Trip Limit Estimation and Proposed Calibration Methodology for Total Loss Monitors in Switchyard

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ABSTRACT

Construction of the Integrated Engineering Research Center ("IERC") necessitates the installation of new Total Loss Monitors ("TLMs")[1] in Switchyard due to the proximity of the building to the beamline and limited radiation shielding. This paper describes the TLM detector layout and estimates the required TLM-to-beamline distance trip limits to maintain accordance with required dose limits without excessively limiting available beam to the experiments. A methodology is proposed for beam-based verification of the TLM trip limits that builds off of previous work for radiation safety TLM installations at Fermilab. In particular, systematic errors in the experimental apparatus are considered in the proposed analysis methodology to provide an estimated certainty of the results.

1 Motivation

The Integrated Engineering Research Center building will take the place of the parking lot on the East side of Wilson Hall, in relatively close proximity to the Switchyard beamline. Site preparation work for the building includes construction a road connecting the East side of IERC to the A0 parking lot; this road will cross a shielding berm, thereby reducing the available shielding. To limit the potential duration of an accident condition beam loss, two new TLM detectors are being installed in Transfer Hall, Enclosure B, and Enclosure C. The approximate layout of new TLMs is pictured in Figure 1, showing both the enclosure outlines and a rough placement of the IERC building itself.

Each TLM's trip limit and distance to the beamline must be determined to satisfy occupancy conditions while still allowing an acceptable amount of operational beam loss. According to the ES&H Interlocks Group Leader, the maximum charge rate trip limit that the TLM electronics can allow is 3000 nano-Coulombs per minute. Furthermore, TLM location is somewhat constrained by the geometry of the beamline enclosures. Each TLM has its own challenges in satisfying the above conditions that will be addressed in the following sections.

2 TLM2 and MLAM Beam Loss

This section estimates the minimum beamline-to-TLM distance for TLM2 using maximum operational loss as the limiting factor. To estimate the charge integrated on a TLM detector for a given beam loss on a magnet, we can scale in both energy and TLM-to-beamline radial distance from past experimental data in the Fermilab Accumulator.[2] The TLM response in nano-Coulombs per proton is shown in Equation 1.

$$TLM_{response}[\frac{nC}{p}] = (\frac{5.5[ft.]}{d[ft.]})^2 * (\frac{E_{beam}[GeV]}{8[GeV]})^{0.8}, \tag{1}$$

where "E_{beam}" is the beam kinetic energy in GeV, and "d" is the radial distance in air from the loss point to the TLM detector in feet.

Multiplying Equation 1 by the beam loss rate, we can estimate the TLM reading in nano-Coulombs per minute, the units for the trip settings in the TLM electronics. Since the Switchyard beam rate is one spill per minute, the TLM response for a given operational loss per spill is:

$$TLM_{rate}[\frac{nC}{min.}] = (\frac{5.5[ft.]}{d[ft.]})^2 * (\frac{E_{beam}[GeV]}{8[GeV]})^{0.8} * \frac{3.2[nC]}{1.0E10[p]} * Loss[\frac{protons}{spill}]. \tag{2}$$

The largest and most consistent operational loss in Switchyard is on the MLAM Lambertson magnets in Enclosure C. Used in splitting the beam to multiple experiments, the MLAM magnets are inherently lossy due to beam interaction with the septum that separates apertures. To estimate the TLM2 reading for normal operational losses on the MLAM Lamberston in Enclosure C, a maximum beam intensity of 1E13 protons per spill and 5% operational beam loss are assumed at a rate of one

