NuMI Primary Beam Monitoring

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This discussion is from the point of view of a 'User' – Looking at the data that is logged on the ACS (Accelerator Control System) data loggers (Lumberjack) Coauthors brought these systems into existence and kept them working so very well !

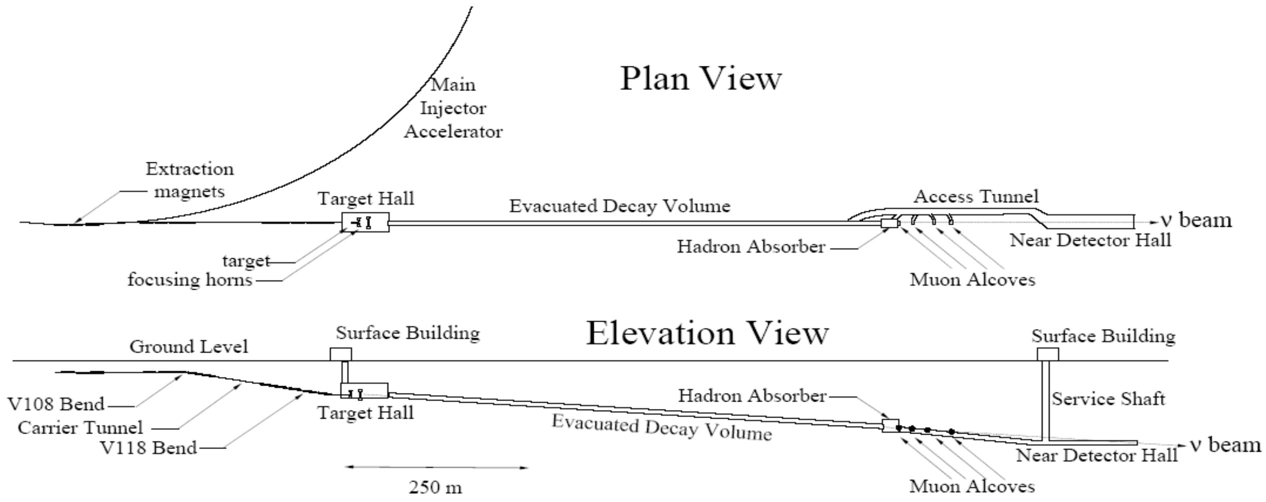
Overview

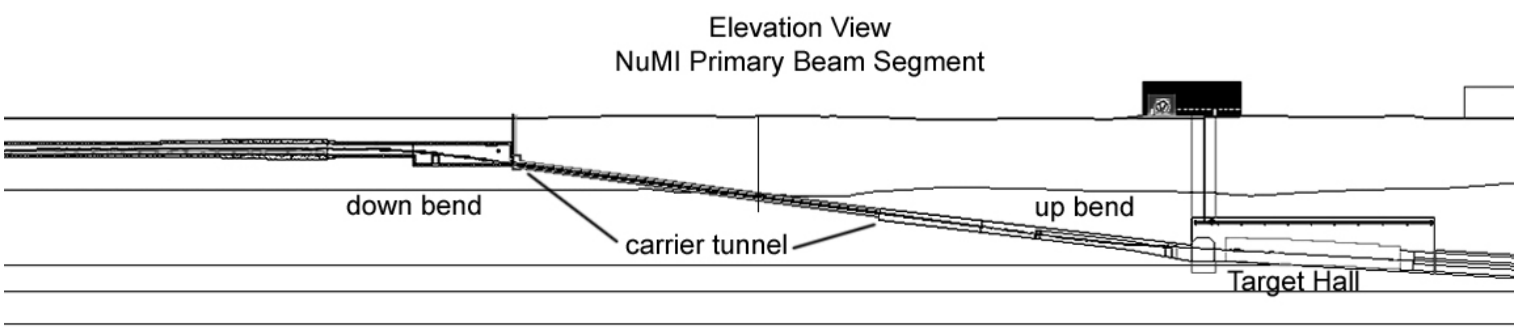
- NvMI – Neutrinos at the Fermilab Main Injector
- 120 GeV Primary beam extracted from the MI and transmitted to the neutrino target - ~40E12 protons/2.2 sec, ~350kw
- Long beam line – require very low (<10^{-5}) beam losses

  Pass through ground water table, Prevent Activation
- Monitor: **how much beam? Where is it?**
- Monitoring the beam over the first 5 years
- Beam line has become a 'test beam' for future high intensity beams – e.g. NOvA and beyond.

