

# Transverse tolerances, correction methods and feedback strategy

30/06/2010

CANDLE-DESY-PSI collaboration workshop

Masamitsu Aiba, PSI

Acknowledgements: M. Böge, H. Braun, M. Calvi, T. Garvey, B. Keil,  
S. Reiche, V. Schlott and T. Schmidt

- Introduction
  - BPM system
  - Survey-based alignment
  - Beam based alignment
  - Feedback
  - Summary
-

- Orbit correction and feedback for SwissFEL
    - is of importance because of the lasing strategy with relatively small emittance and low energy (0.18~0.43 mm.mrad, 5.8 GeV)
    - Study to set up an overall scheme
      - Transverse tolerances have been defined (see Beutner's talk for longitudinal tolerances)
      - Investigations on BBA and feedback with simulation (ELEGANT, MAD)
-

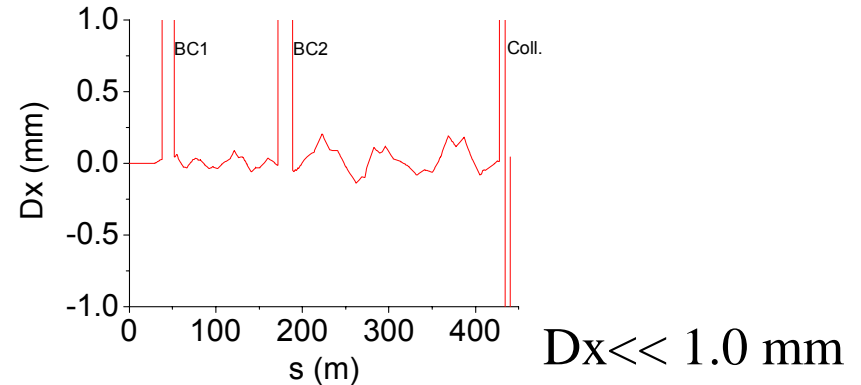
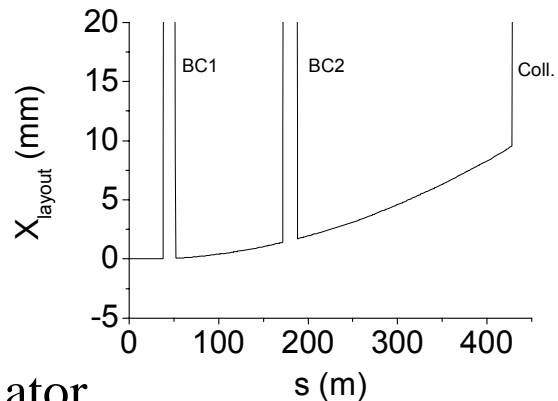
# BPM system

---

	# of BPMs	Type	Noise (StoS)	Remarks
Linac	~120	Cavity BPM	3~5 $\mu\text{m}$ rms	10-200pC, 50ns bunch spacing
Undulator	~20	Cavity BPM	<1 $\mu\text{m}$ rms	Single-bunch (100-400Hz)

- E-XFEL: Switzerland/PSI designs BPM electronics
  - SwissFEL BPM baseline: Cavity BPMs for linac & undulators
    - High resolution & low drift at low charge
    - Higher performance than striplines at comparable costs
    - Unified system: Reduce development/maintenance effort
    - Adaptation of E-XFEL electronics to 10x lower charge (100pC  $\rightarrow$  10pC) & shorter bunch spacing (222ns  $\rightarrow$  50ns) needed. R&D on improvements & alternatives (e.g. resonant striplines, used in SwissFEL test injector).
-

- Long-range
  - Linac
    - Several mm long-range distortion (without reference straight)
      - Result in  $\ll 1$  mm spurious dispersion - not an issue



- Undulator

- Long-range distortion could be small enough for  $\sim 80$  m undulator section

- Short-range

- Linac and Undulator

- $\sim 50$   $\mu\text{m}$  rms
  - Orbit and dispersion error should be minimized with BBA

## Tolerance / Sensitivity

Alignment  
tolerances/sensitivities

Remarks

Linac short range	50 $\mu\text{m}$ rms	“what we can do” with survey
Linac long range	Several mm	Smooth distortion over $\sim 500$ m linac
Undulator Quad.	$< 7 \mu\text{m}$ max*	BBA not included/applied
Undulator	$< 125 \mu\text{m}$ max*	Vertical

Beam orbit  
tolerance/sensitivity

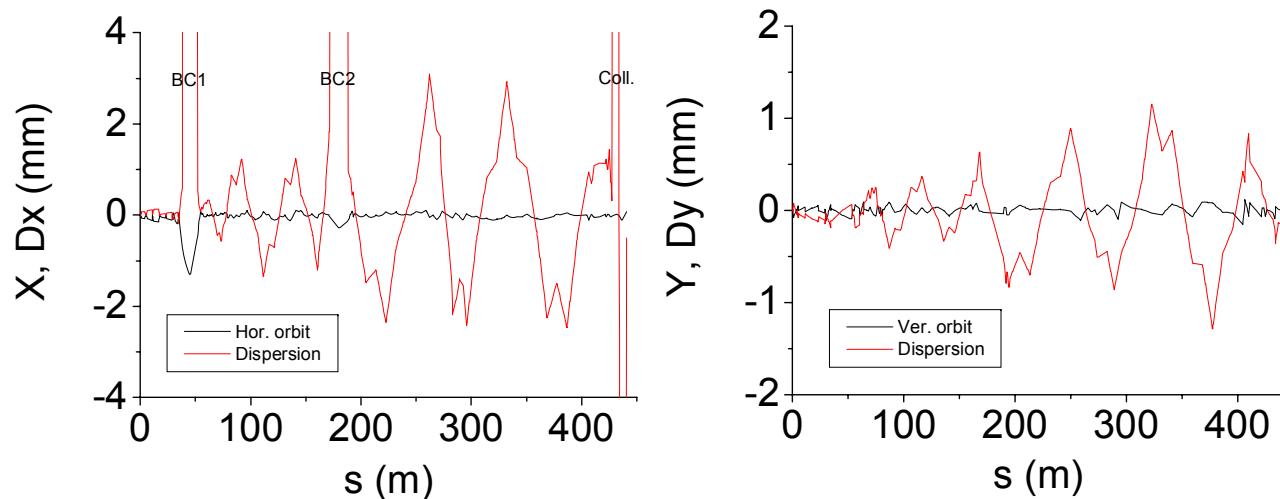
Remarks

Linac	100 ~ 200 $\mu\text{m}$	Correspond to the dispersion of a few mm Probably smaller number for Single Spike mode
Undulator	$< 10 \mu\text{m}$ rms straightness*	$1\sigma \sim 24 \mu\text{m}$ @ $\beta=15$ m ( $\varepsilon_{\text{rms}}=0.43 \mu\text{m}$ , 200 pC mode)

\* Sensitivity where the FEL power  $\sim 40\%$  down  
 $\rightarrow$  Tolerance several times smaller than sensitivity

- Correction scenario for the linac
  - Quick steering for the early stage of commissioning
    - Steer the electron beam to go through BPMs' center
  - Beam Based Alignment
    - BPM re-alignment/calibration (offset) for  $>50\sim 100\ \mu\text{m}$  alignment error
    - Quad re-alignment for  $>50\sim 100\ \mu\text{m}$  alignment error
    - No BBA for RF cavity is foreseen (Tolerance: Quad  $\ll$  RF cavity)
  - Beam Based Steering
    - Dispersion Free Steering (main option)
    - Ballistic Alignment (back-up)
    - D' knob using local orbit bump at Q (additional)
  - Hardware
    - Injector / main linac BPMs:
      - Start with  $\pm 5\ \text{mm}$  range & low charge.  $30\sim 50\ \mu\text{m}$  rms noise acceptable
      - Then change signal attenuation to have  $\pm 500\ \mu\text{m}$  range,  $3\sim 5\ \mu\text{m}$  rms noise
    - Corrector integrated into Q magnet
    - Manual girder/component re-alignment

