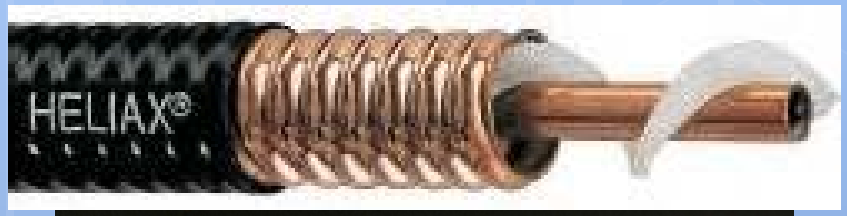
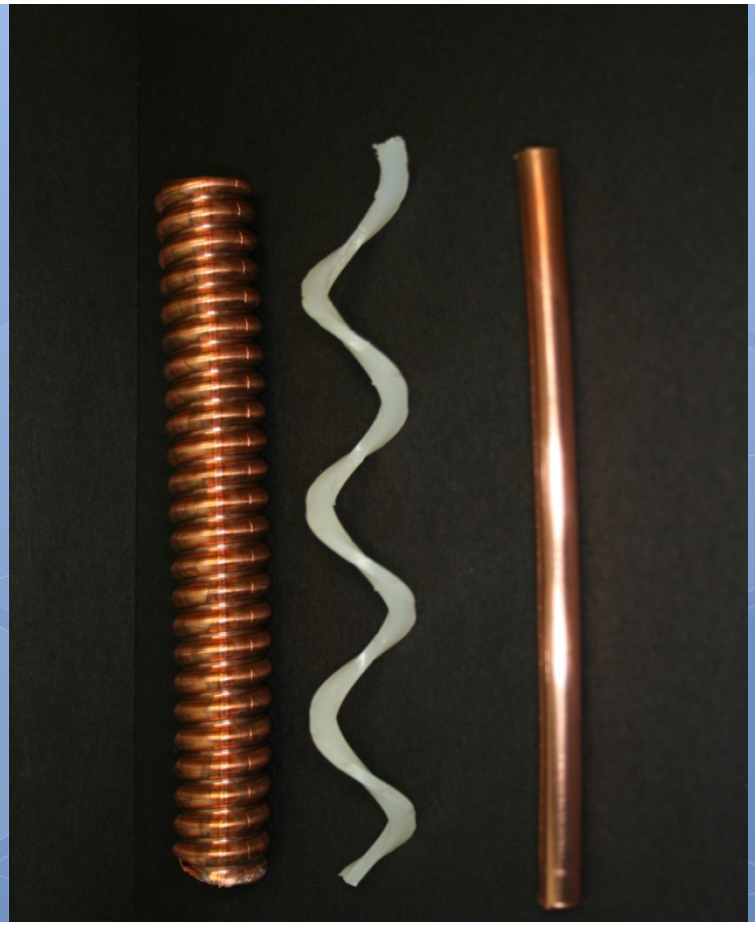




10/7/14

Total Loss Monitor Radiation Safety System

Accelerator Physics Technical Seminar

A. Leveling

Outline

- Background
- Motivation
- Examples of safety systems
- Early days
- Design requirements
- System diagram
- Setting trip levels
- Applications
- Trip level example
- Final pbar studies
- The Booster studies
- The NuMI detector
- Summary

background:

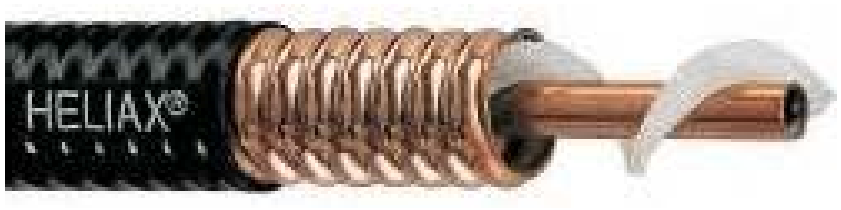
- At Fermilab, high power beams are being planned for existing facilities which have insufficient passive shielding, e.g.,
  - Muon Campus(13 W -> 8 kW)
  - Booster (~35 kW -> 80 kW)
  - Main Injector (700 kW -> 2 MW)
- Supplemental shielding addition is not possible and/or very costly and/or impractical

background:

- Historically, Fermilab has used passive shielding in conjunction with interlocked radiation detectors to provide comprehensive protection necessary to meet the requirements of the FRCM

motivation for TLM:

- Large numbers of additional interlocked detectors (chipmunks) would be required for some installations, e.g.,
  - Muon campus (42->200 - mu2e experiment)
  - Booster (48->? – PIP/PIP-II)
- AD received encouragement from the Fermilab ESH&Q Section in May 2011 to pursue development of a long detector system

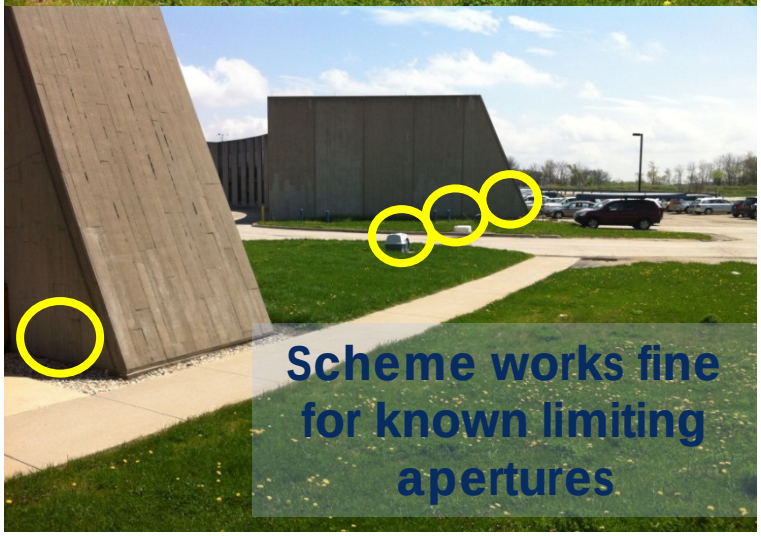


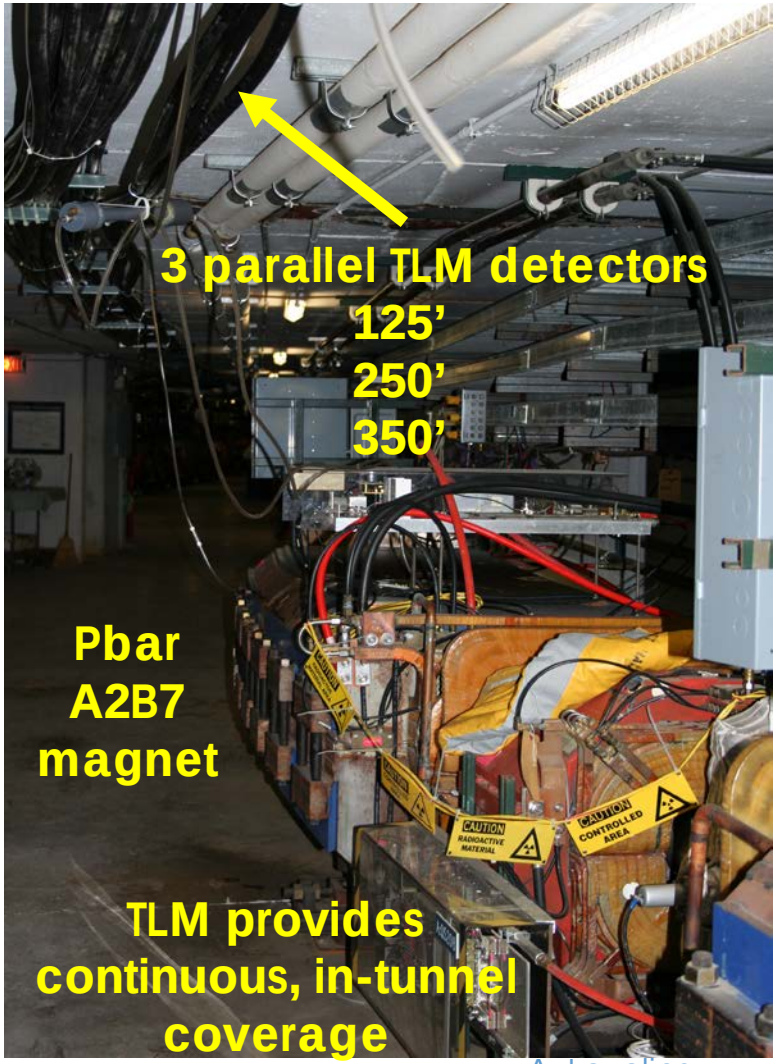
A. Leveling

motivation for TLM:

- March 2011
  - Sam Childress addressed a letter to the AD Head and ESH&Q Head suggesting the need to develop a long detector safety system for high power machines
    - Suggested various possible applications
    - Suggested formation of a working group
  - ESH&Q Head reply was positive/supportive on all counts

Examples of Chipmunk and TLM installations





A. Leveling

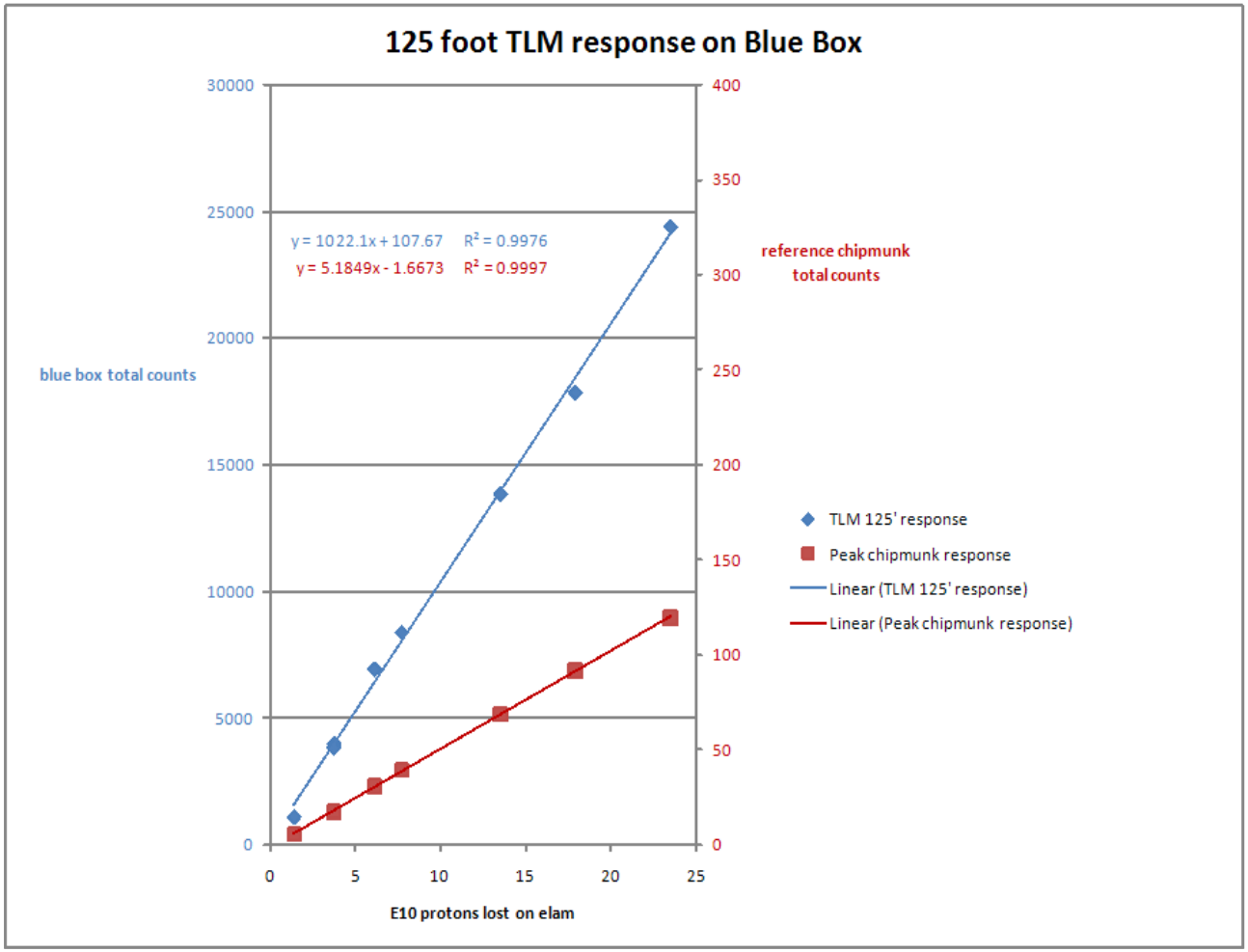
early days:

- June 2011 to August 2011
  - Instrumentation department had detector cable on hand
  - Pbar colleagues helped install the first three detectors at in the Accumulator/Debuncher
  - We were still stacking and storing pbars at the time
  - The TLM detectors could be observed under this normal set of conditions
- Two possibilities to do proton studies at ELAM and A2B7
  - Controlled beam loss of known intensity!

early days:

- June 2011 to August 2011
  - All studies were done with BLM electronics and/or a scope
  - Numerous beam studies attempting to get meaningful data – a confounding time
- August 12, 2011
  - Borrowed a chipmunk electrometer (blue box)from the ES&H Section
  - Reproducible, consistent data became available
  - Limited dynamic range

good correlation between TLM and chipmunk

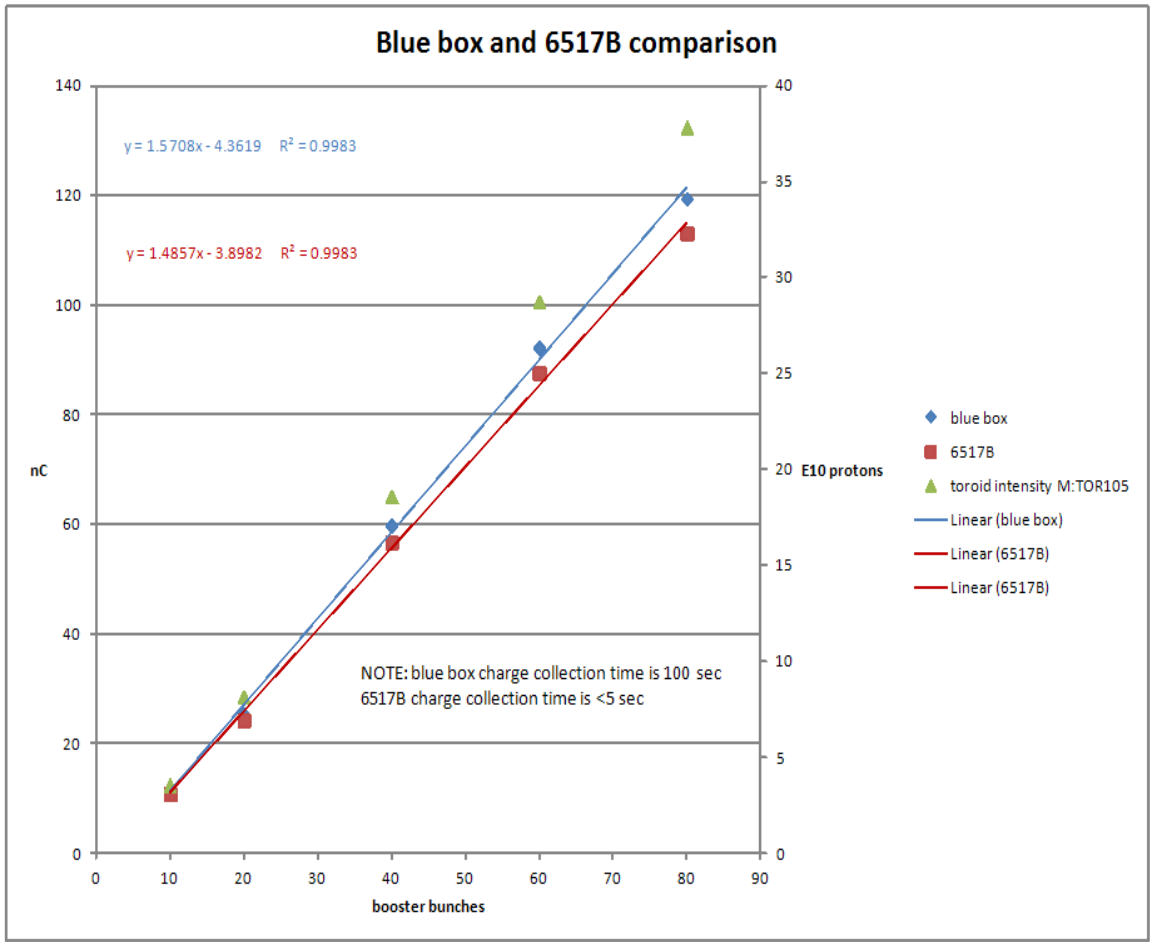


A. Leveling

early days:

- December 8, 2011
  - Simultaneous measurements of a beam loss condition with 2 detectors
  - with Keithley 6517B electrometer and the blue box 2 detectors

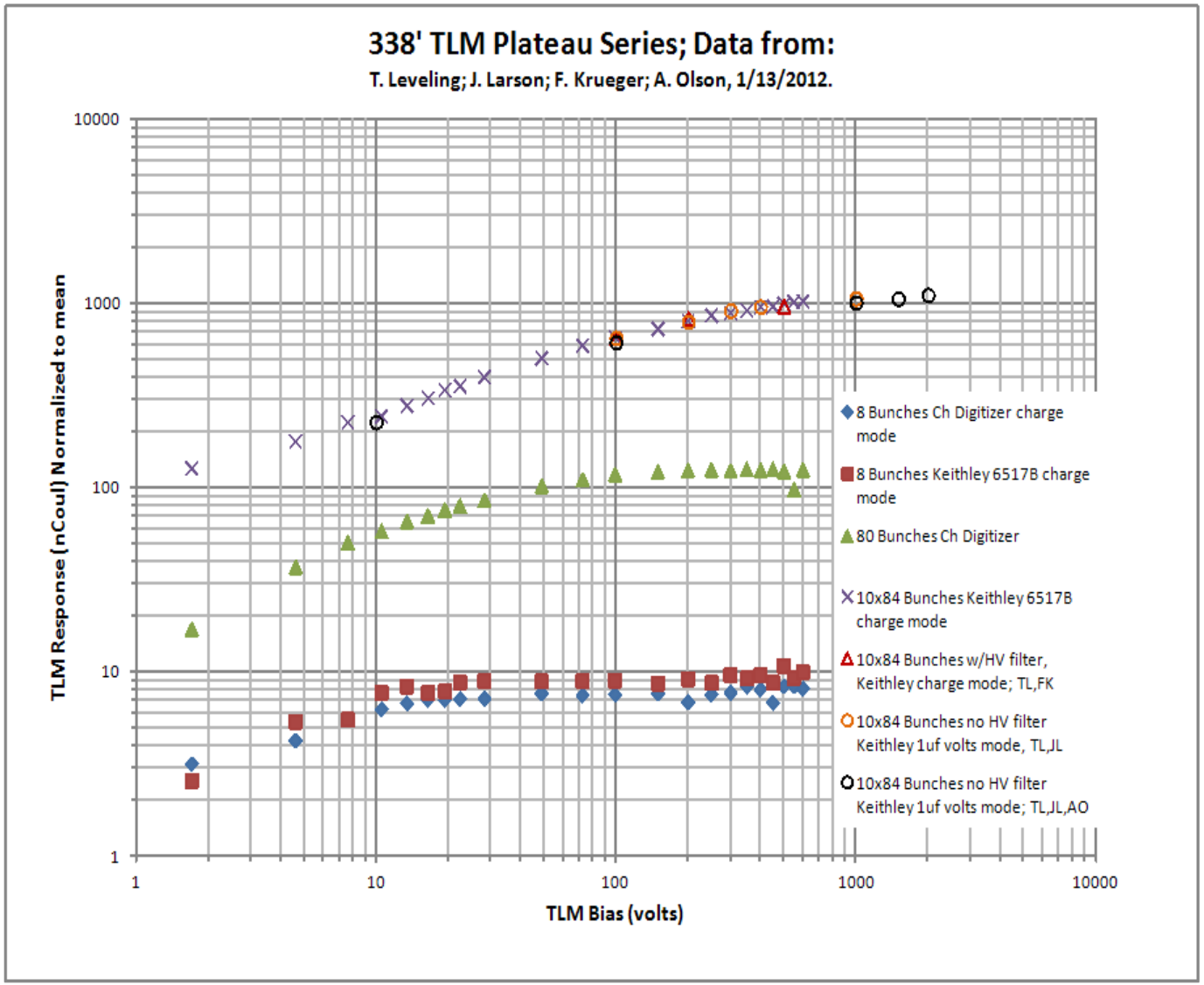
2 detectors simultaneously!



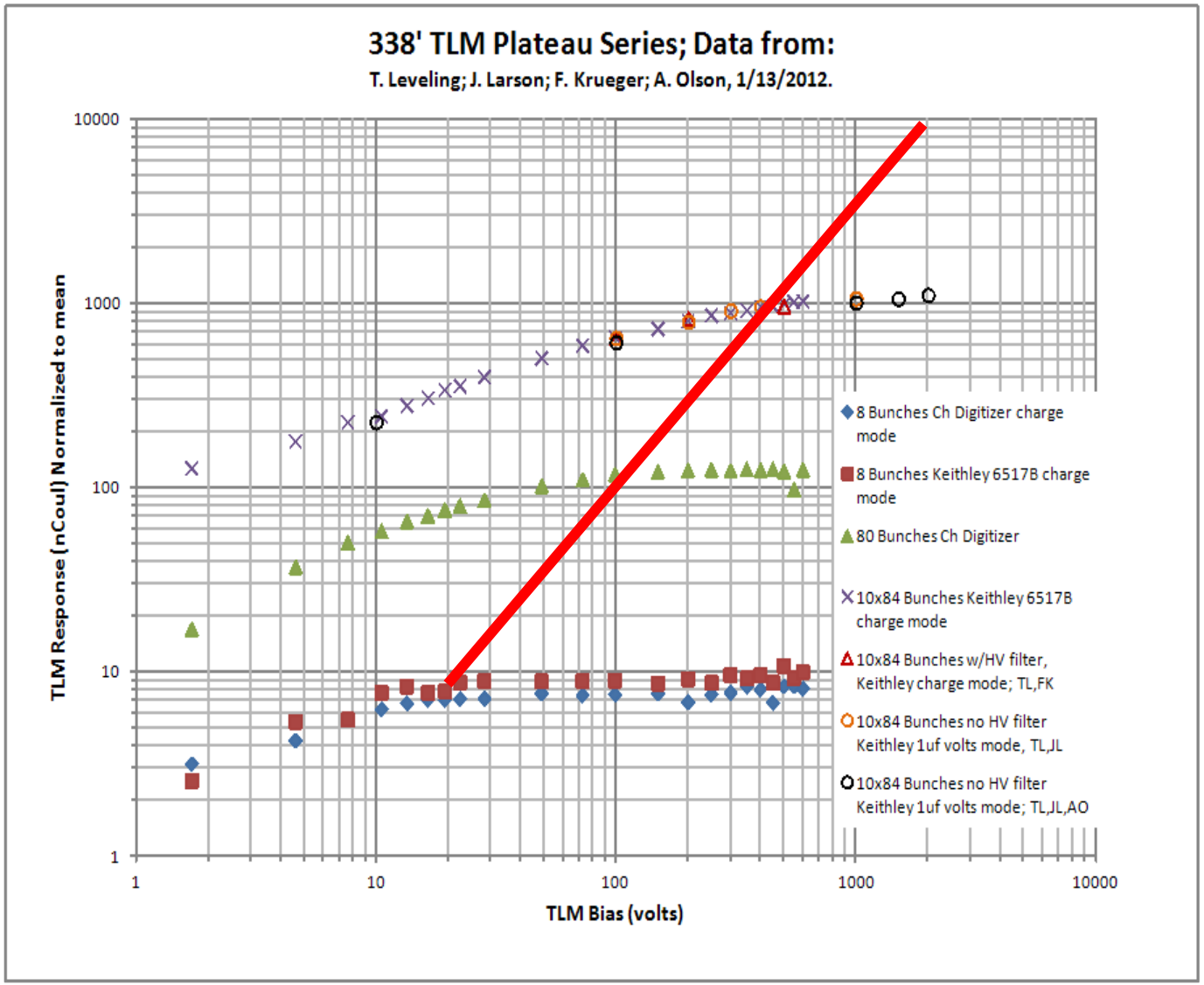
A. Leveling

early days:

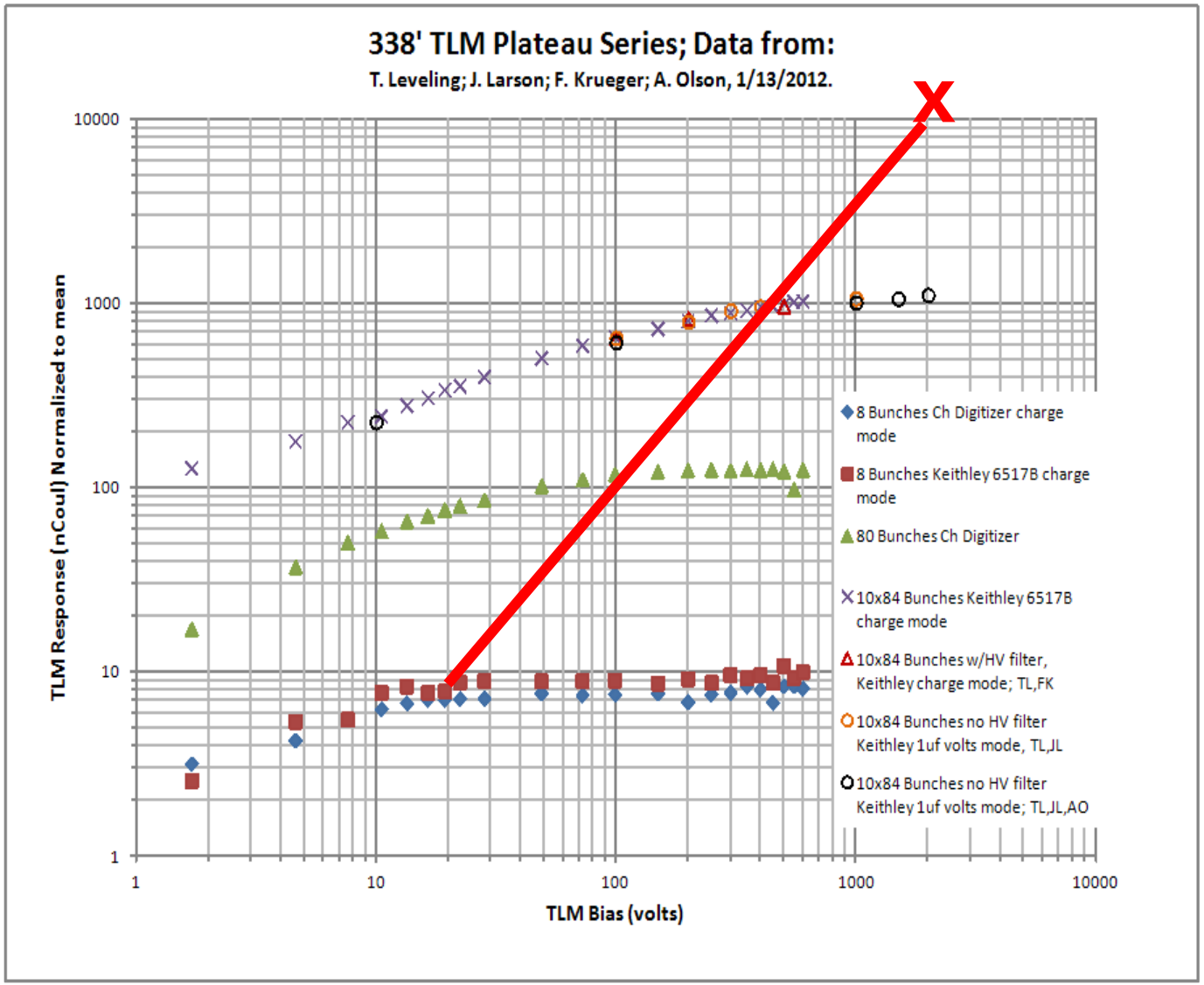
- Keithley electrometer provided extended dynamic range
- We could begin to make a serious attempt at detector response
  - ESH&Q wanted to see at least three data sets with beam intensity in decade intervals
    - Purpose is to determine bias requirement for higher intensity beam loss