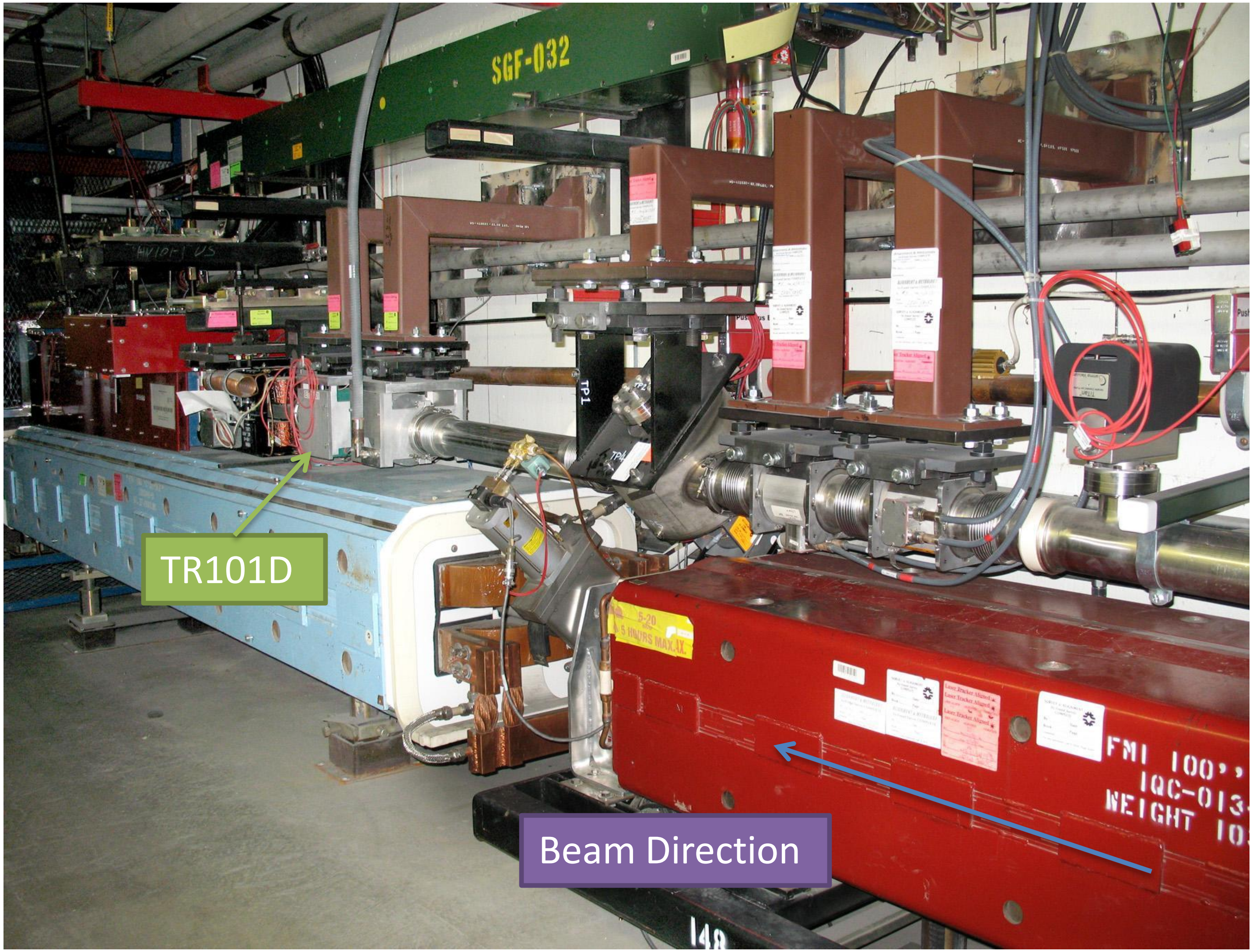
NuMI Beam Line

~370 m, 20 bend, 21 quad, trims

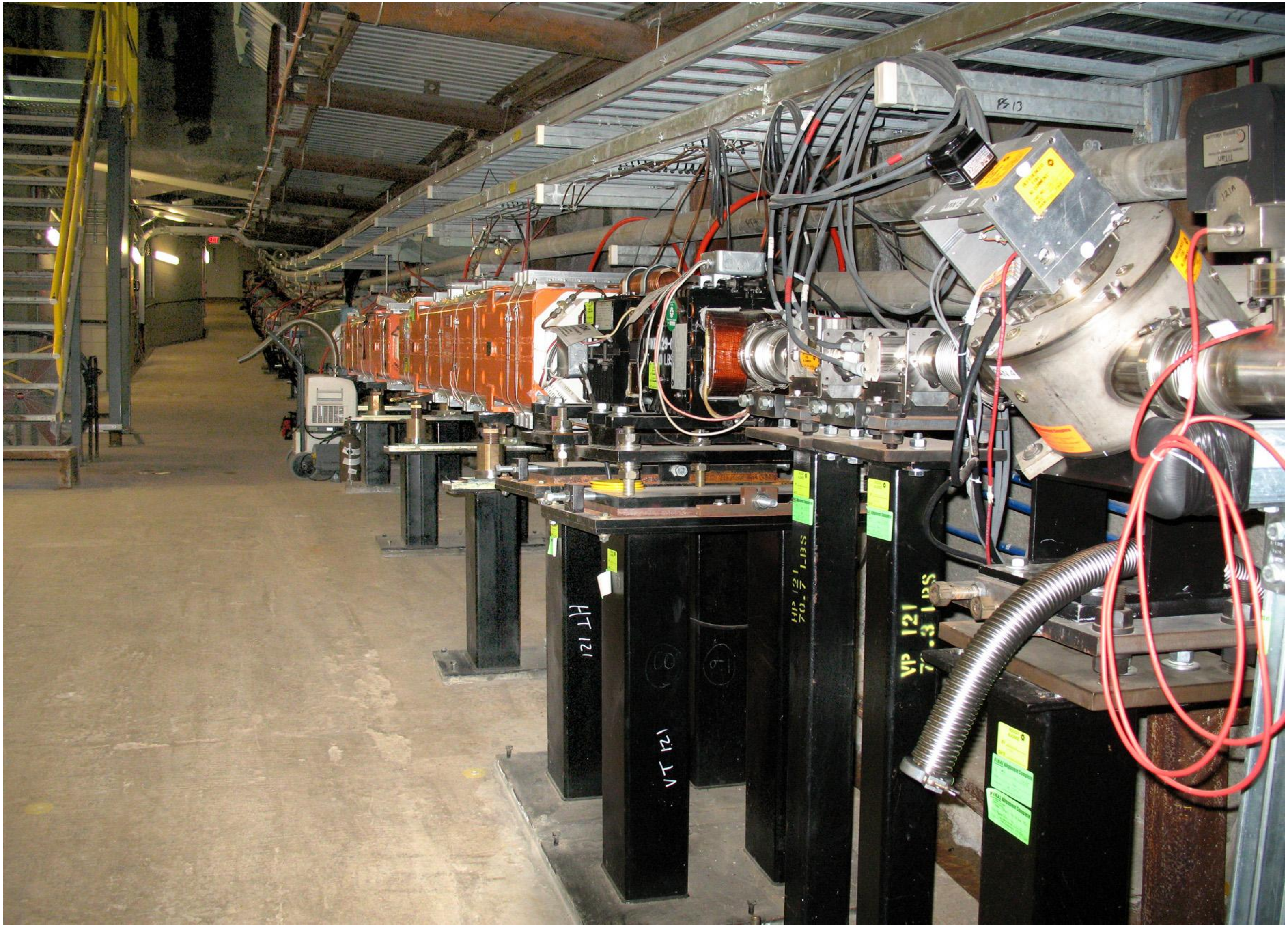




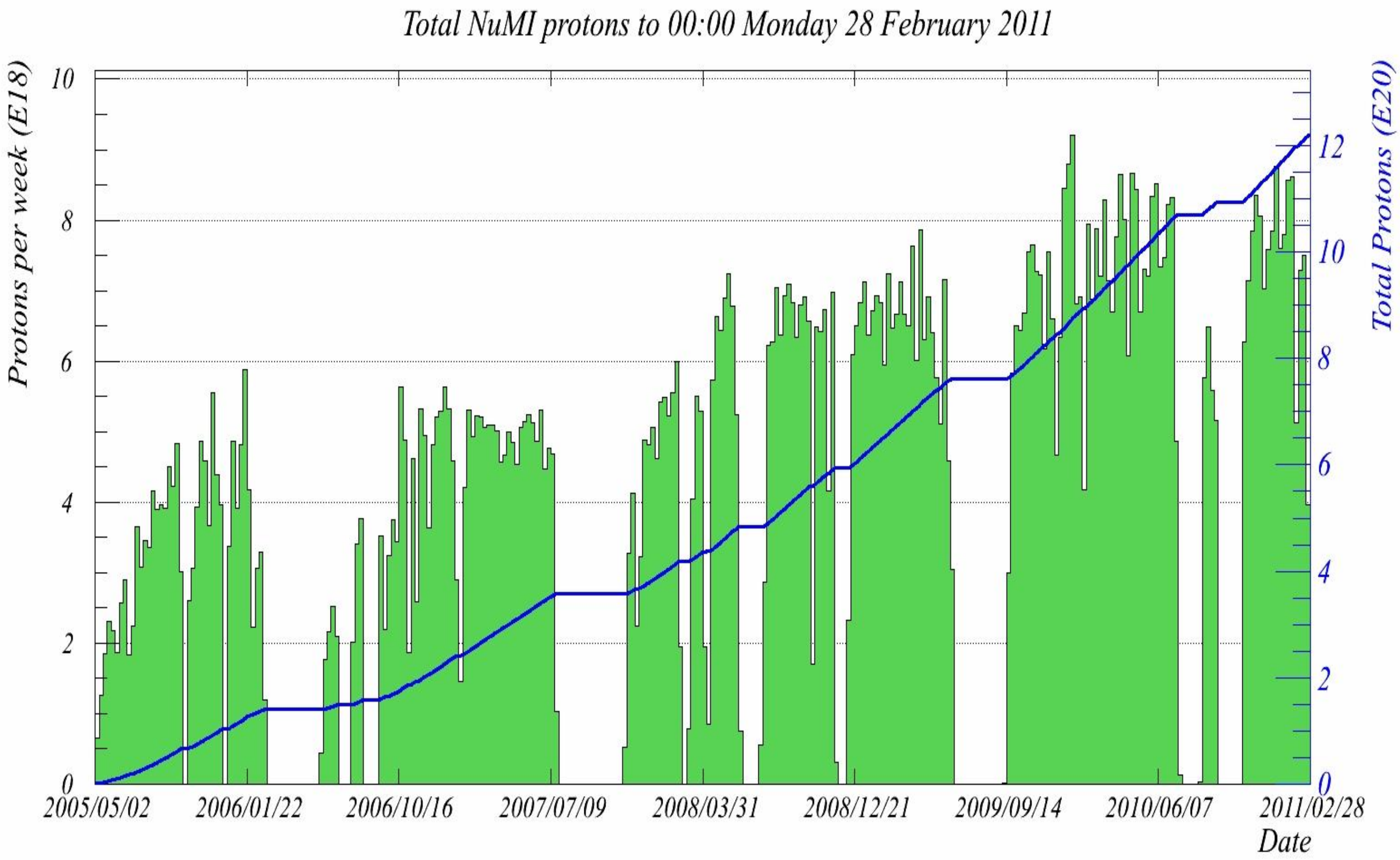
Shortly after extraction



Downstream end of the beam transport



Just upstream of target


Total NuMI protons to 00:00 Monday 28 February 2011
Protons per week (E18)
Total Protons (E20)
0
2
4
6
8
10
12
2005/05/02
2006/01/22
2006/10/16
2007/07/09
2008/03/31
2008/12/21
2009/09/14
2010/06/07
2011/02/28
Date

Intensity Monitoring

- MI beam – DCCT (Direct Coupled Current Transformer)
- NuMI Beam line intensity – 2 toroids TR101D – just after extraction, TRTGTD – just upstream of the target. TRTGTD –primary beam intensity monitoring for the Minos Experiment
- Absolute calibration – send a measured current through the device. All instruments regularly calibrated so calibration better than 1%
- Monitor toroid and dcct ratios monitor the calibration

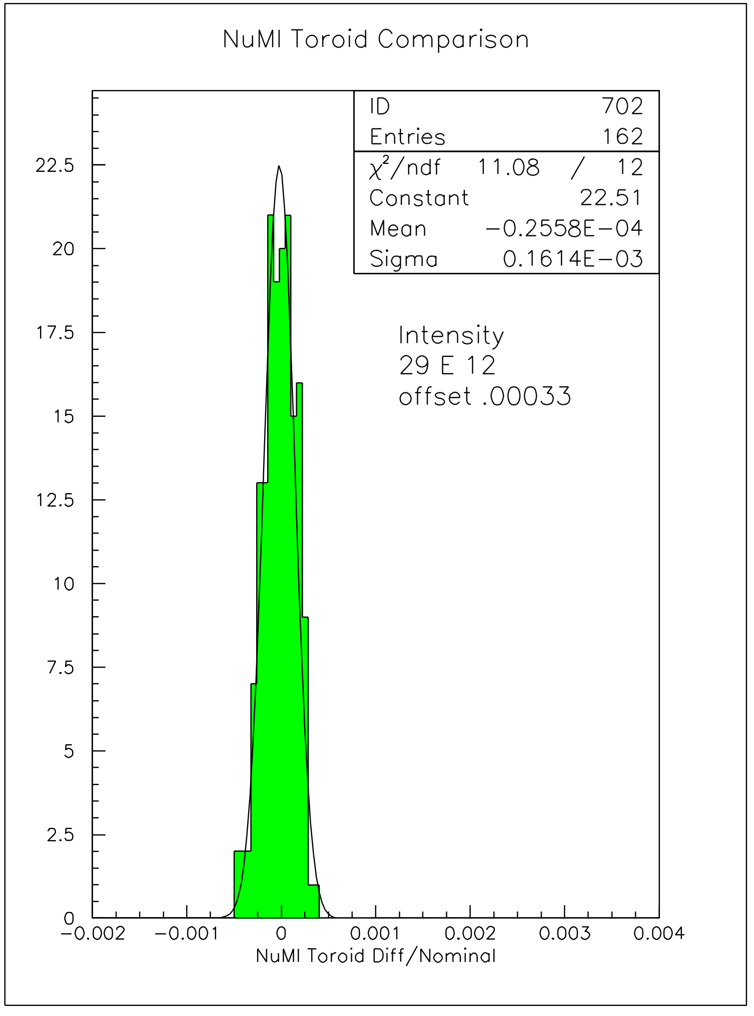
Internal Calibration and Stability Monitoring

- ‘Extraction Eff’ = tr101d/dcct
  - When ‘NuMI Only’ (Actual extraction effeciency is very high – Loss Monitors see very little beam loss)
- ‘Transport Eff.’ = trtgtd/tr101d

  - Always available, nominally = 1, as very little beam loss – again extensive loss monitoring shows essentially no losses during transport.

NuMI Toroid Ratio

short sample

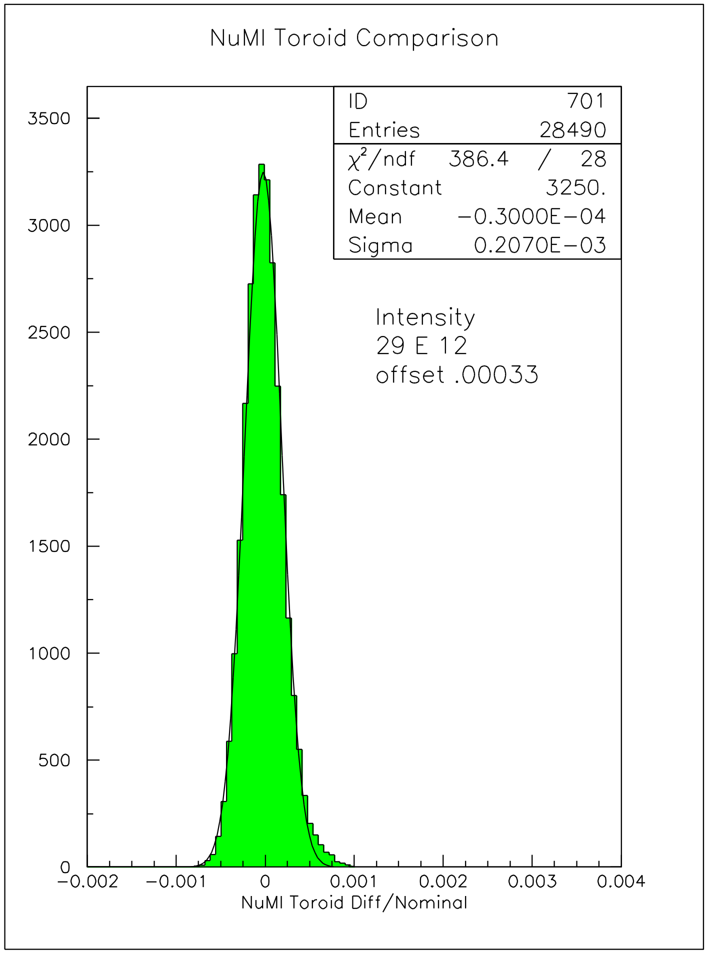


- Measured $\sigma = a/I$
- $\sigma = a / \sqrt{2}$
- Gain = $10V/5.0x10^{13}$
- σ_v = .66 mv (const)

