ČERENKOV RADIATION FOR BEAM LOSS MONITOR SYSTEMS*

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Abstract

Čerenkov radiation has been used by high energy physics to identify the mass of single particles for quite some time. Quartz fiber optics has been used to detect beam loss locations for pulsed electron beams using the time of propagation within the fiber of the light pulse. For the NSLS-II storage ring, it was necessary to detect the amount of charge lost versus location around the ring. To achieve this for a continuously circulating beam, the best solution was found to be large diameter, solid fused silica Čerenkov radiator rods which localized the beam loss to a unit of one magnet girder, which usually corresponds to one peak of transverse beam size or dispersion and therefore one loss point of interest. This paper presents an analysis of the use of Čerenkov radiation as a signal for beam loss, together with a comparison of the advantages and disadvantages of fiber optic cable and solid rod radiators for beam loss monitoring.

INTRODUCTION

The NSLS-II light source [1] is a new 3^{rd} generation high brightness light source, with a 3GeV storage ring (SR) with <1nm emittance and top-off injection. The SR radiation shield consists of 2-cells (injection and the downstream cell) of heavy concrete shielding capable of shielding the experimental floor from the loss of the full top-off injection beam current. The remainder of the ring is shielded for a loss rate of < $1/12^{th}$ that value. A consequence of this shielding decision and a requirement to insure radiation to the experimental floor is maintained below a level that would require the radiation badging of the users, a Loss Control and Monitoring system (LCM) [2] has been specified. The LCM will control and monitor

local beam losses in all of the accelerators systems, to limit beam power losses to less than the shielding design levels. The LCM will consist of components that will:

a) monitor and limit the beam losses in the injector and transport lines,

b) control the major beam losses in the SR to the heavily shielded injection region and

c) monitor the SR beam losses in the injection region, in order to account for losses to the remainder of the SR.

The latter goal will require that the beam losses be measured quantitatively in order to determine the quantity of charge lost from the SR current monitor in the heavily shielded injection region. The difference then will be the unaccounted for charge loss, which will be attributed to losses in the remainder of the ring. In high current and brightness SR's the lifetime will be low and the largest integrated beam loss will be lifetime losses due to Touschek scattering within the high charge bunches. To

* Work supported by U.S. DOE, Contract No.DE-AC02-98CH10886 # skramer@bnl.gov control radiation levels to the experimental floor, the beam loss monitors (BLM) must measure the lifetime losses, as well as the 10⁹ higher peak losses from beam dumps and instabilities. By measuring over this high dynamic range (HDR), the BLMs will allow operators to better control the accelerator parameters to minimize the losses and limit them to the heavily shielded regions. This goal requires a new type of HDR, quantitative BLMs (QBLM) that measures the local charge losses, not the energy absorbed in a detector, as radiation monitors do.

PRINCIPLES OF QUANTITATIVE BLM

The typical BLMs in use are designed for machine or radiation protection. They typically measure the energy deposition in a sensitive volume at one location. Although this is related to beam charge lost, the proportionality will have many terms with different sensitivities to fractional charge lost at different locations and a multiplication from matter between the loss location and the detector, most importantly magnets and their fields. To calculate this sensitivity will require knowledge of the loss distribution, defeating the goal of the QBLM, unless it is designed to minimize these variations.



Figure 1: Geometrical layout of a BLM, a distance R from the point loss location, z at the VCW.

The sensitivity, S of a QBLM detector element of length L, height h and thickness t, a distance R from a single point beam charge loss Q'(z), whose signal depends on the path length of the particle in the detector (p=t/cos(θ)). The geometry is shown in Fig. 1, and S will be the integral over all loss points and angles that intercept the BLM. The differential signal is given by:

$$d^{2}S = \frac{h t}{R}Q'(z)M(z,\theta)\sec(\theta) d\theta dz$$
(1)
+ $\frac{h t}{R_{m}}Q'(z)\int M(z,\theta_{m})N(\theta_{m},\theta_{l})\sec(\theta_{l})d\theta_{m} d\theta_{l} dz$

where the scatter distribution function, $M(z, \theta)$, includes the physics processes for the passage of the beam particle through the VC wall and its conversion to secondaries. $M(z, \theta)$ will vary with the location z and angle θ_b , of the beam particle hitting the VC wall and the distance R to the detector. With $M(z, \theta)$ defined by the beam and VC

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material, θ_b is defined by the beam loss process at location z, the first term can be integrated over the z and θ , yielding calibration constant for Q'(z).

