NSLS-II Beam Loss Monitor System

S.L. Kramer
ERL 2011
October 16-21, 2011

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Outline of Talk

- Beam Loss Control in Storage Rings or ERLs
- Beam Loss Monitoring in Storage Rings or ERLs
- Comparison of Cerenkov Beam Loss Monitors (CBLM)
- Testing of prototype CBLM for NSLS-II
- Design of CBLM for NSLS-II LCM System

LCM Requirements

- Measure beam charge losses (energy) between accelerators to minimize total beam power lost: dipole current (Beam energy) and DCCT/ICT (Beam current / charge)
- SR shielding design limits were:

≤13nC/min at any point in injection region, (septum ≤3nC/sec)

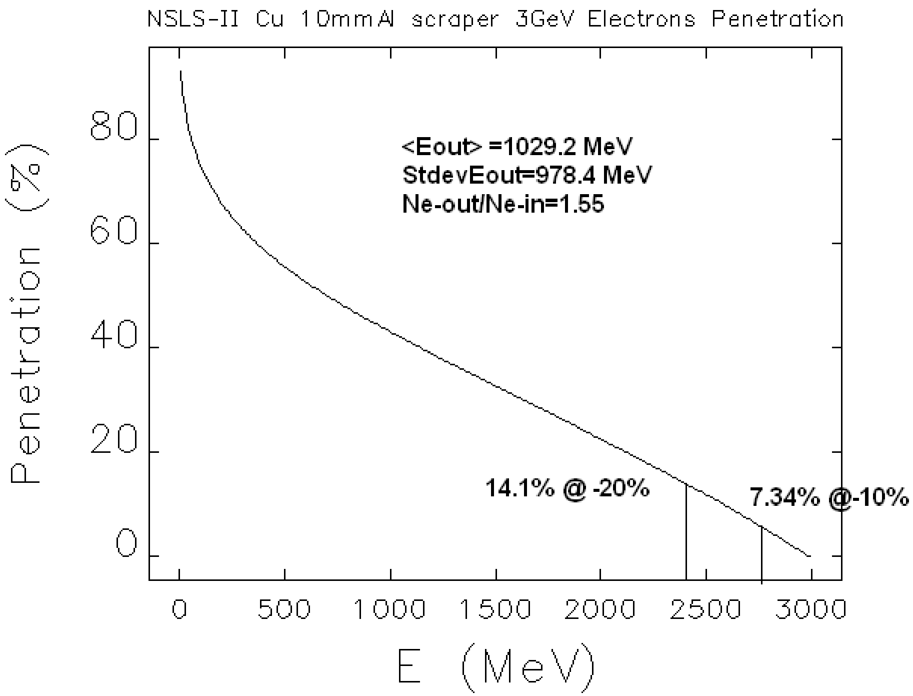
≤ 1.1nC/min any other point of the SR,

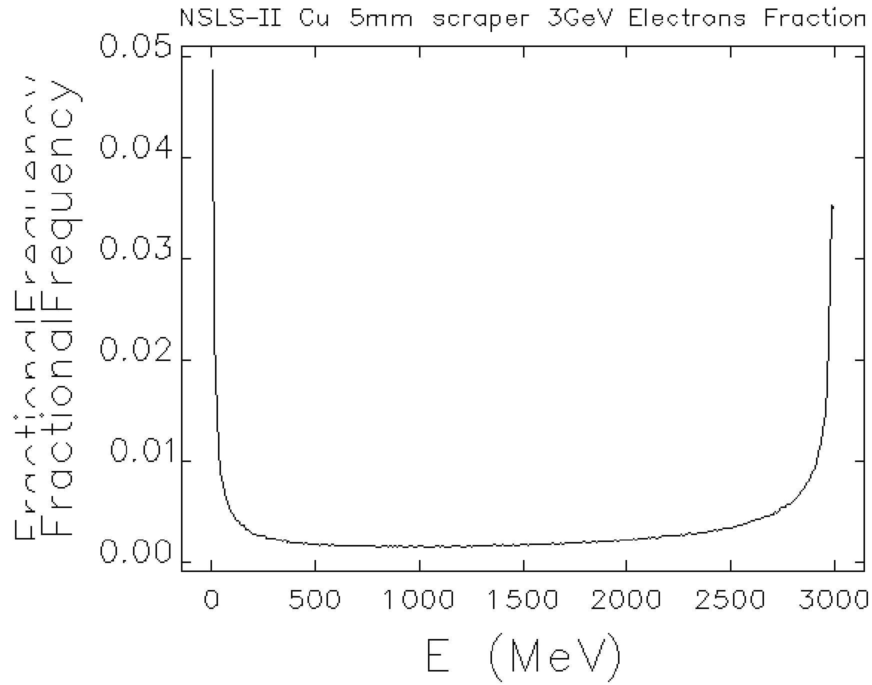
- Need to control beam loss locations in SR and
- Need to verify beam losses in injection region, insuring losses below limit in rest of the ring (unaccounted beam)

NSLS-II SR Loss Control Scrapers

- Blade (thin <1 Xrad) type scrapers inserted into vacuum chamber in injection region degrade beam energy
- Subsequent dipole separates and dumps intercepted beam
- Minimize radiation off scrapers toward experimental floor
- Blades must be cooled to take full synchrotron radiation power
- Beam impedance of scraper design needs to be minimized
- Track penetration electrons and radiation from shower
- Model beam loss mechanisms, calculate fraction intercepted versus aperture (operational studies will be done to determine aperture that captures largest fraction without significantly reducing lifetime), blades locked for ops. at that value

3GeV Electron Penetration of 10mm Cu



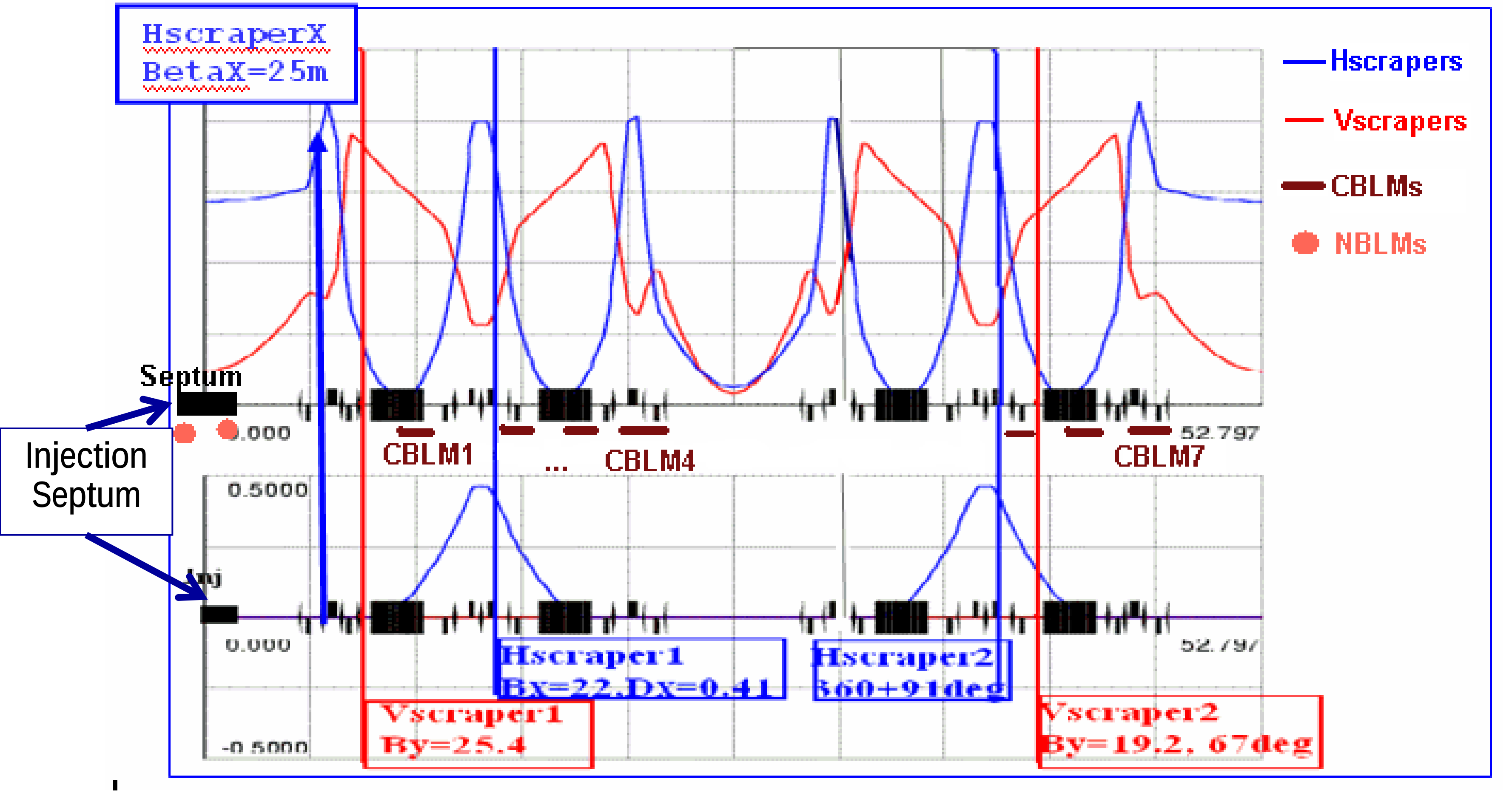


10mm Cu (0.7 Xrad) to reduce Ionization loss peak ~1.2 $MeV/gm/cm^2$

Thin enough to yield electron beam loss signal in magnets

δ < -20% lost upstream of exit from dipole chamber

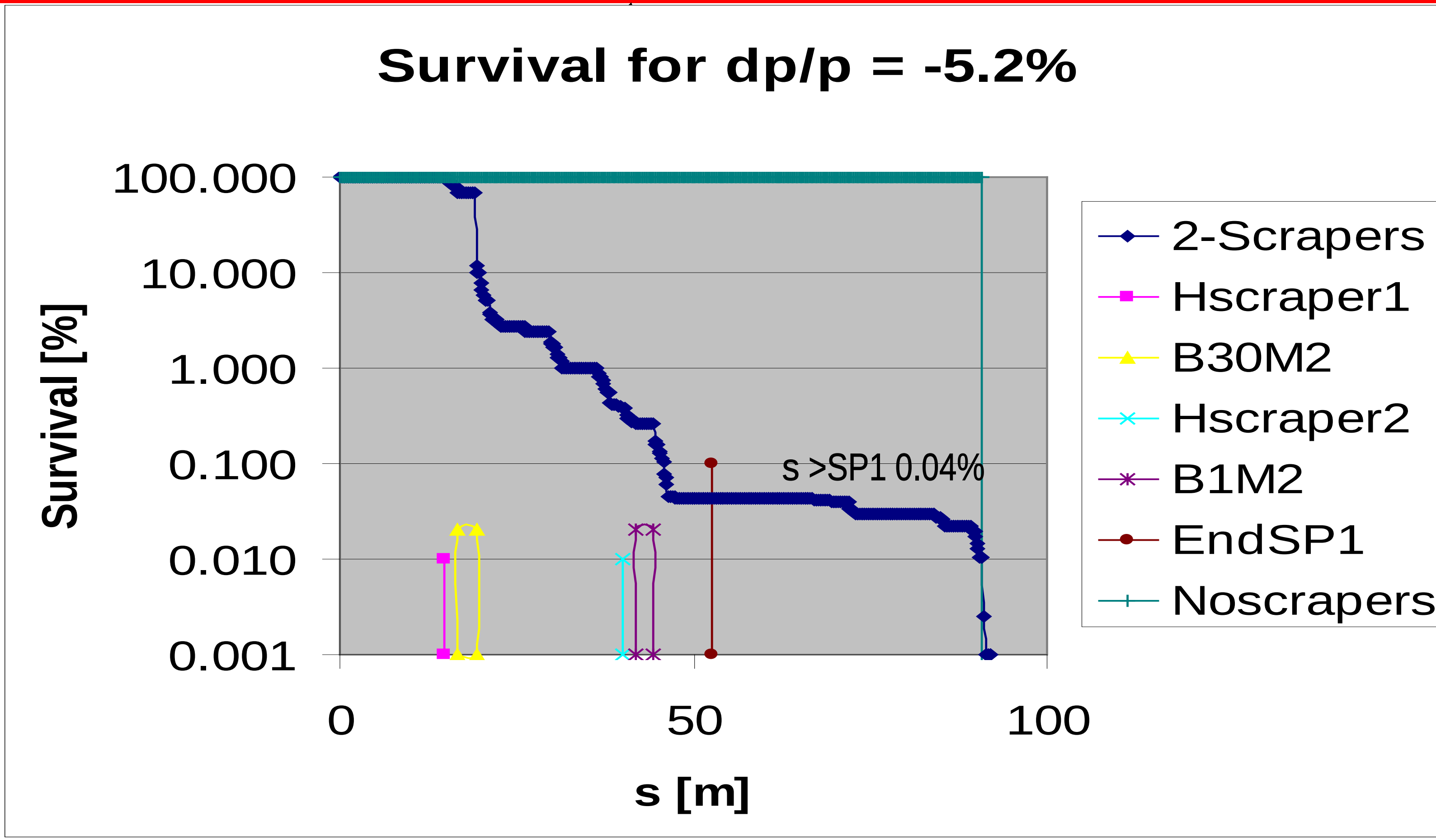
Scrapers for Beam Loss Control



Critical 2- δ<0 inner blades, 2- δ>0 outer blades: Hscraper1 &2

2-Vertical pair and 1-Horizontal pair scrapers for X &Y geometric apertures

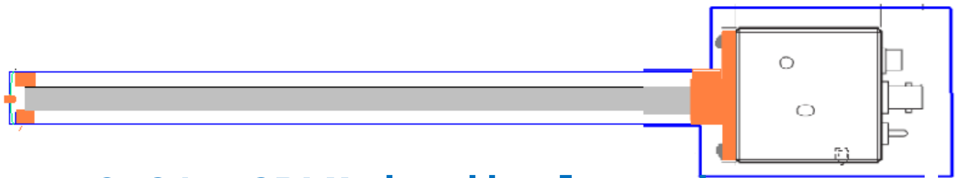
Survival Distribution for 2 & 0 HScrapers



