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PIT Meeting
07/27/04

Fixing Injector Transport
(Coupling and Matching Correction from 100 keV to NL)

Why do we need to do this?

What/Where is the problem?

The Approach

Progress so Far

Roadblocks

What needs be done?

Why do we need to do this?

"Parity Experiments" require that orbit changes on the cathode caused by helicity flipping be reduced to levels small enough not to wash out real helicity-induced signals.

Specs on Experiment-Averaged HC Parameters

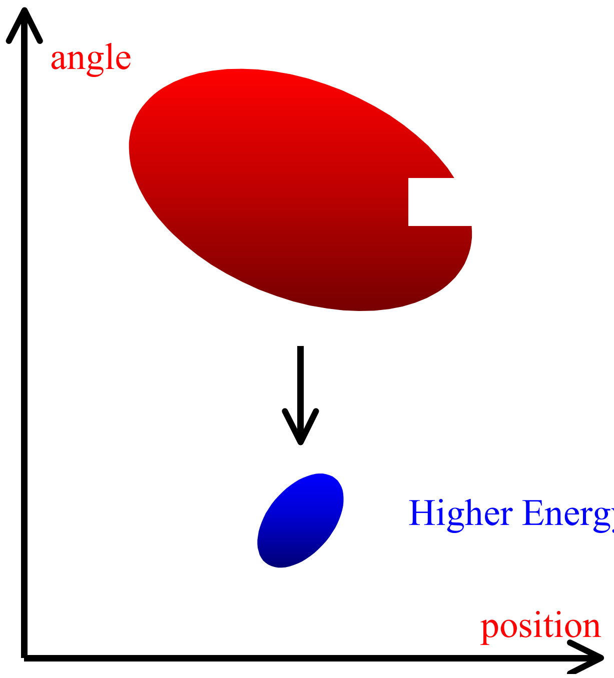
Experiment	Physics Asym. (ppm)	Intensity (ppm)	Position on Target (nm)	Angle on Target (nrad)
HAPPEX-I	13	1.0	10	10
G0	2-50	1.0	20	2
HAPPEX-He	8	0.6	3	3
HAPPEX-II	1.3	0.6	2	2
Qweak	0.3	0.1	20	100
Lead	<1	0.1	1	1

In contrast, orbit changes on the cathode caused by helicity flipping are at μm level → Reduction by 500-1000 needed

- **Reduce initial orbit: Source optics improvement, better cathode performance, ……**
- **Helicity feedback (G0)**
- **Phase trombone to minimize overall orbit impact on detector signal**
- **Claim all <u>adiabatic damping</u> and <u>good matching</u> of orbit that we are entitled to**

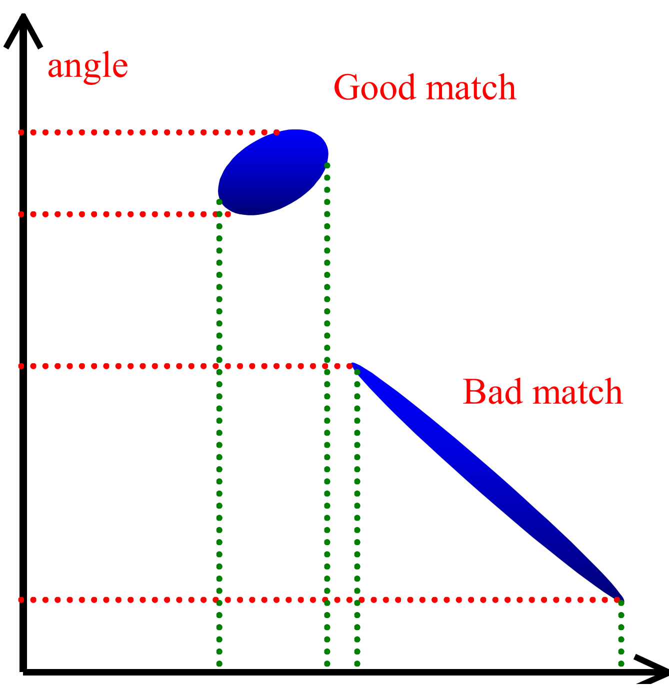
Adiabatic damping: Damping of orbit oscillation due to momentum increase

- Area of beam distribution in the phase space (Emittance) shrinks as momentum goes up, and is inversely proportional to momentum.
- This can be violated if there is X-Y coupling in the transport
- Same applies to orbit amplitudes (inversely proportional to square root of momentum).

