Experimental verification of the effectiveness of linear collider system identification and beam-based alignment algorithms

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Motivation

- The performance of future linear colliders will critically depend on beam-based alignment (BBA) and feedback (FB) systems

- BBA is a tool for mitigating static imperfections and allow the transport of low emittance beams

- Advanced FB systems are vital to preserve beam quality in time, against vibrations and slow drifts - they are based on BBA algorithms

- DFS techniques have never actually been tested on a real linear machine

Simulation of BBA at FACET: Orbit and Dispersion Correction

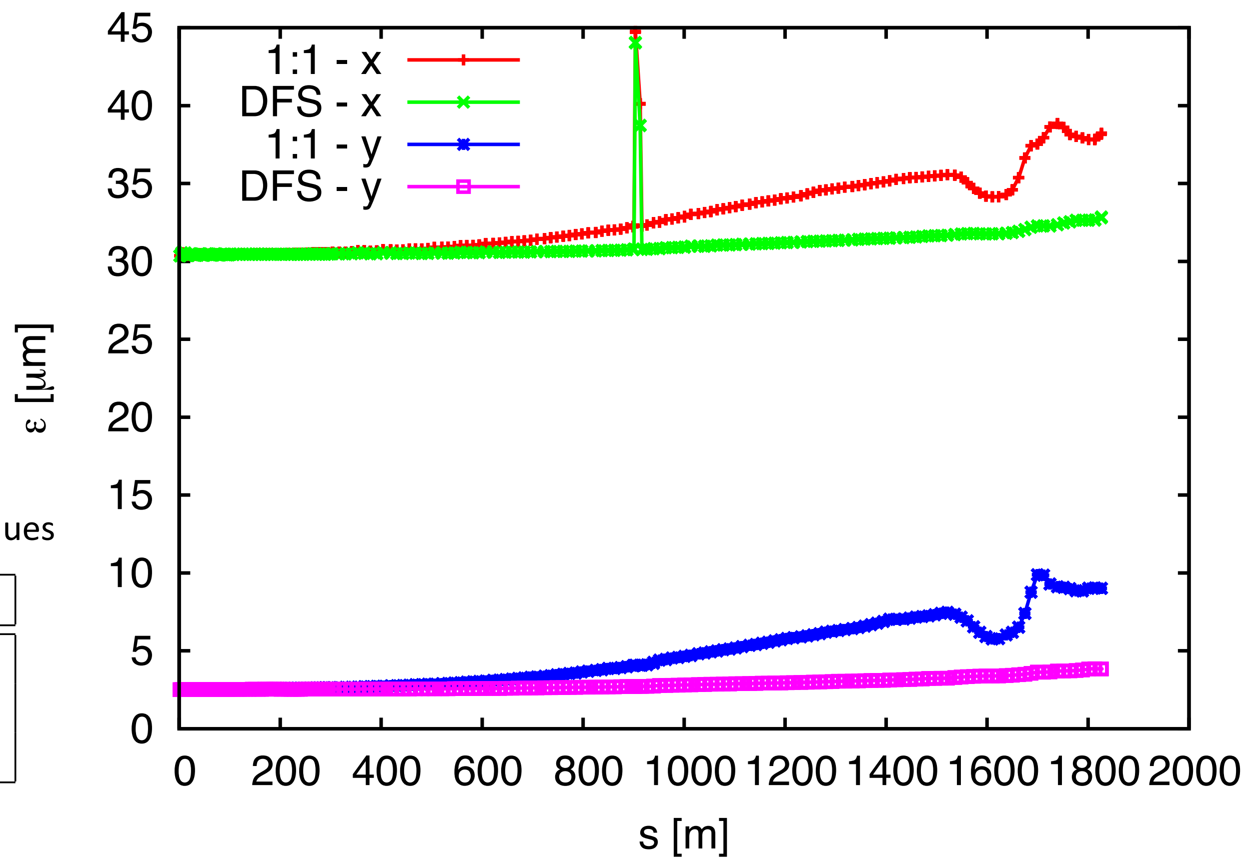
Relevant beam parameters at injection

Symbol	Value
$\gamma\epsilon_x$	$3.0 \cdot 10^{-5}$ m · rad
$\gamma\epsilon_y$	$0.25 \cdot 10^{-5}$ m · rad
σ_z	1 mm
σ_E	1%
q	3.24 nC
E_0	1.19 GeV

Misalignment and BPM precision values

Symbol	Value, RMS
$\sigma_{\text{quadrupole offset}}$	100 μm
$\sigma_{\text{bpm offset}}$	100 μm
$\sigma_{\text{bpm precision}}$	5 μm

Emittance growth with static imperfections, after beam-based alignment. The result is the average of 100 random seeds.



Simulations made with PLACET

Goals of T-501

Experimental verification of the effectiveness of linear collider system identification and beam-based alignment algorithms

System Identification:

- Automatic On-line reconstruction of the Optics Model
    - Response matrix measurement

Beam-based Alignment:

- Reduction of emittance dilution using simultaneous correction of orbit and dispersion
- Heavily relies on the goodness of the aforementioned System Identification algorithms

Summary of the beam-time we got

In 2012 we got beam-time twice:

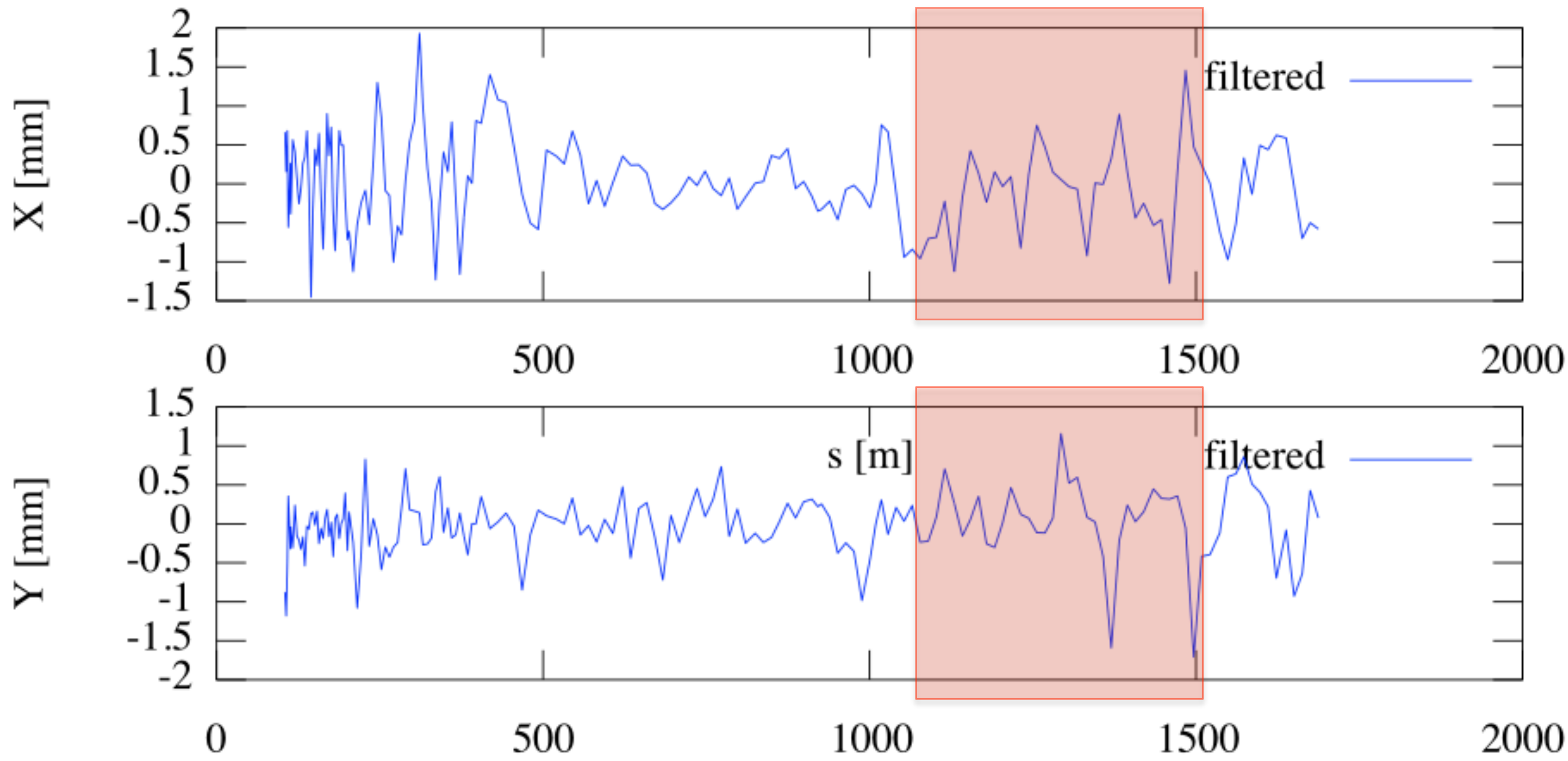
- April 13-15: thunderbolt, but we managed to measure the orbit response during one owl shift

- June 4-6, we got three shifts:

Friday night:	from 20:00 to 4:00	8h (supported*)
Saturday night:	from 24:00 to 8:00	8h
Sunday night:	from 24:00 to 4:00	4h

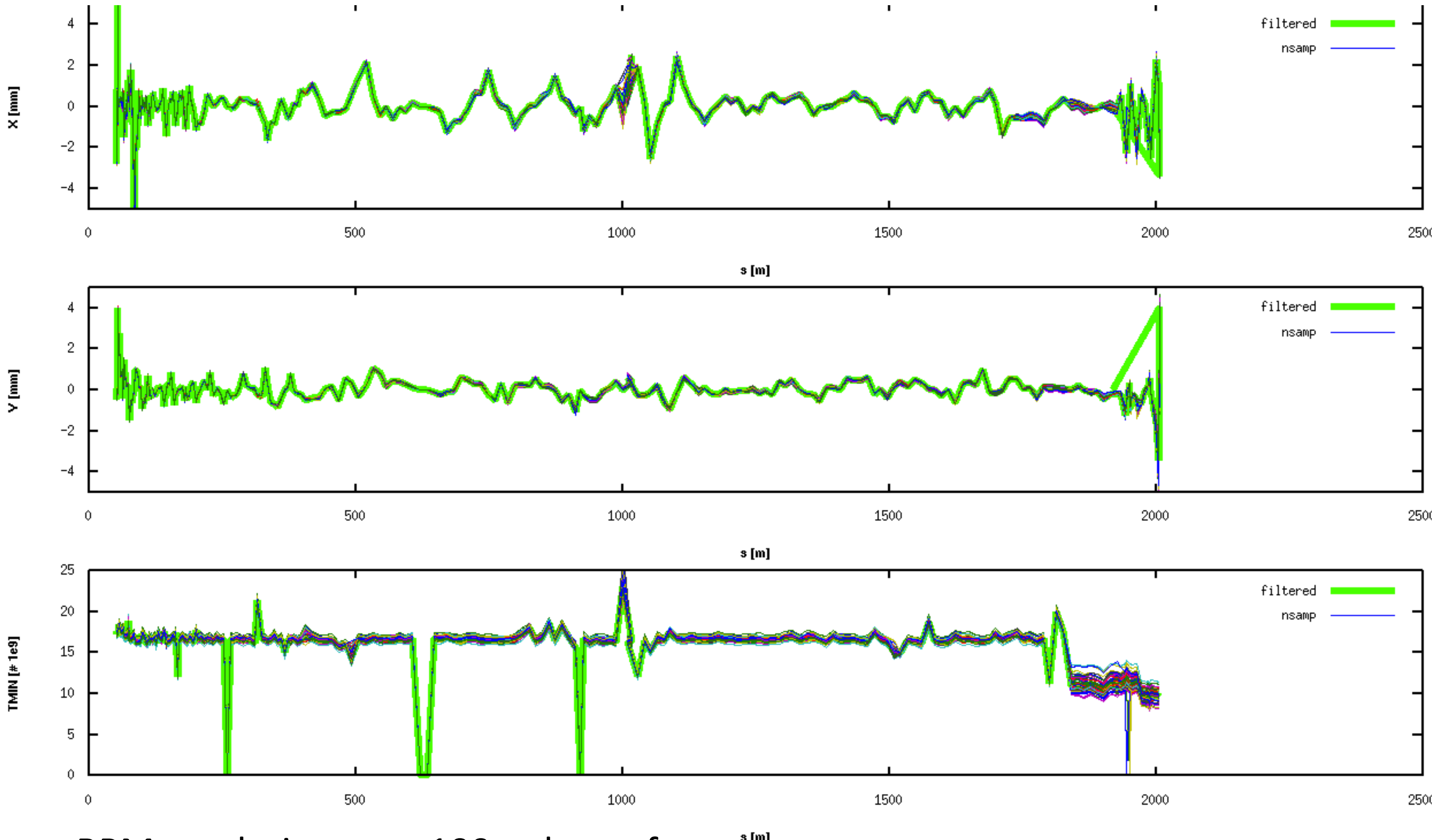
(*) F.J. Decker and N. Lipkowitz

Section of linac we focused on



1150 m – 1650 m (> 4 betatron oscillations) – about 500 m of linac.
Only e- correctors used. Disregarded e+ correctors.
After some tweaking : our system had 31 correctors (in total, X and Y); 37 BPMs.

