Real Beam Optics From A "Synthetic" Beam

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Abstract

- CEBAF cannot use the same methods as a ring to measure Twiss parameters.
- Developing procedure to measure the evolution of the Twiss parameters with a “synthetic” beam.
- Talk will focus on current state of procedure and where it is expected to progress.

Outline

- Goal: Provide understanding of rayTrace procedure, and why it is useful.
- Basic accelerator physics background.
- Current methods used by CEBAF:
  - Beamline characterization and tuning.
  - Weaknesses.
- rayTrace method.
- An example of use.
- What is still to be done.

The Matrix Formalism

- A transfer matrix connects the phase space coordinates at point 2 to those at point 1.

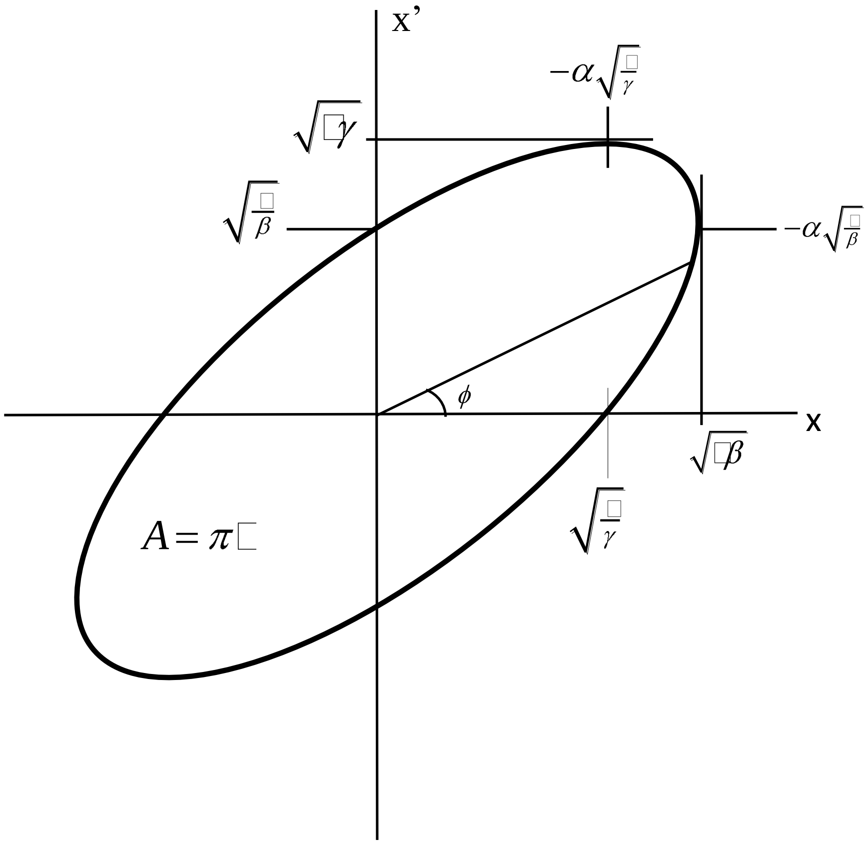
$$\begin{bmatrix} x \\ x' \end{bmatrix}_2 = M(1 \rightarrow 2) \begin{bmatrix} x \\ x' \end{bmatrix}_1$$

- Example transfer matrices for thin lenses and a drift look like these:

$$\begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} = M_{QF}, \quad \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix} = M_{QD}, \quad \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} = M_D$$

Twiss Parameters

- First, the classic phase ellipse, with labeled Twiss parameters:



α is related to the distance to the geometric focus.

β is the amplitude function.

ε is proportional to the area a set of beams will occupy in phase space.

RMS Parameter Definitions

$$\epsilon_{rms}^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2$$

$$\beta_{rms} = \frac{\langle x^2 \rangle}{\epsilon_{rms}}$$

$$\alpha_{rms} = -\frac{\langle xx' \rangle}{\epsilon_{rms}}$$

Transfer Matrix vs. Twiss Parameters

- M is transport matrix containing Twiss parameters.

$$\begin{bmatrix} x \\ x' \end{bmatrix}_2 = M(1 \to 2) \begin{bmatrix} x \\ x' \end{bmatrix}_1$$

$$M = \begin{bmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\Delta\psi + \alpha_1 \sin\Delta\psi) & \sqrt{\beta_1\beta_2}\sin\Delta\psi \\ -\frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\Delta\psi + \frac{\alpha_1 - \alpha_2}{\sqrt{\beta_1\beta_2}}\cos\Delta\psi & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\Delta\psi - \alpha_2 \sin\Delta\psi) \end{bmatrix}$$

Relationship of Beam and Twiss

$$M=\begin{bmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\Delta\psi+\alpha_1\sin\Delta\psi) & \sqrt{\beta_1\beta_2}\sin\Delta\psi \\ -\frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\Delta\psi+\frac{\alpha_1-\alpha_2}{\sqrt{\beta_1\beta_2}}\cos\Delta\psi & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\Delta\psi-\alpha_2\sin\Delta\psi) \end{bmatrix}$$

$$\mathcal{M}=\begin{bmatrix} m_{11}^2 & -2m_{11}m_{12} & m_{12}^2 \\ -m_{11}m_{21} & m_{11}m_{22}+m_{12}m_{21} & -m_{12}m_{22} \\ m_{21}^2 & -2m_{21}m_{22} & m_{22}^2 \end{bmatrix}$$

Relationship of Beam and Twiss

$$\mathcal{M} = \begin{bmatrix} m_{11}^2 & -2m_{11}m_{12} & m_{12}^2 \\ -m_{11}m_{21} & m_{11}m_{22} + m_{12}m_{21} & -m_{12}m_{22} \\ m_{21}^2 & -2m_{21}m_{22} & m_{22}^2 \end{bmatrix}$$

$$\begin{bmatrix} \beta \\ \alpha \\ \gamma \end{bmatrix}_2 = \mathcal{M} \begin{bmatrix} \beta \\ \alpha \\ \gamma \end{bmatrix}_1$$

$$\gamma \equiv \frac{1+\alpha^2}{\beta}$$

$$\Delta\psi = \tan^{-1}\left(\frac{m_{12}}{\beta_1 m_{11} - \alpha_1 m_{12}} \right)$$

Closed vs. Open-Ended System

<u>Circular Machine</u>

- Many passes
  - Equilibrium orbit
- Global, self-consistent lattice
- Periodic condition
- Lattice defines Twiss Parameters
- Beam accommodates Twiss Parameters

