Nuclear Instruments and Methods in Physics Research A 341 (1994) 17–20
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Experiments with undulator radiation of a single electron

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A single electron circulating in a storage ring is a very peculiar object. Permanent emission of synchrotron radiation offers the possibility to observe the electron but also causes the "natural bunch length". In the quasiclassical treatment uncertainties in the electron position arise from the averaging of the energy and position of the point-like electron over many turns in the storage ring. Nevertheless the question about the electron localization remains open. The radiation from a long undulator permits one to obtain "snapshots" of the electron longitudinal distribution. Experiments with a single electron on the VEPP-3 optical klystron are discussed.

The well-known phenomenon of the "natural" energy spread and bunch length (and the corresponding horizontal emittance) in electron storage rings [1,2] have been investigated in detail, both theoretically and experimentally many years ago. According to the quasi-classical theory by Sands, Kolomensky and Lebedev [3,4] the interaction of an electron with a radiation field is treated as statistically independent emission of photons. This causes small jumps in the electron energy and, consequently, a diffusion in phase space. The natural energy spread (and the natural bunch length) is the result of the equilibrium of this diffusion and the radiation damping of synchrotron oscillations. From the point of view of quantum theory, we have to consider the electron using an appropriate density operator which brings us to the question of the particular amplitude and phase of the synchrotron oscillations of the electron (i.e. the energy and the longitudinal coordinate inside the bunch). It should be noted that the system is stationary and that it does not interact with any "thermostat", except an infinite set of field oscillators with zero energy, so it is "simple" and regular.

We have investigated the electron radiation in order to obtain information about its state. We have taken advantage of two distinguished features of the VEPP-3 storage ring: its large bunch length and long undulator. The main parameters of the VEPP-3 storage ring are listed in Table 1. The undulator with 66 periods is installed at a straight section [5].

Layout of the experiment, which is similar to the Brown–Twiss interferometer, is shown in Fig. 1. Light emitted by the electron in the undulator passes through an optical spatial filter and a beam splitter to two photomultipliers. Photocount pulses from each photomultiplier arrive at amplitude discriminator-shapers (see Fig. 2). Pulses from one of the photomultipliers give the start signal to the circuit for the interval measurements and pulses from the other multiplier give the stop signal. The coincidence circuit permits measurement of pulses which have a time interval of less than 14 ns (the revolution period is 250 ns). The time dependence of the count rate of one of the photomultiplier is shown in Fig. 3. One step (about 2 kHz) corresponds to the loss of one electron. Results

Table 1
Main parameters of the VEPP-3 storage ring

Perimeter	74.7 m
RF harmonic number	2
Energy	350 MeV
Relative natural energy spread, σ_E/E	3×10^{-4}
Bunchlength σ_s at $U_{RF}=1.1$ kV	0.9 m

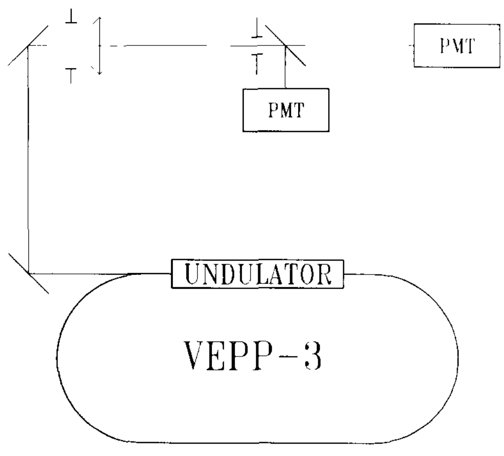

Fig. 1. Layout of the installation.