Measurement of the Golden Orbit



Average BPM resolution over 100 pulses, after filtering:

Sx = 3.3 microm

Sy = 2.5 microm

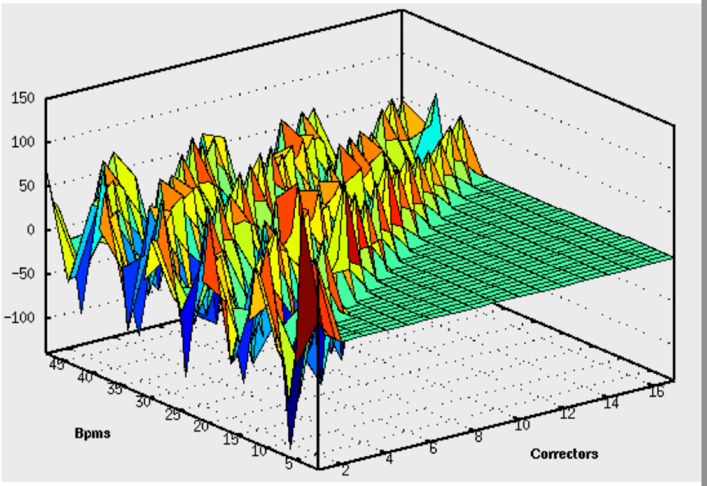
Response measurement

* Automatic response measurement procedure developed :
- For each corrector do +/-, measure 100 samples (increase effective BPM res)
- Iterate loop through correctors; second iteration uses amplitude of 1 mm
- Result from each iteration is combined in a mathematically optimal way

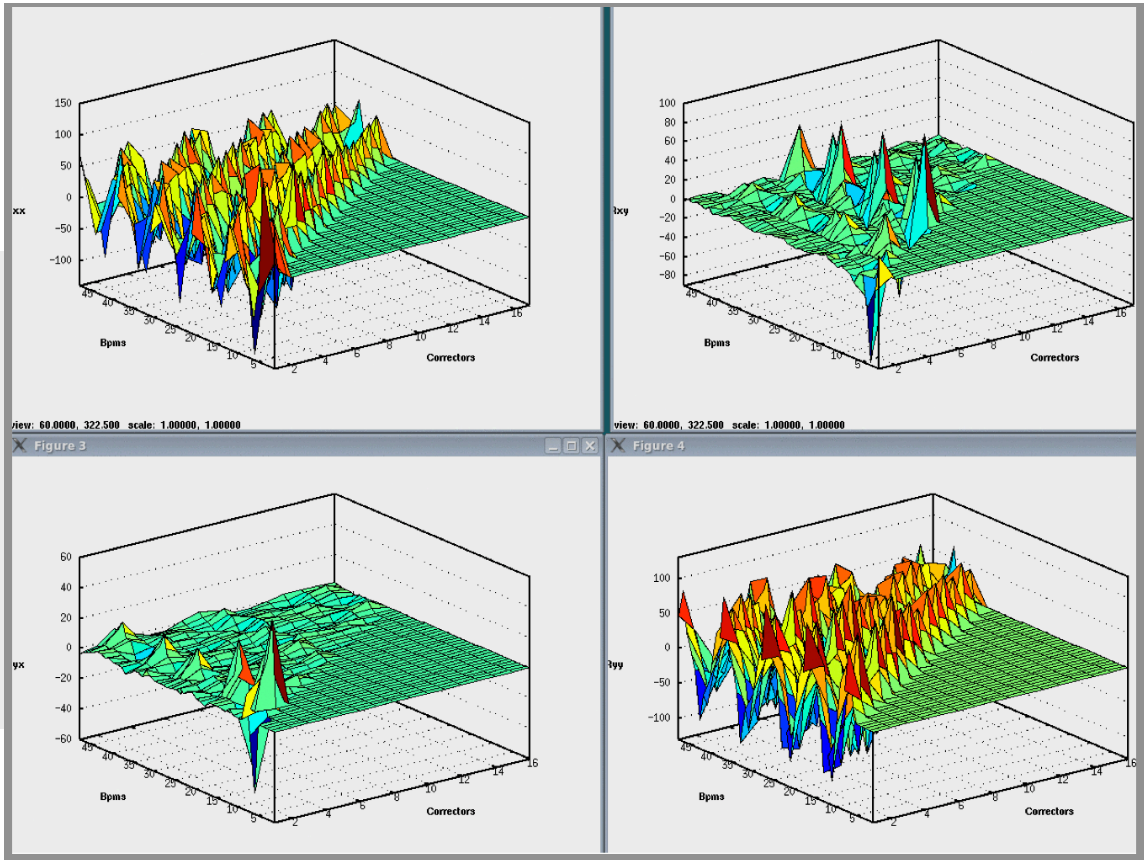
*** Time: 2 hours for 33 correctors**

* Some coupling observed
- Applied to the correction

* Responses demonstrated to be valid one shift later (24 hours later)



(Above) Identified Rxx response matrix for a section of the linac (17 correctors, 48 BPMs)

