BEAM LOSS AND BEAM PROFILE MONITORING WITH OPTICAL FIBERS

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Abstract

Beam losses and beam profiles at particle accelerators are determined by measuring the ionizing radiation outside the vacuum chamber. Four different radiation sensor systems using optical fiber will be presented. Two are based on the increase of radiation-induced attenuation of (Ge+P)-doped multimode graded index fibers, whereas the other two systems detect the Cerenkov light generated by relativistic electrons penetrating radiation hard fibers. The used fiber is an undoped multimode step-index fiber with 300 μm core diameter. Dosimetry at high dose levels uses the radiation induced Bragg wavelength shift of Fiber Bragg Gratings. The selection of a suitable fiber for the individual application is an important requirement and depends on the type, doping, used wavelength and annealing behavior. In addition, the dose range, dose rate and temperature must be considered. After an extensive selection procedure, two types of fibers for the particular application were chosen. One is used as a dosimetry sensor for the *slow* local and distributed beam loss position monitor (BLPM) and the other for *fast* beam loss monitor (BLM) as well as beam profile monitors (BPM). At six accelerators, all systems are used for in-situ particle loss control by measuring the ionization dose and/or Cerenkov light. These monitors provide a technique to improve the beam performance. This paper summarizes the basics of these measurement technologies and the experience at linear accelerators and at storage rings.

INTRODUCTION

Beam loss monitor systems (BLM systems) are an essential part of linear accelerators and storage rings. They allow the understanding of beam loss mechanisms during commissioning and operation and provide an option for an emergency shutdown. A proper understanding of beam loss events can improve machine performance, which consequently reduces also the radiation level for the used accelerator components. Well-known beam loss systems [1], like a) long and short ionization chamber, b) combination of scintillator and photomultiplier and c) PIN photo-diodes, d) scintillation counter, e) electron multipliers, f) cryogenic calorimeters have still some deficiency [2,3,4,5,6,7]. They do not cover the complete sections of the accelerator, particularly large undulator systems, and have an insufficient position and time resolution. It would be of great advantageous to monitor continuously on-line localized beam losses around the complete accelerator complex. Particular total dose measurements at the susceptible undulator magnets are desirable because they are made of radiation sensitive alloys. With in the framework of the TESLA/ILC (International Linear Collider) [8] and FLASH (Free-Electron-Laser Hamburg) [9] design study. New concepts of BLM systems based on special types of optical fiber sensors were developed [10,11,12]. They have been tested during real operation at different accelerator facilities*.

OPTIMIZATION AND SELECTION OF OPTICAL FIBERS

Since 30 years it is well known that the radiation induced attenuation (RIA) of particular optical fibers [13,14,15,16,17,18,19] is a function of the total ionization dose (TID). This mechanism allows a reliable dose measurement up to a level of a few thousand Gray. For high dose applications the changes of the refractive index or Bragg wavelength shift (BWS) can be used. The radiation induced emission of Cerenkov light or luminescence mechanism are used for fast detection of radiation sources without calibration of TID. Fibers can also be made sensitive for thermal and fast neutrons [20,21,22]. The nonsatisfying applications in the past rely at most on insufficient knowledge and control of the producing process of the fibers. An individual characterization of each lot is therefore indispensable. This is a key function for further usage of fiber radiation sensors. The influence of core material, cladding thickness, drawing speed of the fiber and coating material of pure silica core step-index fibers have been investigated in detail [23].

