Optical Restoration of Lead Fluoride Crystals

A. Spilker, P. Cole, T. Forest, S. Naeem, M. Mestari, N. LeBaron
Idaho State University

J. Roche
Ohio University

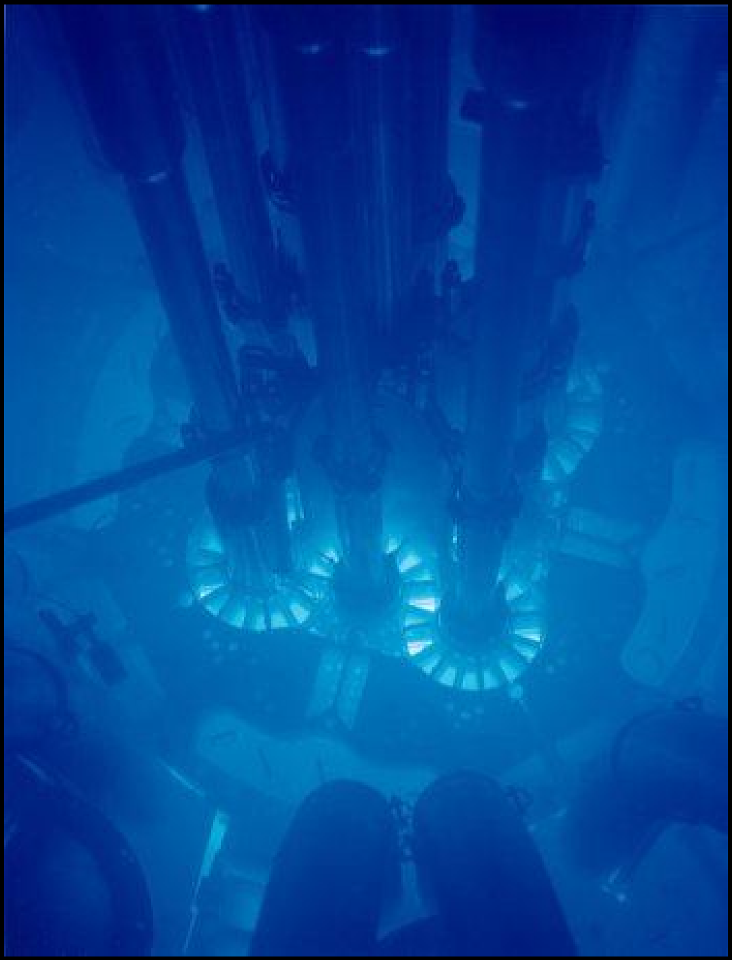
P. Bertin
Université Blaise Pascal

Lead Fluoride (PbF_2)

Purpose: Cherenkov Radiator

Cherenkov Radiation

- Photonic shock wave
- Particle velocity > c/n
- Wake of charged particle creates photons
- Little destructive interference → light cone



