NSLS-II BEAM LOSS MONITOR SYSTEM *

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Abstract

NSLS-II storage ring is shielded for full injected beam loss around injection point, with the remainder shielded for significantly lower losses. To insure these design levels aren't exceeded, a Loss Control and Monitoring system (LCM) was designed. The LCM will control and monitor beam losses in the injection region and monitor injection losses outside that region. In order to measure quantitative charge losses, development of new beam loss monitors using Cerenkov light produced by the electron component of the shower induced by beam particles penetrating the vacuum chamber. These Cerenkov beam loss monitors (CBLM) measure the light from electrons passing through ultra-pure fused silica rods placed close to the inner edge of the VC. These rods will give sufficient light signal to monitor beam losses from several particles lost per turn to a major fraction of the 500mA beam in one to a few turns, about a 9 decade dynamic range of signal. Design and measurements of the prototype CBLM system will be presented. Although designed for light sources, CBLMs will provide quantitative beam loss measurements for accelerators with continuous high energy electron beams, such as ERLs.

NSLS-II DESIGN AND SPECIFICATIONS

The NSLS-II light source, which has started construction in FY2009, is a new 3rd generation light source that will replace the two operating 2nd generation light sources at BNL. It has been designed to provide major improvements in the existing beam properties from IR to hard X-rays, with leading edge electron beam properties.

The Storage Ring (SR) is a 30 cell DBA lattice with a super periodicity (SP) of 15, with alternating long (9.3m, LSS) and short (6.6m, SSS) straight sections. The ultra-low emittance (≤1nm) is obtained not from breaking the achromatic condition for the lattice, but by using a novel approach of increasing the synchrotron radiation damping using damping wigglers, DW, (3-8 7m 1.8T wigglers) in the achromatic straights to reduce the lattice emittance in steps, in addition to the user undulators in the SSS's[1].

In order to maintain the high brightness for the users, the SR is designed for top-off operation with a minimum injection pulse frequency of one injection per minute, in order to maintain a ±1% beam current stability. This requires a full energy booster capable of high injection efficiency.

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 will be shielded for a beam loss rate of up to 1/12th of the top-off injection rate at any one location in the ring. As a consequence of this shielding decision a Loss Control and Monitoring system (LCM)[1] has been specified that will control and monitor local beam power losses in all of the accelerators systems to less than the shielding design levels. The LCM will consist of components that will:

1. monitor and limit the beam power losses from the accelerators and transport lines
2. control a major part of beam losses in the SR to the heavily shielded injection region and
3. monitor the SR beam losses in the injection region and account for losses in the remainder of the SR.

LCM SPECIFICATIONS [1]

The LCM specifications for the accelerators and beam transport lines are based on an analysis of the severity of the potential radiation exposure for a particular beam loss scenario which exceeds the shielding design beam loss specification. For the injection systems, the severity of the full beam power lost at any point could be high enough that engineering solutions maybe required. For example, if the full beam power of the booster were lost at any point other than the extraction region, the area above the booster shielding berm would become a high radiation area. The engineering solution is to fence off this area and post a remote area radiation monitor at this location.

The LCM system will monitor the beam current loss (difference between two consecutive current monitors) times the energy of the system transporting that beam (i.e booster dipole or transport dipole field) to determine the beam power lost. If the lost beam power exceeds the shielding design level at that location, then alarms will be issued to operators and the accelerator control system that will require action to reduce the loss level. If corrective action isn't taken within a specified time period, that insures potential radiation exposures don't exceed administrative control levels (ACL), then the LCM could prevent injection from continuing. The decisions made by the LCM are not as critical, as the Personal Protective System (PPS) and therefore will be made in a non-safety rated micro-computer that will automatically stop injection if the system fails.

This type of decision will be made for each stage of the injection accelerators and alarms sent when ACL are exceeded or are being approached. The analysis of full injection beam losses in the SR doesn't result in as high a potential radiation level as in the injector, but will have a risk of greater exposure due to the greater occupancy of the experimental floor. Therefore, in the SR the LCM

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1 LCM System was previously called Beam Containment System.

