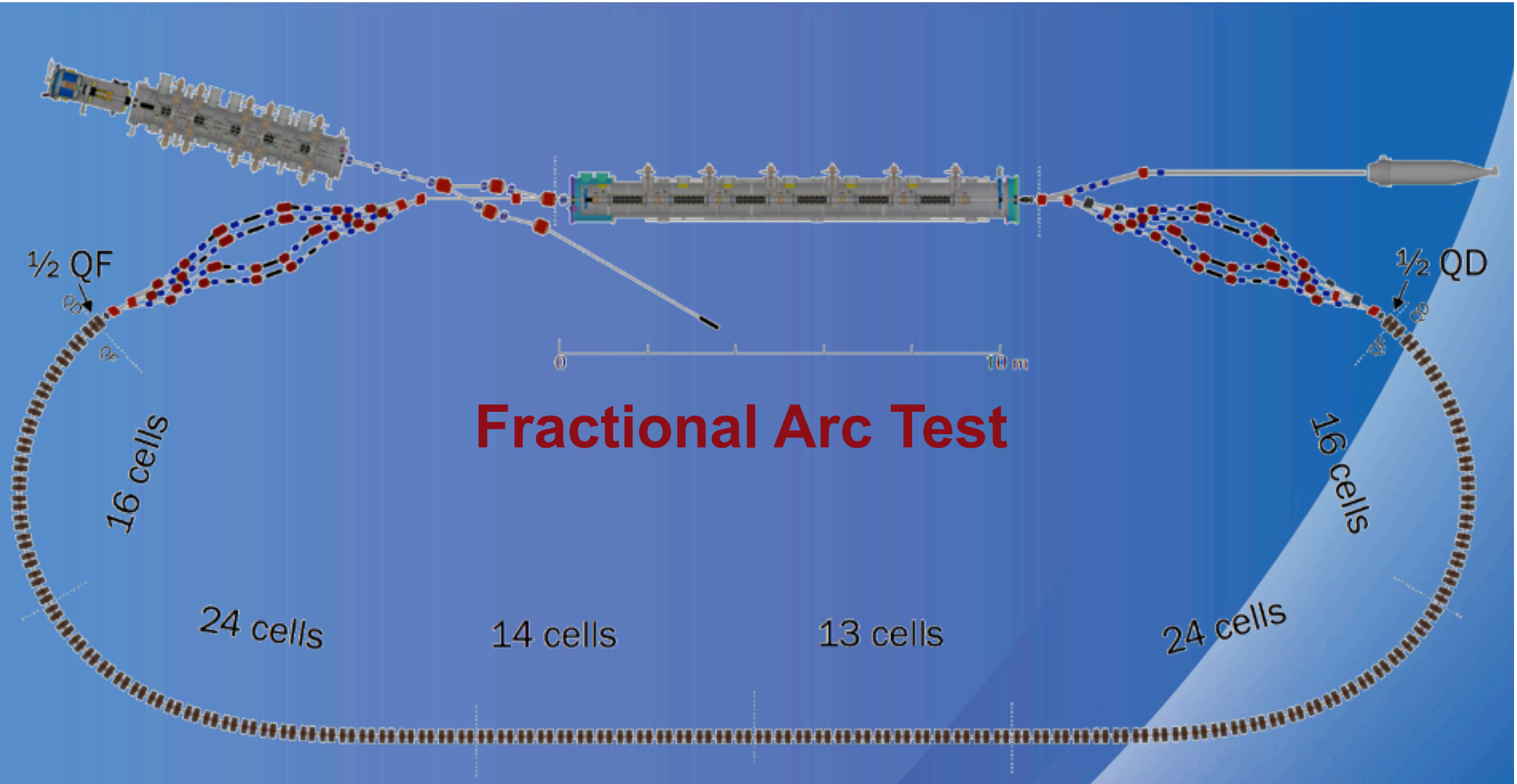


Fractional Arc Test

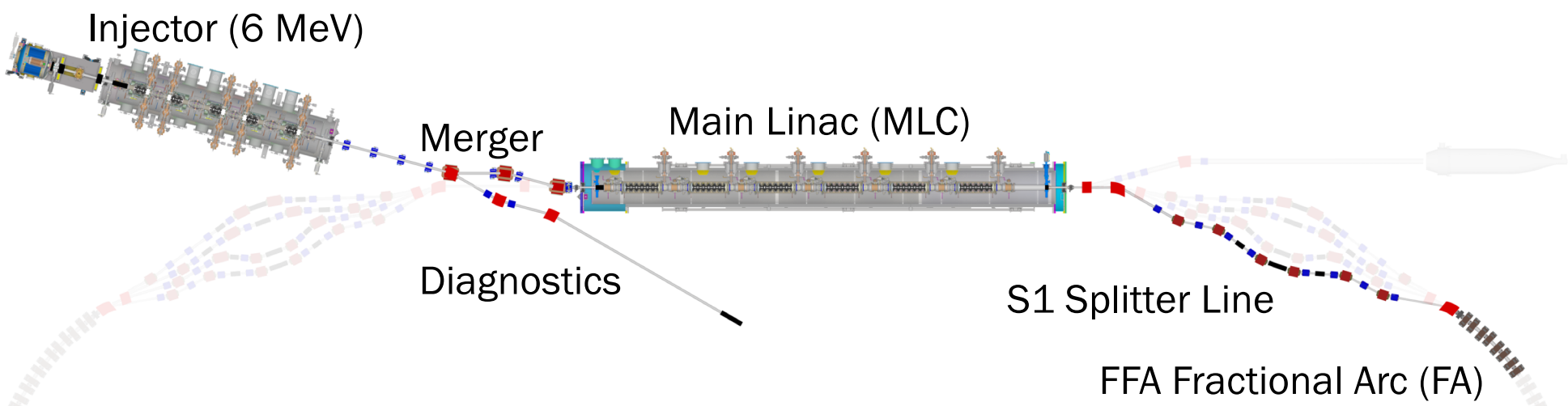
Colwyn Gulliford

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Fractional Arc Layout



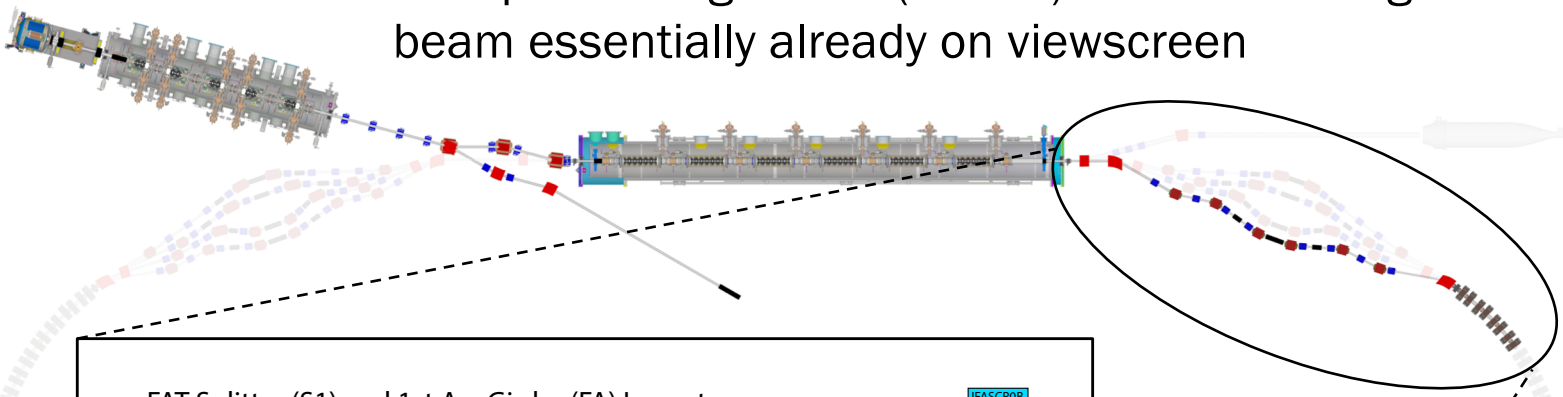
First time combining:
1. Injector
2. MLC
3. Splitter Magnets (Elytt Energy)
4. FFA Permanent Magnets

