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EXPERIMENTAL INVESTIGATION OF X RADIATION OF ULTRARELATIVISTIC ELECTRONS IN MAGNETIC ONDULATORS

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The radiation of fast electrons passing through periodic electric or magnetic fields (ondulators) was considered theoretically in [1 - 3]. Experimental studies of electrons in magnetic ondulators were made only at millimeter and optical frequencies (cf. [3]). We present here preliminary results of an experimental investigation of emission from 3.6-GeV electrons in a magnetic ondulator at x-ray frequencies ($\hbar\omega$ = 10 - 125 keV).

The emission of ultrarelativistic electrons in magnetic ondulators at x-ray frequencies was investigated theoretically in [4, 5]. It was shown that in the case of a sinusoidal distribution of the field in the ondulator, the emission of the fast electrons consists of different "harmonics," each of which has a frequency interval

$$\omega_{1m} = \frac{m\Omega}{2} \leqslant \omega \leqslant 2m\Omega\gamma^2 = \omega_{2m}. \tag{1}$$

where m is the number of the harmonic, $\gamma = (1 - \beta^2)^{-1/2}$, $\Omega = 2\pi c/\ell$ (ℓ is the period of the magnetic field).

The number of quanta emitted in the frequency interval $d\omega$ per unit path length is given by ($\beta \to 1$)

$$\frac{dN_m}{d\omega} = \frac{e^2}{\hbar c}\,\frac{1}{2\pi c}\int_0^{2\pi}\left(\frac{\sigma_m^2}{\sin^2\theta_m\cos^2\phi} - \frac{1}{\beta^2\gamma^2}\right)I_m^2(a_m)d\phi\,, \tag{2}$$

where

$$\sigma_m = \frac{m\Omega}{\beta\omega}\,,\quad \cos\theta_m = \frac{1}{\beta} - \sigma_m\,,\quad a_m = \frac{\omega e H_0}{\gamma\Omega^2 Mc}\sin\theta_m\cos\phi\,,$$

$$\omega^2\sin^2\theta_m = \frac{1}{\gamma^2}(\omega - \omega_{1m})(\omega_{2m} - \omega),$$

I_m is a Bessel function, H_0 the amplitude of the magnetic field, and M the mass of the passing particle.

Formula (2) is valid if the following conditions are satisfied:

$$\left(\frac{M}{M_e}\right)^2\gamma^2 >> 10^{-8}H_0^2\ell^2\,,\quad \frac{2}{3}\left(\frac{e^2}{Mc^2}\right)^2 H_0^2 L\gamma << Mc^2, \tag{3}$$

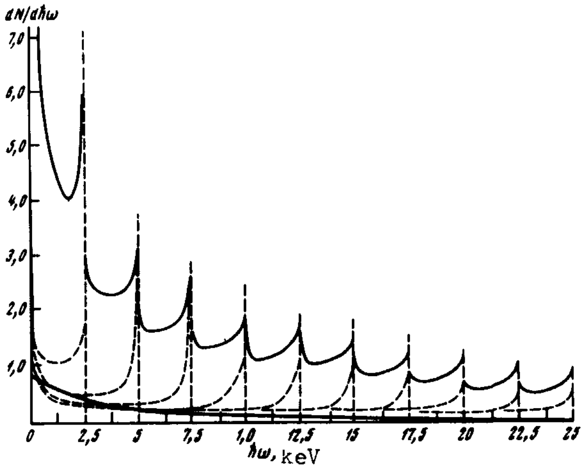

Fig. 1

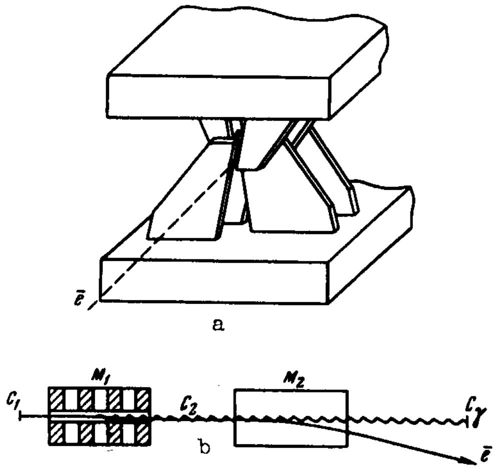

Fig. 2

Fig. 1. Spectral distribution of ondulator and synchrotron radiations: top curve - summary spectrum of ondulator radiation, dashed - harmonics, continuous curve - synchrotron radiation spectrum.

Fig. 2. Experimental setup: a - construction of ondulator, b - diagram of experiment.

where M_e is the electron mass and L the ondulator length.

