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SIMPLE COMPARISON BETWEEN THE YIELDS OF VARIOUS TYPES OF RADIATION OF ELECTRONS

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Yerevan 1980

In connection with the widespread application of photon beams with energies $\hbar\omega = 1$ KeV + 100 MeV it is of interest to carry out some quantitative comparison of the yield of various radiation mechanisms of high energy electrons. Such a comparison is a very difficult task, however, within reasonable approximations it allows to make clear what type of radiation would be preferred in order to obtain maximal number of photons in the given frequency region for the given electron machine.

The choice of the optimal radiator length depends on the concrete available conditions and requires complicated calculations. Nevertheless, as it will be shown below without pretension of high accuracies, one may at the beginning find the yields for unit radiator lengths and then estimate realistic yields obtainable on linear, cyclic accelerators and storage rings of electrons.

The spectral distributions, i.e. the number of photons per KeV versus photon energy, emitted by the single passage of an electron with energies $E = 5$; 1 and 0.1 GeV through one cm of radiator are presented in Figs. 1a, b and c, respectively. The curves BrC and BrLi , the bremsstrahlung spectra for 1 cm diamond and lithium targets, are calculated by the formulae /1, 2/ taking into account the density effect. As it is seen in the region $\omega \gg \omega_{cr} = \omega_p \gamma$, where $\omega_p = \sqrt{4\pi N Z e/m}$ is the plasmon frequency and $\gamma = E/m$, $dN/d\omega \sim 1/\omega$ and does not depend on E, while for $\omega \ll \omega_{cr}$, $dN/d\omega \sim \omega$ and $dN/d\omega \sim 1/E$. Some dotted curves given in this and other figures show the effect of absorption. The curves TR for transition radiation are calculated according to /3-5/ for radiators consisting of $a = 50\mu$ thick ~ 12 lithium foils with $b = 750\mu$ distances between each other. In the region $\hbar\omega = 1 \div 10^5$ KeV the TR intensity is very small at low electron energies up to 0.1 GeV, and reaches saturation at ~ 5 GeV.

The spike DR in Fig.1a illustrates the properties of the so called dynamic radiation /6-7/ arising when a charged particle passes through a crystal. The mechanism of production of DR can be visualized as Bragg reflection of pseudophotons accompanying the particle from the crystallic planes. Though the DR intensity is low, nevertheless, it differs from all the types of radiation by the fact that DR photons are emitted at large $\sim(30^\circ \div 60^\circ)$ angle forming some "plaques". For $\gamma > 1000$ it is practically independent of energy. The spike in Fig.5a is one of these plaques (calculated for $L \approx 2$ cm thick LiH monocrystal) having $\Delta\hbar\omega \approx 100$ eV and total number of photon $N = dN/d(\hbar\omega) \cdot \Delta\hbar\omega \approx 10^{-5}$.

The curves SR are for the well known synchrotron radiation calculated for $H = 10^4$ oe according to /8/. The curves UR represent the results of calculations for undulator radiation /9-13/ in dipole approximation for $H_0 = 10^4$oe and L[illegible]$=0.5$ cm. At certain conditions if the undulator is in medium (similarly to the radiation of channeled particles taking into account the medium /14/) one obtains strongly deformed, almost monochromatic photon spectrum, URM , which is shown as illustration in Fig.1a. The width of the spike URM is $\sim$ 1 KeV so that there are $N \approx 2 \cdot 10^{-4}$ photons under the curve URM . Just as $\mathcal{D}R$, URM is not observed still experimentally and could be used if there will be a need of monochromatic beams.

The next curves, CBz , are for coherent bremsstrahlung, calculated for diamond according to /2/. Here we shall not discuss the applicability of the perturbation theory formulae /2/ and only note that the curves CBz are for "point effect" with entrance angles θ equal to the half of Lindhard angles for planar channeling. (Coming out from formation zone considerations one can crudely show that decreasing the angles up to Lindhard angles CBz dominates over channeling radiation and for some cases the edge energy $\hbar\omega_d \sim E^{3/2}$, $\hbar\omega_d \sim \theta$ while $(dN/d\omega)_d \sim 1/\theta^2$ for small θ and $x_d = \hbar\omega_d/E << 1$) . Finally the curves Ch are the radiation spectra of electrons 100% channeled in (100) planes of diamond, calculated by the simple dipole approximation formula of /16/.