CLASSIFICATION OF BEAM LOSS MONITOR SYSTEMS

As shown in Fig. 1 the BLM systems are distinguished in two categories. One system measure the TID generated by the beam losses as a function of RIA. With an optical power meter, the RIA is measured at local position along the beam line, especially at the undulator. The resolution of the absorbed dose of the so called *local sensor system* is about 60 mGy with an updating time - depending of the number of used sensors - in the range of ms [25]. The *distributed sensor system* makes use of Optical Time Domain Reflectormeter (OTDR) measurements. As a result of the attenuation measurement, the position and TID along the beam line or undulators can be calculated. At FLASH, typical sensor length is less then 100 m. The update time is in the range of some seconds with a position resolution of about 1.5 m. The dose resolution for the presented measurement setup is about 3 Gy [25]. The system of the second category detects the generated Cerenkov light in the fiber over a length of about 40 m with a

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position resolution of 25 cm, a response time below milli-second and a time resolution of nanosecond. This short time response makes the system also applicable for emergency shutdown.
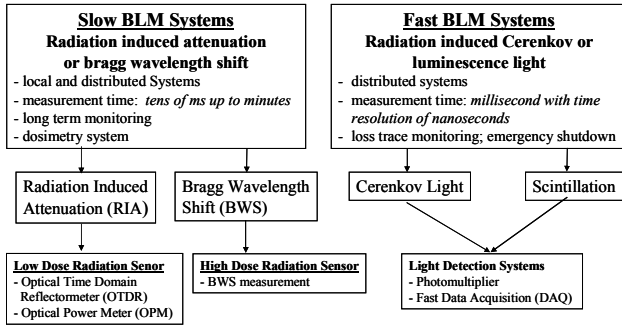

Figure 1: Classification flow chart of beam loss monitors systems using optical fiber sensor.

SLOW BEAM LOSS MONITOR SYSTEMS (DOSIMETER SYSTEM)

Slow BLM (response time between ms and minutes) require a dosimetry fiber with an excellent linearity between the TID and the RIA. They must have a large dose range in combination with small fading and annealing behavior respectively. The fiber must be insensitive against dose rate, temperature and radiation type and their energy. The simultaneous usage of the same fiber for the local and distributed sensor beam loss monitor system requires also a selection with respect to the bandwidth of the fiber. Low bandwidth show higher mode dispersion and increase the pulse broadening of the light pulse, which reduces the achievable position resolution. With an Optical Time Domain Reflectormeter using a 3 nm pulse width and a laser wavelength of 850 nm, a bandwidth of 800 MHz $*$ km is sufficient [24]. The long term experience at the FHG INT[#] and HMI[#] in optical fiber characterization facilitate the collaboration to an intensive selection process. As a result, for the dose measurement a (Ge+P) doped multimode gradient-index (MM GI) fiber [25] and for the measurement of the Cerenkov light a multimode step-index fiber (MM SI) [32, 33] was selected.

The following function approximates the RIA of fibers:

$$RIA \text{ [dB/m]} = c\,(\lambda) \bullet D^{f(\lambda)} \qquad \text{[26] (1)}$$

The constant c [dB/m Gy] expresses the radiation sensitivity, which is a strong function of the used measurement wavelength λ [nm] and D [Gy] the accumulated dose. The exponent f is the linearity factor close to 1 for fibers with low annealing effect. The fitting parameters for the MM GI fiber are:

λ= 678 nm: c = 0.0369 dB/m Gy, f = 0.972 and for
λ= 829 nm: c = 0.0042 dB/m Gy, f = 1.025

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The fibers response passes into a non-linear function above a RIA level of 1 kGy and saturate at higher dose level. It was shown, that the RIA of a P-doped MM-GI covered with a heat resistant polyimide coating can be regenerated in short time at temperatures above 350°C with very little changes of their optical properties [27].