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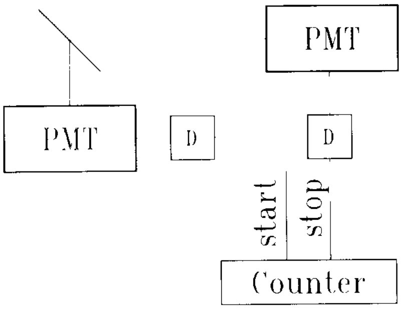

Fig. 2. Layout of the time interval measurements.

of the Brown–Twiss experiment for various numbers of circulating electrons are shown in Fig. 4. We switch on the RF system at the 18th harmonic of the revolution frequency and decrease the bunch length σ_s to less

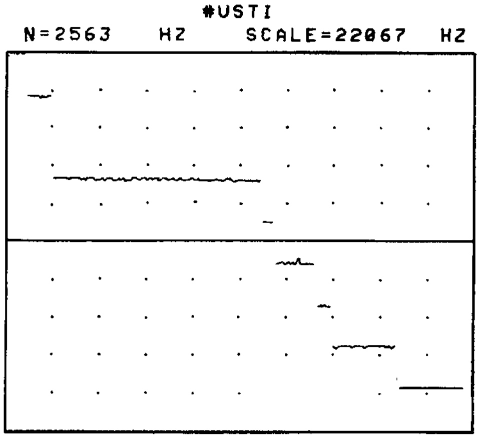

Fig. 3. The time dependence of the counts rate. One step corresponds to the blow out of one electron. (Vertical scale is 22 kHz, horizontal scale is 2560 s).

