Beam Based Alignment in FLASH undulator Sections

“The LCLS–Method”

23.11.2010

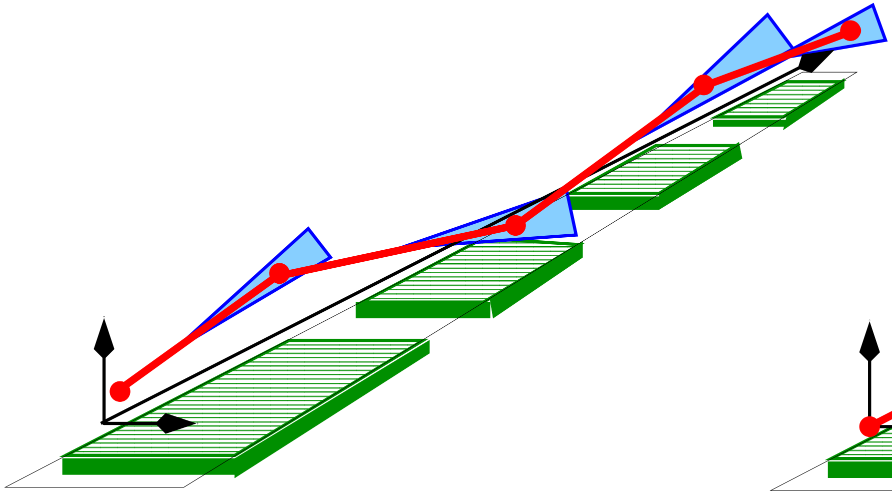
Mathias Vogt (DESY–MFL)

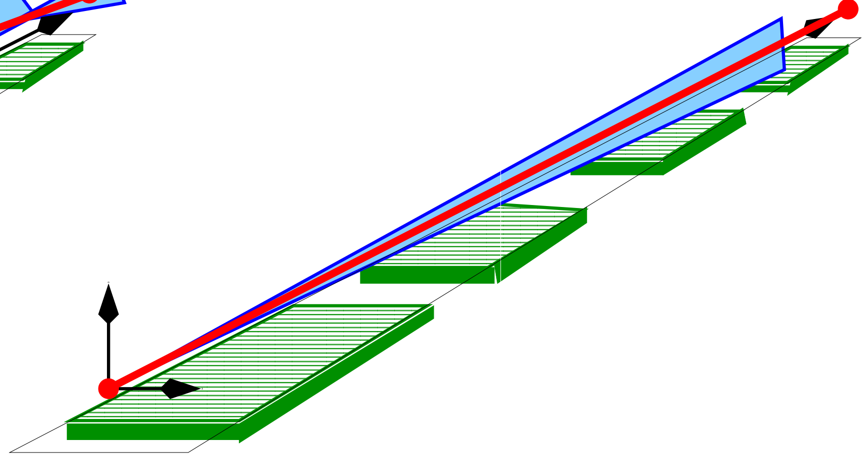
- **Motivation**
- **The LCLS–Method** → **thanx to Hendrik Loos (SLAC)**
- **Implementation** → `SASEBBAGUIMain`
- **Preliminary Data from FLASH Recommissioning/MD 2010-05**
- **Summary and Outlook**

Motivation : Orbit Requirements for the SASE Process

- Resonant interaction of charged particle and undulator radiation
  $\Rightarrow$Particle orbit and radiation cone ($\sim 1/\gamma$) must overlap

$\rightarrow$ Beam orbit excursion in undulator $\ll$ rms beam envelope
$\rightarrow$longitudinal scale $\sim$ gain length





BAD ORBIT :

- Strong orbit fluctuations

$\Rightarrow$ overlap only over short ranges $\ll$ radiation length

$\Rightarrow$ **weak (or no) SASE signal**

GOOD ORBIT :

- Flat orbit

$\Rightarrow$ overlap only over most of undulator $>$ radiation length

$\Rightarrow$ **potentially: "'saturation"**

Motivation : Accuracy/Resolution Issues

- FLASH :
  $\beta\gamma\epsilon \approx 1.4 \cdot 10^{-6} - 2.0 \cdot 10^{-6}$m;
  $\langle\beta\rangle_{\rm undu} \approx 10$m. $\Rightarrow$ $\sigma \approx 70 - 100\mu$m
  at 450–1200 MeV.
- BPM resolution in UNDULATOR section:
  $\sigma_X \approx 10\mu$m $\Rightarrow$ **m.o.l. OK**.
- BPM offsets : $\sim 300\mu$m ?!?

$\Rightarrow$ BBA based on dispersive orbits

- dispersive orbits measured as **difference orbits**.

$\rightarrow$ **Unfortunately :**
Resolution $\sigma_D \propto \sigma_X / \frac{\Delta E}{E}$

$\Rightarrow$ typical $\frac{\Delta E}{E} = 5\% \rightarrow \sigma_D \approx 200\mu$m **:-(**

$\Rightarrow$ **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 mis-alignments and BPM–offsets simultaneously $\Rightarrow$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 $\vec{\xi}_k$

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

- 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) $\vec{z} \equiv (x_0, x_0')_k^{\mathrm{T}}$

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

– **LaunchResponseMatrix (LRM)** $\underline{\mathcal{L}}_k$

– **OrbitResponseMatrix (ORM)** $\underline{\mathcal{O}}_k$

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

$\vec{X} := (\vec{X}_1^{\mathrm{T}}, \cdots, \vec{X}_P^{\mathrm{T}})^{\mathrm{T}}$, $\vec{Y} := \ldots$,

