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Operation of the FEL Upgrade with Skew Quad Reflection and Rotation

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Introduction

A previous note describes how to augment the FEL Upgrade 3F skew quad reflection with upstream and downstream quadrupoles so that the entire 3F region is a pure skew quad rotation [1]. Here we describe how we have inserted the reflection into the Rev 1.1.3 "design" model, evaluate the single turn transfer matrix, and demonstrate that the installed system is in principle capable of producing a single-turn transfer matrix that is a pure reflection. Operational experience with the reflector is described, and a brief discussion of performance issues provided.

Embedding the Reflection

In order to model the system quickly, we simply copied the reflection matrix from its design file and inserted it into the Revision 1.1.3 design file as a DIMAD "matrix" beamline element. It was assigned the length of the installed system, and positioned in the 3F region symmetrically between QX3F04 and QX3F09 to mimic the installed hardware. By using the "matrix" beamline element, we could readily shift between an equivalent uncoupled matrix, in which the betatron-stable 2x2 sub-blocks were on-diagonal, and the nominal fully-coupled matrix, in which the 2x2 sub-blocks were off-diagonal. The "block-diagonalized" form allowed beam envelope matching with DIMAD, which does not compute coupled envelopes. This avoided having to match the beam sigma matrix, which works perfectly well, but is emittance-dependent and requires a bit more numerical entry than use of traditional eigenmode analysis. The "off-diagonal" form is, of course, representative of the nominal operating mode.

This approach supported rapid progress, but precluded careful error analysis for the system upstream of the wiggler (only linear effects were retained in the reflector matrix, though in principle 2nd order was available and had we taken the time to do so, a fully detailed DIMAD model could have been generated). Given that that the primary effects of interest in this region involve the longitudinal match to the wiggler and associated issues of dispersion control, this was not a major constraint.

The modeled system was then configured much as the machine was operated:

- The decoupled (design) system was optimized (betatron fitting as usual).
- The reflector was activated, but with the 2x2 betatron stable sub-blocks *on diagonal* in the model.
- QX3F01-4 were used to recompute the betatron match into the reflector.
- QX3F09-12 were used to rematch to the remainder of the machine.
- The reflector matrix was reconfigured to the nominal form, with off-diagonal 2x2 sub-blocks. As the two sub-blocks are identical and betatron stable, the match based on the block-diagonalized form conveys, but the overall system transfer map now properly describes the cross-plane exchange imposed by the reflection.

System analysis was then performed. In particular, the recirculator transfer matrix and the single turn matrix from center of zone 3 back to center of zone 3 was evaluated for a couple of relevant situations

Results of Modeling

When the process outlined above is followed in the Revision 1.1.3 design data set, the following result is obtained for the recirculator transfer matrix. This is how we "intended" to run the machine (but be aware that I did NOT say "how we ran the machine", because we don't actually know HOW we ran it).

```
-0.2457446E-15  0.2135642E-14  0.1115813E+01 -0.1746083E+02  0.0000000E+00 -0.2304489E-13
 0.1775095E-16  0.1257466E-15 -0.2648603E-01  0.1310675E+01  0.0000000E+00  0.1710437E-14
 0.6789055E+00  0.4891636E+01 -0.6861041E-16  0.3450387E-14  0.0000000E+00  0.1903232E-13
-0.9195742E-01  0.8103891E+00  0.2888057E-16 -0.4494641E-15  0.0000000E+00 -0.4432243E-15
 0.1660172E-14 -0.3552074E-13  0.1325329E-14  0.3053113E-14  0.1000000E+01 -0.1059500E+00
 0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.1000000E+01
```

Notice this is fully out-coupled. When placed between half-linac matrices, it gives the following result for the transform from the center of zone 3 back to center of zone 3.

```
-0.1655140E-15  0.3042870E-14 -0.7450054E-01  0.9694046E+01 -0.3213990E-13  0.1779665E-14
 0.1008618E-16  0.2302595E-15 -0.1041703E+00  0.1337419E+00  0.6998973E-14  0.1448235E-14
-0.8848159E+00 -0.1343076E+01  0.2894918E-15  0.1454096E-14  0.5766538E-13  0.4021491E-14
 0.7642930E-02 -0.1118427E+01  0.1783478E-16 -0.1480823E-15 -0.4053333E-14 -0.1704905E-14
 0.1424517E-14  0.3246589E-14  0.2150093E-15  0.1819950E-13  0.7277470E+00 -0.5634599E-01
-0.6864121E-14 -0.1564389E-13 -0.1036036E-14 -0.8769539E-13  0.1313791E+01  0.1272201E+01
```

This is fairly entertaining because the (31,32,41,42) block is roughly -I and the (13,14,23,24) block looks suspiciously quarter wave-length-like. We therefore returned to use of the "block-diagonalized" decoupled model, and pushed the unreflected y phase advance around the recirculator down by a quarter wavelength. This required use of the match to the recirculator and the reflector (2F and upstream 3F quads), and the match after the energy recovery arc (5F quads), holding the beam envelopes constant into the reflector (and thus downstream) and into the linac while using the remaining free parameters to push the vertical phase advance around while holding the horizontal constant. Once done, restoring the "off-diagonal: matrix for the reflector gives the following result for the recirculation with the reflection on.

```
 0.5765973E-15 -0.2167801E-14  0.5580418E+00  0.6167849E+01  0.0000000E+00 -0.4100085E-14
 0.1861654E-16 -0.2364077E-15 -0.9320302E-01  0.7618387E+00  0.0000000E+00  0.1679212E-14
-0.7722414E+00 -0.2955487E+01 -0.4474399E-15  0.1108250E-14  0.0000000E+00 -0.2328921E-13
 0.9283927E-01 -0.9396216E+00 -0.2925177E-16  0.2869063E-15  0.0000000E+00  0.2177983E-14
 0.5267941E-15 -0.2981658E-13  0.6123574E-15  0.2056688E-13  0.1000000E+01 -0.1059500E+00
 0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.1000000E+01
```