338' TLM Plateau Series; Data from:
T. Leveling; J. Larson; F. Krueger; A. Olson, 1/13/2012.
TLM Response (nCoul) Normalized to mean
TLM Bias (volts)
10000
1000
100
10
1
1
10
100
1000
10000
8 Bunches Ch Digitizer charge mode
8 Bunches Keithley 6517B charge mode
80 Bunches Ch Digitizer
10x84 Bunches Keithley 6517B charge mode
10x84 Bunches w/HV filter, Keithley charge mode; TL,FK
10x84 Bunches no HV filter Keithley 1uf volts mode, TL,JL
10x84 Bunches no HV filter Keithley 1uf volts mode; TL,JL,AO

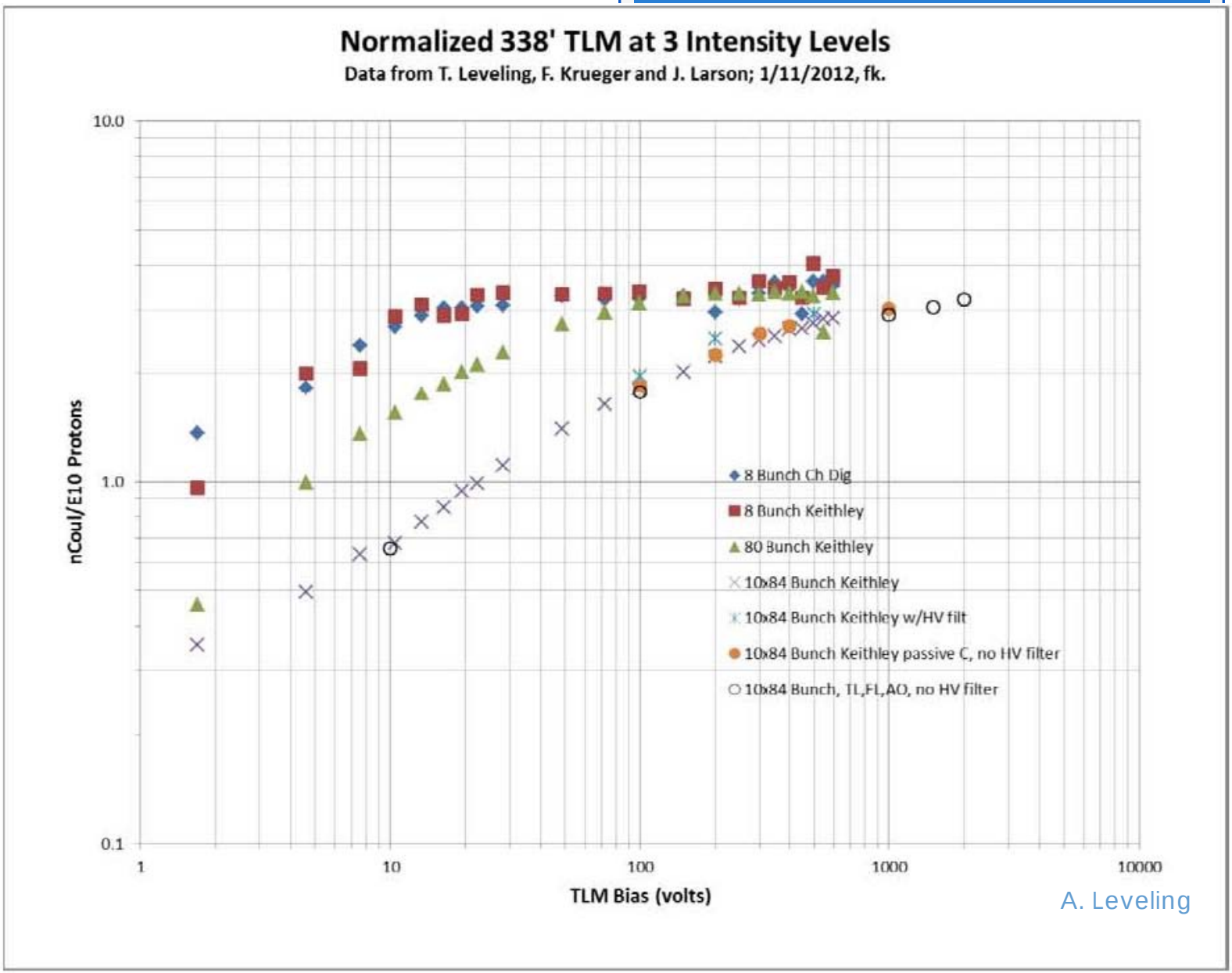
A. Leveling


338' TLM Plateau Series; Data from:
T. Leveling; J. Larson; F. Krueger; A. Olson, 1/13/2012.
TLM Response (nCoul) Normalized to mean
TLM Bias (volts)
10000
1000
100
10
1
1
10
100
1000
10000
8 Bunches Ch Digitizer charge mode
8 Bunches Keithley 6517B charge mode
80 Bunches Ch Digitizer
10x84 Bunches Keithley 6517B charge mode
10x84 Bunches w/HV filter, Keithley charge mode; TL,FK
10x84 Bunches no HV filter Keithley 1uf volts mode, TL,JL
10x84 Bunches no HV filter Keithley 1uf volts mode; TL,JL,AO

A. Leveling


338' TLM Plateau Series; Data from:
T. Leveling; J. Larson; F. Krueger; A. Olson, 1/13/2012.
TLM Response (nCoul) Normalized to mean
TLM Bias (volts)
10000
1000
100
10
1
1
10
100
1000
10000
8 Bunches Ch Digitizer charge mode
8 Bunches Keithley 6517B charge mode
80 Bunches Ch Digitizer
10x84 Bunches Keithley 6517B charge mode
10x84 Bunches w/HV filter, Keithley charge mode; TL,FK
10x84 Bunches no HV filter Keithley 1uf volts mode, TL,JL
10x84 Bunches no HV filter Keithley 1uf volts mode; TL,JL,AO

A. Leveling


Normalized 338' TLM at 3 Intensity Levels
Data from T. Leveling, F. Krueger and J. Larson; 1/11/2012, fk.
10.0
1.0
0.1
nCoul/E10 Protons
1
10
100
1000
10000
TLM Bias (volts)
8 Bunch Ch Dig
8 Bunch Keithley
80 Bunch Keithley
10x84 Bunch Keithley
10x84 Bunch Keithley w/HV filt
10x84 Bunch Keithley passive C, no HV filter
10x84 Bunch, TL,FL,AO, no HV filter

A. Leveling

transition

- At that point, we had an understanding of TLM response as a function of 8 GeV beam loss
- Using shield scaling rules and energy scaling laws we could study dynamic range requirements for TLM applications across the laboratory

8 GeV TLM response constant 3.2nC/E10		TLM baseline energy 8GeV			Energy scaling factor 0.8			Baseline TLM distance to beam center 5.5feet				
Machine/Condition	Notes	Beam power (KW)	Energy (GeV)	Protons per hour	Average intensity per second	Nominal Shielding feet	Magnet to ceiling distance	Shield Category or application basis	beam loss limit (p/s)	normal loss limit p/s	% of beam loss	nC/min **(per meter in bold)**
Mu2e Service Bldg.	1	4	8	1.13E+16	3.13E+12	10	5.5	skyshine	3.3 watts	2.58E+09	0.082%	93
Mu2e Service Bldg.	1	8	8	2.25E+16	6.25E+12	10	5.5	skyshine	3.3 watts	2.58E+09	0.041%	93
Mu2e Shielding Berm	2	4	8	1.13E+16	3.13E+12	13	5.5	1A	3.26E+10	1.63E+09	0.052%	31
Mu2e Shielding Berm	2	8	8	2.25E+16	6.25E+12	13	5.5	1A	3.26E+10	1.63E+09	0.026%	31
Booster May 2013	5	64	8	1.80E+17	5.00E+13	14	4	2A	2.20E+11	1.10E+10	0.022%	399
Booster 2016	5	80	8	2.25E+17	6.25E+13	14	4	2A	2.20E+11	1.10E+10	0.018%	399
Booster (any pwr)	3		8			14	4	1 W/m	NA	4.69E+10		1,701
Main Injector	2	700	120	1.31E+17	3.65E+13	24	5	1A	2.61E+13	1.31E+12	3.582%	265,094
Main Injector	2	2,300	120	4.31E+17	1.20E+14	24	5	1A	2.61E+13	1.31E+12	1.090%	265,094
Main Injector	3	700	120	1.31E+17	3.65E+13	24	5	1 W/m	NA	1.82E+11	0.499%	36,960
Main Injector	3	2,300	120	4.31E+17	1.20E+14	24	5	1 W/m	NA	1.82E+11	0.152%	36,960
Nova	2	700	120	1.31E+17	3.65E+13	26	3	1A	4.87E+13	2.44E+12	6.675%	1,372,243
LBNE	2	2,300	120	4.31E+17	1.20E+14	26	3	1A	4.87E+13	2.44E+12	2.030%	1,372,243
Nova	4	700	120	1.31E+17	3.65E+13	26	4	10 ppm	NA	3.65E+08	0.001%	116
LBNE	4	2,300	120	4.31E+17	1.20E+14	26	3	1 W/m	NA	**5.21E+07**	0.000%	**29**

Not Recommended

1 Distributed or concentrated loss limits public exposure to 1 mrem per year; NB – 6 nC/E10 at ELAM

2 Single point loss limits berm surface normal condition dose rate to 0.05 mrem/hr

3 Total charge limit in tunnel beam loss to 1 W/m - distributed among some number of TLMs

4 Limit total beam loss to 1 part in 1E5

5 Single point loss limits berm surface normal condition dose rate to 5 mrem/hr

A. Leveling

The next step

- With a well developed knowledge of detector response for known beam loss, we could begin to develop an electrometer design

TLM system design requirements:

- Limit beam losses to the level of 1 watt/meter
- The TLM electrometer must be able to collect charge with a 100% duty factor, i.e., no dead time for integrator reset
- TLM system must connect directly to the existing Radiation Safety System (RSS), via existing radiation interlock cards
- Include a rigorous testing program and calibration schedule
- The response of the TLMs must be characterized and /or predictable for a wide range of beam loss conditions

TLM system design requirements:

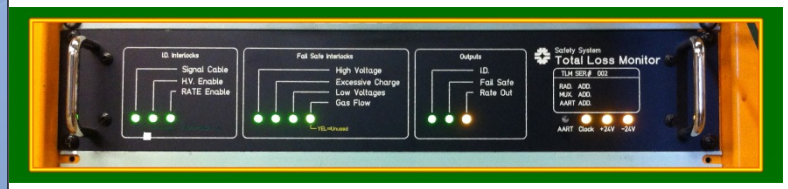
- All activity from TLM detectors had to be captured completely, both by:
  - The radiation safety system “rad card”
  - The site wide monitoring system, aka, the RADMUX system.
- RADMUX system is bandwidth limited to 70 Hz
- TLM electrometer is limited to ~62 Hz to ensure no loss of data monitoring

TLM system design requirements:

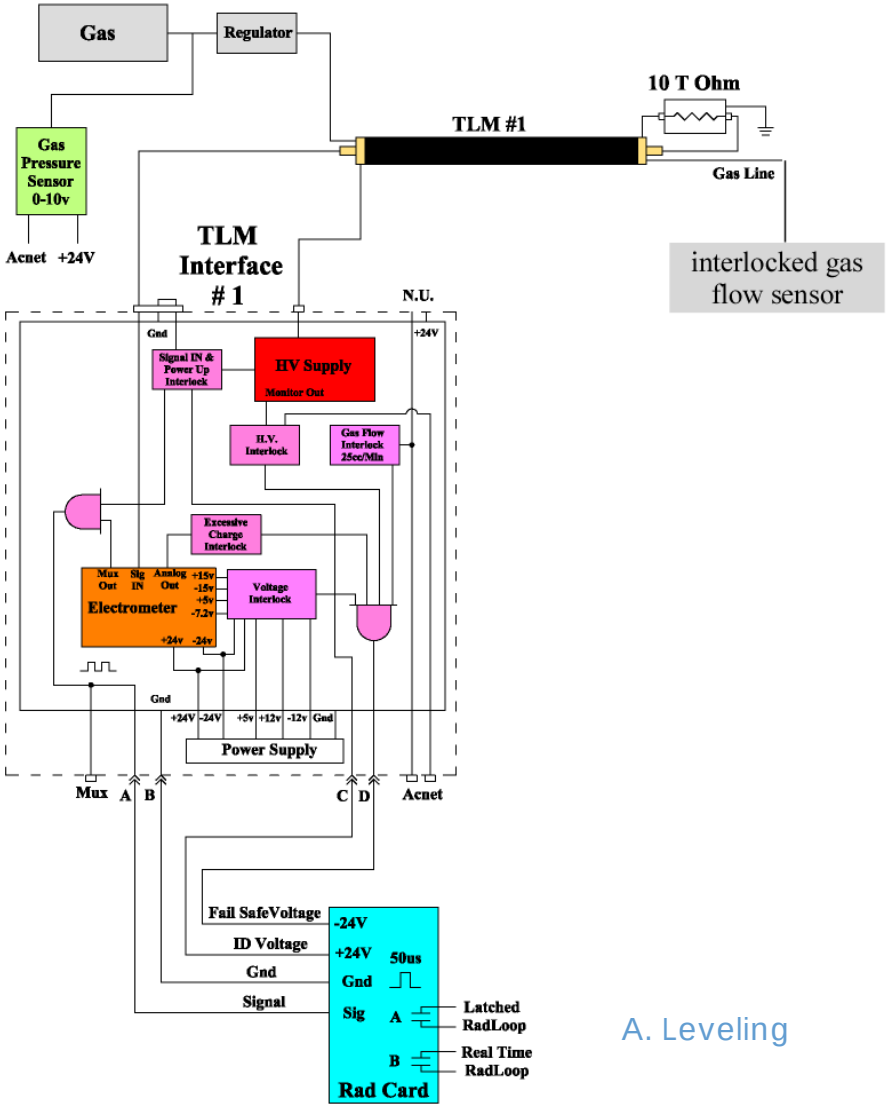
- The TLM system must be fail safe; i.e., the (RSS) must be disabled if:
  - TLM chassis loses power
  - Motherboard voltages go out of tolerance
  - TLM detector is disconnected from its electrometer
  - TLM heartbeat is lost (provided by 83 pA leakage current)
  - TLM bias voltage falls outside tolerance
  - The TLM gas flow is lost, (nominally 25 cc/min)