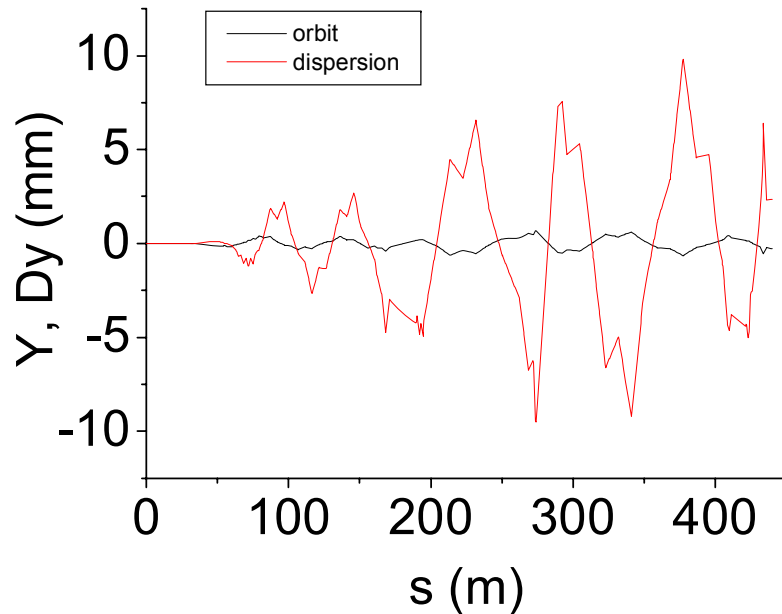
- Quick steering for the early stage of commissioning
  - Steer the electron beam to go through BPMs' center
  - Orbit/dispersion quality depends on the initial alignment
  - Simulation: Earth's field (assume no shielding  $B_y \sim 40 \mu\text{T}$ ,  $B_x \sim$  negligible) + BPM alignment error ( $50 \mu\text{m}$  rms)



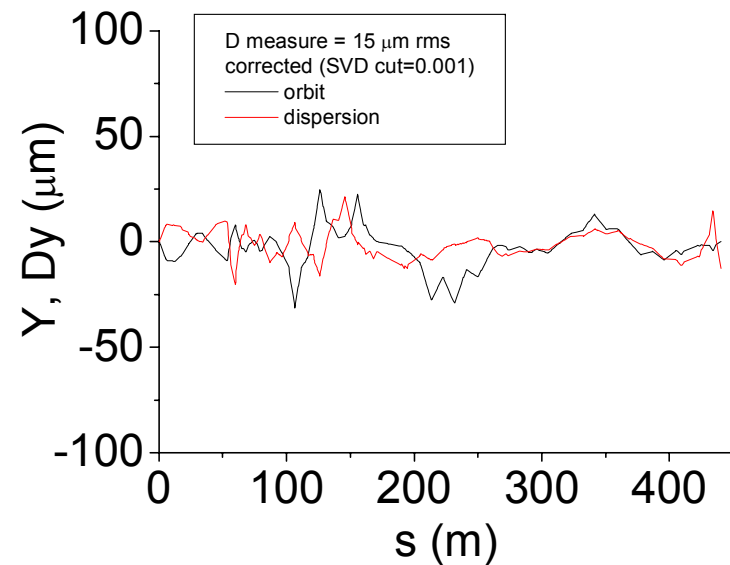
Result in a few mm dispersion not so bad for Day-1  
Earth field will be attenuated by a factor of 5~8

- BBS – Dispersion Free Steering
  - Dispersion measurement error = the order of  $15\ \mu\text{m rms}$  ( $3\ \mu\text{m rms} / 20\%$ )
  - Simulation: Dispersion measurement error  $45\ \mu\text{m max}$  ( $15\ \mu\text{m rms}$ )

Before steering

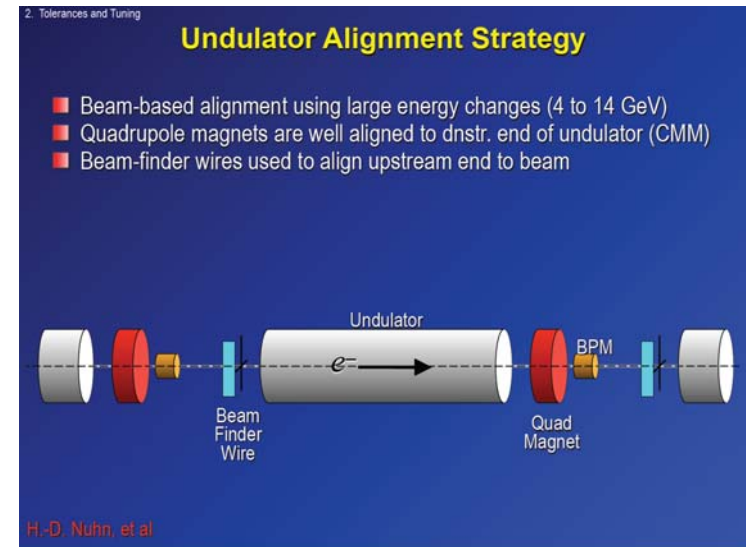


After steering



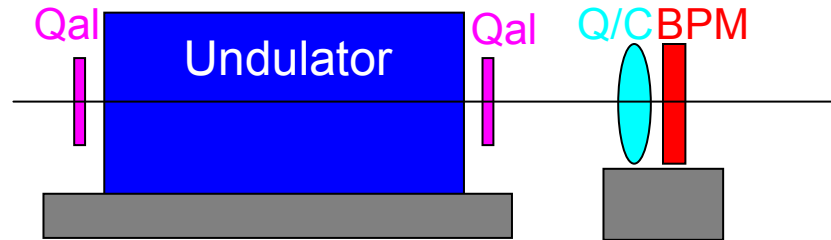
Residual orbit/dispersion  $\sim$  Dispersion measurement error

- Correction scenario for the undulator
  - LCLS BBA method modified for the SwissFEL
    - Quad may move ( $\sim 5 \mu\text{m}$ ) due to gap change if it is on the same girder to undulator
    - Alignment quad instead of beam finder wire
  - Hardware
    - Cavity BPM  $< 1 \mu\text{m}$  rms
    - Q magnet mover  $\sim 1 \mu\text{m}$
    - Weak corrector integrated into Q
    - Undulator girder mover  $\sim 10 \mu\text{m}$
    - Photon beam diagnostics after the undulator section



- Correction scenario (cont'd)

