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Active Scraper and Beam Dump for NSLS-ll Radiation Protection

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I. Introduction and Case for Beam Dump Radiation Calibration

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 5% loss of the top-off injection current at one point in the ring. However, the injection region is shielded for 100% injection losses. This weaker shielding around the ring is a critical 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 this operation at these currents, should the entire beam be lost at an arbitrary point around the lattice, 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 that if a method can be found to quantify the charge (DC current) lost or a major portion of that charge lost from the stored beam was actually lost in the injection region, then shielding should be adequate from the radiation protection design point of view. This would then allow the beam to be refilled for operations and/or studies without regard to the experimental floor occupancy. In addition we propose that a change in direction of the electron beam that is being lost or dumped (e.g. interlock trip induced dump) could also improve the effectiveness of the radiation shield and might allow cost saving in the radiation shield of the tunnel.

At the APS there are beam scrapers that intercept the Touschek scattered electrons (energy lost or gained of ~6%). These scrapers are 7.5 cm of copper in the beam direction, or about 5.25 radiation lengths. These cause the beam to shower with reduced radiation directed straight ahead in the straight section and increased levels of radiation transverse to the beam, which requires additional local shielding. At SPEAR3 a fixed aperture was installed in the injection region to dump the electron beam in a controlled location when the RF is tripped by the interlocks or unintended RF trips. Likewise this local source point is heavily shielded with lead to reduce the level outside the shield wall in that location.

These ideas of controlling the loss point of the electron beam is the basic idea behind the beam scraper/abort system proposed for NSLS-II. However, we will look into improving the idea described above by: 1) reducing the High Energy neutron (HEn) and gamma (HEg) flux directed toward the experimental floor and 2) attempting to quantify the amount of charge lost at the beam dump versus that lost around the ring where the shielding is thinner. In this manner by reducing the radiation source term to the experimental floor and insuring that the beam that was lost was dumped at this controlled location, the need to provide thicker radiation shield wall around the rest of the ring might be reduced.

II. Design low energy loss, low Z scrapers/beam abort

In order to reduce the amount of HEn and HEg directed in the electron beam direction, the scraper should absorb a minimum of the electron beam energy, such that the electrons will be bent out of the beam vacuum chamber and into a well shielded beam dump. Since the bremsstrahlung cross section increases as Z^2 the scraper material should be low Z, which will also reduce the neutron source term for the scattered gamma rays produced in the scraper. The thickness should only be sufficient to absorb enough energy such that the subsequent dipole will bend the attenuated beam energy into the dipole yoke (or aluminum absorber in mid-plane ahead of yoke). Figure 1 below shows that if 22% of the beam energy is lost in the scraper (minimum energy lost), then the downstream dipole (6° bend angle) will bend the beam 7.7° and hit the inner wall of the vacuum chamber as the beam exits the dipole. Consequently all radiation produced after this bend will have > 1.7° angle toward the inside wall of the ring tunnel, reducing the HEn and HEg source term toward the outer shield and ratchet walls. With two scrapers in the injection region they should be able to intercept most Touschek scatter losses (radiation from decay lifetime) as well as the dumped beam when the RF trips off and the synchrotron radiation losses are not restored.

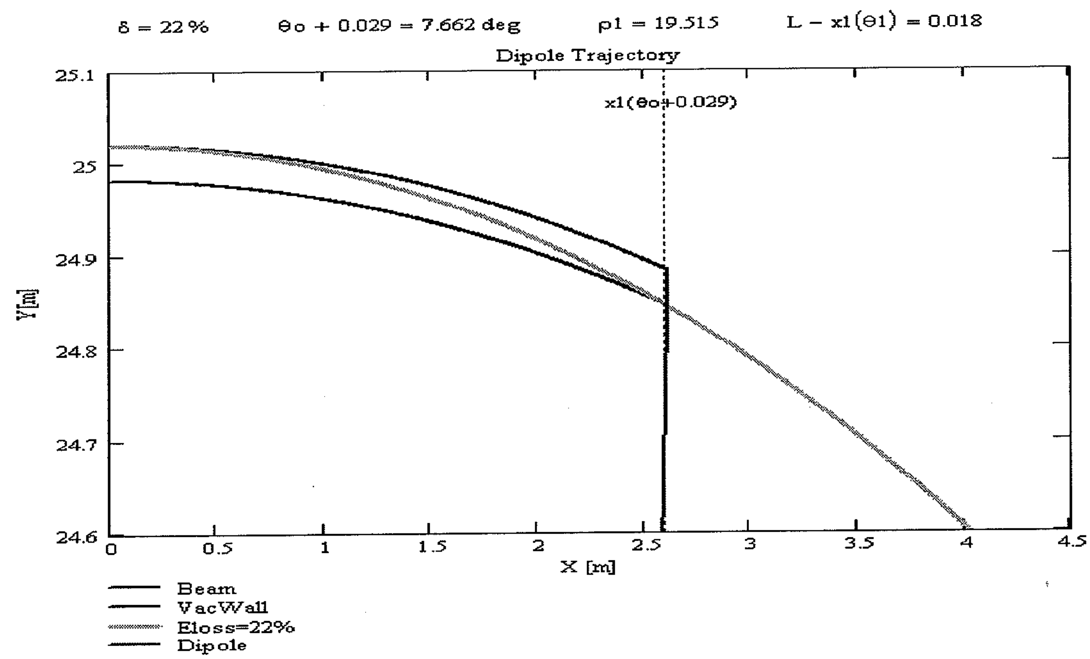


Figure 1 The electron beam trajectory (red) in the NSLS-II 6° bend dipole (length=2.62m) and the trajectory for an on axis beam with 22% energy lost in the scraper (green). The blue curve shows the inner wall of the vacuum chamber in the dipole.

