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A Phase Trombone Based on the IR Upgrade Driver Backleg FODO Transport

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Abstract

We describe a phase trombone to be used for BBU control in the IR Upgrade.

Background

As described in a previous note [1], BBU control has become an important issue for IR Upgrade operation. Guidance has been given by Todd Smith; one suggested suppression method requires control of the betatron phase advance from an unstable cavity back to itself so that a point-source BBU deflection is imaged back to the deflection point [2]. This is most easily implement operationally if the phase advance in question – either horizontal or vertical, can be varied independently of one another and all other betatron parameters.

This notion of a "phase trombone" has implemented and tested in CEBAF [3] and may be readily implemented in the IR Upgrade Driver Backleg (3F) region.

Phase Trombone

We note that a set of focusing perturbations of strength P_k applied at locations k of phase advance ψ_k and beam envelope β_k, and α_k produces at a downstream observation point point "o" deviations in these parameters given by the following relations [4].

$$\frac{\Delta\beta_n}{\beta_o^n} = \mp\sum_{k=1}^{N} P_k\beta_k^n \sin 2(\psi_o^n - \psi_k^n)$$

$$\Delta\alpha_n = \pm\sum_{k=1}^{N} P_k\beta_k^n \left(\cos 2(\psi_o^n - \psi_k^n) - \alpha_o^n \sin 2(\psi_o^n - \psi_k^n)\right)$$

$$\Delta\psi_n = \pm\frac{1}{2\pi}\sum_{k=1}^{N} P_k\beta_k^n \sin^2(\psi_o^n - \psi_k^n), \qquad n = x \text{ or } y$$

Here, the upper sign applies to "x" plane parameters and the lower to "y" plane, so that a single positive focusing perturbation will for example tend, at a point immediately downsteam, to increase the horizontal phase advance and decrease the vertical, while tending to decrease the horizontal beam envelope and increase the vertical.

A "phase trombone" is a beamline module in which such focusing perturbations are applied in such a manner that the betatron phases can be varied independently of the beam envelopes. For a system of arbitrary design, the relationships are linear but may not be orthogonal; the various focusing knobs may have to be varied in a nontransparent fashion to ensure the appropriate response is obtained. This is, however, not universally true. Certain beamline layouts lead to relatively simple decomposition of the above relations and provide obvious orthogonal control parametric dependences.

Such is the case for a periodic FODO channel with 90^o phase advance per cell. In this case, if the perturbations are uniformaly applied over an integral number of betatron wavelengths, the sums for the beam envelop shifts collapse to zero and only the phase advance shifts survive. Moreover, because the envelopes tend to be large only in the focusing plane of the quadrupoles, the horizontal and vertical shifts are rather well decoupled; changing tuning knobs at horizontal quads produces a significant shift in horizontal phase advance, but only a modest shift in vertical, with the reverse true if focusing trims are applied at the vertically focusing quads.

Application to the IR Upgrade 3F Region

We now observe that the 3F (backleg) region of the IR Upgrade Driver is basically a (perturbed) six-period quarter-integer FODO transport. By applying systematic shifts to quads in the first four cells, we can, according to the above discussion, vary the horizontal and vertical phase advances without influencing the beam envelopes (at least insofar as the perturbations remain linear). Noting that the array starts with a vertically focusing quad, one would shift the gradients of the first, third, fifth and seventh quads by a uniform amount to vary the vertical phase. Similarly, a uniform shift in the gradients of the second, fourth, sixth and eighth quads would vary the horizontal phase. A more refined algorithm would, for either case, also apply a weaker compensatory shift in the other family, so as to suppress the (small) phase advance offset also generated in the non-targeted plane, thereby providing a completely orthogonal pair of knobs for the adjustment of phase advances.

A simulation of this has been constructed using the Upgrade beam transport system spreadsheet model. In this simulation, a pair of simulated BBU kicks – one horizontal and one vertical – are applied variously at the front end, center, and back end of Zone 3, and the phase advances of each transverse plane adjusted using the phase trombone to provide point-to-point imaging of the kick in each plane. Beam envelopes are evaluated in each case and compared to the "baseline" tuning, which is shown in Figure 1. Figures 2 through 10 show a) unimaged "BBU orbits" for the configuration under consideration, b) compensated BBU orbits with point-to-point imaging, and c) beam envelopes when orbits are compensated. The model includes x/y coupling in the linac during energy recovery, but does not properly compute beam envelopes through the linac on the second pass with this coupling. It suggests however that use of the phase trombone in this manner does not seriously degrade the betatron match in, and therefore following, the recirculator. Typically, gradient integral shifts of order 300 g are required to achieve the desired tuning.

In some cases (Figures 7 and 9), coupling effects interfered with use of the phase trombone and required a systemic rematch so as to alter the phase advance between trombone and linac second pass. This is an operationally tractable, though somewhat onerous, task. This simulation suggests that should the nodes not move as expected on the machine, the operator should rematch the transport to vary the trombone to linac phase (thereby altering the orbit x/y coupling), and then reoptimize the orbits using the trombone.

References

[1] D. Douglas, "A Skew-Quad Eigenmode Exchange Module (SQEEM) for the FEL Upgrade Driver Backleg Transport", JLAB-TN-04-016, 12 May, 2004.

[2] Rand, R.E. and T.I. Smith, "Beam Optical Control of Beam Breakup In A Recirculating Electron Accelerator", *Particle Accelerators*, Vol. 11, pp.1-13, 1980.

[3] A. Bogacz, private communication.

[4] D. Douglas, "Chromatic Correction in the CEBAF Beam Transport System", Proc. 1991 IEEE Part. Accel. Conf., CEBAF-PR-91-009, May, 1991.

Figure 1: "Nominal" beam optical match for simulated Upgrade recirculator. Phase trombone trims set to zero.