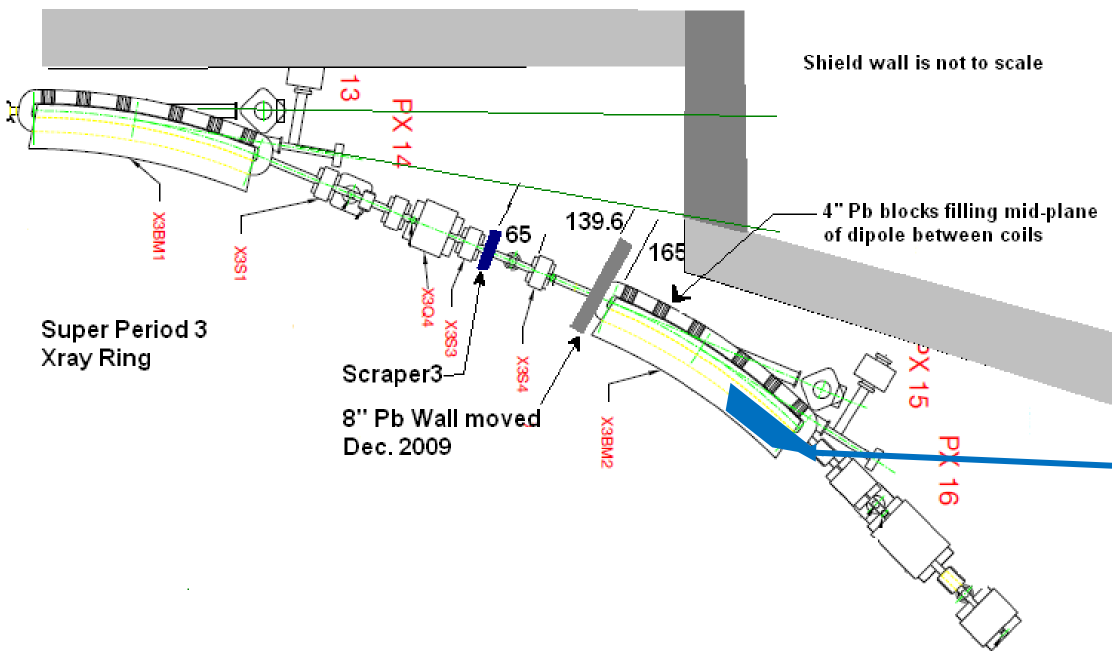
Control of loss for **δ** <-5% (dX =-23mm) but only if one ID ahead of scraper, i.e. minimum loss control for scatters in rest of the ring

Demonstrated Loss Control in Xray Ring

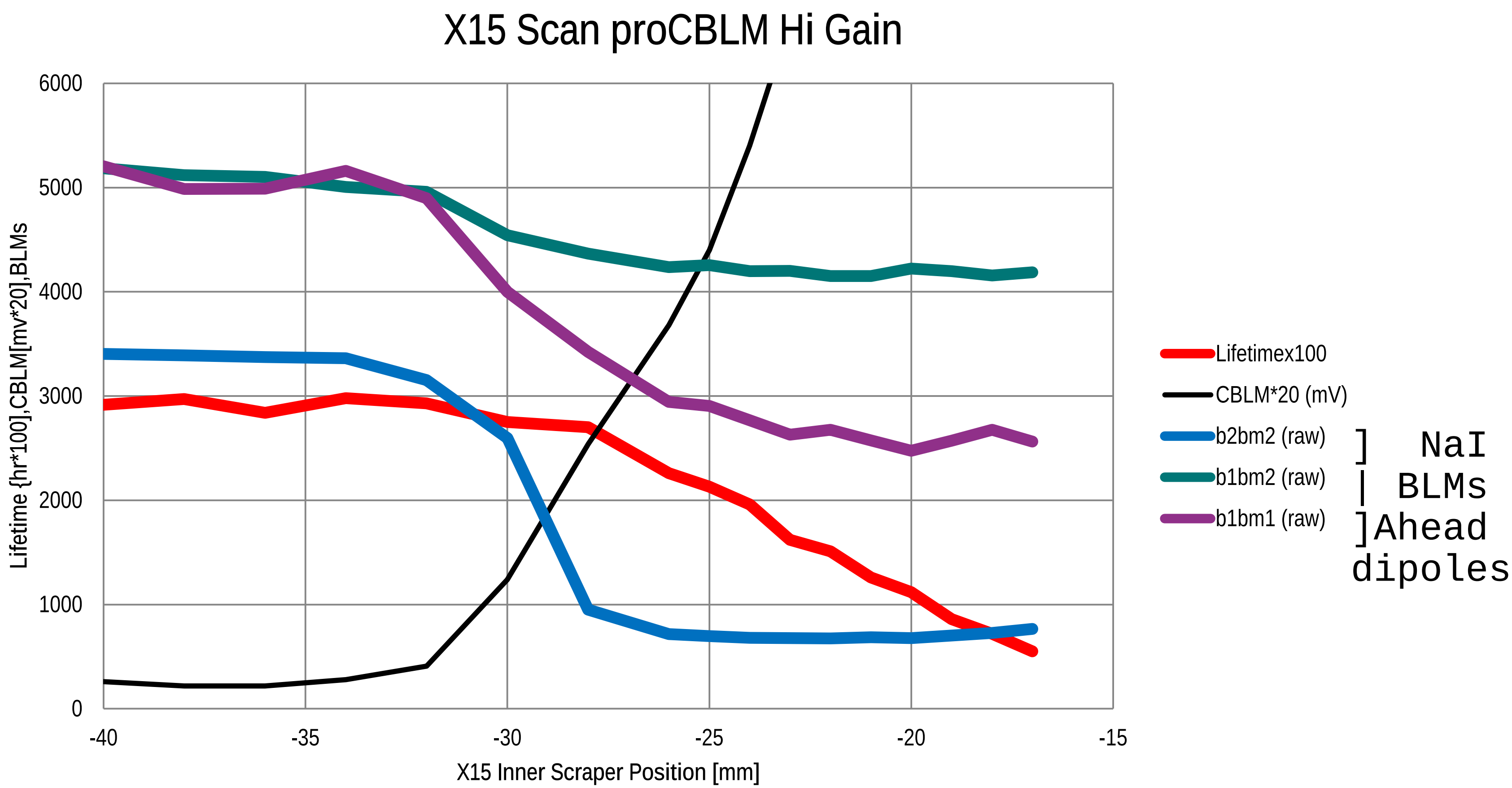
Xray Ring has 5mm Cu scraper near dispersion maximum in SP=3



0.91m CBLM in dipole end



Demonstrated Loss Control in Xray Ring



Reduction of losses at **b1bm1**.. **b2bm2** before **Lifetime** decrease is observed due to the reduction of momentum aperture by the scraper

Beam loss at CBLM after scraper, **charge loss rate used to calibrate CBLM**

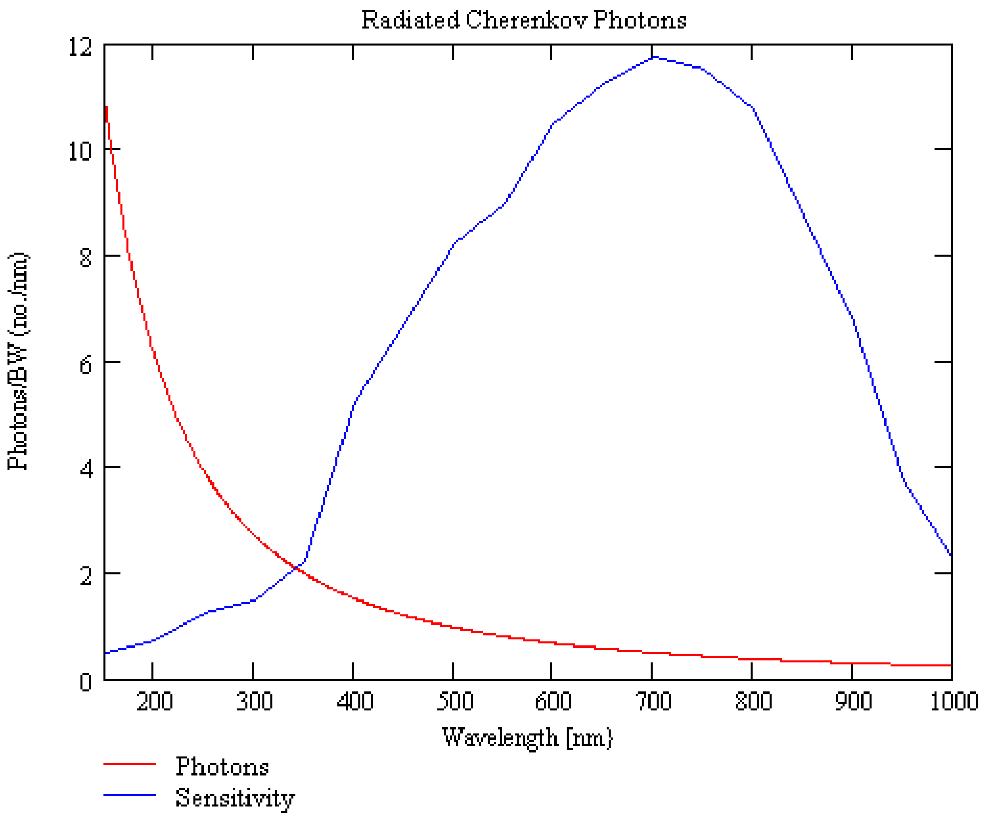
Signal Generation for CBLM

$$\frac{dN}{dE_\gamma dx} = \frac{\alpha Z^2}{\hbar c}\sin^2[\theta_c(E_\gamma)] \approx 370 \sin^2[\theta_c(E_\gamma)] \text{ ev cm}^{-1}$$

Number of photon for 200 - 800nm in 975/cm

$\theta_c(\lambda) = \cos^{-1}[1/(\beta\, n(\lambda))] \sim 46^\circ$ for quartz n=1.458

$dP/dx \sim \alpha * 2\pi * 0.5 * E_\gamma * f\,(d\lambda/\lambda^2)$

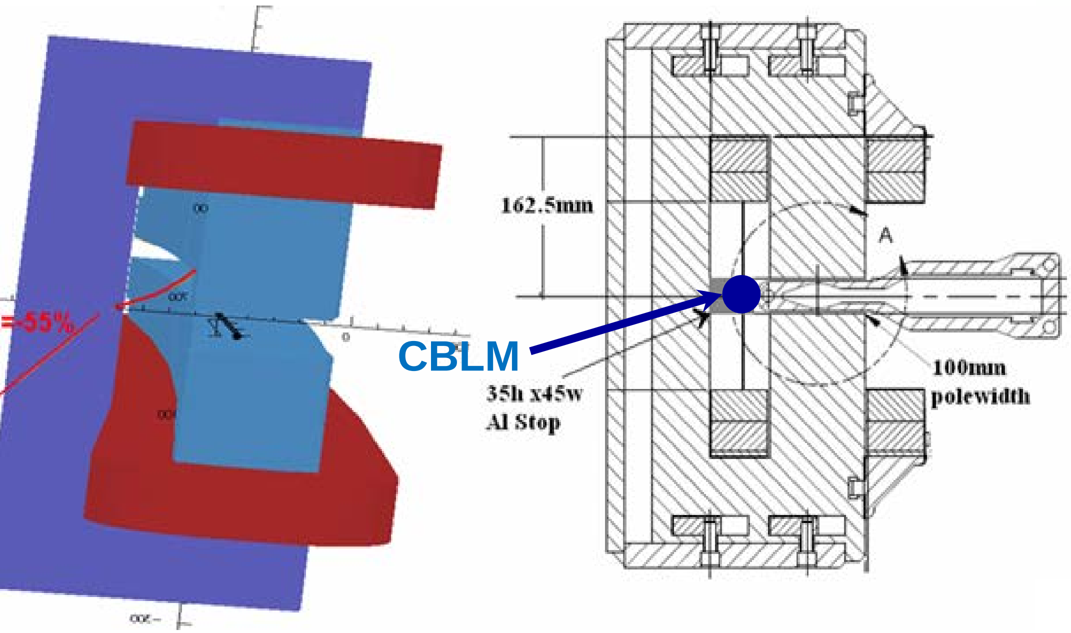


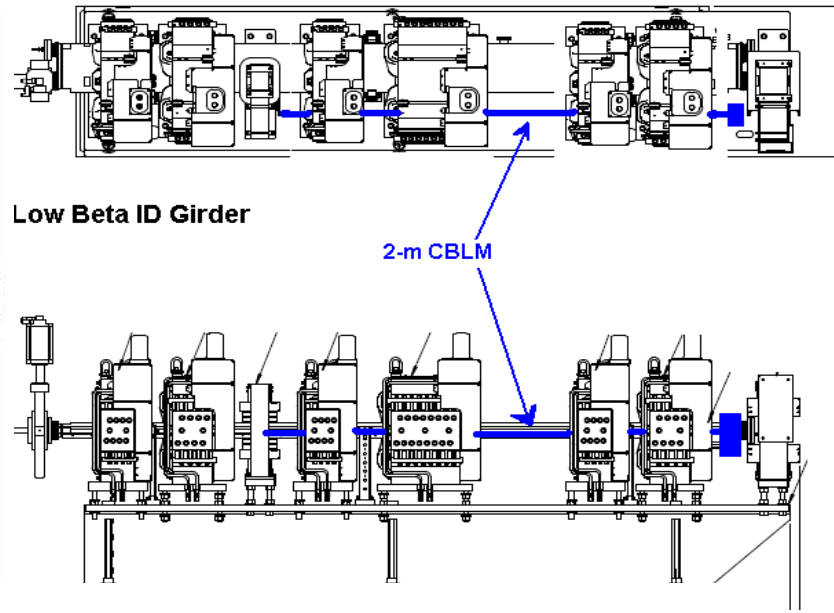
Convolving with diode sensitivity from 190-1000nm

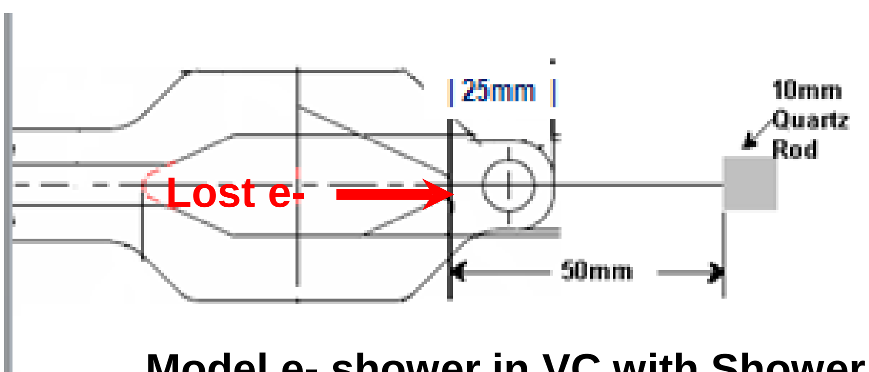
Assuming 50% photons propagate to photodiode (forward cone only TIR)

Gives 0.02nA per electron per turn per cm path length with dark current 0.1 nA S/N ~0.2

