Beam Transport Issues in the Fall/Winter 1998 FEL Run

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Abstract

Maximum transportable current in the FEL driver was limited to 1.6 mA during the Fall/Winter 1998 run. We discuss various orbit and beam envelope issues which may have contributed to this limitation and suggest remedial actions.

Introduction

The maximum energy recovered current achieved with lasing in FEL driver was limited to 1.6 mA during the fall/winter 1998 run. All attempts to run at higher power were terminated by BLM faults. As of mid-February 1999, it was not known if the limitation was due to gross beam instability or scraping. (Subsequent running demonstrated limits were due to scraping). The following observations may be made about the system and its performance during the Fall/Winter running period:

Observations:

1) The injected beam had a relatively large emittance and seemed to have significant halo during this run [1]. This may have been due to the injector setup, which used a novel procedure to “center” in the cryounit.
2) The second large dipole (DY5F02) was not carefully set during this run, but was simply assumed to match its partner, DY3F02.
3) The corrector pattern in the 5F region seemed to require hard steering, particularly at reinjection, to avoid triggering ILM0F062, at least during FEL operation.
4) The recirculated beam was observed far to the right on ITV1F01 and generally not at all on ITV1F02. The only time it was seen, the hard steering at reinjection had been somewhat redistributed
5) Substantial resteering of the recirculator on the final day of the Fall/Winter 1998 run failed to significantly influence the achievable maximum current [2]
6) The design match to the wiggler called for $\beta_x \sim 33$ cm, $\beta_y \sim 50$ cm with zero slope at wiggler center
7) This design match leads to large design vertical envelopes ($\beta_y \sim 20$ m) at the ends of the recirculator end loops
8) Activated beamline components were found immediately after the 3F end loop (just downstream of a peak β_y location) [3]; the 1.6 mA current limitation was due to a persistent BLM fault on ILM0F062, which is immmediately downstream of the 5F endloop, just after another peak β_y

location. In addition, some activation was noted around the center of the cryomodule.

9) There is anecdotal evidence of vertical mismatch at the wiggler, with a suggestion by Benson [4] that $\beta_y \sim 1$ m at the wiggler center.

10) There is less firm anecdotal evidence that the transport system tends to be a bit touchy vertically, with the following observations/recollections a part of operational folklore:
    a) An early match (Spring 1998) from the wiggler to the 2G dump resulted in a vertical orbit hypersensitivity and poor beam transmission to the dump. This problem, diagnosed by Benson [5], was confirmed with difference orbit measurements and remedied with a more judicious choice of beam envelope match.
    b) Initial recirculator operation during the Fall/Winter 1998 run had a poor match from wiggler to recirculator. This in turn led to beam loss in the 5F region, as indicated on the injector CARM. This was temporarily remedied by simply increasing the vertical focussing at the end of the backleg (by pushing QG4F13 negative); the CARM then stopped alarming. The transmission problem was subsequently cured (for currents below 1.6 mA) by optimizing the match at the wiggler and using design values for all quads downstream of the wiggler.
    c) A vacuum event at the dump occurred when the top of dump flange was heated by beam during a high power run on 20 November 1998 [6]. The beam was either poorly steered vertically or vertically large.

The above information suggests that the recirculator may be poorly steered in the 5F region and may not be well matched vertically. Even if the vertical matching is good, the relative large maximum by of 20 m at the ends of the end-loops may lead to scraping even of well-steered beam if there is significant halo. The anecdote that moderate resteering of the beam on the final days of the run (observation #5) had no impact on the current limitation [7], suggesting that the limitation, if due to scraping, was halo related.

We have therefore investigated a few "what-if" scenarios related to the above observations. In particular, we have looked at steering issues in the 5F region and vertical beam envelope behavior throughout the system. We find the following results, justification for which follow.

- Analysis of steering in the 5F region and at reinjection indicates the required steering pattern may be a consequence of mis-excitation of DY5F02 and strong steering of the injected beam by the 1F00H corrector. The resulting steering of the energy recovered beam puts it far to the right at reinjection and very far to the right after the module, and suggests why beam is seen at 1F02 only if steering is significantly modified. Suggestions for steering remedies are made.

- The large design beam envelopes in the end loops, particularly the vertical, may be responsible for activation at 4F01 and BLM hits at reinjection. Both horizontal and vertical envelopes can be significantly reduced in magnitude by appropriate rematching. Solutions for design and conjecturally observed beam envelopes at the wiggler are given. These may be employed to limit the impact of halo.
- A recovery procedure/test plan utilizing the results of this study has been generated.

Orbit Effects in the 5F Region

We have examined the steering through the 5F region for four noteable all-saves made during the Fall/Winter 1998 run. These are:

1) An all-save on 11/24/98 in which beam was first seen at 1F02
2) An all-save on 12/04/98 of the 1st 100 W run with recirculation at 1 mA
3) An all-save from 12/08/98 and
4) One from 12/15/98,

with the final two having led to high laser power and large energy recovered current.

The effect of this steering has been modeled. If certain assumptions are made, the effects of all examined cases of steering are consistent with a 5 – 10 mm error in orbit diameter (2.5 – 5 mm error in radius) in DY5F02. This is equivalent to a 0.25-0.5% error in the magnet excitation. In this note, we attend only to the horizontal orbit effects. We note that the effect of the large horizontal offset in these simulations has been simulated with skew quadrupole effects equivalent to those arising during energy recovery. The vertical correctors imposed during beam operations are consistent with the simulated results in these cases as well.

Assumptions and Recollections:

1) 1F00H is used to correct an error on the injected beam that is upstream of, not local to, the injection point. It consequently steers the recirculated beam by an angle BL/Bρ with BL the field integral of the corrector and Bρ the rigidity of the recirculated beam.
2) The beam is properly centered in the backleg (4F) region and thus is properly injected into the second end loop (5F).
3) The beam is properly centered in QH5F01 by use of 4F12H and 4F13H; thus, only downstream steering (from 5F01H onward) is relevant to this discussion.
4) The beam is centered in QH5F04 by use of the 5F01H corrector. This was a straightforward setup exercise and a step in the standard operating

procedure [8]. The centering in QH5F02 usually was taken to follow from centering in QH5F01, and typically little effort was expended on centering in QH5F03. This is because the latter step requires adjustment of the DY5F02 shunt, which was tedious prior to the installation of ITV5F04 and ITV5F07. Operationally, the shunt on DY5F02 was set to the same value as that on DY3F02; the magnet excitation could therefore easily be “off” by 1 to a few parts per thousand.

5) The recirculated beam is usually well off to the right on the 1F01 OTR.

Table 1: Corrector Excitations for Various Orbits (Values in g-cm)

5F01H	5F03H	5F05H	5F07H	1F00H	1F02H	1G00H	Save set
-100	200	0	200	188	75	“0”	beam visible at 1F02: 11-24-98_12:05:06
-100	0	0	170	210	70	10	Benson optimization: 12-04-98_22:56:07
-100 -110	0 0	465 350	-15 0	265 218	65 70	30 50	high power runs: 12-08-98_00:12:17 12-15-98_11:37:03

The following figures show the result of steering the beam with these corrector excitations. In each figure, case a) illustrates the “raw” steering effect. The reader will note that the raw steering results persistently fail to satisfy one or more of the above assumptions, most typically that the beam is centered in QH5F04 and/or that the energy recovered beam is observed far to the right on ITV1F01. We warn the reader that the illustrated orbit excursion at the front end of the accelerator (from about 0 to 20 m) is simply an artifact of the simulation. This is generated by a need to simulate the effect of 1F00H outlined in assumption 1) within the simple spreadsheet model we employed. The relevant orbit excursions occur beyond the 80 m point of the transport system.

Figure 1 shows the result of the “beam visible on 1F02” steering. Figure 1a) illustrates the steering without a DY excitation error; this case is not centered in QH5F04. With a 7 mm offset after the DY (a 0.35% relative excitation error) the beam is centered in the trim quad, and will be visible on both viewers, somewhat to the right on ITV1F01 and off to the left on ITV1F02 (which was in fact where it was observed). See Figure 1b). This setup had some transmission problems leading to BLM trips on ILM0F062 while lasing. Different steering, with lower losses at the BLM, thus evolved.

One such steering was devised by Benson [9] and is shown in Figure 2. Figure 2a) illustrates the raw steering; it is not well centered at the trim quad. Figure 2b) shows the steeering with the aforementioned DY excitation error. This steering is consistent with the assumptions and recollections outlined above.

Subsequent steerings used in high power runs were similar in character to the preceding. In each of the two cases shown in Table 1 and Figures 3 and 4, the orbit does not satisfy the observed behavior (Figures 3a and 4a) unless the DY is misexcited at about the 1/3% level (Figures 3b and 4b). Neither of these steerings produced significantly different limiting currents, even though the later one was accompanied by a modification of the recirculation dipole buss. We note that the “beam visible at 1F02” steering differs primarily from the others by the use of the 5F03H corrector. It thereby imposes different entrance angles and positions at the module, with the result that the beam is much farther to the left when it arrives at 1F02. It is also farther to the left at 1F01. This may relate to the impression that steering to the right at reinjection is needed to avoid BLM trips on ILM0F062. Other steerings, particularly the later two, from 12/8/9 and 12/15/98, tend to be farther to the right in this region.

We now consider what happens if the DY is “set right” and all correctors are off. This is shown in Figure 5a. Simply put, the 1F00H corrector (nominally excited to ~200 g-cm to fix some unknown injector problem) blows the recirculated beam away in the module. Figure 5b shows a corrected orbit, in which a beam bump is induced using the 5F03H and 5F05H correctors.