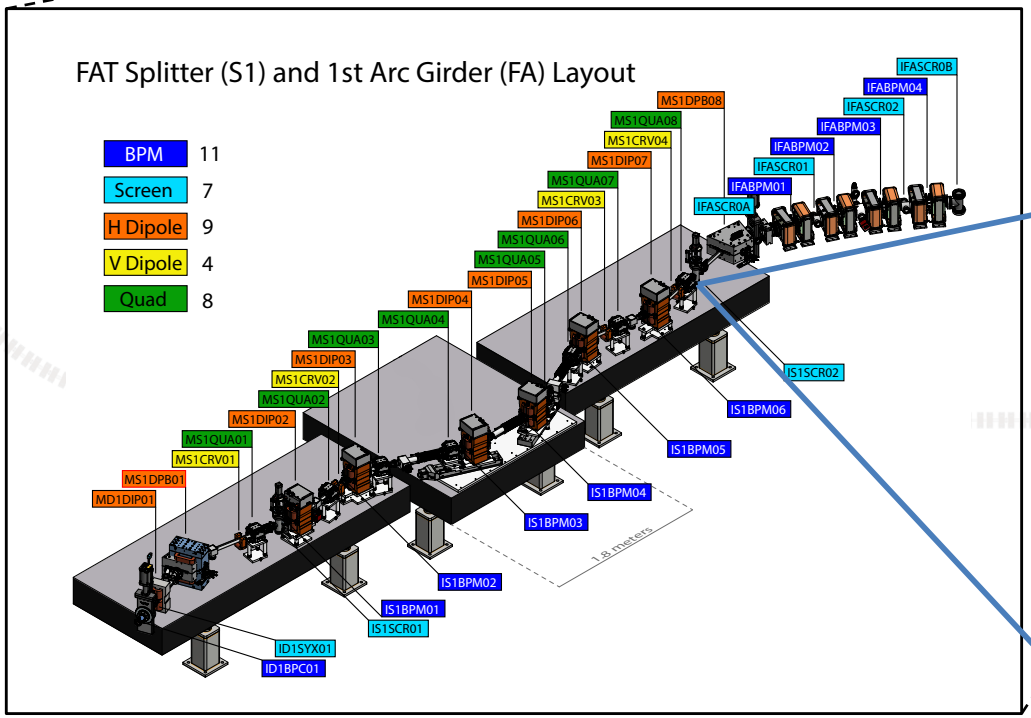
Modeling:
1. GPT for Injector – MLC
2. BMAD afterwards (or for strictly single-particle effects)
3. CBETA-V online model

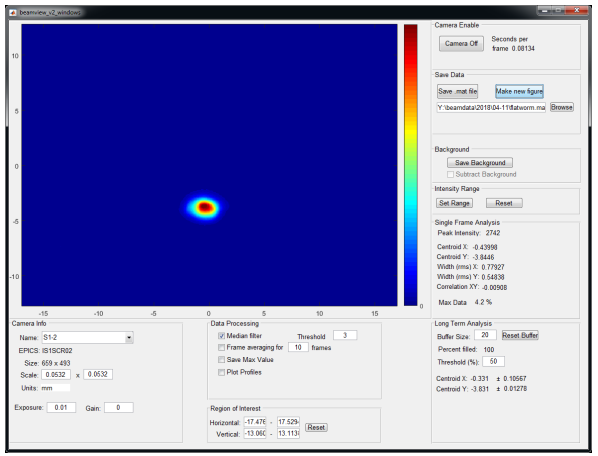
"The CBETA Fraction Arc Test" (CBETA Note 032)

Beam to end of Splitter (6 MeV)

Set splitter magnets to (scaled) nominal settings:
beam essentially already on viewscreen



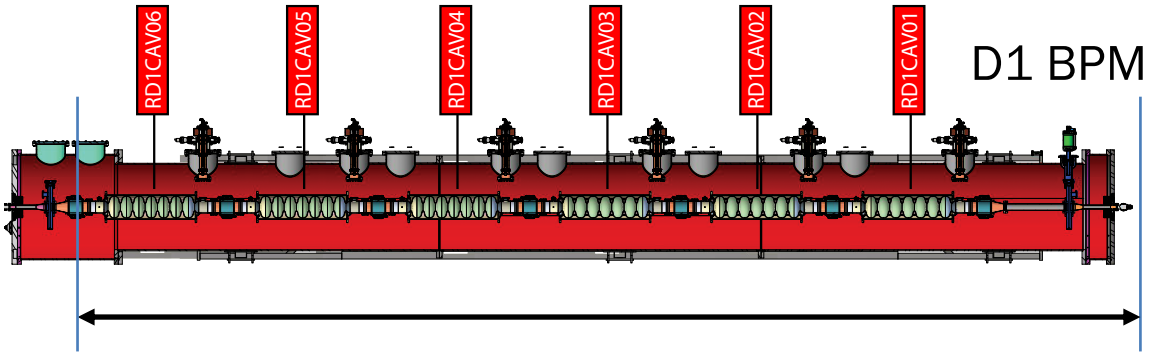




MLC Commissioning with Beam: Energy Gain

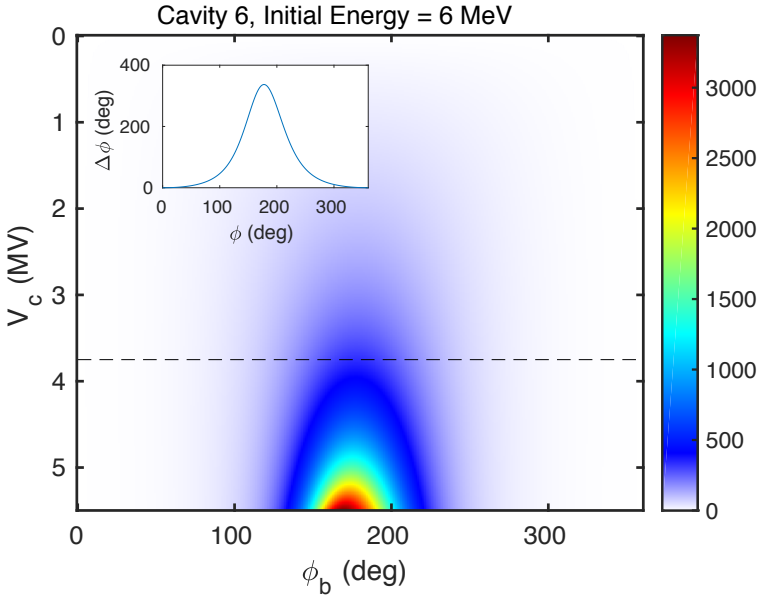
MLC Cavity Energy Gain:

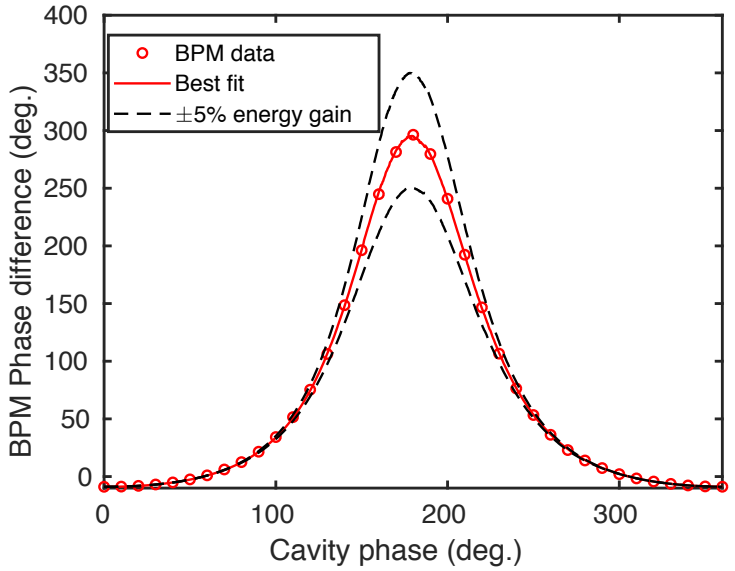
- Fix voltage
- scan cavity phase
- measure $\Delta\phi$ on downstream BPM



