JLAB-TN-08-038
Y. Chao

Concept and Status of the PZT Booster

This is an effort to archive the materials I presented in B Team during the past few years on the proposal and status of development of the PZT Booster. No effort was devoted to structuring this note. The main purpose is to provide a reference link so the collective information is not lost.

The application has been tested online several times in 2005-2006 with satisfactory outcome, although never used in real tuning, partly because G0 in 2006 ran at much less than 1 GeV and did not benefit so much from this possibility. Joe Grames, Michele Joyce and Yves Roblin have contributed significantly to this work. Joe holds all information regarding the helicity magnets. Michele holds all information on the PZT Booster software. Also consult the help menu created by Michele Joyce associated with the PZT Booster application.

Y. Chao
B Team 09/20/05

PZT Booster?

Motivation:

Parity experiments will become the bread and butter of CEBAF, as someone said. It is not too early to think how we can run them like a power plant with well-defined procedures. I happen to have some experience dealing with Injector matching, a small part of it, and am familiar with some of the less well-defined aspects of it in terms of procedure, stemming from fundamental limitations of the PZT signal and its interaction with the BPM's. The following is an idea to circumvent this problem by some hardware/software extension such that this procedure can become less ad hoc, less time consuming, and thus implementable as a standard setup procedure[1].

So far as I can see, such a tuning procedure will be in demand as long as we have parity experiments and as long as the Courant Snyder procedure originating from similar concerns is still needed. In the very long run we'll have a perfect model of the entire machine and none of these tools (plus BPAM) will be needed any more.

I'll first list the facts I gathered from others or from my own observation, which I believe lead to the proposal as an (almost) inescapable path for improvement. You are welcome to argue as always.

[1] Experience indicate that this tuning procedure may need to be invoked with every laser change or 100 keV retuning.

Facts:

- **PZT orbits closely resemble helicity correlated orbits in Hall C (K. Nakahara)**
- **PZT orbits are needed for ascertaining final damping in the Hall line**
  - **Deviation from transport model (e.g. NL grad. CAL)**
  - **Phase space differences**
  - **Other unidentified reason (but consequence is certain)**
- **The above optimization is achieved by tweaking 60 MeV quads**
  - **Only place before CS matching takes over**
  - **Localized damping/matching is absolutely preferable to minimize sensitivity and unfixable error later**
- **PZT/BPM interaction issues:**
  - **Need to run CW beam for stable 30 hz PZT display**
  - **4CH BPM's cannot efficiently pick up PZT signals in the main machine**

→ Not a good idea to run CW all the time for tuning
→ Especially with poorly matched beam and quad tweaking
→ Need to have BSY dump ready if Hall is not available
→ Limited to 1 pass if linac SEE's are relied on

- **PZT signals are limited in amplitude due to sheer power and 100 keV aperture and field aberration constraints.**
- **PZT signals are overwhelmed by noise in the Hall (too weak). Long averaging makes tuning very slow.**
- **PZT based Injector matching may need to happen whenever laser or 100 keV changes.**
- **On the other hand, 30 hz correctors have none of the above problems**
  - **Large amplitude (more power)**
  - **No aperture restriction. No transport nonlinearity.**
  - **Can run pulsed beam and be stably displayed**
  - **Can be seen on 4CH's**
- **We do not do anything to the PZT orbit upstream of 5 MeV.**
- **After coupling suppression, the 5 MeV section is a rigid piece.**
- **5 MeV and 60 MeV <u>magnetic</u> optics is well-modeled, linear and scalable to a large degree.**
- **There are 30 hz helicity correctors in 5 MeV with decent coverage of 4D phase space (Grames).**

Proposal:

- **Capability of standard 30 hz system to drive the 5 MeV helicity correctors**
- **Extension of 30 hz generator capability to drive multiple correctors (4) in phase and at preset amplitude ratios.**
- **Software to read PZT signature at 5 MeV, perform orbit analysis, and translate the outcome into 30 hz corrector combinations at 5 MeV <u>using 4D empirical orbit lock algorithm with multiple BPM's at 60 MeV</u>[2].**
- **OPS-implementable procedure to use the above to quickly converge on optimal damping solution in the hall.**

Advantage:

- **The most ad hoc and time consuming part of the Injector matching procedure is to use 60 MeV quads to optimize damping in the hall line, in a large part due to the configuration demand by PZT/BPM setup and difficulty in reading the PZT signal reliably. As a result this is the part least amenable to conversion into a standard OPS procedure. With the above proposal, I can expect a 20-fold boost in the PZT signal (~4 from momentum ratio; at least 5 from absence of aperture/aberration constraints). We can also do this with pulsed beam and read the signal in the Arcs, thus doing away with the need to set up the rarely ready BSY dump or the limit of 1-pass beam. It would closely resemble a Courant Snyder matching procedure, which OPS excel at.**

- **Side Benefits:**

  - **Orbit lock using multiple BPM's has been an idea floated around here for years. This would provide the impetus to bring it to reality.**
  - **Same with multiple-element 30 hz systems that have been discussed in the past. An example application is finer probing in phase space by 30 hz aperture scan.**

[2] This in fact will be very similar to the G0 4D empirical feedback, except here the BPM's are in the Injector, and the gain will be much greater than one instead of being less than one.

Challenges:

- **Making sure 30 hz system can drive combination of correctors as described may require research and online study.**
- **More online study for the software to confirm its performance.**
- **The real challenge is to make sure the "booster" faithfully reproduces the PZT signature at 60 MeV (tolerance to be worked out). BUT, experience tells me that if we can get this boosted signal to damp properly within the first pass, minor transport error for the remainder of the machine[3] (and reduced unfixable coupling/nonlinear kick error due to damped amplitudes) will change the picture little in the hall. <u>This means the reproduction may not need to be to the 4th decimal place</u>. <u>If we use the empirical lock algorithm to achieve this, we should be able to get as accurate a reproduction of the PZT as needed.</u>**

[3] After Courant Snyder.