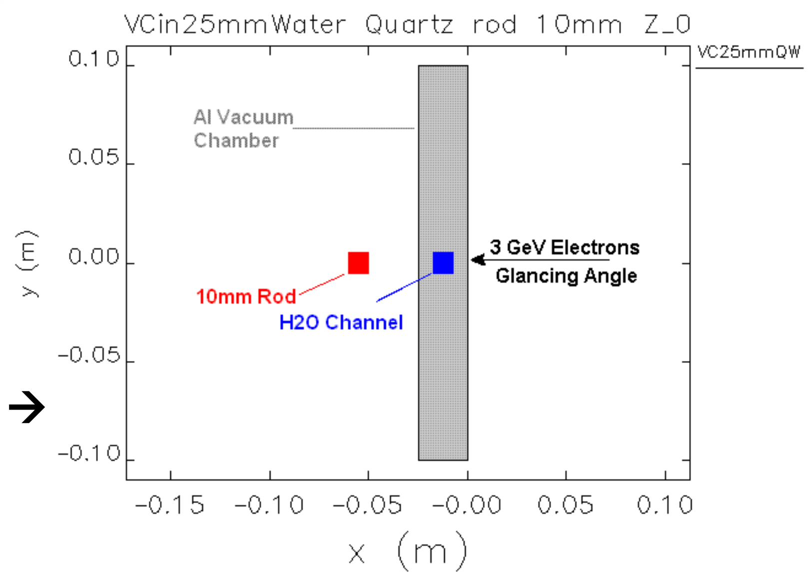
Lost Electrons Shower in Vacuum Chamber



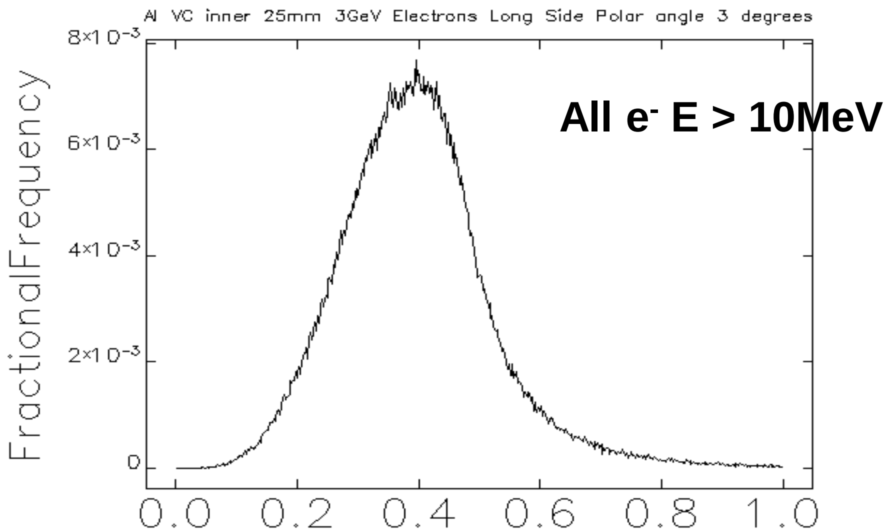


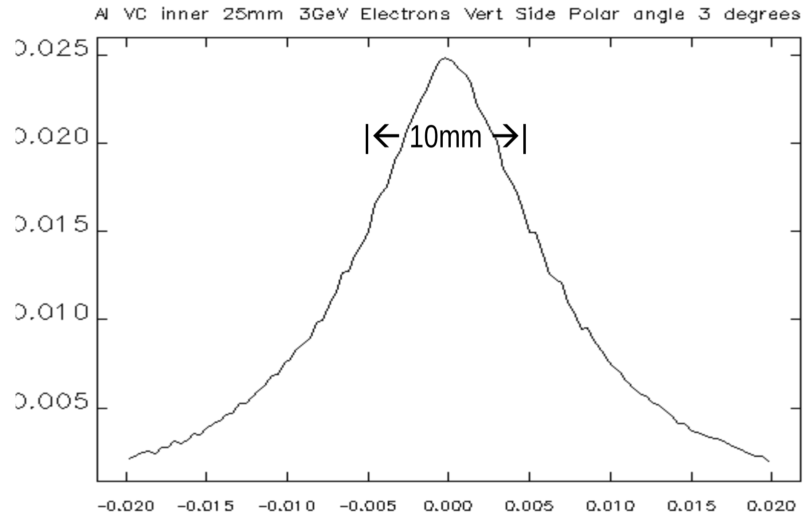


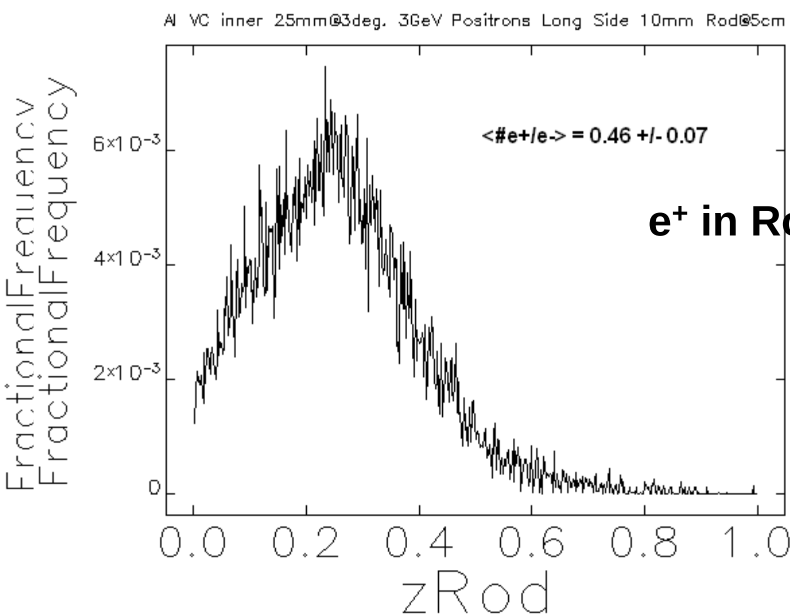
Model e- shower in VC with Shower (EGS4) →

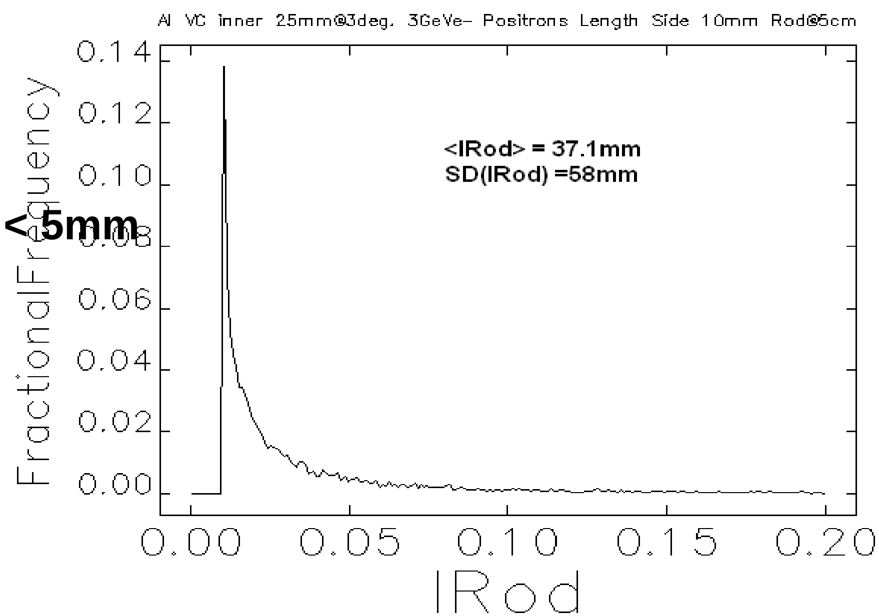


Beam e^- @ 3° e^- & e^+ Generated in VC Walls

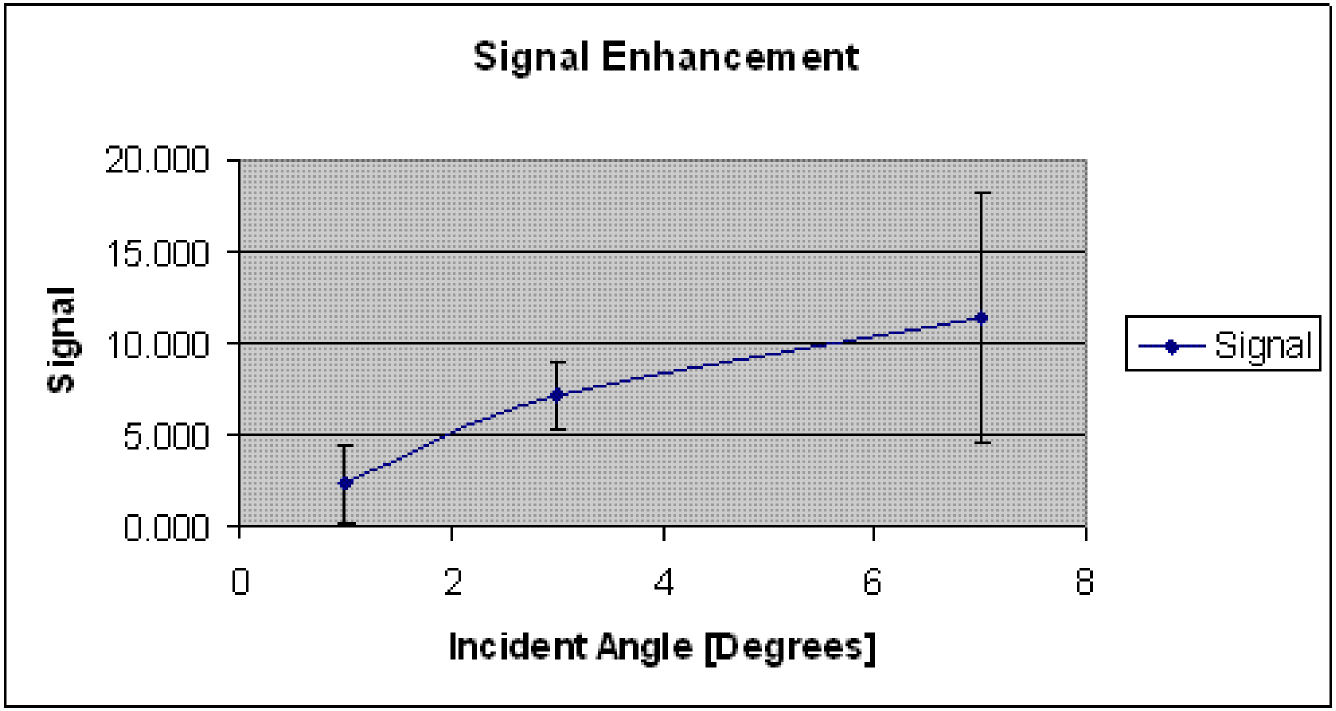








Electrons shower in 25mm Al VC Wall

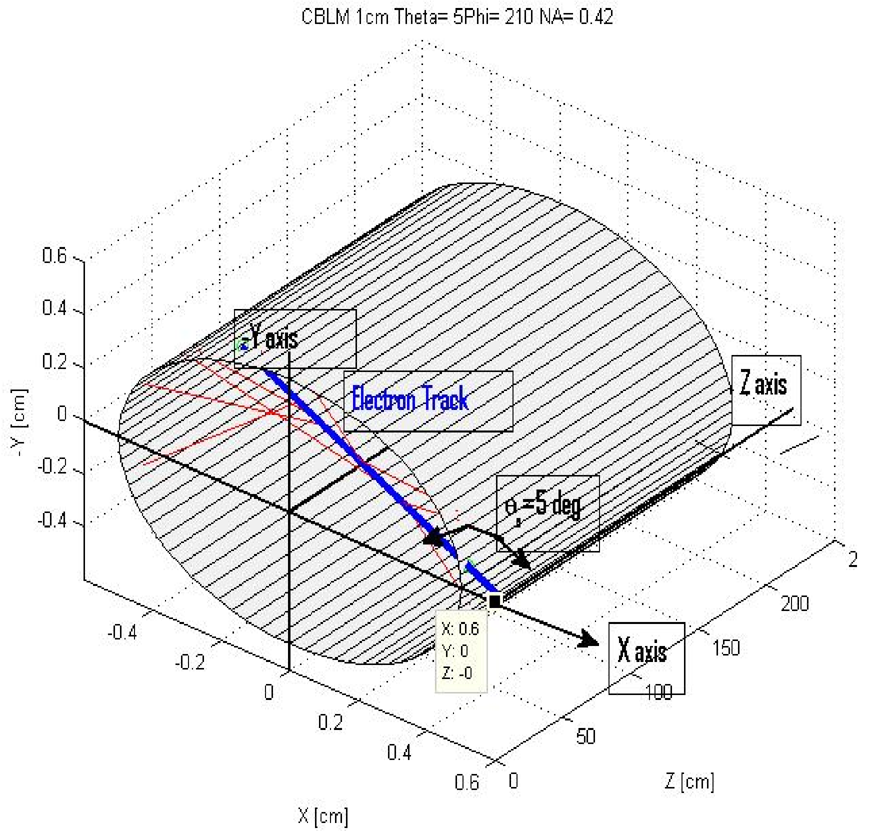


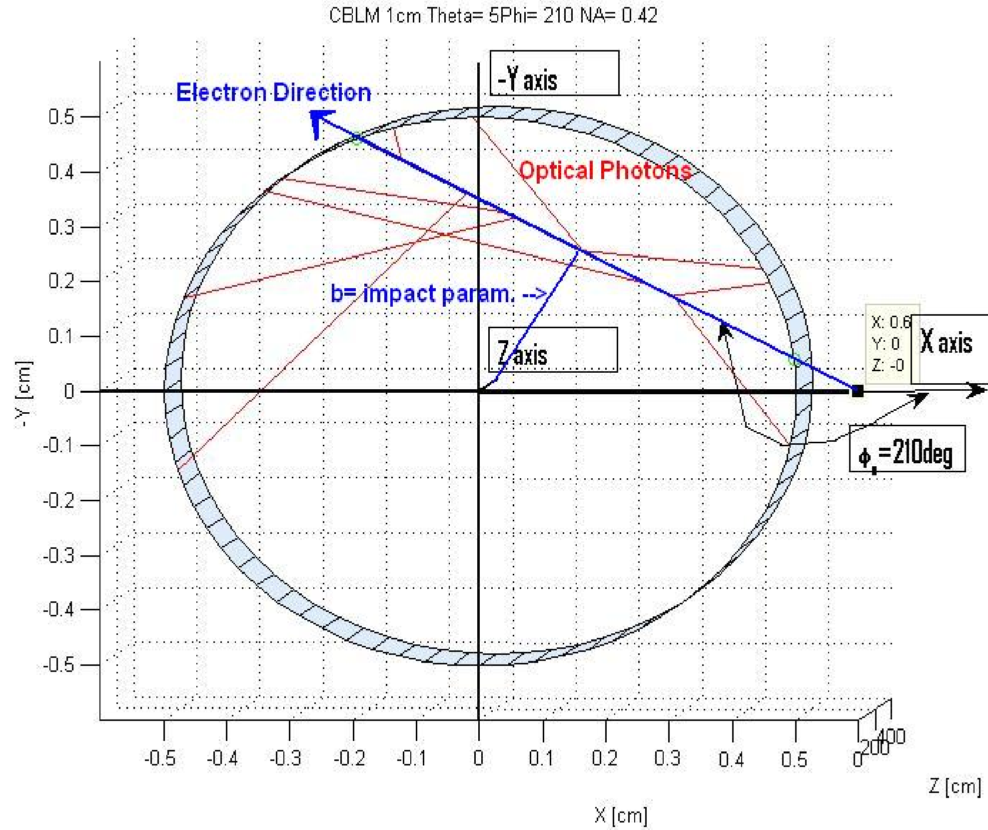
Shower yields more charged particles and longer path length for radiation