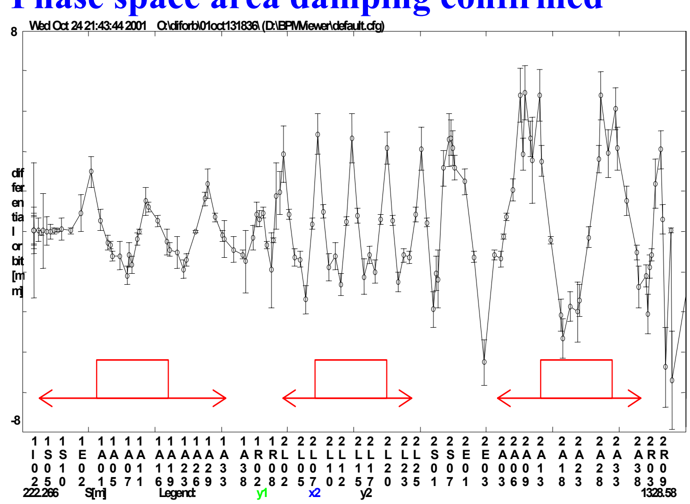


	P (MeV/c)	Orbit Scale	
100 keV	0.335	1.000	
5 MeV	5.5	0.247	↓
Chicane	55.5	0.074	X14
Arc 1	555.5	0.023	↑
Arc 2	1055.5	0.017	↓
Arc 3	1555.5	0.014	X5
Arc 4	2055.5	0.012	↑
Arc 5	2555.5	0.011	
Arc 6	3055.5	0.010	
Arc 7	3555.5	0.009	
Arc 8	4055.5	0.009	
Arc 9	4555.5	0.009	↓
AT	5055.5	0.008	X1.8

- Even if phase space area is properly damped, bad matching can still blow up the orbit by any factor.



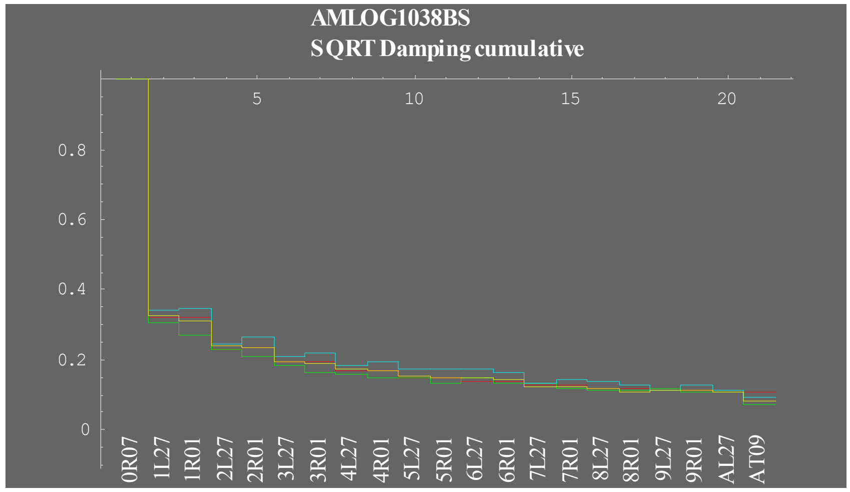
Fopt data Oct 13, 2001
Phase space area damping confirmed



What/Where is the problem?

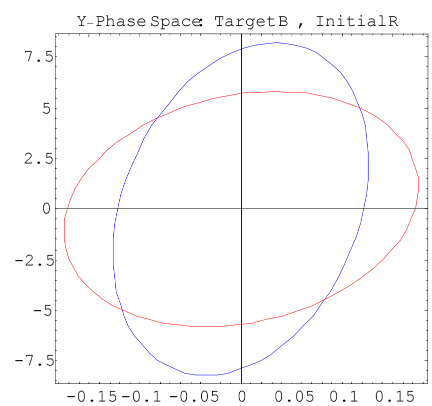
We don't have major problems from 55 MeV to 5 GeV

Momentum damping of phase space area agrees with theory
→ No significant XY coupling



Measured amplitude damping (01/31/03) from 55 MeV to 5 GeV
Red: theory / Yellow: measured

