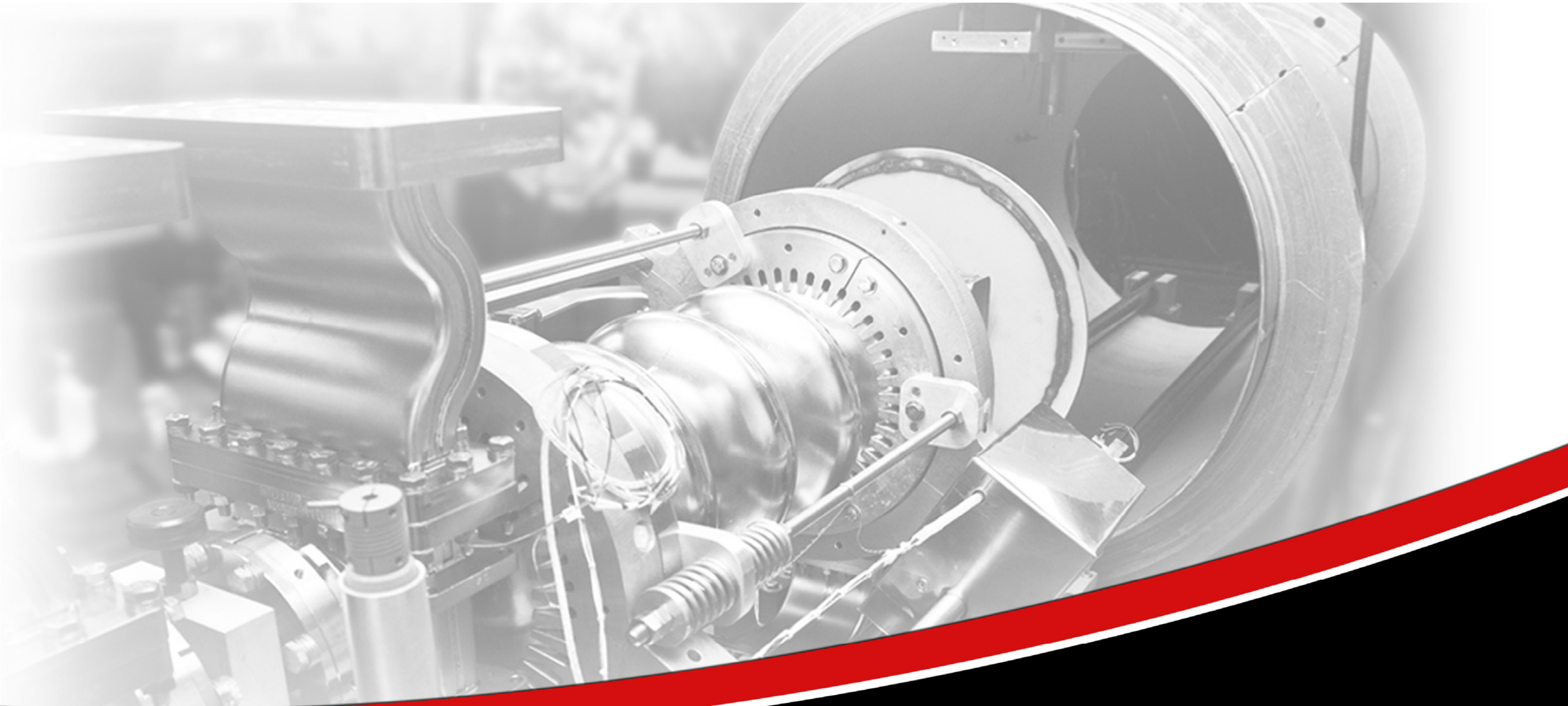

Calibration of CEBAF Linac Cavities

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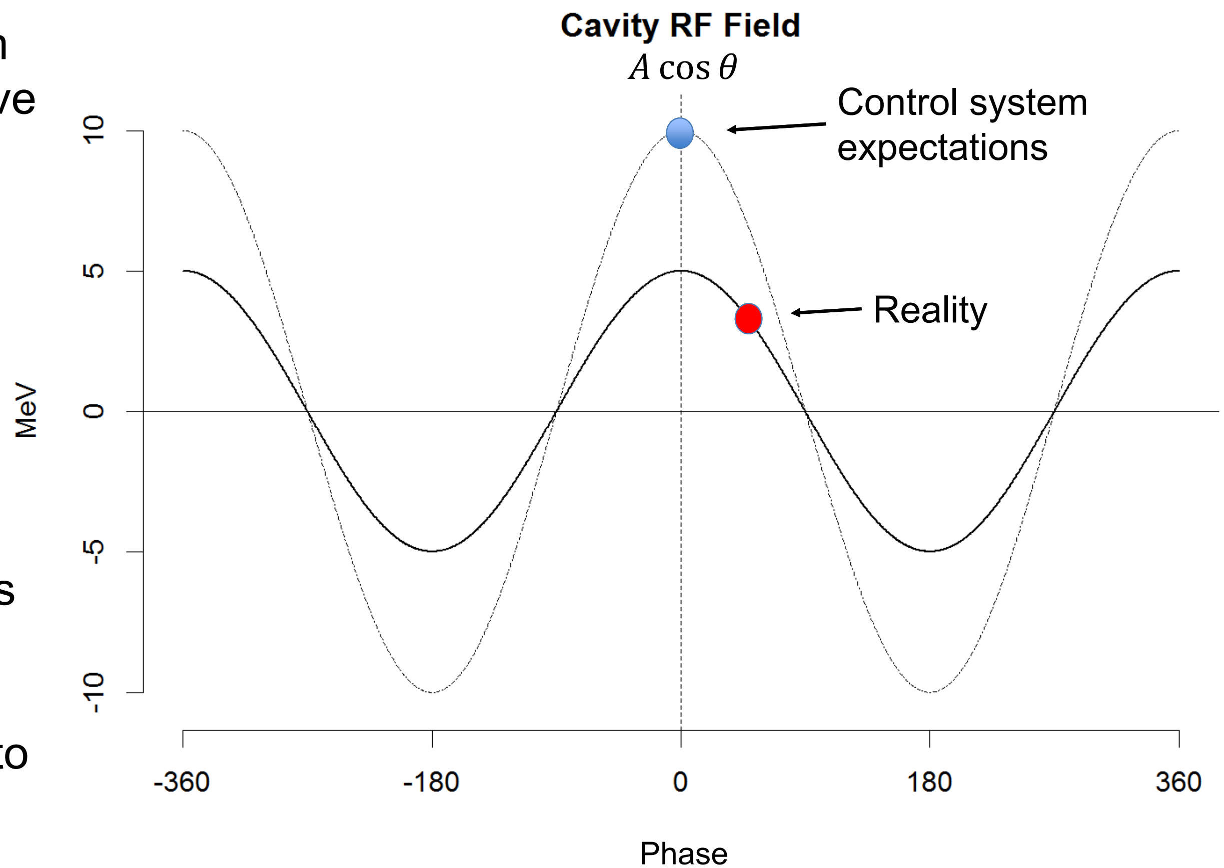
The Calibration Problem

- Naïve control system assumes it will receive properly phased RF field with requested amplitude
- Calibration is important to make control systems assumptions reasonable
- Amplitude error leads to scaling of the requested energy
- Phasing errors lead to inefficient use of requested power