Since the bremsstrahlung loss will have a long tail of lower energy electrons, those electrons that suffer a greater energy loss will hit the vacuum chamber sooner and then eventually the dipole yoke. Since these electrons will pass through the dipole field region outside the pole tip their trajectory will have to take into consideration the magnet design. Figure 2 shows the trajectory obtained using the Opera-3D code (by Ramesh Gupta) with an energy loss of 55%. This trajectory just hits the end of the dipole yoke at the exit end of the dipole. It might be better to fill the inside of the dipole mid-plane with an absorber, like aluminum, that would absorb the remaining energy of the beam with minimum HEn and HEg production and minimum induced radioactivity, as shown in Figure 3. This absorber could be replaced if the induced radioactivity became high enough to be of concern for maintenance work in that area. Figure 4 shows the X-Z(rectangular coordinate) view of this trajectory, which doesn't account for penetration of the vacuum chamber or for the dipole yoke material.

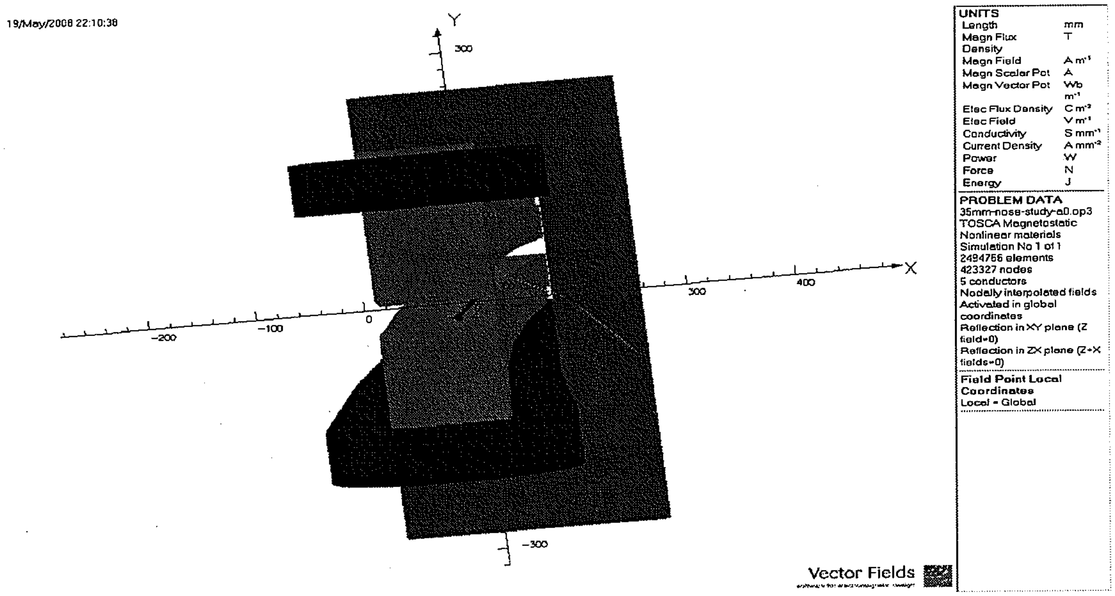


Figure 2- Shows the Opera-3D tracked particle (brown line) with a -55% energy loss difference from the nominal 3 GeV beam energy, (from Ramesh Gupta's calculations).

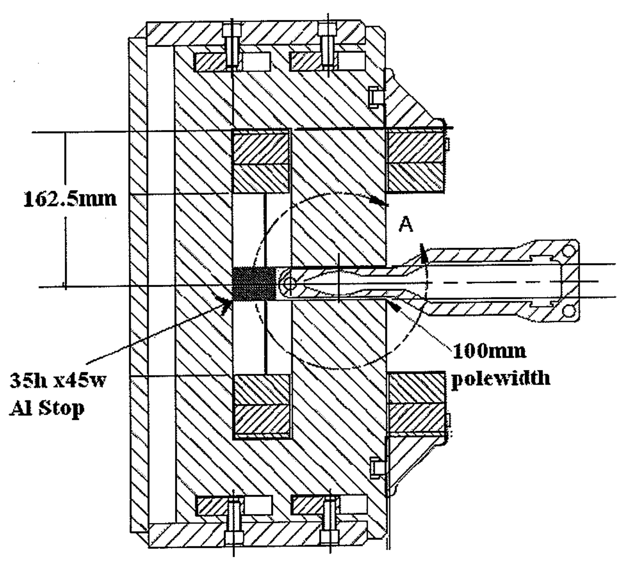


Figure 3- Shows the cross-section of the 35mm gap dipole magnet with a mid-plane Aluminum beam stop installed. This provides the local shielding of the iron yoke with 100mm(poletip) to outside of ring and 60mm(yoke) to inside shield wall, but at a glancing angle of ~2° (or 28X more effective).