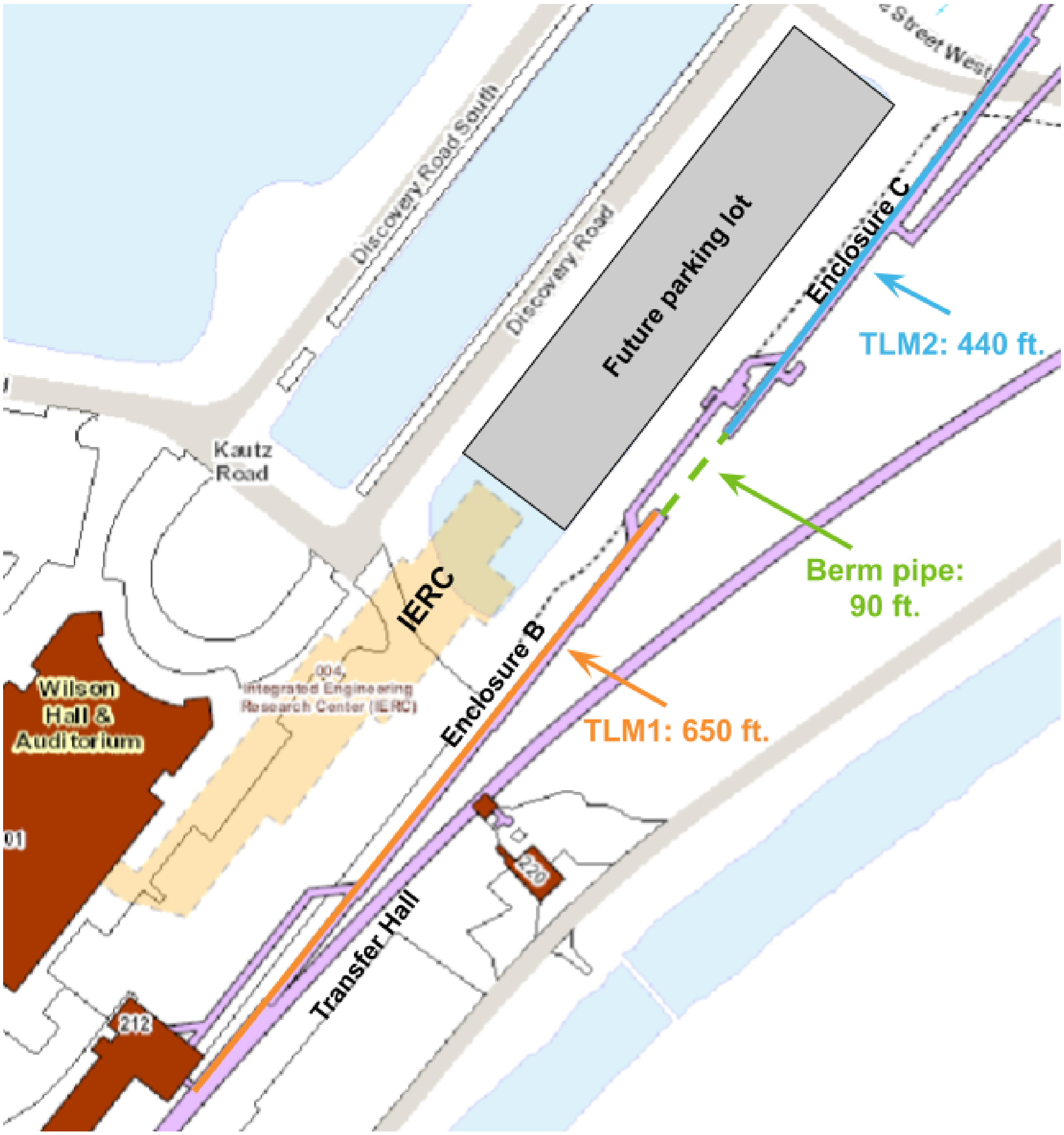

Figure 1. Configuration of two Switchyard TLM detectors that cover the area of the IERC project and provide additional active shielding. The locations of the IERC building and parking lot are approximate.

spill per minute. The 5% loss is an estimate of the worst-case beam loss that would be acceptable operating conditions in Switchyard. The TLM2 response to this loss is plotted in Figure 2 as a function of the radial distance between the magnet and TLM. Also plotted is the 3000 nano-Coulombs per minute maximum trip limit allowed by the current radiation safety system. This result shows that a TLM in Switchyard should be placed at least 3.75 ft. radially from any magnet that may cause a consistent operational loss of up to 5%. However, as shown later in this paper, other factors such as maximum normal operating dose and available shielding will also inform trip limit and beamline-to-TLM distance, so a 3.75 ft. distance to the beamline and trip limit of 3000 $\frac{nC}{min.}$ may not end up being acceptable for TLM2.