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must insure local losses don't exceed the ACL, which as a result of the change in shielding thickness around the SR, will depend on the location of the beam loss. The LCM system for the SR will consist of beam loss control using scrapers and verification of the local beam loss using Cerenkov Beam Loss Monitors (CBLM), both in the heavily shielded injection region. The remaining unaccounted for beam loss will be attributed to losses in the remainder of the SR where the shielding isn't as thick. Each of the two regions will have different ACL values for beam loss rates and will be monitored and alarmed if exceeded. These loss rates can be exceeded during non-operational periods (i.e. commissioning and machine studies) or during operations when the SR is under administrative control.

SR BEAM LOSS CONTROL

The LCM is planned to capture a major portion of the beam losses in the heavily shielded injection region using beam scrapers. It is planned to provide five scraper locations, each with a pair of opposing blades to define the beam aperture channel for the circulating beam at that location. The locations of the scrapers are shown in Figure 1 and were chosen to be near the location of maximum amplitude of the beam particles: two vertical scrapers (Vscraper1 & 2) are at large β_y locations with ~70° phase shift between them, one horizontal scraper (HscraperX) is at a zero dispersion but high β_x location and the two horizontal (Hscraper1 & 2) are at high dispersion locations with a 90° horizontal phase shift between them.

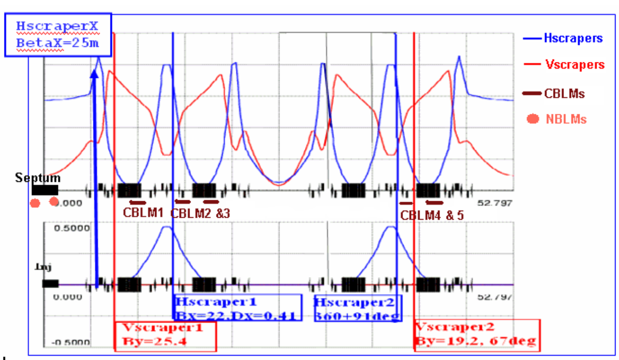

Figure 1: The SR Injection period showing Horizontal (blue) and Vertical (red) scraper locations and Twiss parameters. Also shown are the locations of the CBLM used to monitors the beam losses with or without the scrapers.

The later two, Hscraper1 and Hscraper2 are the only ones planned for use at high current operations, and only the inner blades are considered critical. They will be inserted to ΔX~ -23mm, which will set a closed orbit momentum aperture of $\delta \geq -5.2\%$. This will intercept low momentum particles from beam dumps, Bremsstrahlung, instabilities and the low energy particles from Touschek scattered electrons. The high energy Touschek scattered electrons, if they survive half a synchrotron period will be decelerated by the RF (~60 turns) to lower energies and intercepted at these inner blades.

The scrapers are designed to be only 10mm (0.7 X_{rad}) thick of copper, which will absorb only enough beam energy to insure the subsequent dipole will bend these electrons out of the vacuum chamber in the injection region. For electrons with greater than 20% of their energy lost in the scraper (86% of electrons hitting scraper will loss > 20% of their energy) they will be bent enough by the next dipole to hit the inner vacuum chamber wall (VCW) in or ahead of that dipole magnet. The 13.5% of the incident electrons that penetrate, will be lost on the VCW downstream of the dipole. The 0.5% that have <1% energy loss, will hit the second scraper where they undergo additional energy loss and hit the VCW. The surviving intercepted electrons that might circulate is < 10^{-5}. The thin scraper will produce lower levels of transverse radiation and neutrons off the scraper, requiring less local shielding. The beam that is dumped in the dipole will see considerable self-shielding by the dipole yoke itself, reducing the local scraper shielding[3].

