JLAB-TN-08-039
Y. Chao

Collection of Notes Related to Future Work on Parity Quality Beam

This is an effort to archive the materials I presented in B Team during the past few years on possible next-step directions to improve the overall machine performance in the context of parity quality beam, with emphasis on the low energy end. Many items may already be realized or are being worked on. No effort was devoted to structuring this note. The main purpose is to provide a reference link so the collective information is not lost.

Y. Chao
02/28/06

How Can We Reach the Next Level in Damping?
- Ongoing Activities, Short Term & Long Term Proposals

Motivation: Need to Respond to Ever-Tightening Demand on Helicity Correlated Position & Angle

- **Cannot deliver spec. verifiable on the accelerator side**
- **Cannot confirm delivery on the experiment side**

Observations / Ideas from Many People

Fundamentals:

- **100 keV Model**
- **100 keV Tuning Strategy & Configuration**
- **Transfer Matrix Measurements**
  - **CU: Needs Improvement (RayTrace?)**
  - **CM: Usually Good**
  - **Chicane-NL: Usually Acceptable**
- **Control of Optics beyond 100 keV**
  - **5 MeV Layout**
  - **Quad Accuracy**
  - **Skew Quad Accuracy**

Methodology/Logistics:

- **Improved Global Optimization Process**
  - **Speed: Days → Minutes**
  - **Resolution: 20 G → 1 G**
- **Automated Matching**
  - **Combine Two Existing Modes of Matching**
  - **Contingent on Upright PZT?**
- **Populating Parity DAQ's in Accelerator**
- **PZT Booster**
  - **Freedom & Performance**
  - **Direct Boosting of Parity HC Signals?**
  - **Real Time Tuning of Phase Trombone?**
- **A New Tool for Tuning the Injector**

Problem Seems to Still Come from the Injector

Projected Emittance Growth across a Skew Quad with Inverse Focal Length *k* (Assuming Initial Beam is Uncoupled):

$$\varepsilon^2_{X\,Final} - \varepsilon^2_{X\,Initial} = \langle XX \rangle \langle YY \rangle k^2 = \beta_X \beta_Y \varepsilon_X \varepsilon_Y k^2$$

(See http://www.jlab.org/~chao/Study_Emit_Growth_Skew.pdf)

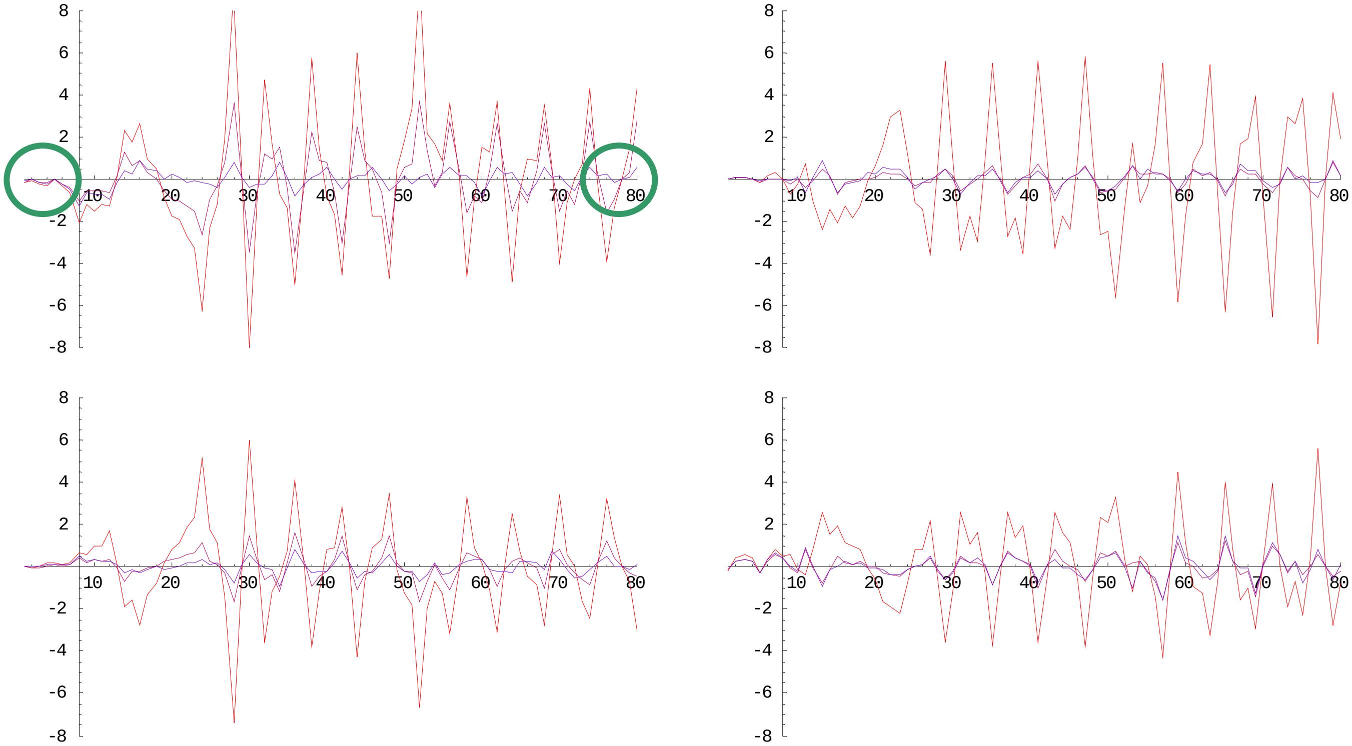
- **Betatron blowup coupled with otherwise benign coupling sources can cause excessive projected emittance growth.**
- **Not a fundamental emittance growth, but uncorrectable without enough skew quads at the end and ability to fine-tune the cancellation.**

Main Accelerator: We have this problem under control by betatron-matching the PZT-defined phase space to downstream transport. There are no known excessive unchecked coupling sources downstream

Injector: In decoupling the transport from 5 MeV to 60 MeV, we need to make sure we do not "seal in" any residual coupling from upstream.

Have We Squeezed out the Last Drop of Damping?

