Generation and Control of High Precision Beams at Lepton Accelerators

Experience of Parity Quality Beam Delivery at CEBAF

Yu-Chiu Chao
TJNAF

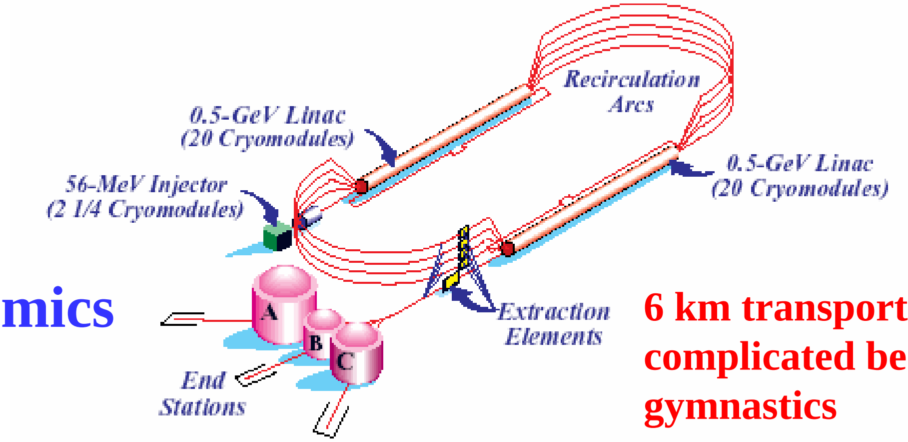
This Talk Represents Work by:

**H. Areti, D. Armstrong, S. Bailey, D. Beck, J. Benesch, B. Bevins, A. Bogacz,
Y. Chao, S. Chattopadhyay, R. Dickson, A. Freyberger, J. Grames,
J. Hansknecht, A. Hutton, M. Joyce, L. Kaufman, R. Kazimi, K. Nakahara, K. Paschke,
M. Pitt, M. Poelker, Y. Roblin, M. Spata, R. Suleiman, M. Tiefenback, Y. Zhang**

And the CEBAF Operations Staff

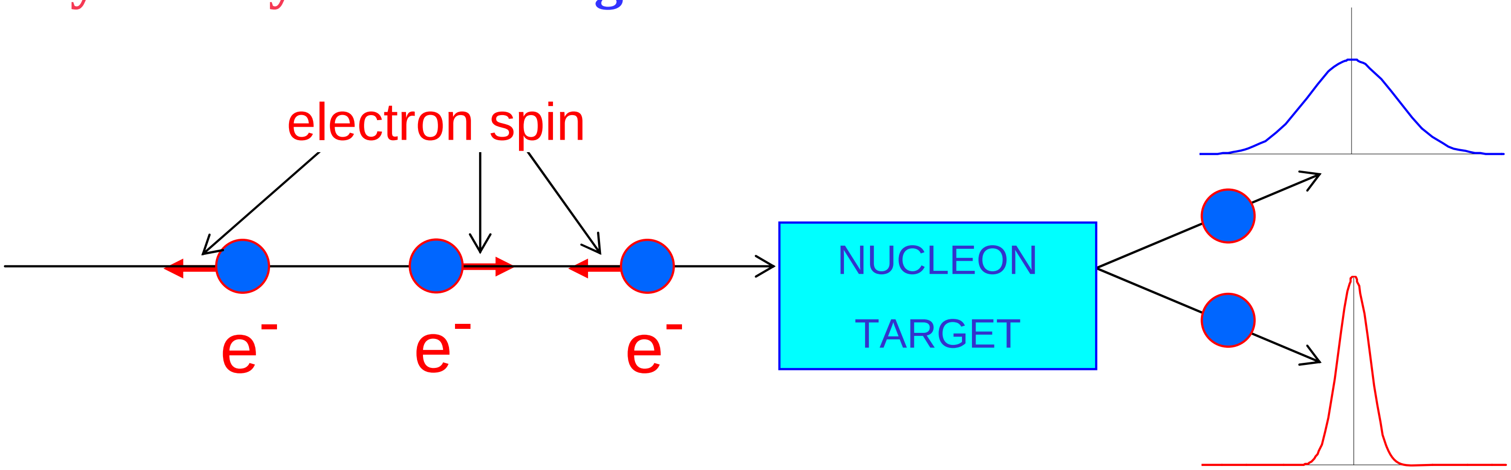
CEBAF and Parity Experiments

- CW electron beam up to 6 GeV
- Fixed target experiments at 3 halls
- nucleon structure and quark-gluon dynamics



6 km transport with complicated beam gymnastics

- Parity Experiments Measure "**Asymmetry**" in elastic electron-nucleon scattering.
- Electrons are polarized (P>70%).
- Measure asymmetry in scattering cross sections between L-R helicities.



$$A_{PV}=\frac{\sigma_R-\sigma_L}{\sigma_R+\sigma_L}\approx\frac{Q^2}{M_Z^2}\approx 10^{-6}-10^{-4} \quad or \quad 1–100\ \text{ppm}$$

Parity Violation Experiments at CEBAF

Asymmetry is of order few ppm

⇒ **Systematic errors must be kept to < 100 ppb**

⇒ **Exacting demands on CEBAF performance**

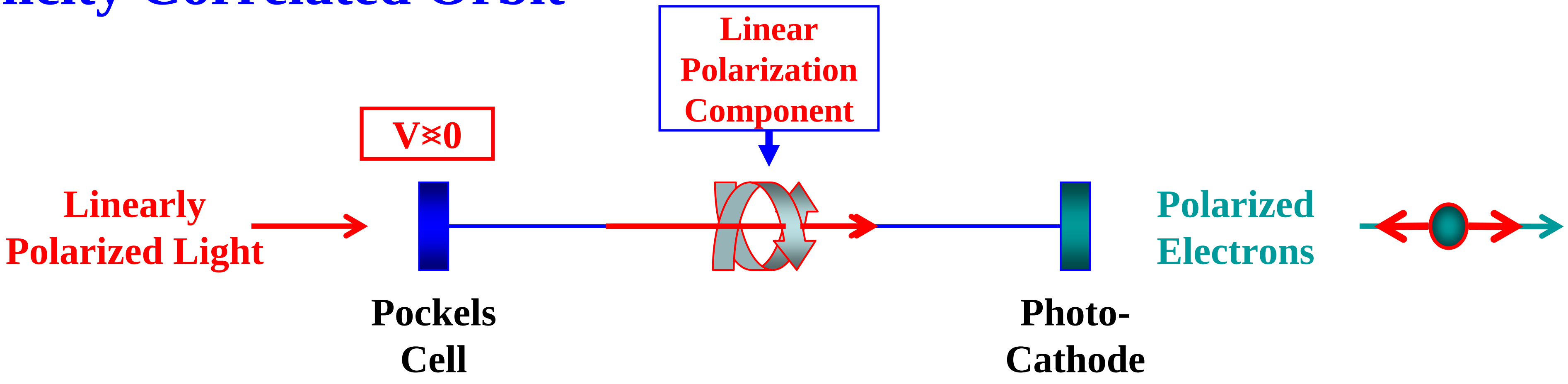
⇒ **Tight specs on Helicity-Correlated beam parameters (position, angle, intensity, ……).**

Tolerance on Helicity Correlated Values

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

Recently Concluded

Helicity Correlated Orbit



Linear Polarization Component

V≬0

Linearly Polarized Light

Pockels Cell

Photo-Cathode

Polarized Electrons

- Circularly polarized light incident on photocathode creates polarized electrons.
- Light (circular) polarization comes from Pockels cell under a voltage.
- Polarity of voltage applied to Pockels cell determines light polarization, and in turn electron polarization.
- Linear component in the light causes asymmetric transmission and electron production for opposite helicities ⇒**Helicity-Correlated Intensity**
- Whatever effect can produce H-C intensity can also produce H-C orbit, if it has a gradient across the beam profile ⇒**Helicity-Correlated Orbit**
- Other sources of H-C; Most come from the polarization process.

Helicity Correlated Orbit

- Helicity correlated orbit contributes to systematic error in the asymmetry through dependence of scattering cross section on orbit.

- 1 ppm Asymmetry, 5% Relative Error, 10% Uncertainty in Beam Based Correction

  ⇒ **On Target: $\langle \Delta X \rangle \leq 2$ nm, $\langle \Delta X' \rangle \leq 2$ nrad Averaged over Run**

What Can be Done?

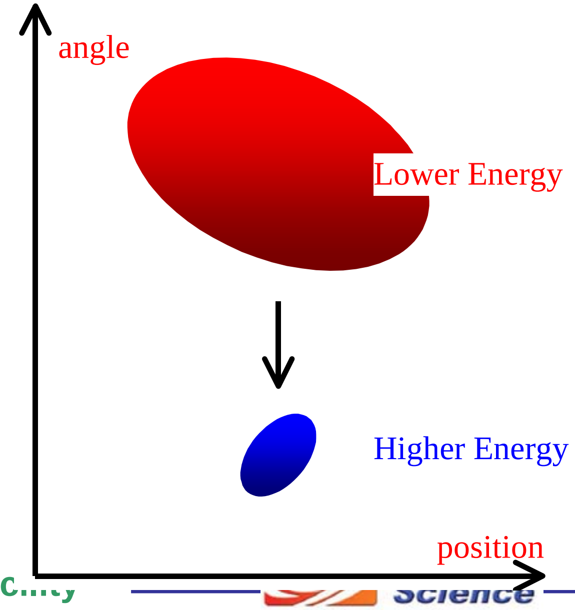
- Minimizing helicity correlated systematics associated with polarized beam formation

- Adiabatic damping of orbit amplitude (~100 from cathode to 3 GeV)

- Correction of beam transport anomalies – Can obliterate natural damping

  ⇒ Combination of XY coupling and near-singular transport can grossly compromise damping.

  ⇒ Must ensure their absence over 6 km transport & 4 decades of momentum gain.

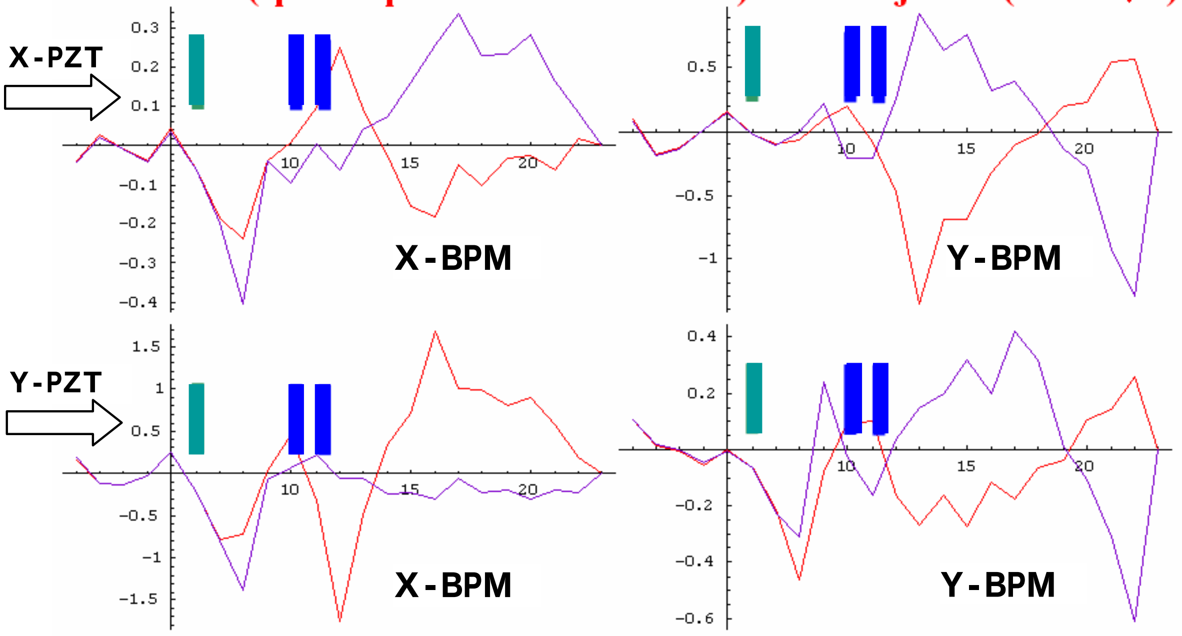


Observation of Damping (or Lack thereof) - 100 keV to 60 MeV

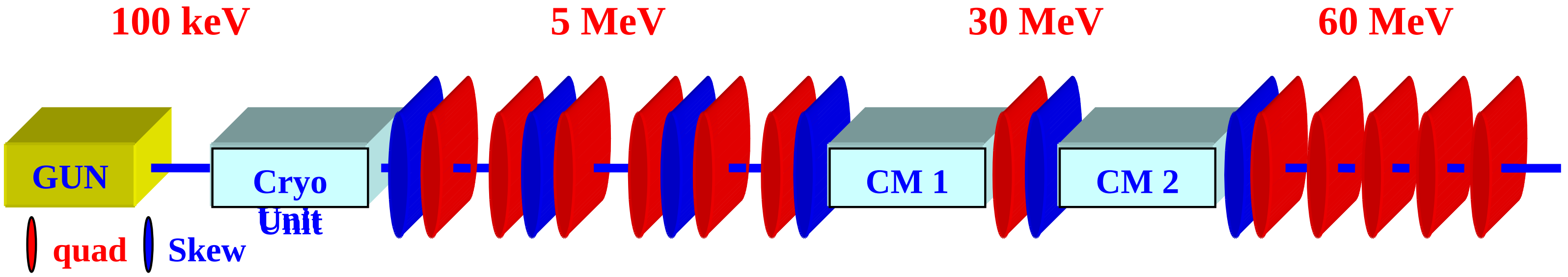
- Propagation of PZT (spot motion on cathode) orbit through Injector indicates **orbit blowup**.
- Blowups coincide with SRF components (Cryo-modules).
- XY coupling from HOM couplers
- Near singular transport from imperfect low energy modeling.