Advanced Test Reactor at INL

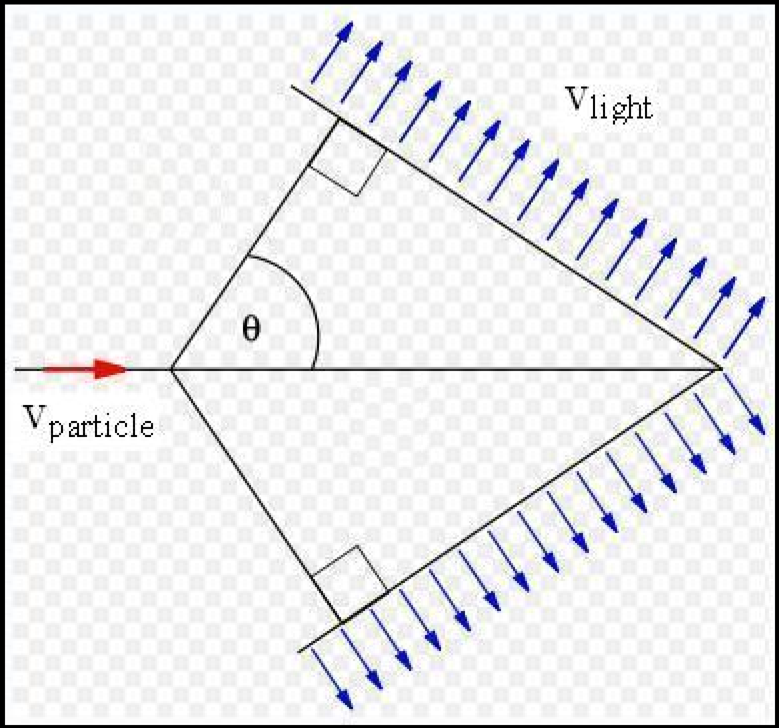
Cherenkov Radiation

- Cherenkov cone is shown

$$\cos(\theta) = v_{light}/v_{particle}$$

$$v_{light} = c/n$$

n is index of refraction



n = 1 for vacuum; n = 1.00029 for air

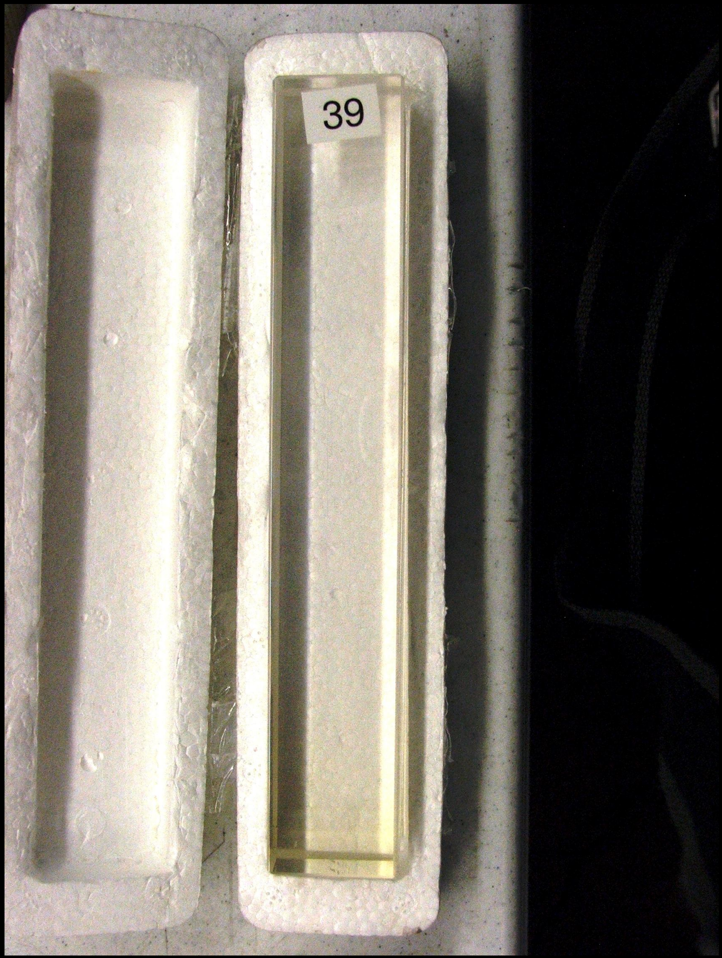
C = 2.99 x 10^8 m/s

Cherenkov Radiators

- In particle physics Cherenkov radiators afford means of distinguishing among particles (such as e^- vs proton). Particles may be identified by the angle of emitted Cherenkov light for a known index of refraction.
- In an investigation of scintillators in the late 80's, lead fluoride was found instead to be a Cherenkov radiator
- 132 blocks of PbF_2 will be used in the Deeply Virtual Compton Scattering experiments at Jefferson Lab (E07-007, E08-025, E12-06-114)

Lead Fluoride (PbF_2)

- Cherenkov Radiator
- Compact
- High Transparency
- Radiation Hard
- Low Hygroscopicity
- Optically restored after radiation exposure (UV/optical bleaching)



Cherenkov Radiators

OPAL EM Calorimeter material

Material	Pb	F5	SF5	SF57	Heavy	PbF2
PbO content (%)	–	40	51	75	85	–
Density (g/cm³)	11.3	3.47	4.07	5.57	6.2	7.8
Index of refraction	–	1.6	1.6	1.85	–	1.82
UV absorption edge (nm)	0.5	370	380	380	450	300
Radiation length (cm)	0.5	2	1.6	1.5	1.4	0.93
Interaction length (g/cm2)	193	104	108	120	120	156
Interaction length (cm)	18	29.9*	26.5*	21.4*	20**	20