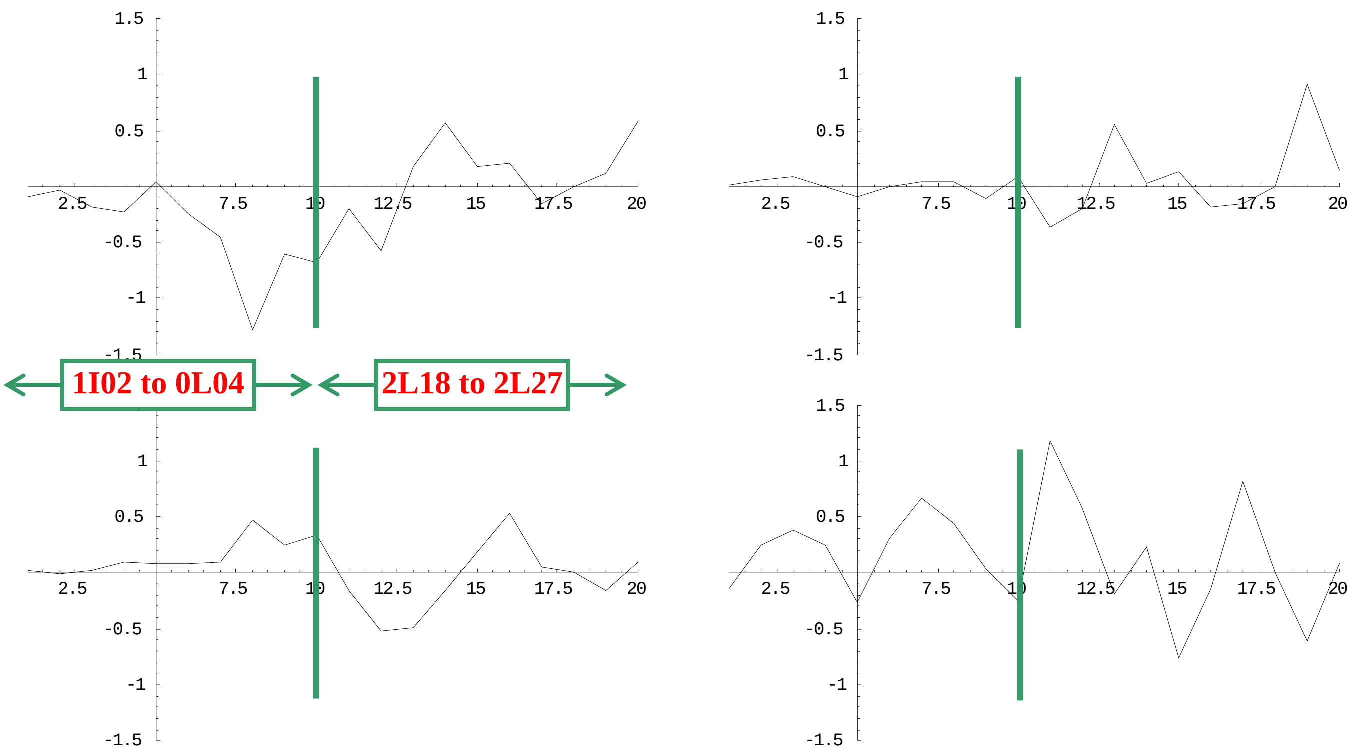
Momentum normalized X & Y components of X PZT in row 1, and the same of Y PZT in row 2
Red: original; Magenta; after 5 MeV Download & BPAM; Blue: after Injector Matching by PZT



(See http://www.jlab.org/~chao/PZT_Match_020406New.pdf)

First & last 10 BPM's from above plots After Correction.

Another factor of ~5 in X to be reclaimed?



Where Can We Look for Improvements?

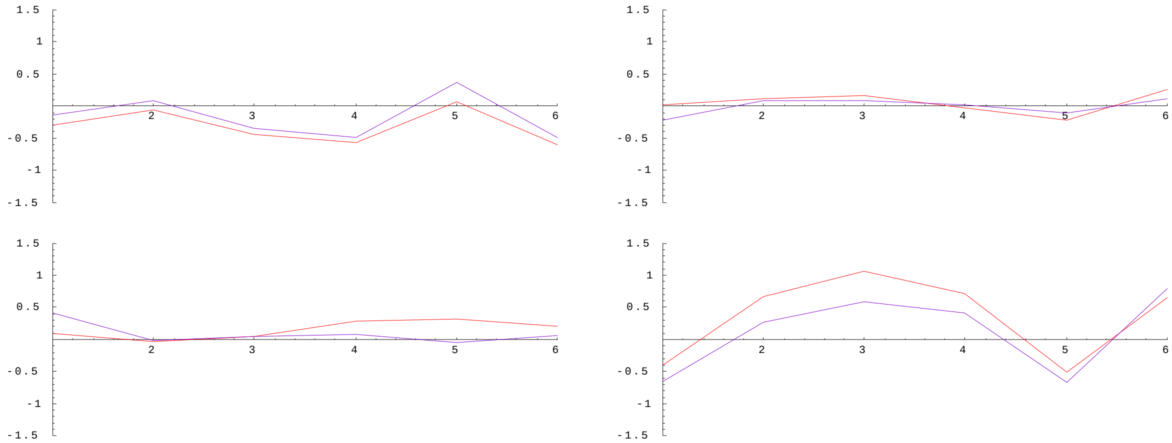
Off-Diagonal Transport is important in 100 keV, and has not received enough attention:

Why: http://www.jlab.org/~chao/Solenoid_PZT_Tuning.pdf

Current State: http://www.jlab.org/~chao/UpRight_PZT_020606_Data.pdf

- **100 keV Model**

X & Y components (mm) of X PZT in row 1, and of Y PZT in row 2
Averaged over ~300 pulses, IPM1I02 to IPM0I05: Data (red); Model (blue)



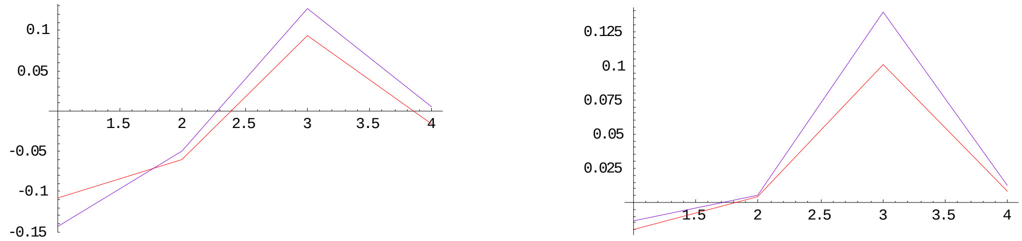
- **100 keV Tuning Strategy: Not enough attention paid to decoupling phase space.**