$\vec{z} := \ldots$, $\vec{\xi} := \ldots$

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

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

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

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

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

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

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

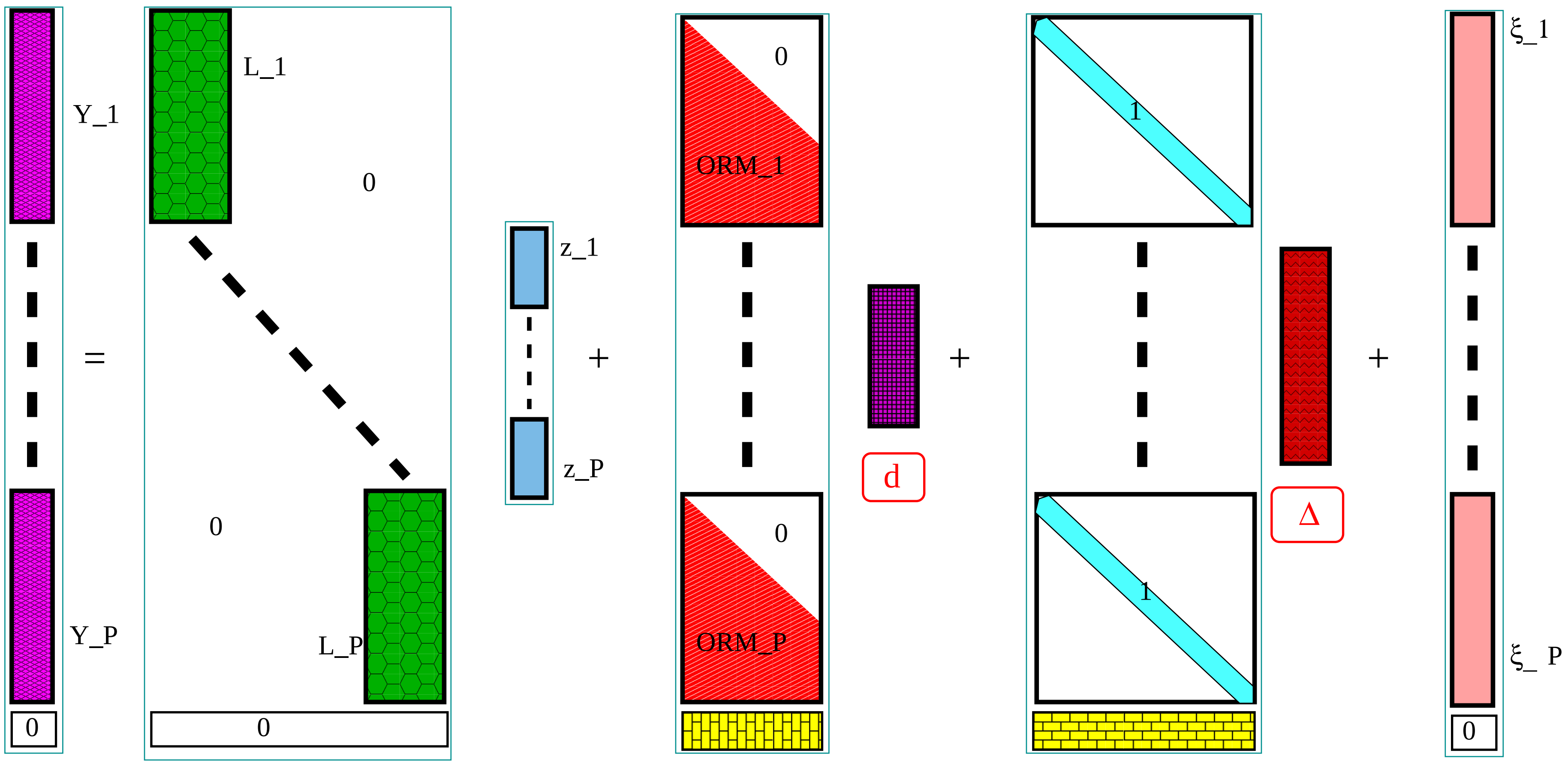
- Add 2 more constraints for "baseline tilt"
  - either $0 = \sum_{i=1}^{M} \Delta_i$ & $0 = \sum_{i=1}^{M} s_i \Delta_i$

  ← $\Delta_i = \Delta^{(0)} + \Delta^{(1)} s_i$
  - or $0 = \sum_{i=1}^{N} d_i$ & $0 = \sum_{i=1}^{N} s_i d_i$

  ← $d_i = d^{(0)} + d^{(1)} s_i$

→ $PM + 2$ **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

$\Rightarrow$ very successful $\longrightarrow$ see LCLS-e-log of 21.05.2009

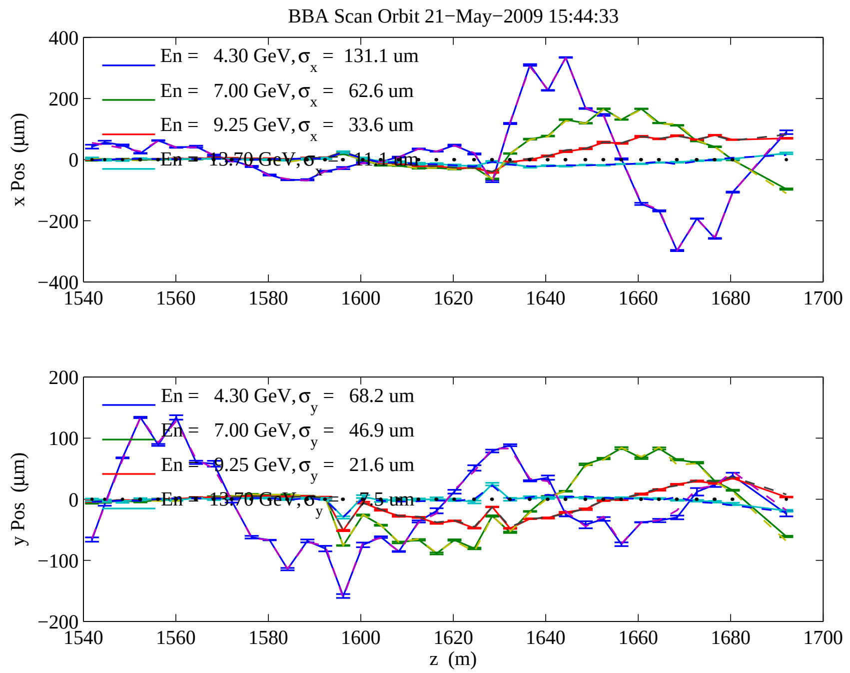
$\longrightarrow$ **example :** local bumps $\longrightarrow\longrightarrow\longrightarrow$

- after preparing clean machine states (for 4.3, 7.0, 9.25, 13.7 GeV)

$\longrightarrow$ measure "up" $\longrightarrow$ correct $\longrightarrow$ measure "down" $\longrightarrow$ verify

