

Beam Based Alignment in FLASH undulator Sections

“The LCLS–Method”

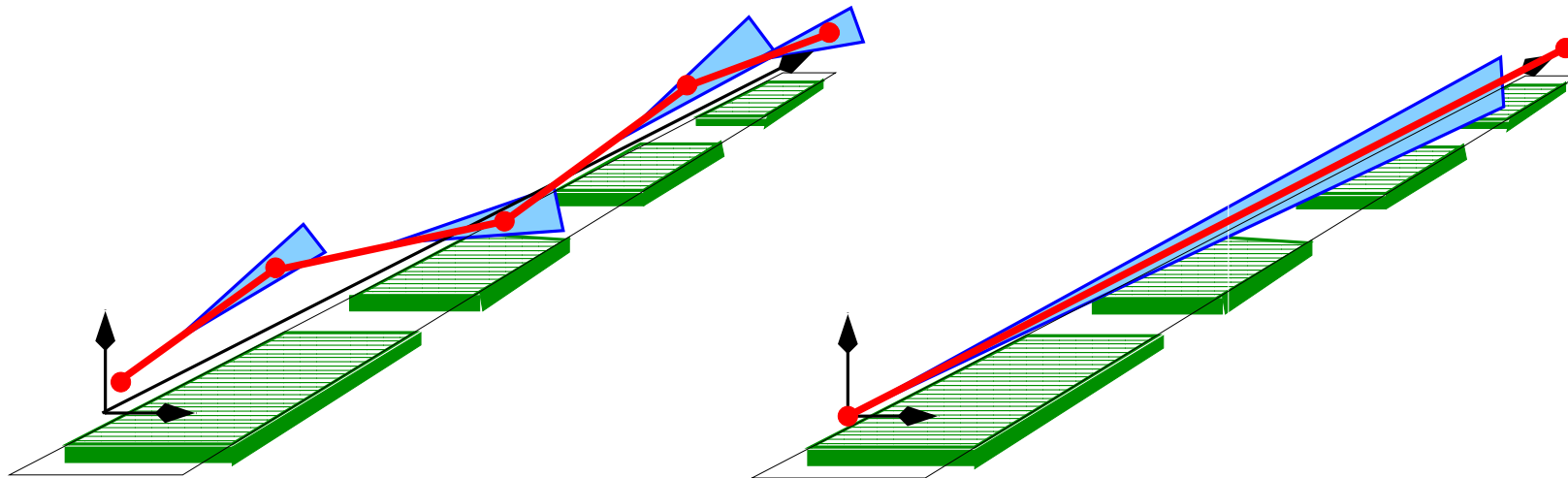
23.11.2010

Mathias Vogt (DESY–MFL)

- **Motivation**
- **The LCLS–Method** → **thanx to Hendrik Loos (SLAC)**
- **Implementation** → [SASEBBAGUIMain](#)
- **Preliminary Data from FLASH Recommissioning/MD 2010-05**
- **Summary and Outlook**

Motivation : Orbit Requirements for the SASE Process

- Resonant interaction of charged particle and undulator radiation
 ⇒ Particle orbit and radiation cone ($\sim 1/\gamma$) must overlap
- Beam orbit excursion in undulator \ll rms beam envelope
 → longitudinal scale \sim gain length



BAD ORBIT :

- Strong orbit fluctuations
- ⇒ overlap only over short ranges \ll radiation length
- ⇒ **weak (or no) SASE signal**

GOOD ORBIT :

- Flat orbit
- ⇒ overlap only over most of undulator $>$ radiation length
- ⇒ **potentially: “saturation”**

Motivation : Accuracy/Resolution Issues

- FLASH :

$$\beta\gamma\epsilon \approx 1.4 \cdot 10^{-6} - 2.0 \cdot 10^{-6} \text{m};$$

$$\langle\beta\rangle_{\text{undu}} \approx 10\text{m.} \Rightarrow \sigma \approx 70 - 100\mu\text{m}$$

at 450–1200 MeV.

- BPM resolution in UNDULATOR section:

$$\sigma_X \approx 10\mu\text{m} \Rightarrow \text{m.o.I. OK.}$$

- BPM offsets : $\sim 300\mu\text{m}$!?!

⇒ BBA based on dispersive orbits

- dispersive orbits measured as

difference orbits.

→ **Unfortunately :**

$$\text{Resolution } \sigma_D \propto \sigma_X / \frac{\Delta E}{E}$$

⇒ typical $\frac{\Delta E}{E} = 5\%$ → $\sigma_D \approx 200\mu\text{m} :-)$

⇒ **LCLS method invented by H.Loos (SLAC)**

– Set up linac for several energies.

(LCLS: **4 to 14 GeV**)

(FLASH: **450 to 1200 MeV**)

– Don't change UNDULATOR quads & movers.

– Have an **OrbitResponseMatrix (ORM)** ready **for each energy.**

(includes h.o. dispersive & chromatic effects)

– Solve **least-square problem** for misalignments and BPM-offsets simultaneously ⇒ see below. . .

The LCLS Method (H.Loos/SLAC) here: for **one Phase-Plane**, say (x, p_x)

- At P different Energies $\{E_k\}_{k=1,P}$
- Given : M BPMs with offsets $\vec{\Delta} \in \mathbb{R}^M$

→ for each k :

- Actual orbit \vec{X}_k , measured Orbit \vec{Y}_k with random errors $\vec{\xi}_k$

$$\Rightarrow \vec{Y}_k = \vec{X}_k + \vec{\Delta} + \vec{\xi}_k$$

- Given : N perturbations(= misaligned quads) and/or correctors(= movers)

→ : misalignments $\vec{d} \in \mathbb{R}^N$ independent of energy !!!

- For each k : initial cond.(= launch) $\vec{z} \equiv (x_0, x'_0)_k^T$

$$\Rightarrow \vec{X}_k = \underline{\mathcal{L}}_k \vec{z}_k + \underline{\mathcal{O}}_k \vec{d}$$

- LaunchResponseMatrix (LRM) $\underline{\mathcal{L}}_k$
- OrbitResponseMatrix (ORM) $\underline{\mathcal{O}}_k$

- Now **join over all P energies** :

$$\vec{X} := (\vec{X}_1^T, \dots, \vec{X}_P^T)^T, \vec{Y} := \dots, \\ \vec{z} := \dots, \vec{\xi} := \dots$$

$$\underline{\mathcal{L}} := \text{diag}(\underline{\mathcal{L}}_1, \dots, \underline{\mathcal{L}}_P) \in \mathbb{R}^{PM \times P2}$$

$$\underline{\mathcal{O}} := (\underline{\mathcal{O}}_1^T, \dots, \underline{\mathcal{O}}_P^T)^T \in \mathbb{R}^{PM \times N}$$

$$\underline{\mathcal{U}} := (\underline{\mathbf{1}}_1^{M \times M}, \dots, \underline{\mathbf{1}}_P^{M \times M})^T \in \mathbb{R}^{PM \times M}$$

$$\Rightarrow \vec{Y} = \underline{\mathcal{L}} \vec{z} + \underline{\mathcal{O}} \vec{d} + \underline{\mathcal{U}} \vec{\Delta} + \vec{\xi}$$

- or: $\vec{Y} = \underline{\mathcal{A}} \vec{v} + \vec{\xi}$

$$\text{with } \underline{\mathcal{A}} := (\underline{\mathcal{L}}, \underline{\mathcal{O}}, \underline{\mathcal{U}})$$

$$\text{and } \vec{v} := (\vec{z}^T, \vec{d}^T, \vec{\Delta}^T)^T$$

- Add 2 more constraints for “baseline tilt”