Local Dosimeter Systems

The functional principle of the local sensor system developed for sensitive TID measurements at selected accelerator positions is shown in Fig. 2. The sensor fiber is linked by radiation resistant fiber to the light source and on the other side to the optical power meter. For temperature control and calibration of the set up, one fiber is directly connected between light source and power meter. A typical set up used at an undulator consist of 16 measurement channels. The light source guided to the 16 output pigtails of a 1:16 splitter made of 50/125 m GI fiber. Depending of the expected dose, the number of windings (typical 5-20) for each sensor can be adjusted. The coils of the sensor are mounted together with optical connectors on a holder (Fig. 3). This holder is mounted in prepared cut out of the vacuum chamber (Fig. 4).
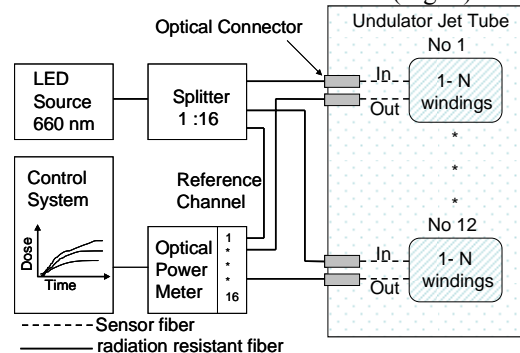

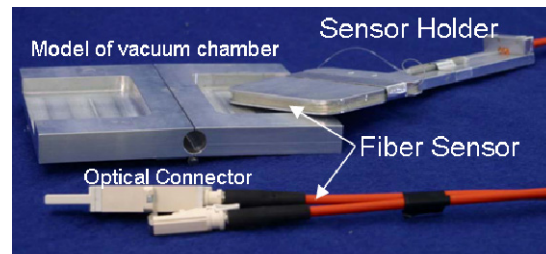Figure 2: Functional principle of a local sensor system.

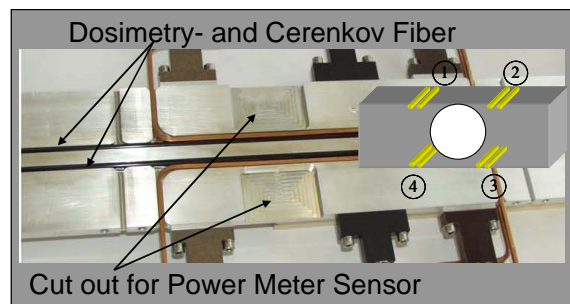Figure 3: Sensor holder of the local sensor system.

Figure 4: Detail of the vacuum chamber line of the undulator show the cut out for the power meter sensor, the OTDR and Cerenkov fiber.

Each output of the sensor module is connected to a power meter, which is controlled by a PC [25] and the data are forwarded to the accelerator control system. The TID values of the local sensor with optical power meter are in good agreement with reference TLD measurements [25,28].

Local Dosimeter System for High Dose Measurement

Fiber Bragg Gratings can be used as radiation sensor in high dose environment by measuring the Bragg wavelength shift (BWS) as a function of the absorbed dose [29]. The influence of the production process leads to a factor of three in BWS using the identical process parameter. A variation of the process parameter provides a BWS difference of nearly a factor of ten [30]. Up to a dose level of 100 kGy the fiber show no saturation and is almost independent of the radiation dose rate. They can be used up to a level of 1 MGy [30].

Distributed Dosimeter System

With standard Optical Time Domain Reflectormeter technology, the change of the attenuation caused by the local irradiation along the beam line is measured. Only a few OTDR systems are available with adequate small pulse width and short wavelength combined with multi-mode modules+. The expected RIA and the dynamic range of the OTDR equipment defines the maximum sensor length for a given monitor section. Behind a fiber segment with a high RIA the following fiber section can not be measured. With a high precision optical switch many segments can be monitored with one OTDR system. At the FLASH undulator four fibers are placed in equidistant radial distance around the vacuum chamber (Fig. 4). That makes it possible to calculate the direction of the highest Bremsstrahlung level (highest beam loss) around the beam line. In the same way but with a larger distance to the beam line, four fibers are installed along the beam line.
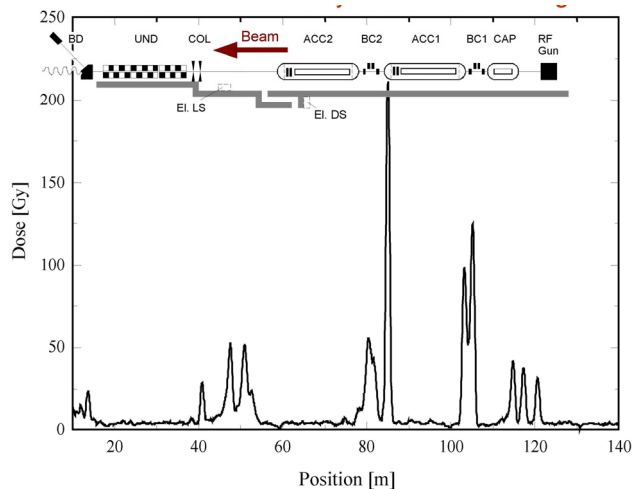

