Gradient Calibration

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Goal

- Calibrate cavity gradients (aka field probe) at typical operating gradient with 3% RMS error
- With eight cavities in a module, adding in quadrature suggests the error of the sum will be ~1%. This error will be placed in the quadrupoles by lem.
- Over the full linac, lem fudge factor alters all cavities as needed to get momentum in arc right but quads aren’t changed. NL 4%, SL 1.6% recently
- 1% local optics error will improve fit to model over present conditions with large lem fudge factors and calibration errors – whether the improvement is worthwhile requires CASA analysis

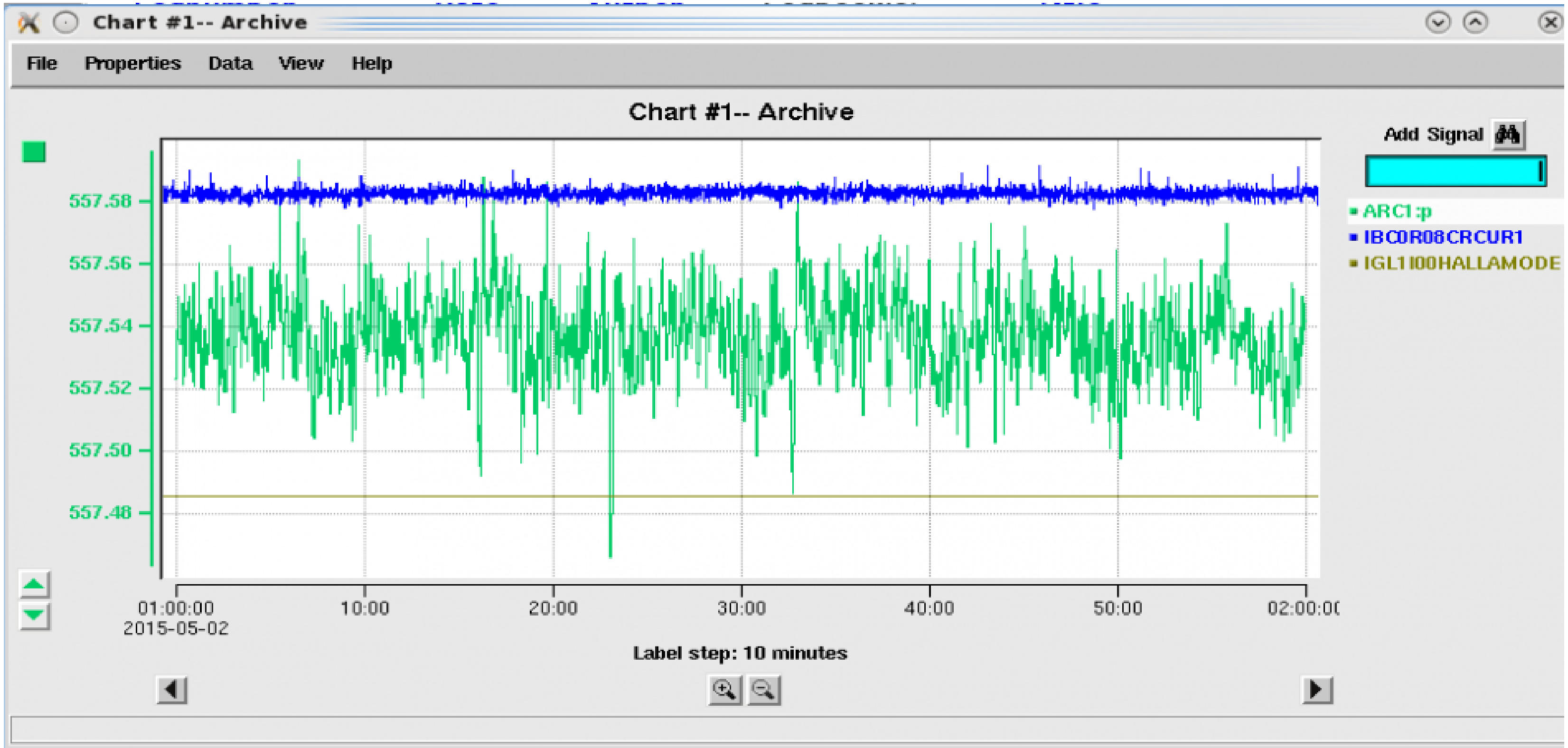
Old method

- Highest gradient cavity in linac as reference
- lem with that cavity at 3 MV/m (7 MV/m for C100)
- Record arc energy baseline
- Lower cavity under test to 3 MV/m while raising reference cavity (balance null measurement)
- Use energy lock system to record arc energy offsets from baseline; correct offline
- Limited by dp/p obtainable with 3 MV/m lower GSET value.
- Error set by RFCM stability and net drift in all other cavities during measurement
- Repeated measurements on single cavity test/reference pair ~ 5 MV/m in SL showed ~7% standard deviation