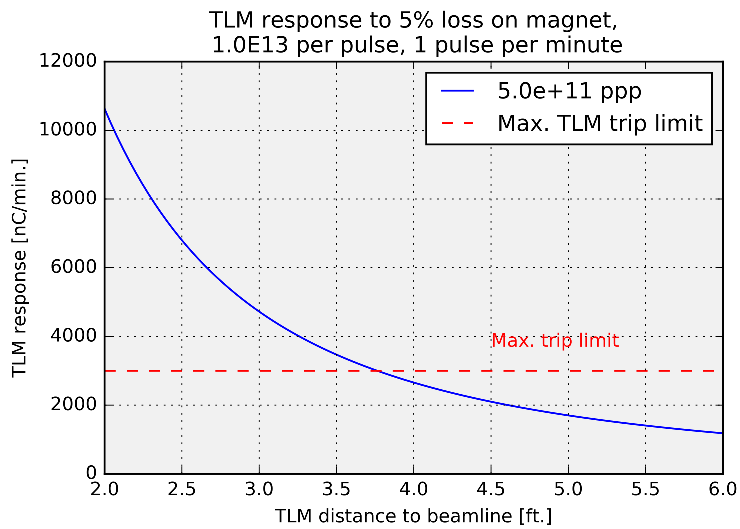

Figure 2. TLM response for 5% operational loss in Switchyard at maximum beam flux vs. detector radial distance from magnet.

As TLM1 does not cover any high-loss beamline components, the maximum allowable operational loss will not be the limiting factor for distance and trip setting as it was for TLM2. Instead, these characteristics for TLM1 will be determined by the maximum surface dose rate allowed by a given distance and trip setting, as TLM1 covers an area of reduced shielding.

3 Maximum Operating Surface Dose Rate

In this section, the maximum operational hourly dose rate is estimated on the surface of the shielding berm as a function of a given TLM's trip limit. This assumes that a beam loss occurs such that a given TLM reads just below its trip limit; this represents the worst-case operating dose rate for a given TLM and trip level. The maximum operating dose rate is also estimated 50 ft. away, which is the approximate location of the IERC building's outer surface. This methodology will also check whether the TLM2 trip level and distance to beamline determined in the previous section are sufficient to comply with occupancy class dose limits.

The dose is estimated using the "Malensek" method, which assumes the worst-case peak of the hadronic shower from protons incident upon an iron cylinder of 15cm radius and 90cm length. This method scales from CASIM Monte Carlo simulation data for distance, shielding thickness, and beam energy.[3] Assuming negligible dose attenuation due to air, the maximum single-pulse effective dose rate per proton of kinetic energy "E" in GeV for shielding thickness "t" and distance "d" in air from the loss point is:

$$H[\frac{mrem}{p}] = (1.0E-5) * (\frac{0.5}{d[ft.]})^2 * (\frac{E[GeV]}{1000})^{0.8} * 10^{\frac{-t[ft.]}{3.38}} \tag{3}$$

Given the single-pulse worst-case dose per proton $H[\frac{mrem}{p}]$ from the Malensek equation, and the TLM response for a given distance from the beamline using Equation 1, the maximum hourly effective dose rate is computed using the following relationship:

$$D_{max}[\frac{mrem}{hour}] = TLM_{trip}[\frac{nC}{min.}] * TLM^{-1}_{response}[\frac{p}{nC}] * H[\frac{mrem}{p}] * 60[\frac{min.}{hour}]. \tag{4}$$

Equation 4 conservatively assumes that there are no other interlocked radiation detectors aside from the TLM protecting an area, and that beam loss occurs such that the maximum TLM response is generated just below the trip point.

Table 3 summarizes the maximum hourly dose rate for the weakest shielding location for each TLM at the surface of and 50 ft. from the berm. The shielding thicknesses are measured in "equivalent feet of dirt" ("e.f.d") and are taken from the "P3 to Switchyard Absorber Incremental Shielding Assessment" spreadsheets.[4] For normal operating beam loss, the dose rate is assumed to fall as $\frac{1}{r}$ for a line source, with r as the radial distance between the berm and the occupied area of interest. The berm surface is considered a limited occupancy area, with maximum allowed operational dose of 5 mrem/hr. Approximately 50 ft. from the berm, the IERC building will be unlimited occupancy, with maximum allowed operational dose of 0.05 mrem/hr. The radial TLM-to-beamline distance and TLM trip limit have been adjusted until the maximum operational dose rate at the berm surface and building comply with these dose limits as specified by the Fermilab Radiological Control Manual.[5]

Beam energy (GeV):	120	Single-pulse accident beam intensity (ppp):		1.30E+13					
Detector	Location	Avg. radial distance, TLM to beamline (ft.)	TLM Trip level (nC/min)	TLM response (nC/proton)	Min. transverse shielding (e.f.d.)	Max. continuous dose rate @ berm (mrem/hr)	Radial distance, berm to occupied area (ft.)	Max. continuous dose rate @ occupied area (mrem/hr)	Maximum tolerable beam loss
TLM1	Transfer Hall	3.0	350	9.39E-09	19	**2.45**	50	**0.049**	0.29%
TLM2	Road D	3.0	1000	9.39E-09	20.5	**2.52**	50	**0.050**	0.82%

Figure 3. Summary the estimated maximum operational dose at the berm surface and 50 ft. away from the berm for each TLM. Weakest shielding point for each TLM is considered, and the radial TLM-to-beamline distance and trip limit are adjusted to keep the maximum estimated dose within specifications.

