Refined Methods for Transfer Matrix Reconstruction Using Beamline Silicon Detectors for Exclusive Processes at the EIC

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The EIC physics program relies on successful measurements of exclusive final states, which produce charged particles (e.g. protons, pions) at far-forward psuedorapidities, placing them very near (few mm separation) to the outgoing hadron beam. Reconstruction of these particles requires use of silicon detectors placed directly into the accelerator vacuum, in the style of Roman Pots used in experiments at HERA, RHIC, and the LHC. However, unlike past and present facilities, the broad range of energies and collision species at the EIC provides a unique challenge in accurately reconstructing the momenta of these far-forward particles. Additionally, some final states decay in the beamline, such is in meson structure studies, complicating accurate reconstruction. Finally, the proposed secondary focus at the second EIC interaction region would benefit greatly from a well-developed far-forward reconstruction algorithm, where reconstruction of nuclear fragments with different magnetic rigidities is also expected. As such, a dedicated effort toward a refined procedure for performing this reconstruction would greatly enhance the entire exclusive physics program at the EIC, as these methods are not specific to any one EIC detector. Leveraging expertise in both fixed-target experiments at JLAB, and collider experiments at RHIC and the LHC, this problem can be solved with modest support from the EIC generic R&D.

I. INTRODUCTION

Study of exclusive final states, such as in the example of electron + proton deeply virtual Compton scattering (DVCS), requires reconstruction of a momentum vector for a scattered proton which has passed through many accelerator magnets, and eventually impinges on a silicon detector in a drift-area of the machine (e.g. no magnetic field). In general, this reconstruction can be achieved using a matrix transport approach. This method employs a matrix which describes the complex motion of the proton orbit through the accelerator magnets, where a simple linear relationship exists between the vector components of the proton at the interaction point, and the vector components at the location of the detector.

II. TRANSFER MATRIX METHOD

Equation 1 shows a generic 6x6 matrix which is used to calculate the IP coordinates from the coordinates at the detector. The details of the coordinate system can be found in chapter 15.4 of the BMAD manual [1]. It should be noted that the z-coordinate is actually a measurement of time, and the momentum loss, $\Delta p/p$, is actually a measurement of the reference particle energy.

$$\begin{pmatrix} x_{ip} \\ \theta_{x,ip} \\ y_{ip} \\ \theta_{y,ip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & a_5 \\ b_0 & b_1 & b_2 & b_3 & b_4 & b_5 \\ c_0 & c_1 & c_2 & c_3 & c_4 & c_5 \\ d_0 & d_1 & d_2 & d_3 & d_4 & d_5 \\ e_0 & e_1 & e_2 & e_3 & e_4 & e_5 \\ f_0 & f_1 & f_2 & f_3 & f_4 & f_5 \end{pmatrix} \begin{pmatrix} x_{det.} \\ \theta_{x,det.} \\ y_{det.} \\ \theta_{y,det.} \\ z_{det.} \\ \Delta p/p \end{pmatrix} \tag{1}$$

In general, one matrix is calculated to describe the transport of a central trajectory proton through the magnetic lattice for the interaction region. However, if the proton energy deviates from the energy

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of the reference orbit by too large an amount, the matrix will fail to correctly describe the transport of the proton. The proton energy is described simply by the ratio of the current proton's z-component of the momentum over the reference orbit momentum,

$$x_L = \frac{p_{z,proton}}{p_{z,reference}}. \tag{2}$$

It has been seen throughout the EIC Yellow Report, as well as in more-current studies, that the reconstructed particle momentum obtained via a particular "static" matrix begins to incorrectly describe the proton trajectory when $\Delta X_L > 2$-3%. At small deviations of x_L, the overall contribution to momentum resolution is smaller than what is seen from effects from the beam itself (e.g. angular divergence), however, this incorrect matrix reconstruction begins to add a competitive smearing contributions when ΔX_L exceeds 5-10%, as is the case for a very broad section of the available exclusive process phase space. Additionally, transport calculations will also be affected by beam alignment with respect to the detectors, exacerbating the overall impact of an incorrect matrix for a particular particle trajectory description.