- $\sigma_T = .0033 / I$ where I is in units of 10^{12}

NuMI Toroid Compare

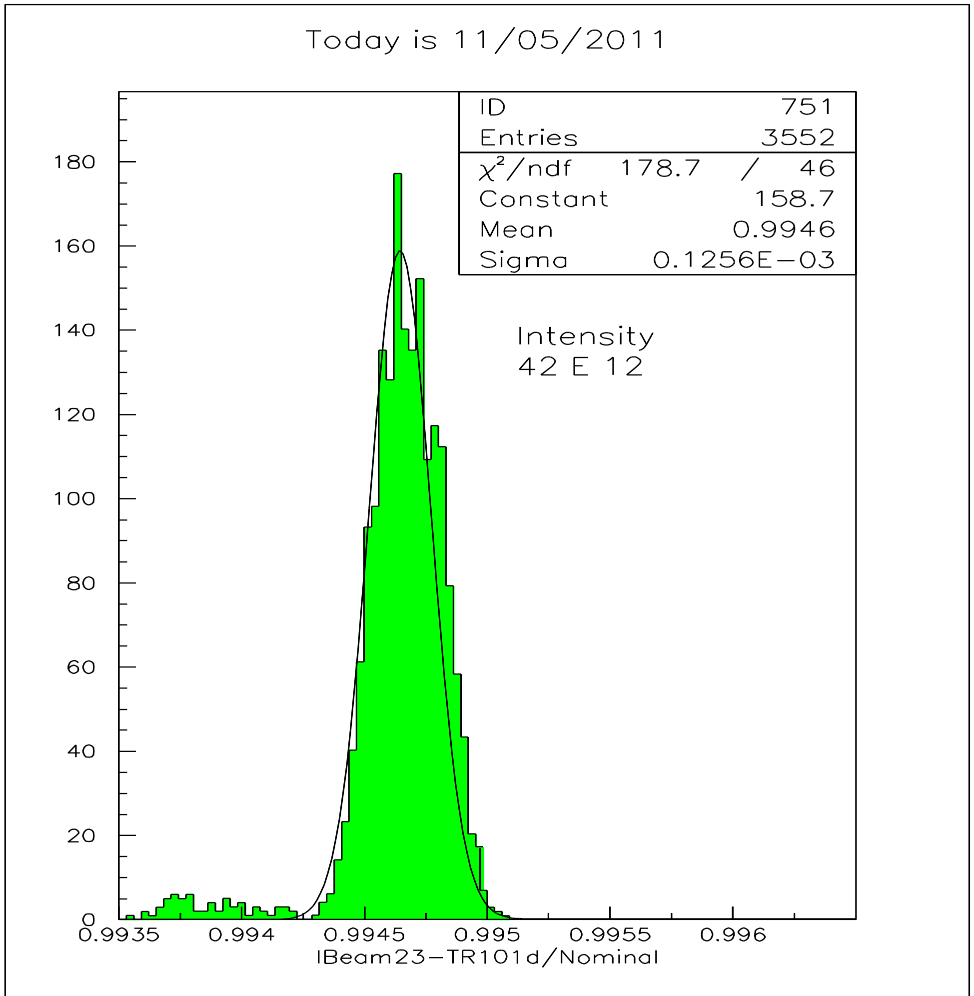
1 day sample



For the 1 day sample, the $\sigma = 2.1 \times 10^{-4}$, added noise and small temperature drifts, particularly in tr101d (trtgtd and electronics is underground)

MI DCCT – NuMI Toroid Compare

short sample (NuMI only running)



For this sample:

subtract single toroid resolution :

DCCT $\sigma = 0.9 \times 10^{-4}$ at an intensity of 42×10^{12}

comparable to the Toroid

Proton Beam Intensity Monitoring Results

- The ratios of the intensity measurements have been monitored since the beginning of the experiment, and have remained stable.

	101D/DCCT	TGTD/101D
• Feb 12, 2008	.996	.998
• Dec 5, 2009	.997	.995
• Sep 20, 2009	.993	.997
• Nov 9, 2010	.992	.998
• Apr 11, 2011	.992	.999

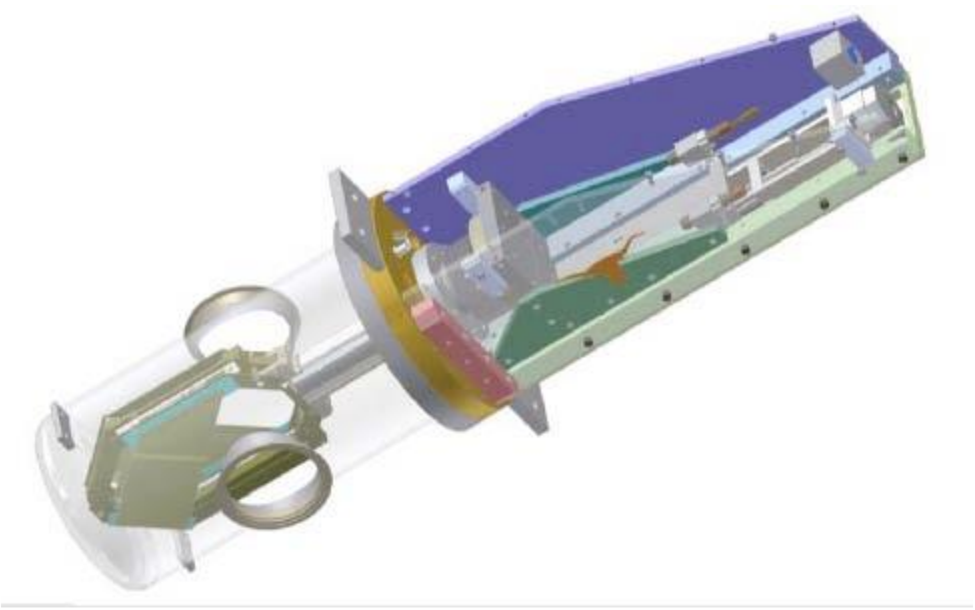
- **Systematic errors are less than 1%**

- **Measurements stable to ~ 0.5%**

Multiwire SEMs

- Secondary Emission Monitor Wire Chambers placed in the primary beam, some always in, some in/out.
- Monitor beam size, position.
- Target SEM Always Monitored, on shift and off-line.
- Compare with position as determined using BPMs
- A SEM consists of two wire planes, where the wires are 2 x 25 micron Ti foils (target), 1 mill Ti wires (101), 33 micron C filaments (118).
- Three SEMs are always in the beam. Several more are put into the beam for 15 min/day. (not discussed here)
- **Study the gain of the SEMs as a function of beam exposure**

SEMs

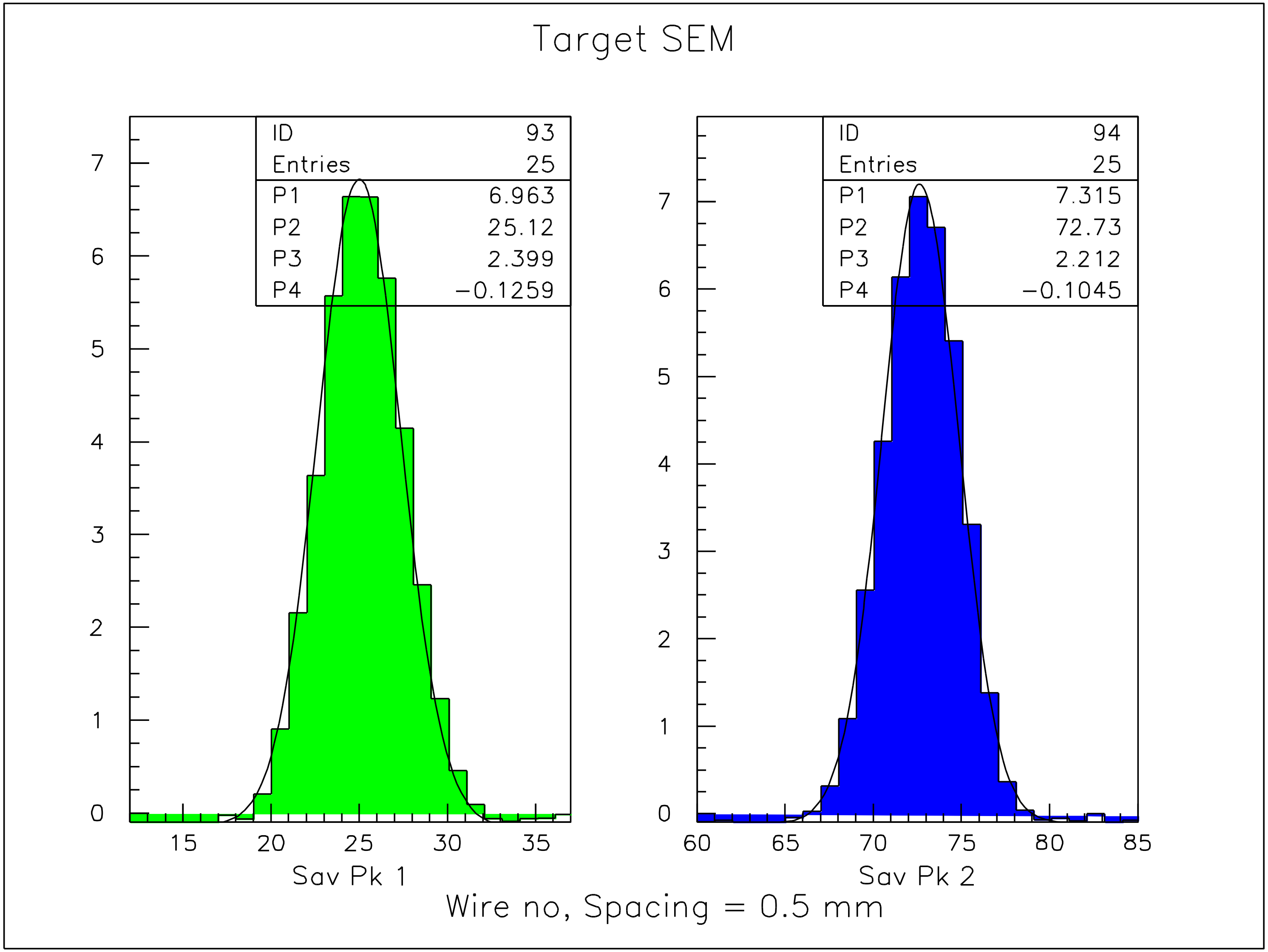


SEM data

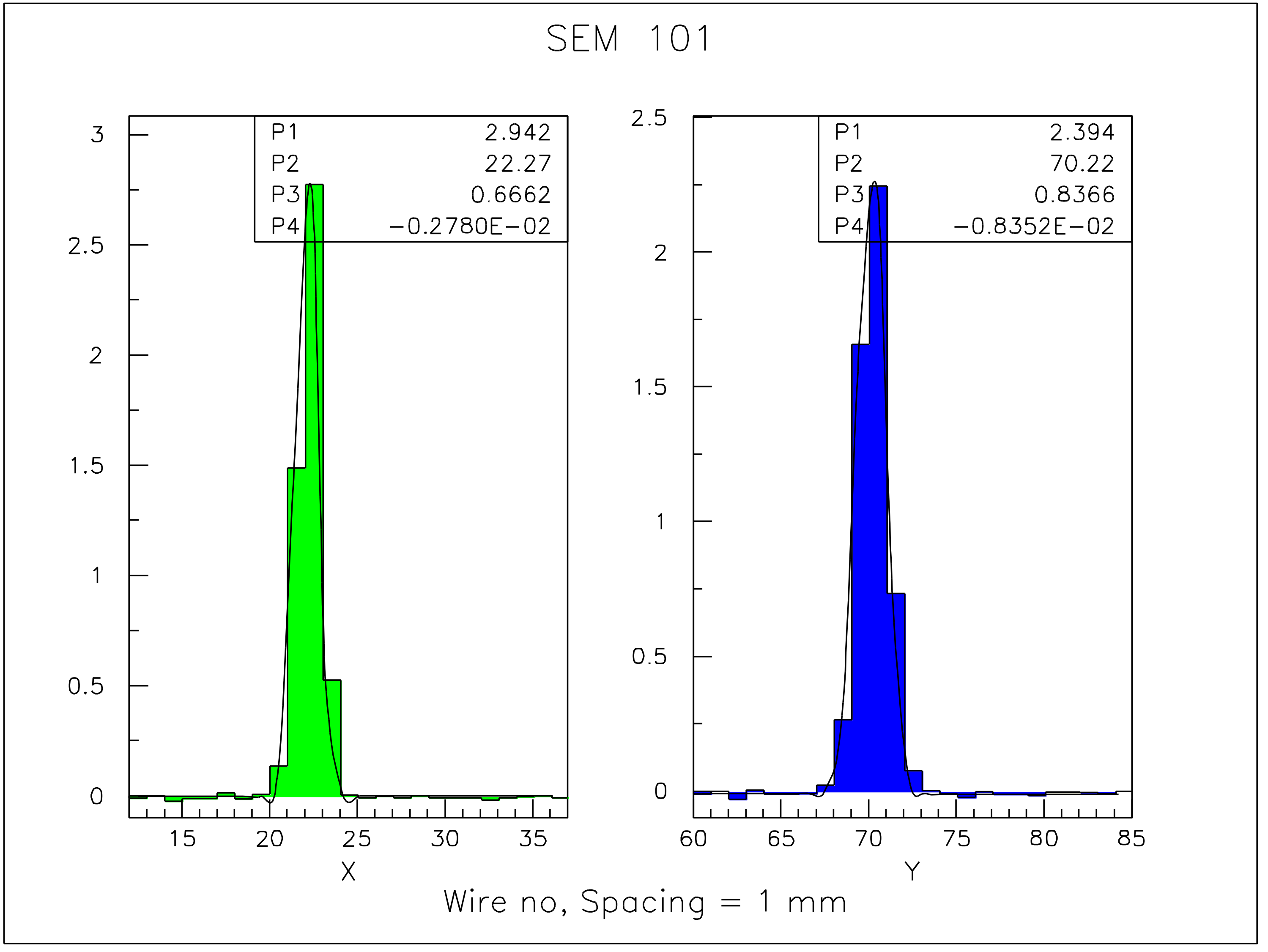
- Data downloaded, time-stamp checked, beam profiles built and fit to a Gaussian plus a flat background to determine beam position, size, signal height, and Gain = Area of the gaussian divided by trtgtd.

