Verification of Beam-Based Alignment Algorithms at FACET

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Outlook of this talk

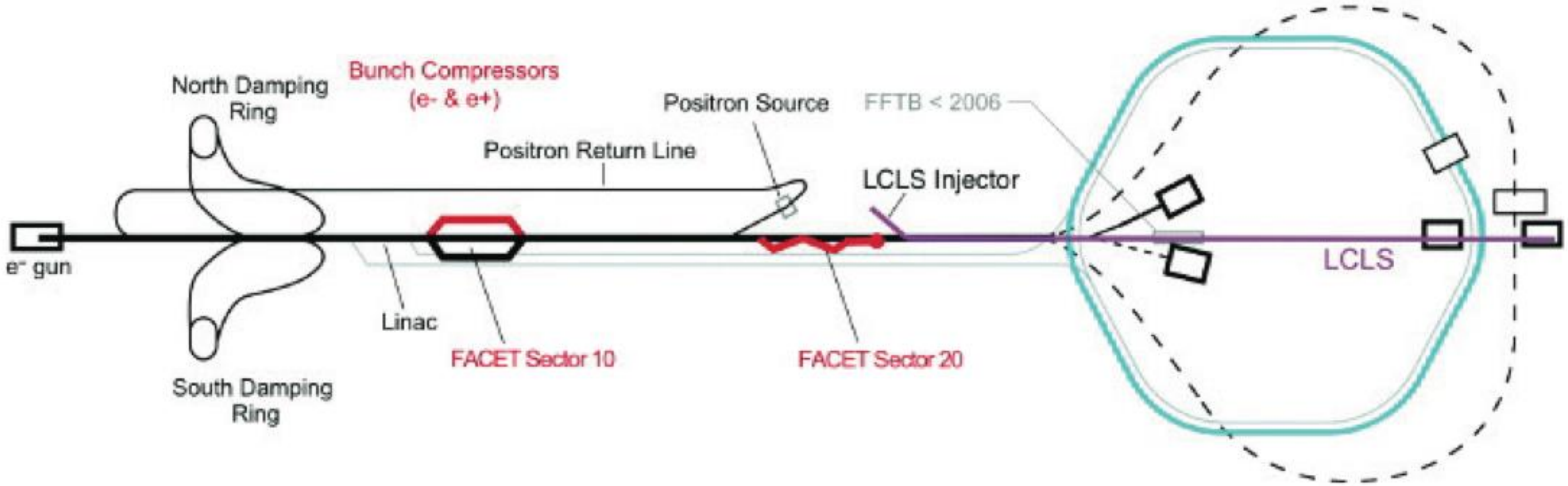
1. FACET scheme - motivations

2. Survey on beam-based techniques
   – Dispersion-Free Steering
   – System Identification

3. Experimental results of DFS: E-211

4. Proposal for a new alignment algorithm, WFS

FACET



- FACET (Facility for Advanced Accelerator Experimental Tests) is a new User Facility at SLAC National Accelerator Laboratory.

- 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.

FACET experiments:

- Plasma wake field acceleration, dielectric structure acceleration,
- Smith-Purcell radiation, magnetic switching, teraherz generation …. and more
- Beam-Based Alignment

Motivation

In a Linac Collider the main linac is one of the most important sources of emittance growth, mainly due to: dispersive and chromatic effects, wakefields

Static imperfections: Misalignments of the elements in the beamline. Possible cures include: excellent pre-alignment, beam-based alignment

Dynamic imperfections:

- ground motion, beam jitter, electronic noise, … Possible cures include : component stabilization, feedback, feed forward, beam-based tuning, …

Beam-based techniques are crucial tools to cure the mentioned imperfections. During the last years a number of automatic beam-based alignment algorithms have been designed, studied and simulated, but never tested on a real linac.

One such techniques is **Dispersion Free Steering**. They rely on **System Knowledge.**

What we propose

We propose a beam-based correction method that is

- Model independent
- Global
- Automatic
- Robust and rapid

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

Simulation of Beam-Based Alignment

- 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

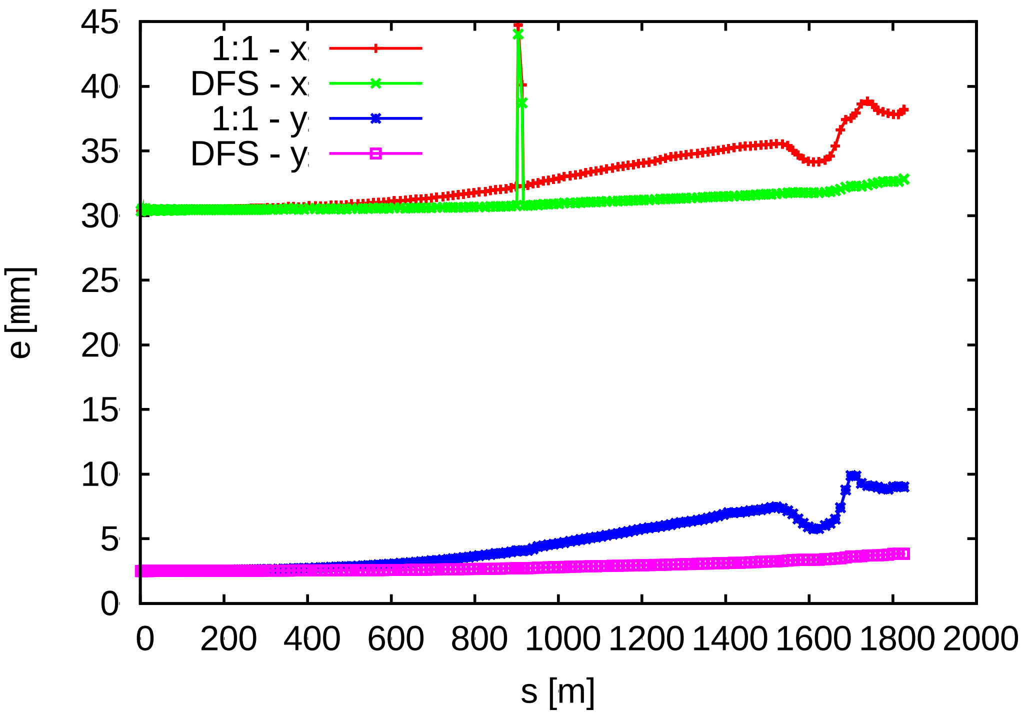
- Misalignment and BPM precision values

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

- Beam-Based Alignment algorithms applied:
  - Orbit Correction, 1:1
  - Dispersion-Free Steering, DFS