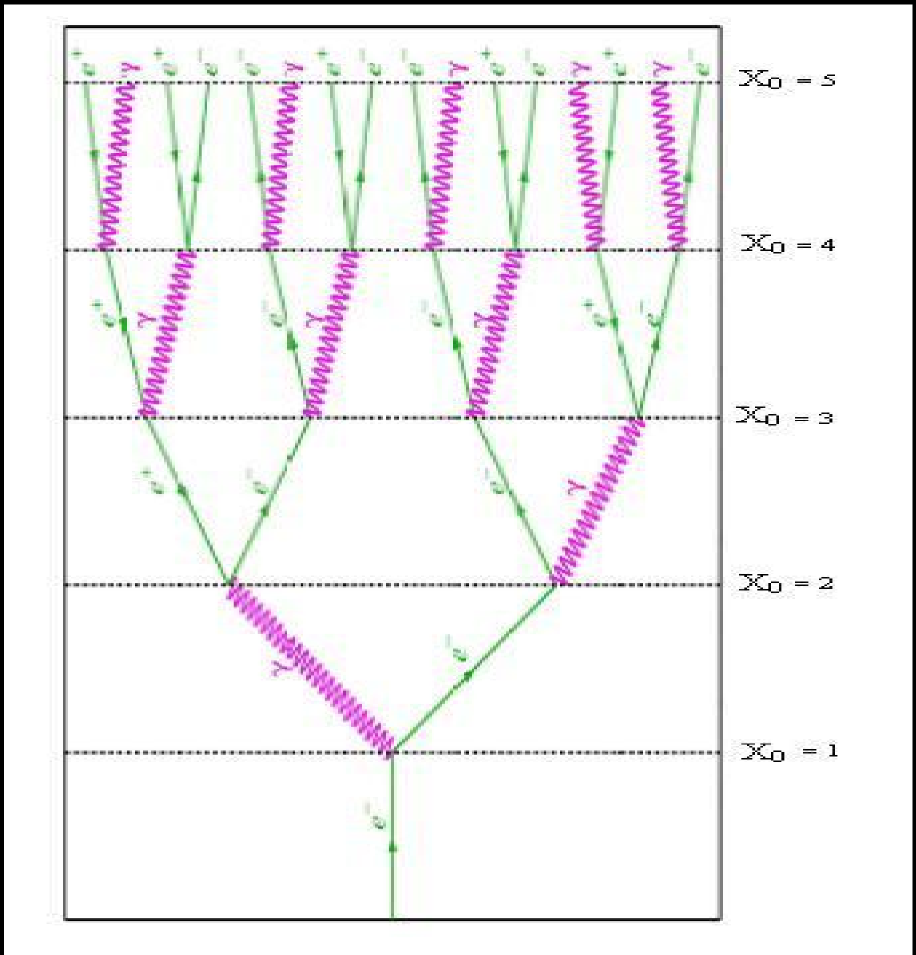
* GEANT4 results

** Estimate

Zhao, Plannar Active Absorber Calorimeter, ACFA 2007

Shower Cascade

- Incoming electron interacts, releasing a photon via bremsstrahlung
- Photon pair produces $\gamma \rightarrow e^- e^+$
- Moving charged pair interacts again, producing more gammas
- Process continues, creating a shower effect
- Shower = big signal
- X_0 is radiation length, i.e. the mean distance over which electron beam intensity is reduced by a factor of e^{-1}



[Photo Reference] Gregoire, DVCS experiment, Ohio University 2007

Moliére Radius

- The Moliére Radius (R_M) is a measure of the size of an electromagnetic shower in some material
- Smaller Moliére radius = better shower containment
- For SF-5 and SF-6 lead glasses R_M = 3.7 cm & 2.7 cm, respectively[1]
- The effective Moliére radius of lead fluoride[2] is 1.8 cm

[1] P. Kozma, R. Bajgar, P. Kozma Jr., Nucl. Instr. & Meth. A 484 (2002) 149
[2] P. Achenbach, I. Altarev, K. Grimm, T. Hammel, D. von Harrach, J. Hoffmann, H. Hofmann, E. –M. Kabuβ, S. Köbis, A. Lopes Ginja, F. E. Maas, E. Schilling, H. Ströher, Nucl. Instr. & Meth. A 416 (1998) 357

Our Experiment

- Measure transmission in samples of lead fluoride scheduled for use in the DVCS experiments at JLab
- Four samples exposed to 7-35 kGy of radiation under controlled, reproducible conditions
- The purpose was to quantify efficiency loss in DVCS detector

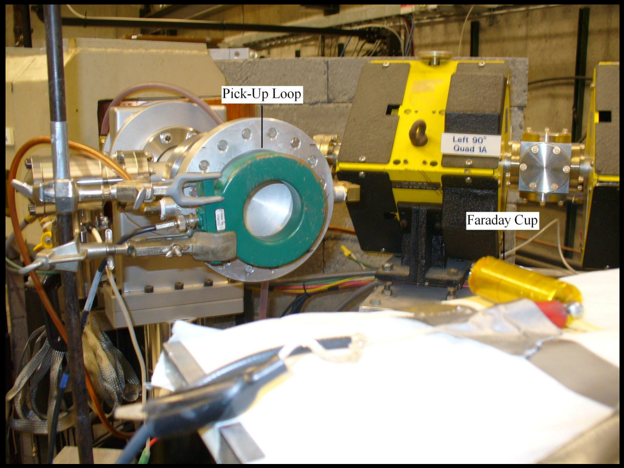
1 Gy = 100 rad = 1 J/kg (10-20 Gy of whole body dose can be fatal to humans)

The Method

- Dose samples with controlled source
- Measure transmission
- Optically bleach samples with blue light
- Measure transmission
- Repeat irradiation/optical restoration cycle
- Compare cycles

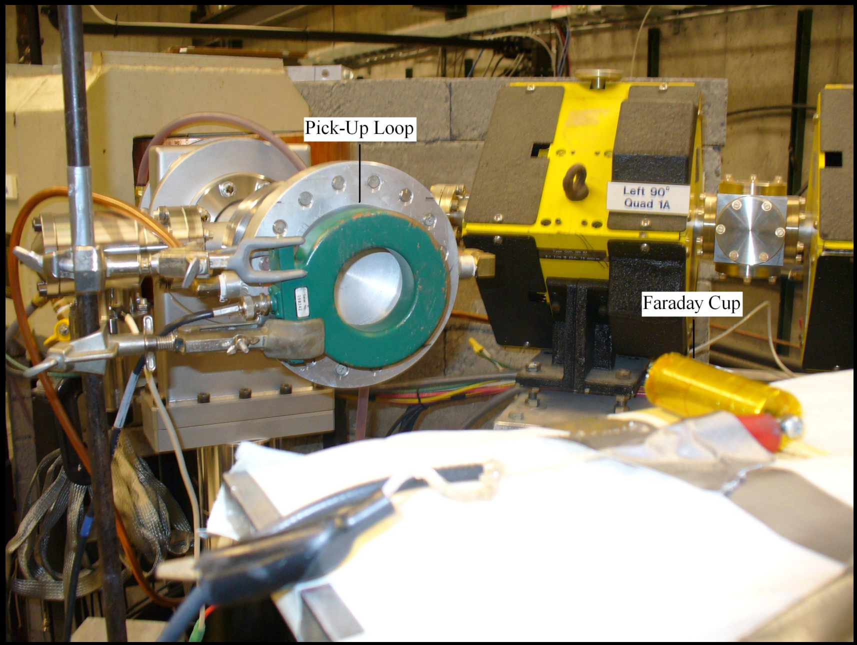
The Apparatus

- The source of exposure was the 25 MeV pulsed electron LINAC in the main hall of the Idaho Accelerator Center
- This facility offers adjustable pulse widths (80 ns – 2 us) and repetition rates (1 Hz – 1000 Hz) → predictable source
- Exposure may be monitored real-time with pick-up coil at the exit window
- Previous experiments[1,2] used isotropic sources of gamma radiation