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B Team 11/03/05

Stage One Preparation for PZT Booster

- **Hardware**

  - Ability to drive all 4 helicity magnets (**HM**), each at a pre-defined (different) amplitude, with the 30 hz function generator. The 4 helicity magnets need to be synchronized to ≤ 2° of the 30 hz waveform[4].
  - Verify synchronization with the 30 hz BPM system, to the same degree achieved by the 30 hz PZT currently.
  - As empirical algorithm will be used, extremely accurate knowledge of settability, i.e., extreme accuracy in BDL output, of the HM's is not a must. <u>However, the HM behavior needs to be linear enough to ensure convergence</u>[5].
  - If, taking a step beyond the G0 helicity feedback analogy, we also allow an iterative algorithm to aid in convergence, in other words, if we keep trying with different HM combinations under some guideline until their combined outcome is close enough to the PZT signature, then the linearity criterion may be further relaxed. But this is a much less desirable approach since it would be much less deterministic and efficient.
  - Therefore my personal preference is that the 4 HM's must
    - exhibit complete independent behavior from each other
    - exhibit very good linearity over the output range of 0.83-16.7 G-cm, corresponding to kick of 0.05-0.5 mrad at 5 MeV.

    Both are important for fast convergence of the empirical approach. We can discuss how these constraints can be relaxed.

- **Algorithm**

  - Development of algorithm can start now, but <u>beam based testing</u> would need to wait for confirmation of the above requirements being met.
  - Algorithm consists of procedures very similar to empirical orbit lock or G0 helicity feedback using HM's, with the following correspondences:

Empirical Orbit Lock	**G0 helicity feedback**	***PZT Booster***
Correctors	Helicity Magnets driven at parity flipping	Helicity Magnets driven at 30 hz
Absolute orbit	G0 helicity correlated orbit	30 hz PZT signature
Gain = –0.1 to –0.5	Gain = –(0-1)	Gain = +1 to +10 (?)
Calibration by individual corrector kick + Relative orbit	Calibration by individual HM modulation + target position/angle	Calibration by individual HM modulation + 30 hz orbit

  - As mentioned above, we may need to invoke iterative convergence if linearity/independence of the HM's is in question. This will be a step beyond either empirical orbit lock or G0 feedback algorithm.

- **Software**

  - Software requirement needs be worked out with more care, once success of the above, especially beam based testing, provides more insight on operational specifics of this tool. On the other hand a sufficiently

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[4] This is my estimate of the precision needed. To perform G0 feedback, the helicity magnets must meet a certain synchronization criterion of the 4 HM's anyway. We can consider adopting that instead if reasonable.

[5] Riad Suleiman mentioned question concerning linearity and independence of the HM's in the G0 meeting. This, if it is indeed the case, needs be understood and resolved, even if only for G0 helicity feedback.

developed software tool, along the lines above, on hand for beam based testing may be a plus for the latter. I do not have preference either way. If it is considered important to start the software development immediately, we need to define in more detail than provided here on what's needed.

01/24/2006
Chao
Grames
Roblin

Testing Helicity Magnet Performance

This is a summary of the analysis done on 30 hz helicity magnet data taken on 12/22/05. The data provided adequate information for analysis of the two critical characteristics of this system, as listed below. As can be seen from the following pages the helicity magnet system appears to perform very well and should be extremely suited to the role of PZT Booster drivers. This is a strong indication that the PZT Booster will perform as expected.

Part 1: Stability & Synchronicity

Part 2: Linear superposition & Orthogonality

Cross-comparison with magnitudes of calculated helicity magnet responses is discussed at the end..

Part 1: Stability & Synchronicity

Legend of each group of plots:

Original File Name:

H:\Math4.0\PQB\HMDAP\HMDAP_2005-12-22_18_20

Number of Data Points:

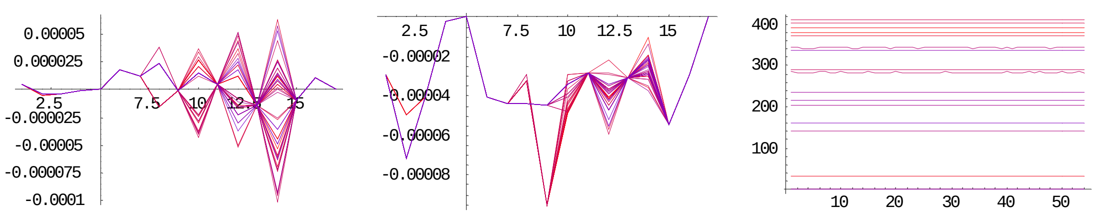
Remaining data {54}

State of HM being Set (hel_even_1, hel_odd_1, hel_even_2, hel_odd_2, hel_even_3, hel_odd_3, hel_even_4, hel_odd_4):

HM States: 0 0 0 0 0 0 0 0

Plots of

- **Cumulative X trajectories from IPM0L01 to IPM0R07**
- **Cumulative Y trajectories from IPM0L01 to IPM0R07**
- **IPM0L01 to IPM0R07 wire sums (red to blue) vs time**
-



Comments:

- HM combinations seem highly stable & synchronized over time at a wide range of amplitudes.
- First 4 sets are either pure noise (HM's off), or not logged in the worksheet[6]. These may correspond to exceptional test conditions.

[6] These turn out to be rejected data due to the 30 hz phase offset not being set right.