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

Simulation: SLC – SLAC Linac



Dispersion-Free Steering principle

Correct the orbit and minimize the difference between the nominal and a dispersive trajectory. Weighted solution:

$$\chi^2 = \sum_{\text{bpms}} y_i^2 + \omega^2 \sum_{\text{bpms}} \left(y_{\Delta E,i} - y_i\right)^2 + \beta^2 \sum_{\text{corrs}} \theta_j^2$$

It is equivalent to solving the system of equations:

$$\begin{pmatrix} y \\ \omega(\eta - \eta_0) \\ 0 \end{pmatrix} = \begin{pmatrix} \mathbf{R} \\ \omega\mathbf{D} \\ \beta\mathbf{I} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_m \end{pmatrix} \qquad \text{with} \quad R_{ij} = \frac{\partial y_i}{\partial \theta_j}$$

It is a least-square problem, that can be solved with SVD techniques.

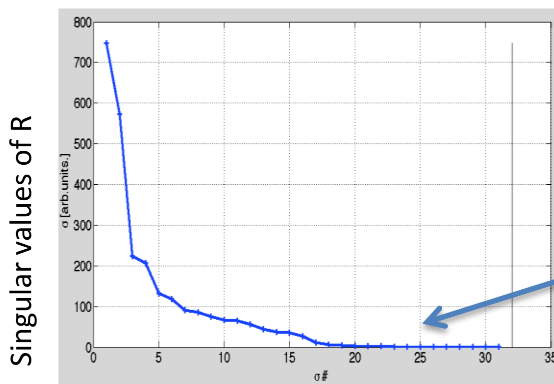
The free parameter ω accounts for the relative weight of the orbit w.r.t. the dispersive term ; β is a regularization parameter to modify the condition number of the system matrix.

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

The response matrix

Special care is needed for preparing the response matrix, because the response matrix impacts the performance of BBA algorithms in many profound ways:

- **It represents the optics**
- **It might be ill-conditioned**: an ill-conditioned matrix leads to an inaccurate solution of the system of equations



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

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

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

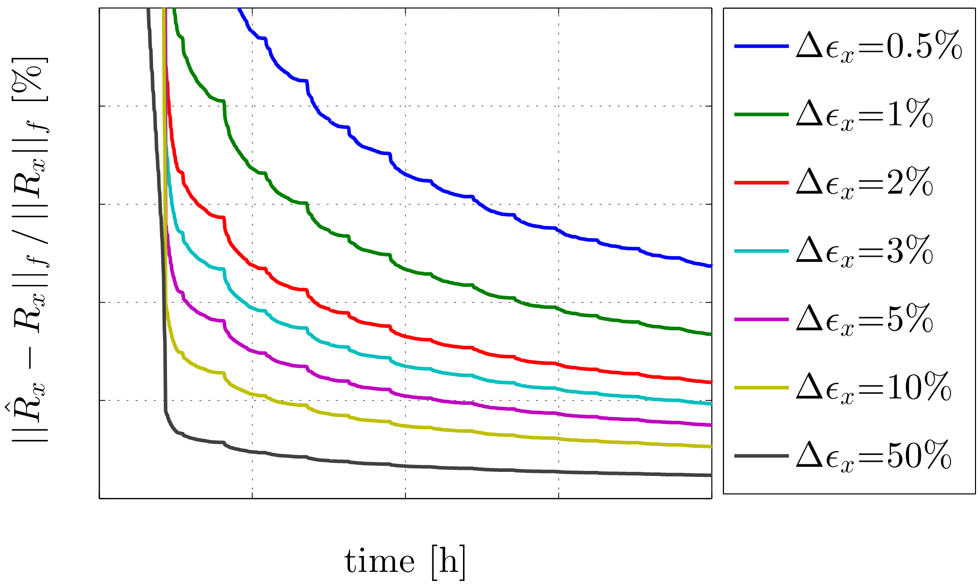
We propose an algorithm that *learns the optics* : **System Identification (or SYSID)**

System Identification Algorithms

We use an automatic **kick-measurement system identification algorithm,** where the model is inferred recursively using a Recursive Least-Square method.

J. Pfingstner at A. Latina, *"Feasibility study of system identification of orbit response matrices at FACET"*, CERN-OPEN-2012-020, CLIC-Note-947