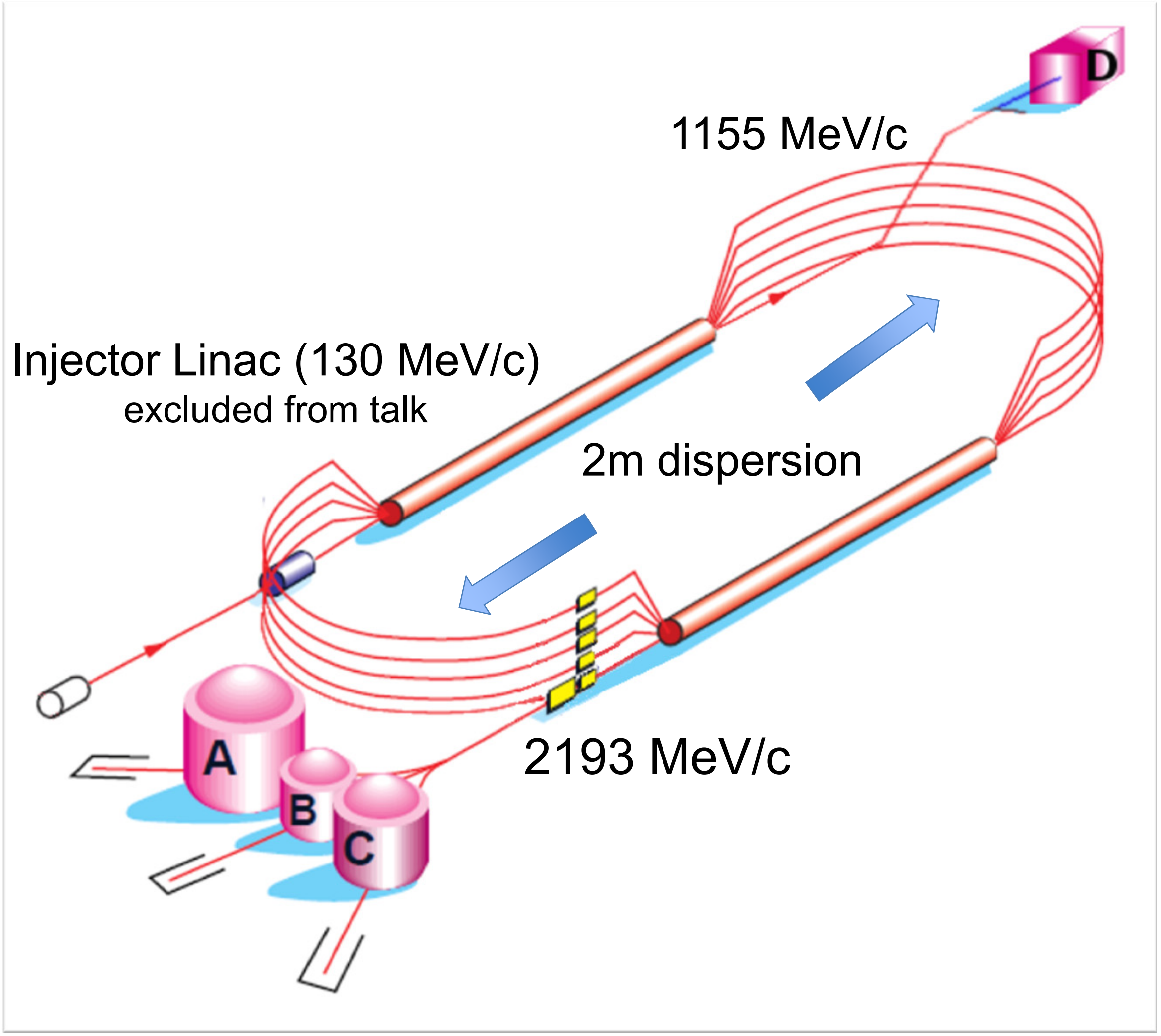


CEBAF

Continuous Electron Beam Accelerator Facility

SRF Linacs
- 25 Cryomodules
  - 5 “high” gradient (7-cell cavities, ~15 MV/m)
  - 20 “low”/”med” gradient (5-cell cavities, ~3-13 MV/m)
- 400 Cavities Total

Peak beam displacement:
- ±4mm for minimizing BPM non-linearity effects

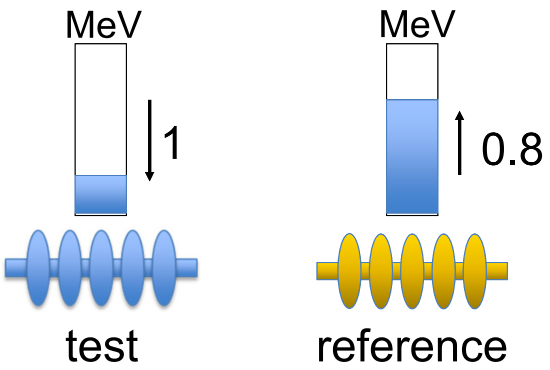


At time of data collection

Cavity RF Field Calibration Approaches

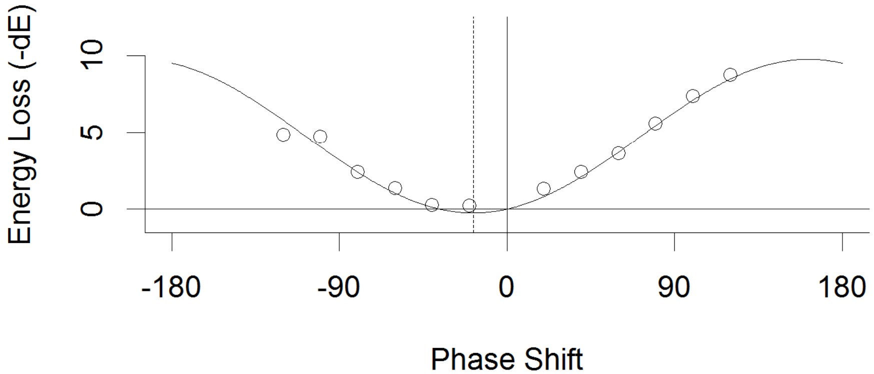
Null Balance (old)