H:\Math4.0\PQB\HMDAP\HMDAP_2005-12-22_18_20

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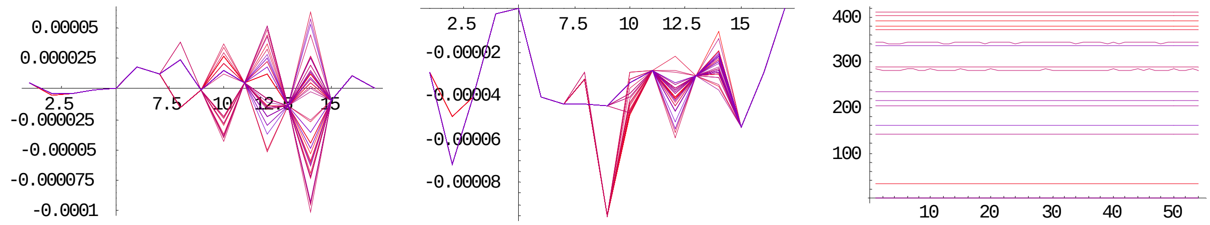
HM States: 0 0 0 0 0 0 0 0



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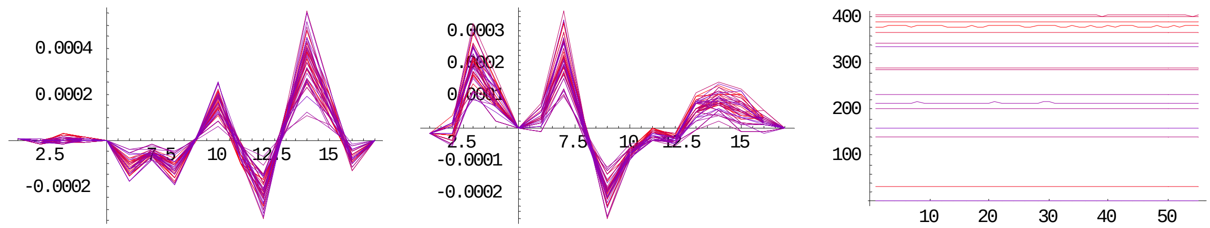

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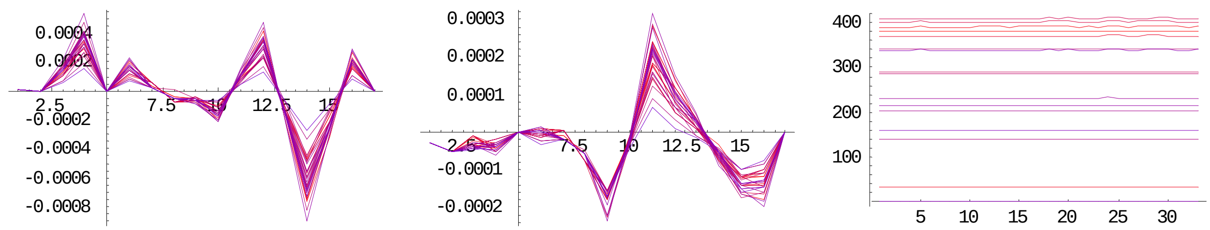
Remaining data {33}

HM States: 0 0 2000 -2000 0 0 0 0



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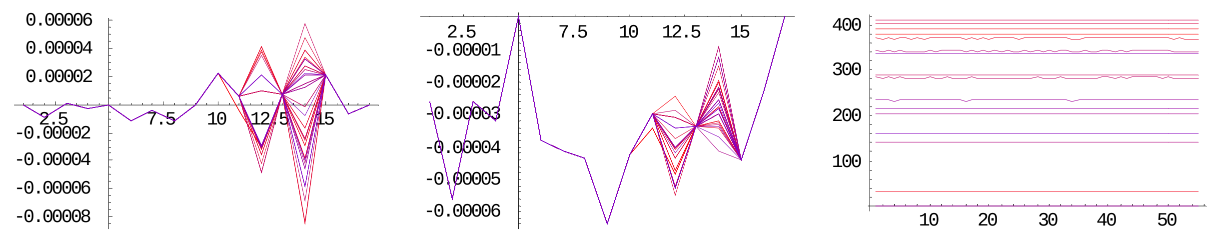
Remaining data {55}

HM States: 0 0 0 0 0 0 0 0



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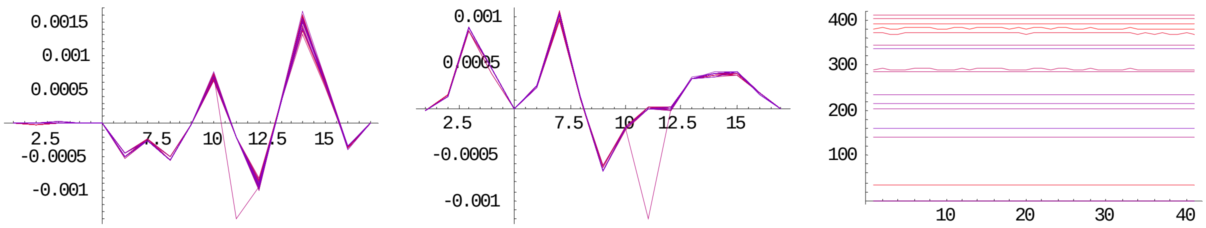