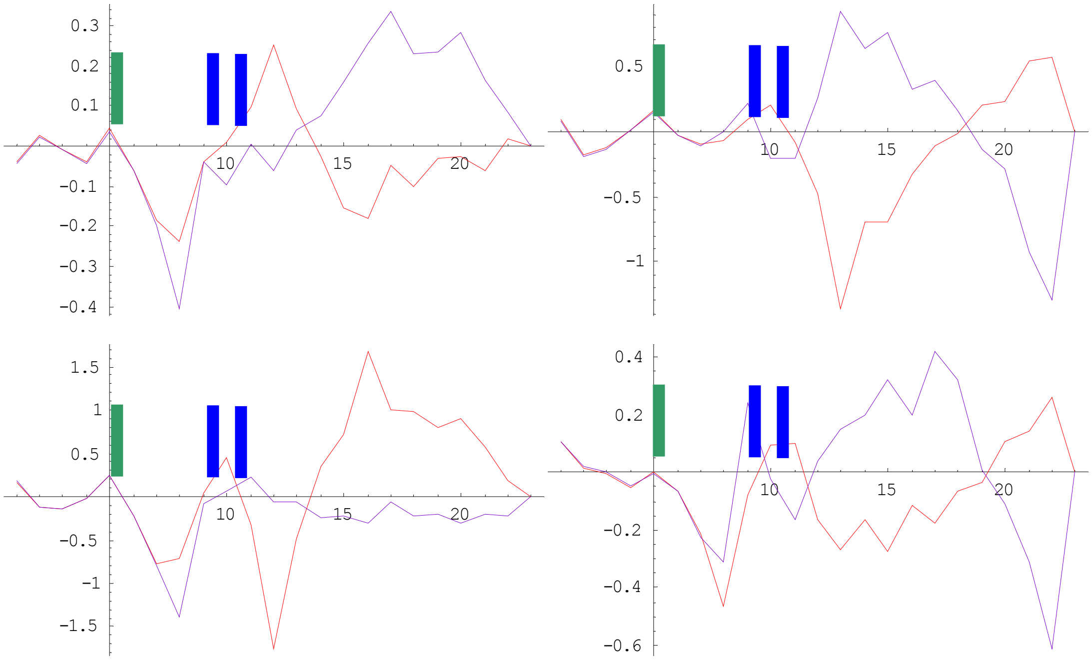
Propagation of design beam is well-contained at the end
→ No significant mismatch



Propagation of X/Y design phase ellipse (01/31/03) from 55 MeV to 5 GeV
Blue: design / Red: measured

All the problems come from 100 keV to 55 MeV (including Chicane-NL junction)

PZT orbits (spot displacement on cathode) in the Injector (times $\sqrt{P}$)



Green: Cryo-Unit **Blue: Cryo-Modules**

Source of blowup:

- **XY coupling in the cryo-unit and cryomodules. These are not well modeled at such low energy**

  → Increased phase space area

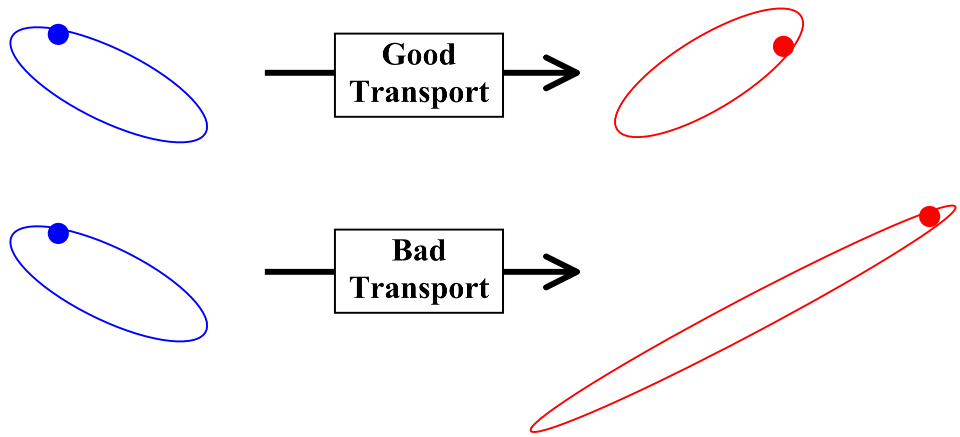
- **Mismatch of PZT orbits to the transport channel formed by <u>the capture, the cryo-unit, the cryomodules and possibly the Chicane-NL junction</u>, for which we don't have a good model.**

  → Orbit blowup

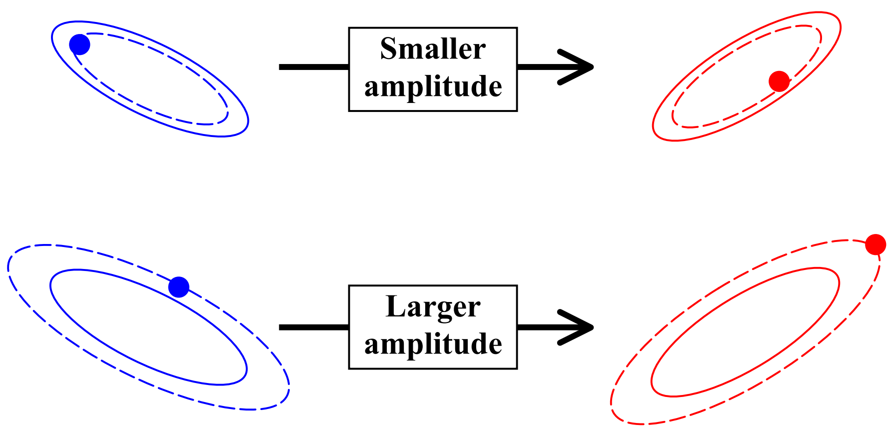
So the fundamental problem is that we don't know how to transport the orbit through this region correctly due to insufficient model information.