Proposed method

- Use phase shifter, calibrated to 0.1^{o} on the bench, to alter momentum due to test cavity
- Offsets from crest of 165^{o} possible, so much more dp/p available even on poor cavities
- Two variations will be presented
- M15 BPMs +-6 mm linear response within 4% error if beam starts centered, so high dispersion optics may be counterproductive
- Coding time may decide which of two options is chosen

Arc 1 momentum stability

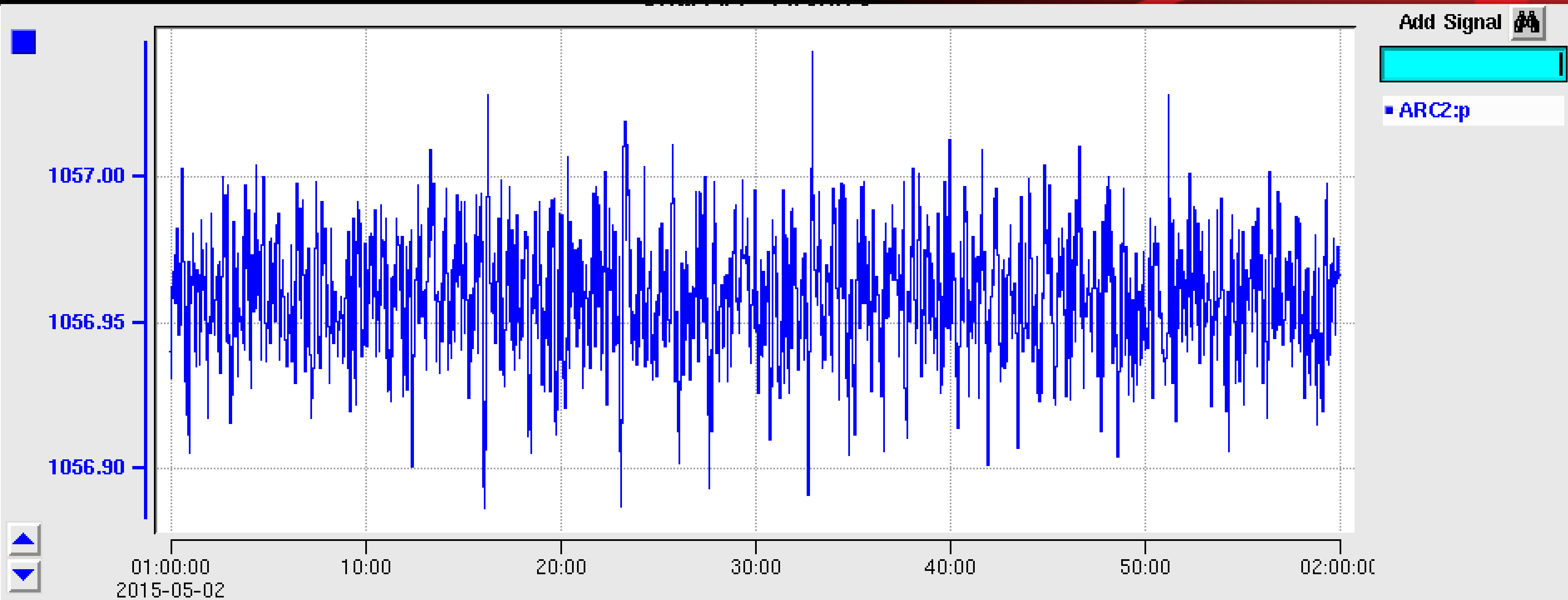


Statistics Info

Channel	ARC1:p
Min	557.466
Max	557.593
Mean	557.537
rms	557.537
SDEV	0.014

SDEV 0.014/557.537 = 2.5E-05
Half-span ~ 0.07/557.537 ~ 1.25E-4
~18 μA CW to hall A
Energy lock on per R1QXGMES behavior
15 of 25 zones on, so might decrease 20%