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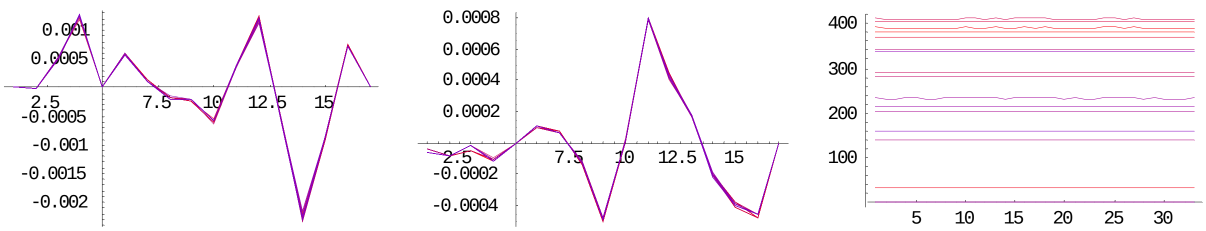

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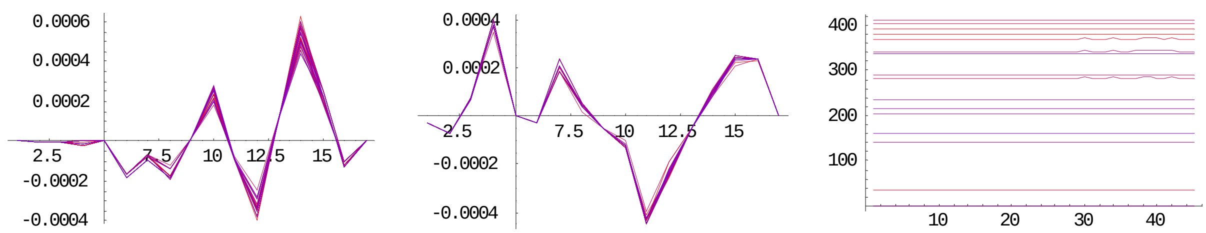

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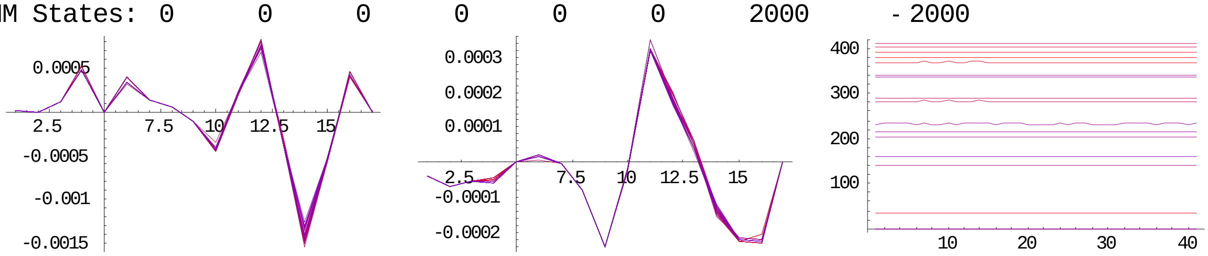

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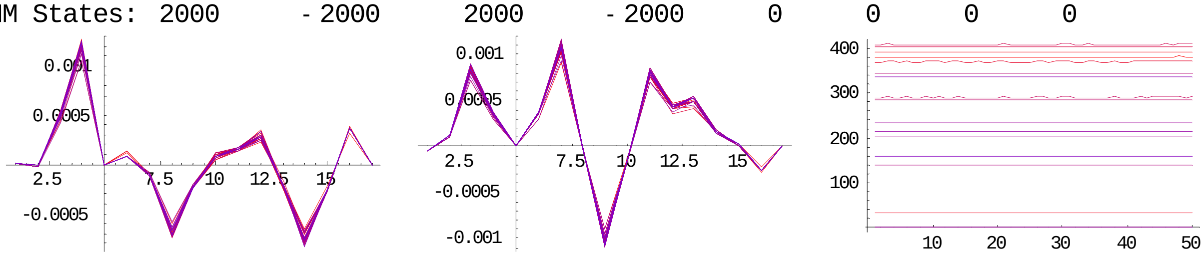

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Remaining data {43}

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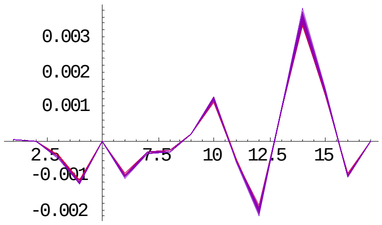

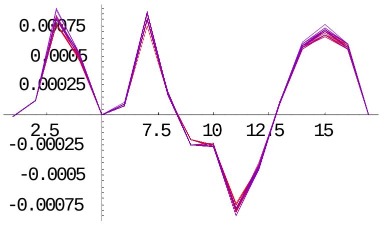

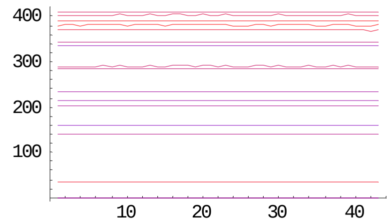

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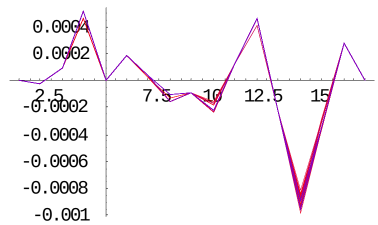

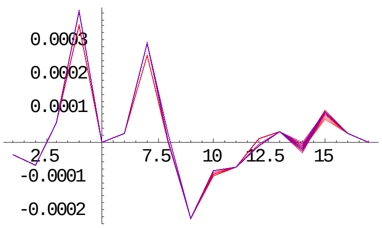

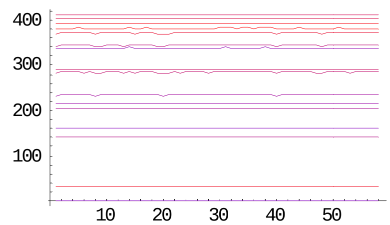

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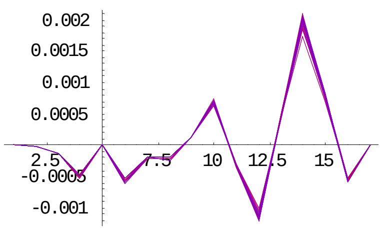