The second term shows the signal dependence on the scattered particles that are intercepted by magnets, B-fields or other components before the BLM. This term includes the initial scatter distribution $M(z, \theta_m)$, as well as a secondary scatter function, $N(\theta_m, \theta_1)$ that must be integrated over the angles θ_1 , which maybe at locations closer or more distant to the BLM than the local loss point itself. This makes the estimate of Q'(z) very model dependent. Therefore it is desirable to minimize the impact of this second term in Eq.(1) if a QBLM is hoped to be achieved.

Several basic principles for BLM detector design will reduce the 2^{nd} term relative to the 1^{st} term in Eq. (1). These are:

a) detector should be sensitive only to initial beam particles (i.e. minimized number of physics processes that contribute to signal generation),

b) detector should have small R with large t and h for greater signal and reduced position and angle dependence

c) avoid matter and fields between the VCW and BLM,d) make the detector as >1m long to capture the major

portion of the shower particles, e) adequate response time of BLM detector to measure beam loss times and dynamic range (DR) of O'(t).

f) practical consideration the detector must be able to withstand the high levels of radiation possible, especially if R is reduced (i.e. its calibration should not change too rapidly to be useful).

BLM Detector Choices

A. Zhukov [3], provided an excellent summary of BLM detectors and their properties. For the present we will only consider BLMs for high energy e⁻SR, although the most will be applicable for HE proton beams. The major groups of practical BLMs that are useful for electron beams are: ionization and long ionization chambers (IC and LICs), scintillation detectors (SBLM), PIN diode coincidence detectors PBLM, and Čerenkov beam loss detectors (CBLM).

The CBLM is the only BLM to show promise for meeting the basic principles listed above. The CBLM is only sensitive to high energy (HE) e^{\pm} and is insensitive to B-fields with photo-diodes (PD) but also for PMTs located away from magnets. The light signal is instantaneous and has no saturation limit, allowing very high DR. The geometry of CBLMs needs to carefully consider the beam loss process, to optimize the light generation and propagation to the detector for greatest sensitivity and minimal sensitivity to z. There also needs to be a means to calibrate the CBLM in situ. The radiator material needs to have a high radiation damage resistance to reduce calibration variations.

ČERENKOV RADIATION FOR BLMS

When a high energy charged particle (relativistic velocity $\beta = v/c$) passes through a medium with a

refractive index, $n(\lambda)$, they will emit light photons of wavelength, λ , at an angle of, $\cos(\theta_c(\lambda)) = 1/(\beta * n(\lambda))$ relative to the particle direction, for photons with $n(\lambda) \ge 1/\beta$. The number of photons emitted per unit photon energy per unit path length, x, of the particle is a constant and depends only on the threshold angle, $\theta_c(\lambda)$, at that energy[4]. Expressed in terms of the photon wavelength the photon number spectrum is given by

$$\frac{d^2 N}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2} \sin^2(\theta_c(\lambda)) \approx \frac{0.0459}{\lambda^2} \sin^2(\theta_c(\lambda))$$
(2)

where α is the fine structure constant ~1/137. This shows the greater emission in the UV range of the spectra. For a constant index, $n(\lambda)$ (~1.46 for SiO₂ sin²(θ_c)~0.53 and β =1) the number of photons depends only on the bandwidth of the detected photons and the path length

$$\frac{\mathrm{dN}}{\mathrm{dx}} = 2\pi\alpha \left(\lambda_1^{-1} - \lambda_2^{-1}\right) \sin^2(\theta_{\rm c}) \approx 960 \,\mathrm{cm}^{-1} \quad (3)$$

