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Injection Beam Loss Monitor for NSLS-II Radiation Protection

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I. Beam Containment during Injection

The NSLS-II with its high stored beam energy operation and top-off injection, makes the radiation protection a critical issue. The radiation shield wall of the tunnel is being designed to be adequate for a 10% loss of the injection current (1.4nC/min) at any one location. The injection region is shielded for 100% injection losses (14nC/min). This thinner shielding around the ring is a concern should the beam develop high current instabilities, that would cause the beam to dump or develop a very short lifetime. In order to overcome these instabilities, studies and operations in the high current conditions that might drive these instabilities would be required. If the radiation shielding would not allow operation at these currents, then the ability to study and correct these instabilities may not be allowed or at least not without greatly restriction the users access to the experimental floor.

We propose a detector that could be used to quantify the amount of charge (DC current) lost around the ring, verifying that beam losses didn't exceed the design levels. This would then allow the beam to be refilled for operations and/or studies without regard to the experimental floor occupancy. In a earlier Tech Note we proposed a method to control the location of the beam dumped during intentional (interlock trips) and unintentional beam losses, this Tech Note will deal mostly with accounting for beam lost during injection.

Accounting for where the beam is lost in a quantitative manner isn't easy. The proposed area radiation monitors cannot distinguish between one unit of charge lost one meter from the detector from nine units of charge lost three meters away from the detector. In addition with the material in the magnets surrounding the beam pipe, showers from the high energy electron beam lost in this material upstream from the detectors may be more effective at producing signals in the detector than beam lost closer to but adjacent to the detector. Therefore, verification that the beam lost during injection didn't exceed the beam containment levels, will be difficult at best.

There is a plan to include 60 electron beam loss monitors (BLM) for NSLS-II. The advantage of these monitor is that they see electrons by requiring a coincidence between two photodiodes assuring that a charged particles passed through the diodes. I have tried to use them years ago in the NSLS- VUV ring but with little success. The problem is that the individual diodes see X-rays and they may have a singles rate of 10KHz and a coincidence rate of 100's, most of which are accidentals. In the Xray ring this would be much worst since singles rate will be orders of magnitude greater from the X-rays in the synchrotron radiation. Also since they give 100nsec output pulses the only way I know to get a meaningful output of radiation flux is to put the signal into a rate meter. The commercially available units have update rates of the flux signal at about 100Hz rate, too slow to see synchrotron or betatron oscillations. Additionally the diodes are so small and directional that they cover a very small portion of the ring that many are needed to cover the ring losses.

Recent measurements with the BLM in the VUV ring showed it is useful for measuring losses due to reduced lifetime when the NSLS thin scraper was used to reduce the momentum aperture of the ring. The BLM was placed on the horizontal plane of the orbit right against the vacuum chamber after the dipole following the scraper. The electrons that lose energy in the scraper were bent more than 45° and hit the inner vacuum chamber wall after the next dipole and were detected on the BLM. Figure 1 shows the result of a scan of the momentum aperture with the inner scraper blade. The BLM signal was measured with a ratemeter with an update rate of ~100Hz. The large noise on the signal after the scraper cuts the momentum aperture below the RF bucket height is quite evident. This noise induces energy modulations of the beam with frequencies from 60Hz to 11KHz(the synchrotron frequency). However measuring these components with the ratemeter is impossible and even a spectrum analyzer can only see the lowest 60 -720Hz signals, due to the poor duty cycle of the 100nsec pulses from the BLM.

