ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-TUAO03

BEAM LOSS MEASUREMENTS USING THE CHERENKOV EFFECT IN OPTICAL FIBER FOR THE BINP E-E+ INJECTION COMPLEX

Yu.I. Maltseva*, V.G. Prisekin, A.R. Frolov
Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russian Federation

Abstract

Optical fiber based beam loss monitor (OFBLM) has been developed for the 500 MeV BINP Injection Complex (IC). Such monitor is useful for accelerator commissioning and beam alignment, and allows real-time monitoring of e-e+ beam loss position and intensity. Single optical fiber (OF) section can cover the entire accelerator instead of using a large number of local beam loss monitors. In this paper brief OFBLM selection in comparison with other distributed loss monitors was given. Methods to improve monitor spatial resolution are discussed. By selecting 45 m long silica fiber (with a large core of 550 μm) and microchannel plate photomultiplier (MCP-PMT), less than 1 m spatial resolution can be achieved.

INTRODUCTION

Beam loss diagnostics is one of the most important tasks during machine commissioning and operation. Beam loss monitors (BLMs) are useful for real-time beam loss monitoring during beam alignment and advanced beam diagnostics. The most common BLMs are long and short ion chambers, scintillation and Cherenkov radiation counters, secondary emission chambers and PIN-diodes. For the past two decades, a distributed BLM based on the Cherenkov effect in the OF is widely used as an alternative method to the local BLMs.

This type of BLM has been developed at several facilities such as CTF3 (CERN), Australian Synchrotron (ANSTO), ALICE (Cockcroft Institute), FLASH (DESY), SPring-8 (RIKEN/JASRI), IC (BINP) [1–7], etc.

Compared with other distributed beam loss monitors such as long ionization chamber and scintillating fiber, monitor based on the OF has the following advantages: fast response time of less than 1 ms, near-zero sensitivity to background signal (mainly gamma radiation) and synchrotron radiation, unlike scintillating fiber. The OF is insensitive to the magnetic field, but it is susceptible to radiation damage (except silica fiber), which limits its lifetime. Moreover, due to the fast process of the Cherenkov light generation (< 1 ns), this device allows detecting turn-by-turn beam losses in storage rings. The main disadvantage of all distributed BLMs is an issue with signal calibration due to signal distortion by transmitting it over long distances.

PARTICLE LOSS DETECTION

The basic idea behind the OFBLM is to detect a burst of the Cherenkov radiation (CR) generated in the OF by means of relativistic particles created in electromagnetic shower after highly relativistic beam particles (electrons or positrons) hit the vacuum pipe. Some of the CR photons propagate in the fiber and can be detected by a photodetector, e.g. PMT. Scheme of the OFBLM is presented in Fig. 1.

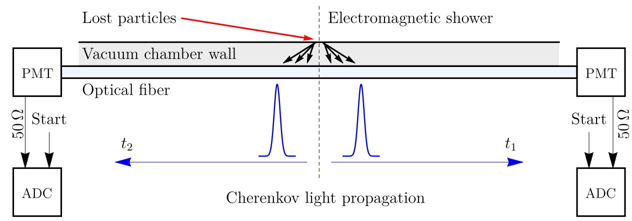

Figure 1: Beam loss detection with the OFBLM.

In our case, the timing of the PMT signal together with the beam injection/extraction trigger gives the location of the beam losses along the beamline. And the signal form gives us information about the number of registered lost particles.

The optical signal can be detected at either downstream or upstream ends of the fiber. Since beam velocity βc is greater than speed of light c/n in the OF, number of samples per meter can be written as: $1/s_d \approx f(n-1)/c$ and $1/s_u \approx f(n+1)/c$ for downstream and upstream fiber end, respectively, where n – core refractive index, f – ADC sampling frequency.

Hence, for $n = 1.5$ five times greater monitor spatial resolution can be achieved by detecting the CR at the upstream end of the fiber compared with the downstream one. Despite upstream signal sensitivity is ~10 times lower than downstream one, the former is preferable.

MONITOR REQUIREMENTS

Since 2016 the IC supplies two BINP colliders with high energy electron and positron beams via recently constructed K-500 beam transfer line [8–10]. It consists of two successive 300 MeV electron linac and 500 MeV positron linac and dumping ring (DR). The DR stores electron or positron beams for further extraction to the K-500 beam transfer line.