- Layout

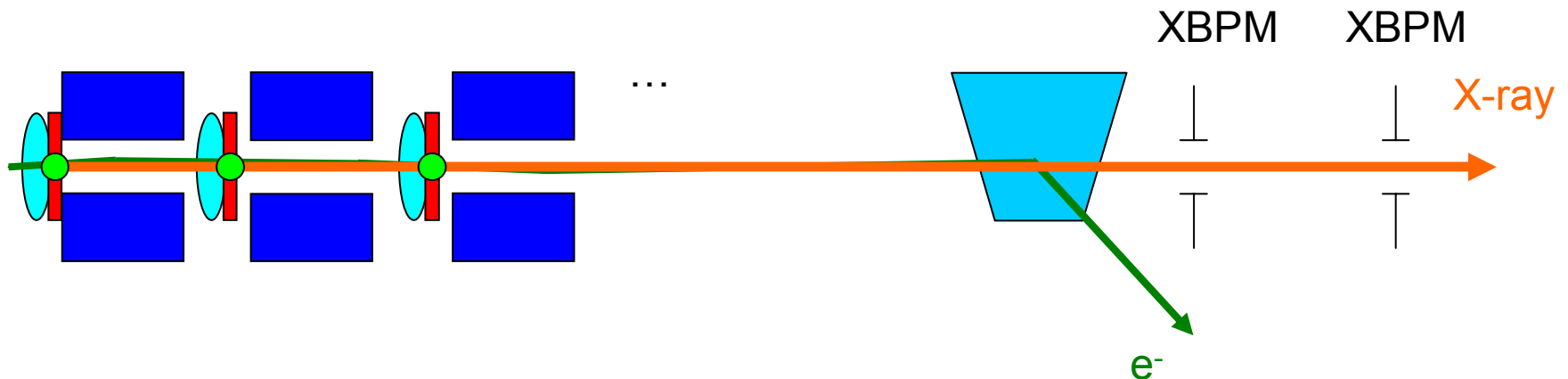


- Procedure

- 1) Open all undulator and align quadrupoles
  - Tolerance on orbit straightness  $\ll 10 \mu\text{m}$  rms (sensitivity)
    - » A few  $\mu\text{m}$  alignment is feasible with precise BPM
- 2) Align undulators with alignment quad
  - Tolerance on vertical position  $\ll 125 \mu\text{m}$  (sensitivity)
    - » Positioning resolution  $\sim 10 \mu\text{m}$  with girder mover
    - 1-by-1 as compensating kick due to undulator with correctors
      - » 3-bump of corrector-undulator-corrector
- 3) Adjust phase and K
- 4) Iterate 2) and 3), Fine tuning
  - Looking at FEL performance

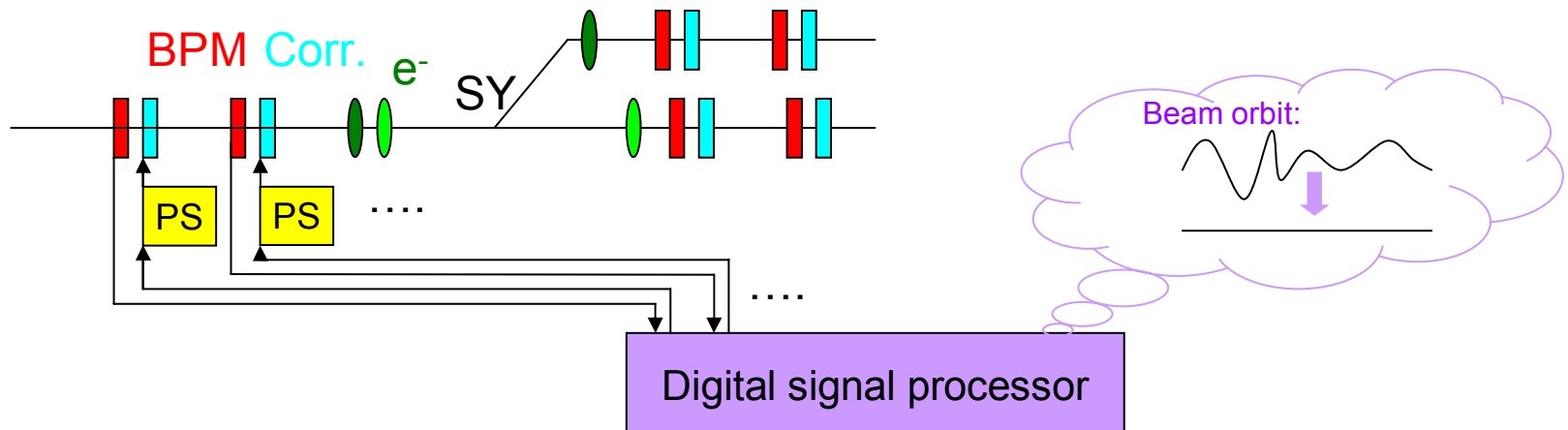
Start with 2)  
for gap change

- Alternative – Photon beam based alignment



- 1) Close undulator one by one, and steer e-beam as X-ray going through XBPM
- 2) Record aligned electron beam orbit
- 3) Close all undulator and reproduce the aligned orbit
- 4) Fine tuning, K tapering, phase

- System outline (Fast orbit feedback)
  - Feedback correction rate 100 Hz (or 400 Hz)
  - Latency 2.5 ms (400 Hz compatible)
  - Corrector power supply with several kHz bandwidth (PSI in-house know-how of the SLS corrector PS)
  - Laminated magnet and thin steel beam pipe to suppress eddy current
  - One possible topology: Feedback based on the first bunch position up to switchyard and individual bunch afterwards

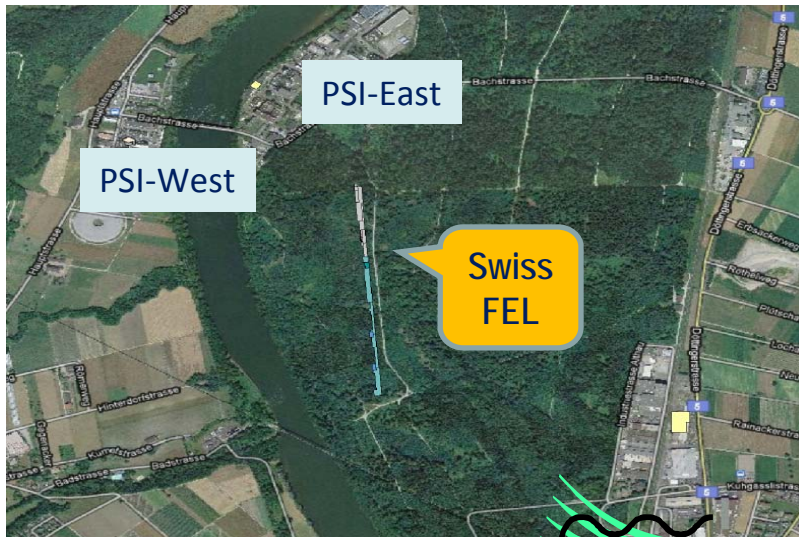


- Feedback strategy
  - Measure and analyze beam motion with open loop
  - Optimize PID feedback parameters then close the loop
  - Correction algorithm based on SVD matrix inversion
  - Harmonic suppression can be applied
- Tolerance/Sensitivity

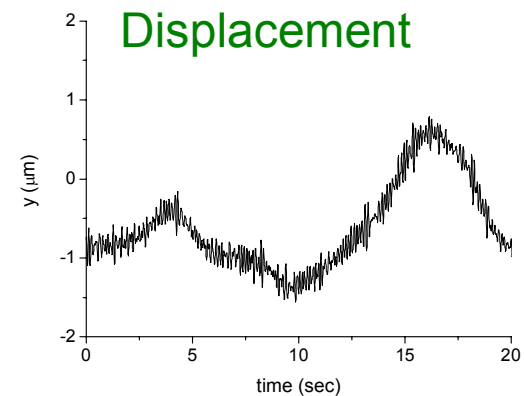
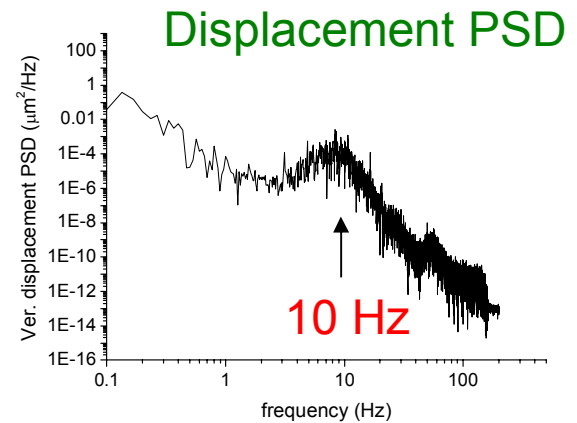
	Beam orbit fluctuation tolerance/sensitivity (@ 0dB)	Remarks
Linac	50 ~ 150 $\mu\text{m}$	Tolerance for emittance preservation, Assuming that BBA is well done (<50 $\mu\text{m}$ )
At undulator entrance	0.6 $\sigma^*$	Sensitivity for lasing ( $\sim 0.1\sigma$ tolerance) Correspond to 10 $\mu\text{m}$ rms straightness* in undulators

