Beam-Based Alignment Tests at FACET and at Fermi

A. Latina (CERN), E. Adli (Oslo),
D. Pellegrini (CERN), J. Pfingstner (CERN), D. Schulte (CERN)

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Objectives

We propose *automated beam-steering methods* to improve the linacs performance by correcting *orbit, dispersion,* and *wakefields* simultaneously.

Our technique is:

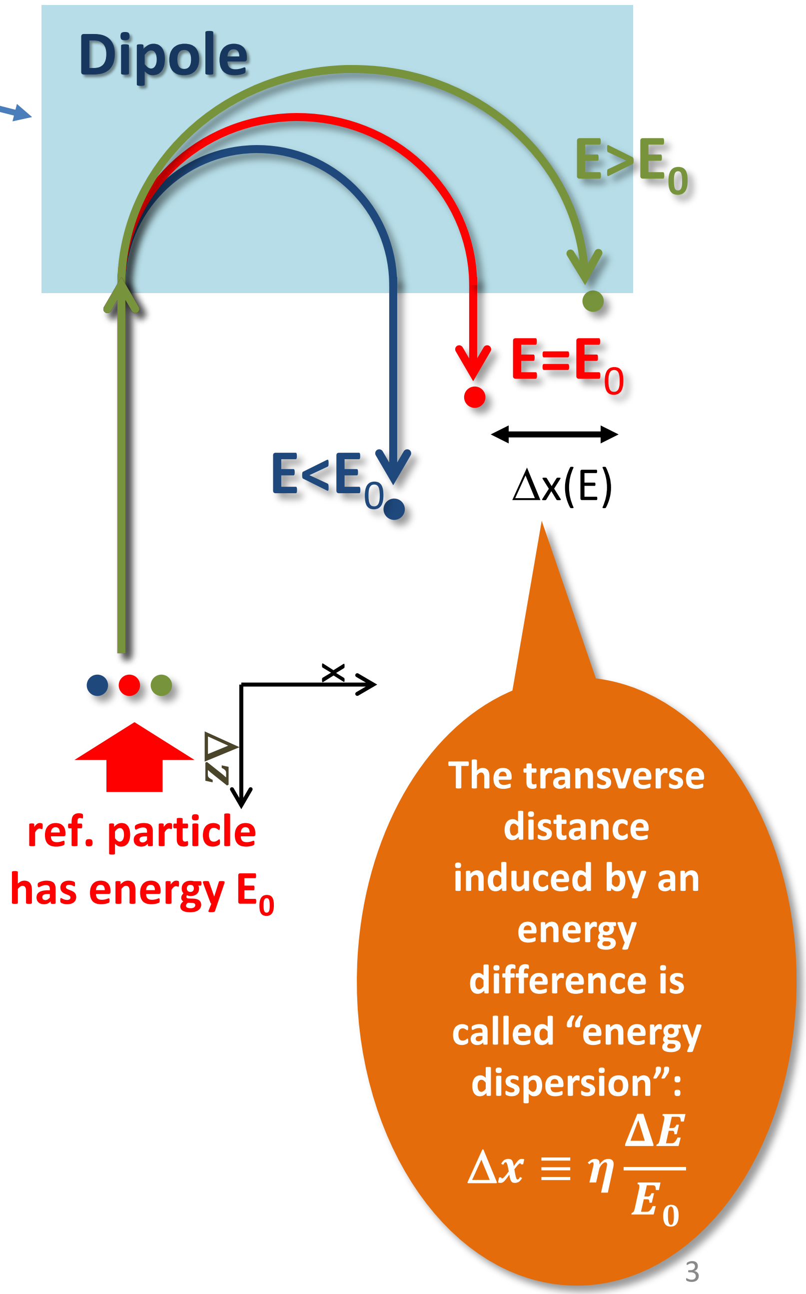
- *Model independent*
- *Global*
- *Automatic*
- *Robust and rapid*

We base our algorithms operate in two phases: **automatic system identification**, and **BBA**

It is a considerable step forward with respect to traditional alignment techniques.

Recap on dispersion

In real lattice, this dipole is replaced by:
- Quadrupoles traversed off-axis
- Steering magnets
- Residual field in spectrometers
- RF focusing, etc.



Single-particle eq. of motion with quads (k), dipoles (R) and energy deviation from nominal (δ):

$$x''(s) + k(s)(1-\delta)x(s) = \frac{\delta}{R(s)}$$

- The solution of the complete e.o.m. describes the **energy-dispersion**, η_x.
- We search the solution (i.e., the trajectory) that is independent from δ.
- By definition, that is equivalent to a "dispersion-free" motion.

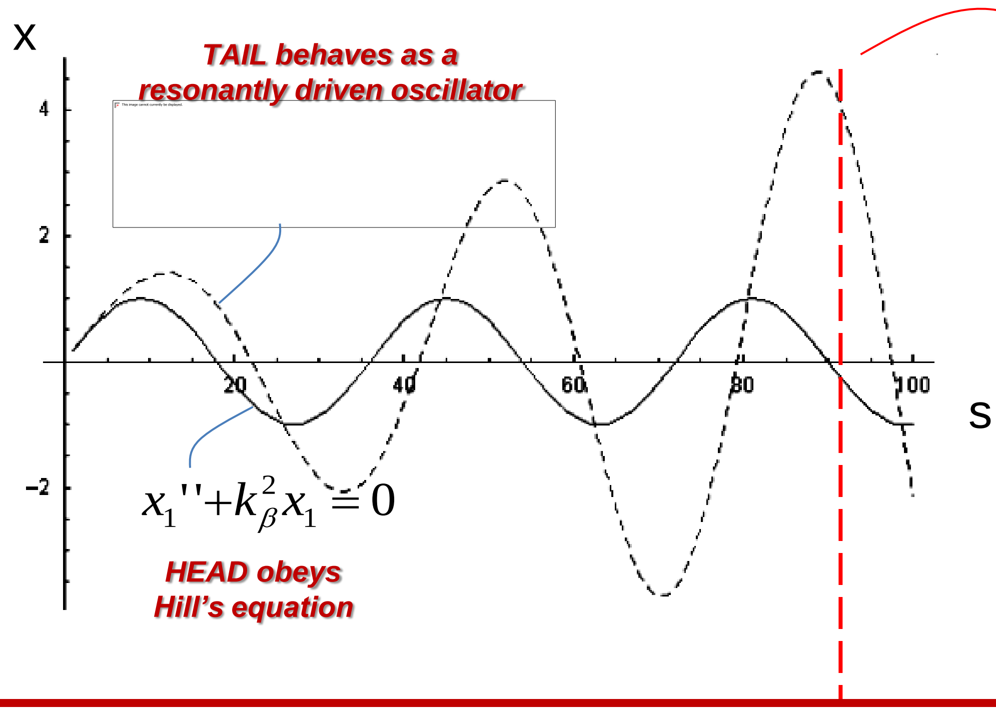
Recap on wakefields

Equation of motion for x(z,s) in the presence of w_T (exact):