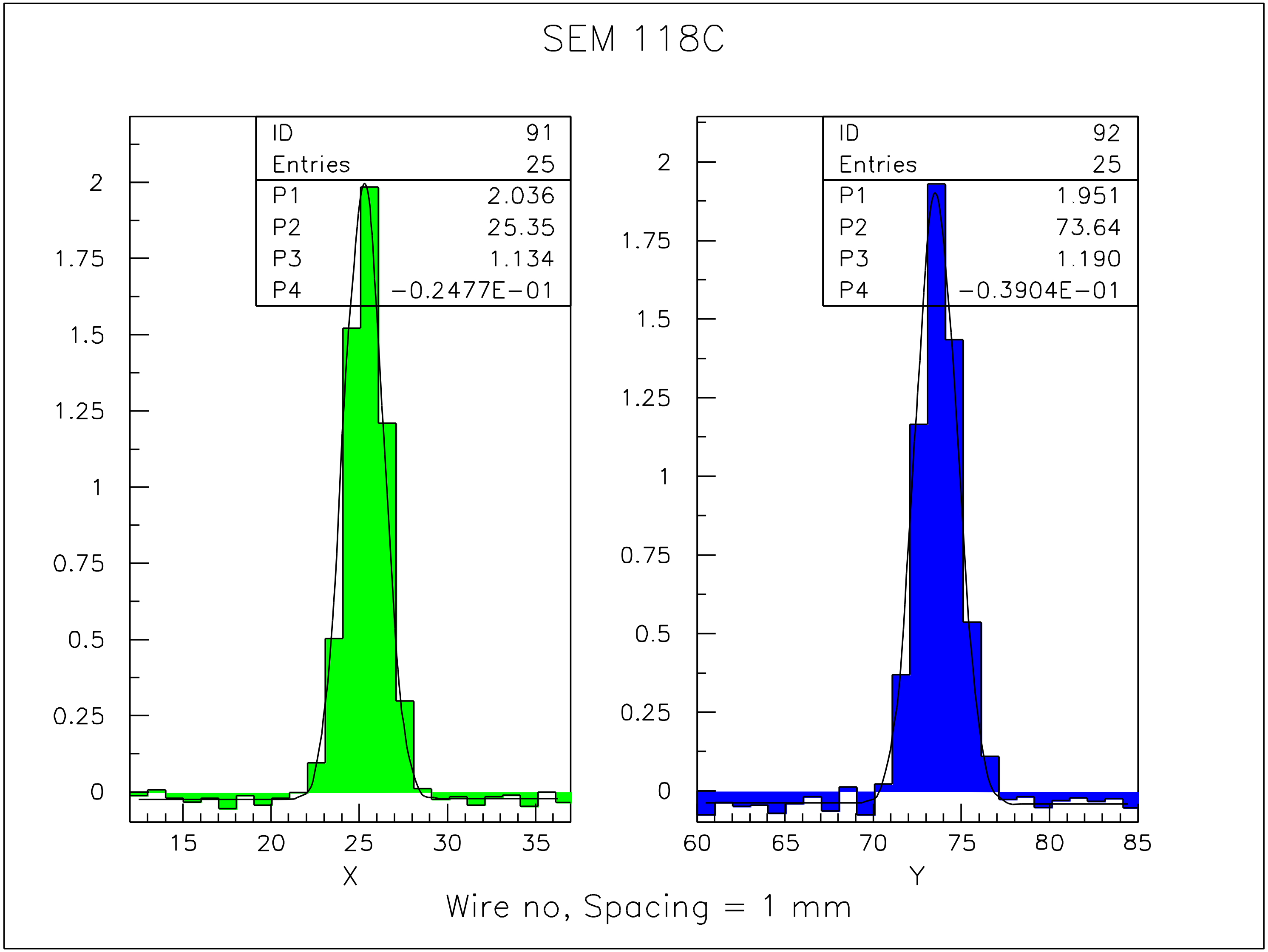
- Data from each wire is integrated over the beam spill, digitized and saved through a DAQ – Fermilab Lumberjack Data Loggers.

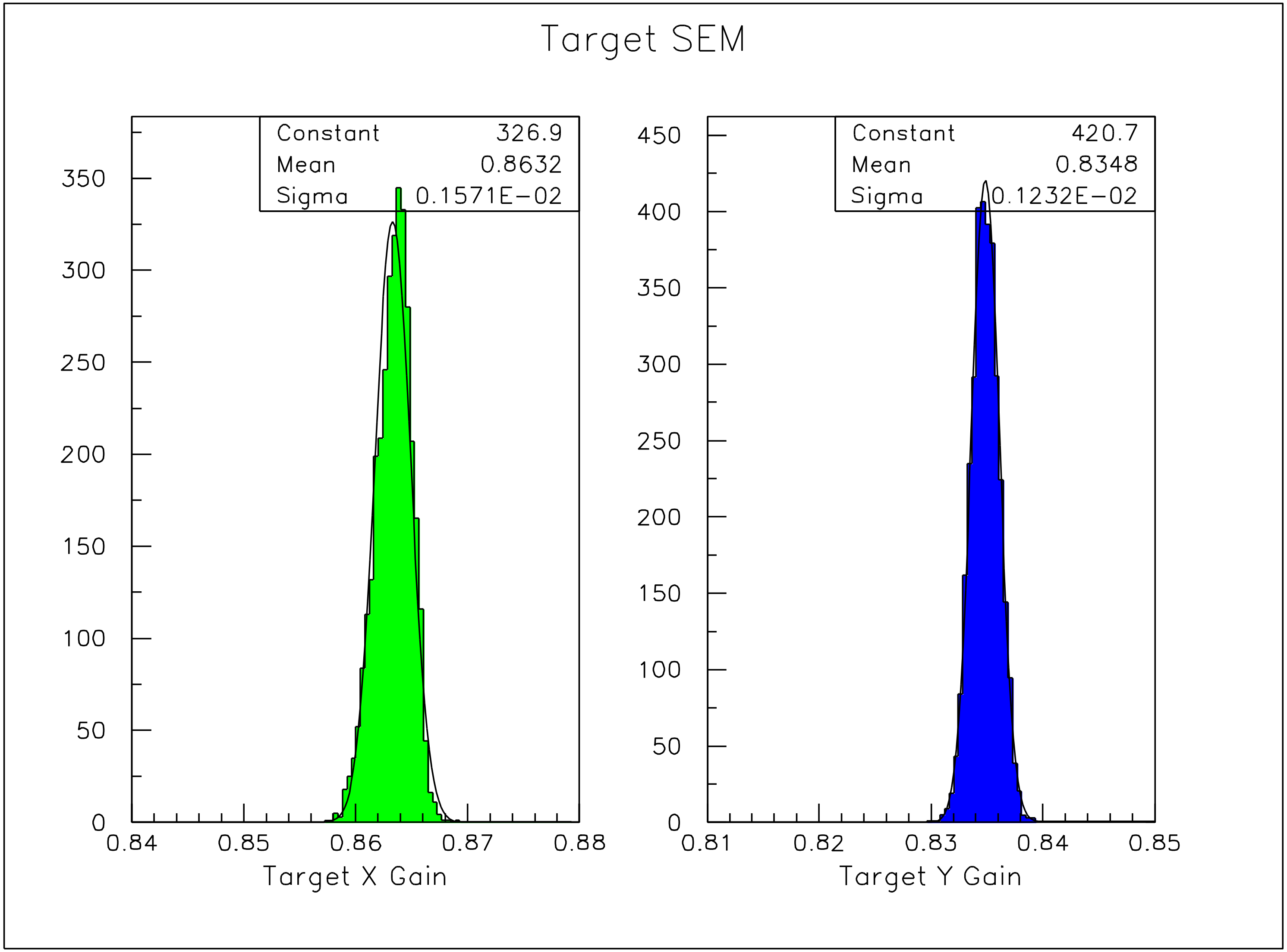
- Data as displayed = -10 * voltage on 10^4 pf

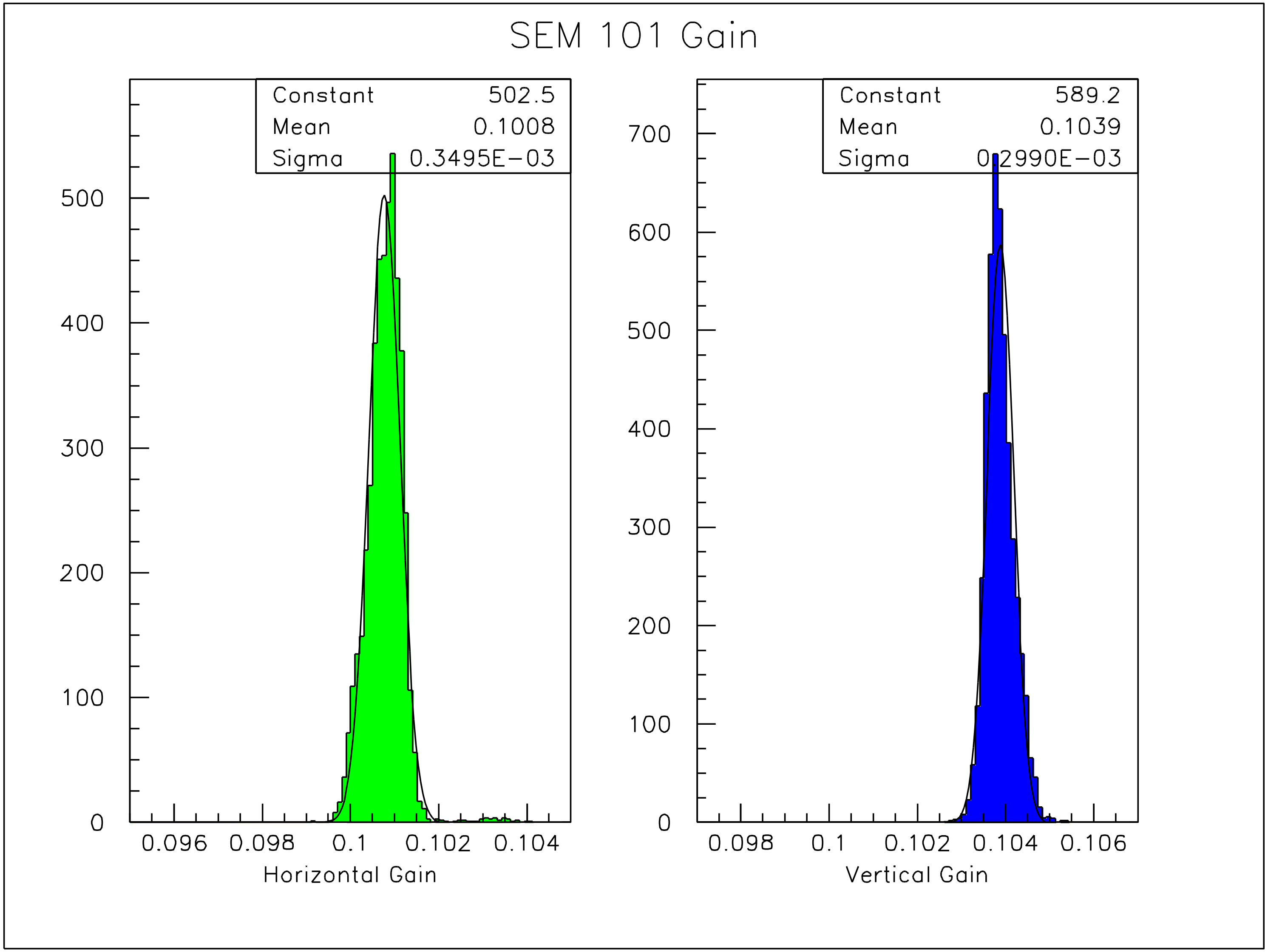


Target SEM
ID 93
Entries 25
P1 6.963
P2 25.12
P3 2.399
P4 −0.1259
0 1 2 3 4 5 6 7
15 20 25 30 35
Sav Pk 1
ID 94
Entries 25
P1 7.315
P2 72.73
P3 2.212
P4 −0.1045
0 1 2 3 4 5 6 7
60 65 70 75 80 85
Sav Pk 2
Wire no, Spacing = 0.5 mm