$\longrightarrow$ 20-30 min per E-step

- **Now : routine operation performed by operators**

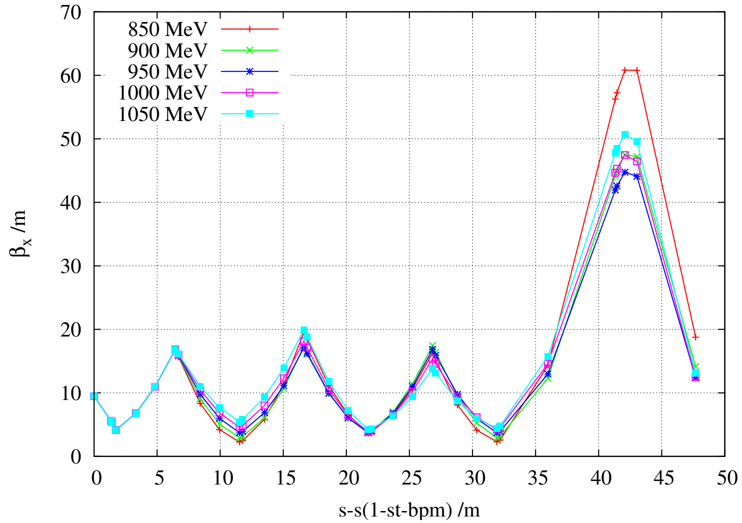


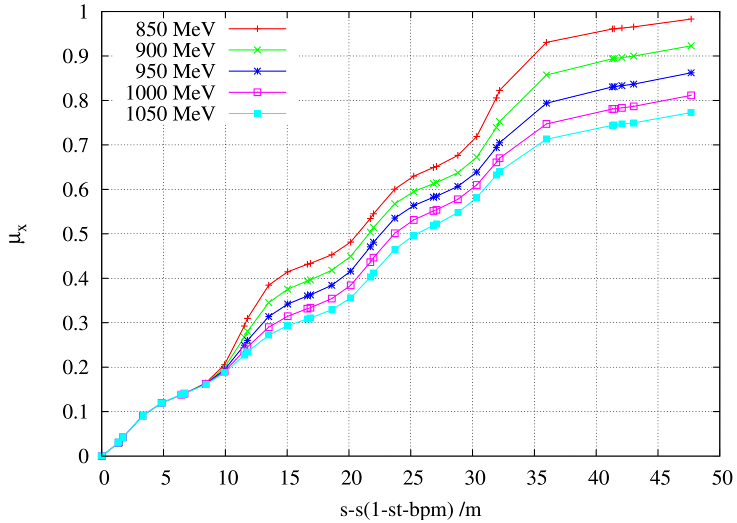
(Pictures thanx to H.Loos and the LCLS team at SLAC)

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



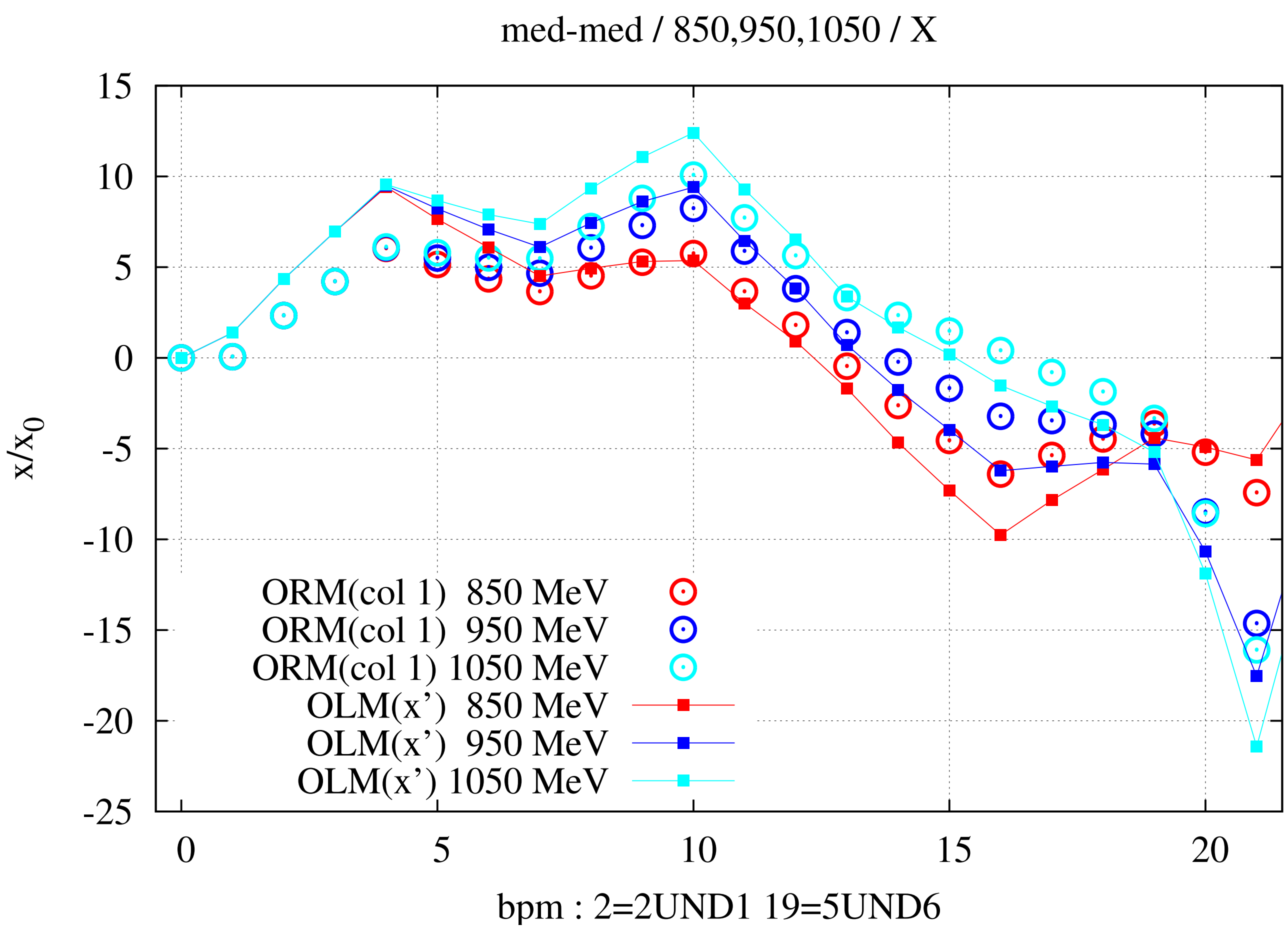


- Standard optics ("Med–Med") established during commissioning.
- Reference energy for k_1 values in "Med–Med" : 950 MeV.
- Don't be too brave . . .
  $\Rightarrow$ ***E* range only ± 100 MeV**
  $\rightarrow$850, 900, 950, 1000, 1050 MeV.