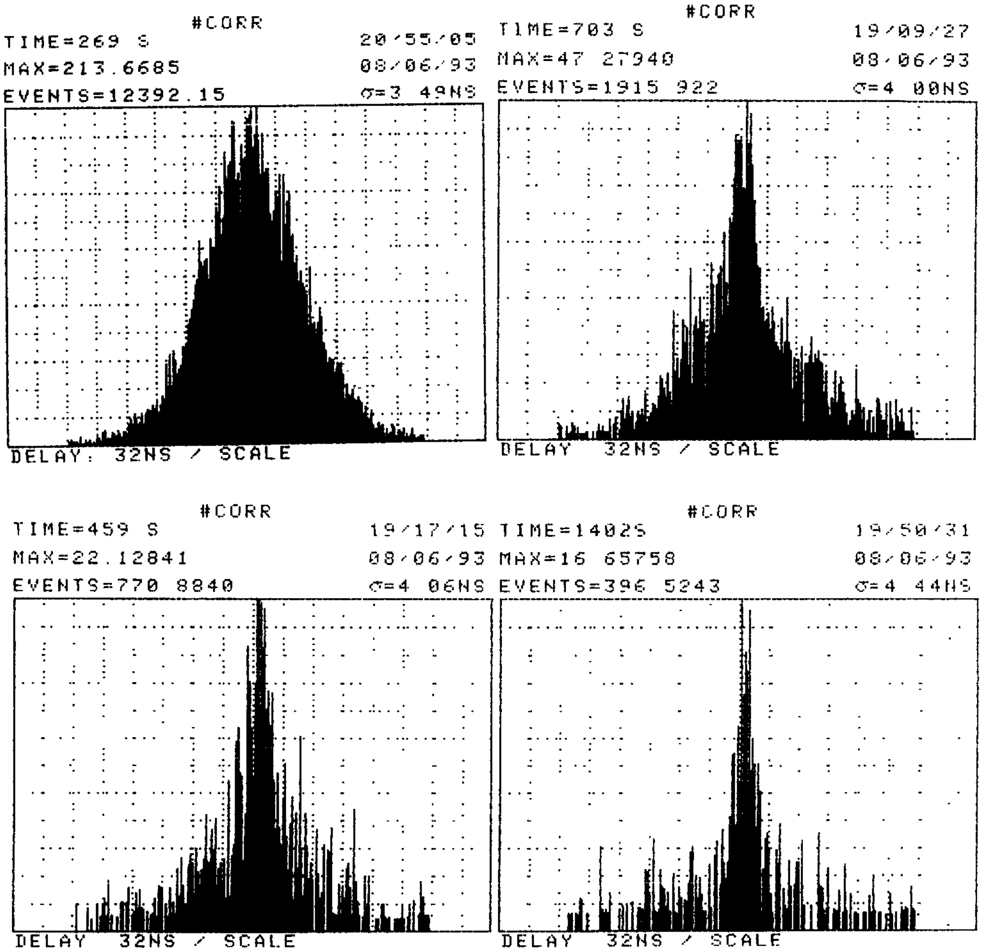

Fig. 4. The dependence of the number of photocount pairs on the time interval between photocounts. Number of electrons for upper left figure is approximately 20, for upper right 4, for bottom left 3, and for bottom right 1. Horizontal scale is 2 ns/div.

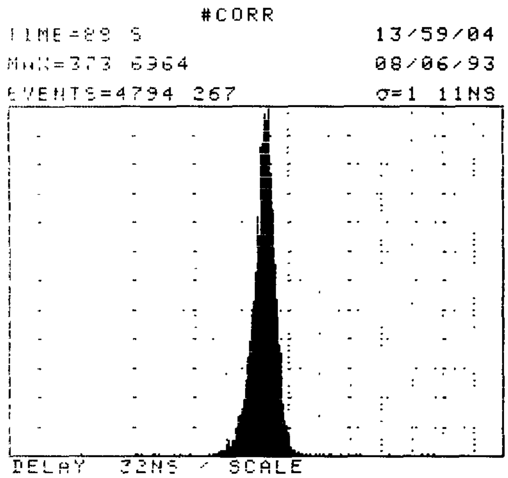

Fig. 5. The dependence of the number of photocount pairs on the time interval between photocounts for a short electron bunch (150 ps).

than 5 cm to check the resolution of the system. The time distribution of the interval between the photocounts shown in Fig. 5 demonstrates a 1.1 ns time resolution (standard deviation).

According to well-known results of quantum optics [6], the probability of a photocount from the first photomultiplier during a time interval from t_1 to $t_1 + \mathrm{d}t_1$ and a photocount from the second one from t_2 to $t_2 + \mathrm{d}t_2$ is proportional to the second order correlation function of the incident light:

$$w(t_1, t_2)\,\mathrm{d}t_1\,\mathrm{d}t_2 \propto G^{(2)}(\boldsymbol{r}_1, t_1; \boldsymbol{r}_1, t_2; \boldsymbol{r}_1, t_2; \boldsymbol{r}_1, t_1)\,\mathrm{d}t_1\,\mathrm{d}t_2. \qquad (1)$$

where

$$G^{(2)}(\boldsymbol{r}_1, t_1; \boldsymbol{r}_2, t_2; \boldsymbol{r}_3, t_3; \boldsymbol{r}_4, t_4) = \mathrm{Sp}[\rho E^-(\boldsymbol{r}_1 t_1)E^-(\boldsymbol{r}_2, t_2)E^+(\boldsymbol{r}_3, t_3) \times E^+(\boldsymbol{r}_4, t_4)],$$

E^+, E^- are the field operators, and ρ is the density matrix.

The probability of registration of two photocounts separated by a interval τ during the revolution period T is equal to

$$W(\tau) = \int_{-T/2}^{T/2} w(t_1, t_1 + \tau)\,\mathrm{d}t_1. \qquad (2)$$

In our case the bunch length is much less than the perimeter of the ring and so we may choose the integration limits in the region where $w = 0$. In the classical limit, for the radiation of N uncorrelated electrons

$$w(t_1, t_2) \sim N[\delta(t_1 - t_2)f(t_2) + (N-1)f(t_1)f(t_2)], \qquad (3)$$

where

$$f(t) = \frac{c}{\sqrt{2\theta}\,\sigma_s}\mathrm{e}^{-c^2t^2/2\sigma_s^2}$$

is the longitudinal distribution of electrons, and

$$W(\tau) \sim N\left[\delta(\tau) + (N-1)\frac{c}{\sqrt{2\pi}\,\sigma_s}\mathrm{e}^{-c^2t^2/2\sigma_s^2}\right]. \qquad (4)$$