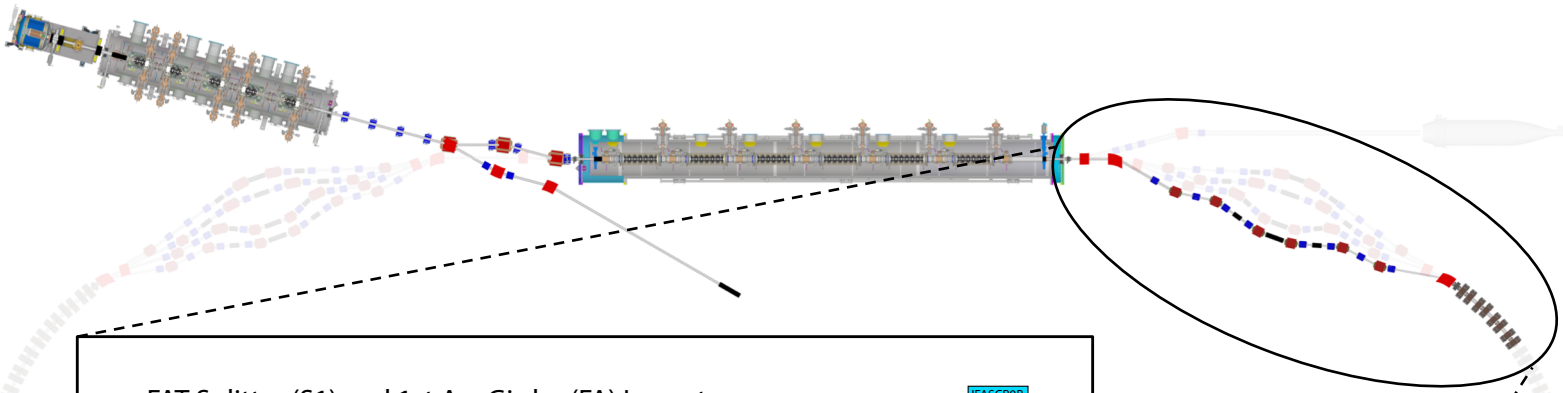
Model: Runge-Kutta tracking of on-axis particle from cavity entrance to BPM (E_0, V_c, L, ϕ_{off}):

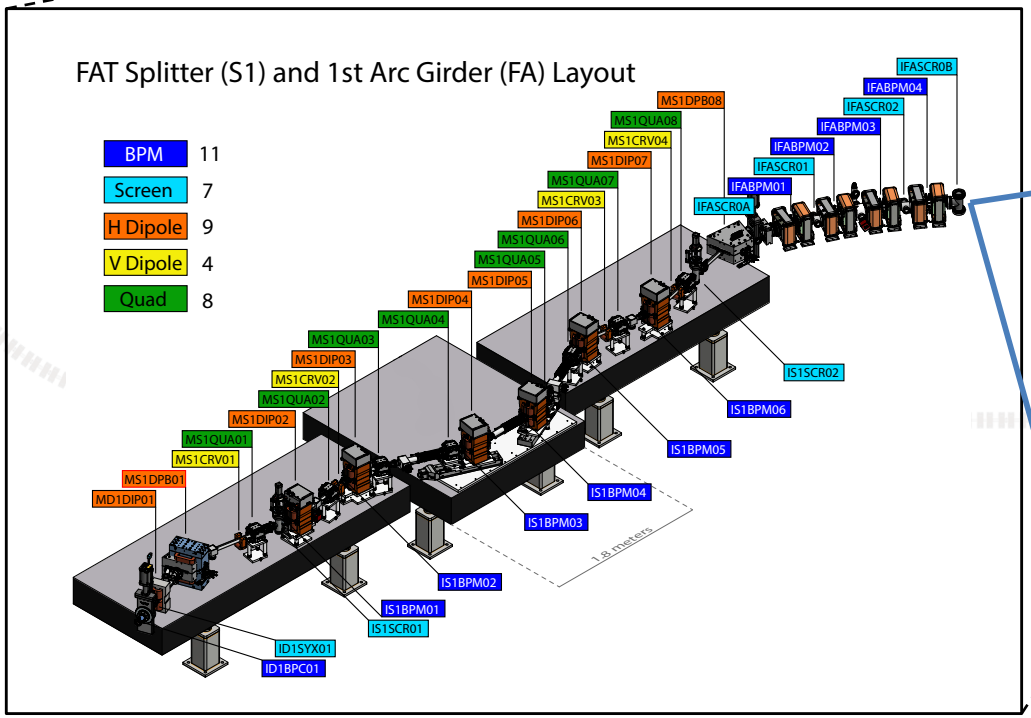
$$\Delta\phi = \frac{\omega}{c}\int_{\text{cav}}^{\text{bpm}} dz\left(\frac{1}{\beta(V_c,\phi_b)} - \frac{1}{\beta(V_c,\phi_b=0)}\right)$$

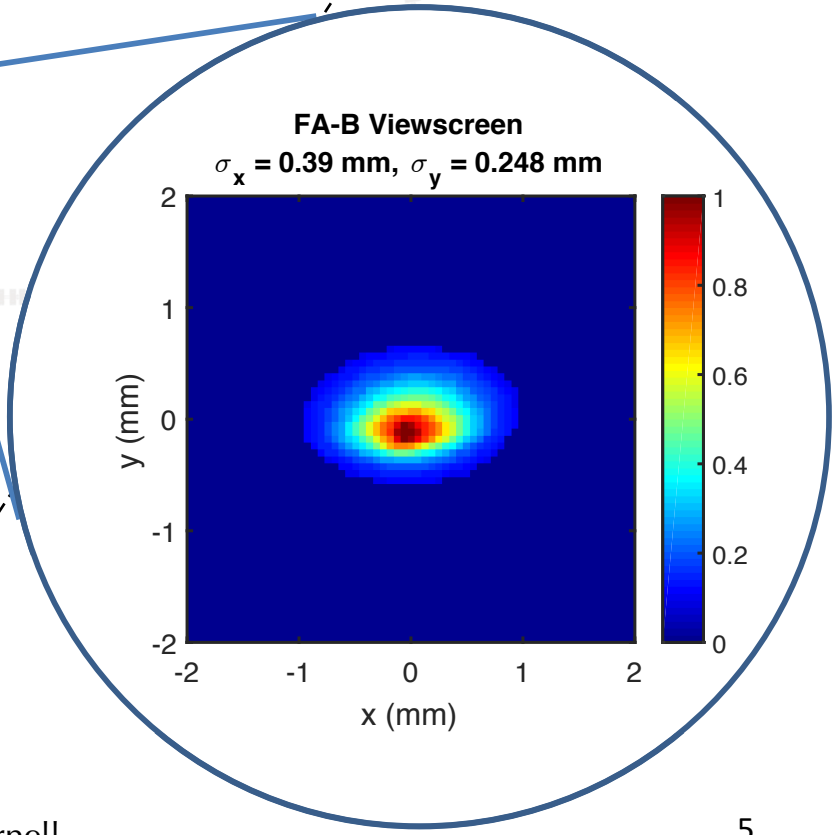




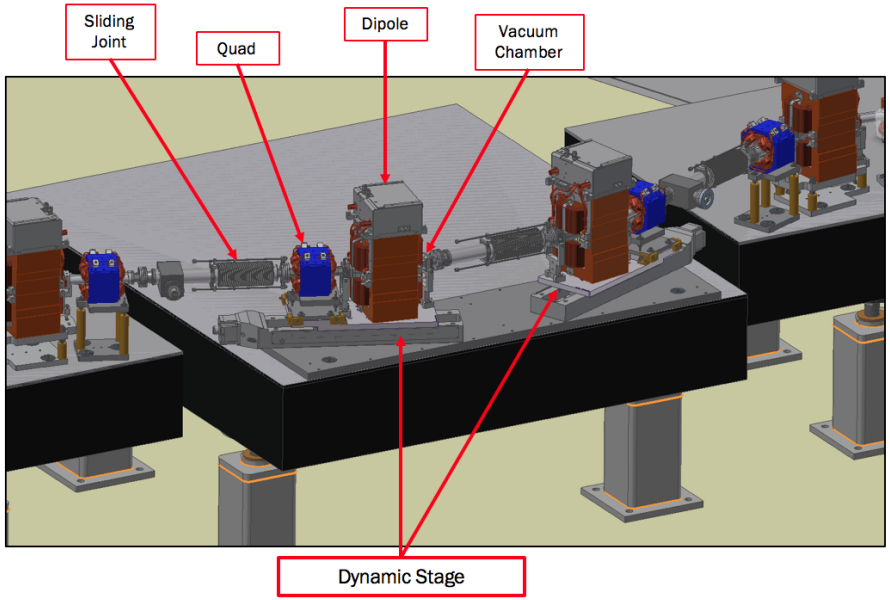
Beam to end of Fractional FFA Arc @ 42 MeV!

