Quantum Electronics **46** (9) 860–862 (2016) ©2016 Kvantovaya Elektronika and Turpion Ltd

DOI: 10.1070/QEL16080

Recording Vavilov–Cherenkov radiation in a linear accelerator using a picosecond streak camera

N.S. Vorob'ev, P.B. Gornostaev, S.M. Gurov, V.L. Dorokhov, A.E. Zubko, V.I. Lozovoi,
O.I. Meshkov, D.A. Nikiforov, A.V. Smirnov, E.V. Shashkov, M.Ya. Schelev

Abstract. **Using a picosecond image converter camera with a linear sweep (PS-1/S1 streak camera developed at GPI RAS, Moscow), we have measured temporal parameters of Vavilov–Cherenkov radiation pulses. The radiation was generated by relativistic electrons passing through a quartz cone mounted on the axis of a vacuum chamber of a linear accelerator, which is a part of the VEPP-5 injection complex at the Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences (BINP SB RAS, Novosibirsk). The data obtained in these experiments provide an insight into the processes of formation of electron bunches and their 'quality' in a linear accelerator prior to injection of electrons into the accumulator-cooler. A conclusion is made regarding the advisability of streak camera application in tuning the linear accelerators for optimisation of electron bunch parameters.**

Keywords: *Vavilov–Cherenkov radiation, image converter camera, dissector, optical diagnostics, cyclic accelerator, linear accelerator.*

1. Introduction

Until recently, image converter cameras (ICCs) have been most widely used in laser physics, laser plasma diagnostics, laser spectroscopy, etc. [1]. A relatively new field of application of ICCs with a linear sweep (streak cameras) is optical diagnostics of synchrotron radiation emitted by electrons or positrons in cyclic accelerators [2]. This use of the camera has enabled, in particular, optimising the operation regimes of the accumulator-cooler (AC) in the VEPP-5 injection complex at the BINP SB RAS (Novosibirsk) and improving the injection of particles from the linear accelerator (linac) [3].

The aim of this work is to study the parameters of a bunch generated by a linac using a PS-1/S1streak camera, which has been developed and manufactured at the GPI RAS (Moscow) [3]. Because the repetition rate of electron bunches in this accelerator is tens of hertz, their longitudinal profile cannot be investigated using a dissector [4], which is designed for the pulse repetition rate of a few megahertz. In this connection, the use of streak cameras operating with an external triggering frequency ranging from a single pulse to a few kilohertz is justified. In this paper, we have recorded the Vavilov–Cherenkov radiation (VCR) emitted by relativistic electrons passing through a quartz cone mounted on the axis of a vacuum chamber of an accelerator.

2. Experiment

The VEPP-5 injection complex is a source of intense electron and positron bunches (the energy of 510 MeV), the number of particles in which is capable of satisfying with a margin all the needs of the working installations with colliding electron–positron bunches at the BINP RAS. The complex includes a linear accelerator of electrons up to an energy of 285 MeV and a linear accelerator of positrons up to an energy of 510 MeV, and also an AC with the channels for input and output of the bunches [5]. Electron and positron bunches, having been produced and accelerated by the linac, are sequentially captured into the cooler and cooled; in this case, due to radiation friction, their transverse and longitudinal phase volumes are reduced. The cooled bunches are released into the image converter channels for sequential injection into the VEPP 2000 and VEPP-4M colliders.

During the linac operation, temporal parameters of electron and positron bunches must be monitored. Unlike cyclic accelerators in which the longitudinal size of electron and positron bunches is controlled by synchrotron radiation (noninvasive method), there is no such a possibility in the linac. Temporal parameters of the bunch of particles in such an accelerator are measured using the invasive method by introducing a foil for generating the transition radiation or by installing a quartz cone for VCR generation. In the present experiment, we have used a quartz cone (Fig. 1), which was designed for tuning the one-bunch regime of accelerator operation by using the streak camera (developed at the BINP) with a sweep based on a high-Q cavity at the linac frequency of 2.856 GHz [6].

The duration of VCR pulses in the interaction of the bunches of particles with the cone medium coincides with the temporal distribution of particles along the propagation axis in their travelling within the accelerator, which allows us to determine the temporal profile and, as a consequence, the longitudinal size of the bunches of electrons and positrons in their acceleration in the linac.

