DISTRIBUTED BEAM LOSS MONITOR BASED ON THE CHERENKOV EFFECT IN OPTICAL FIBER

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Abstract

A distributed beam loss monitor based on the Cherenkov effect in optical fiber has been implemented for the VEPP-5 electron and positron linacs and the 510 MeV damping ring at the Budker INP. The monitor operation is based on detection of the Cherenkov radiation generated in optical fiber by means of relativistic particles created in electromagnetic shower after highly relativistic beam particles (electrons or positrons) hit the vacuum pipe. The main advantage of the distributed monitor compared to local ones is that a long optical fiber section can be used instead of a large number of local beam loss monitors. In our experiments the Cherenkov light was detected by photomultiplier tube (PMT). Timing of PMT signal gives the location of the beam loss. In the experiment with 20 m long optical fiber we achieved 3 m spatial resolution. To improve spatial resolution optimization and selection process of optical fiber and PMT are needed and according to our theoretical estimations 0.5 m spatial resolution can be achieved. We also suggest similar techniques for detection of electron (or positron) losses due to Touschek effect in storage rings.

INTRODUCTION

VEPP-5 Injection Complex [1] now is under commission and will supply BINP RAS colliders with electron and positron beams. The VEPP-5 Injection Complex consists of 270 MeV driving electron linac, 510 MeV positron linac and dumping ring. Since the Complex is not equipped with any operational beam loss monitor system we proposed to use a distributed beam loss monitor based on the Cherenkov effect in optical fiber.

This type of beam loss monitor has been developed at several facilities such as FLASH (DESY), SPring-8 (RIKEN/JASRI), CLIC Test Facility (CERN) [2–4]. The monitor overview is given by T. Obina [5]. The basic idea behind optical fiber beam loss monitor (OFBLM) is to detect a burst of the Cherenkov radiation (CR) generated in optical fiber by means of relativistic particles created in electromagnetic shower after highly relativistic beam particles (electrons or positrons) hit the vacuum pipe. Some of the Cherenkov photons propagate through the fiber and can be detected by PMT (Fig. 1).

Compared with other distributed beam loss monitors such as long ionization chamber and scintillating fiber, the OFBLM has the following advantages: fast response time (< 1 ns) which allows to detect multi-turn beam losses in a storage ring, near zero sensitivity to background signal (mainly gamma radiation) and synchrotron radiation, unlike scintillating fiber. Moreover, optical fiber is insensitive to magnetic field, but it is susceptible to radiation damage (except quartz fiber), which limits fiber lifetime. Another disadvantage of the OFBLM is an issue with its calibration.

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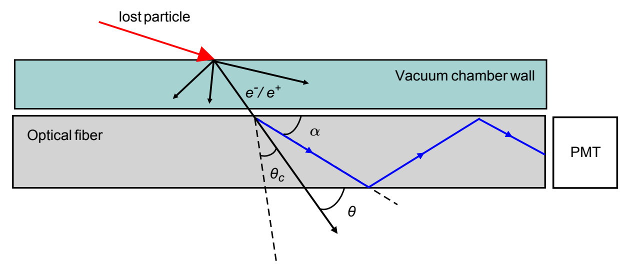

Figure 1: Scheme of beam loss monitor.

PRINCIPLE OF BEAM LOSS MONITOR

The following physical processes determine the OFBLM spatial resolution.

Electromagnetic Shower

For electromagnetic shower simulation G4beamline code [6] was used. Angular distribution of secondary electrons and positrons relative to beam direction was obtained (Fig. 2).

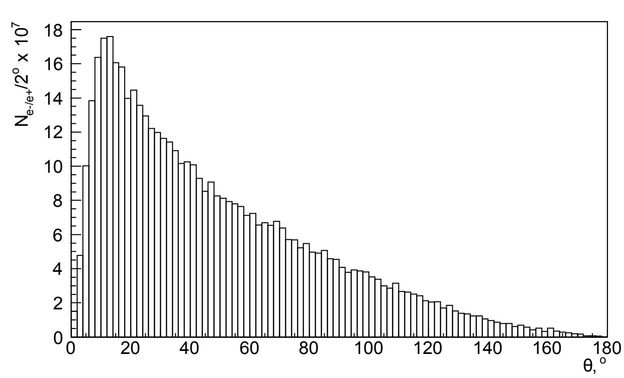

Figure 2: Angular distribution of secondary e-/e+ relative to beam direction passing through optical fiber. 270 MeV electron beam with 10^{10} electrons hits 2 mm steel vacuum pipe with 1° incident angle. Fiber is placed at the loss point. Total number of charged particles is $0.5 \cdot 10^{10}$.

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For the CR to be generated kinetic energy of charged particle traveling through a dielectric medium must be:

$$E > E_0\left(\frac{n}{\sqrt{n^2-1}} - 1\right) \quad (1)$$

where E_0 – particle rest energy, n – medium refractive index. To obtain such particles from electromagnetic shower with energies satisfying eq. (1), lost particle energy must be greater than 10 MeV for electron (or positron) beams and greater than 5 GeV for proton beams.