In summary, we find some evidence in the recorded corrector patterns that the second DY is improperly excited, at a level consistent with the knowledge available from magnetic measurements. We suggest increasing the shunt setting by ~1/3rd percent, and resteering the 5F region, making use of quad centering in the trim quads and the new 5F05 viewer to generate a beam bump in the reinjection telescope so as to offset the apparently necessary excitation of the 1F00H corrector.

Beam Envelopes in the Recirculator

As noted above, the design values for the driver’s vertical envelopes approach 20 m at the beginning and end of the end loops. As the system the end loops are not inherently vertically betatron stable (the matrix being –I and the phase advance being a half-wavelength) the design solution is not unique and may well be optimized by different matching to and from the end loops. We have therefore investigated the issue of beam envelopes through the recirculator and have made certain observations.

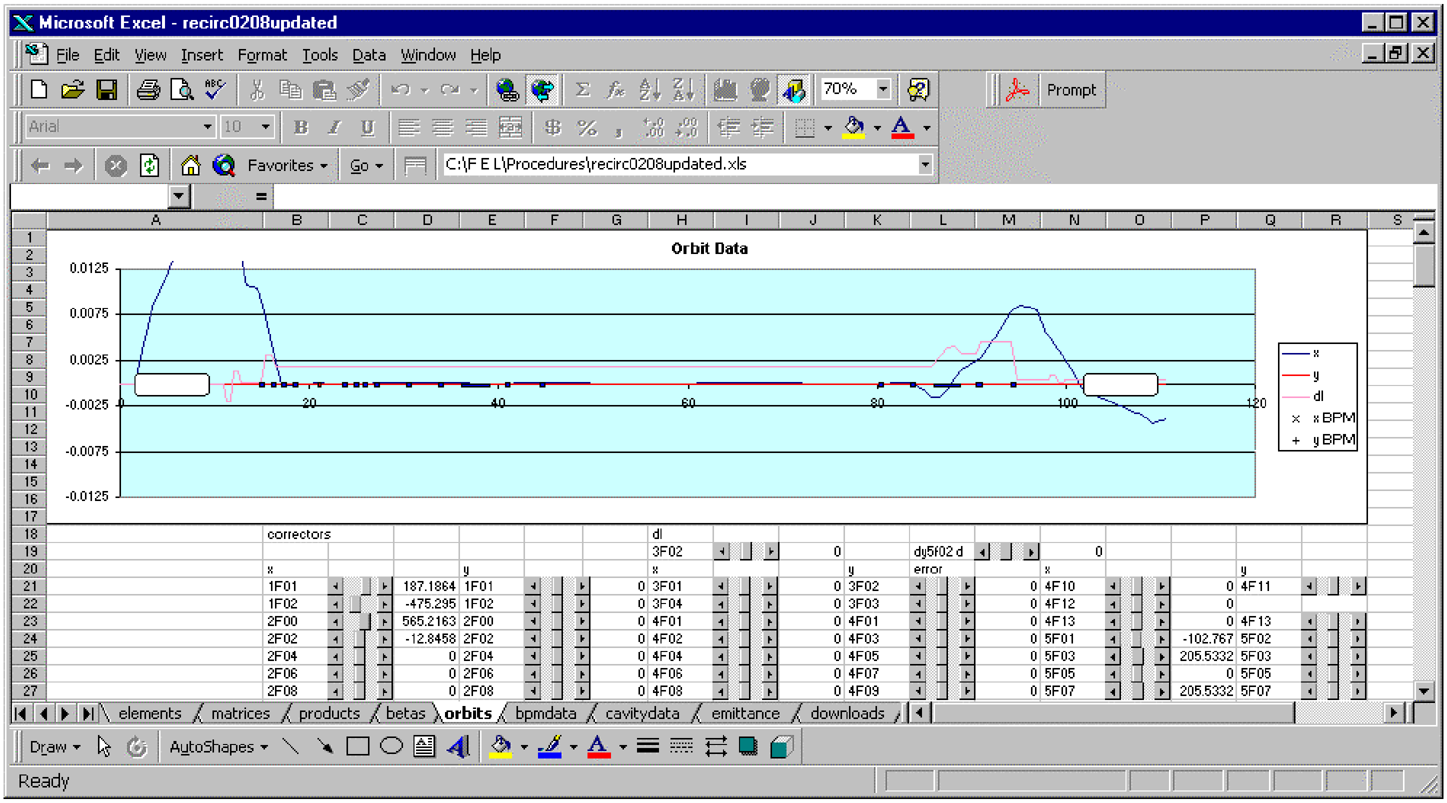

Figure 1a): “Beam visible on 1F02” raw steering; no DY5F02 excitation error.

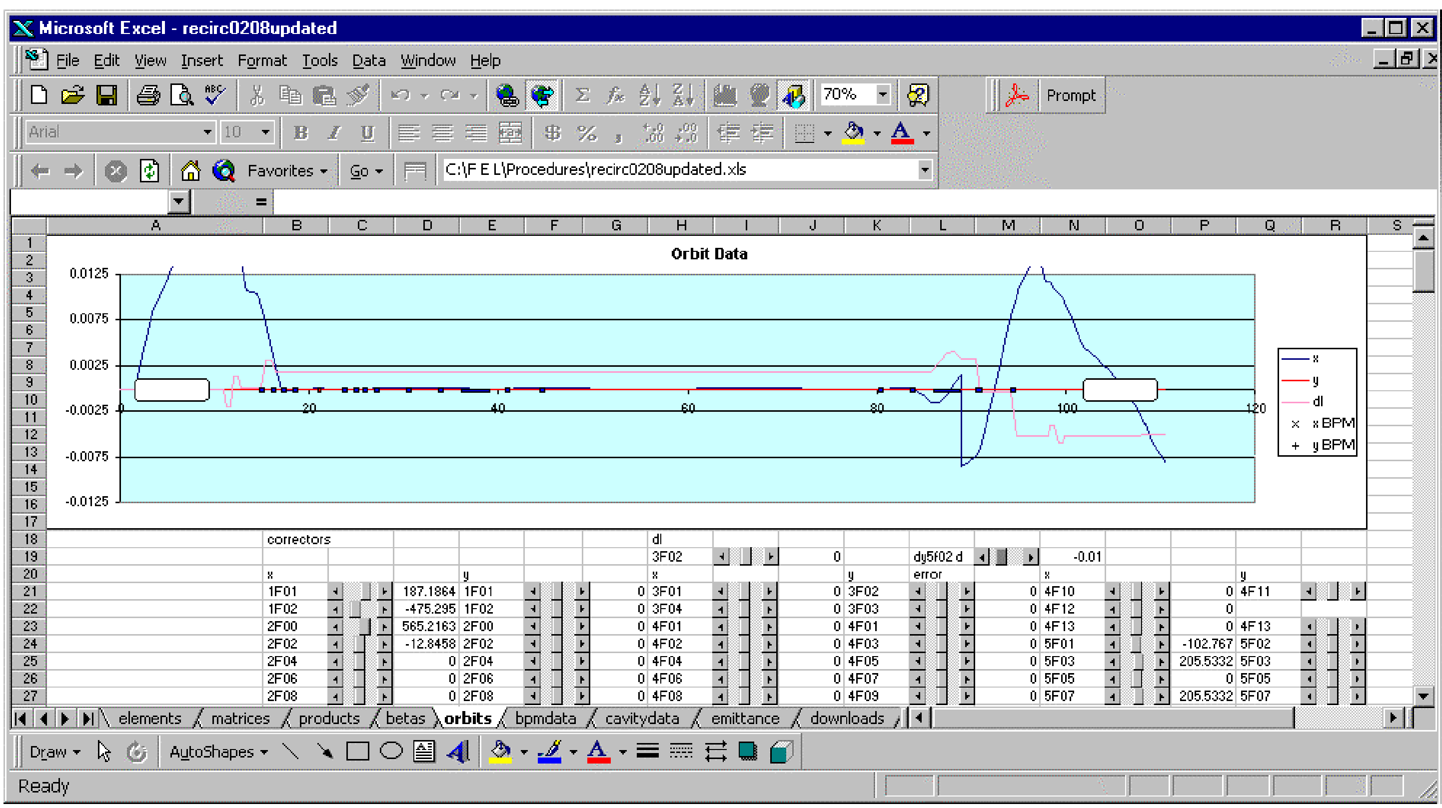

Figure 1b): “Beam visible on 1F02" steering with 0.35% DY excitation error.