Significance of the PZT orbit and its matching to machine transport

- **Machine transport should be well designed such that it keeps amplitude of most orbits contained**



- **However, there is no magic transport that will treat all orbits equally well → This is why there is a need to "match" the beam in the first place.**

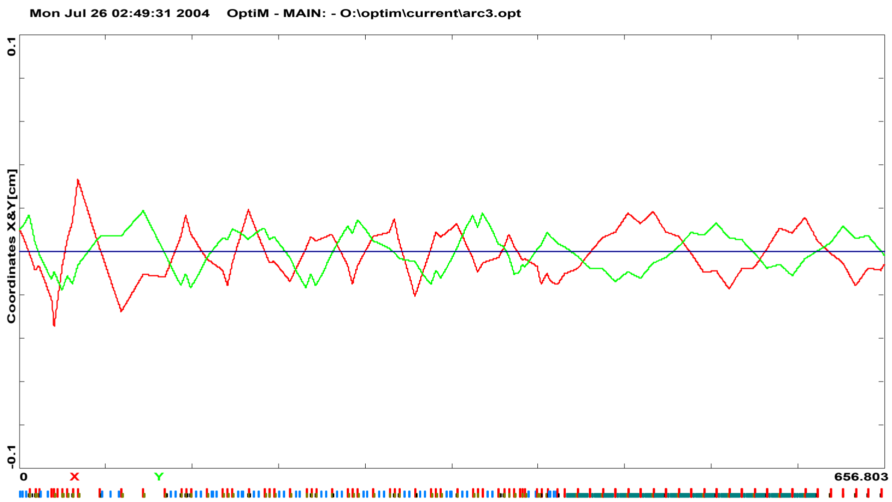


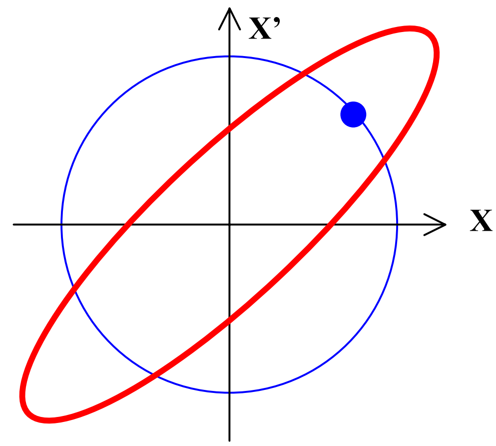
- **In the rest of the machine, we match the beam to the design transport, but here we need to match the transport to the beam, or rather the PZT orbits, which are what the parity experiments really care about, and which cannot and should not be changed until 5 MeV.**

Example: Arc 3 Transport of Orbit Oscillations

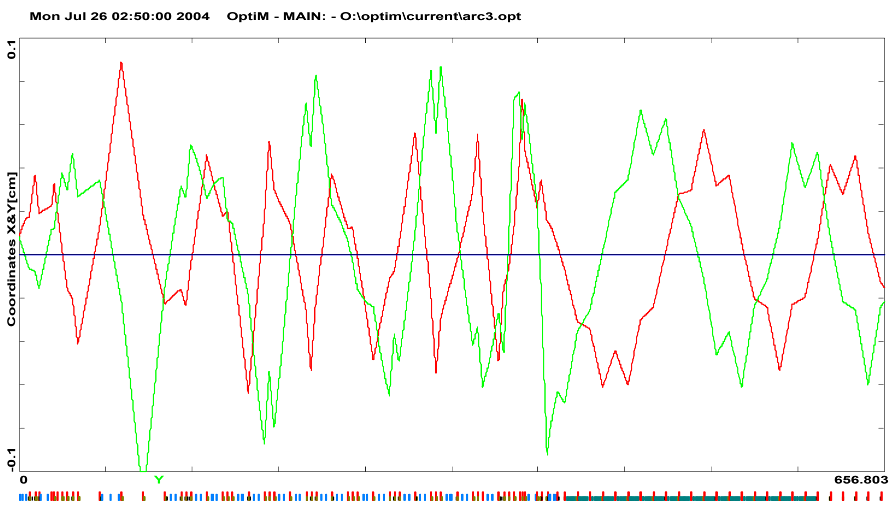
Arc 3 constitutes a well-behaved transport system capable of transporting reasonable orbit oscillations from beginning to end. However, depending on the exact detail of these orbits, the resulting amplitudes can be quite different.