\* Sensitivity where the FEL power  $\sim 40\%$  down

- SVD+PID numerical exercise (simulation)
  - Disturbance: Ground motion of SwissFEL site

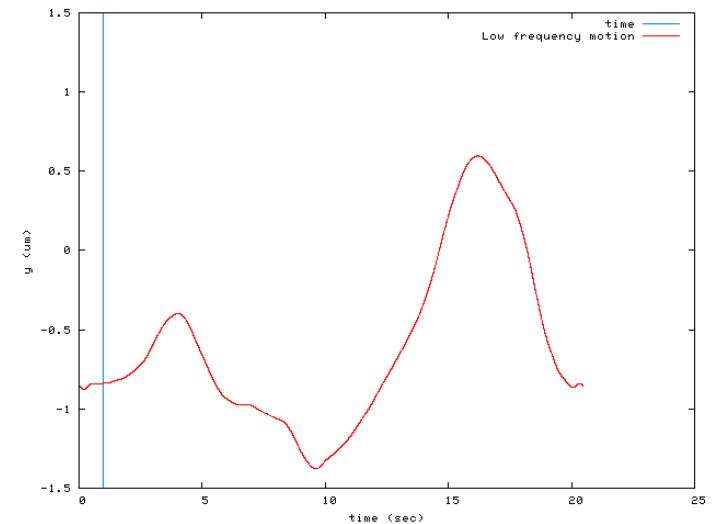
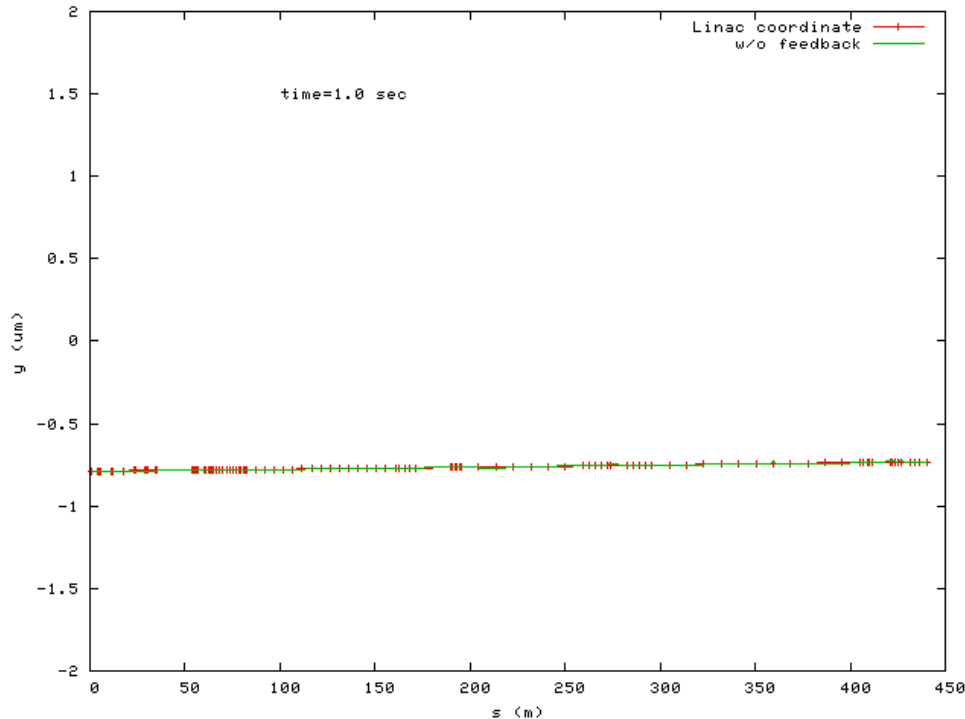


Cement  
factory



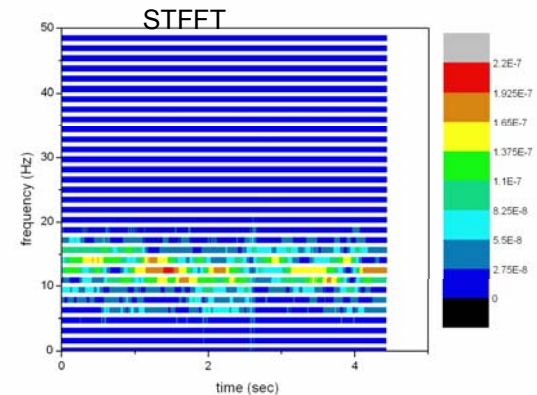
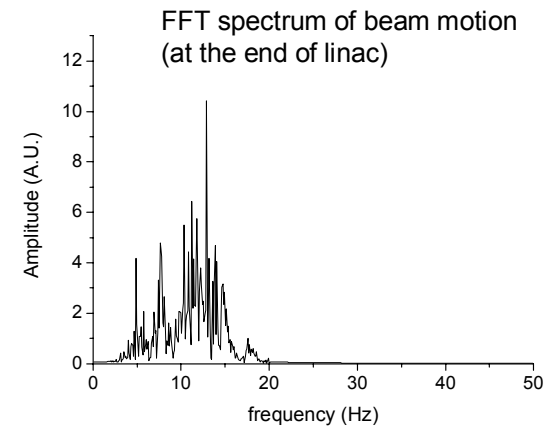
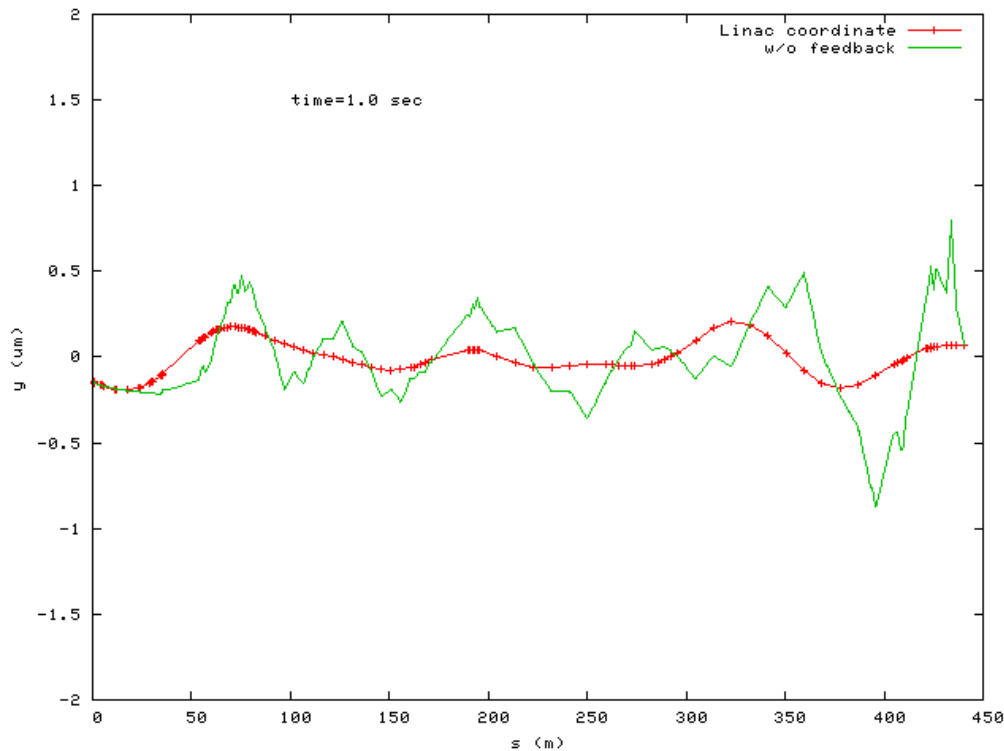
Low frequency and  $\sim 10$  Hz are dominant

- Beam motion due to low frequency
  - Frequency 0-2 Hz
  - Propagation velocity of 1 km/s is assumed (overestimate beam motion if faster)



Low frequency ground motion is ignorable as expected

- Beam motion due to 2-20 Hz ground motion (open loop)
  - FFT of “beam motion”  $\Leftrightarrow$  frequency spectrum of disturbances
  - Short Time FFT  $\Rightarrow$  stationary, quasi-stationary or random
  - **FFT for all BPMs  $\Rightarrow$  localization of disturbance(s)**



(Beam motion < BPM noise, BPM noise is ignored in this exercise...)