TLM system diagram

- Detector works in ion chamber mode
  - 800 volt detector bias
- Argon/CO_2 detector gas
  - Nominally 25 cc/min



- Electrometer output is calibrated in units of nC/TTL pulse
- Heartbeat provided by 10 Tohm resistor (83 pA = 5 nC/min)



A. Leveling

TLM electrometer design

- Two electrometer design paths were pursued
  - Digital electrometer design
    - Created by Dave Peterson
    - Trial version was implemented in December 2012
    - Ran for several months in 400 MeV region of Linac
  - Analog design
    - Created by Dan Schoo
    - Implemented in March 2013
    - A second version was created in April 2013

TLM electrometer design

- Dan's second version electrometer design was chosen for its simplicity of design and operation
- Meets all of our design requirements
- Over 2 years of operating experience with the design
  - Flawless performance!
    - Three detectors at pbar
    - One detector at Linac
    - 3 detectors at ASTA
    - 1 detector at NuMI
    - 1 detector at Booster

Setting TLM trip levels:

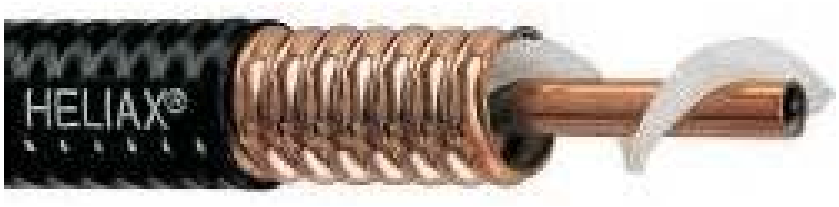
- Determine the worst case beam loss condition by:
  - Evaluation of the possibilities, then
    - MARS simulation(s), and/or
    - Measurement
- The worst case condition includes consideration of:
  - Beam enclosure geometry
  - Maximum beam intensity lost (MBL)
  - Beam energy
  - Amount of shielding present

Setting TLM trip levels:

- Posting and controls for region determined allowable beam intensity lost (ABL)
- The TLM response to the worst case condition (TLM_{max}) is determined by:
  - Measurement, or
  - By MARS simulation
- TLM trip level is set by scaling:
  - Trip Level = TLM_{max} x ABL / MBL

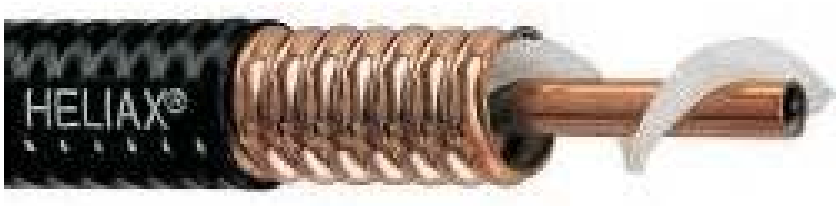
TLM trip level philosophy:

- The trip level has to be safe AND it has to allow normal losses with reasonable margin for variances in operation
  - Avoid spurious/unnecessary system trips
- TLM cannot distinguish between single point, localized losses and losses distributed over its entire length
  - This implies the trip levels are conservative
- Trip levels are to be determined by the laboratory's well-developed, shielding assessment process



Possible applications:

- Limit effective dose rate outside of radiation shields
  - Implicitly includes control of radiation skyshine
- Limit beam loss to 1 W/m
- Limit surface water, ground water, and/or air activation
- Limit radiation levels outside of exit labyrinths and cable penetrations



for example:

- Delivery Ring Arc has 13 feet of shielding
- Length of the arc is 117 meters
- Assume we want to:
  - limit radiation dose rate to < 5 mrem/hr (controlled area)
  - limit 8 GeV beam loss to 1 W/m or 7.8E8 p/m/s
- 117 watts is 9.1E10 p/s
- From site-wide shielding criteria, a single point 117 W beam loss results in dose rate of 12.6 mrem/hr – TILT!!
  - Exceeds the 5 mrem/hr goal

for example:

- So we cannot use the 1 W/meter basis for the delivery ring arc for the 117 meter cable
- However, if we subdivide the cable into three parts:
  - ~40 meters
  - 40 watts is equivalent to about 3.1E10 p/s
  - With three ~40 meter detectors, we could use the 1W/m basis and meet the limit of 5 mrem/hr for a single point accident

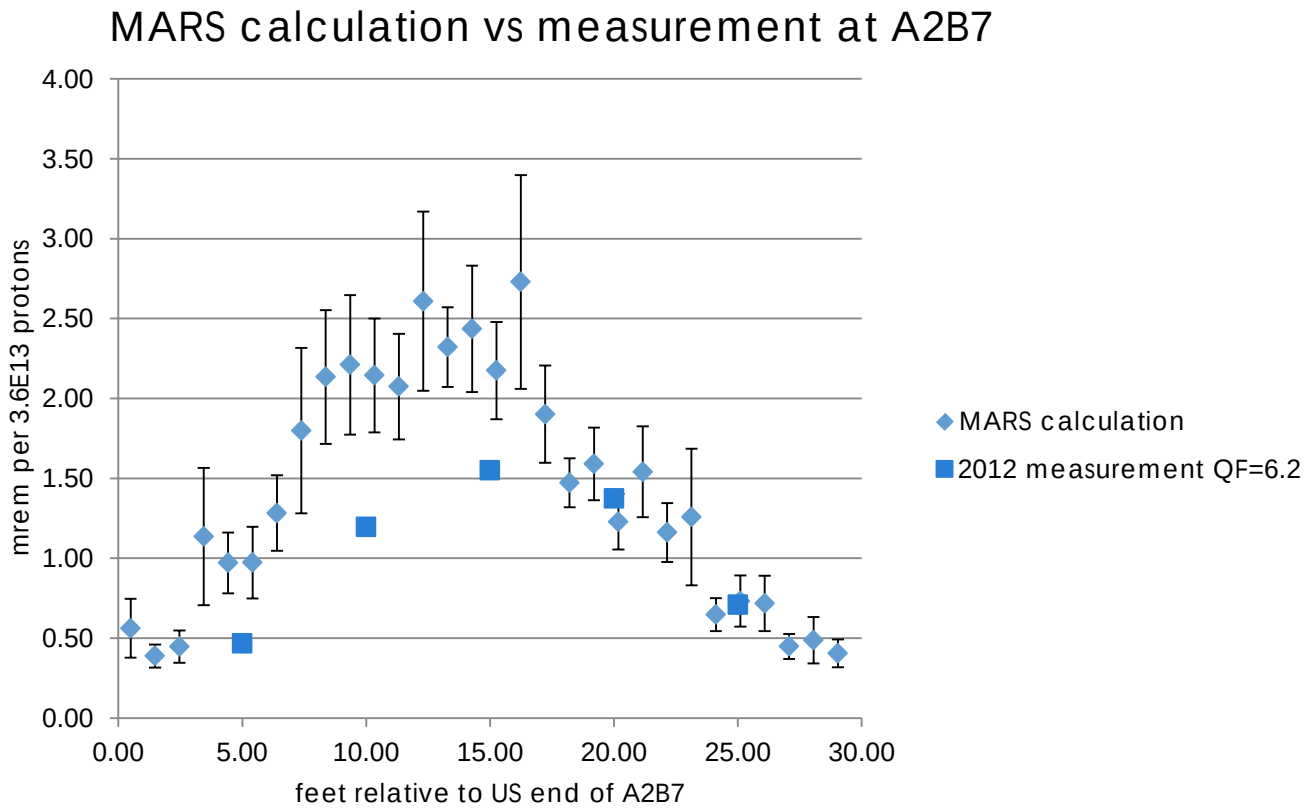
for example:

- If we stick with the 117 meter cable:
  - Losses would be limited to 3.6E10 p/s (0.39 W/m)
  - The maximum dose rate on the shielding berm would not exceed 5 mrem/hr

- The TLM trip level setting for this case would be:

3.6E10 p/s * 60 seconds * 3 nC/E10 protons =
648 nC/min

consistency check:

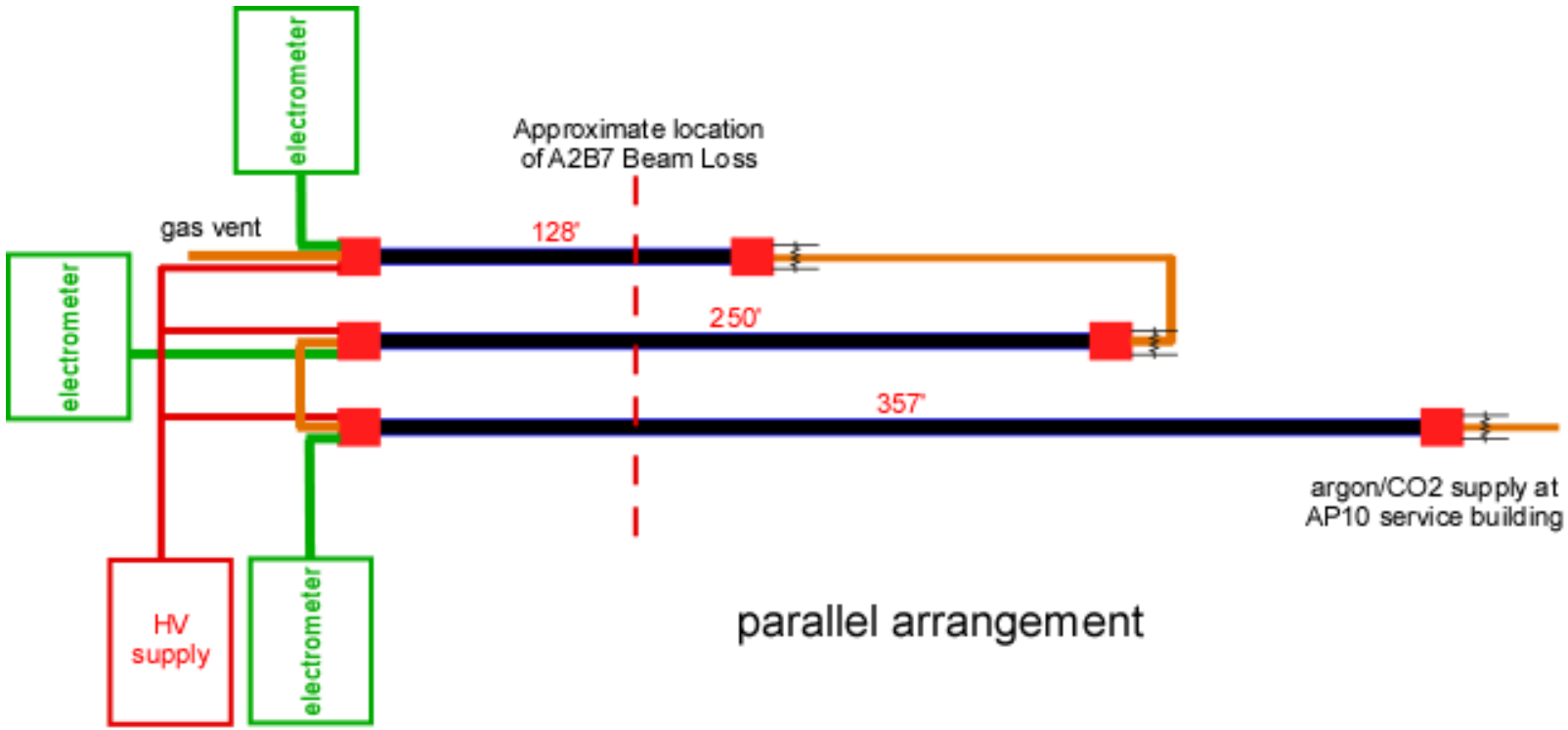


648 nC/min*60min/hr*1e10protons/3nC*1.5mrem/3.6E13protons = 5.4mrem/hr **(reasonably good agreement!)**

A. Leveling

Final Pbar Source Study Results

- Two final studies were done in pbar before Accumulator/Debuncher Disassembly began
- Using a common, controlled beam loss at A2B7
  - Response of 3 parallel detectors
  - Response of the 3 detectors connected in series