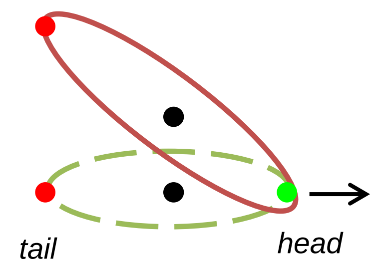
$$\frac{d}{ds}\left[\gamma(s)\frac{d}{ds}x(z,s)\right]+k_\beta^2\gamma(s)x(z,s)=r_e\int_z^\infty dz'\,\rho(z')w_T(z'-z)\left[x(z',s)-d_c(s)\right]$$

acceleration *β-focusing* ***charge distribution*** ***wake function*** ***cavity displacement relative to the particle free β-oscillation***

In the two-particle model, at constant energy, the **bunch head drives resonantly the tail**:



centroid lateral shift and projected emittance growth



- We search the solution (i.e., the trajectory) that is independent from charge (ρ).
- By definition, that is equivalent to a "wakefield-free" motion.

Recap on Dispersion-Free Steering and Wakefield-Free Steering

- DFS: measure and correct the system response to a change in energy
  (we off-phased one klystron either in sectors S02 or in S04, depending on the case)
- WFS: measure and correct the system response to a **change in the bunch charge**
  (this time we used 70% of the nominal charge, 2e10 e^- and 1.3e10 e^-)

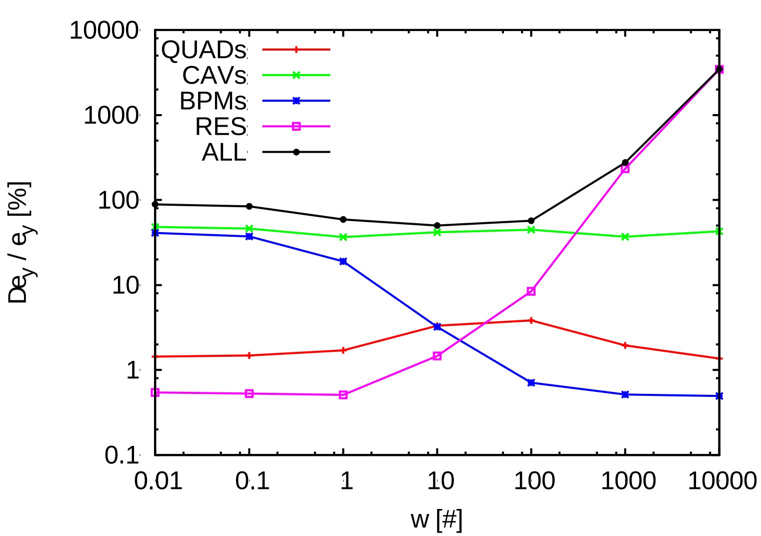
Recap of the equations

$$\begin{pmatrix} & & y \\ \omega_{\mathrm{DFS}} & \cdot & (\eta - \eta_0) \\ \omega_{\mathrm{WFS}} & \cdot & y_{\mathrm{w}} \\ & & 0 \end{pmatrix} = \begin{pmatrix} & & \mathbf{R} \\ \omega_{\mathrm{DFS}} & \cdot & \mathbf{D} \\ \omega_{\mathrm{WFS}} & \cdot & \mathbf{W} \\ \beta & \cdot & \mathbf{I} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_m \end{pmatrix}$$

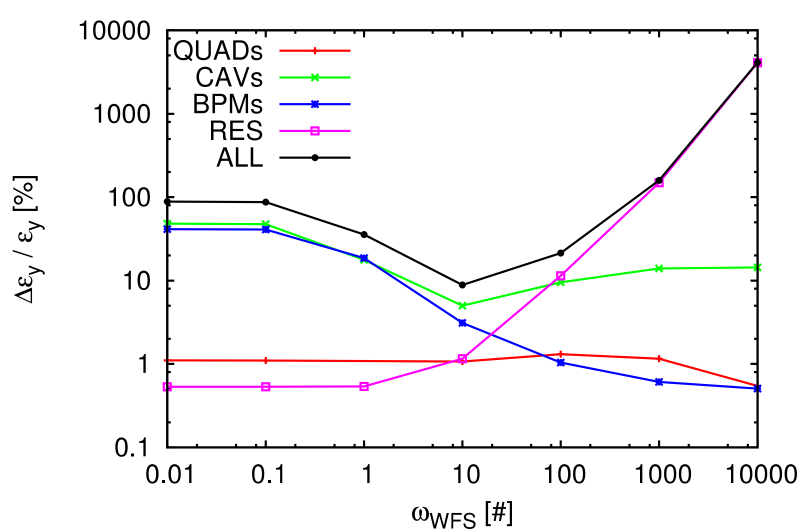
$$\omega^2 = \frac{\sigma^2_{\text{bpm resolution}} + \sigma^2_{\text{bpm position}}}{2\sigma^2_{\text{bpm resolution}}}$$

w_{optimal} = ~40

Simulation: DFS weight scan



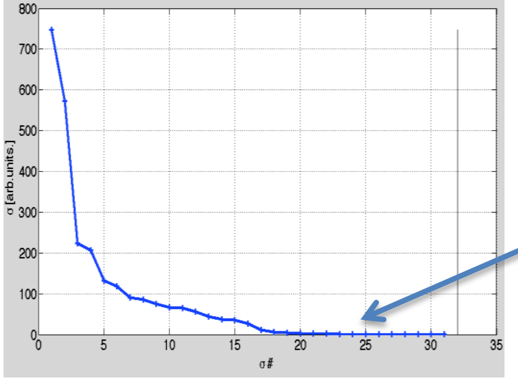
Simulation: WFS weight scan



Response matrix

The response matrix might compromise the performance of BBA algorithms in several ways:

- **It can misrepresent the optics** (computer model vs real machine)
- **It can be ill-conditioned**: an ill-conditioned matrix leads to bad solutions of the system of equations
- Very little information in the small singular values directions



$$\Delta\theta = -\mathbf{R}^{\dagger} y$$

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

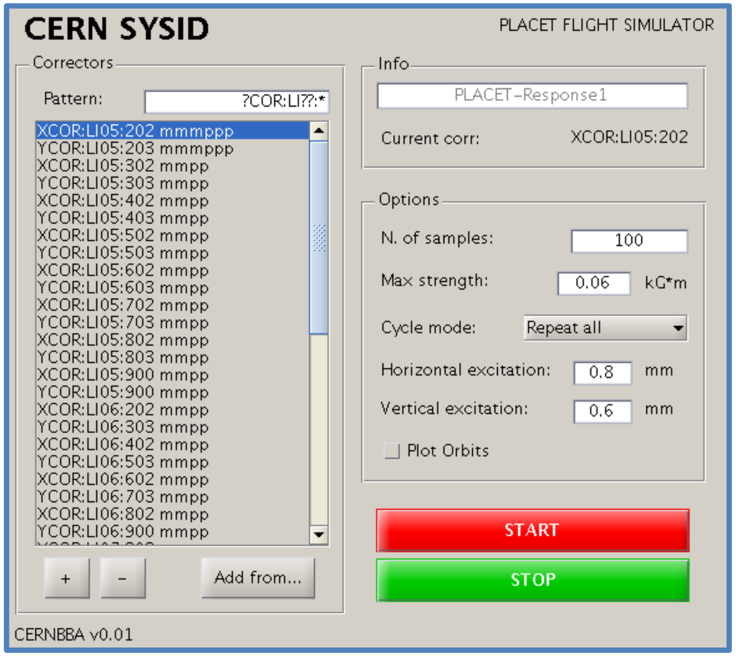
We can control this via the parameter β, or by zeroing the smallest singular values.

- **If measured, it is affected by instrumentation noise:** an inaccurate response matrix misrepresents the optics of the system and compromises BBA

1) We use an algorithm that *measures the optics* : **System Identification (or SYSID)**
2) The matrix needs to be **conditioned** (SVD cut, or beta parameter)

An (almost) automatic correction

- We want to make our BBA algorithms as automatic as possible. Two tools have been developed. SYSID and BBA tools

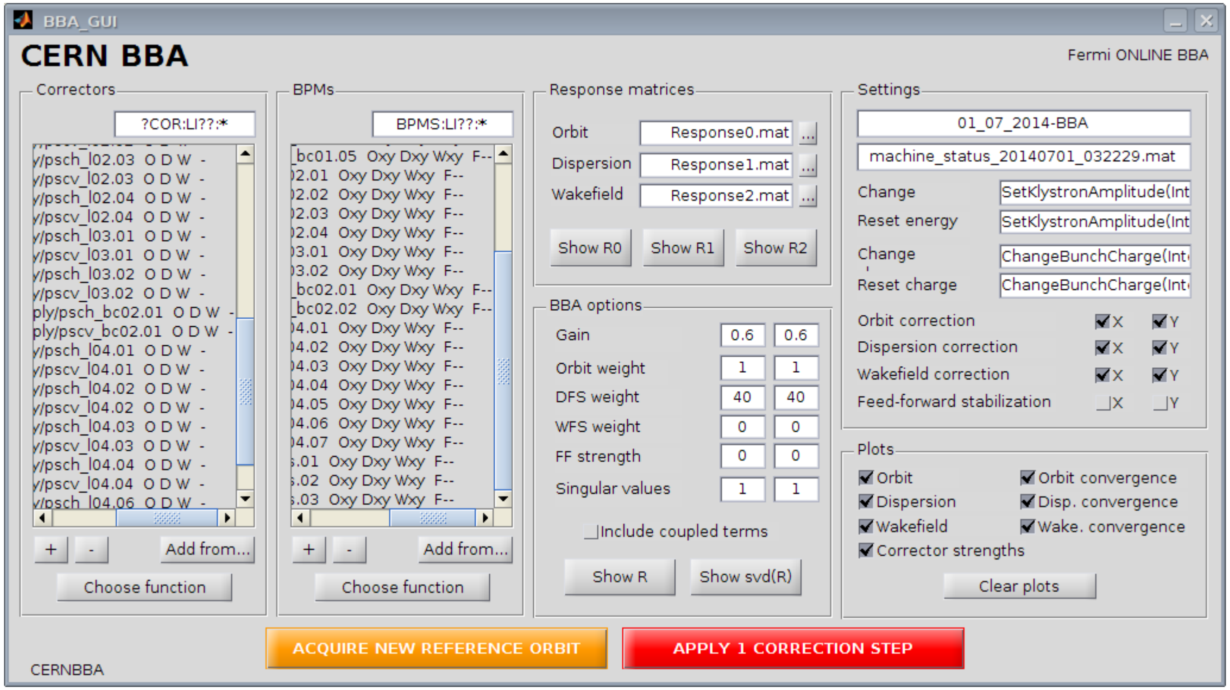


- The left-hand side panel shows the list of selected correctors, and displays how many iterations have been performed for each of them
- The right-hand side panel allows to set the desired amplitude of the orbit oscillations excited to measure the trajectory response

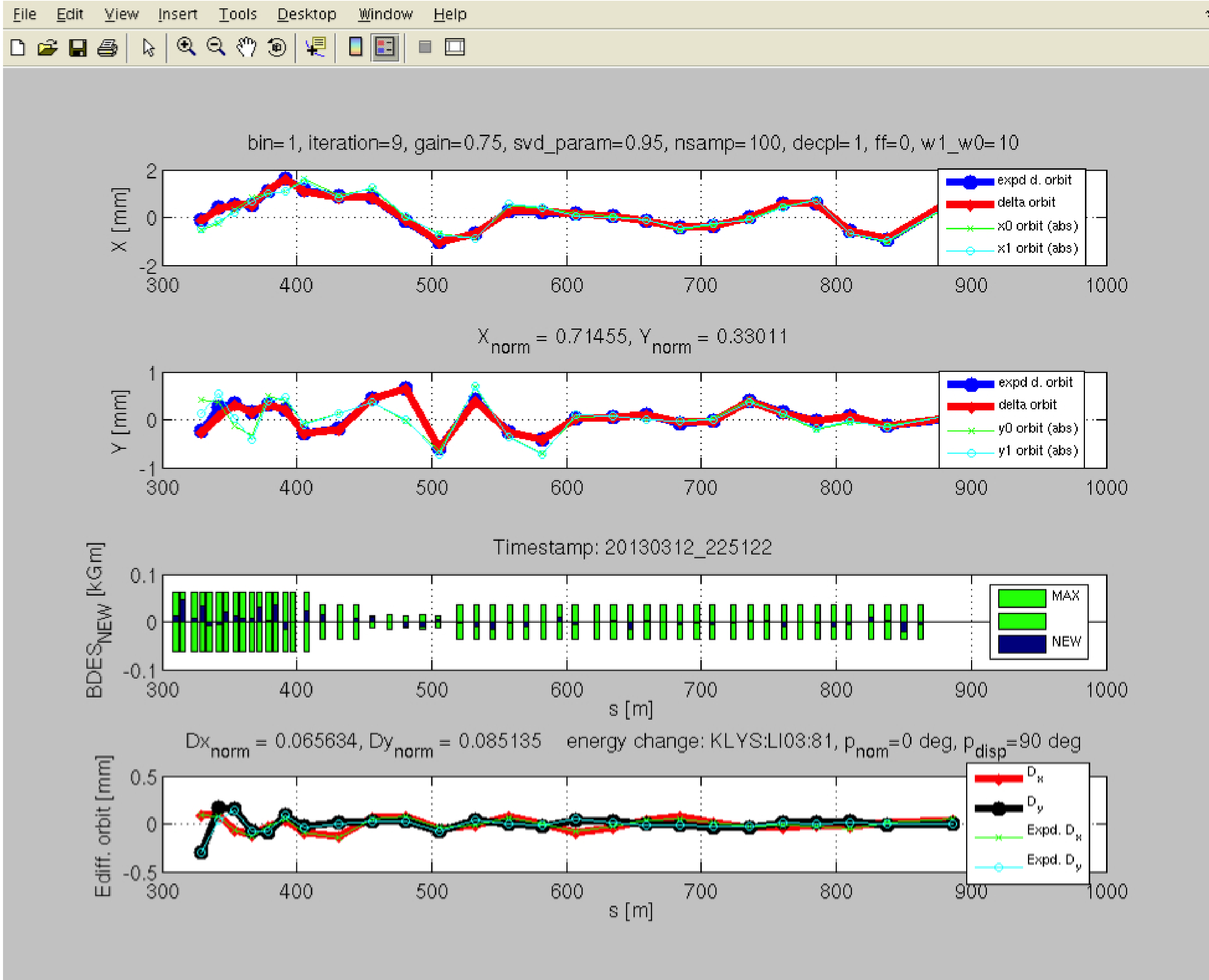
The tool implements an adaptive scheme, that tunes the corrector strength to reach target amplitude according to the information from previous measurements.