In addition to the transfer matrix itself, the momentum reconstruction calculation must be done in the coordinate system of the reference orbit used to produce the matrix, as shown in Fig. 15.2 of [1]. So if the particle of interest has an energy which deviates from the reference orbit, both the matrix and coordinate system offset values will be incorrect for the proton (or charged particle) of interest, effectively increasing the number of independent values needed for successful reconstruction from 36 (from the 6x6 matrix) to 40 (with the four offset values for the (x,y) position, and associated angles).

Finally, for final-states where an unstable decay (e.g. $\Lambda \rightarrow p\pi^-$) occurs and reconstruction of the final-state charged particles is still required, an advanced reconstruction method will also be required. This is crucial for studies of meson structure, as noted in the EIC Yellow Report [2]. These needs are clearly overlapping, and the development of a robust method for performing this reconstruction will be of great benefit to the entire EIC physics programs for both Interaction Regions.

What is required is a method which allows for a dynamical calculation of the correct matrix and offset values for a given set of detector coordinates. The method which was devised for the present time, and for which we would like to acquire R&D support to drastically improve, is described in the next section.

A. Dynamic Transfer Matrix Method

In the first attempt at producing a method which can be used to more-accurately perform the matrix reconstruction, a chromaticity plot was produced, as in Fig. 1, which shows how the x-position and x-slope (at the detector) relates to the various values of x_L possible at the EIC (here, only $0.75 < x_L < 1.0$ was studied). This table enables extraction of a unique value of x_L for any given set of coordinates at the detector.

This table was used as input to a fitting code which samples reference trajectories for various values of x_L, calculates the matrix and offset values, and then produces a set of one-dimensional fit functions (40 in total: 36 matrix elements, 4 offsets) which can be used to calculate the correct matrix for a particular x_L value using only the local detector coordinate as input. Figs. 2 and 3 show the improvement in the overall momentum smearing achieved with this dynamic method.

However, as can be seen from Fig. 3, this method does not fully capture the non-linear effects of the lattice possible for higher transverse-momentum (or polar scattering angle), when the protons will be traversing the edges of the machine quadrupoles and experience dipole-like steering effects not fully reflected in the calculation.

When this method is applied to more complicated final states (e.g. from the meson structure studies with Λ decay in the beamline), with the additional complication of a pion having $\sim$1/7th the mass of the proton, it's clear that a more generalized approach with optimization across all possibilities is required to successfully cover the available exclusive processes.

B. Possible Improved Method

Given the problem briefly outlined above, we propose an approach which leverages basic machine learning techniques (e.g. Deep Neural Networks or GrafNet), which enable for a robust optimization of

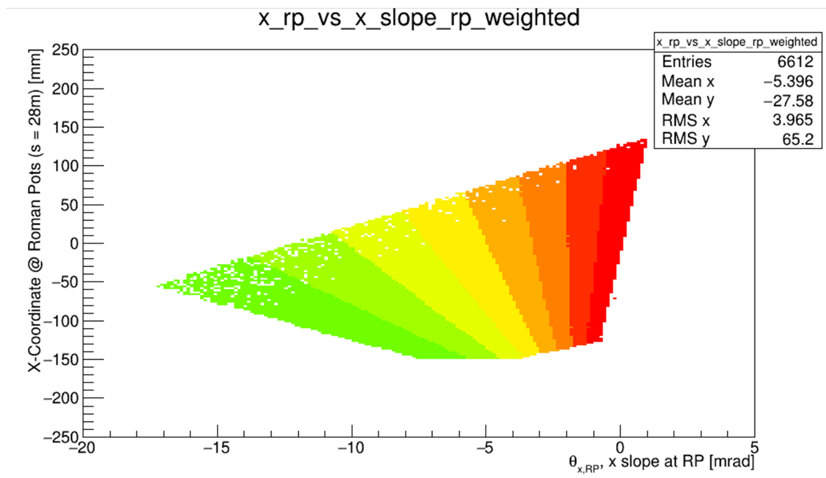

Figure 1. Chromaticity plot for the x-coordinate of the sample protons. The colors represent different ranges of x_L, which were computed using weight factors for each bin. This chromaticity plot serves as a lookup table for x_L for a given set of detector x-coordinates.