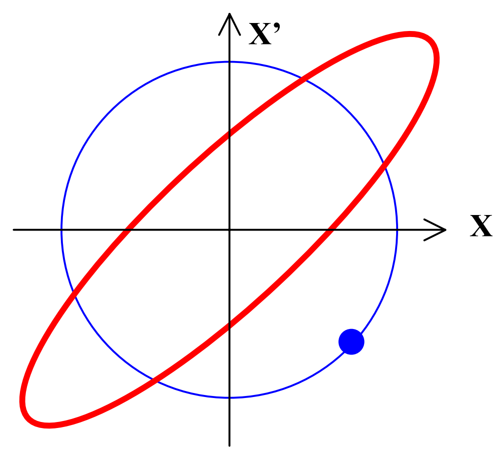
Orbit More Matched to the Lattice





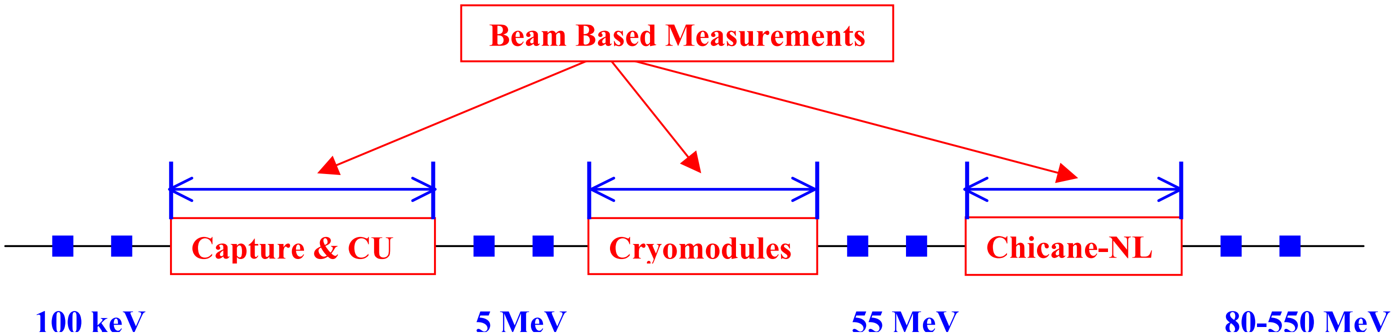
Orbit Less Matched to the Lattice



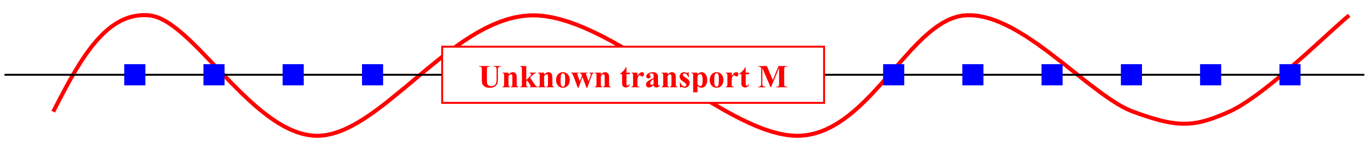


The Approach

- First we need to obtain the model for all segments whose transport has eluded us so far.



- Standard technique of measuring 4×4 transfer matrix across unknown sections based on difference orbits has been applied routinely to CEBAF at 55 MeV and above.



Measured transfer matrices will contain XY coupling.

- Replace missing pieces in the model with measured transfer matrices and

A. Calculate quad and skew quad changes needed to achieve well-behaved overall transport (Skew quad contribution, unfortunately, is a non-negligible part of this process)
   - Need to know CU transport accurately
   - Less sensitive to 100 keV changes
   - Has to be done eventually

B. Calculate quad changes needed to bring observed PZT orbits at 5 MeV to match to optics at 55 MeV, and then into NL
   - More tailored to PZT minimization
   - Don't need to know CU transport
   - More sensitive to 100 keV changes

Progress so Far

- **April to June 2004:**

  - **It was realized that difference orbit data taken across the CU and CM support interpretation of 4×4 symplectic transfer matrices to very high degree of accuracy**

  → Transport across CU and CM can be completely modeled and corrected by quad and skew quad fields only

  - **4 skew quads were installed in 5 MeV section**
  - **Extensive offline analyses led to quad+skew quad solutions meeting various criteria for the 100 keV to 55 MeV transport, in addition to eliminating XY coupling:**
    - **Minimal skew quad strengths**
    - **Most uniform adiabatically damped transport**
    - **Optimal beam shape (Twiss param.) for given input beam**
    - **……**