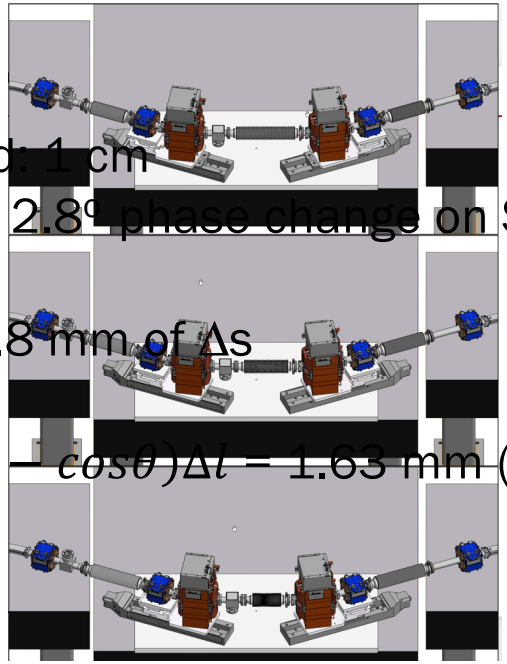






S1 Splitter Line: Path Length Adjustment



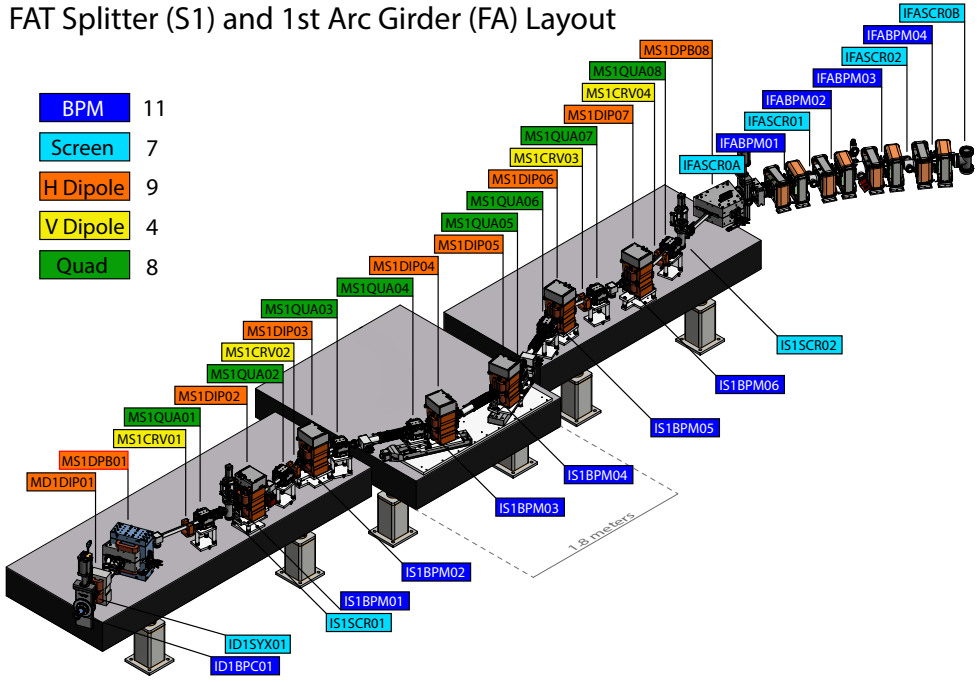


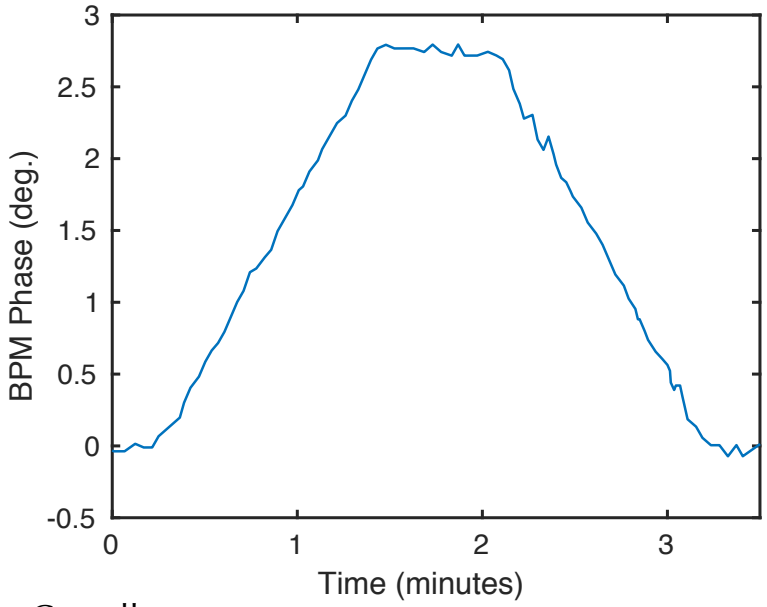
Command: 1 cm
Measure: 2.8º phase change on S1BPM06

2.8º ↔ 1.8 mm of Δs

$\Delta s = 2(1 - cos\theta)\Delta l = 1.63$ mm (θ=23.3º)

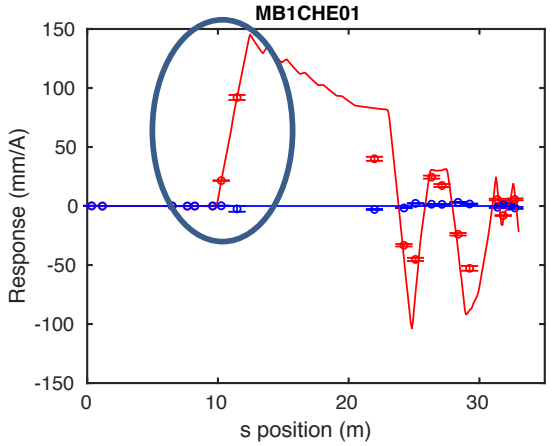
FAT Splitter (S1) and 1st Arc Girder (FA) Layout

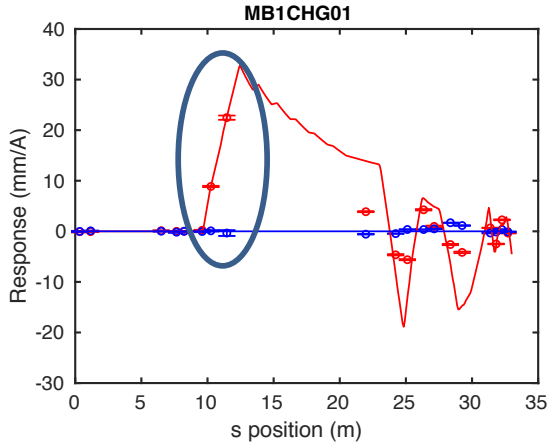


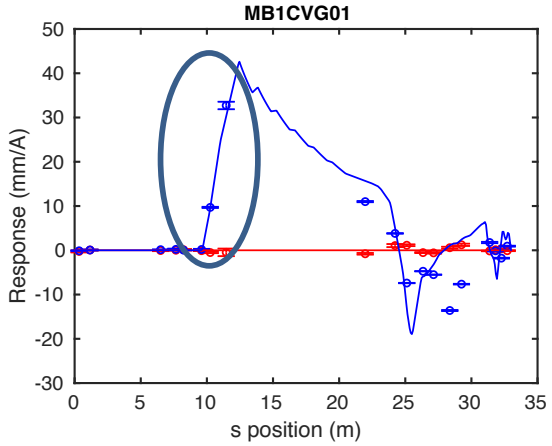


Orbit Response (42 MeV)