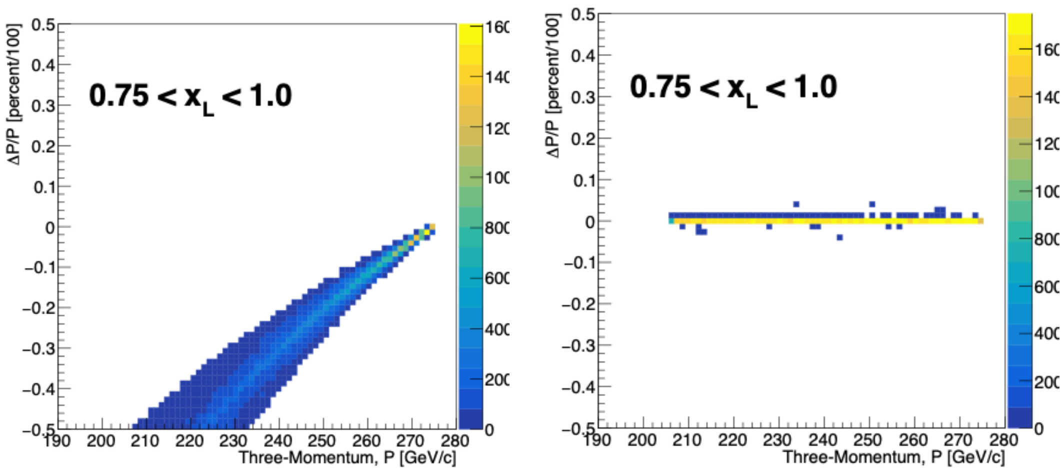

Figure 2. Three-momentum smearing as a function of the reconstructed three-momentum using the static matrix extracted from BMAD (left), and the dynamic matrix calculation from the method described in this proposal (right).

the 40 parameters needed for accurate reconstruction with the large number of possible inputs (particle species, decay location in z, x_L). The main outputs we wish to optimize are simply the three spatial momentum vector components of the final state particles.

In addition to modern machine learning methods, algorithms currently employed in fixed-target spectrometers (e.g. JLAB experiments) which leverage polynomial expansion of accelerator magnetic fields to more accurately describe the trajectory of off-momentum particles could also be employed [3].

It seems clear that a detailed study to identify an optimized approach would be appropriate, given the complexity of the problem, and we hope the R&D support would provide the necessary resources to study the most-efficient and accurate manner for which this reconstruction algorithm could be carried out.

III. COST AND MANPOWER NEEDS

Given that this is a project focused on the development of a reconstruction algorithm, the costs are comparably modest. We only request funding for a either a partial postdoc, or a couple of graduate

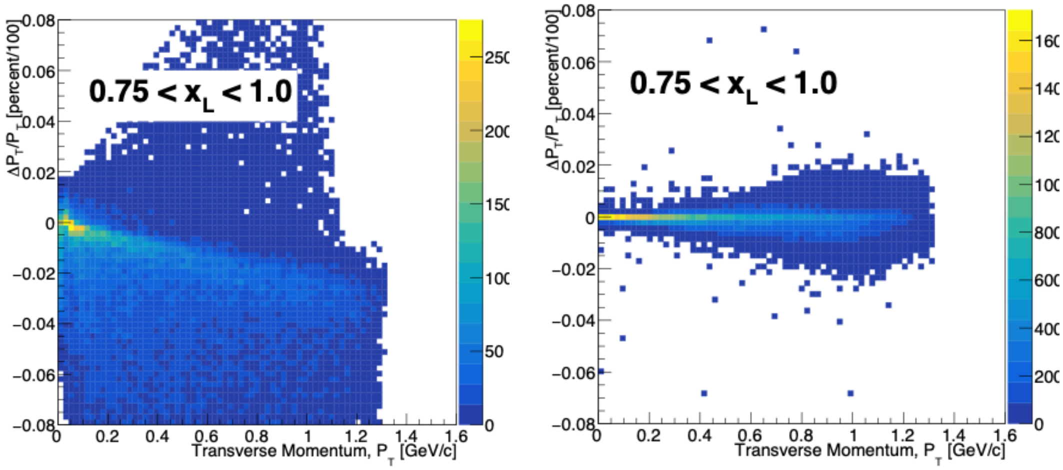

Figure 3. Transverse momentum (p_T) smearing as a function of the reconstructed three-momentum using the static matrix extracted from BMAD (left), and the dynamic matrix calculation from the method described in this proposal (right).

students, either of which will be supervised by the PIs and collaborators. We additionally request funding for a 10% FTE for A. Jentsch to fund his time to oversee the project.

