Control Systems Development for the Thomas Jefferson National Accelerator Facility Free Electron Laser: Preliminary Results for Trajectory Response Data

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The output of free electron lasers (FELs) is highly sensitive to perturbations in electron beam parameters. Consequently, development and validation of robust control systems for accelerators is of particular importance. Currently, an effort is underway at Colorado State University (CSU) to develop and implement automated beam control at the Jefferson Laboratory FEL. Initial work toward implementing basic feedback control of the beam trajectory at Jefferson Laboratory, as well as an overview of the long-term aims of the project, are presented here.

Introduction

At present, the Jefferson Laboratory FEL has little automated beam control. In light of this, CSU recently began collaboration with members of the FEL group at Jefferson Laboratory to supplement the existing system with further automated tuning and control, starting with cases which should be relatively straightforward to implement. CSU's role also includes involvement in machine studies necessary for completion of this task.

As the project progresses, the effort will eventually be focused on development and testing of more advanced and novel control techniques which could be implemented both at Jefferson Laboratory and at the upcoming CSU accelerator facility. In particular, there has been growing interest in applying advances in the field of artificial intelligence to the development of a beam-based control system for accelerators.[1, 2] Such a control system would be capable of adapting to and compensating for changes in beam parameters in real time during machine operation.

Background

Ostensibly, one of the simplest control schemes to implement is basic trajectory control. This type of feedback control is already used extensively at other accelerator facilities and thus is a natural starting point for implementation of beam control at Jefferson Laboratory.

Trajectory control is achieved by applying changes in steering magnet field strengths such that observed deviation in the beam position can be corrected. To this end, beam position monitor (BPM) readings are used in conjunction with a response matrix to determine the appropriate magnet strength adjustments.

The response matrix is given by

$$M_{ij} = \frac{\Delta O_i}{\Delta C_j}$$

where ΔC_j is the change in the j^{th} compensator (j^{th} magnet strength) which corresponds to a ΔO_i change in the i^{th} observable (i^{th} BPM reading). This matrix can then be inverted for use in the following control equation

$$\Delta C = M^{-1} \Delta O$$

To obtain the response matrix, the correctors are changed iteratively while the resulting BPM readings are recorded. From this, the response matrix is constructed using the slope of a linear fit to the ith group of BPM readings vs. the jth group of corrector settings. Note that consequently we need the BPM responses to be linear (or close to linear) over the range of corrector settings applied in order to make use of this control method.

Measurements

In order to implement basic feedback control, we first needed to obtain the response matrix. For this purpose, trajectory data were collected at Jefferson Laboratory by the Jefferson Laboratory FEL group on July 30-31, 2012 using scripts written at CSU. The field strengths of twelve magnet correctors were iteratively changed using an *sddsexperiment* [3] script, and the corresponding readings for 70 BPMs were recorded. Three full sets of these data were obtained, and each of these consist of

- 5 set points per corrector
- The average of 64 readings per BPM per corrector set point

A 10-second pause was included after each field strength change in order to allow the machine to settle. A 1-second pause was inserted between individual BPM readings.

In order to obtain more information about the noise characteristics of the BPMs, the pause time was lengthened to 4-seconds for a fourth set of data. Data from only four correctors were obtained for this set because the window of machine stability was in general shorter than the amount of time it took to run each script, and there was also limited machine time available for this effort. This fourth set of data may later be supplemented with data from all twelve correctors.

Analysis

Sets of slope data for each BPM and corrector pair were combined to generate the measured response matrices (one for horizontal position response and one for vertical position response). These matrices are displayed in Figures I and II, respectively.

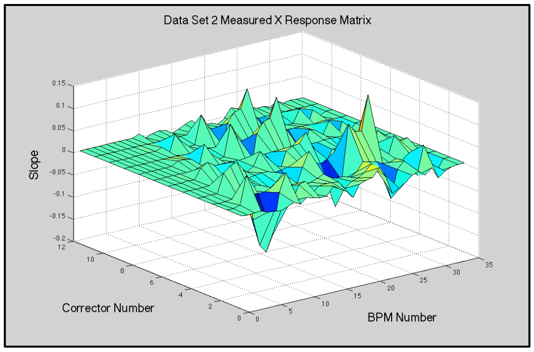

Figure I. Measured response matrix for horizontal position with respect to changes in corrector field strengths.

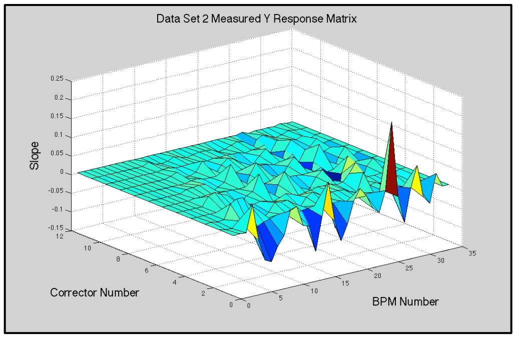

Figure II. Measured response matrix for vertical position with respect to changes in corrector field strengths.