An (almost) automatic correction

- BBA tool



- **Large space of parameters** have to be tuned to achieve best performance:
  - Correction gain, g
  - Weight of the DFS term, ω_{DFS}
  - Weight of the WFS term, ω_{WFS}
  - Regularization term of the global matrix, by means of:
    - Cut off the smallest singular values, n_{SVD}, or
    - Beta parameter, β


File Edit View Insert Tools Desktop Window Help
bin=1, iteration=9, gain=0.75, svd_param=0.95, nsamp=100, decpl=1, ff=0, w1_w0=10
X [mm]
expd d. orbit
delta orbit
x0 orbit (abs)
x1 orbit (abs)
X norm = 0.71455, Y norm = 0.33011
Y [mm]
expd d. orbit
delta orbit
y0 orbit (abs)
y1 orbit (abs)
Timestamp: 20130312_225122
BDES NEW [kGm]
MAX
NEW
s [m]
Dx norm = 0.065634, Dy norm = 0.085135 energy change: KLYS:LI03:81, p nom=0 deg, p disp=90 deg
Ediff. orbit [mm]
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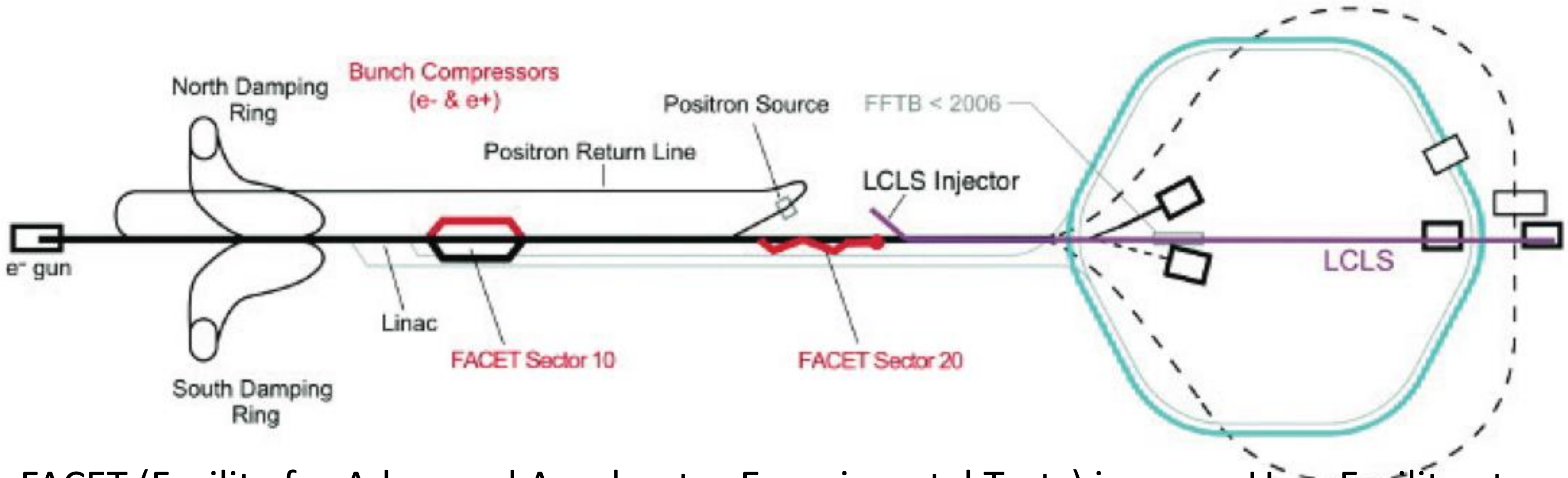
FACET @ SLAC

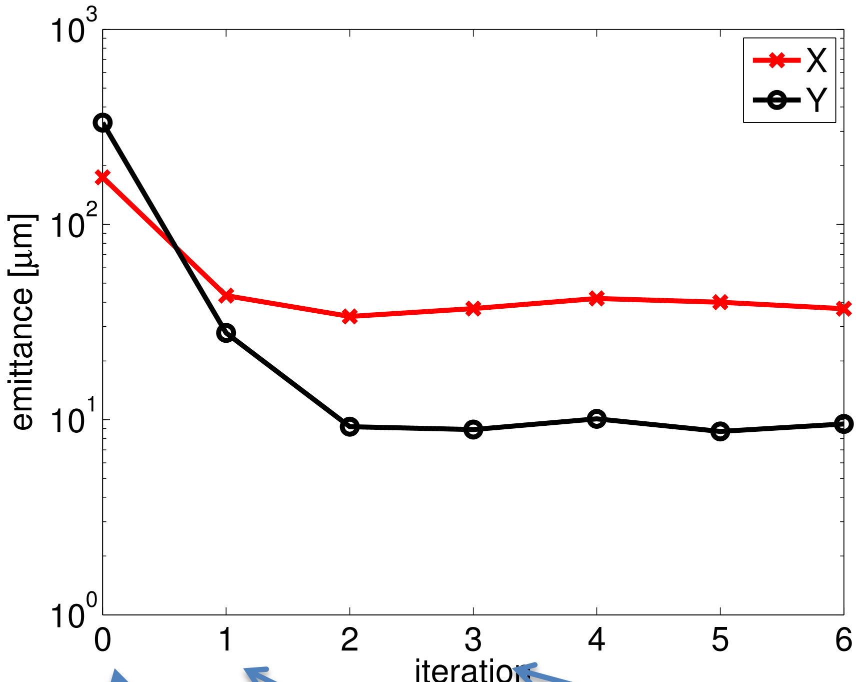


- FACET (Facility for Advanced Accelerator Experimental Tests) is a new User Facility at SLAC National Accelerator Laboratory. Experiments apply for beam time to a scientific committee.
- E = 1.19 to 20 GeV Linac, q up to 3.2 nC, 1.5 mm long bunches (injection)
- The first User Run started in spring 2012 with 20 GeV, 3 nC electron beams.
- The facility is designed to provide short (20 µm) bunches and small (20 µm wide) spot sizes.