- **100 keV Configuration (Long Term): Not conceived with anything beyond steering in mind.**
  - **Optics**
  - **Diagnostics**

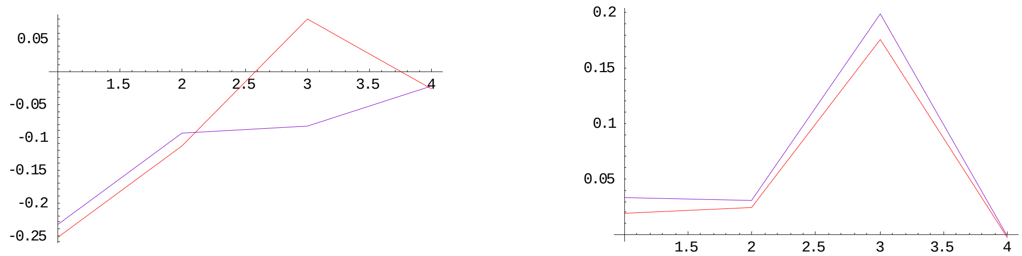
- **Transfer Matrix Measurements**
  - **Cryo-Unit: Needs Improvement (RayTrace?)**

X, X', Y, Y' at exit of CU: Red: Data; Blue: Prediction by empirical 03/05 CU model

May 2005 X & Y PZT



Jan 2006 X & Y PZT



In any case, house cleaning has not been done in 100 keV to level needed for next phase of damping.

- **Transfer Matrix Measurements (Cont.)**
  - **Cryo-Module: Usually Good**
  - **Chicane-NL: Acceptable with NL gradient calibration**

- **Control of Optics beyond 100 keV**
  - **5 MeV Layout (Long Term): Need to configure 50 MeV line more reasonably (quad spacing, diagnostics, ……)**
  - **Quad Accuracy: MQD at high field (>600 G?)**
  - **Skew Quad Accuracy (Long Term): Real skew quads?**

Have we successfully decoupled the 5 MeV transport?

- **Impossible to tell given the state of the PZT**
- **Only confirmation from 03/04/05 via very elaborate measurement → YES**
- **Things may have changed.**

Methodology/Logistics:

- **Improved Global Optimization Process (Medium Term): Run on JLab parallel cluster**
  - **Speed: Days → Minutes**
  - **Resolution: 10-20 G → 1 G**

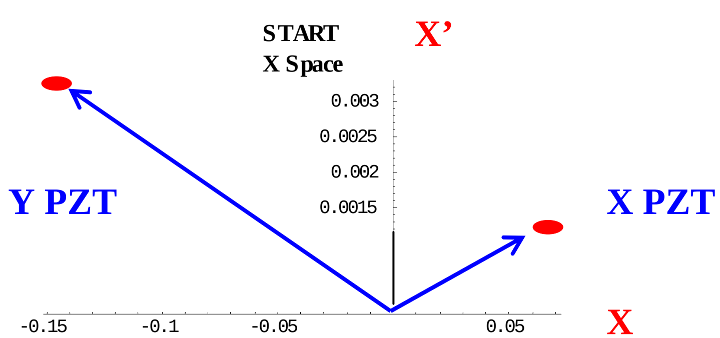
Current experience: Quad tuning 'granularity" needs be ~1 G at 35 MeV
→ Smaller resolution necessary at 5 MeV

- **Automated <u>Deterministic</u> Matching (Medium Term)**
  - **Combine Two Well-Established Modes of Matching**

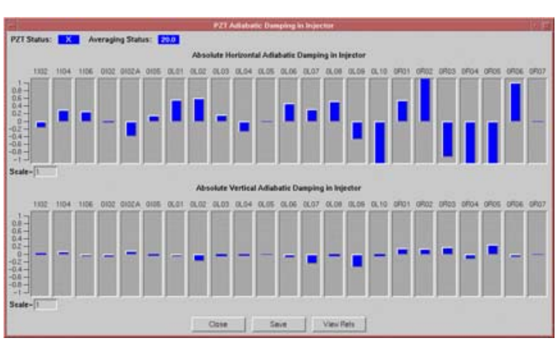
	Design Twiss	Empirical Twiss
Design Transport	Optics Design Tools	BPAM
Empirical Transport	OTAM 30 hz CS RayTrace	Matching PZT from 60 MeV to • NL/SL • Arc 1/2 • Hall A/C

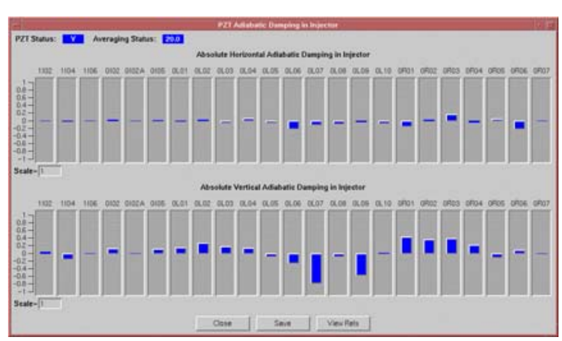
  - **Works deterministically only with Upright PZT**

Incongruent PZT signatures in the same plane (09/23/05)
→ Can't effectively match



09/19/05
PZT's





- **Populating Parity DAQ's in Accelerator (Long Term)**
    - **Important for locally confirming experimenter's claims and pinpointing problems**
    - **Can provide independent input to PZT Booster**

- **PZT Booster**
    - **Freedom from Operational Constraints**
    - **Performance Advantage**
    - **Direct Boosting of Parity HC Signals? → Poor man's DAQ**
    - **Real Time Tuning of Phase Trombone?**

- **A New Tool for Tuning the Injector**

Steps: **http://www.jlab.org/~chao/Solenoid_PZT_Tuning.pdf**

Tool: **http://www.jlab.org/~chao/New_PZT_Tool.pdf**

Want to Accomplish Two Things:

- **Make sure we do not have residual projected emittance growth out of 100 keV that got "sealed in".**
- **Be able to verify decoupling of transport from Cathode to 60 MeV or NL without elaborate FOPTs.**

Pre-Requisites:

- Align PZT mirror to high accuracy in terms of its uprightness.
- Ensure uprightness of all BPM's from Cathode to 60 MeV by alignment.
- Ensure uprightness of all magnetic components from 5 MeV to 60 MeV by alignment.