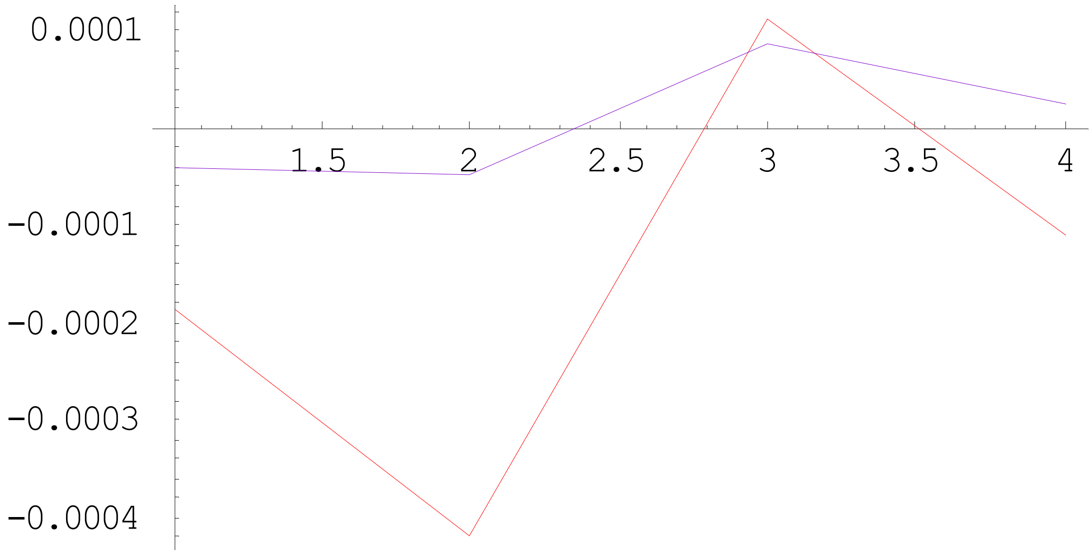
- **June 2004 to Now:**

  - **Since 06/02 nine MD sessions went into testing this approach.**
  - **Emphasis has shifted from option A to B due to significant change in CU behavior in early June and skepticism over newly measured CU transport.**
  - **So far the main outcome is identification of myriad roadblocks and learning what to avoid for the next test.**
  - **Secondary outcome includes usable measured transport across CM and Chicane-NL junction**
  - **However we should be one test away from partial proof-of-principle for option B if nothing breaks again.**

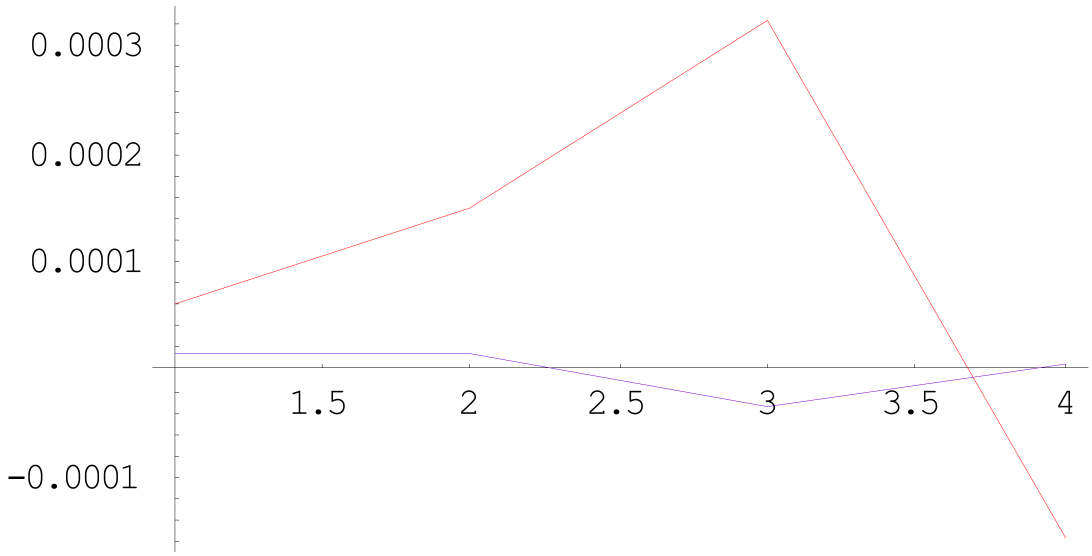
Example of predicted solution

Optimization applied <u>only</u> to the X components of X PZT and Y components of Y PZT

X, X'×10, Y, X'×10 of X PZT trajectory at exit of CU (red, 5 MeV) and exit of CM (blue, 55 MeV)



X, X'×10, Y, X'×10 of Y PZT trajectory at exit of CU (red, 5 MeV) and exit of CM (blue, 55 MeV)



These are also matched to the 55 MeV optics.

