Generation and Control of High Precision Beams at Lepton Accelerators

Experience of Parity Quality Beam Delivery at CEBAF

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This Talk Represents Work by:


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

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

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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Physics Asym. (ppm)</th>
<th>Intensity (ppm)</th>
<th>Position on Target (nm)</th>
<th>Angle on Target (nrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAPPEX-I</td>
<td>13</td>
<td>1.0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>G0</td>
<td>2-50</td>
<td>1.0</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>HAPPEX-He</td>
<td>8</td>
<td>0.6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>HAPPEX-II</td>
<td>1.3</td>
<td>0.6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Qweak</td>
<td>0.3</td>
<td>0.1</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Lead</td>
<td>&lt;1</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Recently Concluded
Helicity Correlated Orbit

- 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: $<ΔX> \leq 2$ nm, $<ΔX'> \leq 2$ 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**
Observation of Damping (or Lack thereof) – Injector to Main Acc.

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 \((\varepsilon, \alpha, \beta)\) 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

\[ CS_{TD} = \sqrt{X_T^T \cdot \Sigma_D^{-1} \cdot X_T} = \sqrt{\gamma_D \cdot x_T^2 + 2 \cdot \alpha_D \cdot x_T \cdot x'_T + \beta_D \cdot x'_T^2} \]

Beam-Design Mismatch

\[ CS_{BD} = \sqrt{\text{Tr}(\Sigma_D^{-1} \cdot \Sigma_B)} / 2 = \sqrt{\beta_D \cdot \gamma_B - 2 \cdot \alpha_D \cdot \alpha_B + \gamma_D \cdot \beta_B} / 2 \]

Beam-Trajectory Mismatch

\[ CS_{BT} = \sqrt{X_T^T \cdot \Sigma_B^{-1} \cdot X_T} = \sqrt{\gamma_B \cdot x_T^2 + 2 \cdot \alpha_B \cdot x_T \cdot x'_T + \beta_B \cdot x'_T^2} \]

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

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

\[ \varepsilon_{x, \text{Final}}^2 - \varepsilon_{x, \text{Initial}}^2 = \langle XX \rangle \langle YY \rangle k^2 = \beta_x \beta_y \varepsilon_x \varepsilon_y k^2 \]
Coupling and Transport Singularity – Injector

4D Transfer 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.

<table>
<thead>
<tr>
<th>2005 Beam Based Data</th>
<th>Ideal</th>
<th>Meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Off-Diagonal Determinant</td>
<td>0</td>
<td>40.67</td>
</tr>
<tr>
<td>X-Sub Matrix SVD Condition Number</td>
<td>~10</td>
<td>863.79</td>
</tr>
<tr>
<td>Y-Sub Matrix SVD Condition Number</td>
<td>~10</td>
<td>9.651</td>
</tr>
<tr>
<td>4 X 4 Matrix SVD Condition Number</td>
<td>~10</td>
<td>562.68</td>
</tr>
</tbody>
</table>
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 \( CS \neq 1 \) 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!

Up to 20% residual HOM induced coupling after compensation in main linacs
A systematic effect - Can add coherently – Weak, no problem if no mismatch
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And beam-orbit mismatch \( CS \) ⇒ Measures ease to control HC orbit!

Skew Coupling

Betatron Mismatch \( CS \neq 1 \)

Problem at 3 GeV (P-V Exp.)

Projected Emittance
5 Pass CEBAF
(Initial=1)

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

CS=1
CS=2
CS=5
CS=6
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

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

➢ 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

<table>
<thead>
<tr>
<th>100 keV-60 MeV Transfer Before</th>
<th>100 keV-60 MeV Transfer After</th>
</tr>
</thead>
</table>
| \[\begin{pmatrix}
-1.22833 & 1.05712 & 0.415562 & 0.184011 \\
-0.0840176 & 0.0698204 & 0.0285021 & 0.0176597 \\
-0.14413 & 0.187408 & -0.0662305 & 0.15709 \\
-0.0230667 & 0.0154644 & -0.0115026 & -0.0100966
\end{pmatrix}\] | \[\begin{pmatrix}
-0.0227606 & 0.346927 & 0.00305693 & -0.0103931 \\
-0.0155276 & 0.0115317 & -0.000466868 & 0.0103269 \\
-0.00724513 & 0.0515986 & -0.0567142 & -0.236438 \\
-0.00307405 & 0.0102054 & -0.0160936 & -0.155004
\end{pmatrix}\] |