This is even more amusing, not because it looks like anything of particular interest in and of itself, but rather because, when embedded between linac halves it gives the following result for the matrix from center of zone 3 back to center of zone 3.

```
 0.5110793E-15  0.5651103E-14 -0.1130756E+01 -0.7732064E+00  0.5798945E-13  0.1417913E-13
-0.7706202E-17 -0.2729339E-15 -0.2907372E-01 -0.9041271E+00  0.8089666E-14  0.9595379E-15
 0.9005197E+00  0.5395879E+00 -0.4132093E-15 -0.4539133E-14 -0.3795696E-13  0.6417264E-14
 0.5338356E-02  0.1113521E+01  0.2372736E-16  0.4928350E-15  0.3200107E-14  0.1599614E-14
 0.1324444E-14 -0.1392854E-13 -0.4093196E-15  0.1315025E-13  0.7277470E+00 -0.5634599E-01
-0.6381914E-14  0.6711551E-13  0.1972332E-14 -0.6336527E-13  0.1313791E+01  0.1272201E+01
```

The result is thus quite close to the following idealized pure rotation, which is (naively) about as well as it seems possible to do – not only does it give the heuristically "right" coupling, it gives the "right" phasing: a HOM-driven kick returns not only out of plane but also at a node in position.

$$\begin{pmatrix} 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

We don't however know exactly *how* we were running the machine. Through bitter experience, we can say with conviction that we don't know the phase advance to a quarter wavelength unless a difference orbit measurement has been done recently – and it wasn't. We also don't know quantitatively how well matched we were into or out of the recirculator and, moreover, we don't know that we were particularly well matched into and out of the reflection region. That match was established by matching into the backleg with the reflection off, and then a DIMAD computation for the match into and out of the reflector dialed in when the reflector was turned on. This appeared reasonable through most of the 3F region, but required adjustment of the back-end quads (QX3F12 in particular, if I recall correctly) to get a good match to the wiggler. So, it is entirely possible we were not running the first case (-I x quarter wave) and it is conceivably possible we were even running something resembling a true rotation. It is also possible we were running something entirely different than either.

What *can* be asserted is that this simulation provides an existence proof that the embedded reflection can give (to the tolerances you see here) a pure rotation from at least one point of the linac back to itself while using only installed elements. What is not clear is that the machine will run particularly well if we try to *force* to run in this manner. We therefore turn our attention to this issue, first presenting a little information on how the machine acted with the reflection activated, and then discussing some simulation results that suggest how the machine might act were we to deliberately set up a pure rotation.

Observations on Machine

Initial operation of the reflection included cursory difference orbit measurements, wherein sine-like and cosine-like orbits were lauched into the rotator and the output orbit measured. Figure 1 presents the results; each orbit fully out-couples into the other plane. Out-coupled amplitudes in the latter portion of the 3F region also roughly match the launch amplitudes. We therefore conclude the reflector works essentially as intended.

Instability thresholds ranged from 1 mA to 5+ mA before the reflection was activated. We ran 8+ mA with the reflection activated, both pulsed and CW. This configuration was also used for high power pulsed and CW lasing as well. It thus provides reasonably robust operation and seems to improve performance with respect to the instability.

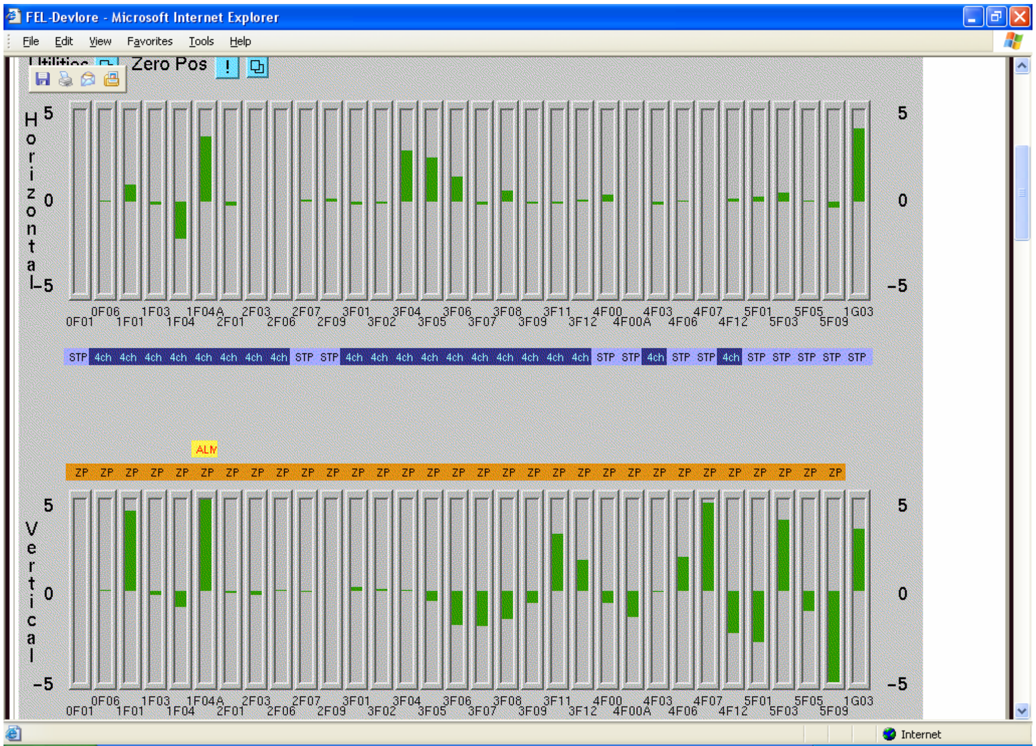


Figure 1a: Cosine-like horizontal kick (at 3F02) upstream of skew reflector (between 3F04 and 3f09) out-couples to vertical.