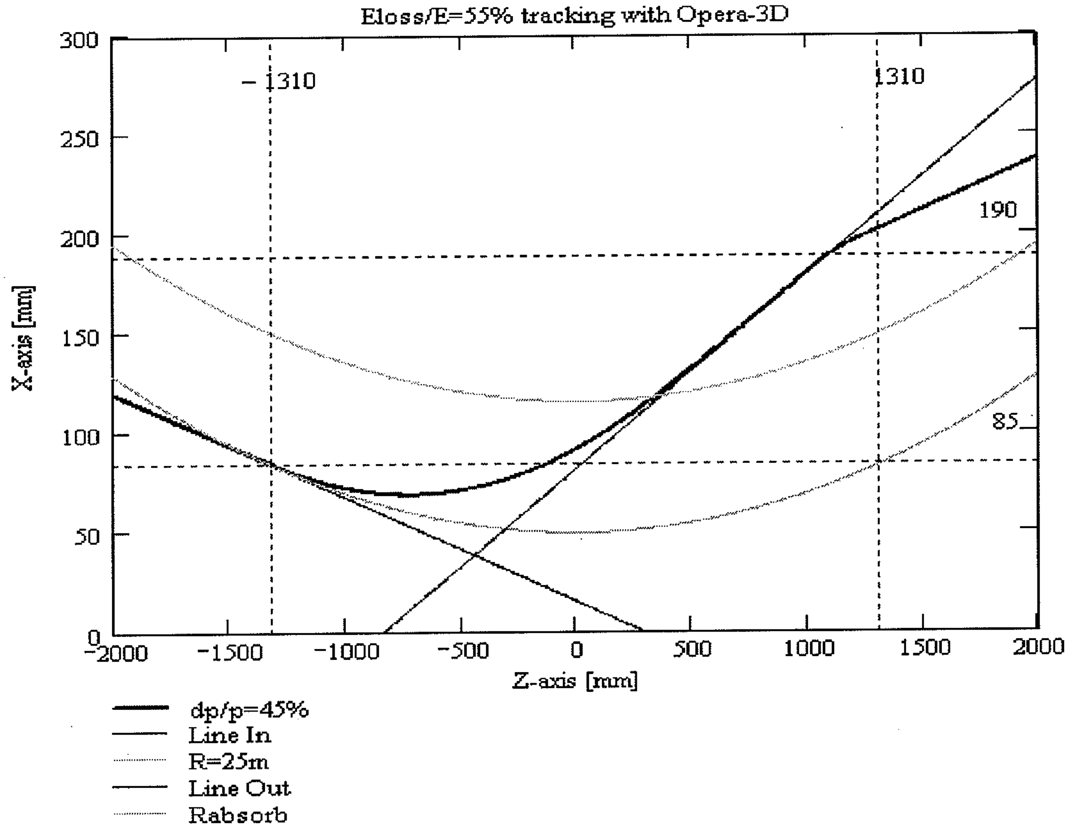
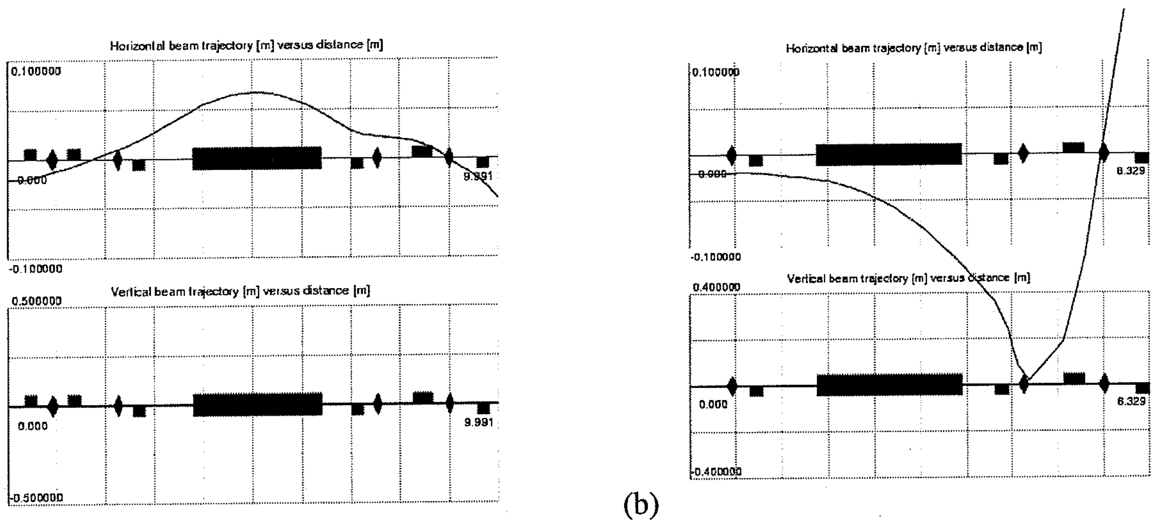


Figure 4- The X-Z plane view of the tracked dp/p=45% (E_{loss}/E_o=55%) particle in Figure 2, is shown in red and the dp/p=0 (R=25m bend radius) is shown in green. The dipole yoke is at ~190mm (yoke is on radius) at the exit end of the dipole Z= ~1310mm. The blue and magenta lines show the input and exit angles, respectively, with total bend of 8.6° or 2.6° inward from the on energy electron beam direction. The light blue shows where the 45mm Al absorber would start intercepting the deflected beam.

Clearly from Figure 4, the core of the radiation produced in the iron yoke or an Al absorber between the vacuum chamber and dipole yoke, will be directed at least 2.6° away from the outer shield and ratchet walls. The 55% energy loss particle will hit the vacuum chamber before the midpoint of the dipole chamber, where the deviation from the on momentum ray is >38mm to the inside of the chamber. The bremmsstrahlung energy loss in the scraper will have a low energy tail, that beam will be directed even further away from the outside shield wall and will hit the vacuum chamber earlier. The scraper will need to insure that particles penetrating the scraper will have at least a 20-25% energy loss in the scraper. The lower this energy loss is the less the local shielding (around the scraper) will be needed, but that beam will hit the vacuum chamber further after the dipole magnet, which may require local shielding after the dipole. However, this may not be needed since the source is a distributed line source well ahead of the ID straight section.

The initial design location for the scrapers assumed they were installed ahead of the horizontally focusing quadrupoles at the center of the dispersion region. This is a bad location since the trajectory of the low energy beam penetrating the scraper will be over focused be the pair of these quadrupoles and will hit the outer vacuum chamber wall before being deflected by the dipole, as shown in Figure 5(a). Moving the scraper just downstream of this pair of quadrupoles will eliminate this problem, but will require greater mechanical changes in the vacuum chamber in that region. However it is essential for this controlled loss of the beam energy. The beam abort scrapers are only the inner horizontal baldes (low energy from RF trip) and these might require the active scraper idea discussed below. The outer blade could be a different design and should be water cooled to handle the synchrotron radiation power. These could be incorporated into the proposed synchrotron radiation absorbers already proposed but they should be low Z or thin copper (Xrad=1.4cm).



(a) (b)

Figure 5- (a)Left graph shows the trajectory for a particle (dp/p= -5% or dx=-0.02m at the inner scarper blade) which loses 55% of its energy in the scraper for the original scraper location (i.e. ahead of the two QF dispersion quadrupoles). (b)Right graph is for the same particle trajectory for the scraper located just after the QF pair. The dipole is assumed to have a uniform field over the entire transverse plane and therefore over estimates the bend for this low energy trajectory.