Two intensities of beam loss were created at A2B7

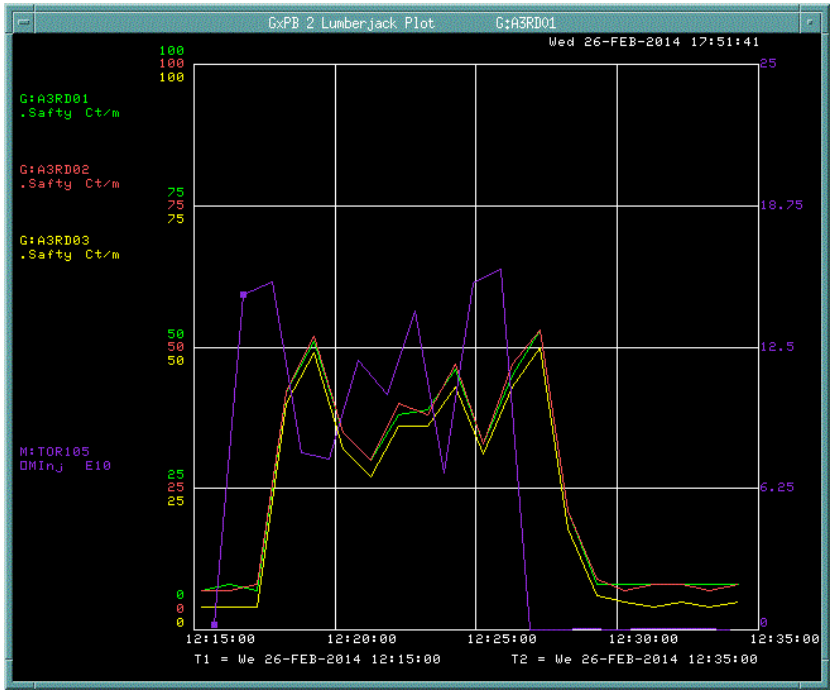
1.5E11

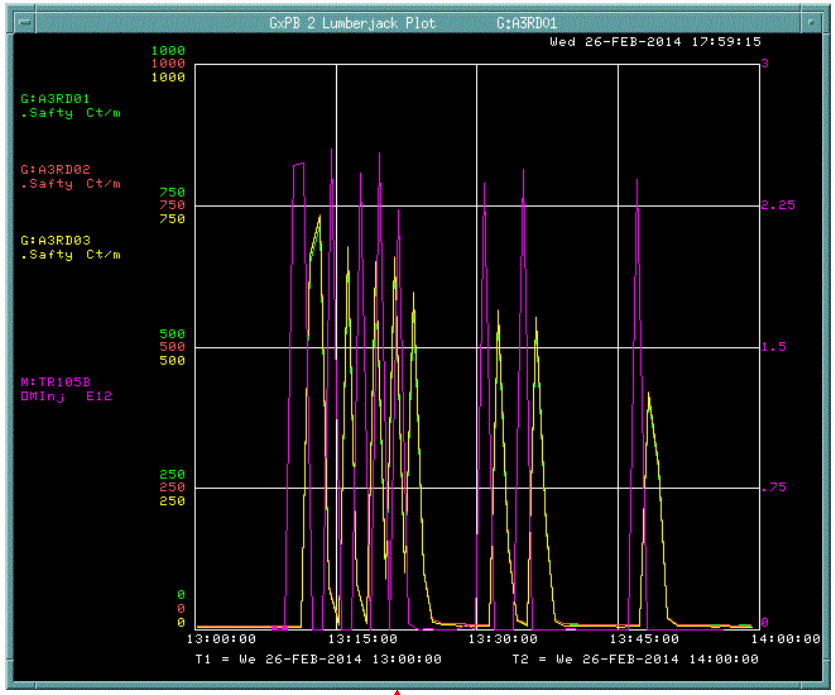
2.5E12

A. Leveling

parallel arrangement

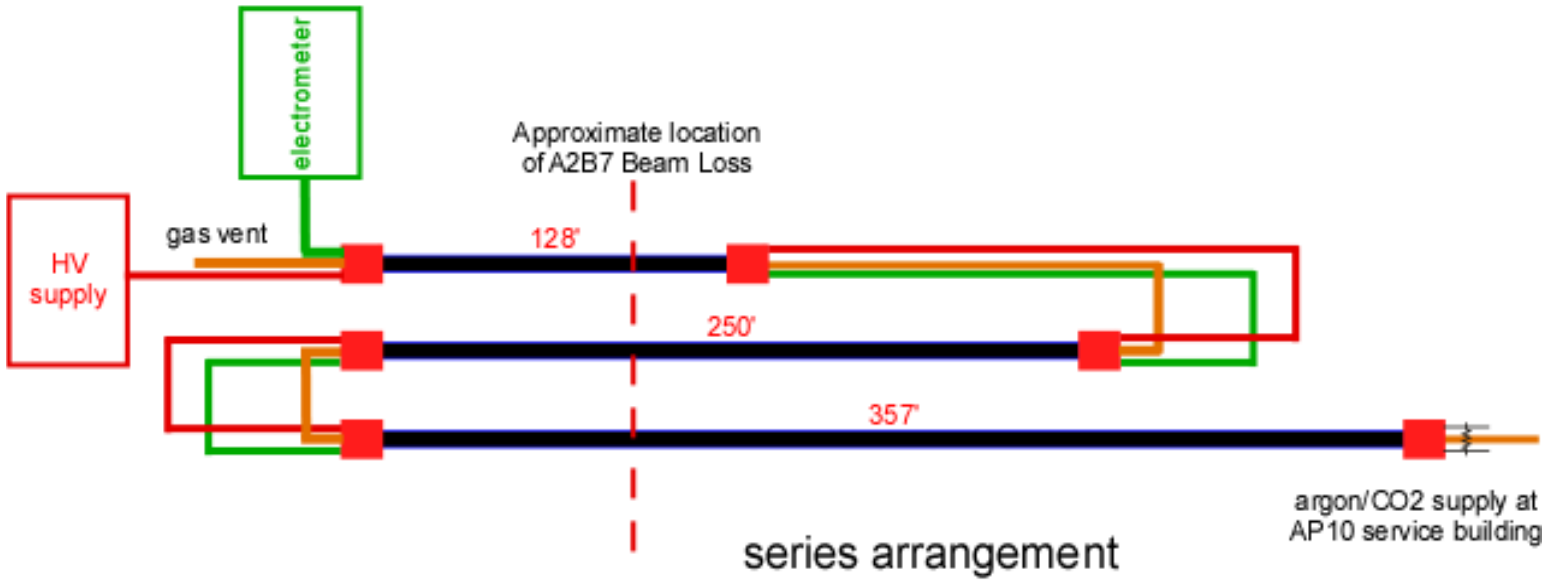
Low intensity run





High intensity run

A. Leveling



Legend

detector cable

TLM end cap

copper gas line

heartbeat resistor

2.5E12 beam loss created at A2B7

A. Leveling

Low intensity
Parallel arrangement

record	time stamp	E10 protons	128'	250'	357'
	sum	120.22	503	507	446
	background cpm		7.04	7.21	4.08
	total background		140.8	144.2	81.6
	net counts		362.2	362.8	364.4
	nC per E10 protons		3.01	3.02	3.03

High intensity
Parallel
arrangement

record	time stamp	E12 protons	128'	250'	357'
	sum	21.865625	6871	7052	6879
	background cpm		7.04	7.21	4.08
	total background		422.4	432.6	244.8
	net counts		6448.6	6619.4	6634.2
	nC per E10 protons		2.95	3.03	3.03

High intensity
Series arrangement

record	time stamp	E10 protons	735'
	sum	111.88	1174
	Average background cpm		5.69
	total background		176.3125
	net counts		997.6875
	nC per E10 protons		8.92
	nC per E10 protons per detector		2.97

A. Leveling

record	time stamp	E10 protons	128'	250'	357'
	sum	120.22	503	507	446
	background cpm		7.04	7.21	4.08
	total background		140.8	144.2	81.6
	net counts		362.2	362.8	364.4
	nC per E10 protons		3.01	3.02	3.03

Low intensity
Parallel arrangement

High intensity
Parallel
arrangement

record	time stamp	E12 protons	128'	250'	357'
	sum	21.865625	6871	7052	6879
	background cpm		7.04	7.21	4.08
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	net counts		6448.6	6619.4	6634.2
	nC per E10 protons		2.95	3.03	3.03

record	time stamp	E10 protons	735'
		111.88	1174
	nd		5.69
			176.3125
			997.6875
	s		8.92
	per		2.97

Conclusions:

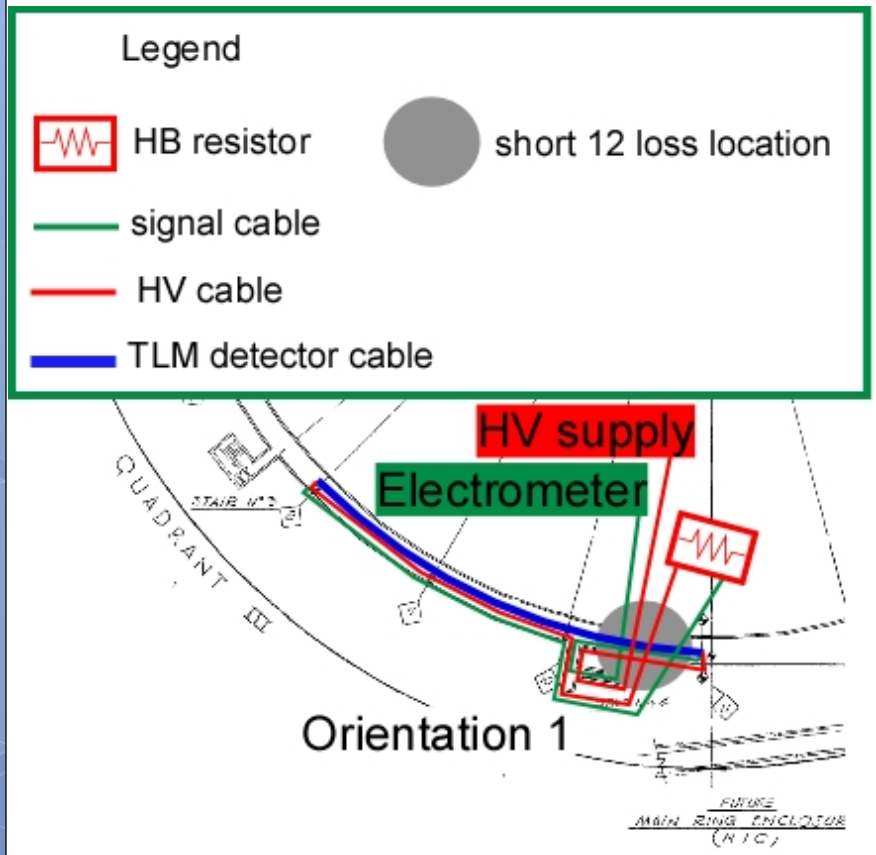
1. Detector cable length is irrelevant
2. Location of beam loss along the detector length is irrelevant
3. Cables can be connected in series with RG58 cable, for example, to repair a damaged cable

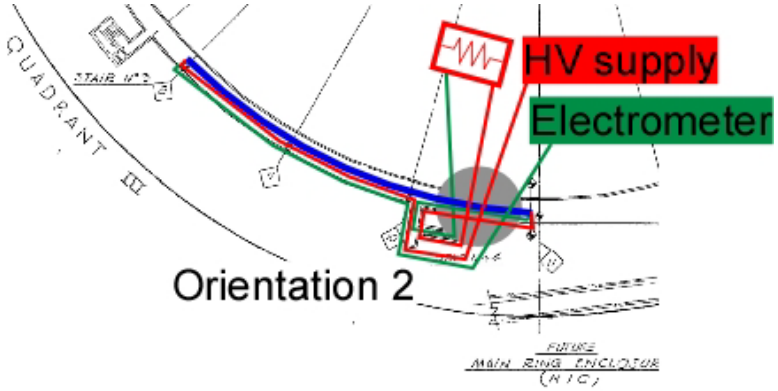
A. Leveling

Booster Study Results

- TLM response to localized high field loss
  - In this study, also checked TLM response as a function of location along the detector
- Compare TLM response as function of Detector gas type (argon and argon-CO_2)
- Provisional Booster shielding assessment trip point determination
  - TLM response to 400 MeV beam loss
  - TLM response to normal beam losses