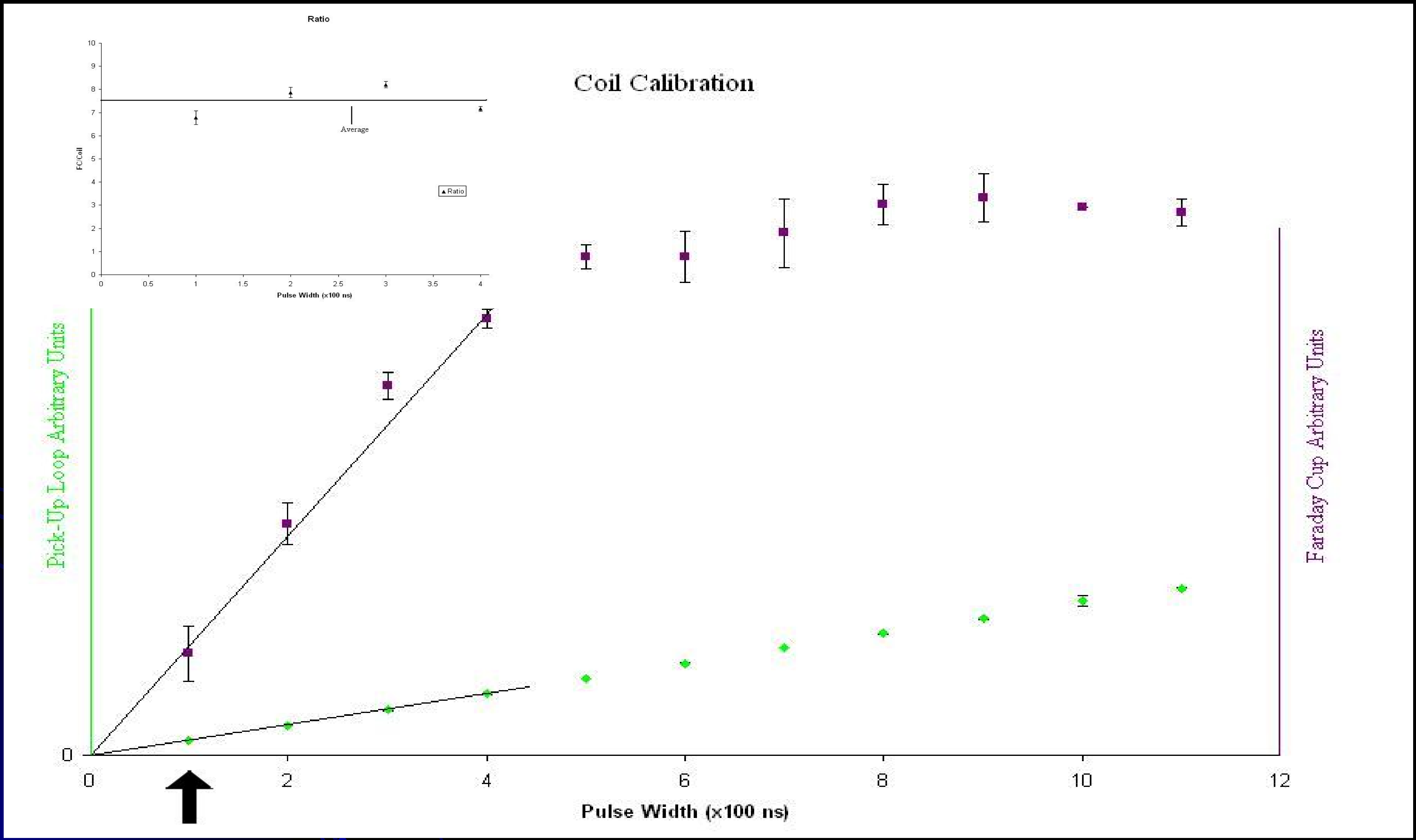


Calibration

- We wanted an accurate determination of dosage for all exposures from current monitor
- We tested the response of the current monitor with respect to a Faraday cup
- Check the proportionality of measurements of beam current to beam charge.