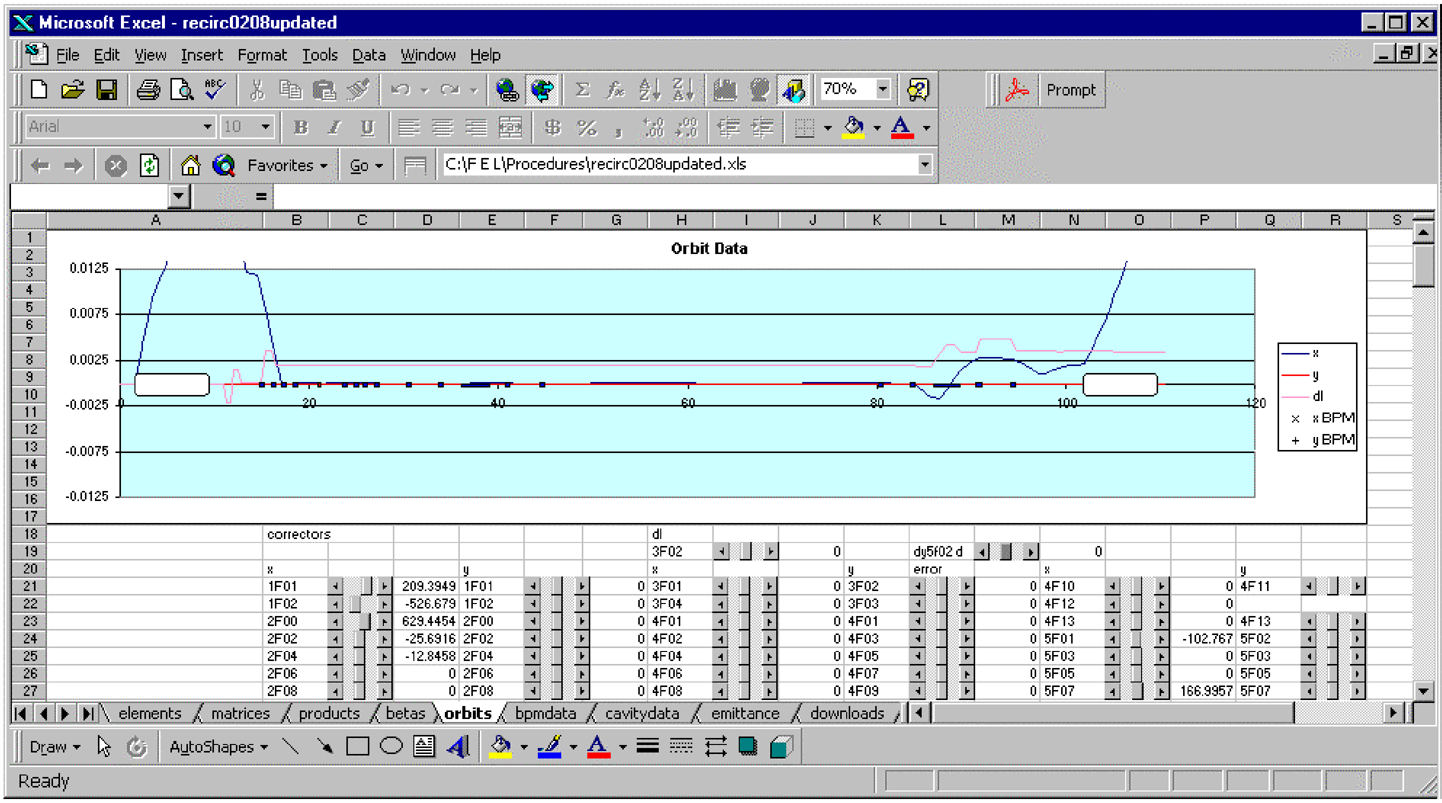

Figure 2a): Benson optimization without DY5F02 excitation error

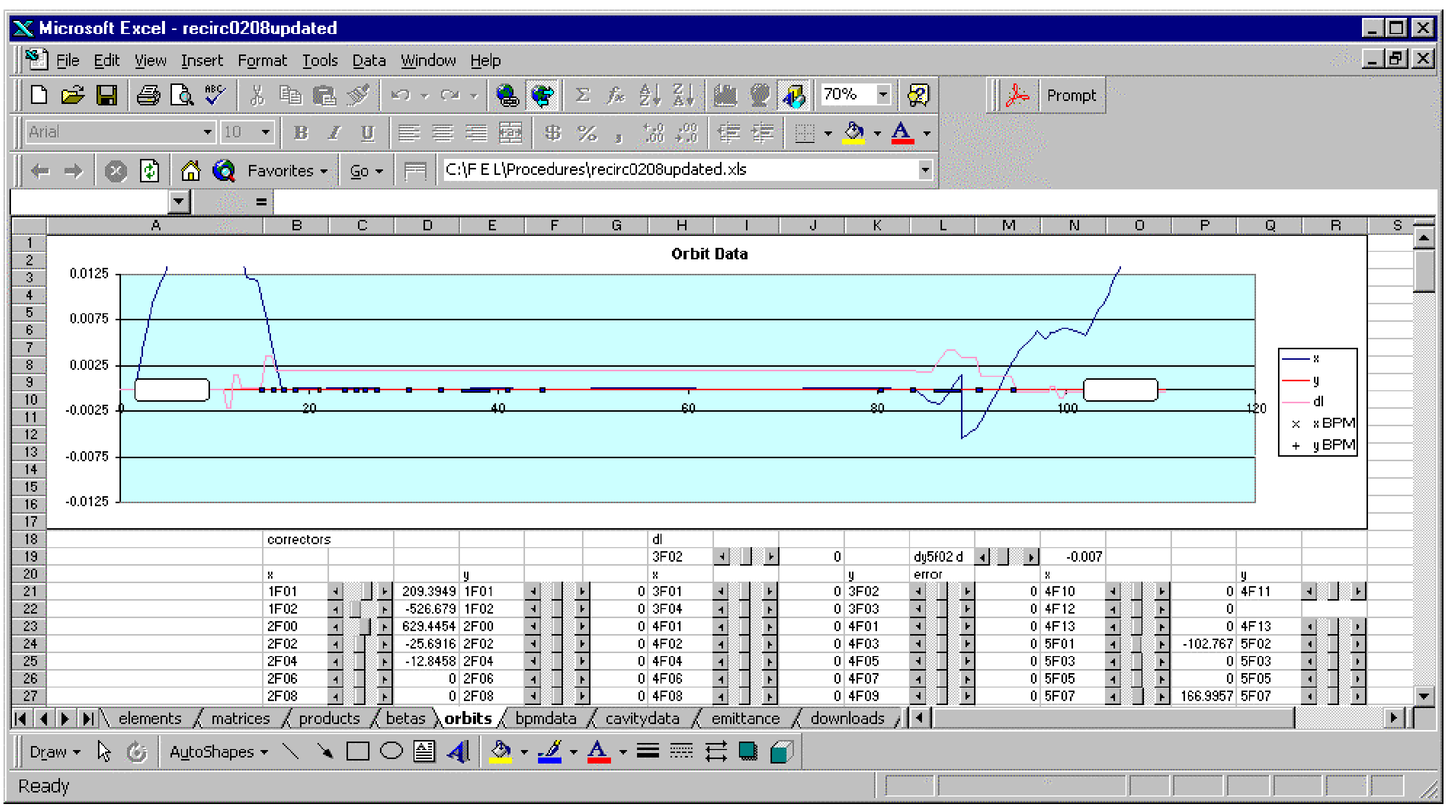

Figure 2b): Benson optimization with 0.35% DY excitation error.

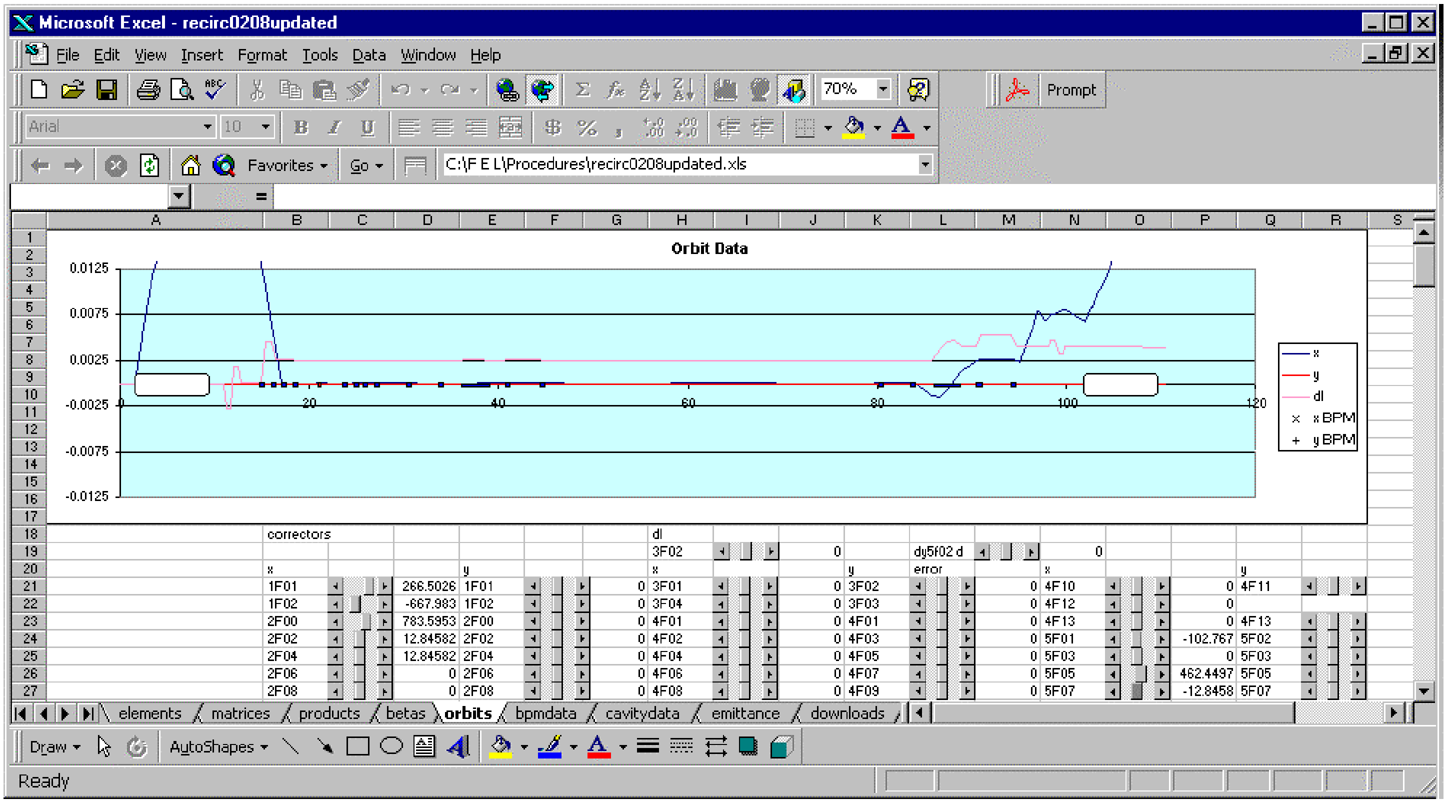

Figure 3a): High power running configuration of 12/8/98; no DY error.