Beam Based Tuning to Ensure Maximal Damping:

- PZT inter-plane orthogonality and in-plane co-linearity at exit of 100 keV achieved through 100 keV steering and non-solenoid field adjustments.
- PZT uprightness at exit of 100 keV achieved through solenoid field adjustments.
- PZT uprightness at exit of second Cryo-module achieved through 5 MeV quad & skew quad fine adjustments.
- Fall back plan: PZT uprightness at exit of second Cryo-module achieved through 5 MeV quad & skew quad adjustments, in case the first two goals cannot be achieved independently.
- Deterministic betatron matching of PZT defined, decoupled phase space vectors at 60 MeV into North Linac.
- Switch to PZT Booster if needed; with help of the new tool, perform diagnosis/correction of phase space coupling for the rest of the machine.

Remaining Questions

- What constitutes a sufficient set of conditions for zero off-diagonal transport from Cathode to 60 MeV?
  - → May need to include kickers besides PZT
- How do we define a deterministic tuning flow chart, linking symptoms to tuning knobs?

Y. Chao
02/28/06

More in-Depth Look at the PZT, the Solenoids, and the Way to Tune the Injector

What's in This Note?

- **Understanding what the solenoids do, what the PZT's are telling us, how to evaluate them, and what is good/bad based on all this.**

  Some results are derived on rigorous interpretation of PZT patterns that convey useful information on the transport quality, counter-intuitive results that can lead to misguided machine setup, and conditions that must be satisfied to ensure error-free transport.

- **A proposed tuning sequence focused on extracting the residual missing damping from the Injector, with accompanying operational tool to be detailed separately.**

  A rigorous operation sequence is proposed based on findings from the first bullet. The next level detail remains to be worked out. If perform to its promise this procedure should eliminate major phase space distortions that are keeping us from reaching the theoretical minimum of the projected phase space area, and achieving maximum damping of the helicity correlated orbits.

  An operational tool is being conceived for realizing this procedure. Detail will be spelled out separately.

First Order Solenoid Transport (R. Helm, SLAC-4)

LL: Effective Length
BB: Longitudinal Field
Bro: Rigidity
KK: BB/Bro
KL: KK*LL

$$\begin{pmatrix} \cos^2 KL & \frac{\cos KL \sin KL}{KK} & \cos KL \sin KL & \frac{\sin^2 KL}{KK} \\ -KK \cos KL \sin KL & \cos^2 KL & -KK \sin^2 KL & \cos KL \sin KL \\ -\cos KL \sin KL & -\frac{\sin^2 KL}{KK} & \cos^2 KL & \frac{\cos KL \sin KL}{KK} \\ KK \sin^2 KL & -\cos KL \sin KL & -KK \cos KL \sin KL & \cos^2 KL \end{pmatrix}$$

Initial Beam Covariance Matrix

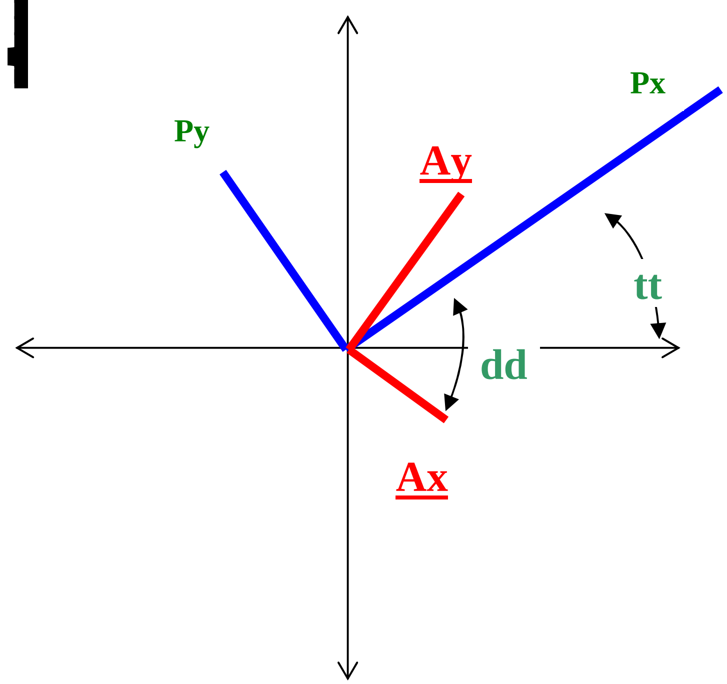
$$\begin{pmatrix} sigx & sgxa & 0 & 0 \\ sgxa & siga & 0 & 0 \\ 0 & 0 & sigy & sgyb \\ 0 & 0 & sgyb & sigb \end{pmatrix}$$

Initial Beam Trajectory 4-Vectors X & Y

Not the most general configuration, but with all relevant degrees of freedom included