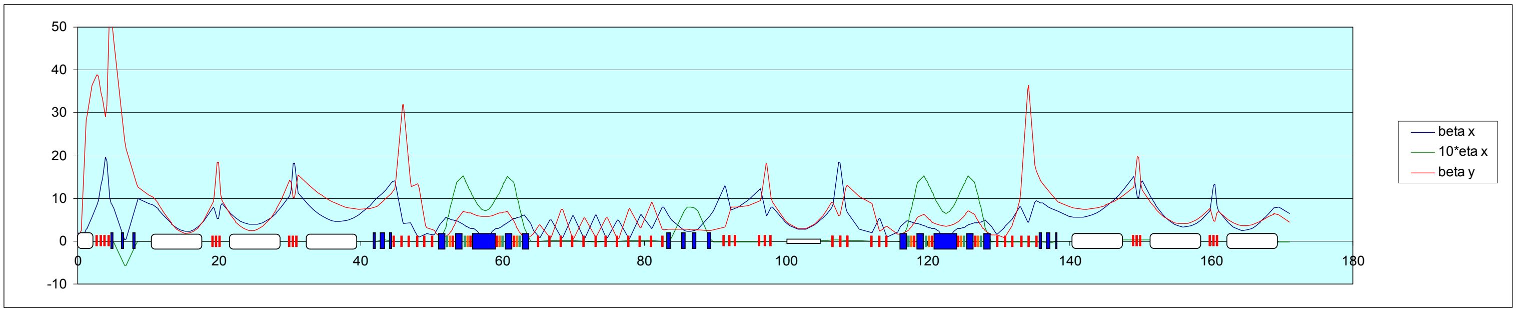


Figure 2: BBU kicks: H @ start of zone 3, V @ start of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at 280 g, V trim at -170 g; c) envelopes with point to point imaging.

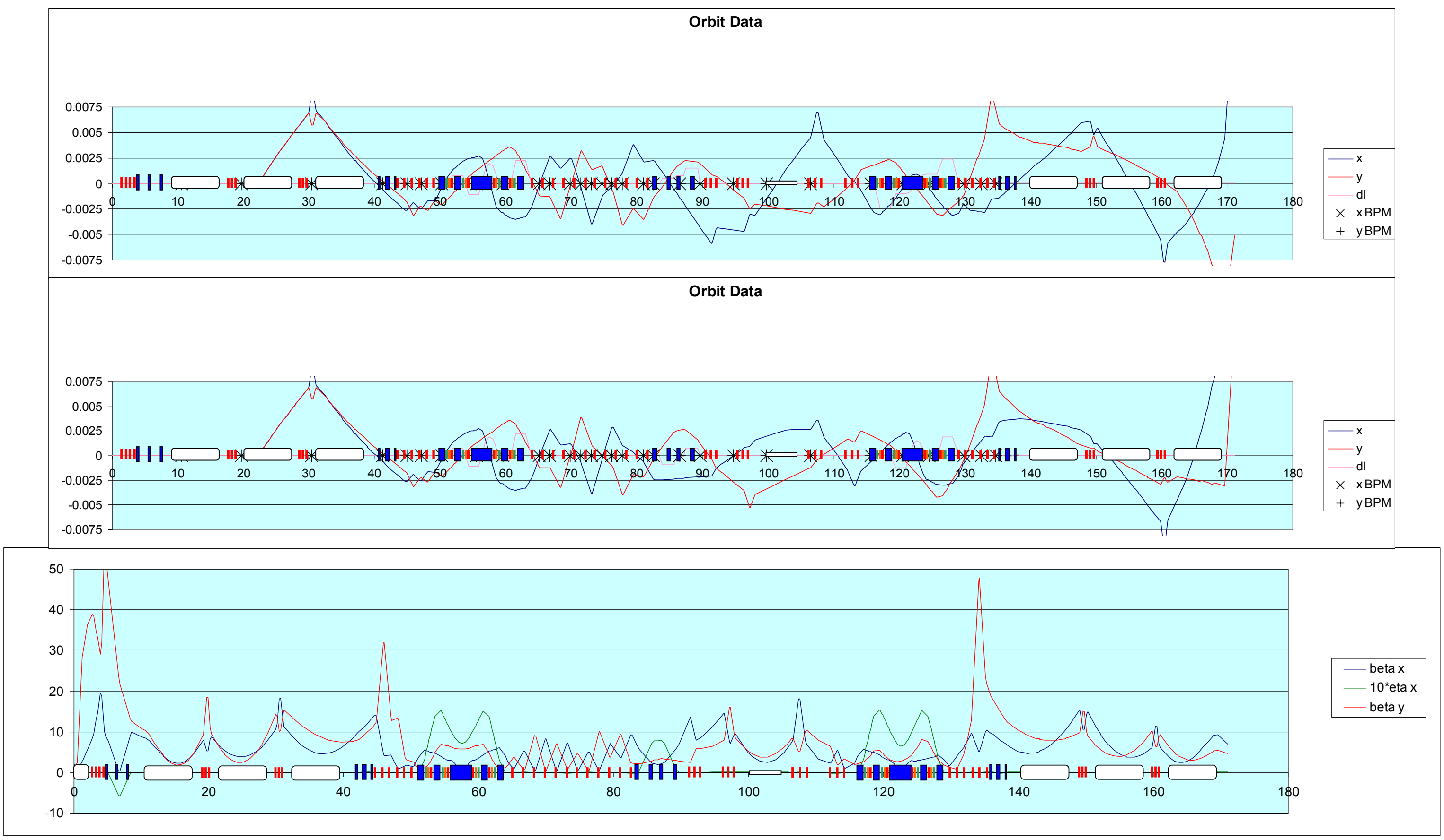


Figure 3: BBU kicks: H @ start of zone 3, V @ middle of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at 290 g, V trim at -300 g; c) envelopes with point to point imaging.