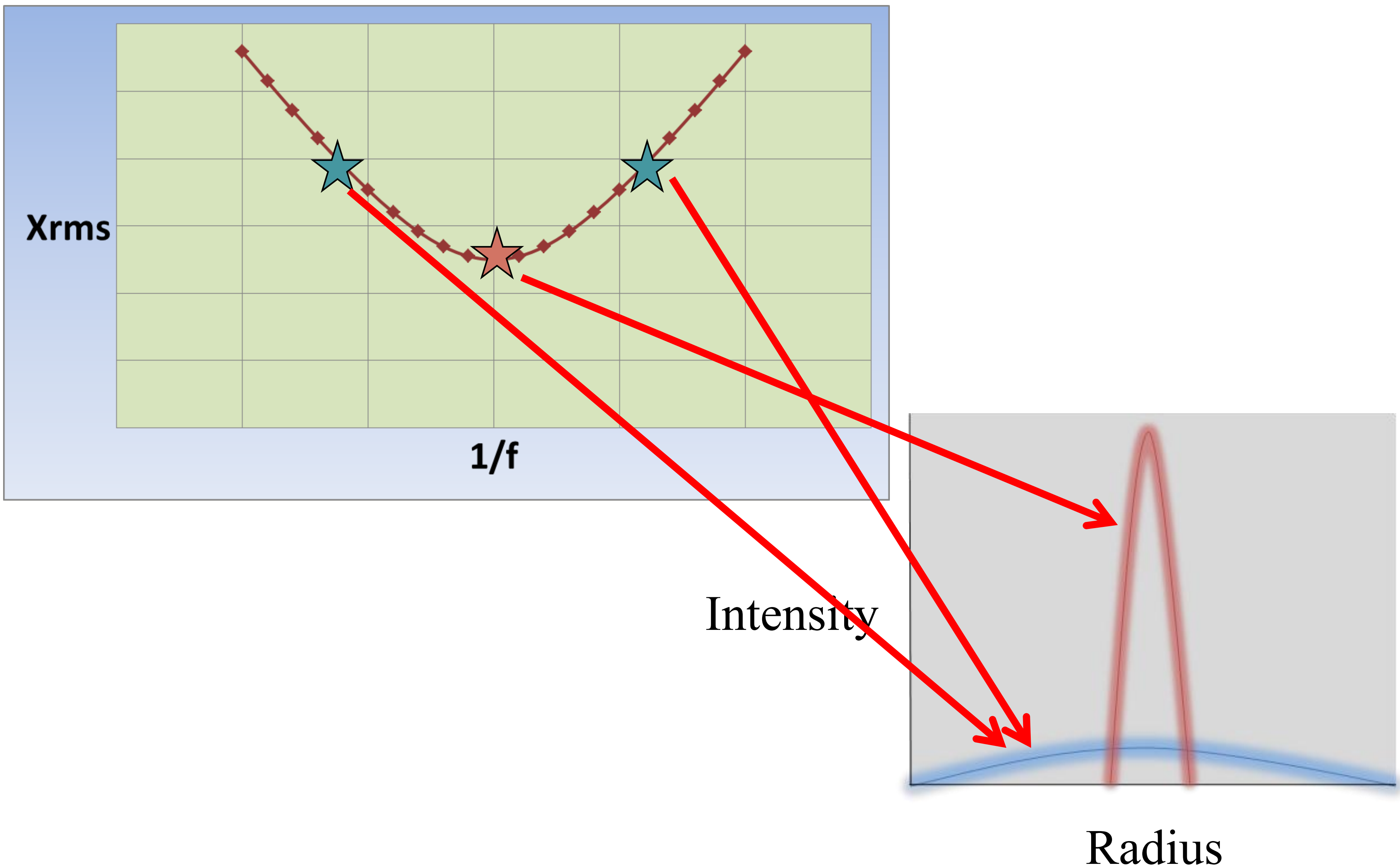
<u>Open-Ended Machine</u>

- Single pass through system
  - No equilibrium orbit
- No periodicity constraints like circular
- Lattice defines path of beam
- Lattice transforms Twiss Parameters
- How can they be measured?

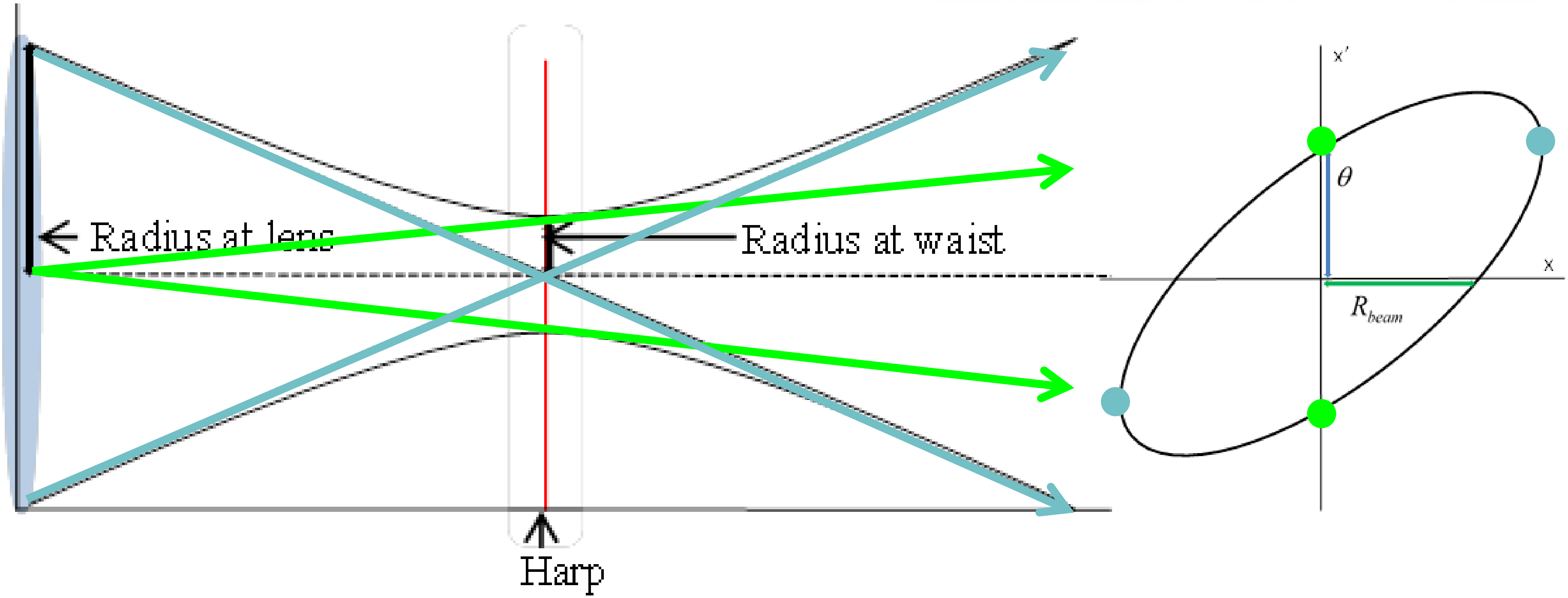
CEBAF's Methods: Quadrupole Scan

- Twiss parameters measured at CEBAF with quadrupole scan.
- Vary quadrupole strength by known amounts.
- Measure the varying beam size at a beam profile monitor.
- Find the smallest beam size at the monitor.
- Relationship between smallest beam radius to beam radius at lens can be used to calculate the uncorrelated angular spread (aka emittance angle).
- Beam that is located centrally will keep the same angular spread, regardless of lens setting.
- Smallest waist achievable gives emittance angle.

Quadrupole Scan (cont.)



Quadrupole Scan (cont.)