{ Px cos(tt), Ax cos(tt+dd), Px sin(tt), Ax sin(tt+dd)}

{-Py sin(tt), -Ay sin(tt+dd), Py cos(tt), Ay cos(tt+dd)}



Condition on Beam or Orbits	Condition on Input Beam Properties Needed in Case the Total Rotation is not Zero	Automatically Satisfied by Total Solenoid Rotation = 0?	Satisfied by Additional Condition dd = 0?	Satisfied by Additional Condition tt = 0?	Satisfied by Additional Condition dd = 0 AND tt = 0?
Off-Diagonal Determinant of Covariance Matrix 0	sgxa = sgyb AND (siga = sigb OR sigx = sigy)	**YES**	**YES**	**YES**	**YES**
Orthogonal Positions in XY Space Remain Orthogonal	Ax Py – Ay Px = 0 OR dd = 0	**NO**	**YES**	**YES IF** Ax Py – Ay Px = 0	**YES**
Orthogonal Angles in XY Space Remain Orthogonal	Ax Py – Ay Px = 0 OR dd = 0	**NO**	**YES**	**YES IF** Ax Py – Ay Px = 0	**YES**
Rotated (Originally Orthogonal) Orbits are Linearly Dependent in XX' Space	(Ax Py – Ay Px = 0 AND dd = 0) OR (Ax Py + Ay Px = 0 AND dd = 2 KL– 2 tt)	**NO**	**YES IF** (Ax Py – Ay Px = 0 OR tt = 0)	**YES IF** (Ay Px = 0 OR dd = 0)	**YES**
Rotated (Originally Orthogonal) Orbits are Linearly Dependent in YY' Space	(Ax Py – Ay Px = 0 AND dd = 0) OR (Ax Py + Ay Px = 0 AND dd = 2 KL– 2 tt)	**NO**	**YES IF** (Ax Py – Ay Px = 0 OR tt = 0)	**YES IF** (Ax Py = 0 OR dd = 0)	**YES**
X Orbit Position & Angle Remain Collinear	Ax Px = 0 OR dd = 0	**NO**	**YES**	**YES IF** (Ax Px = 0 OR dd = 0)	**YES**
Y Orbit Position & Angle Remain Collinear	Ay Py = 0 OR dd = 0	**NO**	**YES**	**YES IF** (Ay Py = 0 OR dd = 0)	**YES**
X Orbit Position & Angle Remain Upright	tt = KL AND dd = 0	**YES**	**YES**	**YES**	**YES**
Y Orbit Position & Angle Remain Upright	tt = KL AND dd = 0	**YES**	**YES**	**YES**	**YES**

What Does This All Mean?

- To prevent adverse effects in a beam, with solenoid-induced XY correlation, entering a channel with mid-plane symmetry, the beam distribution has to start round in either position or angle space, and without in-plane correlations.

- Intuitive understanding of transport by solenoids, whether with zero net rotation or not, of orthogonal orbits in XY space (e.g., PZT) can be misleading. For example,

  - It does not require the presence of skew quad fields for the orbits to lose orthogonality, even if the total solenoid rotation is zero.
  - Projected emittance growth can happen with solenoid as well as skew quads.
  - Internal correlation between X & Y PZT's can still be lost after zero net solenoid rotation.
  - As a result the projected emittance growth of a beam with XY correlation in a section with mid-plane symmetry can be equally bad whether the correlation is solenoid or skew quad induced.

- Often one or more of the following conditions have to be met for these intuitive pictures to hold:

  - Upright initial orbit (when the preferred direction forced by mid-plane symmetry downstream is important) (tt = 0)
  - Zero initial position or angle entering the solenoid region (Ax Ay Px Py = 0)
  - Zero initial angle subtended by position and angle components (dd = 0)
  - Same initial slope in the position-angle space for the two orbit vectors (Ax Py – Ay Px = 0)

- The above understanding is important since the behavior of these orbits is used as a measure of coupling induced projected phase space blowup.

- In the mean time keep in mind special case of zero sigma's or coordinates that can trivially satisfy the above conditions.

- Obits with special characteristics (and thus limited span in phase space), such as the PZT, can be used for transport diagnosis. But to ensure proper transport of the entire phase space the above conditions must be referred to in order to guarantee no hidden transport anomalies exist.

→ Doesn't Help to Focus on the Negative. What Should We Do to Get Rid of All this?

So, What Would Unambiguously Signify <u>Elimination</u> of Coupling Induced Growth from Cathode to 60 MeV (and Beyond)? → A Proposed Tuning Sequence (with Some Ideas on Tools to be Defined Elsewhere)

As can be seen from the table, the following are inescapable conclusions:

- With negligible initial angle in the X & Y PZT's and near perfect orthogonality between them, any significant deviation from these final conditions indicate non-solenoid effects:

    - Orthogonality between position vectors of X & Y PZT's
    - Orthogonality between angle vectors of X & Y PZT's
    - Co-linearity between X position & angle vectors
    - Co-linearity between Y position & angle vectors

    Such deviation must be corrected with non-solenoid components in the 100 keV section. Uncorrected deviation from orthogonality in this case represents potential for projected emittance blowup

- Once the above orthogonality and co-linearity are restored by adjusting non-solenoid components, with sufficient confidence in the uprightness of the X & Y PZT at the cathode, solenoids should be adjusted to achieve upright X & Y PZT again at the exit to 100 keV. In the most general sense we only need to ensure zero total rotation by demanding that each PZT comes out at the same orientation in X-Y space as it is at the cathode, but since we are entering a section with mid-plane symmetry, failure to ensure uprightness has the following adverse consequences:

    - Real projected emittance (either beam or single-particle) blowup due to orientation mismatch between beam and quads (quad symmetry plane at an angle to beam symmetry plane) → Potential for projected emittance blowup.
    - Loss of important indicator for XY coupling suppression across the entire 5 MeV to 60 MeV region: If PZT's do not come in upright, it is very difficult to use them as measure of good XY decoupling or as guide to skew quad adjustment. → Potential for projected emittance blowup
    - Loss of ability to deterministically betatron-match: Above table indicates that it is not easy to have both PZT's to lie along the same slope in X-X' or Y-Y' space unless extra conditions are satisfied. This means <u>simultaneous</u> betatron matching of PZT's to downstream optics can be nontrivial due to the need to satisfy possibly incompatible Twiss parameters. → Potential for amplitude blowup. On the other hand if the PZT's are upright then there is a non-issue since each phase space has only one PZT.

- With upright PZT's entering the 5 MeV region, the next step involves (most likely starting with a pre-calculated X-Y decoupled 5 MeV optics) using the 60 MeV PZT responses as a guide to achieve complete X-Y decoupling from the quarter-cryo to the cryomodules. This happens when 5 MeV skew quads (and quads) are fine-tuned to take the (already upright) PZT's at 100 keV to upright PZT's at 60 MeV. So far this section is treated as a rigid piece whose optics is determined by demanding that the net transport is decoupled. While to lowest order this may be the case, without independent validation we are definitely vulnerable to errors, and can be under the risk of "sealing in" emittance blowup from upstream errors[1]. With the guidance of upright-in, upright-out PZT's we can achieve coupling suppression at a much higher confidence level.