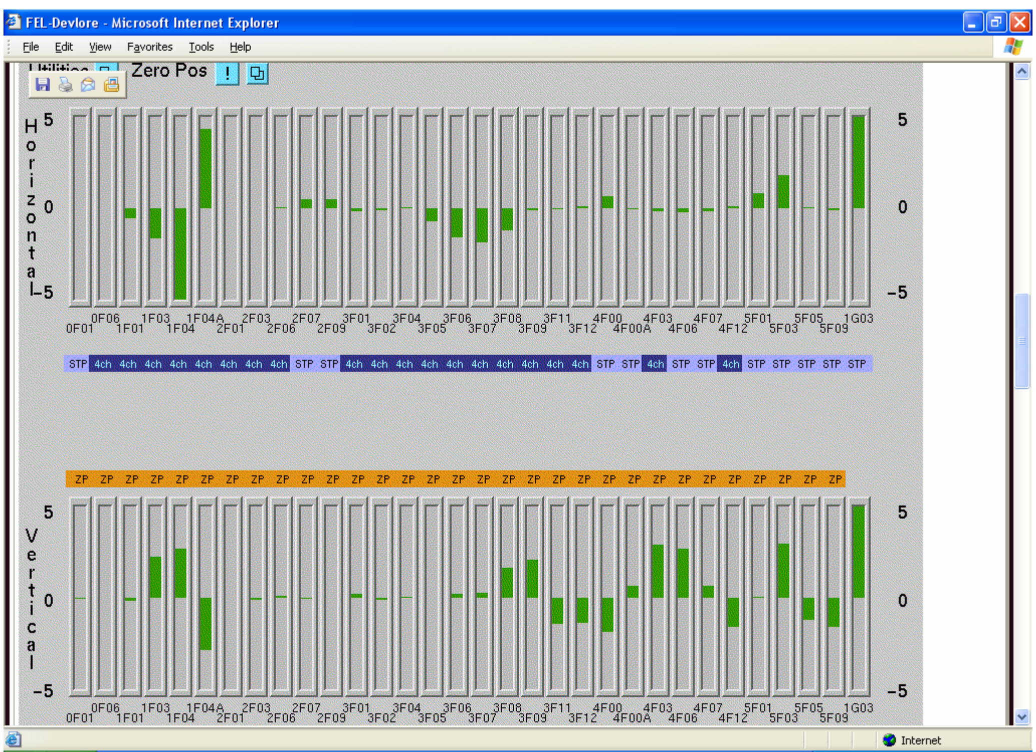


Figure 1b: Sin-like horizontal kick (at 3F04) upstream of skew quad reflector (between 3F04 and 3F09) out-couples to vertical.

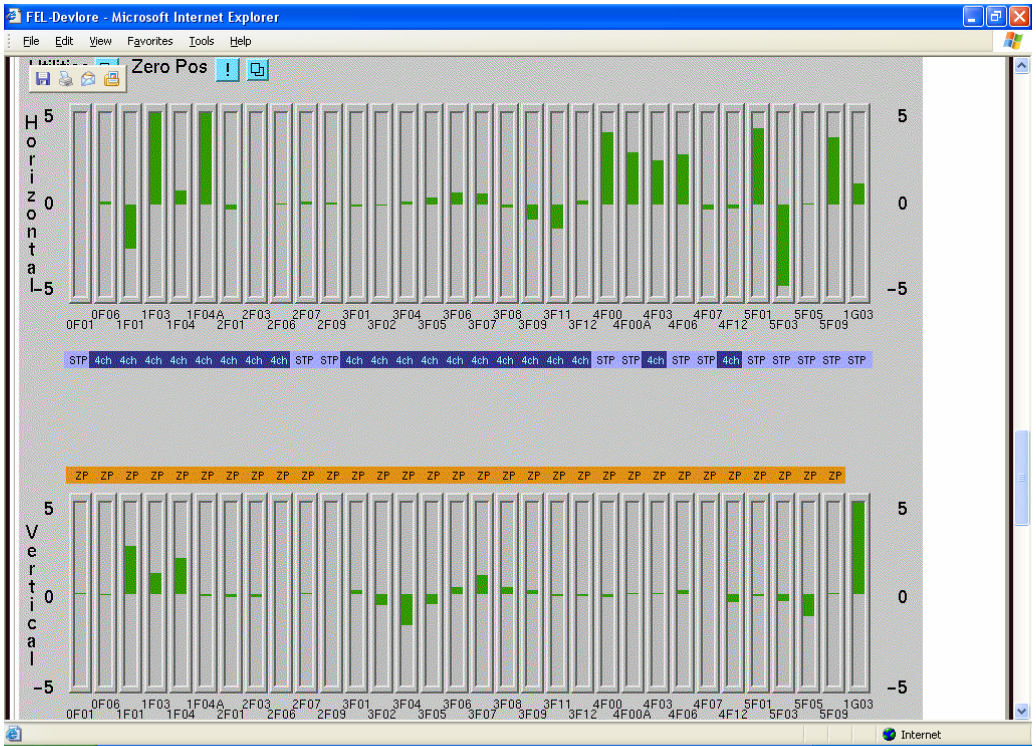


Figure 1c: Cosine-like vertical kick (at 3F01) upstream of skew quad reflector (between 3F04 and 3F09) out-couples to horizontal.

