchrotron radiation.

The general layout of the experiment is shown in Fig. 1. The magnetic system of the electron storage ring Siberia-1 forming a closed orbit of electrons consists of four 90° bending magnets M1–M4 separated by four 60-cm-long rectilinear segments and forms a closed orbit of electrons. The radius *R* of the stationary orbit of electrons in the bending magnets is 1 m.

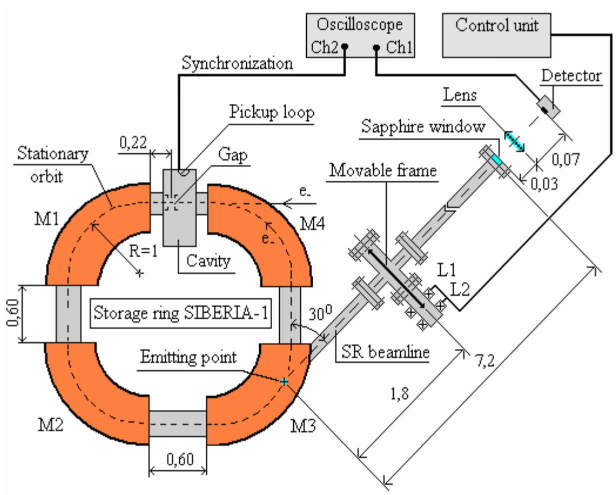

Figure 1: Layout of the experiment: L1, L2-magnetic drive coils of carriage; M1-M4 - bending magnets. Distances are given in meters.

The magnetic flux density on the stationary orbit is 1.5 T at a nominal electron energy of 450 MeV. Synchrotron radiation emitted by relativistic electrons in bending magnets covers a wide spectral range from infrared to X-ray with a characteristic wavelength of 61.3 Å. This emission leads to a 3.69 keV energy loss of each electron per round trip.

To compensate for these losses, a high-frequency cavity was placed in the first segment of the storage ring. Due to the high-frequency power supplied to the cavity, a voltage with an amplitude of 15 kV and a frequency of

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34.53 MHz, which is equal to the frequency of the rotation of the electron bunch in the storage ring, is created in the accelerating gap of the cavity.

The distribution of the transverse electron density in the bunch is Gaussian with a standard size of $\sigma = 0.30$ m.

The angle between the axis of the synchrotron radiation output channel, which is tangent to the stationary orbit in magnet M3, and the axis of the fourth rectilinear segment succeeding magnet M3 was 30°. This means that the emission point (the beginning of the path of the synchrotron radiation along the channel axis) is at a distance of $\pi R/3$ from the input end of magnet M3. The length of the channel from the emission point to the output sapphire window was L = 7.2 m. The chamber of the storage ring and the synchrotron radiation output channel compose a single vacuum volume.

A collecting lens placed behind the output window focused the synchrotron radiation beam on the window of a photodetector. As the detector, we used a silicon PIN photodiode Hamamatsu S5972, which has a spectral range of (0.32–1) µm, a frequency bandwidth of 500 MHz, and an effective sensitive area of 0.5 mm^2. The voltage created by the photocurrent of the diode on the 50 Ohm load (optical signal) was fed to the first input of a two-channel oscilloscope Tektronix 3052C (bandwidth of 500 MHz). Electric circuit of the photodetector is shown in Fig. 2.

A continuous sinusoidal high-frequency synchronization signal from the pickup loop of the cavity was fed to the second input of the oscilloscope. The pickup loop is oriented in such a way that the phase of its output voltage is shifted by 180^0 with respect to that of the voltage of the accelerating gap of the cavity. To exclude the error that results from different phase shifts of signals, the signals were transmitted through identical anti-interference (with a double screen) coaxial cables of the same length.

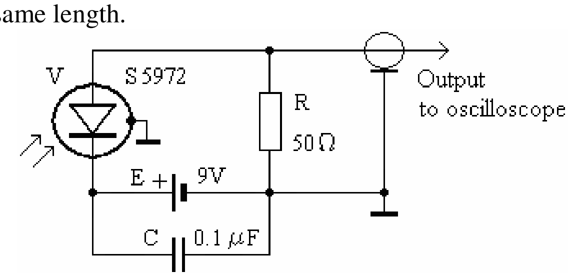

Figure 2: Schematic of the photodetector circuit.