⇒ **A Potent Combination**

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

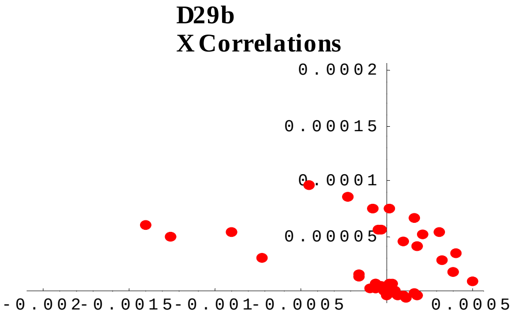


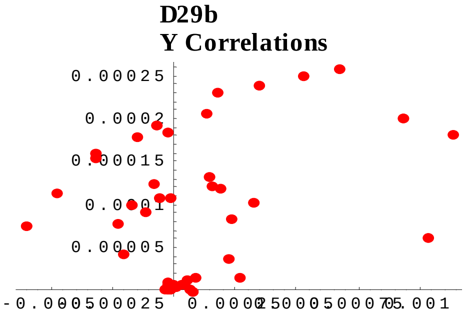
Green: Cryo-Unit Blue: Cryo-Modules



CEBAF Injector 100 keV-60 MeV

Observation of Damping (or Lack thereof) – Injector to Main Acc.


D29b
X Correlations

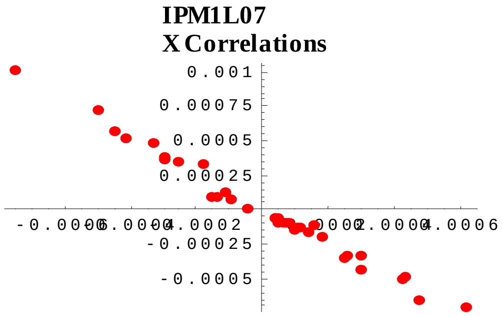

D29b
Y Correlations

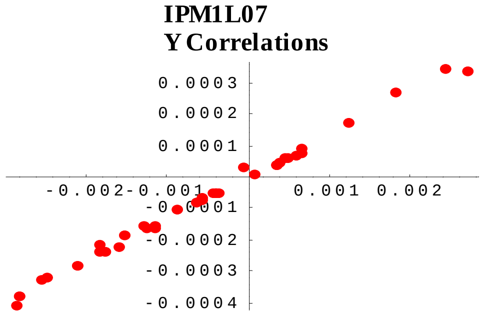
Injector
60 MeV

→

Linac
140 MeV

Position and angle at 140 MeV
Both Increased!


IPM1L07
X Correlations


IPM1L07
Y Correlations

This is more betatron mismatch than XY coupling

Mostly due to imperfect model, field cross talk, and inaccurate linac energy profile.

What Exactly, Is the Problem?
What Is To Be Accomplished?

Normally, need transport to ensure a good final beam spot (ε, α, β) only.

Now, good transport is needed for an independent orbit (X, X', Y, Y').

Helicity correlated orbit is typically 100-1000 times smaller than spot size, thus can be much more mismatched to optics without being noticed.

⇒ This can be a hidden challenge to later attempts to control it.

Doesn't matching the beam spot fix the problem? **NO**

- Beam spot is not necessarily congruent with HC orbit
- Demand on beam spot matching is less stringent
- Herein lies an opportunity ⇒ Bias toward matching HC orbit

Bottom Line:

⇒ Need exquisite transport, far more than is adequate for beam spot transport alone

A Technicality

Courant Snyder Factor (CS) Will be Used in All Subsequent Contexts to Quantify Mismatch

Trajectory-Design Mismatch

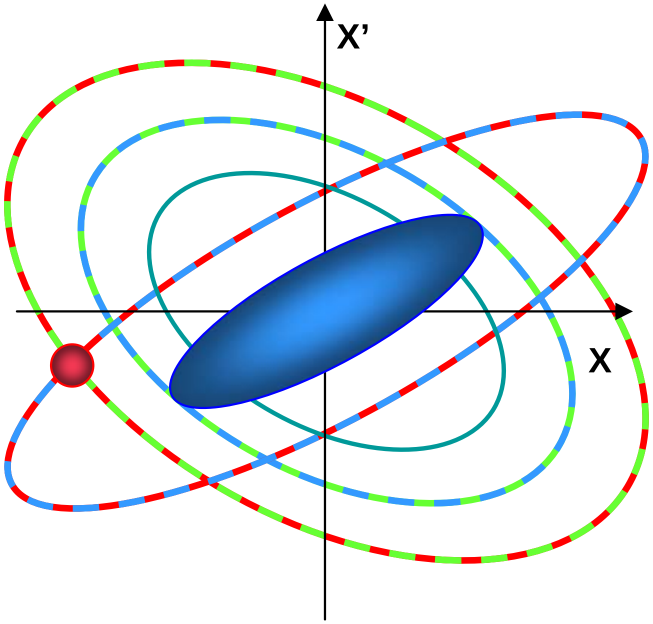
$$CS_{TD}=\sqrt{\vec{X}_T^{\mathrm{T}}\cdot\Sigma_D^{-1}\cdot\vec{X}_T}=\sqrt{\gamma_D\cdot x_T^2+2\cdot\alpha_D\cdot x_T\cdot x'_T+\beta_D\cdot x'^2_T}$$

Beam-Design Mismatch

$$CS_{BD}=\sqrt{\mathrm{Tr}\left(\Sigma_D^{-1}\cdot\Sigma_B\right)/2}=\sqrt{\left(\beta_D\cdot\gamma_B-2\cdot\alpha_D\cdot\alpha_B+\gamma_D\cdot\beta_B\right)/2}$$

Beam-Trajectory Mismatch

$$CS_{BT}=\sqrt{\vec{X}_T^{\mathrm{T}}\cdot\Sigma_B^{-1}\cdot\vec{X}_T}=\sqrt{\gamma_B\cdot x_T^2+2\cdot\alpha_B\cdot x_T\cdot x'_T+\beta_B\cdot x'^2_T}$$



$$\Sigma_D^{-1}=\begin{pmatrix}\gamma_D & \alpha_D\\ \alpha_D & \beta_D\end{pmatrix}\qquad \Sigma_B=\begin{pmatrix}\beta_B & -\alpha_B\\ -\alpha_B & \gamma_B\end{pmatrix}\qquad \vec{X}_T=\begin{pmatrix}x_T\\ x'_T\end{pmatrix}$$

DESIGN BEAM TRAJECTORY

Use the same term CS to characterize all mismatch

What’s so Bad about Coupling + Singularity?

Near-Singular Transport

Transport that leads to excessive correlation between independent coordinates → Effectively no longer independent for given precision in measurement and control.

Consequences

Excessive increase in projected coordinates

Extreme demand on the accuracy to measure or control

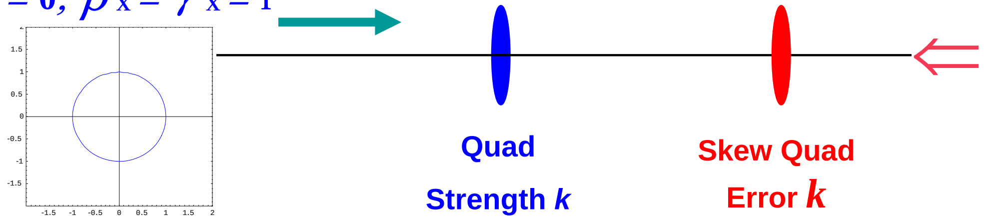
Extreme sensitivity to minor perturbations

Large projected emittance growth from (otherwise benign) optical errors

Last two points are why
One can't wait until the end before fixing a near-singular transport.

Tiny XY coupling can cause major uncorrectable blowup under near-singular transport

$\alpha_x = 0,\ \beta_x = \gamma_x = 1$



OBSERVE HERE

Quad
Strength *k*

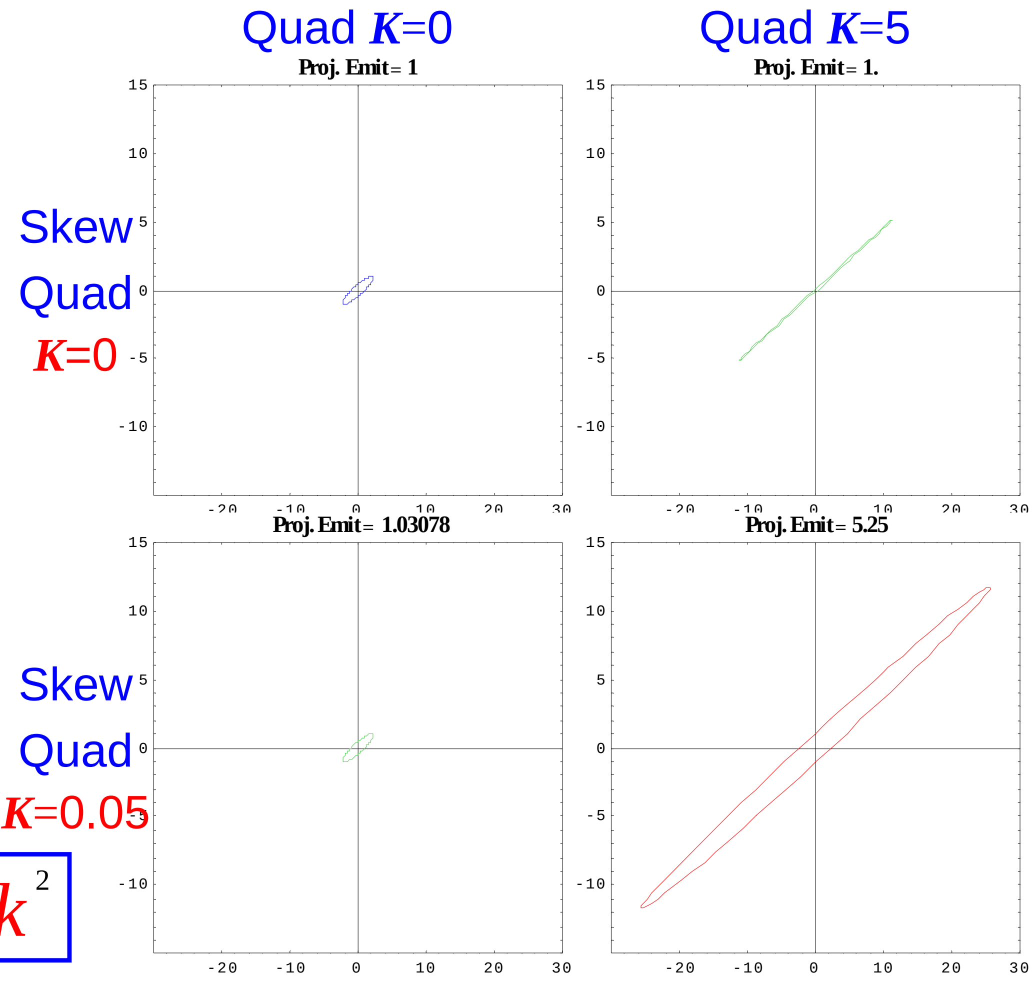
Skew Quad
Error *k*

Quad=0 Skew=0 Emittance=1.0

Quad=5 Skew=0 Emittance=1.0
Near singular; Can be restored

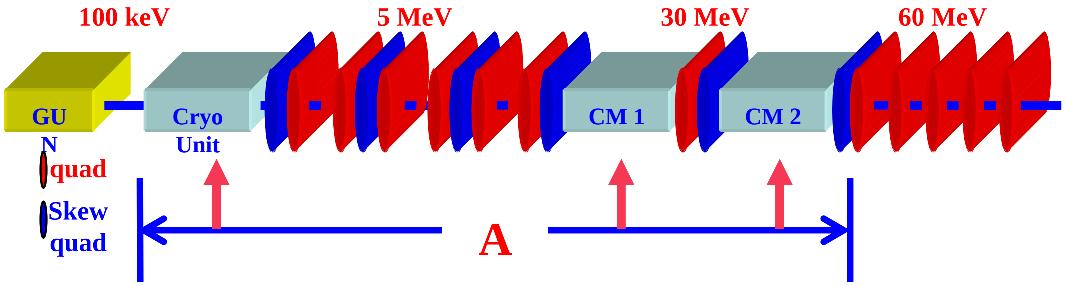
Quad=0 Skew=0.05 Emittance=1.03
Slight emittance increase

Quad=5 Skew=0.05 Emittance=**5.25**
Major blowup; **Cannot be restored**



$$\varepsilon_{X\ Final}^{2} - \varepsilon_{X\ Initial}^{2} = \langle XX \rangle \langle YY \rangle k^{2} = \beta_{X}\beta_{Y}\varepsilon_{X}\varepsilon_{Y}k^{2}$$

Coupling and Transport Singularity – Injector



4D Transfer Matrix 100 keV-60 MeV

$$
\begin{pmatrix}
-1.228 & 1.057 & 0.416 & 0.184 \\
-0.084 & 0.07 & 0.029 & 0.018 \\
-0.144 & 0.187 & -0.068 & 0.157 \\
-0.023 & 0.015 & -0.012 & -0.018
\end{pmatrix}
$$

4D Transfer Matrices measured across cryo-unit and each cryo-module.

- ➢Difference orbit with high statistics; Good accuracy (Explains data well)
- ➢Global Matrix (100 keV-60 MeV) is 4D Symplectic ⇒ Only linear effects at work
- ➢Strong XY coupling
- ➢Strong Singularity
- ➢Do not see ~13 reduction in matrix elements
- ➢In-plane & Cross-plane effects exacerbate each other. ⇒ Must be fixed at the same time.