$\Rightarrow$ chromatic optics effects very small
(+) no rematch necessary
(−) combined BBA–matrix (from 3$\rightarrow$5) ORMs/OLMs is almost singular ($\Rightarrow$ill–conditioned)

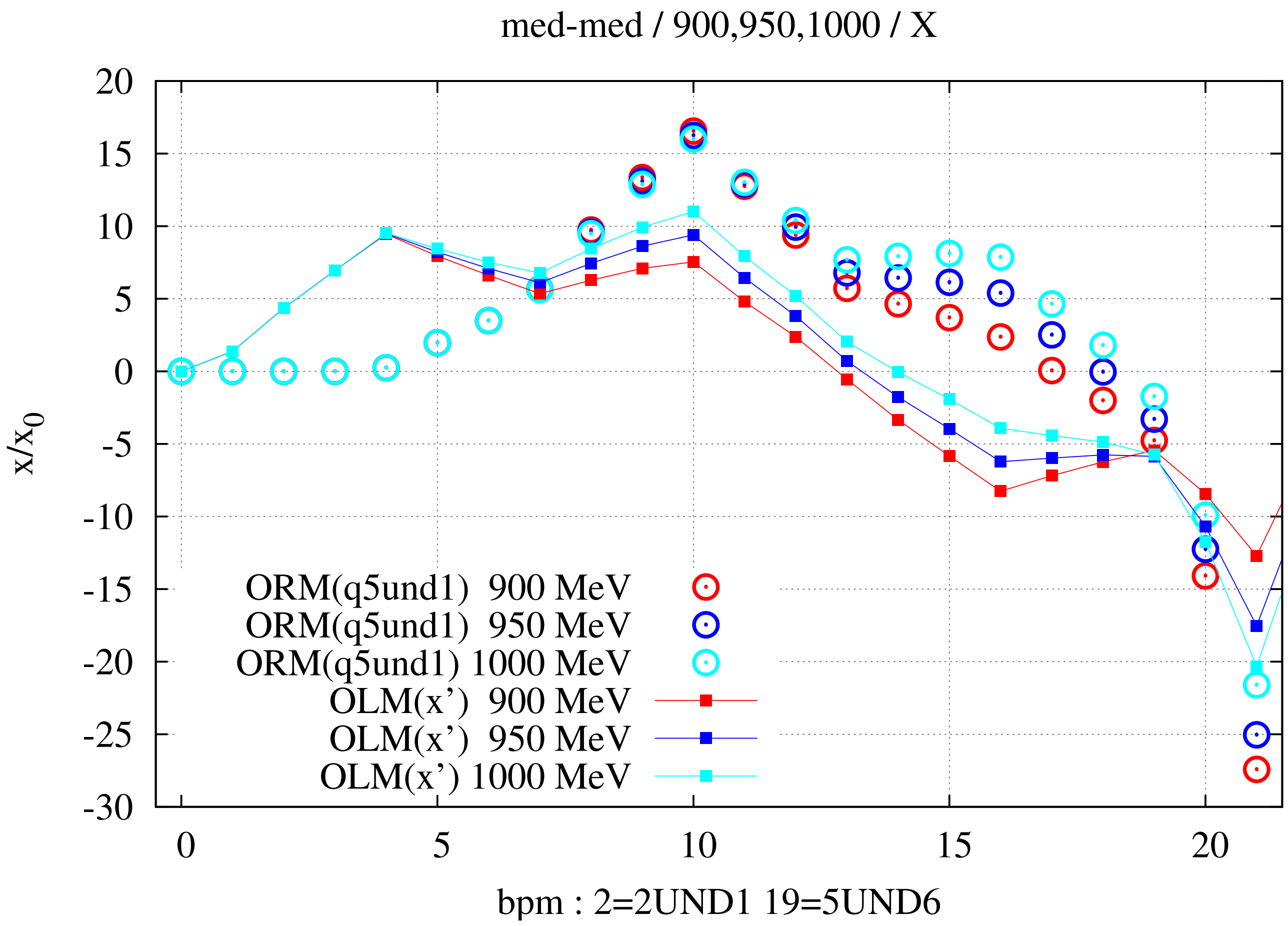
Set up for FLASH-BBA MD End of May 2010 (2)

Effects from last quads upstream of undulator and launch almost indistinguishable



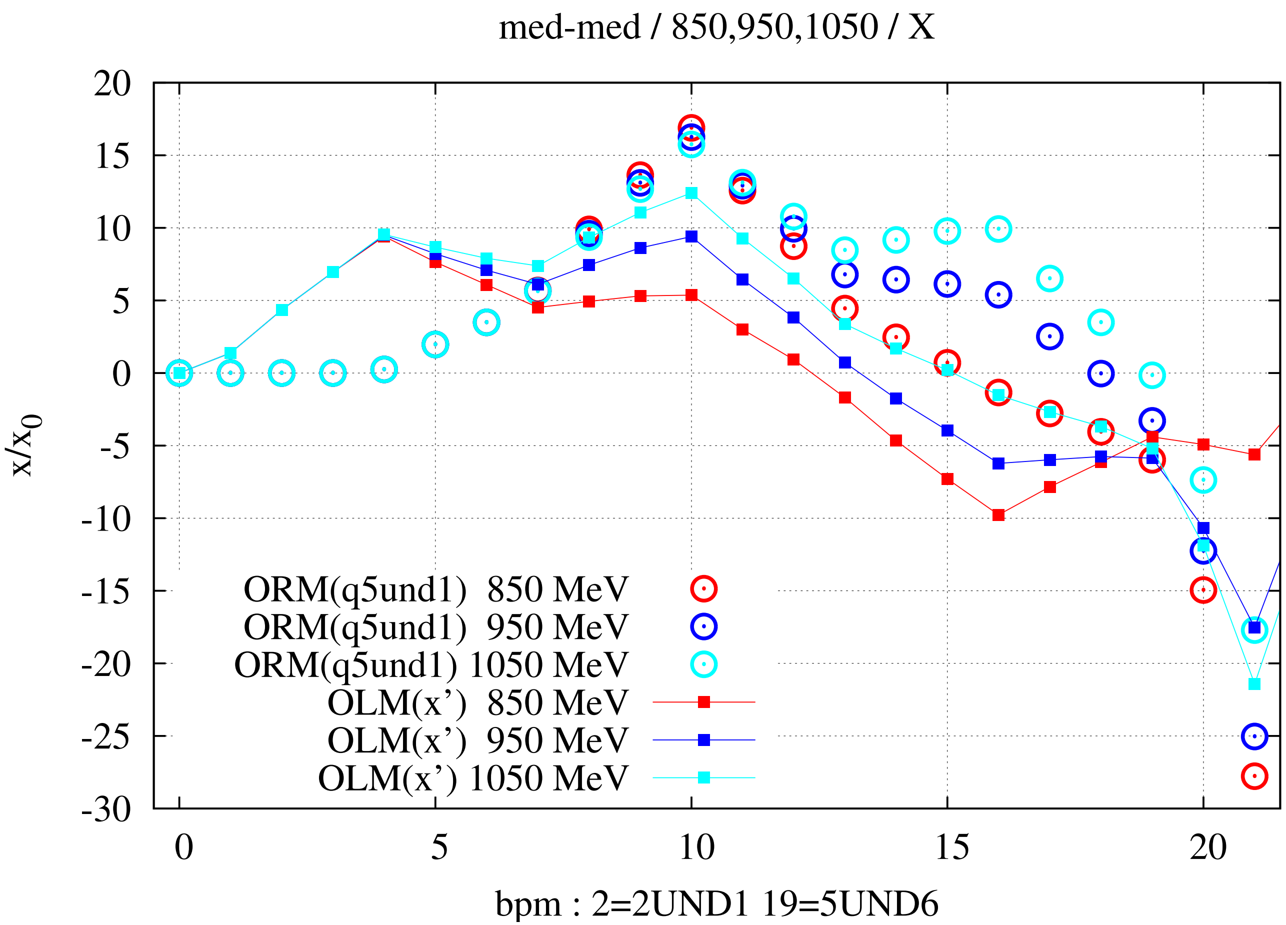
Set up for FLASH-BBA MD End of May 2010 (3)