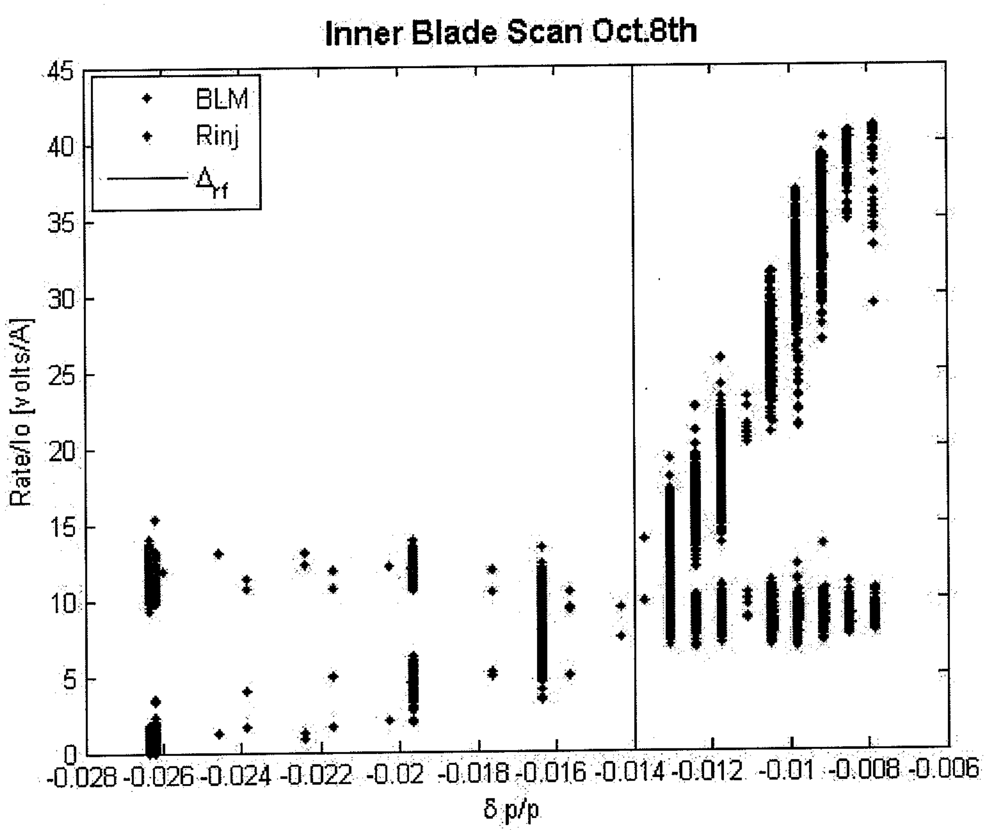

Figure 1 Scan of the momentum aperture of the VUV ring using the inner blade (located at the peak dispersion η_x ~1.5m) with measurements of the radiation rate at the Injection septum (using NaI detector) and electron loss rate at the dipole after the scraper (using the BLM).

This problem of seeing fast changes of the electron flux with the BLM's, make their usefulness in seeing fast injection losses questionable. Their small area of coverage would mean that the 60 proposed will not be adequate to get quantitative losses of beam charge possible and only qualitative losses will be measured. The best use for injection losses that might be possible is to zero a counter before the injection pulse and then 100msec later read the count for an integrated loss as a function of position around the ring. This timed operation may not be possible since the triggered operation seems to be more like a gating of the counters in the **microIOC** unit that is planned as the interface to the BLM's and it appears that the minimum counter interval is 1 sec. However, there is no way to see the losses in the 2 to 4 μsec time period that would be indicative of betatron injection miss-match or the ~300 μsec time period of a injection energy or timing mismatch. The lack of this diagnostic timing information and the small area of coverage which will make quantitative charge loss impossible, suggesting that there maybe a better system for a beam loss monitoring. The proposal of a an active scraper to measure the amount of charge hitting the beam scarper and therefore getting lost in a beam dump dipole (NSLS-II Tech Note ?) suggest that there might be another solution.

II. Longitudinal Beam Electron Beam Loss Monitors

The idea of using Cerenkov radiation to see the lost beam electrons directly when they pass through the vacuum chamber walls has the same advantage as the BLM's have, they are only sensitive to electrons. However, since the Cerenkov radiator does see X-rays there will be no high singles rate in the diodes and therefore no accidental rate to contend with. Also the passive radiator could be of long length, it can provide much greater coverage of the ring losses than the 3mm diameter by few mm separation diode pair in the Bergoz BLM units.