The above calculations as summarized by Table 3 suggest adjustments to the TLM-to-beamline radial distance and trip level for TLM2. Accordingly, both TLM detectors will be installed about 3 ft. radially from the beamline, with trip limits much lower than estimated in Figure 2 to keep the maximum normal operating dose at the building below 0.05 $\frac{mrem}{hour}$ for unlimited occupancy. However, the estimated trip levels must be verified with a beam-based calibration study, and the following section proposes a method for such verification.

Proposed Beam Study Methodology

A methodology is proposed for defining satisfactory statistical confidence in the determination of the TLM trip points, taking into account the largest sources of estimated systematic inherent in the experimental equipment. Quantification of how much beam-based data is required for trip level determination allows for minimum necessary activation of the beamline magnets as per the laboratory's "ALARA" principle.

Borrowing from the methodology of Leveling *et. al.* in Booster and Muon Campus, beam will be steered into the steel yoke of a large magnet to create total beam loss at a point covered by each TLM[6].[7] An array of chipmunk detectors on the surface of the shielding berm above the loss point will measure the maximum dose for the beam loss, which will be used to compare the accumulated charge rate of the TLM. These data will provide a cross-calibration between the TLM and the measured maximum dose on the surface of the shielding berm. This study will be conducted at one loss point per TLM where a massive magnet is available into which beam may be reliably steered. From the resulting correlation between TLM accumulated charge rate and maximum surface dose, a suitable trip level for the safety system can be determined to ensure the dose will not exceed safety limits in either single-pulse accident or normal operating condition. This is a beam-based experimental verification of the theoretically-estimated trip levels earlier in this paper.

Figure 4 shows a to-scale diagram of the Switchard beamline elements covered by TLM1 and TLM2, with beam stationing coordinates expressed as northing coordinates in feet past the A0 Fermi Site Coordinate System reference.[8] The positioning of TLM detectors, as well as the location of the IERC service road crossing the berm are also shown in relation to the beamline elements.

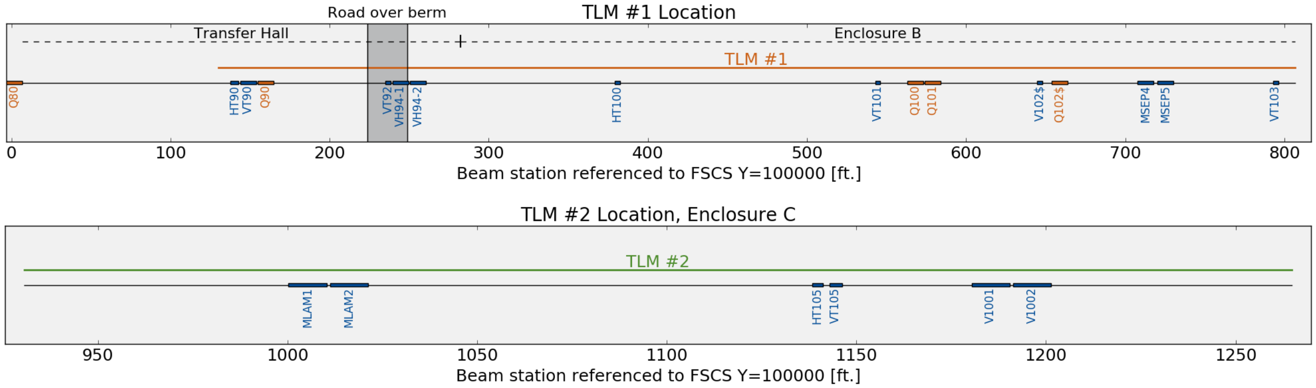

Figure 4. Switchyard TLM locations in relation to beamline elements and the new IERC service road across the berm. Beam study loss point for TLM1 will be the VH94-1 magnet steel, and for TLM2 will be the MLAM1 magnet steel.

