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Requirements to the Position Sensitive Single Photon Detector for IOTA

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1. Properties of the synchrotron radiation

The undulator parameter, K, is determined by the following equation:

$$K = \frac{eB\lambda_u}{2\pi m_e c^2} \ , \tag{1}$$

where B is the peak magnetic field, λ_u is the period of the undulator, m_e is the electron mass, and c is the speed of light. All formulas are in the SGS system.

For small undulator parameter, K<<1, the probability of photon radiation into one octave band [$\omega_0/2$, ω_0] from a single electron coming through an undulator is:

$$W_\gamma = \frac{\pi}{3}\alpha n_{per} K^2 \tag{2}$$

where α is the fine structure constant, and n_{per} is the number of periods in the undulator, and we accounted only horizontally polarized photons. Accounting for the vertical polarization increases the result by ~15%. The frequency of forward radiation is equal to

$$\omega_0 = 2\gamma^2 \frac{2\pi c}{\lambda_u} \ . \tag{3}$$

where γ is the relativistic factor of electron. The radiation frequency depends on the angle of the photon relative to the electron direction, θ:

$$\omega(\theta) = \frac{\omega_0}{1+\gamma^2\theta^2} \tag{4}$$

In the case of non-small undulator parameter the equations become more complicated. The dependence of frequency on the angle is:

$$\omega(\theta) = \frac{\omega_0\left(1+K^2/2\right)}{1+\gamma^2\theta^2+K^2/2}, \quad \omega_0 = \frac{2\pi c}{\lambda_u}\frac{2\gamma^2}{1+K^2/2}. \tag{5}$$

The number of photons stops to grow as K^2 with K increase at K~1. Figure 1 shows the number of photons radiated in the angle $1/\gamma$ as a function of the undulator parameter. As one can see the maximum is achieved at K≈1.5. A reduction with further K increase is related with an increase of radiation divergence. Thus, K in the range of [1, 1.5] is optimal for our studies. With an increase of K the radiation at higher harmonics increases fast. Figure 2 shows the spectral density of radiation for K=1. As one can see the radiation of higher harmonics is already significant. As can be seen from Figure 3 the spectral density of radiation coming from the IOTA dipoles is about an order of magnitude lower than from the undulator. Therefore, a dipole radiation does not fit well to the needs of experiments described below.

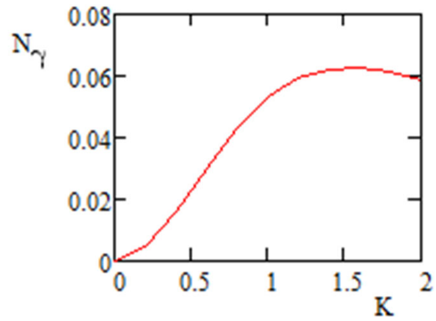

Figure 1: Dependence of the photon radiation probability for photons radiated into the 1/γ angle as a function of undulator parameter for the first harmonic of radiation for the 16 period undulator.

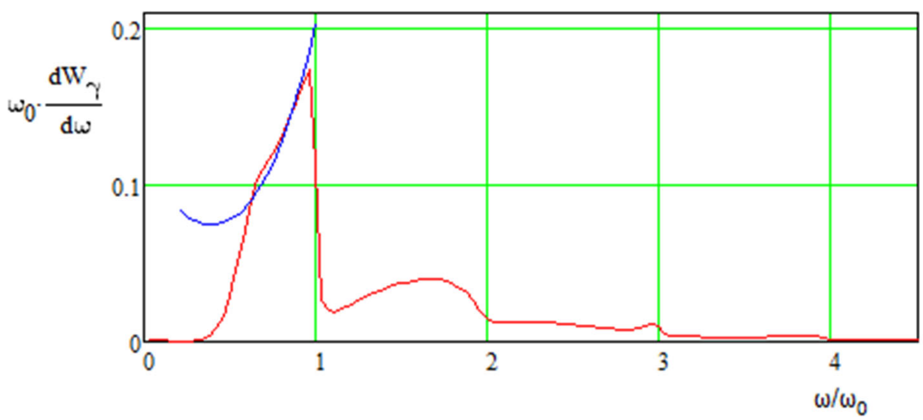

Figure 2: Dependence of probability density of photon radiation into the dimensionless bandwidth on the relative photon energy for the 16-period pickup undulator with K=1. Th signal is integrated over the cone with angle $\theta = 0.8/\gamma$; red line - the SRW simulations, blue line - analytical calculations for unlimited aperture.