BBA experiments:

- DFS Sectors 04-10
- WFS Sectors 02-04

March 2013: DFS correction



LI04-LI10:
Incoming oscillation/dispersion is taken out and flattened; emittance in LI11 and emittance growth significantly reduced.

Emittance at LI11 (iteraton 1)
X: 43.2 x 10^{-5} m
Y: 27.82 x 10^{-5} m

Emittance at LI11 (iteration 4)
X: 3.71 x 10^{-5} m
Y: 0.87 x 10^{-5} m

S19 phos, PR185 :

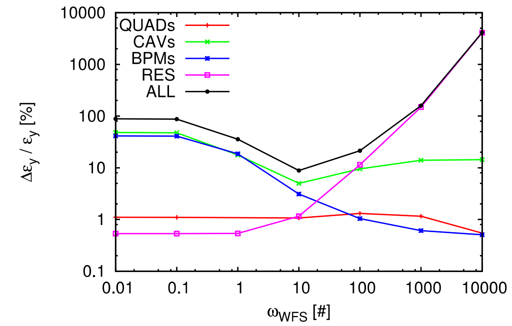
Before correction

After 1 iteration

After 3 iterations

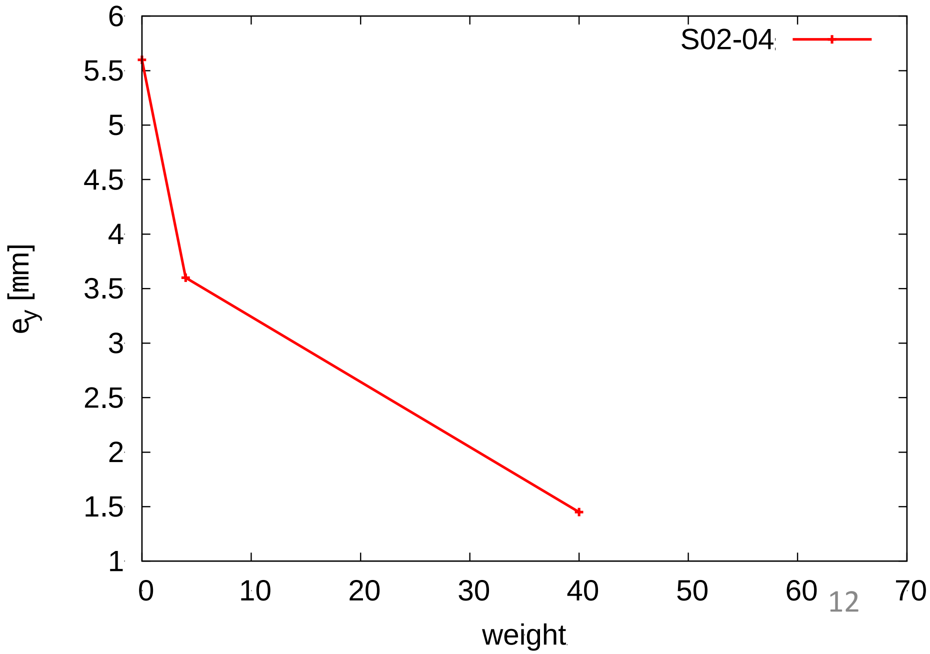
March 2014: WFS correction

LI02-LI04: Weight scan vs. emittance. We tried w = 4, 40, 160, 400 i.
Used 90% of the nominal charge to measure the wakes.



Vertical emittance measured in sector 04 (quad scan)
-w = 0 initial vertical emittance: **0.56 / 1.10**
-w = 4, vertical emittance = **0.36 / 1.63**
-w = 40, vertical emittance = **0.12 / 1.16** (re-measured: 0.17 / 1.20)
-w = 160, emittance not measurable
-w = 400, emittance not measurable

From simulation, one expects something like the black line in the plot:



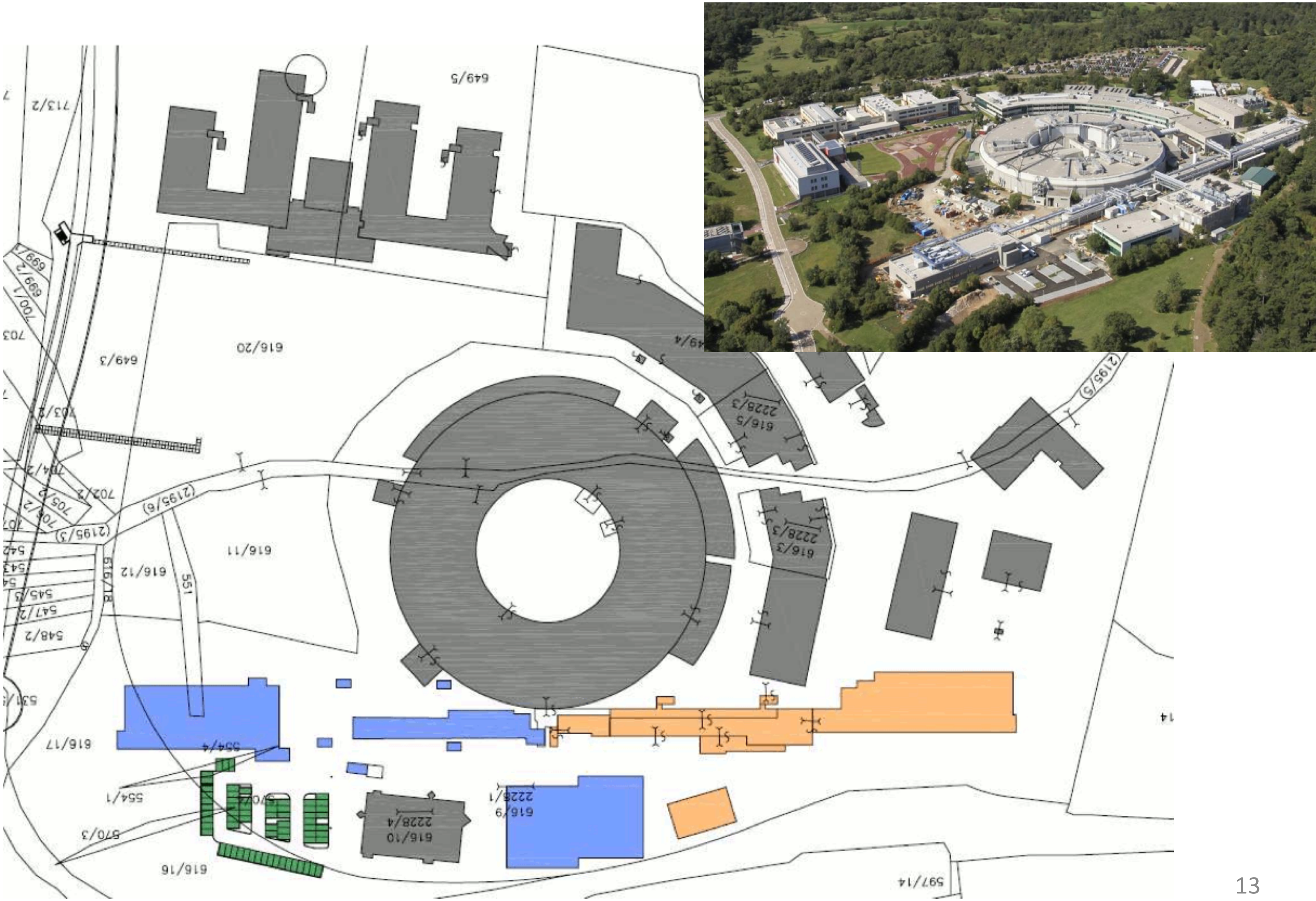
Conclusion:

- Emittance scan gives expected results
- No time for measuring more points

Vertical emittance reduced
From **0.56 ± 0.05 x 10^{-5} m**
to **0.15 ± 0.05 x 10^{-5} m**, in few minutes.

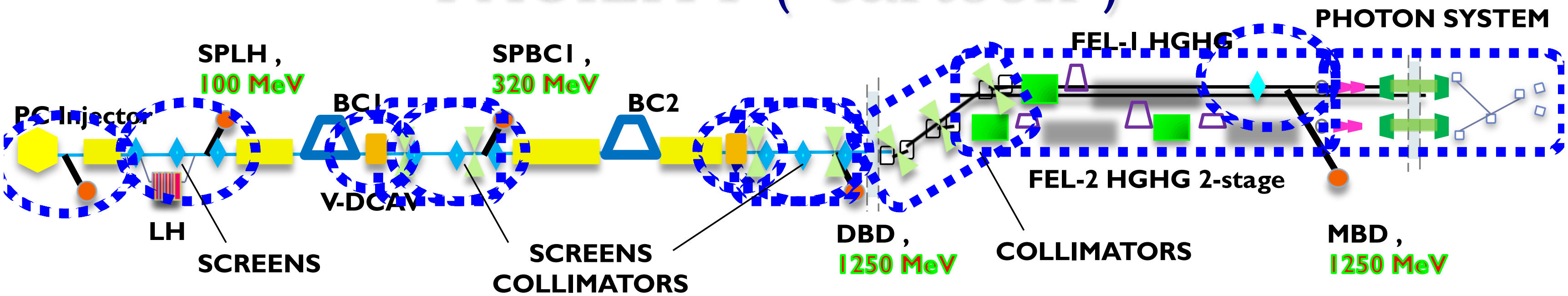
Fermi @ Elettra

Free Electron Laser for Multidisciplinary Investigations



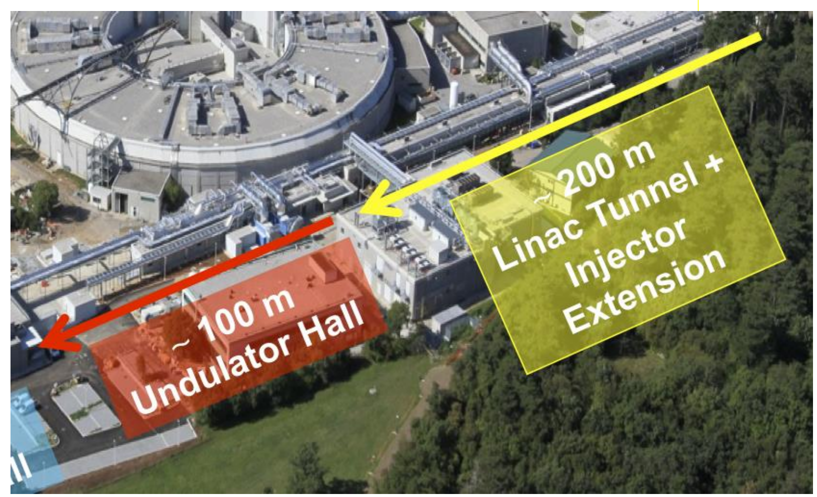
FERMI electron beamlines

FACILITY ("cartoon")



- RF Photo-cathode Gun and Injector + up to1.35 GeV Linac
- 2 Magnetic Bunch Length Compressors + 2 Bunch Length Monitors
- 2 RF Vertical Deflectors for time-resolved measurements
- 4 Diagnostic Stations + 5 Spectrometers
- 3 Collimation sections