2005 Beam Based Data	Ideal	Meas.
Percent Off-Diagonal Determinant	0	40.67
X-Sub Matrix SVD Condition Number	~10	863.79
Y-Sub Matrix SVD Condition Number	~10	9.651
4 X 4 Matrix SVD Condition Number	~10	562.68

Coupling and Transport Singularity – Beyond Injector

Up to 20% residual HOM induced coupling after compensation in main linacs

A systematic effect - Can add coherently – Weak, no problem if no mismatch

Simulation Based on

A betatron mismatch CS≠1 from the Injector into the main accelerator,

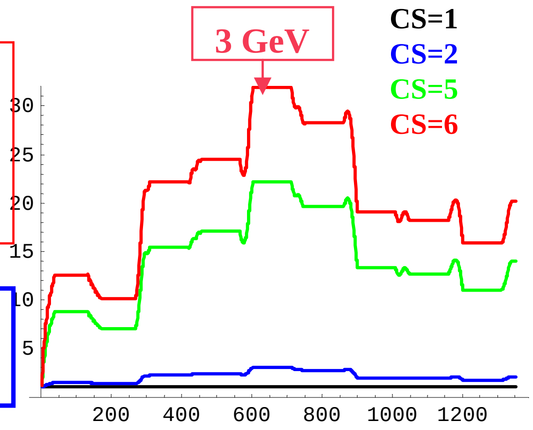
Compounded by above cumulative skew quad effects.

Look at 5-pass emittance blowup,

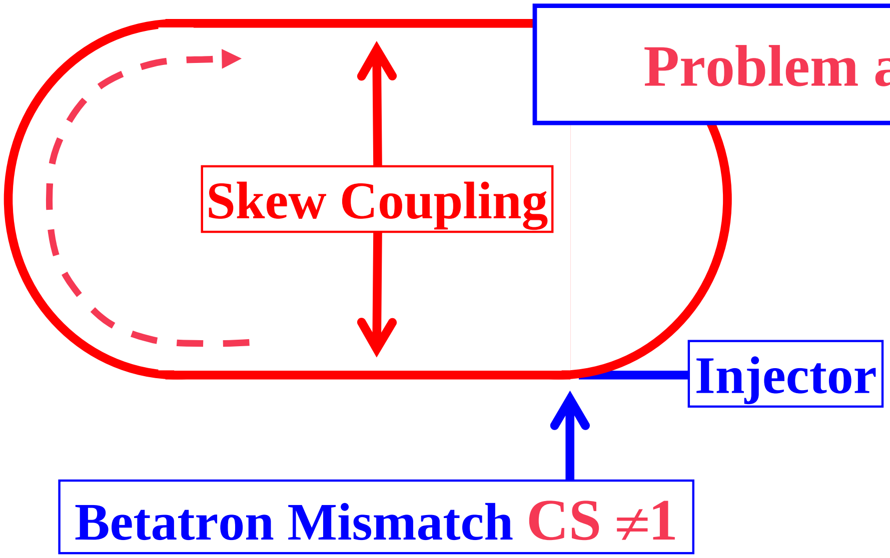
And beam-orbit mismatch CS

⇒ Measures ease to control HC orbit!

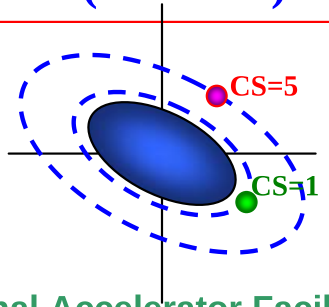
Projected Emittance
5 Pass CEBAF
(Initial=1)

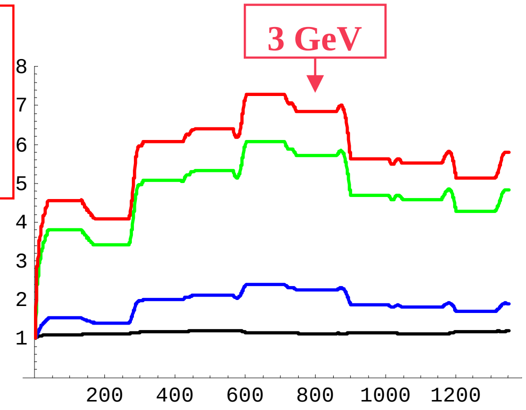


Problem at 3 GeV (P-V Exp.)



Beam-Orbit Mismatch
5 Pass CEBAF
(Initial=1)





Strategy for Suppressing Coupling and Transport Singularity

4D Symplecticity is Intact

⇒ Only Linear Elements Are Needed (Quads + Skew Quads)

Case One: – 100 keV to 60 MeV

With accurately measured transport and sufficient correction elements

⇒ A model-based solution is possible.

- **Can accurately measure the transport (Big IF).**
- **Solution works, and can be accurately implemented.**
- **Machine does not change too much in between.**

Case Two: – 60 MeV to 3 GeV

Optimizing global transport, lacking accurate long-range modeling

⇒ An empirical approach is more practical.

- **Clear, stable signal can be used as tuning guidance.**
- **Orthogonal, effective knobs can be used for control.**
- **Machine is sufficiently forgiving.**

Fixing Transport
100 keV-60 MeV
(Empirical) Model Based

Dedicated Optimization Program to Obtain Matching Solutions

Many Control Knobs, But Also Many Constraints beyond Fixing Coupling

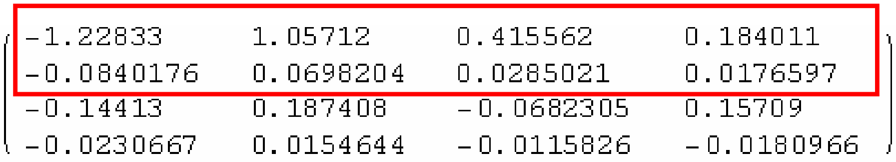
Criterion	Figure of Merit	Tolerance
No XY coupling	Off-diagonal elements in 4D transfer matrix	0
Non-singular transport	SVD Cond. No. in X & Y; M11/M22/M33/M44	SVD Cond. No. < 250; M11 < 1.0
PZT matched downstream	Courant Snyder mismatch parameter X & Y	<3
PZT amplitude reduction	Amplitude peak & RMS	Peak: >10; RMS: >10
Spot size	Spot size everywhere	Depending on beam condition
Beam spot matched downstream	Courant Snyder mismatch parameter X & Y	<3
Skew quad strength	Gradient * Length	5 MeV: <20 G; Other: <40 G
Quad strength	Gradient * Length	Physical limit
Feedback response orthogonality	SVD Cond. No. of 4D feedback response matrix	< 500

- Exhaustive Scan in Parameter Space for Decoupled Thin Lens Solutions
- Multiple Constraints to Isolate Viable Solution Neighborhoods
  - Reduction in Transport Singularity
  - Beam/Orbit Compatibility with Downstream Optics
  - Beam Size/Orbit Amplitude at ALL Locations
  - Quad/Skew Quad Strength (Field Quality and Alignment Concerns)
  - Response Orthogonality for Feedback System
  - Operational Concerns (Scraping, Beam Line Function Modularity, ……)
- Local Thick Lens Optimization for Final Solution(s)

Suppression of Coupling and Transport Singularity – 100 keV to 60 MeV

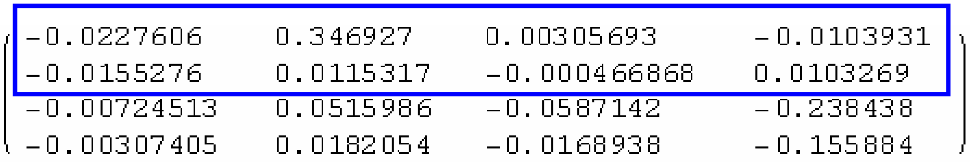
Real Beam-Based Measurements Before and After Correction

100 keV-60 MeV Transfer Before



$$\begin{pmatrix} -1.22833 & 1.05712 & 0.415562 & 0.184011 \\ -0.0840176 & 0.0698204 & 0.0285021 & 0.0176597 \\ -0.14413 & 0.187408 & -0.0682305 & 0.15709 \\ -0.0230667 & 0.0154644 & -0.0115826 & -0.0180966 \end{pmatrix}$$

100 keV-60 MeV Transfer After



$$\begin{pmatrix} -0.0227606 & 0.346927 & 0.00305693 & -0.0103931 \\ -0.0155276 & 0.0115317 & -0.000466868 & 0.0103269 \\ -0.00724513 & 0.0515986 & -0.0587142 & -0.238438 \\ -0.00307405 & 0.0182054 & -0.0168938 & -0.155884 \end{pmatrix}$$

Proper damping is evident from the magnitude of the new matrix elements

2005 Beam Based Data	Ideal	Before	After
Fractional Off-Diagonal Determinant	0	40.67%	0.518%
X-Sub Matrix SVD Condition Number	~10	863.79	23.62
Y-Sub Matrix SVD Condition Number	~10	9.651	16.50
4 X 4 Matrix SVD Condition Number	~10	562.68	25.55

Fixing Transport
60 MeV-3 GeV
Empirical Tuning

Suppression of Coupling and Transport Singularity– 60 MeV to 3 GeV

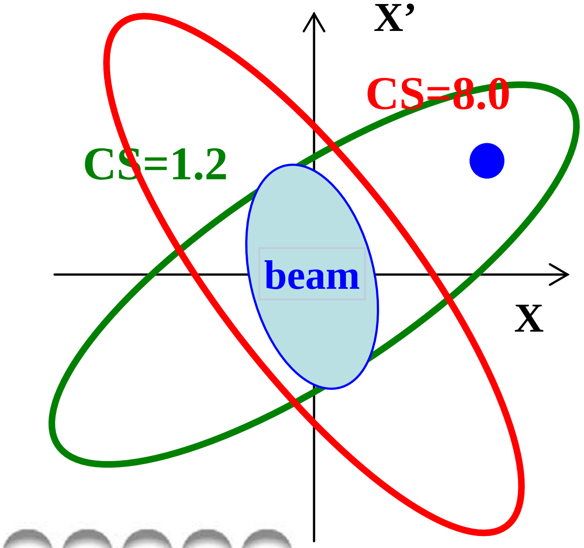
Fixing transport over long range, lacking accurate modeling
⇒ Empirically optimize global PZT amplitude by adjusting matching.

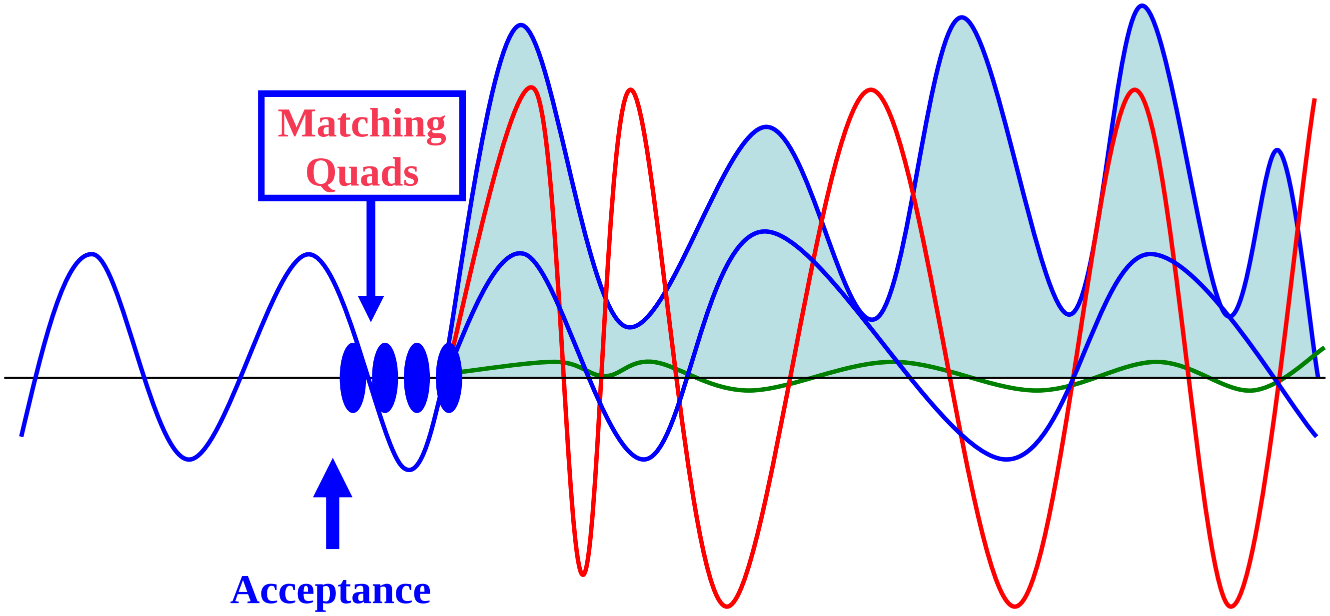
- **The major area to fix is the mismatch from Injector into the main accelerator:**
  60 MeV to ~200 MeV

- **Also, we would like to bias the match more in favor of PZT defined phase space.**