for 200 < λ <1000nm with an emission angle $\theta_c \sim 46.8^\circ$. Most photo detectors have their sensitivity listed in output current per incident power at wavelength λ , (P(λ) A/W). The photo-current output signal from PD is given by:

$$I_{p} = 568(\mu m^{2}W/A)Q'(A)t[\int P(\lambda)\frac{\sin^{2}(\theta_{c})}{\lambda^{3}}d\lambda]$$
⁽⁴⁾

where Q' is the electron current hitting the radiator rod of thickness, t(cm) at right angles, assuming all photons are collected and converted by the PD. For fused silica assuming a constant $n(\lambda)$ and $P(\lambda)=0.1(A/W)$, the PD will have a photo-current of 1.42 (nA/pA) of beam loss at 90° on a 1 cm radiator rod for a bandwidth of 200 < λ <1000nm. Fig. 2 shows the photon flux spectrum and a sensitivity curve a UV sensitive photo-diode. For one particle per turn (2.6 μ s) hitting the RR at right angles, 0.08nA of output signal would be produced, compared with a 0.1nA dark current from the PD.



Figure 2: The Cherenkov photon flux spectrum (red curve) versus photon wavelength and a UV-PD sensitivity curve in (A/W) (blue).

To calculate the CBLM signal we need to consider the beam loss electrons hitting the VC wall (VCW) and the shower electrons that are produced and intercepted by the radiator rod (RR). Then the e- (also e+) that pass through the RR will generate photons which need to be tracked to the detector and converted to signal.

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BEAM LOSS PROCESS IN VC

The Touschek losses will be the dominant loss mechanism once the desorption process has reduced the residual gas. This process results in scattered beam particles losing and gaining a momentum error, δ , causing the scattered particles to hit the VCW in the dispersion regions. The minimum angle of these particles that hit in the dispersion region of NSLS -II is shown in Fig. 3, and peaks around $\theta_{\rm b} \sim 1.5 - 2^{\circ}$ with the VC wall. Particles with greater δ will hit earlier and with larger angles. As part of the NSLS-II LCM system, thin scrapers will be used to intercept the beam at smaller values of δ , inducing greater energy loss in the scraper and the subsequent dipoles will bend these particles into the VCW with angles $\theta_b \sim 6-10^\circ$. These losses will account for 60-90% of the beam losses. Fig. 4 shows the location of the NSLS-II CBLM in a dipole and quadrupole magnets in the dispersion regions with a distance R~50mm from the VCW.

The NSLS-II VC has the NEG pumping chamber preventing the CBLMs from being mounted on the outside, but the majority of the losses will be toward the inner wall. Since the VC wall is 25 mm of Al with a water channel, the secondary particles from the EM shower need to be considered. We simulated particles produced in the electron shower for the 25mm thick VCW using the Shower [5] interface to the EGS4 program [6]. The angle $\theta_{\rm b}$ of the e⁻ to the VCW was varied from 1° to 7° and the distribution of e⁻ and e⁺ particles exiting the inner VCW with $E_e > 10 MeV$ was computed at the position of the RR. For incident angle, $\theta = 3^{\circ}$, the vertical position of e⁻ at the RR are shown in [7]. A 10mm OD RR intercepts >30% of these e⁻ and e⁺ with reduced sensitivity (<10%) to the vertical position and angle of beam e⁻, as compared with a smaller diameter RR (e.g. a 400µm fiber optic RR intercepts $\sim 5\%$ with > 40% variations).



Figure 3: The minimum value for θ_b for Touschek scattered particles that hit the VCW in the dispersion region of NSLS-II.



Figure 4: Locations of the CBLM RR inside the magnet yokes toward the inside of ring VC for NSLS-II.