Arc 2 momentum stability



ARC2:p

Statistics Info

Channel	ARC2:p
Min	1056.886
Max	1057.043
Mean	1056.959
rms	1056.959
SDEV	0.020

SDEV 0.020/1056.959 = 1.9E-5

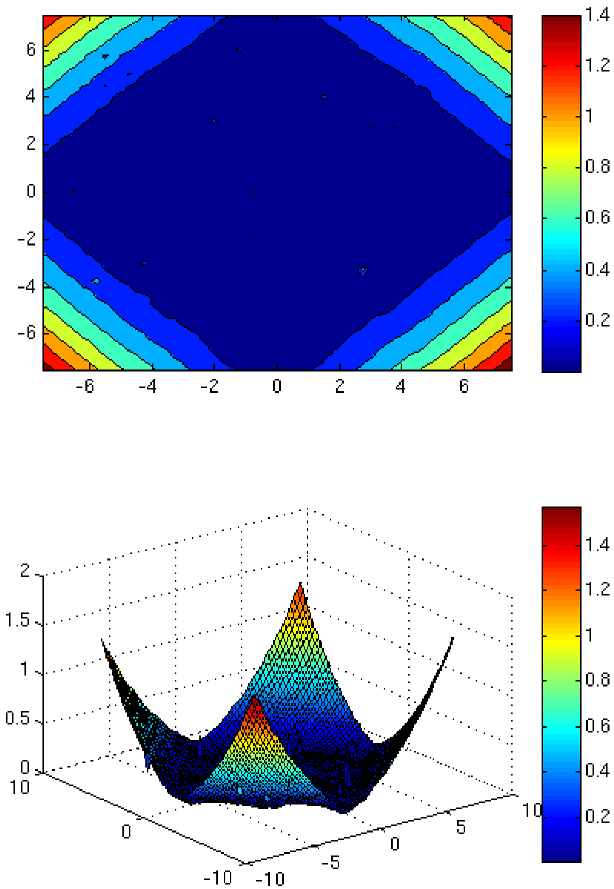
Half-span ~ 0.08/1057 ~ 8E-5

~18 mA CW to hall A

R2QXGMES indicates arc 2 energy lock on.

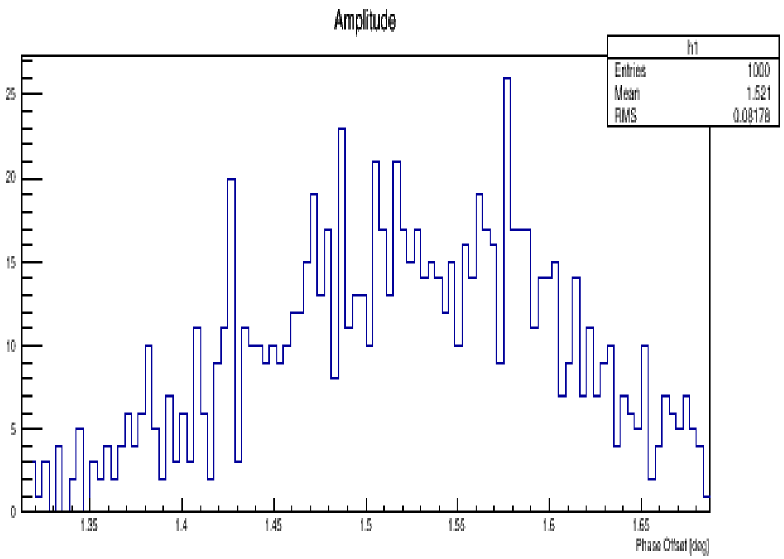
15 of 25 zones on, so might decrease 20%