Simulated SysID convergence



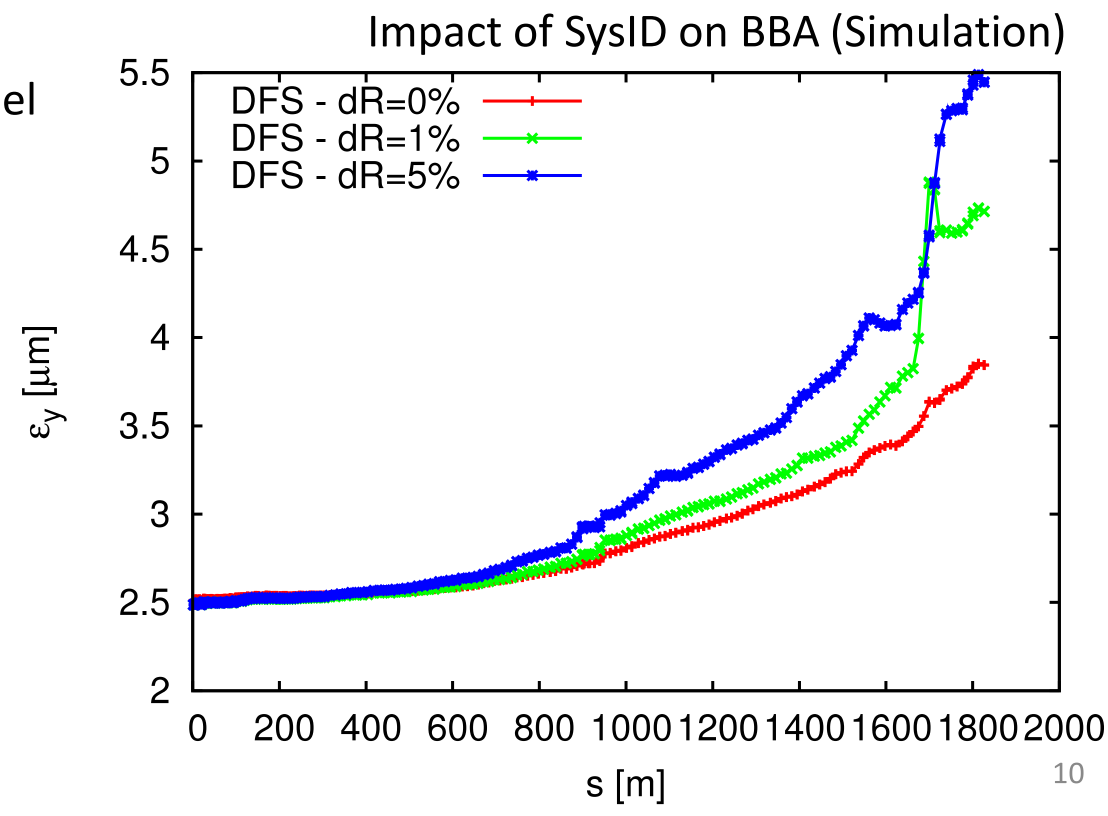
The plots shows how the time of convergence varies with the excitation. This is equivalent to showing how the time of convergence varies with the BPM precision.

Response matrix and Beam-Based Alignment

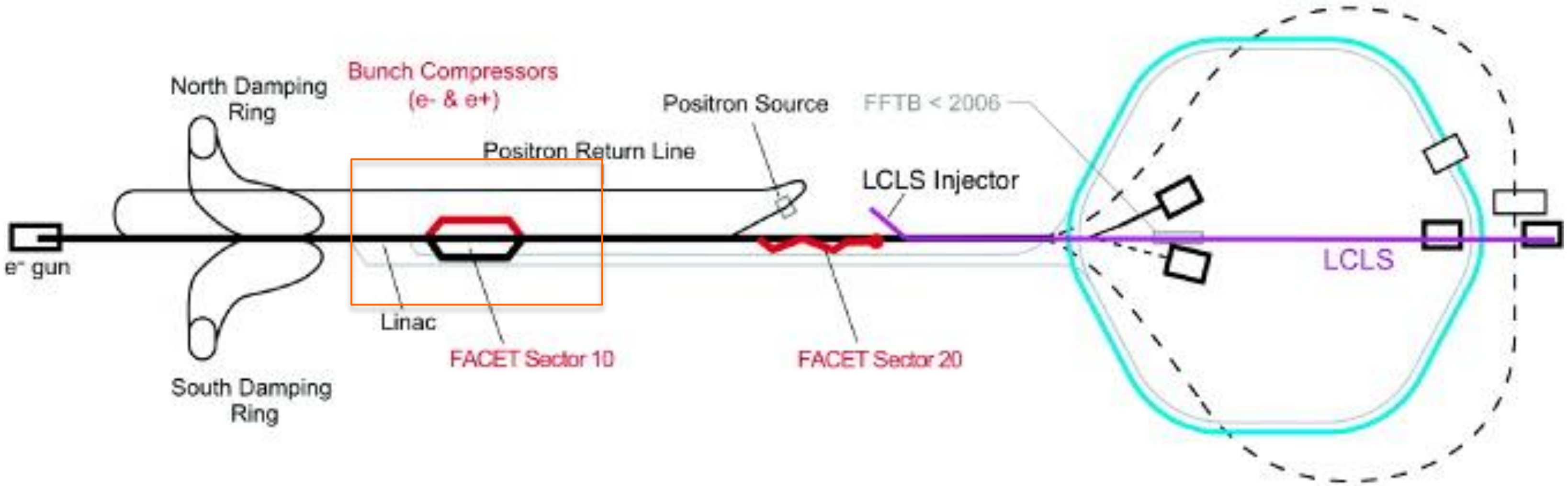
In simulation we utilize an idealized model that in reality we don't know.

The figure shows the emittance growth after dispersion-free steering, using an imperfect model. The result is the average of 100 seeds.

- Red line : the ideal optics model
- Green line : an optics model incorrect by 1%
- Blue line : an optics model incorrect by 5%