The details on the beam loss control function of the scrapers were presented in Ref. [4]. The scraped beam that hits the VCW will be the source of the electron signal for the CBLM, also located in this region.

SR BEAM LOSS MONITORING

The use of beam scrapers to intercept beam losses in the injection region was deemed insufficient and it was suggested this beam losses in the injection region needed to be verified. The beam charge loss rate will be determined from DC beam current measurements (I_o), plus any injected charge (Q_{inj}), during injection periods that wasn't stored will be given by:

$$Q'_{loss} = \{Q_{inj} - [I_o(t+dt) - I_o(t)] * T_o\} / dt \qquad (1)$$

where T_o is the SR revolution period.

If the amount of charge that hits the scraper can be measured, then the remaining unaccounted charge loss $Q'_{sdl,}$ would be attributed to the lower shielded region of the SR. If this loss rate was below the design limit, then it doesn't matter where it is lost. Even if this limit is exceeded for short time periods, the average over administrative time periods could be maintained below this limit, by reducing the injection rate, as a last resort.

Several methods have been considered for measuring this charge hitting the scraper directly. Beam loss monitor studies from the NSLS [5] showed radiation measurements outside the magnets would not yield quantitative charge loss rates. The approach that appears most promising is to measure the electrons shower after the dipole magnet bends the electrons into the VCW. The high energy charged particles (e^- and e^+) from this shower will have relatively small angular and spatial spread and a Cerenkov radiator placed close to the vacuum chamber (inside the magnet yokes) will provide a signal proportional to the initial charge loss, with a large signal variance due to variation in charged particles production in the shower. The NSLS-II vacuum chamber uses a

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NEG pumping ante-chamber toward the outside of ring. This leaves a gap in the magnets toward the inside of the ring where a fused silica Cerenkov radiator rod (RR) can be placed in between the coils of quadrupole and sextupole magnets as shown Figure 2. A similar rod can be placed in the gap of the dipole magnet to measure charged particles that hit the scraper at that location. If these rods are placed downstream of a thin scraper, then the scraper aperture can be used to control the beam loss rate at that location and the signal output from a CBLM could be calibrated relative to the DCCT measured charge loss.

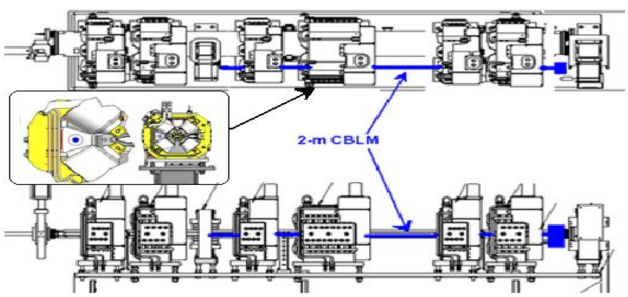

Figure 2: Two meter long CBLM placed inside quadrupole and sextupole magnets on a SR girder.

SIGNAL GENERATION IN CBLM

If the beam electrons passed through the RR (fused silica with refractive index n=1.46) each would produce about 900 photons per centimetre of path length with a uniform energy distribution from 1.55 eV (800nm) to 6.2 eV (200nm). With this amount of light produced for a 10mm diameter RR, a photodiode (PD) could be used as the detector rather than a photomultiplier tube (PMT). The advantage of a PD over a PMT is: higher dynamic range, greater linearity over that range, lower cost and no need of high voltage. The signal from a PD was estimated by convolving the PD sensitivity with the photon flux spectrum for Cerenkov radiation versus wavelength ($N \sim \lambda^{-2}$) as shown in Figure 3. The resulting current for one electron lost per revolution of NSLS-II passing orthogonally through a 10mm RR was calculated to be ~0.02nA, compared to the 0.1nA dark current for the PD. However the number of electrons generated in the shower that occurs when the electron hits the vacuum chamber needs to be estimated, which could enhance this signal.