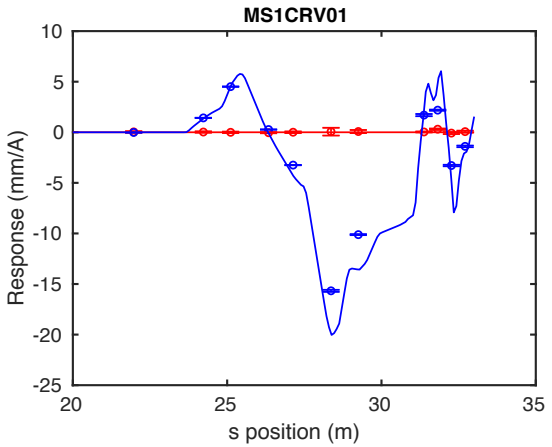
Measured corrector to BPM orbit response matrix

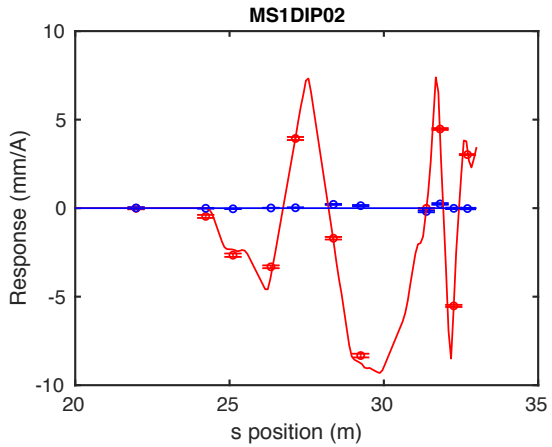


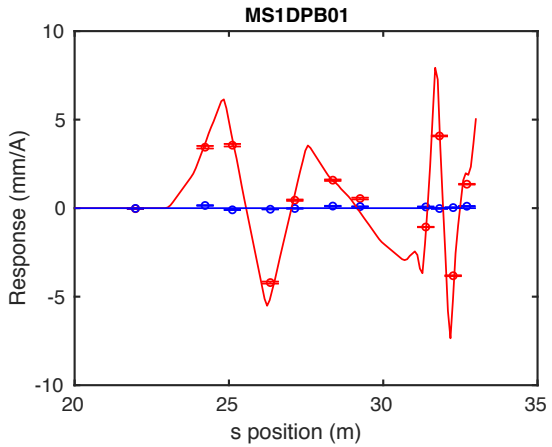




After Main Linac:



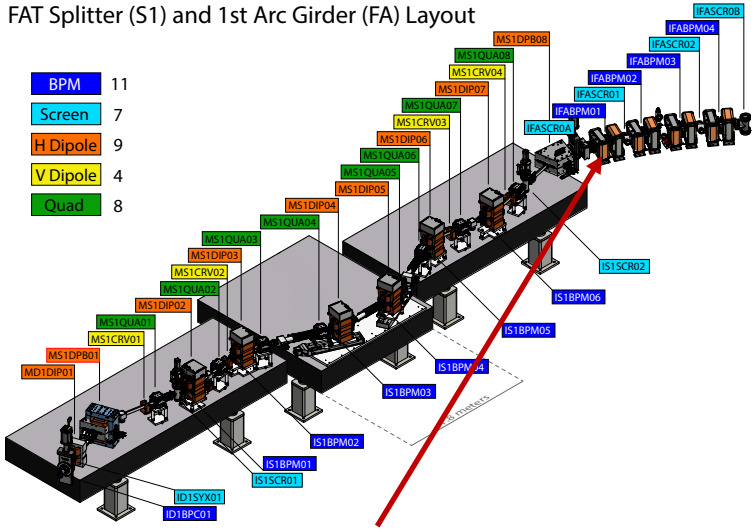


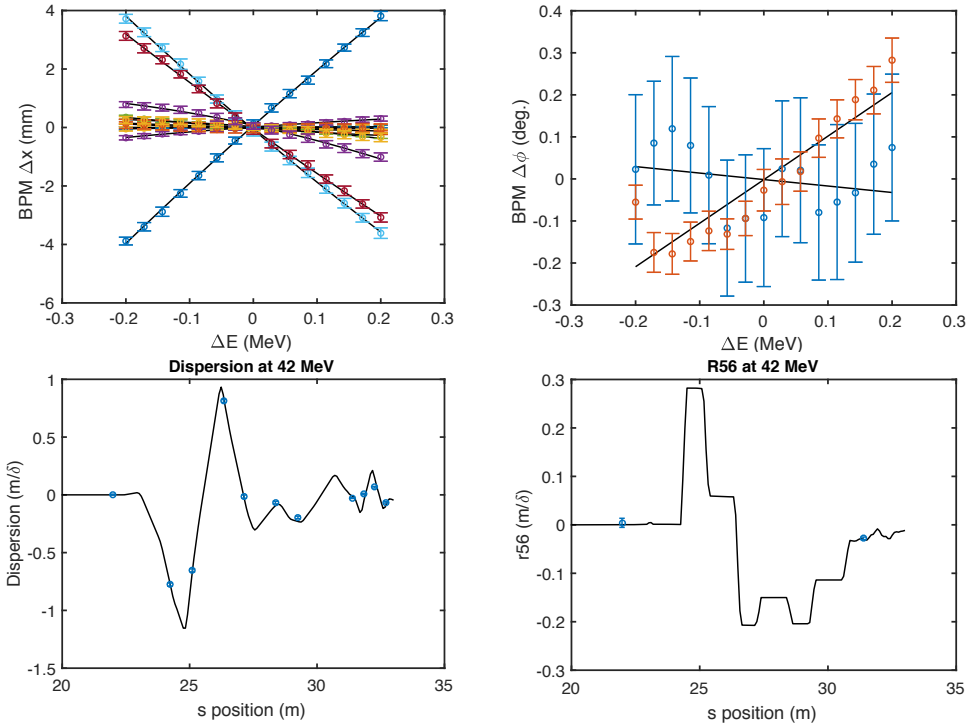


Nice way to verify online model/magnet calibrations

Dispersion and R56 @ 42 MeV

Scan voltage on last MLC cavity by ±200 kV, measure positions on all downstream BPMs

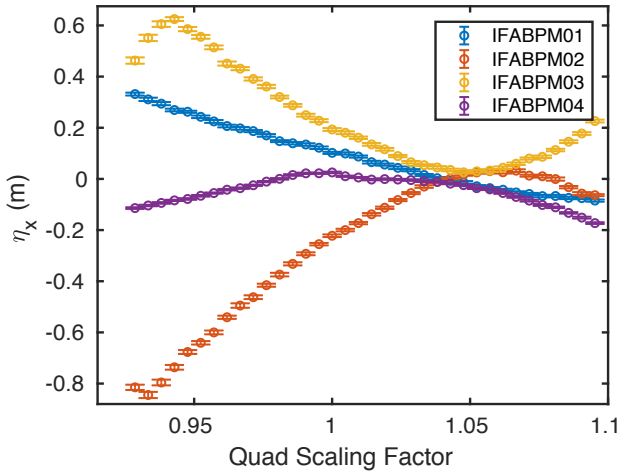




R56: measure phase on FABPM01

Ideally, dispersion is periodic in the FA section
Target value @ 42 MeV = -11 mm

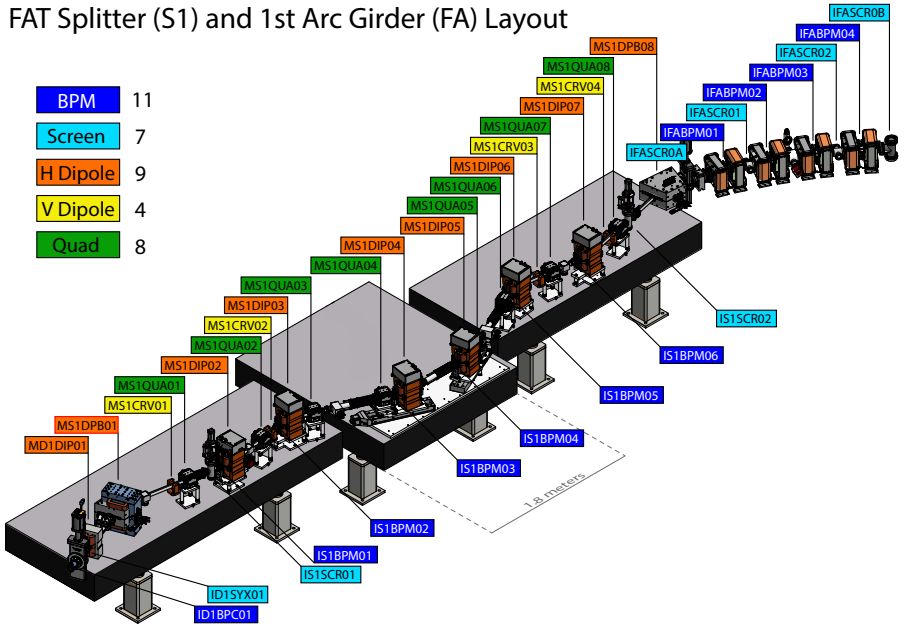
Initial measurements gave -400 to 250 mm, and not periodic



