OPTICAL FIBER CHERENKOV DETECTOR FOR BEAM CURRENT MONITORING

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ABSTRACT

The results obtained in calculation of an optical fiber Cherenkov detector for accelerated beam current monitoring are presented. The technique of beam parameters monitoring is based on Cherenkov radiation excitation by accelerated electrons in the optical fiber. The formulaes for calculations of optical power and time dependence of Cherenkov radiation pulse are given. The detector sensitivity and time resolution dependence on the fiber material characteristics are investigated. Parameters of a 10μm one-mode quartz optical fiber detector for the free electron laser photoinjector are calculated. The structure of a monitoring system with the optical fiber Cherenkov detector is considered. Possible applications of this tecnique are discussed and some recomendations are given.

INTRODUCTION

Cherenkov detectors are widely used for energy measurements of high energy beams [1]. There are many types of Cherenkov radiators which were tested in particle energy registration. It's known that Cherenkov radiation is emitted in a cone with the Cherenkov angle

$$\theta = \cos^{-1}\frac{1}{n\beta}$$

where n is Cherenkov detector medium index of reflaction, β is the beam velocity normalized to the vacuum speed of light c.

In this paper a version of Cherenkov detector for the low energy beam current monitoring is described. The main component of the detector is a quartz optical fiber. It is inserted into the beamline. The angle between the beam line and the fiber is determined by the fiber core index of refraction. Cherenkov radiation is generated in the fiber core and transmitted along the optical fiber. In the present work the goal of the authors was to calculate the sensitivity and the time parameters of the optical fiber detector which would be used for current measurements of the single pulse bunched beam generated by photoinjector [2]. Such measurements require the detector time resolution less then 25 ps. It was proved that the radiation output power is sufficient to be registered by a high speed photochronograph.

OUTPUT POWER OF AN OPTICAL FIBER CHERENKOV DETECTOR

Let's assume that the beam crossing the optical fiber has the charge density ρ_s, which is uniform over the beam cross-section. The beam diameter is If a fiber with square crosssection is placed at the angle θ to the beam line one can be find out the fraction of the beam charge q_f that crosses the optical fiber with the diameter d_f

$$q_f = \frac{4 q_B d_f}{\pi d_B \sin\theta}$$

where $\sin\theta = \sqrt{1 - 1/(n\beta)^2}$

The Cherenkov radiation power is given by [1]

$$P = P_0 f(n)$$

$$P = 32 \frac{d_f^2}{d_B^2\sqrt{1-\frac{1}{n^2\beta^2}}} \frac{\lambda_2^2 - \lambda_1^2}{\lambda_1^2 \lambda_2^2} I_B^2 t_B ,$$

where I_B is the beam current amplitude, t_B is the beam pulse duration, $\lambda_1 = \bar{\lambda} - \Delta\lambda$, $\lambda_2 = \bar{\lambda}_1 + \Delta\lambda$ and $\bar{\lambda}$ is the wavelength in the centre of the band, $f(n) = 1/\sqrt{1 - 1/(n^2 - \beta^2)}$.

For the beam energy 200 keV, the current amplitude 500A, the pulse duration 250ps, the beam diameter 0,01m and for the index of refraction value of 1,5 in the wavelength band of 0,3-0,7μm the maximum power value is equal 162W. In practice the registration in such wide wavelength band is very difficalt. Taking account of the dependence $P(\lambda)$, the dependence the optical power losses in fiber on wavelength λ and the selectivity of photoreceiver the real value of optical power will be much less. In any case the output power depends on the photoreceiver wave length band, on the optical power losses and on the wave length. The middle $\bar{\lambda}$ is chosen on the basis of requirement of needed bandwidth and sufficient detector output power.

Fig.1 shows the one mode optical fiber output power P as a function of the wavelength λ with $\Delta\lambda = 0{,}1\mu m$ at various beam normalized velocities β.