5-10 times signal for a single e- loss per turn approaches a S/N ~1 for photodiode

(dark current ~0.1nA)

Generation of Photons in Radiator Rod





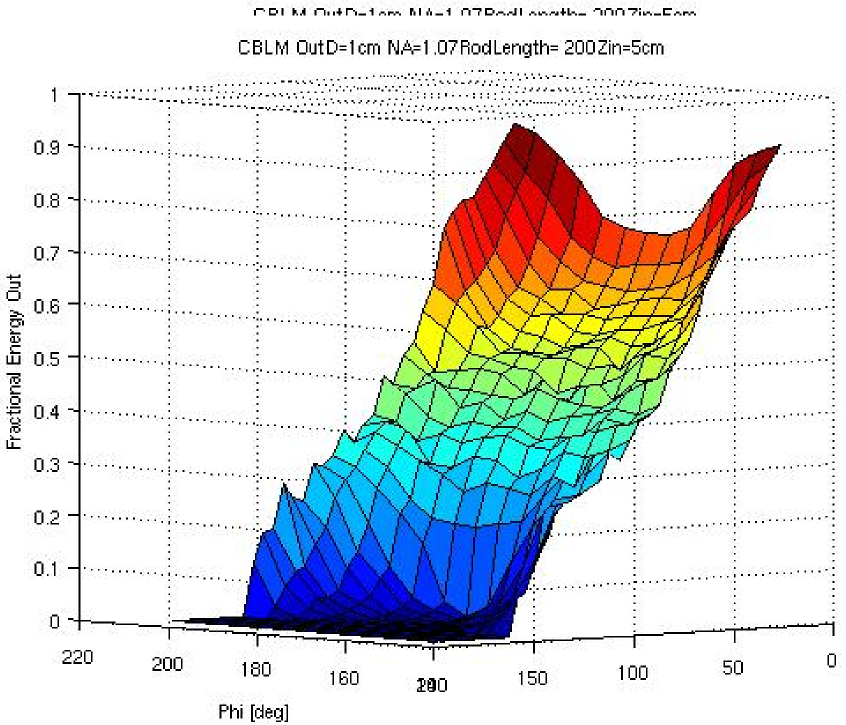
The incident electron direction (θ_e , Φ_e , x, y, z) gives path length p

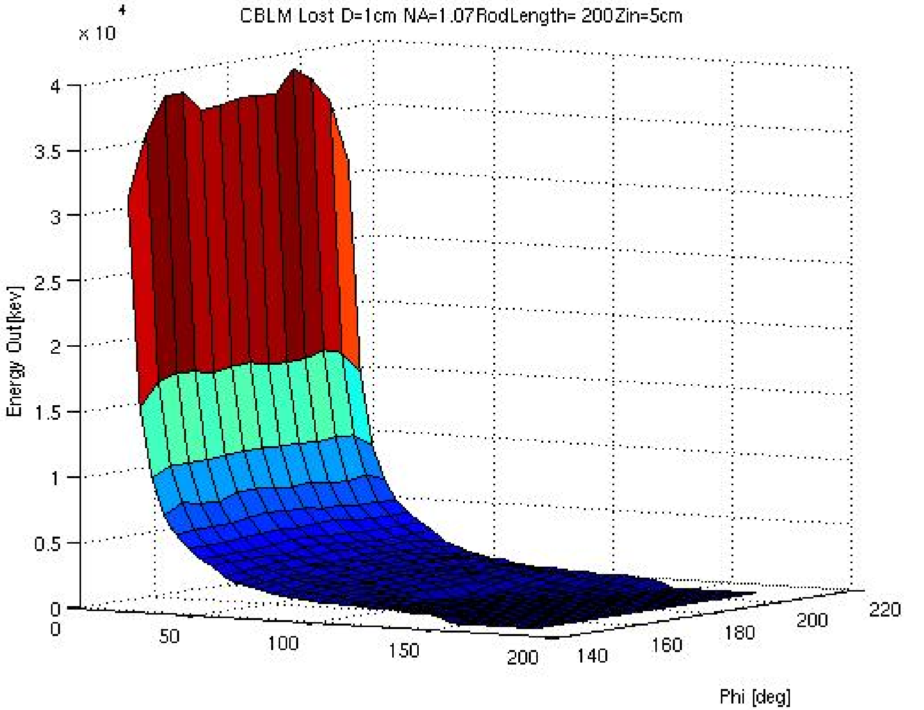
θ_e polar angle to axis of rod (z-axis), Φ_e azimuthal angle in x-y plane

Nγ photons = p* 975 /cm uniform in energy for (200-800nm)

With θ_c angle to electron direction

Propagation of Photons to Detector





Fraction of energy transmitted

Out rod to detector (z= 200cm)

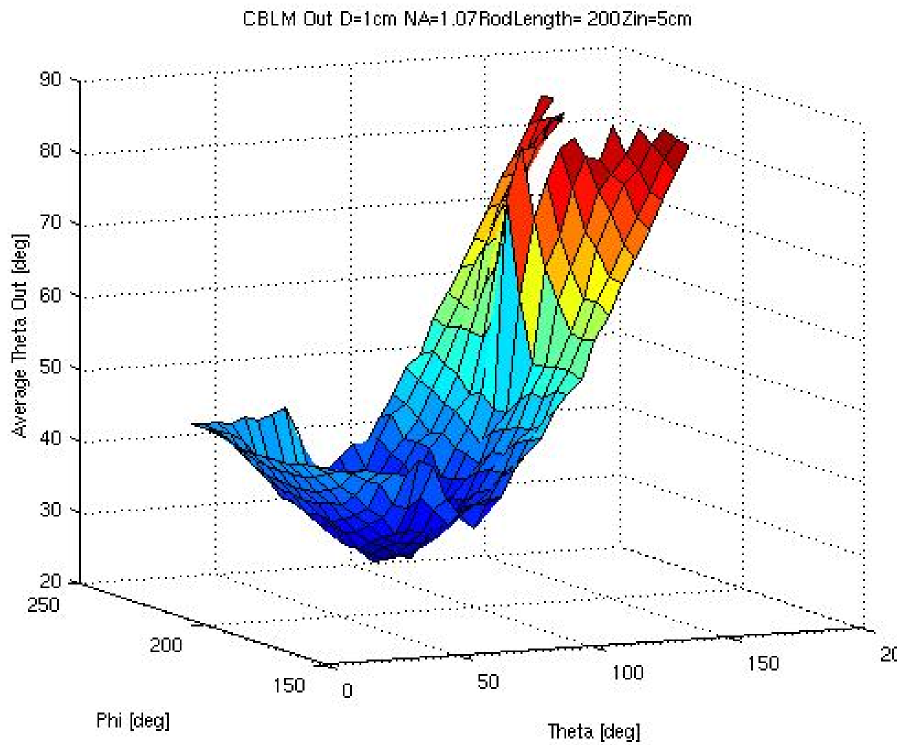
Peaks θe = 0: 85%, 90° : 18%

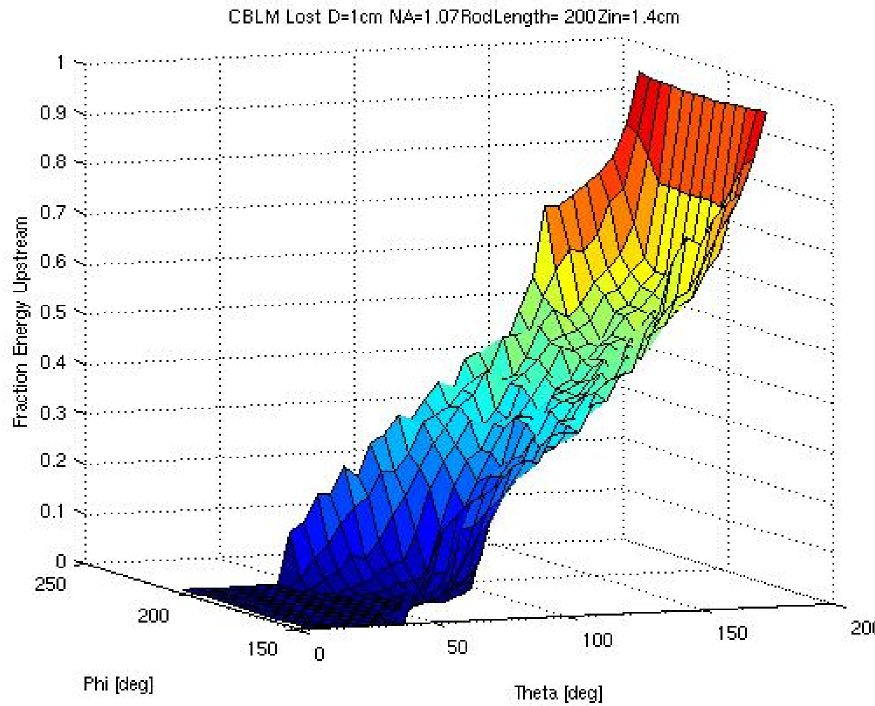
> 110° < 0.1%

Total energy transmitted

Out rod to detector (z= 200cm)

Output Photon are at Large Angles



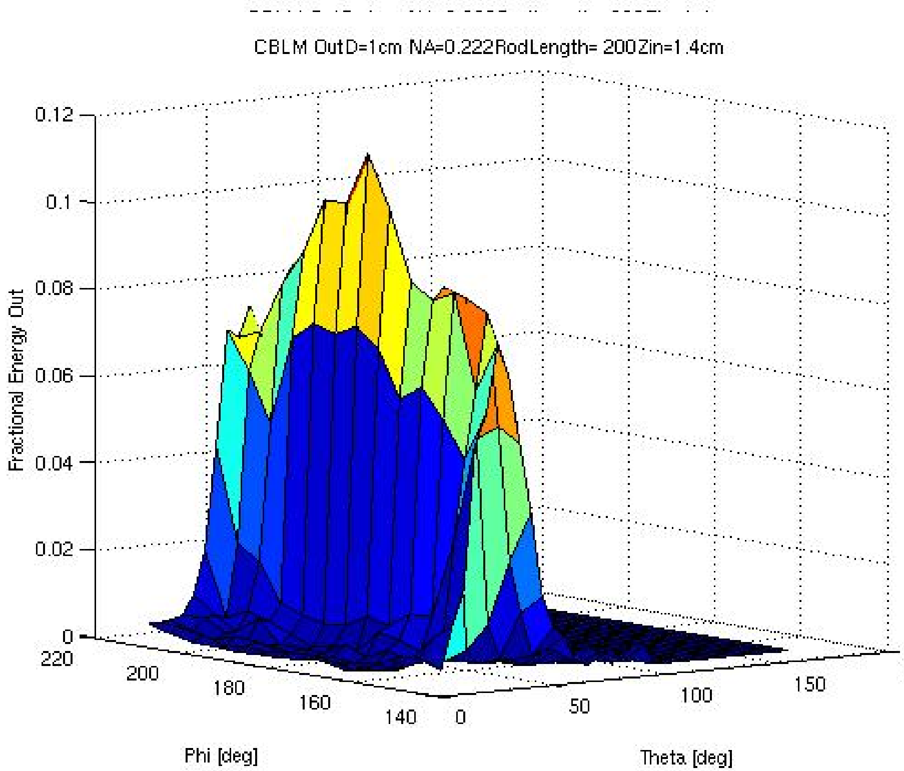


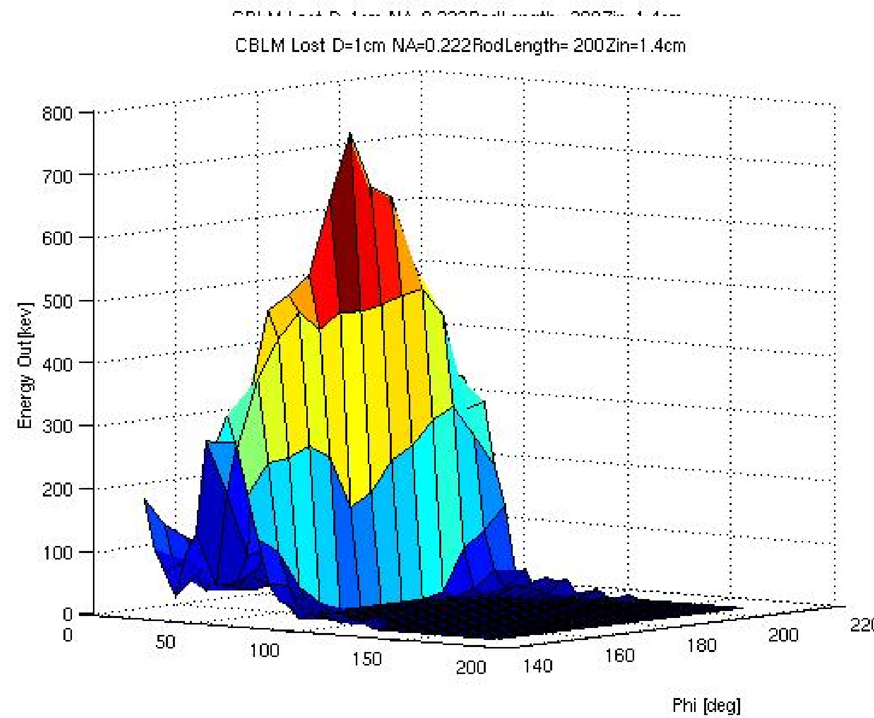
Output photon divergence angle

Since NA > 1

Fractional energy reflected symmetric except for electron path is closer to upstream

Fiber Optics Cable has smaller NA





Fraction of energy transmitted

Out fiber detector (z= 200cm)