Though the spectra of Fig.1 reveal visually several properties (ω, E -dependence etc.) of various radiations, nevertheless, once again it must be emphasised that they are obtained for single electron passage through 1 cm radiator neglecting effects, some of which must be taken into account. In order to obtain possible realistic yield one must take into account, even though crudely, such factors as geometry, multiple scattering as well as the possibility of multiple passage of the same electron through the radiator for cyclic machines.

In Fig.2 the yields per electron are shown for linear accelerators and extracted beams when a single passage through the radiator only is provided. The curves Br are calculated for 1 radiation length amorphous radiator which is sufficiently close to the optimal target thicknesses used at linacs. The curves TR are for radiator consisting of 1000 lithium foils with $a = 50\mu$; $b = 750\mu$, which is also near the optimum since the TR yield saturates at such radiator lengths. Independently on electron energy the length of the radiator for SR and UR is assumed to be 100 cm, while the calculations for CBr and Ch are carried out for radiators having various lengths for various energies. Namely, the target thicknesses for CBr and Ch are chosen from the condition that the mean square multiple scattering angle to be less than the entrance angle θ and Lindhard angle for planar channeling. respectively.

Taking into account the existing conditions and several requirements, one may, of course, use somewhat shorter or longer radiators at linacs, however, this circumstance does not alter the pattern of Fig.2 essentially. By multiplying the spectra of Fig.2 by the numbers of electron per pulse or second one obtains the corresponding yields per pulse or second. As it is seen for $E=(1\div5)$GeV TR, SR and UR provide largest yield in the region $\hbar\omega=(1\div100)$KeV, while CB_{r} and Ch dominate in the region $\hbar\omega=(10^2\div10^5)$KeV. At $E\lesssim 100$ MeV the best yield is provided by the usual B_{r}, the contribution of TR, SR and UR being negligible in all the region under consideration.

Now let us consider the yield at synchrotrons (Fig.3). In this case it is very important to take into account the fact that the same accelerated electron may many times pass through the radiator, i.e. the passage multiplicity. Therefore, it is reasonable to calculate the yields per electron, per acceleration cycle which are plotted in Fig.3. In order to obtain the yields per second it is necessary to multiply the curves of Fig.3 by the number of electrons accelerated on the given synchrotron per cycle and by the number of cycles per second.

The radiator lengths, for which the calculations have beeen carried out, were chosen taking into account the following facts. It has been shown both theoretically and experimentally that due to scattering and radiation energy losses the radiation yield on synchrotron thin internal targets does not depend on the target thickness and it is approximately equal to the one passage yield on 0.1 radiation length thick target. This means the thiner the internal target, the greater the number of passages. Therefore one can assume that the number (multiplicity) of passages is approximately equal to

0.1 rad. length divided by the target thickness in rad.length.

In Fig.3 the curves Br , CBr and Ch are simply the yields of single passage through 0.1 rad.length targets. As mentioned above, it is necessary to use targets with thicknesses much less than 0.1 rad. units in order to decrease the role of multiple scattering. The curves TR are calculated for ~ 12 lithium foils with $a=50\,\mu$ and $b\approx 750\,\mu$ the passage multiplicity being $K \approx 0.1$ rad.units/0.0004 rad.units= =250. For SR and UR the radiator lengths are assumed to be equal to $L_{SR} \approx 1$ cm (from such lengths the synchrotron radiation is usually accepted at synchrotrons) and $L_{UR} \approx 10^2$ cm (the length of straight sections), respectively. It is also taken into account the passage multiplicity which is taken to be $K \approx T_{spill}/T$ where T_{spill} is the spill time and T is the circulation period. (This means that the contribution of the low energy electrons into SR and UR is neglected).