Experimental Setup, March 2013



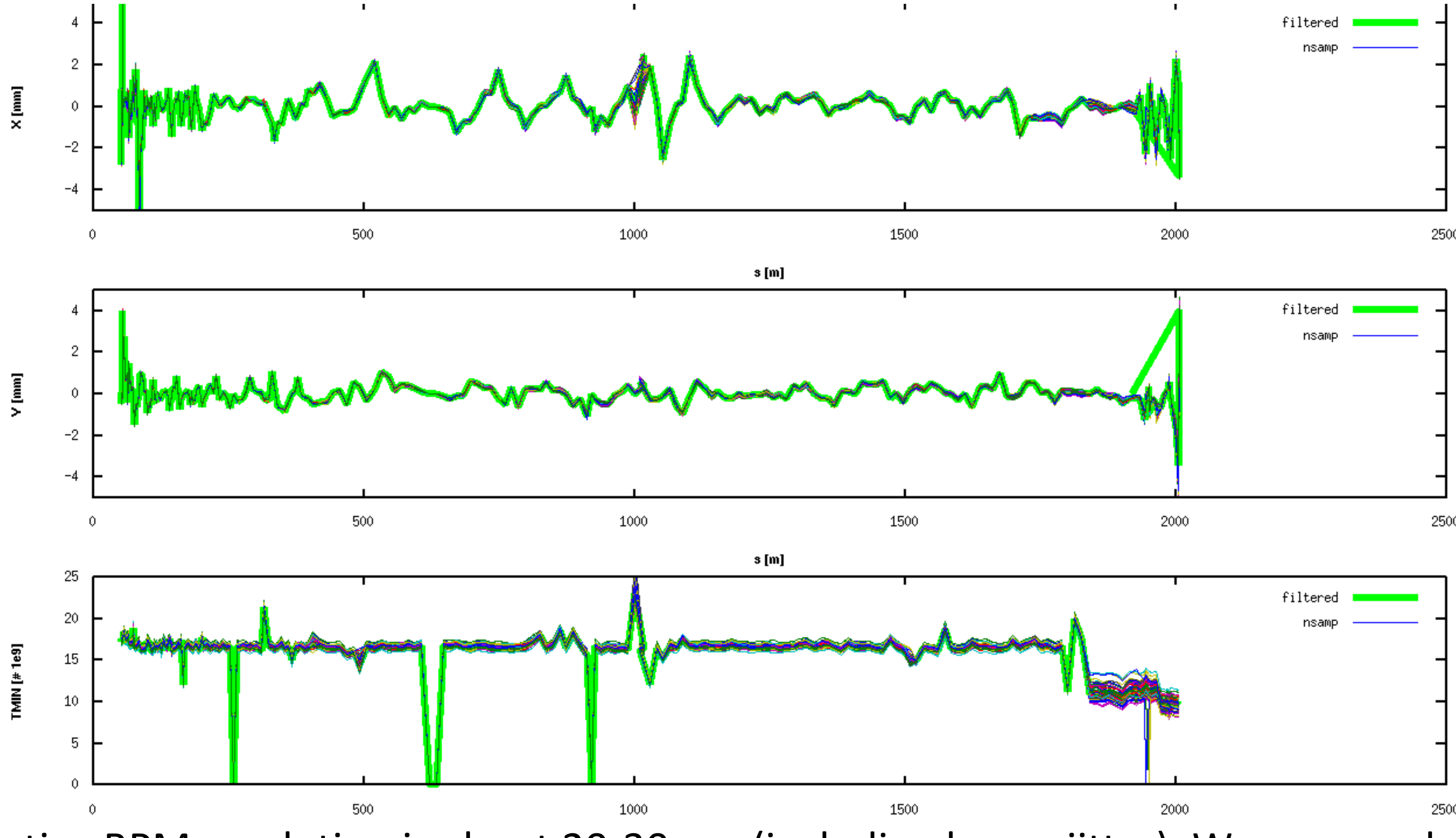
- We run with a ‘pencil beam’
  - 1 nC charge

- Linac was in *no compression* mode
  - 1.0-1.5 mm bunch length

  (reduced wakes w.r.t. max charge 3.2nC, but still quite long bunches)

- We focused on sectors **LI04 thru LI08** (500 meters of Linac)
  - We used 52 correctors and 52 bpms (one every two)
  - Dispersion was created off-phasing (by 90^o) one klystron in sector LI03

Golden Orbit and BPM resolution



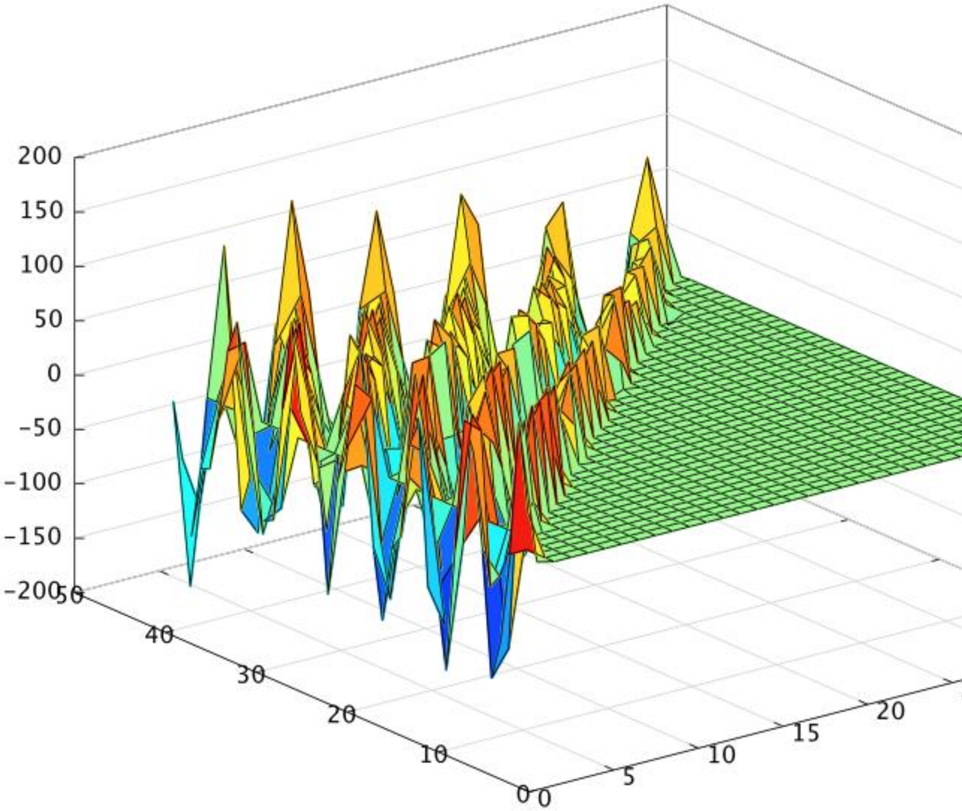
The effective BPM resolution is about 20-30 um (including beam-jitter). We averaged the BPM readings over 100 pulses, reaching an equivalent BPM resolution of:

Sx = 3.3 microm

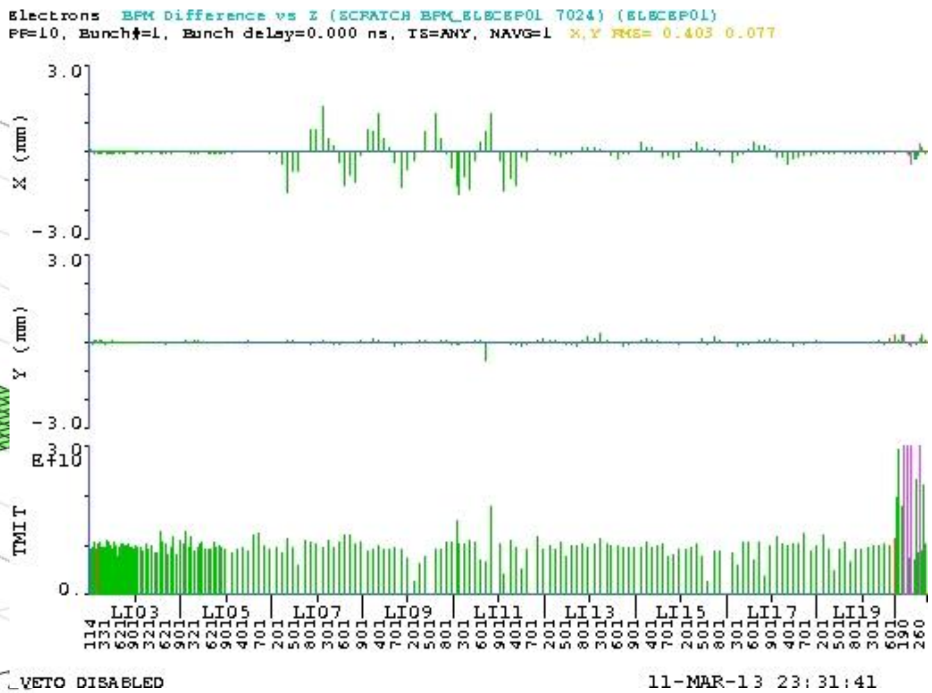
Sy = 2.5 microm

Results: SysID + orbit control

- Focused on Sectors 04 through 08 (500 m of linac)
- Used 52 correctors in total (1h15 acquisition time)
- Measured orbit and dispersion (2h30 in total)
- Applied Orbit and DFS



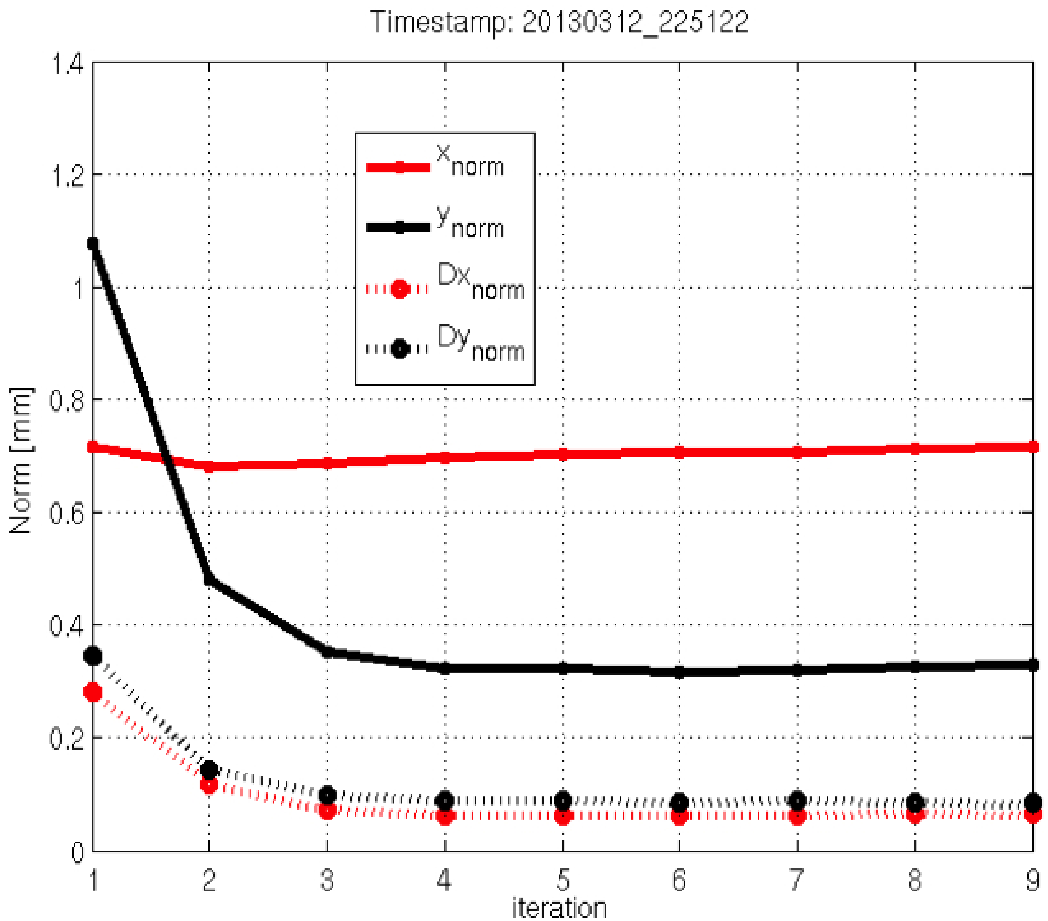
We excited a bump in X



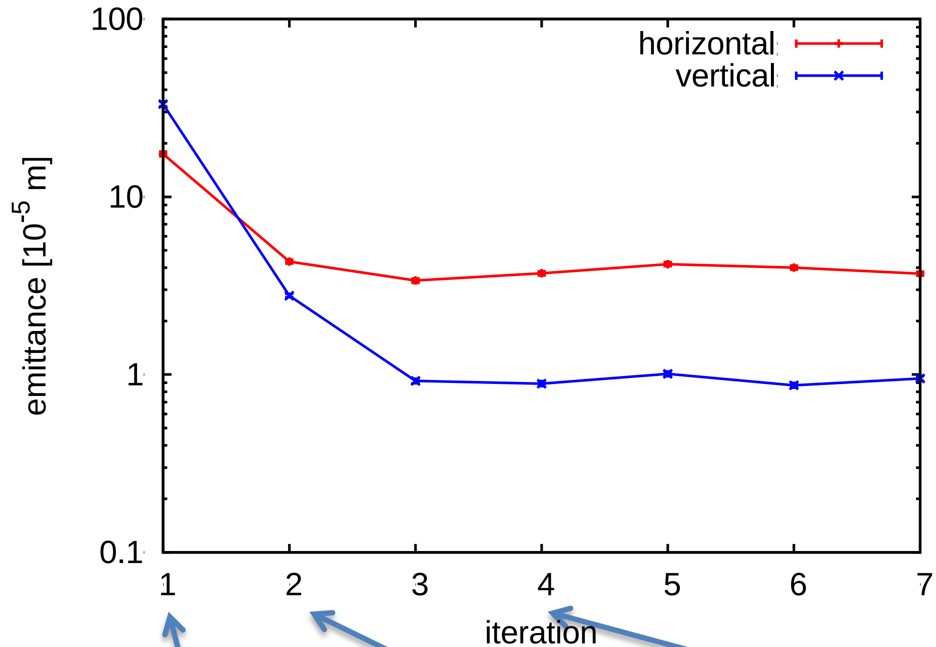
Dispersion-Free Steering

First Dispersion correction: dispersion was measured and corrected. We iterated DFS a few times with SVD cut 0.90, and gain 0.75.