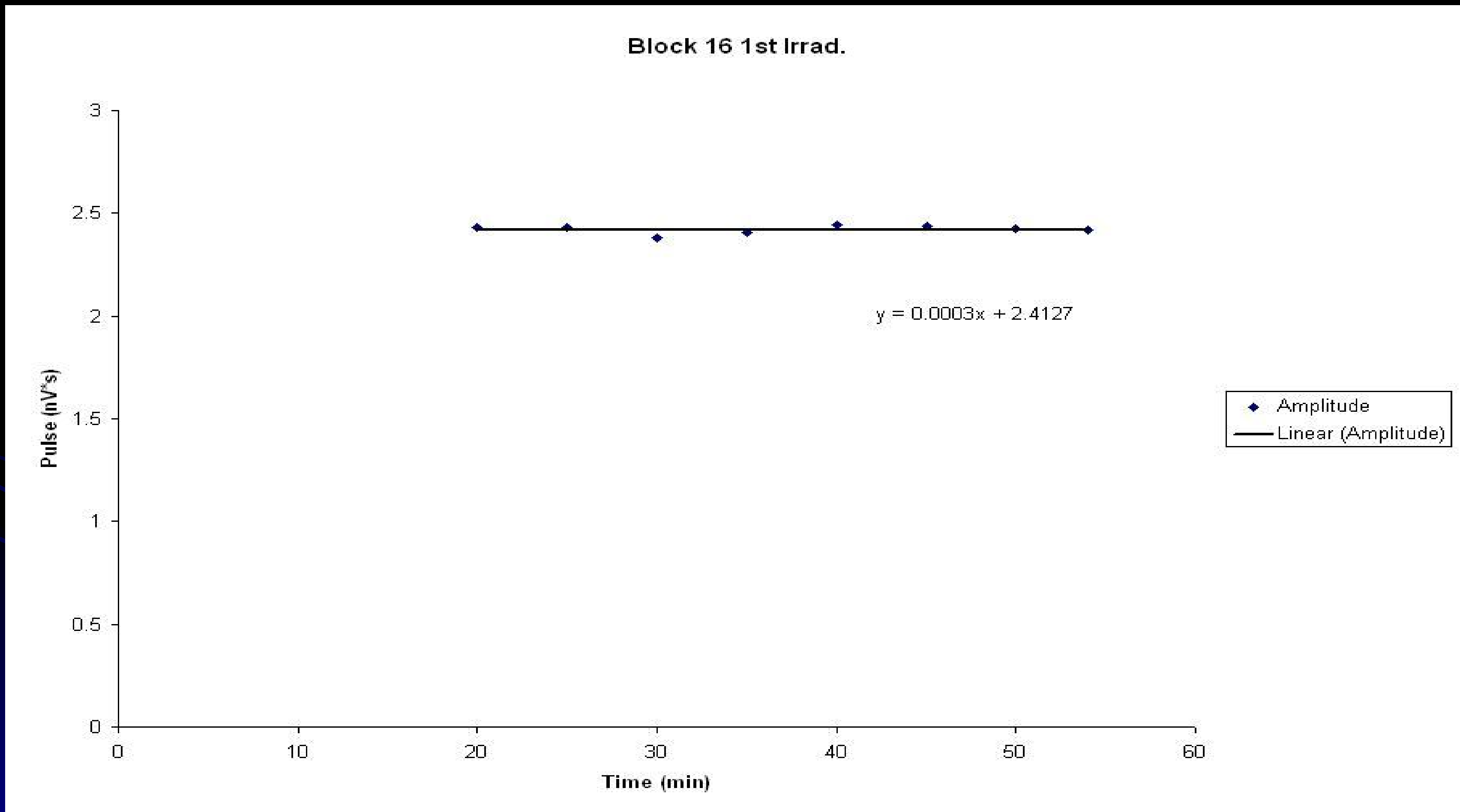


Coil Calibration



Faraday Cup saturates around 400 ns pulse width ~ 4.5 x 10^{12} electrons (Q = Idt)

Our Experiment



Beam dose is uniform throughout exposure

Dose Calculation

- Blocks were placed a distance from the exit window where it was known that the beam divergence (angular spread) would span only the face of a crystal (1 inch by 1 inch)
- Assuming that the total energy in the beam is absorbed in the block, dose may be calculated from beam pulses tracked by the pick-up coil
- Particles Per Second x Beam Energy x Time of Exposure = Total Energy Deposited

Example Calculation

- Beam intensity I depositing power P depends on energy E & electron charge e → P = E/e x I
- Dose = (P x Time of Exposure)/Mass
- P in watts, E in MeV and I in microamp
- For a window of 100 ns, repetition rate of 10 Hz, energy of 20 MeV and peak beam intensity of 50 mA we have

I = ((50 mA) x (100 ns))/(10 Hz) = 0.05 uA

P = E/e x I = 20 MV x 0.05 uA = 1 Watt

For 1 Hour exposure of 1 kg mass,

Dose = (1 W x 3600 s)/(1 kg) = 3.6 kGy

Color Center

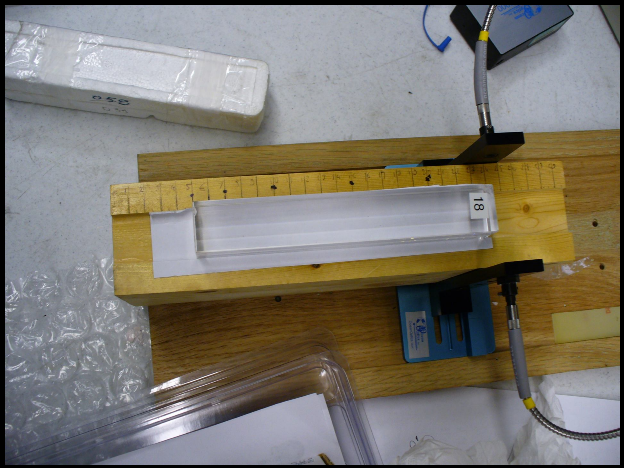
- Lattice defects are introduced by exposure to high-energy photons (X, γ radiation)
- Negative ion vacancies attract electrons
- Since these electrons are bound to a positively-charged center, there is a spectrum of energy levels, as for atoms
- Excitations between energy levels result in optical absorption/emission spectra

Color Center

- Trapped electrons give rise to a discolored crystal
- This is qualitative evidence for the presence of color centers, absorbent portions of the lattice that hinder detection of the “good stuff” (Cherenkov light)
- This photo was taken just after exposure to radiation.