During 2018/2019 season facility operated at 400 MeV with linac repetition rate of up to 2 Hz for electrons and 5 Hz for positrons. Extraction repetition rate is up to 1 Hz. Beam production parameters are 2 – 5 nC (with bunch train of < 1 ns), which correspond to a 20 – 40 mA circulating beam in the 27.4 m DR. The typical value of beam losses during the transfer to the users is near 50%.

The main requirements for the OFBLM at the IC are the following:

- spatial resolution of < 1 m due to magnet spacing;

* yu.i.maltseva@inp.nsk.su

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- ability to detect small losses of about 0.1 pC;
- radiation hardness (operation at doses up to 10^3 Gy);
- cost-efficiency.

Monitor spatial resolution depends on the output pulse duration caused by the light dispersion in the OF, PMT and ADC time resolutions as well as spatial sampling rate.

In any type of silica OF the light dispersion is less than 0.1 ns/m [11], unlike plastic one – 0.25 ns/m. To minimize light pulse duration exiting the plastic one a collimator attached to the fiber end face can be used. However plastic OF has the most attractive cost, while the cost of silica one significantly increases with diameter value. Among silica OF graded-index or single-mode ones are ~10 – 100 times more expensive than step-index one.

In terms of radiation hardness, plastic OF is more influenced by ionizing radiation than silica one. When OF is exposed to radiation with doses lower than 10^3 Gy, radiation effects on OF transmission properties can be neglected for any material type [12, 13]. The average dose rate caused by the beam losses at the IC is measured to be 200 Gy/yr and hence the OF lifetime was estimated to be over 5 yrs.

As a result, to improve monitor spatial resolution silica step-index multimode fiber with a core diameter of 400 or 550 μm should be used.

Considering photodetectors, MCP-PMT and SiPMT have better time resolution compared to conventional ones. The former one is preferable since it has 10 times greater gain, over 10^6, which allows detecting beam losses of 0.1 pC. The MCP-PMT has spectral sensitivity range in the CR spectrum (300 – 900 nm), rise-time of about 0.5 ns and output pulse FWHM of 1.5 ns. PMT readout electronics should be fast with no less than 500 MS/s and 200 MHz bandwidth.

MODEL VERIFICATION

Description

For studying physical processes responsible for monitor spatial resolution, FLUKA code [14] was used. The main results of numerical simulations of electromagnetic shower generation and the CR photon propagation are described in the previous work [7]. To verify simulation results a prototype of the OFBLM was installed at the end of 300 MeV electron linac and tested in a controlled manner by steering beam with dipole corrector.

We used plastic fiber (Broadcom, HFBR-RUS) with $n = 1.492$, attenuation of 0.22 dB/m @ 660 nm, other parameters are listed in Table 1. At the downstream fiber end, the CR signal was detected by MCP-PMT. Output pulse FWHM of the MCP-PMT is measured to be about 3.3 ns and mostly due to parasitic elements in the anode circuit. More accurate anode current measurements are required. Fast ADC with a 2 GHz sampling rate and 200 MHz bandwidth was used.