A central chipmunk on the berm above the approximate loss location, surrounded on all four sides by chipmunks approximately 10 ft. apart, will form the surface detector array to determine the maximum dose. The chipmunk with maximum reading in the array will used for the TLM calibration. For TLM1, the beam loss point will be first VH94 dipole magnet, which is directly below the new IERC service road. For TLM2, the loss point will be the first MLAM Lambertson magnet, as it is the most massive and convenient loss location in the downstream area. Total beam loss will be verified by maximizing the signal on local loss monitors, the TLM, and surface chipmunks; downstream beam instrumentation (loss monitors, ion chambers, SEMs, multiwire profile monitors, and beam position monitors) will verify no further beam transmission past the intended loss point.

Estimated Systematic Errors

Chipmunks

For the chipmunk detectors, the estimated total systematic error is due to two main contributions: the estimated calibration error of the detectors, and the spread in no-beam background. The calibration error is determined by the calibration tolerance $\varepsilon_{CALchip}$ as reported by the head of ES&H Radion Physics Engineering, which is +/- 10%.

A no-beam background data run will be recorded once the entire system is installed and complete; duration of the background run will be at least 24 hours to capture any day/night effects. Chipmunk background data will be taken with the array configured at the TLM1 loss point, then another set of background data will be recorded after the first beam study is complete and the array is moved to TLM2's location. Fluctuation in the chimpunk background is assumed to be a random process and thus represented as a Gaussian distribution; therefore, the fractional systematic error due to background fluctuation will be computed as shown in Equation 5:

$$\varepsilon_{BGchip} = \frac{\sigma_{BGchip}/\sqrt{N_{BGchip}}}{\mu_{BGchip}}, \tag{5}$$

where N_{BGchip} is the number of background data points, μ_{BGchip} the mean of all background readings, and σ_{BGchip} the standard deviation in background readings. Only the chipmunk reporting the maximum dose in the array will be considered for the data analysis. The mean background level for that chipmunk μ_{BGchip} will be subtracted from beam-on measurements during the study, and the fractional error in background ε_{BGchip} will be added in quadrature to the aforementioned calibration error to form the total estimated chipmunk fractional systematic error in Equation 6:

$$\varepsilon_{chip} = \sqrt{\varepsilon^2_{CALchip} + \varepsilon^2_{BGchip}}. \tag{6}$$

TLMs

For the TLMs, the total estimated systematic error is a combination of fluctuation in background and possible leftover integrator charge.

Background analysis will proceed similarly to the method described above for the chipmunk. Background runs of at least 24 hours with the full system installed and operating will determine the mean and standard error of the background level for each TLM. The background mean will be subtracted off from beam-on study readings, and the fractional standard error on the mean ε_{BGtlm} will be added in quadrature with the other estimated systematic errors.

Since the TLM detectors are read out by an integrating digitizer, there is the possibility of leftover charge not read out before the next beam spill. The integration time constant is 20 seconds,[9] and beam spills once per minute (i.e. three time-constants later), so the maximum possible left-over charge is $\varepsilon_{TLMQ} = e^{-3}$, or about 5%.

Another major source of systematic uncertainty for the TLMs is the variation in radial distance to the beamline. This will be measured after TLM installation is complete. The fractional variation in distance $\varepsilon_{RDISTtlm}$ will be added in quadrature with the other estimated fractional systematic errors, forming the total estimated TLM fractional systematic error in Equation 7:

$$\varepsilon_{TLM} = \sqrt{\varepsilon^2_{BGtlm} + \varepsilon^2_{Qtlm} + \varepsilon^2_{RDISTtlm}}. \quad (7)$$

Other potential sources of uncertainty, such as variation in the $ArCO_2$ gas[10] and uncertainty in integrator calibration,[9] were found to be estimated at far less than 1% and are therefore not considered in this analysis.

TLM Trip Limit Determination

For each TLM detector, its response will be plotted as a function of the maximum chipmunk reading in the array above the loss point. This section demonstrates a sample analysis of simulated chipmunk and TLM data. Error bars on the scatter plot correspond to the total estimated systematic error in the chipmunk (horizontal) and TLM (vertical) readings; the error bar is computed for each data point by multiplying the total fractional systematic error (described above) with the value of that data point (X or Y respectively).