Peaks θe = 45: 12%, 5° : 2%

90° : <0.1%

Total energy transmitted

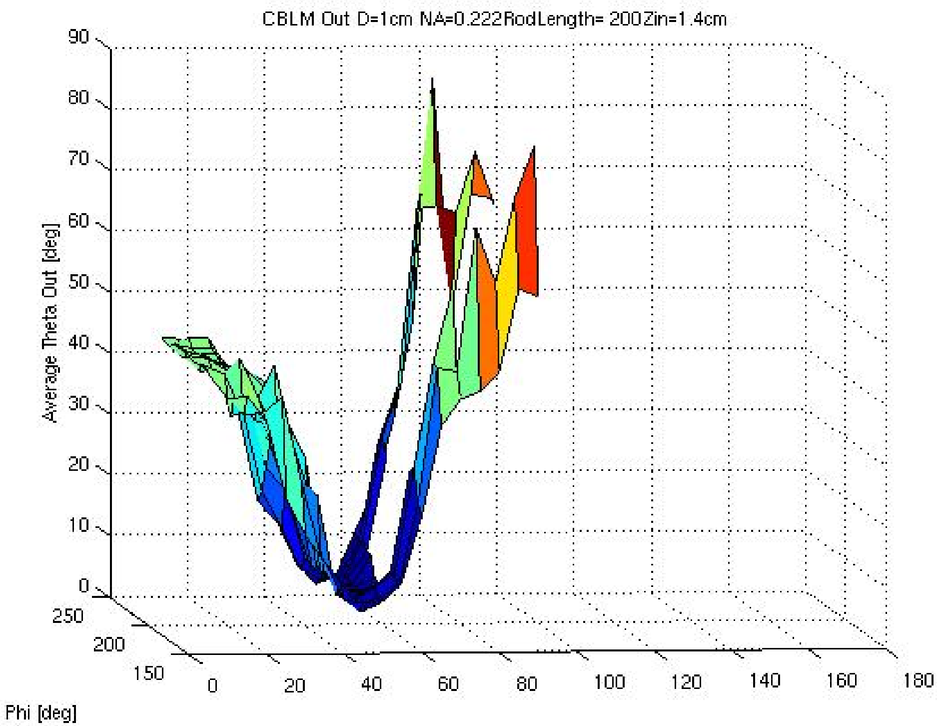
Peak at Cerenkov angle

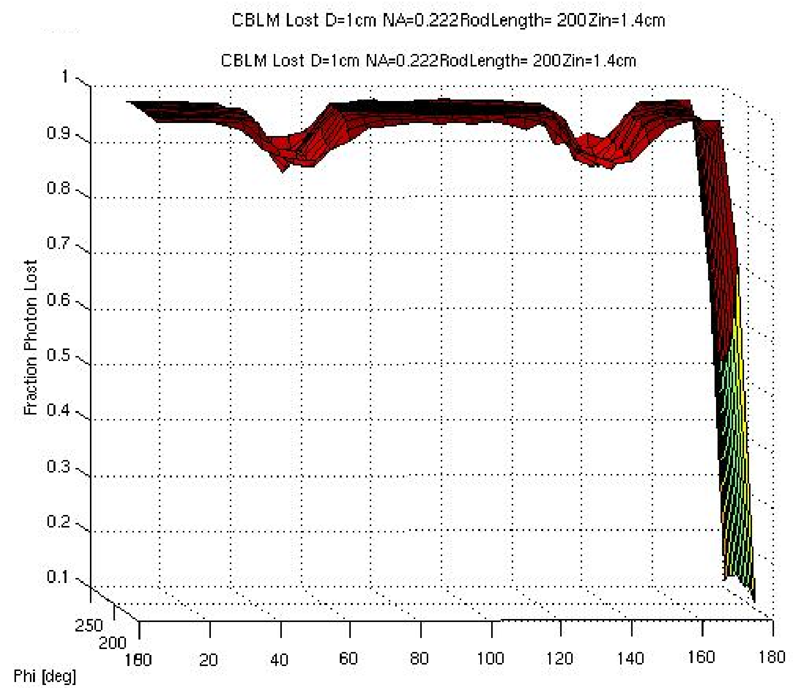
Out fiber detector (z= 200cm)

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Output Photon at Smaller Angles





Output photon divergence angle

Since NA =0.22 = sin(θ) ~13°

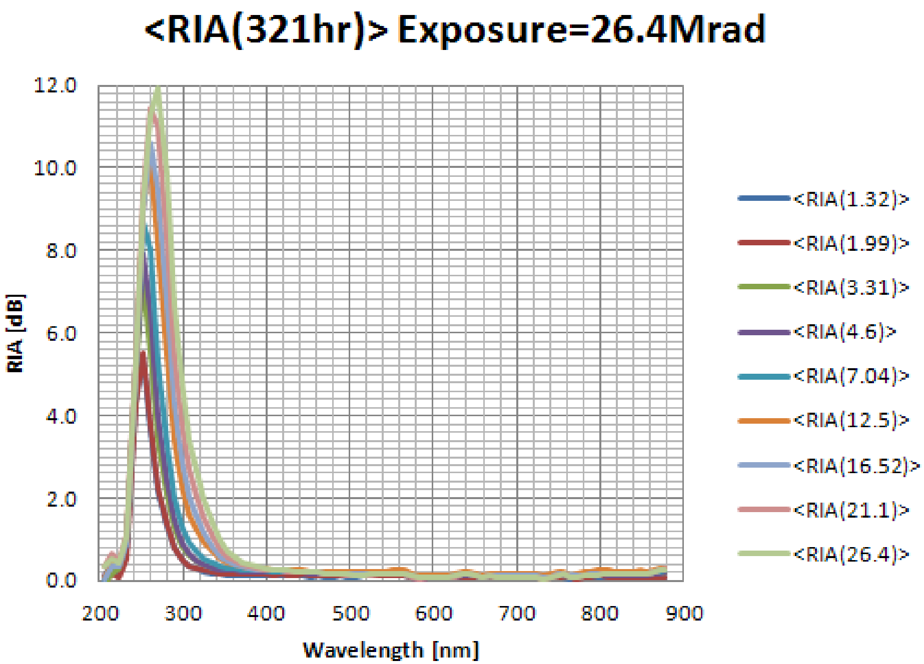
Fraction of lost photons
s out sides of fiber

i.e. not TIR

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

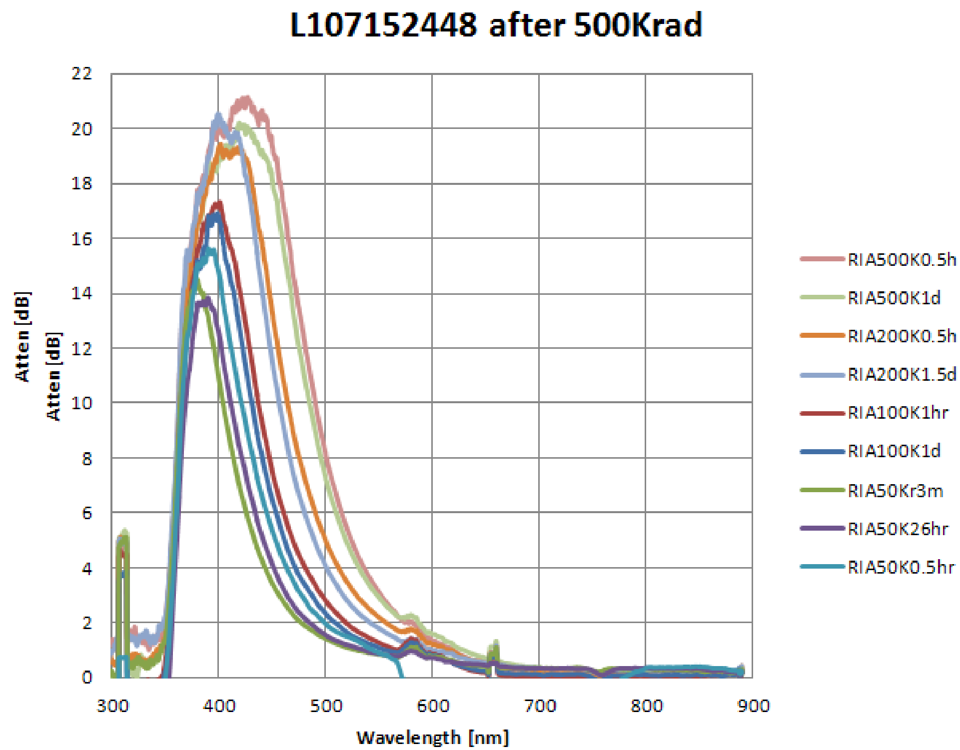
Rods Have Lower Radiation Induced Atten.



Suprasil 2B 99.9999% SiO_2

Measured Radiation Induced Attenuation (RIA) to 26 Mrad

(One year NSLS-II Ops)



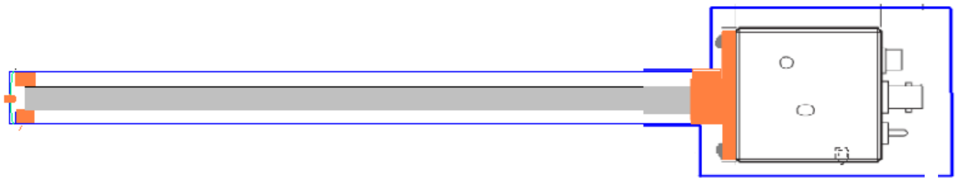
Similar peak RIA for UV fiber at 0.5Mrad exposure and larger in visible fibers

U.S. DEPARTMENT OF ENERGY

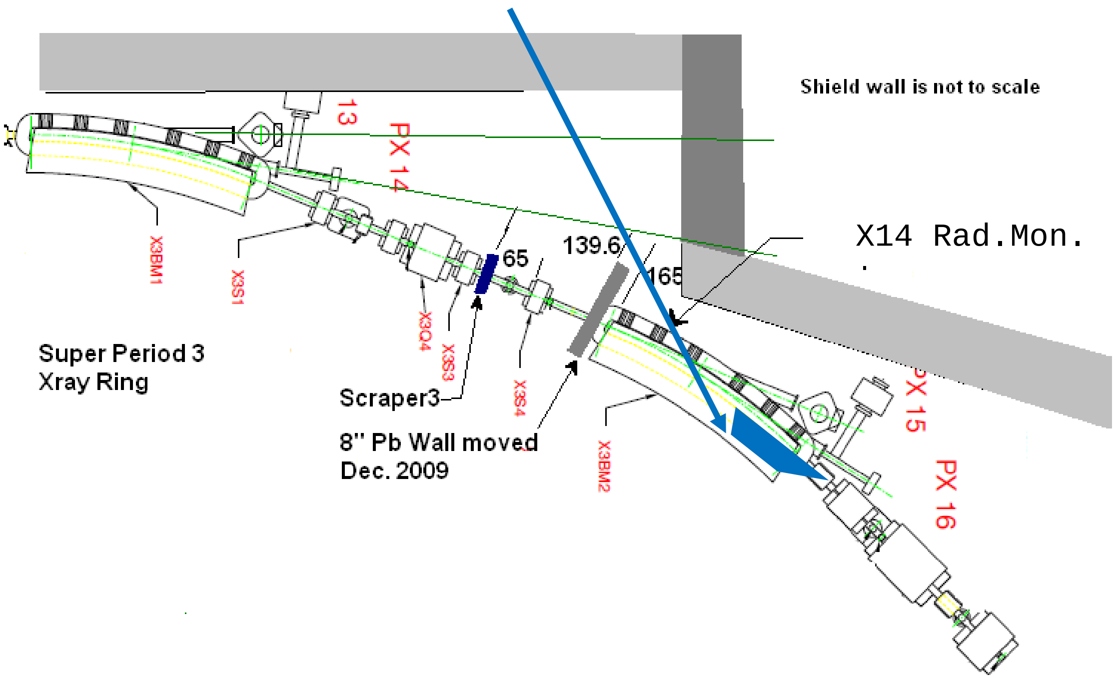
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Testing Prototype CBLM in Xray Ring

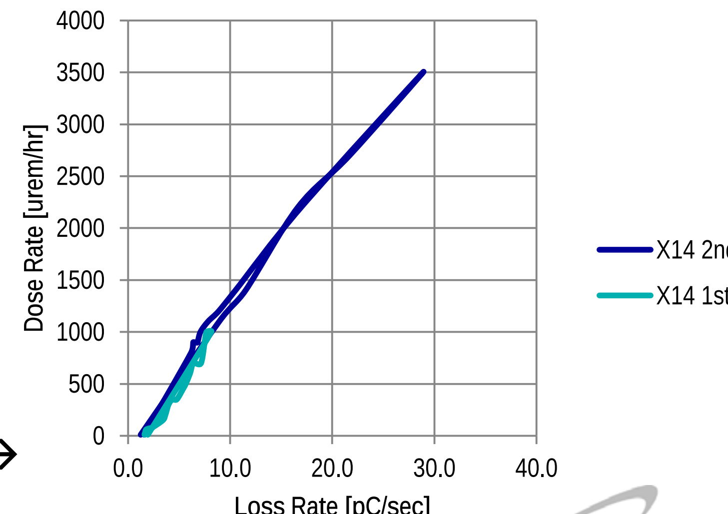
Prototype CBLM: Suprasil fused silica rods and Hamamatsu Photodiode Mod.