⇒ Shape downstream acceptance to match PZT coordinates

- **This is done with moderation to prevent adverse effects on beam matching.**

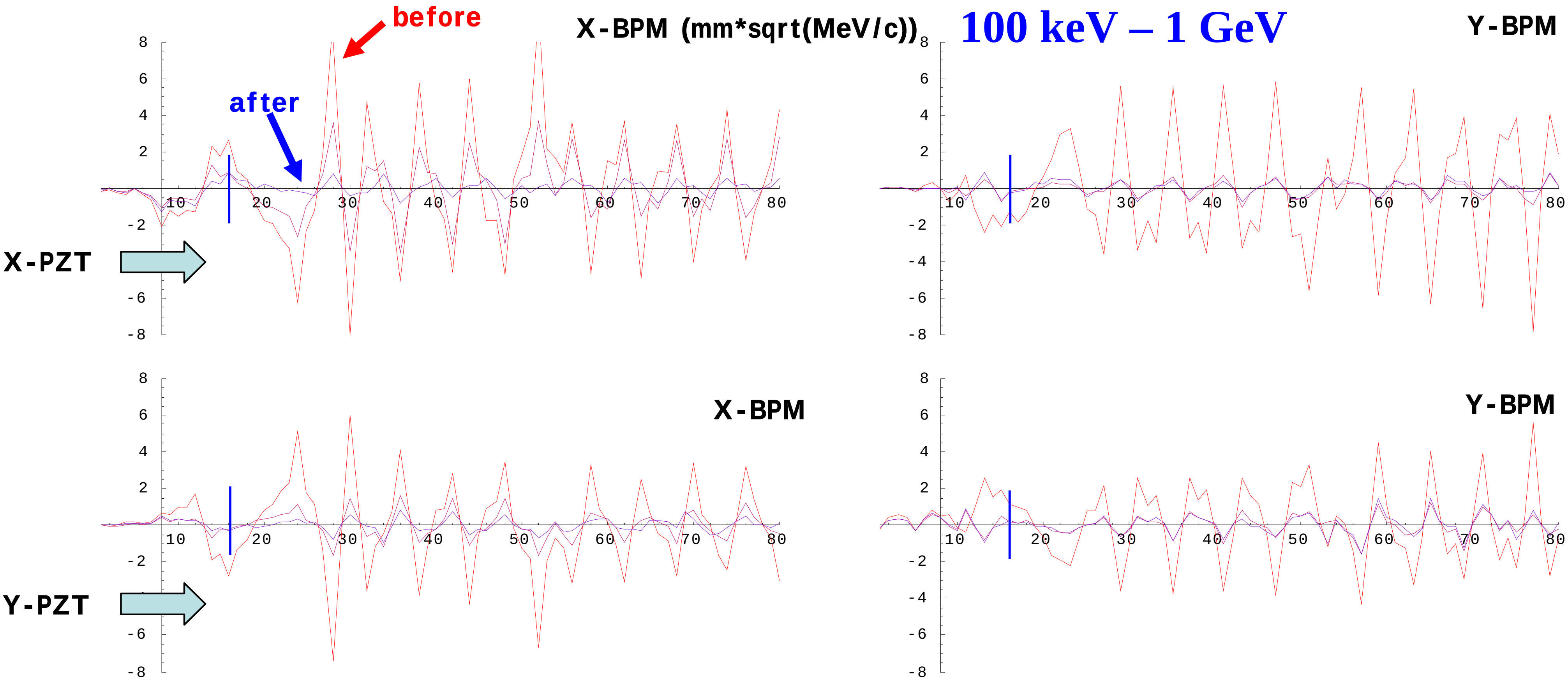




Suppression of Coupling and Transport Singularity – 60 MeV to 800 MeV

Re-matching of PZT into the main linacs resulted in greatly reduced blowup

⇒ Otherwise irrecoverable due to coupling



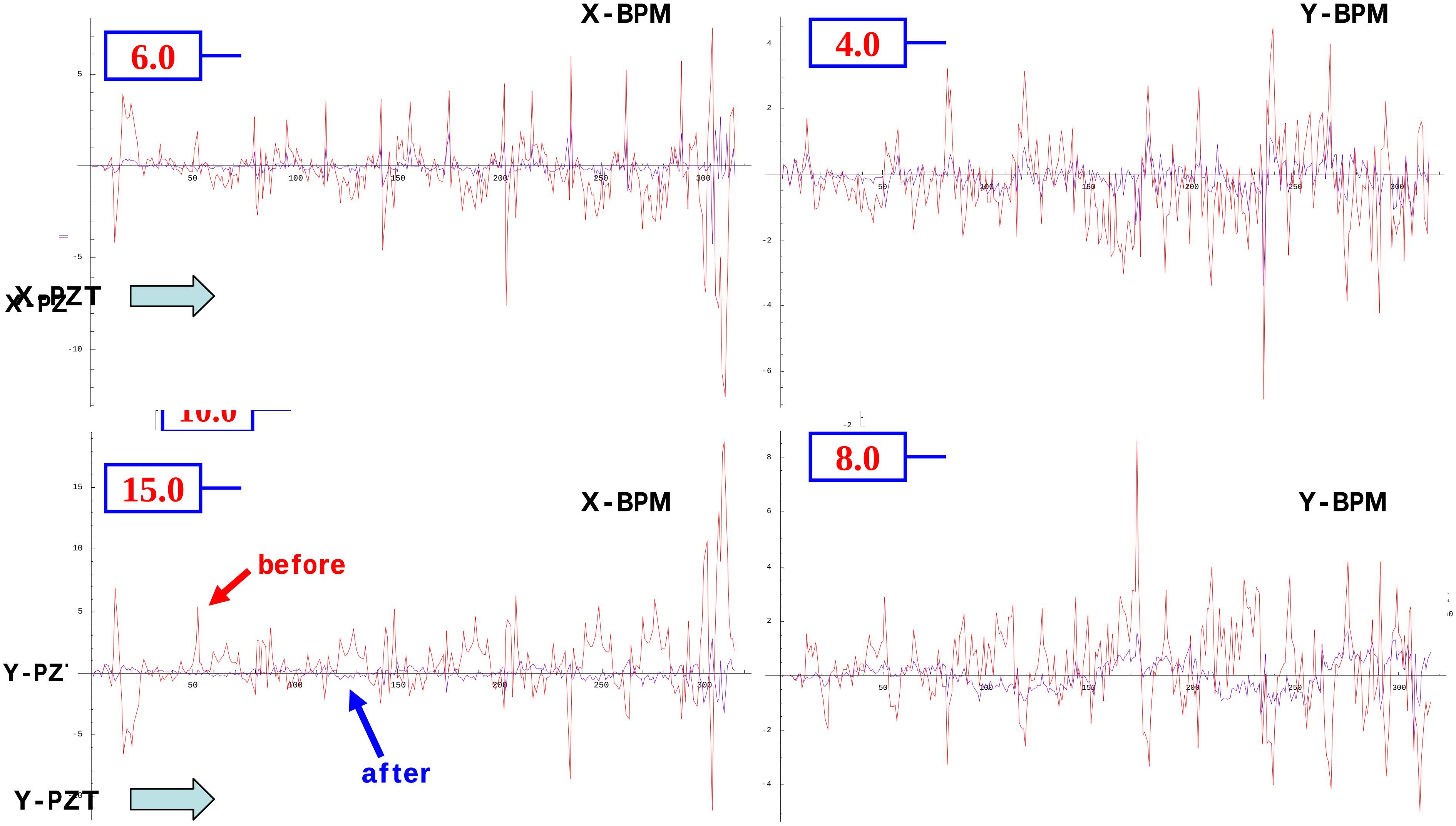
Momentum normalized X & Y components of X (Y) PZT in row 1 (2) for **Injector, North & South Linacs**

Red: original; Blue: after Injector Matching by PZT

Global Damping
Seen at 3 GeV

Suppression of Coupling and Transport Singularity – 100 keV to 3 GeV

Momentum Normalized Amplitude of PZT from Cathode to Target in mm*Sqrt(MeV/C)



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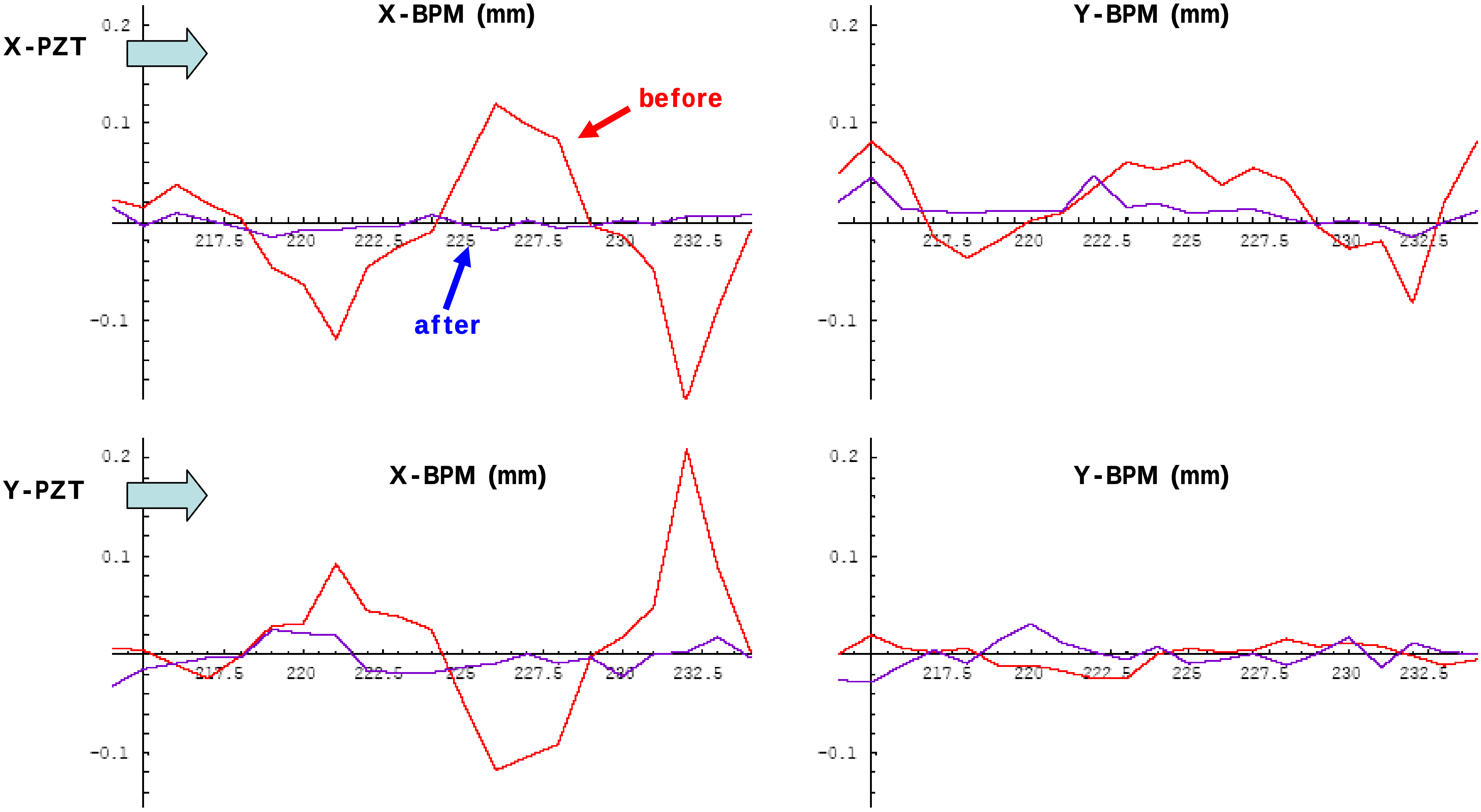
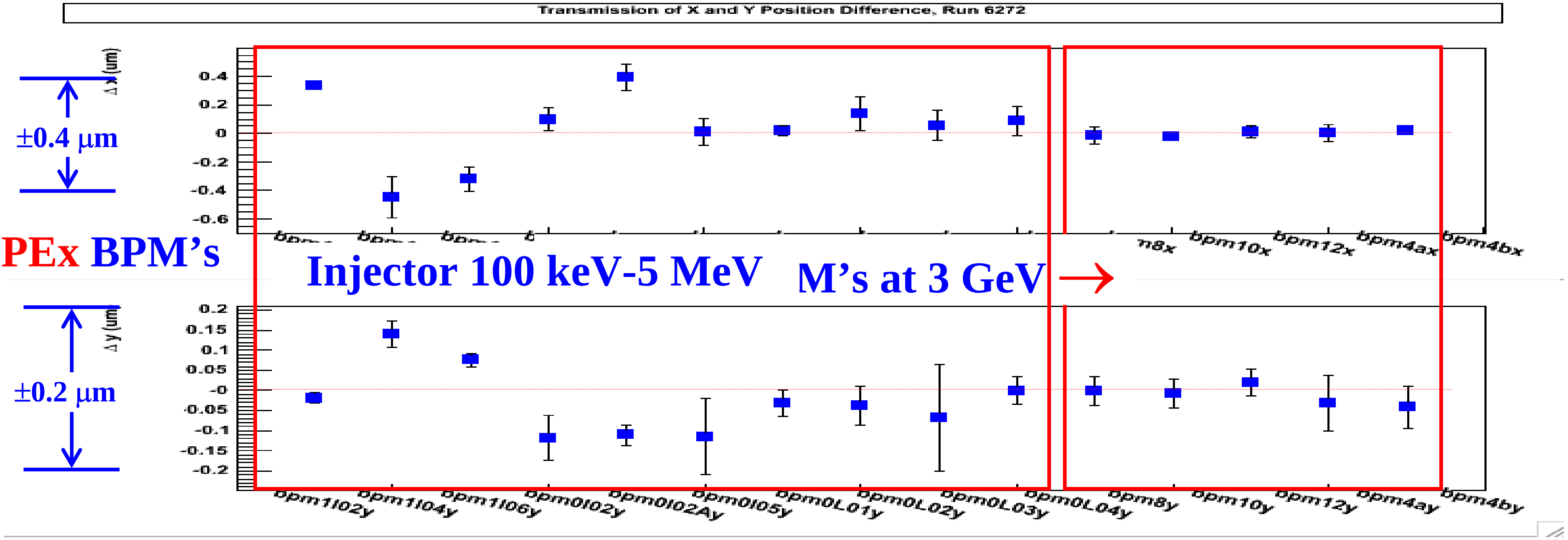
Damping Observed in Hall A at 3 GeV ⇒ PZT Signal



