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Radiation Damage Studies and Operation of the DØ Luminosity Monitor

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Abstract

The D0 Luminosity Monitor (LM) employs scintillating wedges with photomultiplier tube readout to detect particles from inelastic collisions in $p\bar{p}$ interactions at the Fermilab Tevatron Collider. The Luminosity Monitor provides the luminosity measurement used for normalization of D0 physics results. In the course of normal Tevatron operations these scintillators accrue significant radiation damage. Operating parameters are monitored and adjusted to compensate for this degradation, and the scintillators are periodically replaced to facilitate stable performance. Results from radiation damage studies to the scintillator as well as the stability of the luminosity measurement will be presented.

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Keywords: Radiation Damage, Luminosity Monitor, Machine Detector Interface and Beam Instrumentation

1. D0 Detector

The D0 detector, Fig. 1, is a general purpose particle detector that has a central tracking system, consisting of a silicon micro-strip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet. This system is designed for tracking and vertexing at pseudorapidities[1] $|\eta| < 3$ and $|\eta| < 2.5$, for the SMT and CFT respectively. Central and forward preshower detectors are positioned just outside of the superconducting coil, followed by liquid-argon and uranium calorimeters divided in a central section covering $|\eta| \approx 1.1$, and two end sections that extend coverage to $|\eta| \approx 4.2$, all three housed in separate cryostats. An outer muon system, at $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids. The detector also has a Luminosity Monitor (LM) that provides a measurement of Tevatron's instantaneous luminosity at the D0 interaction point by detecting inelastic collisions, while also providing information about proton and antiproton halos. A detailed description of the D0 detector can be found in Refs. [1] and [2].

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[1] Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle relative to the proton-beam direction.

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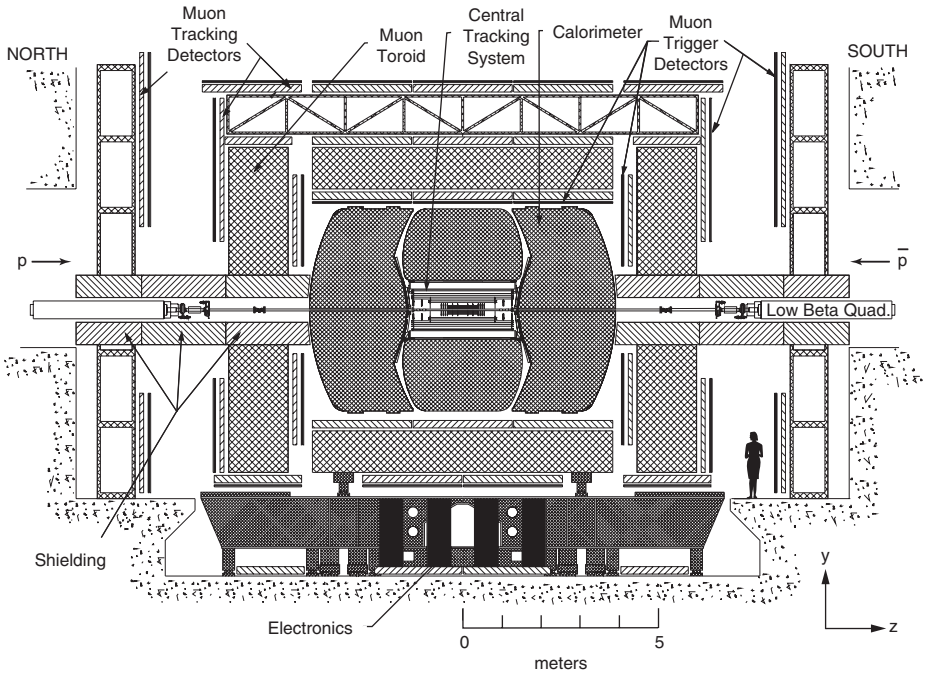


Fig. 1: Cross sectional diagram of the upgraded D0 detector, as installed in the collision hall. Taken from Ref. [1].

2. Luminosity Monitor

The D0 Luminosity Monitor consists of two arrays of scintillation counters arranged symmetrically about the beam pipe, mounted on the inside faces of the end calorimeters. They are 140 cm from the center of the detector along the beam axis covering $2.7 < |\eta| < 4.4$ for a 99% acceptance for the detection of non-diffractive inelastic collisions.