Calculating the bremesstrahlung loss process will require more detailed effort, but has been estimated using the SLAC online version of EGS4 program. This version is limited to 1GeV electron beam energy but will be illustrative of the process. The scraper material was taken as to be NaI scintillator (see active absorber below) which has low Z Na but high Z Iodine. The ideal material might be Quartz (SiO) but this wasn't available in the EGS version online. The thickness was assumed to be 2 radiation lengths or 5.4cm. Figure 6(a) shows the electrons and positrons having energy above 0.8GeV or less than a 20% energy loss in the material. After one radiation length (2.7cm) only 4/100 electrons survive with energy >0.8GeV and their direction is still quite parallel with the incident angle. The remaining 96 electrons have scattered and lost even more energy and are shown in Figure 6(b) for energies >0.10GeV (90% energy loss). These electrons that penetrate the 2.7cm position (for a one radiation length scraper) would then be strongly bent in the dipole hitting the inner yoke or beam stop downstream of the dipole. The positrons that would penetrate will be bent toward the outside shield wall but will be spread out in angle and be strongly bent ahead of the ratchet wall. However, Fig.6(a) shows no positrons exit the 2.7cm length with energy >0.8GeV, although one was generated after that thickness for the longer material shown. The lower energy positrons in Fig.6(b) will be bend strongly in the quadrupoles and dipole and will need to be looked at in more detail, but this is a small fraction of the energy radiated in a one radiation length scraper.

In addition to reducing the amount of radiation generated in the scraper, the low Z material will also reduce the amount of neutrons produced in beam pipe region. This is result of lower photo-neutron for the lower Z scrapers. Figure 7 compares these cross sections for Aluminum and Tungsten which are factors of 10 to 40X less for Aluminum, reducing the source term in the beam pipe region.

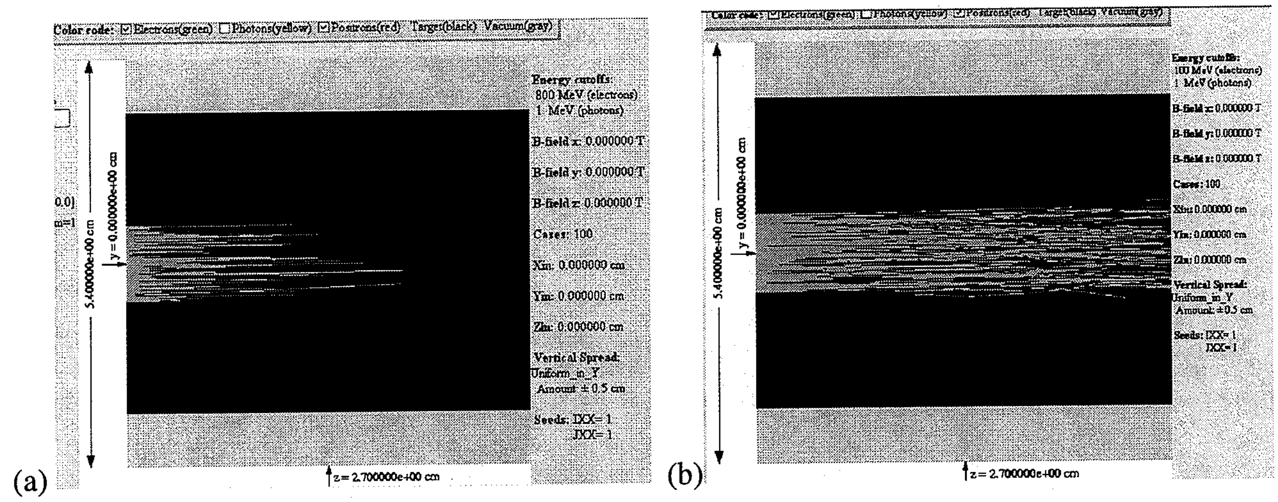


Figure 6- (a-left)A beam of 100, 1 GeV electrons incident on block of NaI material 5.4cm long, with only electrons and positrons shown with energy >0.8 GeV. (b) The same beam incident on the same material but with electrons (green) and positrons (red) shown with energy >0.1GeV.

$\gamma + {}^{27}$Al

Abundance (%)	Threshold Energies (MeV) γ,n	γ,p	γ,t	γ,He-3	γ,α	γ,2n	γ,np	γ,2p	γ,3n
100.00	13.06	8.27	18.21	23.71	10.09	24.42	19.36	22.41	41.36

$\gamma + {}^{184}$W

Abundance (%)	Threshold Energies (MeV) γ,n	γ,p	γ,t	γ,He-3	γ,α	γ,2n	γ,np	γ,2p	γ,3n
30.70	7.41	7.70	12.22	13.22	-1.66	13.60	14.63	14.23	21.67

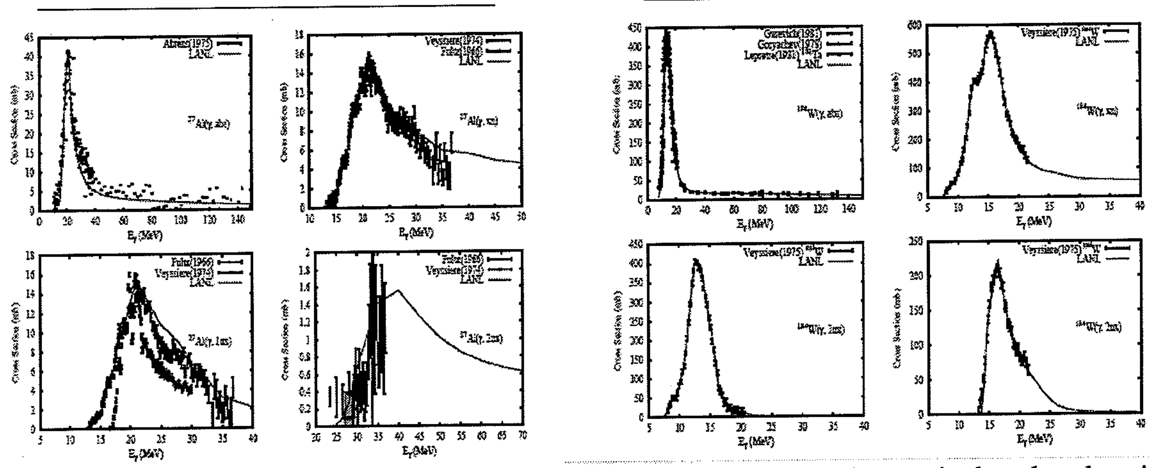


Figure 7 Photo-neutron cross sections for Al(left) and W(right), note the vertical scales showing factors of 10-40X less for Aluminum compared to Tungsten.