After computing the weighted fit using Orthogonal Distance Regression to take horizontal and vertical errors into account, the linear fit and 95% confidence band on the fit are plotted together. For an error (as reported by the ODR fitting algorithm) in linear fit slope σ_m and intercept σ_b, the 99.7% confidence band is computed by plotting $y = (m_{fit} \pm 3\sigma_m)x + (b_{fit} \pm 3\sigma_b)$. Beam data will be taken while varying the beam intensity to fill out the dynamic range of both detectors. Data is determined to be sufficient once the total fractional error in the fit parameters becomes smaller than the estimated total fractional systematic error; in other words, data will be deemed sufficient when the inequality in Equation 8 is satisfied, which is when the systematic errors dominate over the random errors.

$$\sqrt{\varepsilon^2_m + \varepsilon^2_b} \leq \sqrt{\varepsilon^2_{TLM} + \varepsilon^2_{chip}} \quad (8)$$

The fractional fit parameter error for the slope is $\varepsilon_m = \sigma_m/m$ and for the intercept is $\varepsilon_b = \sigma_b/b$. The conservative TLM trip limit is determined by locating where the lower edge of the 99.7% confidence interval intercepts the desired maximum surface dose. An example plot for analysis of simulated data is pictured in Figure 5 to provide a visual representation of the proposed methodology.

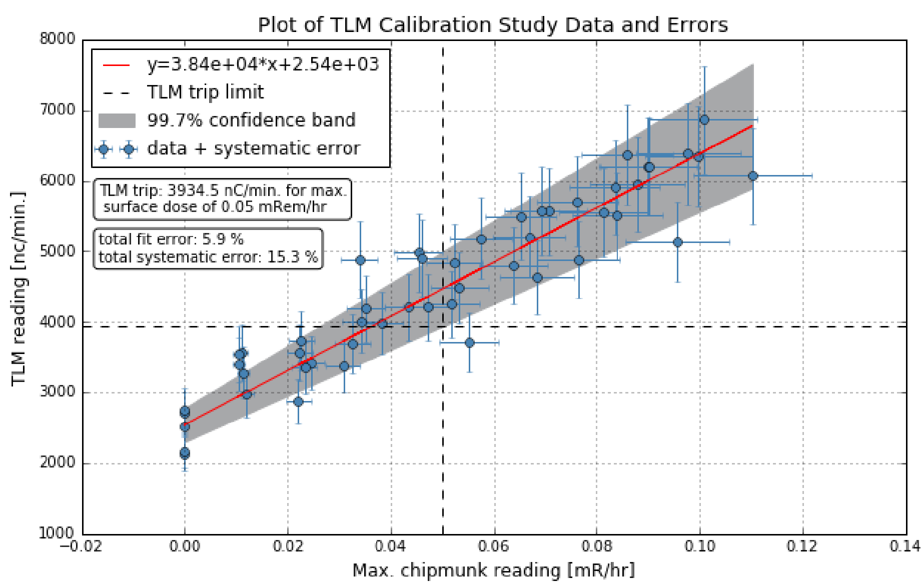

Figure 5. Analysis of simulated beam study data to visually demonstrate errors, fit, confidence band, and trip level determination.

Conclusion

Modifications to the shielding in the Switchyard beamline necessitated by the construction of the IERC building require new TLM detectors for active radiological protection. Trip levels and required distances from the beamline have been estimated for the two proposed TLM detectors in Switchyard to provide enough protection for the desired occupancy classifications outside each section of beamline while allowing for reasonable operational beam loss. A statistics-based methodology for beam-based TLM trip level verification has been proposed, which builds on previous TLM calibration beam-based studies. Estimates are given of the relevant dominating systematic errors in the measurement equipment and are included in the analysis of simulated TLM and chipmunk data. This method will experimentally verify estimated TLM trip limits to keep accident and normal operating condition losses on the surface of shielding berms in Switchyard below limits specified by the Fermi Radiological Control Manual.

References

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10. Fermialb Stockroom Catalog (2019).

TLM Beam Study Analysis Code

The following is the Python code used for analysis of simulated TLM and Chipmunk beam study data. This same code will analyze live data from the study.