- either $0 = \sum_{i=1}^M \Delta_i$ & $0 = \sum_{i=1}^M s_i \Delta_i$

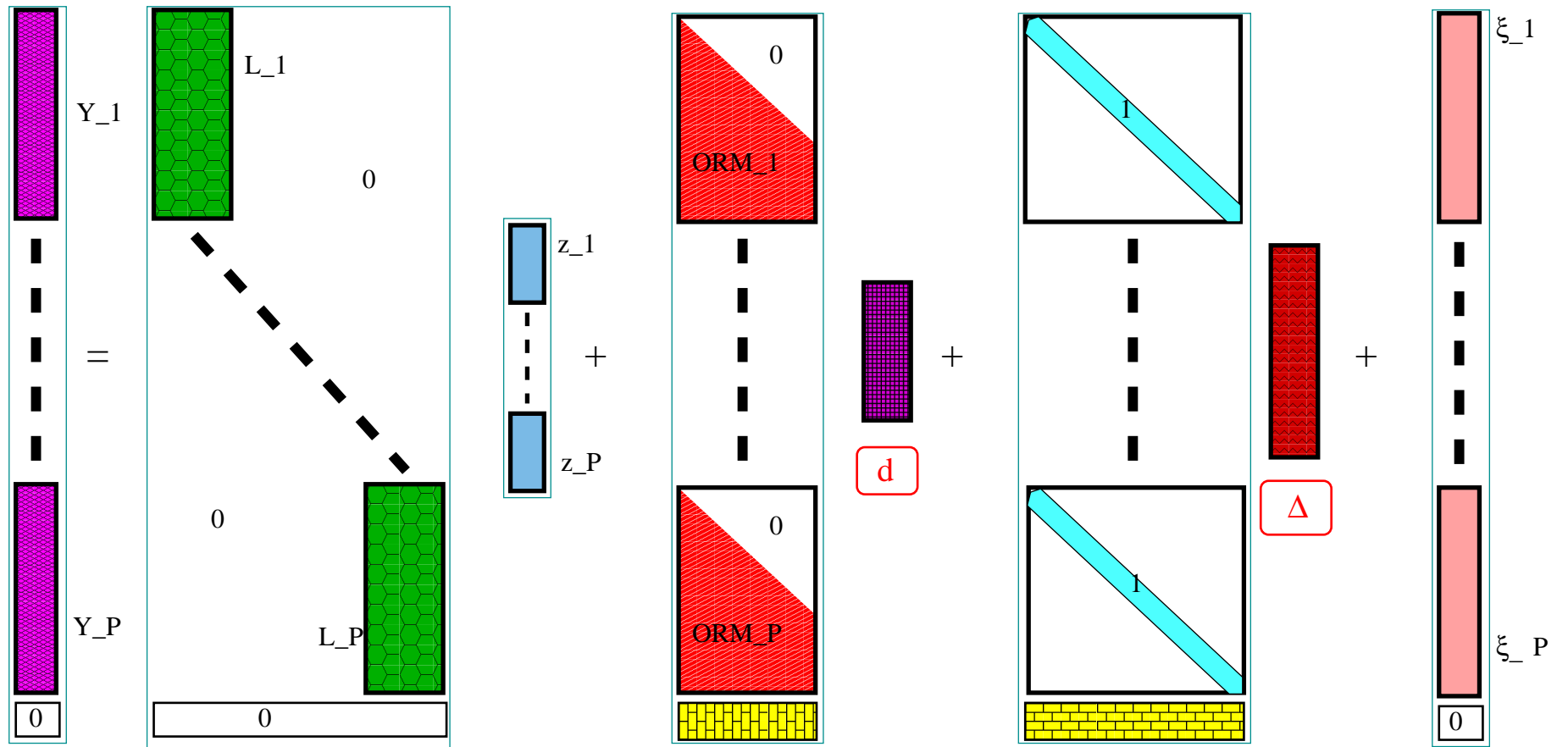
$$\leftarrow \Delta_i = \Delta^{(0)} + \Delta^{(1)} s_i$$

- or $0 = \sum_{i=1}^N d_i$ & $0 = \sum_{i=1}^N s_i d_i$

$$\leftarrow d_i = d^{(0)} + d^{(1)} s_i$$

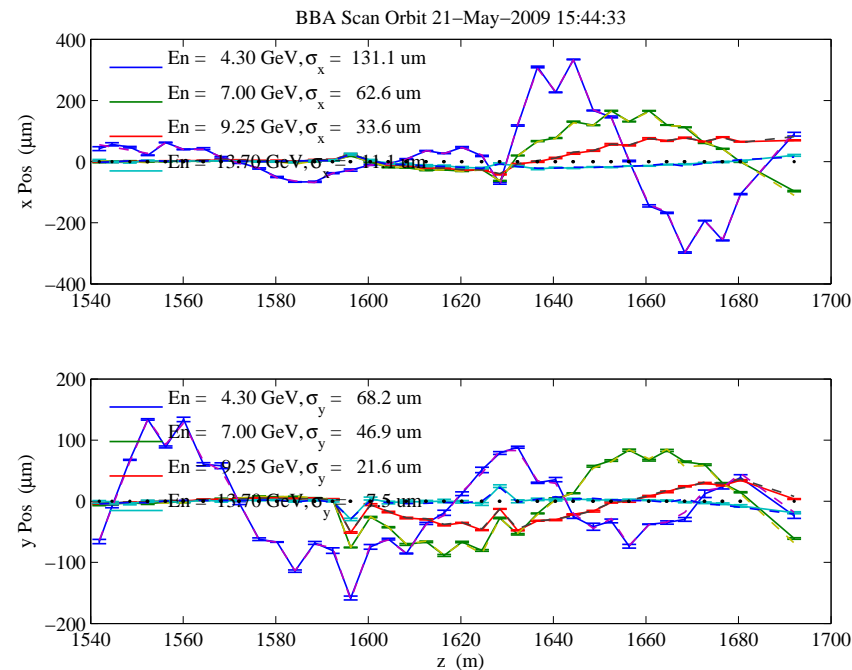
→ **$PM + 2$ constraints for $2P + N + M$ variables**

The LCLS Method (2)



The LCLS Method (**Application**)

- Visit at LCLS : M.V. May 2009
 - discussion w/experts (H.Loos)
 - MDs for undulator BBA
- ⇒ very successful → see LCLS-e-log of 21.05.2009
- **example** : local bumps → → →
- after preparing clean machine states (for 4.3, 7.0, 9.25, 13.7 GeV)
- measure “up” → correct → measure “down” → verify
- 20-30 min per E -step
- **Now : routine operation performed by operators**

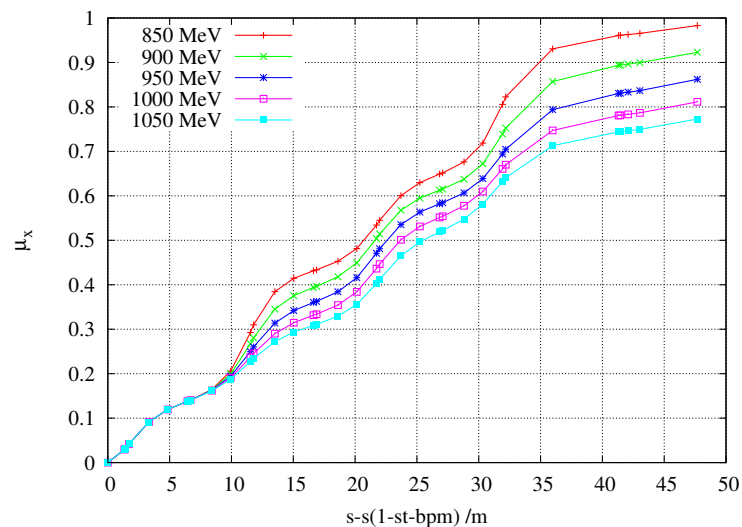
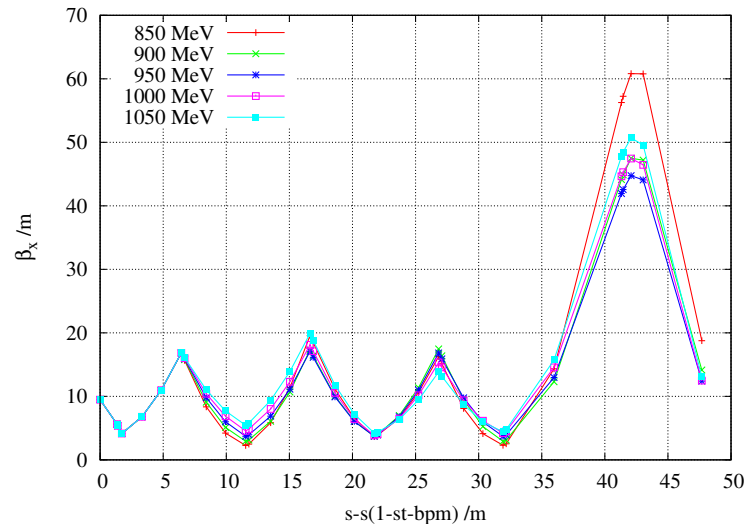


(Pictures thanx to H.Loos and the LCLS team at SLAC)

Prerequisites

- **Established transmission through undulator (down to dump)** for a **wide range of energies** and **dedicated, well established bba-optics**
 - RF-phases → on crest.
 - 1 bunch sufficient.
- **Reliable RF controls.**
- **Stable machine (gun, magnets, RF).**
- **Working and well calibrated diagnostics** : mainly BPMs (!!!), but wire-scanners & screens (optics match and verification), toroids & BLMs (loss-control) should be operable. . .
- **Optics : matching and control** . . .