ò $= \theta R_{beam}$

$$\delta\theta = \frac{R_{lens}}{f}$$

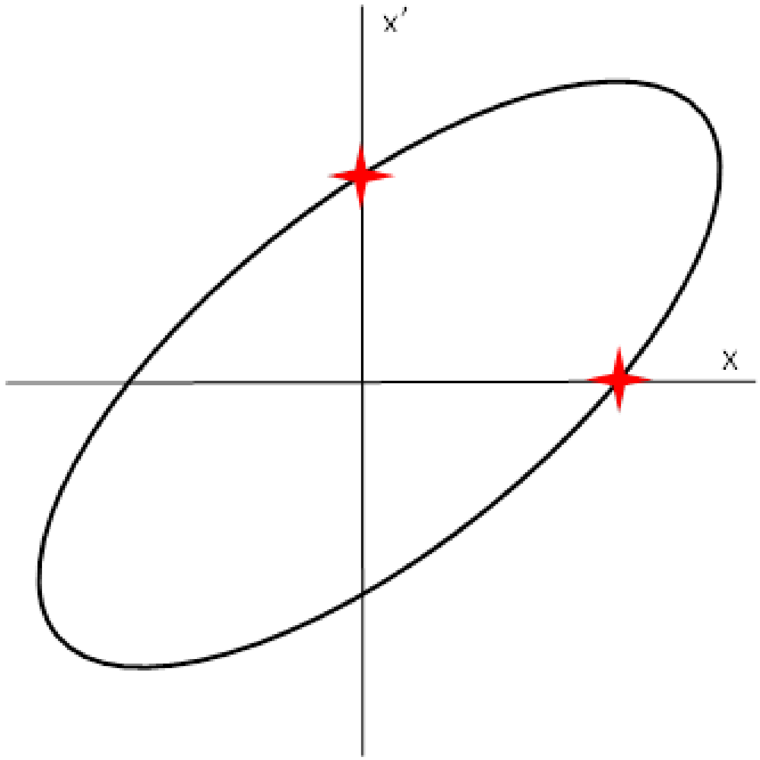
$$\theta \times l = R_{waist}$$

Quadrupole Scan: Weaknesses

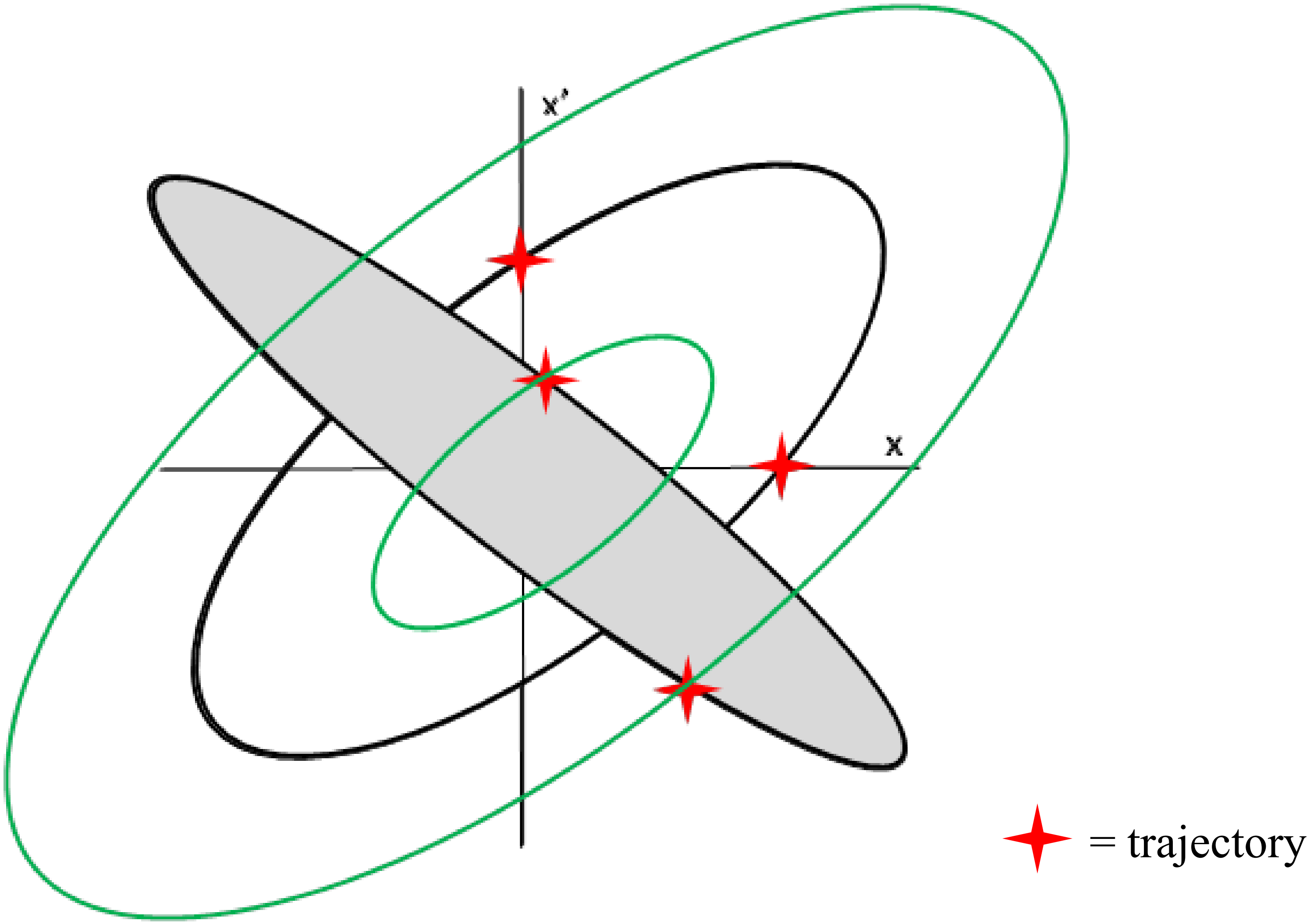
- Noisy electronics (harps).
- Sparse coverage.
- Small emittance.
- Time consuming. Takes ~30 minutes to find complete for ONE location.
- Invasive. In order to characterize a section of the beamline, the nuclear physics program must be put on hold for a long time.

CEBAF's Methods: Courant-Snyder

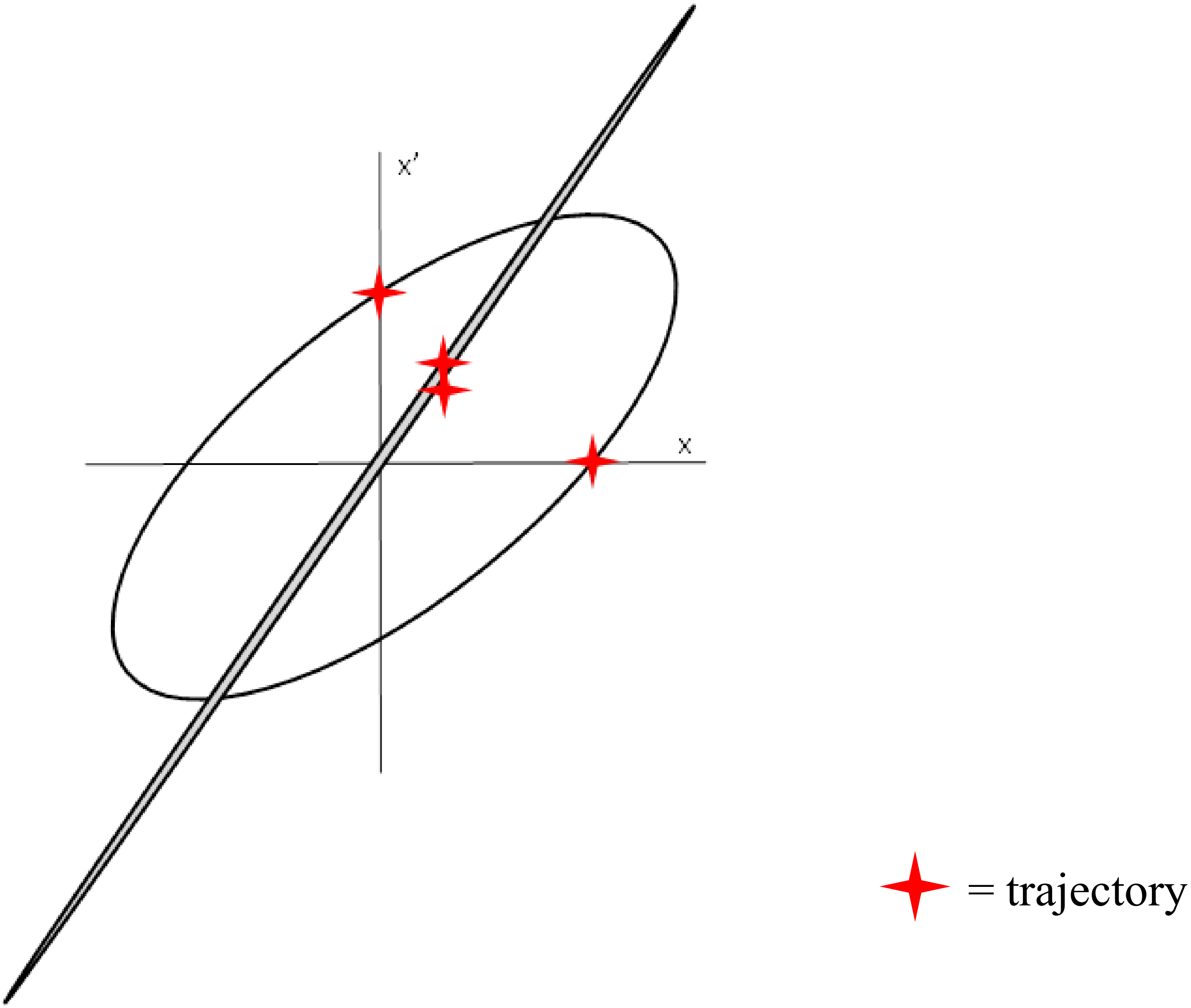
- Used to maintain beam envelope matching.
- Takes x and x' from measured trajectories, and uses α and β from the design model to calculate the matched phase ellipse corresponding to the measured trajectory.