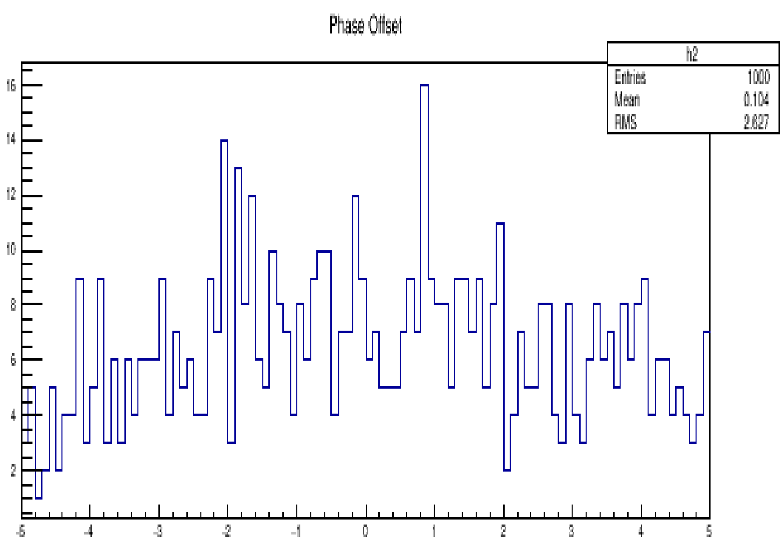
M15 error estimate

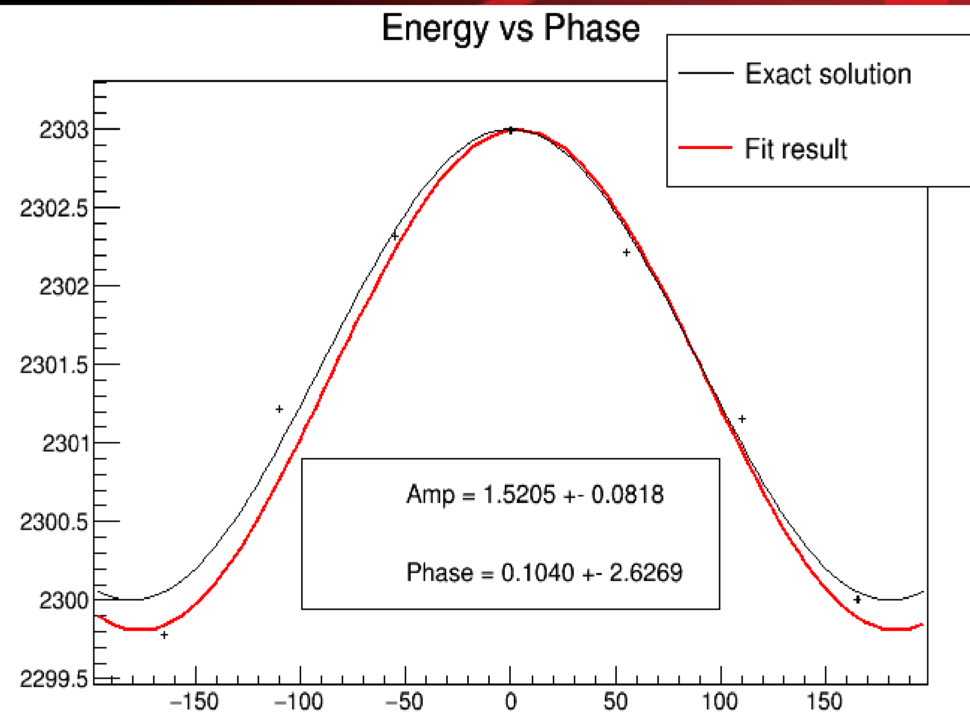


- Matlab simulation by John Musson
- Dimensions in mm, so first lighter band is 200 microns error
- Actual BPM is rotated 45° from model, so +X is towards corner
- If 3% location error desired, must keep X displacement under ~ 6mm
- With 7.5 m peak dispersion optics, 6 mm = dp/p 8E-4, too small given linac drifts
- 2.5 m dispersion yields 2E-3 at 5 mm excursion, OK if 140 μm error (5.6E-5)

Monte Carlo results – worst cavity







MC coded in ROOT by Luke Myers, Hall A 1000 iterations of 3 MV/m (1.5 MeV) cavity assuming energy measurement error **6E-5** and phase set error **0.1** degrees. Seven phase offsets equally spaced. RMS 0.08 of 1.5 MeV, 5.4%. Energy error includes 5.6E-5 from BPMs and 2E-5 from arc energy variation in quadrature.

Pre-requisites

- Quad center all BPMs in 1A and 2A. If SOF is greater than 1 mm, consider turning off BPM. (1A33 2.5 mm)
- Install 2.5 m dispersion optics so dp/p +-2E-3 can be obtained within good region of BPM and net drift of linac during measurement is less of an issue.
- Steer within 0.5 mm of (0,0) through arc
- Run Krest replacement Phaser on all cavities (8h).
- (option B) Absolute calibration of NL26 and SL26 cavities individually against arc (24h)