Dispersion is reduced by a factor 3-4 in X and Y.



Emittance Growth and Dispersion-Free Steering



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

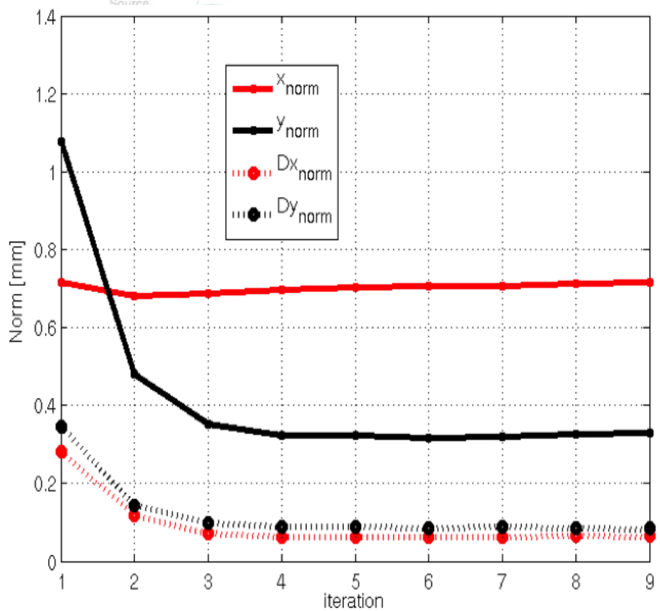
After 1 iteration

After 3 iterations

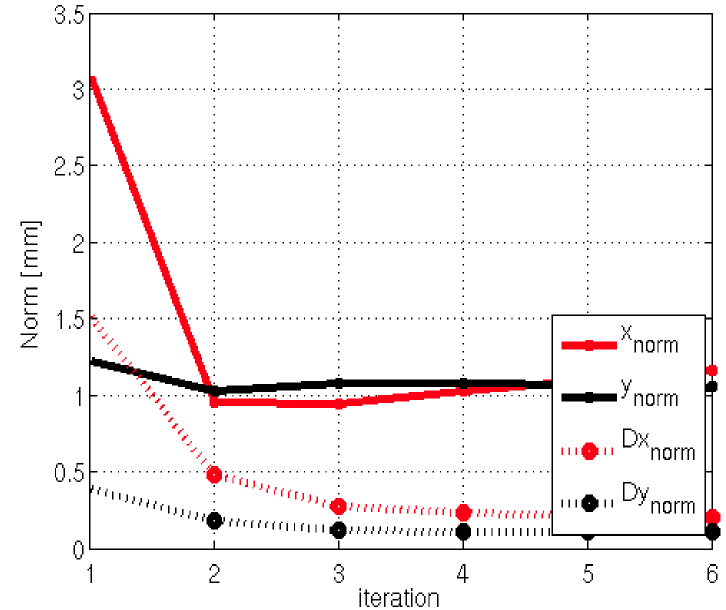
Flight Simulator

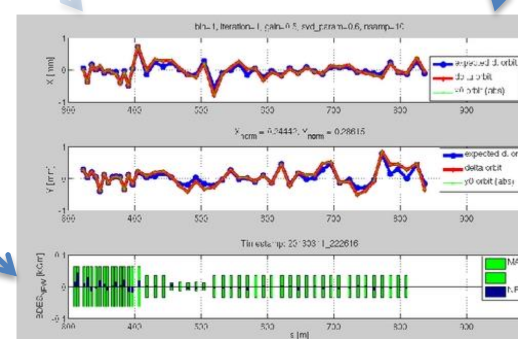
Extensive analysis of the space of parameters

Real Data



Simulated Data (PLACET)





Our BBA routines (Matlab)

Conclusions from this experiment

- We have demonstrated the proof of principle of a model-independent, global, automatic, dispersion-free correction algorithm on 500 m of the SLC linac
- We have demonstrated the performance of a machine system identification algorithm and its validity over hours and even days
- The DFS algorithm rapidly and robustly converged to a solution where the difference of a nominal and a dispersive orbit is minimized
- Applying DFS lead to an emittance reduction in the first half of the SLC linac