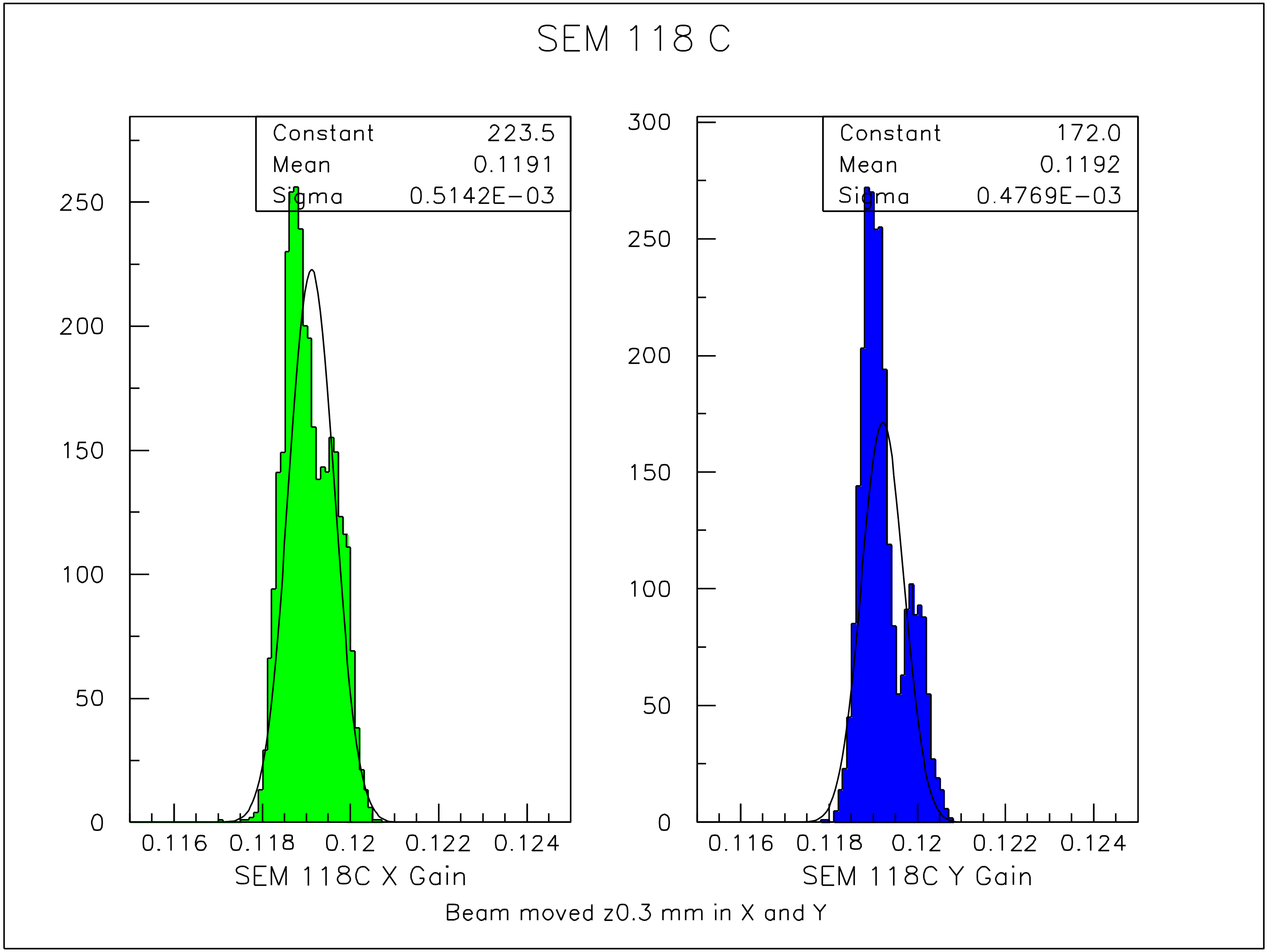

SEM 101
P1 2.942
P2 22.27
P3 0.6662
P4 −0.2780E−02
P1 2.394
P2 70.22
P3 0.8366
P4 −0.8352E−02
X
Y
Wire no, Spacing = 1 mm


SEM 118C
ID 91
Entries 25
P1 2.036
P2 25.35
P3 1.134
P4 −0.2477E−01
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
15 20 25 30 35
X
ID 92
Entries 25
P1 1.951
P2 73.64
P3 1.190
P4 −0.3904E−01
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
60 65 70 75 80 85
Y
Wire no, Spacing = 1 mm

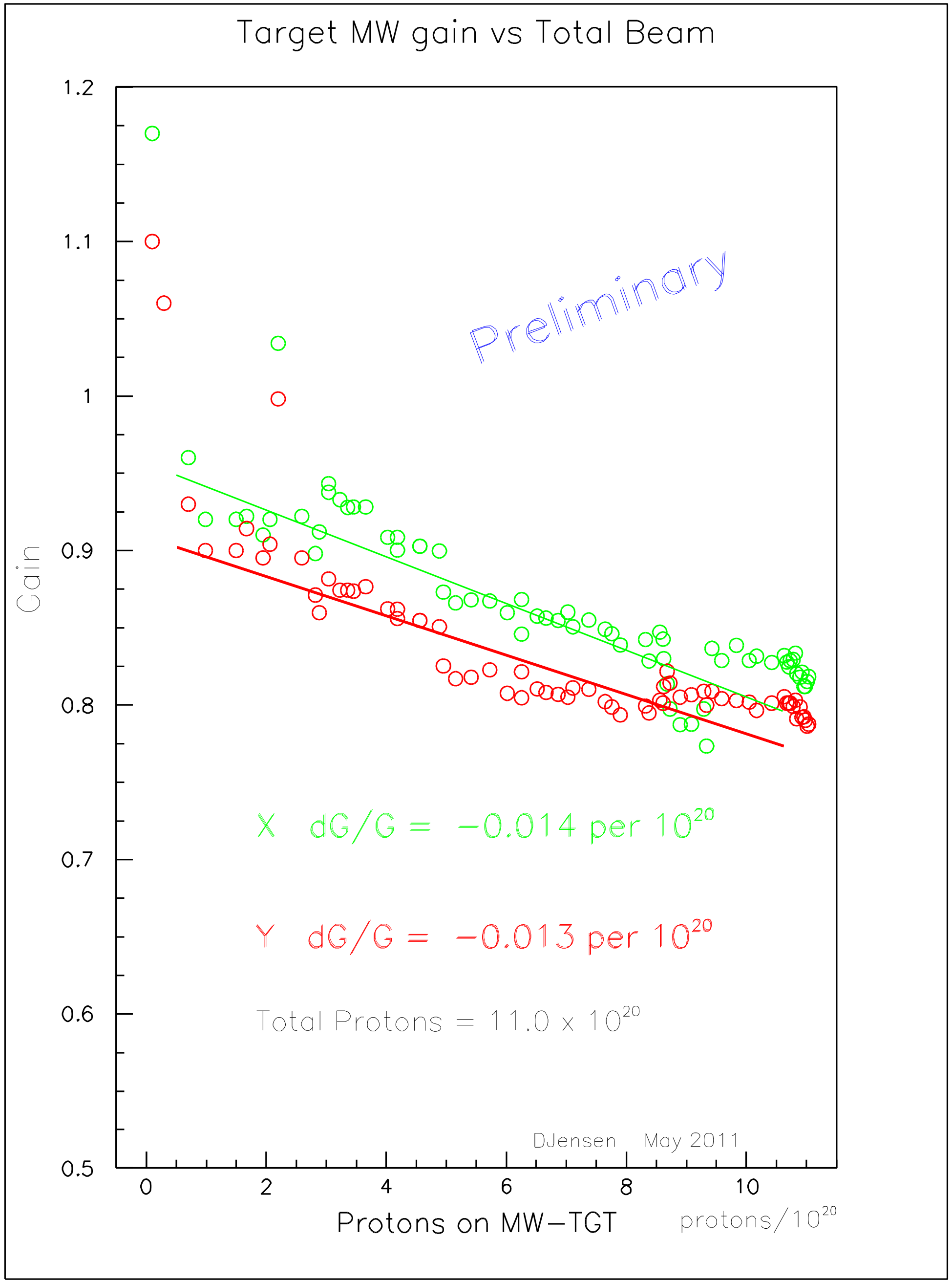

Target SEM
Constant 326.9
Mean 0.8632
Sigma 0.1571E−02
0
50
100
150
200
250
300
350
0.84
0.85
0.86
0.87
0.88
Target X Gain
Constant 420.7
Mean 0.8348
Sigma 0.1232E−02
0
50
100
150
200
250
300
350
400
450
0.81
0.82
0.83
0.84
0.85
Target Y Gain



SEM 101 Gain
Constant 502.5
Mean 0.1008
Sigma 0.3495E-03
500
400
300
200
100
0
0.096 0.098 0.1 0.102 0.104
Horizontal Gain
Constant 589.2
Mean 0.1039
Sigma 0.2990E-03
700
600
500
400
300
200
100
0
0.098 0.1 0.102 0.104 0.106
Vertical Gain