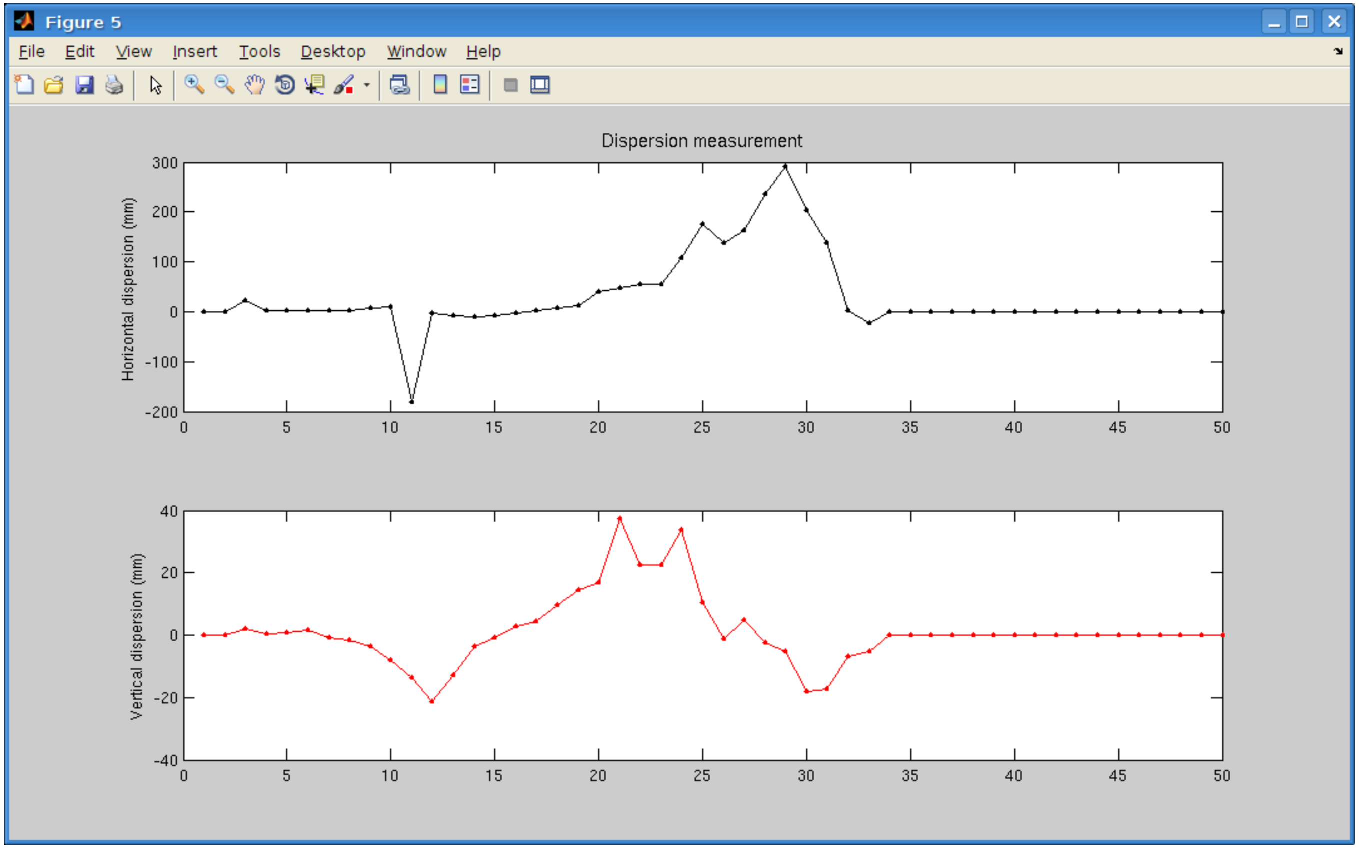
Single-pass FEL w/ 10 Hz repetition rate
Linac energy: from 100 MeV to ~1.2 GeV
Bunch charge: 800 pC
Bunch length: from 1.5 mm to 60 micron
Emittance at gun: ~1.2 mm mrad



Dispersion measurement (before correction)

Sat 05-07-2014, 9:08.

Initial energy dispersion measure with K2 RF AMP:



With S. Di Mitri, G. Gaio, E. Ferrari (Elettra)

Dispersion measurement (after correction)

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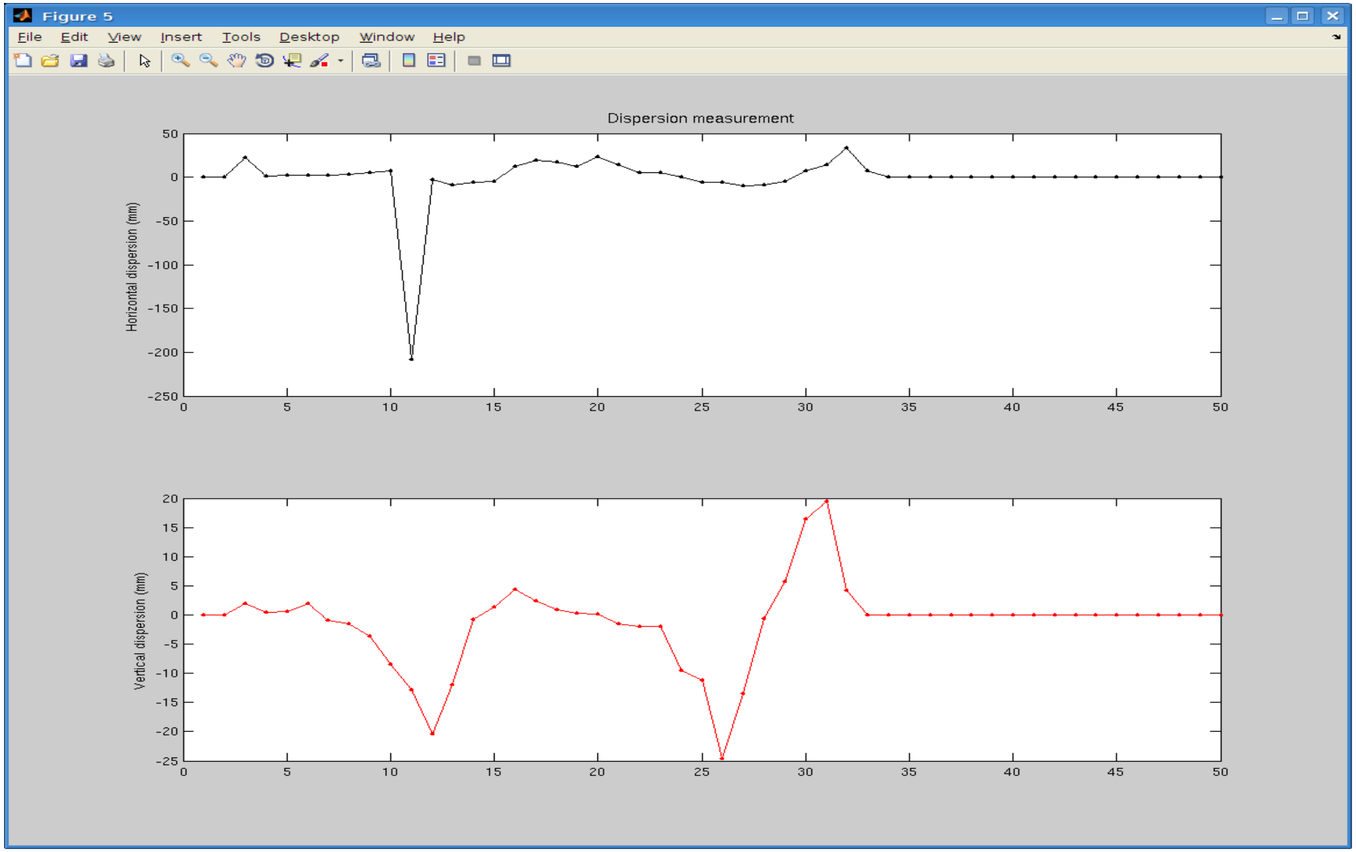


The dispersion correction suppressed by a factor up to 10 in the hor. plane and up to 2 in the vertical. It seems there is a lower limit in the accuracy of the correction around 20 mm energy dispersion, in the region far from the energy change.