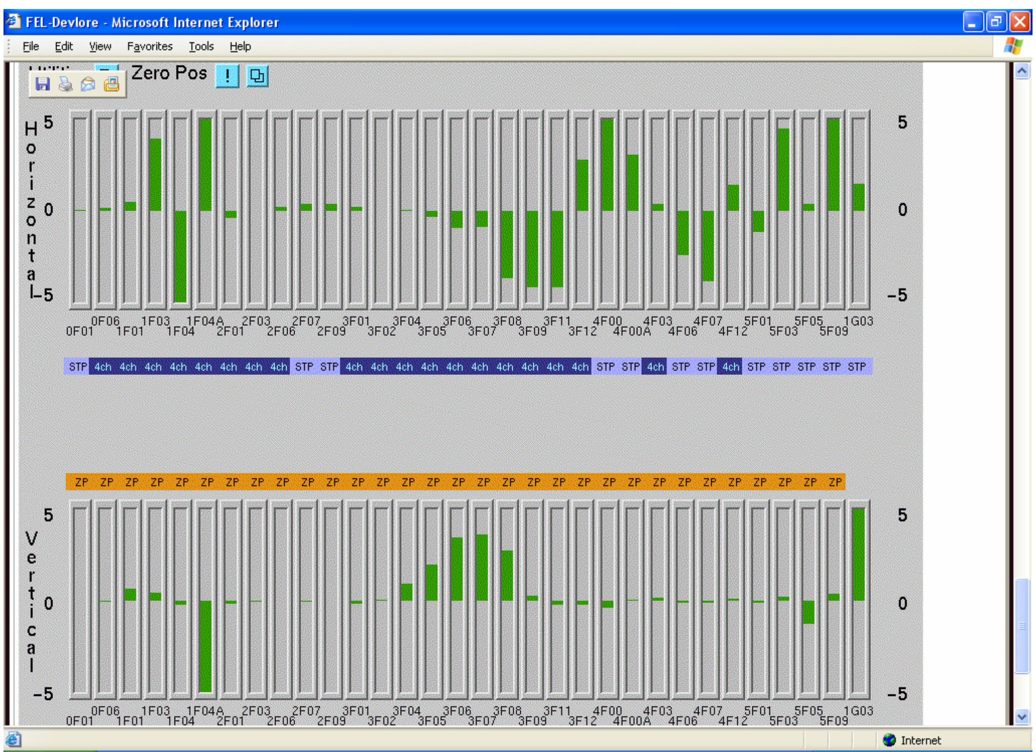


Figure 1d: Sine-like vertical kick (at 3F03) upstream of skew quad reflector (between 3F04 and 3F09) out-couples to horizontal.

This said, we note that because of the lack of two-pass BPMs, the turn-to-turn betatron phase advances are not well-characterized by this measurement. Furthermore, the phase advances don't necessarily reproduce well from setup to setup and can vary by a quarter-wavelength or more over the course of several days. Though locally consistent with design, the above data therefore cannot be extrapolated to draw conclusions about the machine as a whole. We might have been running "design" reflection matrix configuration (with -I/-90^{o} off-diagonal sub-matrices), or we might equally well have been running a true rotation (with -I, I off-diagonal sub-matrices), as discussed above.

It is possible to measure the phase advance through the recirculator and model it with some precision (to probably better than a tenth of a wavelength, perhaps to better than 20^{o} with a bit of care and 10^{o} with considerable care). However, for a specific setup this must be done at the time it is in use; quadrupole irreproducibility will wipe the result out should the quads be changed significantly and restored. Sadly, that was not done at the time of this measurement.

It *has* been possible to predictably move the phase advance around from such measured set points and to tune the machine repeatedly to a number of desired operational configurations. Given this, it is completely reasonable to consider setting the machine up to impose a pure rotation on the transverse phase space from turn to turn. As indicated above, this is clearly mathematically possible with the installed hardware. We now study (via simulation) some of the issues that may be associated with this activity.

Performance Analysis When Tuned for Pure Rotation

Key performance issues are beam scraping at high current and chromatic acceptance of the transport downstream of the wiggler. The first is associated with poor betatron matching and poor dispersion suppression – in particular poor suppression of second order dispersion. The betatron matching issue can be resolved by ensuring spot sizes do not get "too large" (e.g., a centimeter at an undispersed location), as this would indicate the presence of large envelopes and with them a potential for scraping of halo and tails. This is of particular importance when running a fully coupled system, as only the four-dimensional emittance is invariant and there is the possibility that the projected transverse emittances will both grow as the beam propagates down the linac.

Figure 2 presents "before" and "after" values for the design spot sizes through the recirculator. Figure 2a, "before", is the design, decoupled machine. Figure 2b is the design machine after tuning to provide a pure rotation from the middle of Zone 3 on the 1st pass back to the same location on the second. The beam sizes are not notably different, suggesting that scraping is not likely any more of an issue in the coupled system than in the decoupled.

Dispersion suppression is orthogonal to betatron envelope management in this system. We have learned that proper adjustment of trim quads and sextupoles will provide adequate performance in this regard; there is no reason to think that there will be any difference in the behavior of the coupled system from that of the decoupled.

Figure 2a: Spot sizes in Revision 1.1.3 design recirculator, assuming ¼% rms momentum spread upstream of wiggler and 2% rms spread downstream.

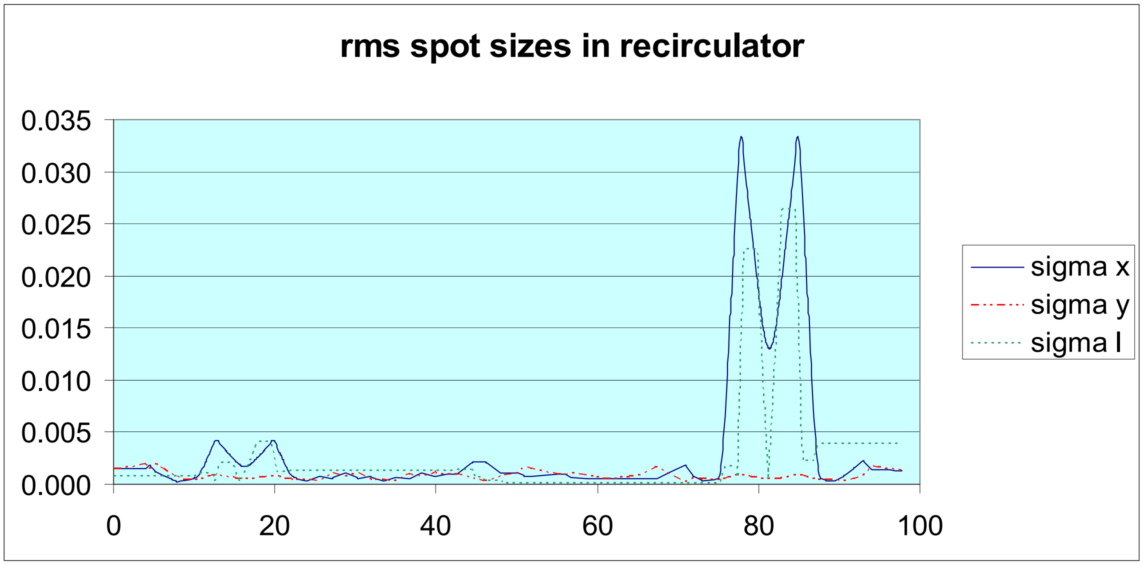
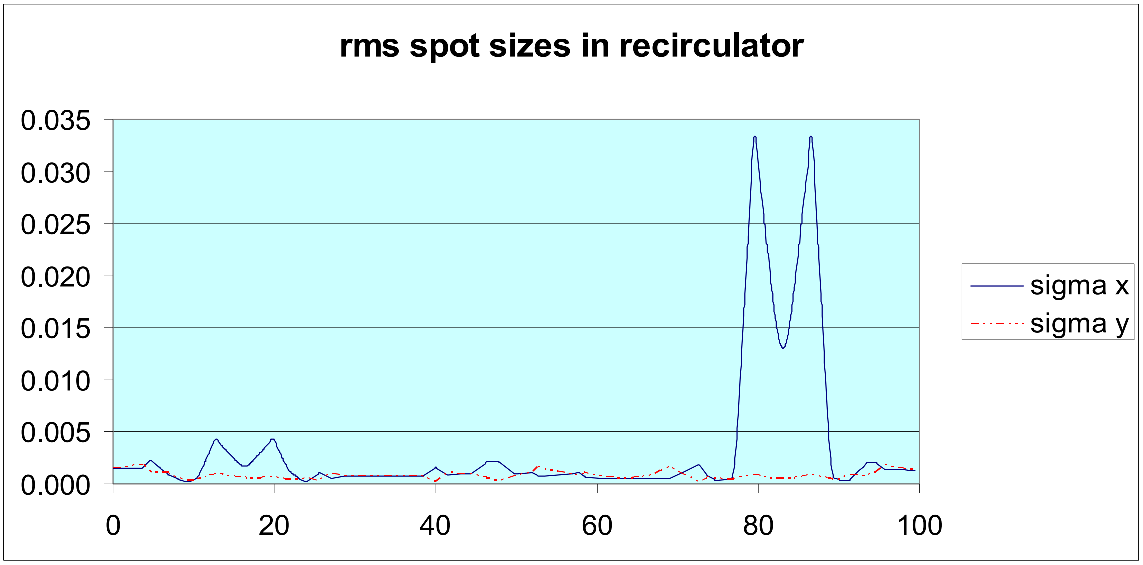