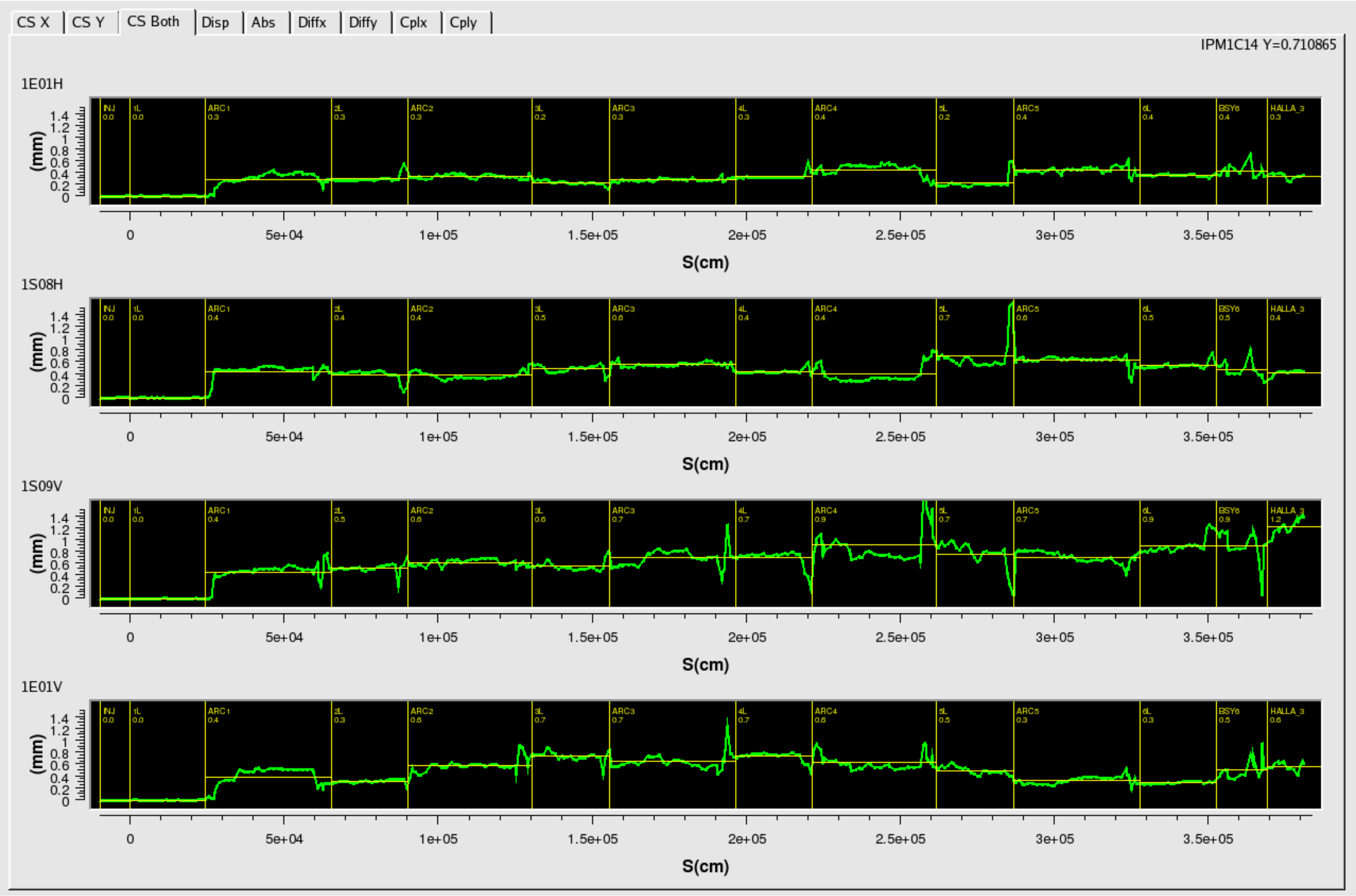
Courant-Snyder



Courant-Snyder



Courant-Snyder



Jefferson Lab

Courant-Snyder: Weaknesses

- Unguided, guess-and-check tuning.
- Ignores phase advance
  - Leads to problems with degeneracy in severely mismatched beams.

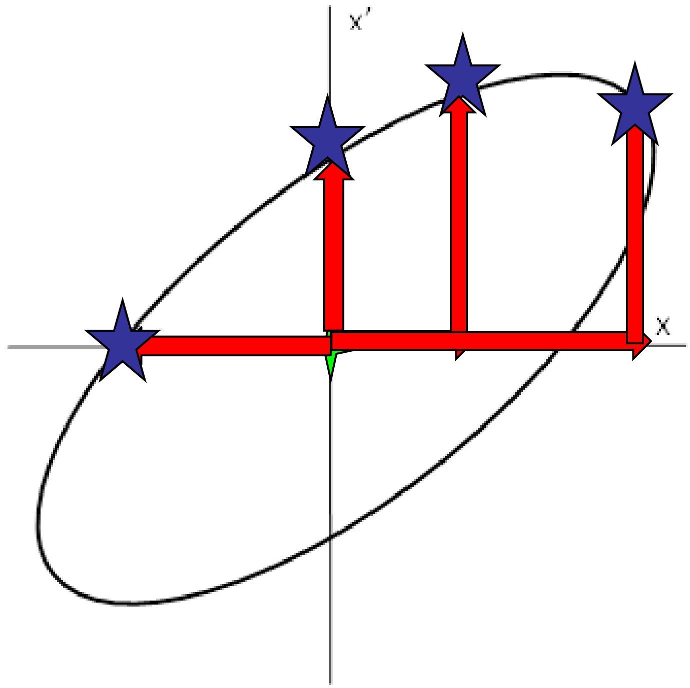
So, what is the answer?

- CEBAF needs a method that is minimally invasive to the nuclear physics program.
- Must be able to either take into account cumulative phase advance errors, or provide a way in which it can be ignored without detriment.
- Must be able to characterize the beamline both locally and globally.
- We have an answer:

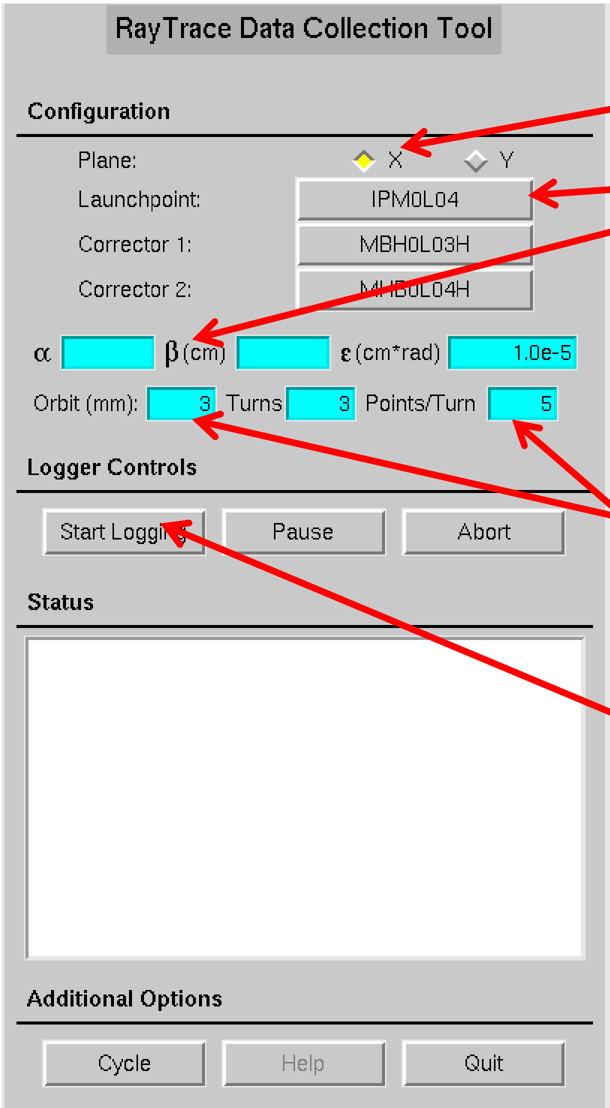
rayTrace

rayTrace: What is it?

- Measures the differential orbit of the real beam at every location simultaneously.
- Corrector kicks are set to follow the boundary of the model's phase ellipse.
- Allows for calculation of the Twiss parameters of the real beam.



rayTrace – How it Works



1. Select plane.
2. Choose launchpoint. α and β are automatically entered from the design model at the launchpoint. They can also be manually entered.
3. Set orbit size/emittance.
4. Choose number of turns and points/turn.
5. Start Logging.
6. Corrector conditioning
7. Simultaneously, acquire the model Twiss parameters.

rayTrace - How it Works

- Acquire Twiss parameters from both design and current (GOLD) models.
  - Using the Accelerator High Level Application (AHLA) group's elegant toolkit, acquire values from model.
  - Automated process using Perl.
    - Also formats data into Twiss tables.
- Twiss tables contain data for element number, element name, S, β in both planes, α in both planes, η (both position and momentum), ν in both planes, and momentum.