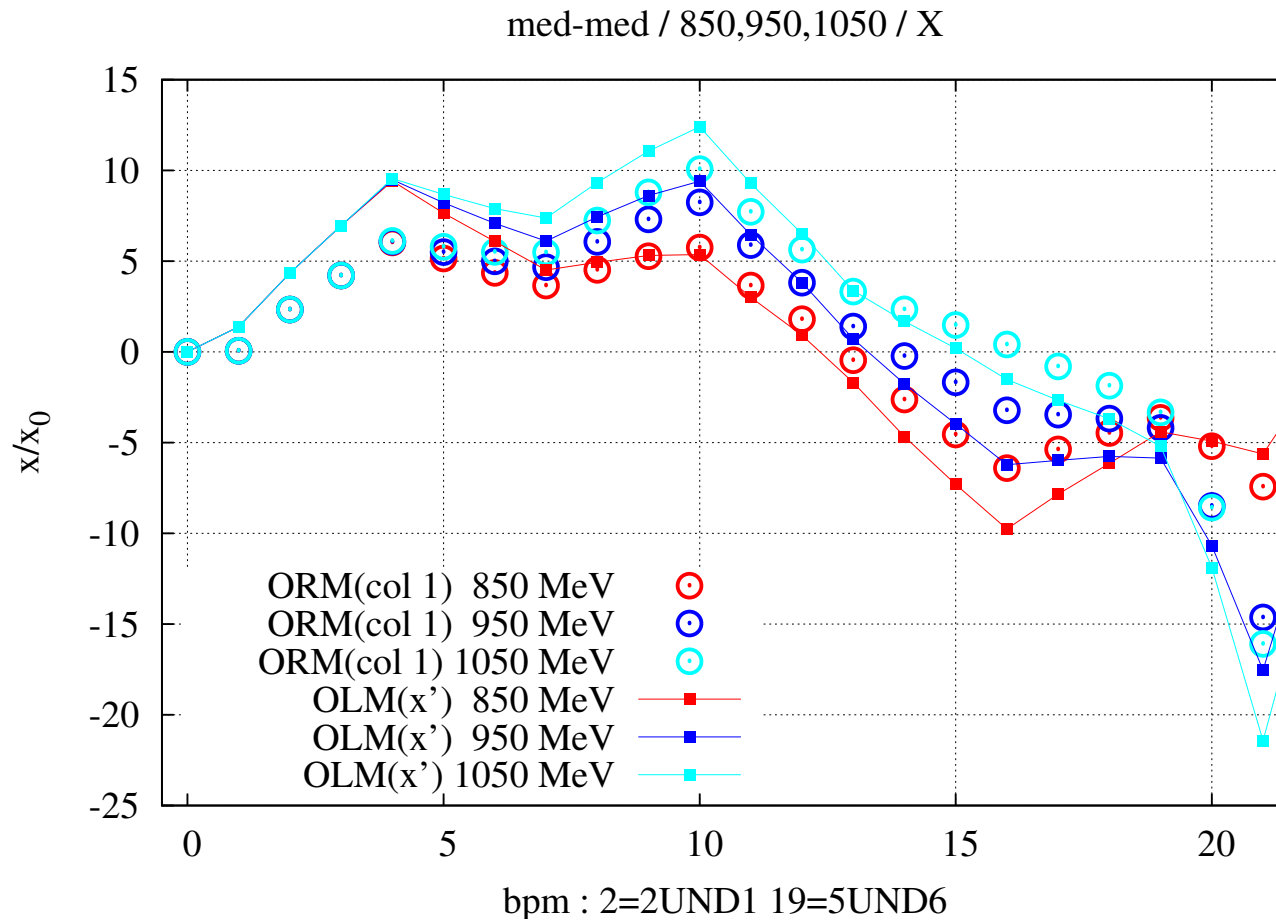
Set up for FLASH-BBA MD End of May 2010



- Standard optics (“Med–Med”) established during commissioning.
 - Reference energy for k_1 values in “Med–Med” : 950 MeV.
 - Don't be too brave ...
 - ⇒ **E range only ± 100 MeV**
 - 850, 900, 950, 1000, 1050 MeV.
- ⇒ chromatic optics effects very small
- (+) no rematch necessary
 - (-) combined BBA–matrix (from 3→5) ORMs/OLMs is almost singular (⇒ ill-conditioned)

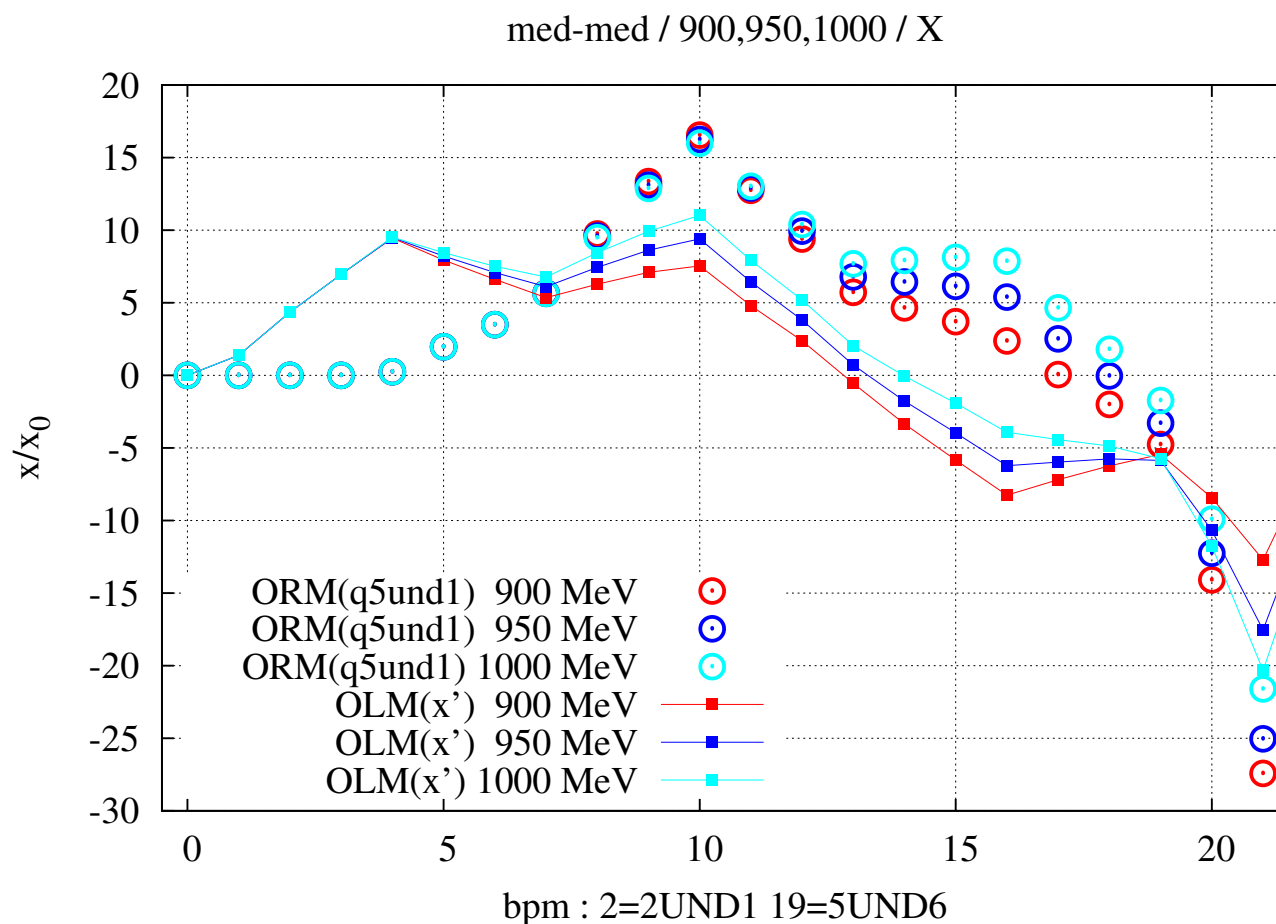
Set up for FLASH-BBA MD End of May 2010 (2)

Effects from last quads upstream of undulator and launch almost indistinguishable



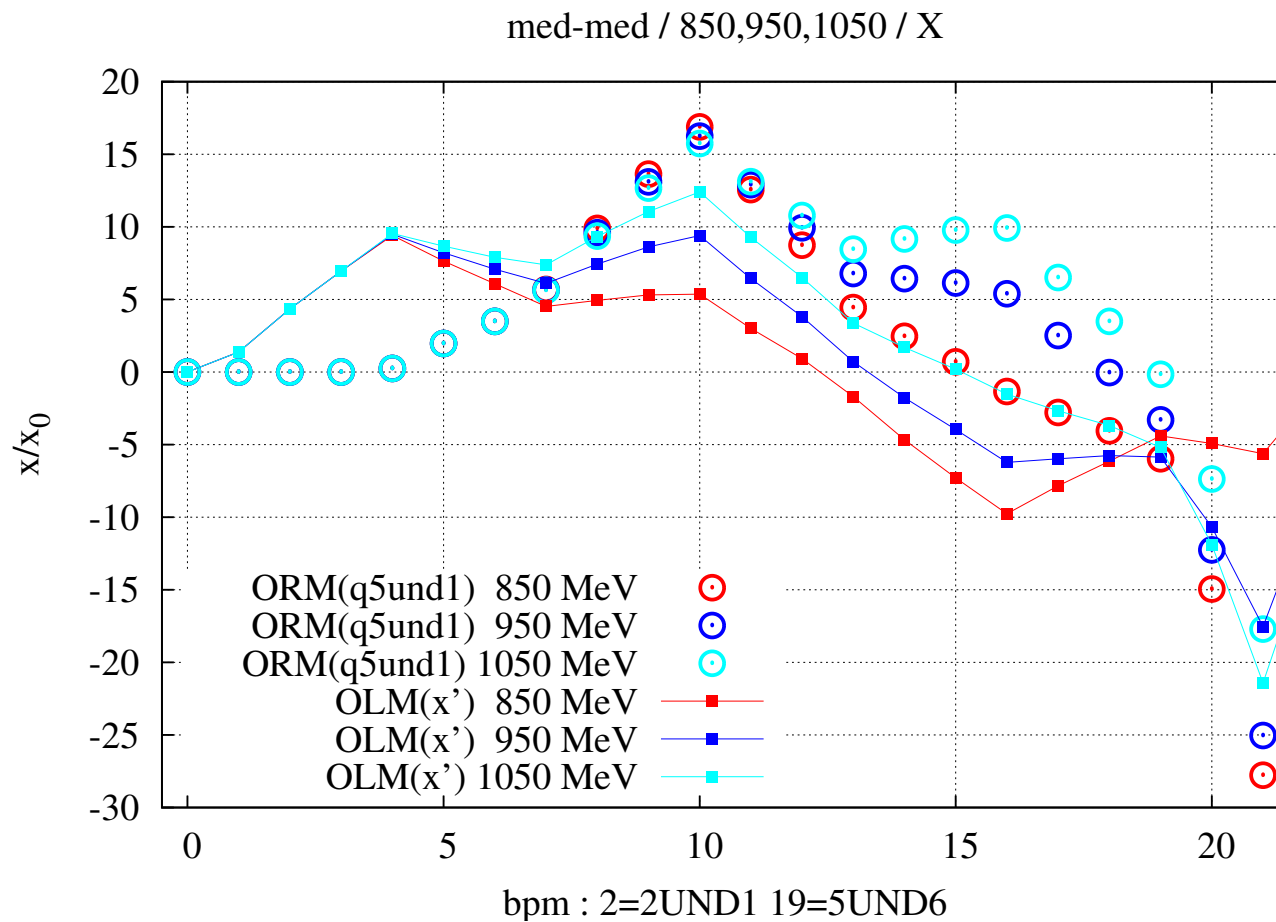
Set up for FLASH-BBA MD End of May 2010 (3)

900, 950, 1000 MeV : very close \Rightarrow almost equivalent to “dispersion-free steering” (just more singular!)