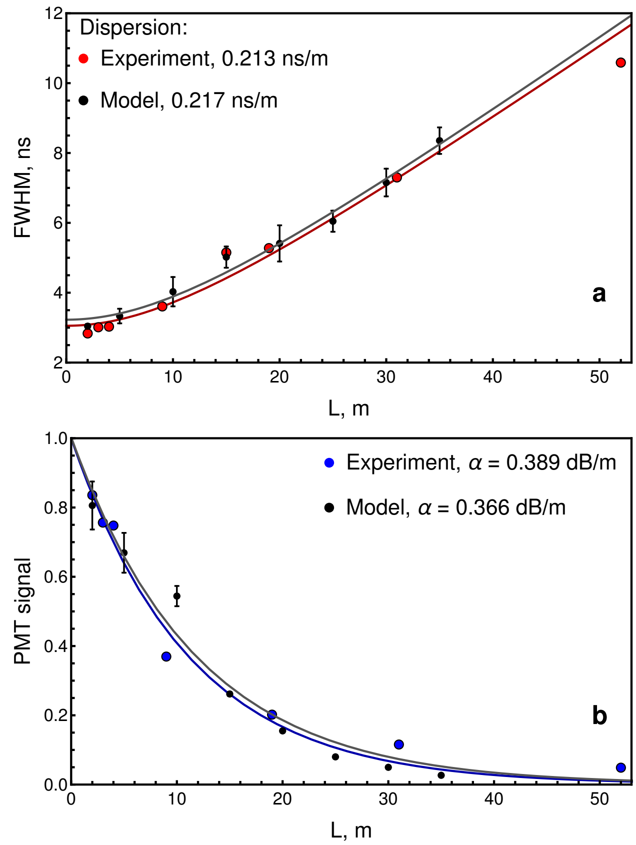

Figure 2: a) Measured (red) and model (black) FWHM of the PMT signal as a function of the plastic fiber length, b) Measured (blue) and model (black) signal intensity as function of the fiber length.

Pulse Duration vs Fiber Length

There are two main dispersion types in the OF: modal and chromatic. In plastic step-index multimode OF that we used, each dispersion contribution to pulse broadening in UV-visible spectrum (300-700 nm) can be estimated as follows:

$$t_{\mathrm{mod}}/L \approx NA^2/(2nc) \approx 0.25\,\mathrm{ns/m},$$
$$t_{\mathrm{chr}}/L \approx \Delta n(\lambda)/c \approx 0.08\,\mathrm{ns/m},$$

where $\Delta n(\lambda)$ determines spectral range. Thus, modal dispersion contributes 3 times greater to monitor spatial resolution than chromatic one.

Figure 2a shows FWHM of the measured and calculated PMT signals as a function of the fiber length for plastic OF. PMT time resolution was taken into account in the FLUKA model. As one can see from this figure, model and experimental data are in good agreement. Using data approximation the dispersion of the CR signal in plastic OF is calculated to be 0.213 ns/m and is mainly due to modal dispersion. For the fiber length over 20 m, contribution to pulse broadening is mostly caused by light dispersion in the OF.

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Signal Intensity vs Fiber Length

During propagation in the OF light signal undergoes attenuation. PMT signal attenuation as a function of the fiber length is $\sim\ 10^{-0.1\alpha L}$, where α – attenuation coefficient in dB/m, L – fiber length in m. Figure 2b shows the CR signal normalized by input one as a function of the OF length. The fit line gives a value of attenuation coefficient equal to 0.389 dB/m. This value is slightly different from datasheet one since the major part of the CR photons is in near-UV range of the spectrum and thus undergoes attenuation stronger.

Using plastic OF, desired monitor spatial resolution of less than 1 m for the IC, can be obtained by 40 m long fiber section along with MCP-PMT at the upstream fiber end face. The CR signal undergoes attenuation by a factor of 10.

OPTICAL FIBER SELECTION

To determine the fiber contribution to a pulse broadening different types of the OF were tested. Their parameters are listed in Table 1. First 3 fibers were attached to the vacuum chamber at the same position of expected beam loss.

Figure 3 shows measured and fitted FWHM of the PMT signal as a function of the OF length for different fiber types. MCP-PMT time contribution was taken into account. Plastic fiber dispersion is measured to be 0.241 ns/m, which is in good agreement with numerical results. For graded-index fiber dispersion is 0.177 ns/m, for single-mode one – 0.185 ns/m. For both silica fibers values are two times higher than expected, it might be due to radiation being partly transmitted via cladding and thus undergoing modal dispersion. Silica step-index multimode fiber was tested separately and a dispersion value of 0.19 ns/m was obtained.

Any type of silica fibers has less dispersion value than plastic one. However, single-mode OF is an unreliable and unpractical option since it has a small outer diameter of 250 µm. In terms of cost and robustness among all tested silica OF, step-index multimode one is the best candidate. By selecting 45 m long silica OF (with a large core of 550 µm) and MCP-PMT, less than 1 m spatial resolution can be achieved.