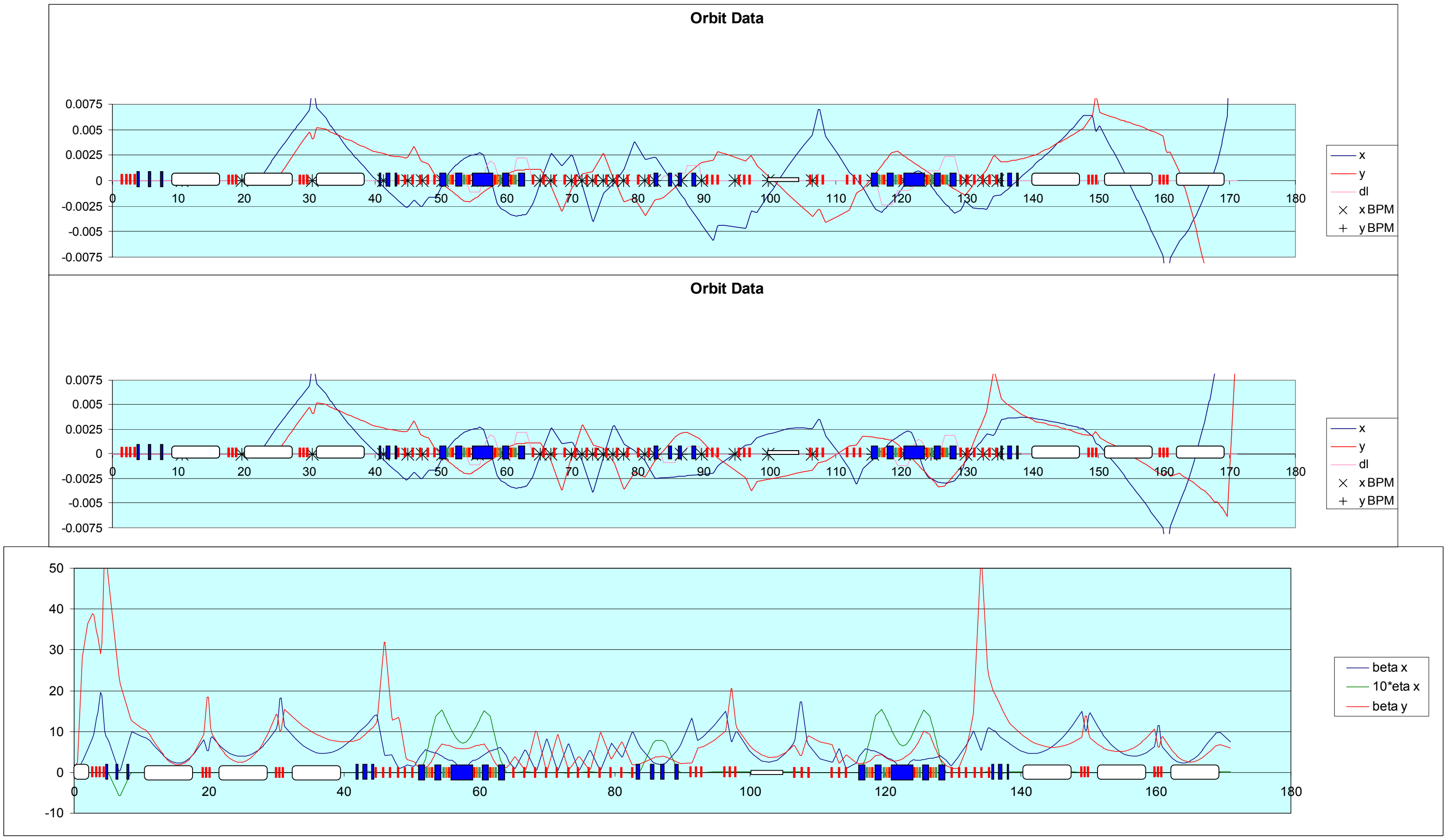


Figure 4: BBU kicks: H @ start of zone 3, V @ end of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at 160 g, V trim at -300 g; c) envelopes with point to point imaging.