Figure 2b: Spot sizes in recirculator tuning for pure rotation with similar momentum spread assumptions.



Chromatic acceptance of the energy recovery transport is a significant issue. During Upgrade operation we frequently were limited by transmission during lasing and consequently spent considerable time and effort optimizing the transport to alleviate chromatic-aberration-driven growth in beam size and attendant beam loss. This was most frequently associated with the vertical envelope aberration $\partial\beta_y/\partial(\delta p/p)$, which to some extent drove the system design. Matching telescopes in the energy recovery transport were specifically laid out to cause interferences amongst themselves so as to suppress this effect. Tuning the match away from design is therefore done at some peril, inasmuch as changes in phase advance across the matches can impede the intended suppression.

This runs somewhat counter to the needs of this study, wherein we specifically attempt to tune the machine by changing the phase advances around the recirculation path. Initial attempts to do this without placing some of the burden on the energy recovery transport were unsuccessful; we were forced to distribute the change in phase retain the desired transverse envelope behavior. As the change seems unavoidable, we therefore have attempted to characterize what the effects of this modification may be.

Figure 3 shows momentum scans in the energy recovery transport "before" and "after" activation of the reflection (with tuning to rotation). The "before" result is simply that for the design Revision 1.1.3 system. The "after" is for the energy recovery transport tuned to support use of a pure rotation. We note that although the vertical chromatics are not severly degraded, the horizontal does develop some variation, particularly in beam divergence at reinjection ($\partial\alpha_x/\partial(\delta p/p)$). This may prove problematic and suggests a need for further optimization.

Figure 3a: Momentum scan for design machine (envelopes and phase advances from wiggler center to reinjection point vs. momentum). Note hard roll-off vertical parameters.