For the shower generated e^- and e^+ particles that pass through this RR their properties were reported in Ref. [7]. For each beam particle incident on the VCW at θ_b the average number of e^- and e^+ produced that pass through the RR times their average fractional path length increase relative to the RR diameter will yield an increase in the RR signal relative to the single electron passing perpendicular to as RR signal calculated above. This signal enhancement factor is shown in [7] and has a signal increase of 11X at $\theta_b \sim 7^\circ$. This will yield a S/N ~10 for one e^- /turn loss on the VCW and seen in the CBLM-PD detector. To yield this enhancement the RR must have a length sufficient to capture most of the e^- and e^+ produced in the shower, requiring L > 1m [7].

This signal enhancement assumes all Čerenkov photons generated in the RR are collected and converted by the PD. This actual coupling efficiency will be calculated below but will require knowledge of the angular distribution of the shower e^- and e^+ in the RR. The most important is the polar angle of the charged particles relative to the central axis of the RR, θ_e . This distribution is shown in Fig. 5 and is peaked in the direction of the incident particle that created the shower and has an average value $\langle \theta_e \rangle \sim 20-25^\circ$ with small variations for the range of θ_b possible from the beam losses considered here. A similar average and spread of $\theta_e \sim 20 \pm 15^\circ$ was found for the e^+ distribution, although peaked more $\sim 4^\circ$.



Figure 5: The polar angle, θe , distribution of e^- shower from the VCW passing through the RR.

COLLECTING THE ČERENKOV LIGHT

This use of CBLMs is not new[8,9]. Linear accelerators or injection into SR used fiber-optical BLM (FOBLM), where fiber optical cables serve as the RR coupled to PMTs. They measure relative losses as a function of position, using the timing of the light signal relative to the beam pulse. For stored beam losses in SRs or ERLs, there is no beam loss pulse to time against, making long FOBLM less useful. They still could be used in shorter lengths like the solid RR proposed here, but they will suffer from low signal, high cost and low DR for the necessary PMTs.

The Čerenkov photons generated by e⁻ and e⁺ in the RR (fibers or rods), are the trapped by total internal reflection (TIR) if the angle relative to the surface normal exceeds the critical angle, $\theta_r \sim \sin^{-1}(n_c/n_r)$, where n_r and n_c are the refractive index for the RR material and its cladding, respectively. The solid RR has air cladding giving $\theta_r > 43.6^\circ$, where a large numerical aperture (NA) fiber with NA=0.37, $\theta_r > 75^\circ$. This means that for e⁻ with $\theta_e \sim 0$, none of the photons are trapped in the fiber but all of them are just trapped in the air clad RR. However, some will be reflected from the end of the rod unless an output index with n>1.05 is provided.

The coupling efficiency, ε , (the fraction of generated photon energy coupled out the RR downstream end), will depend on the polar angle, θ_e of e⁻relative to the central axis of the RR and the azimuthal angle, φ_e in a plane orthogonal to the axis, as shown in Fig.5. This has been calculated for optical fiber cable for particle detectors [10,11] which showed small ε (<1%) at $\theta_e \sim 5^\circ$ and a peak (~12%) near $\theta_e \sim \theta_c$. This peak value increases with increasing NA. For e⁻ from beam loss optical fibers will have small ε and will require PMTs to provide sufficient gain.

The air clad RR has NA > 1 meaning that some of the trapped photons will not couple out the end but will be reflected. Fig. 6 shows the angles used here which are similar to refs.[10,11] but we ignores the impact parameter b, since this will mainly affects the number photons emitted, but not ε . If the RR to detector has an air gap some photons suffer TIR at the end, reducing the output coupling efficiency ε shown in Fig. 7, versus (θ_e , ϕ_e). This shows $\varepsilon \sim 22\%$ at $\theta_e \sim 5^\circ$, with a peak $\varepsilon \sim 44\%$ for $\theta_e \sim \theta_c$ before decreasing to $\varepsilon \sim 0.1\%$ at $\theta_e \sim 110^\circ$.

This coupling is compared to a fiber optic RR with NA=0.37 shown in Fig. 8, which has $\varepsilon \sim 1\%$ for $\theta_e \sim 0$, a peak value $\varepsilon \sim 16\%$ near the $\theta_e \sim \theta_c$ and $\varepsilon = 0$ for $\theta_e > 60^\circ$. This will lead to very small signals for FOBLM due to small number of photons generated and output coupling.