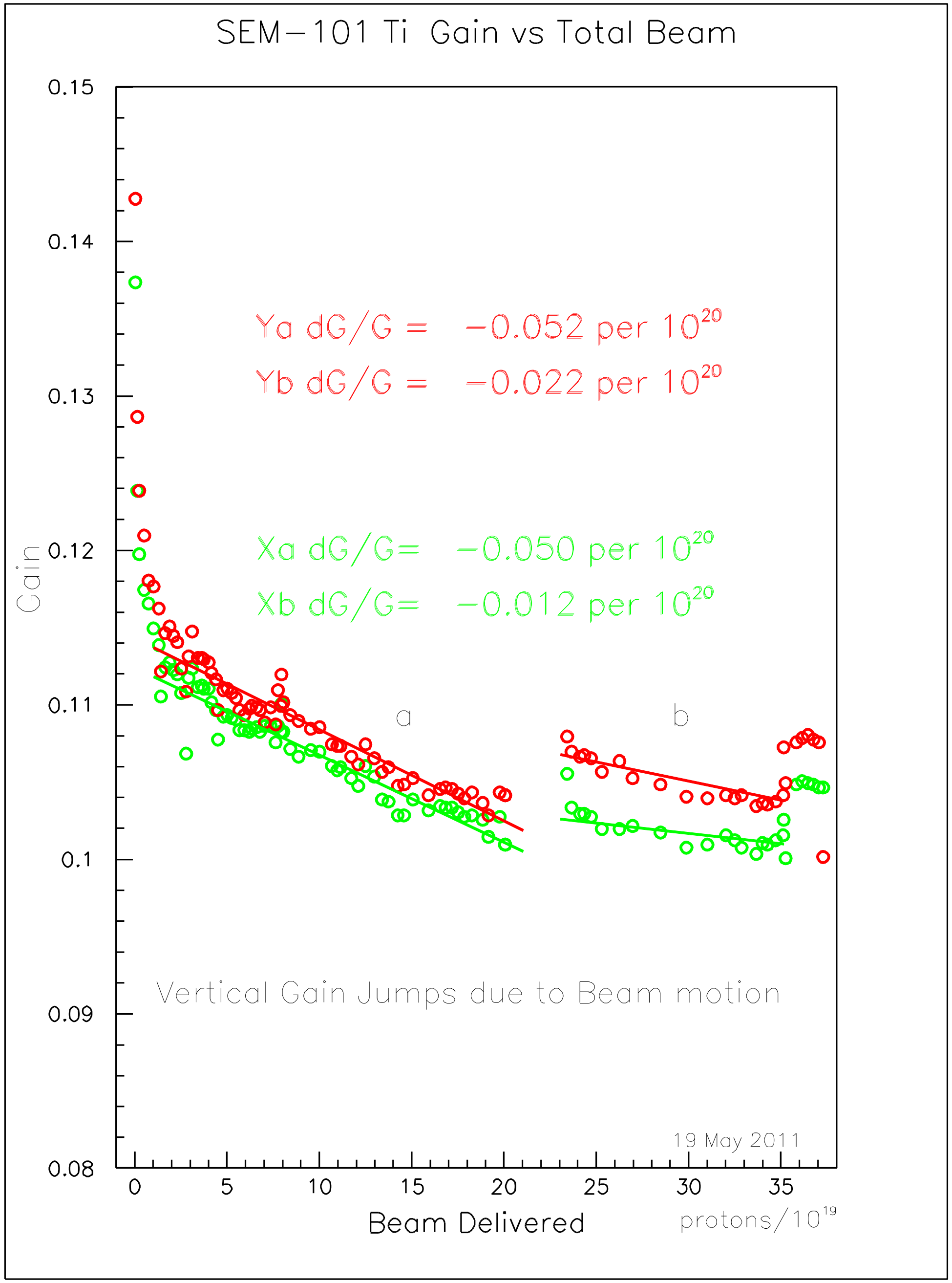


SEM 118 C
Constant 223.5
Mean 0.1191
Sigma 0.5142E−03
0
50
100
150
200
250
0.116
0.118
0.12
0.122
0.124
SEM 118C X Gain
Constant 172.0
Mean 0.1192
Sigma 0.4769E−03
0
50
100
150
200
250
300
0.116
0.118
0.12
0.122
0.124
SEM 118C Y Gain
Beam moved z0.3 mm in X and Y



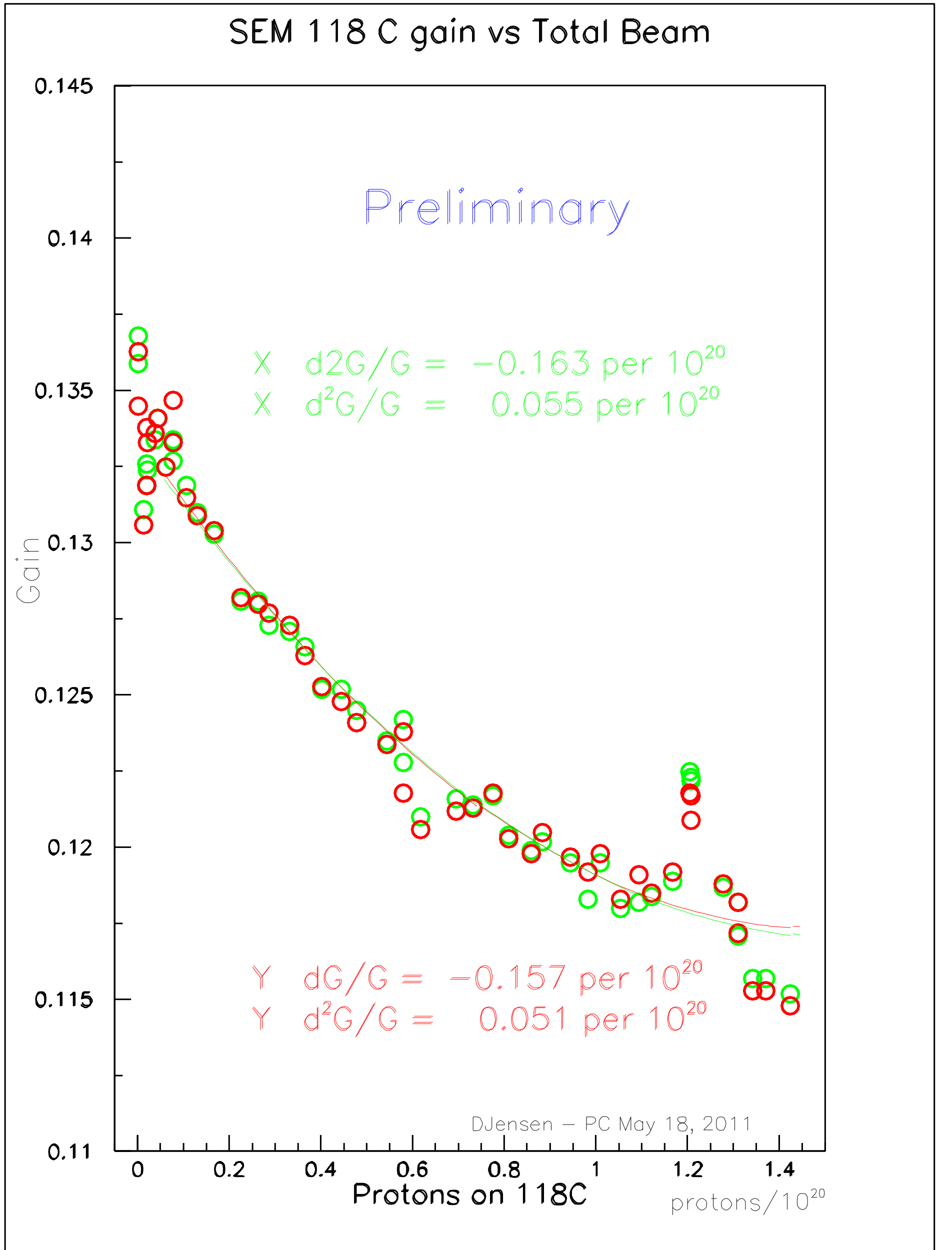
- Data Start – June 6, 2006
- Data End – May 16, 2011
- Shutdowns etc not reflected in the plot

- Total exposure **~12 x 10^{20}**



- Start Date – Dec 30, 2009
- End Date - May 16, 2011
- Gain jumps due to vertical beam motion.

- Total Exposure ~ **3.8×10^{20}**



Start Date – Nov 1, 2010

End Date – May 16, 2011

Total Exposure ~ **1.4×10^{20}**

Carbon Filament 33 micron

Fit to quadratic.

Note lack of initial dramatic gain decrease.

To test the mechanical robustness – cycled in and out of the beam (it was off) 125,000 cycles !

No problems

Looking like C filaments are acceptable. Time will tell.

SEM Aging Summary

- As the beam size is different at different SEMs, correct aging for relative intensity. Normalize to a 1 mm beam in x, y

Device	Wire Diameter (inches)	Beam Size σ_x x σ_y (mm)	Observed dG/G	**Normalized dG/G** x10^{-3} / 10^{19} p
mw101	.001	0.68 x 0.86	5.	**2.9**
mw118C	.00132	1.08 x 1.18	11.	**14.**
mwtgt	25µ	1.8 x 1.1	1.8	**3.6**

(note – dG/G for mw118C is based on a linear fit, not the quadratic shown above)

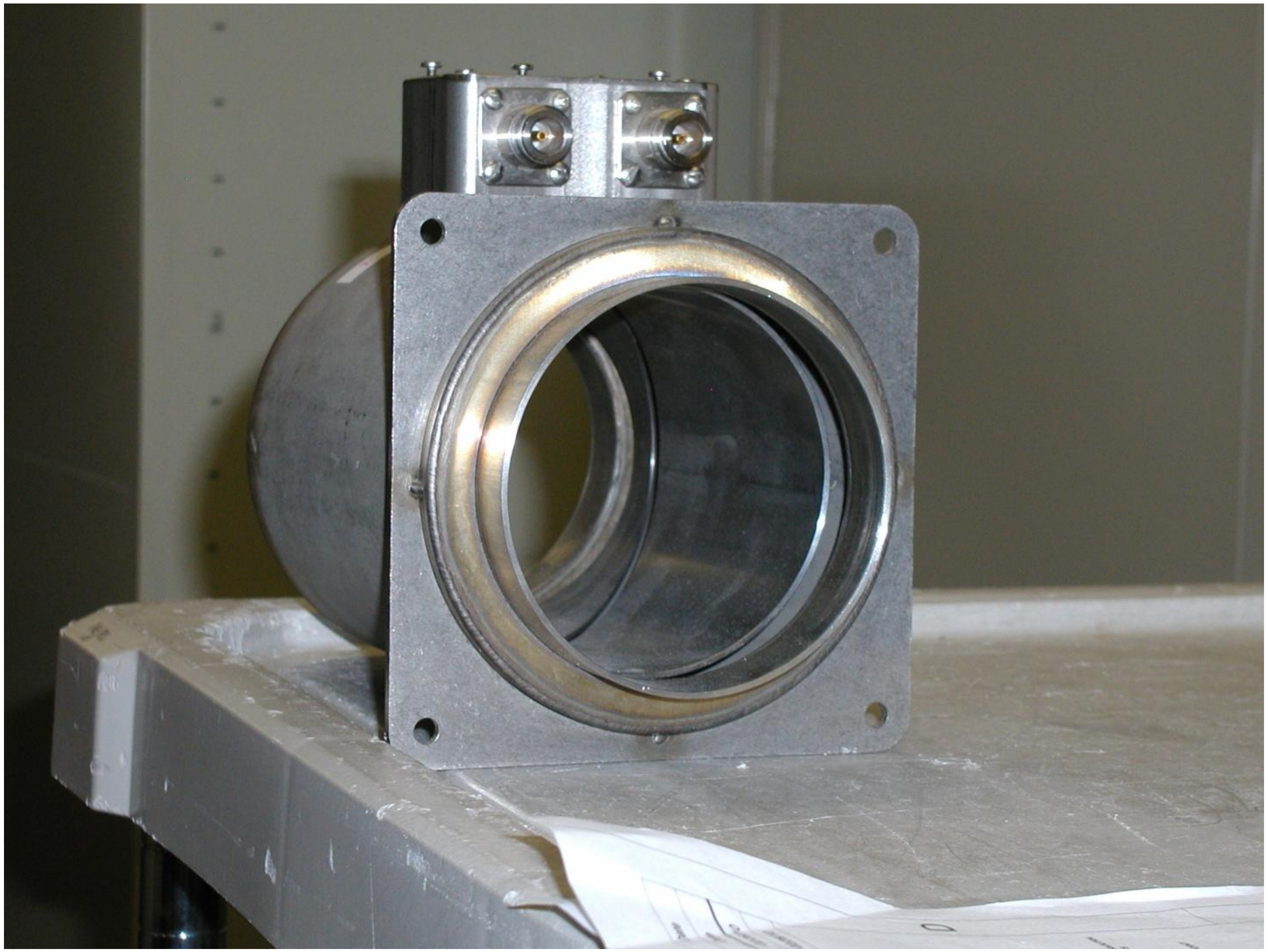
The two Ti dG/G estimeates *'Are not all that different'*, but the C wires clearly age more rapidly