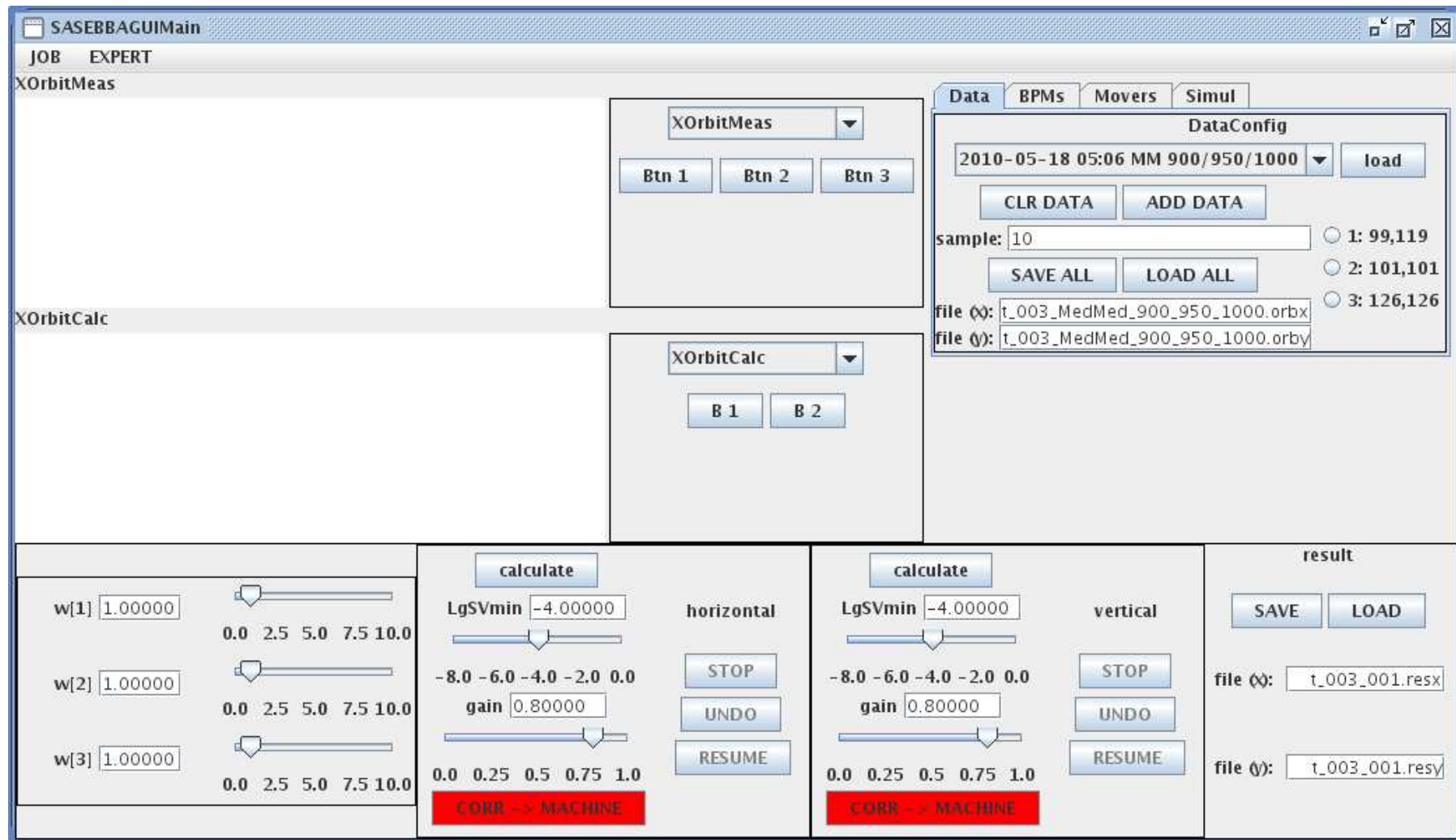


Set up for FLASH-BBA MD End of May 2010 (4)

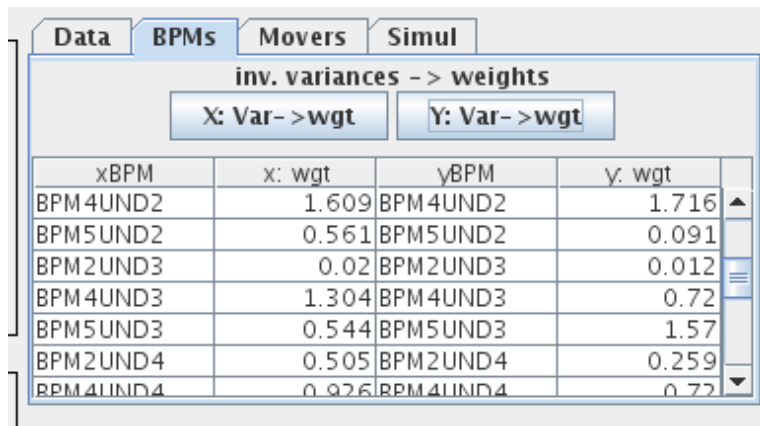
850, 950, 1050 MeV : looks better in theory, but data turned out as low quality



"java -cp \$CLASSPATH desy/csfel/sasebba/gui/SASEBBAGUIMain &"



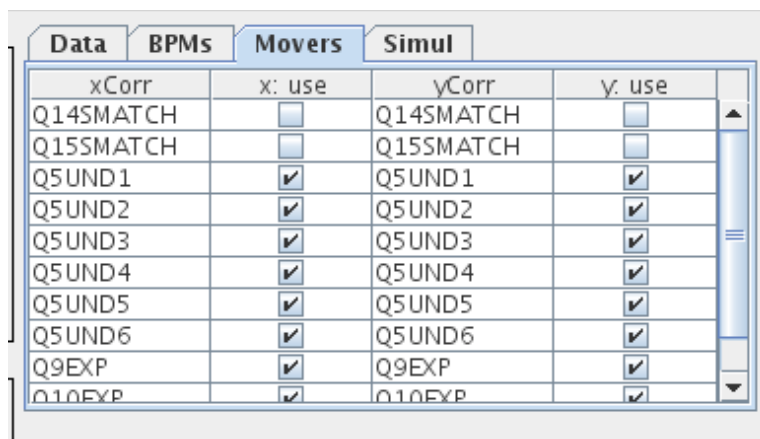
"java -cp \$CLASSPATH desy/csfel/sasebba/gui/SASEBBAGUIMain &"



xBPM	x: wgt	yBPM	y: wgt
BPM4UND2	1.609	BPM4UND2	1.716
BPM5UND2	0.561	BPM5UND2	0.091
BPM2UND3	0.02	BPM2UND3	0.012
BPM4UND3	1.304	BPM4UND3	0.72
BPM5UND3	0.544	BPM5UND3	1.57
BPM2UND4	0.505	BPM2UND4	0.259
BPM4UND4	0.926	BPM4UND4	0.72

← Weights can be assigned to BPMs

← e.g. $w_i \propto 1/\text{Var}_k(x_{i,k})$



xCorr	x: use	yCorr	y: use
Q14SMATCH	<input type="checkbox"/>	Q14SMATCH	<input type="checkbox"/>
Q15SMATCH	<input type="checkbox"/>	Q15SMATCH	<input type="checkbox"/>
Q5UND1	<input checked="" type="checkbox"/>	Q5UND1	<input checked="" type="checkbox"/>
Q5UND2	<input checked="" type="checkbox"/>	Q5UND2	<input checked="" type="checkbox"/>
Q5UND3	<input checked="" type="checkbox"/>	Q5UND3	<input checked="" type="checkbox"/>
Q5UND4	<input checked="" type="checkbox"/>	Q5UND4	<input checked="" type="checkbox"/>
Q5UND5	<input checked="" type="checkbox"/>	Q5UND5	<input checked="" type="checkbox"/>
Q5UND6	<input checked="" type="checkbox"/>	Q5UND6	<input checked="" type="checkbox"/>
Q9EXP	<input checked="" type="checkbox"/>	Q9EXP	<input checked="" type="checkbox"/>
Q10EXP	<input checked="" type="checkbox"/>	Q10EXP	<input checked="" type="checkbox"/>