Figure 5: Measured TID along the entire beam line at the TESLA Test Facility, DESY Hamburg [31].

+ like Tektronix Fiber Master TFP2A

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The accumulated dose during a long-term operation of 3 weeks at the TESLA Test Facility is shown in Fig. 5.

FAST BEAM LOSS MONITOR SYSTEMS (CERENKOV LIGHT)

Many previous publications describe the measurement of ionizing radiation by detection of the generated Cerenkov light in optical fibers. The implementation and systematic optimization of this technology was missing. The precondition is the selection of an optimal fiber as explained in the previous chapter. Two measurement systems are installed. The measurement set up for the undulator section and upstream beam line section is shown in Fig. 7. At the undulators four fibers are grouped together in equidistant radial distance around the vacuum chamber sharing the same cut outs with the OTDR fiber (Fig. 4). The fibers are connected in the tunnel to photomultipliers (PMT), which are selected with respect to their sensitivity.

Fast Beam Loss Monitor

Fast BLM require radiation resistant fiber with high bandwidth and large core diameter. Electrons with energies above 175 keV generate Cerenkov light in pure quartz fiber (n=1.46). Based on this effect, powerful BLM systems like beam loss position monitor (BLPM) [32] and beam profile monitor (BPM) [33] were developed. They use Fiber with pure silica core and high OH-content which are in general radiation resistant. However, F-doped fiber could reach higher radiation level without increasing the RIA [34]. The presented BLM systems use a multi-mode step-index fiber with a core diameter of 300 μm. The core diameter is a good compromise between the irradiation sensitivity and a required bandwidth. A black nylon buffer shields the fiber against the ambient light. The total diameter of the fiber is only 900 μm. In contrast scintillation fibers have high attenuations values and are radiation sensitive. This fiber type cannot be used for measurements over long distance or in applications with high dose level.

Typical curves of the Cerenkov light generated in the optical fibers over a length of six undulators during routine operation at FLASH are shown in Fig. 6.
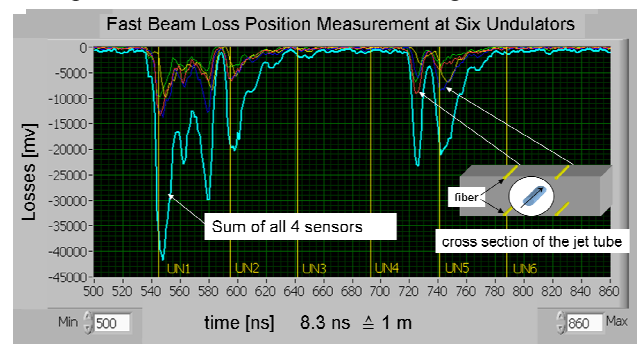