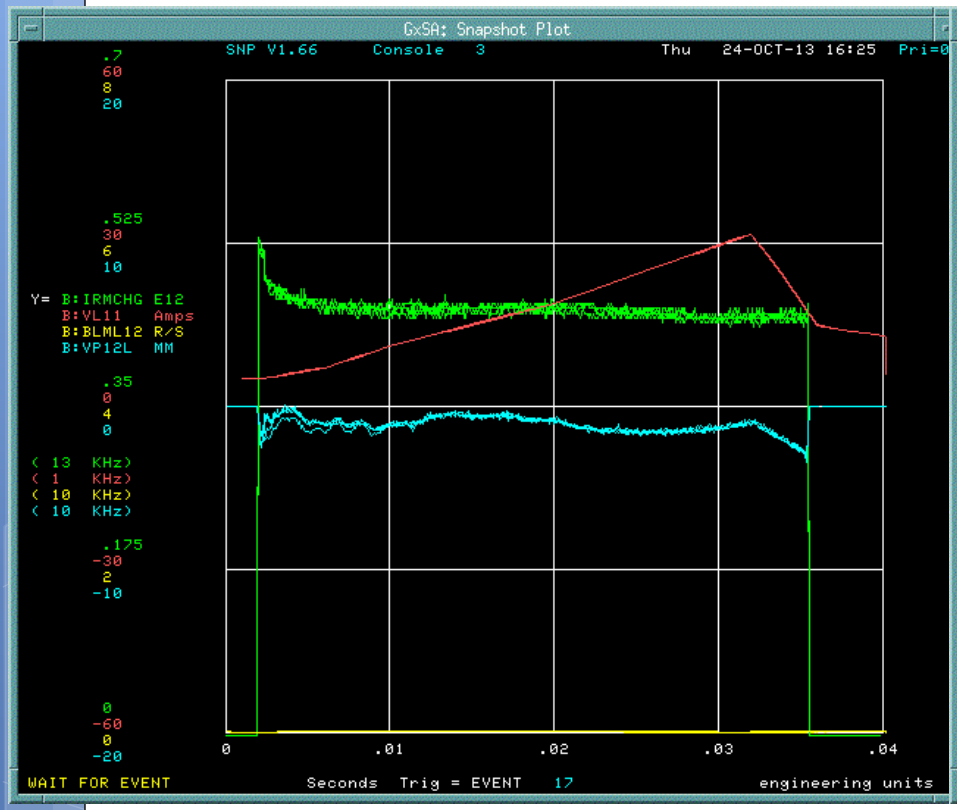
TLM response as function of position



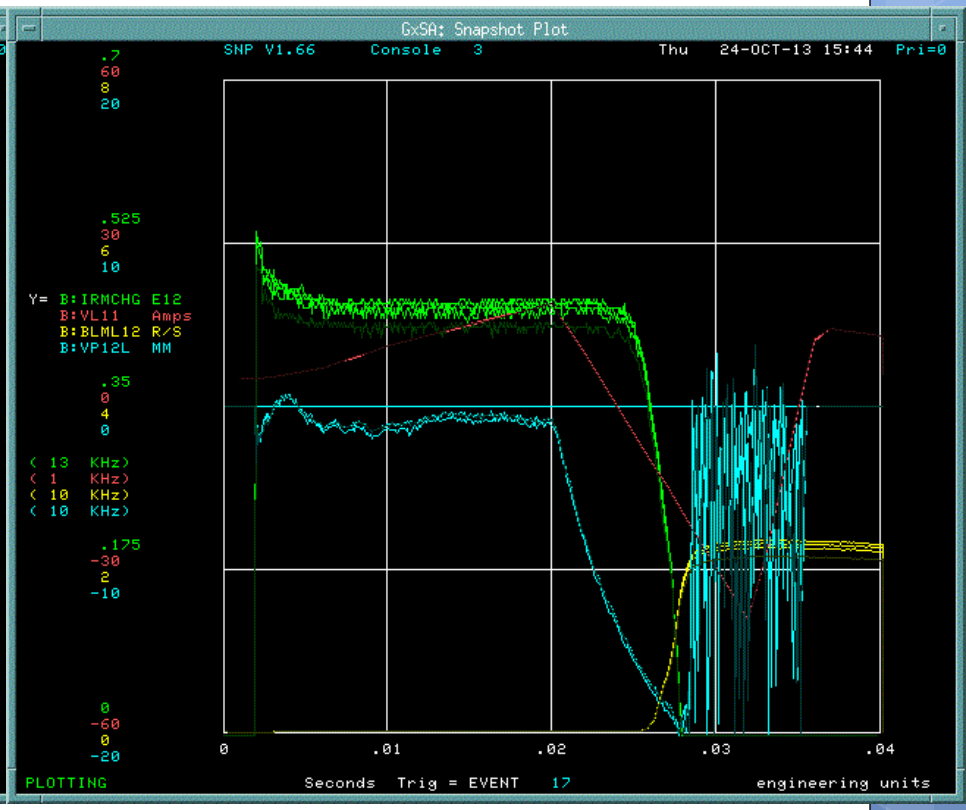


A. Leveling

Booster acceleration cycles

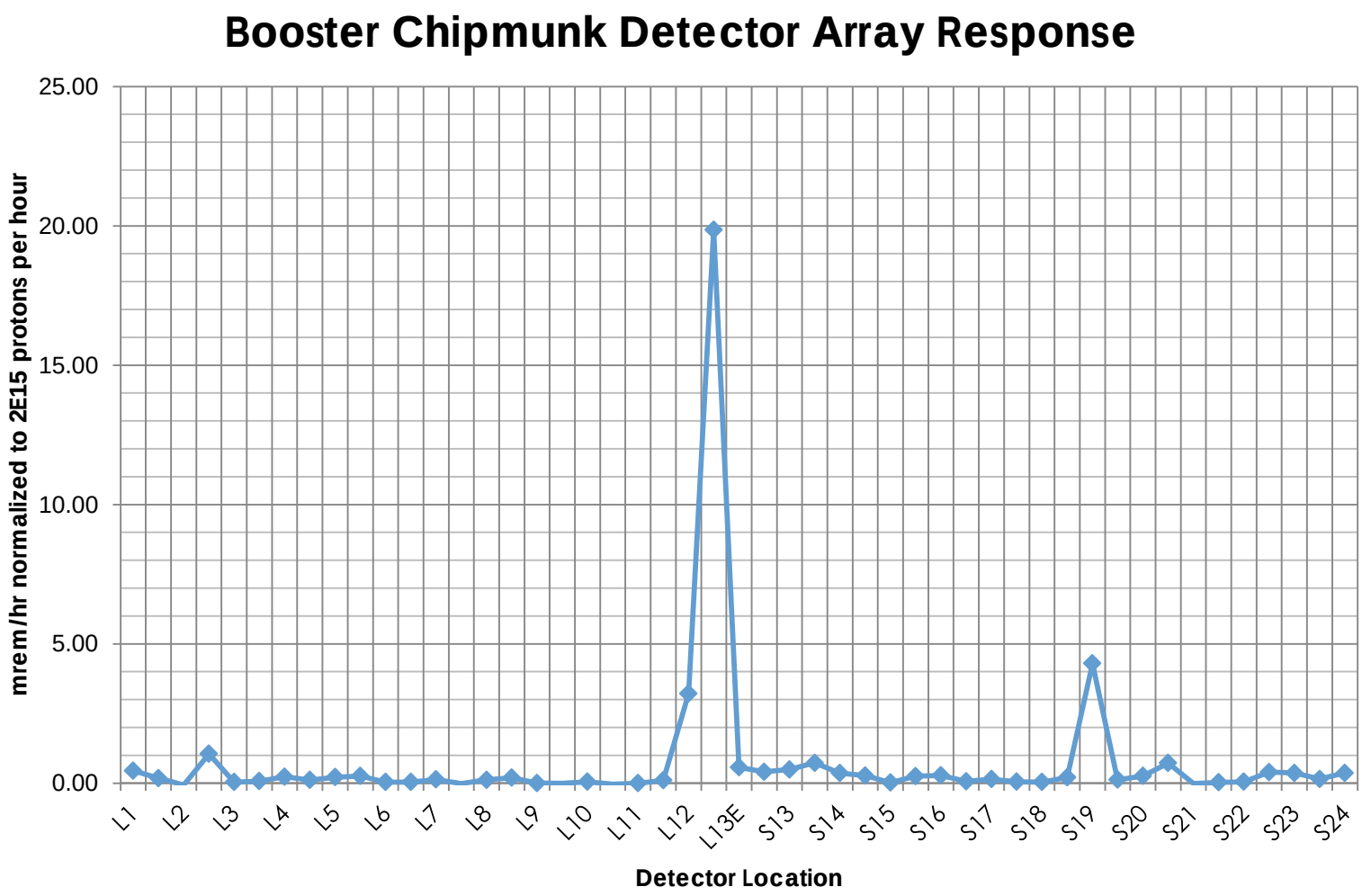


Normal cycle



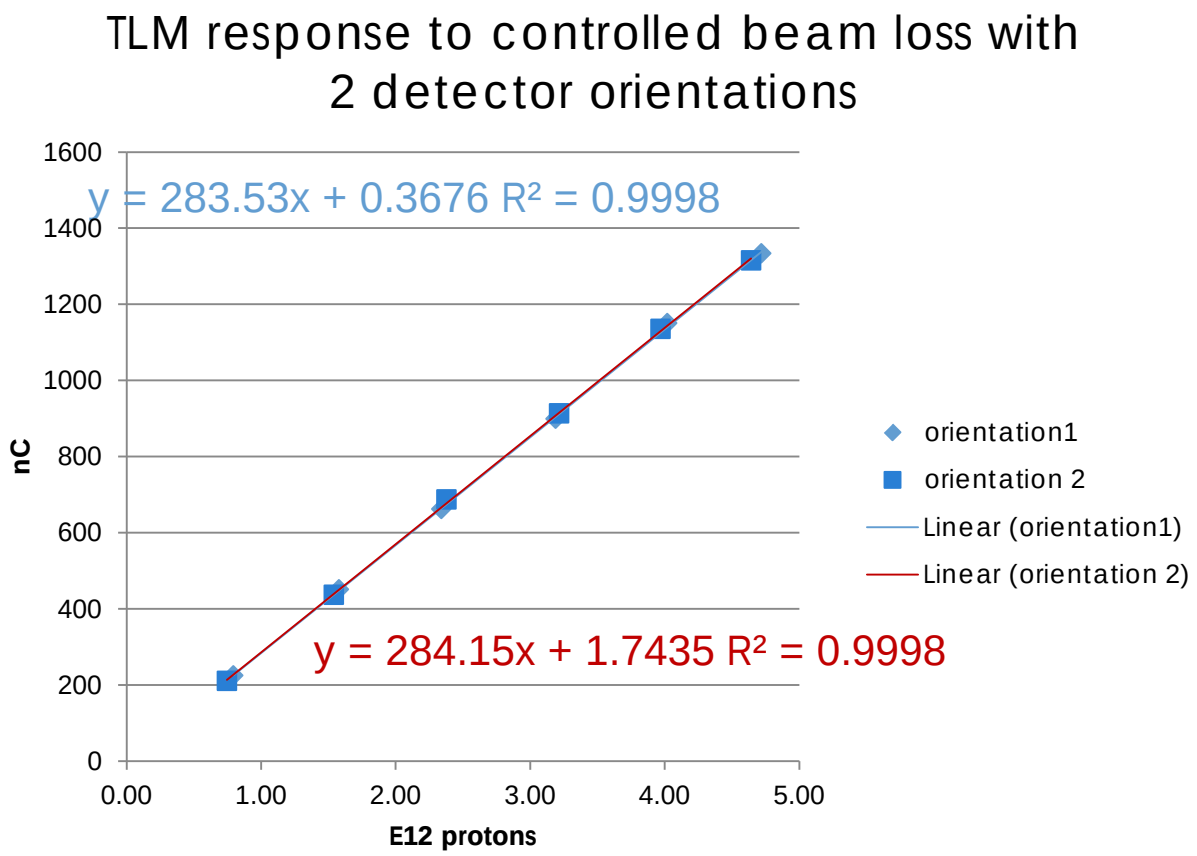
High field loss cycle

A. Leveling


Booster Chipmunk Detector Array Response
mrem/hr normalized to 2E15 protons per hour
25.00
20.00
15.00
10.00
5.00
0.00
L1
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11
L12
L13E
S13
S14
S15
S16
S17
S18
S19
S20
S21
S22
S23
S24
Detector Location

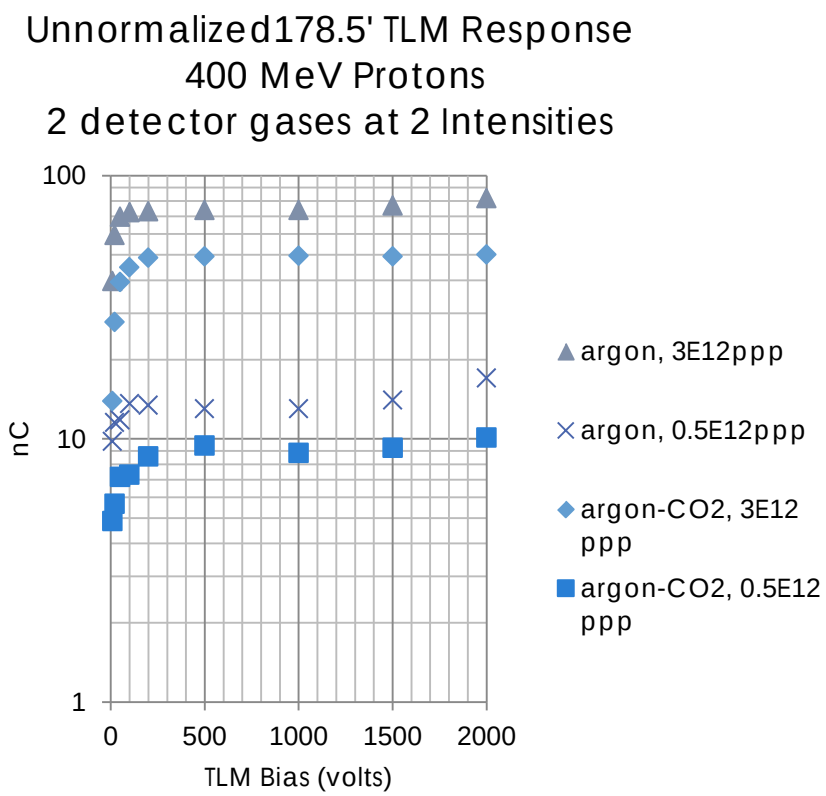
A. Leveling

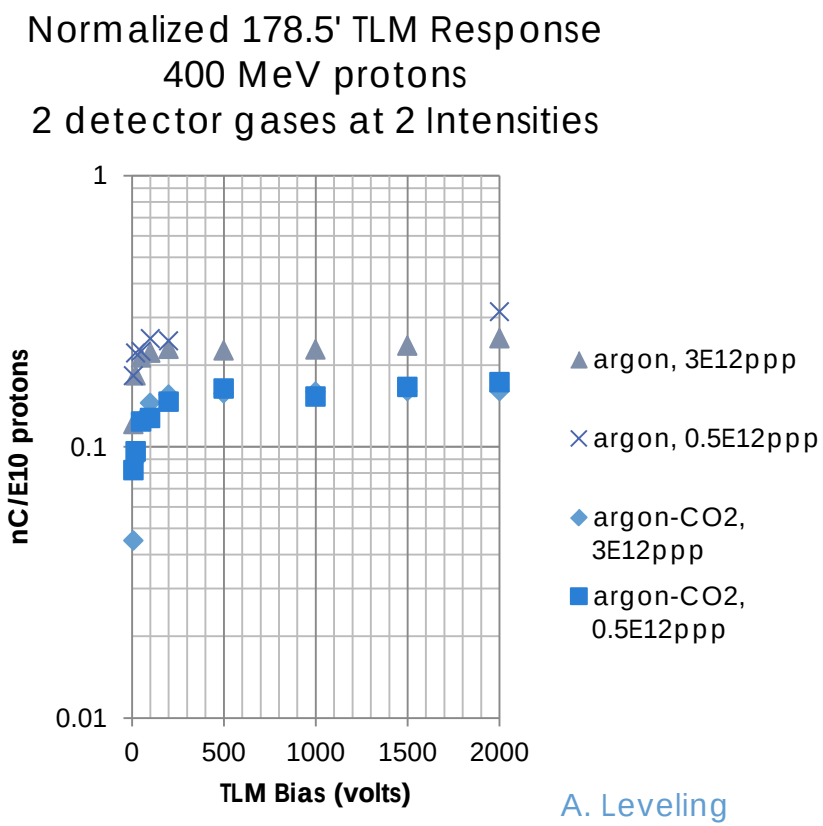
TLM response as function of detector position