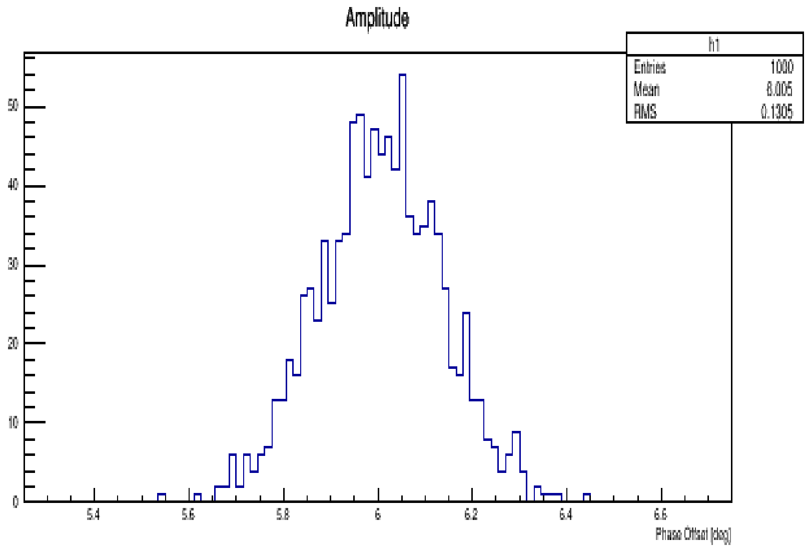
Option A

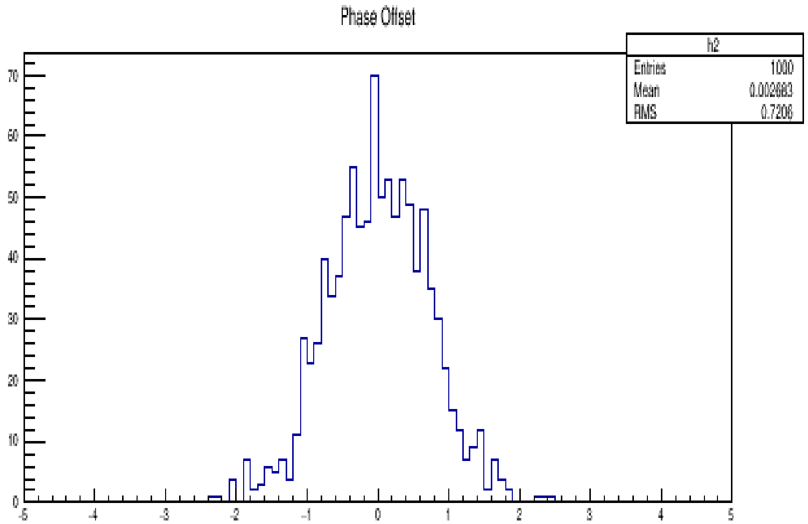
- This option an extension of Phaser
- Adjust arc dipole bus so beam near x= 5 mm
- Within 4E-3, calculate maximum phase shift and two lower values, about equally spaced in sine(theta)
- Energy lock off
- Measure energy at seven phases with BEM, as in Monte Carlo. ~3 minutes
- Fit amplitude and phase of sine, including errors
- Restore cavity and repeat for each of 416. Four to five shifts total, given usual inefficiencies.
- Evaluate data offline. Apply to download files, CED.

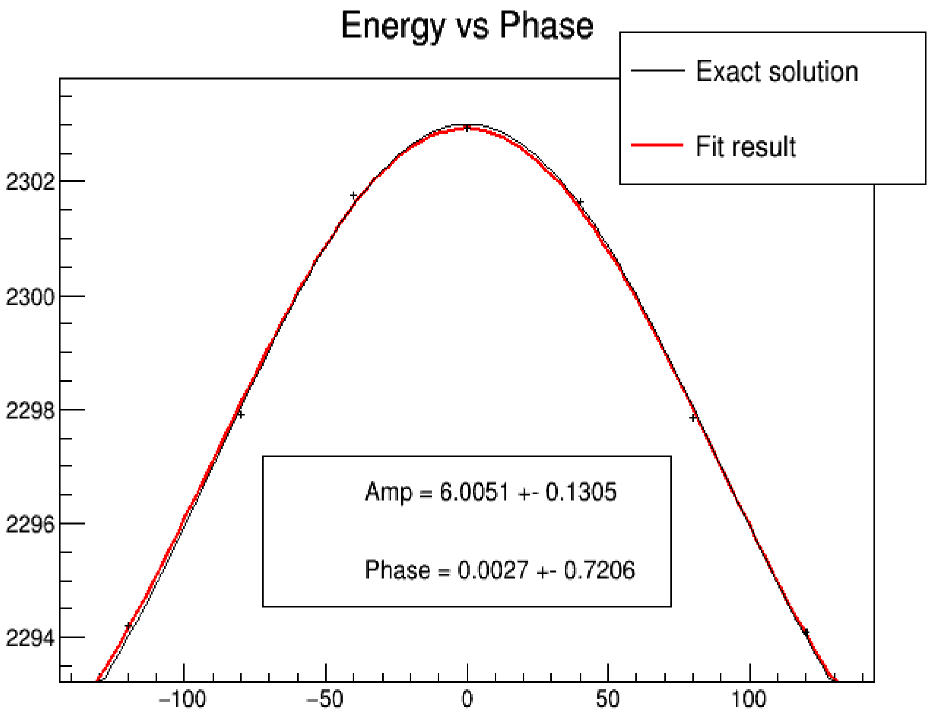
Option B

- Longer to code (6 weeks vs 2 weeks?)
- Needs energy lock cavity absolute calibration (one day)
- Calculate shifts for 165^{o} (C25), 120^{o} (C50) and 75^{o} (C100) .
- For three phase shifts on either side of crest, download phase and energy lock offset calculated to keep beam centered if test cavity calibration already correct.
- Using applied energy lock offset and BEM reading of arc energy, calculate actual energy offset as function of phase
- Fit seven points to sine
- Data acquisition about twice as long, say three days (+1)
- Beam stays close to zero so BPM accuracy and linac stability in quadrature likely 3E-5 vs 6E-5 as in MC