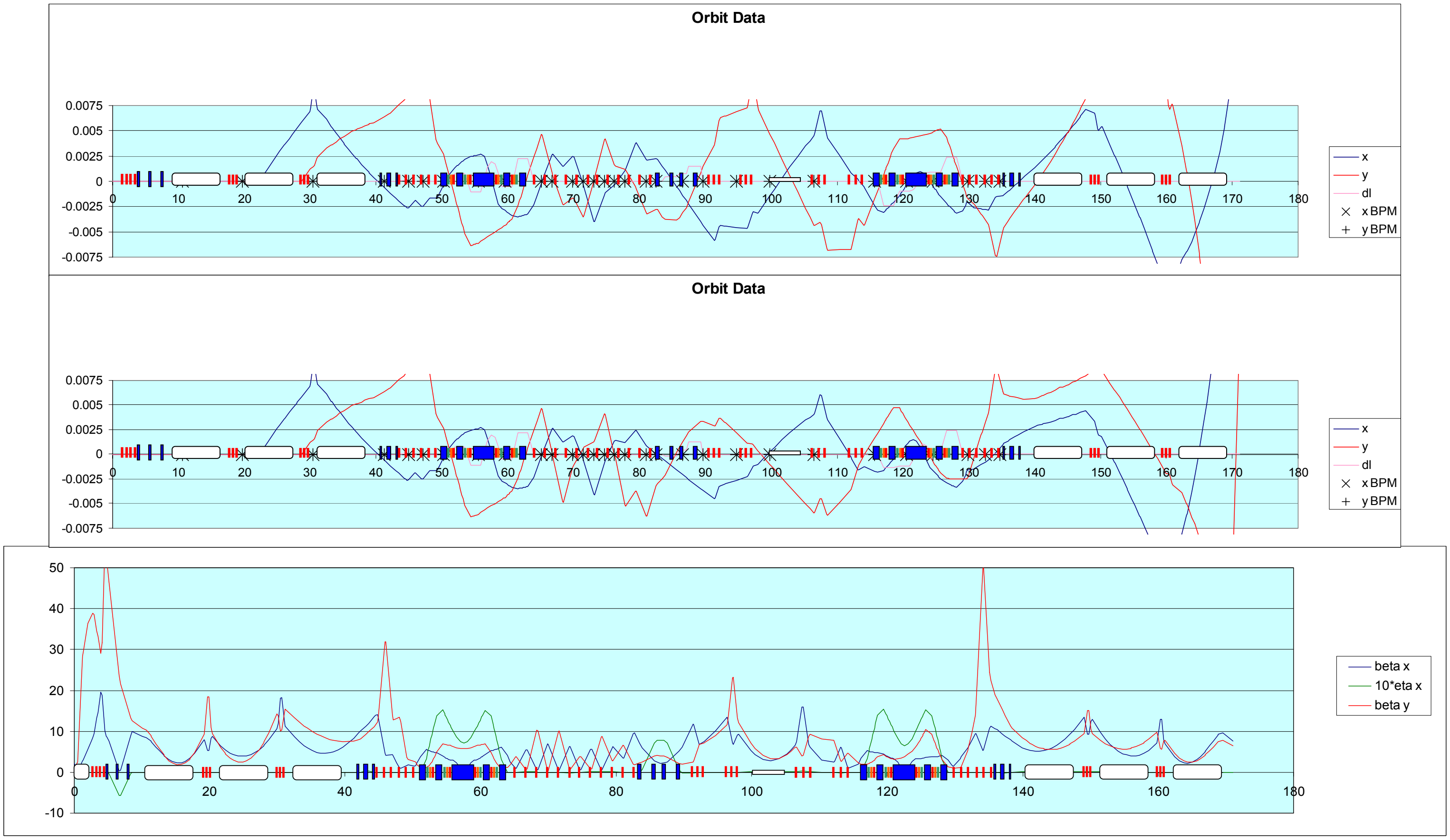


Figure 5: BBU kicks: H @ middle of zone 3, V @ start of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at 320 g-cm, V trim at -200 g-cm; c) envelopes with point to point imaging.

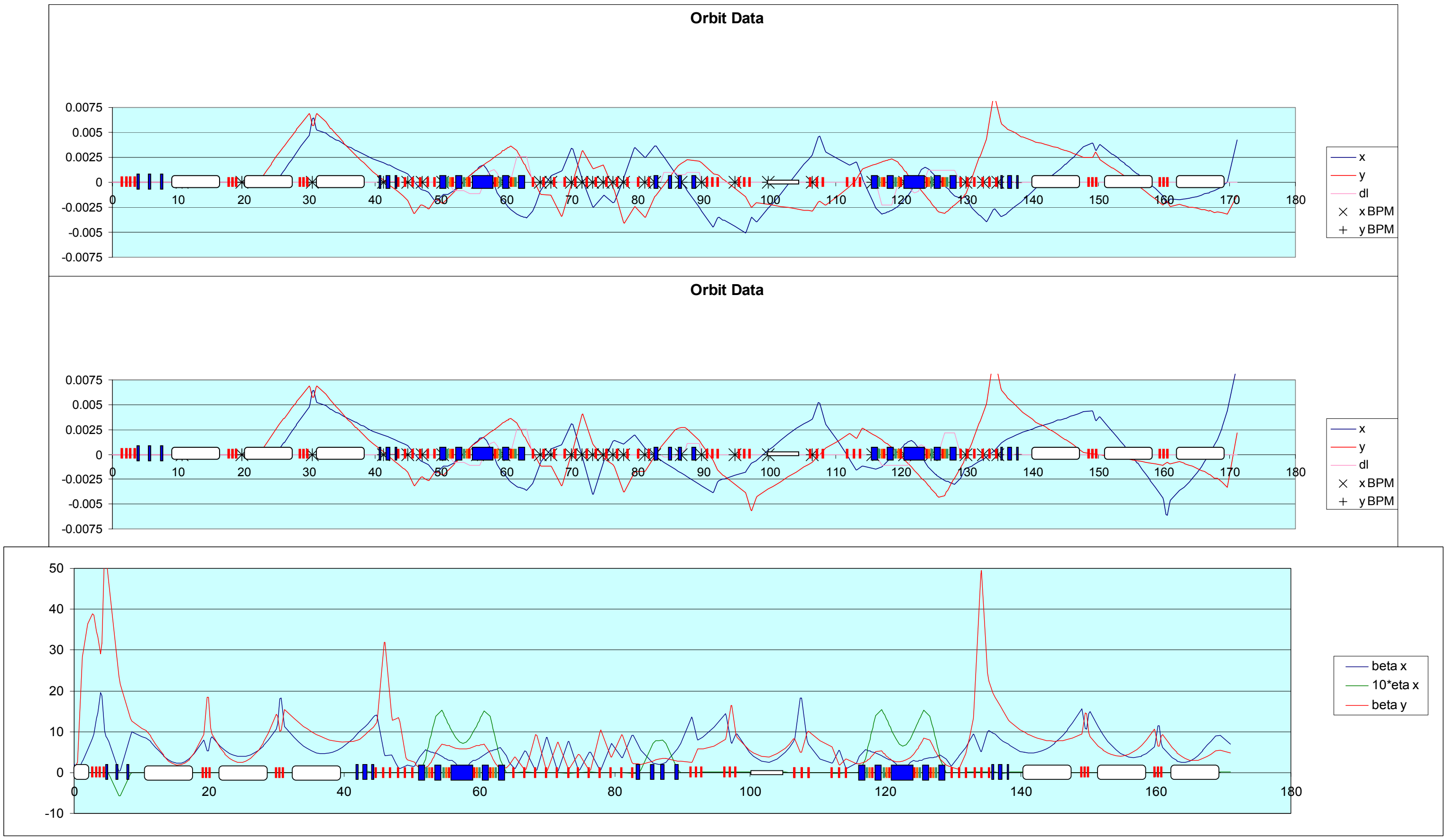


Figure 6: BBU kicks: H @ middle of zone 3, V @ middle of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at 340 g-cm, V trim at -370 g-cm; c) envelopes with point to point imaging. Notice (entertainingly) that the 2nd pass skew quad mode in the linac suppresses the vertical orbit in Zone 3.