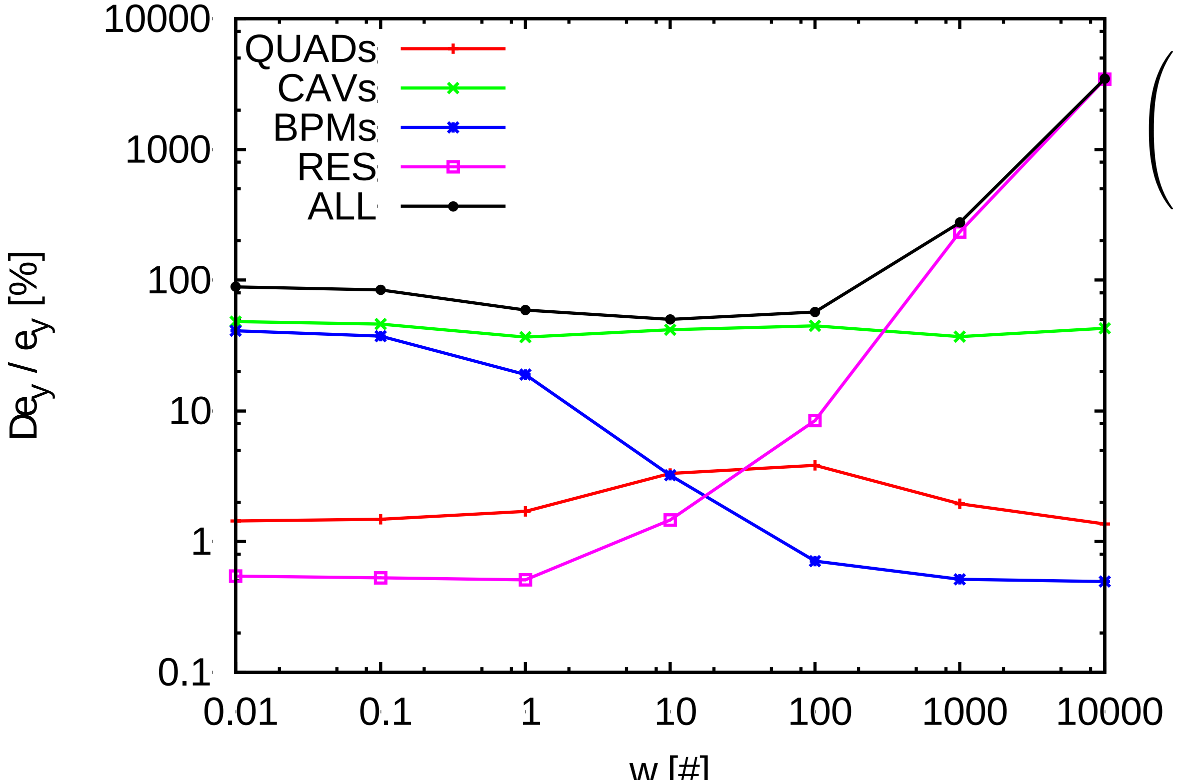
…Flattening Sectors 11-18

- On the spur of our success we attempted to correct the second part of the linac: LI11-18 (900m)
- We managed to flatten orbit and reduce the dispersion (gaining a factor 3 in both axes)
- But the emittance did not improve
  - The reason being, probably, that with such long bunches the wakefield-induced emittance growth was larger than the dispersive one
- So, we studied a new algorithm…

Analysis of DFS

- Lattice v31 of the optics, 2e10 bunch charge 3.2 nC
- Emittance growth for each individual imperfection

Simulation



DFS equations

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

Scan of the weights, ω:

- Small weight : 1:1 correction
- Large weight : DFS correction

Wakefield-Free Steering (WFS)

- In DFS one measures the system response to a change in the energy
- In WFS one measures the system response to a **change in the charge**

  (for the test beam we used 80% of the nominal charge, i.e. ~2.6 nC)

Recall: the DFS system of equations

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

We propose: the WFS system of equations:

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

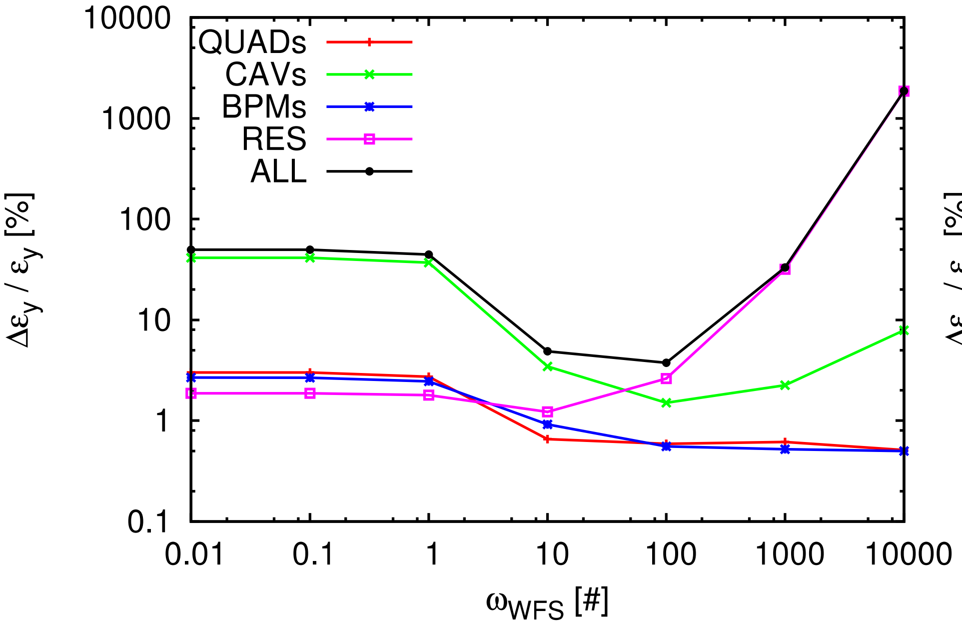
The success is not obvious: DFS relies on an effect which affect the bunch as a whole; WFS relies on an effect with act **within** the same bunch!

Analysis of WFS

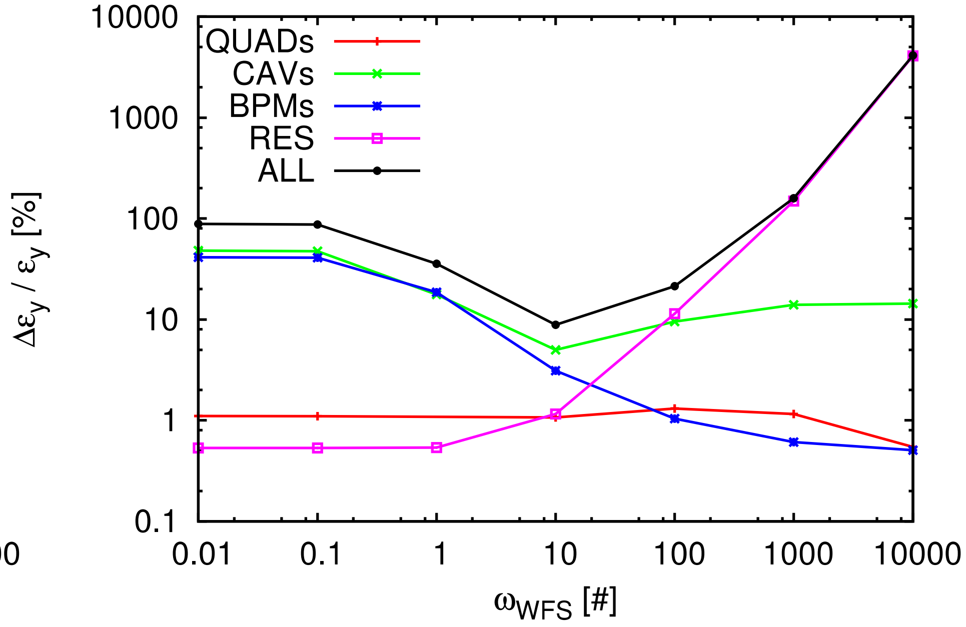
Simulation of each individual imperfection in two cases