Monte Carlo: 6 MeV cavity

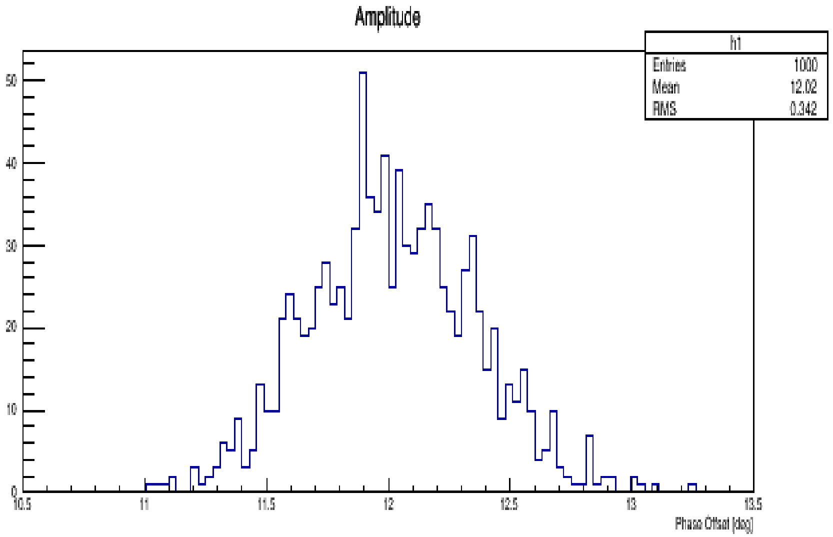


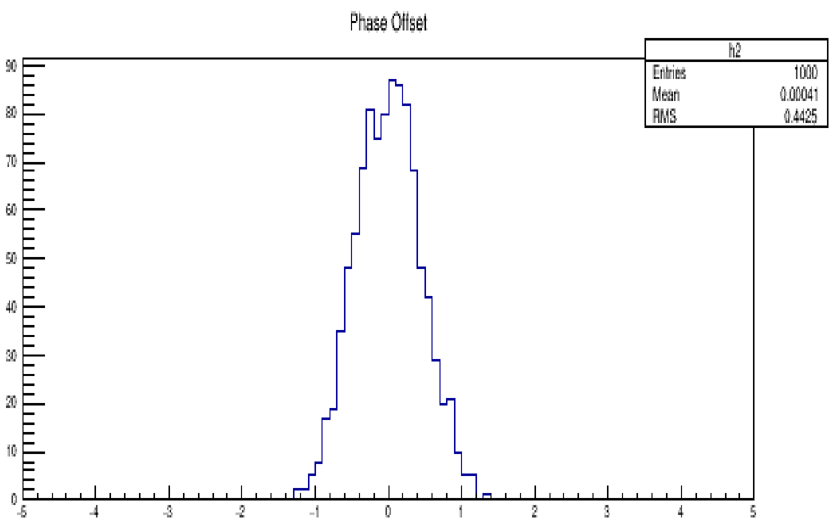


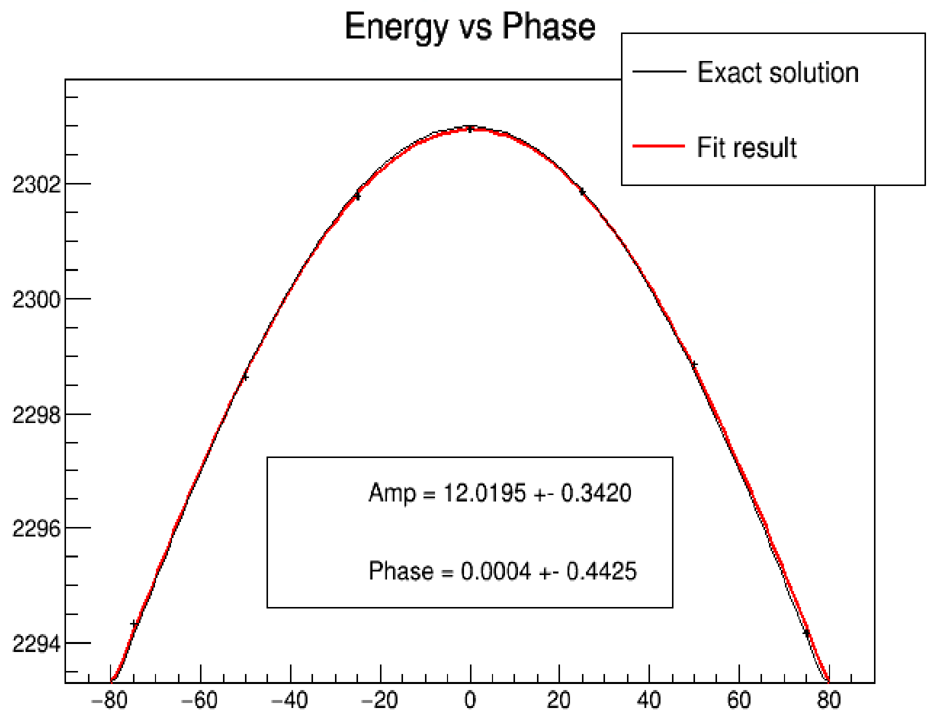


Sigmas used: energy 6E-5, phase 0.1 degrees.