→ Elimination of projected emittance blowup (that can be built up anywhere from the cathode to here)

- As mentioned earlier, with the upright PZT at 60 MeV, simultaneous betatron matching will be much more deterministic and effective since there will be no competing matching criteria within the same plane. This statement applies to either PZT guided matching using PZT or PZT Booster, or full-blown BPAM style matching. → Minimized amplitude blowup

- From this point on matching is mostly taken over by PZT Booster and downstream quads at strategic locations. We have taken measures to eliminate as much as possible phase space distortions that can cause most emittance and amplitude blowup up in the machine, namely, up to 60 MeV or into early North Linac. Without amplitude blowup, XY coupling sources in the rest of the machine are known to not cause too much problem. → Minimized amplitude blowup, resulting in minimized <u>projected emittance blowup</u> due to weak XY coupling sources

- For some parity experiments such as HAPPEX, the last bit of gain in position/angle difference can be had with the phase trombone at the target. It is conceivable that, with the signal level of the PZT Booster at 3 GeV, in conjunction with a new tool to be proposed, <u>real time</u> tuning of the phase trombone (or any 1C/3C quad) is possible, instead of relying on off line analysis of data acquired at successive settings of the phase trombone.

- Notice that we called for monitoring PZT position and angle in 100 keV and 60 MeV, but not in 5 MeV. This is designed with a specific tool in mind. Specification of this tool, which realizes the sequence outlined above, will be spelled out elsewhere.

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[1] Here I am implicitly advocating canceling the global coupling from Cathode to 60 MeV without necessarily enforcing it at the 100 keV-5 MeV interface. This is mathematically sound but maybe operationally indefensible. So you can object to this sub-sentence. This proposition will gain much more justification if we ever conclude that the skew (or even yes, rotation) components in 100 keV are impossible to correct and have to resort to 5 MeV for global cancellation, otherwise what we do now serves exactly to seal in this error. **The 5 MeV line is the last place where we have enough skew quads to do a complete diagonalization of the sigma matrix, and thus the last place where coupling-rotation-induced blowup can be fixed. If we don't use them to straighten up the phase space errors, <u>whether originating from 5 MeV or not</u>, all errors will be sealed in for good.** The question is of course, how?

Y. Chao
11/01/05

Injector Matching in the Context of G0 Backward Angle

Numerology (Very Hand-waving)

	30 hz PZT	Happex Helicity Correlated Orbit[2]	Extrapolated HC-Orbit at 360 MeV/c	Extrapolated HC-Orbit at 680 MeV/c
5 MeV Orbit Amplitude	200-400 μm	100-400 nm		
Happex Target Position	3-20 μm	10 nm	30 nm	22 nm
3 GeV Pos / 5 MeV Amp	10-100	10-40		
Happex Target Angle	2-5 μrad	3 nrad	9.0 nrad	6.6 nrad
3 GeV Ang / 5 MeV Amp	40-200 m^{-1}	30-120 m^{-1}		

Will also need all the tricks pulled by Happex Laser table setup.

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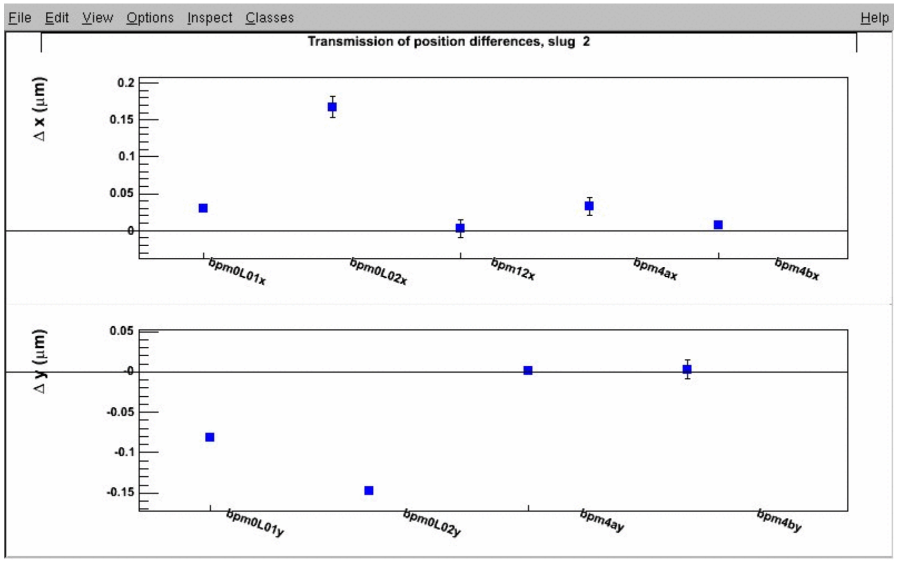
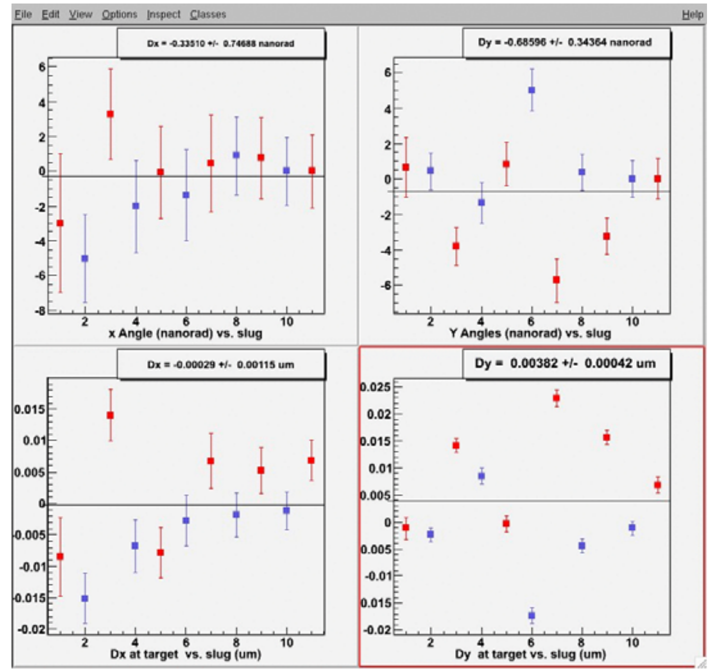
[2] **From Paschke & Snyder**