III. Beam Abort Active Scraper (Inner Horizontal Aperture)

In order to verify that the charge lost during an intentional (beam abort) or unintentional beam dump, was lost in the injection region with its thicker shield wall, we consider two alternatives: 1) external radiation levels emitted from the scraper or the dipole beam dump and 2) from an active signal from the scraper itself indicating the amount of charge passing thru the scraper blade. The first idea would require a detector very near the scraper with large solid angle coverage. It would have to be shielded from the synchrotron radiation from the beam. This type of detectors (using NaI scintillator with a PMT) have been used in the NSLS VUV ring for years to measure the Touschek and RF bucket losses for stored beam, but has been difficult to calibrate in terms of charge lost. Studies will be proposed to attempt to quantify a beam dump during an RF trip. Similar detectors have recently been installed in the Xray ring with several millimeters of lead shielding to avoid the synchrotron radiation Xrays. These will attempt to be calibrated for the charge lost. However, there isn't a well defined momentum aperture in the Xray ring to dump the beam on, making the distributed lost pattern very unlikely to yield reliable calibration factors. However, there could be an NSLS-II funded R&D study that would install such an aperture.

The second approach could be more easily calibrated, since the beam actually passing through the scraper could be more directly measured. The idea of using the NaI was looked at but the light yield might change due to the high levels of accumulated radiation exposure this scraper might see over the years. Also the low energy synchrotron radiation x-rays would give a signal and would require the scraper to be shielded from this background radiation. A simpler material would be pure Quartz (SiO_2), which isn't a scintillator like NaI, but a Cerenkov radiator with index of refraction 1.458. This should make it naturally insensitive to the synchrotron radiation since only electrons with kinetic energy above 100KeV will generate light. The highest purity Quartz's (6-9's like Spectrosil) are very radiation resistant to yellowing, but even this could be calibrated out with an LED source. Quartz has very small fluorescence yield but the light shield could be made thicker to insure that any x-rays don't give too high a background level. However, the light shield should be very thin in the long direction to insure that very few beam particles are lost in it and not yield a light signal. This could be improved by a slight slope of the inner surface of the quartz block. Basically the quartz block is maybe 3x5 cm on the face that the beam would hit and the length would be ~12cm for one radiation length of material, as shown in Figure 8. This rectangular prism could have a tapered light pipe to a photomultiplier tube(PMT), which could be either molded together or in two pieces, but if two pieces it should be held together without any glue or gel to avoid radiation damage changes. The PMT should be operated with +HV to allow DC current to be read from the output signal.

The output signal will be a DC current level that will be proportional to the light level seen by the PMT. This will be proportional to the loss rate of electrons (dN/dt) hitting the scraper. If this level is integrated over some time interval set by the RF voltage decay time, then the N_{loss}/I_{loss} will indicate the fraction of the current lost per time interval during a beam dump. Once calibrated for a controlled RF dump this ratio will indicate the fraction of the beam lost that was lost in the dipole magnet beam dump.

Alternatively the derivative of the Io current monitor should be proportional to the signal measured in the scraper, if the fraction of the beam loss rate on the momentum aperture defined at the scraper remains a constant. If this fraction of the observed beam loss drops off, then the increase in the beam lost on other apertures in the ring will be increasing and that maybe cause to dump the beam, if the loss rate is too high.

Moving the beam abort scraper to the new location makes its installation harder for the Vacuum Group on the outside of the vacuum pipe. However, the Vacuum Group was planning to install an absorber at that location on the outside of the vacuum chamber for synchrotron radiation. If this planned absorber was installed on a movable bellows then it could function as the outboard scraper for intercepting Touschek scattered particles or for accelerator physics studies of dynamic aperture. The only blade that would be helpful to have active would be the inner blade of the scraper, in order to quantify the charge lost on a beam dump or low lifetime instability problem. However, all blades should be low Z and low beam energy loss type.

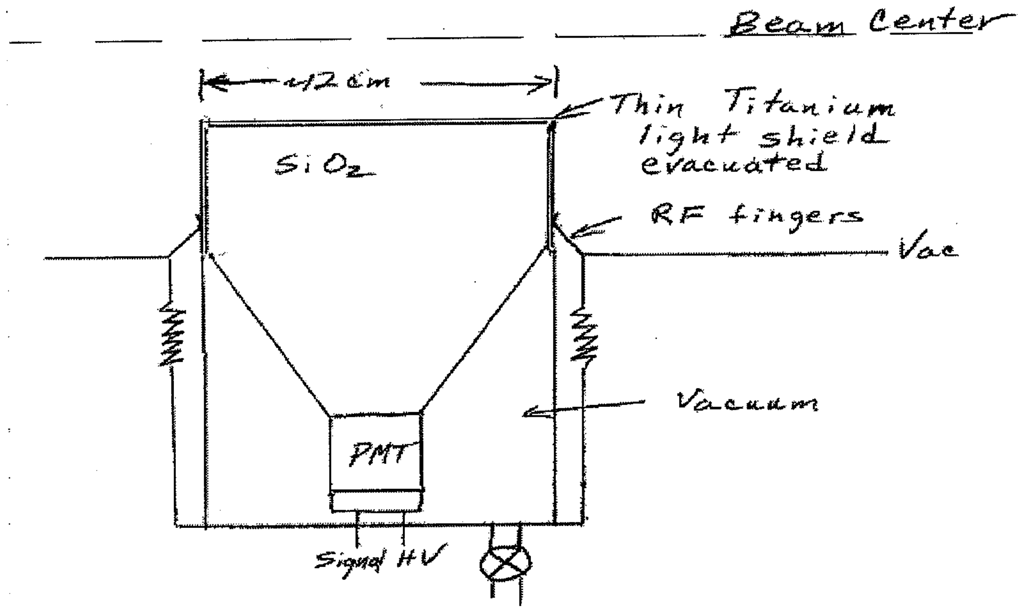


Figure 8 Sketch of the active scraper using Quartz radiator and with a thin Titanium light shield in an evacuated enclosure that is mounted to the beam vacuum chamber with bellows and has mechanical position control.