Quartz Cerenkov detectors have been used in high energy experiment to measure the mass of particle whose momentum or energy is known. Therefore this method could be used to distinguish between gamma's and electrons, since only charged particles would radiate. The index of refraction for Quartz is n= 1.458, so electrons with velocity $\beta_t \geq \frac{1}{n}$ will radiate a cone of Cerenkov light with critical angle $\theta_c = \cos^{-1}(\frac{1}{n\beta})$. For 3 GeV electrons θ_c=46.7 [deg] in quartz and electrons radiate for energies above E_e > 0.7MeV. The photon spectrum per unit of photon energy Eγ per unit length is

$$
\begin{aligned}
\frac{d^2N}{dE_\gamma dx} &= \frac{\alpha}{hc}\sin^2(\theta_c) \\
&\approx 370 \sin^2(\theta_c) \;\; [eV \cdot cm]^{-1}
\end{aligned}
\tag{1}
$$

This yields the wavelength dependence that peaks at the short wavelength giving the blue light, the photon spectrum is given by

$$
\begin{aligned}
\frac{d^2N}{d\lambda dx} &= \frac{2\pi\alpha}{\lambda^2}\sin^2(\theta_c) \\
&\approx 370 \cdot 1239 \frac{\sin^2(\theta_c)}{\lambda^2} \;\; [nm \cdot cm]^{-1}
\end{aligned}
\tag{2}
$$

The power spectrum for one electron per turn (f_o = 378.5 KHz) is obtained by multiplying Eq.(2) the energy at each wavelength $E_\gamma(\lambda)$ times f_o times the length of radiator, L in cm.

$$P(\lambda) = \frac{d^2N}{d\lambda\, dx} E_\gamma(\lambda)\, e\, f_o\, L \;\; [W/nm] \tag{3}$$

Figure 2 show the power spectrum and the sensitivity for a VUV silicon photodiodes for one electron per turn with normal incidence angle on a 1cm quartz radiator. Also show is the spectral sensitivity curve for a VUV photodiode in A/Watt *0.3(scale factor)

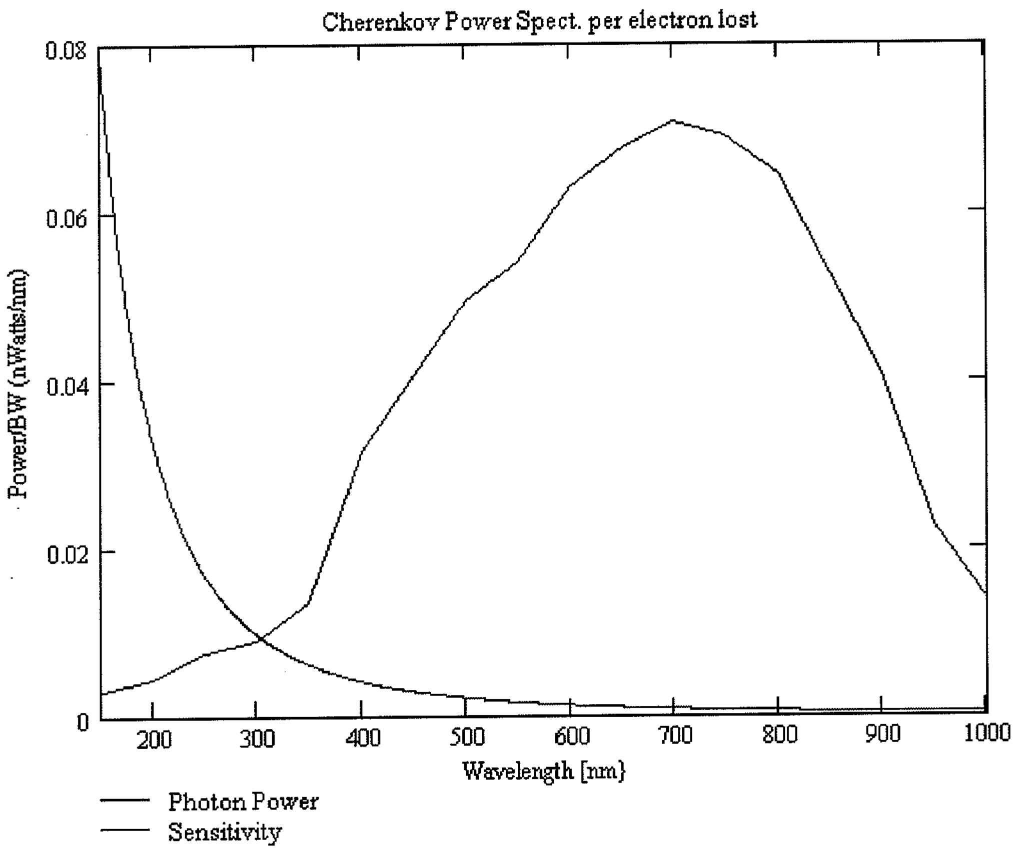

Figure 2 power spectrum for one 3 GeV electron per turn hitting a 1cm quartz radiator at normal incidence(red curve) and a VUV photodiode sensitivity curve in A/Watt*0.3 as a function of photon wavelength.