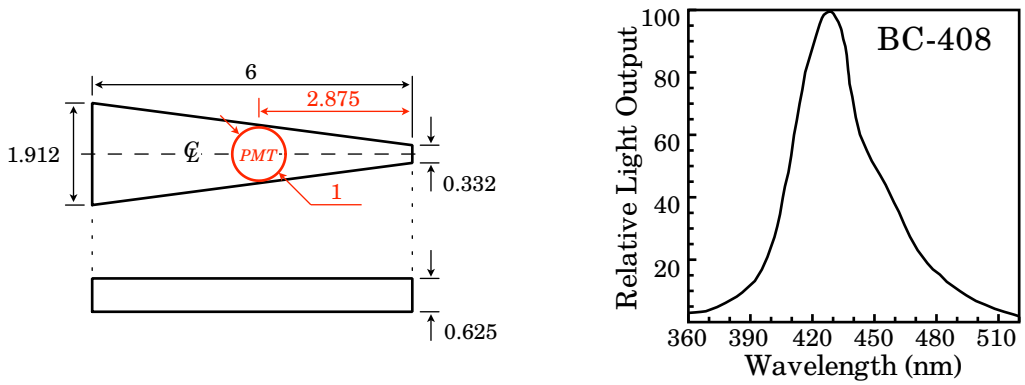
Each array consist of 24 individual wedges of scintillator material (Saint-Gobain BC-408, Ref. [3]), Fig. 2a, composed by polyvinyl toluene and anthracene with a peak output wavelength at 425 nm, Fig. 2b. Custom made HAMAMATSU R7494 fine mesh photo multiplier tubes are glued to every wedge at 7.3 cm from the narrow edge to the center of the 1" diameter tube. The tubes operate at negative voltages and have quartz windows to improve radiation hardness and also because quartz is more permeable to helium[2] than glass. A scintillator wedge together with its corresponding PMT form an individual luminosity readout channel, and the Luminosity Monitor has 48 of them in total.

The Luminosity Monitor enclosures are purged with gas to retard helium infiltration. Until the summer of 2007 this gas was nitrogen which later was replaced with dry air, after tests proved it also helped in the annealing process of the scintillator, Sec. 3.1.

3. Radiation Damage

The Tevatron produces $p\bar{p}$ collisions at 1.96 TeV in the center of mass, and because of the conditions in which it operates, the LM is constantly bombarded by ionizing radiation from beam interactions, with just a few opportunities to perform maintenance in the LM enclosures.

[2] Helium is used in various places on the D0 Detector.



(a) Scintillator wedge. Dimensions in inches.

(b) Relative light output. Taken from manufacturer data sheet, Ref [3].

Fig. 2: Scintillator used on the D0 Luminosity Monitor.

The damage experienced by the scintillator is not uniform, as the number of particles hitting the scintillator in regions closer to the beam line is larger, more damage happens there. The bombardment of radiation causes changes at the molecular level in the scintillator. This damage can cause degradation in the scintillation mechanism as well as a decrease in the transmittance in the scintillation substrate, Ref. [4]. While some of this damage can be corrected, a large fraction is considered permanent due to the type of change in the molecular structure.

The modification in scintillator properties of material that has been exposed and is then removed from the detector for replacement is not only evident after visual inspection, Fig. 3a, but also measured as its transmittance and light yield decrease as the material accumulates more damage.

Different parameters are monitored during operation to maintain a reliable[3] luminosity measurement. One of the parameters checked is the gain in the PMT, which is related to light yield. The gain is periodically evaluated individually for every channel and shows directly the decrease in light yield as the scintillator is exposed to increasing values of integrated luminosity, Fig. 3b.

Three different methods of compensation/correction for radiation damage are used: annealing, high voltage adjustment and replacement of the scintillator material. The first two do not need direct access to the LM while the third one is only possible during shutdowns with enough time to extract the LM enclosures.

3.1. Annealing

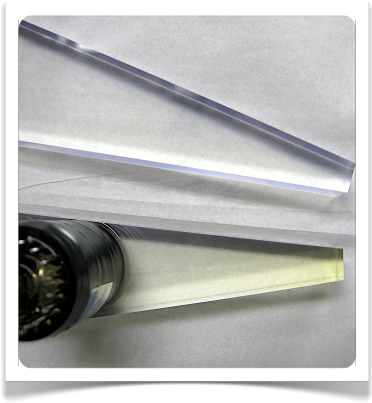
Measurements of transmittance on the wedges show a large absorption increase immediately after irradiation. A fraction of this absorption is transient in nature and will disappear with time. The annealing process is accomplished by treating the samples with oxygen but due to the operational environment, dry air rather than pure oxygen is used since it is safer. Preliminary tests conducted in 2007 showed an increased light yield when the LM is purged with dry air, Fig. 4, and since the summer of that year the LM was purged with dry air rather than nitrogen.