- Close feedback loop

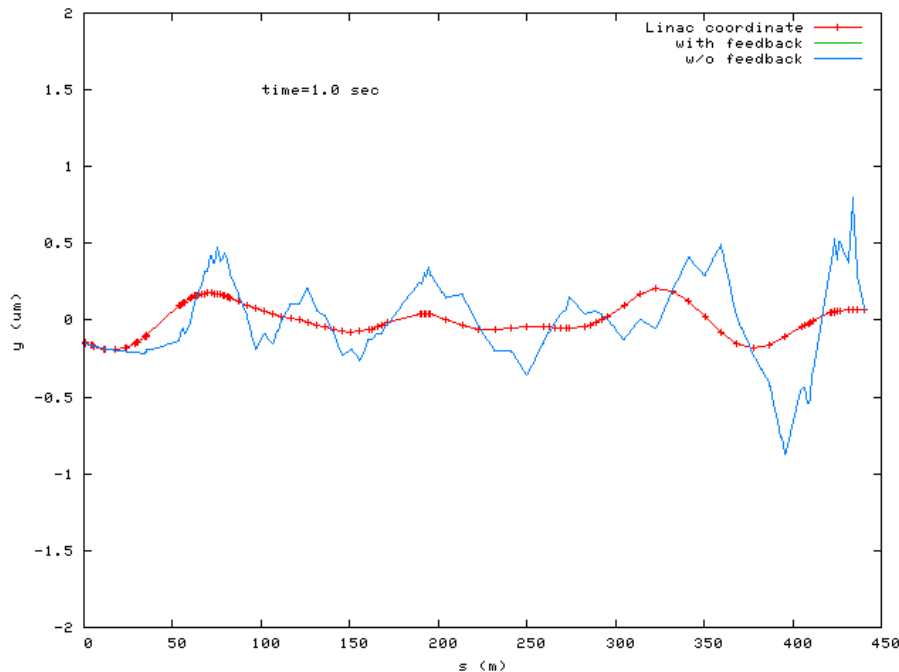
Some optimization

Proportional term:  $K_p=0.1$  rather small as  $f_{\text{beam}} \sim f_{\text{feedback}}/10$  (difficult to damp...)

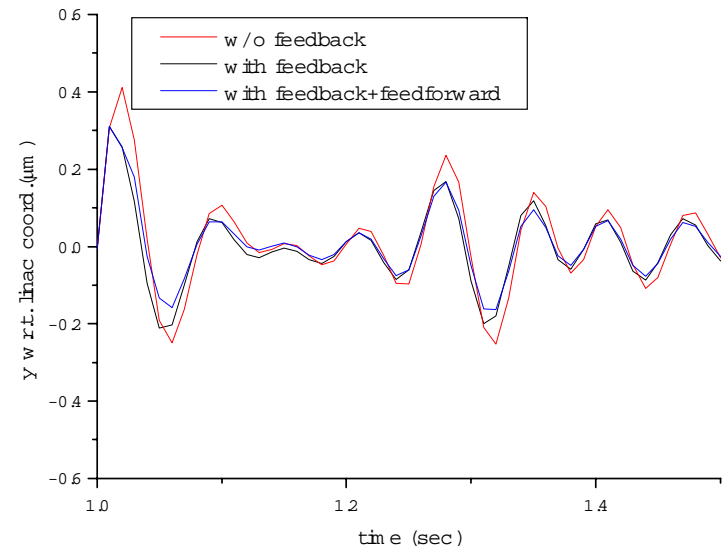
Derivative term:  $K_d=0.4$  rather big because of no high frequency  $>20$  Hz beam motion

Integral term:  $K_i=0$  because of no low frequency beam motion

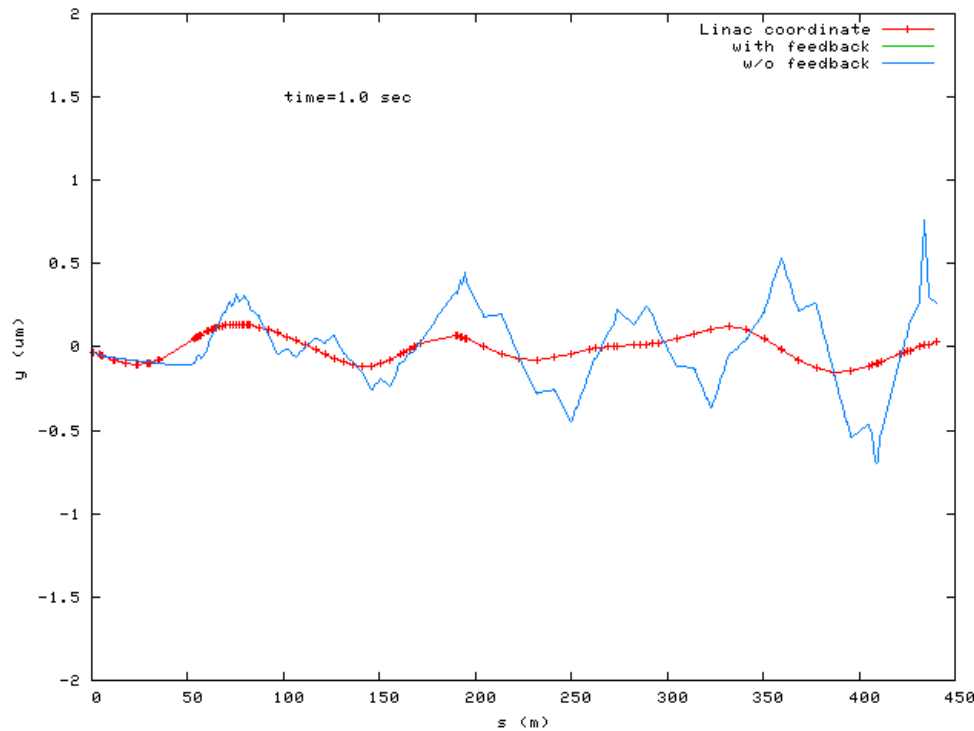
+ (simple) feed-forward term since the disturbance is quasi-stationary



## Beam position @ end of linac



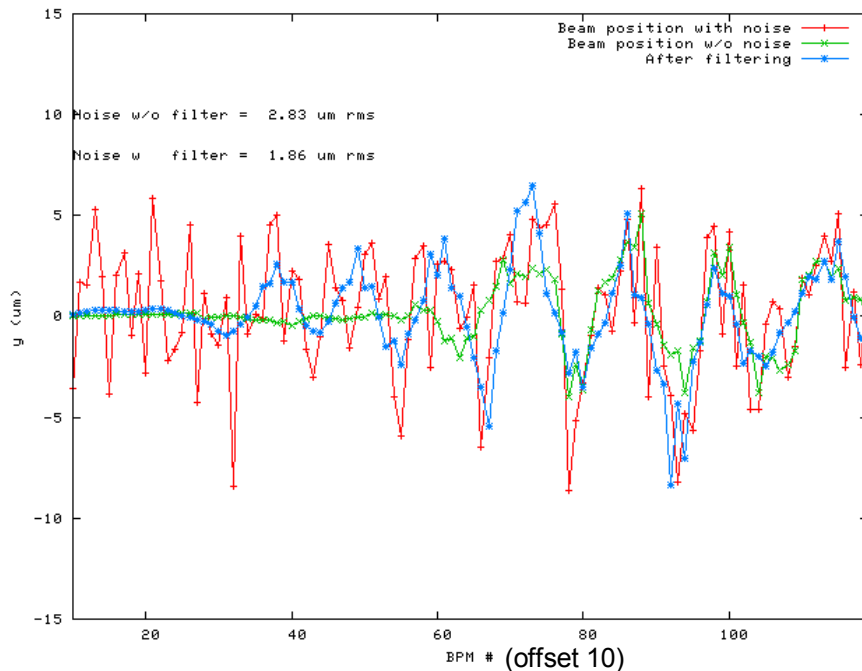
- Feedback for low frequency
  - Artificial 1 Hz disturbance so as not to give a wrong message with the 10 Hz exercise!