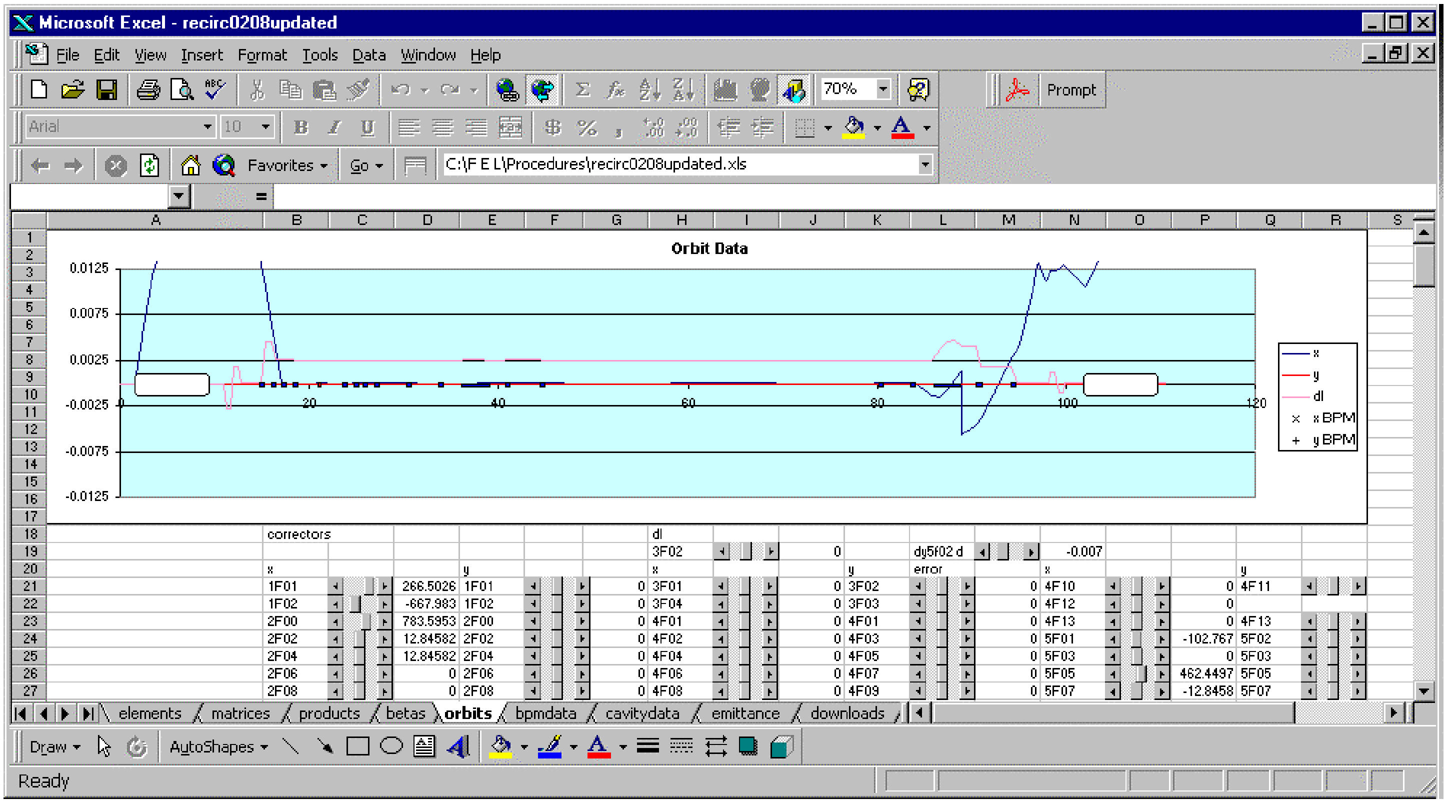

Figure 3b): 12/8/98 configuration with DY error.

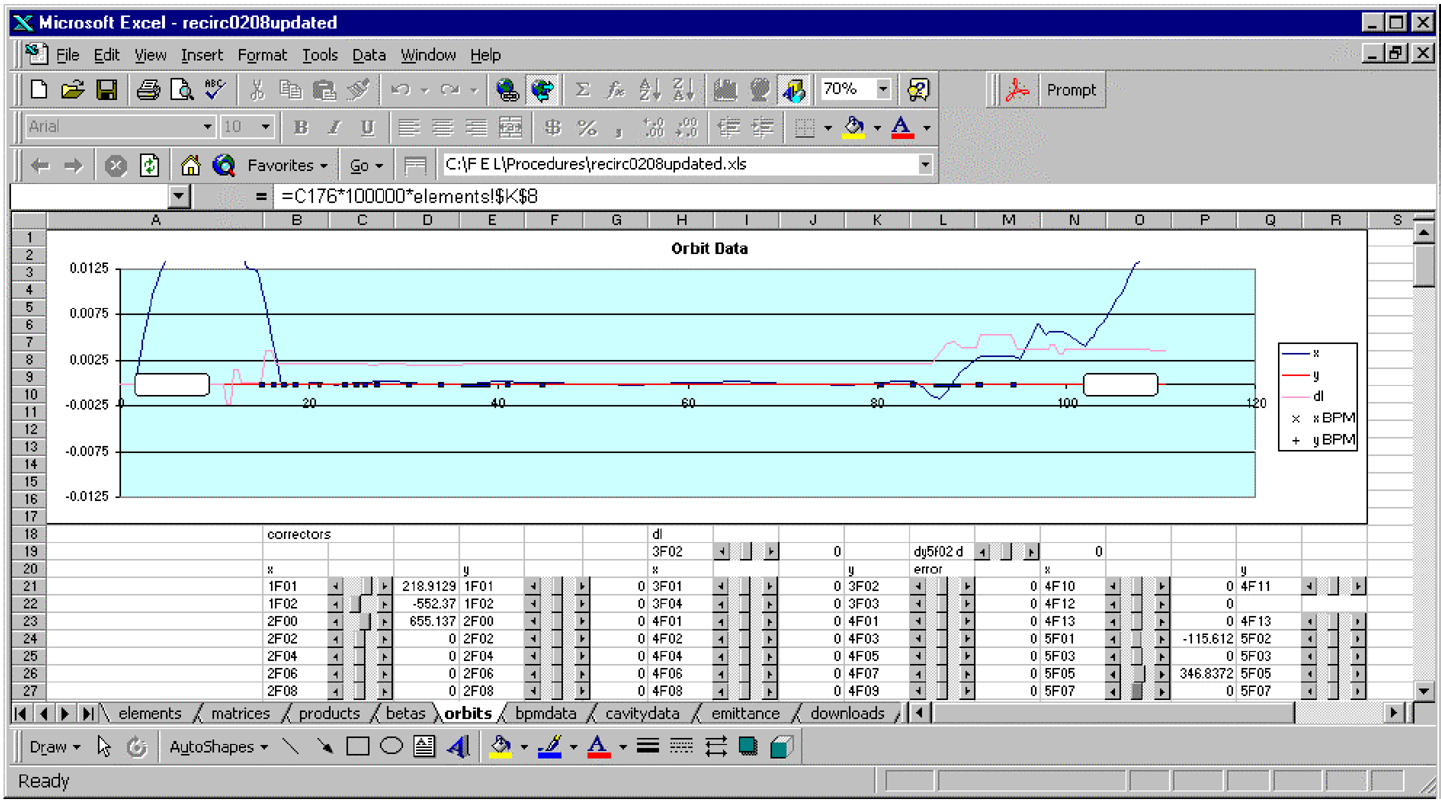

Figure 4a): High power configuration of 12/15/98, no DY error.