These calculations assumed there was no absorption in the RR or fiber. If the photons are not TIR they will escape the RR and be absorbed or reflected from the outer material. This may be the reason FOBLM see signal in the reverse direction of 1-10% of the forward signal calculated here. In the air clad RR this is not the case, those photons not TIR are absorbed in the air space. If a PMT is placed 90° to the axis of the RR, very little signal will be seen since most of the signal is propagated to the detector end of the RR. This is why some CBLMs that used this arrangement [12] see small signals and large signal variations with loss position.



Figure 6: Geometry for e⁻ passing through the RR with the angles (θ_e , ϕ_e) and a distance b from the central axis, the z-axis for the RR.



Figure 7: Output coupling, ϵ versus (θ_e , φ_e) for an air clad RR, used in NSLS-II.

In addition to the reduced coupling the FOBLM will suffer greater radiation induced attenuation (RIA) damage. This is not as great an issue for linear accelerators used for FEL's, since the total charge losses are considerably less than for a high brightness SR's. This RIA is due to the cladding material in fibers adding impurities into the pure fused silica, which will increase the rate of color center formation with dose. This was measured to be >50X less attenuation loss per unit of exposure for the air clad solid RR as compared to fiber RR [13]. However in NSLS-II we will use thin scrapers ahead of the CBLM, that will provide a controlled local loss rate that will allow calibration of the CBLM in situ, accounting for any of these changes in signal attenuation.

TESTING OF PROTOTYPE CBLM

A prototype CBLM was made using 10mm Suprasil 2B rods available from existing stock [14]. A standard Hamamatsu PD module [15] was used from to detect the light signals from this RR. The CBLM was installed in the NSLS X-ray ring and the local beam loss was ISBN 978-3-95450-121-2

controlled using a horizontal scraper near the peak dispersion point as in the NSLS-II proposal. Fig. 9 shows the CBLM output voltage versus the scraper controlled local loss rate. The signal is linear over 5-decades of dynamic range with a minimum resolution of 0.3 fC/s DC loss rate. The beam loss signal during injection [7], has a peak loss rate that saturated the amplifier output, but the DC coupled PD module allowed integral values during the pulse to still yield the total beam charge lost, but without the pulse shape of the loss pattern. The integral under the injection peak showed a beam charge loss of about 85 pC or 5% of the injection current, over a 15ms period.



Figure 8: Output coupling, ε , versus (θ_e , ϕ_e) for a fiber optical RR with NA=0.37.

A custom PD module was obtained with a 64 KHz BW and significantly lower gain. This PD module will allow the injection peak loss rate to be measured on a turn by turn basis for NSLS-II, as well as for beam dump intensities without saturation of the peak signal, as shown in Figure 10. However the low level resolution for DC beam loss rate for this PD gain is ~8pC/s. We have a R&D effort to develop a HDR detector that will allow the beam loss signals to be measured over the 10⁹ DR loss rate between lifetime losses and the peak loss rate during beam dumps.



CONCLUSIONS

The Čerenkov signal has been shown to be the most appropriate beam loss monitor to quantify the local beam charge losses. The air clad RR has been compared to the

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fiber optic RR and shown to have greatly improved signal that allows detections with PD rather than PMTs, that have limited DR. A prototype CBLM was built and tested in the NSLS X-ray ring which demonstrated over 8decades of dynamic range with a switched gain photodiode system. The large diameter radiator rods yield high signal output that will verify the beam losses over an 8-10 decades of dynamic range. The use of thin scrapers provided the ability to control the local beam loss rate and therefore calibrate the CBLM. Development of a HDR-CBLM detector will allow measurements of beam loss from few electrons/ turn to peak losses from beam dumps and instabilities. They will also provide the operators with local beam loss information that could better control radiations levels to the experimental floor of SR's.



Figure 10: The CBLM beam loss signal of the 64 KHz PD module to 2nsec electron beam pulse with \sim 16 pC.

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