Gun-to-Target Damping Observed in Hall A & C ⇒ Helicity Correlated Orbit



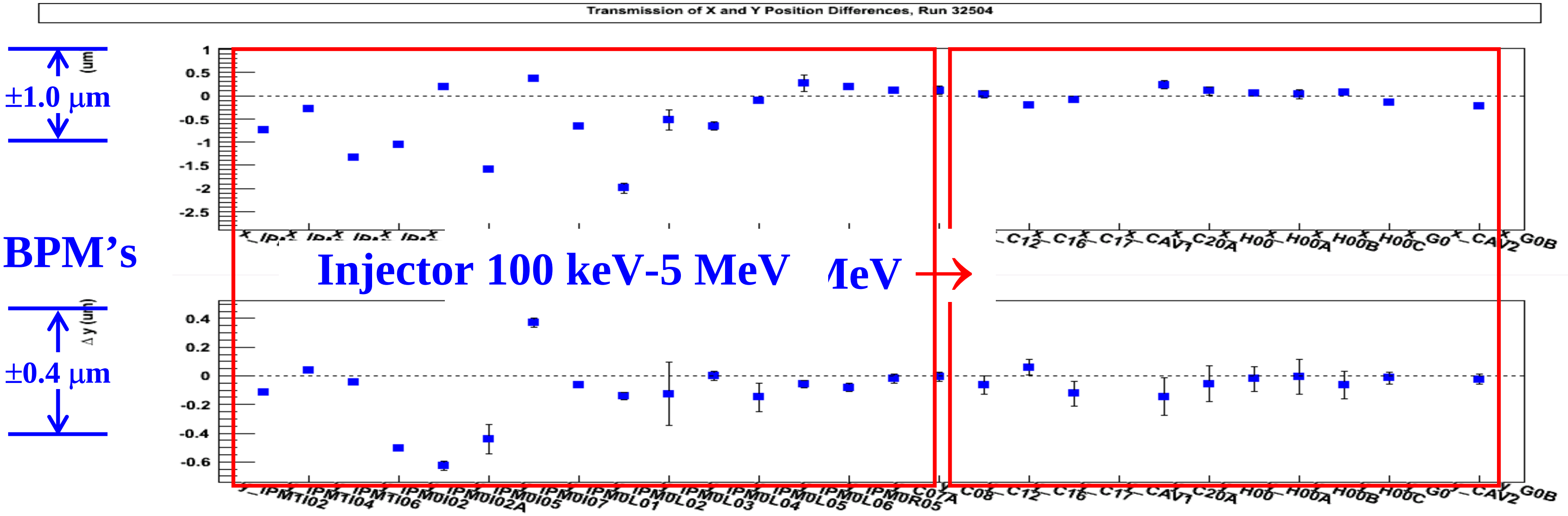
±0.4 µm

HAPPEx BPM's

Injector 100 keV-5 MeV

M's at 3 GeV →

±0.2 µm



±1.0 µm

G0 BPM's

Injector 100 keV-5 MeV

MeV →

±0.4 µm

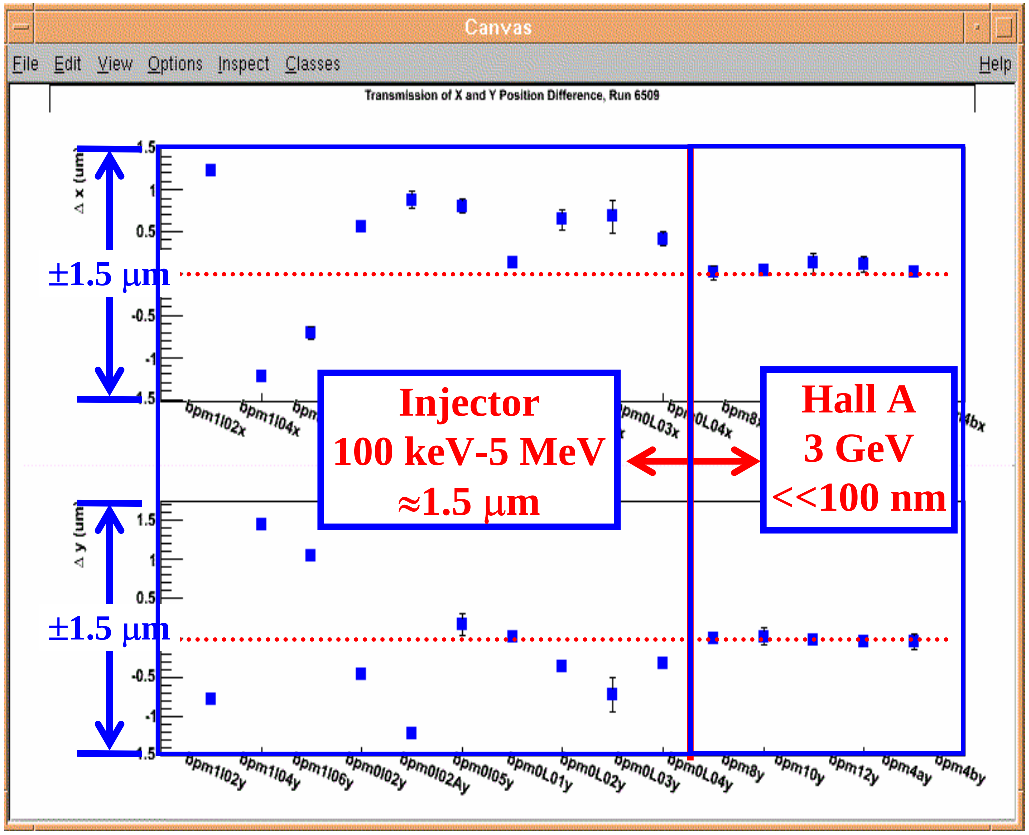
Gun-to-Target Damping Observed in Hall A & C ⇒ Helicity Correlated Orbit

Achieved Average H-C Orbits for HAPPEX 2005[1],[2]

	Helium 2005 (w/o matching)	Hydrogen 2005 (with matching)
Δx (nm)	-0.2	0.5
$\Delta x'$ (nrad)	4.4	-0.2
Δy (nm)	-26	1.7
$\Delta y'$ (nrad)	-4.4	0.2

[1] A. Acha et al, Phys.Rev.Lett.98:032301,2007

[2] Laser alignment work also made helicity correlated orbit small in the Injector



Direct benefit on HC orbit from improved beam transport, as reported by HAPPEX, is about a factor of 5-30.

Transport fix was sufficiently robust against rare occurrence of helicity correlated orbit degradation from the source.

What's Next ?

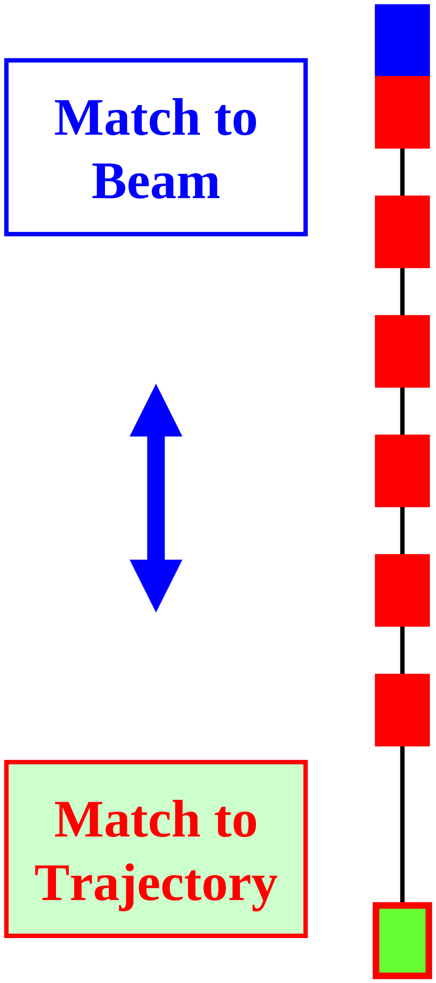
What's Next?

Need to Meet Tightening Future Specs on Helicity Correlated Position & Angle

- *Fundamentals*:
  - ➢ 100 keV Model
  - ➢ 100 keV Tuning Strategy & Configuration
  - ➢ Improved Transfer Matrix Measurements
  - ➢ Control of Optics beyond 100 keV
- *Methodology / Tool / Logistics*:
  - ➢ Improved Global Optimization Process (Speed & resolution)
  - ➢ Automated PZT Matching from Injector to Main Accelerator
  - ➢ Populating HC-capable beam monitors in Main Accelerator
  - ➢ PZT Booster development (Operability and accuracy)
  - ➢ More efficient 100 keV Tuning Tool focused on coupling suppression
  - ➢ Deterministic matching using linac FODO lattice

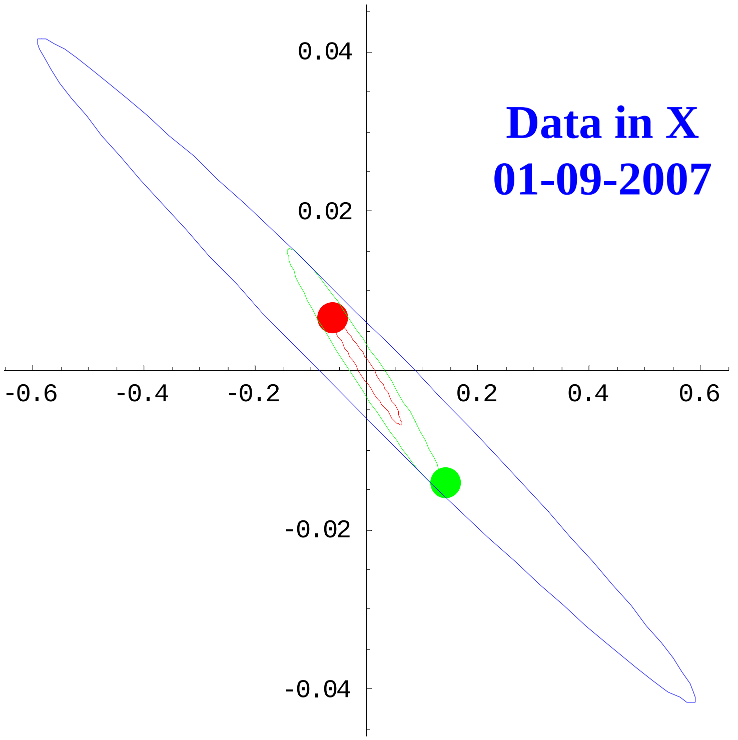
Deterministic Matching from Injector into the Main Accelerator

- **Automated betatron matching engine exists capable of finding global matching solutions.**
- **Goal: Shape accelerator acceptance to “ease” PZT trajectory into it.**
- **Should not cause mismatch in the beam.**
- **An algorithm is developed providing a continuous interpolation of biases, from completely beam-dictated to completely PZT-dictated matching targets.**



Match to Beam

Match to Trajectory



Data in X 01-09-2007

Trajectory 1	Trajectory 2	Beam
???	???	???

Trajectory Mismatch Factor $CS_T = \sqrt{\vec{X}_T^{\,T} \cdot \Sigma^{-1} \cdot \vec{X}}$

A Systematic Recipe to Deterministically Handle Beam and Orbit Matching at the Same Time

$\Sigma_M = \begin{pmatrix} & \\ \alpha_M & \beta_M \end{pmatrix}, \Sigma_B = \begin{pmatrix} & \\ -\alpha_B & \gamma_B \end{pmatrix}, X_T = \begin{pmatrix} \\ X'_T \end{pmatrix}$

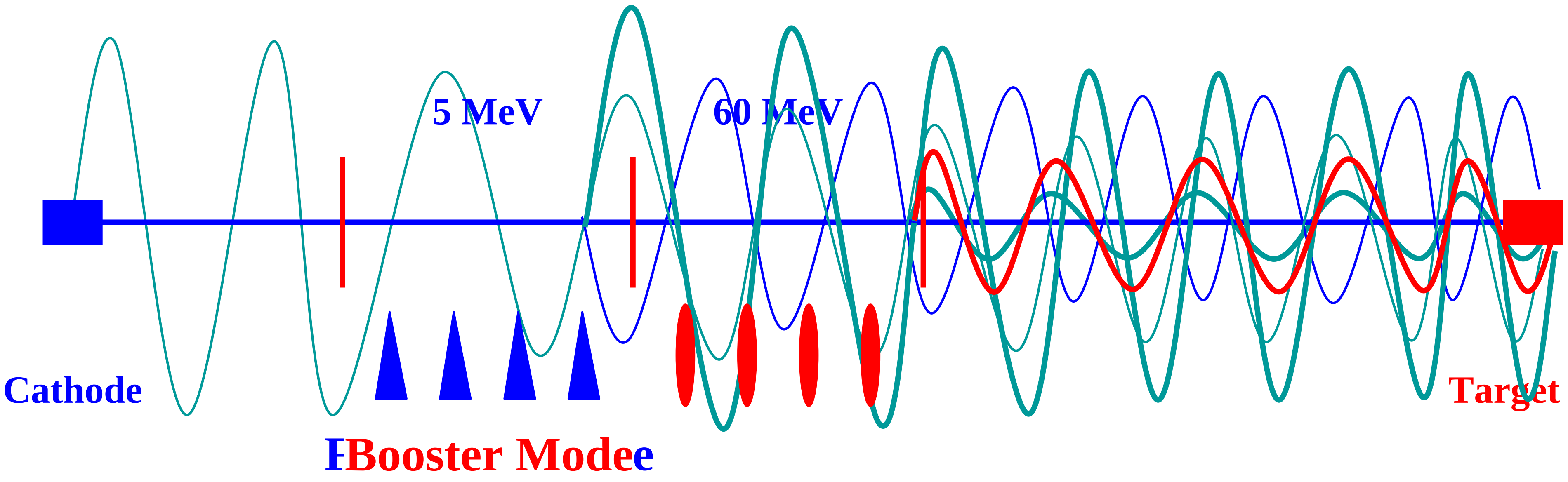
PZT "Booster"

Empirical transport matching guided by PZT signals has many shortcomings:

- **Weak signal (20-50 μm at 60 MeV, much smaller at higher energy)**
  - **Aperture and linearity/abberation constraints in Injector**
  - **Damping**
- **CW beam required to enhance signal stability**
  - **Impose extra operational limitations (beamline setup, beam loss trips, ……)**
  - **Cannot see multiple pass transport**

Solution: "Boosting" the PZT Signal to more visible amplitude

Turning 4-D Helicity Feedback System into Empirical Amplifier with Gain >>1



Conclusion

Parity Violation Experiments at CEBAF Measure Asymmetry to State-of-the-Art Level, Imposing Exacting Demands on Beam Transport Quality.

Transport Singularity is a Potent Source of Uncorrectable Blowup – Caught Attention Due to Helicity-Correlated Orbit Issues.

Techniques Developed to Minimize Helicity Correlated Beam Parameters include

- **Precision Setup of Laser System (Alignment, Tuning, etc.)**
- **Precision Measurement and Correction of global transport**
    - **Model-Based 4D Transport Optimization 100 keV-60 MeV**
    - **Empirical PZT-Guided Tuning 60 MeV-3 GeV**
    - **Improvement by Factor of 5-30**
    - **Robust against Occasional Source Degradation**

JLAB Parity Experiment Achieved <100 ppb Precision in Asymmetry at 3 GeV in 2005.