The VCR emerging from the crystal cone (Fig. 2) should be collimated, in the course of reflection from the walls, into

---

N.S. Vorob'ev, P.B. Gornostaev, A.E. Zubko, V.I. Lozovoi, A.V. Smirnov, E.V. Shashkov, M.Ya. Schelev A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: vor@kapella.gpi.ru, shashkov@kapella.gpi.ru, m.schelev@ran.gpi.ru;
S.M. Gurov, V.L. Dorokhov, D.A. Nikiforov G.I. Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 11, 630090 Novosibirsk, Russia;
O.I. Meshkov G.I. Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 11, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; e-mail: o.i.meshkov@ngs.ru

Received 22 March 2016
Kvantovaya Elektronika **46** (9) 860–862 (2016)
Translated by M.A. Monastyrskiy

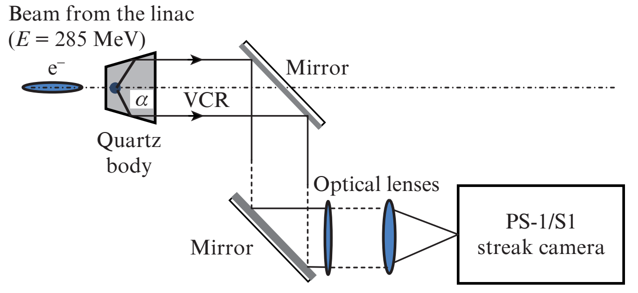

Figure 1. Optical scheme of the experiment.

a slightly divergent light bunch. However, due to the axis misalignment of the bunch and cone, and a variety of optical aberrations, the observed picture is far from ideal. In fact, a demagnified image of the glowing region of the quartz cone was obtained on the streak camera photocathode by means of a lens, the bunch entry angle being adjusted towards the maximal signal using the vertical and horizontal magnetic corrector.

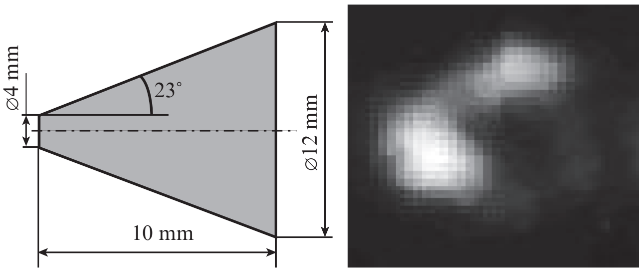

Figure 2. Quartz cone dimensions and a photograph of the VCR with the emitted electron bunch.

In our experiment, the PS-1/S1 streak camera has been used to measure the VCR duration, the main characteristics of which are given in [7]. The camera was placed on the optical table located in the premises of the linear accelerator. A quartz cone with an opening angle θ, such that $\cos\theta = 1/n$ ($n = 1.51$ is the refractive index of light in quartz), was located inside a special diagnostic unit and placed on the vacuum chamber axis using an electromagnet. The VCR was released outside using a pair of mirrors and directly focused by means of two lenses on the streak camera photocathode (see Fig. 1), inasmuch as the purpose of these experiments was to measure not spatial, but the longitudinal (temporal) bunch profile. In the static regime of camera operation, the image on the output screen, due to the bunch nonideality, was similar to an ellipse with the dimensions in the time–space coordinates of 1–1.4 mm, respectively. This size (1 mm) of the resolvable image element limits the temporal resolution of this method, which, with allowance for the streak camera limiting resolution (~1 ps), deteriorated down to $\geqslant 10$ ps. Moreover, in these circumstances, the test signal intensity falls, and the amount of the light incident on the photocathode may be insufficient for its detailed studying in the case of rather fast sweeps having a duration, as example, more than 100 ps.

Analysis of the images obtained on the camera output screen was conducted with the use of a readout system. It should be noted that, in the course of measurements, we have shown stable interference resistance and reliable workability of the ICC in the conditions of high-level electromagnetic radiation and high (more than 40 °C) temperature.

The number of photons in VCR, emitted by an electron in the optical range during its passing through the cone, is [8]

$$N_\gamma = 2\pi\alpha d\left(\frac{1}{\lambda_{\min}} - \frac{1}{\lambda_{\max}}\right)\left(1 - \frac{1}{n^2}\right).$$

Consequently, for a bunch with a charge of 1 pC, the number of photons is equal to 10^9. Here, α is the fine structure constant; $\lambda_{\min}$ (400 nm) – $\lambda_{\max}$ (700 nm) is the VCR wavelength range; and $d = 1$ cm is the cone length. With allowance for the quantum efficiency of the streak camera photocathode, which is no less than 10^{-3} in the visible spectrum range, we obtain 10^6 electrons per static resolvable element having a size of 1×1.4 mm. This amount of electrons may turn out insufficient for recording the long-wavelength duration (more than 100 ps) VCR in the case of a fast sweep, which was confirmed by subsequent measurements.