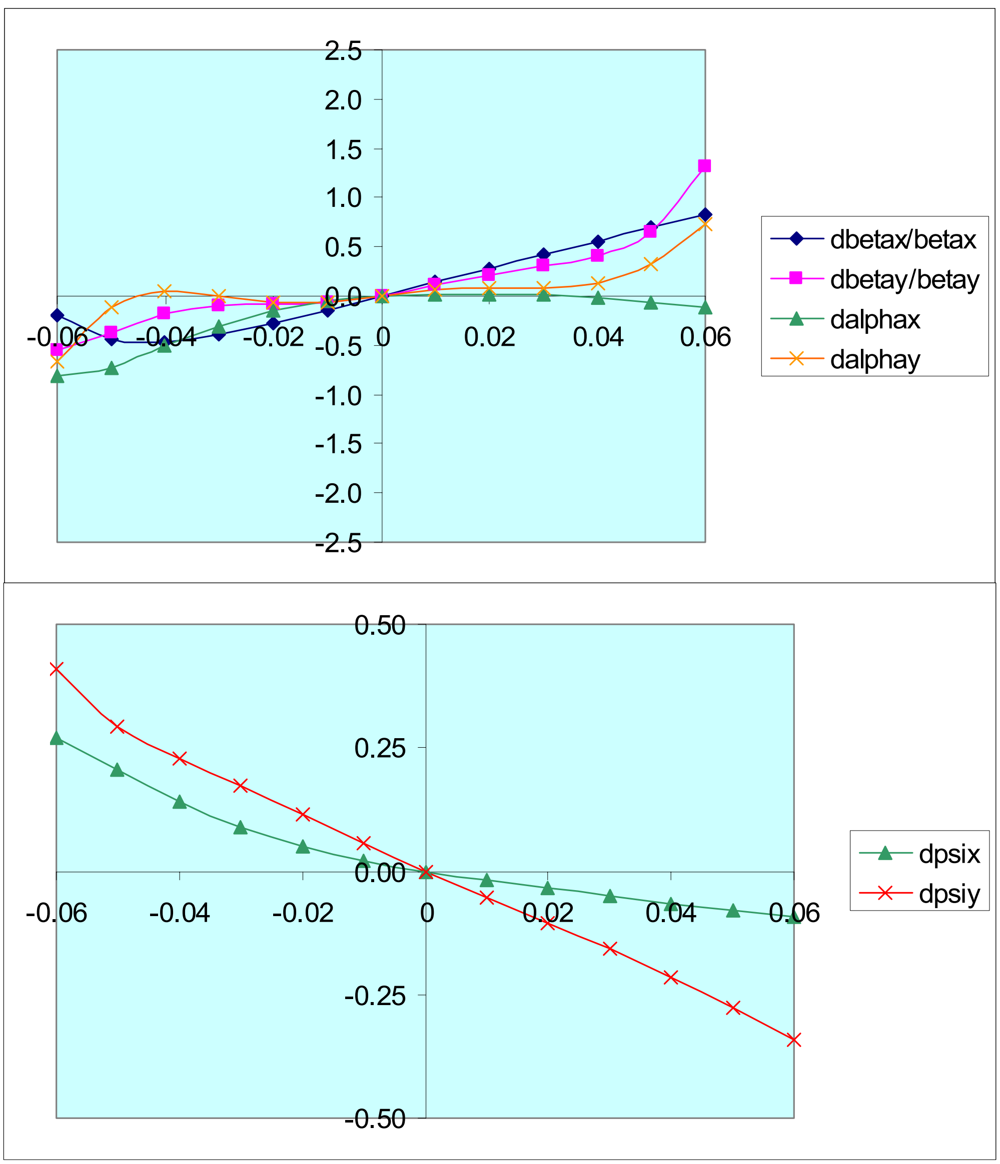
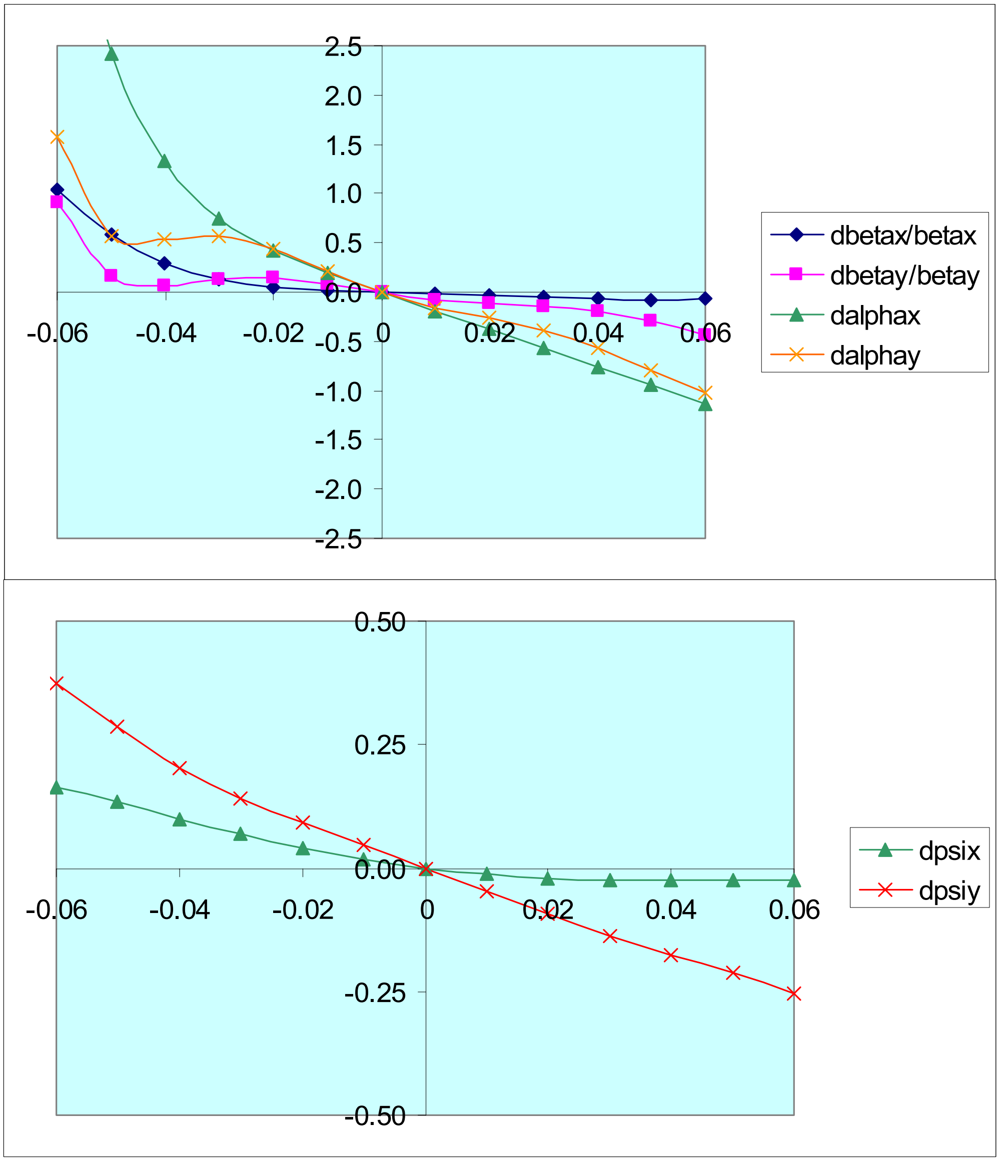
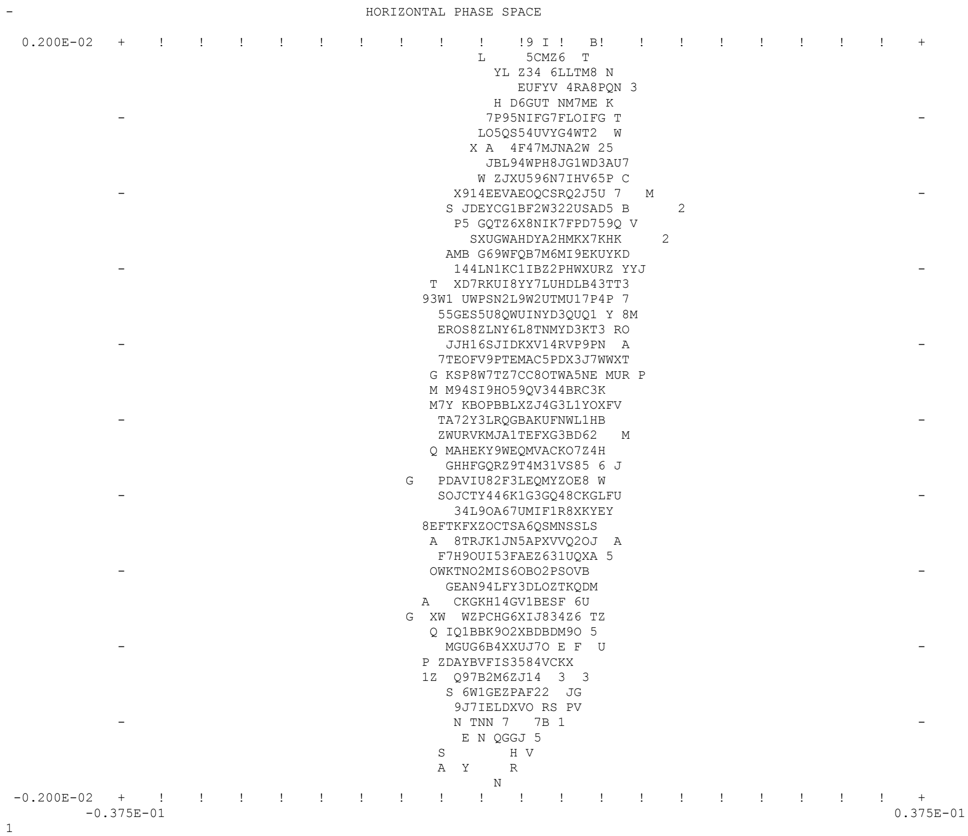