Figure 6: Screen shot at FLASH, in March 2009. At six undulators the Bremsstrahlung level at four positions is shown. An adjustable persistence mode improves the quality of the visualisation.
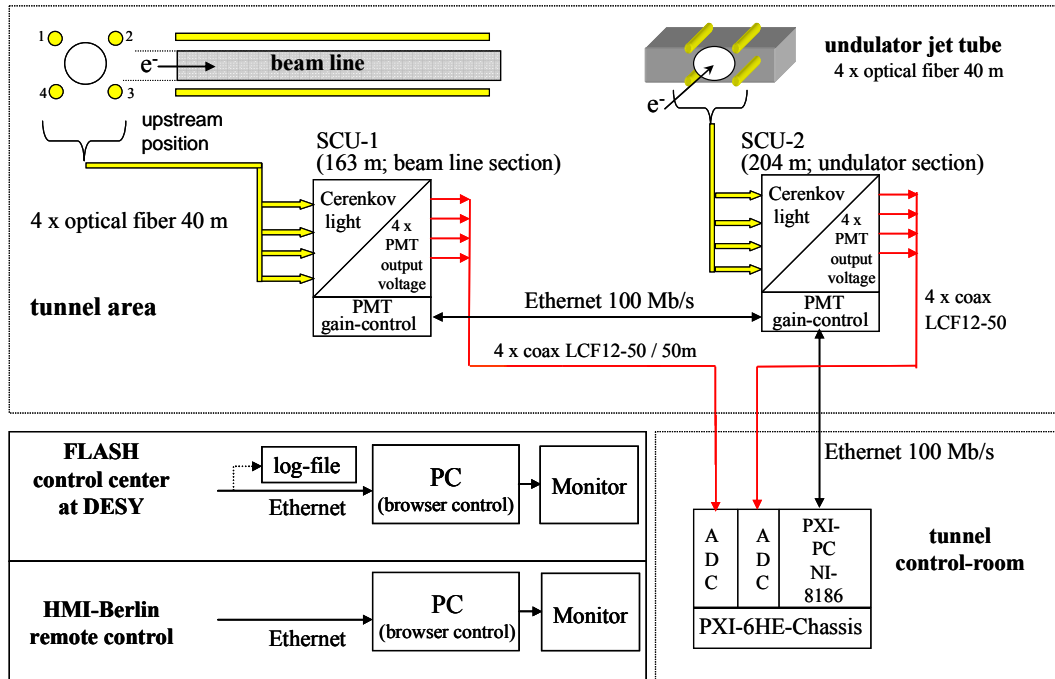
Figure 7: Measurement set up for BLPM and BPM at FLASH. One sensor group controls the undulator and a second one the beam line.

Measurement Set Up

The outputs of low noise preamplifiers are connected to fast ADCs (1 GS/s; 1 GHz bandwidth) installed outside the radiation area of the tunnel in a modular PXI-System. The system is synchronized with the bunch clock and controlled by an embedded CPU. The system is integrated in the FLASH control system. Selected events can be logged together with the machine status. Maintenance is executed via remote control from the HMI. This system is used for BLPM and BPM.

Beam Loss Position Monitor

The position of the radiation source is calculated by the time difference between a maximum peak height of the light pulse and the bunch clock trigger. The accurate location of the secondary shower with respect to the beam line layout can be determined by vacuum components like optical transition radiation (OTR) screen or wire scanner with their know position. It has been shown, that the position can be determined with an accuracy of about 25 cm measured at PITZ [35]. Due to the fact, that the velocity of relativistic electrons in vacuum (~ c) is higher than the light velocity in the fiber (~ 0.66•c) the measured light signals are expanded or compressed depending on the position of the PMTs relative to the beam line. If the PMTs are installed at the upstream position, the measured light signals are stretched by a factor of 2.5 relatively to the electrons in the vacuum chamber. Installing the PMTs at the downstream position, the signals are compressed by a factor of two. This gives the possibility to detect single bunches at the downstream position with five times higher repetition rate as at the upstream position. However, with