A. Leveling

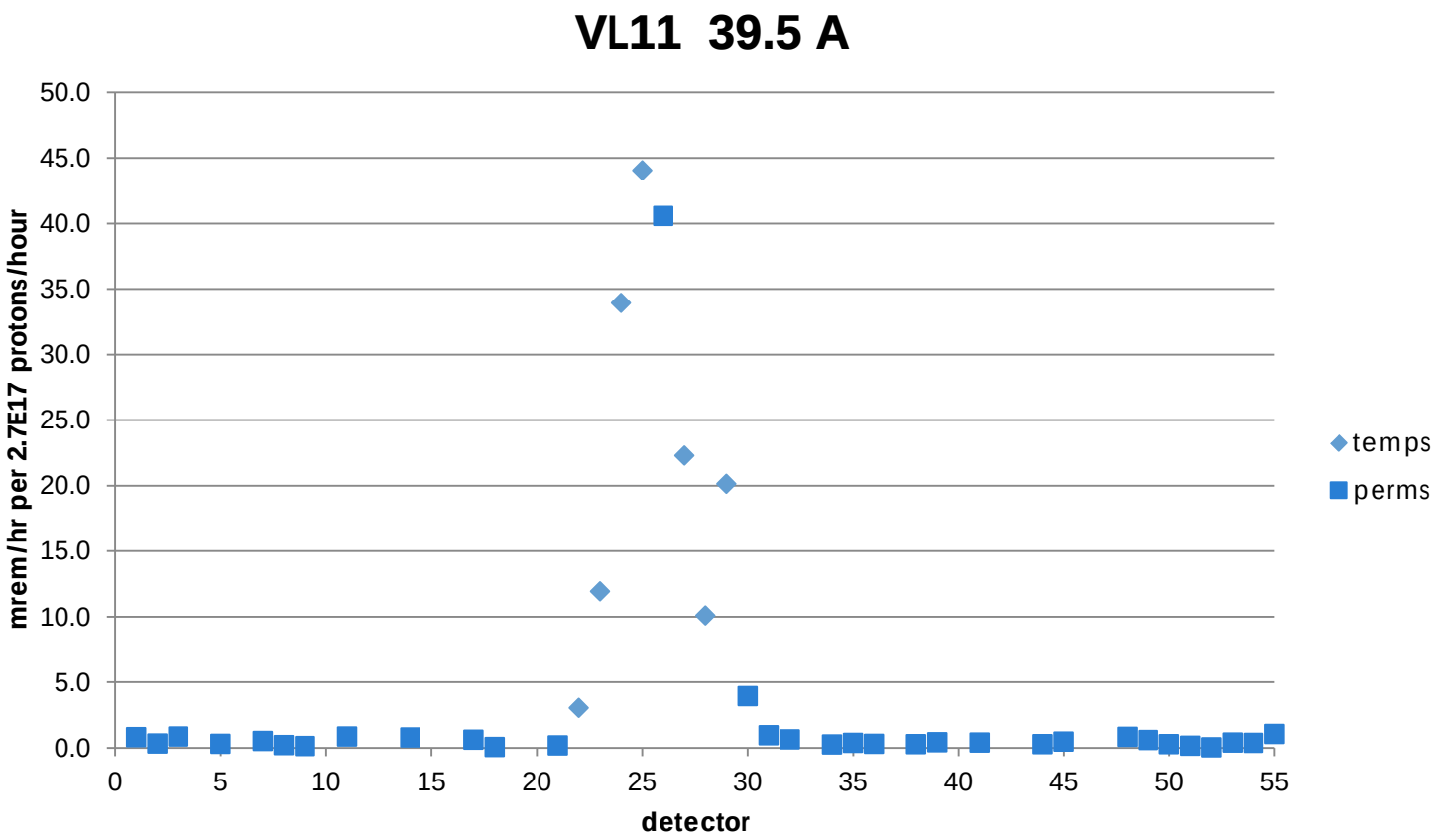
TLM response as function of detector bias for 2 gas types





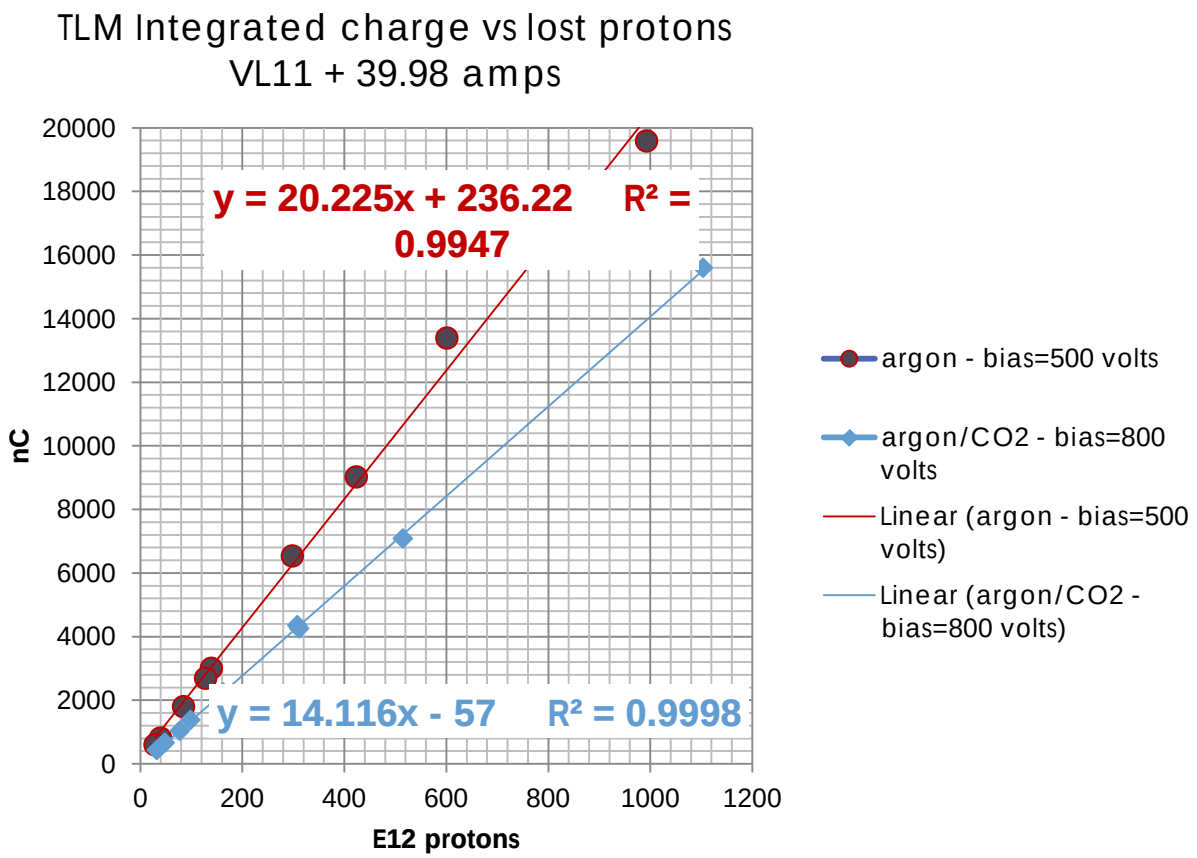
A. Leveling

Chipmunk response for Booster 400 MeV beam loss



A. Leveling

TLM response for Booster 400 MeV beam loss



A. Leveling

TLM trip level determination of Booster 400 MeV beam loss

Proposed TLM trip limit

Booster beam power

180' TLM response

A thirty-eight day operating period July 14 -> August 21, 2014

Booster TLM trip level

- Assume 2400 nC/min TLM trip level
- For VL11 loss (+39.5 A):
  - 44 mrem per 2.7E17 protons
  - 0.14 nC/1E10 protons

(2400 nC/minute) *(1E10 protons/0.14 nC)* (44 mrem/2.7E17 protons)

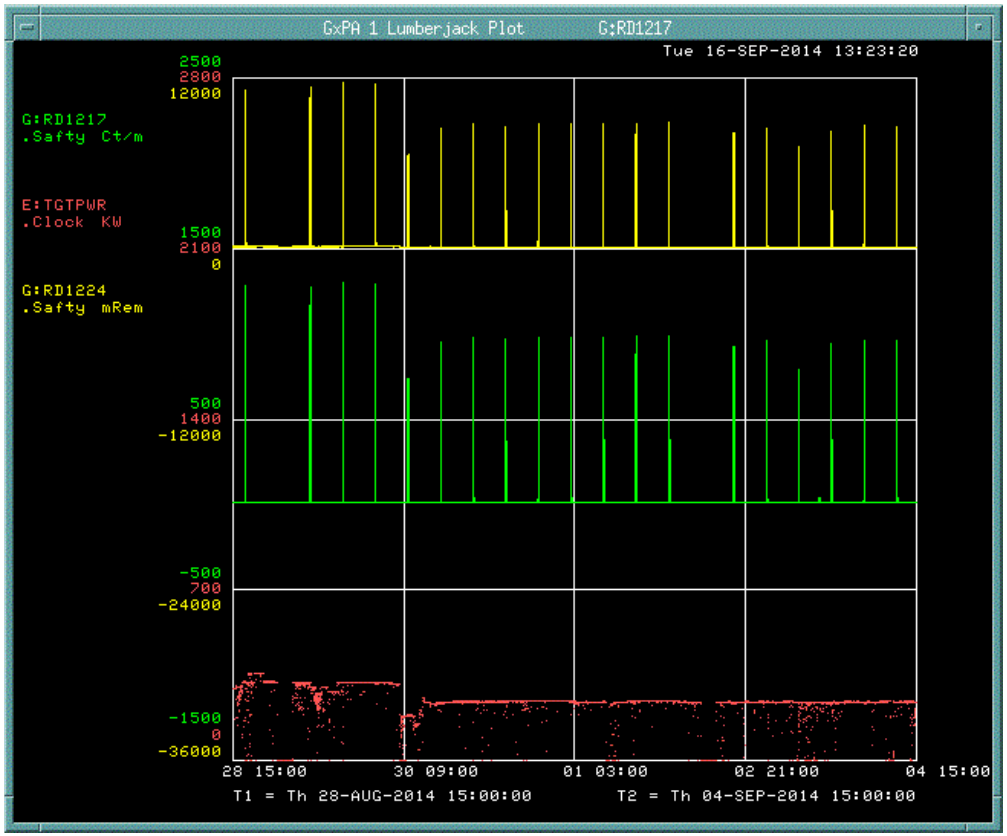
= 1.7 mrem/hr

NuMI TLM

- Four 200' detectors connected in series (covers 800'of beam line)
- Runs from MI through Pre-Target
- A scarecrow is used for groundwater protection
- TLM responses recorded for past 12 months
  - Observations:
    - Normal losses
    - The single point beam loss on 2/5/14

A. Leveling

Normal Losses



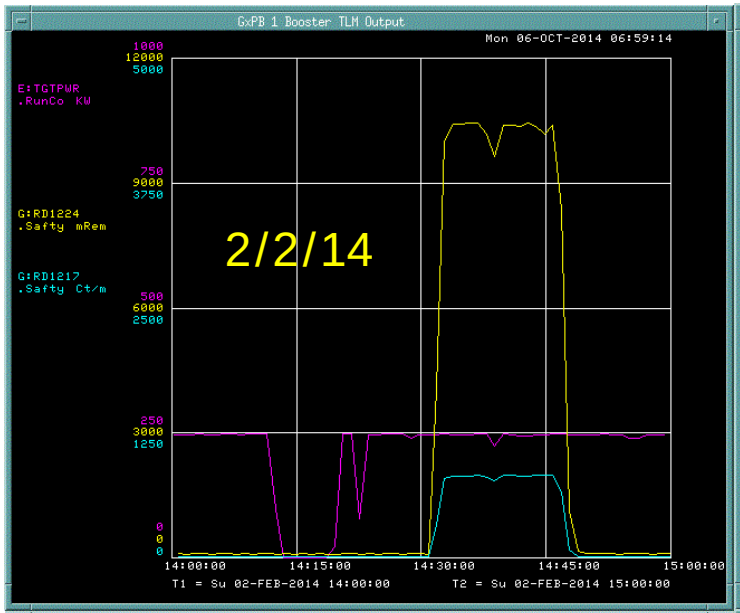
Scarecrow in NuMI tunnel (existing GW protection)

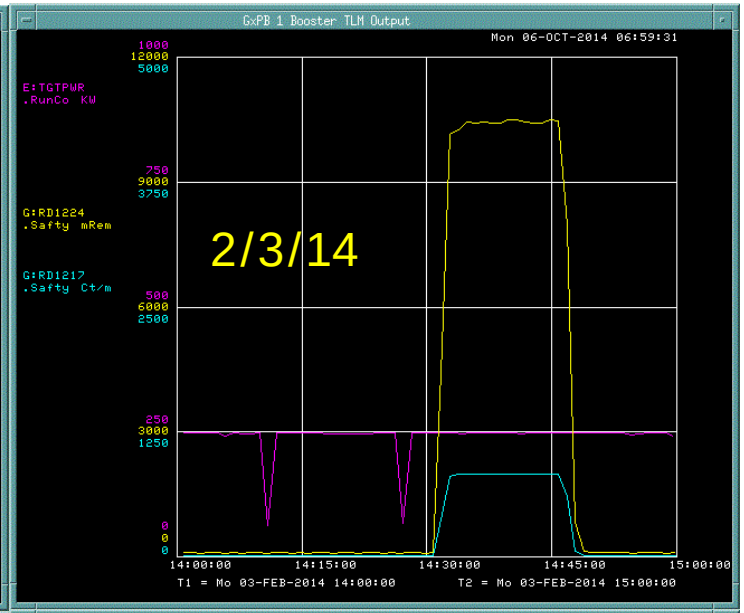
800' TLM response

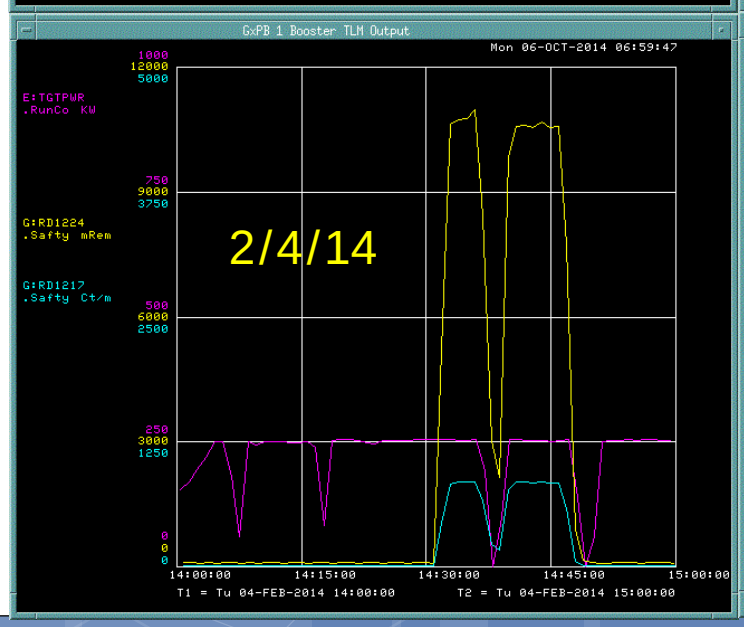
NuMI beam power

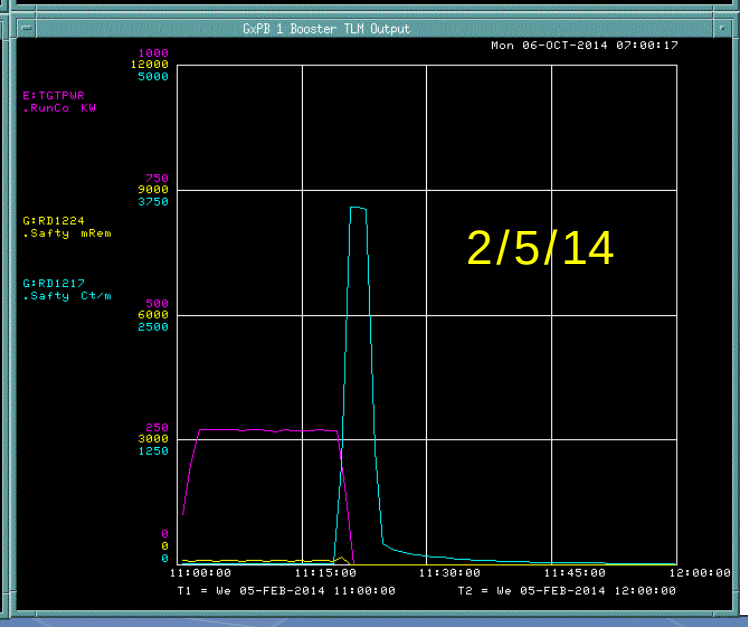
A seven day operating period August 20 -> September 4, 2014