Subsequent Parity Experiments Met Respective Precision Specs at Still Lower Energies (340-650 MeV).

Future Improvements Focus on Even Tighter Transport and More Efficient Tools.

BACKUP SLIDES

Minimizing Energy Spread

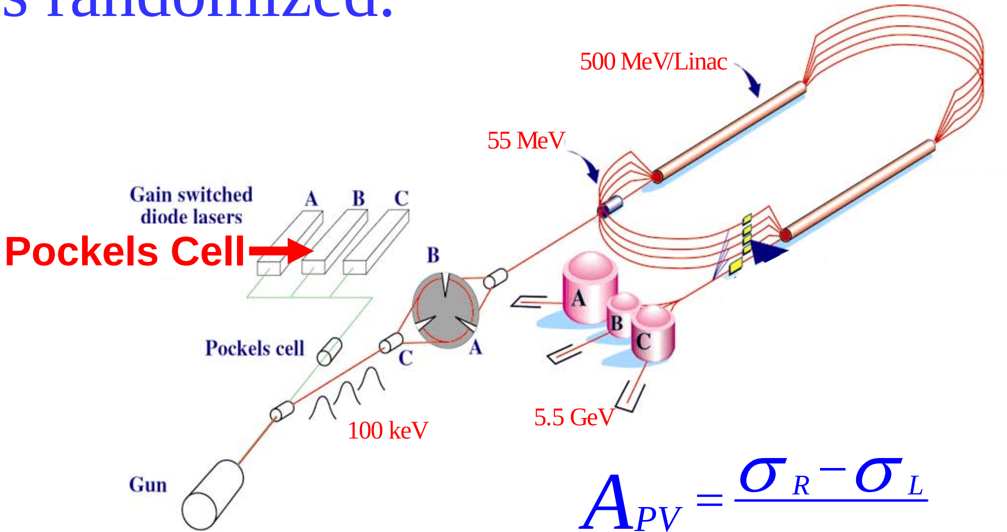
Generation of Helicity Flipped Electron Beam

- Electron beam comes in pairs of 33.3 ms windows of opposite longitudinal polarization – Flipping Pockels cell voltage at 30 hz.

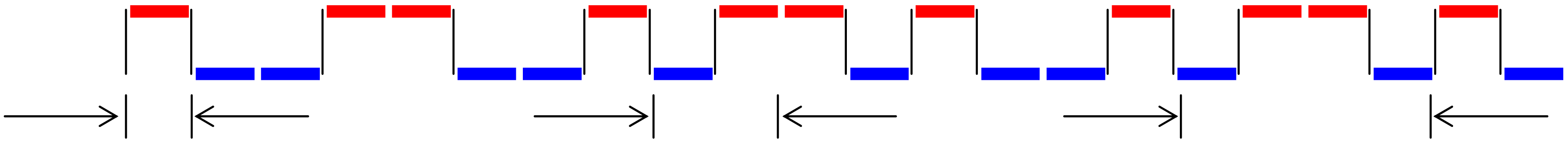
- The overall polarity of each pair is randomized.

- ***A_{PV}*** (raw) is obtained from each pair to minimize systematics.

- Correction is applied to ***A_{PV}*** to account for beam parameter induced systematics.



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



	100 keV	60 MeV	3 GeV
Beam Size Theory	<10 mm	~1 mm	~100 μm
Beam Size Measured	<10 mm	~2-5 mm	~2-500 μm
HC Before	< 1 μm	?	~200-1000 nm
HC After	< 1 μm	~100-200 nm	~5-10 nm

All assume 100 m β function, which may be too large in Injector

Beam Based Correction to Asymmetry

Correcting for A_{PV} with beam-based calibration:

$$\boxed{A_{PV} = A_{DET} - \boxed{A_Q}} - \boxed{\boxed{\alpha}\boxed{A_E} - \sum_i \boxed{\beta_i}\cdot\boxed{\Delta X_i}}$$

$$\boxed{\beta_i = \frac{\partial A}{\partial(\Delta X_i)}, \quad \alpha = }\frac{\partial A}{\partial \Delta E}$$

- Sensitivity coefficients α, β are determined by measuring dependence of detector rates on beam parameters (energy, position and angle).
- Beam parameter asymmetries are monitored during data runs.
- Raw asymmetry A_{DET} is corrected by subtracting off false contribution due to beam parameter variation.
- Inherent correlation of beam parameter to helicity states introduces systematic error through errors in α, β etc.

$$A_{PV} = -A_{DET} - \alpha A_E - \sum_i \beta_i \cdot \Delta X_i$$

$$A_{DET} \approx \frac{\sigma_R + \left(\frac{\partial\sigma}{\partial X}\right)\cdot\delta X_R - \sigma_L - \left(\frac{\partial\sigma}{\partial X}\right)\cdot\delta X_L}{2\sigma}$$

$$= \frac{\sigma_R - \sigma_L}{2\sigma} + \left(\frac{\partial\sigma}{\partial X}\right)\cdot\left(\frac{\delta X_R - \delta X_L}{2\sigma}\right)$$

$$= A_{PV} + \left(\frac{\partial\sigma}{\partial X}\right)\cdot \Delta X$$

$$= A_{PV} + \beta \cdot \Delta X$$

$$\beta = \frac{\partial\sigma}{\partial X} = \frac{\partial A_{DET}}{\partial \Delta X}$$

Constraints on Helicity Correlated Orbits

$$A_{PV} = A_{DET} - A_Q - \alpha A_E - \sum_i \beta_i \cdot \Delta X_i$$

$$\beta_i = \frac{\partial A}{\partial(\Delta X_i)}, \quad \alpha = \frac{\partial A}{\partial \Delta E}$$

For asymmetry of 1 ppm and allowed relative error of 5%

→ precision = 50 ppb

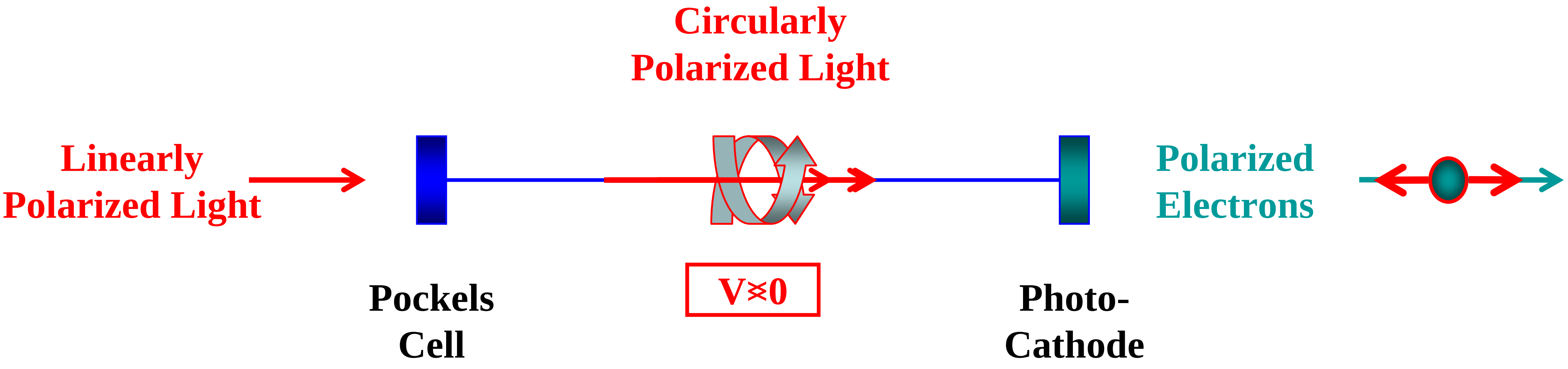
Allowing for 10 ppb error budget for each correction

βx=40 ppb/nm, $\beta x'$=40 ppb/nrad. Assume 10% uncertainty:

→ Helicity correlated beam parameters after averaging:

<ΔX> ≤ 2 nm, **<ΔX'>** ≤ 2 nrad

Helicity Flipping and Source of Helicity-Correlated Beam Parameters



Circularly Polarized Light

Linearly Polarized Light

Polarized Electrons

Pockels Cell

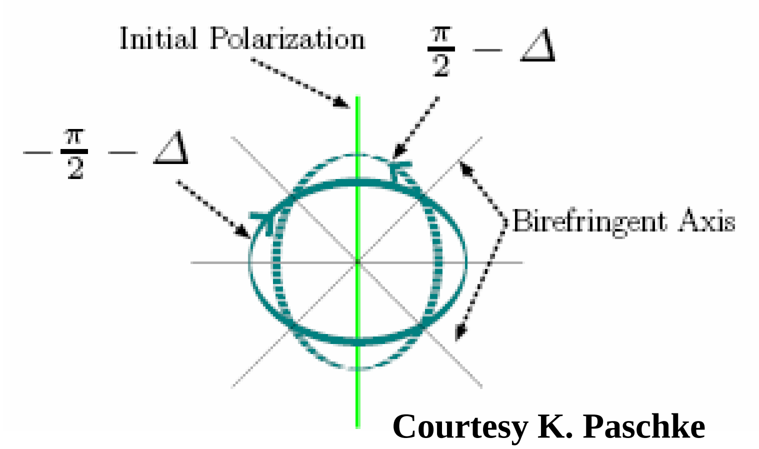
V≍0

Photo-Cathode

- ➢Circularly polarized light incident on photocathode creates polarized electrons.

- ➢Polarity of voltage applied to Pockels cell determines light polarization, and in turn electron polarization.

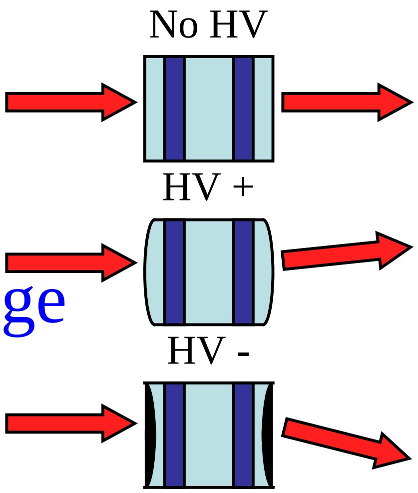
- ➢Linear component in the light causes asymmetric transmission and electron production at the photocathode for opposite helicities.
⇒**Helicity-Correlated Intensity**



Courtesy K. Paschke

Source of Helicity-Correlated Beam Parameters

- Helicity–Correlated Intensity
  - Linearly polarized component in the laser + Analyzing power of photocathode or other elements
  - Beam scraping at tight apertures
- Helicity–Correlated Orbit:
  - Non-uniform H-C intensity across laser/beam profile
    - Linear polarized component in the laser
    - Analyzing power of photocathode
  - Dependence of laser profile on Pockels cell voltage



G. Cates, PAVI04

Can be magnified by erratic beam transport!

Correcting for Asymmetry A_{PV} with beam-based calibration:

$$A_{PV} = A_{DET} - A_Q - \alpha A_E - \sum_i \beta_i \Delta X_i$$

$$\beta_i = \frac{\partial A}{\partial(\Delta X_i)}, \quad \alpha = \frac{\partial A}{\partial \Delta E}$$

- Sensitivity coefficients on beam parameters (energy, position and angle) α, β are empirically measured.
- Beam parameter asymmetries are monitored during data runs.
- False contributions are subtracted off raw asymmetry A_{DET}.
- Helicity correlated beam parameters introduce systematic error through errors in α, β etc.
- 1 ppm Asymmetry, 5% Relative error, 10% Uncertainty in βx & $\beta x'$:

→ precision = 50 ppb

Allowing for 10 ppb error budget for each correction

βx=40 ppb/nm, $\beta x'$=40 ppb/nrad. Assume 10% uncertainty:

→ Helicity correlated beam parameters after averaging:

⇒ $\langle \Delta X \rangle \leq$ 2 nm, $\langle \Delta X' \rangle \leq$ 2 nrad Averaged over Run

Suppression of Coupling and Transport Singularity – General

- 4D symplecticity guarantees transport fix by quads and skew quads alone.
  - ➢Eliminate XY coupling
  - ➢Reduce transport singularity ⇒ Must do **BOTH**

- **What makes this program challenging?**

➢High precision measurements needed to battle singularity

➢Unfriendly machine configuration (degenerate optics)

➢Inaccurate modeling of optics

➢Stability/reproducibility of 6 km of beam line

➢Long range transport over 4 decades of momentum range

➢Weak, noise-saturated signal

➢Aperture constraints for difference orbit measurements

➢Inaccuracy / side effects of correction magnets (quad & skew quad)

➢Reconciling between beam spot and orbit.

➢Multiple constraints that must be satisfied simultaneously

Coupling and Transport Singularity – Beyond Injector

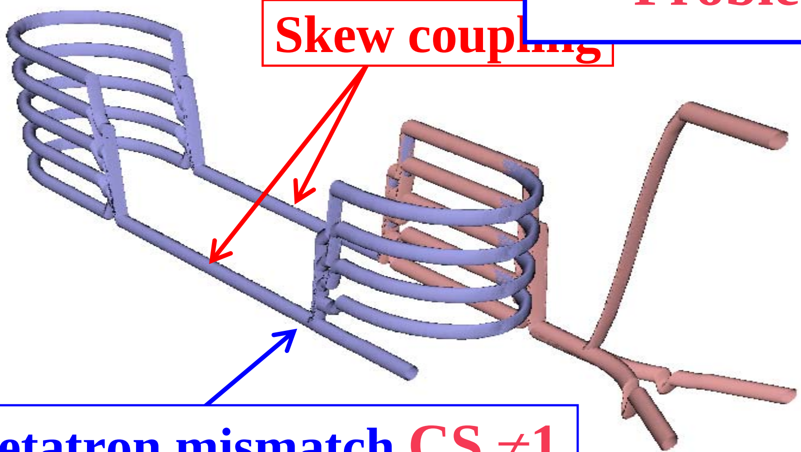
Up to 20% residual HOM induced coupling after compensation in main linacs

A systematic effect - Can add coherently – Weak, no problem if no mismatch

Simulation Based on

- **A betatron mismatch CS≠1 from the Injector into the main accelerator,**
- **Compounded by above cumulative skew quad effects,**
- **Can lead to large emittance blowup,**
- **And beam-orbit mismatch**
- **⇒ Measures ease to control HC orbit later on!**

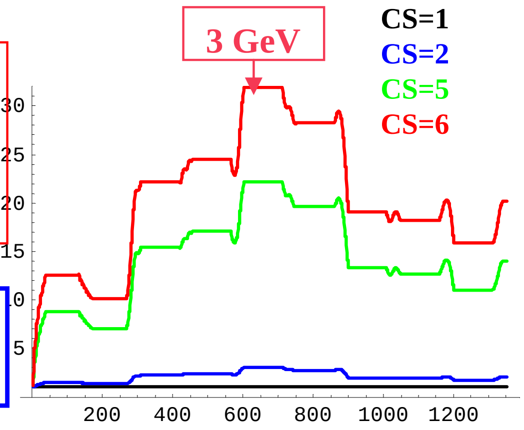
Problem at 3 GeV (P-V Exp.)