Integrating the power spectrum times the sensitivity curve from 150 to 1100nm yields a signal of $I_e \sim 0.24$nA per electron per turn. The diode is said to have a 0.1nA dark current, giving a S/N of 2.4. Assuming a 0.01nC/turn loss during injection the signal would be 37μA or with a shunt impedance of 1KΩ a 35mV signal well above the 0.1μV dark current level. However, most electrons will not be normal incident so the radiator length will increase as $1/\sin(\theta_i)$. If we use the energy degraded electrons from the scraper, they are bent by the dipole to the inside of the vacuum chamber by about 2.6 degrees this angle would increase the radiator length to 22cm and the signal by the same amount.

The quartz rod not only serves as the radiator but also as a light pipe and will collect the light over the length of radiator by internal reflection. The angle of incidence relative to the normal for total internal reflection (TIR) in quartz is $\theta_t = \sin^{-1}(\frac{1}{n}) \approx 43.3$ [deg]. For angles greater than that θ_t

there will be TIR. For quartz the normal incident electron (θ_i = 90 deg.) radiates light that will hit at just the angle θ_t, allowing both the forward (toward detector, assuming one detectors at one end of rod) and backward (away from the detector) to be TIR. Figure 3 shows the photon light cone angle of incidence on the rod surface as a function of the electron incidence angle on the rod. This angle for the forward light θ_a is given by $\theta_a = 180 - (\theta_i + \theta_c)$ and for the backward light is θ_b by $\theta_b = (\theta_i - \theta_c)$. Figure 3 shows that the forward light wave is TIR for all angles of the incident electron and once θ_a hits 90 degrees the light is directed parallel to the rod's length and above that it hits the opposite wall first with angle $\theta_a = (\theta_i + \theta_c)$. The backward light wave is just TIR at normal incidence but as the angle is decreased it is below the angle for TIR until about 3 degrees when the TIR angle is satisfied again. Also below an incidence angle of $\theta_i < \theta_c$ the backward wave is actually launched forward and both waves are collected. Countering this loss of light collection is the increase in radiator path length as θ_i decreases, increasing the signal as the light collection degrades. However, some of the non-TIR light may also be collected if a reflective housing is provided. Despite the complicated light collection issues, there appears to be more than adequate signal to detect quantitative measurements of electron charge lost in short time periods using long radiators coupled to photodiodes, not expensive photomultipliers as used in the nuclear physics experiments.Clearly an R&D study is required to answer the question related to these quantitative issues.