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

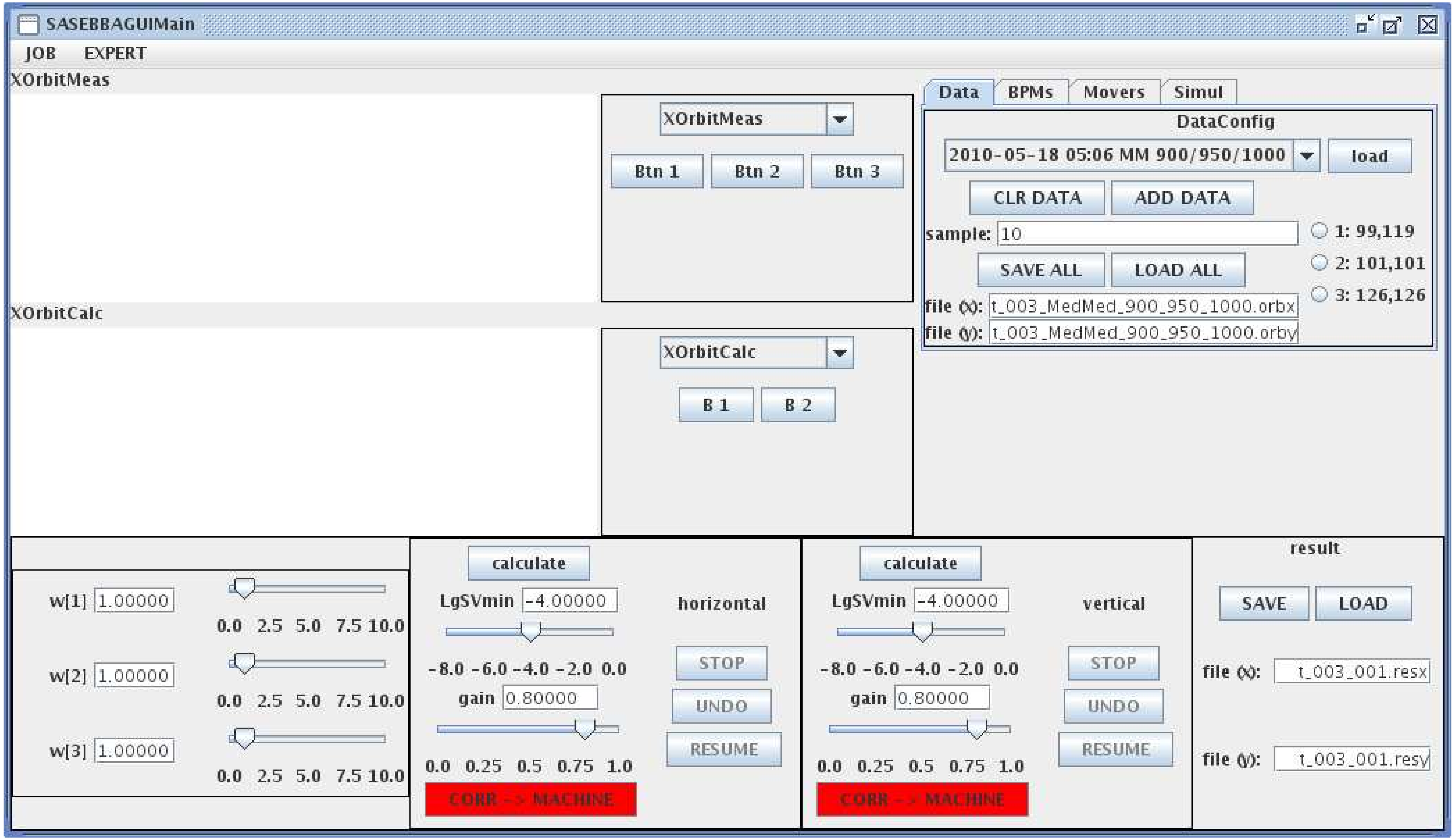


Set up for FLASH-BBA MD End of May 2010 (4)

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



“java -cp $CLASSPATH desy/csfel/sasebba/gui/SASEBBAGUIMain &”



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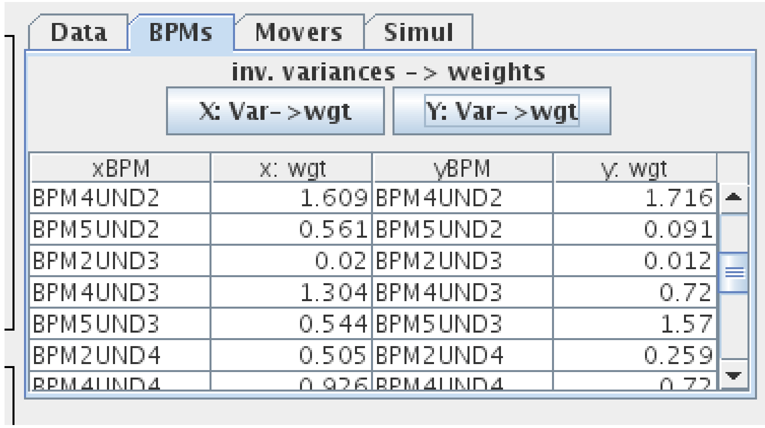
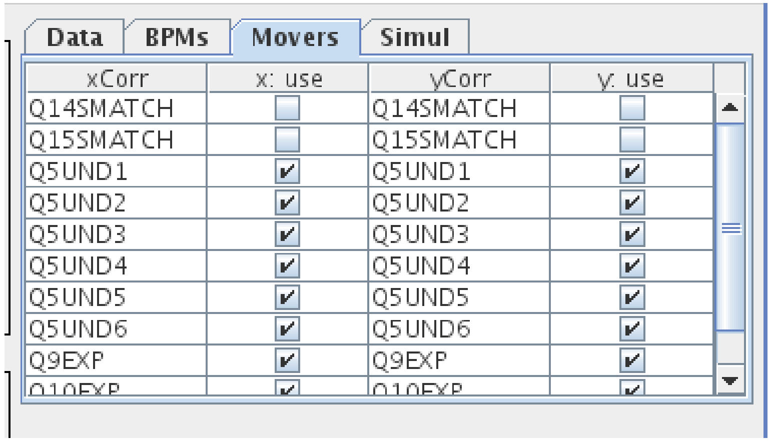