Cherenkov Radiation

The Cherenkov radiation is an electromagnetic radiation emitted in a cone around the moving charged particle with cone semi-angle θ_c:

$$\cos\theta_c(\lambda) = \frac{1}{\beta n(\lambda)}$$

where λ – radiation wavelength, β – particle velocity ($\beta = v/c$), n – medium refractive index. Neglecting refractive index dispersion, the number of the Cherenkov photons from a single electron or positron per particle path length in a medium is given by:

$$\frac{dN}{dx} = 2\pi\alpha\sin^2\theta_c\int_{\lambda_1}^{\lambda_2}\frac{d\lambda}{\lambda^2} \quad (2)$$

where α is the fine structure constant, λ_1 and λ_2 determine spectrum range. According to eq. (2), the greater part of the Cherenkov photons is emitted in the UV range of the spectrum. For relativistic electron passing through plastic optical fiber ($n = 1.492$) the CR in visible spectrum (400 nm < λ < 700 nm) will be generated with 30 photons per mm and emission semi-angle θ_c about 48°.

Besides the CR, optical transition radiation [7] can be detected by PMT. However, the number of optical transition radiation photons was estimated to be 10^4 times less than the number of the CR photons and thus can be neglected.

Signal Propagation

The emitted Cherenkov radiation propagates through optical fiber by means of total internal reflection. This is the case when light (see Fig. 1) propagates with angle α relative to the fiber axis lower than:

$$\alpha \le \alpha_{max} = \arcsin(NA/n_{co})$$

where NA – optical fiber numerical aperture, n_{co} – refractive index of optical fiber core. For example, for optical fiber with $NA = 0.47$ and $n_{co} = 1.492$, $\alpha \le 18°$. This leads to secondary charged particles passing through optical fiber with angle θ between 30° - 66° and 114° - 150° relative to the fiber axis will generate the Cherenkov radiation which is able to be trapped in optical fiber. This results in trapping of about 33% and 5% of generated radiation, respectively. Consequently, downstream signal sensitivity is 7 times higher than upstream one.

MONITOR SPATIAL RESOLUTION

Monitor spatial resolution depends on light dispersion in optical fiber, PMT and electronics resolution. There are two main dispersion types in fiber: modal and chromatic. Modal dispersion originates from the fact that light rays with different trapping angles travel the same distance with different times. Chromatic one is caused by different propagation times for different light wavelengths. When transmitting signal through optical fiber of length L each dispersion contribution to pulse broadening can be estimated as:

$$t_{mod}/L = 1/cn_{co}(1/\cos\alpha_{max} - 1),$$

$$t_{chr}/L \approx 1/c(n_{co}(\lambda_1) - n_{co}(\lambda_2)).$$

In multimode optical fiber with step-index profile signal lengthening is effected mainly by modal dispersion, in multimode optical fiber with graded-index profile chromatic one is dominant and modal one is negligible. In singlemode fiber there is no modal dispersion, but its lower pulse distortion comes at the expense of lower signal sensitivity. For step-index multimode fiber which was used in our tests $t_{mod}/L = 0.25$ ns/m, $t_{chr}/L = 0.05$ ns/m, i.e. modal dispersion contributes 5 times greater to monitor spatial resolution then chromatic dispersion. Therefore, to make spatial resolution smaller graded-index multimode optical fiber or singlemode one should be used as well as PMT and electronics with small time resolution. Micro-channel plate PMT is a good candidate.

The Cherenkov signal can be detected at either downstream or upstream end of the fiber. In case of multiple losses originated from successive magnet elements 5 times better spatial discrimination between losses can be achieved by signal detection at the upstream end of the fiber compared with the downstream one. This is due to the fact that beam velocity βc is greater than speed of light in optical fiber c/n. Despite upstream signal sensitivity is 7 times lower than downstream one, the former is preferable.

EXPERIMENTAL RESULTS

A prototype of the OFBLM was made using 20 m and 60 m long plastic step-index multimode fibers Avago Tech. HFBR-RUS500Z (1 mm core diameter, $n_{co} = 1.492$ and $NA = 0.47$). To detect the CR signal at the downstream end of the fiber FEU-85 PMT (300-600 nm spectral sensitivity range) was used. The prototype of the OFBLM was installed in the VEPP-5 electron linac and tested in a controlled manner by dumping beam with dipole correctors. The experimental results are shown in Fig. 3.

As one can see from Fig. 3a) FWHM of the signal approximately corresponds to 3 meters for 20 m long optical fiber and 1.5 m beam length. For single bunch (4 mm) using graded-index multimode optical fiber or singlemode one and micro-channel PMT will allow us to achieve 0.5 m monitor spatial resolution limited mostly by ADC characteristics. In Fig. 3b) for 60 m long optical fiber besides controlled beam loss at the end of the 4th RF-structure one can see beam losses in multiple locations along linac.