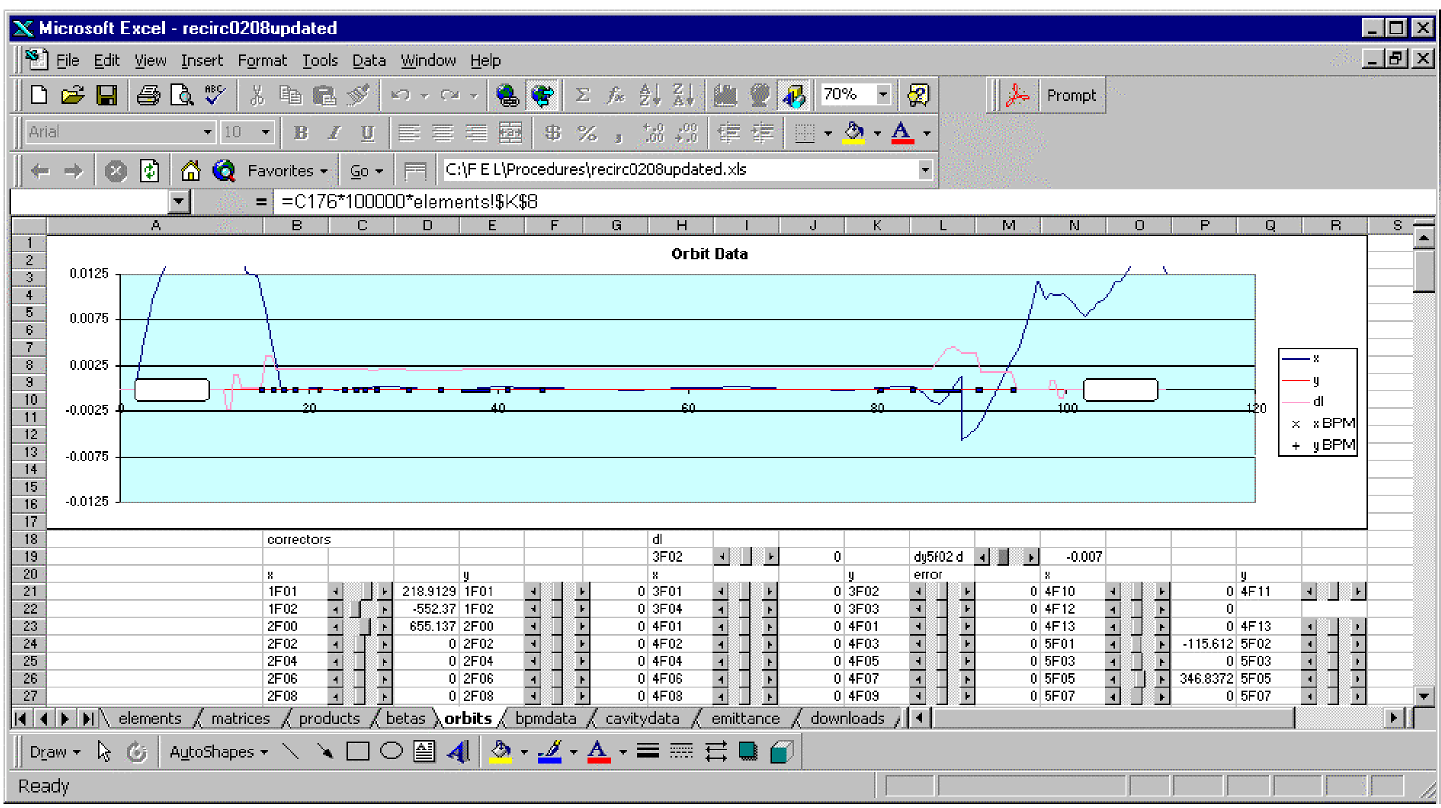

Figure 4b): 12/15/98 configuration with DY error.

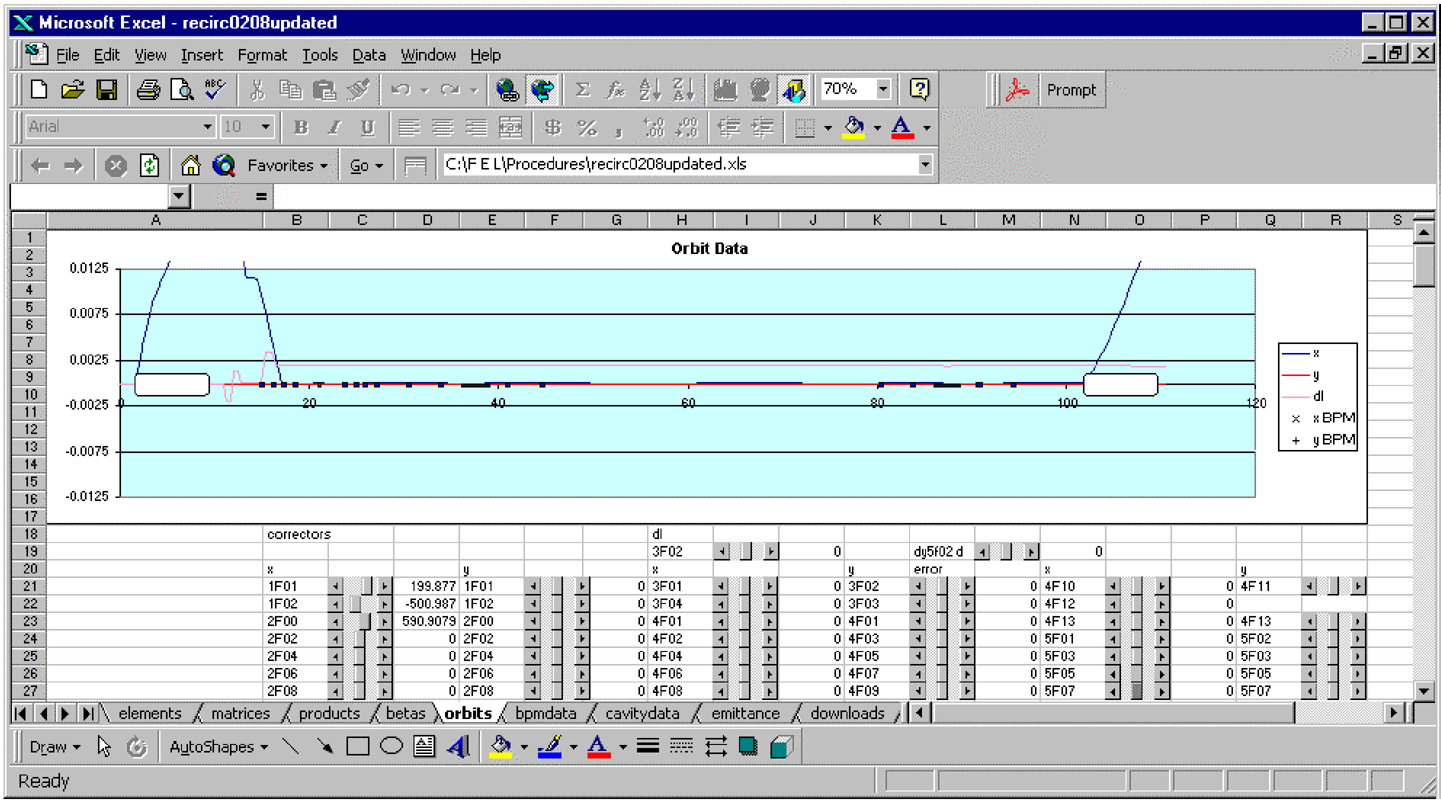

Figure 5a): Corrected DY and 5F region, no compensation for 1F00H field.

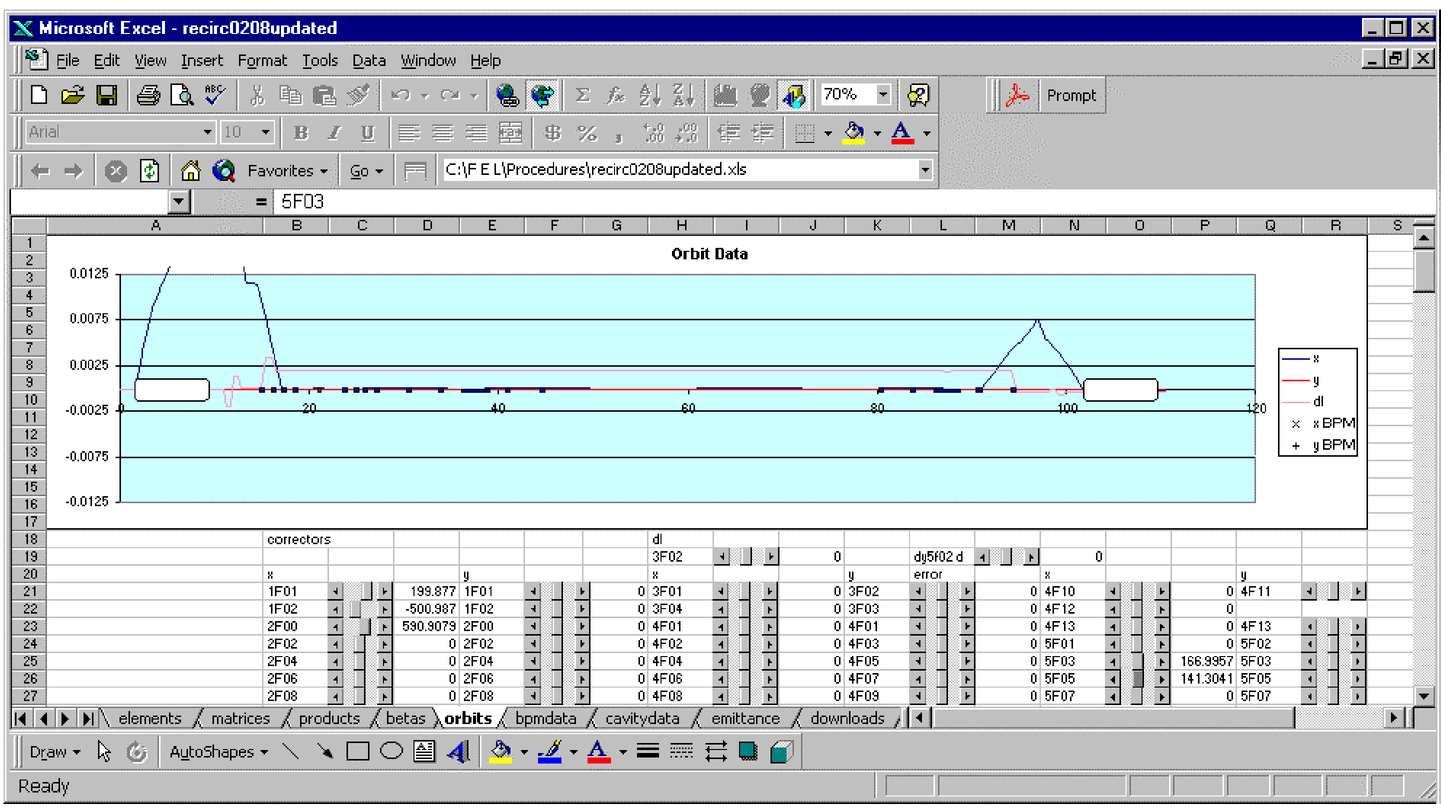

Figure 5b): Corrected DY and 5F region with compensation for 1F00H field.

- The conjectured $\beta_y \sim 1$m mismatch does not seem to lead to the observed scraping or activation, but a $\beta_y < ½$ m mismatch may do so.
- It is possible to reduce significantly the beam envelopes through the end loops, particularly at locations that may contribute to scraping.
- The modular nature of the lattice (in particular, the availability of the downstream telescope) allows an optimized rematch for a variety of conditions in the wiggler – not only $\beta_y \sim 1$ m but $\beta_y < ½$ m as well.