BPM – Beam Position Monitor

- Two electrodes in beam pipe, induced signal from the beam is compared to determine the beam position (and may be summed to determine the beam intensity)
- Rapid response, so beam from each batch is processed individually.
- **BPM positions used to control the beam position through the beam line and onto the target.**

Split Pipe BPM

26 BPMs in the NvMI line (mostly as shown)

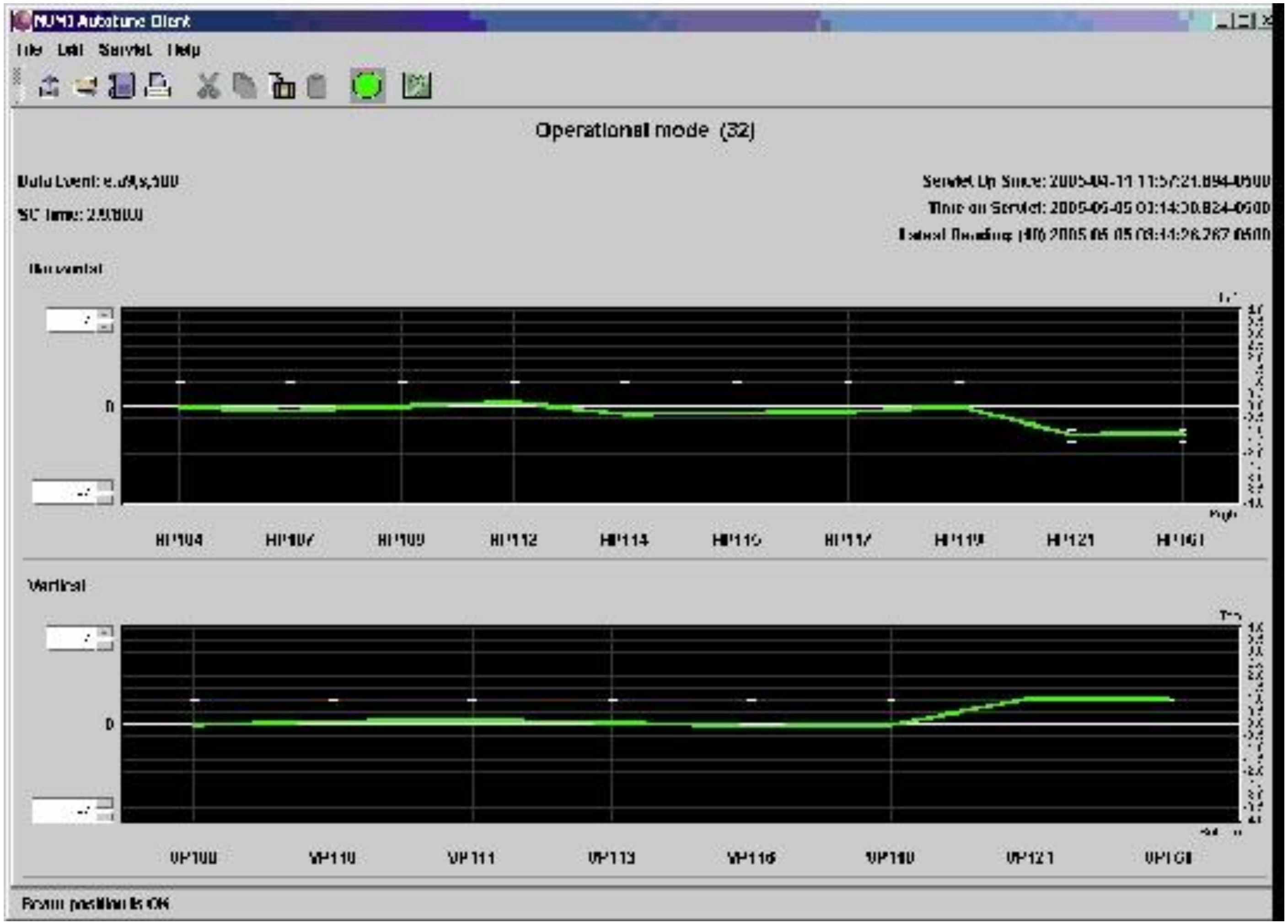


Compare BPM –SEM position

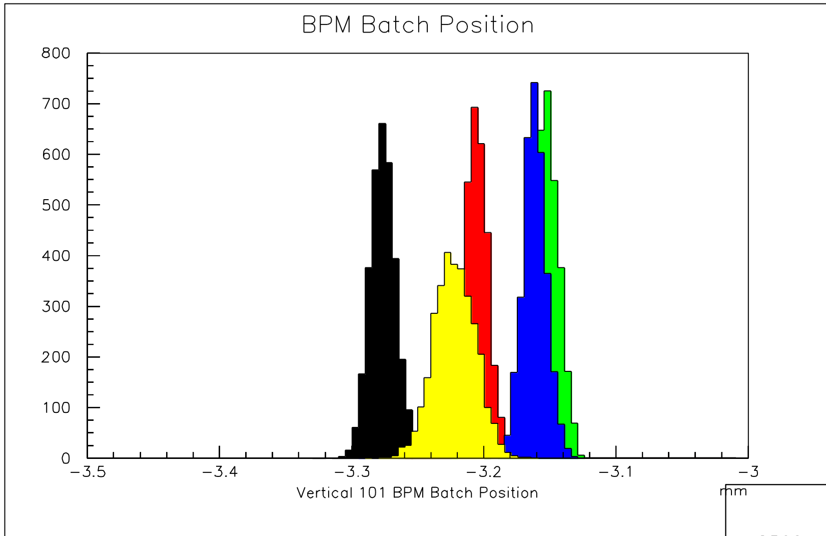
- In a number of locations, there are SEMs located adjacent to the BPMs.
- May compare the positions as measured by the BPMs and SEMs.
- The comparison also makes it possible to study the position resolution.

On-line view of Autotune In Action

BPM position information used to adjust trim magnets



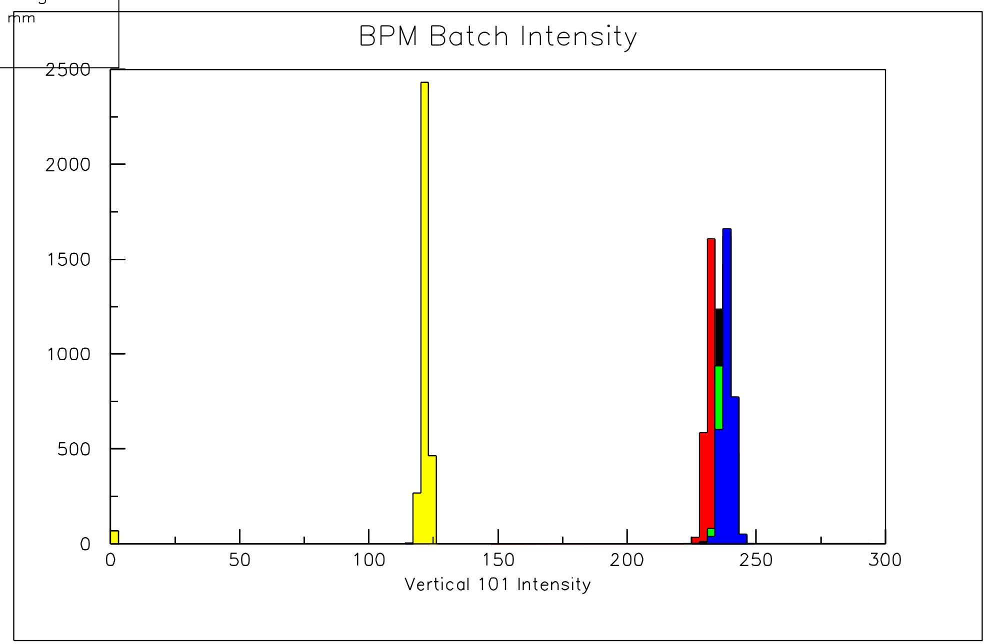
BPM sensitive to the position and intensity in each beam batch.



Black – first batch
Yellow – 5th bach
Red, Green, Blue 2nd,3rd, 4th
Middle 3 used for beam control

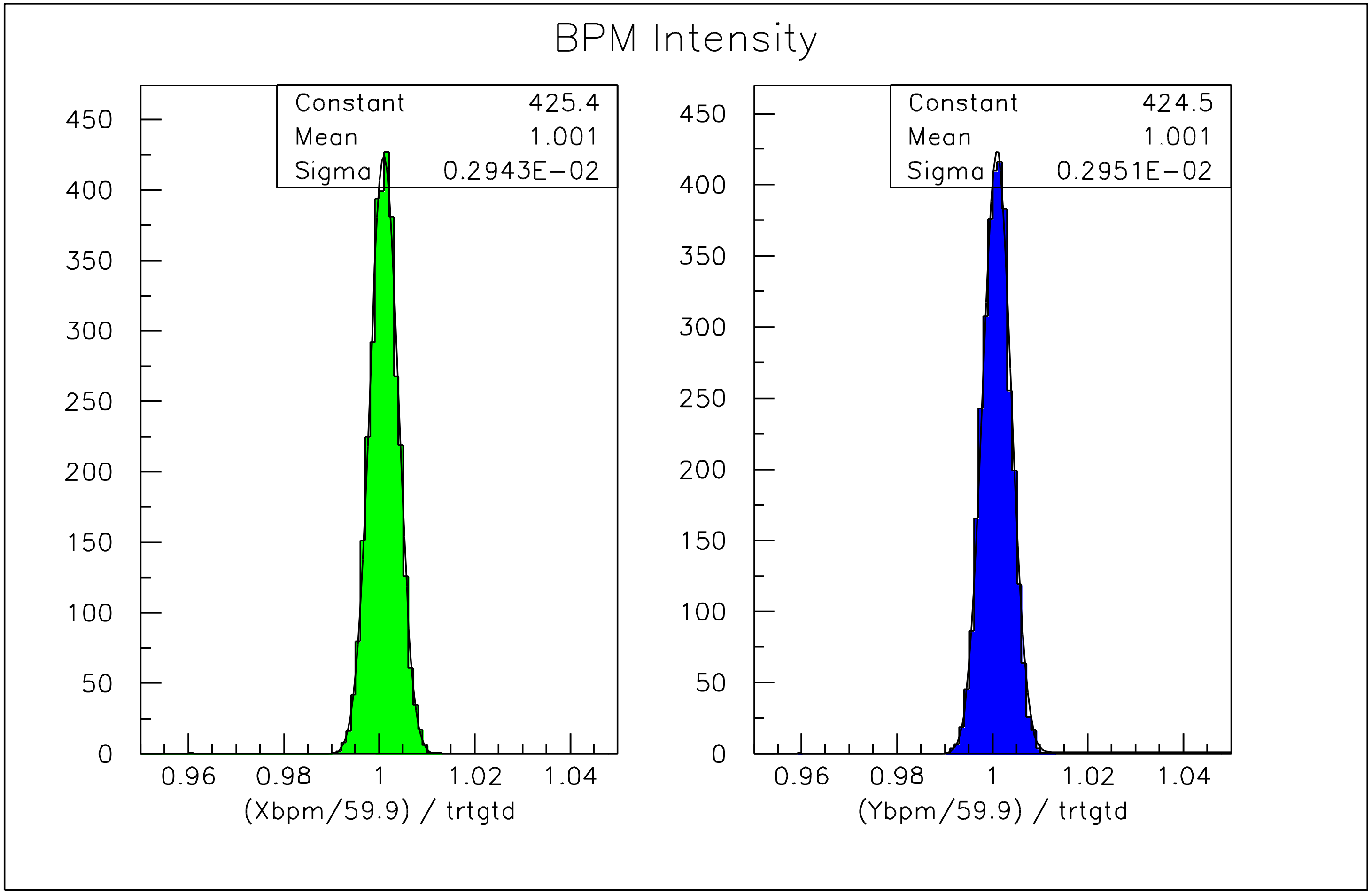
Intensity of 5th batch is ~1/2 of the first 4.