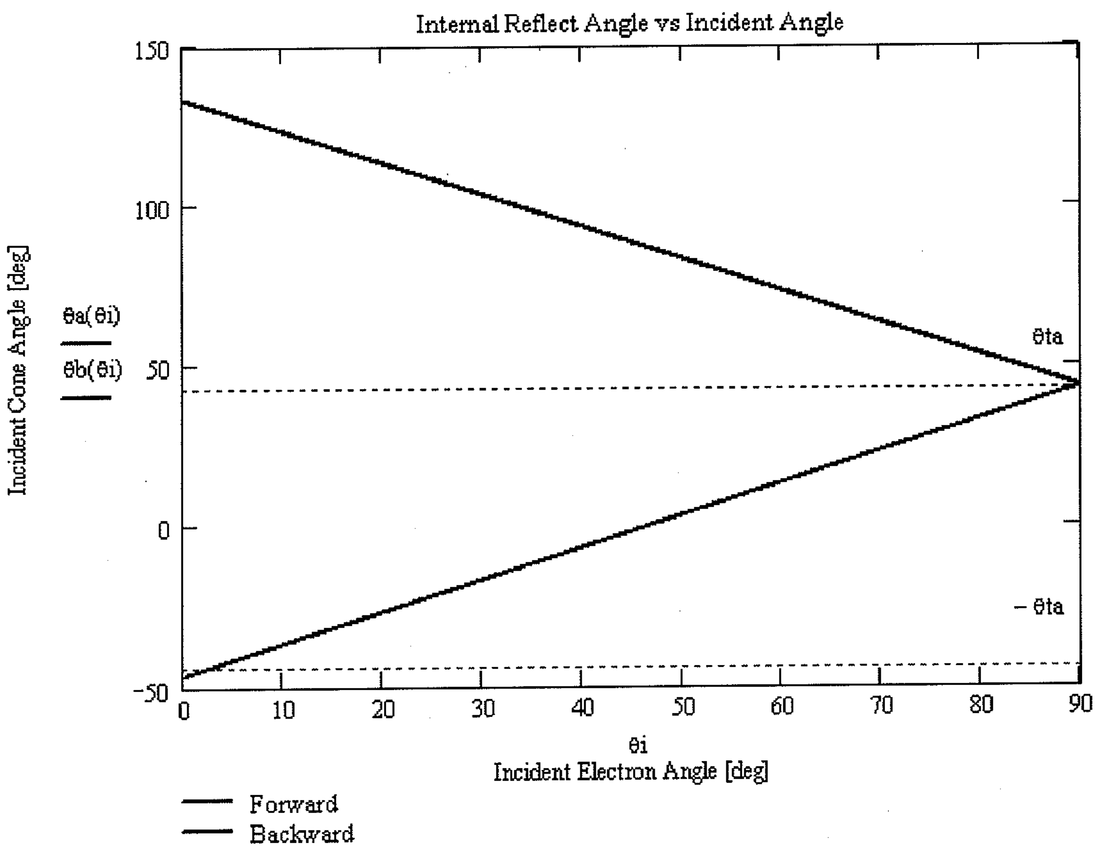

Figure 3 show the incidence angle for the Cerenkov light radiated in quartz versus the incident electron angle. The photon angle of incidence for TIR is shown as $\pm\theta$ta marker lines.

III. Electron Beam Loss Monitor for NSLS-II

The use of long Cerenkov radiator rods is proposed to replace the Bergoz BLM's, as a beam loss monitor could provide quantitative measurements of the amount of charge lost during injection and during operations. High energy experiments uses photomultipliers to couple to the radiators, but they are interested in single particle detection and the largest signals possible for distinguishing the amount of light from each particle which depends on the velocity of the particle. Spectrosil rods are available in length up to 1.5m and I was told maybe up to 2m long. If they can make them in the 10mm diameter rods then they can be coupled to a 10mm active area photodiode without the need of tapered transitions. They will have an air gap for TIR in the rods and an optical shield which should also be reflective for additional collection of light, not TIR. The light shield could include several mm of lead that might enhance the signal with gamma ray produced secondary electrons adding to the electron signals already present after penetrating the Aluminum vacuum chamber. These rods need to be placed close to the ring vacuum chamber with a minimum of material in between. An idea spot would be on the plane of the horizontal bending on both sides of the beam pipe. However with the anti-chamber on the outside of the ring it could go on the inside (x<0) side of the ring chamber and placed in the quadrupole and sextupole space between the coils as taken by the anti-chamber on the outside of the ring. Figure 4 and 5 shows a 10mm radiator with 10mm of shielding around the radiator for about a 35mm diameter rod. Since both the rod and its shield and the photodiode are insensitive to magnetic field and non-magnetic this location should be no problem to install. The detector will be damaged by the radiation at these locations so it will need to be shielded with Pb to minimize damage over time, possibly 1cm of Pb is needed.