Table 1: Main parameters of tested fibers

model	Broadcom, HFBR-RUS	Fiberware, G400/560A	Fiberware, SM400/125PI	Thorlabs, FG550UEC
material	plastic	silica	silica	silica
mode	multi	multi	single	multi
index	stepped	graded	stepped	stepped
⌀core /clad, µm	1000/-	400/560	2.2/125	550/600
NA	0.47	0.29	0.2	0.22

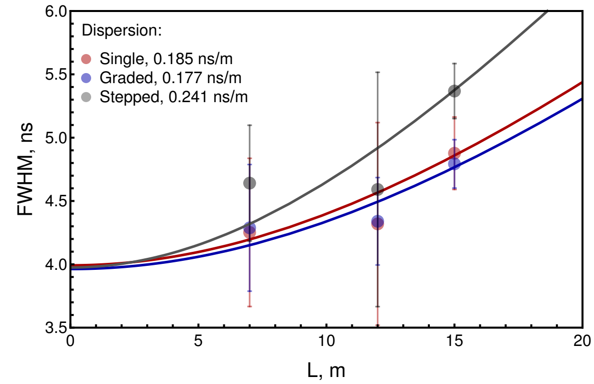

Figure 3: Measured (dots) and fitted (lines) FWHM of the PMT signal as function of the fiber length.

Collimator

Another way to minimize light pulse duration at the fiber end face is to use a collimator. In the simplest case, it is a hollow cylinder that absorbs light rays propagating with large angles due to modal dispersion. The effect of modal dispersion decreases as a function of collimator length as:

$$t_{mod}/L \approx \frac{1}{cn}\frac{1}{1+4l^2/d^2} \tag{1}$$

where l, d – collimator length and inner diameter.

According to Eq. (1), a 2 mm long collimator is enough to reduce the contribution of modal dispersion in the 10 m long plastic OF. Dependence of the monitor spatial resolution and number of output photons on the collimator length was studied in beam tests. For 10 m long plastic OF collimator can improve monitor spatial resolution by 20 %. The signal intensity is reduced by a factor of 4.

EXPERIMENTAL RESULTS

Experimental Setup

In this study, the OFBLM was installed in both the IC DR and e- extraction channel and tested with controlled beam losses by steering beam via dipole correction. For the DR we used 50 m plastic fiber (HFBR-RUS) covering the entire 27.4 m circumference. For e- extraction line we selected 50 m long silica fiber manufactured by Thorlabs (FG550UEC). In all these cases fiber ends were attached to MCP-PMTs. The experimental setup is shown in Fig. 4.

Extraction Measurements

The experimental results of electron loss monitoring at the DR extraction channel for both downstream and upstream fiber ends are shown in Fig. 5. As one can see from the upstream signal, three significant losses were detected. Loss A is a typical loss and occurs due to extraction point right after the septum-magnet SM, loss B and C were intentionally generated using 3M5 dipole magnet. Only single loss D is observed from the downstream signal, which is a combination of losses B and C due to intersymbol interference.

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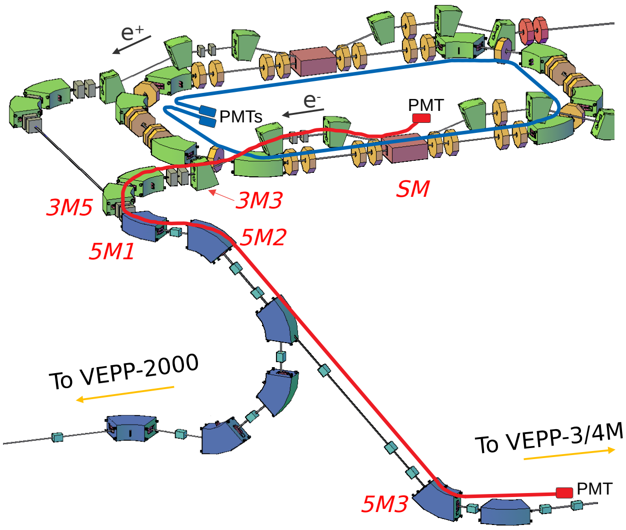

Figure 4: Layout of the DR and e- extraction channel components along with the OFBLM location.