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

<table>
<thead>
<tr>
<th>2005 Beam Based Data</th>
<th>Ideal</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional Off-Diagonal Determinant</td>
<td>0</td>
<td>40.67%</td>
<td>0.518%</td>
</tr>
<tr>
<td>X-Sub Matrix SVD Condition Number</td>
<td>~10</td>
<td>863.79</td>
<td>23.62</td>
</tr>
<tr>
<td>Y-Sub Matrix SVD Condition Number</td>
<td>~10</td>
<td>9.651</td>
<td>16.50</td>
</tr>
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<td>4 X 4 Matrix SVD Condition Number</td>
<td>~10</td>
<td>562.68</td>
<td>25.55</td>
</tr>
</tbody>
</table>
Fixing Transport
60 MeV-3 GeV
Empirical Tuning
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.

\[
\text{Acceptance}
\]

\[
\text{Matching Quads}
\]
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)

Zooming in on First 60 BPM’s (mm*Sqrt(MeV/C))

Before

After
Damping Observed in Hall A at 3 GeV ⇒ PZT Signal

X-PZT

Y-PZT

before

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

HAPPEx BPM’s

±0.4 µm

±0.2 µm

Injector 100 keV-5 MeV M’s at 3 GeV

G0 BPM’s

±1.0 µm

±0.4 µm
Gun-to-Target Damping Observed in Hall A & C $\Rightarrow$ Helicity Correlated Orbit

Achieved Average H-C Orbits for HAPPEX 2005\textsuperscript{[1],[2]}

<table>
<thead>
<tr>
<th></th>
<th>Helium 2005 (w/o matching)</th>
<th>Hydrogen 2005 (with matching)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$ (nm)</td>
<td>-0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Delta x'$ (nrad)</td>
<td>4.4</td>
<td>-0.2</td>
</tr>
<tr>
<td>$\Delta y$ (nm)</td>
<td>-26</td>
<td>1.7</td>
</tr>
<tr>
<td>$\Delta y'$ (nrad)</td>
<td>-4.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

\textsuperscript{[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.

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

\[ C_{S_T} = \sqrt{X_T^T \cdot \Sigma^{-1} \cdot X_T} \]

Match to Beam

Trajectory Mismatch Factor

\[ \Sigma_M = \begin{pmatrix} \alpha_M & \beta_M \end{pmatrix}, \quad \Sigma_B = \begin{pmatrix} -\alpha_B & \gamma_B \end{pmatrix}, \quad X_T = X_T' \]
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.
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.

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$
<table>
<thead>
<tr>
<th></th>
<th>100 keV</th>
<th>60 MeV</th>
<th>3 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Size Theory</td>
<td>&lt;10 mm</td>
<td>~1 mm</td>
<td>~100 µm</td>
</tr>
<tr>
<td>Beam Size Measured</td>
<td>&lt;10 mm</td>
<td>~2-5 mm</td>
<td>~2-500 µm</td>
</tr>
<tr>
<td>HC Before</td>
<td>&lt; 1 µm</td>
<td>?</td>
<td>~200-1000 nm</td>
</tr>
<tr>
<td>HC After</td>
<td>&lt; 1 µm</td>
<td>~100-200 nm</td>
<td>~5-10 nm</td>
</tr>
</tbody>
</table>

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:

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

- Sensitivity coefficients $\alpha, \beta$ 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 $\alpha, \beta$ etc.
\[ A_{PV} = -A_{DET} - \alpha A_e \sum_i \beta_i \Delta X_i \]

\[ \sigma_R + \left( \frac{\partial \sigma}{\partial X} \right) \cdot \delta X_R - \sigma_L - \left( \frac{\partial \sigma}{\partial X} \right) \cdot \delta X_L \]

\[ A_{DET} \approx \frac{2\sigma}{2\sigma} \]

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

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

\[ = A_{PV} + \beta \cdot \Delta X \]

\[ \beta = \frac{\partial \sigma}{\partial X} = \frac{\partial A_{DET}}{\partial \Delta X} \]
Constraints on **Helicity Correlated Orbits**

\[
A_{PV} = A_{DET} - A_Q - \alpha A_E - \sum \beta_i \cdot \Delta X_i
\]

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

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

→ precision = 50 ppb

Allowing for 10 ppb error budget for each correction

\( \beta x = 40 \text{ ppb/nm}, \, \beta x' = 40 \text{ ppb/nrad} \). Assume 10% uncertainty:

→ Helicity correlated beam parameters after averaging:

\[<\Delta X> \leq 2 \text{ nm}, \quad <\Delta X'> \leq 2 \text{ nrad} \]
Helicity Flipping and Source of Helicity-Correlated Beam Parameters

- 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

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Can be magnified by erratic beam transport!

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G. Cates, PAVI04
Correcting for Asymmetry $A_{PV}$ with beam-based calibration:

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

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

- Sensitivity coefficients on beam parameters (energy, position and angle) $\alpha$, $\beta$ 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 $\alpha$, $\beta$ etc.

1 ppm Asymmetry, 5% Relative error, 10% Uncertainty in $\beta x$ & $\beta x'$:

$\rightarrow$ precision = 50 ppb

Allowing for 10 ppb error budget for each correction

$\beta x = 40$ ppb/nm, $\beta x' = 40$ ppb/nrad.

Assume 10% uncertainty:

$\rightarrow$ Helicity correlated beam parameters after averaging:

$$\langle \Delta X \rangle \leq 2 \text{ nm}, \quad \langle \Delta X' \rangle \leq 2 \text{ nrad} \quad \text{Averaged over Run}$$
Suppression of Coupling and Transport Singularity – General

- 4D symplecticity guarantees transport fix by quads and skew quads alone.
  - Eliminate XY coupling
  - Reduce transport singularity \( \Rightarrow \) 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 $CS \neq 1$ 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.)

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

**Predicted**

**Capture & CU**

Diff. Orbit launched at 100 keV after cathode

Response Measured at 5 MeV

**Cryomodule**

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

**Transport is visibly near-singular**

**Empirical matrix displays full damping of 4D phase space**

⇒ Correctable by linear optics

\[
\begin{bmatrix}
0 & 1 & 0 & 0 \\
-1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & -1 & 0
\end{bmatrix}
\]

\[
M = \begin{bmatrix}
3.30352 & 0.525507 & 1.23678 & 0.250991 \\
1.89627 & 0.320357 & 0.571336 & 0.115218 \\
0.893923 & 0.183311 & 2.06575 & 0.309412 \\
0.109193 & 0.021383 & 0.76451 & 0.144428
\end{bmatrix}
\]

\[
M \cdot S \cdot M^T = \begin{bmatrix}
0 & 0.0609027 & 0 & 0 \\
-0.0609027 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.0609027 \\
0 & 0 & -0.0609027 & 0
\end{bmatrix}
\]
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

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

AMLOG1038BS
SQRT Damping cumulative

SQRT of Determinant of Measured Transfer Matrix
Red: theory
Yellow: measured
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

**X-Plane**
- Easy to match both

**Y-Plane**
- 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

$$CS_B = \sqrt{\gamma_B \cdot x_T^2 + 2 \cdot \alpha_B \cdot x_T \cdot x_T^I + \beta_B \cdot x_T^{I2}}$$

No Initial Mismatch

Initially Mismatched CS=6
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