In a realistic scenario, a 70% FTE postdoc would be sufficient to carry-out this study, which would amount to \$110k (assuming 100% fully-burdened FTE for a postdoc at BNL in FY23 is \$157k), plus the 10% FTE for A. Jentsch, which amounts to \$17k. The numbers are summarized in Table I, and include the values for the 20% and 40% budget reduction scenarios. If a 20% reduced budget scenario were assumed, but a suitable postdoc were found in a university group where overhead and salary costs are reduced, the R&D could be still be carried out successfully. We only assume a reduction in the money associated with the funding of the postdoc to carry-out the work, as A. Jentsch will still require a fixed amount of time to oversee the project.

In all of the above assumptions, we expect that the one partial postdoc could also be two more-advanced graduate students splitting the effort, assuming that a postdoc costs roughly twice that of a graduate student. In this scenario, one graduate student would focus on the mathematical formulation of the algorithm, while the other would focus on implementation of the algorithm in the coding and simulation framework (e.g. meaning they could perform their work in serial, rather than parallel, if needed).

In the 20% reduced budget scenario assuming the BNL salary + overhead numbers, it seems likely that only partial completion of a suitable, generalized reconstruction algorithm will be achieved, and almost-certain that it will be integrated into the global detector simulation framework, which will reduce the effectiveness of the R&D.

In the 40% budget-reduction scenario, it seems reasonable to expect a mathematical formulation for an algorithm could be acheived, with only small progress in translating this to a coding and simulation framework for iteration and refinement.

Collaborators not-listed in Table I will serve in advisory roles, and therefore be of no cost to the proposal, while listed collaborators in Table I are assumed to provide their time as in-kind contributions to the effort.

	R&D Effort (FTE)	Proposal Funded	100% Amount	20% reduction	40% reduction
A. Jentsch	10%	Yes	\$17k	\$17k	\$17k
Furletova & Higinbotham	10%	No	N/A	N/A	N/A
M. Murray	10%	No	N/A	N/A	N/A
Postdoc (TBD)	70%	Yes	\$110k	\$85k	\$60k
TOTALS	100%	-	\$127k	\$102k	\$76k

Table I. Cost breakdown of collaborating institutions.

We don't anticipate the need for any travel for this project, as updates and reports can be carried out remotely.

IV. DELIVERABLES AND MILESTONE

For a fully funded proposal, within the first six months we shall review and select the most appropriate procedure for doing the momentum reconstruction.

By the end of this project, which we currently expect to take one year to fully complete, we envision a suitable deliverable being not only a robust method for performing the advanced reconstruction of these complicated exclusive final states, but the inclusion of the relevant code in the forthcoming EIC simulation software which will be used by the whole community developing the first, and eventually second EIC detector. If this project is not fully funded, the length of the project would scale proportionally to the reduction of funds.

V. DIVERSITY AND INCLUSION

Our present team is comprised of scientists from a broad range of backgrounds, and with a high-degree of skill in the necessary topics needed to lead this R&D effort (e.g. simulations, detector design, exclusive physics).

We are committed to ensuring inclusion of under-represented groups in our R&D efforts, and as such will bear this in mind when searching for suitable candidates to fill the needed role for this project, and have aimed this project at promoting an early-career scientist (or scientists).

[1] D. Sagan, The bmad reference manual, `https://www.classe.cornell.edu/bmad/manual.html` (2022).
[2] R. Abdul Khalek *et al.*, Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report (2021), arXiv:2103.05419 [physics.ins-det].
[3] E. Offermann, C. De Jager, and H. De Vries, Nucl. Instr. and Meth. A **262**, 298 (1987).