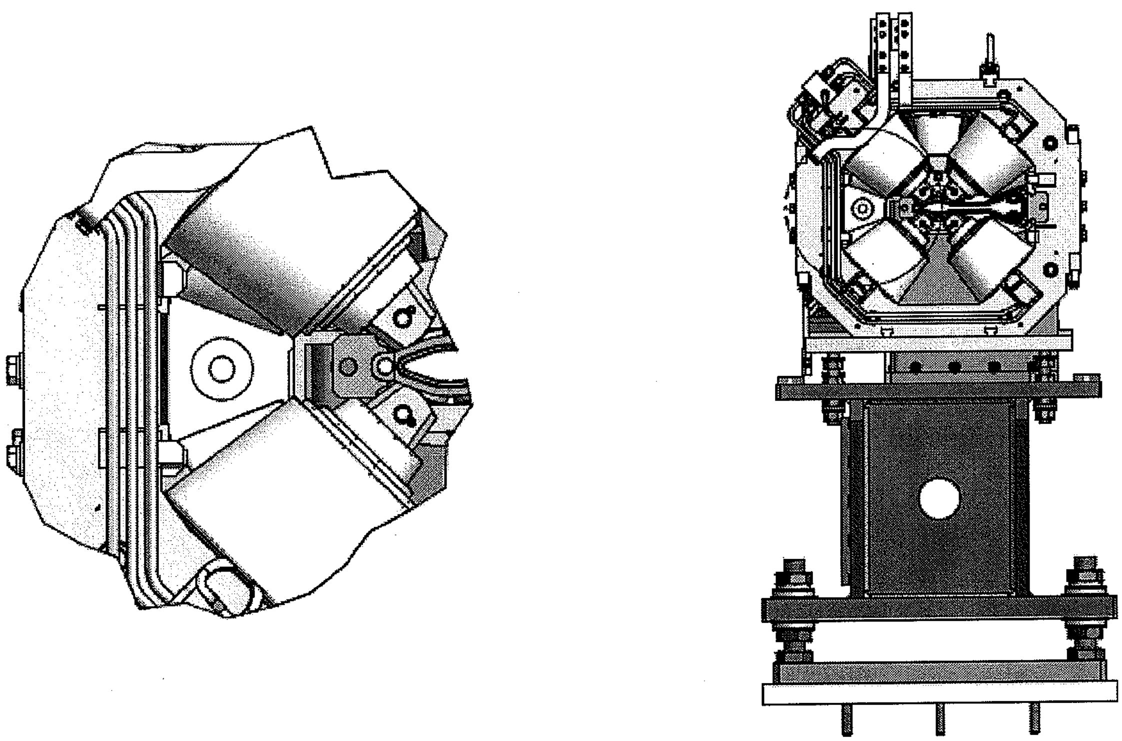

Figure 4 Schematic drawing of the long beam loss monitor in the aperture of the quadrupole magnets. The monitor is ~10mm diameter radiator/lightpipe and a 20mm Pb or aluminum light shield.

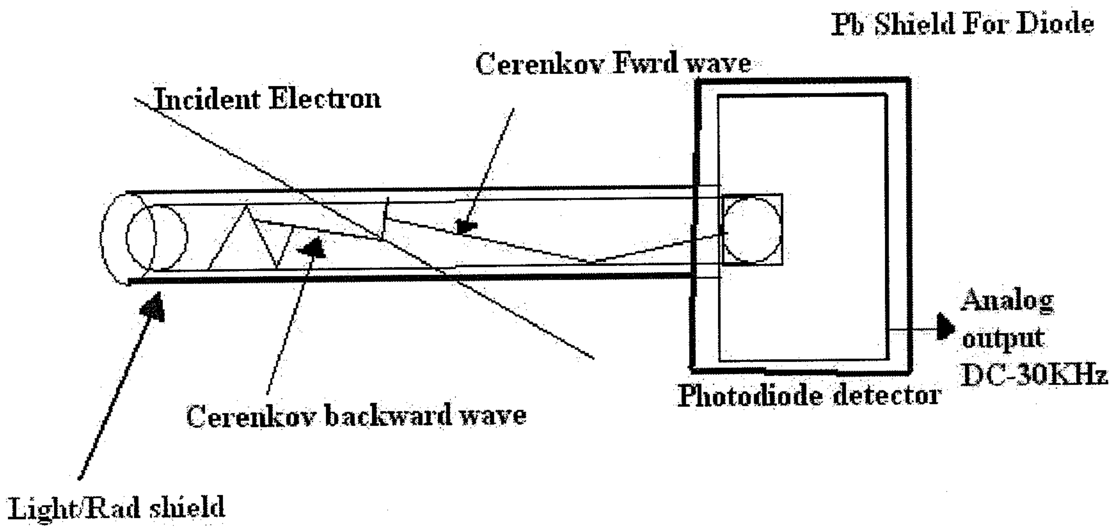

Figure 5 a schematic drawing of the long beam loss monitor (10mm diameter Quartz rod) with photodiode in the radiation shielding enclosure.