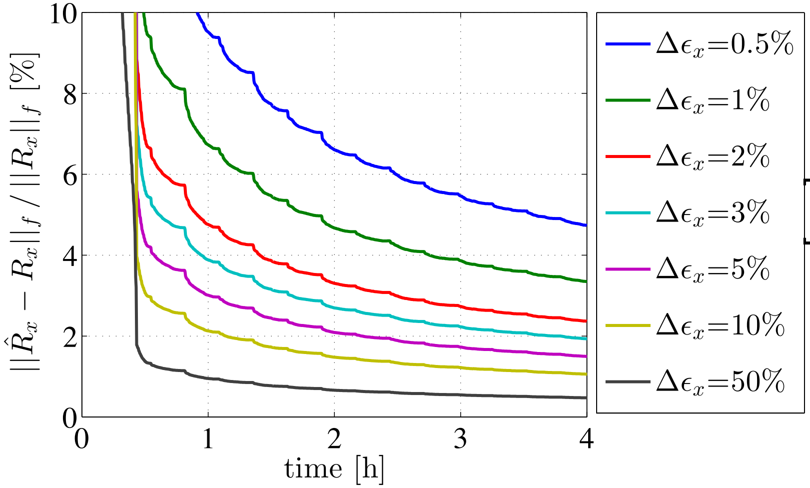


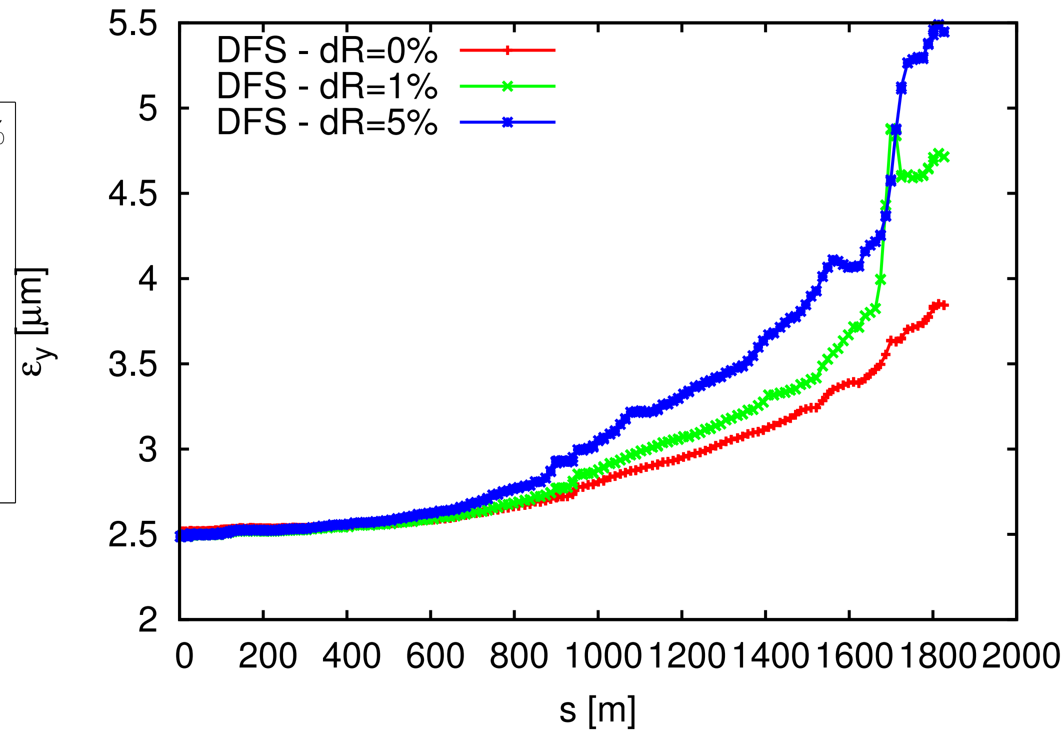
Rxx, Rxy, Ryx and Ryy. *Some coupling is observed (some spikes can also be due to jitter during the measurement).*

System Identification and BBA Simulation

Left: Speed of convergence assumed BPM resolution = 10 um (1 iteration = 15 seconds)

Right: Emittance growth after dispersion-free steering with imperfect model, compared to the case with perfect mode. The results are the average of 1000 random seeds.





Orbit correction - principle

Linear response matrix from corrector j to BPM i:

$$R_{ij} = \frac{\partial y_i}{\partial \theta_j}$$

The measured linear response includes all linear effects in the system:

- Quadrupole offsets (inducing dipole kicks)
- Dipole wake from beam offset in acc. Structures

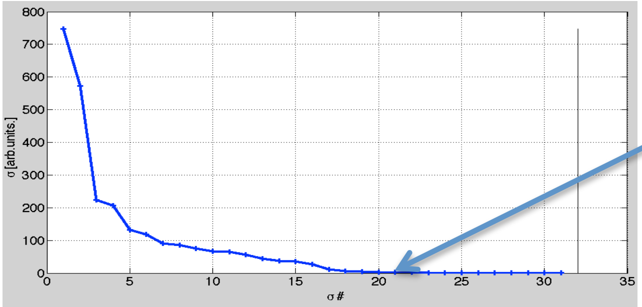
The response is found by difference measurements; is independent of absolute orbit.

Correction that finds the global solution, through the LS-inverse

$$\min_{\Delta\theta} = ||\mathbf{y} - \mathbf{R}\Delta\theta|| \quad \rightarrow \quad \Delta\theta = -R^{\dagger}\mathbf{y},$$

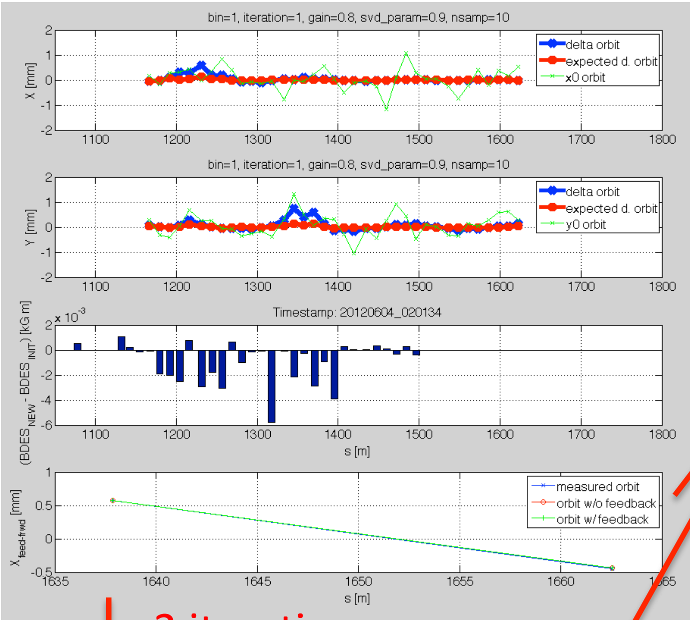
Need a way to take out correction directions due to noise in the measurement. We use a straight SVD-cut.