Monte Carlo: 12 MeV cavity







Sigmas used: energy 6E-5, phase 0.1 degrees.

Table of Monte Carlo results

MeV input to MC	Mean	RMS	RMS/ mean
1.5	1.521	0.082	**5.4%**
2	2.018	0.087	**4.3%**
2.5	2.510	0.088	**3.5%**
3	3.010	0.089	3.0%
4.5	4.509	0.085	1.9%
6	6.005	0.130	2.2%
7.5	7.510	0.188	2.5%
9	9.023	0.231	2.6%
10.5	10.514	0.298	2.8%

Monte Carlo results for Gaussians with energy error sigma 6E-5 and phase error sigma 0.1 degrees, in arc 2 at 2303 MeV. Corresponds roughly to Option A. *3.2% max arc 1*.

Conclusions

- It is possible to reach ~3% error per cavity as desired for all of NL and perhaps three-fourths of SL using phase shifter and Option A
- Option B provides a factor of two better accuracy than Option A, but takes a lot longer to code – perhaps too long for October 2015 testing and deployment given other HLA tasks
- Recommendation: ask HLA to code Option A. Allocate two four hour code testing periods and 4-5 shifts for measurement.
- $Q_0(E_{typical})$ should be measured for zone **after** gradient calibration and CED then adjusted for Cryo

Monte Carlo results 1213 MeV

MeV input to MC	Mean	RMS	RMS/ mean
1.5	1.507	0.046	3.1%
2	2.006	0.046	2.3%
2.5	2.501	0.047	1.9%
3	3.003	0.066	2.2%
4.5	4.511	0.123	2.7%
6	6.014	0.173	2.9%
7.5	7.508	0.242	3.2%
9	9.031	0.287	3.2%
10.5	10.513	0.318	3.0%

Monte Carlo results for Gaussians with E error sigma **6E-5** and phase error sigma 0.1 degrees, in arc 1 at 1213 MeV. If we have only one 2K cold box when calibration is done, these RMS errors would obtain for arc 2.

Monte Carlo results 1213 MeV, 3E-5

MeV input to MC	Mean	RMS	RMS/mean
1.5	1.502	0.024	1.6%
2	2.001	0.023	1.1%
2.5	2.501	0.024	1.0%
3	3.001	0.033	1.1%
4.5	4.502	0.056	1.2%
6	6.001	0.086	1.4%
7.5	7.505	0.088	1.2%
9	9.009	0.130	1.4%
10.5	10.505	0.157	1.5%
12	12.002	0.177	1.5%

Monte Carlo results for Gaussians with E error sigma **3E-5** and phase error sigma 0.1 degrees, in arc 1 at 1213 MeV.

Monte Carlo results 2303 MeV, 3E-5

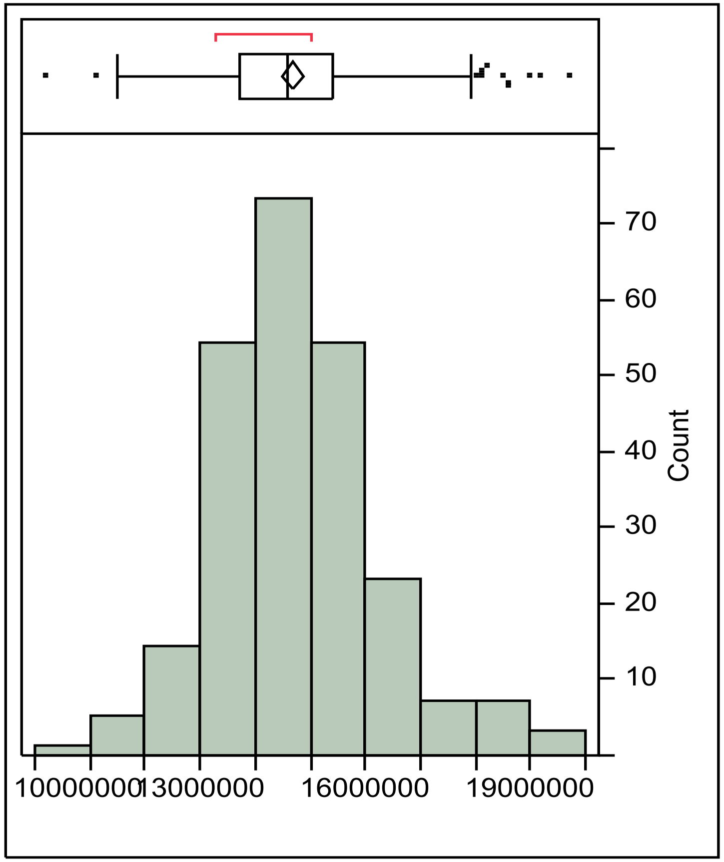
MeV input to MC	Mean	RMS	RMS/mean
1.5	1.507	0.043	2.9%
2	2.007	0.045	2.3%
2.5	2.504	0.043	1.7%
3	3.004	0.044	1.5%
4.5	4.501	0.043	1.0%
6	6.003	0.065	1.1%
7.5	7.505	0.095	1.3%
9	9.007	0.119	1.3%
10.5	10.504	0.149	1.4%
12	11.997	0.176	1.5%