The active scraper blades will require a R&D effort to answer the questions: 1) how to make a thin light tight metal enclosure without absorbing too many of the electrons in the metal, 2) calibration and sensitivity of the light to electrons absorbed in near the end of the block and 3) radiation resistance of the quartz radiator to yellowing and changes in sensitivity.

IV. Beam Scrapers Non-Active

The R&D and mechanical effort to implement an active scraper/abort system could be eliminated if radiation detector was mounted inside or just downstream of the dipole where the low energy beam will be lost. This will be more uncertain measurement of lost charge, since the electrons will be spread out in space where the collide with the Al(absorber), Fe(yoke) and Al beam pipe in the dispersion region for the lowest energy lost beam. Since the sensitivity changes inversely as the square of distance to the detector this will not be a reliable measurement for all types of loss mechanisms. This has been used at the NSLS for years on the VUV ring and similar detectors have been installed on the Xray ring. Although they give qualitative measurements of the change in the injected beam loss levels at one point. A study could be made that would try to calibrate these detectors with the loss of beam charge. One difficulty would be to lose the beam on an aperture ahead of these detectors. The existing scrapers (not working at the moment) are not near these detectors, however with some effort a fast bump might be implemented using the kickers that could lose the beam on an aperture near one of these detectors. This study could be done at minimal cost and effort.

V. Location of Scrapers in the Lattice

The proposed location of the vertical and horizontal scrapers is specified to intercept the beam at two locations in each plane (2-H and 2-V). They are at large beta functions and dispersion, with close to 90 degrees betatron phase advance between them. The locations are shown in Figure 9 together with the shield wall drawing in the injection region. The last two scrapers occur at the end of the heavy concrete shielding and should be extended one or two ratchet walls to absorb the radiation from the dipole beam dumps. The horizontal scrapers are in the drift regions between the QM2 and SM1 magnets, but the vertical scrapers require eliminating a corrector magnet CH2 in the injection straight (Cell 30) and a TPW in the Cell 1 dispersion region.

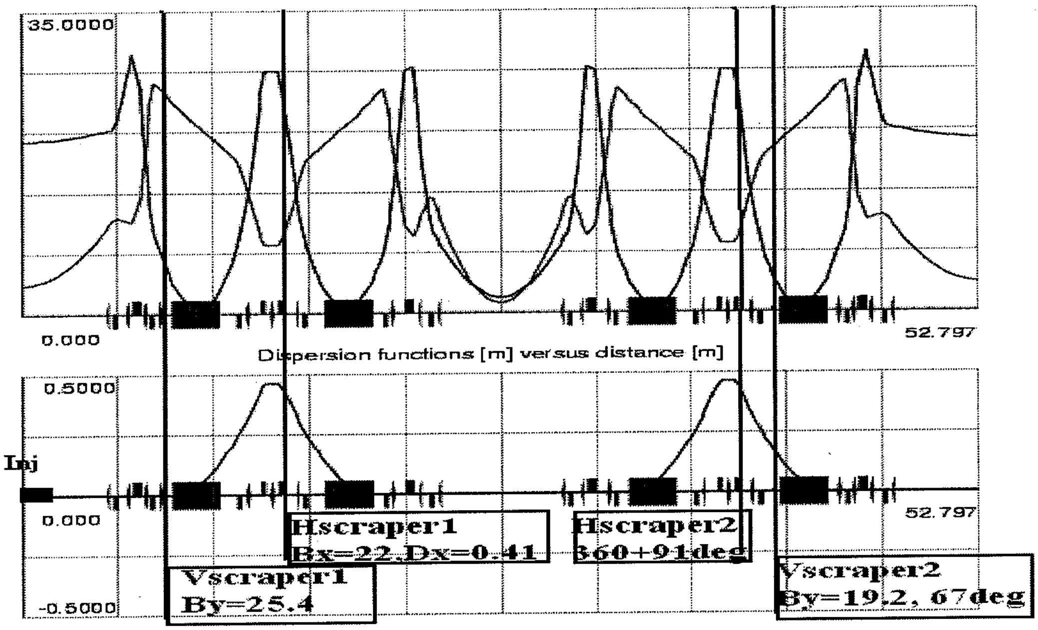


Figure 9 Proposed scrapers locations in the lattice in cells number 30 and 1. The injection septum is shown on the left edge of the plot.