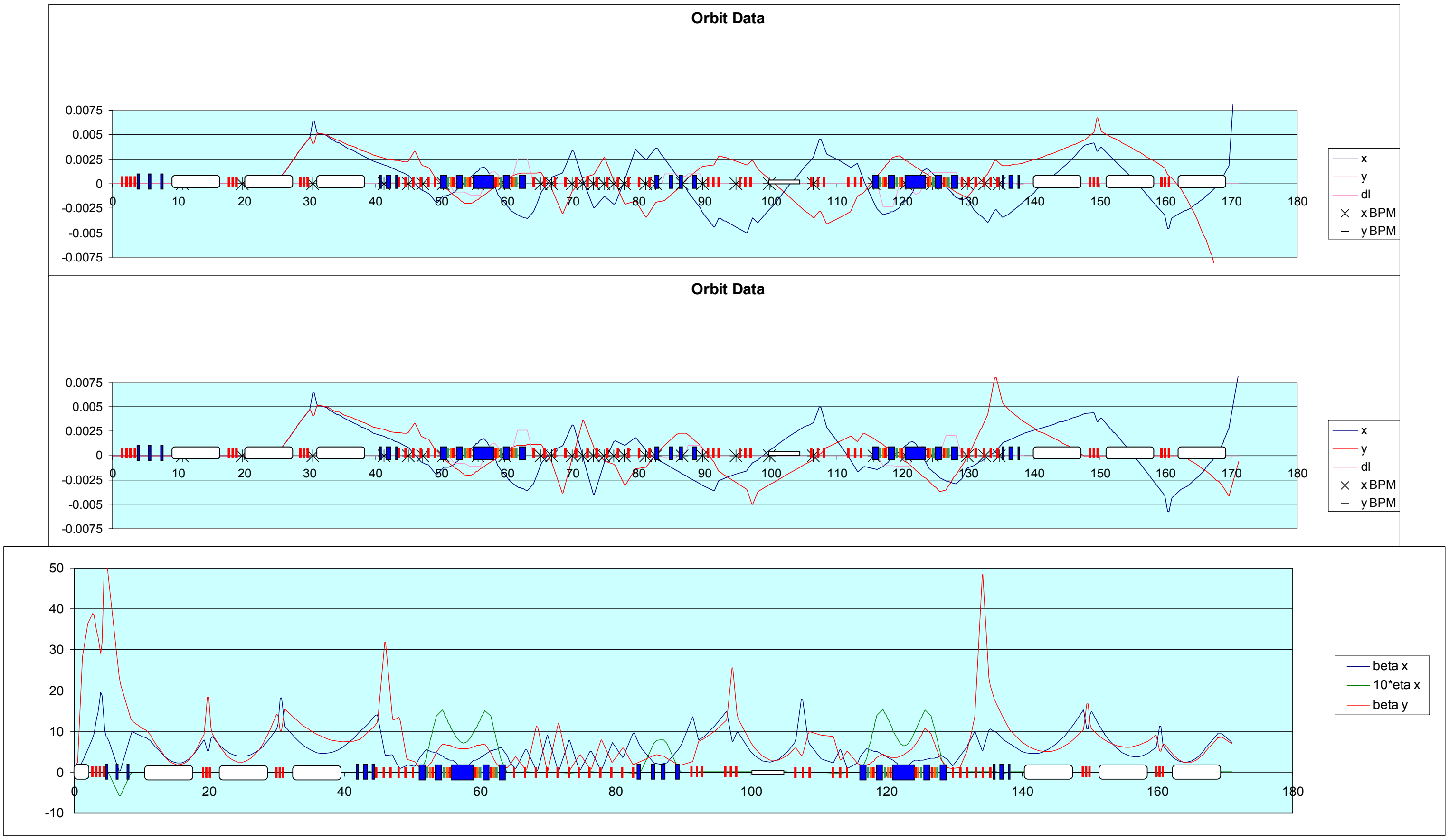
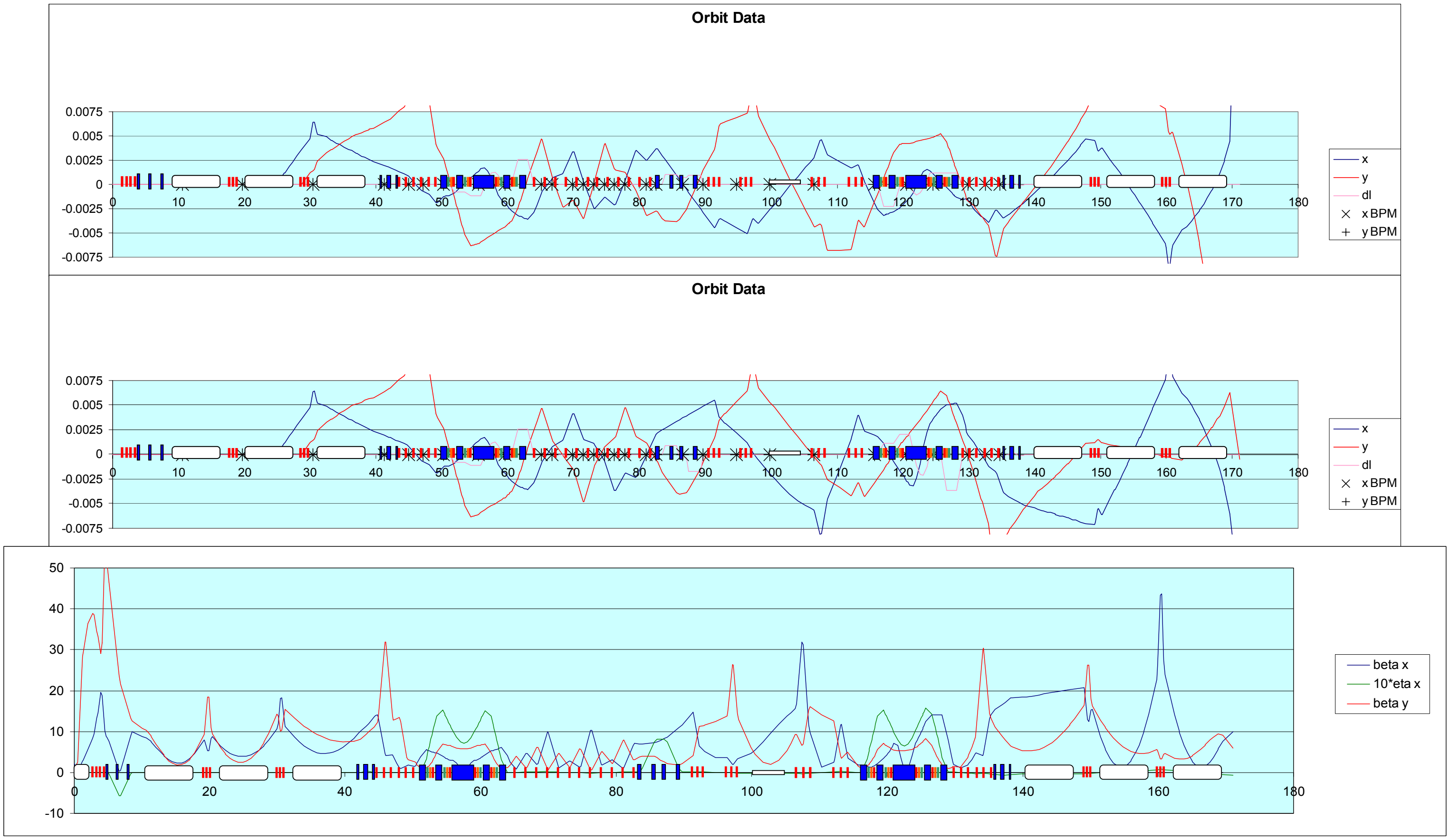