Annealing can only occur during periods when the scintillator is not exposed to radiation from the beam. Annealing can take place in the period when the Tevatron is preparing to deliver stable beam for collisions and most notably over the large interruptions in which Tevatron stops operation to perform maintenance activities.

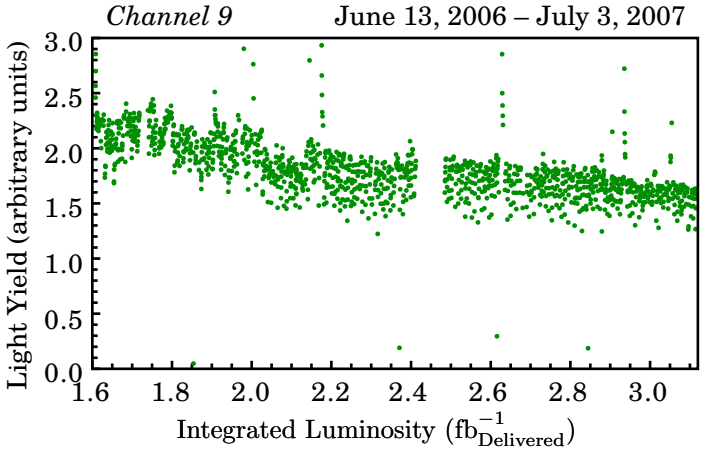
3.2. HV Adjustment

The light yield of every individual channel is constantly monitored, by means of plots like the one shown on Fig. 3b. When this yield drops to a minimum limit, a high voltage adjustment is made on a per channel

[3] Within a 0.5% stability range.



(a) Comparison between unused (top) and exposed (bottom) scintillator.



(b) Light yield drop as a function of integrated delivered luminosity. This plot is for an individual channel but shows typical channel behavior.

Fig. 3: Modification of scintillator properties due to radiation damage.

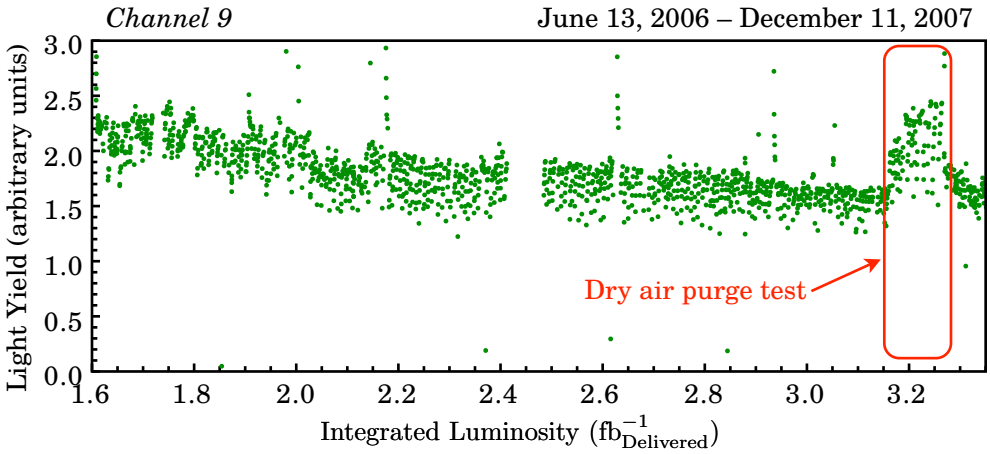


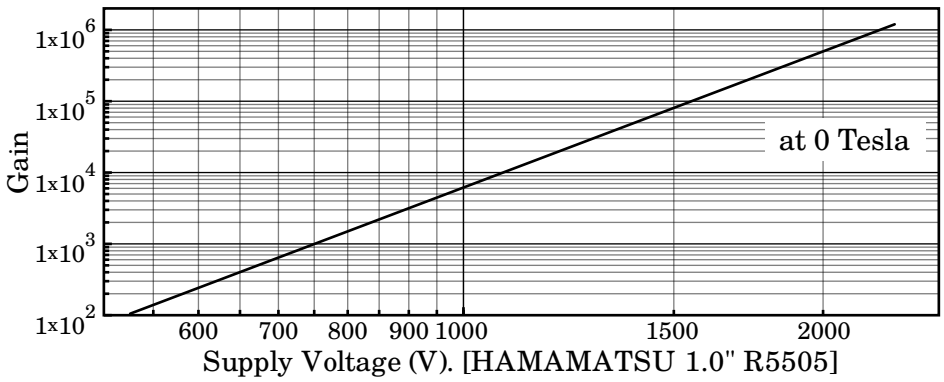
Fig. 4: Light yield recovery during dry air purge test.