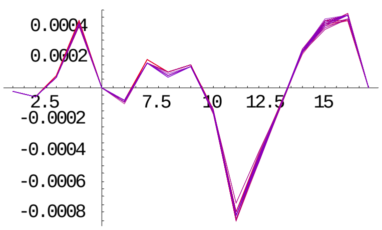

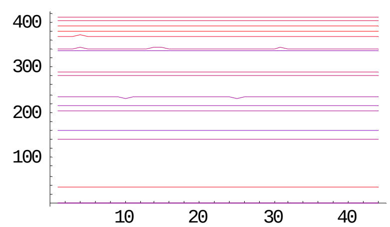

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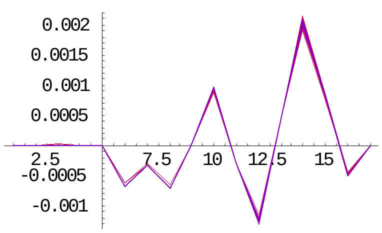

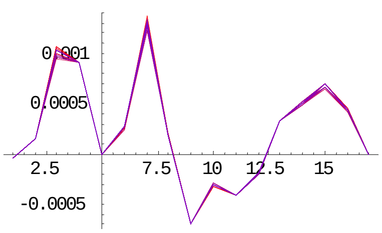

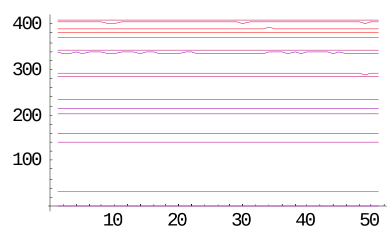

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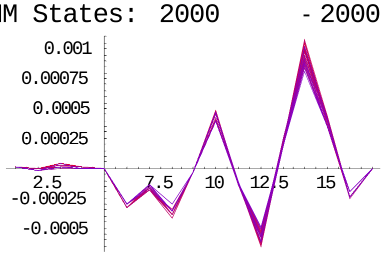

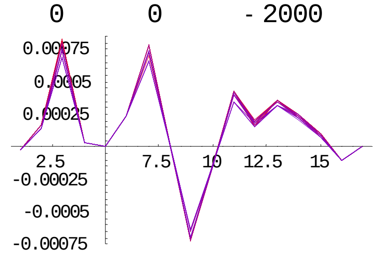

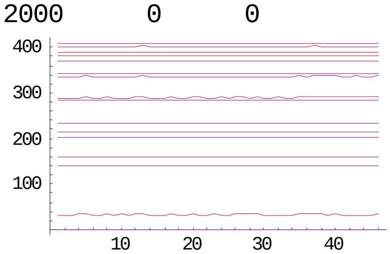

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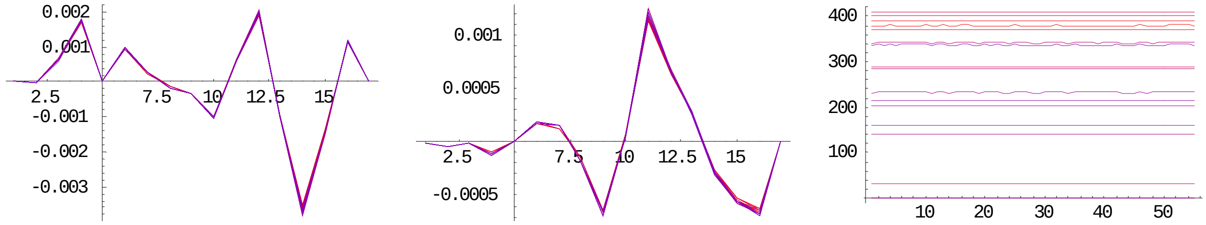

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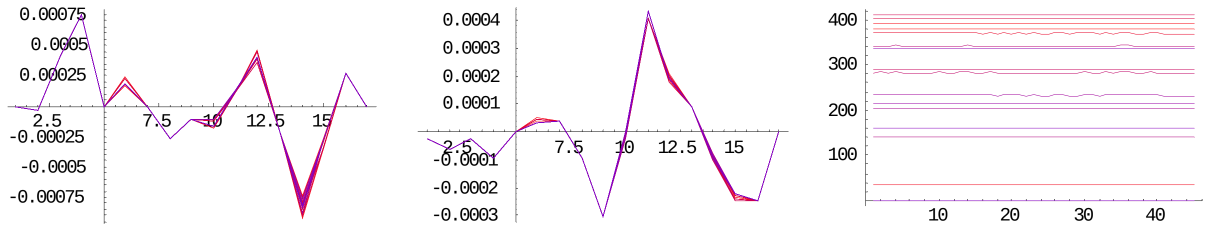

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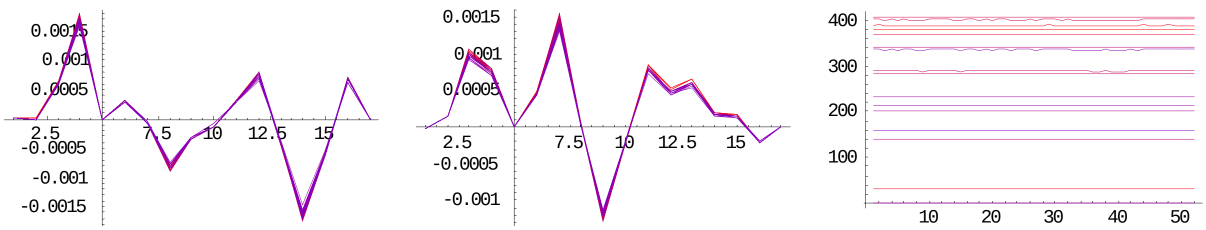