Costs for the long beam loss monitor (LBLM) have been estimated assuming that every girder would have one of them installed in the central quadrupole magnet (QF = 40cm) and a 2m long rod would fit between QH1 to QH3 on the HID girder and QM2 to QM2 on the dispersion girder, encompassing the maximum beta X and Y and the peak dispersion functions of the lattice. With three girders per cell this would give 90 LBLM's in the ring. With each 2meters long this would give almost 25% coverage of the ring circumference but at the most likely loss points due to betatron and energy aperture losses. Rods have estimated to be £250 or \$375 each in quantity of 20s, the light shield is still questionable but shouldn't increase the cost to more than \$500 each. The diode is about \$350 in units of 100 but a commercial diode module is available in units of 5 for \$662, which includes bias network and an amplifier to 1KHz (30KHz could be made available at little cost increase). The signal processor would just be a slow 100KHz 16-18bits ADC with trigger on the injection pulse. This gives a unit cost of:

Rods 10mmOD x 2m long	= \$375	
Sheilding for 2m long and diode	~ \$125	
Diode detector module(units of 5)	~ \$662	
Power supply ± 5VDC	~ \$ 15	
16 bit ADC with trigger input	~\$1200	
Total	~ \$2377	x 90 ~\$215K

IV. Electron Beam Loss Monitor R&D Effort

Quartz rods with high radiation resistance need to be very pure and nuclear physics experimenters have measure this property in Spectrosil 2000 which is available from Saint-Gobain which has recently been acquire by Heraeus Quartz LTD of Great Britain. They have a production facility in Georgia, USA that dose a free draw to any diameter 6mm to 75mm, with a surface that may not need polishing, this could mean lower prices for NSLS-II than quoted above. However for the R&D effort the GB facility of Heraeus has 10mm diameter rods 1meter long that have a rougher outside surface. Polishing them would run the cost up to £285 = \$435, however they have a minimum order of £300 so it might be good to order a second rod, unpolished for £155 for a total of

£440 = \$671. The diode module in single unit from Hamamatsu costs \$816. The mounting and light and radiation shielding would require the major effort of the project and the plan would be to involve the Instrumentation Division here at BNL. The readout will be oscilloscopes and maybe gated integrators using ADC's already available, directly to Matlab or Agilent VEE. If NSLS software people can interface it to existing channels of 16bit ADC then the NSLS orbit history will be available for long term operational experience. These channels are already available in the VUV Orbit micro and would only need the signal level to be amplified to the ADC levels of + 10V.

1) Once the diode and quartz rods are available there will be several in lab tests that will be done using a LED pulse to characterize the diode and coupling to the quartz rod.
2) With the rod/diode coupling worked out and a light shield built, testing on the VUV ring with the rod mounted vertically and scanned through the beam plane with the scraper providing the source of the electrons (as demonstrated in Figure 1). This will measure the response to position of the electrons hitting the radiator.
3) Studies will be made on the impact of a Pb shield to the shielding around the rod and the linearity of the diode signal with charge hitting the radiator. This linearity with charge of the diode signal will be measured by putting the scraper to zero and letting the injected electron get extracted, by the subsequent dipole, to the radiator rod mounted horizontally in the quadrupoles in the RF straight section.
4) Once the measurements in the VUV ring are completed and the radiation shield decided, the radiator will be mounted in the Xray ring near the injection septum, where the injected beam will hit as the septum current is varied to zero. This will prove this systems linearity with current hitting the radiator and the levels of light generated by the knock off electrons from Xrays and gamma rays in the tunnel.
5) Long term operation and radiation levels will be monitored using TLD dosimeters that will be changed and recorded at each shutdown of the Xray ring (once/month) and the LED characterization measured to look for radiation induced changes in the rod or diode sensitivity.