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# IDENTIFYING ANOMALIES AT CEBAF USING CROSS-PLANE COVARIANCE SVD

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# Problem: coherent cross-plane motion is easy to miss

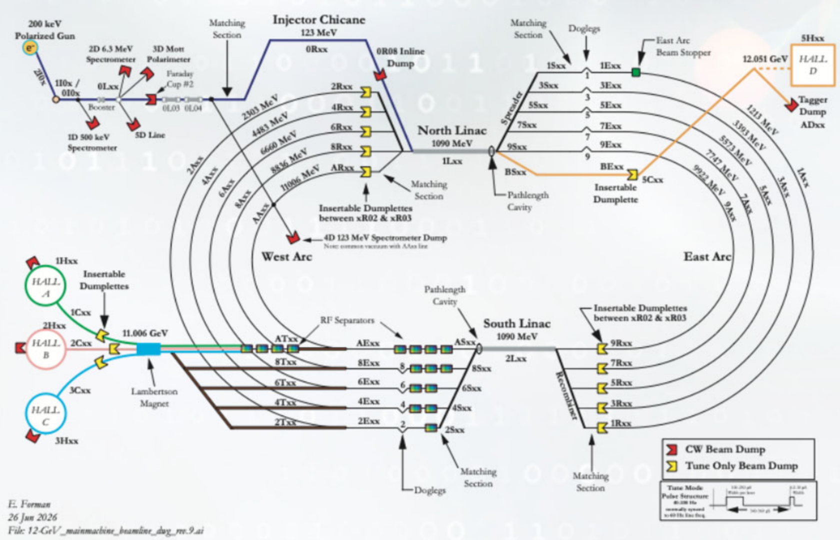
- CEBAF is nominally decoupled, but shared transport and recirculation can mix horizontal and vertical signatures.

- Residual dispersion, skew fields, feedback cross-feed, beam loss, and faults can produce coherent X–Y motion.

- BPM data identify when a coupled pattern turns on and where it becomes visible, but difficult to detect visually

**Goal: model-light anomaly detection that complements detailed optics studies.**

JEFFERSON LAB 12 GeV BEAMLINE




# Problem: coherent cross-plane motion is easy to miss

- Build synchronized BPM matrices X and Y with BPMs in rows and time samples in columns.
- Center each BPM row over the analysis window.
- Compute the zero-lag cross-plane covariance Cxy = (1/T)$XY^T$.
- Use SVD to obtain paired spatial patterns and temporal projections.

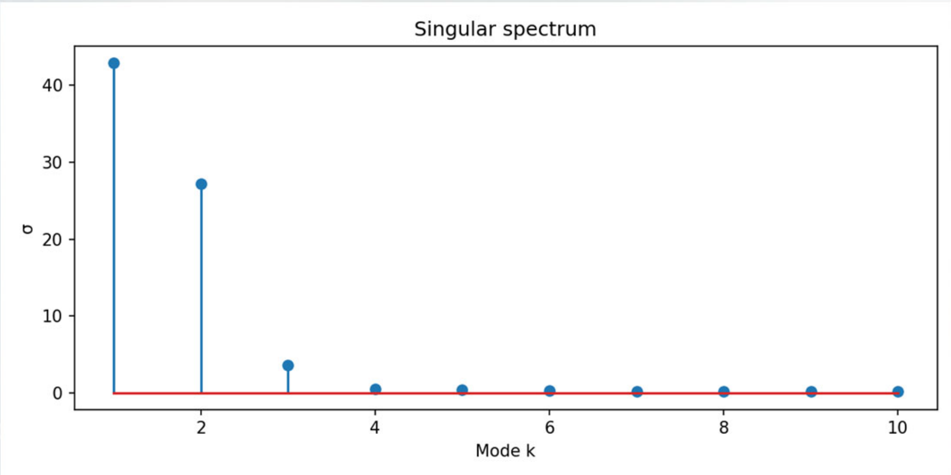
$$\frac{1}{T}\begin{bmatrix} x_1(t_1)-\bar{x}_1 & \dots & x_1(t_T)-\bar{x}_1 \\ \dots & \dots & \dots \\ x_n(t_1)-\bar{x}_n & \dots & x_n(t_T)-\bar{x}_n \end{bmatrix}\begin{bmatrix} y_1(t_1)-\bar{y}_1 & \dots & y_n(t_1)-\bar{y}_n \\ \dots & \dots & \dots \\ y_1(t_T)-\bar{y}_1 & \dots & y_n(t_T)-\bar{y}_n \end{bmatrix}$$