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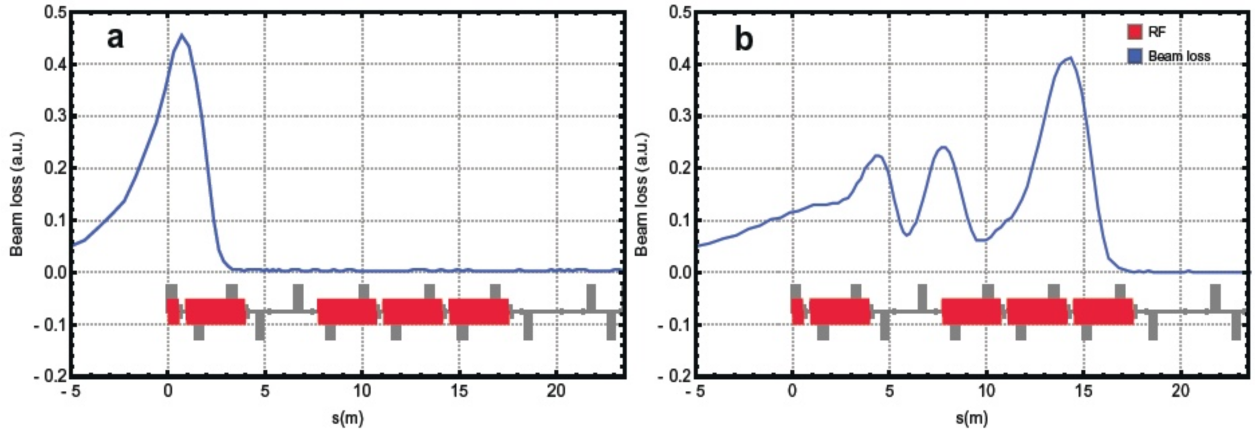

Figure 3: Beam losses: a) beam was dumped at the end of the 1st RF-structure, 20 m fiber was used; b) at the end of the 4th RF-structure, 60 m fiber was used.

TOUSCHEK EFFECT

In storage rings besides irregular beam losses there are beam lifetime losses due to Touschek effect [8] (loss mechanism driven by large-angle Coulomb scattering within the high charge bunch). This effect results in losses of scattered particles with energy variation exceeding the energy acceptance of the ring. For the VEPP-5 dumping ring with 28 m circumference and $2 \cdot 10^{10}$ electron bunch charge the beam lifetime is roughly 10 min and the average number of lost electrons per turn is 2. According to our theoretical estimations, the OFBLM can detect a single electron (or positron) hitting the vacuum pipe with probability about 1% for the VEPP-5 beam parameters. Hence, using two optical fibers placed on both sides of vacuum chamber the monitor can detect 10^8 Touschek events. It's sufficient to obtain precise distribution of the beam losses due to Touschek effect in a storage ring.

CONCLUSION

The distributed beam loss monitor based on the Cherenkov effect in optical fiber has been tested in the VEPP-5 electron linac. 3 m monitor spatial resolution for 20 m long optical fiber was obtained. Using graded-index multimode optical fiber or singlemode one and micro-channel plate PMT 0.5 m spatial resolution can be achieved. To achieve better spatial discrimination between successive losses one should detect the light signal at the upstream end of the fiber. The monitor ability to detect single particle losses and high signal-to-noise ratio make it possible to use the monitor for detection of electron (or positron) losses due to Touschek effect in storage rings.

REFERENCES

[1] K.V. Astrelina et al. "Production of Intense Positron Beams at the VEPP-5 Injection Complex", Journal of Experimental and Theoretical Physics, Vol. 106, Issue 1, p. 77 (2008)

[2] F. Wulf, M. Körfer, "Beam Loss and Beam Profile Monitoring with Optical Fibers", Proc. DIPAC09, Basel, Switzerland (2009) 411

[3] X.-M. Maréchal et al. "Beam Based Development of a Fiber Beam Loss Monitor for the Spring-8/XFEL", Proc. DIPAC09, Basel, Switzerland (2009) 234

[4] S. Mallows et al. "Fiber Based BLM System Research and Development at CERN", Proc. HB2012, Beijing, China (2012) 596

[5] T. Obina, "Optical Fiber Based Loss Monitor for Electron Storage Ring", Proc. of IBIC2013, Oxford, UK (2013) 638

[6] `http://www.muonsinternal.com/muons3/G4beamline`

[7] V.L. Ginzburg, "Transition Radiation and Transition Scattering", 16th International Cosmic Ray Conference, Vol. 14, p. 42 (1979)

[8] C. Bernardini et al. "Lifetime and Beam Size in a Storage Ring", Phys. Rev. Lett. 10, 407 (1963)

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