Detailed quantitative analysis of these data is still underway. Individual BPM vs. corrector readings for each of the three data sets are being examined to determine whether individual BPM responses are sufficiently linear, sufficiently consistent from run to run, and have a sufficiently high SNR to be used for feedback control.

So far, the quality of these results has been mixed. Many of the responses are consistent between the three data sets and match reasonably well with the simulated data (for an example of such a response, see Figure III). Other responses are consistent between the three data sets but are nonlinear (as seen in Figure IV). Some responses are roughly linear but show some deviation between each data set (as seen in Figure V), and some are simply inconsistent between runs (see Figure VI).

The consistency and linearity of the responses are correlated with how far downstream from the corrector a given BPM is (as is to be expected). This is more pronounced (as expected) for the horizontal responses to changes in horizontal steering and vertical responses to changes in vertical steering. However, there are some BPM responses which deviate significantly from this expected pattern. Full quantitative analysis of these data is currently underway, but even these preliminary qualitative observations suggest that there will be interesting challenges in using these BPM measurements for feedback control.

In addition, the measured data are being compared with simulated response data generously provided by Christopher Tennant of Jefferson Laboratory.[4] These simulated data consist of magnet kick angles (for the same integrated field strengths used in the measurements) and resulting BPM readings generated by Jefferson Laboratory's *elegant* machine model.[5] All BPMs except those in the injector/merger region and beam dump are included.

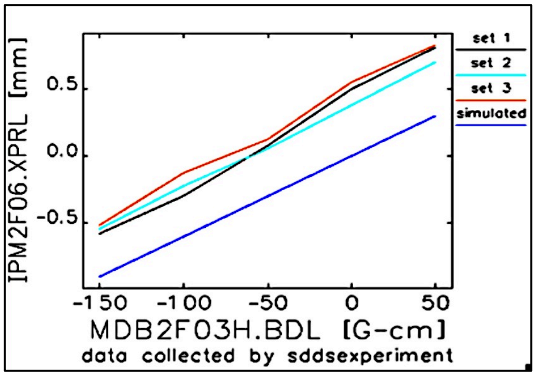

Figure III. Example of one BPM vs. corrector response which shows good linearity, reasonably good agreement with simulated results, and consistency between data sets.

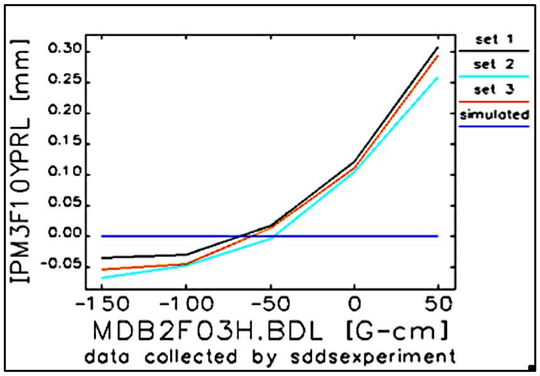

Figure IV. Example of one BPM vs. corrector response which is consistent between runs but is nonlinear and shows poor agreement with simulation.

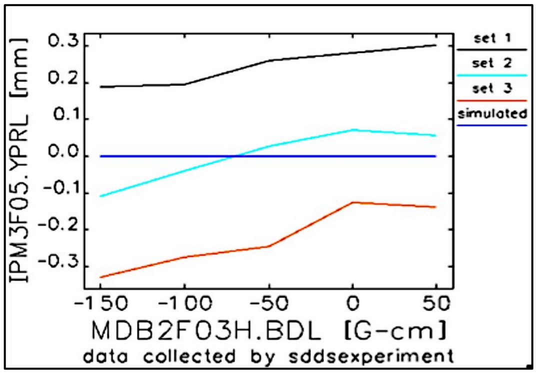

Figure V. Example of one BPM vs. corrector response which is roughly linear but shows some deviation between runs.

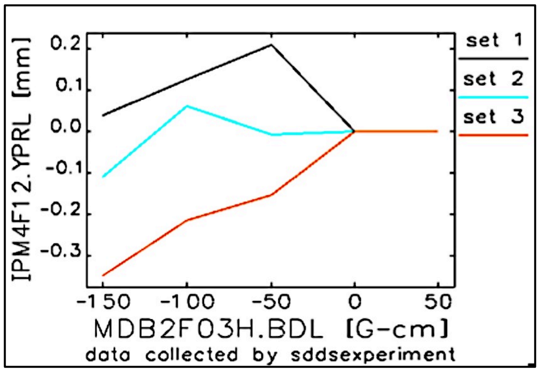

Figure VI. Example of one BPM vs. corrector response which is inconsistent between runs. Simulated data is not shown in this case because this particular BPM is not included in the model.

Conclusions

Although measurements of the response matrix have been made, initial qualitative observations suggest that implementing feedback control may problematic due to peculiarities in the BPM responses and/or correctors. However, the data presented here represent only a portion of the entire set (70 BPM readings for 5 corrector set points on each of 12 correctors). Further analysis and characterization of all BPM responses are needed in order to determine which BPMs and/or correctors will be suitable for use in an automated trajectory control scheme. Additional data and detailed analysis will be presented in forthcoming papers.

Acknowledgements

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