10mm x 0.91m CBLM in dipole end



Scan X15 Inner Blade Scan

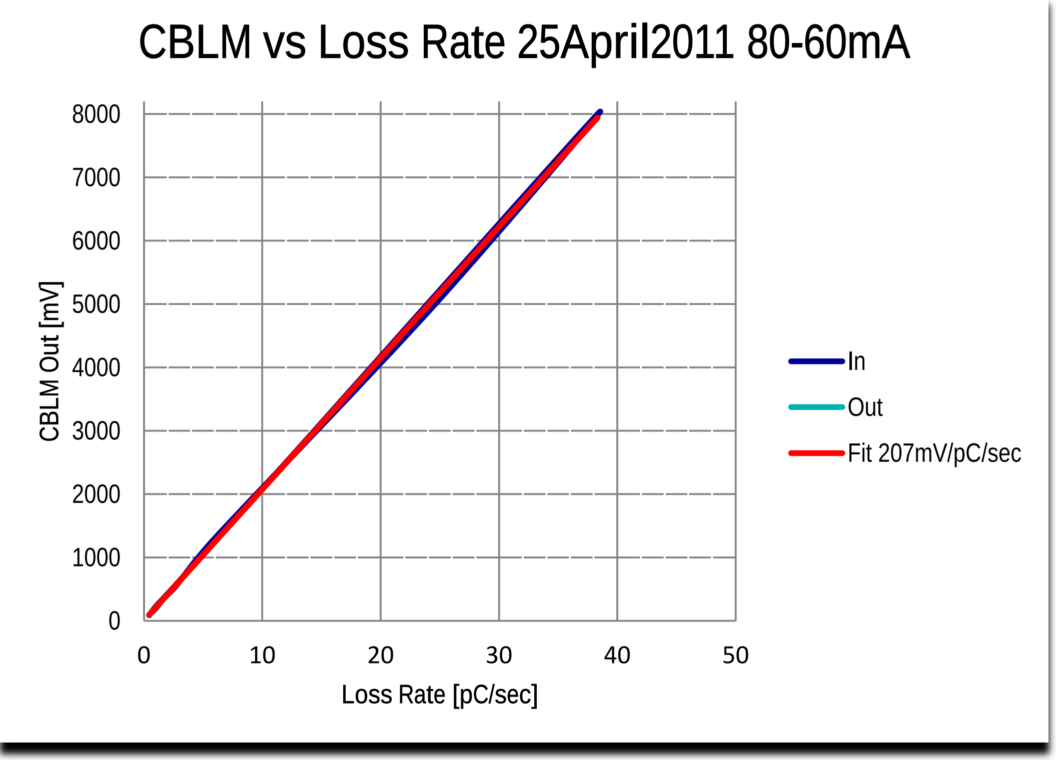


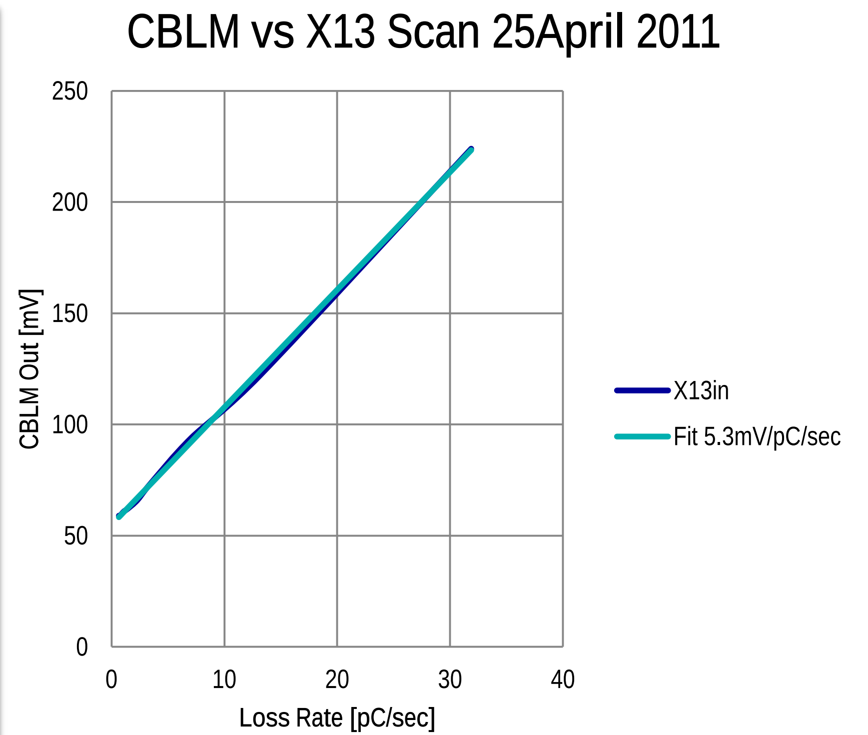
Beam Loss Rate $Q' = Io * To/\tau \rightarrow$

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Scraper Controls Local Loss Rate seen by CBLM





CBLM signal scales linearly with local loss rate Io/τ over >40dB

Zero current level is 0.5 -0.7mV or Noise level ~2-3 fC/sec

Lab noise was 0.035mV or 0.2 fC/sec noise level

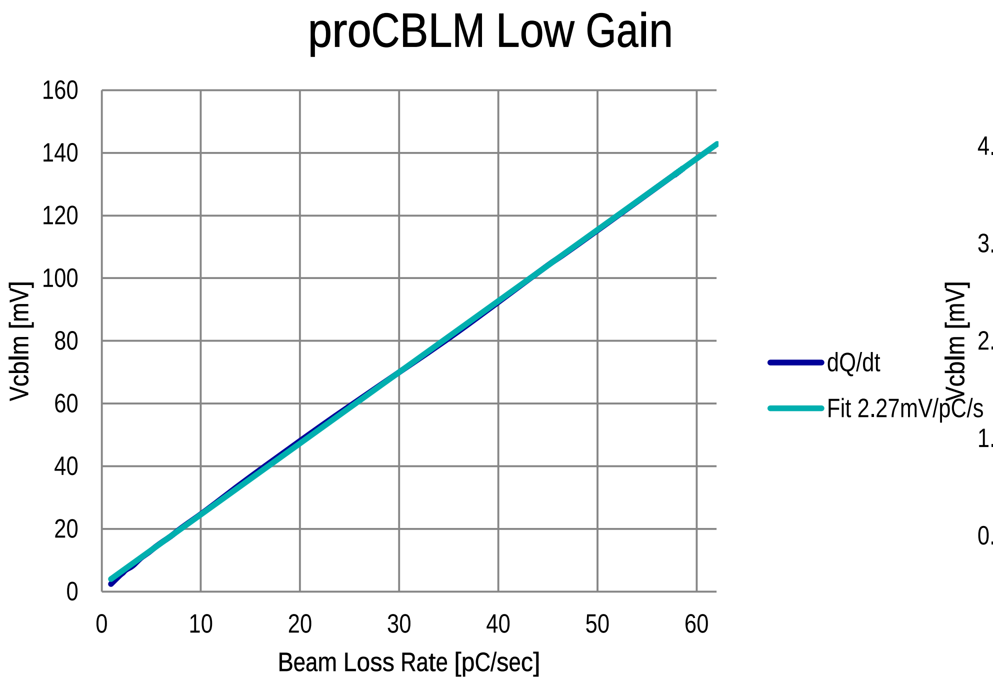
Scraper out CBLM ~ lifetime loss or I^2 for Touschek lifetime

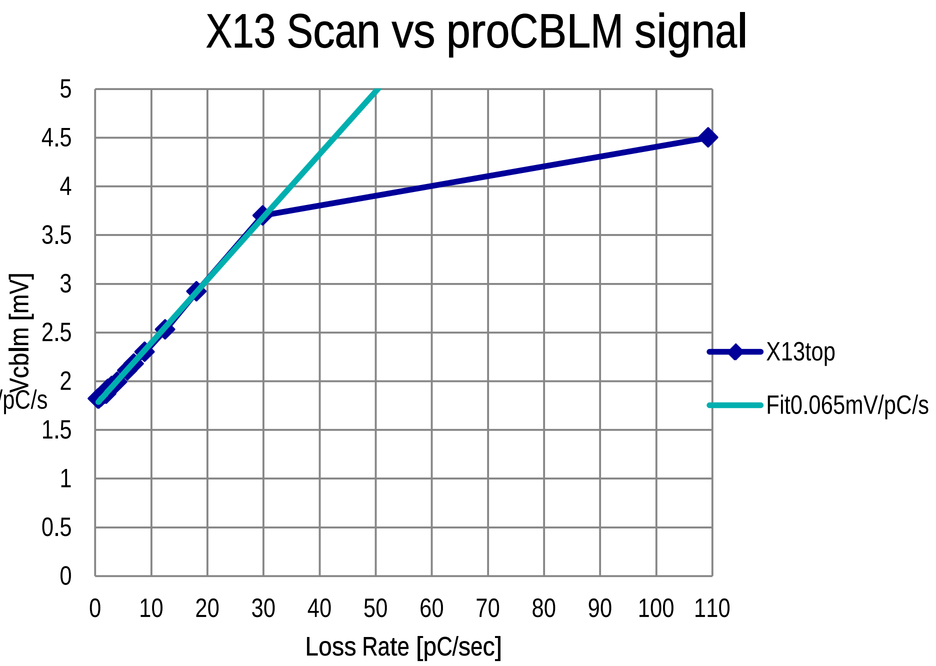
X13 scraper not local to CBLM signal ~40X less

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Lower Gain (~100X) PD module





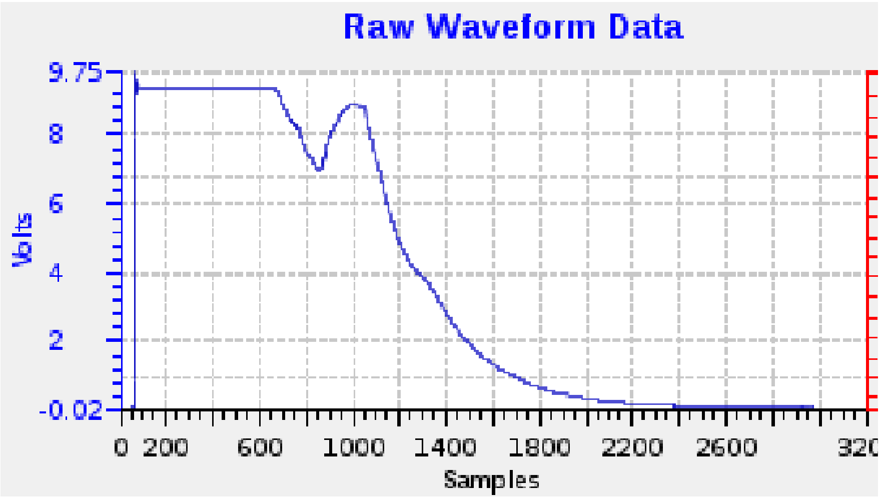
As for NSLS-II the upstream scraper will provide calibration signal once local loss rate (Io /tau) dominates total loss

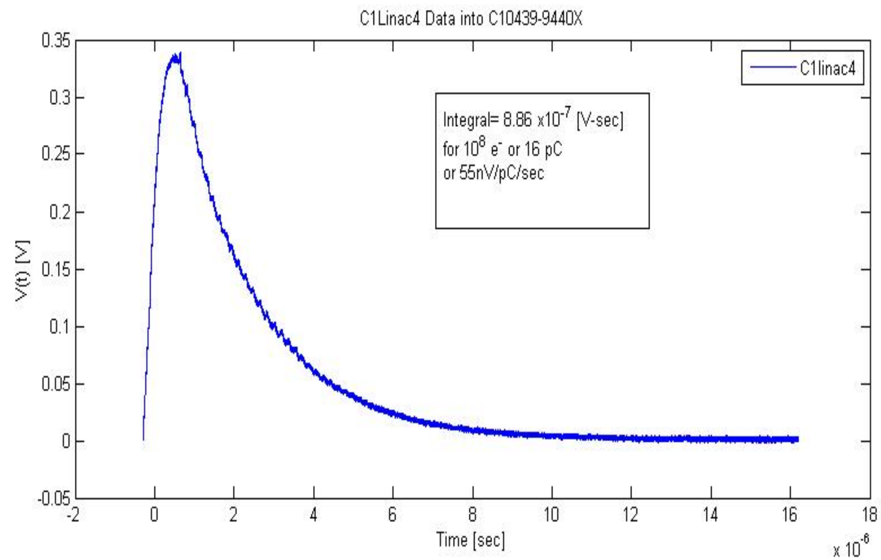
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

BROOKHAVEN SCIENCE ASSOCIATES

Gain too High for Injection Loss





High gain saturates with normal injection losses for ~32 msec

Loss in SP=3 dispersion region

BW= 10Hz so falltime 16msec or 320 samples

The lowest gain ~10^{-6} V/A of PDM has BW=64KHz or 2.4μsec

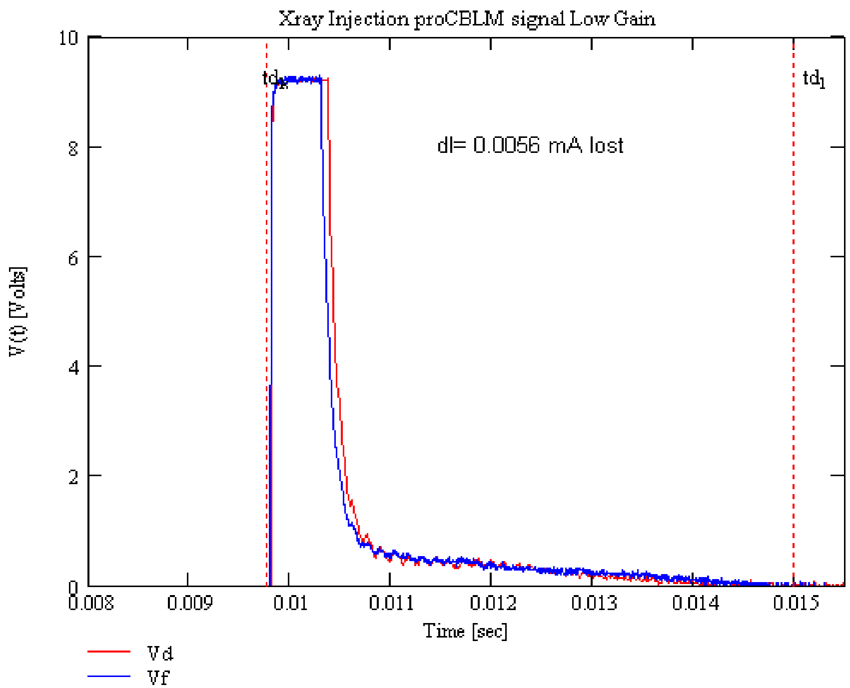
Testing in Linac with 120MeV e^{-} beam at normal incidence with 10^{8} (~16 pC) e^{-}/pulse (2nsec long)

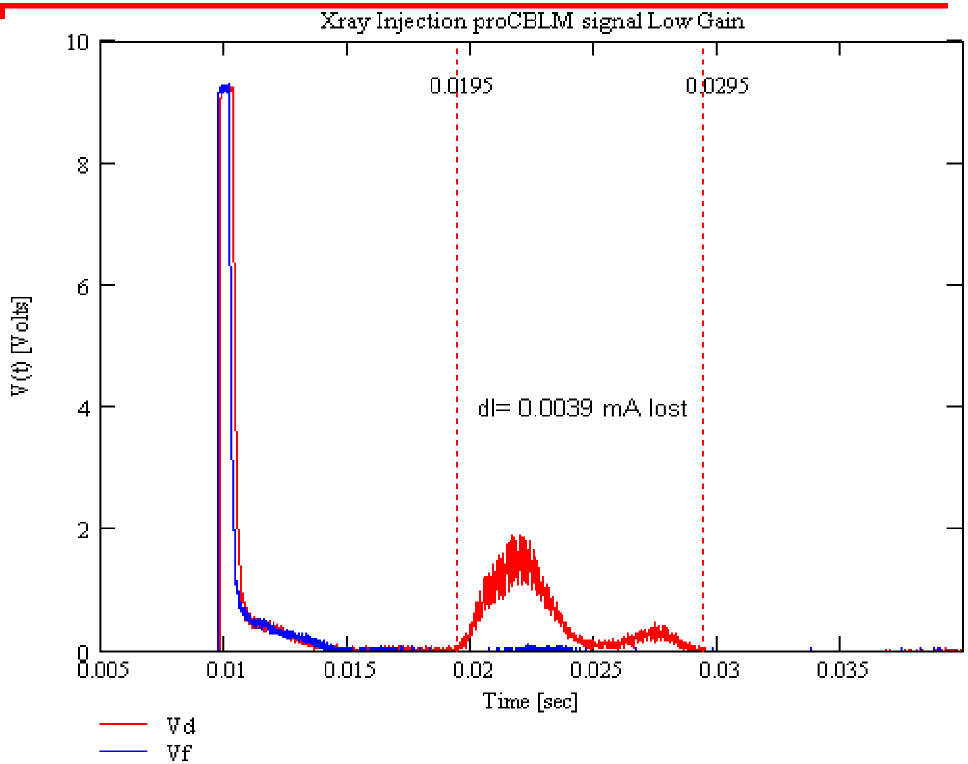
Integral or DC term 55nV/pC/sec

Split lowest gain (hi BW) output to multiple channels of gain or

Use log amplifier and count rate for low loss

Inject. Beam Loss for Low Gain, BW~1KHz





Injection pulse in proCBLM saturates at 9.3V but integral still gives total charge lost, width changes with charge