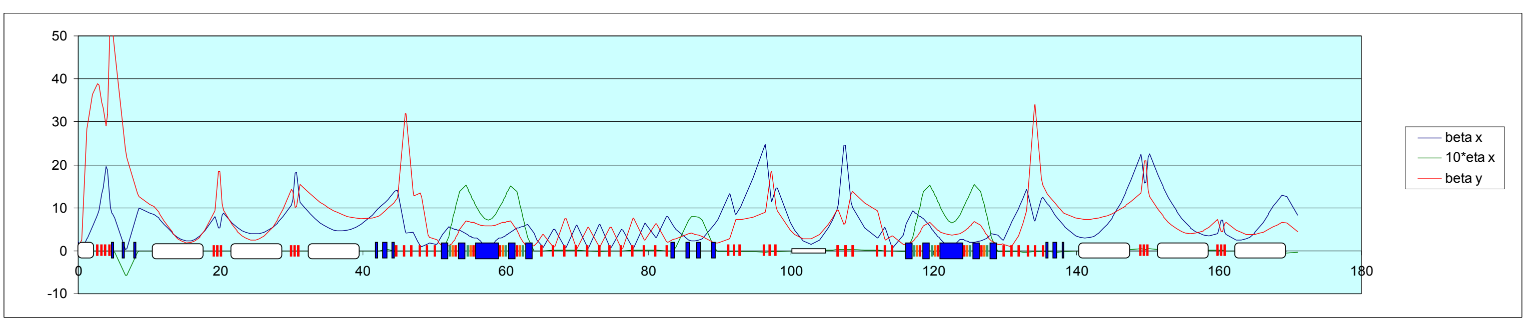
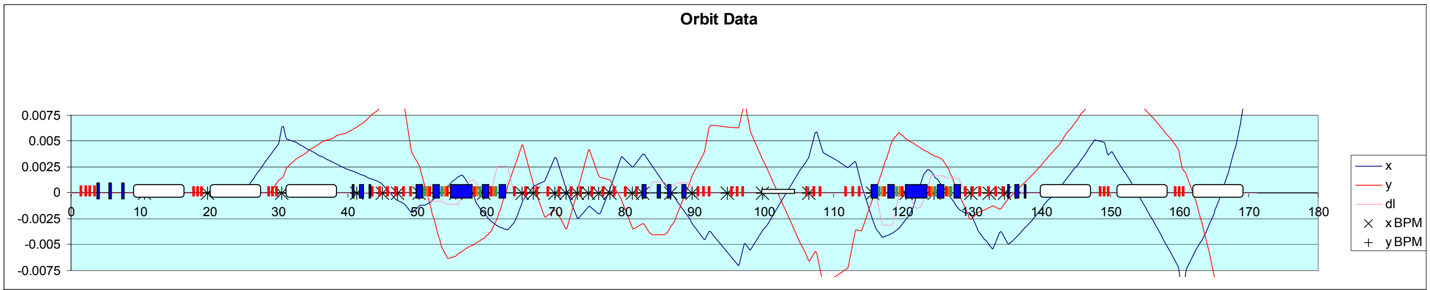