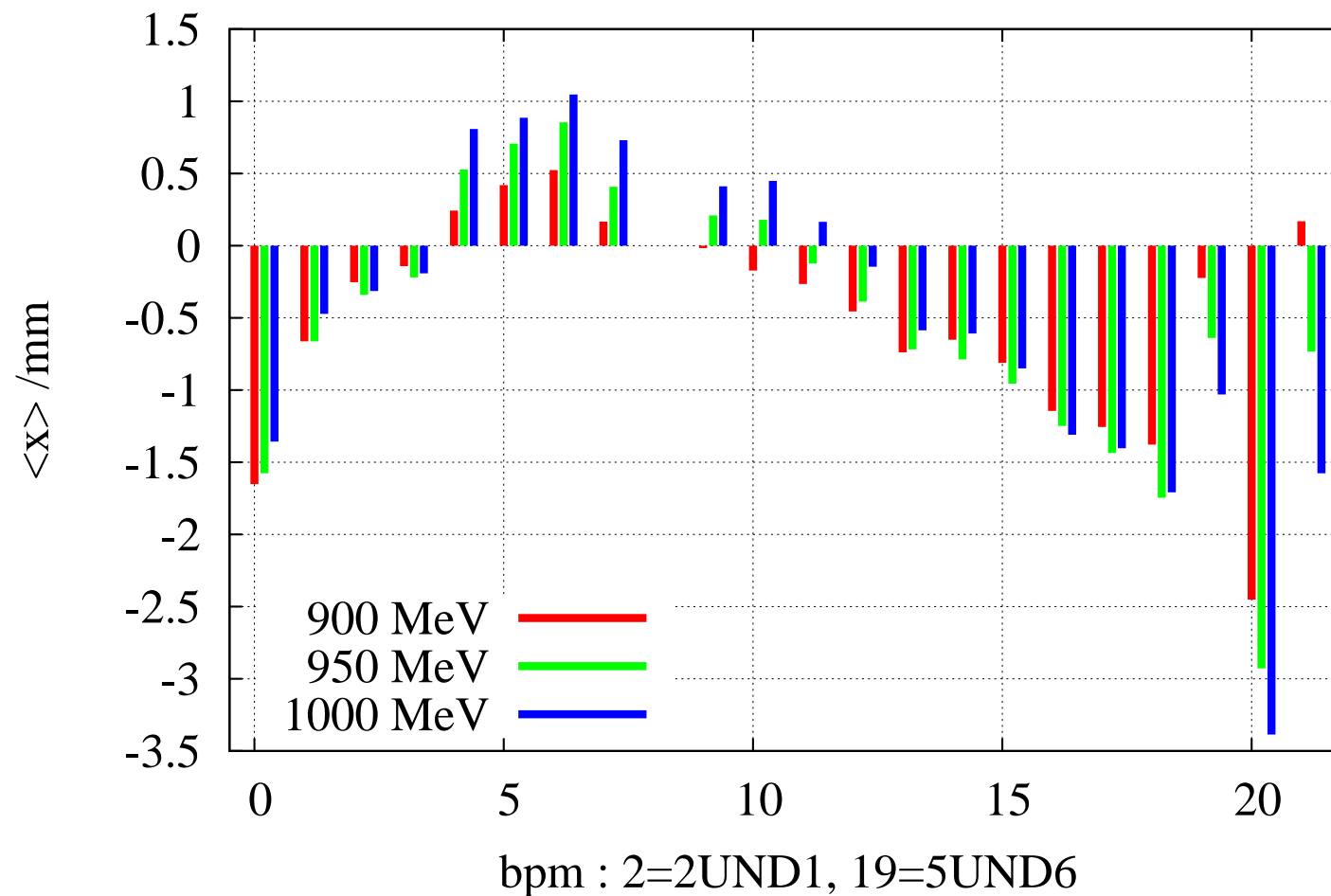
← Knobs (quads/movers) can be disabled

← e.g. those which compete with initial conditions

Preliminary FLASH Data

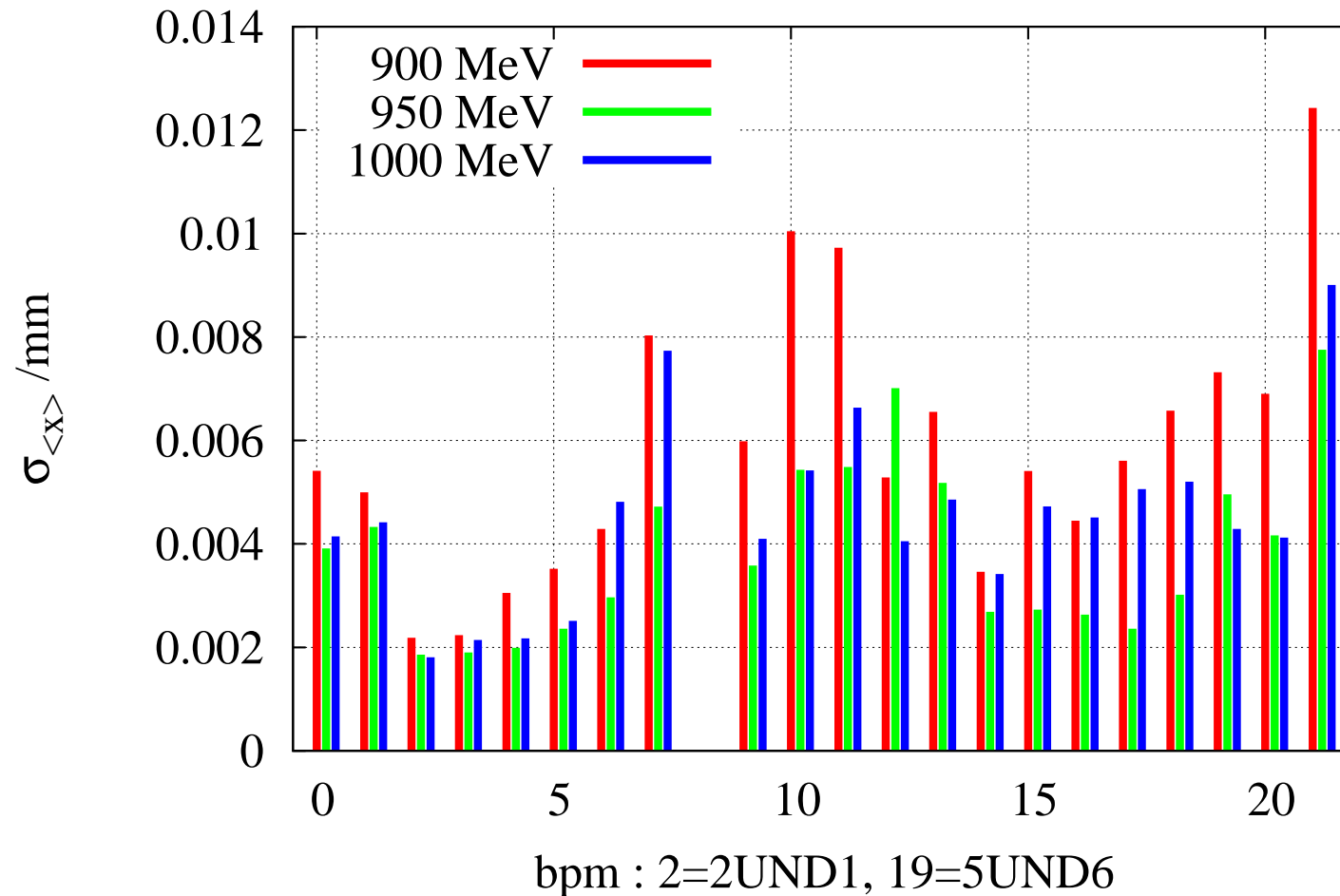
worst two BPMs deselected

2010-05-17-n / med-med / 900,950,1000 / X



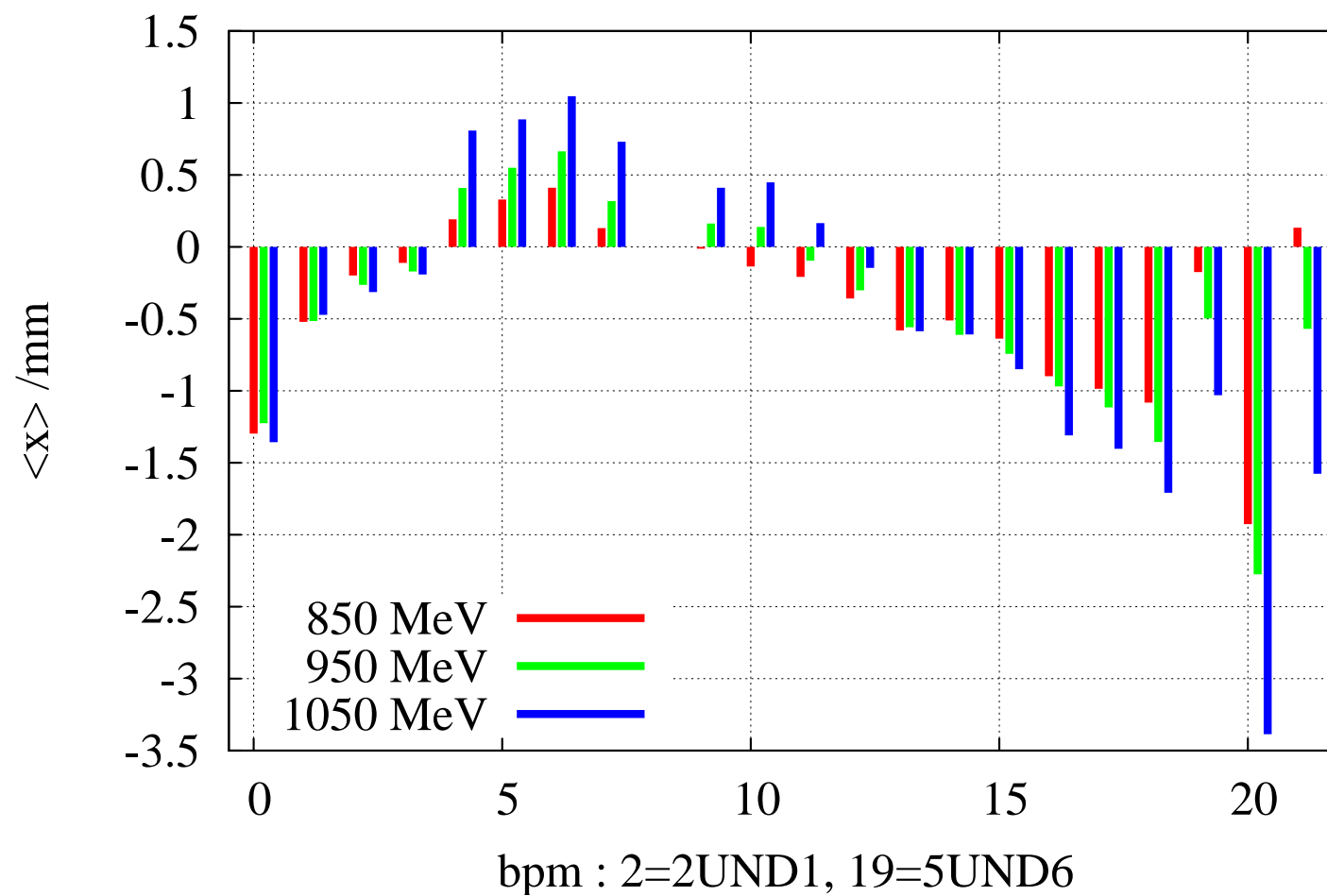
Preliminary FLASH Data (2)**worst two BPMs deselected**