Tests of WFS at Fermi@Elettra

To test and scan the efficiency of WFS we decided to excite an even larger emittance in the horizontal plane only, passing from 2.8um to 4.5um with a bump in the horizontal plane only, at bpm_l04.02, from 0mm to 0.9mm offset.

With S. Di Mitri, G. Gaio, E. Ferrari (Elettra)

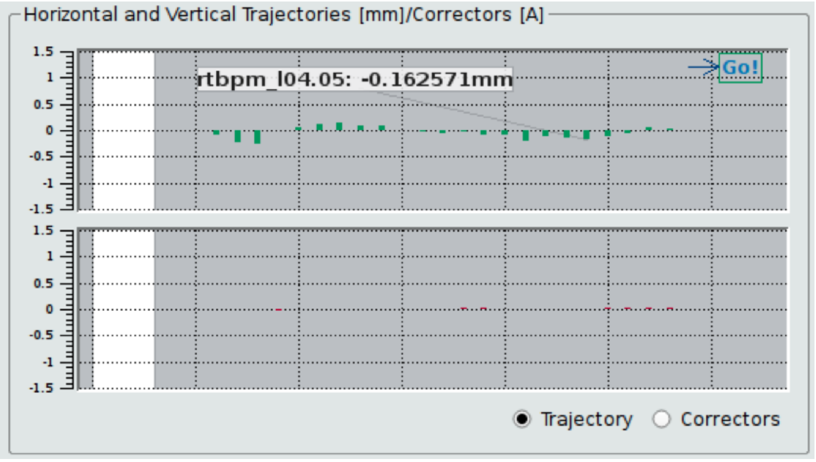
We found the following, as function of the weight on the WFS:

H-Emittance before correction = **4.5um**

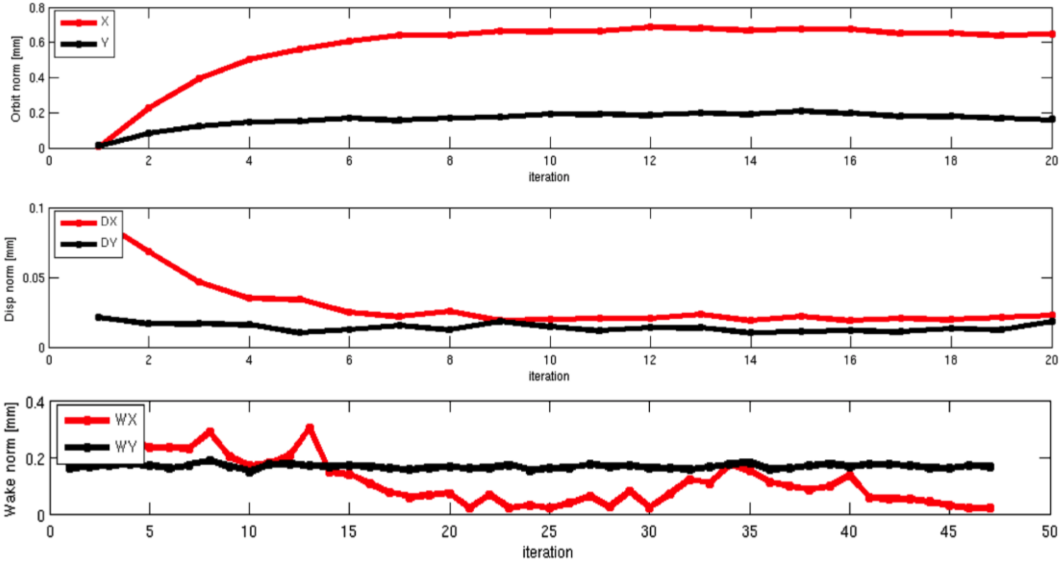
H-Emittance after correction **= 2.84um**

Emittance is totally recovered in just few minutes.

Charge-independent orbit



Orbit, Dispersion, Wakefield convergence (bottom plot)

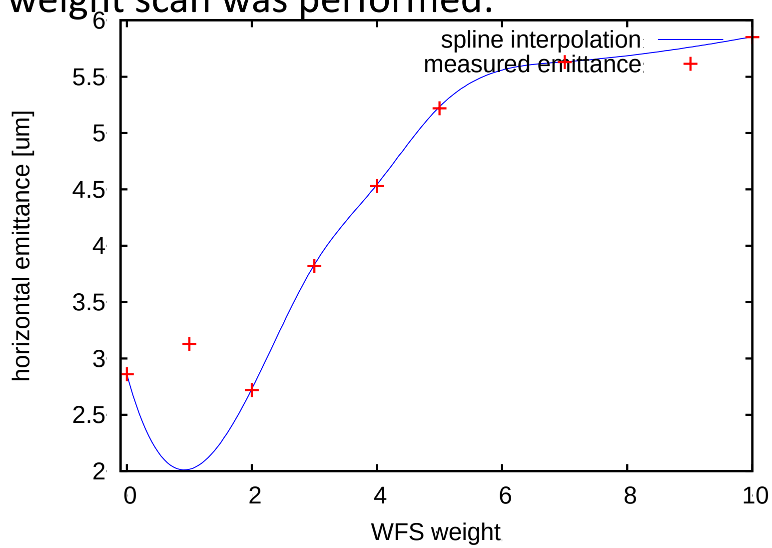


WFS scan at FERMI@Elettra

WFS should reduce the emittance growth of any orbit which is affected by wakefield kicks.
Test charge was -20% of the nominal one.

After removing the horizontal bump introduced earlier, a weight scan was performed:

- w=0: emitt_x = 2.86 um ; 2.89 um
- w=1: emitt_x = 3.13 um (5 SV) ;
- **w=2: emitt_x = 2.72 ± 0.03 um (12 SV) ; (BEST)**
- w=3: emitt_x = 3.82 um (5 SV) ; 3.91 (18 SV)
- w=4: emitt_x = 4.53 um (5 SV) ; 3.88 (15 SV)
- w=5: emitt_x = 5.22 um (5 SV) ; 5.23 (10 SV)
- w=7: emitt_x = 5.63 um
- w=10: emitt_x = 5.85 um



(w=1 is affected by measurement error)

Optimum seems to be for w=2, but one should expect a larger value.

Remembering,

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

With bpm resolution = 5 um, and bpm rms misalignment = 100 um, one should expect:

optimal weight w= ~15

Summary

Results of automatic DFS and WFS have been very promising:

- Dispersion-free and charge-independent trajectories are found
- Vertical emittance gets systematically reduced

Two user-friendly tools have been created, to ease SysID, and to apply the correction in minutes. These tools have been tested at FACET and at Fermi@Elettra FEL

- Application of WFS to ATF2 is foreseen

FACET's limiting factor seems to be the acquisition time of the response matrices, which requires 5 to 6 hours for applying DFS and WFS to 50 correctors. The correction itself needs just few minutes.

Routinely on-line application of DFS is being considered at Fermi.