Sing.values of R :

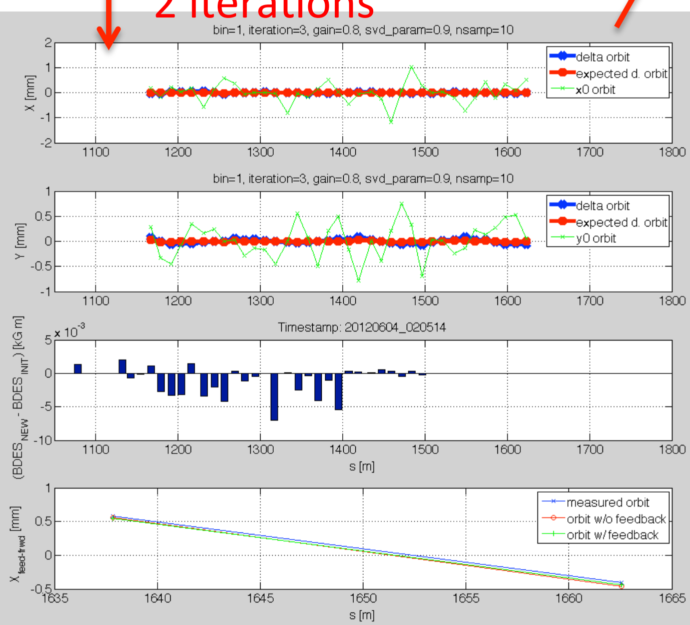


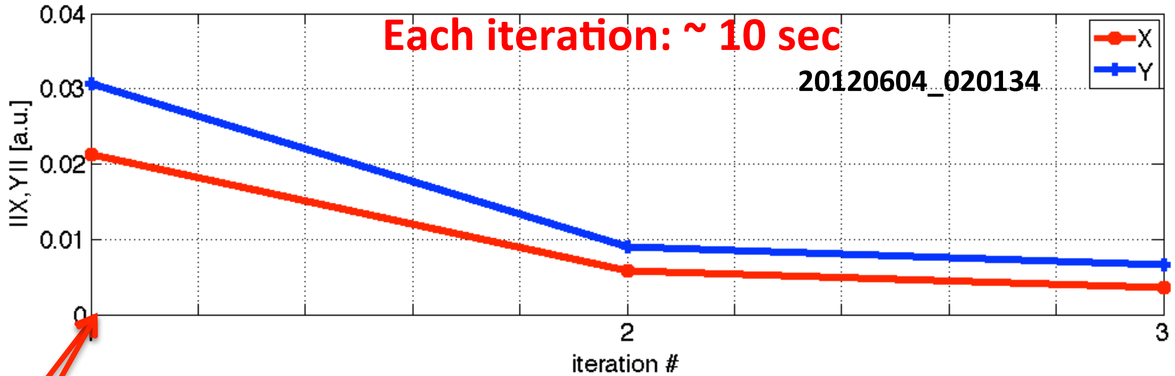
Very little information in the low sing.val. directions -> huge corrector strength needed to make a small adjustment to correction -> ignore these directions.

Orbit correction - results

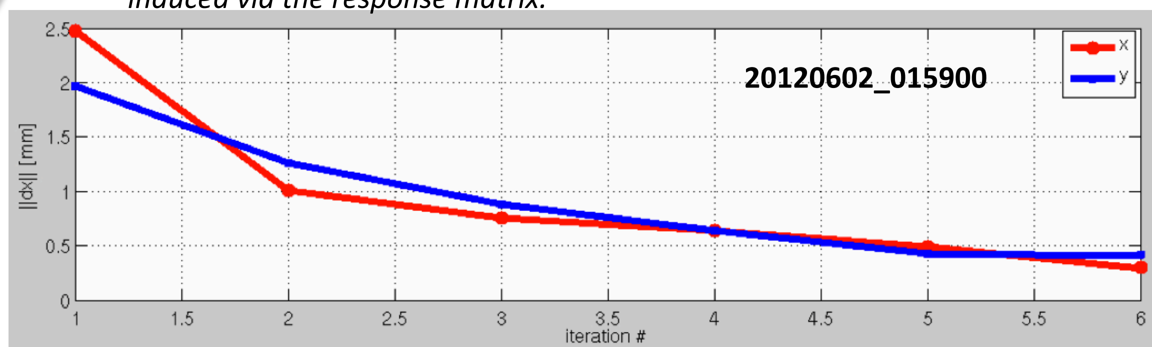


2 iterations





Example to the top (||X||/N) after orbit correction from an arbitrary bump; induced via the response matrix.



Different example: basically we always converge to within ||X||/N ~ 10 um (here ||X|| is displayed)

06/02/2012 01:59 T501 Latina, Delahaye, Nate, FJD, Adli **SUCCESS : We are happy with the orbit correction and the feed-forward!**

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- we can go back to gold almost perfectly, from an arbitrary state
  - with exception of start of y; not enough correctors
- we did not kill or even rate limit the machine a single time tonight
  - feed-forward seems to work perfectly!
- note: we have included BPMs 200 m downstream of the last corrector

(-note: even if display is after 13 iteration, we converged after ~6-7)