Transmission

- Transmission was measured along the length of each sample before and after exposure to violet/blue light
- Significant gains in transmission were observed after 19 – 24 hours of optical curing

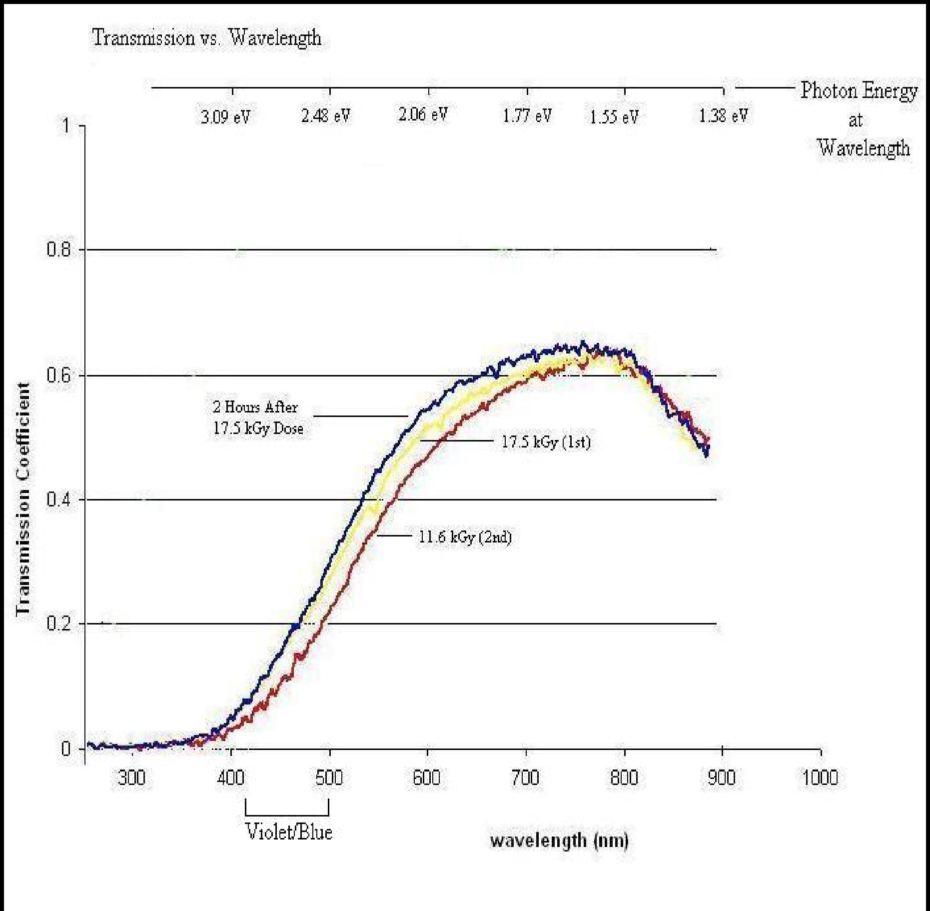


Before Optical Curing

- Data for the sample exhibiting the best response to optical bleaching is shown
- Transmission coefficient

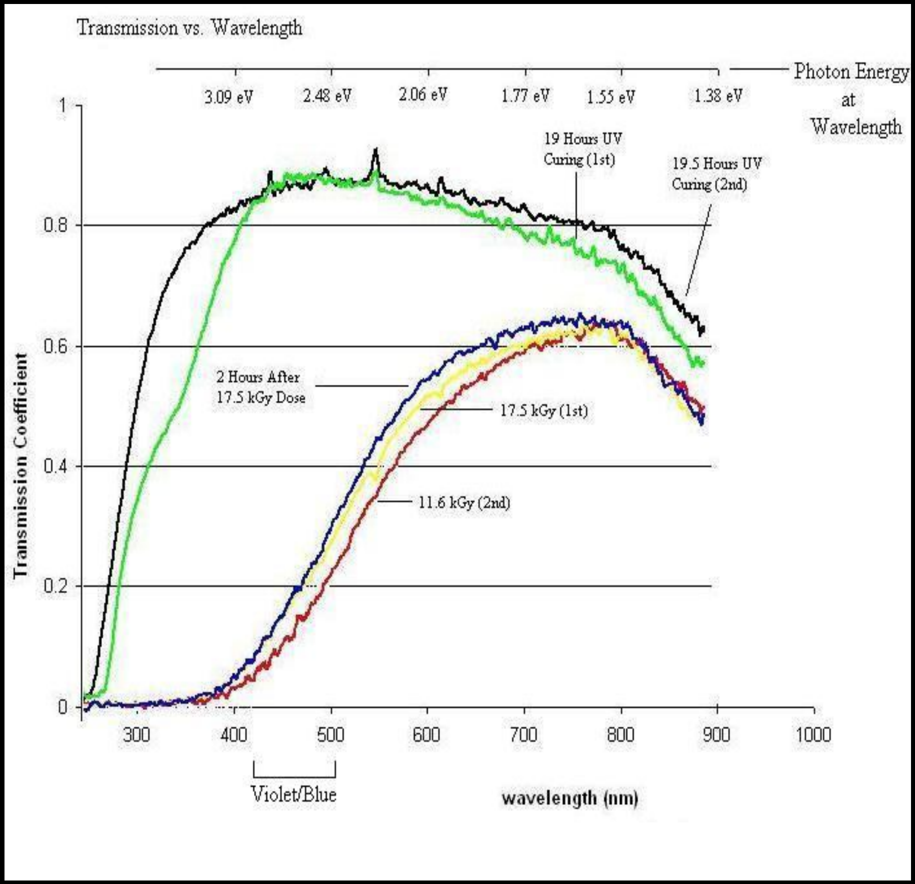
$$T = I_{transmitted}/I_{incident}$$

- Measurements were taken at 1 cm along the length of the sample – this region shows the biggest loss in transmission
- Color centers lower transmission efficiency significantly in the violet/blue region