Calculated recirculator optics (based on operational quad settings and an assumed match at the wiggler back-propagated to the injection point) are shown in Figure 6. The wiggler matched values of $\beta_x \sim 33$ cm and $\beta_y \sim 50$ cm are called out in the screen shot. The regularity of the envelopes in the backleg region indicates correct matching to the recirculator.

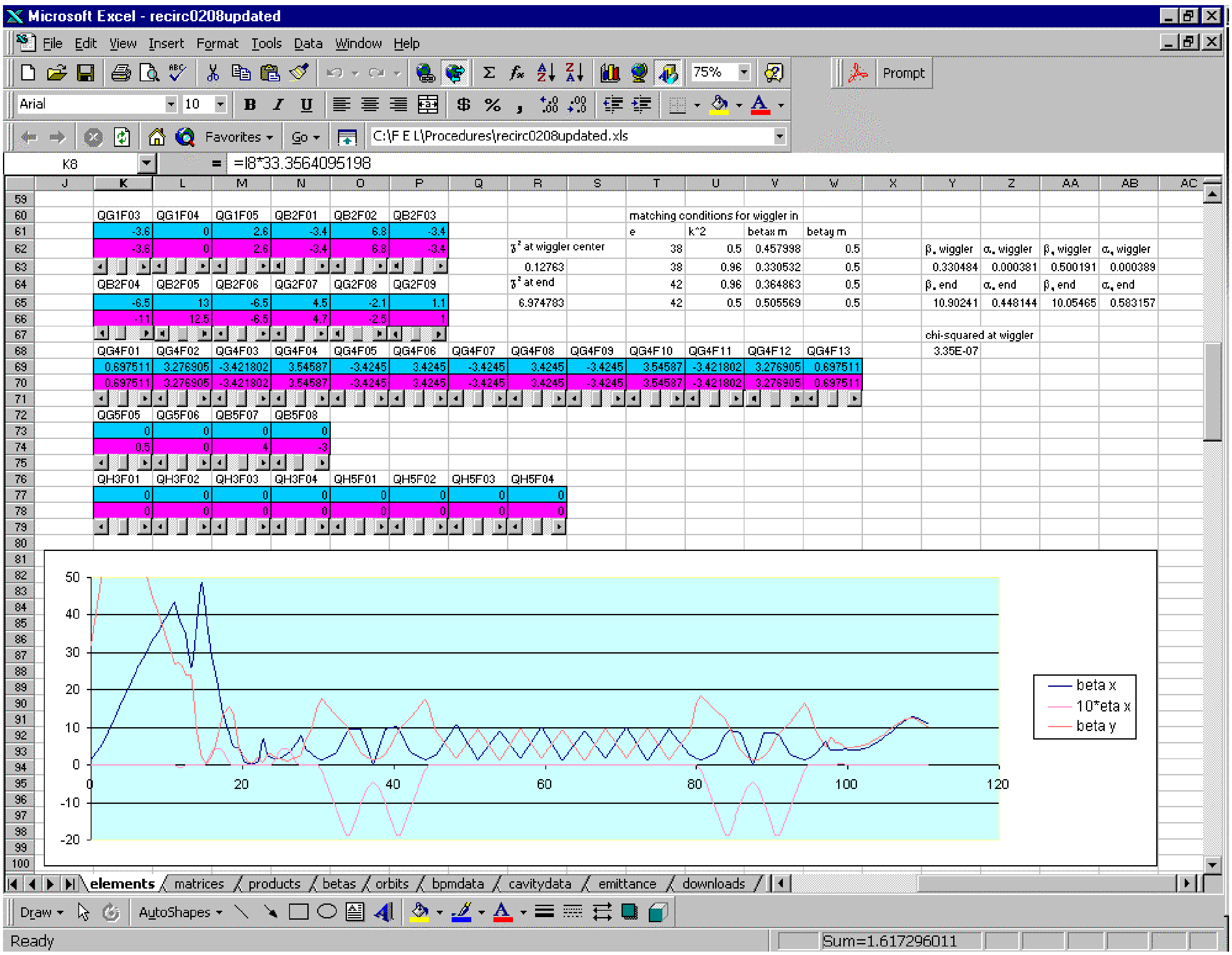

Figure 6: Calculated beam envelopes through recirculator.

Figure 7 shows the recirculator with the above “design” optics while transporting a vertically mismatched beam with $\beta_y \sim 1$ m at the wiggler. This situation does not seem to lead to conditions particularly conducive to the observed scraping at 4F01 and at reinjection. The peak vertical beam envelopes remain less than 20 m, and the maxima move from the end loops to regions of the back leg that were operationally clean. Figure 8 shows these optics while transporting a vertically mismatched beam with $\beta_y \sim 1/3$ m at the wiggler. This mismatch does appear to lead to conditions conducive to the observed scraping – particularly inasmuch as the peak vertical beam envelopes in the end loops increase to values well in excess of 20 m.

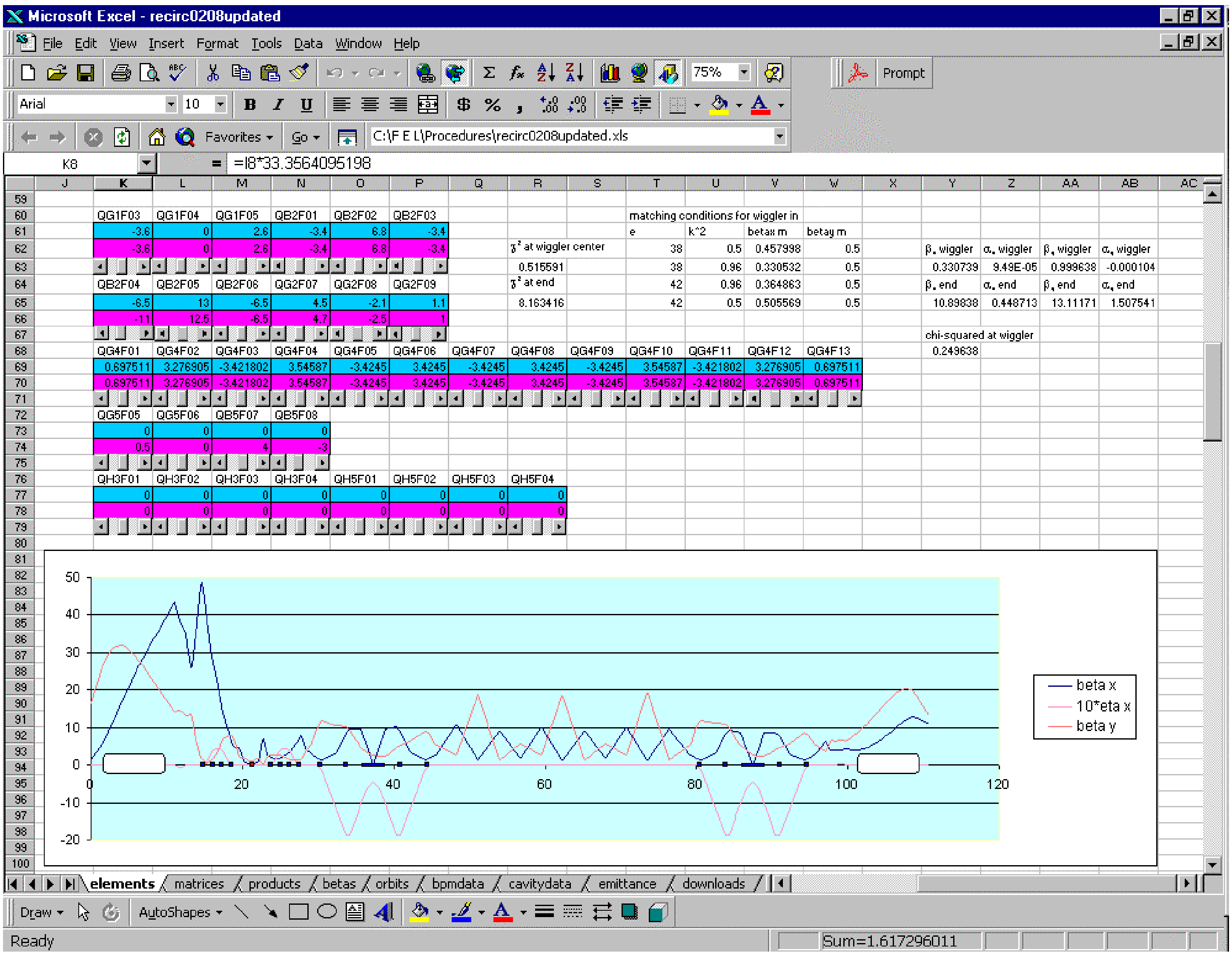

Figure 7: “Design” optics with vertical mismatch $\beta_y \sim 1$ m at wiggler.