2010-05-17-n / med-med / 900,950,1000 / X



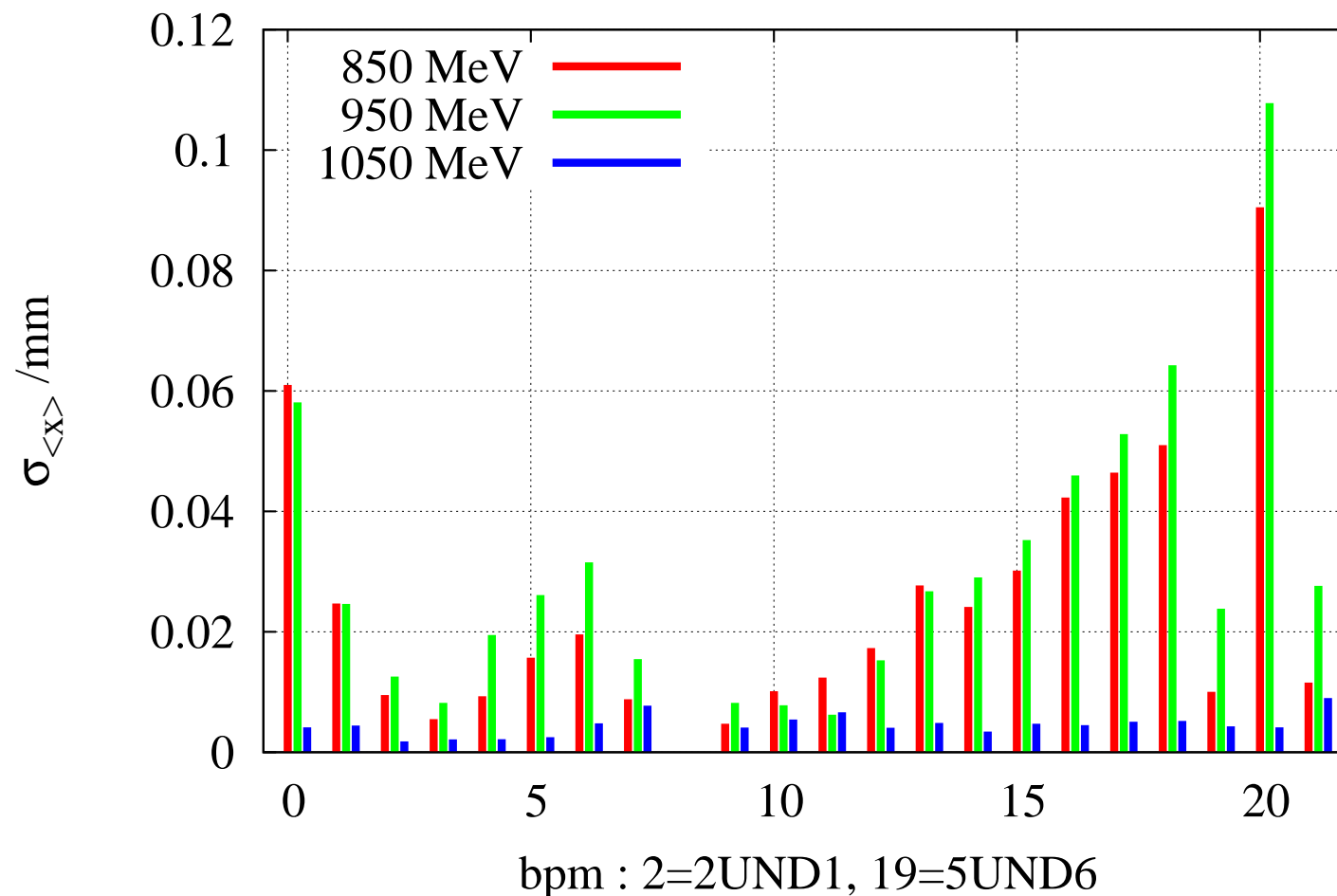
Preliminary FLASH Data (3)

2010-05-17-n / med-med / 850,950,1050 / X



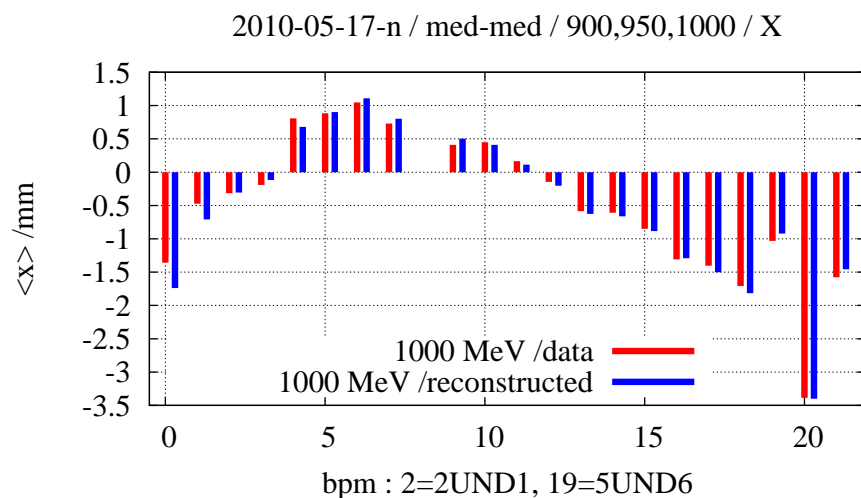
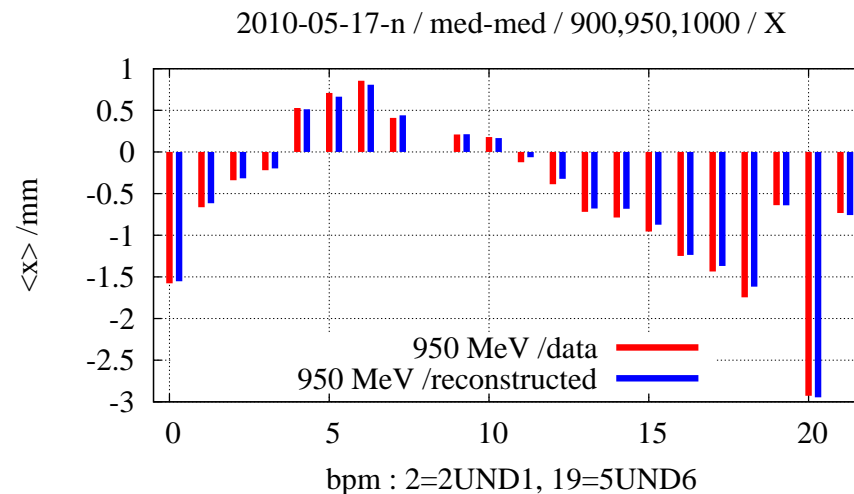
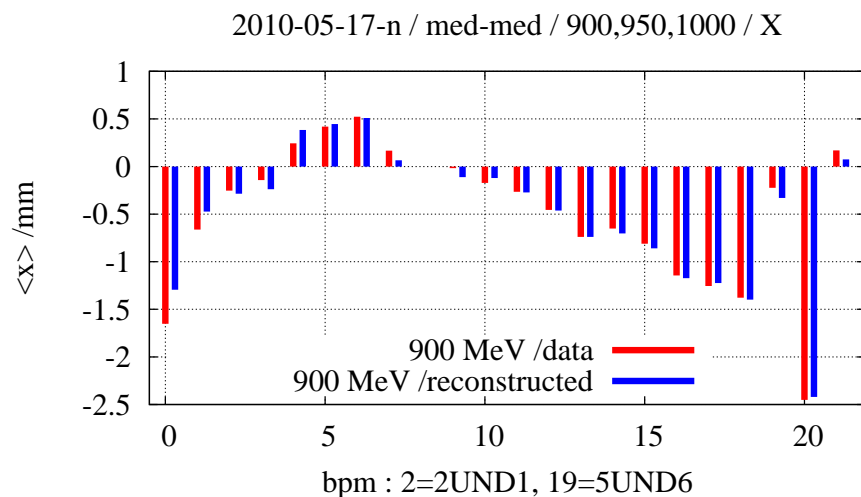
Preliminary FLASH Data (4)