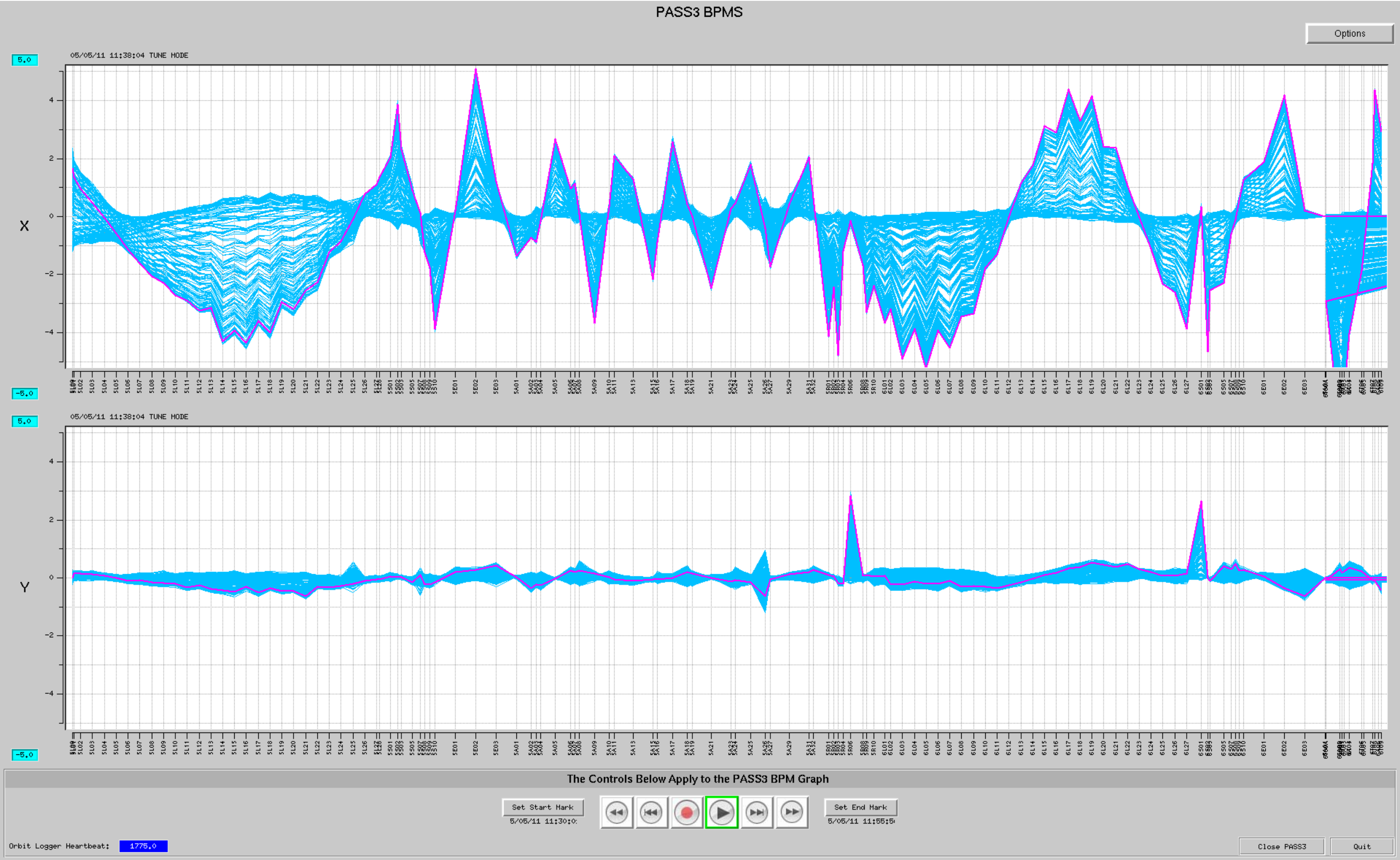
rayTrace - Analysis

- fitphase, written by Yves Roblin, is used for the analysis.
- Algorithm originally used to ID ellipses in image data.
  - Raw statistical data can provide this information as well.
- Iterating through 1 BPM at a time, fits the model over a short range to acquire x' values.
- Trajectory data used to compute ε, α, and β at each BPM.
- Plots data points, fitted ellipse, and model ellipse.
- Plots variation of α and β along the transverse direction.
- Will show more on this in the example.

Model Independent β

$$\beta \approx \frac{(x_{\max} - x_{\min})^2}{\text{ò}}$$

(as long as we agree on ε)

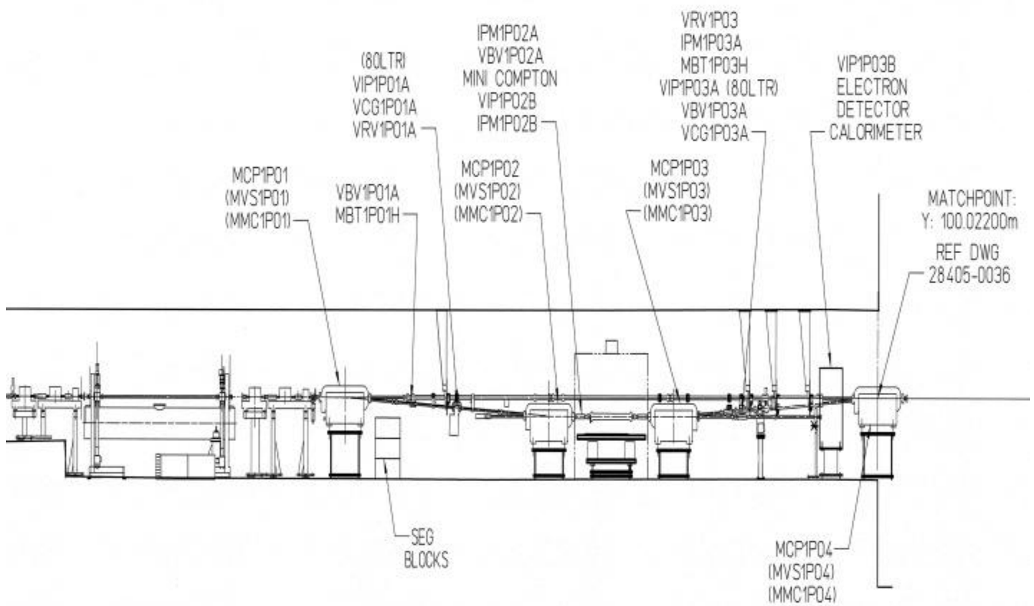


rayTrace: Tuning

- Have data at every BPM location.
  - Known local optics supplies transverse angles.
  - Can generate Twiss parameters for every BPM.
  - Can discriminate between distributed and point errors.
- Synthetic beam is a surrogate for real beam.
  - Magnified emittance.
  - Same α and β.
  - Exact linear model in zero current limit.
- Allows measurement of phase advance.

rayTrace in Action

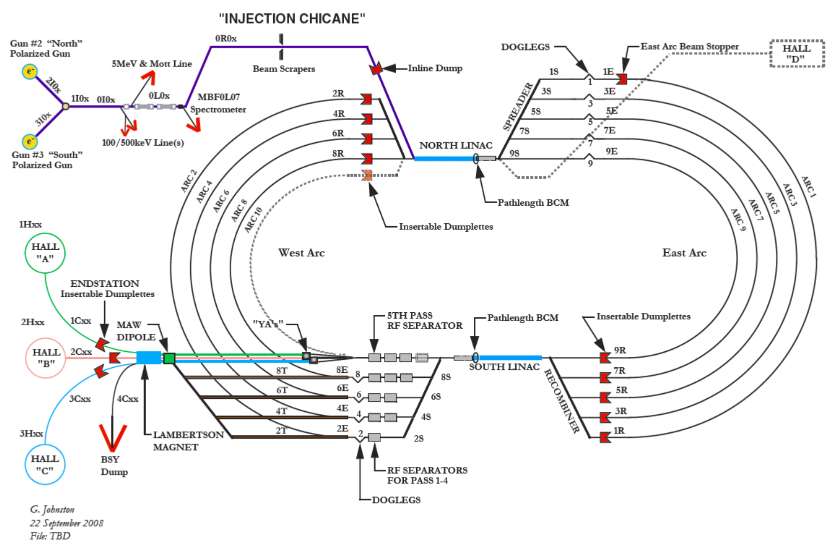
- Example of use from earlier stage of development: Hall A Compton Background Test of October, 2009.
- Hall A reports unreasonably high background count rates at their Compton polarimeter.
- Limited beam diagnostic tools available.