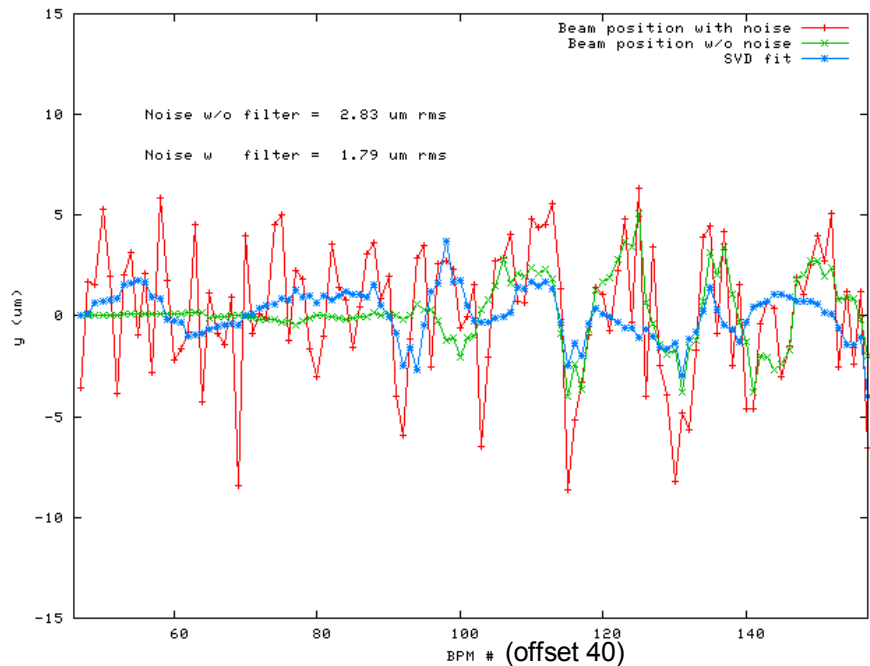
Feedback works well when the disturbance frequency  $< f_{\text{feedback}}/10$

- BPM noise filtering
  - BMP noise < BPM signal
    - Play with SVD cut just to drop small Eigenvalues
  - BPM noise ~ BPM signal (need no orbit correction anymore?)
    - Need to drop relatively large Eigenvalue, then fitting is not very good
    - Apply spatial low-pass filter  $< \sim 2f_{\text{betatron}}$  OK for latency?

### Low pass filter



### SVD (cut < 5% of largest Eigenvalue)

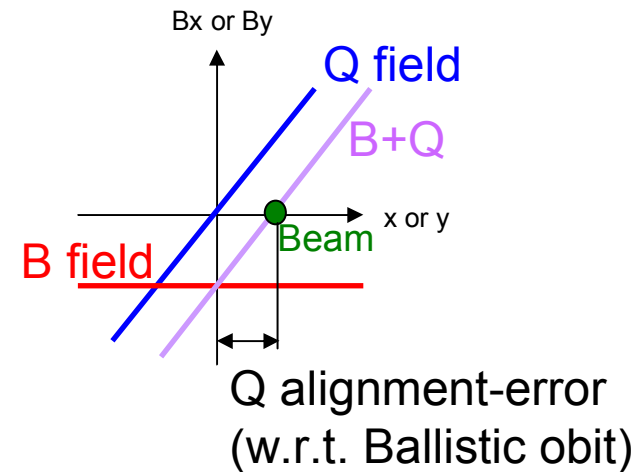
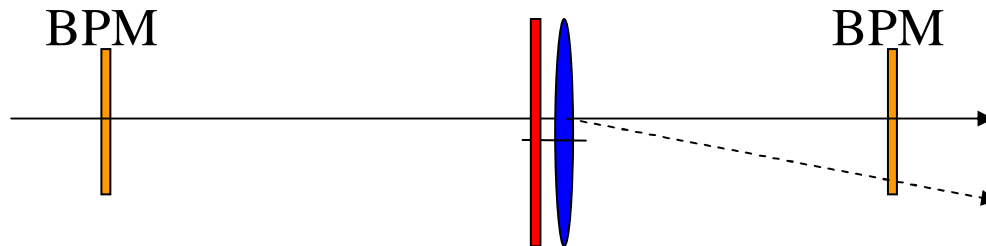


- BPM system
    - Cavity BPM everywhere: Good cost-performance ratio
  - Survey-based and beam-based alignment
    - Linac
      - Survey-based alignment: “What we can do” is enough to start
        - Long range alignment error is not an issue in terms of optics
        - Survey-based alignment + Quick steering could almost achieve the tolerances of normal operation modes
      - BBA for BPMs and Q magnets for a better performance
      - DFS will result in an orbit straightness much better than the tolerances of normal operation modes
    - Undulator
      - LCLS BBA method modified for SwissFEL
      - Alternative method based on photon beam
  - Feedback strategy
    - PID control +SVD matrix inversion
    - Study with open loop, then optimize and close the loop
    - Identification and localization of disturbance with beam
-

Backup slides

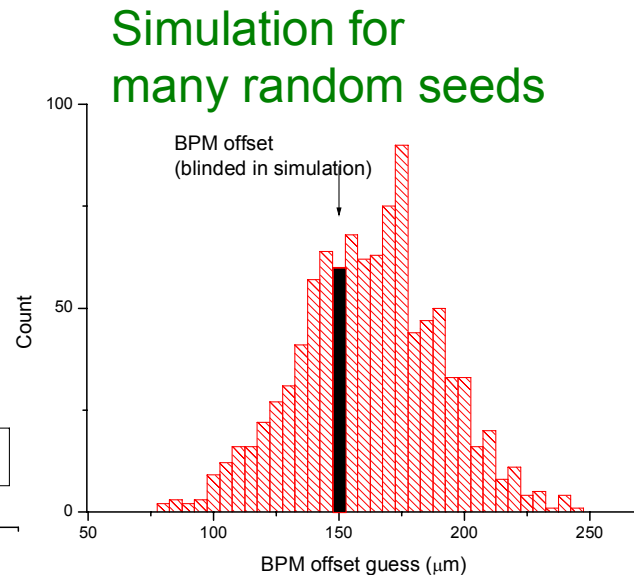
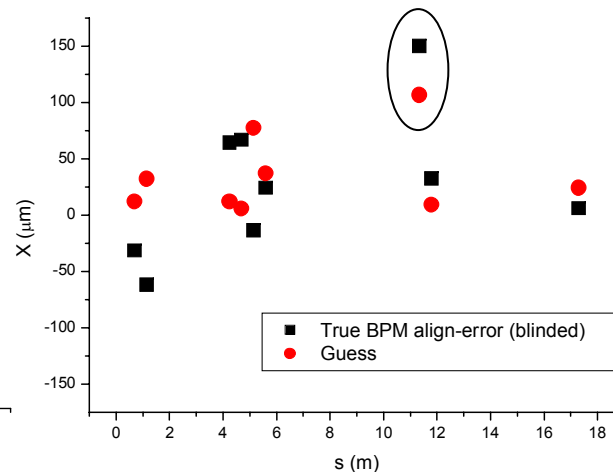
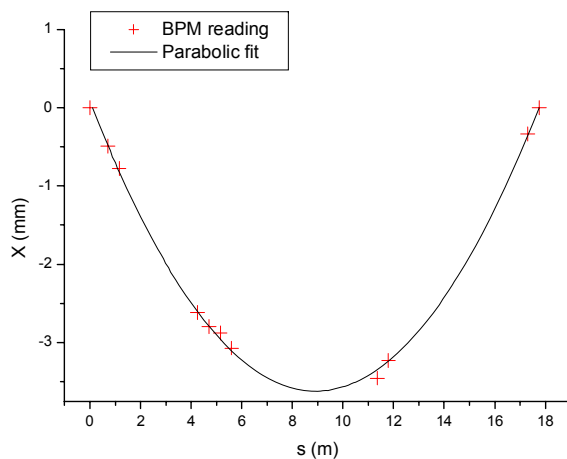
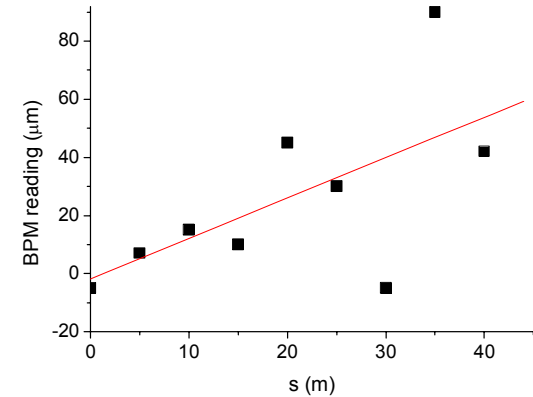
---