2010-05-17-n / med-med / 850,950,1050 / X



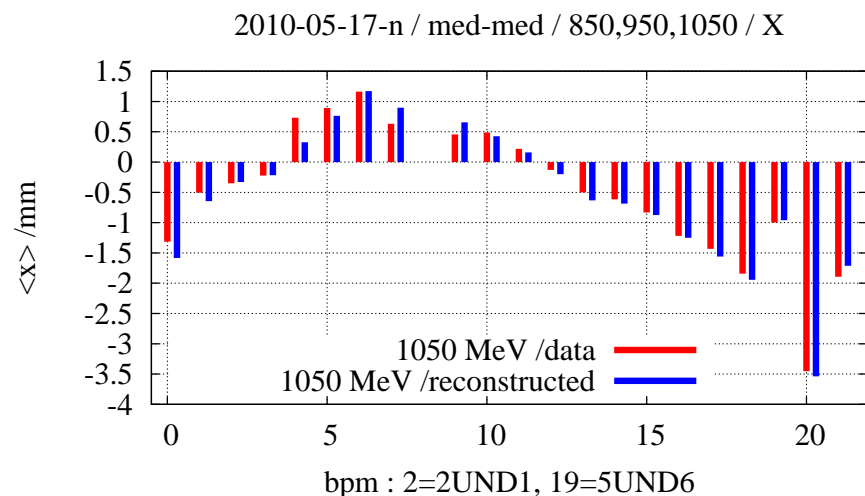
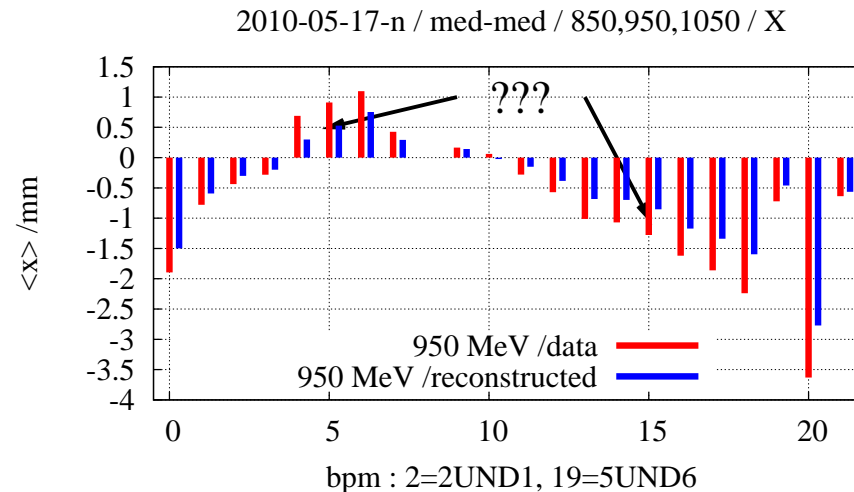
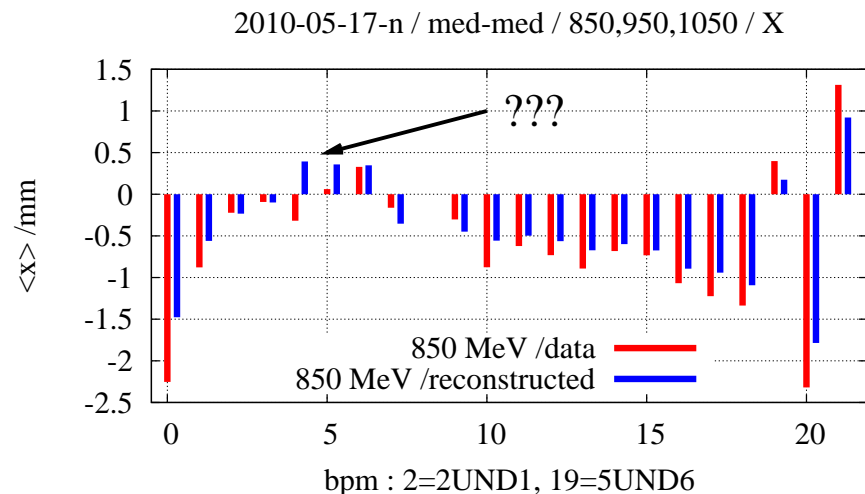
1050MeV looks weirded ??? \Rightarrow redo in November \rightarrow got no beam-time \Rightarrow redo in January

Measured and Reconstructed Orbits



- Data set for small E -range (950 ± 50) MeV.
- $w_i \propto 1/\text{Var}_k(x_{i,k})$; worst 2 : $w \rightarrow 0$
- First to movers upstream undulator deselected.
- $\tau \approx 10^{-5}$ necessary :-(
- **However:**
 \Rightarrow reasonably good agreement !

Measured and Reconstructed Orbits (2)



- Data set for large E -range $(950 \pm 100) \text{MeV}$.
 - $w_i \propto 1/\text{Var}_k(x_{i,k})$; worst 2 : $w \rightarrow 0$
 - First to movers upstream undulator deselected.
 - Subset at 1050MeV corrupted
→ not suff. many d.o.f.
- ⇒ **redo !** (and do better!)

SUMMARY :

- LCLS-BBA-Method allows for offset independent measurement at highest resolutions.
- ⇒ **Well established at SLAC!!**
- Requires properly set up linac : reliable (and quick) switching of energies **for full range of energies**
- BBA-application : “pre-beta-version” (java) $\exists \rightarrow$ work in progress !
- Pre-calculated ORMs/OLMs : easy to generate (\rightarrow bash-f77-lmad script) from MAD file
- **Ultimate goal : should become standard-procedure!!**
- Planned for FLASH and E-XFEL

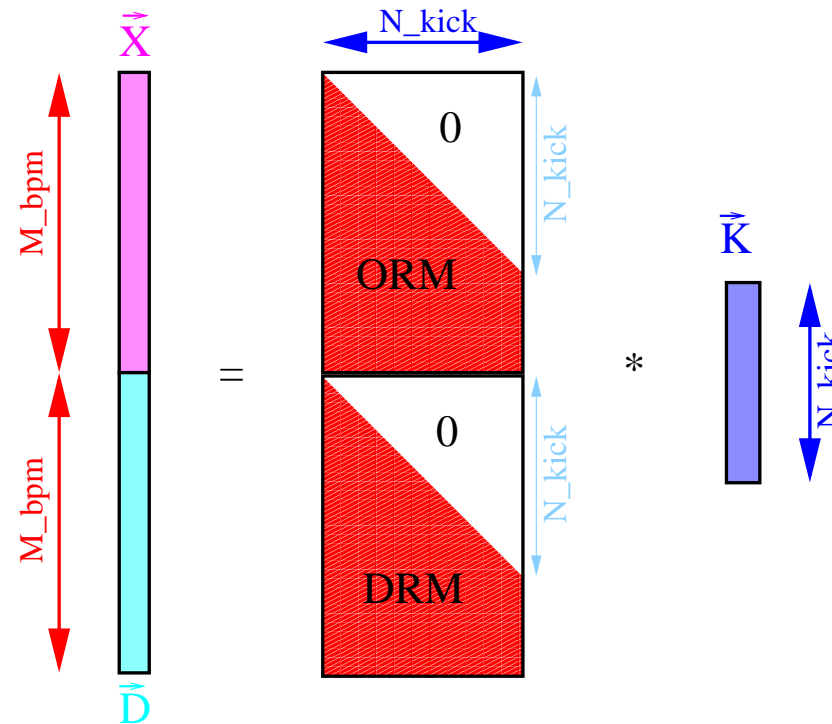
OUTLOOK :

- Preliminary evaluation of first set of measurements finished!
- ⇐ **major bugs fixed**
- ⇐ **Repeat measurement with adequate energy range !**
- ⇐ **Improve and establish standard procedure.**

* * * SPARES * * *

Dispersion-Free Steering

- Orbit (= dipole) kicks create (spurious) dispersion
- + **given** N **perturbations** (=correctors) $\{K_i\}_{1 \leq i \leq N}$ and M **BPMs**
- + **yields** M **measured orbits** $\{X_i\}_{1 \leq i \leq M}$
- + **and** M **measured dispersions** $\{D_i\}_{1 \leq i \leq M}$
- + **measured** \vec{X} ← **offset** + **statistical fluctuations**
- + **measured** \vec{D} ← **statistical fluctuations only**



- ↗ causality in beam line : each upper right $\rightarrow 0$
- ↗ $2M$ conditions for N corrector settings \Rightarrow
- ↗ **overdetermined system** :
w/o errors \rightarrow conditions linearly dependent
w/ errors \rightarrow **least squares solution** \rightarrow **SVD**

Dispersion-Free Steering (2)

- Introduce **weight** w

(**0** → orbit-only, **1** → dispersion-only)

$$\begin{pmatrix} (1-w)\vec{X} \\ w\vec{D} \end{pmatrix} = \begin{pmatrix} (1-w)\underline{\mathcal{O}} \\ w\underline{\mathcal{D}} \end{pmatrix} \vec{K}$$

or shorthand:

$$\vec{\Xi}(w) = \underline{\mathcal{A}}(w) \vec{K}$$

↗ $\vec{\Xi} \in \mathbb{R}^{2M} :=$ “real” orbit/dispersion,
 $\underline{\mathcal{A}} \in \mathbb{R}^{2N \times M} :=$
combined orbit dispersion response matrix

- **i -th Measurement**: add systematic (const \vec{C}) and statistical (\vec{S}_i) errors

$$\vec{\xi}_i(w) = \underline{\mathcal{A}}(w)\vec{K}_i + \vec{C} + \vec{S}_i$$

- and iterate **corrected** dipole kicks → $\vec{\Phi}_i$
 with **error** → $\vec{\Delta}_i$

$$\vec{K}_i = \vec{K}_{i-1} - \vec{\Phi}_i - \vec{\Delta}_i$$

How to compute $\vec{\Phi}_i$?