← Weights can be assigned to BPMs

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

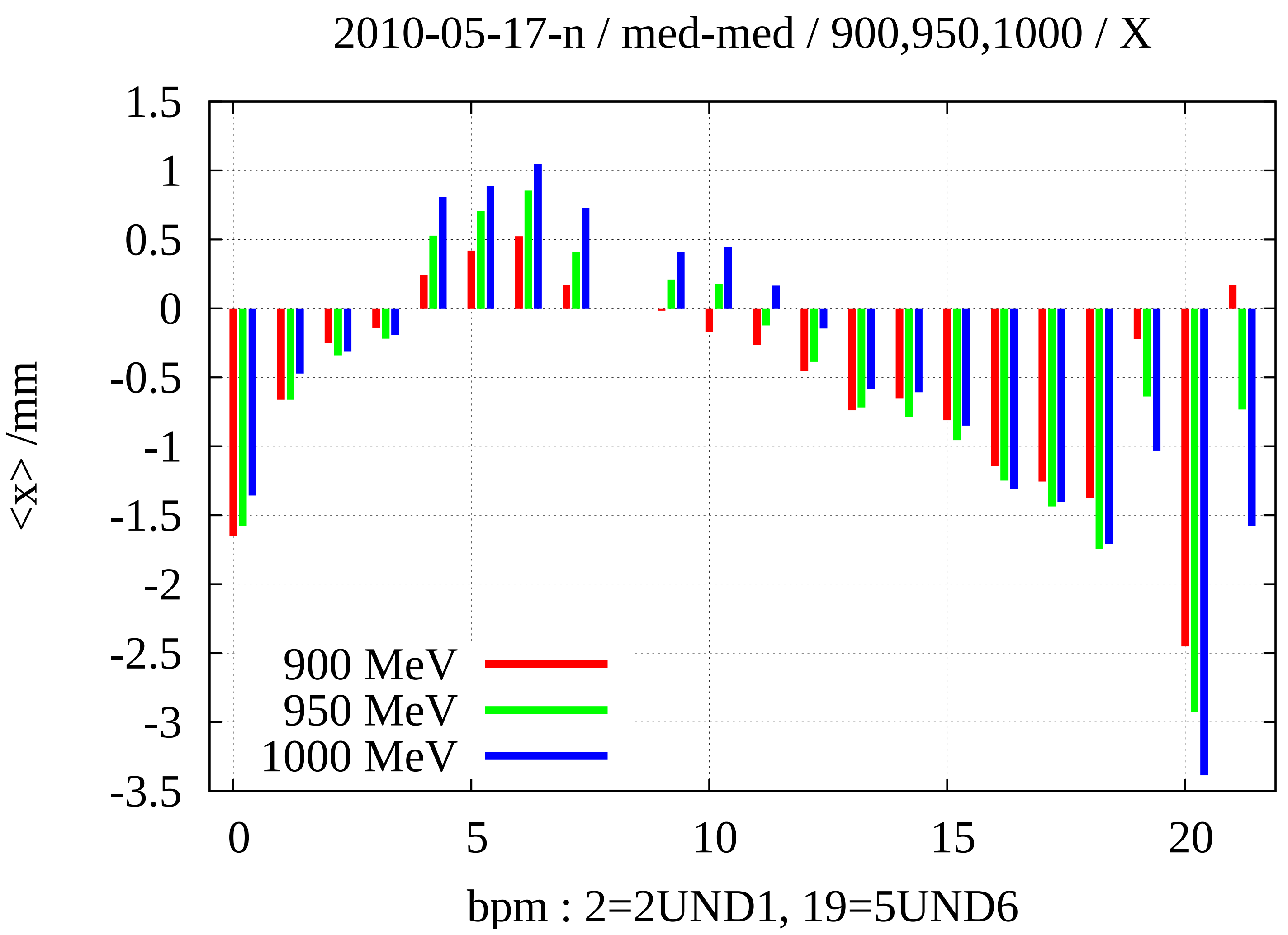


← Knobs (quads/movers) can be disabled