When comparing BPMs and SEMs - must properly weight BPM data.



Intensity may be measured using the BPMs

(BPM Intensity)/ const / trtgtd



Compare Beam Position as determined using the BPMs and SEMs

SEM position – from fits to the profiles shown above.
Subtract an empirical offset.

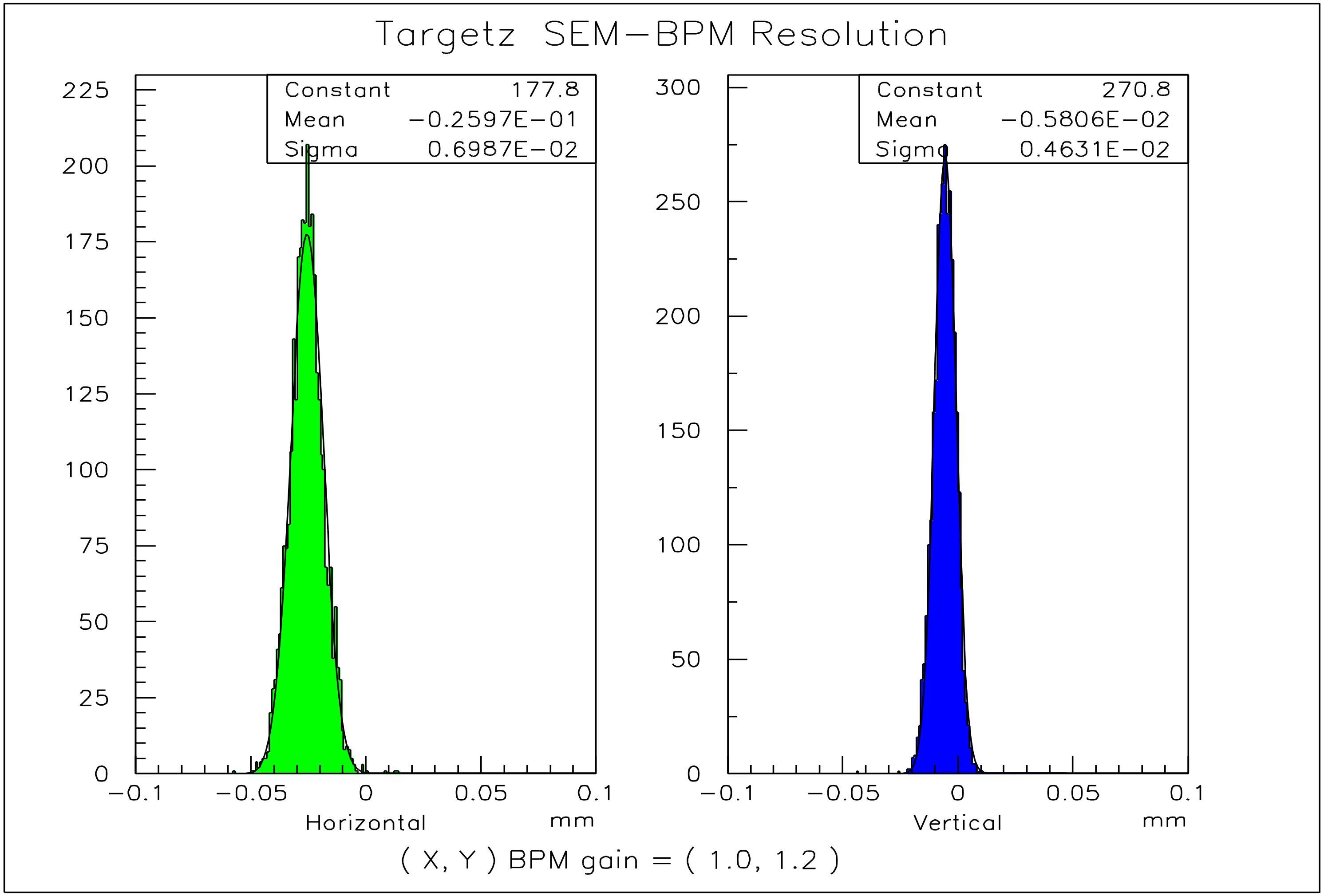
BPM position – as reported from the BPM system.

Subtract an empirical offset.

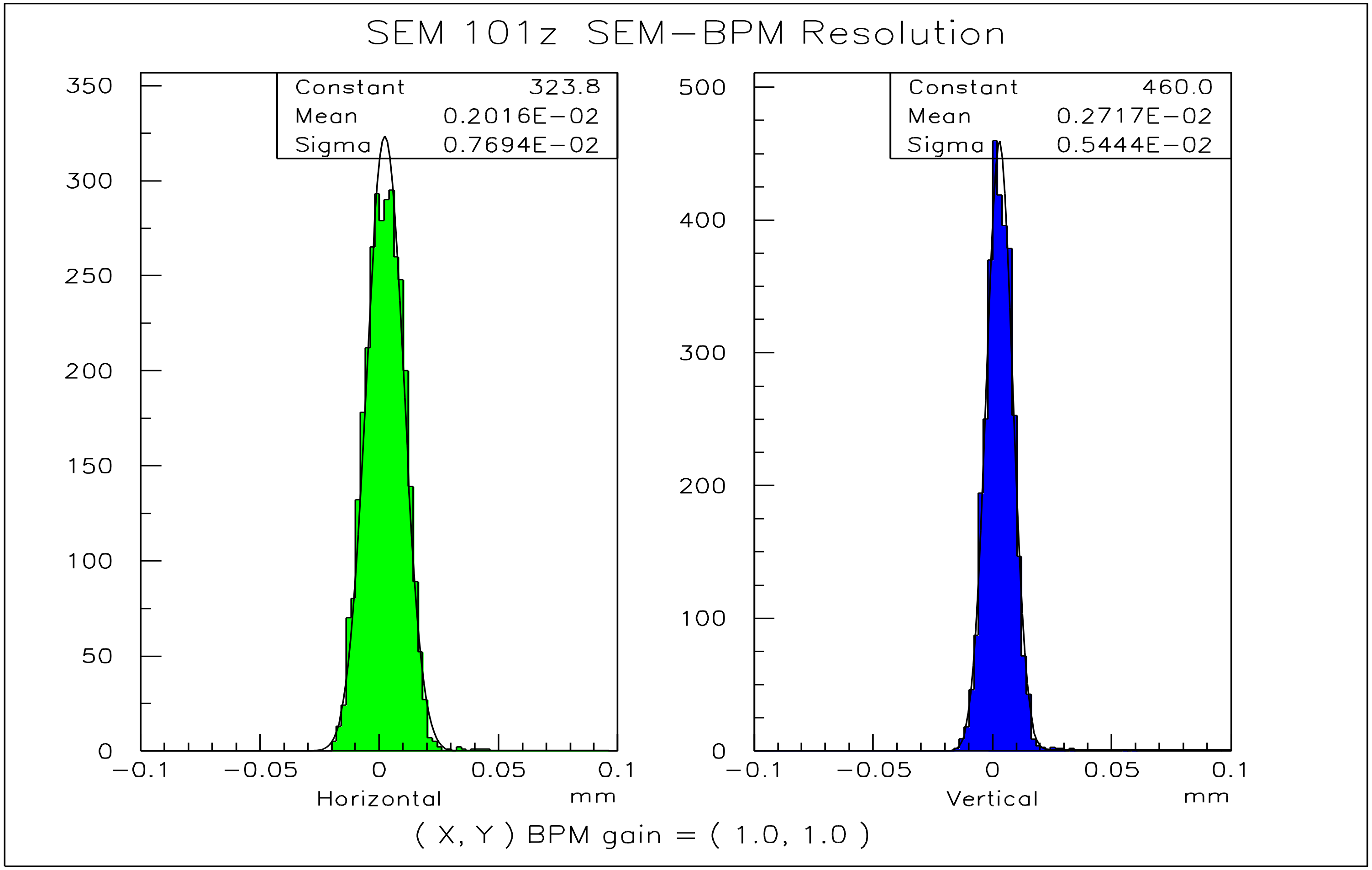
Subject to a gain correction.   Determine by:

1. Minimize the resolution.
2. Require observed beam motion be the same in both devices. Assume – BPM needs gain factor

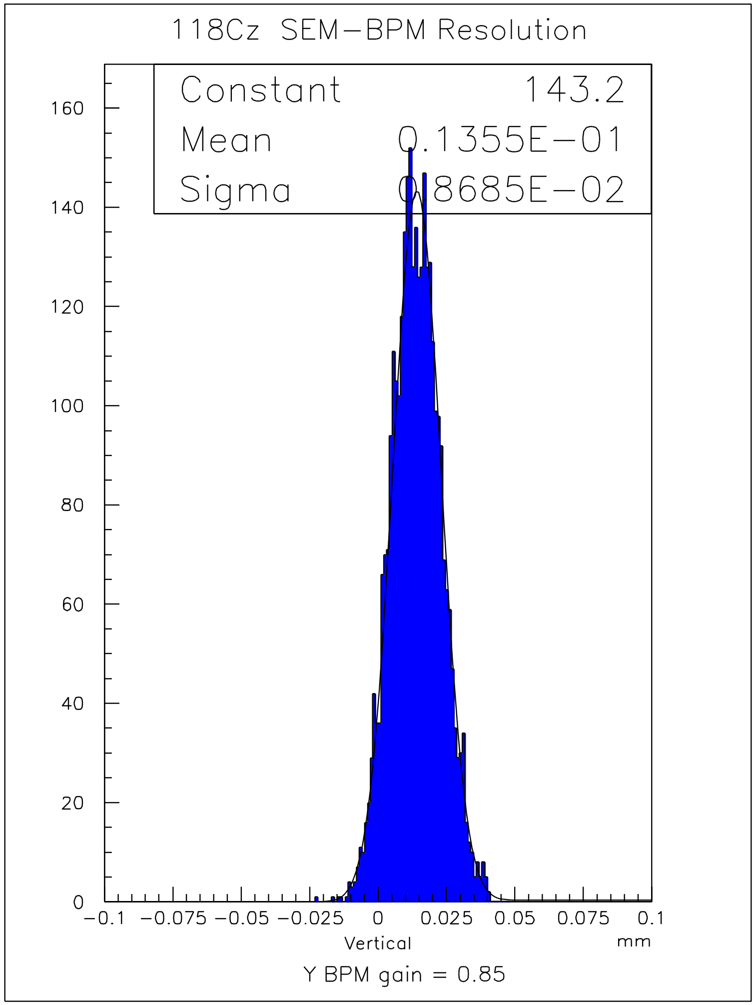
25µ x 5µ foils – Target SEM (Texas)



1 mill Ti wire SEM at 101



Carbon wire SEM at 118



For 118C, only a vertical BPM is near by.

Carbon ‘wires’ not distinguishable from Ti wires or foils.

Conclusions

- Beam intensity is measured and stable to < 1%
- Beam position is well controlled in the beam line and on the target
- Beam size at the target is well understood.
- Aging of the SEMs is clear. Studies Continue
- Position resolutions are impressive. The resolutions of less than 10 microns provide an upper limit on the resolution of BPMs and SEMs.