Roadblocks

- Measurement of transfer matrices, especially across CU
  - 180° optics in 100 keV
  - Limited number of BPMs
  - Limited aperture / scraping
  - Trajectory resolution
  - Accuracy and dynamic range of correctors
- Injector model
  - Model error (element order, dimensions, ……)
  - 100 keV model quality
  - Unaccounted coupling effects in 5 MeV
  - MQJ and MQD at higher field
- Stability / Reproducibility
  - 30 hz PZT
  - 100 keV transport
  - Capture + CU
  - Energy fluctuation in 55 MeV
- Machine settability
  - Skew quad polarity
  - Skew quad "field map"
  - MQJ and MQD at higher field
  - Spot blowup in 5 MeV
- Definition of input phase space
- 30 hz PZT
  - Reliability (sign flipping, anomaly due to spot move)
  - Agreement with DC orbit
  - Rotated PZT signature (can't match 2 components)
  - "DC" PZT overwhelmed by noise
- BPM issues
  - Impact of defective BPM in 5 MeV region
  - 4CH 30 hz anomaly
  - Scaling issue
- Logistics & Procedure complication
  - Need to re-steer 5 MeV line extensively every time
  - Skew quad kick
  - Test cycle incompatible with MD pattern
- Finally, an Optim problem

What needs be done?

Problems with well-defined path to solution (not necessarily easy)

- **5 MeV & 55 MeV model (Geometry & Quad Strength)**
- **Source of fluctuation at & after 5 MeV**
- **Skew quad polarity**
- **MQD & MQJ field map**
- **Un-rotating PZT orbits before CU**
- **4CH 30 hz behavior**
- **5 MeV steering**
- **Adapting MD schedule to test cycle**
- **Optim problem**

Problems with less clear path (not that they can be bypassed)

- **Measure transfer matrix across CU (Change 100 keV optics? Revive 6-corrector FOPT using Gun 2?)**
- **100 keV model (Open up apertures? Diagnostics upgrade?)**
- **Stability of PZT, 100 keV transport, and CU (May imply matching solution needs to be more real-time)**
- **More accurate field map for skew quads (or real skew quads?)**

We are in the process of learning how to do this right given a system far from optimized for this purpose.

The payoff is nonetheless considerable (The blowup in the Injector is typically by an order of magnitude). CEBAF is the state-of-art machine for parity experiments.

With the pressure to deliver immediate results off, hopefully we can evaluate the situation more wisely, develop needed tools correctly and come up with a more sustainable approach to this process.

Most Outstanding Issues Should Be Addressed in the Next Few Months

Option B Should Take Precedence to Option A Because These Are More Long Term Issues:

- **Measuring CU transport**
- **Skew quad control**

A Proposed Test Cycle for Option B

- **10 minute data on 30 hz PZT**
- **1 day offline optimization**
- **Return within 24 hours to test solution (2-4 hours)**

A "relative screen" for the PZT Zoom tool would be useful to tell if PZT has changed.

One more question: **What will this do to the beam spot?**

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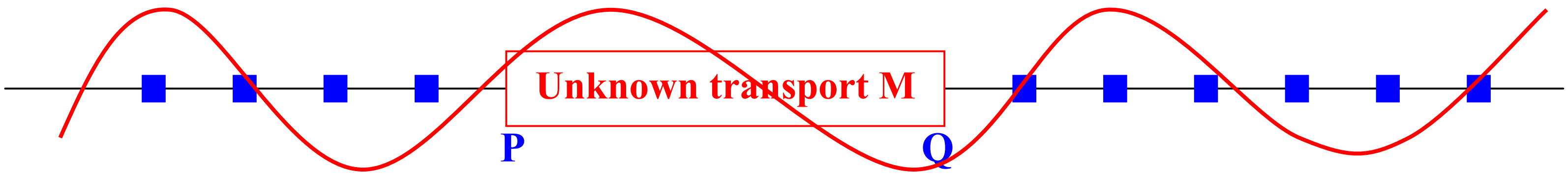
Measurement of transfer matrices based on difference orbits



Almost everything works toward <u>increasing the error</u> in measured transfer matrix from P to Q for the cryo-unit measurement.

$$\left\langle \delta M^{pq}_{ij} \cdot \delta M^{pq}_{km} \right\rangle = 2 \cdot \frac{1}{N_O} \cdot S^{jm}_B \cdot \frac{1}{T^{jm}_{(d)}} \cdot \left[\frac{1}{N_{Bq}} \cdot \mathcal{M}^i_b \cdot \mathcal{M}^k_b + \frac{1}{N_{Bp}} \cdot \mathcal{M}^i_a \cdot \mathcal{M}^k_a \cdot \left(\frac{P_p}{P_q} \right) \right], \quad i, j, k, m = 1, 2.$$

Number of Orbits (N_O)

Noise to Signal Ratio (S^{jm}_B)

Orbit Orthogonality ($T^{jm}_{(d)}$)

Number of BPMs (N_{Bq}, N_{Bp})