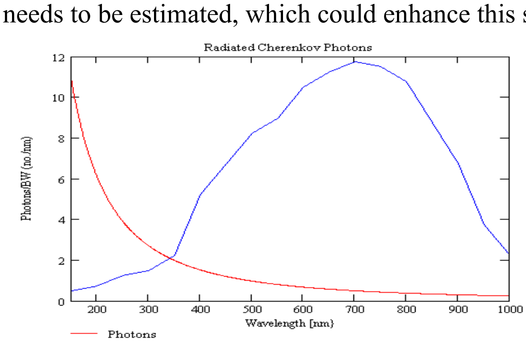

Figure 3: The Cerenkov photon flux spectrum (red curve) versus wavelength and the PD sensitivity (blue).

In order to simulate the signal produced in the CBLM RR, the electron shower was generated for beam hitting the 25mm thick inner vacuum chamber wall (VCW) using the Shower [5] interface to the EGS4 program [6]. The glancing angle of the electrons to the VCW was varied from 1° to 10° and the parameters of the e^- and e^+ particles exiting the inner wall with energy >10MeV (Cerenkov energy critical energy is >0.7 MeV but the magnitude of light emission and the penetration in fused silica is small below 10 MeV) were computed at the position of the RR. For incident angle, θ = 3°, the vertical position of the particles at the RR are shown in Figure 4. A 10mm diameter RR will intercept >30% of the electrons and will reduce the sensitivity of signal variations to the vertical position and angle of the initial electron, as compared to a smaller diameter RR (e.g. a 400µm fiber optic cable). For the e^- particles that pass through this RR ($|y| \leq 5$mm) their longitudinal position and path length in the RR are computed and shown in Figure 5. For each beam particle incident on the VCW at 3°: 1.66 ± 0.13 e^- pass through the RR with an average path length of 33 ± 53 mm and 0.46 ± 0.06 e^+ with path length of 17 ± 4.7mm. This increase in number of charged particles times the increase of the photons from the increased path length of the charged particles in the RR gives a signal enhancement factor of 6.3 ± 1.5 times an electron incident on the RR at 90°. This increase is over 11X at an angle of 7° as shown in Figure 6, allowing the signal to noise to exceed unity for single electron losses per turn in the CBLM with the PD module.

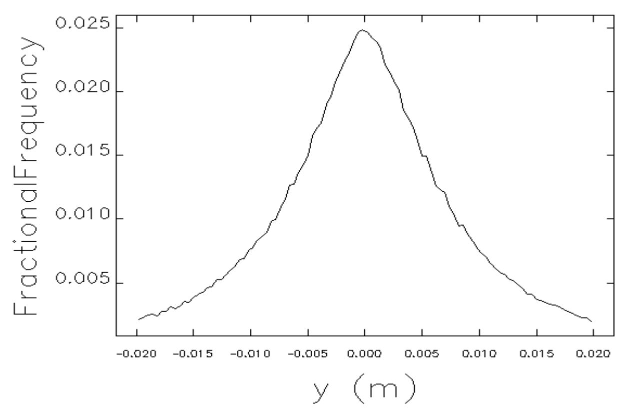

Figure 4: The vertical position of shower electrons at the RR generated in the 25mm Al VCW for a 3GeV e^- beam incident at 3 ° to the wall.

The electrons from the shower have a large spread in longitudinal position, requiring a RR that is at least 1meter long in order to capture a large part of the beam loss signal. These optical quality rods are free drawn and have a natural polished barrel that will propagate the light generated by the electrons to the PD by total internal reflection (TIR). Drawing a rod with 10mm OD longer than 1meter isn't easy, however a 25mm OD rod could be up to 2meters long [7]. NSLS-II will use 29.5mm OD rods, 1.2m long which was available from existing stock.