ORBIT CORRECTION PARAMETERS:
gain = 1.0
svd_cut_percentage = 0.9
```

Also feed-forward worked perfectly. *Took less than one shift to reach this state, with the help of FJD and Nate.* ***Declared success, and moved on to dispersion.***

Dispersion Correction – principle

Besides minimizing orbit, we minimize the difference between the nominal orbit and the dispersive orbit. We also need to constraint nominal orbit. Weighted solution; weight for difference orbit ~ BPM_{acc} / BPM_{res} .

$$\chi^2 = w_0^2 \Sigma y_{0,i}^2 + w_1^2 \Sigma (y_{1,i} - y_{0,i})^2 .$$

Need to solve the following system of equations:

$$\begin{pmatrix} y - y_0 \\ \omega(\eta - \eta_0) \\ 0 \end{pmatrix} = \begin{pmatrix} \mathbf{R} \\ \omega\mathbf{D} \\ \beta\mathbf{I} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_m \end{pmatrix}$$

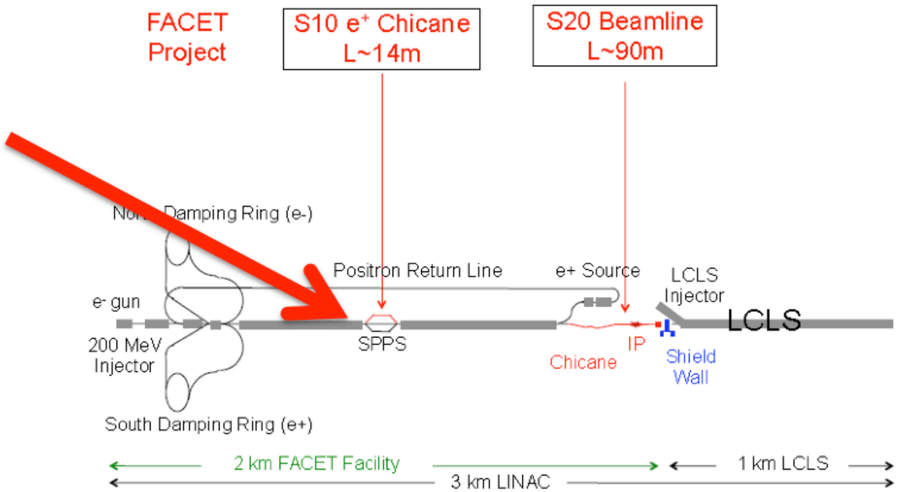
This reduces to a LS-problem, analogous to the orbit correction.

Parameter ω accounts for the relative weight to give to orbit and dispersion correction, β is a regularization parameter to better condition the response matrices.

$$\omega^2 = \frac{\sigma^2_{\text{bpm resolution}} + \sigma^2_{\text{bpm position}}}{2\sigma^2_{\text{bpm resolution}}}$$

Dispersion generation

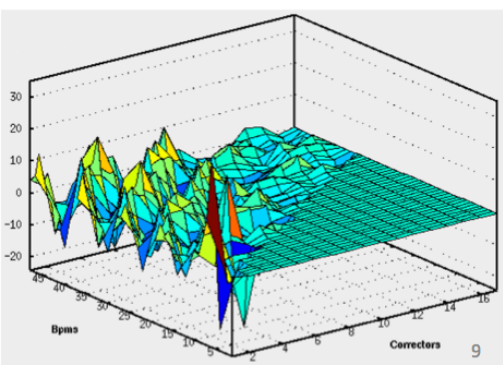
- Energy difference was induced offsetting the RF-phase of 1 klystron ‘KLYS:LI10:61’ by 90 degrees
  - This induced a -1.3% energy difference at the end of the linac, about 300 MeV
  - (simulations showed that it is sufficient)



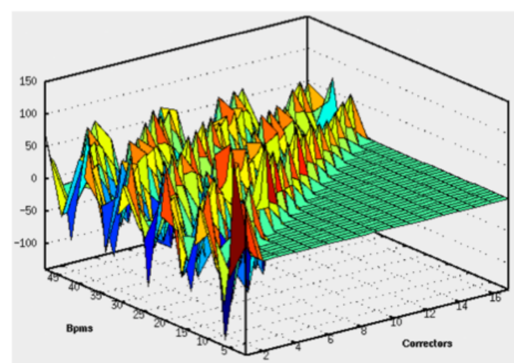
- Dispersion response is: D = R1 – R0

Need to measure dispersive responses (2 hours more of measurEment).

Dxx : less precise towards end

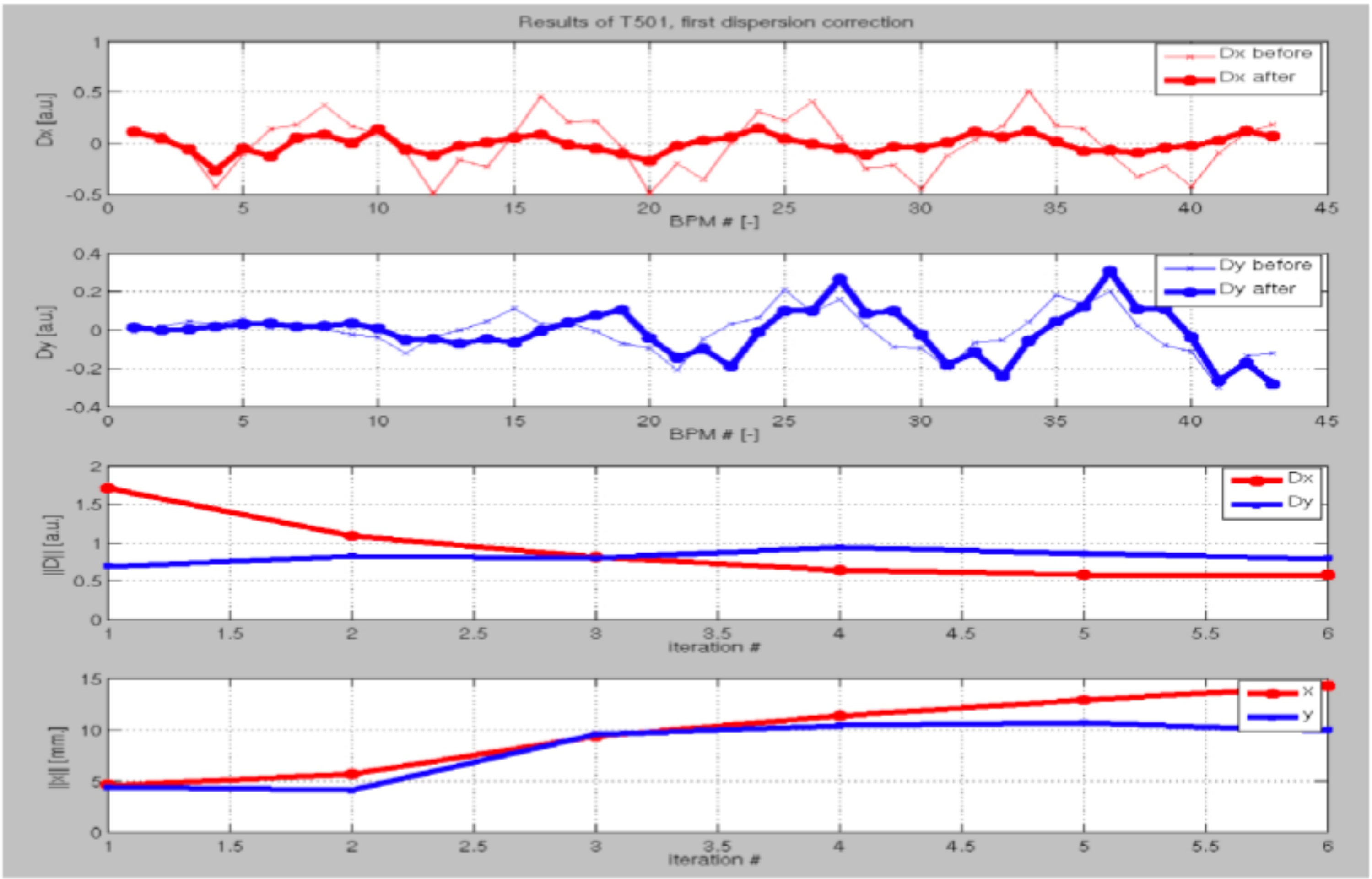


Rxx for comparison



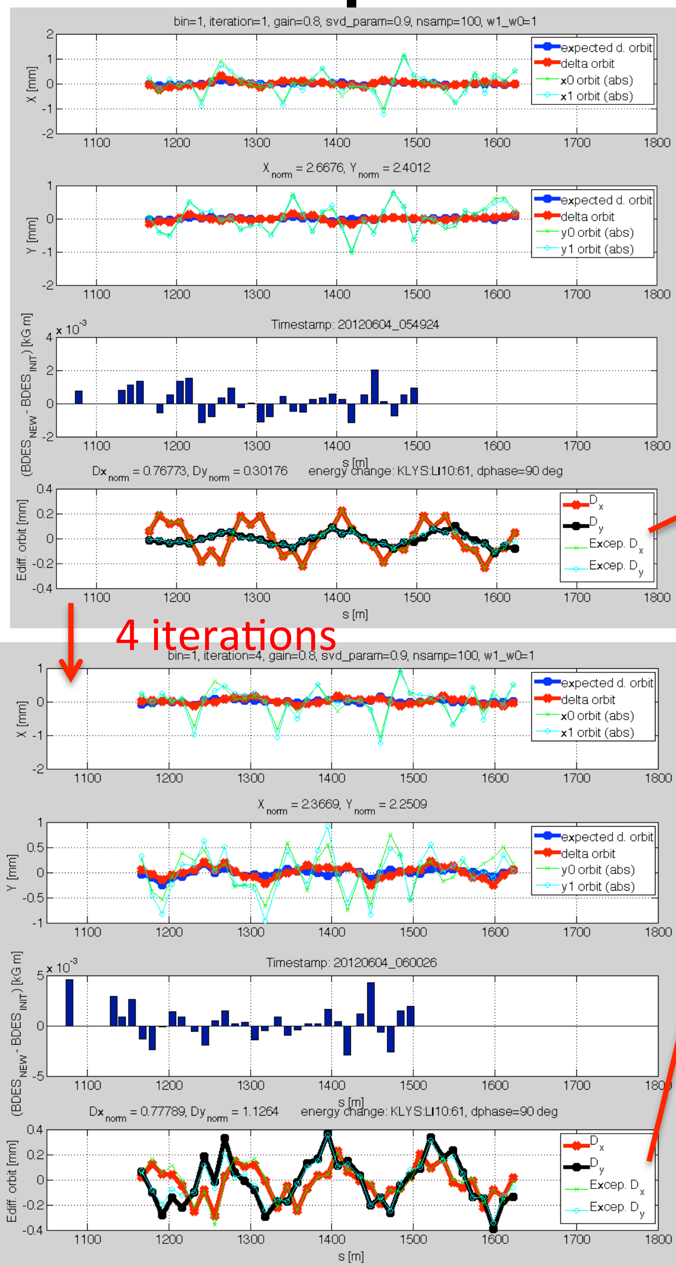
Dispersion correction – results 1

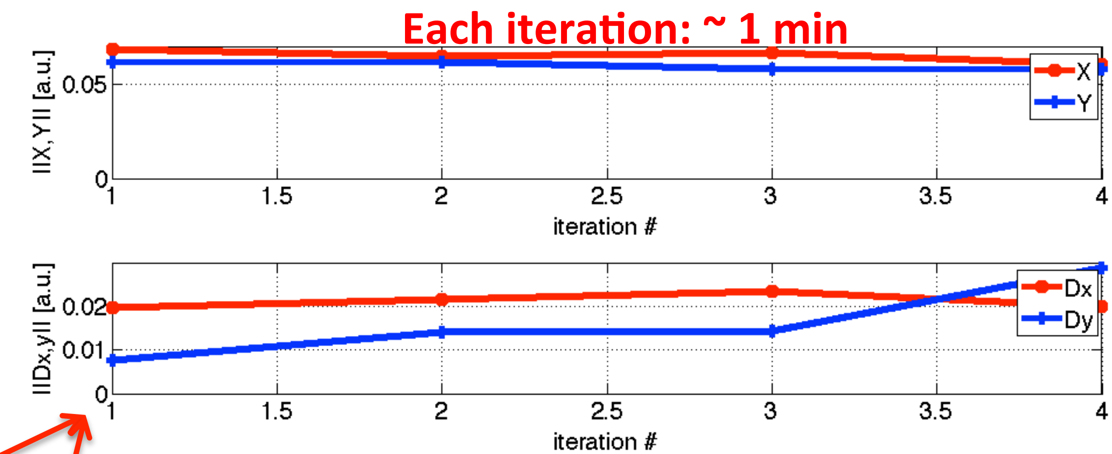
First dispersion correction (success?)



Initial attempts showed algorithm in principle worked well; however, not always reproducible.

Dispersion correction – results 2





We started from the dispersion of the golden orbit (10-20 mm).

We had several results where the dispersion did not converge well.

As in this example : we start with a given dispersion, and end up with a significantly worse.

Moreover, the expected correction for next iteration is also significantly worse than what we started with.