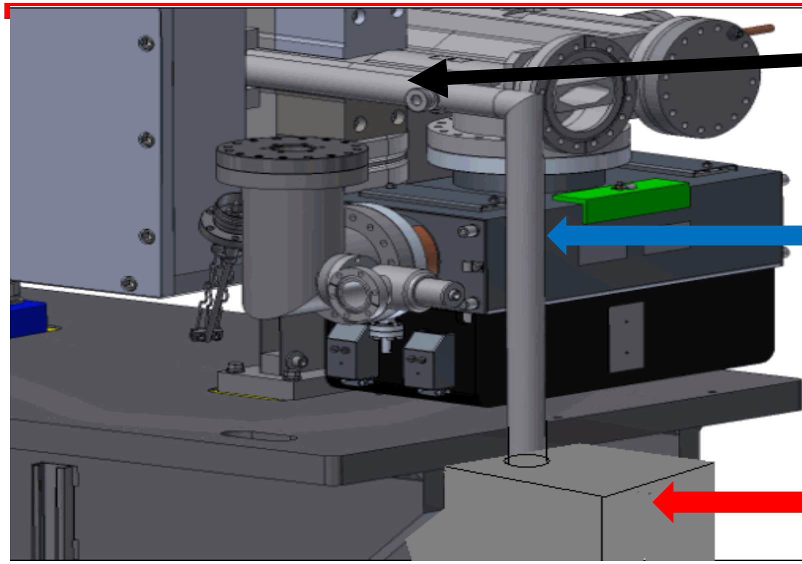
At high current a 2nd loss occurs ~22ms but represents only a small fraction of the 600 to 800μA/pulse injection rate

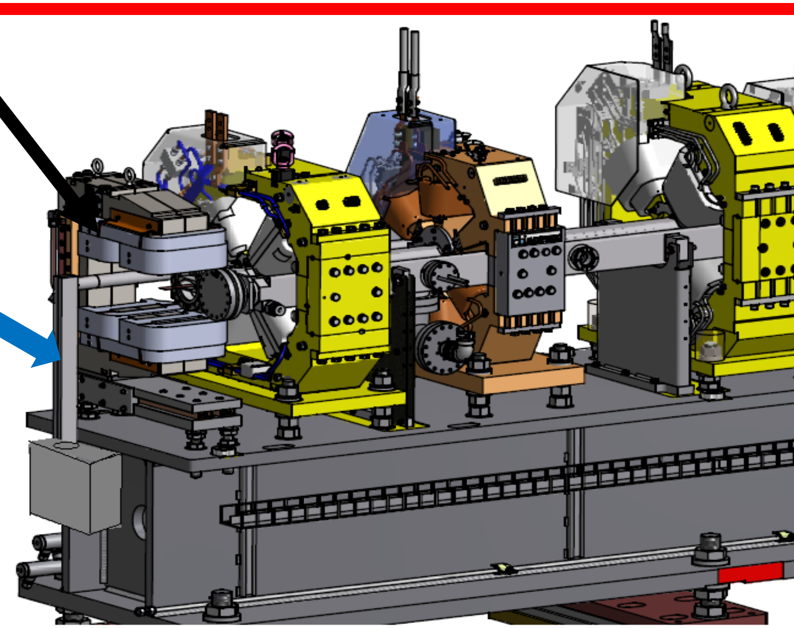
Loss at 50ms after injection was seen with high gain as well.

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

NSLS-II CBLM System Components





Modular design-

Radiator Rods(RR)- 3 dipole, 2 quadrupole

Light Output Couplers (LOC)- 5 and Photo Detector Module(PDM)- 5

Dipole RR- 29.5 mm diameter, 1.2m long and 25m bend radius

Quad RR – 29.5mm diameter , 1.2m long straight

LOC – 90° prisms with Light pipe to PDM for reduced Rad Exposure

PDM's – 9 decade DR detector module, R&D effort ongoing

Cerenkov Radiator Rods and Couplers

Hereaus Quartz: provides two ultra-pure Fused silica materials and rods

Suprasil 2B: tested in Xray ring (120Krad), in Co^{60} (>26Mrad)

Spectrosil 2000: (no Chlorine) (existing stock 29.5mm OD 1.2m)

Free draw of rods: flame polished, excellent clarity, low scatter, TIR

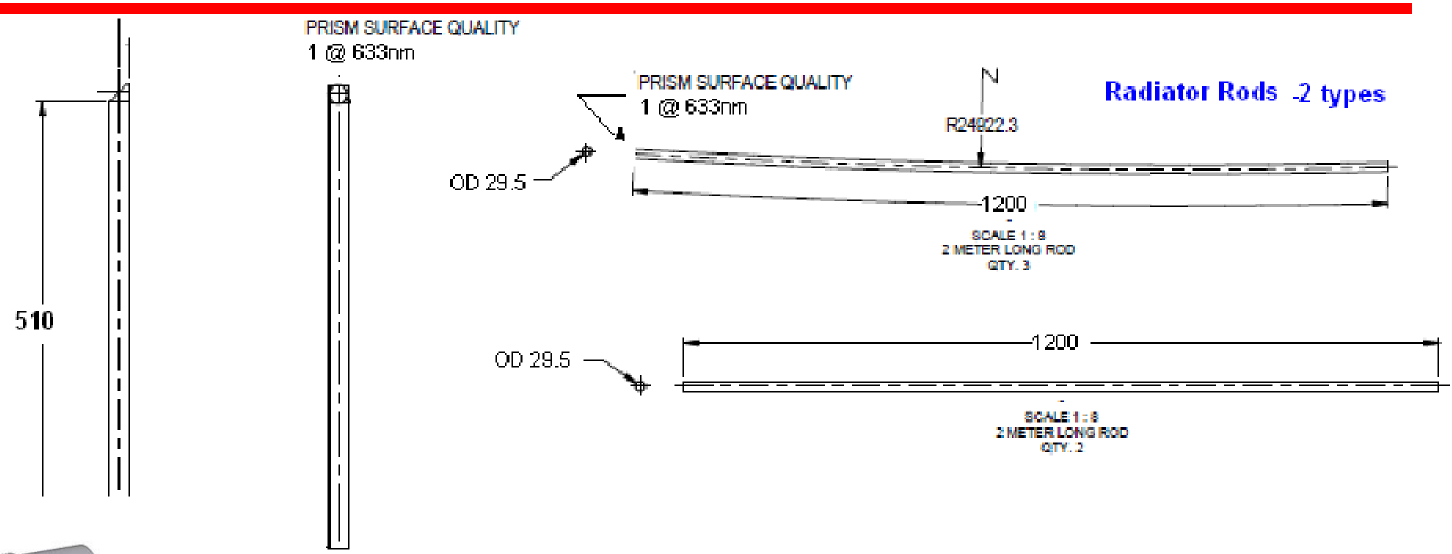
10mm OD length up to 1meter , 25mm OD up to 2meters

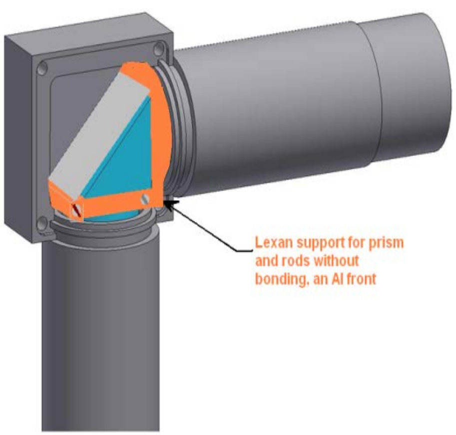
Corning Fused silica 7980 O-A similar quality fused silica but need fabricator to draw rods

Prisms and tapered collectors will be made with 7980 raw material

Rods and prisms supported with lexan spacers with minimum width for TIR

Output Coupler and RR Components





Heraeus Quartz USA has existing Spectrosil 2000 rods 29.5mm OD and will bend to 25m.

Use air gap between rod to prism and prism to down rod loses 8-10% light.

Could be chemically activated bonded with only 4% loss.

Goals for beam loss monitor sensitivity

3hr lifetime loss rate ~ 2000 e^-/ turn (2.6 µsec) for 10 e^-/ turn or 0.6 pC/sec

in CBLM → S/N > 10 or 1nA into 1KΩ ~ 10µV x 10K gain 100mV pulse

for count rate measurements from 1K to 1M cps (1 to 1000 bunches/turn)

Losses of 0.001µA/turn 16K e^-/ turn 75KHz(5 turns) time for betatron losses

0.98 nC/sec → 3.2µA into 1KΩ give 3.2mV x 100 gain

Losses of 0.1µA/turn 1.6M e^-/ turn 3.3 KHz (114 turns) time for synch. losses

0.1µC/sec → 0.32mA into 1KΩ give 320mV x10 gain

Losses of 3mA/turn 4G e-/turn over 100 turn pulse: dump, injection, steering

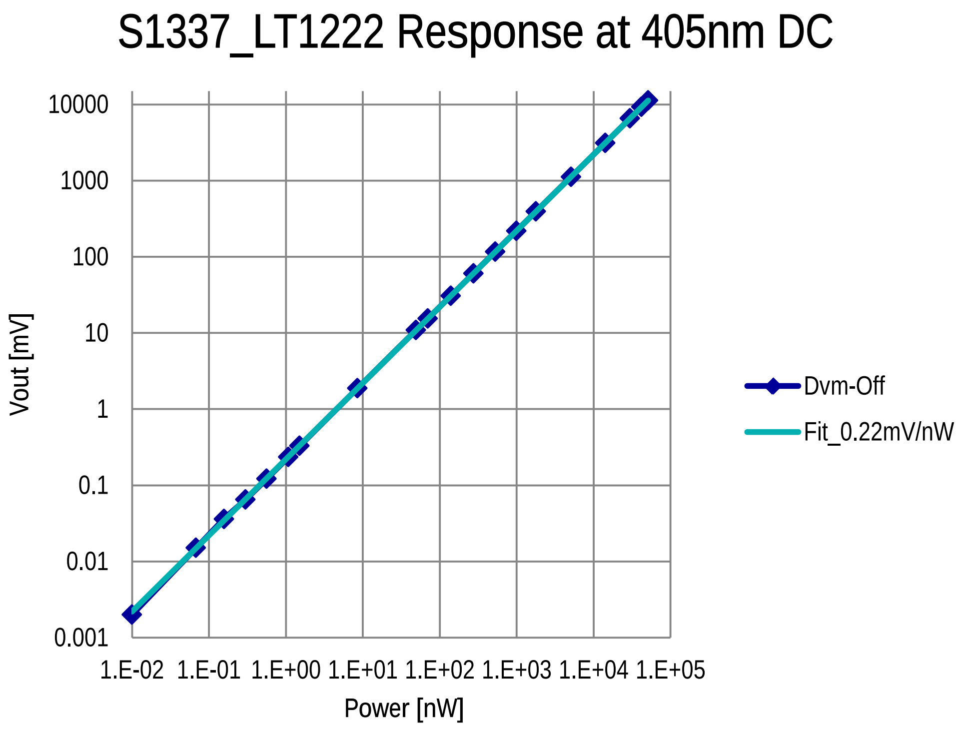
3 mC/sec → 800mA peak pulse into 10 Ω 8V peak x 1 gain

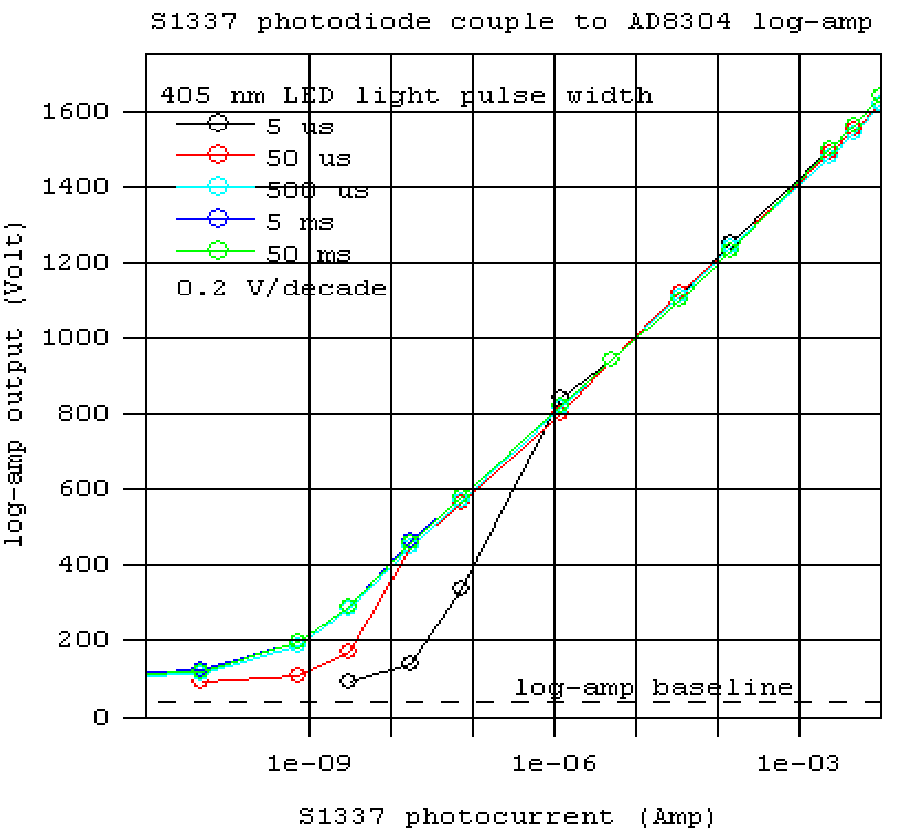
Large Dynamic Range ~>10^9 for detector output current with BW from 50MHz – 100 Hz and DC

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Progress in HDR Photodiode Modules





Low Noise Amplifier 7-Decades but boxed in by noise floor and amplifier bias

Log-amplifier shows 8 to 10 decades but have a lower BW at low levels, not serious issue

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Design of High Dynamic Range Detector