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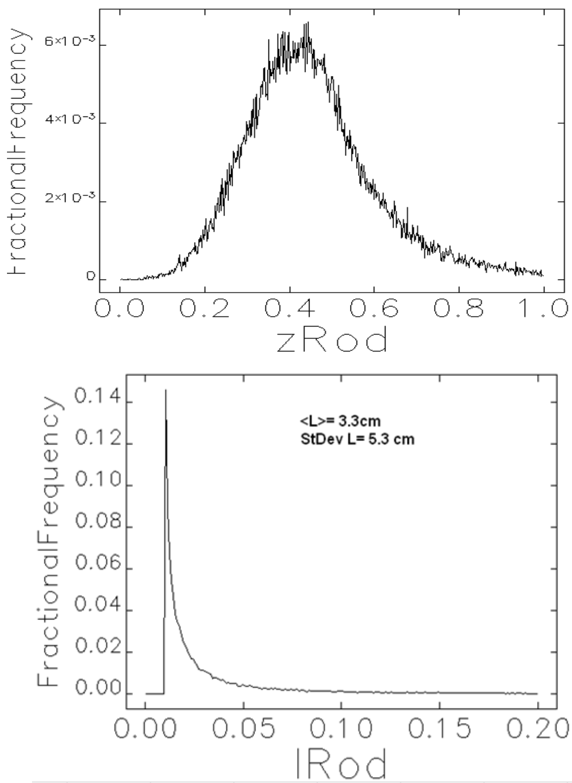

Figure 5: The longitudinal distribution of electrons with > 10 MeV energy that penetrate the VC wall and pass through the RR is shown (upper) and their path length in the 10mm RR is shown (lower).

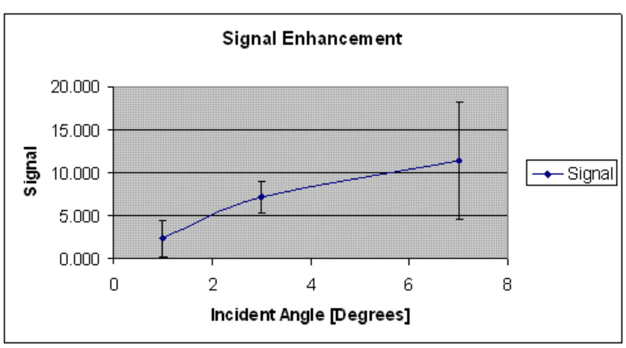

Figure 6: The signal enhancement from the electron shower in the VCW versus the incident angle of the electron.

TESTING OF PROTOTYPE CBLM

A prototype CBLM was made using 10mm Suprasil 2B rods available from existing stock [7]. A standard Hamamatsu PD module [8] 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 controlled using a horizontal scraper near the peak dispersion point as in the NSLS-II proposal. Figure 7 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 0.3fC/s DC loss rate. The high gain of this unit (10^9 V/A and low bandwidth of 10 Hz) make this unit saturate at a rate of 60pC/sec. The lower gain setting of this PD module has a 1 KHz bandwidth has a dynamic range of 0.1 pC/s to 10 nC/s. The beam loss signal during injection had a peak loss rate that saturated the signal output but the DC coupled PD module allowed integral values during the pulse to still yield the total beam charge lost, but not the peak loss rate nor the pulse shape of the loss. The injection beam loss on the CBLM is shown in Figure 8 for the lower gain PD module with a 1 KHz BW. 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. At higher stored current a second loss signal appears about 22 ms after the injection pulse was captured, that wasn't seen at lower stored currents.

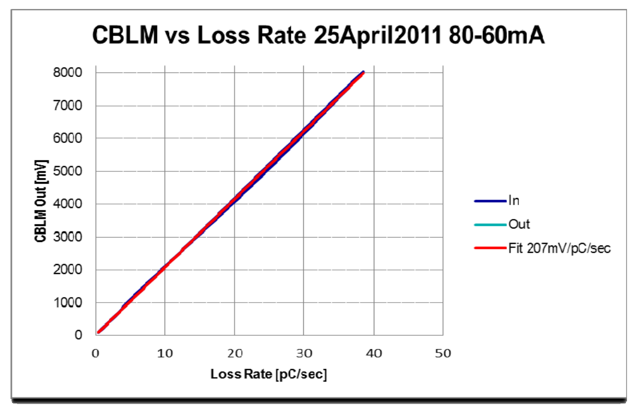

Figure 7: High gain PD module output of the CBLM versus calibrated loss rate in the X-ray ring.