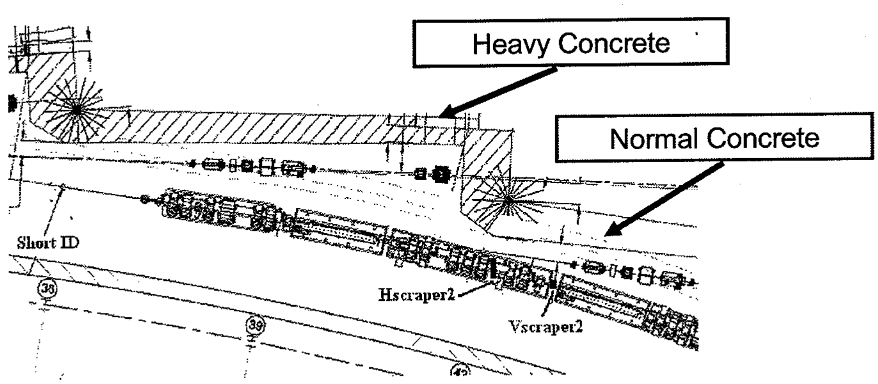
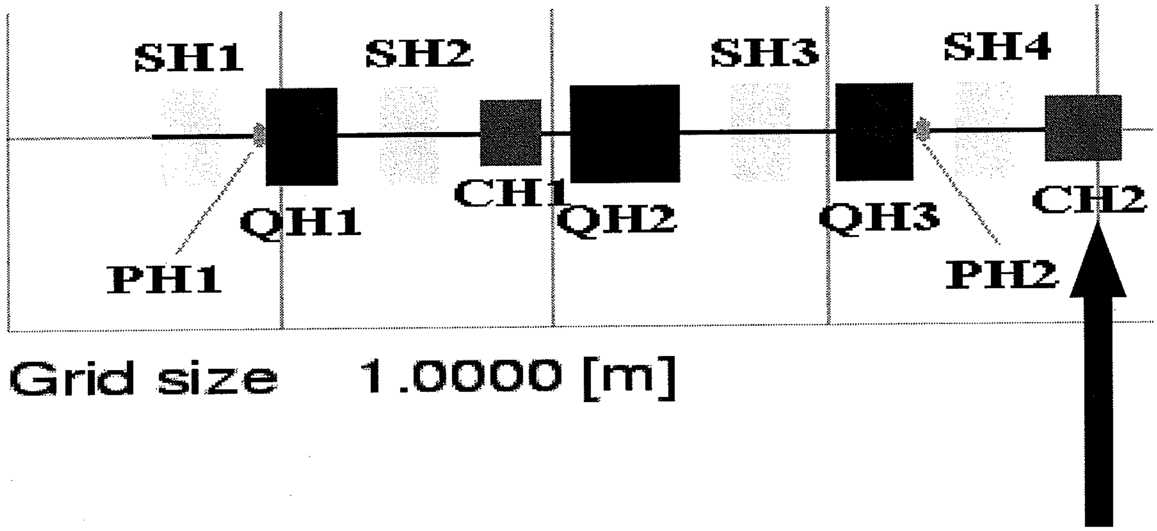
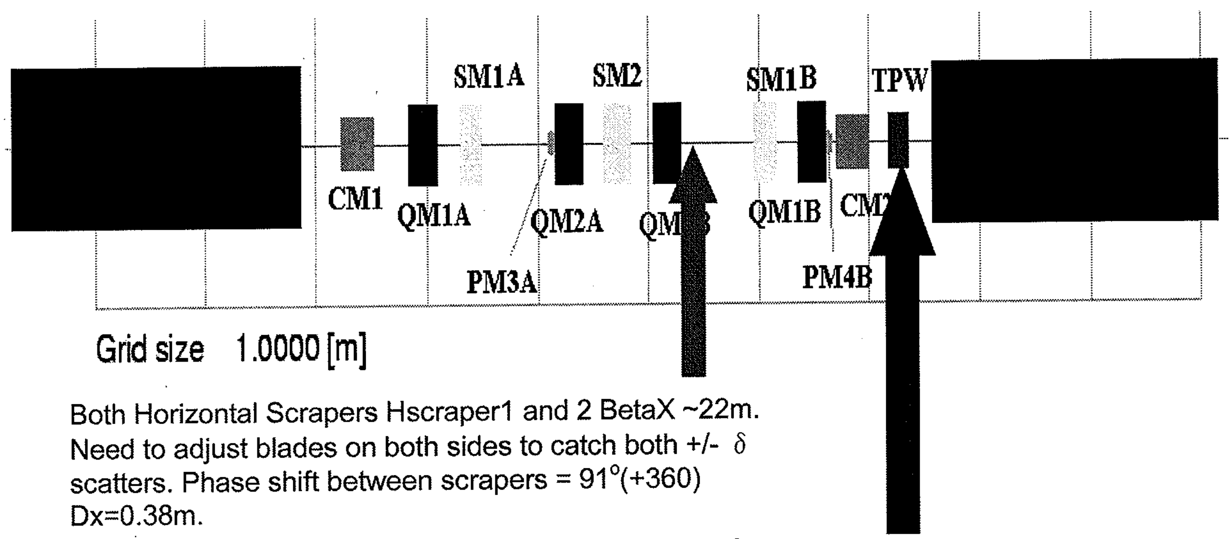


Figure 10 Show the shield wall in the Cell 1 and the present limits of the heavy concrete shielding.



Replacing the corrector CH2 on Girder No.2 after Injection
With vertical blades only one needs to be active at a time

Figure 11 Shows the position of vertical scraper number 1 in Cell 30, injection straight section. This would require replacing the CH2 corrector magnet with the scraper, but the injection straight has additional steering that should not require this magnet.



Both Horizontal Scrapers Hscraper1 and 2 BetaX ~22m.
Need to adjust blades on both sides to catch both +/- δ scatters. Phase shift between scrapers = 91°(+360)
Dx=0.38m.

Vscraper2 ahead of HID dipole Betay~19m but only 67° (+180) from Vscraper1.
Downstream of dipole has same Betay as Vscraper1 ~25m and 75° but intercepted (Eloss) beam passes thru HID straight before energy deflecting dipole.

Figure 12 Shows the position of the horizontal and vertical scrapers in Cell 1. The vertical scraper would be in the location indicated by the Three Pole Wiggler TPW. The horizontal scrapers are is in the same location of the dispersion regions for Cells 30 and 1, but only Cell 1 is shown.

VI. Conclusions and Future Work

The ideas of the APS Touschek scatters being intercepted by a scraper in the dispersion region and the Spear3 beam abort aperture have been combined to handle both types of beam losses. In addition, the design of low energy loss and low Z scrapers will allow the intercepted beam to be lost in a well shielded dump outside the vacuum chamber of the ring. The electron momentum will be bent away from the outer shield wall reducing the need for local shielding to a minimum and reducing the high energy component directed toward the experimental floor. Additionally, to idea of an active signal from the scraper or beam dump will allow for a measure of the charge lost in this controlled manner reducing the uncertainty that beam could be lost in a place where the shield wall is reduced and the potential radiation the users could be high. This loss mechanism and reduction of transverse radiation has been verified by P.K. Job with the FLUKA code.

VII. Proposal to Test Low Z and/or Active Scrapers in X-ray Ring

Both the VUV and the Xray rings have scrapers which are only 5mm (5/14.3 = 0.35 x Radiation length) of copper. The VUV has horizontal and vertical scraper blades in near the maximum dispersion. The Xray has only the vertical installed blades installed in the X13 straight section with low but non-zero dispersion. There are another pair of scraper blades that are not mounted in the ring, that could be installed in the dispersion region of the ring. These also need stepper motors and a controlled to move them and read back their positions. The cost to have the scrapers made operational and for installing them in the Xray ring was estimated to be ~$40 to $50K with about $30K for the electrical equipment. This could be installed in the May shutdown of 2009 if the project is approved rather quickly.