basis in order to compensate by increasing the gain in the PMT, Fig. 5a. When an adjustment is needed, all channels are evaluated and modified independently of each other. The effect of HV adjustment on light yield can be seen in Fig. 5b.

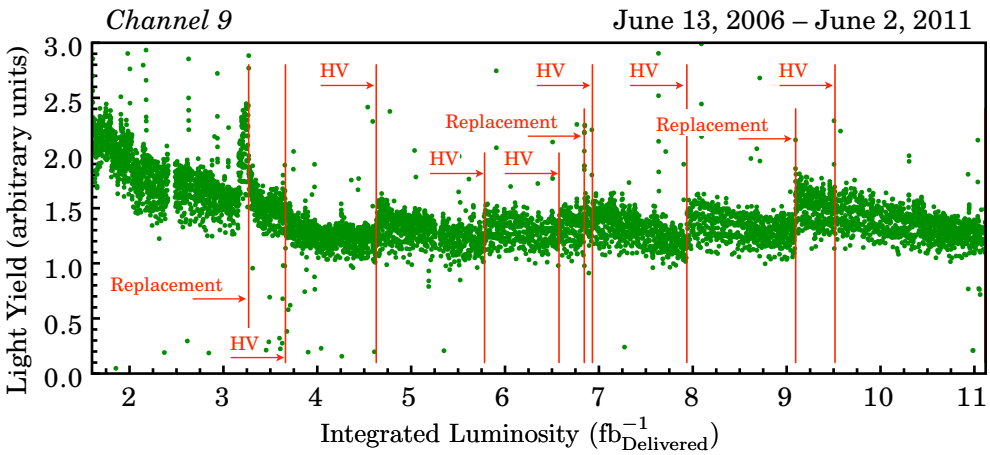
3.3. Scintillator Replacement for Light Yield Compensation

The last resort is the replacement of the scintillator. To do this, a relatively long shutdown is needed and because of this there are just a few opportunities to perform a replacement.

Since the start of data taking in 2002, the LM scintillator has been replaced four times, corresponding to the Tevatron shutdown 2006, 2007, 2009 and 2010, Fig. 6. The worst period of scintillator exposure was from 2007 to 2009, for a total integrated delivered luminosity of 3.58 fb^{-1}. The degradation in the scintillator can be seen in the comparison shown in Fig. 3a. Despite the short period of time available in 2010, 14 PMTs were also replaced, this was the quickest replacement, accomplished in only two weeks.



(a) Typical gain characteristics of a HAMAMATSU PMT. **Note**: the graph does not show the actual behavior of the installed PMTs but a close one commercially available. Ref. [5].



(b) HV adjustments and scintillator replacement on a particular channel.

Fig. 5: High Voltage adjustment to the LM to compensate for light yield drop.

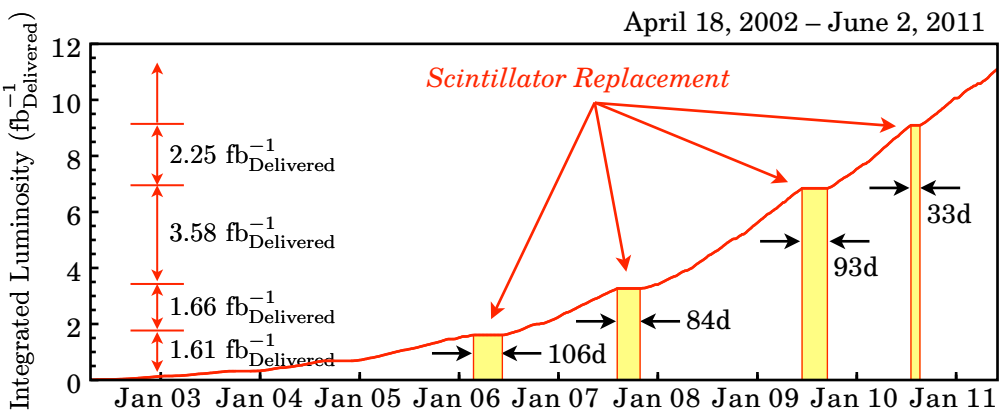
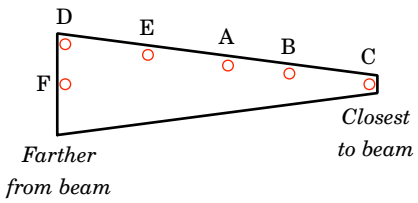