-> was a mystery!

Dispersion correction – analysis

A careful post-mortem analysis of the above data showed what happened :

- drifts upstream the bin slightly changed the orbits between iterations (not unexpected)
- we did not manage to go back to the better orbit we started with (unexpected)
- the reason: the upstream drift induced a perturbation in the orbit that is not correctable with our selection of correction**; inside the null-space of the (total) R^+**
- we have 31 correctors (variables) and 148 constraints (37 BPMs x 2 x 2); large nullspace
- We expect that using more correctors we will get better performance

$$\begin{pmatrix} b - b_0 \\ \omega(\eta - \eta_0) \\ 0 \end{pmatrix} = \begin{pmatrix} \mathbf{R} \\ \omega\mathbf{D} \\ \beta\mathbf{I} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_m \end{pmatrix}$$

Summary CERNBBA nullspace issue:

* The DFS algorithm tries to solve an over-determined system with 31 variables, $\mathbf{c}$, (correctors) to satisfy 148 equations, $\mathbf{y}$, (X, Y orbit and X, Y difference orbigt for each of the 37 BPMs). The relation is given by the total response (orbit and difference), $\mathbf{R}$.

* It can only do this in the least square sense with solution

$$min_{\mathbf{c}} \parallel \mathbf{y} - \mathbf{Rc} \parallel$$

where the correction is found by the solving using the pseudo-inverse

$$\mathbf{c} = \mathbf{R}^{\dagger}\mathbf{y}$$

Because the system is over-determined there is a space of vectors $\mathbf{y}^0$ that cannot be corrected because they are in the nullspace of $\mathbf{R}^{\dagger}$:

$$\mathbf{R}^{\dagger}\mathbf{y} = 0$$

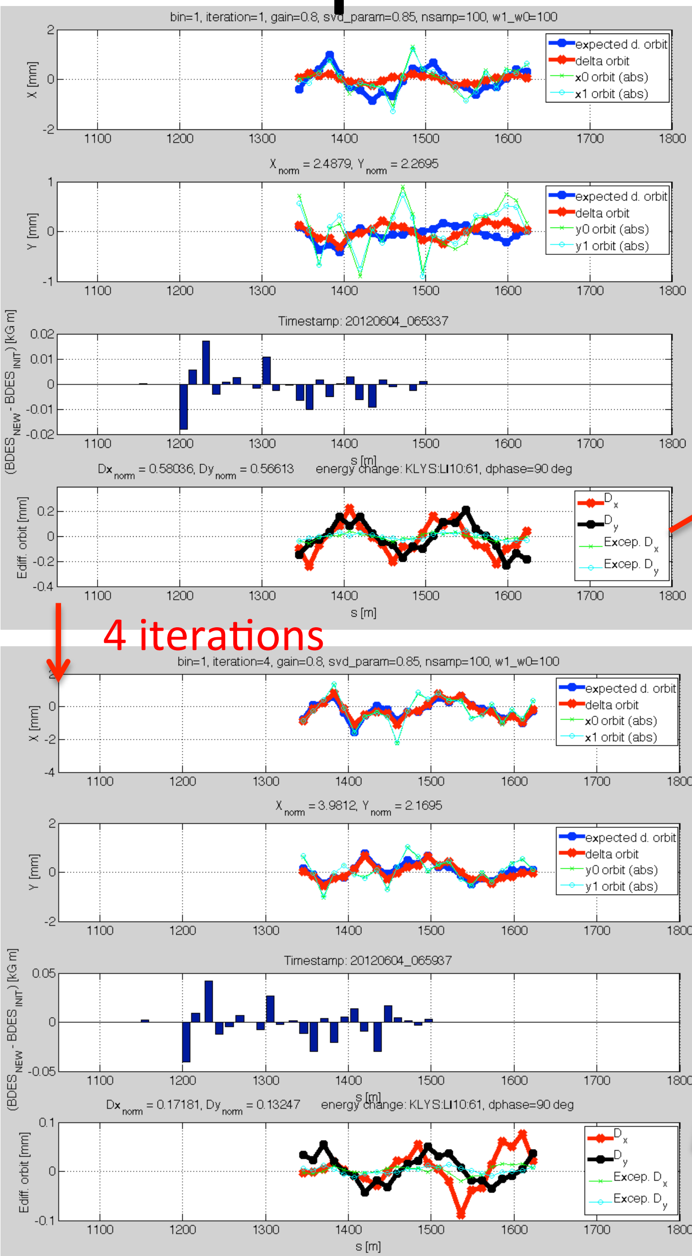
This nullspace is rather large because of the 31/148 ratio.

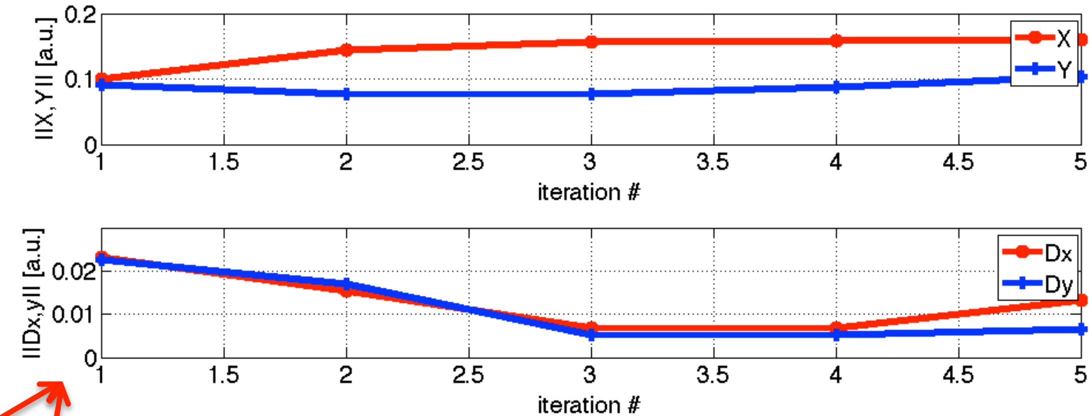
I confirm that for both slide 11 (perfect solution starting from iteration 4) and slide 13 (perfect solution starting from iteration 4), I find that

$$\parallel \mathbf{y} \parallel \neq \mathbf{0} \wedge \parallel \mathbf{R} \parallel \neq 0, \mathbf{R}^{\dagger}\mathbf{y} = 0$$

This confirms that drift seen between iteration 3 and iteration 4 is indeed in the nullspace of $\mathbf{R}^{\dagger}$, thus uncorrectable.

Dispersion correction – results 3





Using the same number of correctors but ~**half the numbers of BPM** we managed to reduce the dispersion below the initial (to ~ 5 mm) for 300 m of the linac.