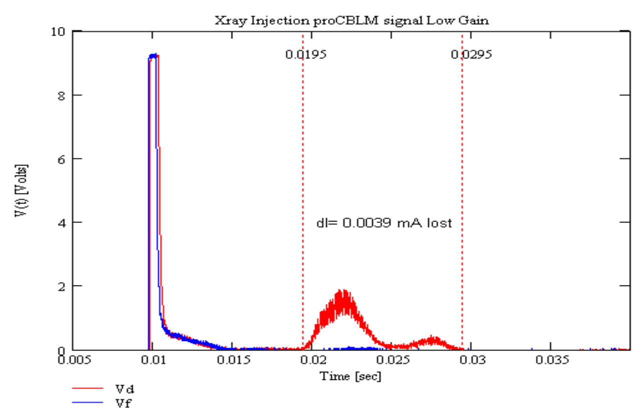

Figure 8: The injection beam loss signal from the prototype CBLM for a lower gain PD, with a 1KHz BW.

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 9. However the low level resolution for DC beam loss rate for this PD gain is ~80pC/s.

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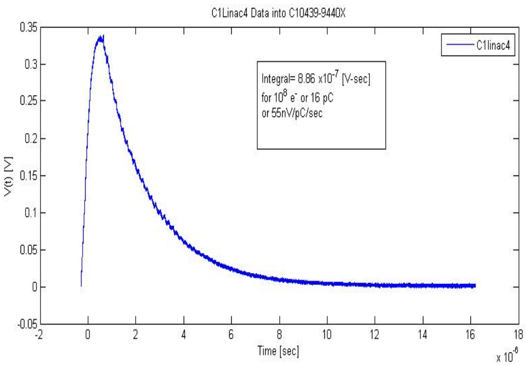

Figure 9: The CBLM beam loss signal of the 64 KHz PD module to 2nsec electron beam pulse with ~16 pC.

HIGH DYNAMIC RANGE CBLM

NSLS-II is developing a high dynamic range detector module that will provide the high peak intensity beam loss capabilities of the high BW low gain detector shown in Figure 9, with the low intensity beam loss of the high gain detector shown in Figure 7. This is possible with a logarithmic output amplifier using the existing PD (an 8-decade log amplifier is being tested and a 10-decade is being considered), but the large area PDs will always have low BW output. An alternative approach being pursued is to introduce a dual detector using a PMT to use the high gain and high BW of the PMT for the low intensity range using count rate to extend to the lowest beam loss rates and average current when the pulses start to pile-up but before the PMT starts to develop a nonlinear response. The two detectors will be cross calibrated in the overlap region using the installed scrapers.

Also the NSLS-II design will include a light output coupler (light pipe) to propagate the light away from the plane of radiation from the lost beam to a location under the magnet girder where the PD module will be placed. This will lower the radiation level at the PD module and reduce the amount of shielding required around the detector box. This will simplify installation and repair access to the detectors since only the RR and its light shield need to be installed prior to the magnets in the tunnel.

CONCLUSIONS

A Cerenkov signal beam loss monitor will be used to quantify the beam charge losses in the heavily shielded injection region and used to verify that the majority of the beam losses occur in that region as controlled by the inserted beam scrapers. A prototype CBLM was built and tested in the NSLS X-ray ring which demonstrated over 8-decades 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. However, to extend the range to the lowest loss rate (useful for diagnostics of the storage ring beam dynamics: diffusion and resonant structures) a dual detector system is being proposed.

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