Two Versions of the Experiment

The *first version* implied operative shutdown of the light beam in the synchrotron radiation output channel by a glass plate that was fixed in a movable frame and was introduce into the beam using a magnetic drive. In terms of the ballistic hypothesis, the refracting plate is considered as a secondary source of light at rest. For this reason, the light should pass section l of the synchrotron radiation output channel from the plate to the output window at a velocity of c (rather than $2c$, as in the absence of the plate). The length of section l is 5.4 m (Fig. 1); thus, the shutdown of the synchrotron radiation beam by the glass plate will lead to a time delay in the optical signals by 9.0 ns.

The *second version* of the experiment implied the direct measurement of the velocity of the synchrotron radiation pulse by dividing the section length $L = 7.2$ m of the output channel to the output sapphire window by the pulse passage time τ. This time can be measured by the oscilloscope using the synchronization signal and taking into account its calculated phase shift with respect to the time instant of passage of the electron bunch by the window of the synchrotron radiation-output channel.

EXPERIMENTAL RESULTS

In the *first version*, the time shift of the optical pulses was measured when the glass plate was introduced into the synchrotron radiation beam. With an accuracy of about 0.05 ns, no shift was detected (see Fig. 3 and Fig. 4).

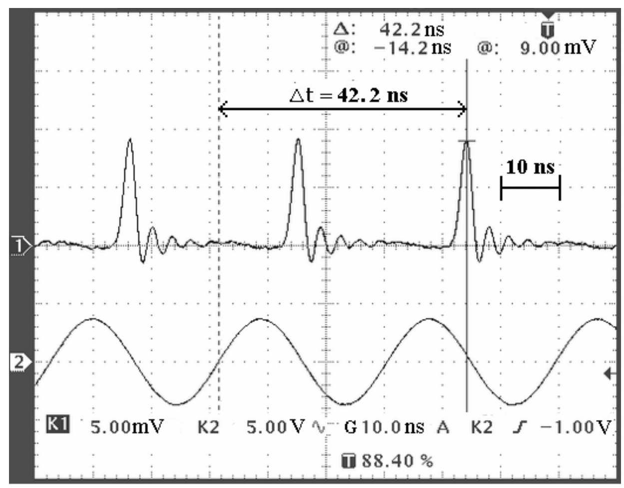

Figure 3: The optical signal (channel 1) for the light propagating through the radiation output channel in vacuum with open aperture at the entrance and the synchronization signal (channel 2).

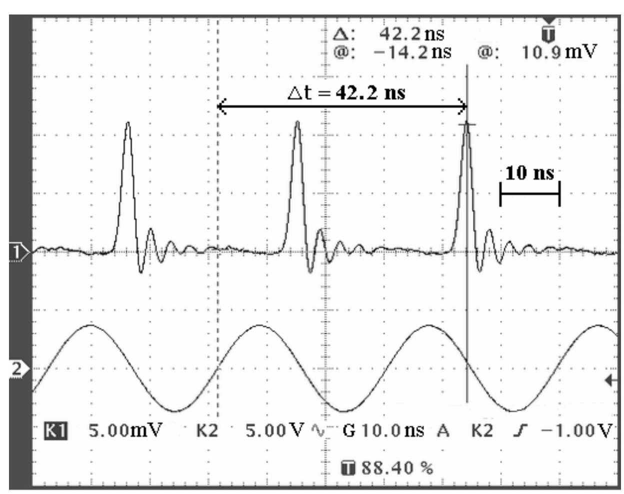

Figure 4: The optical signal (channel 1) for the light propagating through the radiation output channel in vacuum with the aperture at the entrance blocked by the glass plate and the synchronization signal (channel 2).

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The delay related to the refraction of light in the thin plate is negligibly small. As can be seen, the optical signal in shape and duration is very close to the ideal expected pattern, which is a periodic sequence of Gaussian pulses with FWHM of 2.35 ns. The only difference is the ringing on the trailing edge of the photocurrent pulses due to oscillatory processes in the circuits of the photodetector. However, this distortion of the pulse shape does not prevent the solution of the formulated problem.

Note that amplitude of the optical signal in Fig. 3 is slightly smaller than that in Fig. 4, which is explained by insignificant vignetting of the transmitted light beam by side edge of the aperture with no glass.