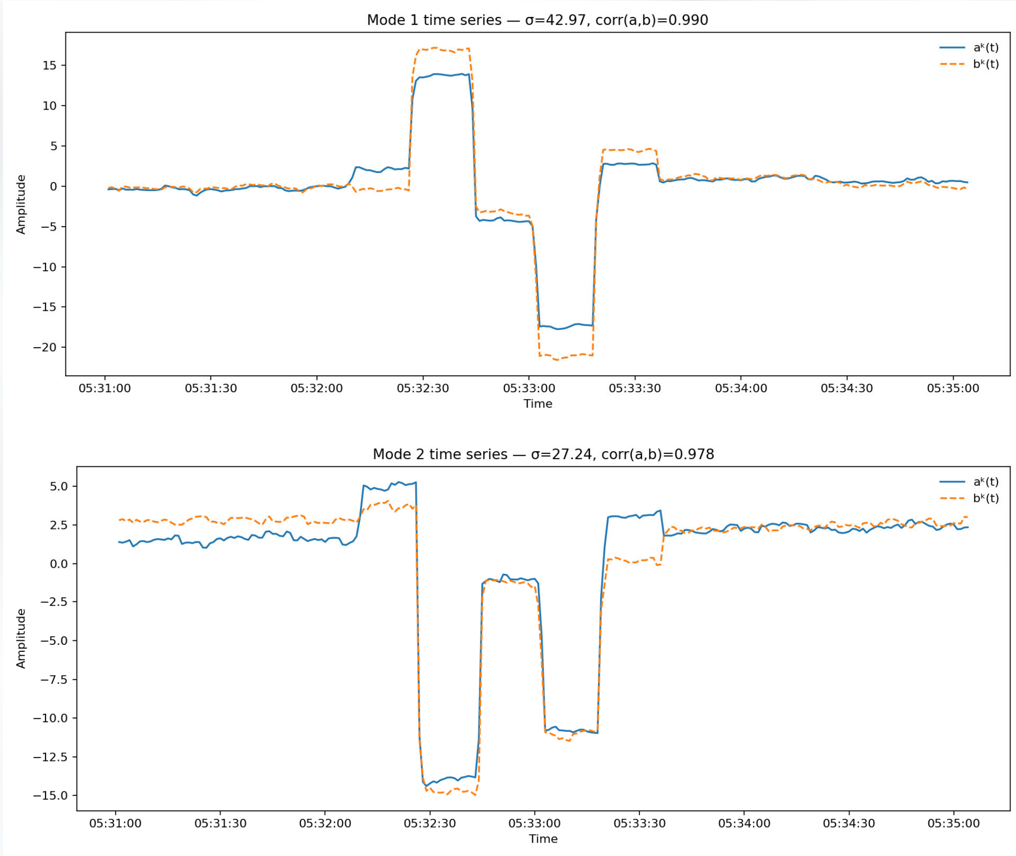
$$= \frac{1}{T}\begin{bmatrix} \sum_t (x_1(t)-\bar{x}_1)(y_1(t)-\bar{y}_1) & \dots & \sum_t (x_1(t)-\bar{x}_1)(y_n(t)-\bar{y}_n) \\ \dots & \dots & \dots \\ \sum_t (x_n(t)-\bar{x}_n)(y_1(t)-\bar{y}_1) & \dots & \sum_t (x_n(t)-\bar{x}_n)(y_n(t)-\bar{y}_n) \end{bmatrix}$$

- **Core calculation**
  - **$C = XY^T \iff P\,\Sigma\,Q^T$**
  - **$A = X^T P$, $B = Y^T Q$**
  - **$(1/T)\, A^T B = \Sigma$**
- $p_k$ and $q_k$: paired horizontal/vertical spatial response vectors from within P and QT
- $\sigma_k$: strength of shared X–Y motion, square of eigenvalues
- $a_k(t)$, $b_k(t)$: when the coupled pattern is active, projection of the time axis vectors onto the spatial eigenmode vectors

# Controlled Optics Excitation sequence validates mode separation

- Five known inputs: $X_1$, $X_2$, $Y_1$, $Y_2$, and E, each applied for 15 s.
- Modes 1–2 respond most strongly to corrector-excitation intervals.
- Paired temporal correlations are 0.990 and 0.978.
- The steep singular spectrum shows that a few modes capture the dominant cross-plane covariance.