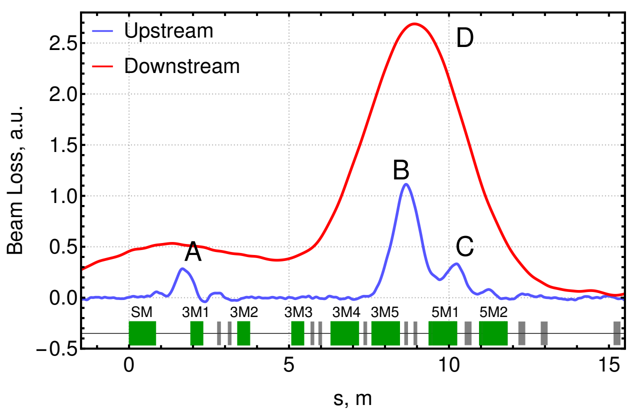

Figure 5: Upstream (blue) and downstream (red) loss distributions of the electron beam at the extraction channel.

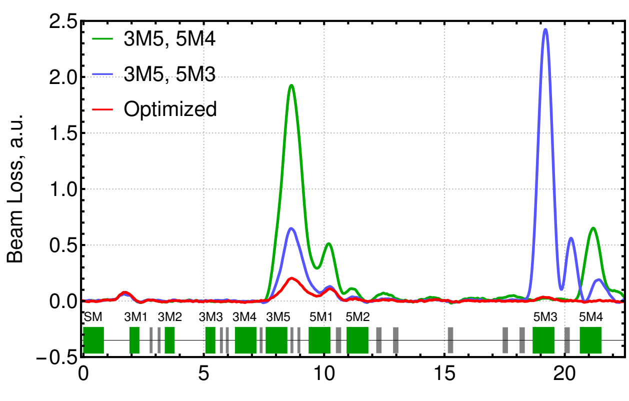

Figure 6: Upstream beam losses along the extraction beamline. Blue and green lines are loss distributions during beam alignment, red - for optimized beam trajectory. The same PMT voltage was applied.

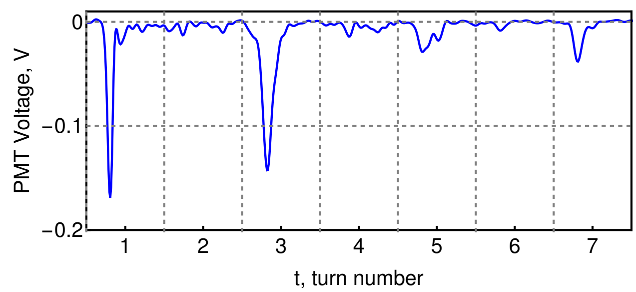

Figure 7: Turn-by-turn beam losses during electron beam injection into the DR.

Although loss B is almost equidistant from both fiber ends, FWHM of the second signal corresponds to 0.96 m (@19m) and 3.8 m (@31m) for the upstream and downstream cases, respectively. Which leads to 4 times better spatial resolution at the upstream fiber end, and allows detecting beam losses from successive magnet elements. Taking into account the difference between PMT gains, the ratio of the downstream signal intensity to the upstream one for the second signals is equal to 20.

Figure 6 shows a typical upstream signals during alignment of e- beam extraction channel. In all cases, there is a small loss during extraction right after the septum-magnet SM. Blue line demonstrates beam losses due to 3M5 and 5M3 dipole corrections. Green line shows losses due to 3M5 and 5M4 dipole corrections. Red line shows beam loss distribution at normal operating.

Turn-by-Turn Measurements

Figure 7 shows the results for turn-by-turn loss measurements for electron beam injected into 27.4 m DR. 50 m long plastic OF was placed horizontally. For detecting downstream signal MCP-PMT and fast electronics were used. The significant losses on the 1st, 3rd, 5th and 7th turns are observed. The OFBLM can be used as a useful tool for optimal tune alignment. However, due to the difference between beam velocity and speed of light in the OF, two fiber sections at the DR should be used to avoid overlapping of beam losses from different turns.

CONCLUSION

The OFBLM has been developed for the 500 MeV BINP IC. Numerical studies for plastic OF were shown to be in good agreement with experimental data. Methods to optimize monitor spatial resolution are discussed and as a result, silica step-index multimode fiber (with a large core of 550 µm) together with MCP-PMT were considered as best candidates for the OFBLM. Required less than 1 m monitor spatial resolution for 45 m long OF was obtained. By selecting 15 m long fiber, 0.5 m spatial resolution can be achieved. Moreover, the OFBLM can be used as a useful tool for optimal tune alignment at the 27.4 m DR.

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