As is seen from Fig.3a and b, at electron energies $E=(1+5)$ GeV UR , TR and SR give the largest contribution into the region $\hbar\omega$ =(1+100) KeV, while for $\hbar\omega \gtrsim$ 100 KeV CBr and Ch are more productive. At energies $E \lesssim$ 100 MeV CBr and Ch provide the highest yield for all the region of $\hbar\omega$ though the density effect for them must be taken into account.

Finally, some considerations for electron storage rings. For radiation types with non-material radiators (SR , UR) the storage rings have no concurent. To obtain the SR and UR yields per second at storage rings it is necessary to multiply the corresponding curves of Fig.3 by the number of the electron per cycle, by number of cycles per second and by the ratio T/T_{spill}. For radiation types with material target-radiators (Br , CBr , Ch) the storage rings have the same productivity (or worse) as the synchrotrons due to the particle losses. However, at present depending on the electron current and energy at electron storage rings one can obtain $\sim 10^5 \div 10^7$ photons/sec with $\hbar\omega \approx 5 \div 80$ MeV and energy resolution $\sim$ 1% (FWHM) /17, 18/ by the inverse Compton scattering.

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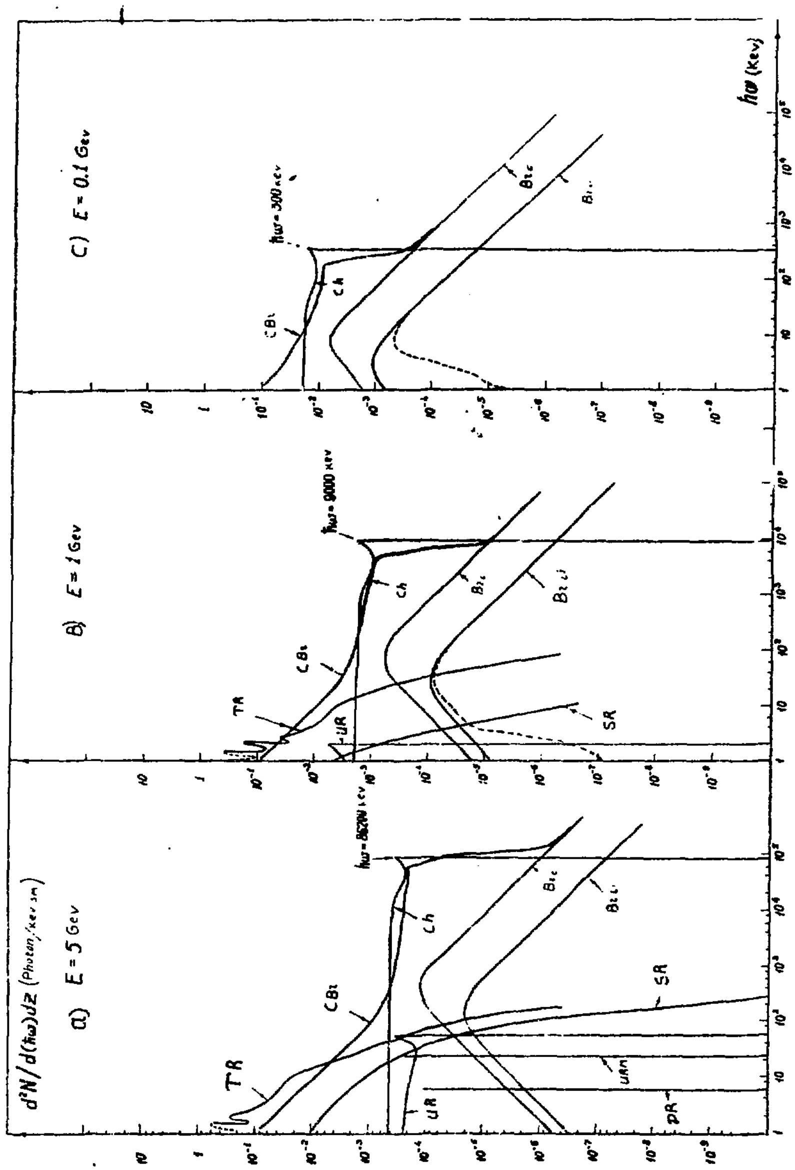
d²N/d(ħω)dz (Photon/kev sm)
a) E = 5 Gev
B) E = 1 Gev
C) E = 0.1 Gev
ħω = 8620 kev
ħω = 9000 kev
ħω = 300 kev
ħω (kev)
TR
CBt
Ch
Btc
Btci
SR
UR
URR
DR
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹