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# Energy excitation appears as a dispersive mode


Mode 3 spatial vector and paired temporal projections during the energy excitation

Mode 3 is selected because it peaks during the known E excitation.

The horizontal spatial vector has a dispersive response pattern.

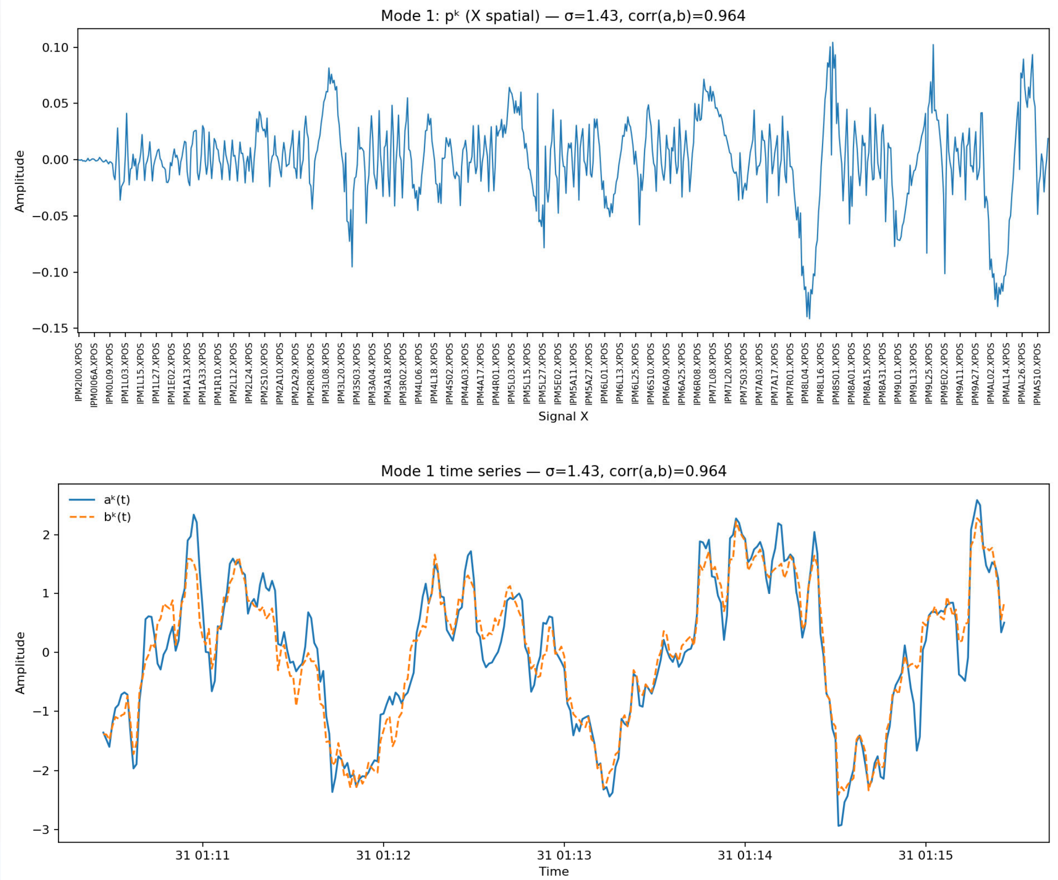
**$corr(a_3,b_3) = 0.928$**

The response can be reconstructed and compared with standard differential-orbit views.

Distinguishes anomaly caused by energy, and can localize it to the pre-dispersive accelerating section

# Archived magnet anomaly: ~80-s coherent motion

- The same analysis was applied to an archived magnet oscillation with an approximately 80 s period.
- The dominant paired temporal traces follow the oscillation with correlation 0.964.
- The spatial response becomes prominent at the end of the injector region, where the magnet was located.
- Able to localize where the beam response begins, and its associated time signature
- Non-dispersion pattern-like spatial vector confirms it's not due to energy




Leading spatial mode and paired time traces for the archived 80 second oscillation.

# Summary and poster discussion

- Detect singular values and paired correlations flag coherent cross-plane covariance in archived BPM windows.
- Localize paired spatial vectors show where the horizontal and vertical responses appear in the machine and tie modes to known patterns like dispersion
- Connect temporal projections tie to known excitations, machine events, or time signatures.
- Bottom line: cross-plane covariance SVD is a compact, model-light screen for CEBAF BPM anomalies, and it can work for nominally decoupled transport lines with residual coupling.
- Next Steps: robust baseline scores, and automated archive monitoring, and clustering modes