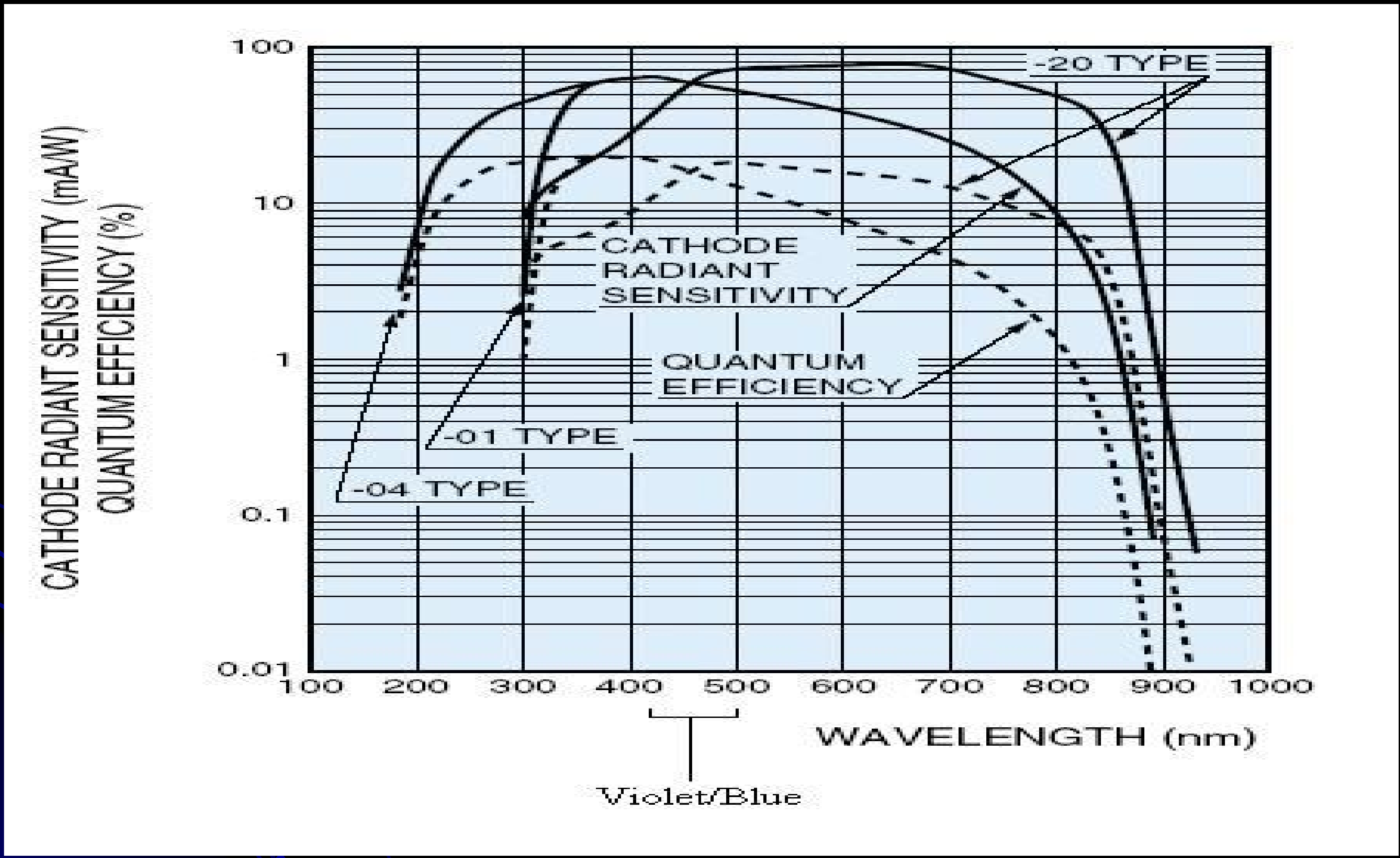


After Optical Bleaching

- Additional spectra are transmission measurements after 19 hours of optical bleaching
- There are significant gains in violet/blue region
- Transmission is gained throughout entire spectral region



Why do we need blue?



Quantum Efficiency of Hamamatsu photomultiplier tube – peaks in blue

Optical Bleaching

- Out of place electrons in the lattice are endowed with enough energy from an outside light source to be repositioned
- In the barium fluoride experiment[3], the most effective wavelengths (frequencies) were found to be 400-450 nm (violet/blue)
- Transmission measurements suggest that optical bleaching snaps the crystal lattice back into place, thus restoring its optical properties

[3] D. Ma, R. Zhu, On optical bleaching of barium fluoride crystals, Nucl. Meth. & Instr. A 332 (1993) 113

A Work In Progress

- Optical bleaching effective in PbF_2 for doses of up to 20 kGy
- Good for DVCS calorimeter
- Currently extracting n for comparison w/Fermilab[4]
- Spike in transmission at 410 nm (3.02 eV), 550 (2.25 eV) nm & 610 nm (2.03 eV)
- Objective – prescriptive method for optical bleaching for DVCS calorimeter

[4] D.F. Anderson at al., Lead Fluoride: an Ultra-compact Cherenkov Radiator for EM Calorimetry, Nucl. Instr. & Meth. A 290 (1990) 385