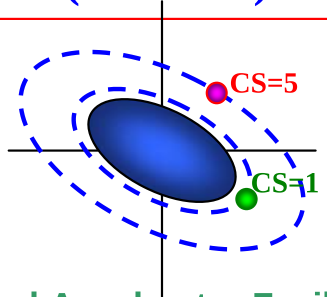
Skew coupling

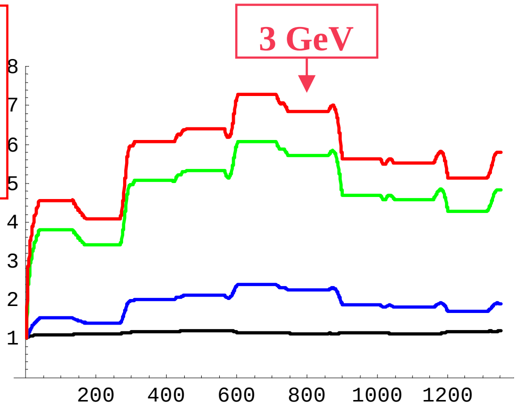
Betatron mismatch CS ≠1

Projected Emittance
5 Pass CEBAF
(Initial=1)



Beam-Orbit Mismatch
5 Pass CEBAF
(Initial=1)

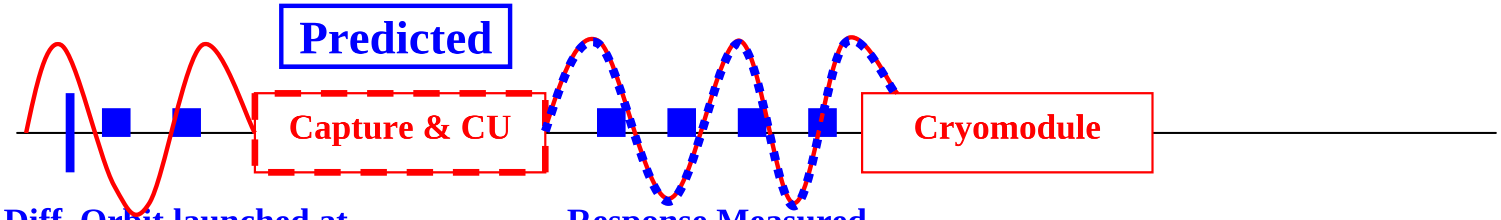




Compounded Effects of Coupling and Transport Singularity

– Observation in CEBAF: Case One – 100 keV to 60 MeV

- **4 by 4 Transfer matrix is empirically measured across the cryo-unit**



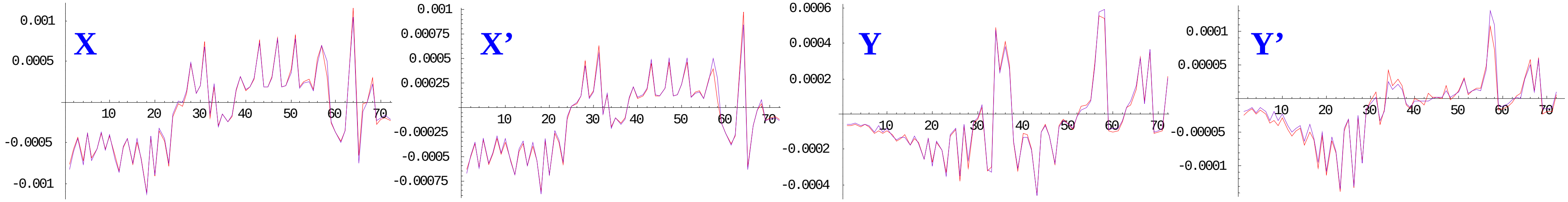
Diff. Orbit launched at 100 keV after cathode

Response Measured at 5 MeV

$$S=\begin{pmatrix}0&1&0&0\\-1&0&0&0\\0&0&0&1\\0&0&-1&0\end{pmatrix}$$

RED: X, X', Y, Y' responses to 72 input orbits **measured** at exit

BLUE: X, X', Y, Y' responses **predicted** by empirical 4×4 matrix



$$M=\begin{pmatrix}3.30352&0.525507&1.23678&0.250991\\1.89627&0.320357&0.571336&0.115218\\0.893923&0.183311&2.06575&0.309412\\0.109193&0.0213833&0.76451&0.144428\end{pmatrix}$$

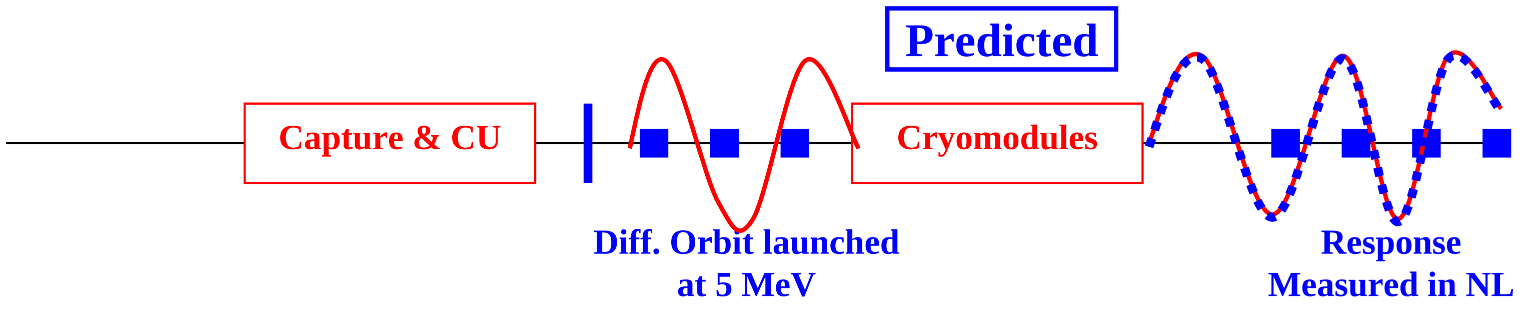
$$M\cdot S\cdot M^T=\begin{pmatrix}0&0.0609027&0&0\\-0.0609027&0&0&0\\0&0&0&0.0609027\\0&0&-0.0609027&0\end{pmatrix}$$

- **Transport is visibly near-singular**
- **Empirical matrix displays full damping of 4D phase space**

⇒ Correctable by linear optics

Compounded Effects of Coupling and Transport Singularity
– Observation in CEBAF: Case One – 100 keV to 60 MeV

- 4 by 4 Transfer matrix is empirically measured across the cryo-modules



Predicted

Capture & CU

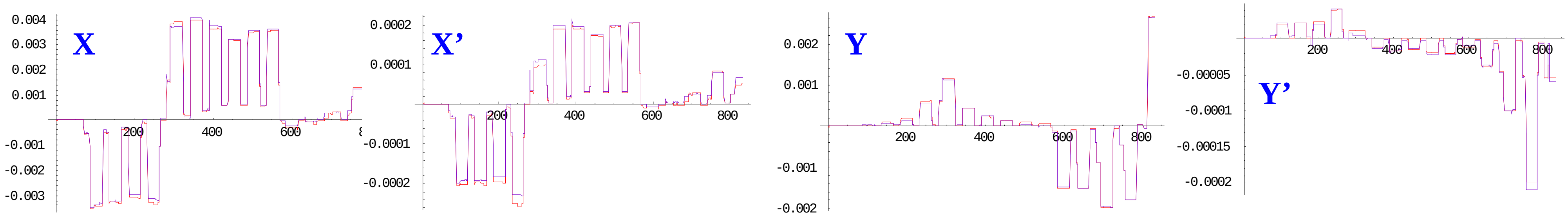
Cryomodules

Diff. Orbit launched
at 5 MeV

Response
Measured in NL

RED: X, X', Y, Y' responses to 850 input orbits **measured** at exit

BLUE: X, X', Y, Y' responses **predicted** by empirical 4×4 matrix



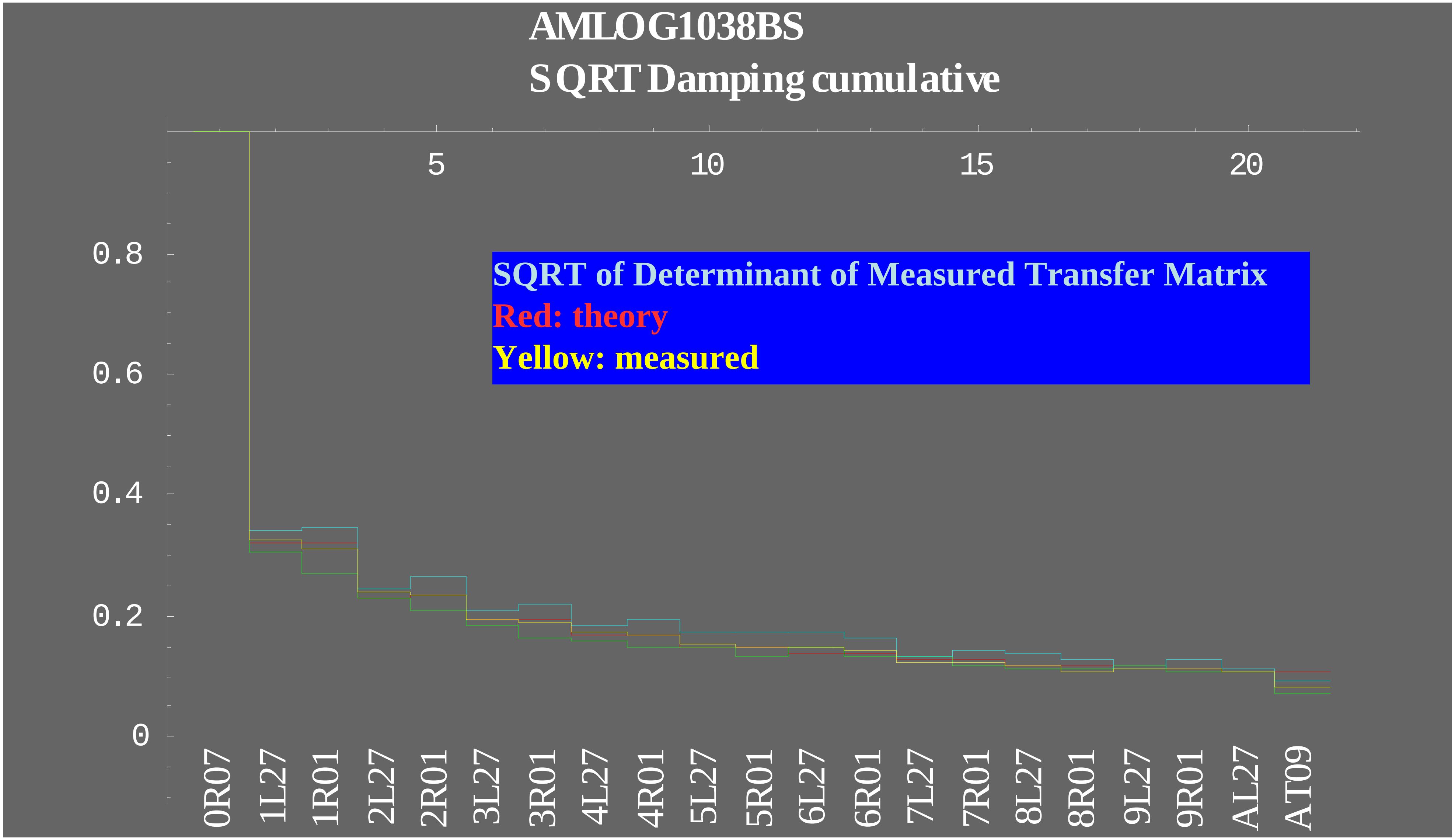
$$M = \begin{pmatrix} -1.95779 & 2.03353 & 0.146685 & 0.915682 \\ -0.10142 & 0.0519668 & 0.0135454 & 0.0490508 \\ -0.074597 & 0.502861 & -0.838734 & 0.441695 \\ 0.0110684 & -0.00479406 & -0.0316214 & -0.107939 \end{pmatrix}$$

$$M \cdot S \cdot M^T = \begin{pmatrix} 0 & 0.0992913 & 0 & 0 \\ -0.0992913 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0992913 \\ 0 & 0 & -0.0992913 & 0 \end{pmatrix}$$

- Transport is visibly near-singular
- Empirical matrix displays full damping of 4D phase space
- ⇒Correctable by linear optics