← e.g. those which compete with initial conditions

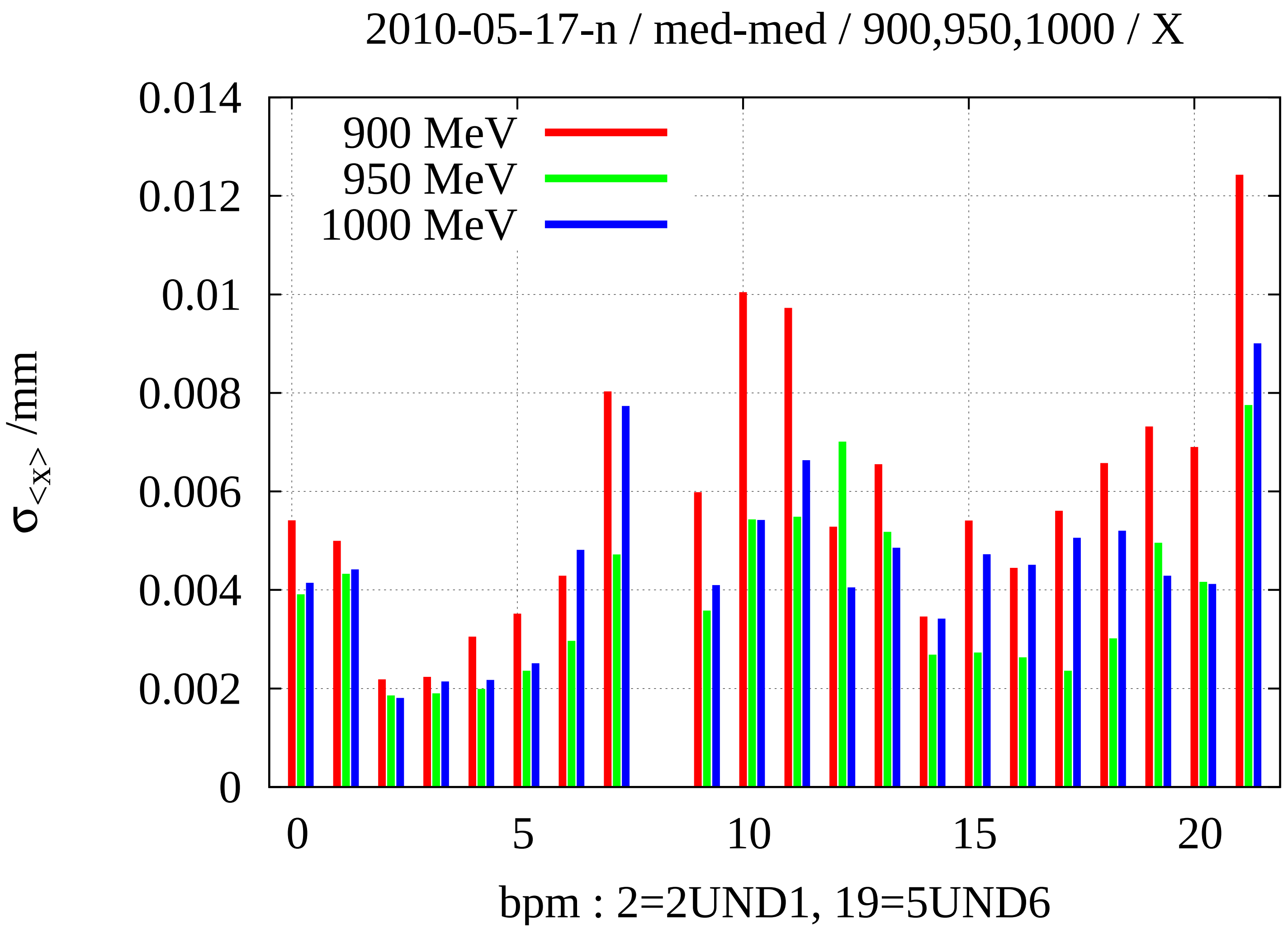
Preliminary FLASH Data

worst two BPMs deselected

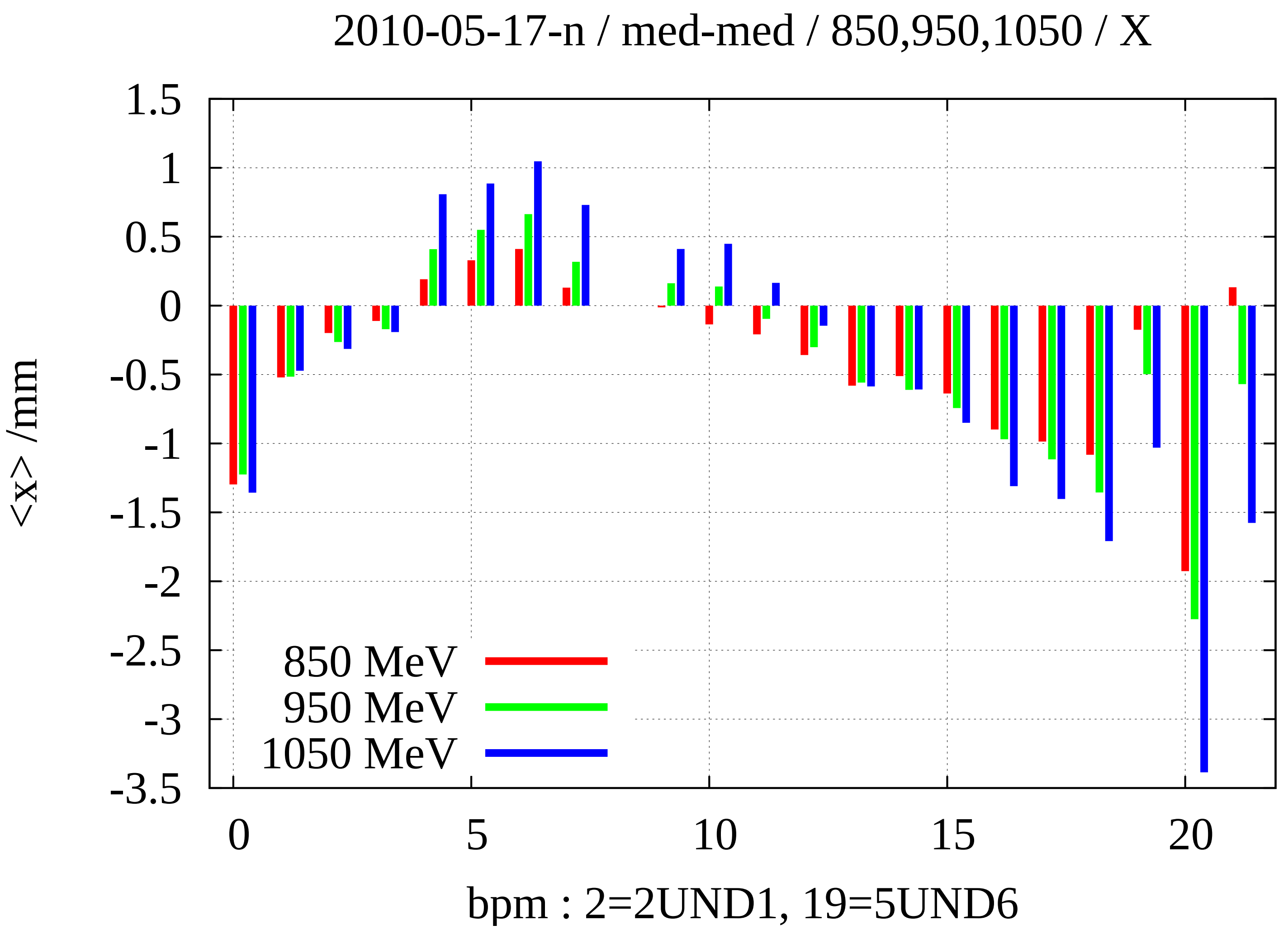


Preliminary FLASH Data (2)