Figure 7: BBU kicks: H @ middle of zone 3, V @ end of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at -600 g, V trim at 350 g; c) envelopes with point to point imaging. We remark that this focusing solution differed in polarity from all others and the position response of the nodes was not coupled in the same way.



This inflexibility seems to be due to 2nd pass H/V coupling (at least, the problem goes away if you turn off the coupling), and note that the betatron match is so severely degraded that a rematch of the system would likely be required. Given this need, we have altered the downstream match and recomputed the corrections. d) rematched untrimmed envelopes e) rematched untrimmed orbit f) orbits with H trim at -10 g, V trim at -180 g, g) trimmed envelopes.

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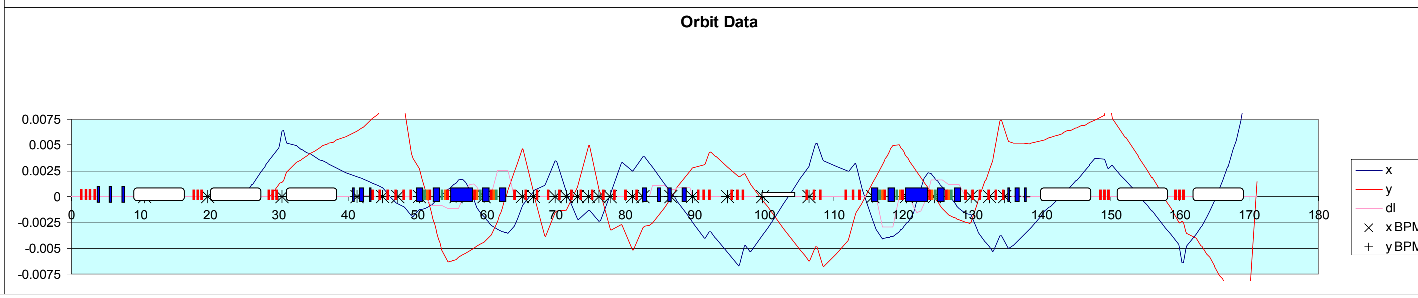
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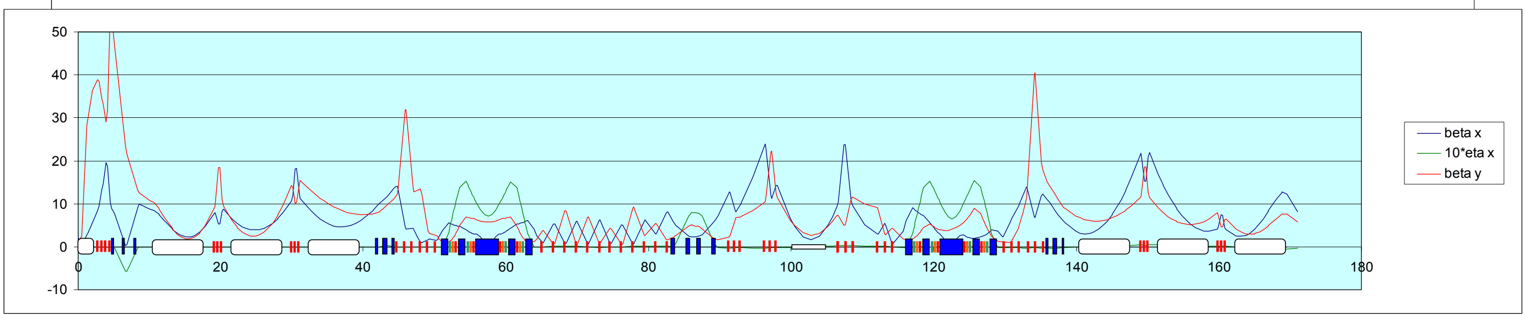
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-10
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beta x
10*eta x
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Figure 8: BBU kicks: H @ end of zone 3, V @ start of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at 350 g, V trim at -240 g; c) envelopes with point to point imaging.