If we approximate the resolution curve of our measurements system (Fig. 5) by a Gaussian with a standard

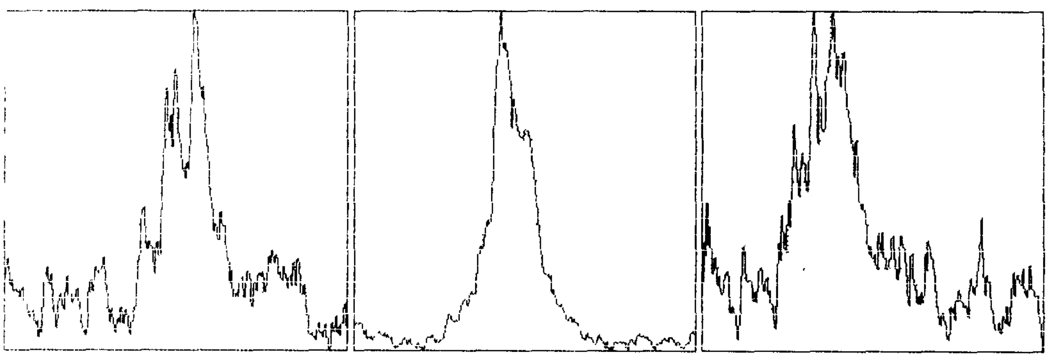

Fig. 6. The sidebands near the 17th harmonic of the revolution frequency for one electron caused by synchrotron oscillations. Left – lower sideband, center – central line, right – upper sideband. Distance between the central line and the sidebands is 1 kHz. Horizontal scale is 6.25 Hz/div. The ratio of the amplitude of the central line to that of the sideband is approximately 5:1.

deviation σ_r, we can derive the theoretical dependence, corresponding to the results, shown in Fig. 4:

$$\frac{c}{\sqrt{2\pi}\,\sigma_r} e^{-\tau^2/2\sigma_r^2} + (N-1)\frac{c}{2\sqrt{\pi(\sigma_s^2 + c^2\sigma_r^2)}} e^{-\tau^2 c^2/4(\sigma_s^2 + c^2\sigma_r^2)}. \quad (5)$$

Thus we can see a fairly good agreement of the experimental results with the model of quasiclassical point-like electrons.

We have also performed another experiment in which we measure the long-time correlation in the light intensity. We used one photomultiplier and put its signal into an RF spectrum analyzer with a resolution of 3 Hz. Investigating the spectrum near the harmonics of the revolution frequency we have detected sidebands corresponding to the synchrotron oscillations of a single electron (Fig. 6). The width of these sidebands was in agreement with the damping time of the synchrotron oscillations.

The results of our experiments have shown that the electron behaves like a classical oscillator excited by quantum noise and probably is an interesting example of the appearance of a stochastic process in a regular quantum dynamical system.

References

[1] A.A. Kolomensky and A.N. Lebedev, The Theory of Cyclic Accelerators (Moscow, 1962).

[2] M Sands, in: 46th Corso, Enrico Fermi School (Academic Press, New York, 1971) p. 257.

[3] M. Sands, Phys. Rev. 97 (1955) 470.

[4] A.A. Kolomensky and A.N. Lebedev, Dokl. Sov. Acad. Sci. 106 (1956) 87, Soviet JETP 30 (1956) 207, 1161.

[5] N.G. Gavrilov et al., Nucl. Instr. and Meth. A 282 (1989) 422.

[6] R.J. Glauber, in: Quantum Optics and Electronics, Les Houches 1964 Summer School, ed. C. De Witt, New York, 1965, p. 63.