Performance still limited by jitter.

To improve performance, also for a larger part of linac :

- need more correctors (more measurement time)
- the more upstream the better (ideally: whole linac)
- analyze sources of jitter

Summary

- **Demonstrated automatic machine identification** : about 3.5+3.5 minutes/ corrector (nominal + dispersive) -> 4 hours for 33 correctors. Can possibly be optimized.
  - need factor ~4-8 more correctors for whole linac. Exactly how many to be studies with simulations.
- **Demonstrated converged orbit correction on 500 m of linac** from arbitrary generated orbit bumps back to golden orbit, within ~ 10 um. **Repeatable** with day-old machine identification. **Feed-forward to keep downstream machine in place worked perfectly.**
- **Demonstrated principle of dispersion correction**, however, did not manage to improve the present dispersion over the whole 500 m test-section of the linac. Got improved results when reducing the number of BPMs per corrector. Ultimate performance sees limited by jitter.
- **Progress of the experiment was significantly enhanced when FACET physicists were present** (FJD and Nate); it is **not ideal** to work alone during weekend owl shifts for this kind of experiment.

Future steps

- **Demonstrate a clear reduction in dispersion, over a larger section of the linac** (> 500 m), by inducing dispersion bumps If necessary, and see a clear stable convergence
- **Demonstrate a clear reduction in emittance** by applying this dispersion correction
- Study new optics (weak lattice) to find a good number of correctors / BPMs and optimal performance. Study more carefully the amount of jitter and its effect.
- Requires more beam time; ideally in 12 hours blocks (larger responses).
- **We plan to apply for more beam time in 2013**
- We hope for the continued support and collaboration with FACET machine physicists

Acknowledgments

- Uli Wienands and Christine Clarke for their prompt support, guidance and patience throughout the entire process and during the preparatory trips

- Nate Lipkowitz and Franz-Josef Decker: Nate for his precious work on the Matlab interface for SCP, Franz-Josef for his invaluable contribution

- The entice MCC team and the FACET Collaboration for their helpful and support during the shifts