the same bandwidth and sample rate the position resolution is than five times lower [36]. In Fig. 8 the principle result of BLPM measurement is shown. The losses are generated by an inserted OTR-screen. The intensity of the loss shower increases at the first quadrupole. The local minima of the signal are caused by the shielding effect of the components (quadrupoles, vacuum pumps e.g.) and transversal distance variation of the fiber with respect to the beam line. Nevertheless, using the maximum values of the signals, an envelope function can be calculated to define the direction of the centroid of the Bremsstrahlung shower as shown in Fig. 9.
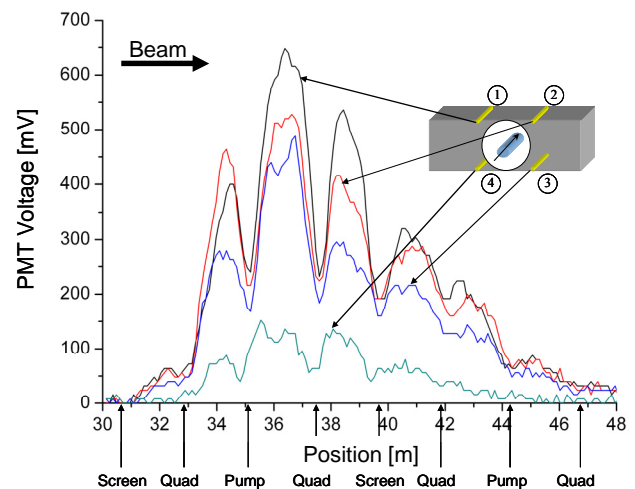

Figure 8: Typical results of the BLPM measurement at an interesting section of the beam line. The shielding effect of the beam components causes the minima of the signal amplitude.
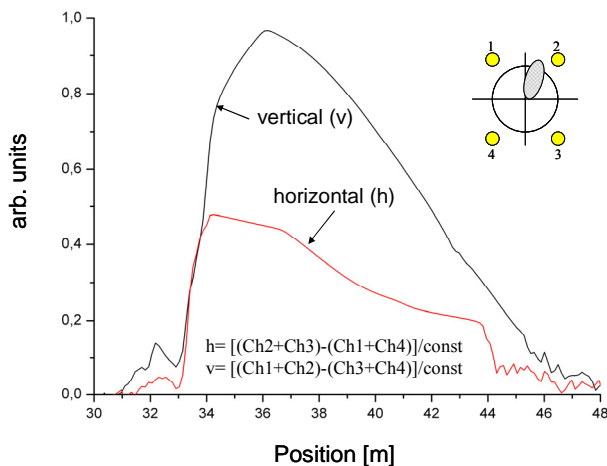
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Figure 9: Enveloped function of the Bremsstrahlung shower as shown in Fig. 8.

Beam Profile Monitor

Beam profile measurement is an essential part of the beam diagnostic. Conventional systems use wire scanner systems (WS) [37] where only a fraction of the generated Bremsstrahlung in longitudinally direction is measured by a PMT at the end of a beam line section. The efficiency of this measurement principle is additionally reduced due to the shielding effect of the beam line components. The built in BLPM can be used to measure the Bremsstrahlung in the longitudinal as well as in the transversal direction, particularly direct after the wire scanner. The interesting parts of the beam are the beam core and tails. The measurement of the beam profile requires a large dynamic range of the detection system. In addition, parallel to the installed Cerenkov fiber group a second set of fibers are used. This gives the opportunity to measure at the same time with low and high amplification ranges of the PMT. This is necessary, because the sensitivity of the PMT after high illumination level needs a too long recovery time with respect to the fast movement of the wire
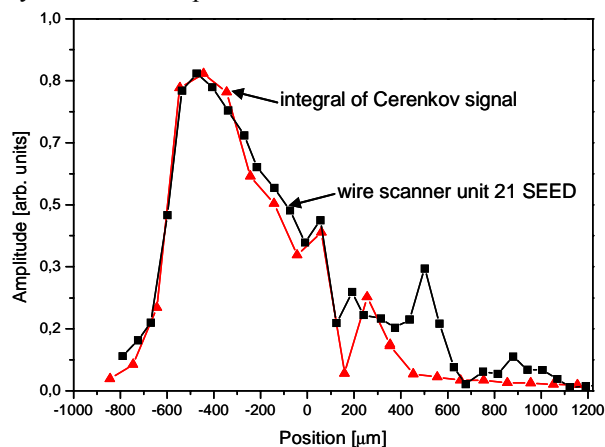

Figure 10: Horizontal beam profile measured with a standard wire scanner system compared to results obtained with an optical fiber BPM system. The maximum values are normalized. The measurements were taken one after another.

scanner itself. Figure 10 shows the good correlation between measurements with standard WS systems and the new BPM system. Detailed experimental results are given in [33]. A novel pre-amplifier increases the sensitivity of the BPM system by a factor of 10. This offers more detailed information about the beam tails. The combination of BLPM and BPM using the same measurement system gives fast information about the beam quality.