- **assuming NO orbit/dispersion from upstream SASE-1 !**

- iff $\vec{C} \equiv \vec{S}_i \equiv \vec{\Delta}_i \equiv 0 \forall i$

(& assuming $\underline{\mathcal{A}}$ is completely known)

⇒ $\vec{\xi} \equiv \vec{\Xi} = \underline{\mathcal{A}}\vec{K}$ is fully redundant, i.e.

∃ $\underline{\mathcal{A}}^* \in \mathbb{R}^{M \times 2N}$ with $\vec{K} \equiv \vec{\Phi} := \underline{\mathcal{A}}^*\vec{\Xi}$

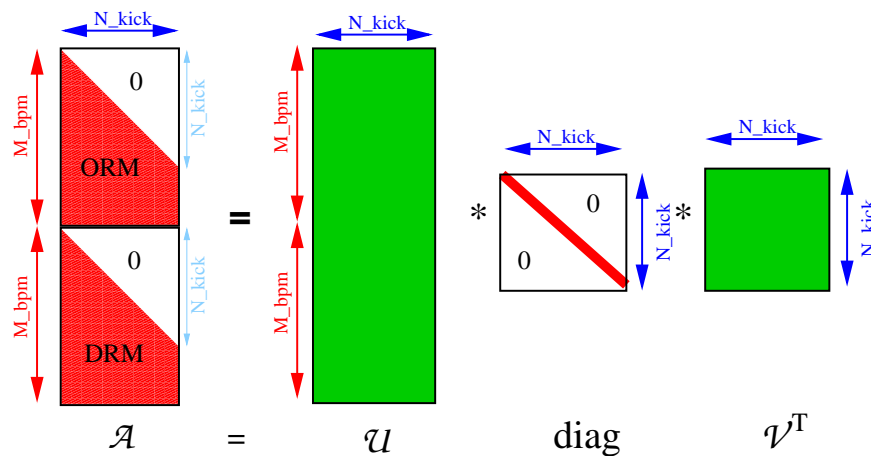
- The **“pseudo-inverse”** $\underline{\mathcal{A}}^*$ can be computed using a *Singular Value Decomposition (SVD)*

- In fact **SVD + “ τ -regularization”** allow some control over correcting the highly correlated (= potentially “real”) orbit/dispn. components rather than the weakly correlated (= contaminated) components

⇒ ...

SVD + for DispFree Steering

$$\underline{\mathcal{A}} = \underline{\mathcal{U}} \underline{\text{diag}}(\{\sigma_k\}) \underline{\mathcal{V}}^T$$



- $\underline{\mathcal{U}} \in \mathbb{R}^{2M \times N}$, $\underline{\mathcal{U}}^T \underline{\mathcal{U}} = \underline{\mathbf{1}}_{N \times N}$
 $\rightarrow \underline{\mathcal{U}}^T \vec{\Xi} :=$ *orthogonal orbit/dispn mode*
- $\underline{\mathcal{V}} \in \mathbf{O}(N) \rightarrow \underline{\mathcal{V}}^T \vec{K} :=$ *orth. knob for mode*
- $\{\sigma_k\}_{1 \leq k \leq N}$, $\sigma_k \geq 0$: **singular values**
 \rightarrow “knob–strengths”

- for non–degenerate phase advances $\Rightarrow \underline{\mathcal{A}}$ has full rank
 $\Leftrightarrow \sigma_k > 0 \forall k$

$$\Rightarrow \underline{\mathcal{A}}^* := \underline{\mathcal{V}} \underline{\text{diag}}(\{\sigma_k^{-1}\}) \underline{\mathcal{U}}^T$$

- if system is **underdetermined**

\Rightarrow solution of $\vec{\Xi} = \underline{\mathcal{A}} \vec{K}$ is
 $\vec{K} \in \vec{K}_{\text{part}} + \text{kern}(\underline{\mathcal{A}})$

\Rightarrow SVD gives “minimal”
 solution : $\left\| \underline{\mathcal{A}}^* \vec{\Xi} \right\|_2 = \min$

- if system is **overdetermined** \Rightarrow solution \exists only in the
 “least square” sense

\Rightarrow SVD yields solution
 with minimal residue :
 $\left\| \vec{\Xi} - \underline{\mathcal{A}} (\underline{\mathcal{A}}^* \vec{\Xi}) \right\|_2 = \min$

τ -regularization for DispFree Steering

- **What if some $\sigma_i = 0$???**

→ just **redefine** $\underline{\mathcal{A}}^* := \underline{\mathcal{V}} \underline{\text{diag}}(\{(\sigma_k > 0)^{-1}, 0 \dots\}) \underline{\mathcal{U}}^T$

⇒ yields least square solution !

- MORE GENERAL : *condition* of $\underline{\mathcal{A}}$: $\text{cond}(\underline{\mathcal{A}}) := \frac{\max_i \{\sigma_i\}}{\min_{i, \sigma_i > 0} \{\sigma_i\}}$
 → large cond means that solutions \vec{K} of linear system $\underline{\mathcal{A}} \vec{K} = \vec{\Xi}$ strongly depend on small variations (←errors!) of $\vec{\Xi}$

→ to improve (=decrease) condition : set $\sigma_j \rightarrow 0$, $\forall \sigma_j < \tau$ with some **regularization parameter τ**

- ... and **redefine** $\underline{\mathcal{A}}^*(\tau) := \underline{\mathcal{V}} \underline{\text{diag}}(\{(\sigma_k > \tau)^{-1}, 0 \dots\}) \underline{\mathcal{U}}^T$

⇒ for **Dipersion-Free Steering** :

⇔ **use only highly correlated orbit/dispn modes !!!**

& ignore strongly contaminated orbit/dispn modes !!!

⇒ **correct orbit/dispn with:** $\Phi_i = \underline{\mathcal{A}}^*(\tau) \vec{\xi}_{i-1}$

The LCLS Method (Example : **in the Limit** → **Disp. Free Steering**)

- Let $P = 2$, $|E_2 - E_1| \ll E_1 \Rightarrow \underline{\mathcal{L}}_2 \approx \underline{\mathcal{L}}_1, \underline{\mathcal{O}}_2 \approx \underline{\mathcal{O}}_1 + \frac{\Delta E}{E} \underline{\mathcal{D}}_1$

- Measured orbit at E_1 :

$$\vec{Y}_1 = \underline{\mathcal{L}}_1 \vec{z}_1 + \underline{\mathcal{O}}_1 \vec{d} + \vec{\Delta} + \vec{\xi}_1$$

- Measured orbit at E_2 :

$$\vec{Y}_2 \approx \underline{\mathcal{L}}_1 \vec{z}_2 + \underline{\mathcal{O}}_1 \vec{d} + \frac{\Delta E}{E} \underline{\mathcal{D}}_1 \vec{d} + \vec{\Delta} + \vec{\xi}_2$$

⇒ **Dispersive Difference Orbit** :

$$\vec{Y}_2 - \vec{Y}_1 \approx \underline{\mathcal{L}}_1 (\vec{z}_2 - \vec{z}_1) + \frac{\Delta E}{E} \underline{\mathcal{D}}_1 \vec{d} + (\vec{\xi}_2 - \vec{\xi}_1)$$

→ **Eliminates the offsets !!!!**

- If $\vec{z}_2 \approx \vec{z}_1$, then solving

$$w (\vec{Y}_1 = \underline{\mathcal{O}}_1 \vec{d}) \text{ and}$$

$$(1 - w) ((\vec{Y}_2 - \vec{Y}_1) \frac{E}{\Delta E} = \underline{\mathcal{D}}_1 \vec{d}) \text{ simultaneously for } \vec{d}$$

is exactly the well known dispersion-free steering algorithm with weight w !!!

Extending the LCLS Method for More Flexibility

⇒ introduce various weights for various constraints $(w_i(k), \dots)$

Preliminary Commissioning Ideas / Outline of MD

- **Establish machine states** (transmission, optics matched → undulator)

Energies: $E_1 < E_2 < E_3 < E_4, \dots$

 1. change energy using ACC4–7,
 2. scale optics **w/o** UNDULATOR,
 3. tune transmiss. **w/o** UNDULATOR,
 4. match to UNDULATOR optics w/ last quads upstream UNDULATOR,
 5. match UNDULATOR to dump w/ downstream quads,
 6. (tune launch into UNDULATOR),

⇒ **one special file F_i per E_i**
 ⇐ **reproducible!!**
- **BBA measurement** :
 1. load & cycle into F_i ; setup RF for E_i ,
 2. check transmission & losses (& launch),
 3. don't touch the UNDULATOR quads !!!!
 4. measure orbit at E_i
 → **BBA-application.**
- **BBA correction** :
 1. compute & set new set points for quad movers → **BBA-application**,
 2. re-optimize orbit (transmission, losses...),
- Probably (at least initially) several iterations w/ ≈ 4 energies needed :

BBA₁ := ($E_1 \rightarrow E_2 \rightarrow E_3 \rightarrow E_4 \dots$) →
 BBA₂ := ($\dots E_4 \rightarrow E_3 \rightarrow E_2 \rightarrow E_1$) →
 ...