In the *second version* of the experiment, the velocity of the synchrotron radiation pulse was measured directly Details of the calculation and measurement of τ were reported in [6].

Oscillogram of Fig. 5 shows the measured delay of the detected optical pulse with respect to the moment of passing the center of the accelerating gap by the electron bunch.

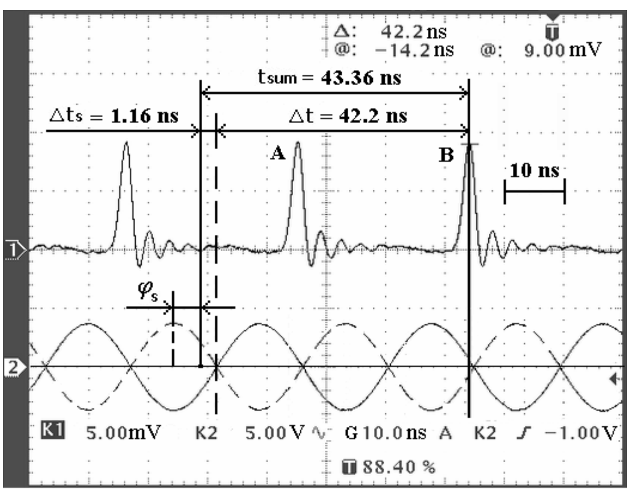

Figure 5: Measuring the light pulse delay in the photodetector with respect to phase of the synchronized particle in the accelerating gap of the cavity.

The solid and dashed lines in channel 2 show the output voltage of the pickup loop and voltage of the cavity gap, respectively. Synchronized particles of the bunch pass through the accelerating gap with a certain phase φ_S, counted from maximum of the falling part of the accelerating voltage. The value of φ_S depends on amplitude of the HF voltage on the cavity and electron energy loss per round trip. In [6], this value was calculated to be $\varphi_S = 75.61^o$, and, with allowance for the period of the HF oscillations (at 34.53 MHz) equal to 28.96 ns, the corresponding time interval was found to be $\Delta t_s = 1.16$ ns. As is seen from Fig. 5, time delay of the optical pulse in the photodetector with respect to phase of a synchronized particle in the accelerating gap of the cavity t_{sum} is obtained by summing up the calculated quantity Δt_s with the value of the time interval $\Delta t = 42.2$ ns measured with the oscilloscope. We analyzed here the light pulse B emitted by the electron bunch entering the accelerating gap of the cavity with the phase φ_S. The light pulse A is emitted by the electron bunch that enters the gap one round trip earlier. With allowance for geometry of the stationary orbit of the storage ring Siberia-1 (Fig. 1), the time of flight, by the electron bunch, of the distance from the center of the accelerating gap to the point of emission was found to be $t_e = 18.7$ ns (the electron bunch velocity was taken equal to standard speed of light in vacuum).

To calculate velocity of the light emitted by the electron bunch we subtracted from t_{sum} the time t_e and the times of propagation of light through the output sapphire window, 2.4 cm thick, the air gap, 10 cm in length, and glass of the collecting lens, 1.4 cm thick, obtained using refractive indices of the appropriate media (total time 0.55 ns). Thus we have found the time of propagation of the distance $L = 7.2$ m by the light pulse: $\tau = 24.1$ ns. The delay of the electric signal formation in the photodiode was here neglected. As a result, by dividing L by τ, the velocity of the synchrotron radiation pulse was found to be 2.99×10^{10} cm/s, which was only ~0.3 % lower than the standard speed of light in a vacuum.

The standard statistical error of the measurement was about 0.2 %. The systematic error was determined by the accuracy of the measurement of the electron and synchrotron radiation pathlengths and did not exceed 0.5 %.

CONCLUSIONS

In this work, the speed of the light emitted by the relativistic source is directly measured. The results are inconsistent with the Ritz ballistic hypothesis, which assumes the Galilean summation of the speed of light and the velocity of the source. It is shown that introduction of a glass plate into the light beam emitted by the ultrarelativistic source does not change the speed of light to within fractions of a percent, whereas according to the Ritz hypothesis, this speed would be halved after passing through the plate at rest. In addition, the direct measurement of the synchrotron radiation pulse velocity in a vacuum yielded a value in agreement with the standard speed of light with an accuracy of 0.3 %.

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