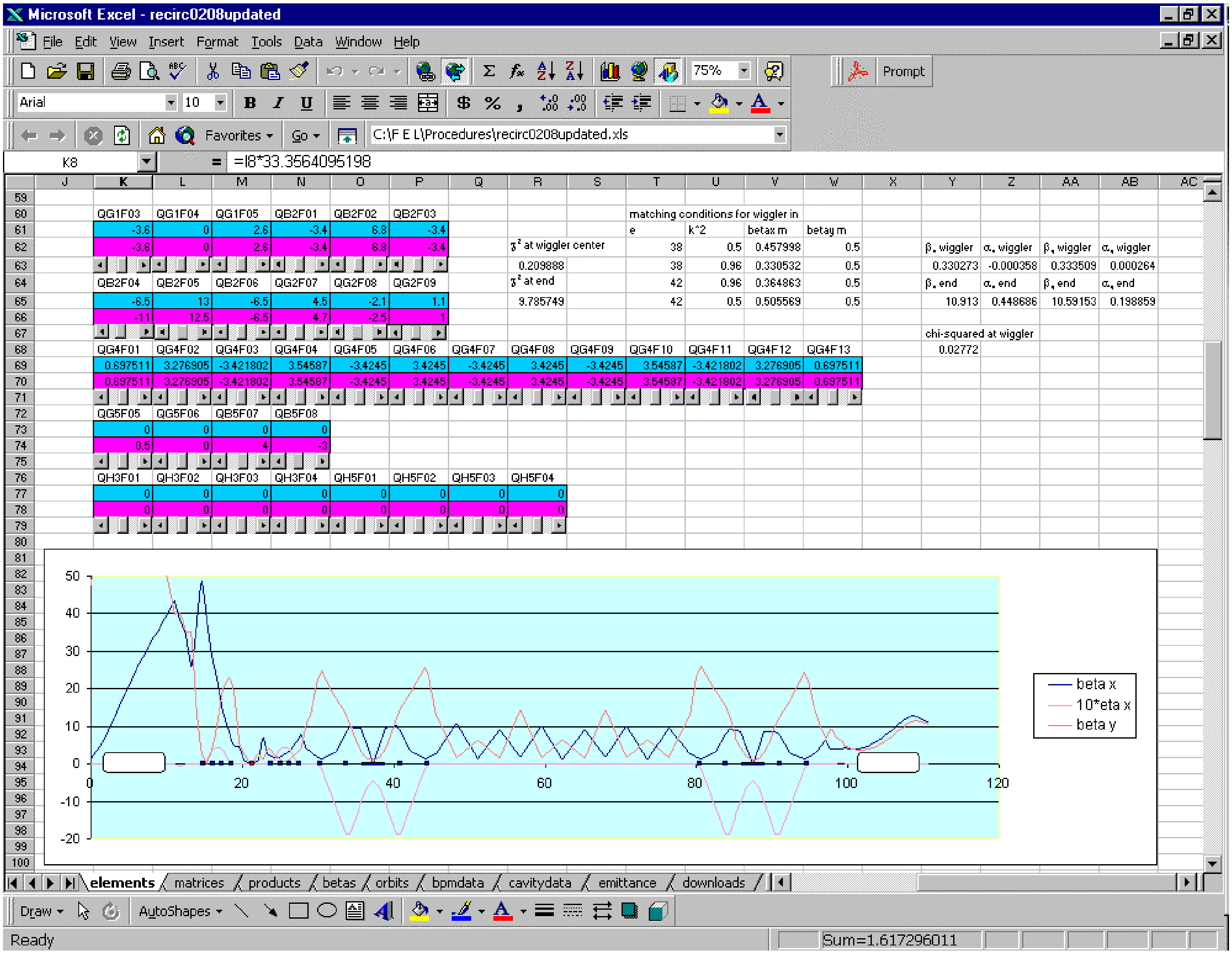

Figure 8: “Design” recirculator with vertical mismatch $\beta_y \sim 1/3$ m at wiggler

These potential sensitivities to vertical mismatch, together with the observed patterns of beam loss and activation, have motivated us to search for betatron solutions with smaller maximum beam envelopes. Such solutions should, at least in principle, be more tolerant of halo and less prone to induce scraping. The modular nature of the transport system design readily allows such investigations. The downstream and reinjection matching telescopes provide opportunity to adjust envelopes over a wide range of values; the backleg transport can be (and in the design is) used as a matching region to regularize the beam phase space between the end loops. We note that the vertical phase advance across the end loops is nominally ½ wavelength, so there is not a unique betatron solution for this region. Various values can thus be accepted, provided beam envelopes elsewhere are not degraded.

The optimization goal is simply to reduce the vertical beam size while maintaining (or reducing) the horizontal beam size. The optimization process used the Excel-based machine model to interactively adjust the lattice with the goal in mind. The specific steps were as follows.

1) The quads in latter half of the backleg (4F08 through 4F13) were used to reduce the envelopes in the second end loop (5F). This was done with a subsidiary constraint that the beam envelopes remain fairly regular in the backleg through the quads that had been varied.
2) The reinjection telescope was used to rematch into the module for energy recovery, maintaining small beam envelopes during the second pass.
3) The solution from Step 1) was reflectively imposed on the first half of the backleg (4F01 through 4F06).
4) The downstream telescope (2F04 through 2F09) and the central quad of the backleg (4F07) were used to match from the wiggler into/through the backleg by achieving a reflectively symmetric, fairly regular (*i.e.*, nicely periodic) solution in the backleg. The imposed symmetry ensured that the match achieved in Step 2) was maintained.

Results of rematching the design phase space ($\beta_x \sim 33$ cm, $\beta_y \sim 50$ cm and upright at the wiggler) are shown in Figure 9. Reduction of beam envelopes (particularly the vertical) in regions with observed scraping and activation is significant and occurs at the expense of minor increases elsewhere (primarily in the backleg). Figures 10 and 11 show the retuned lattice for non-design phase spaces at the wiggler. Figure 10 illustrates the case of a $\beta_y = 1$ m vertical mismatch, Figure 11 the case of a $\beta_y \sim 1/3$ m mismatch. Unlike the design optics, the system is relatively sensitive to large envelopes at the wiggler; it is insensitive to small envelopes at the wiggler. Provided difference orbit methods can be used to certify the lattice, implementation of these alternate matches could allow us to discern the nature of envelope mismatch at the wiggler.

It is our expectation that such optics can also be used to assist in halo management. We note that horizontal halo can be handled, at least in part, using the 3F scraper. There is presently no corresponding system for vertically displaced halo, so management of particles with large vertical amplitude must be performed by limitation of betatron offsets. We presently plan to implement such schemes during FEL beam operations this spring.

Recovery Procedure and Test Plan

The steering and focussing issues discussed in this note have been addressed in a test plan presently being applied to the accelerator [10]. It is available at http://www.jlab.org/~douglas/FEL/procedures/recoveryoptimizerev0_2.pdf.

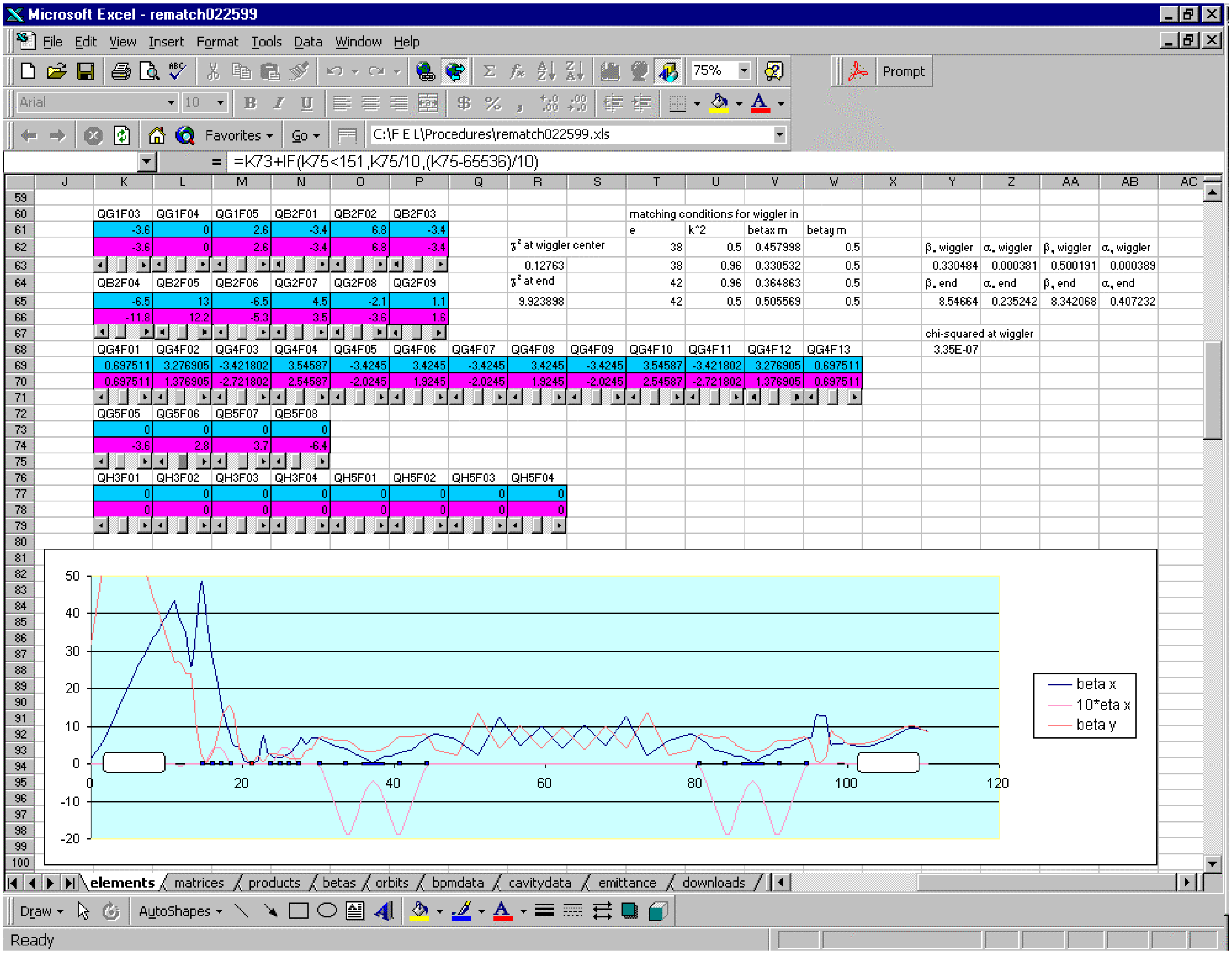

Figure 9: Design phase space at wiggler rematched to recirculator to reduce envelopes in end loops.