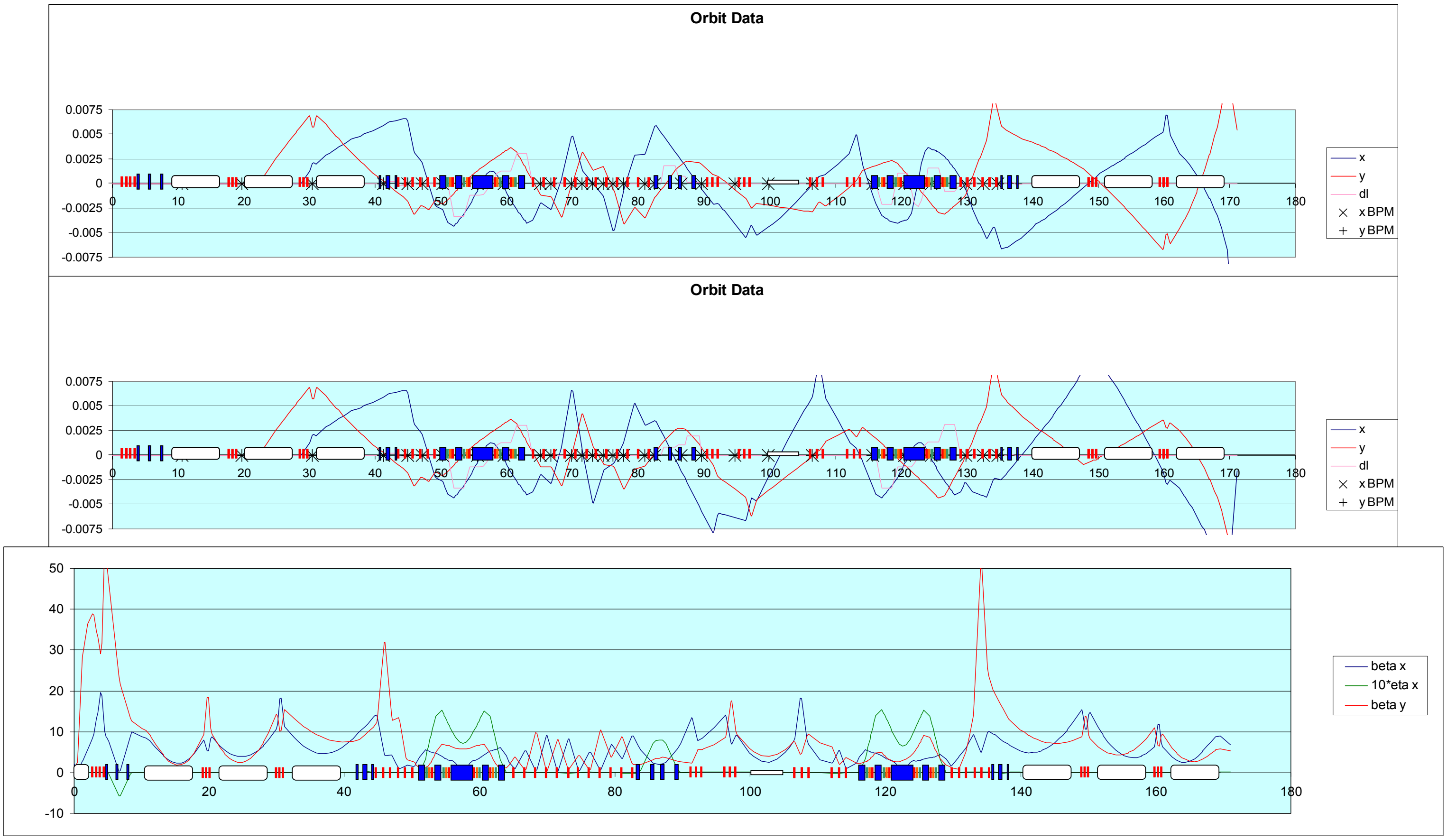

Figure 9: BBU kicks: H @ end of zone 3, V @ middle of zone 3.a) uncompensated kicks. As in Figure 7, coupling interfered with the compensation, and a rematch was done. b) shows the rematched uncompensated orbits, c) the envelopes before compensation.
d) compensated kicks, H trim at *** g, V trim at *** g; e) rematched compensated envelopes with point to point imaging.

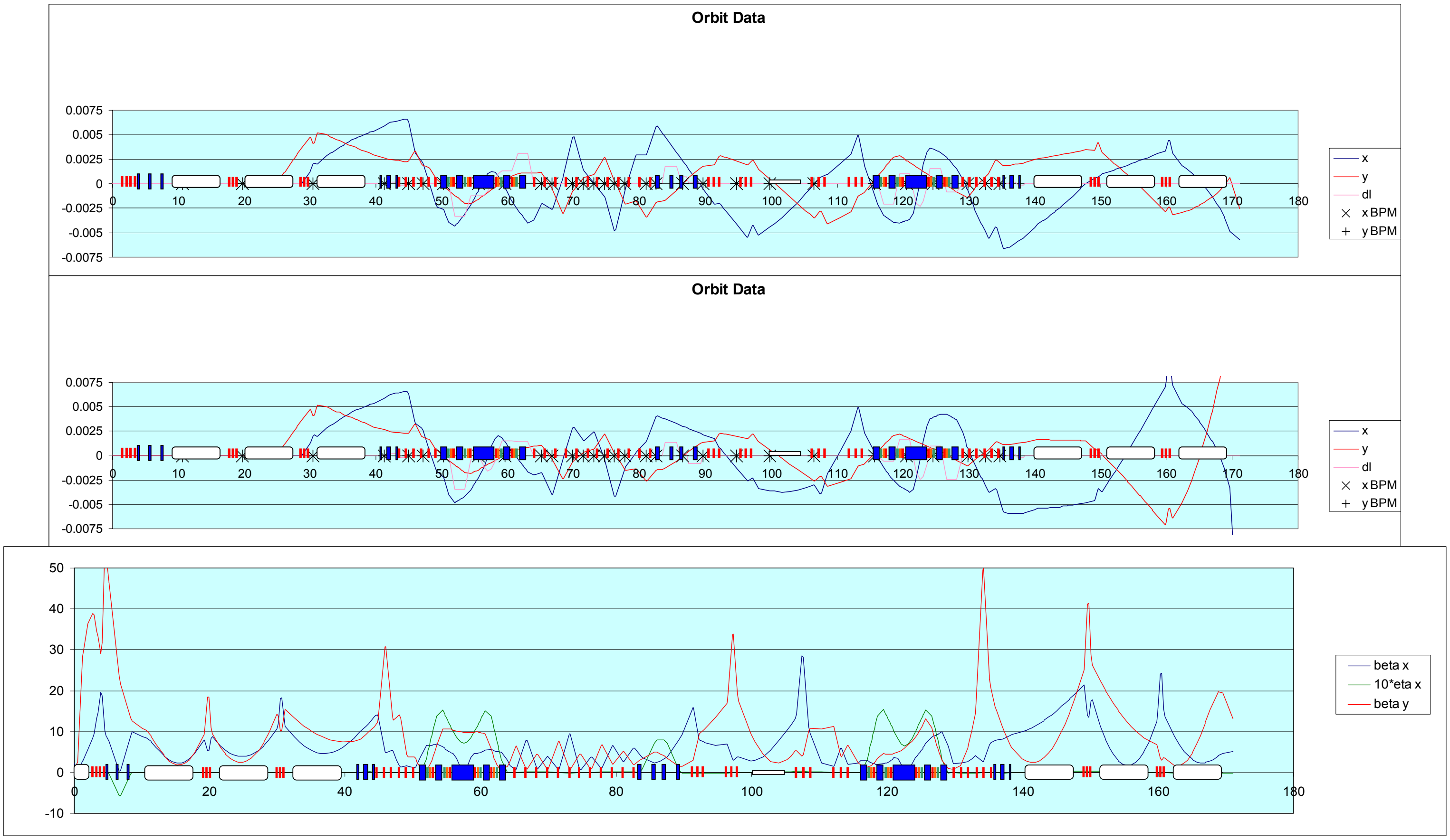

Figure 10: BBU kicks: H @ end of zone 3, V @ end of zone 3. a) uncompensated kicks, b) compensated kicks, H trim at -100 g, V trim at -30 g; c) envelopes with point to point imaging.