Figure 3b: Momentum scan (wiggler to reinjection point) for machine tuned to give pure rotation from center of zone 3 back to center of zone 3.



This opinion is reinforced when results of a ray-tracing simulation of energy recovery are examined (Figure 4). The nominal system provides a good, tightly bounded phase space with few outliers at the end of the machine (Figure 4a) while the skew-coupled system leads to leakage of beam to relatively large amplitudes (Figure 4b). This configuration will therefore likely require more optimization before it will run high currents while lasing, and may prove rather touchy to run.

Figure 4a: Horizontal and vertical phase spaces, configuration space in uncoupled design.



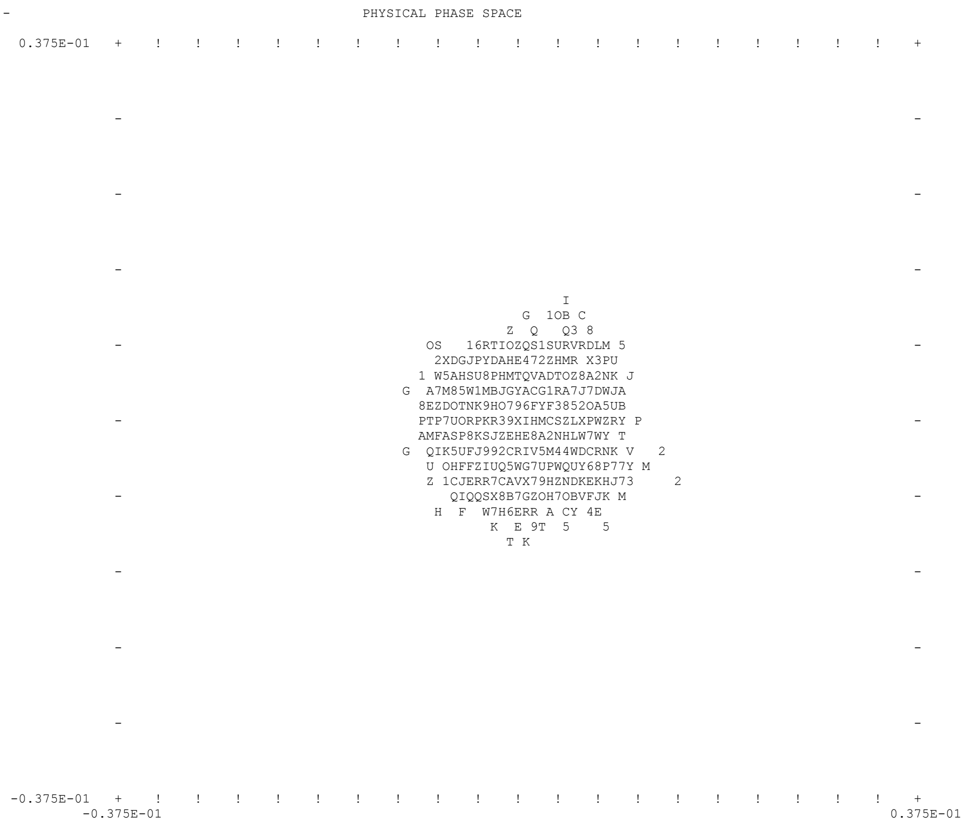
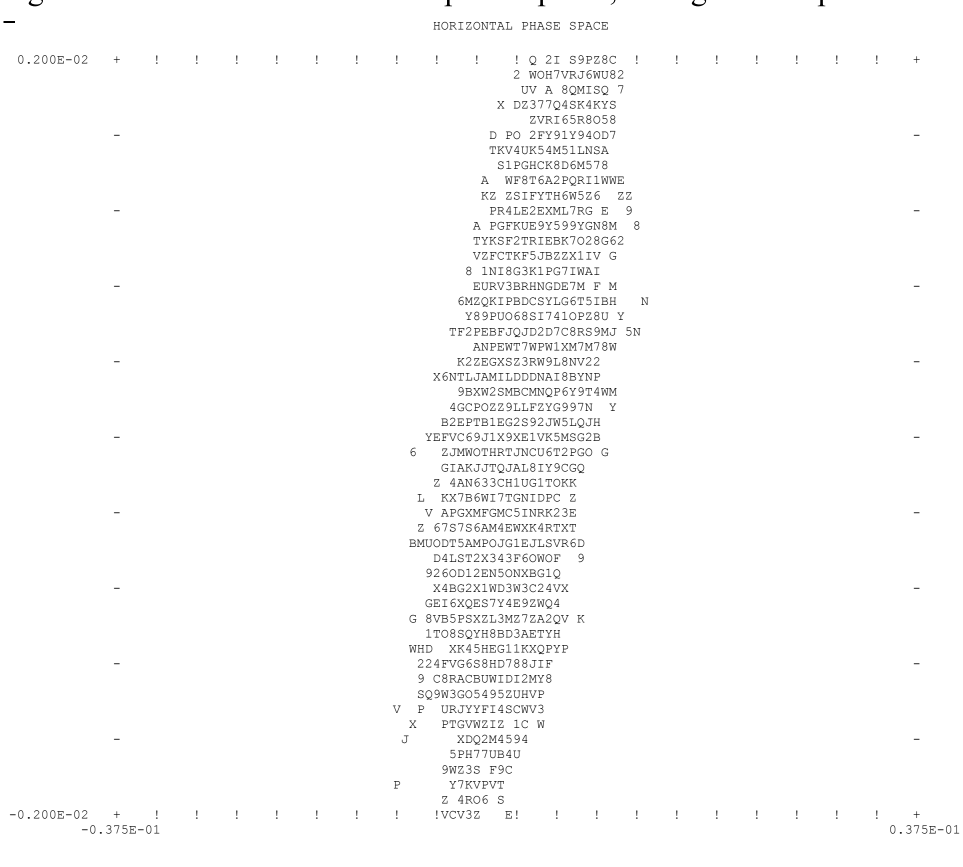