Transport within the Main Accelerator

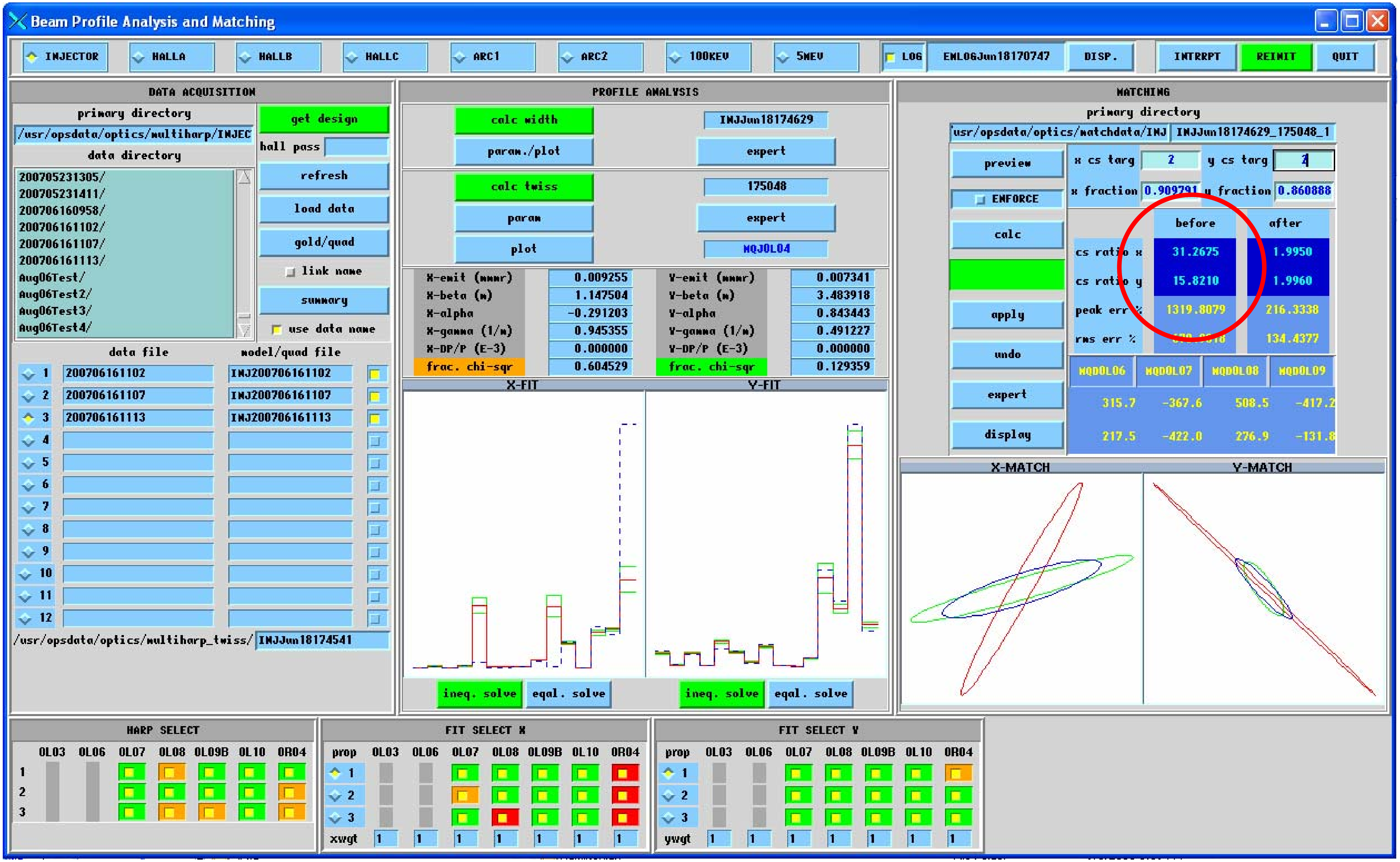
Transport consistent with proper adiabatic damping



SQRT of Determinant of Measured Transfer Matrix

Red: theory

Yellow: measured



EMLOGJun18170747

primary directory: /usr/opsdata/optics/multiharp/INJEC

hall pass:

data directory:

200705231305/
200705231411/
200706160958/
200706161102/
200706161107/
200706161113/
Aug06Test/
Aug06Test2/
Aug06Test3/
Aug06Test4/

	data file	model/quad file
1	200706161102	INJ200706161102
2	200706161107	INJ200706161107
3	200706161113	INJ200706161113
4		
5		
6		
7		
8		
9		
10		
11		
12		

/usr/opsdata/optics/multiharp_twiss/ INJJun18174541

INJJun18174629

175048

MQJ0L04

X-emit (mmmr)	0.009255	Y-emit (mmmr)	0.007341
X-beta (m)	1.147504	Y-beta (m)	3.483918
X-alpha	-0.291203	Y-alpha	0.843443
X-gamma (1/m)	0.945355	Y-gamma (1/m)	0.491227
X-DP/P (E-3)	0.000000	Y-DP/P (E-3)	0.000000
frac. chi-sqr	0.604529	frac. chi-sqr	0.129359

primary directory: /usr/opsdata/optics/matchdata/INJ INJJun18174629_175048_1

x cs targ: 2 y cs targ: 2

x fraction: 0.909791 y fraction: 0.860888

	before	after
cs ratio x	31.2675	1.9950
cs ratio y	15.8210	1.9960
peak err %	1319.8079	216.3338
rms err %	[illegible]	134.4377

MQD0L06	MQD0L07	MQD0L08	MQD0L09
315.7	-367.6	508.5	-417.2
217.5	-422.0	276.9	-131.8

HARP SELECT

	0L03	0L06	0L07	0L08	0L09B	0L10	0R04
1	▒	▒	🟩	🟧	🟩	🟩	🟩
2	▒	▒	🟩	🟩	🟩	🟩	🟧
3	▒	▒	🟩	🟧	🟧	🟩	🟧

FIT SELECT X

prop	0L03	0L06	0L07	0L08	0L09B	0L10	0R04
1	▒	▒	🟩	🟩	🟩	🟩	🟥
2	▒	▒	🟧	🟩	🟩	🟩	🟥
3	▒	▒	🟩	🟥	🟩	🟩	🟥
xwgt	1	1	1	1	1	1	1

FIT SELECT Y

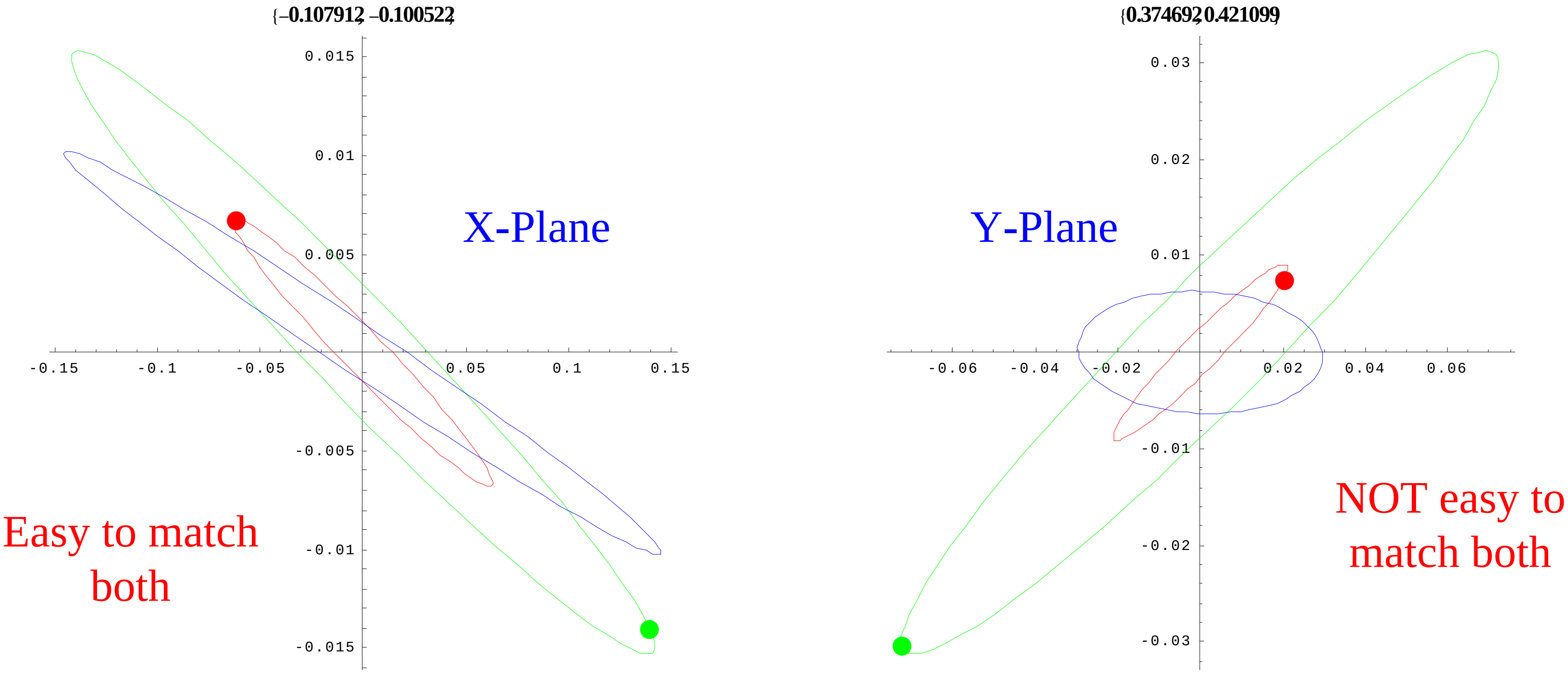
prop	0L03	0L06	0L07	0L08	0L09B	0L10	0R04
1	▒	▒	🟩	🟩	🟩	🟩	🟧
2	▒	▒	🟩	🟩	🟩	🟩	🟩
3	▒	▒	🟩	🟩	🟩	🟩	🟩
ywgt	1	1	1	1	1	1	1

CS Mismatch on 06/16/07: 5.6 in X, 4.0 in Y

Compounded Effects of Coupling and Transport Singularity
– Observation in CEBAF: Case Two – 60 MeV to 3 GeV

Initial Betatron Mismatch Also Drives Incongruence between (Helicity Correlated) Orbit and Beam Spot, Making Simultaneous Matching of BOTH Difficult.

Real Measured Phase Space Coordinates for PZT Orbits (RED & GREEN), and Beam Spot (BLUE) of 01/09/2007 at IHA0L10



Easy to match both

NOT easy to match both

Compounded Effects of Coupling and Transport Singularity– 60 MeV to 3 GeV

- Real problem with reducing orbit amplitude is its incompatibility with the beam spot in phase space.
- This is exacerbated by coupling.

- For the same amount of coupling, initially well matched beam and orbit stay close later on.

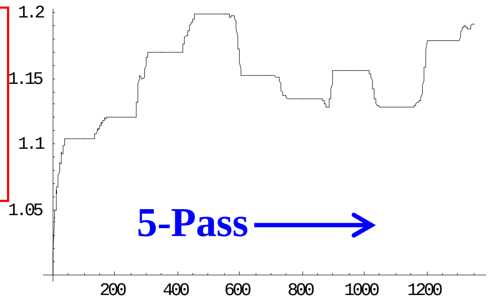
- Initially mismatched beam and orbit develop large incompatibility.

- For well matched orbit and beam, orbit stays close to the phase ellipse with constant emittance.

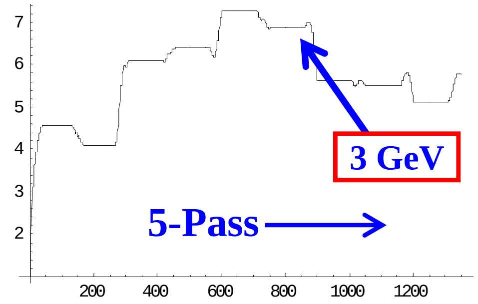
- For mismatched orbit and beam, orbit drifts away from the constant-emittance ellipse.

Beam-Orbit Mismatch $$CS_B = \sqrt{\gamma_B \cdot x_T^2 + 2 \cdot \alpha_B \cdot x_T \cdot x'_T + \beta_B \cdot x'^2_T} = \sqrt{\overrightarrow{X}_T^{T} \cdot \Sigma_B^{-1} \cdot \overrightarrow{X}_T}$$

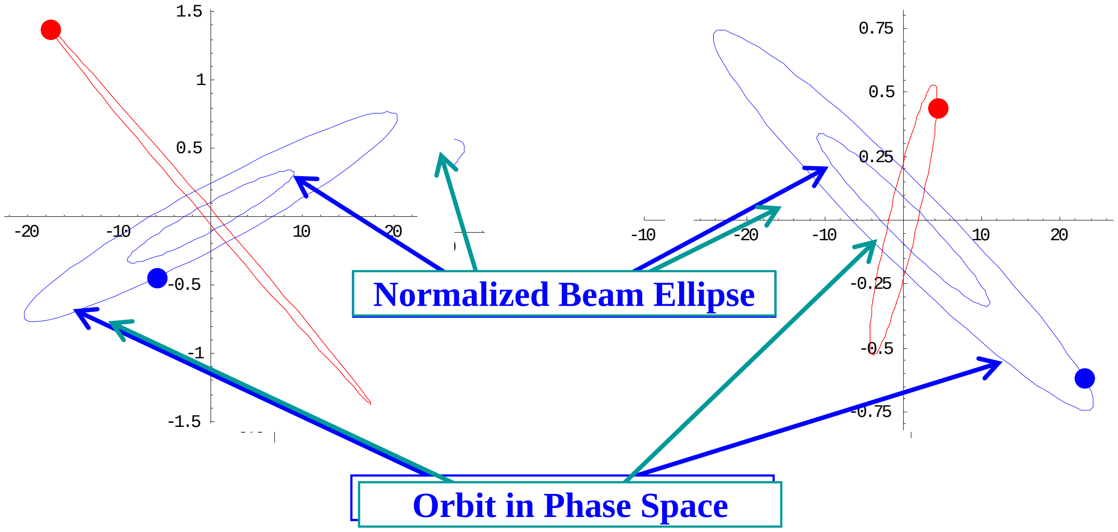
No Initial Mismatch



Initially Mismatched CS=6



Target at 3 GeV **No Initial Mismatch**



PZT "Booster"

Empirical transport matching guided by PZT signals has many shortcomings:

- **Weak signal (20-50 μm at 60 MeV, much smaller at higher energy)**
  - **Aperture and linearity/abberation constraints in Injector**
  - **Damping**
- **CW beam required to enhance signal stability**
  - **Impose extra operational limitations (beamline setup, beam loss trips, ……)**
  - **Cannot see multiple pass transport**

Solution: "Boosting" the PZT Signal to more visible amplitude

Turning 4-D Helicity Feedback System into Empirical Amplifier with Gain >>1