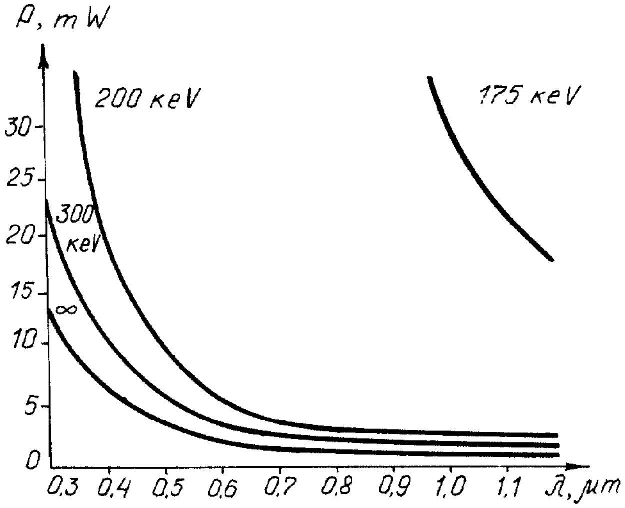

Fig.1. Cherenkov radiation power dependence on wave length.

$d_B = 1sm$, $d_f = 10\mu m$, $I_B = 100A$, $t_B = 250ps$
$n = 1{,}5$

Fig.2 shows the detector output power as a function of the index of refraction n.

It was expected, that the output power would be decreased with increasing n. Minimum n for given β is determined from the Cherenkov radiation generation threshold. For Cherenkov radiators with high value of n the energy range is widened at the low energy end.

For example it is possible to carry out current measurement of the beam with energy less than 50keV by using GaAs fiber ($n = 3{,}34$).

The output optical radiation is registed by a high speed photochronograph, which requires very low

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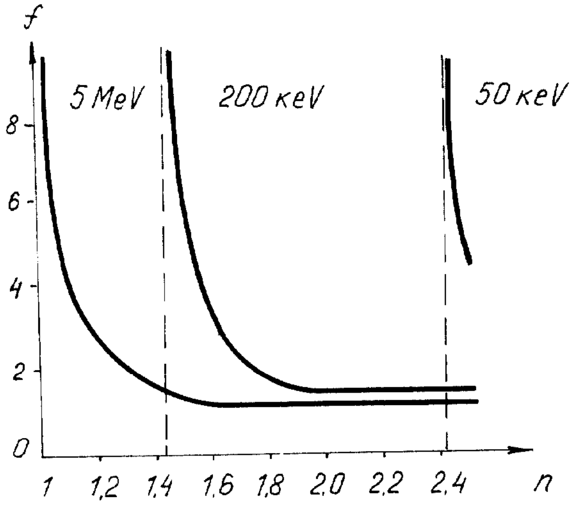

Fig.2. Cherenkov radiation power dependence on the index of the refraction.

power level for its operation. For the chosen photochronograph "Agat" the required incident power density is about 100 W/cm^2 . So if the fiber diameter d_f is equal 10μm than Pmin=78,5·10^{-6}W. In practice detector output power levels are higher than Pmin (see Fig.1,2).

TIME RESOLUTION OF OPTICAL FIBER CHERENKOV DETECTOR.

The time resolution of an optical fiber Cherenkov detector is determined by the nonsynchronizm between the optical radiation and electron beam and by the fiber time distortion. Fig.3 illustrates a beam and a fiber sizes and typical time moments.

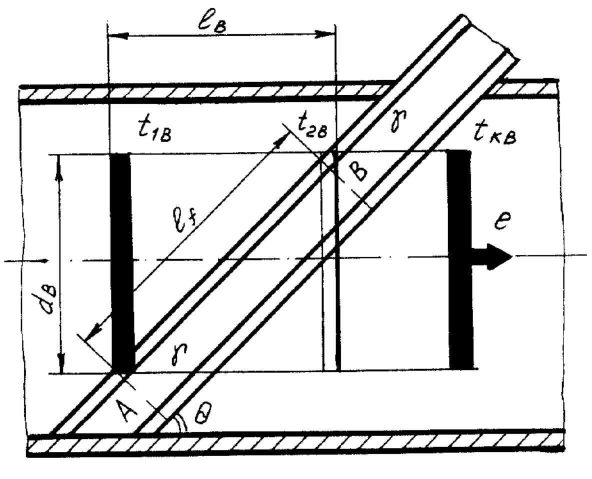

Fig.3. A beam and a fiber sizes and typical time moments.