- Manually balance gradient differences between test and reference cavities
- 7% RMS Error on repeated measurement of single cavity
- Estimates amplitude error only



RfPhaser (new)

- Programmatically measure change in region energy while applying phase shifts to individual cavities
- Ordinary Least-Squares (OLS) fit on recast data
- Use OLS fit to estimate amplitude and phase error



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RfPhaser Algorithm

- Apply set of regularly spaced phase shifts, measure energy change

$$\delta E_i = A\cos(\theta + \varphi_i) - A\cos\theta$$

- Recast Equation

$$\delta E_i = A\cos\theta\cos\varphi_i - A\sin\theta\sin\varphi_i - A\cos\theta$$

$$\beta_1 = A\cos\theta$$
$$\beta_2 = A\sin\theta$$

$$= (\cos\varphi_i - 1) \times \beta_1 - \sin\varphi_i \times \beta_2$$
$$= X_{1i}\beta_1 + X_{2i}\beta_2$$

$$X_1 = (\cos\varphi_i - 1)$$
$$X_2 = -\sin\varphi_i$$

- Perform OLS estimation and solve for phase, amplitude

$$\boldsymbol{\delta E} = \mathbf{X}\boldsymbol{\beta}$$
$$\boldsymbol{\beta} = \left(\boldsymbol{X}^{\boldsymbol{T}}\boldsymbol{X}\right)^{-1}\boldsymbol{X}^{\boldsymbol{T}}\boldsymbol{\delta E}$$

$\Rightarrow$

$$\theta = \tan^{-1}(\beta_2/\beta_1)$$
$$A = \beta_1/\cos\theta$$

Cavity Parameter Benchmark

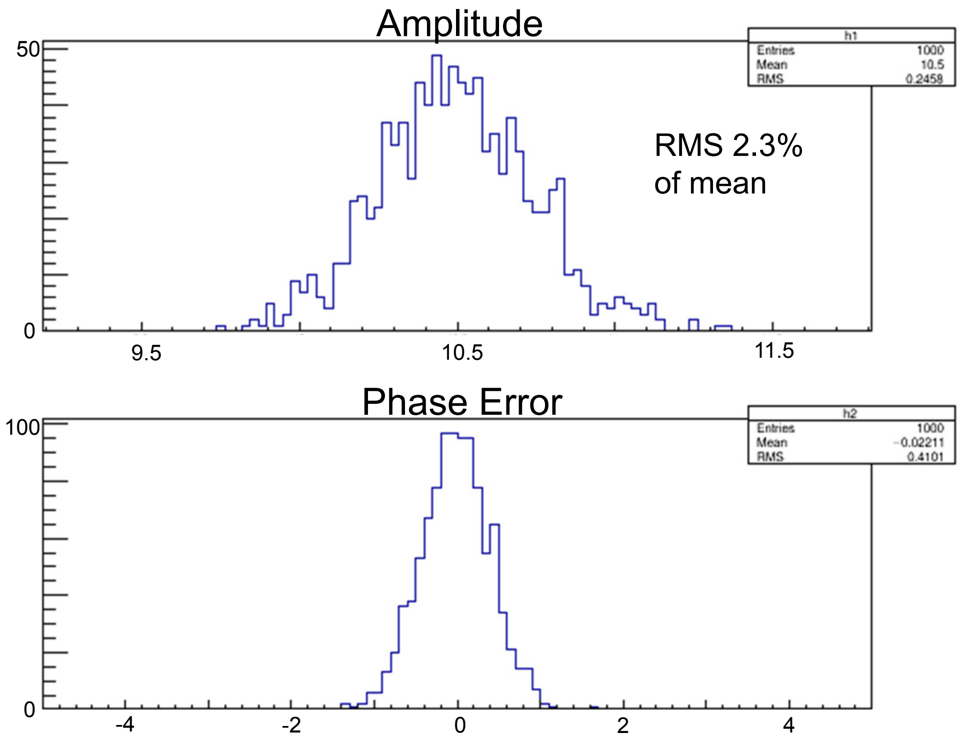
- Monte Carlo Simulation
- Assumed standard machine configuration (execption: 2m disp., max dp/p ±2e-3)
- Select region momentum (1213 MeV/c or 2303 MeV/c)
- Select cavity momentum change (1.5 MeV/c, 6 MeV/c, 10.5 MeV/c)
- Above informs choice of phase shifts
  - E.g., $\boldsymbol{\varphi} = [-150, -120, \ldots, 150]$ degrees
- Calculate energy change

$$\delta E_i = A\cos(\theta + \varphi_i + Err_{shift}) - A\cos\theta + Err_{energy}$$