Photodiode Detectors-

QE > 25% down to 200nm

DC coupling, high peak current, no HV,

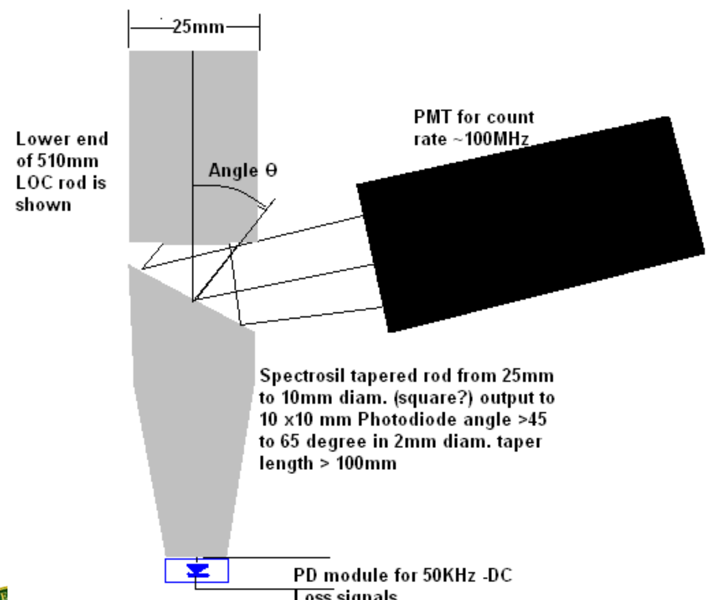
Compact, simpler, external gain, limited by noise floor and amplifier rail

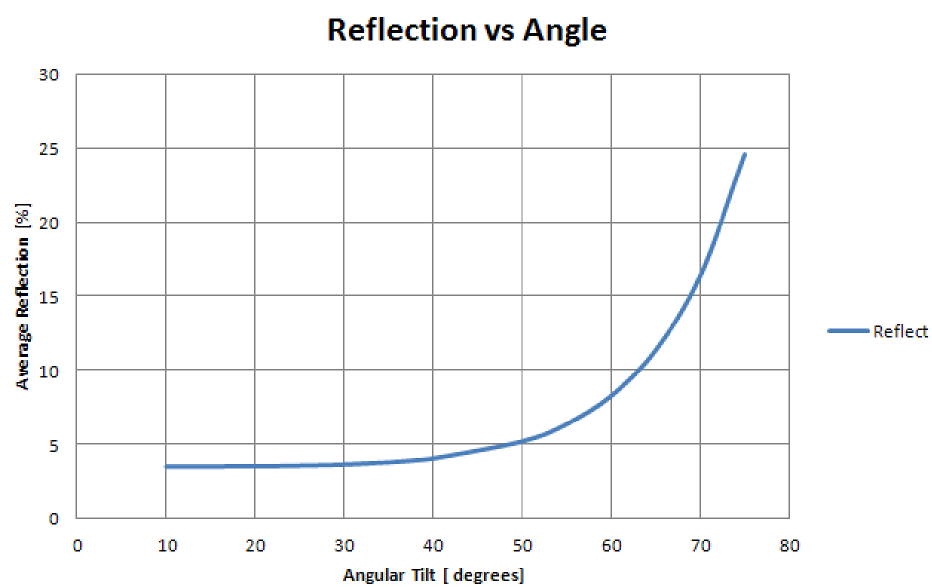
low BW for high gain and large area

PMT Detectors-

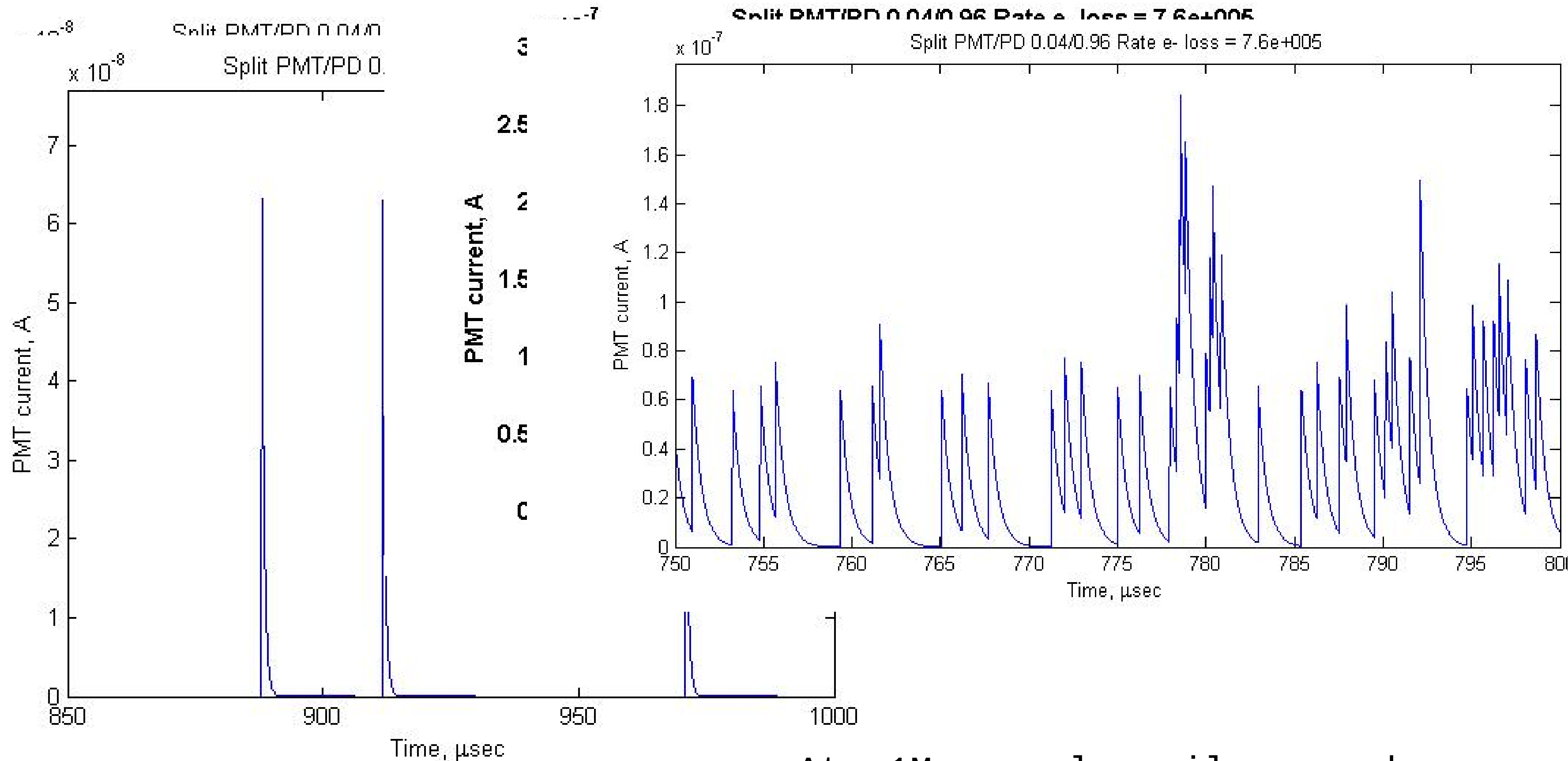
High Gain, High BW, pulse count rate

QE < 25% peak , DC coupling HV issue, HV required, high peak current vs gain response complicated,





PMT Output for Count Rate to Low levels



At ~1Mcps pulse pile-up makes count rate miss charge signals but integrated signal still yields accurate Q′, need FPGA

PMT signals at ~1Kcps clean single e- signal count rate C → Q′ = e * C

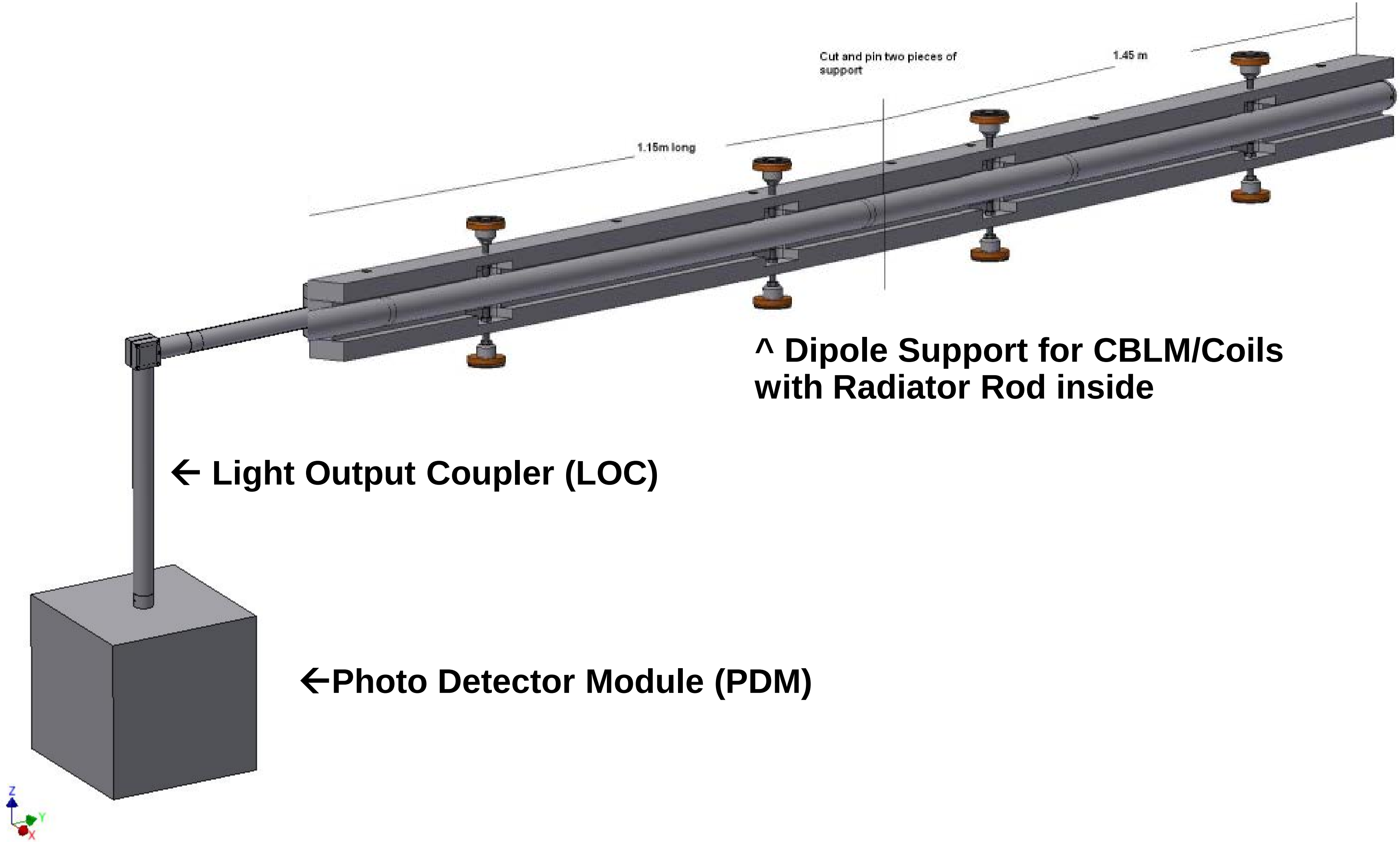
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

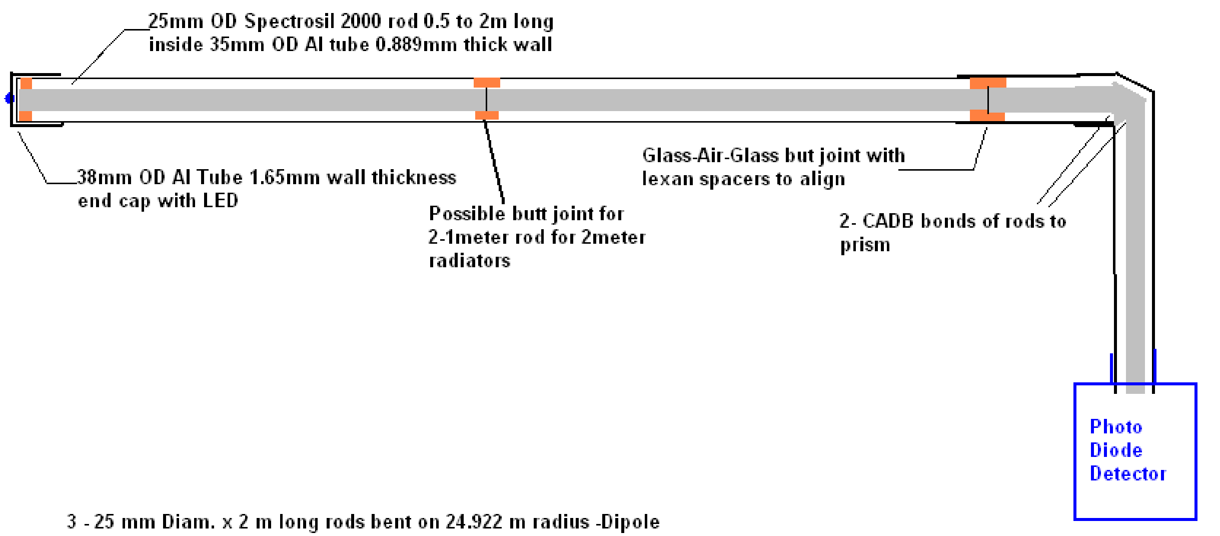
Summary of CBLM System for NSLS-II

- Use of thin scrapers gives clear beam loss signal, with physics of shower in VC walls modifiying collection of charge signal (+ & -)
- Scraper controlled beam loss rate for calibration of detector signal
- Calibration without scraper needs modeled capture efficiency
- CBLM can be used without scraper but need model for fraction of scraper beam intercepted by RR
- Fused silica rods have greater Cerenkov light collection and radiation resistance and less directional variation than Fiber Optics
- Can be used for continuous or pulsed beam losses, will need higher BW (smaller PDs or PMTs), Location determined by RR length.
- Dual detector and log amplifier could yield new generation of HDR PDM especially if FPGA can deal with data streaming and transition from pulse counting to analog levels in smooth way (overlapping ranges)

Dipole CBLM/Coil Support New Design



Replacement of Radiator Rods



3 - 25 mm Diam. x 2 m long rods bent on 24.922 m radius -Dipole
2 - 25 mm Diam. x 2 m long straight rods- Quad
2 - 25 mm Diam. X 1 m long straight rods - Quad
7 - 25 mm Diam. X 0.105 m long input to prism
7 - 25mm square input/output 90 degree bend prisms
7 - 25mm Diam. X 0.510 m long straight rod to PD detector

Spectrosil 2000 is best glass for low RIA >10years ops

If attenuation is too low for calibration of high end loss rates then replace

1. Cut damaged rod too removable pieces as pulled out
2. Replace with new glass cut and polished to shorter lengths with air splice joints (7-10% loss per joint)

Need for HDR Detector

Assuming 500mA operations at 3hr lifetime for 5500 hrs per year

Top-off charge injection rate into SR 7.3 nC/min Total = 2.42 mC/ yr
CBLM rate 50 to 100 e-/turn 6pC/sec 0.36 pC/min

55 dumps per year = 73 µC /yr or 3% of total charge lost for operation year
1.32 µC/ turns 500 mC/sec dump rate into CBLM
20% inject losses /turn 1.46nC/turn   0.1mC/sec into CBLM