Figure 4b: Horizontal and vertical phase spaces, configuration space with reflection.



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1
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  0.200E-02  +    !    !    !    !    !    !    !    !    !    !    !   CZ    !    !    !    !    !    !    !    !    +
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             -                                        8V 4 UH4BDV5PU L                                             -
                                                      WYTXAZO3X4BOI 8F
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                                                   RLOPG1OOC15H979ZG        2
             -                                  I HQ FNHU813D9QG8W8PP45 E                                          -
                                                  N6V586TX8LJFOFI271QGRW
                                                S  TDJEG4IKLFWYJPT13KD   9
                                                  6RTUAMFG785FM3EOCU5J7D   7
                                                   4KMX4HS5FL78TVWF9TPB  1
             -                                    G RJ7MLA6K7HFZ71OWSL A                                           -
                                                 WU5A7R9P5QUIDZ53GIA5I9 4
                                                 H 62N25YYB6PBAN9J3OD  JHZ
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                                              F  PAO8CSGCXVR6MKO1ZSACNH9
             -                                   39K2BSWD2CJBP54IP1WU1 J3                                          -
                                               DUGULRA3YNYRINQJHM3TVZO1 G
                                             V  I2EYUSENKG96IL3MJ2DX HD
                                              7 NZRH3B6YAFX2EGLS5T1E3  4
                                              E QZW4S1DJ3924J6JIXYLV
             -                                  NB3ZJIMK1CHZEECNS5BH 6                                             -
                                            Z W8 TXY2632IWUBJPNWF8HPK5
                                                TP 2PV6VCAC3RRCSIISOE  T
                                       D        TIYZNWGAW15F43VWEOVI7 1
                                        7    S  T 2W6I8EHEMJOSOQ21DIV
             -                               BF  EH MU74UXWG2G2FKX R                                               -
                                                O 8G87YQT66FVIFKSWG7
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                                               Q GV65Q851GY4MBJPO T8
                                                YR9VFD48LG7BBRWF   8
             -                                T   CJQHX2EYSA75I8 A                                                 -
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                                                  QFPHP767CS7
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                                                2C2O7DN 5VW4  4 R
             -                                    33QHIG2JXV6Q                                                     -
                                               FL MN6R41Q6  C
                                                 JC5J BAU
                                                U  I  D E
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 -0.200E-02  +    !    !    !    !    !    !    ! S  6    !    !    !    !    !    !    !    !    !    !    !    +
         -0.375E-01                                                                                            0.375E-01
1
-                                           PHYSICAL PHASE SPACE

  0.375E-01  +    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    +


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                                               Q T1  4 RY6 KG9WJ3AKGHD         12  IR
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                                        U 5MX     DVKGA1E7P3LPDFGVCAPOOH 7FU2OF6               6
                                      6      T G98EB43VZ8LX1OJ72TLP1FGI4TF TLWXV  G5 C8 Z5CD
                                             RUBBDDO4LK224FZEBAN8OCCWVNCYUHFNPNBT9D9M4 C                          X
                                       L   J AUWSO4K7DDVFMRJFPOLPH8WBMI5ZG9C5T5IDRGF4 N   9          I   R
             -                       6       VJ WY9DRSB6JK44X8CIYCKY5G8UDTI1GT1VKN     H9       S     Q        -
                                             O K YG7YB765N3DT6UFXYIZ6Q68ACB8QVHT 9Z5  U5         O W
                                  P       22A  WKBV1BPS2WGMGK2N4ETMKJA1GHEQ84 M 6BGEE  P D            D
                                          E  YHM2PFSMBJSH3C5N82ATE7WZ2YN2Q  4  PN E   S5
                                               3LOV2726JNUOLXFUI26WH5HSZ  S5 Y53    N
             -                               O  ND CPWH5GGJSGTLHWI725RCD    C    T    J2D                      -
                                          X         Y7  W OD C NFF ZY2    D     1     U               L
                                                        E W E BSV  9TFP
                                  M                      Z      K
                                                                    O   E K
             -                                  S   7       D    1      E                                      -


             -                                                                                                     -


             -                                                                                                     -


 -0.375E-01  +    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    !    +
         -0.375E-01                                                                                            0.375E-01
```

Conclusions

When activated in the IR upgrade, the reflection module completely cross-couples the transverse optics, improves the BBU instability threshold, and allows tuning the machine to an operational robust configuration.

It is possible, at least in principle, to activate the reflection and tune the rest of the transport system to produce a (nearly) pure rotation single-turn transfer matrix. A performance analysis of this configuration (based on simulation) suggests that such a tuning to a pure rotation is not obviously fatally flawed but is likely to be touchy, need considerable tuning, and not reproduce well. An improved tuning might be possible, but an analysis of BBU performance to define detailed requirements should occur before considerable effort is expended in pursuing both the required design analysis and machine reconfiguration. "Better is the enemy of good enough".

Acknowledgements

Thanks to several people for precipitating a crisis in my understanding of this topic and thereby forcing me to try to sort out what we did on the machine. It has been an informative exercise. In particular, I thank Todd Smith, Chris Tennant, Eduard Pozdeyev, Steve Benson, and Lia Merminga.

References

[1] D. Douglas, "Reflections on Rotators, or, How to Turn the FEL Upgrade 3F Skew Quad 'Rotator' Into a Skew Quad Rotator", JLAB-TN-04-023, 4 August 2004.