  - Err_{shift}~ Gaus(0, 0.1)
  - Err_{energy}~ Gaus(0, 4E−5)
- Estimate amplitude (A) and phase error (θ) using χ^2minimization of

$$\delta E_i = A\cos(\theta + \varphi_i) - A\cos\theta$$

- Replicate 1000 times across cavity types



Higher gradient CM: 10.5/2303 MeV/c

Courtesy Luke Meyers

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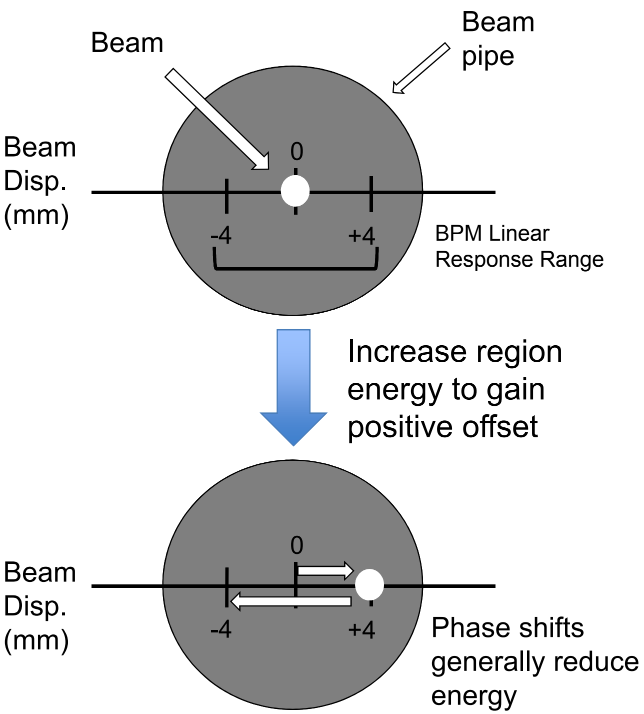
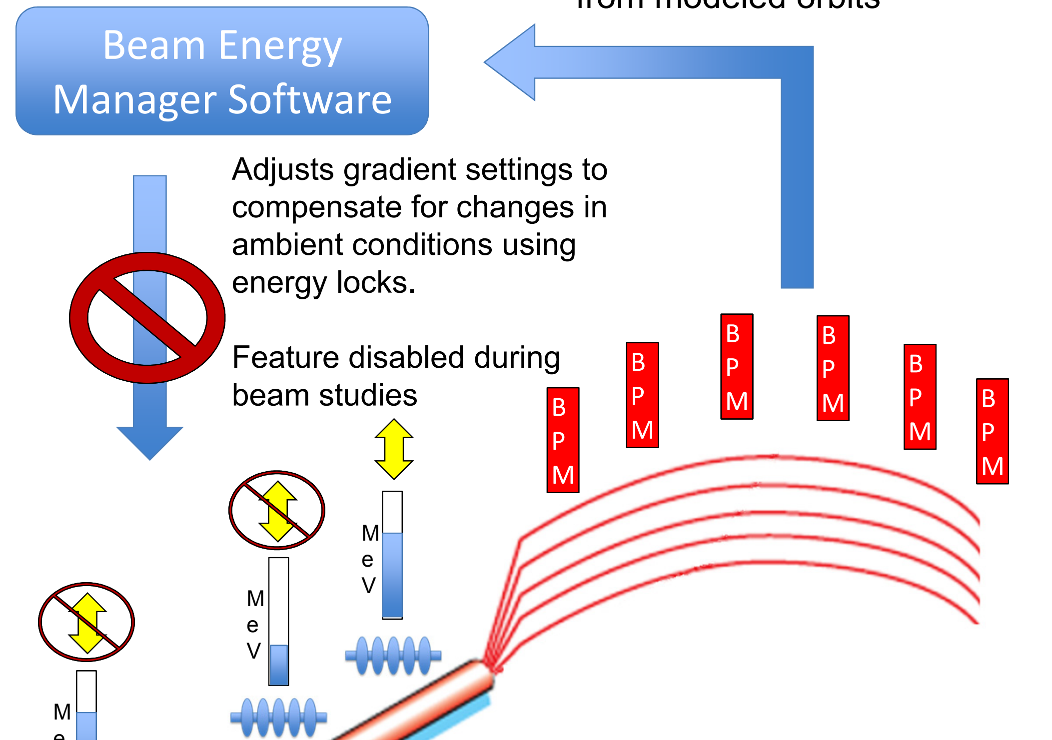
Experimental Environment