A. Leveling


GxPB 1 Booster TLM Output
Mon 06-OCT-2014 06:59:14
E:TGTPWR
.RunCo KW
G:RD1224
.Safty mRem
G:RD1217
.Safty Ct/m
2/2/14
14:00:00
14:15:00
14:30:00
14:45:00
15:00:00
T1 = Su 02-FEB-2014 14:00:00
T2 = Su 02-FEB-2014 15:00:00


GxPB 1 Booster TLM Output
Mon 06-OCT-2014 06:59:31
E:TGTPWR
.RunCo KW
G:RD1224
.Safty mRem
G:RD1217
.Safty Ct/m
2/3/14
14:00:00
14:15:00
14:30:00
14:45:00
15:00:00
T1 = Mo 03-FEB-2014 14:00:00
T2 = Mo 03-FEB-2014 15:00:00

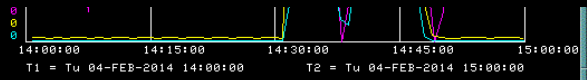

GxPB 1 Booster TLM Output
Mon 06-OCT-2014 06:59:47
E:TGTPWR
.RunCo KW
G:RD1224
.Safty mRem
G:RD1217
.Safty Ct/m
2/4/14
14:00:00
14:15:00
14:30:00
14:45:00
15:00:00
T1 = Tu 04-FEB-2014 14:00:00
T2 = Tu 04-FEB-2014 15:00:00

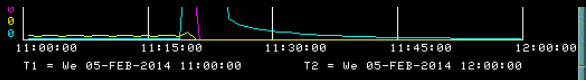

GxPB 1 Booster TLM Output
Mon 06-OCT-2014 07:00:17
E:TGTPWR
.RunCo KW
G:RD1224
.Safty mRem
G:RD1217
.Safty Ct/m
2/5/14
11:00:00
11:15:00
11:30:00
11:45:00
12:00:00
T1 = We 05-FEB-2014 11:00:00
T2 = We 05-FEB-2014 12:00:00

GxPB 1 Booster TLM Output

Format List

Time	G:RD1217
Wed Feb 5 11:15:45.903	9
Wed Feb 5 11:16:45.887	9
Wed Feb 5 11:17:45.903	8
Wed Feb 5 11:18:45.903	9
Wed Feb 5 11:19:45.903	1010
Wed Feb 5 11:20:45.903	3580
Wed Feb 5 11:21:45.887	3579
Wed Feb 5 11:22:45.887	3557
Wed Feb 5 11:23:45.887	1152
Wed Feb 5 11:24:45.887	213
Wed Feb 5 11:25:45.887	152
Wed Feb 5 11:26:45.887	133
Wed Feb 5 11:27:45.887	117
Wed Feb 5 11:28:45.887	104
Wed Feb 5 11:29:45.887	92





GxPB 1 Booster TLM Output

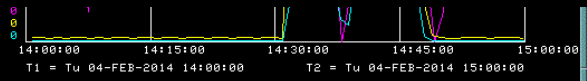
Format List

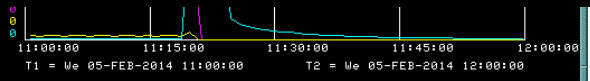
Time	G:RD1217
Wed Feb 5 11:15:45.903	9
Wed Feb 5 11:16:45.887	9
Wed Feb 5 11:17:45.903	8
Wed Feb 5 11:18:45.903	9
Wed Feb 5 11:19:45.903	1010
Wed Feb 5 11:25:45.887	152
Wed Feb 5 11:26:45.887	133
Wed Feb 5 11:27:45.887	117
Wed Feb 5 11:28:45.887	104
Wed Feb 5 11:29:45.887	92

13,100 nC *1/(120/8)^0.8*3nC/1E10 protons =5E12 protons

NuMI was running 2.4E13 protons per pulse at the time

TLM system efficiency is about 20% for this single point loss





Summary:

- Development began in May 2011
- Extensive detector response testing August 2011 to present
- Preliminary approval granted by Fermilab ESH&Q in May 2014
- Full demonstration application begins October 2014
  - Entire Booster Ring covered by 8 systems
  - In parallel with the existing system of 48 chipmunks
  - One redundant detector cable
- Accelerator Division will seek final approval of the system in CY2015

Contributors:

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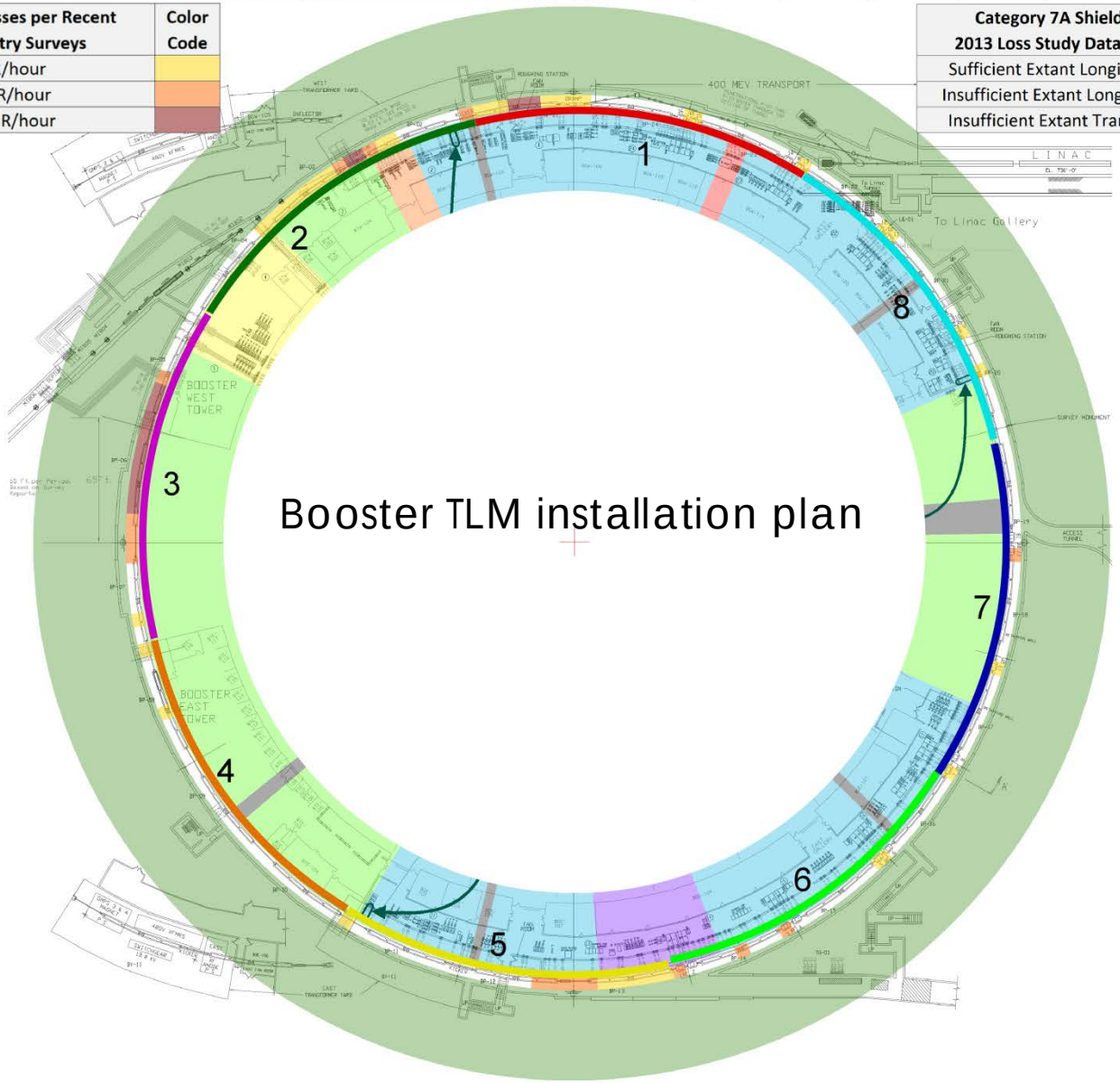
Linda Purcell-Taylor
Peter Seifrid
Pbar Department
Muon Department
ESH&Q Section
Operations Department
Instrumentation Department

Extra slides

Penetration Type	Color Code	Total Number of Each Type	Description of Penetration	R (ft)	d (ft)	400MeV Exit Dose Rate (mrem/pulse)	8GeV Exit Dose Rate (mrem/pulse)	Notes on Exit Dose Rates
1		151	19' long single-leg 6.5" by 6.5" penetration	3.30	1.38	3.17E-03	3.48E-02	*with 12' of poly beads (MARS attenuation for single pen. used)*
2		4	16.6' long single-leg 6.5" by 6.5" penetration in ceiling of Period 23	4.60	1.33	1.84E-03	2.02E-02	*with 12' of poly beads (MARS attenuation for single pen. used)*
3		8	Four-leg, 6" diameter circular penetration in Period 2	3.30	1.38	4.42E-12	4.85E-11	*for an empty penetration*
4		17	16.25' long single-leg 6.5" by 6.5" penetration high on wall of Period 13	2.50	6.27	3.58E-04	3.93E-03	*with 12' of poly beads (MARS attenuation for single pen. used)*
5		12	Three-leg, 5" diameter circular penetrations from Periods 4 & 5 to West Booster Tower	3.30	1.38	4.15E-14	4.55E-13	*for an empty penetration*
None		N/A	No penetrations in this region	N/A	N/A	N/A	N/A	*N/A*
Labyrinth		N/A	Some kind of labyrinth	N/A	N/A	N/A	N/A	*labyrinth calculations are not included here*

Regions of Booster Losses per Recent AD ES&H Initial Entry Surveys	Color Code
Losses ≥ 5 mR/hour	
Losses ≥ 20 mR/hour	
Losses ≥ 100 mR/hour	

Category 7A Shielding Based on 2013 Loss Study Data Scaled to 8GeV	Color Code
Sufficient Extant Longitudinal Shielding	
Insufficient Extant Longitudinal Shielding	
Insufficient Extant Transverse Shielding	

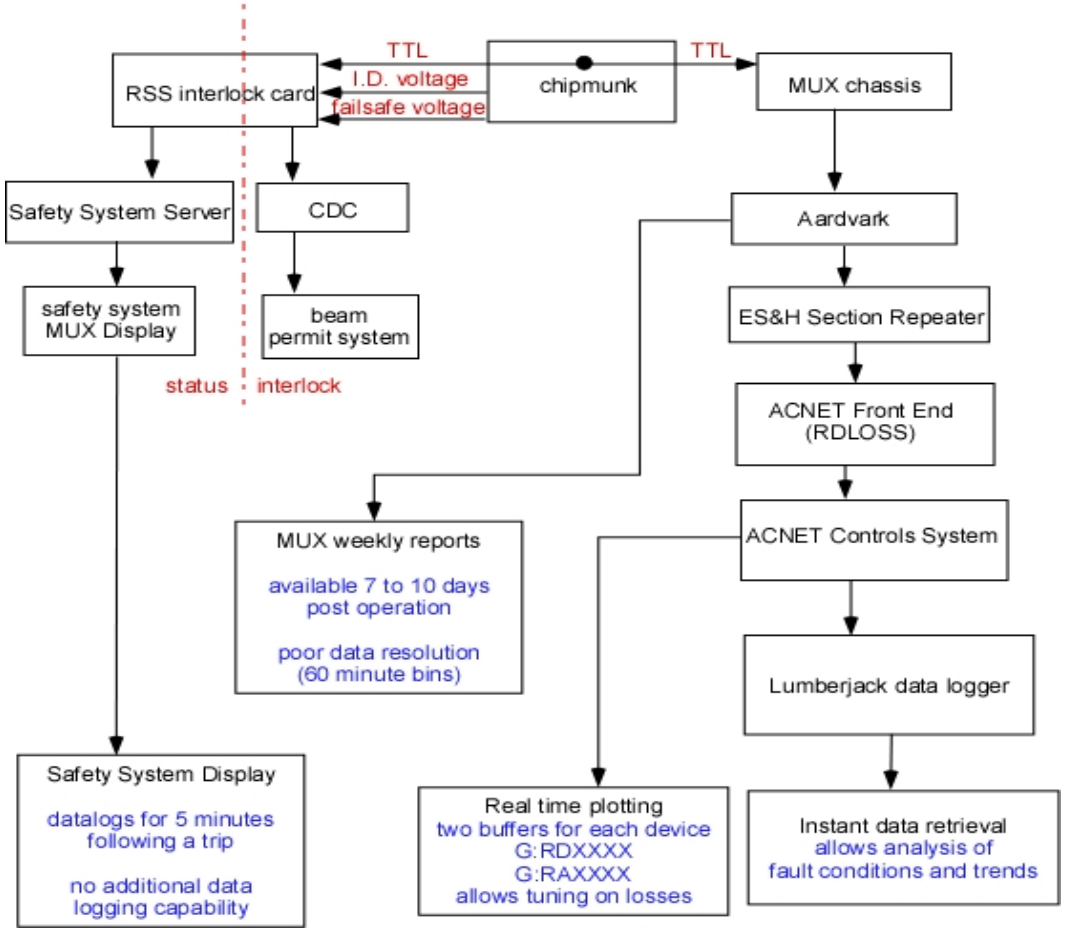


Booster Color Wheel
M. VINCENT
1 AUGUST, 2014

Detector Cable

- **HJ5-50, HELIAX® Standard Air Dielectric Coaxial Cable, corrugated copper, 7/8 in,**
- **black PE jacket**
- **About $8.50/foot**

Interrelationship and Features of Chipmunk Electrometer, RSS, MUX, ACNET, and Lumberjack systems



A. Leveling