File Edit View Options Inspect Classes Help
Transmission of position differences, slug 2
Δ x (μm)
0.2
0.15
0.1
0.05
0
bpm0L01x
bpm0L02x
bpm12x
bpm4ax
bpm4bx
Δ y (μm)
0.05
0
-0.05
-0.1
-0.15
bpm0L01y
bpm0L02y
bpm4ay
bpm4by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Dx = -0.33510 +/- 0.74688 nanorad
x Angle (nanorad) vs. slug
Dy = -0.68596 +/- 0.34364 nanorad
Y Angles (nanorad) vs. slug
Dx = -0.00029 +/- 0.00115 um
Dx at target vs. slug (um)
Dy = 0.00382 +/- 0.00042 um
Dy at target vs. slug (um)

Have not Exploited Disparate M_{12}'s in the Accelerator and the Detectors

Detector Sensitivity to Helicity-Correlated Position & Angle:

$$R \propto \left(\frac{x}{A}\right)^2 + \left(\frac{x'}{B}\right)^2$$

Happex: **A/B = 1 m**

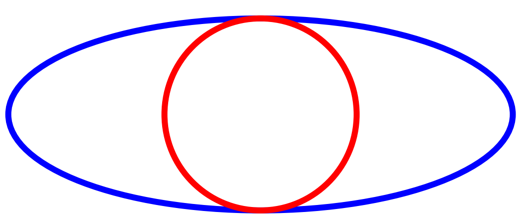
G0: **A/B = 10 m**

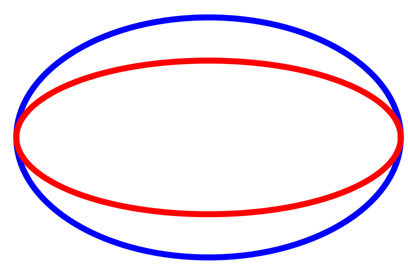
Courant Snyder Invariant in the Accelerator:

$$C \propto \gamma x^2 + \beta x'^2 \propto \left(\frac{x}{m_{12}}\right)^2 + \left(\frac{x'}{1}\right)^2, \; \alpha = 0$$

Typical *M_{12}*: **~ 10 m**

- We can manipulate phase before target to achieve minimal detector sensitivity while conforming to CS constraints (Phase trombone).
- Currently this phase has not been optimized for Happex and it sits somewhere between the two extremes. The Extrapolated G0 numbers are based on this semi-Happex-optimized data.
- We may need to exploit this for G0 with its specific geometry.





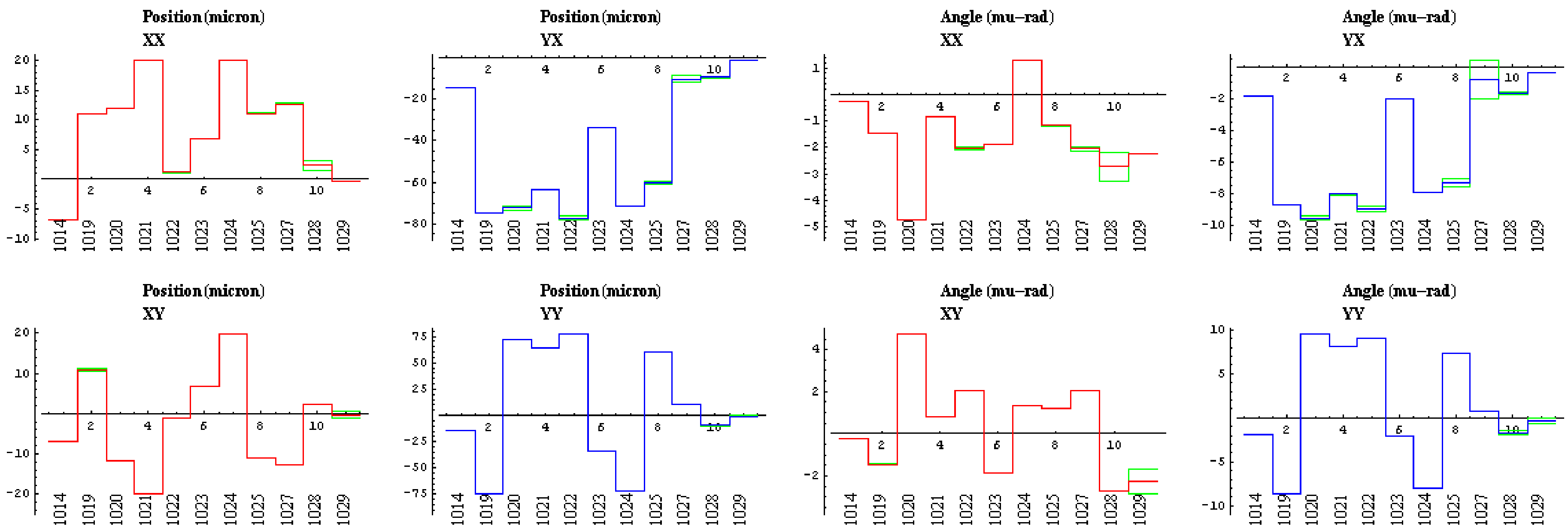
Emphasis Now is on Efficiency, Speed and Robustness

- Timely and deterministic setup procedure is highly desirable.
- Frequently changing transport throughout the machine may need to be acted upon frequently.
- An efficient and robust procedure at all times would be necessary in this case.
- Signal quality is also important.

Position & Angle at TARGET Using only IPM1H04A and IPM1H04B

All plots show fitted X & Y position & Angle from X PZT in row 1, and the same from Y PZT in row 2 in μm.

<u>Spreads of fit are shown in green</u>



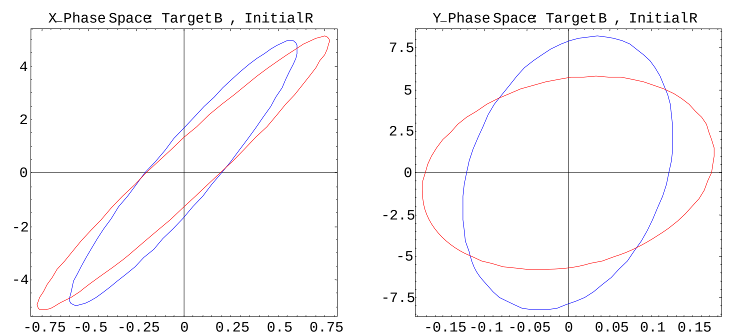
We need to come up with an OPS procedure complete with working tools, such that this process can be run by OPS like the 30 hz CS matching.