- DFS+WFS (longer learning time for the SysID)
- WFS only

Simulation: DFS+WFS



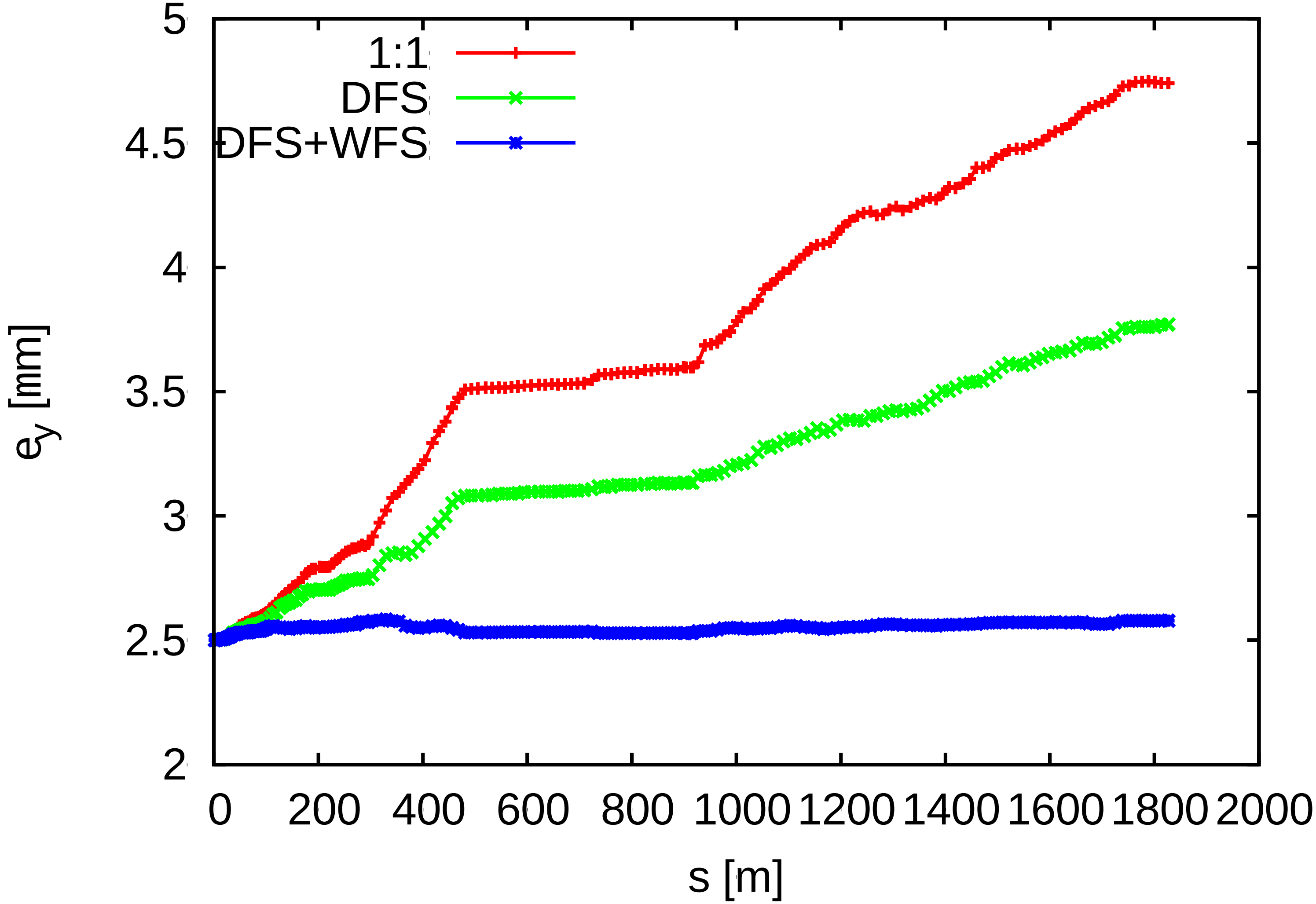
Simulation: WFS only



There is a significant improvement in the emittance.

Emittance growth along the SLC linac

Simulation. Nominal beam: q=2e10 e^- ; WFS test beam: q=1.6e10 e^-



WFS implementation and test at SLAC

- It occurred: Last week!

- WFS requires a test beam to measure the wakefield response:
  - Modify the bunch charge (we used 80% of nominal charge)

Potential issues intrinsic to WFS:
- The test beam must be transported through the uncorrected linac
- The impact of the wakes on the orbit might be difficult to measure for very short bunches

First tests:
- Very promising results – although preliminary
- Worked on first 200 meters of linac, with **all** correctors:
  - Vertical emittance reduced from 4.4 um to 2.0 um
  - 2.0 um was the measured injected emittance!

Summary

- ✓ E-211 was successful: Dispersion-Free Steering has proven to be effective in reducing the dispersion and the emittance

- For wakefield-dominated linacs a new technique, designed to reduce the impact of the wakes, is presented: Wakefield-Free Steering (WFS)
  - Although WFS presents some additional difficulty and risks w.r.t. DFS, in simulation significantly reduced the emittance growth in SLC

- ✓ WFS has been tested on the first 200m of SLAC linac with very promising results (vertical emittance reduced from 4.4 um to 2.0 um -> it is the nominal value!) - more measurements needed

- ✓ WFS might be attractive also for other projects (ATF2)