Energy Scan: Dispersion, R56, Betatron Oscillations

Goals:

- Demonstrate capabilities of MLC
- Determine FA BPM offsets
- Verify optics properties vs. Energy



Procedure:

- Set MLC cavities for desired energy (E)
- Use pre-determined S1 settings @ E from model
- Steer on to periodic orbit
- Measure dispersion, R56, FA orbit response to Betatron Oscillations

MLC provided up to roughly 53 MeV energy gain
1.5 X the required 36 MeV!

Betatron Oscillations vs. Energy: BPM offsets and Tunes

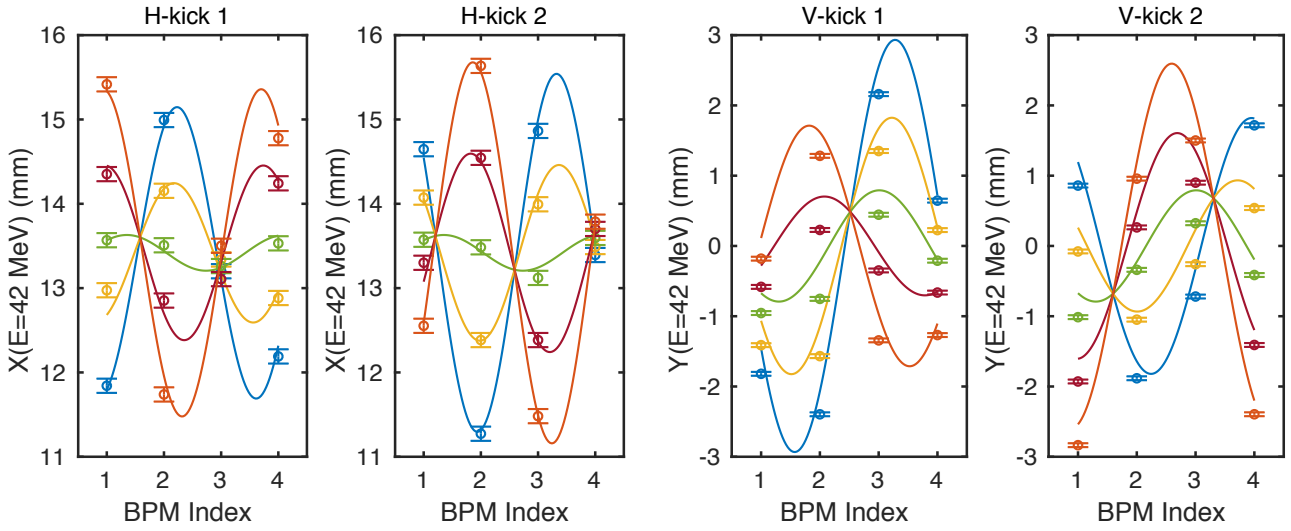
Recall: MLC cavities set, S1 Quads + Dipoles set (tweaked for periodic orbit)

- 2 Linear combinations of the last two S1 Dipoles, Vertical Correctors
- In model: 2 betatron oscillations $\pi/2$ phase apart, amplitude ~1 mm in FFA
- Scan each kick from -2 to +2 in unit steps

$$x_{mn} = \left(s_x^{(1)} A_{x,n}^{(1)} + B_{x,n}^{(1)}\right) \cos\left(2\pi m \nu_{x,n} + \phi_{x,n}^{(1)}\right) + \left(s_x^{(2)} A_{x,n}^{(2)} + B_{x,n}^{(2)}\right) \cos\left(2\pi m \nu_{x,n} + \phi_{x,n}^{(2)}\right) + C_{x,m} + D_n$$

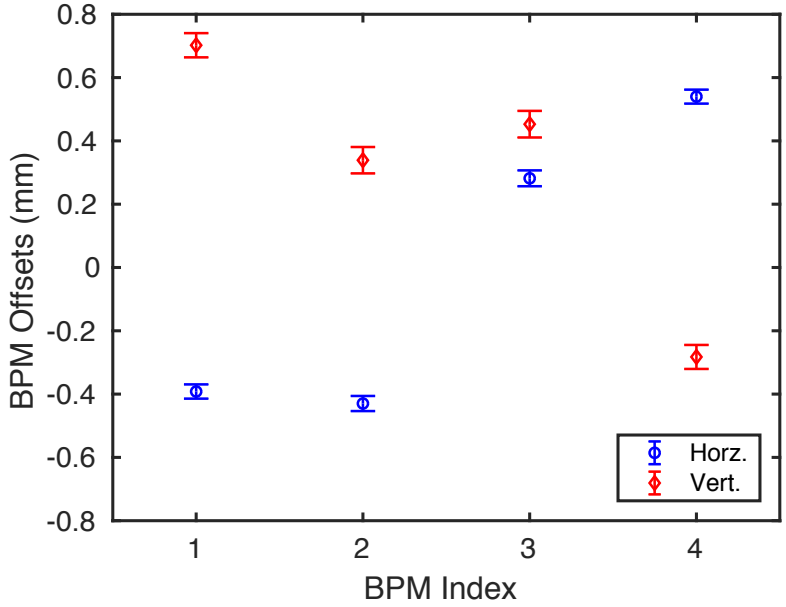
$$y_{mn} = \left(s_y^{(1)} A_{y,n}^{(1)} + B_{y,n}^{(1)}\right) \cos\left(2\pi m \nu_{y,n} + \phi_{y,n}^{(1)}\right) + \left(s_y^{(2)} A_{y,n}^{(2)} + B_{y,n}^{(2)}\right) \cos\left(2\pi m \nu_{y,n} + \phi_{y,n}^{(2)}\right) + C_{y,m}$$

Guess for A's ~ 1 mm
Guess for B's ~ 0 mm
Guess for C's ~ 0 mm
Guess for D's from 3D tracking

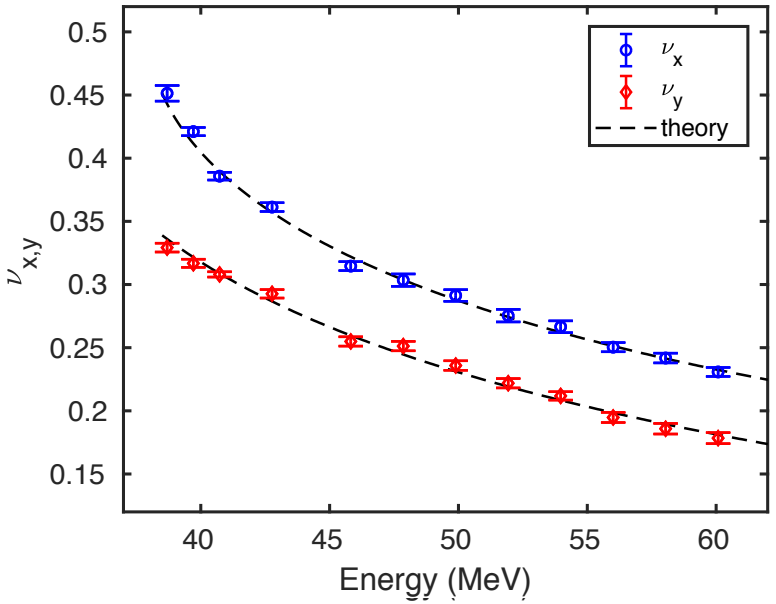


Betatron Oscillations vs. Energy: BPM offsets and Tunes

Determined BPM Offsets:

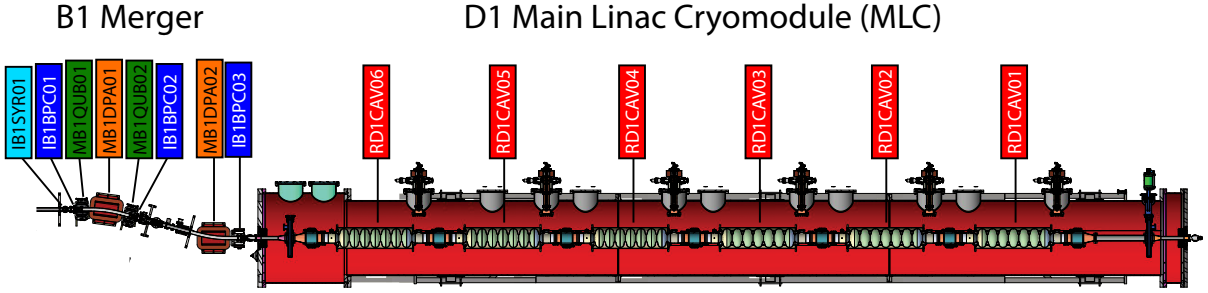


Energy = 1.018*E



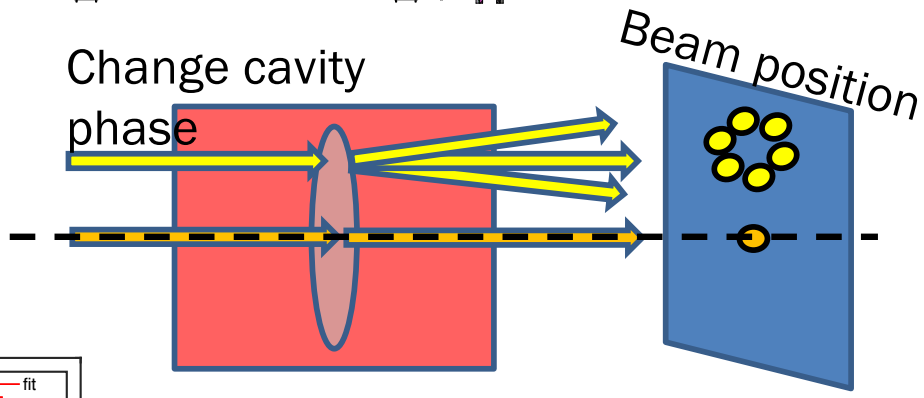
MLC Vertical Offset(s)

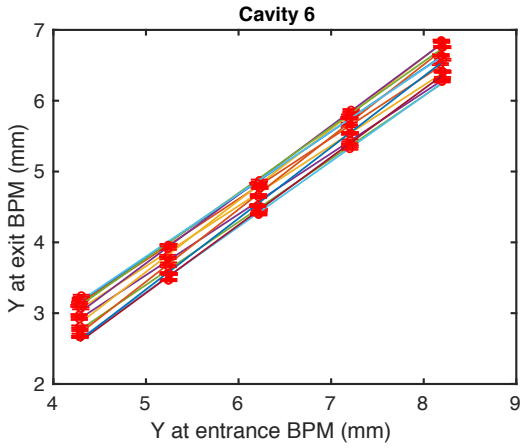
Centering the beam in the cavities by hand seemed to show ~5 mm offset of MLC

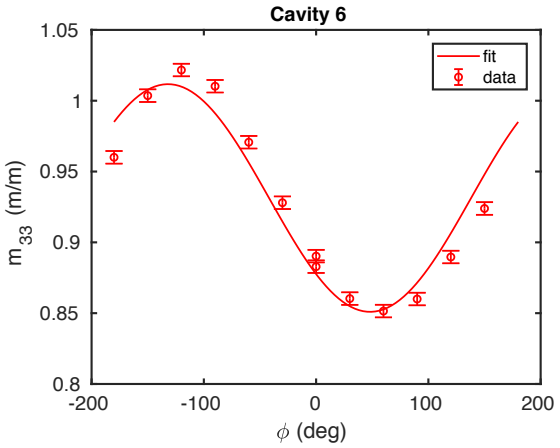


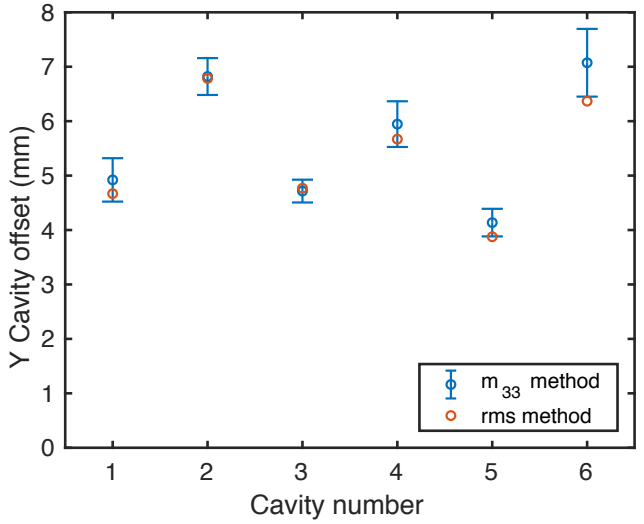
Procedure:

1. One cavity on (at a time)
2. Scan H/V beam position entering cavity hold beam angle constant (small)
3. Measure x,y on BPM before/after cavity vs. phase









$$y_f(\phi) = m_{33}(\phi)y_i + m_{34}(\phi)y_i' + (1 - m_{33})y_{\text{cav}}$$

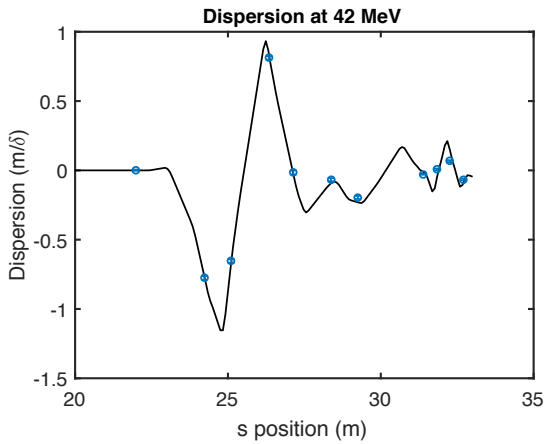
$$\begin{aligned} m_{33} &= A\cos(\phi + \phi_0) + B \\ (1 - m_{33})y_{\text{cav}} &= C\cos(\phi + \phi_0) + D \end{aligned}$$

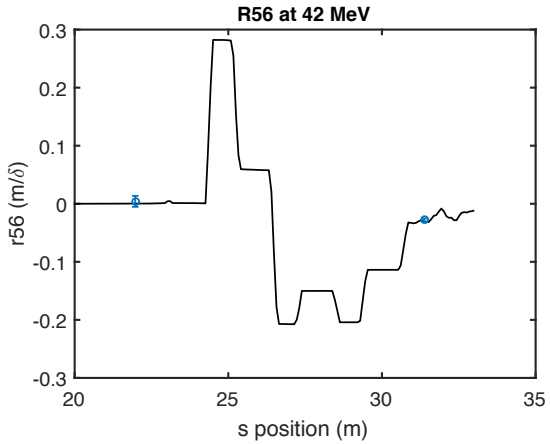
Conclusion

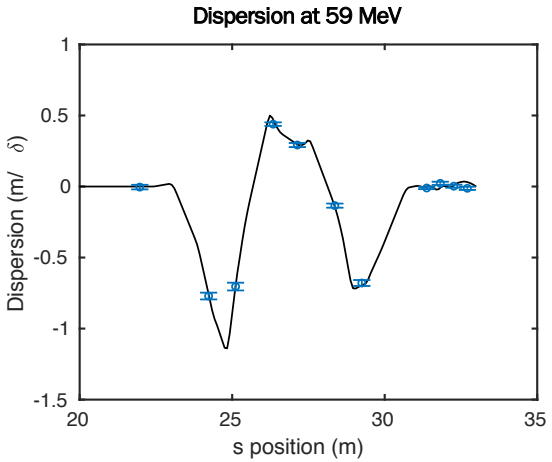
Achievements/Concerns	Solutions
Injector	
• Best performance shows suitable match	
• Level of agreement shown not reproduced during FAT	New settings via MOGA optimization
MLC	
• Cavity energy gains calibrated (to ~0.5%)	
• Energy gain up to 53 MeV (1.5 X required 36 MeV)	
• At 6 MV, field stability of 10^{-4} for several hours (no trips*)	
• Developed phasing procedure, but not automated	Script development
• Cavities offset vertically by 5.5 mm (average)	Analysis of original survey, re-survey
Splitter	
• Demonstration of Elytt magnets	
• Analysis of quad data underway	
• BPM non-linearity quantified	
• Successful path length adjustment test	
Fractional Arc (Prototype FFA girder)	
• Threaded beam to the end of FFA section	
• Tunes vs. energy (agree with 3D tracking @ % level)	
• Did not quantify FA BPM non-linearity	3D RF simulations
Misc:	
• Measured machine wide corrector-BPM response matrix	
• Successful tests of online model/virtual machine	
• Didn't significantly test correction algorithm(s)	Tested SVD with online model after FAT