In [160]:
```
% reset -f
import numpy as np
import matplotlib.pyplot as plt
from scipy.odr import *
% matplotlib inline
```

In [161]:
```
# This is a test of TLM calibration algorithms using simulated noisy TLM and Ch
ipmunk data
```

In [162]:
```
### Create simulated data
# Chipunk background and error
chipmunk_background = np.random.normal(0.001,0.001/10.0,10)
chipmunk_BG = np.mean(chipmunk_background)
chipmunk_BG_error = (np.std(chipmunk_background)/np.sqrt(chipmunk_background.si
ze))/chipmunk_BG
# List of simulated chimpunk readings in mrem/hr
chipmunk_array = np.linspace(0.001,0.1,10)
chipmunk_readings = []
for i in range(len(chipmunk_array)):
    chipmunk_readings.append(np.random.normal(chipmunk_array[i],0.05*chipmunk_a
rray[i],5))
chipmunk_readings = np.ndarray.flatten(np.asarray(chipmunk_readings))
# Generate simulated TLM readings from chimpunk readings
TLM_readings = 40000.0*np.asarray(chipmunk_readings) + np.random.normal(2500,50
0,len(chipmunk_readings))
```

In [163]:
```
# Subtract off background from Chipmunk readings
chipmunk_readings = chipmunk_readings - chipmunk_BG
# Calibration error
chipmunk_cal_error = 10.0E-2 # 10.0%
# Chipmunk total errors
chipmunk_sys = np.sqrt(chipmunk_BG_error**2 + chipmunk_cal_error**2)
chipmunk_errors = chipmunk_sys*chipmunk_readings
```

In [164]:
```
# Systematic TLM error is estimated from charge that could be left after 3 time
constants
TLM_chg_error = np.exp(-(3))
# Variation in radial distance to beamline
TLM_distance_variation = 0.1 # 10% variation

TLM_sys = np.sqrt(TLM_distance_variation**2+TLM_chg_error**2)
TLM_sys_errors = TLM_sys*TLM_readings
```

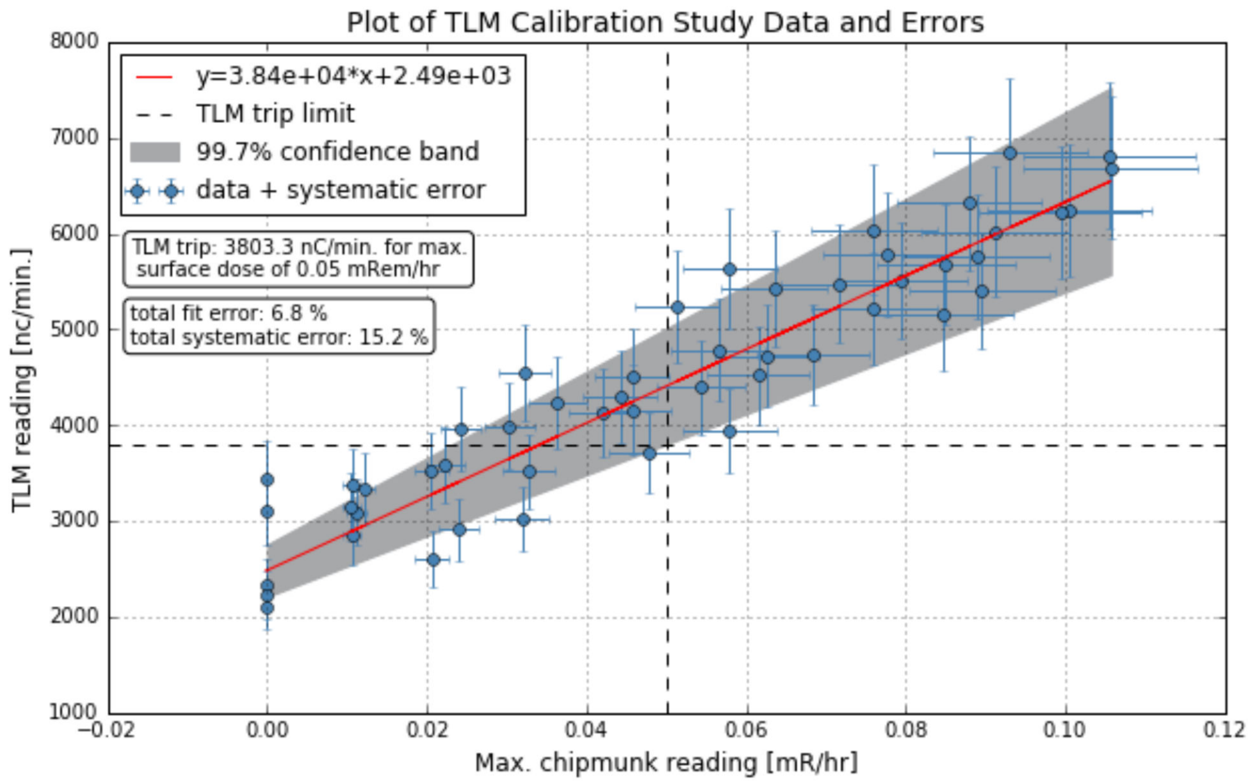
In [165]:
```
# Do a y-weighted linear fit to get a rough idea of the fit params
# This provides an initial "guess" for the ODR algorithm, and only uses vertica
l errors
weights = TLM_sys_errors
# Compute fit parameters and errors
p,cov = np.polyfit(chipmunk_readings,TLM_readings,1,cov=True,w=weights)
m0 = p[0]
b0 = p[1]
```