Conclusions

During Fall/Winter 1998 FEL driver operations, the beam was badly steered because of mis-excitation of the DY and hard steering of the injected beam. It is possible the beam envelopes are bigger than necessary in the end loops (3F and 5F regions). Reduction through rematching may result in better transmission. A procedure to address some of the ills discussed in this study has been developed [11].

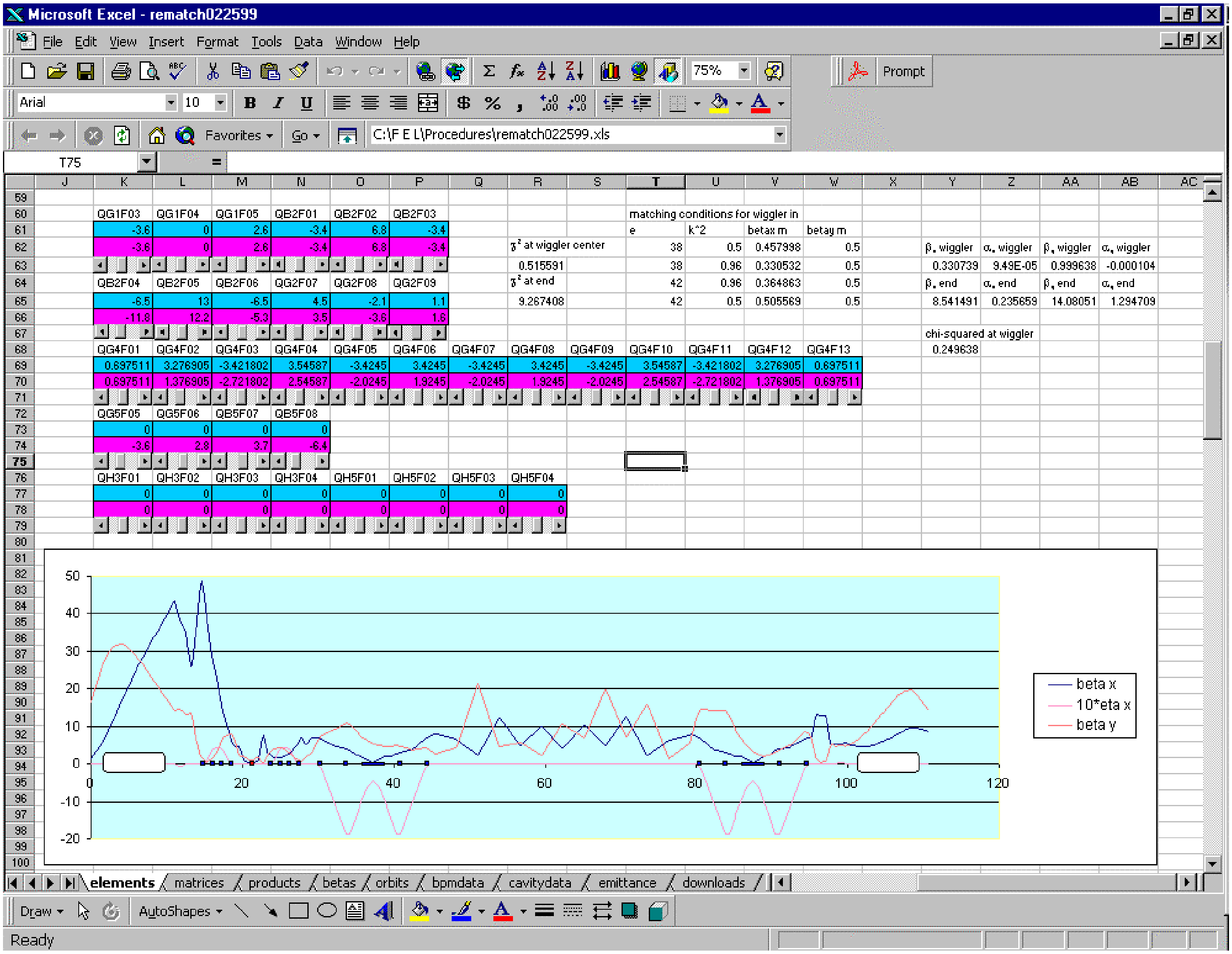

Figure 10: Rematched beam envelopes with erroneous β_y = 1 m at the wiggler.

Acknowledgments

We would like to thank Steve Benson, Court Bohn, Geoff Krafft, George Neil, Phillipe Piot, and Richard Walker for useful discussions about FEL driver behavior.

References

[1] Both Steve Benson and Phillipe Piot made several remarks about halo; Phillipe logged several observations about the same. See, for example, FLOG Entry # 3567, 11 December 1998.

[2] See FLOG entries on December 14 and 15 1998, especially Entry #3615 and 3622.

[3] G. Neil, radiation surveys following high power runs in December 1998.

[4] S. Benson, private communication.

[5] *ibid*., and see log entries through March and April 1998, particularly FLOG Entry #841.

[6] See FLOG on 20 November 1998, particularly FLOG Entry #3258.

[7] See reference [2]; in this resteer the recirculator dipole buss was dropped to center the beam in the aperture while lasing. This had no discernable impact on the maximum achievable current, despite the fact it moved the beam by as much as 1 cm. Other attempts to “steer away from scraping” by moving the beam several mm (using steering of order 100 g-cm or more) also had no discernable impact on the current limitation.

[8] D. Douglas, “High Power Setup Procedure, Revision 2.2”, 15 January 1999; available on the World Wide Web at http://www.jlab.org/~douglas/FEL/procedures/onekwsetuprev2_2.pdf .

[9] S. Benson, FEL All-Save #191 (under user “neil”) at 22:56:07 on 4 December 1998; see also S. Benson and T. Siggins, FLOG entries #3446 and 3447, 4 December 1998.

[10] D. Douglas, “FEL Driver Recovery Procedure/Optimization Test Plan, Revision 0.2”, 1 February 1999, available on the World Wide Web at http://www.jlab.org/~douglas/FEL/procedures/recoveryoptimizerev0_2.pdf .

[11] *ibid*.

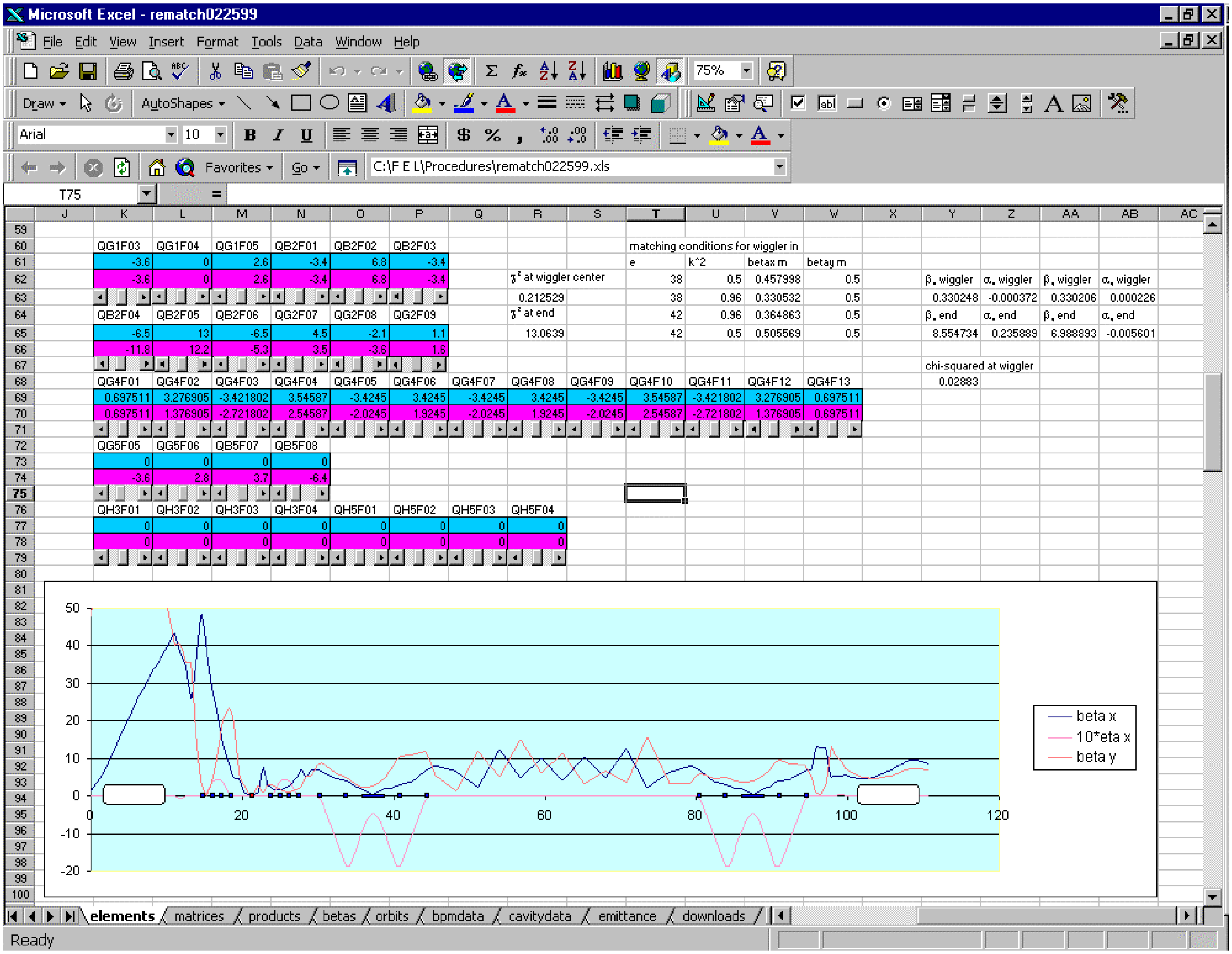

Figure 11: Rematched beam envelopes with erroneous β_y = 33 cm at the wiggler.