rayTrace in Action

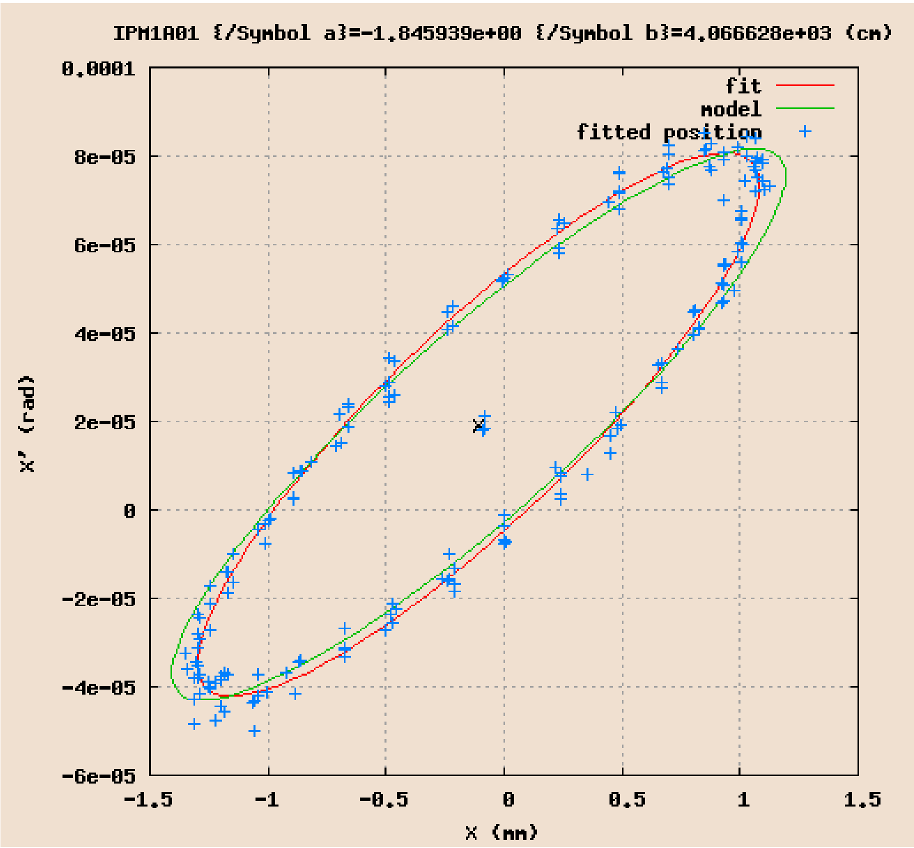
- Set the launchpoint at the beginning of ARC 1
- Set ε to ~5e-6 cm-rad at this point, and used the model values for α and β.
- Used 32 injected rays to trace out the phase ellipse at the launchpoint.
- Traced the ellipse twice to check for closure.

CEBAF BEAMLINE

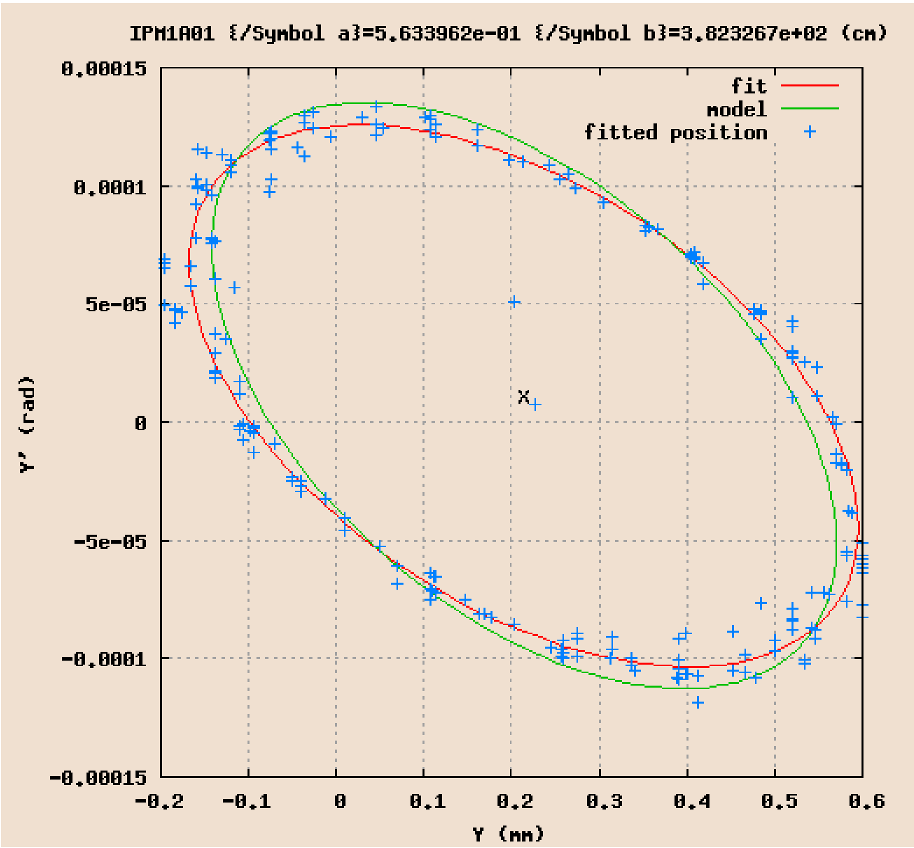


Launchpoint

IPM1A01 X Plane



IPM1A01 Y Plane



$$\alpha = 1.846 \quad \beta = 4.067\times10^{3}$$

$$\alpha = 5.634\times10^{-}1 \quad \beta = 3.823\times10^{2}$$

JSA

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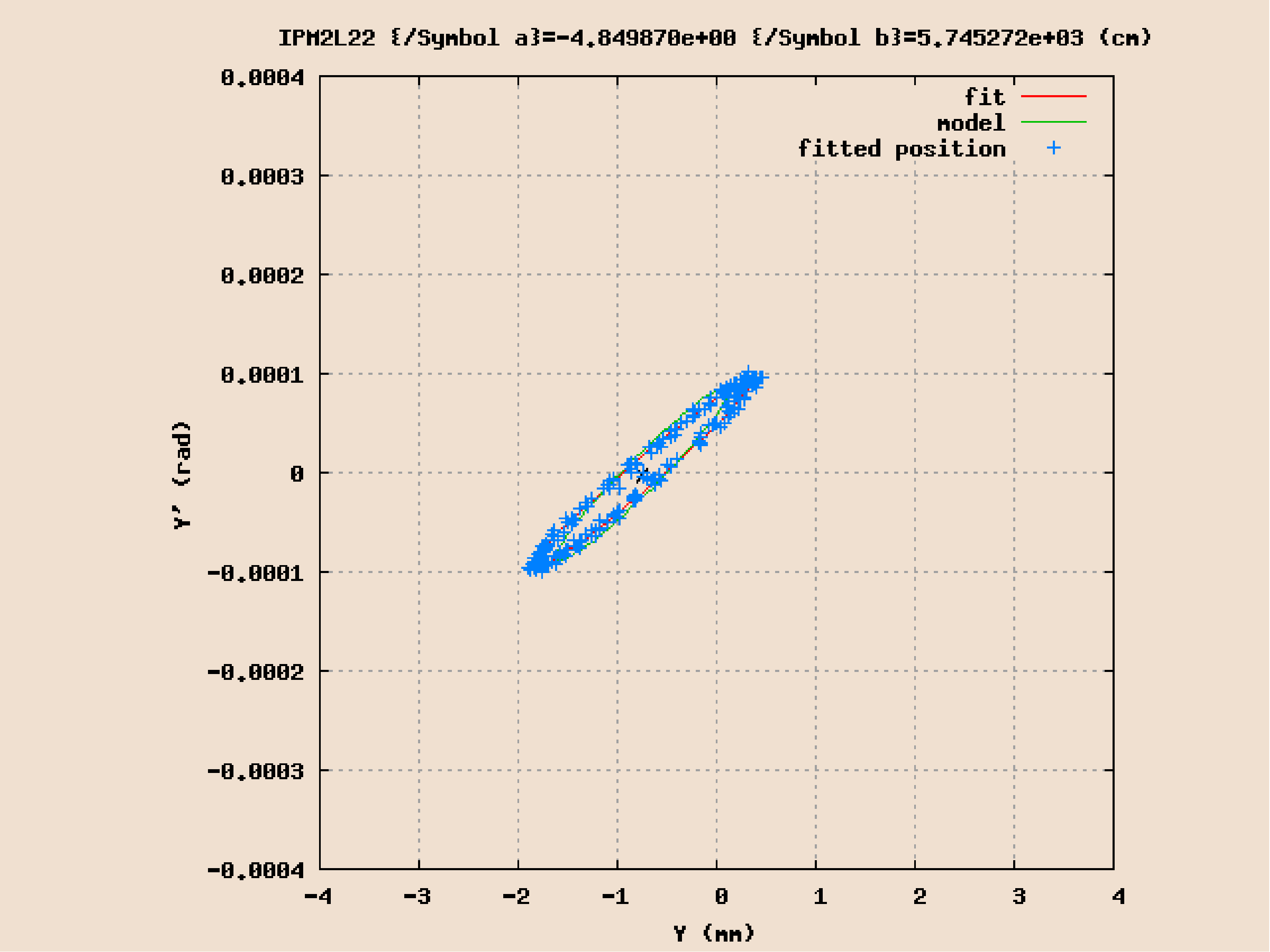
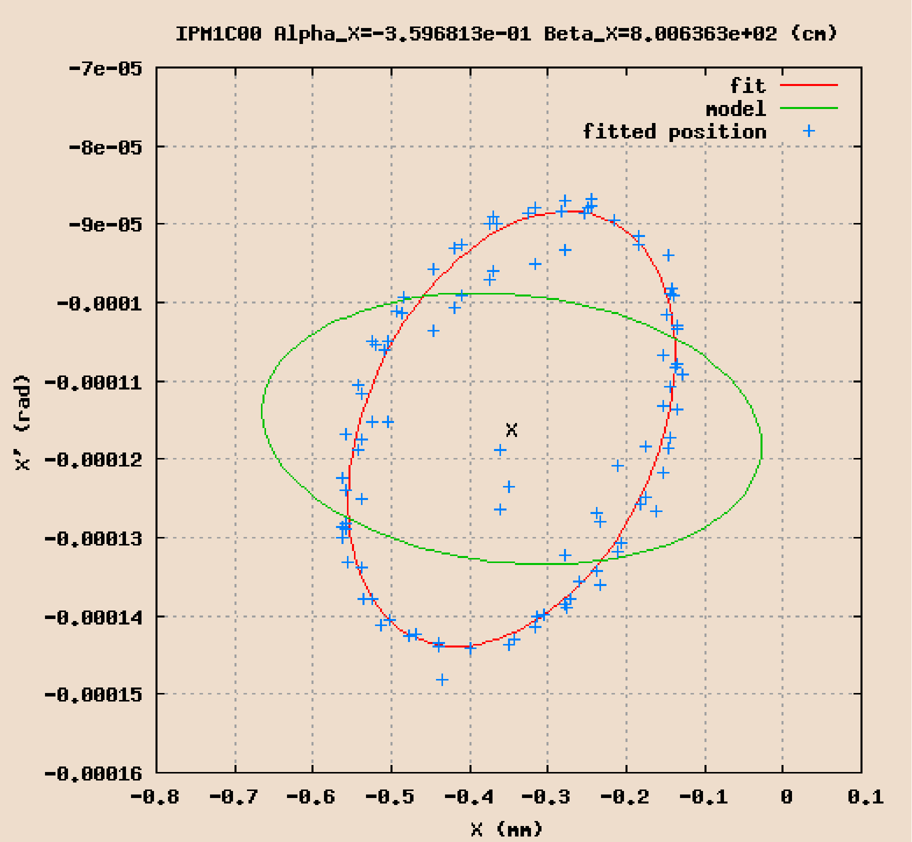
Evolution through LINAC2

