Two-photon correlations in synchrotron radiation as a method of studying the beam

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The use of wavelengths shorter than optical in the Hanbury-Brown–Twiss correlation method opens up possibilities for the study of the spatial structure of sources of radiation in cases when the use of optics is not possible. An example is considered of measuring the size of the beam in electron storage rings.

The effect of two-photon correlations noted already by Einstein[1] has been studied theoretically[2] and experimentally[3] in the papers of Hanbury-Brown and Twiss who have utilized the extremely high resolving power of the method for measuring the angular sizes of stars[4]. Analogous phenomena are known also in other fields. For example, such phenomena are the two-pion correlations in reactions of multiple production[5-7].

This effect can be utilized in different problems with the aim of studying the spatial structure of the source by investigating the radiation emitted by it. An important advantage of the method is the possibility of utilizing radiation over a wide frequency range, since the detecting apparatus utilizes the photoeffect (for example, a photoelectric multiplier). Therefore the correlation method is particularly useful in problems where the utilization of optics is not possible for one reason or another. The simplest example is the case in which the dimensions of the source are less than or of the order of an optical wavelength. Such, for example, is the situation in the study of the spatial structure of processes occurring at the focus of a laser beam. In the present paper we consider the possibilities of applying this method to another example of practical importance—the measurement of the vertical dimensions of the beam in electron storage rings. In this case the resolving power of optics is limited by the diffraction on the size of the spot.

Briefly, the idea of the method of measurement consists of the following. It is well known that in the case of incoherent emission of light its intensity varies randomly in time due to the random interference of the contributions of individual sources. Of course, on time-averaging the interference drops out. But for two detectors at close points yielding signals $S_1(t)$ and $S_2(t)$ the intensity beats are correlated as a result of which the quantity $S = \overline{S_1 S_2} - \overline{S}_1 \overline{S}_2$ (the bar denotes averaging over the measurement time T) is different from zero.

The magnitude of the correlator depends on the wavelength λ, on the distance between the detectors l, on the distance to the source $R \gg l$ and, mainly, on the structure of the source. The experimental arrangement whose schematic diagram is shown in the figure yields a signal at the correlator[3]

$$S = T\,\Delta f\,|F(l/R\lambda)|^2 \int \alpha^2(\omega)\,n^2(\omega)\,d\omega, \qquad (1)$$

where $\alpha(\omega)$ is the efficiency of the photoelectric multiplier, $n(\omega)$ is the spectral flux of quanta falling on the photoelectric multiplier, Δf is the transmission band width of the system. The function $F(k)$ is the Fourier transform of the distribution of intensity of the source along the axis perpendicular to the slits (the axis AB in the diagram). Varying the distance l between the slits one can measure $F(k)$ which is directly related to the distribution of the electron density along a certain direction in the transverse section of the beam. In carrying this out averaging takes place along the other axis, as well as along the longitudinal coordinate, over the smaller of the following quantities: the length of the electron bunch and the magnitude of $c/\Delta f$ or the portion of the trajectory which emits radiation in the direction of the detector. We note that since the characteristic arguments of $F(k)$ are of the order of $1/d$ (d is the dimension of the beam) correlations are noticeable under the condition of spatial coherence of light at the detectors:

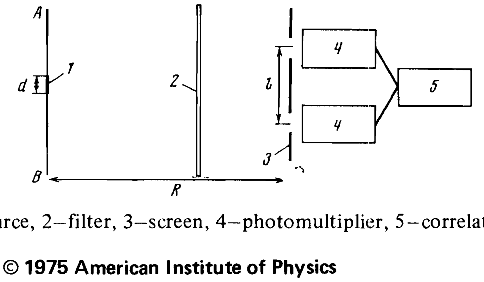
$$l \leqslant \lambda R/d. \qquad (2)$$

A characteristic feature of synchrotron radiation is its narrow directional property. Thus, radiation of wavelength λ enters a cone of angle $\theta_0 \sim (\lambda/R_0)^{1/3}$, where R_0 is the radius of curvature of the electron trajectory[1)]. It is clear that in order for light to reach the detector it is necessary that $l \lesssim R_0$, and from this we obtain a limitation on the resolving power of the method

$$d \geqslant (R_0 \lambda^2)^{1/3}. \qquad (3)$$

In the case of optical measurements due to the diffraction involving the dimensions of the light spot the resolving power is also limited, and the corresponding condition coincides with (3). As estimates show, already for the storage rings in existence one should choose λ at the boundary, and preferably beyond the boundary, of the optical range. In such a situation it is particularly significant that in the case of correlation measurements utilizing the photoeffect (photoelectron multiplier) the frequency range can in principle be arbitrary.

Another important advantage of the correlation method is its stability with respect to different kinds of disturbances. If one measures the normalized correlator (i.e., referred to the product of average currents from the photomultiplier), then the following disappear: dependence on total luminosity, on nonidentity of the photomultiplier and their illumination, etc. In the case of motion of the beam (oscillations) this method gives the dimensions of the beam and not a spot averaged out in time. Finally, a measurement of the Fourier trans-



1—Source, 2—filter, 3—screen, 4—photomultiplier, 5—correlator.

form of the distribution of intensity can turn out to be more convenient for the study of its fine structure.

The principal defect of the correlation method is its low sensitivity, i.e., the necessity of lengthy measurements. Indeed, due to the quantum noise which is in principle unavoidable (random coincidences) in the photomultiplier signal the correlator also yields the noise signal which is equal to[3]

$$N=(T\,\Delta f)^{1/2}\int\alpha(\omega)\,n(\omega)\,d\omega. \qquad (4)$$

In order that the signal (1) should exceed the noise (4) the time of measurement required is $T \gg [\Delta f\cdot\alpha^2(\omega)n^2(\omega)]^{-1}$ which is quite large in the case of a weak light source (a star). In the case of synchrotron radiation $n(\omega)$ is given by the formula

$$n(\omega)\approx 0.52\frac{e^2}{\hbar c}N_{\rm el}\left(\frac{\lambda}{2\pi R_0}\right)^{1/3}\delta, \qquad (5)$$

where N_{el} is the number of electrons in the ring, while δ is a geometrical factor which indicates the fraction of the total radiation which reaches the photomultiplier. An estimate shows that the tremendous intensity of synchrotron radiation results in this problem not being particularly significant: $T \lesssim 0.1$ sec. The application of this method to other problems is particularly convenient for sufficiently bright sources.

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[1]) All the formulas for synchrotron radiation are given on the assumption: $\lambda \gg R_0(mc^2/E_{el})^3$.

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