The proposed method of measuring the temporal structure of the bunch has another limitation on the temporal resolution associated with light dispersion in the cone. In this case, the pulse broadening can be estimated as

$$\tau = \frac{d}{c}\frac{\mathrm{d}n}{\mathrm{d}\lambda_{\mathrm{m}}}(\lambda_{\max} - \lambda_{\min}) \approx 2\ \text{ps}.$$

Here, c is the speed of light in vacuum; and $\lambda_{\mathrm{m}} = 0.5(\lambda_{\max} + \lambda_{\min})$. In our case, this limitation is not essential for determining the temporal resolution of the method, constituting, as already noted, $\geqslant 10$ ps. We should also mention an alternative technique for diagnostics of relativistic charged particle bunches, based on the use of inertialess transition radiation; however, its intensity is 2–3 orders of magnitude lower [9, 10].

The bunch radiation recording at the streak camera's sweep duration of 33 ns on the screen of 25 mm revealed the presence of two clusters generated by the linac per one pulse (Fig. 3). The appearance of the second cluster is explained by a defect in the forming line of the linac's electron gun and represents an undesirable circumstance, because these particles do not fall into the AC but are lost on the vacuum chamber walls and generate the induced radiation background within the protected hall of the accelerator.

The structure of the first cluster captured into the AC has been studied at an increased (10 ns/screen) sweep speed and is

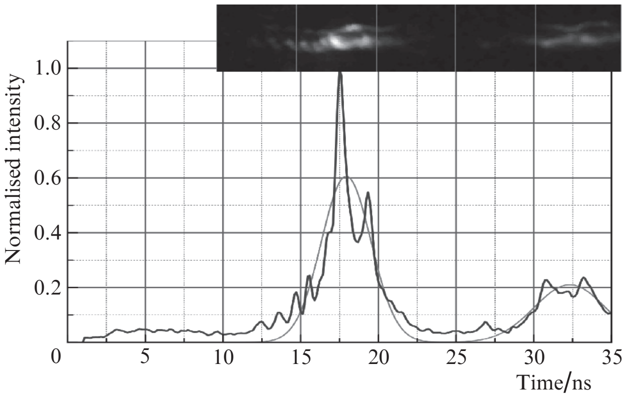

Figure 3. Two bunches generated by the linac per one pulse (inset) and their two-dimensional profile. Sweep speed is 33 ns/screen. Thin curve is the standard approximation.

shown in Fig. 4. Clearly visible is the intensity modulation, the period of which corresponds to a frequency of ~ 3 GHz used in the linac grouping section. Figure 5 shows the temporal structure of two adjacent pulses (the sweep speed is 3.5 ns/screen) as shown in Fig. 4. Here we also clearly observe a fine temporal structure, the character of which indicates the complexity of the processes occurring in the linac. With a further increase in the sweep speed up to 1.4 ns/screen, we could not obtain an image sufficient for reliable recording.

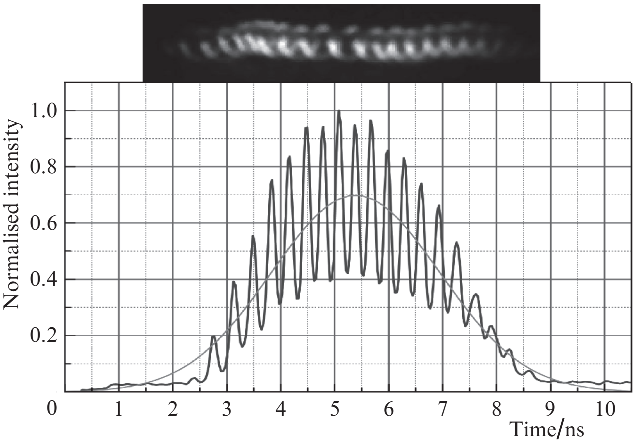

Figure 4. Structure of the first bunch trapped into the AC. The sweep speed is 10 ns/screen.