Fig.1

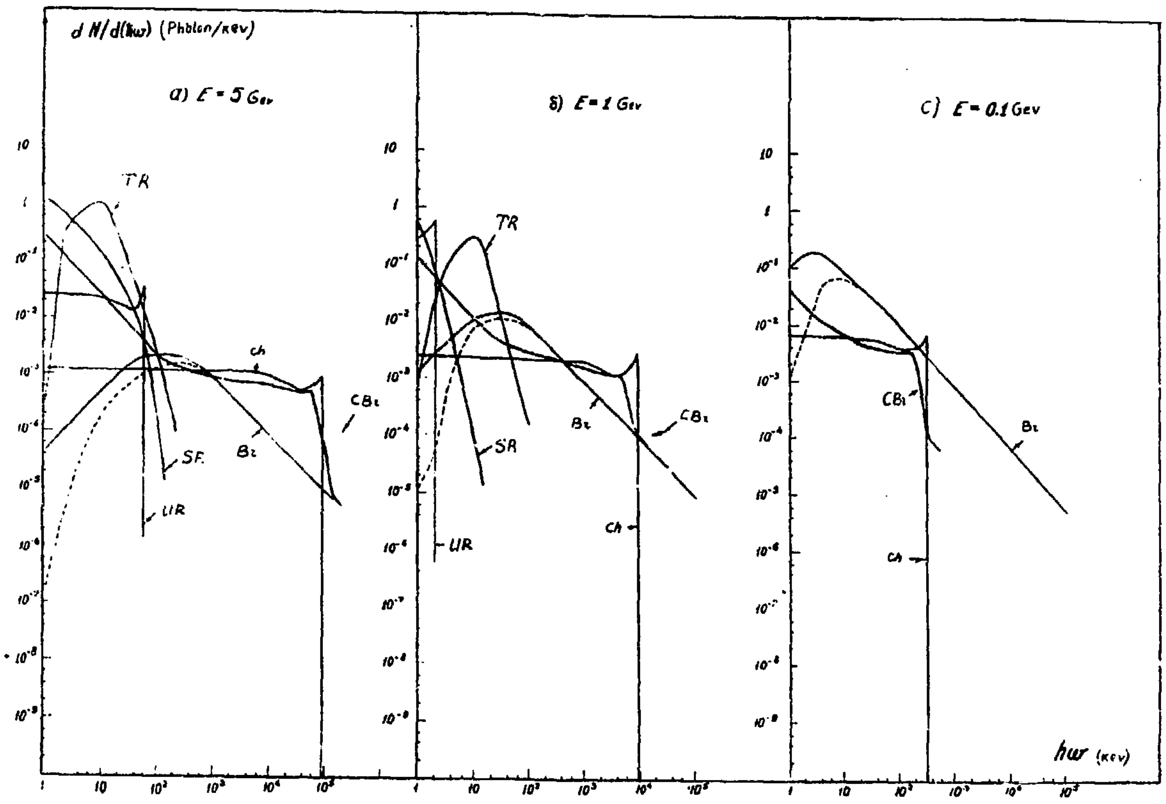
d N/d(ħω) (Photon/keV)
a) E = 5 GeV
б) E = 1 GeV
c) E = 0.1 GeV
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
TR
SF
SR
UR
Ch
Br
CBr
ħω (keV)
1
10
10^{2}
10^{3}
10^{4}
10^{5}