- BBA – Quad alignment error
  - To reduce corrector strength
  - With negligible Earth's field
    - Let the beam go straight by turning-off the magnets and cavities
    - Steer the beam go through two pivots BPM (Ballistic orbit)
    - Turn-on one of quadrupoles in between the BPMs → orbit change
    - Restore the orbit with corrector
    - Compute Quad alignment error w.r.t. Ballistic orbit

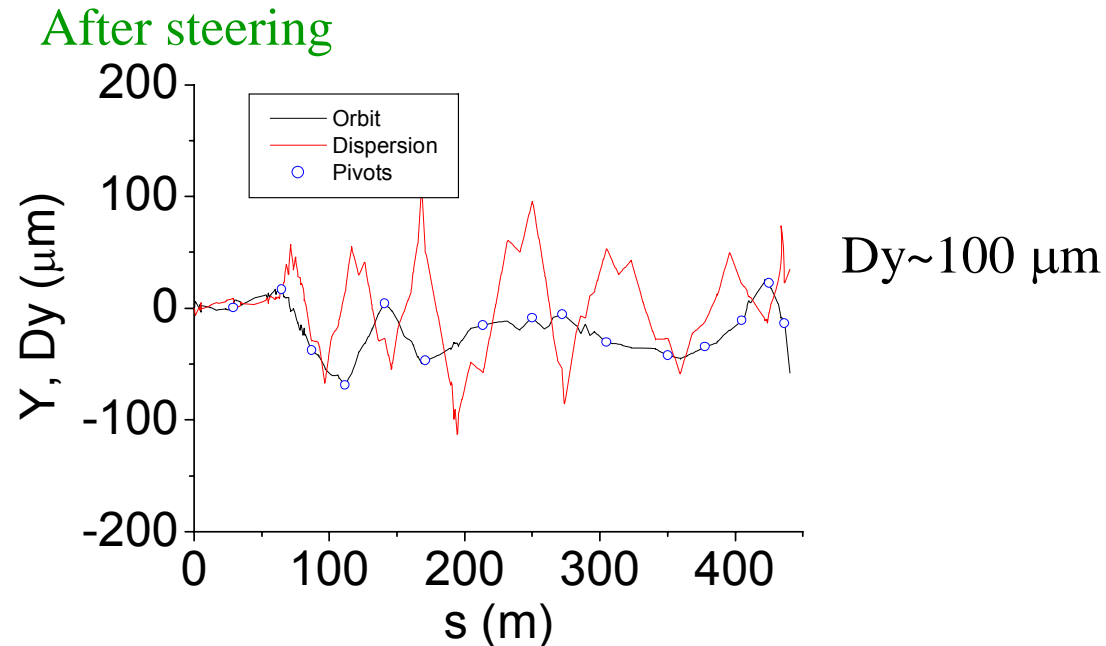


- With non-negligible Earth's field
  - Guess from corrector strength pattern?
- BBA – RF cavity
  - Tolerance: Quad alignment  $\ll$  RF alignment
    - Would be achieved with survey-based

- BBA – BPM alignment error
  - The better BPM alignment, the better performance
  - With negligible Earth's field (Ver. HE)
    - Let the beam go straight by turning-off the magnets and cavities
    - Re-align the BPMs far from the straight line
  - With non-negligible Earth's field (Hor., Ver. LE)
    - Let the beam go “quasi-parabolic orbit” by turning-off the magnets and cavities
    - Alignment error more than  $100\ \mu\text{m}$  seems to be detectable (figures below)
    - Study the impact of EF in the 250MeV injector



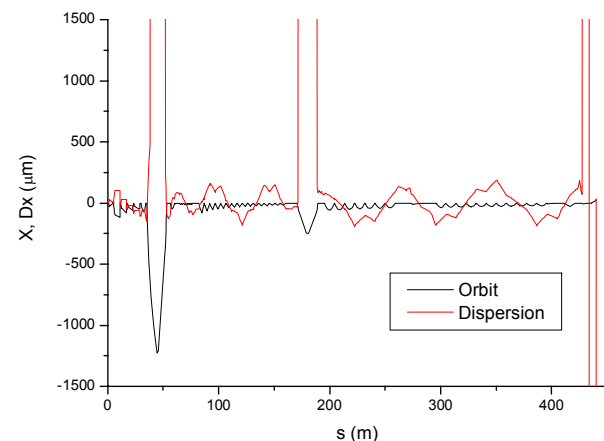
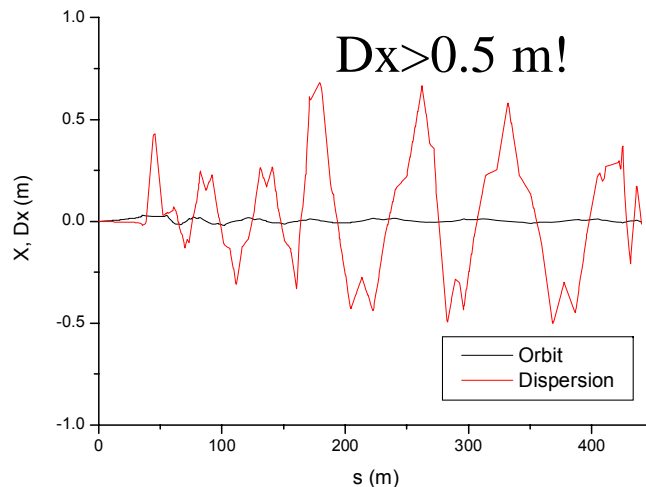
- BBS – Ballistic Alignment
  - Back-up and for comparison to DFS
  - Work well for the relatively short linac, and much better than the quick steering
  - Affected by Earth's field
  - Simulation: **BPM shift 25  $\mu\text{m}$  rms (after BBA), BBS precision 3  $\mu\text{m}$  rms**



- Estimation of DFS performance for the undulator section
  - BPM reading 3  $\mu\text{m}$  max (1  $\mu\text{m}$  rms)
  - Assume improvement by a factor of 3 with averaging many measurements  $\rightarrow$  1  $\mu\text{m}$  max
  - $dP/P = p \%$   $\rightarrow$  200/p  $\mu\text{m}$  max dispersion measurement error
  - Orbit straightness  $\sim$  Dispersion measurement error  $\rightarrow$  200/p  $\mu\text{m}$  max
  - $dP/P = -20\%$   $\rightarrow$  10  $\mu\text{m}$  max would be OK
  - if  $dP/P = -40\%$   $\rightarrow$  5  $\mu\text{m}$  max