Fig. 6: Scintillator replacement. Suffix ‘d’ stands for days.

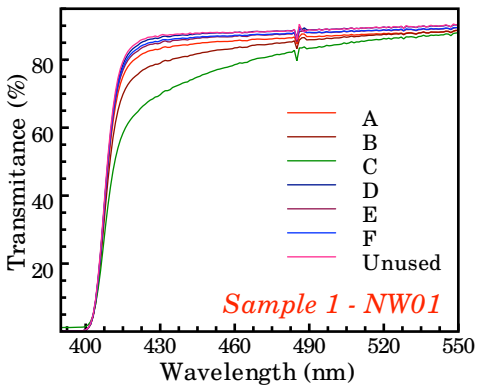
4. Spectrophotometry

Spectrophotometry studies were done on scintillator taken out in 2009 and 2010. One component of this effort was to look at the longevity of the scintillator during an extended period of Tevatron running without replacing the scintillator. The spectrophotometry measurements were performed at Fermilab[4] using an HP 8452A spectrophotometer in 2009 and an upgraded UV/Vis 8453 in 2010. Both machines use a deuterium light source integrated over a 2 s exposure. While the newer model can test over a larger spectrum, the 200 nm to 800 nm range was used to give consistency with the tests in 2009 and because that covers the full sensitivity range of the scintillator and PMTs. Another difference is a 2 nm step was used in 2009 while a 1 nm step was used in 2010.

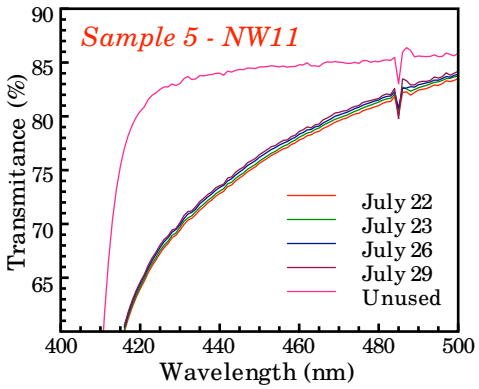
The transmittance was measured on the wedges at six different positions on the exposed scintillator, Fig. 7a, for all the channels plus a piece of unused scintillator to be taken as reference. A set of measurements was also made over time for a few pieces in order to look for evidence of annealing.



(a) Approximate location of the spectrophotometry measurements and labels used for reference.



(b) Measurements of transmittance at different positions for the same wedge. Labeled according to Fig. 7a.



(c) Measurements of transmittance over time for the same wedge on the spot closest to the beam, label 'C' on Fig. 7a.

Fig. 7: Measurements of transmittance.

The measurements of transmittance show the amount of damage with respect to position. The damage is at a maximum closest to the beam and decreases with increasing distance of the beam. The lower the transmittance, the less likely the light from particle interactions will reach the PMT. As shown in Fig. 7, the position labeled as 'C' is closest to the beam and has the least transmittance. Note that even in unexposed scintillator the transmittance is not 100%. The maximum transmittance is dependent on many conditions of the scintillator, including internal and external flaws like bubbles or scratches. The "turn on" around 400 nm is a property of the type of scintillator used in the LM.

As previously stated, some of the scintillator replaced in 2010 was measured specifically for evidence of annealing. Five pieces of scintillator were first measured just five days after their last exposure to beam

[4] The authors want to thank Anna Pla-Dalmau for the facilities provided for this study at Fermilab's Lab. 6, and the undergraduate students from Rice University Michael Eastwood and Rebecca Kusko for taking the measurements in 2009 and 2010, respectively.

interactions. Follow up measurements were repeated over the next week. According to literature, Ref. [6], the maximum amount of annealing takes place on a time scale from hours to days, but it could be up to 8 days to see the full recovery. The measured transmittance for the five pieces did show a small increase with time. Even though the effect is not large, it suggests some recovery of the material due to annealing over the days where replacement took place. Fig. 7c and Fig. 8 show the transmittance measurements for the five pieces of scintillator.