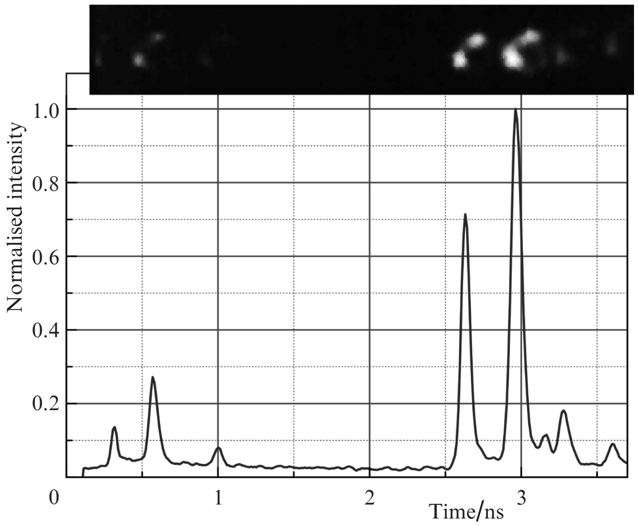

Figure 5. Structure of two adjacent pulses presented in Fig. 4. The sweep speed is 3.5 ns/screen.

Further investigation of the temporal structure of a single pulse requires a significant improvement of the quality of the optical recording tract of the VCR generated by the quartz cone in order to perform tight radiation focusing onto the streak camera photocathode. This will allow us to achieve the limiting temporal resolution of the technique, comparable with the resolution of the ICC itself, and also increase the density of the test signal intensity to ensure its reliable recording when the camera operates in the fast sweep regime. However, even the already obtained results give an insight into the operation regimes of the linear accelerator and allow optimisation of its parameters.

Thus, using the PS-1/S1 streak camera, we have investigated the structure of an electron bunch emitted from a linear accelerator of the VEPP-5 injection complex. We have recorded the longitudinal particle distribution in the bunch injected by the linear accelerator per one pulse. The data obtained allow optimisation of the installation operation regimes. The PS-1/S1 camera has demonstrated high operation versatility and reliability in the conditions of high-level electromagnetic interference and background radiation.

Acknowledgements. This work was supported by the Russian Science Foundation (Project No. 14-29-00295).

References

1. Schelev M.Ya., Monastyrskiy M.A., Vorobiev N.S., Garnov S.V., Greenfield D.E. *Aspects of Streak Image Tube Photography* (Amsterdam: Elsevier Publ., 2013, Adv. Imag. Electron. Phys.) Vol. 180.
2. Scheidt K. *Proc. Europ. Particle Accelerator Conf.* (Vienna 2000) p. 182.
3. Vereshchagin A.K., Vorob'ev N.S., Gornostaev P.B., Dorokhov V.L., Kryukov S.S., Lozovoi V.I., Meshkov O.I., Nikiforov D.A., Smirnov A.V., Shashkov E.V., Schelev M.Ya. *Kvantovaya Elektron.*, **46**, 185 (2016) [*Quantum Electron.*, **46**, 185 (2016)].
4. Zinin E.I. *Nucl. Instrum. Meth. Phys. Research*, **208**, 439 (1983).
5. Starostenko A.A., Logachev P.V., Meshkov O.I., Nikiforov D.A., Andrianov A.V., Levichev A.E., Emanov F.A., Astrelin K.V., Blinov M.F., Tsyganov A.S., Berkaev D.E., Koop I.A., Bolkhovityanov D.Yu., Dorokhov V.L. *Pis'ma Zh. Fiz. Elem. Chastits At. Yadra*, **7** (2016) (in print).
6. Gurov S.M., Bak P.A., Chernousov Y.D., Logatchov P.V., Pyata E.E. *Proc. SPIE Int. Soc. Opt. Eng.*, **6279**, 62790B (2007).
7. Garanin S.G., Bel'kov S.A., Rogozhnikov G.S., Rukavishnikov N.N., Romanov V.V., Voronich I.N., Vorob'ev N.S., Gornostaev P.B., Lozovoy V.I., Schelev M.Ya. *Kvantovaya Elektron.*, **44**, 798 (2014) [*Quantum Electronics*, **44**, 798 (2014)].
8. Landau L.D., Lifshitz E.M. *Electrodynamics of Continuous Media* (Oxford: Pergamon Press: 1960; Moscow: GITTL, 1957).
9. Ginzburg V.L., Tsytovich V.N. *Usp. Fiz. Nauk*, **126**, 553 (1978).
10. Hollack K., Kamps T., Kuske P. *Proc. Europ. Part. Accelerators Conf.* (Lucerne: EPS-AG, 2004) p. 2532.