Peak Beam Displacement



Can use larger phase shifts that would result in maximum **-8mm** displacement (0.004 dp/p)

Uses BPM readings to calculate energy based on deviations from modeled orbits



Used 2m dispersion optics (normally 7m).
Allows larger phase shifts

RfPhaser Beam Studies and Analysis

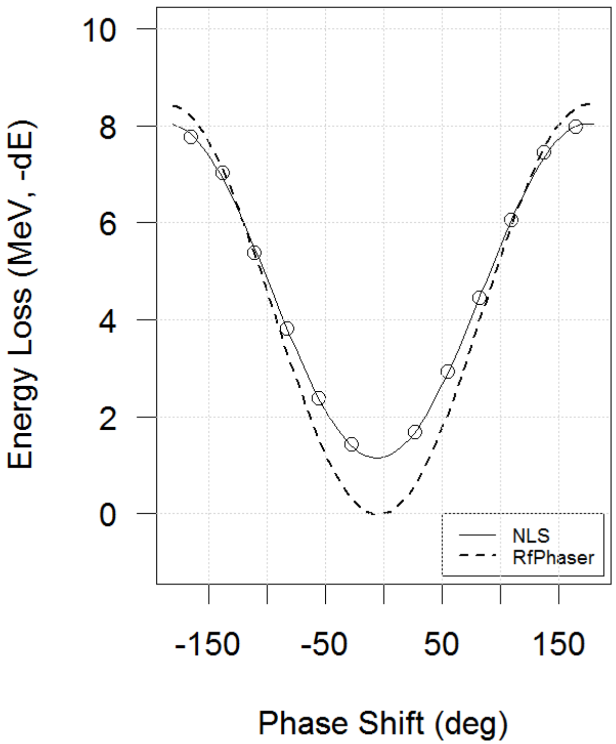
- 876 cavity data sets, 12 phase shifts per set, energy readings averaged over 5 BEM measurement cycles
  - ~20 datasets yielded unusual fits
- Classical OLS analysis techniques fail due to recast formulation
- Non-linear least squares (NLS, R's implementation) was chosen with equation:

$$\delta E_i = X_0 + A\cos(\theta + \varphi_i) - A\cos\theta$$

- Intercept allowed for easier identification of 21 problematic calibration runs (X_0 > 0.2 and X_0 < -0.4) .
- Used RfPhaser estimates as initial parameter list for NLS
- Future work: Incorporate intercept into RfPhaser

Non-linear LS Vs RfPhaser (OLS)