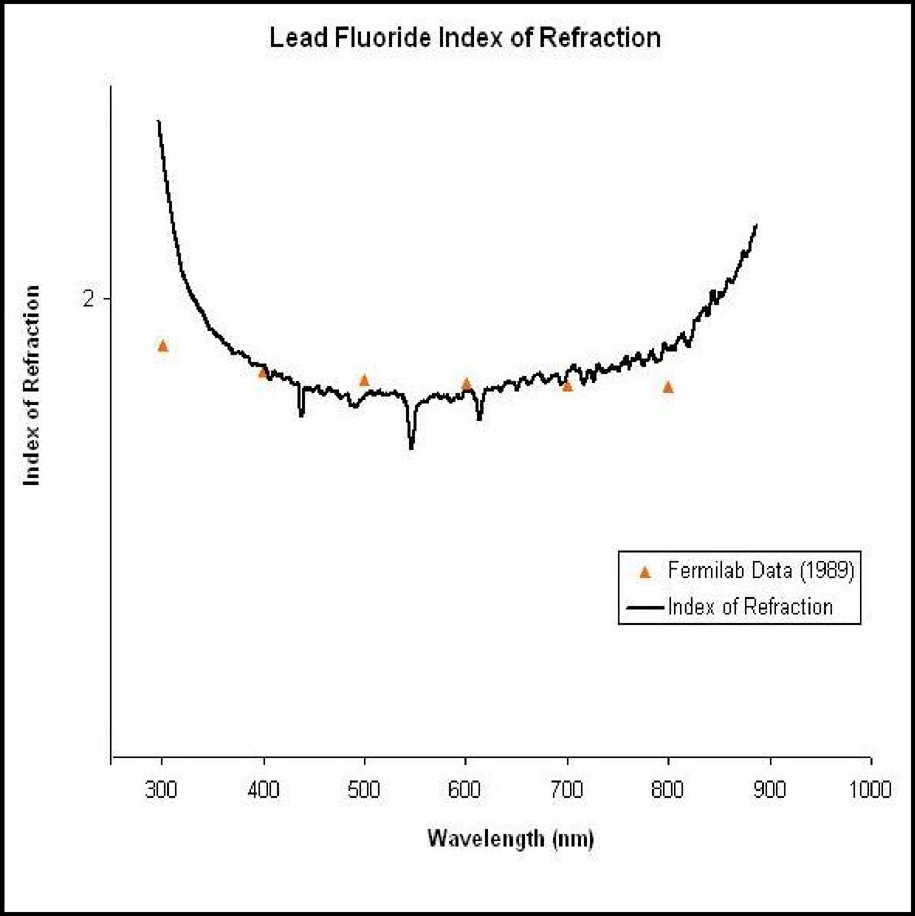
Thank You

Extra Slides

(Questions?)

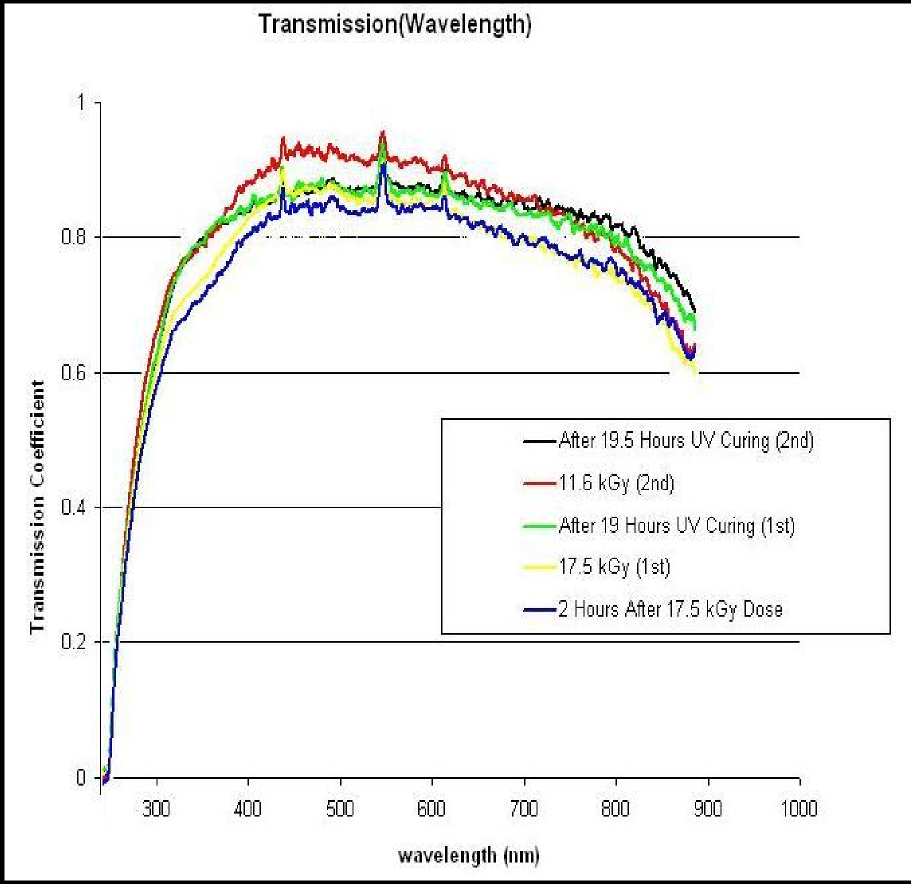
Index of Refraction

- Index of refraction as a function of wavelength, extracted from transmission data
- Agrees with measurements from Fermilab[4] 20 years ago in the range of 400-700 nm



Energy Deposition

- Transmission data for same block at 16 cm along the length of the sample
- No significant difference in transmission is clear
- Color centers are formed closest to beam interface (the majority of the beam energy is deposited in the first few centimeters)



Contaminated Sample?

- Transmission data for block 16 at 16 cm is shown
- This sample shows anomalous behavior
- Spikes in transmission are suspected to be due to contaminants in this crystal