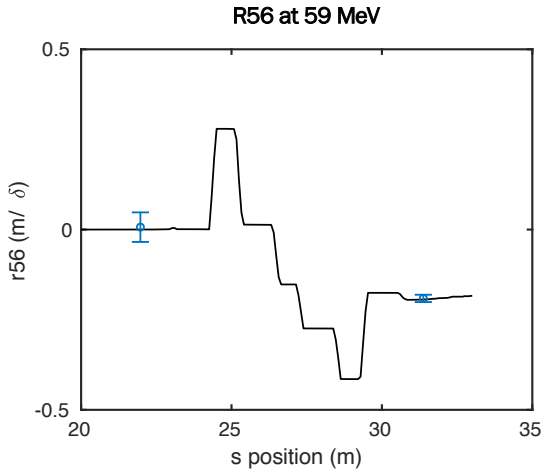
Dispersion and R56 vs. Energy

Splitter Line – FA

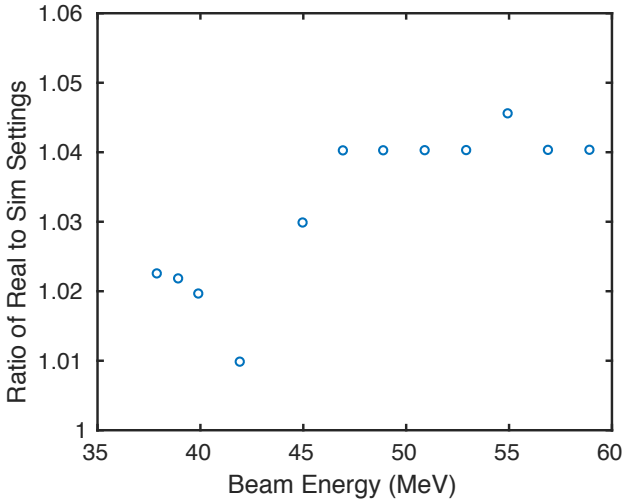








Quad scaling factor to make model agree with measurement:

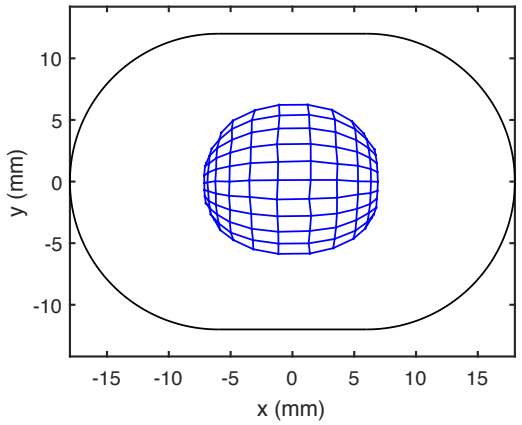


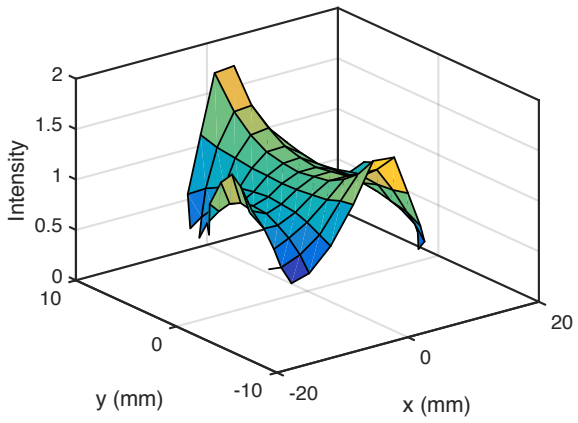
Model agrees to within a few % - GOOD for first set of measurements

For future, need dispersion response matrix for finding periodic value

S1 Splitter Line

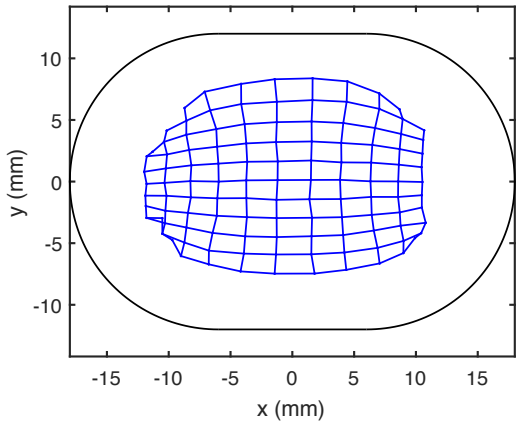
Diff/Sum

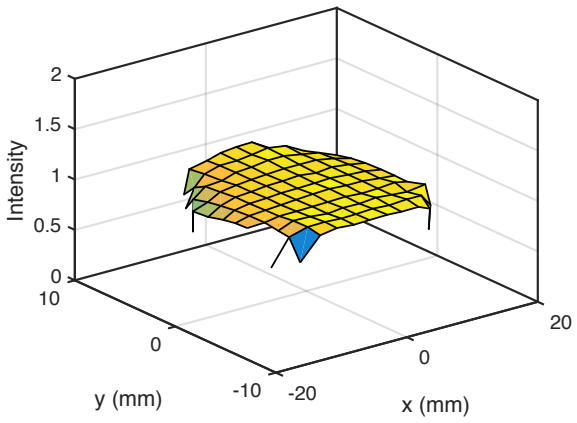




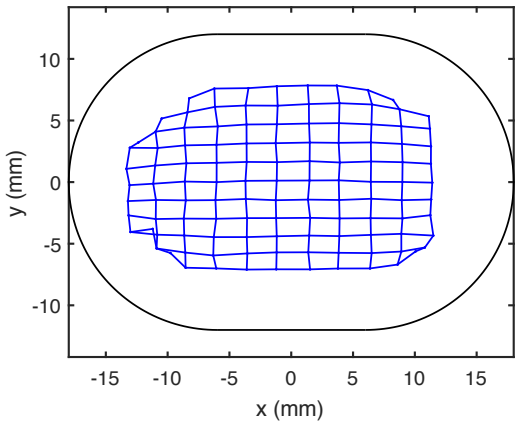
Analytic Model

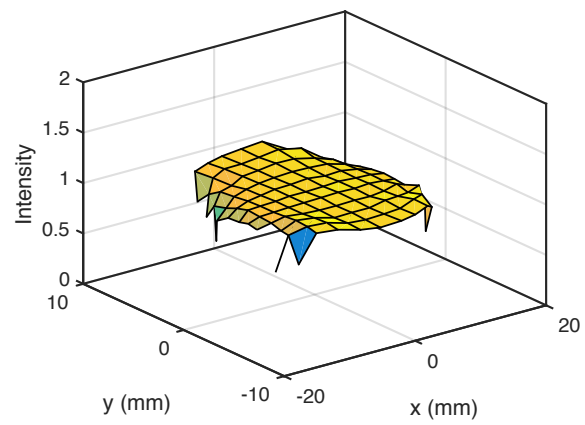
$R_{eff} = (R_x + R_y)/2$





2D Poisson





FAT Virtual Orbit Correction Tests