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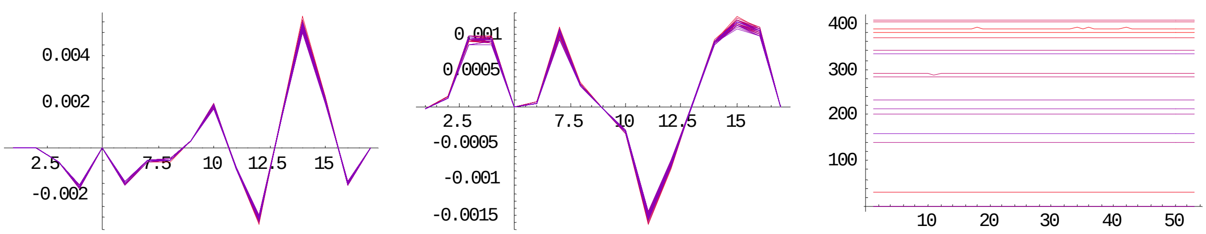

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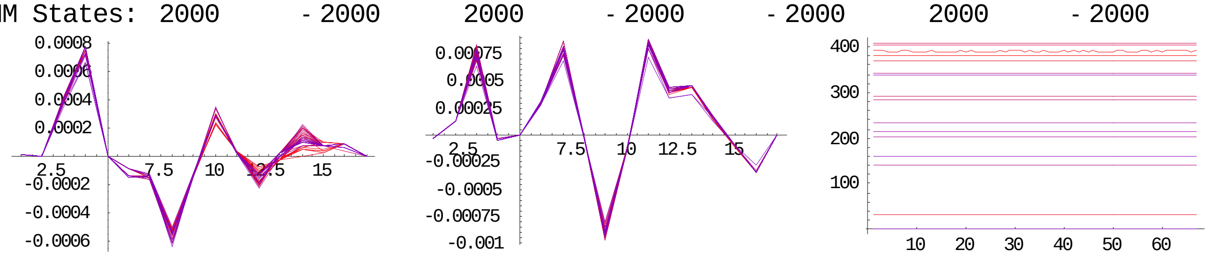

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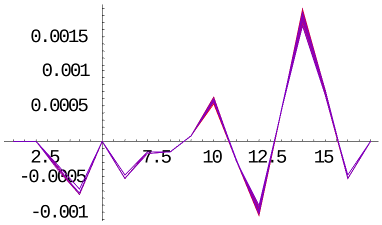
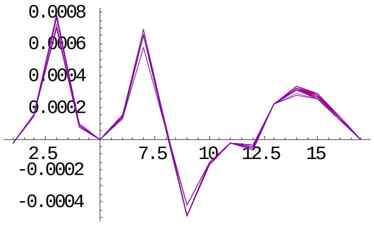
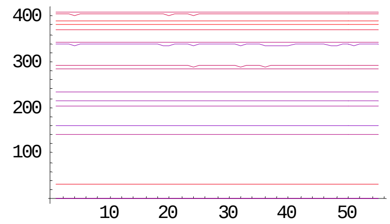






Part 2: Linear superposition & Orthogonality

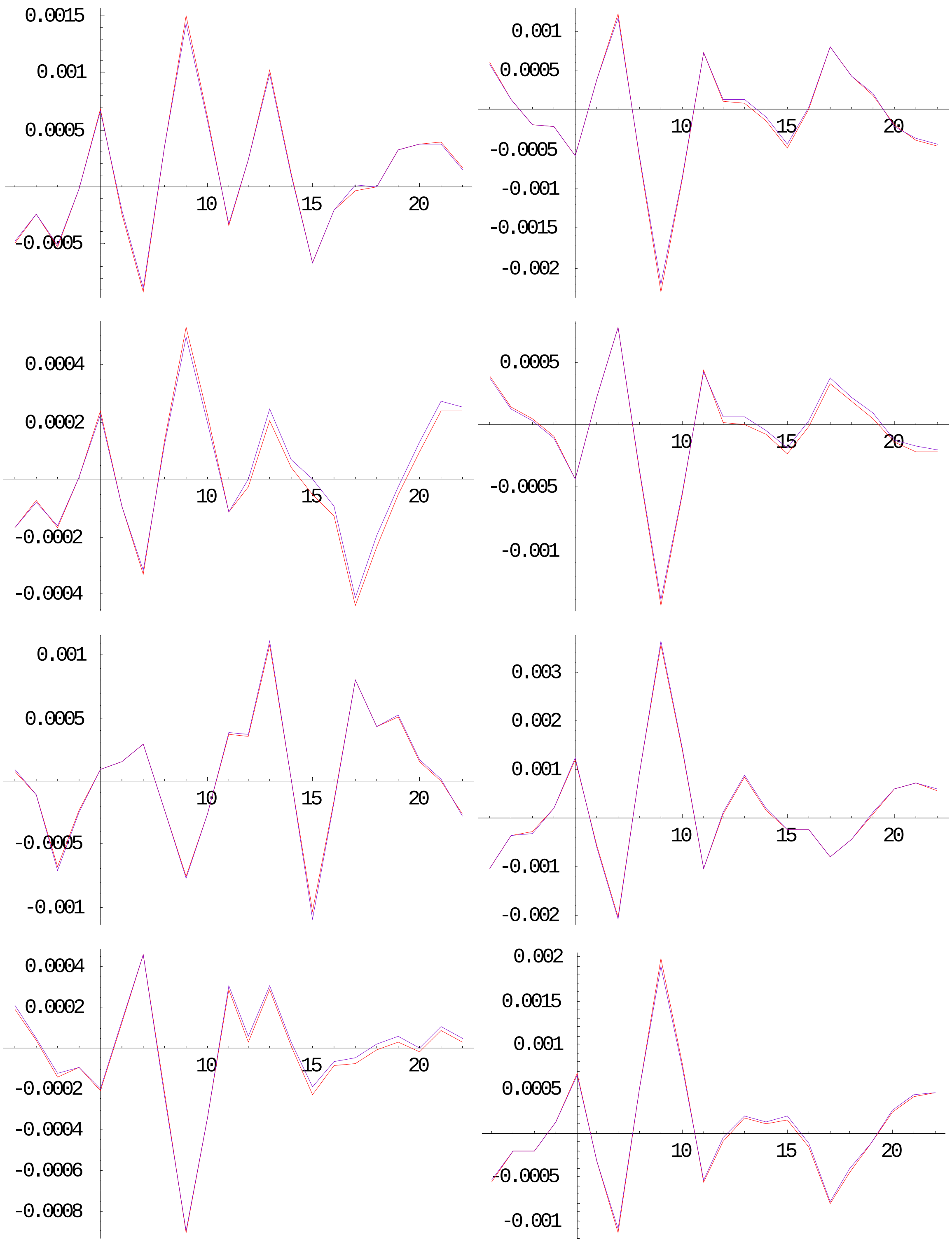
Apart from the first 4 orbits where 30 hz phase offset was not optimal, all the other HM-induced 30 hz orbits (16 total), with corresponding HM settings, were used to obtain the “empirical response matrix” with dimensionality 22 × 4 (11 X + 11 Y BPM from 0L06 to 0R06; 4 Helicity Magnets). Unit is 1 mm per 2000 DAQ points.