CONCLUSIONS

It has been shown that fiber used in *slow* beam loss monitor (BLM) systems - like distributed dosimeter system - and in *fast* BLM systems - like beam loss position monitor (BLPM) and beam profile monitor (BPM) - are useful tools for the optimization and control process of particle accelerators. In general, fiber sensors can be used in nearly inaccessible gaps or regions with high electrical or electromagnetic fields. It is an indispensable precondition, that a careful selection of the sensor fiber is necessary to meet the essential requirements. The local dosimeter system can be placed anywhere with individually adapted sensitivity and detection area. These sensors measure local doses with a resolution of some tens of milligrays in real time. Various numbers of sensors - connected together via an optical switch and splitter - can be measured in few milliseconds. Distributed dosimeters use the same fiber type. The fibers are installed up to several hundred meters along the accelerator beam line, tunnel or undulators, measuring the total ionization dose (TID) down to a few Gray with a position resolution of about 1.5 m. The measurement time is in a range of some minutes, depending on the required dose accuracy. The system is applicable to supervise the radiation level of the total accelerator environment. The (Ge+P) doped multimode gradient-index fiber with a heat resistant polyimide coating can be regenerated with very little changes of their optical properties. In a high dose environment the usage of Fiber Bragg Gratings seems to be a possible solution.

Fast BLM systems like BLPM and BPM enable the operator to control the beam loss along the entire beam line in transversal and longitudinal dimensions. It allows the identification of single bunches within one bunch train. The system response is in the range of millisecond with a time resolution of nanoseconds and a position resolution of about 25 cm. This allows an interactive control of the beam optimization process and gives the opportunity to trace the stability over all setting parameters of the beam. In addition, this system is applicable for fast emergency shut down. Optimized BPM systems provide a beam profile measurement with higher sensitivity to the beam core and beam tail compared to FLASH undulator wire scanner system. The important parameters of BLM with optical fibers are summarized in table 1. In the last years the presented BLM systems are not only used at FLASH but also at PITZ at DESY Zeuthen [35], Germany, MAX-Lab [38], Lund University, Sweden and at storage rings at BESSY II, Berlin, Germany and DELTA [39,40] in Dortmund, Germany.

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Table 1: Summary of the Beam Loss Monitor Systems

Application	Slow BLM Systems			Fast BLM Systems
	Distributed Dosimeter System	Local Dosimeter System	Local Dosimeter System (High Dose)	Beam Loss Position Monitor and Beam Profile Monitor
Measurement principle:	Optical Time Domain Reflectormeter	Optical Power Meter	Bragg Wavelength shifting (Δ BWS)	Cerenkov Light
Bunch resolution	No	No	No	Yes, within one train
Measurement time (detection response)	minutes	ms to minutes	ms to sec	$\leq$ ms with time resolution of 1 ns
Range of maximum dose TID [Gy]	3 – 450 limited by OTDR	0.06- 2000 limited by fiber type	$2 *10^3$- 10^6 limited by fiber type	only a rough estimation possible, fiber can used until $1*10^5$
Wavelength range	850 - 1330 nm	860 nm	820 nm - 1,55 μm $\Delta\lambda_B$ = 5-350 pm	200 - 850 nm
Position resolution	1.5 m	0.05 m	0,5 m	0.25 m
Reasonable fiber length*	$\leq$ 5 km typical $\leq$100 m sections	-	-	$\leq$ 1 km typical 50 - 100 m sections

* Depending on max. Dose and required position resolution

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