According to the theory, the total radiation energy, just as in the case of synchrotron radiation, is proportional to the square of the energy of the passing particle, whereas the total number of emitted quanta does not depend on the particle energy. With increasing particle energy, the spectrum shifts toward shorter wavelengths. If radiation in a definite frequency interval is registered, then the number of photons, and also the energy carried away by the photons, should depend on γ of the primary particle, so that the fast-particle energies can be measured.

The spectral distributions of the individual harmonics, and also of the summary radiation of 5-GeV electrons passing through an ondulator with a magnetic field amplitude $H_0 = 10^4$ Oe, a period $\ell = 10$ cm, and a length L = 100 cm are shown in Fig. 1. On the average, each harmonic contains about three quanta. The same figure shows, for comparison, the spectral distribution of synchrotron radiation of electrons having the same energy and passing through a uniform field with $H_0 = 10^4$ Oe and L = 100 cm. As seen from the figure, in the frequency region under consideration the intensity of the ondulator radiation exceeds the intensity of the synchrotron radiation and, as shown by estimates, has $\sim$10 times more quanta in the interval $\hbar\omega \simeq 1.5 - 30$ keV. The ondulator radiation has several advantages over the synchrotron radiation: a) it is obvious that in the case of the ondulator the quanta arriving at the same observation point will come from larger sections of the particle trajectory than in the case of a uniform magnetic field, for in the latter the particle trajectory is circular; b) the number of ondulator-radiation protons increases in proportion to the square of the magnetic field intensity, as against direct proportionality in the case of synchrotron radiation; c) since the fundamental frequency of each harmonic equals $2\pi c\gamma^2/\ell$, it is possible to vary over a sufficiently wide range the frequency region where the radiation is maximal, by suitably choosing the value of ℓ.

It follows from the foregoing that the ondulator radiation can be used to separate electrons from heavy particles and to obtain intense beams of x-ray

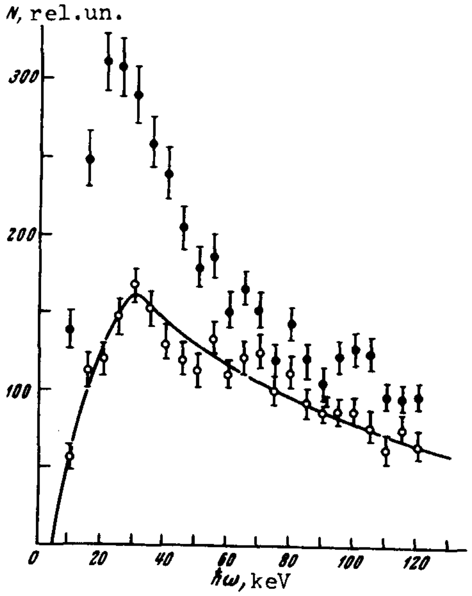

Fig. 3. Spectral distribution of registered radiation in the presence (o) and in the absence (●) of a magnetic field in the ondulator.

quanta. If the electrons are passed through thin ferromagnetic films or laser fields, it can also serve as a source of harder γ quanta with line spectra.

The ondulator used in the present experiment comprised a system of poles placed in the gap of a type SP-57 magnet along the beam direction, in such a way that their fields were perpendicular to the beam axis and reversed direction periodically along the axis. By way of illustration, Fig. 2a shows the arrangement of one period. We used altogether eight periods with ℓ = 8 cm. The field distribution in the horizontal plane was almost sinusoidal with H_0 = 5200 Oe. The ondulator poles were suitably shaped to calcel out the vertical dc component of the magnetic field.

The experimental scheme is shown in Fig. 2b. Electrons of energy 3.6 GeV were registered with scintillation counters C_1 and C_2 placed ahead and past the ondulator M_1, and were then deflected by magnet M_2. The electron radiation was registered with an NaI(Tl) crystal scintillator. The radiation spectrum was investigated with a 512-channel pulse-height analyzer. The energy calibration was with the isotope Sn^{119m}. To determine the contribution of the background radiation, the measurements were made alternately with and without the ondulator magnetic field.

Figure 3 shows the radiation spectra measured with and without the ondulator magnetic field. It is obvious that the difference spectrum is the investigated ondulator radiation. The background contribution, due mainly to the electron bremsstrahlung in the air and in scintillators C_1 and C_2, coincides in form with the Bethe-Heitler spectrum with allowance for the absorption. As seen from Fig. 3, in spectral region $\sim$10 - 50 keV the summary radiation greatly exceeds the background radiation. Measurements performed at E = 2.5 GeV have shown that the summary and background radiations coincide within the limits of statistical errors, a fact which does not contradict the theoretical estimates.

It follows thus from the experimental results that we have observed ondulator radiation at x-ray frequencies.

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