In the meantime studies have been done on the VUV ring to demonstrate the use of thin scrapers for controlling the loss of electrons from the ring. This ring has two loss monitors that look at high energy particles or gamma rays using NaI scintillators (udiag05 in the injection septum region and udiag04 in the peak dispersion region). These monitors measure the rate of high intensity light pulses from the NaI detectors using PMT's and NIM rate-meters. These monitors are placed close to the vacuum chamber to avoid reducing the energy of the particles in the shower from lost electrons, by looking outside the shielding. There are also ionization chamber radiation monitors in the Injection, U5U and RF straight sections (radm1, radm2 and radm3 respectively), these are useful for seeing changes of the loss rate in their respective ID's at the update rate of ~1 Hz. Since they see x-rays they are only useful with shielding between them and the vacuum chamber. One Bergoz electron beam loss monitor has been available for sometime but hasn't been useful due to the ring shielding that prevents them from seeing high energy electrons. However, for the scraper studies this BLM (udiag07 or BLM) was installed after the dipole downstream of the scraper. It will see the electron that lose energy in the scraper and are over bent by that dipole to the inside wall of the vacuum chamber downstream of the dipole. Figure 13 shows the rate measured in the BLM and the NaI detector near the injection septum as the momentum aperture of the ring is reduced using the inner scraper blade. Clearly the BLM shows the large increase in electrons being swept out by the dipole, but would be less useful if there was a significantly higher X-ray intensity, which would increase the accidental rate and might saturate the detectors. Figure 14 show the radiation monitors in the Injection and RF (downstream of the dipole after the scraper) straight sections.

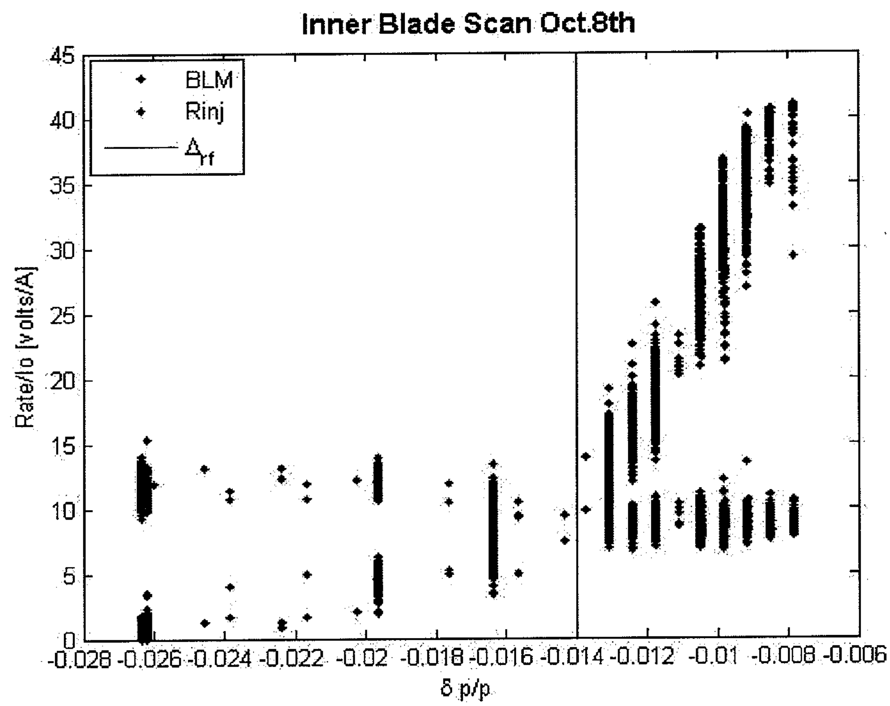


Figure 13 The signal rate per unit of beam current, measured by the electron BLM downstream of the dipole following the beam scraper and at the injection septum (NaI detector) as the momentum aperture of the VUV ring is reduced using the inner scraper blade.

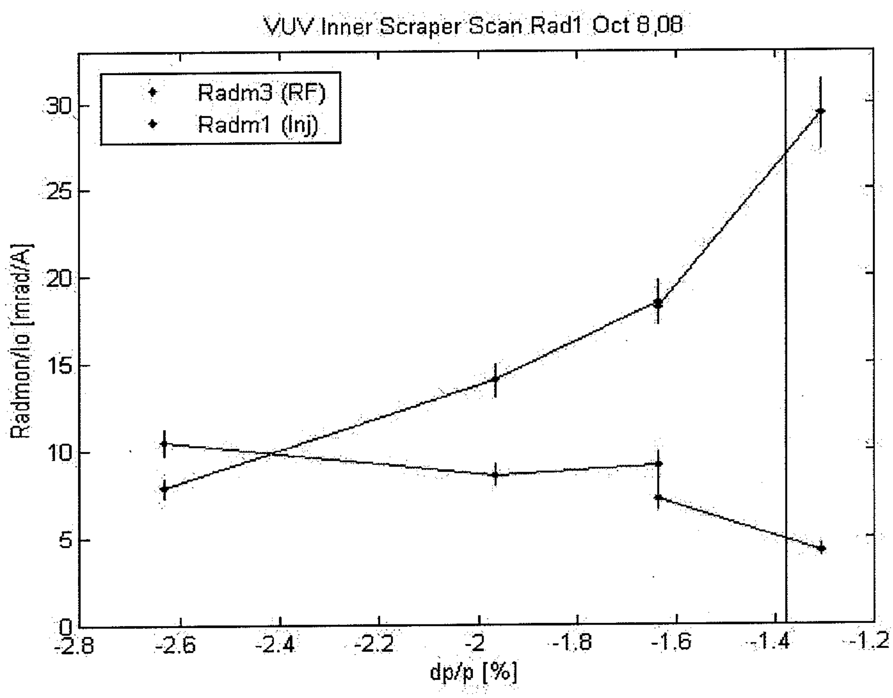


Figure 14 Radiation intensity per unit of beam current at the Injection ID and the RF ID (next ID after the dipole downstream of the scraper) as a function of the momentum aperture defined by the scraper.

Both Figures 13 and 14 show that there are electron out beyond momentum aperture defined by the RF bucket height and that they hit the injection septum, in agreement with the location of the betatron aperture for Touschek scattered particles in the dispersion region of the ring. As the scraper reduces the momentum aperture, more of these electrons are intercepted by the scraper and hit the vacuum chamber downstream of the dipole, due to their reduced energy by the scraper.