Monte Carlo results for Gaussians with E error sigma **3E-5** and phase error sigma 0.1 degrees, in arc 2 at 2303 MeV

Probe Q: C25

Distributions

probeQ



Quantiles

100.0%	maximum	1.97e+7
99.5%		1.96e+7
97.5%		1.85e+7
90.0%		1.65e+7
75.0%	quartile	1.54e+7
50.0%	median	1.46e+7
25.0%	quartile	1.37e+7
10.0%		1.3e+7
2.5%		1.18e+7
0.5%		1.04e+7
0.0%	minimum	1.02e+7

Moments

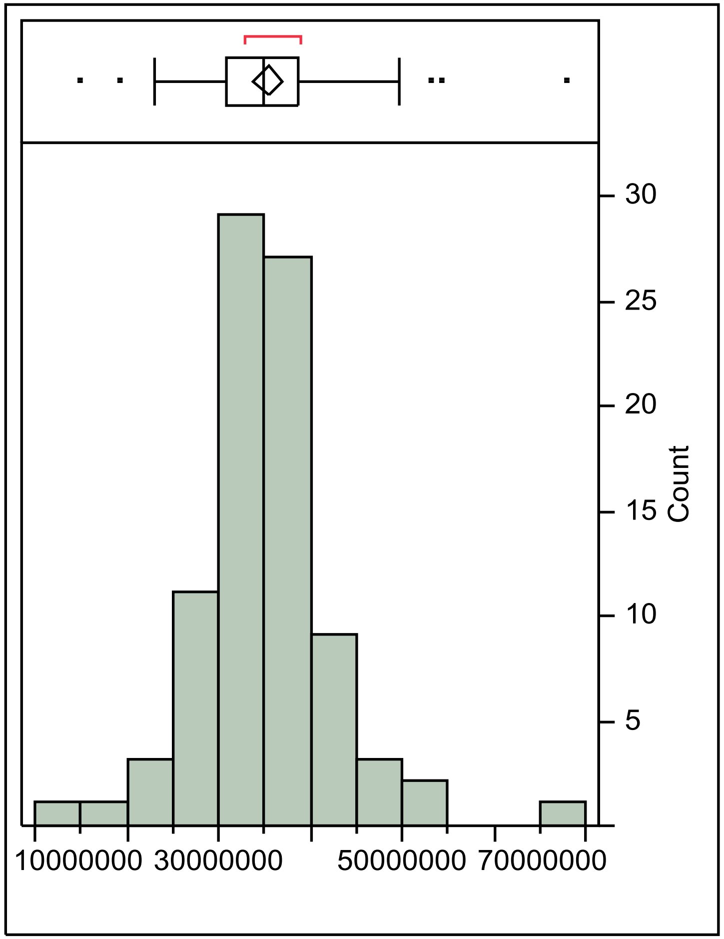
Mean	14691701
Std Dev	1503001.7
Std Err Mean	96816.852
Upper 95% Mean	14882421
Lower 95% Mean	14500982
N	241

Specification **1.5E7 +- 40%**
met in original production

Probe Q: C50

Distributions

probeQ



Quantiles

100.0%	maximum	6.81e+7
99.5%		6.81e+7
97.5%		5.41e+7
90.0%		4.38e+7
75.0%	quartile	3.87e+7
50.0%	median	3.48e+7
25.0%	quartile	3.1e+7
10.0%		2.79e+7
2.5%		2.01e+7
0.5%		1.48e+7
0.0%	minimum	1.48e+7

Moments

Mean	35433333
Std Dev	7479455.1
Std Err Mean	801881.75
Upper 95% Mean	37027421
Lower 95% Mean	33839245
N	87

Specification unknown. Change not coordinated with LLRF or Operations. Span broader than original production, **3.5E7 +- 60%** plus one outlier. LLRF has had 3db attenuators on all cavities for ~15 years, so this change was counterproductive.

Very long term

- Upgrade BPM electronics in arcs 1 and 2 to reduce position and therefore energy error
- Code and run Option B
- The last time we calibrated the cavities with beam and used the measurements was 1995, so goal for this is 2035 if JLab still exists.