In [166]:
```
### Now use results from rough fit as initial guess for a x and y weighted fit
# Create a model for fitting.
def lin_func(p, x):
     m, b = p
     return m*x + b
lin_model = Model(lin_func)
# Create a RealData object using our initiated data from above.
data = RealData(chipmunk_readings, TLM_readings, sx=chipmunk_errors, sy=TLM_sys
_errors)
# Set up ODR with the model and data.
odr_instance = ODR(data, lin_model, beta0=[m0, b0])
# Run the regression.
out = ODR.run(odr_instance)
m = out.beta[0]
m_err = out.sd_beta[0]
b = out.beta[1]
b_err = out.sd_beta[1]
total_fit_error = np.sqrt((out.sum_square))

# Print output of algorithm to make sure it converged and didn't fail
print out.stopreason[0]
```

```
Sum of squares convergence
```

In [167]:

```
chipmunk_limit = 0.05 # maximum desired surface dose in mR/hr

nsigma = 3.0
fit = m*chipmunk_readings + b
fit_plus = (m+nsigma*m_err)*chipmunk_readings+(b+nsigma*b_err)
fit_minus = (m-nsigma*m_err)*chipmunk_readings+(b-nsigma*b_err)

TLM_trip = (m-nsigma*m_err)*chipmunk_limit+(b-nsigma*b_err)

# Scatter plot fake study data
fig, ax = plt.subplots(figsize=(10,6))
ax.errorbar(chipmunk_readings, TLM_readings, xerr=chipmunk_errors, yerr=TLM_sys
_errors, fmt='o',
             ecolor='steelblue', color='steelblue', capsize=2, label='data + sy
stematic error')
ax.plot(chipmunk_readings,fit,color='red',label='y=%.2e*x+%.2e'%(m,b))
x = np.linspace(0,np.max(chipmunk_readings),100)
plt.fill_between(x, (m-nsigma*m_err)*x+(b-nsigma*b_err), (m+nsigma*m_err)*x+(b+
nsigma*b_err), color='#A7A8AA',label='99.7% confidence band')
# Draw a line to show TLM trip point for 0.05 mr/hr
plt.axvline(x=chipmunk_limit,linestyle='--',color='black',label='TLM trip limit
')
plt.axhline(y=TLM_trip,linestyle='--',color='black')
textstr = 'TLM trip: %.1f nC/min. for max.\n surface dose of %.2f mRem/hr'%(TLM
_trip,chipmunk_limit)
plt.text(0.020,
         0.65,
         textstr,
         transform=plt.gca().transAxes,
         fontsize=10,
         color='black',
         bbox=dict(facecolor='white', edgecolor='black', boxstyle='round,pad=0.
3'))

total_sys = np.sqrt((np.sum(chipmunk_sys**2)+np.sum(TLM_sys**2)))*100.0
total_fit_error = np.sqrt((m_err/m)**2 + (b_err/b)**2)*100.0
textstr2 = 'total fit error: %.1f %% \ntotal systematic error: %.1f %%'%(total_
fit_error, total_sys)
plt.text(0.020,
         0.55,
         textstr2,
         transform=plt.gca().transAxes,
         fontsize=10,
         color='black',
         bbox=dict(facecolor='white', edgecolor='black', boxstyle='round,pad=0.
3'))

ax.set_title('Plot of TLM Calibration Study Data and Errors', fontsize=14)
ax.set_xlabel('Max. chipmunk reading [mR/hr]', fontsize=12)
ax.set_ylabel('TLM reading [nc/min.]', fontsize=12)
ax.grid()
ax.legend(loc='upper left');
```



Plot of TLM Calibration Study Data and Errors
y=3.84e+04*x+2.49e+03
TLM trip limit
99.7% confidence band
data + systematic error
TLM trip: 3803.3 nC/min. for max. surface dose of 0.05 mRem/hr
total fit error: 6.8 %
total systematic error: 15.2 %
TLM reading [nc/min.]
Max. chipmunk reading [mR/hr]