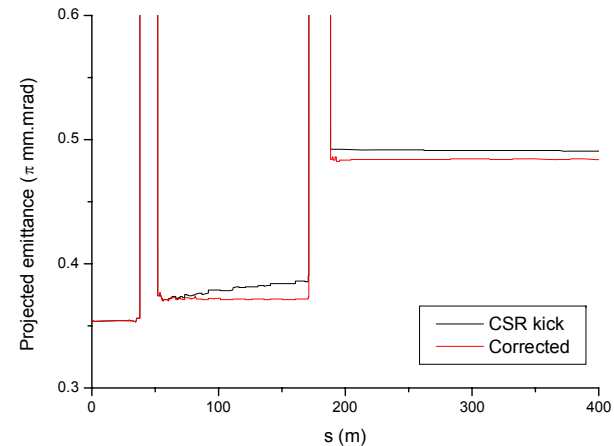
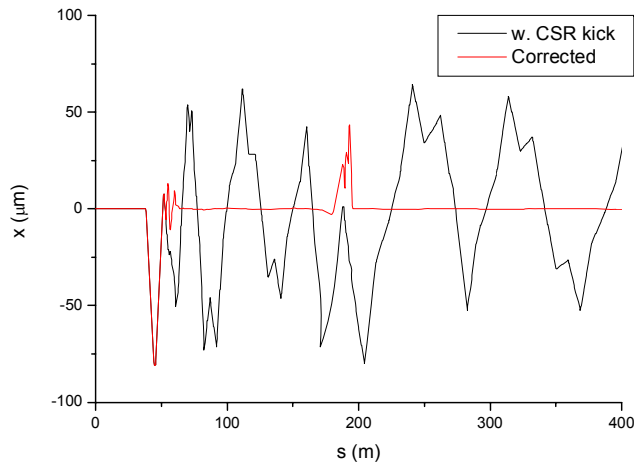
- Earth's field – Impact on the linac orbit and disp.
  - Horizontal component:  $\sim 20 \mu\text{T}$ 
    - Solenoid like field, impact under study
  - Vertical component:  $\sim 40 \mu\text{T}$

Steering to go through BPMs' center  
(w/o alignment error)



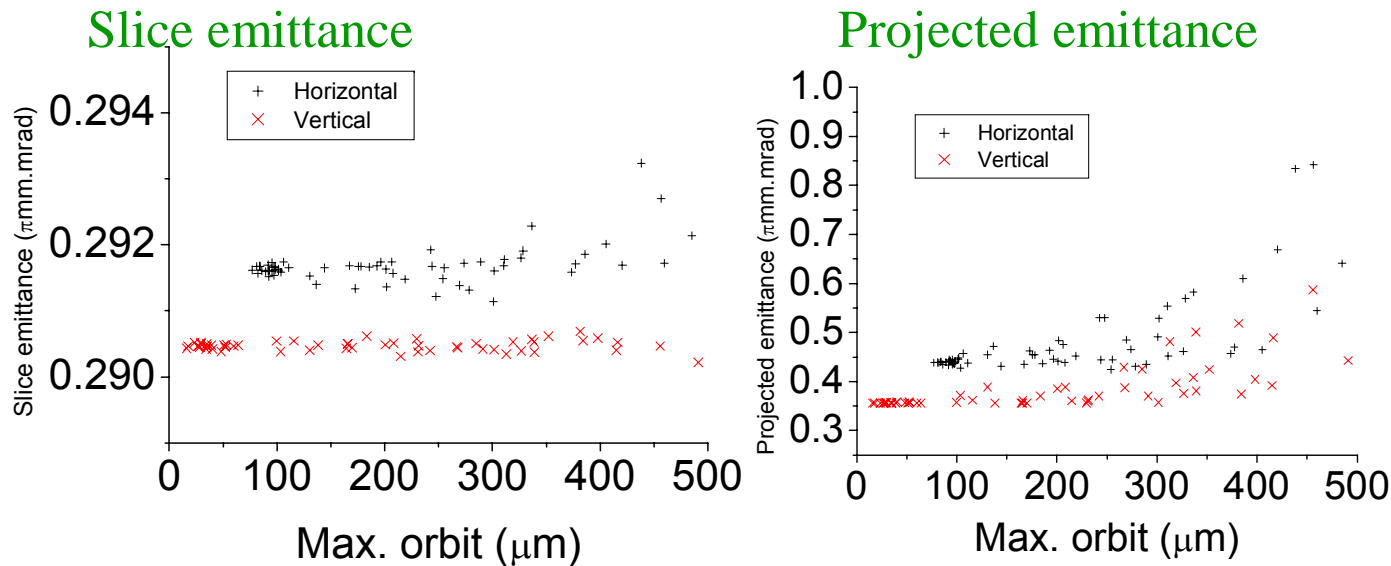
Earth's field has a large impact...but OK after proper BBA/S  
Attenuation  $1/5 \sim 1/8$  by shielding is expected

- CSR kick correction
  - Measure difference orbit
    - With low and design charge, averaging over beam jitter
    - With and without BCs
  - Correct CSR kick with correctors right after the BC1 and BC2



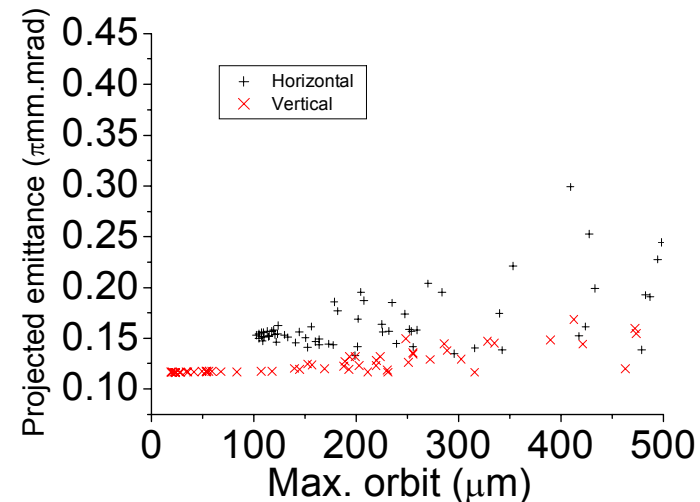
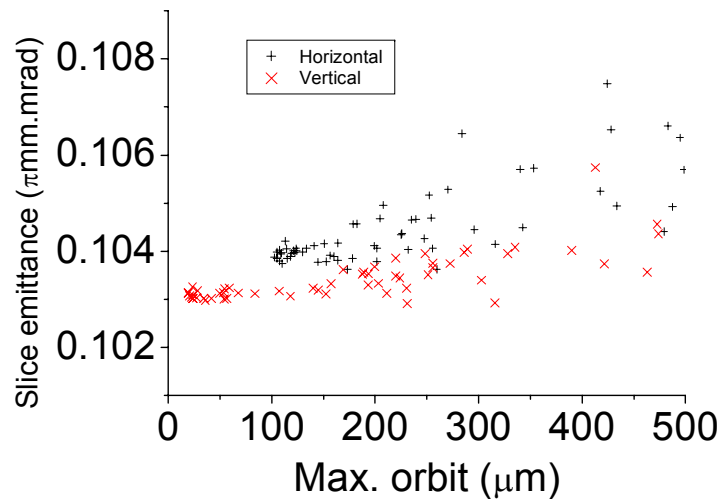
- Separate the sources of orbit error
  - Orbit error from misalignment and error from CSR kick
  - In principle, the same BBA/S for 200 pC and 10 pC modes except for the CSR kick correction

- Tolerance for the orbit error in the linac
  - ELEGANT simulation
    - Shift Quadrupole randomly
    - Observe the emittance at the end of linac vs orbit error



The tolerance would be 100~200 μm orbit in the linac  
(corresponding to a few mm dispersion for random error)

- Preliminary simulation with lattice under optimization



\*CSR kick not corrected in horizontal plane

Slice emittance is more fragile than in 200 pC mode because of higher compression (larger  $dP/P$  in slice).

Still, 100 ~ 200  $\mu$ m orbit would be tolerable.

- Tolerance for the orbit error in the undulator section
  - Error budget study by S. Reiche