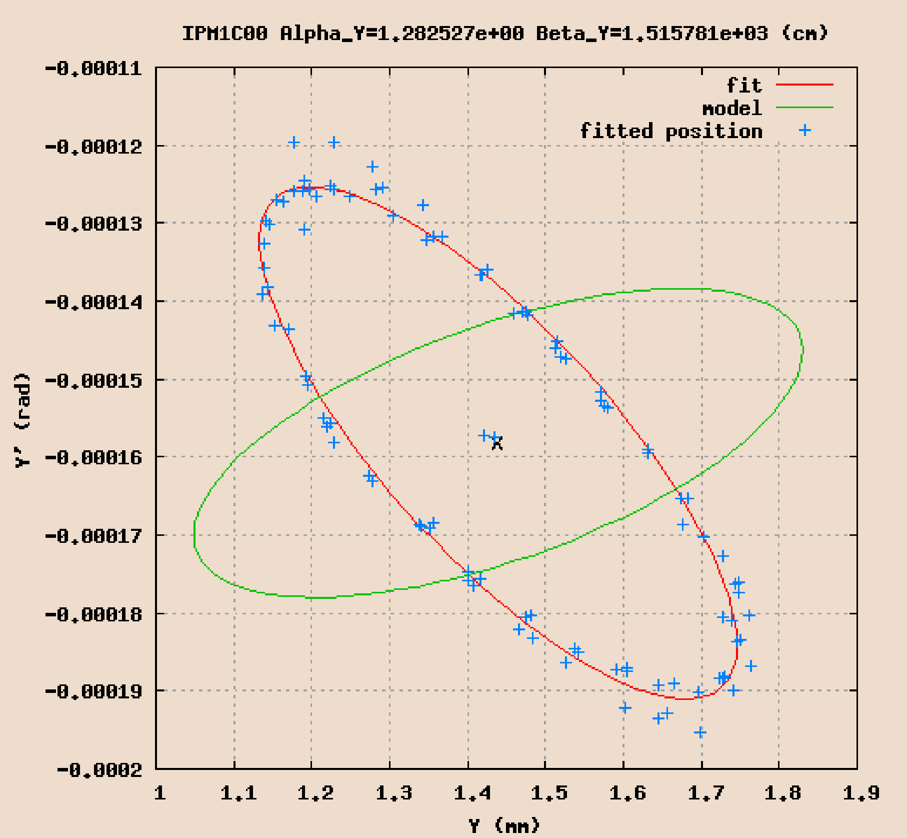


Entrance of Hall A

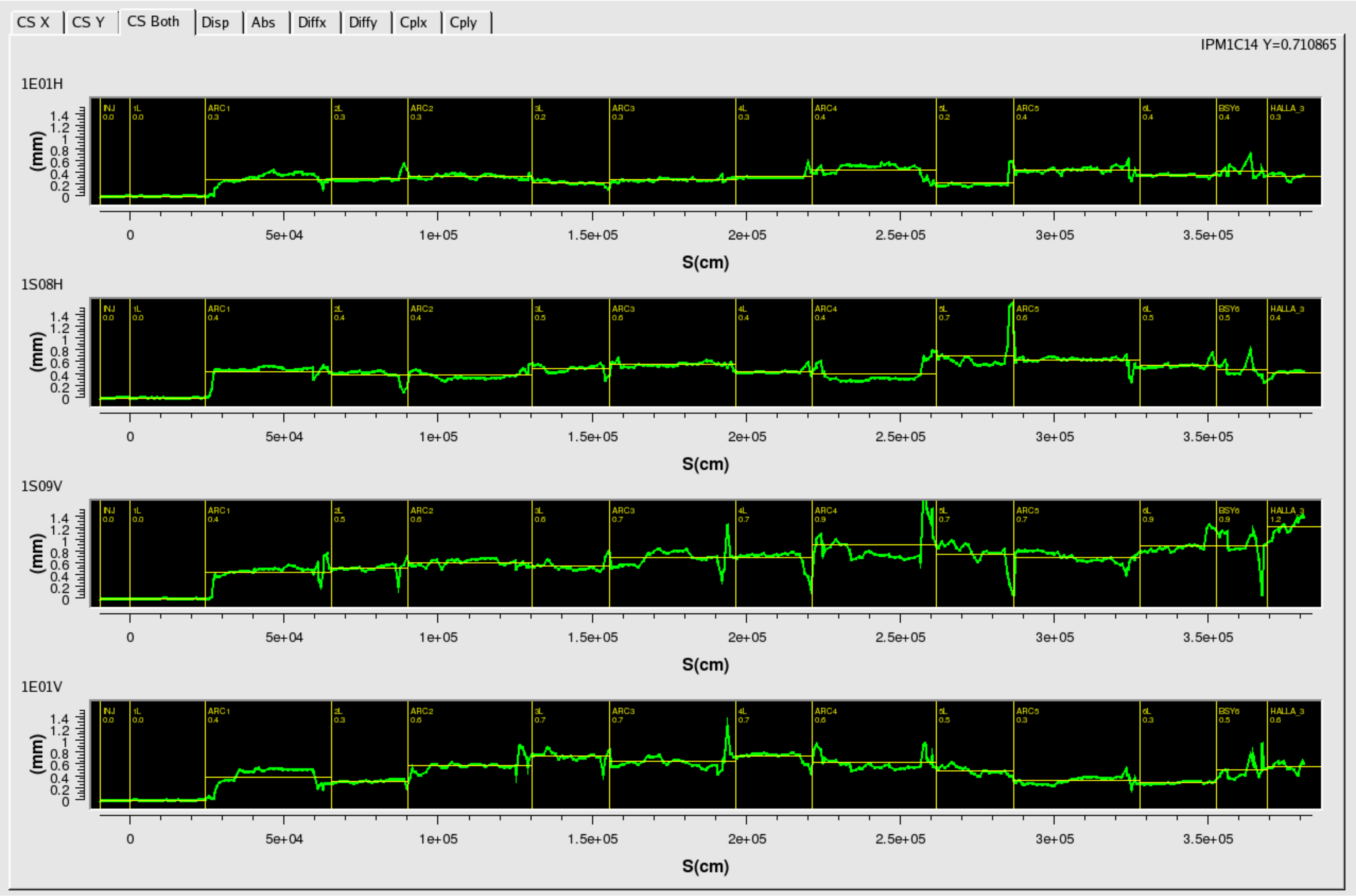
IPM1C00 X Plane



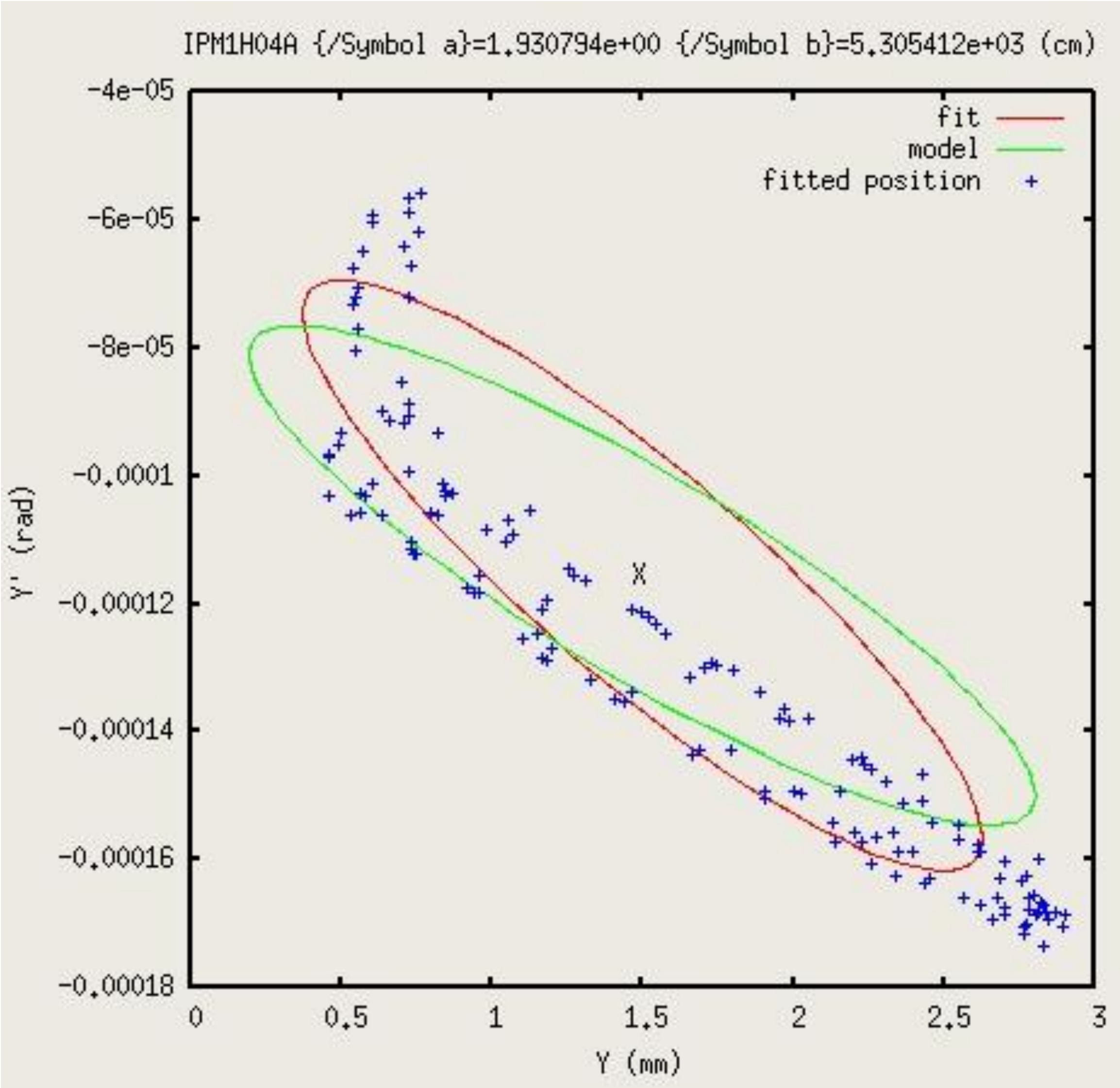
IPM1C00 Y Plane



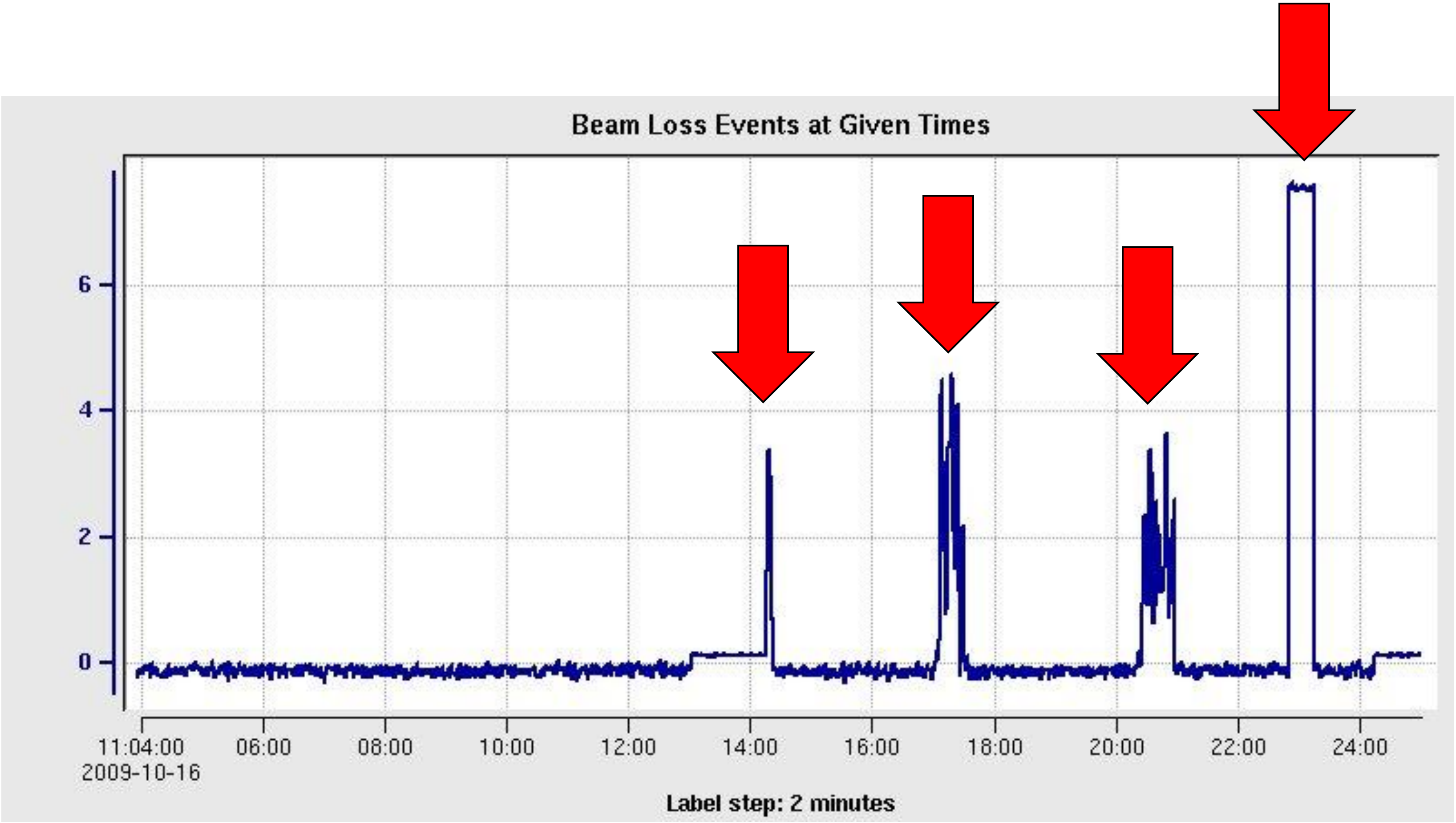
From the Courant-Snyder



Unexpected Observations



rayTrace in Action



Compton rayTrace Conclusions

- Beam entered Hall A line mismatched.
  - Rematched.
- Partial beam loss in Compton chicane.
  - Re-steered to avoid aperture, beamline adjusted, sychrotron radiation baffled.
- Compared against quadrupole scans
  - rayTrace showed appropriate amount of acceleration damping.
  - Some quad scan data had significantly asymmetric emittances in both planes.

Future Work

- Error Analysis
  - BPM noise
  - XY Coupling
- Injection to terminus transfer function fit
- Something about 12GeV. Get help here.
- Full deterministic tuning demonstration.

Summary

- Current diagnostic tools at CEBAF
  - Quadrupole scan
  - Courant-Snyder
- rayTrace
  - Collects data at all BPMs simultaneously.
  - Analysis uses model to find x'.
    - Data useful without model.
  - Enables deterministic retuning.
  - Extensible to 4D coupled motion.

Conclusion

- The rayTrace procedure is a developing diagnostic tool.
- Has been used in beamline diagnostics and tuning.
- The completed procedure promises to be a powerful tool for characterizing and tuning an open-ended system.

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UVA

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