$$
\begin{bmatrix}
-0.000475704 & 0.000566692 & -0.000164336 & 0.000374759 \\
-0.000232355 & 0.000121598 & -0.0000815317 & 0.000126794 \\
-0.00051984 & -0.000196814 & -0.000163949 & 0.0000359399 \\
-0.0000218876 & -0.000218267 & 0.0000108611 & -0.000104922 \\
0.000658934 & -0.000570266 & 0.000225591 & -0.000429426 \\
-0.000211909 & 0.000367555 & -0.0000895572 & 0.000222444 \\
-0.000883959 & 0.00117214 & -0.000315701 & 0.000771438 \\
0.000352641 & -0.000581096 & 0.000125281 & -0.00036265 \\
0.00142712 & -0.00219159 & 0.000495417 & -0.00138754 \\
0.000580222 & -0.00084442 & 0.000201662 & -0.000545152 \\
-0.000332972 & 0.000711225 & -0.000114801 & 0.000422345 \\
0.000234926 & 0.000128494 & 7.00147\times 10^{-7} & 0.0000591061 \\
0.000984499 & 0.000123745 & 0.000244436 & 0.0000565576 \\
0.000103548 & -0.0000942895 & 0.000072015 & -0.0000403914 \\
-0.000661475 & -0.000428921 & 4.94109\times 10^{-7} & -0.000193443 \\
-0.000207953 & 0.0000409192 & -0.000091848 & 0.0000230897 \\
7.87211\times 10^{-6} & 0.000799457 & -0.000410568 & 0.000364736 \\
3.83669\times 10^{-6} & 0.000432808 & -0.000195386 & 0.000212098 \\
0.000320264 & 0.000196243 & -0.0000253063 & 0.0000855719 \\
0.000376598 & -0.000205655 & 0.000128972 & -0.000127835 \\
0.000371437 & -0.000359404 & 0.000274282 & -0.000167942 \\
0.000158254 & -0.000436771 & 0.00025392 & -0.000206753
\end{bmatrix}
$$