Development/Testing before March to Meet this Demand

Automatch for PZT

We have all the ingredients for this. Need to put all empirical processes together

	Design Input Twiss	**Empirical Input Twiss**
Design Transport	**Lattice design tools**	**BPAM**
Empirical Transport	**OTAM** **30 hz CS** **RayTrace**	**Matching PZT from 60 MeV to** • **NL** • **Arc 1/2** • **Hall A/C**



2003 Measurement of 60 MeV to 3 GeV Transport

Algorithm/Software: Chao One week
MD beam based: 8 hours plus possible 4-hour iteration

PZT Booster

This frees us from multiple constraints under which we must operate now; it also promises much better signal quality and robustness.

Hardware: Helicity magnets driven by 30 hz generator / Synchronization with 30 hz BPM's: ???
Algorithm/Software: Two FTE weeks ???
Software testing: 1 hour
MD beam based: 6 hours plus possible 2 hour iteration.
Detail to be worked out (Grames, Spata, Chao, ……)

An OPS procedure needs be developed shortly after these are successfully tested.

Less-Critical Tasks

Modularized Injector Coupling Correction

Current scheme seems to do the job

Algorithm: Chao Two weeks
MD beam based: 4 hours without verification. 8 hours with verification.

Resolve Signal Latency Issue with Averaged CW PZT Zoom Signal

No longer care if we have PZT Booster

Task: ???
MD beam based: ???

Correlate PZT Transport Changes with Changes in Machine State

Have daily information and baseline mug shots. Need to mine machine/operation data.
Not extremely urgent if more efficient Injector matching tools/procedures are available.

Example: Capture phase/Amplitude affects transport considerably (Parmela by Zhang; observed in the machine by Spata)

Task: ???
MD beam based: ???

Measure Transport in Main Accelerator

Do not really expect surprises

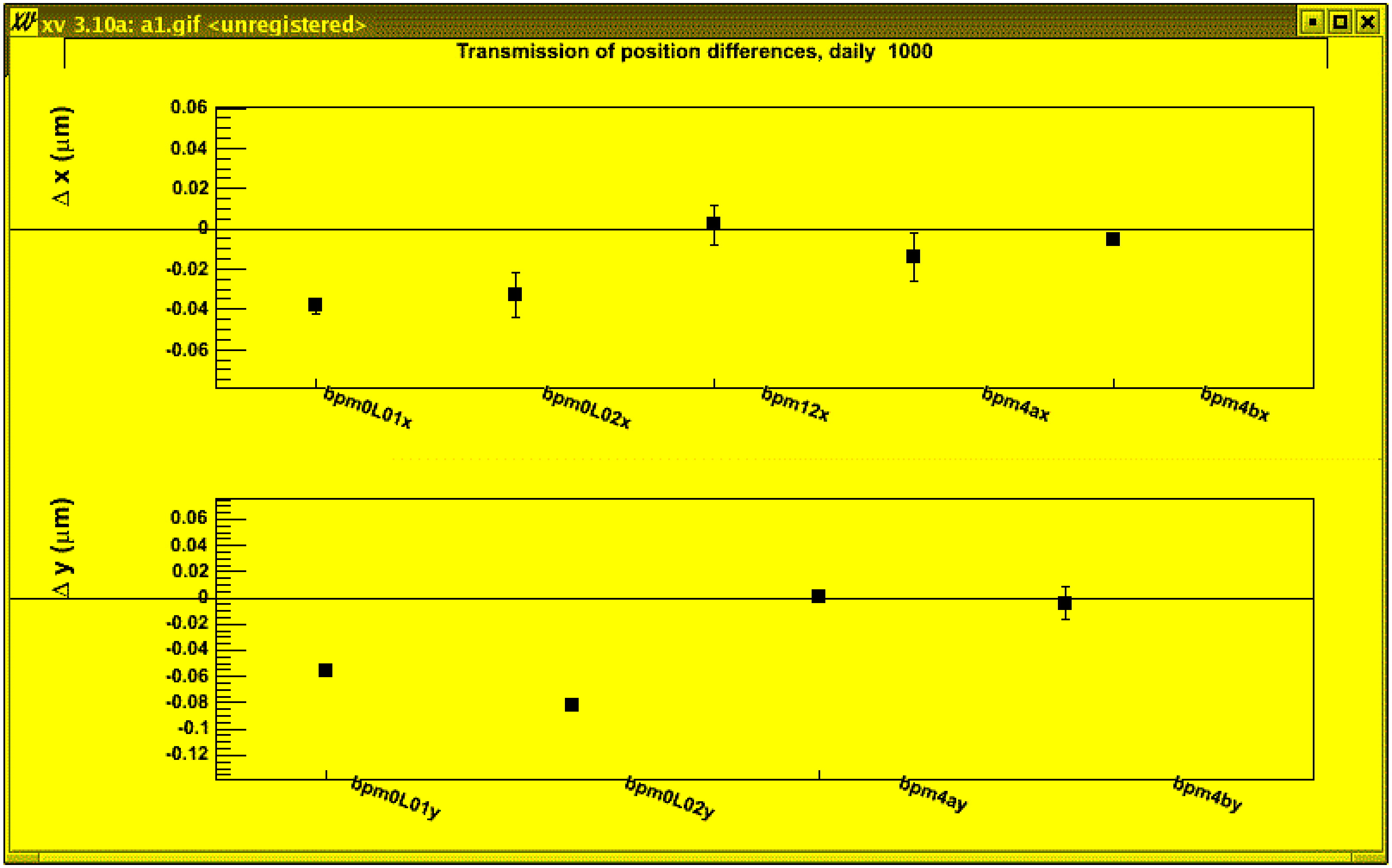
2003 example:

Damping of phase space area 0R-3C (all SQRT**)**

Theoretical	X measured	Y measured	4 X 4 measured
0.137656	**0.137271**	**0.138735**	**0.136716**

Amplitude mismatch 0R-3C: (all SQRT**)**

Theoretical	X Max. CS	Y Max. CS
1	**1.476**	**1.418**



xv 3.10a: a1.gif <unregistered>
Transmission of position differences, daily 1000
Δ x (μm)
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
bpm0L01x
bpm0L02x
bpm12x
bpm4ax
bpm4bx
Δ y (μm)
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
bpm0L01y
bpm0L02y
bpm4ay
bpm4by