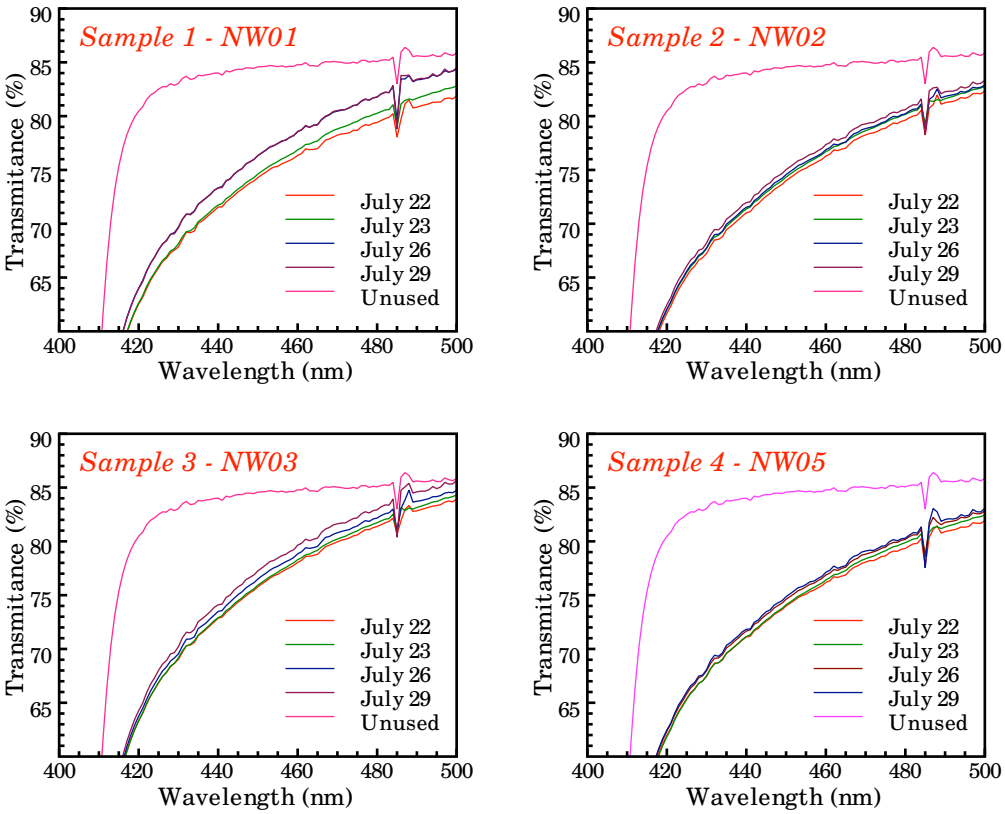


Fig. 8: Measurements of transmittance over time performed on four different wedges looking for evidence of annealing. Each plot contain the measurements for the same wedge.

5. Summary

The D0 Luminosity Monitor operates in an environment where its plastic scintillator is constantly bombarded by ionizing radiation which modifies the scintillator properties and results in a drop in light yield. Purging the LM with dry air not only helps to anneal the scintillator reducing the drop in light yield, but also retards the infiltration of helium which can damage the photo multiplier tubes. Another way to compensate for radiation damage is to adjust the high voltage at which the PMTs operate to increase its gain. These two techniques have proven to be very helpful for optimal LM operation, but in a few opportunities the replacement of both of the main LM components, the plastic scintillator and some of the PMTs, have allowed us to extend the lifetime of the system.

Radiation-damaged pieces of scintillator material have been analyzed to see the effects of the prolonged exposure to radiation. The transmittance of the material is degraded in a non uniform way with the maximum degradation taking place in positions closest to the beam. Some recovery in the transmittance is seen on five wedges measured over time promptly after their last exposure to radiation, suggesting some evidence of annealing.

Since the beginning of data taking in 2002, the Luminosity Monitor has provided not only a reliable luminosity measurement, important for physics analyses, but also gives feedback to the Tevatron about the proton and antiproton halo measurements at the D0 interaction point. The efficient work of the Luminosity Group at D0, keeps the current luminosity measurement within a 0.5% stability range.

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