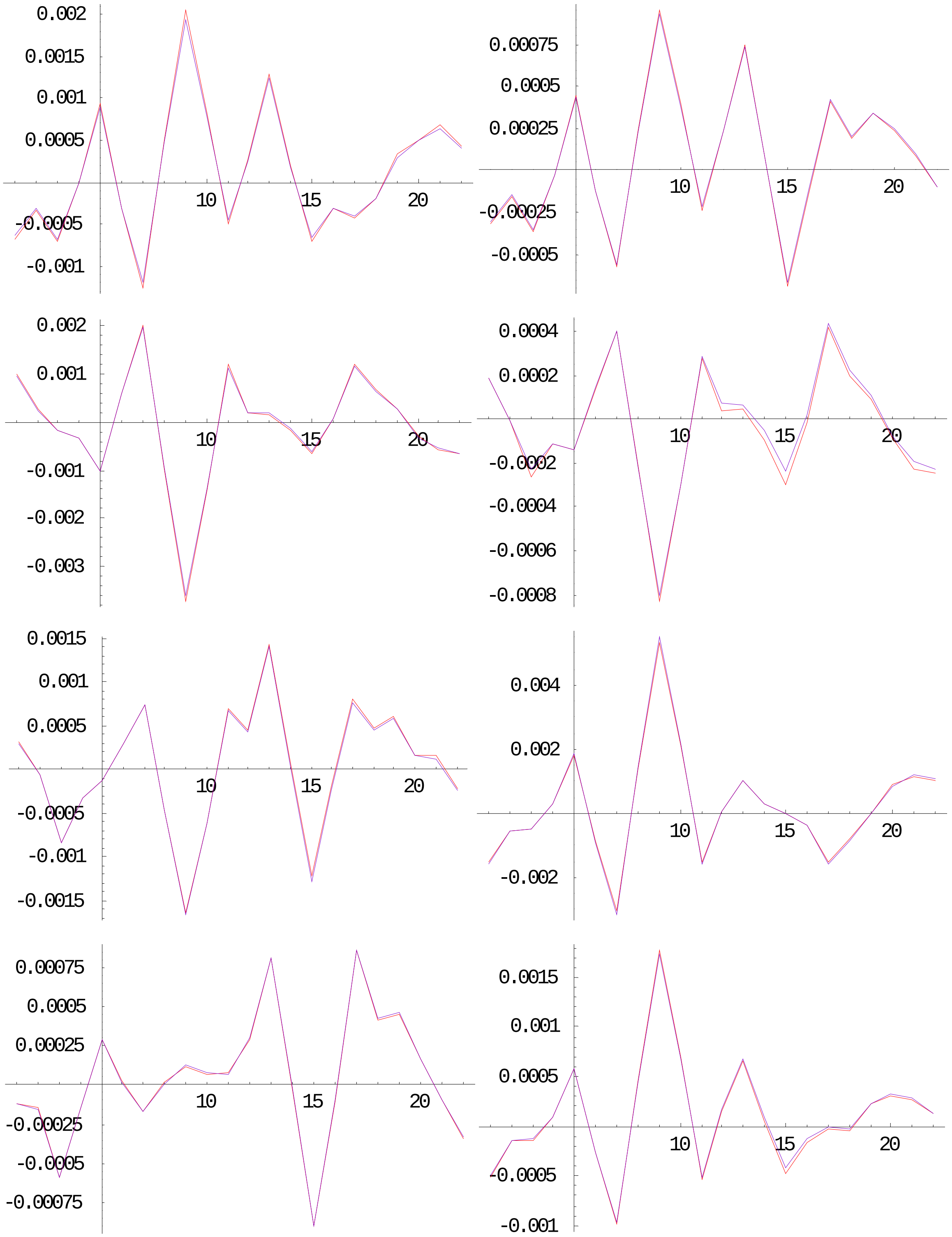
Not surprisingly it is XY coupled. However the really important questions are: (A). Can they be predictably superposed? (B) Do they form a non-singular coverage of the <u>4D</u> orbit space? The answers seem to be both YES.

The 16 plots below show, for the 16 test cases, comparison between measured (red) and predicted (blue) 30 hz orbits, with the latter based on the above empirical matrix. It is clear that the 16 orbits did not incompatibly constrain the matrix such that it fails to reproduce any part of the 16 patterns. This in itself is proof of linear superposition of the HM’s.

Since we will be determining the HM combinations empirically, whether they create effects in agreement with the model is really less important than whether they can be linearly superposed and whether they cover the phase space effectively. Thus we will not analyze their agreement to the optical model here.



0.0015
0.001
0.0005
-0.0005
10
15
20
0.001
0.0005
-0.0005
-0.001
-0.0015
-0.002
10
15
20
0.0004
0.0002
-0.0002
-0.0004
10
15
20
0.0005
-0.0005
-0.001
10
15
20
0.001
0.0005
-0.0005
-0.001
10
15
20
0.003
0.002
0.001
-0.001
-0.002
10
15
20
0.0004
0.0002
-0.0002
-0.0004
-0.0006
-0.0008
10
15
20
0.002
0.0015
0.001
0.0005
-0.0005
-0.001
10
15
20


0.002
0.0015
0.001
0.0005
10
15
20
-0.0005
-0.001
0.00075
0.0005
0.00025
10
15
20
-0.00025
-0.0005
0.002
0.001
10
15
20
-0.001
-0.002
-0.003
0.0004
0.0002
10
15
20
-0.0002
-0.0004
-0.0006
-0.0008
0.0015
0.001
0.0005
10
15
20
-0.0005
-0.001
-0.0015
0.004
0.002
10
15
20
-0.002
0.00075
0.0005
0.00025
10
15
20
-0.00025
-0.0005
-0.00075
0.0015
0.001
0.0005
10
15
20
-0.0005
-0.001

Finally an SVD was performed on the empirical matrix, with the resulting singular values:

0.00430472 0.00157601 0.000447362 0.000137871

Thus the condition number is a decent **31.2**. This means the current HM configuration should be adequate to facilitate the PZT Booster, or even G0 feedback. Of course this can change with different optics, which is what we need to guard against while doing Injector matching.

It is also interesting to look at the order of magnitude of each HM and compare with what is expected from the model. The matrix below gives the model-based response matrix from the kick angle at the 4 HM's (0L02H, 0L03H, 0L01V & 0L03V) to the 4D coordinates at the entrance to MQJ0L03A. Ignoring further optics downstream, 0L01V has the largest response. This is quite consistent with the data shown in Part 1[7].

$$\begin{pmatrix} 4.35 & 0.67 & 0.290105 & 0 \\ 1. & 1 & 0.0531409 & 0 \\ 0 & 0 & 10.112 & 0.81 \\ 0 & 0 & 1.56072 & 1. \end{pmatrix}$$

This becomes the following matrix into 60 MeV (at exit of MQS0L06):

$$\begin{pmatrix} 6.20802 & 4.16544 & -0.481445 & 1.53846 \\ 1.05017 & 1.2985 & -0.0529876 & 0.99174 \\ -2.3091 & -1.04346 & 4.42312 & 0.698856 \\ -4.5335 & -1.929 & 8.82559 & 3.3378 \end{pmatrix}$$

After properly accounting for M12/M34 artifacts, the SVD condition number for this matrix is **36.2**, consistent with the one above derived from direct measurements.

[7] The order of HM correctors shown in DAQ points there is: 0L01V, 0L02H, 0L03V, 0L03H, reflecting the assignment of channels at the time of test according to the worksheet.