Trajectory Resolution ($\mathcal{M}^k_b$, $\mathcal{M}^k_a$)

$$S^{jm}_B = \frac{\sigma^2_B}{\sigma^{pj}_O \cdot \sigma^{pm}_O}, \quad T^{jm}_{(d)} = \begin{cases} \left(1 - R^2_p\right), & j = m \\ \left(1 - R^{-2}_p\right), & j \neq m \end{cases}, \quad R^2_p = \frac{\left\langle x^p_1 \cdot x^p_2 \right\rangle^2}{\left\langle x^p_1 \cdot x^p_1 \right\rangle \cdot \left\langle x^p_2 \cdot x^p_2 \right\rangle}.$$

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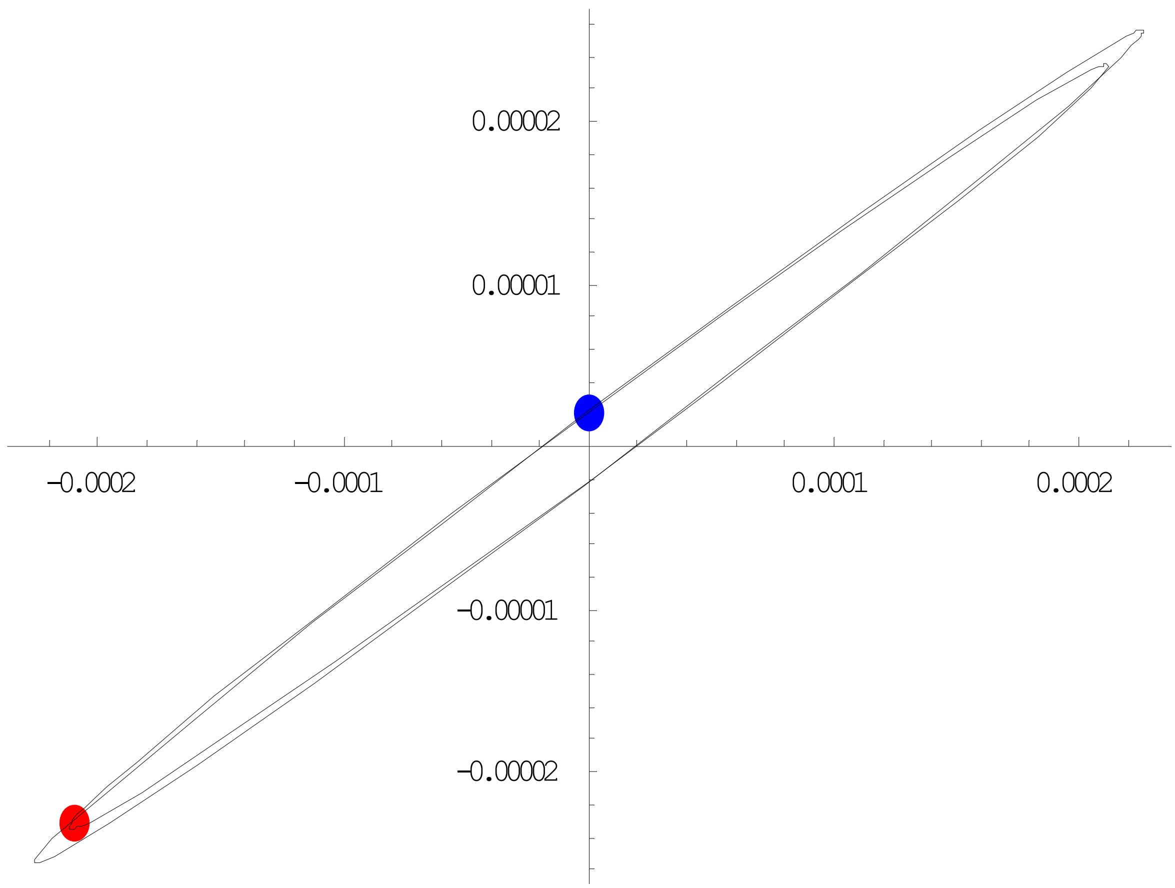
Defining input phase space distribution based on PZT orbits

The input phase space used for betatron matching is defined to be as compatible with the PZT orbit as possible

$\{x1 \to -0.00021024,\ t1 \to -0.0000229746,\ x2 \to -2.29746\ 10^{-7},\ t2 \to 2.1024\ 10^{-6},\ RR \to 1.\}$



$$\alpha^2 \geq \alpha_{Min}^2 = \boldsymbol{Max}\left(\frac{\left(t_1^2 - \mathbf{K} t_2^2\right)\left(x_1^2 - \mathbf{K} x_2^2\right)}{\mathbf{K}\left(t_2 x_1 - t_1 x_2\right)^2}, 0 \right)$$

$$\beta_{Min}^2 = \left| \frac{\left(t_1 x_1 - \mathbf{K} t_2 x_2\right)^2 \left(x_1^2 - \mathbf{K} x_2^2\right)}{\mathbf{K}\left(t_2 x_1 - t_1 x_2\right)^2 \left(t_1^2 - \mathbf{K} t_2^2\right)} \right|$$