Cavity 2L11-1

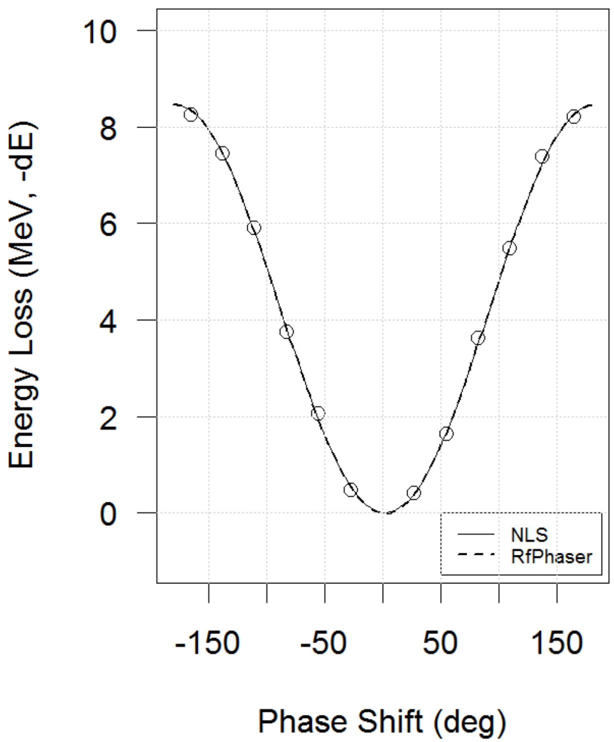


X_0=-1.17

NLS:
A=3.45
θ=-5.55

RfPhaser:
A=4.4.22
θ=-4.52

Cavity 2L19-5



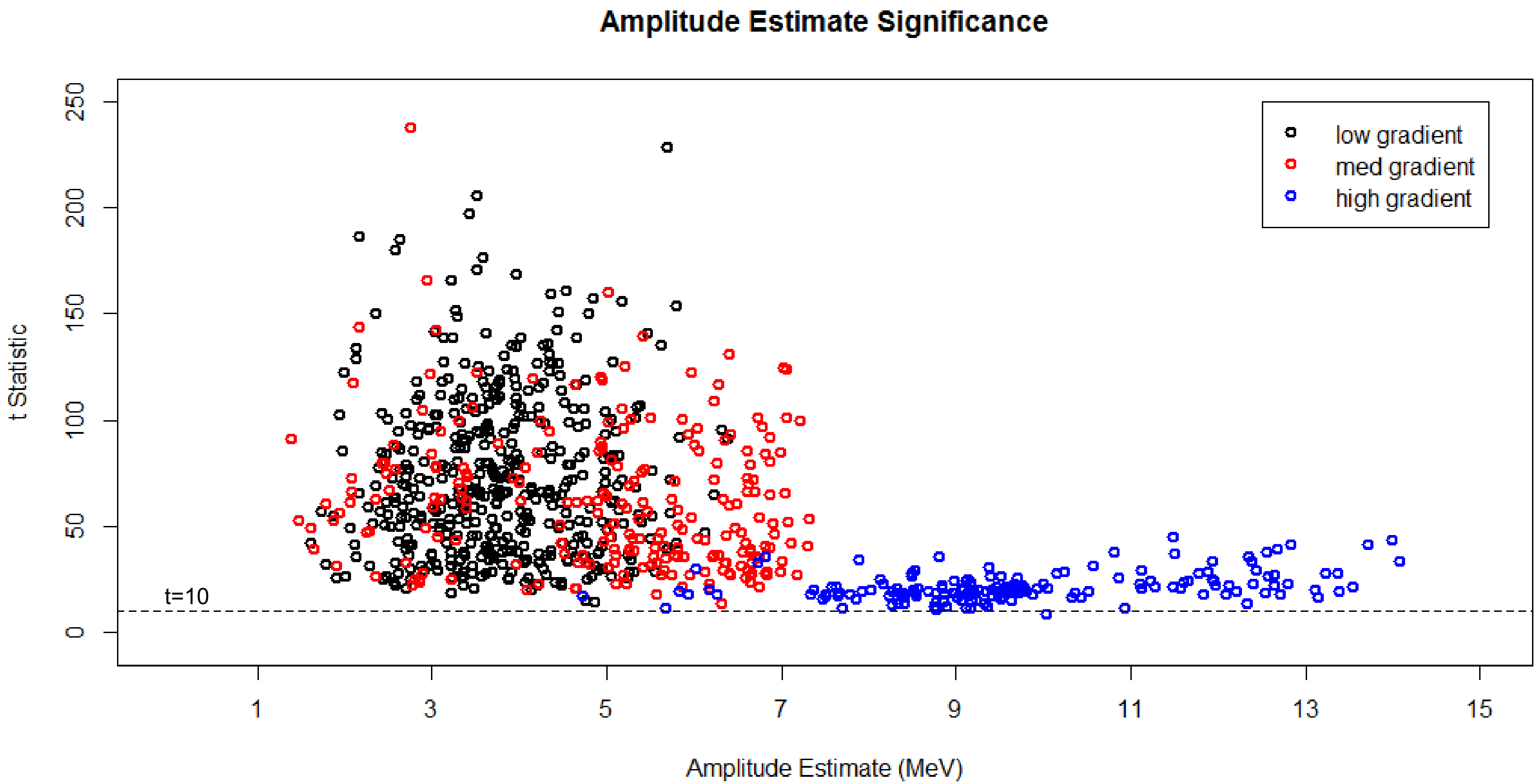
X_0=-0.01

NLS:
A=4.22
θ=-2.04

RfPhaser:
A=4.22
θ=-2.04

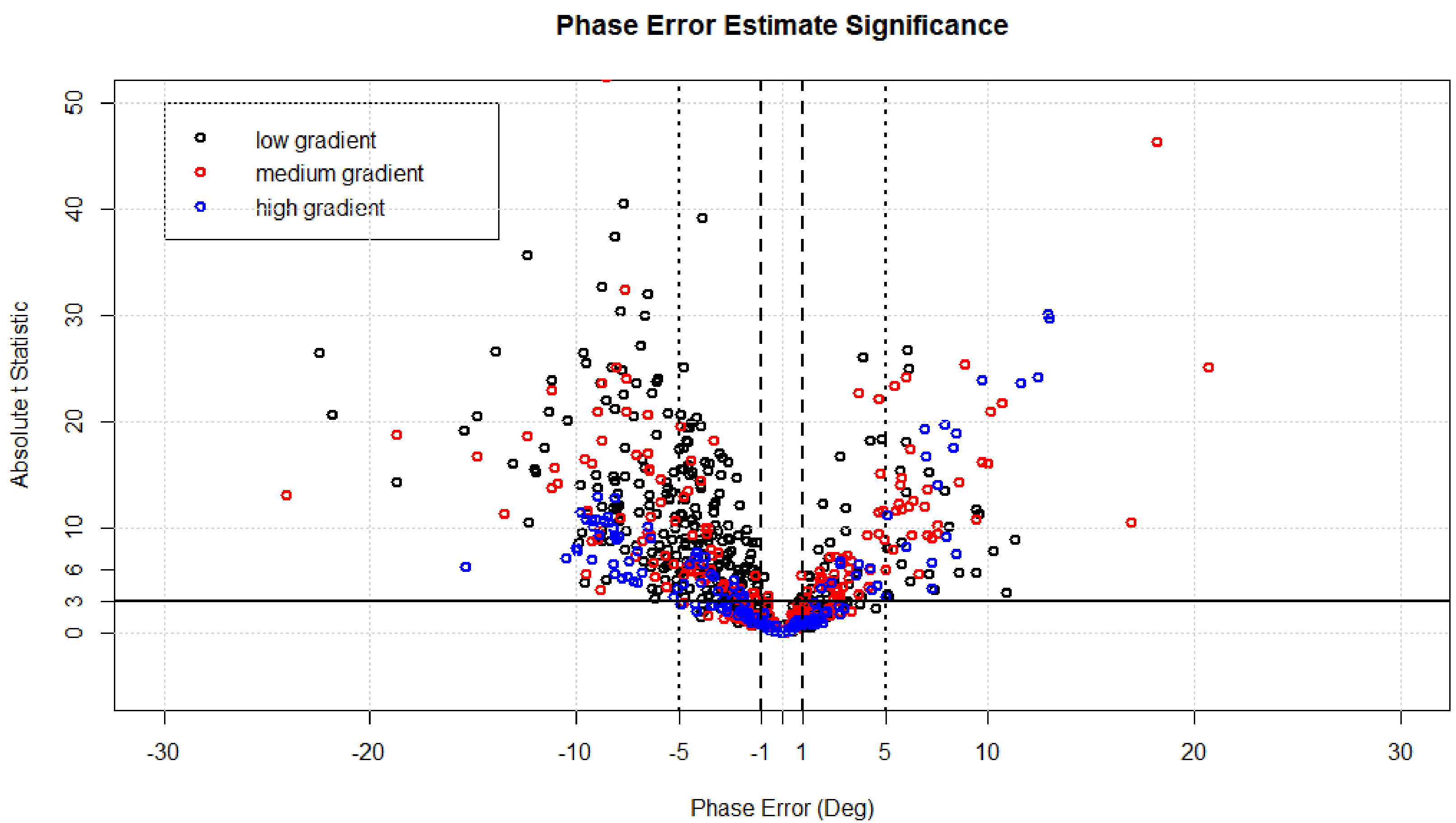
Parameter	Mean Abs. Diff.	Mean % Diff.
Amplitude (MeV/c)	-0.1	-1.4
Phase Error (degrees)	-0.04	1.0

Amplitude Error Trends



t statistic ≡ # standard errors from null hypothesis (Amplitude A = 0)

Phase Error Trends



t statistic ≡ # standard errors from null hypothesis ($\theta = 0$)

RfPhaser NLS Vs Simulation

Beam Studies	Phase Error RMS	Amplitude RMS	Amplitude RMS % of Mean
Low Gradient Cav	0.71	0.07	**2.0**
Medium Gradient Cav	0.68	0.11	**1.9**
High Gradient Cav	1.02	0.48	**5.0**

Monte Carlo	Phase Error RMS	Amplitude RMS	Amplitude RMS % of Mean
Low Gradient Cav	2.64	0.07	**4.6**
Medium Gradient Cav	0.58	0.12	**2.0**
High Gradient Cav	0.41	0.25	**2.3**

Summary

- RfPhaser provides a fully automated and accurate method for calibrating cavities.
- Low/Medium Gradient cavities:
  - ~2% RMS error on amplitude
  - Similar or better than Monte Carlo
  - Faster and more accurate than older methods
- High Gradient cavities:
  - ~5% RMS error on amplitude
  - Twice the RMS %error of Monte Carlo (reasons unknown)
  - Faster than and with similar accuracy to older methods

Thank you!

- Contributors:
  - Jay Benesch: concept and accelerator expertise
  - Chris Slominski: data acquisition and analysis software
  - Adam Carpenter: NLS and model analysis