Fig.2

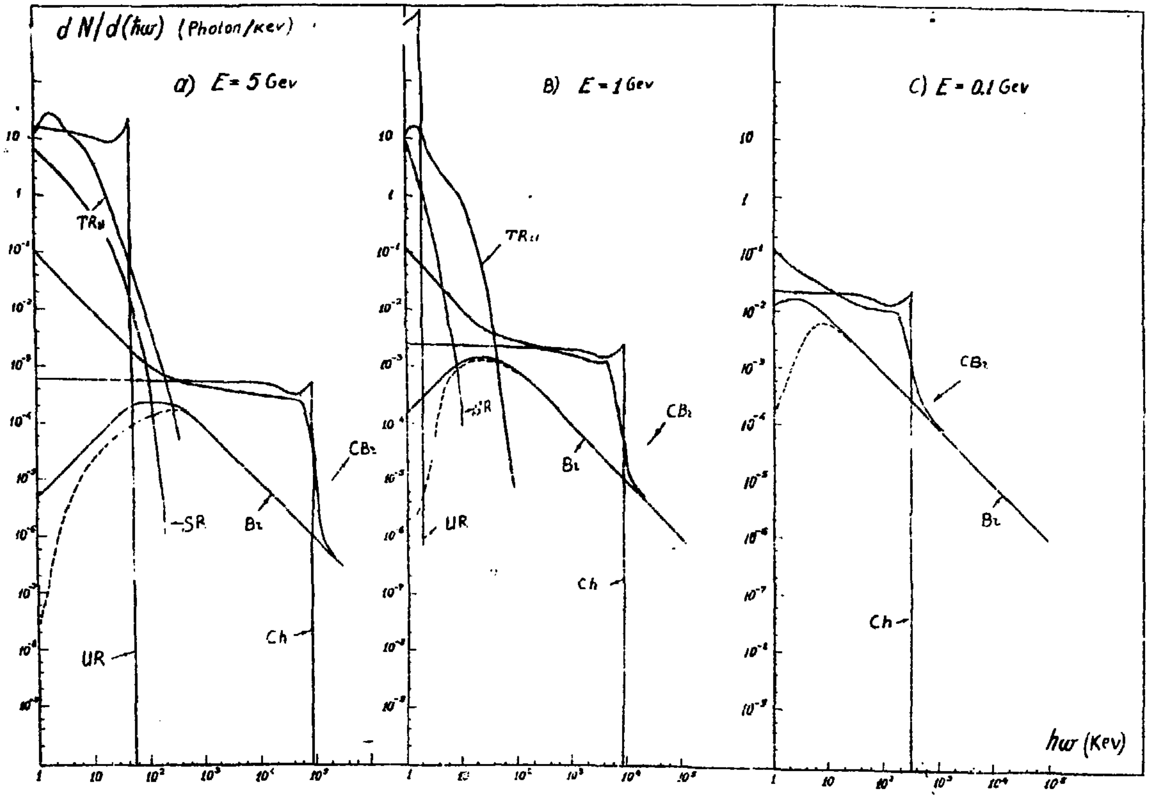
dN/d(ħω) (Photon/kev)
a) E = 5 Gev
B) E = 1 Gev
C) E = 0.1 Gev
TR
SR
Bt
CBt
UR
Ch
ħω (Kev)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
1
10
10²
10³
10⁴
10⁵

Fig.3

FIGURE CAPTIONS

Fig.1 The spectral distributions of radiation of electrons in 1 cm radiators:

Br -Bremsstrahlung; TR - Transition radiation; DR- Dynamic radiation; SR - Synchrotron radiation; UR - Undulator radiation; URM - Undulator radiation in media; CBr - Coherent bremsstrahlung; Ch -Radiation in case of 100% planar channeling.

Fig.2 The spectral distributions of radiation of an electron at linear accelerators.

Fig.3 The spectral distributions of radiation of an electron per cycle at synchrotrons.

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ПРОСТОЕ СРАВНЕНИЕ ВЫХОДОВ РАЗЛИЧНЫХ ТИПОВ ИЗЛУЧЕНИЯ ЭЛЕКТРОНОВ

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