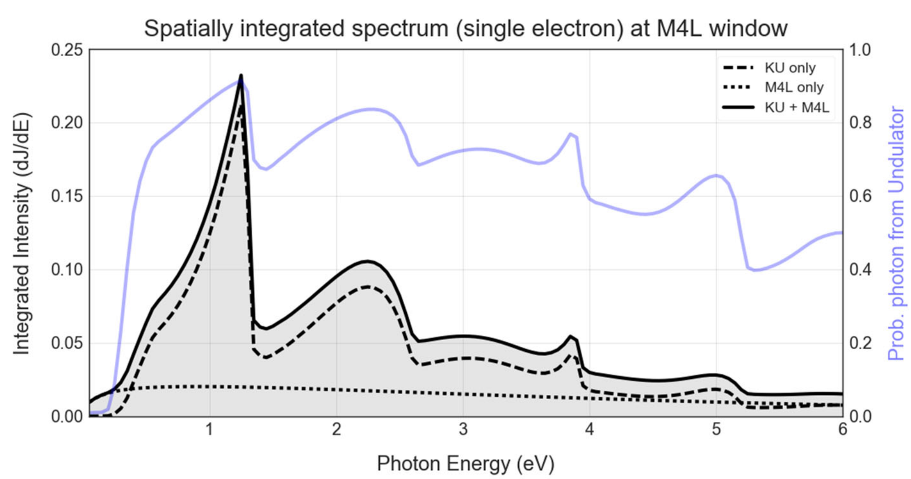

Figure 3: The integrated spectral densities for radiation from the OSC kicker undulator and the downstream IOTA dipole at 100 MeV energy of the electron beam.

The radiation wavelength is decreasing fast with IOTA energy. In further estimates we assume a usage of 16-period OSC undulator with period of 4.84 cm. Figure 4 presents dependence of radiation wavelength on the IOTA beam energy. As one can see in the case of GaAs cathode the optimal energy is between 127 and 160 MeV. Operation in the middle of this energy range at ~140 MeV would be optimal.

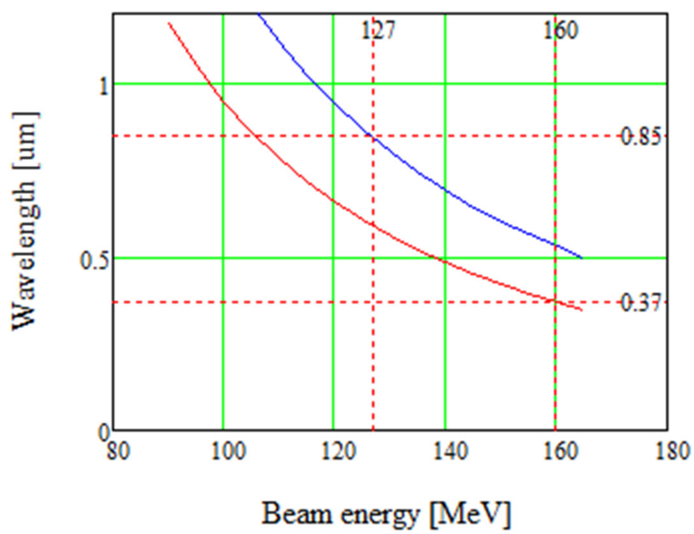

Figure 4: Dependence of synchrotron radiation band on the IOTA beam energy for the undulator with 4.84 cm period: blue line – upper boundary, red line – lower boundary, horizontal dashed line – boundaries of sensitivity for GaAs photocathode, vertical dashed lines mark boundaries of optimal energy operation for GaAs photocathode.

1. Requirements to position sensitive single photon detector

Presently we envisage two types of experiments where a usage of position sensitive single photon detector is required.

The first type of experiments is related to tracking turn-by-turn positions of a single electron in a ring with very large non-linearity of betatron motion. A usage of a beam in such conditions results very fast decoherence of betatron motion due to significant spread of initial beam positions resulting in the spread of betatron motion. In our best expectations/measurements the beam decohere in the course of few hundred turns and only small fraction of this time is useful for actual turn-by-turn tracking in a strongly non-linear lattice. With a single electron the decoherence time is increased to ~10^7 turns out of which ~100,000 turns represent actual, basically non-perturbed betatron oscillations. In this case the beam decoherence time is a few seconds; and it is limited by SR damping and diffusion due quantum nature of synchrotron motion, as well as by scattering on the residual gas. This type of experiments presents the strictest requirements to the detector: the coordinate resolution of 30-50 μm and the best practical quantum efficiency. The required area of sensitivity is ~10-20 mm (diameter). If the OSC undulator is used the probability of a photon radiation inside of the detector sensitivity band (about 1 octave) is ~6%. With 30% quantum efficiency we could see a single photon every 50-th turn, which should allow us to restore the electron coordinates in missed turns. During 100,000 turns of a measurement we should see ~2000 positions. The time resolution of ~10 ns or better would be sufficient. An improvement of time resolution would allow noise rejection since we know the photon arrival time relative to the beam marker with accuracy better than 0.5 ns. 15% quantum efficiency puts a stretch on reconstruction of turn-by-turn positions but still looks as a possibility. The dead time should be less than ~1 μs.

Another experiment we are presently considering is an observation of position correlation in the two-photon radiation in the undulator. In this case the radiation is split equally between two channels by a splitter and observed by two identical detectors. In such experiment the space resolution can be increased to ~100 μm. Quantum efficiency ~5-10% still looks reasonable. For 5% quantum efficiency we should see a coincidence at every $\sim 4 \cdot 10^5$ turns or ~with 200 Hz frequency. However, the noise requirements are stricter for this experiment. 100 Hz or smaller would certainly be sufficient.