For calculations the following terms are used:
Δt_1 is the delay time, which depends on the fiber material dispersion. It is essentially the difference between the time required to travel from the surface "A" to the surface "B" to the first photon emitted on the surface "A" at the moment t_{1B} and that for the last photon;
t_1 is the fly time of the fastest photon to the surface "B";
t_2 is the fly time of the slowest photon to the surface "B";
Δt_B is the fly time to the beam front from the surface "A" to the surface "B".

The calculations were carried out on the basis of the following formulas

$$\ell = \frac{d_B}{\sin\theta} \ ; \ \ell_B = \frac{d_B}{n\beta \sin\theta} \ ; \ U_B = \beta c \ ;$$

$$\Delta t_1 = \frac{d\tau}{d\lambda}\Delta\lambda \ ; \ t_1 = \frac{d_B n}{c \sin[\cos^{-1}\frac{1}{n\beta}]} \ ;$$

$$t_2 = t_1 + \Delta t_1 \ ; \ \Delta t_B = \frac{\ell_B}{U_B} = \frac{d_B}{c \sin[\cos^{-1}\frac{1}{n\beta}]} \ ;$$

where ℓ_f is the fiber length, ℓ_B is the beam length, $\frac{d\tau}{d\lambda}$ is the fiber material dispersion and $\Delta\lambda$ is the spectral line width.

We considered three possible cases:
a) $\Delta t_B > t_2 > t_1$, in this case the optical pulse distortion is $\Delta = \Delta t_B - \Delta t_1$;
b) $\Delta t_B \leq t_1 < t_2$, $\Delta = t_2 - \Delta t_B$;
c) $\Delta t_1 = \Delta t_B$, $\Delta = \Delta t_1$.

The results of Δt_1, t_1 and Δt_B calculations show that for any wave length $\Delta t_B < t_1$. So that the optical distortion being expressed as the difference between the optical pulse duration and the beam pulse duration can be written

$$\Delta = t_1 + \Delta t_1 - \Delta t_B$$

This distortion depends on the angle θ to the beam line and the fiber material dispersion $d\tau/d\lambda$. The calculations results show that Δ is less then 35ps and it can be seen from Table 1. Table 2 illustrates the optical pulse time distortion in the one mode optical fiber which has the length 10m.
Results of Table 1,2 show that total pulse time distortions are less than 30ps by wave length band 0,6-0,95μm, $\Delta\lambda$ is less than $10^{-2}\mu m$ and β is less than 0,8.

Table 1. The calculations results of Δ , ps.

$\lambda, \mu m$ / $\Delta\lambda$ / β	0,4 0,2	0,6 0,2	0,8 0,2	0,95 0,35	1,3 0,2
0,7	19,6	17,6	16,2	16,8	15,0
0,8	30,2	29,1	28,35	28,7	27,7
0,9	35,7	34,8	34,1	34,4	33,6

Table 2. The calculation results of Δt_1 in one mode optical fiber, ps.

λ, μm $\Delta\lambda$, μm	0,4	0,6	0,8	0,95
$5\cdot10^{-3}$	35	20	10	8
10^{-2}	70	40	18	16
$3\cdot10^{-2}$	210	120	54	48

CONCLUSION

An optical fiber Cherenkov detector was investigated. It has the advantage of combining the functions of a detector and transmission line. The results of this investigation lead to the following conclusions.

1. Quartz optical fibers can be used as Cherenkov radiators for low energy beam current monitor.
2. The optical fiber detector are able to measure the beam pulse duration with the time resolution of 30ps.
3. If the beam energy is less then 175 keV it is necessary to choose the fiber material with high index of refraction values. With GaAs fibers it is possible to measure currents of beams with energies less than 50 keV.

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