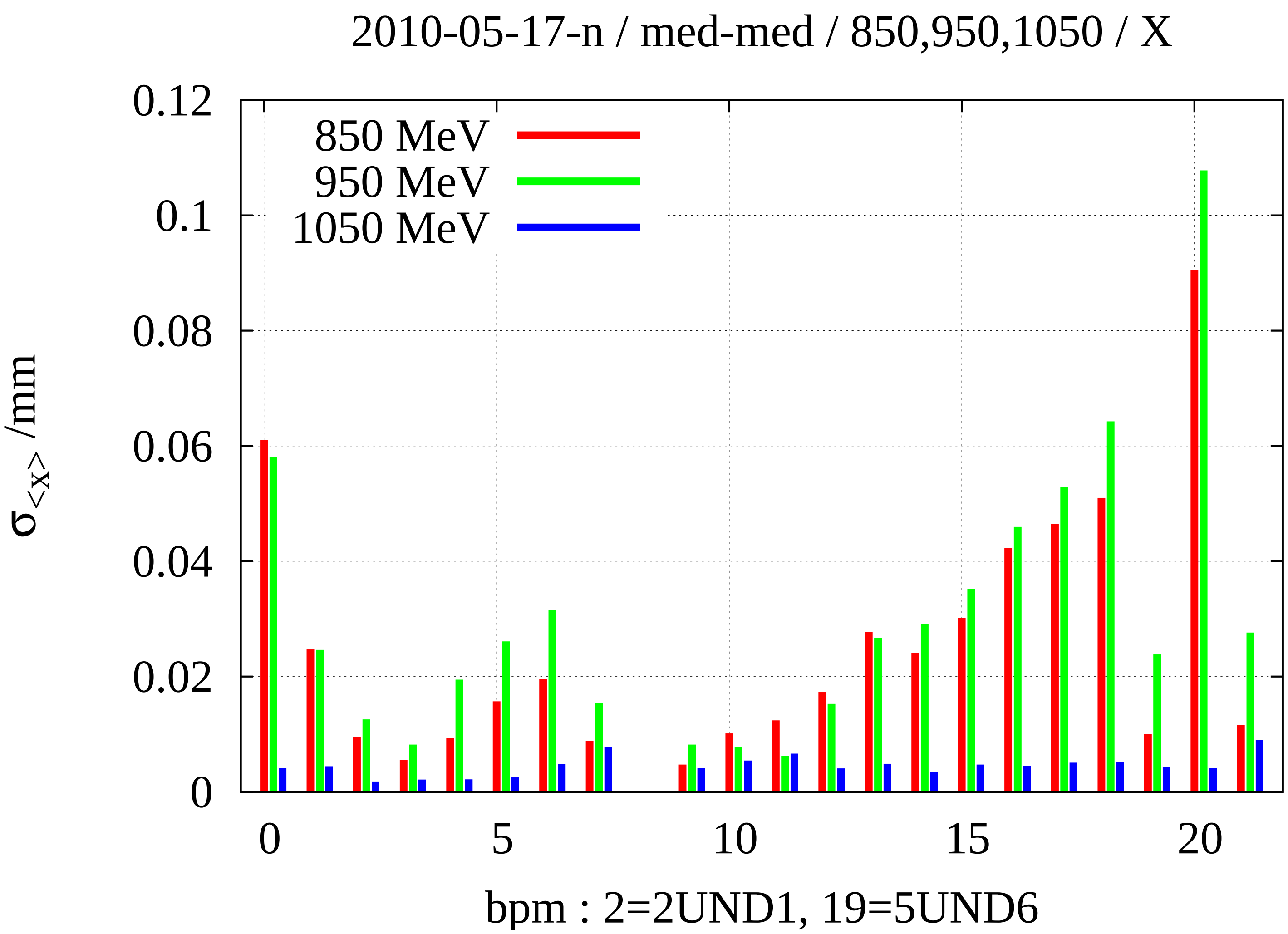
worst two BPMs deselected



Preliminary FLASH Data (3)

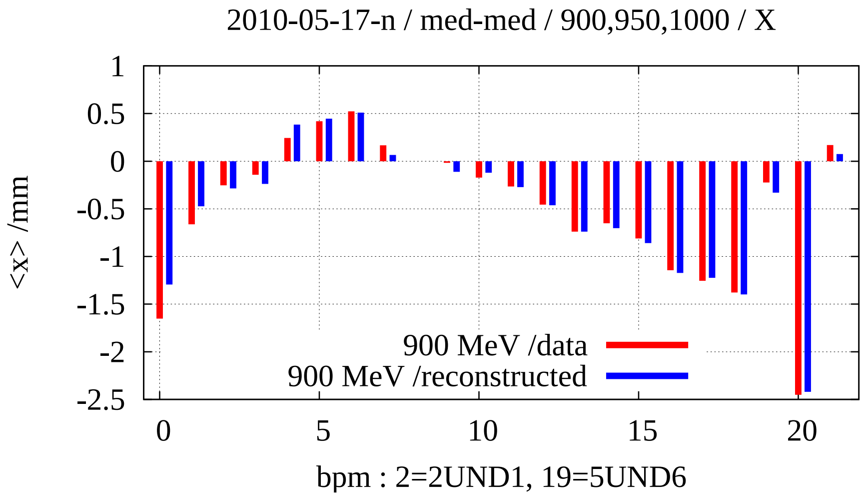


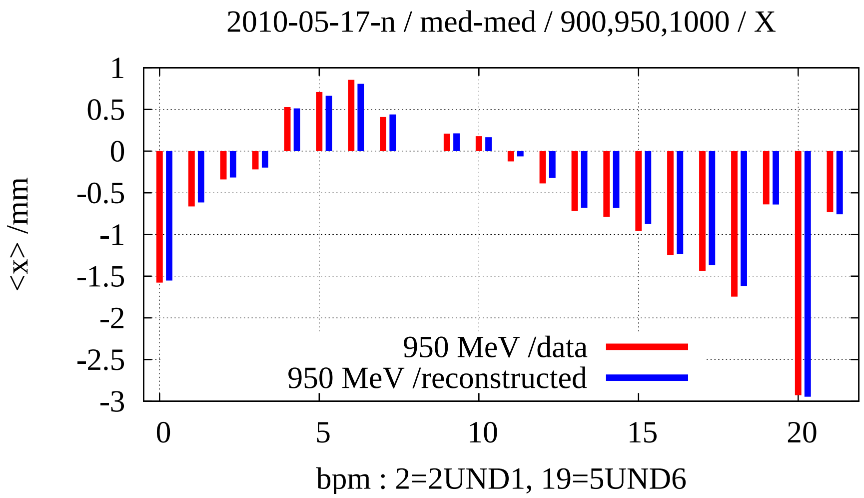
Preliminary FLASH Data (4)

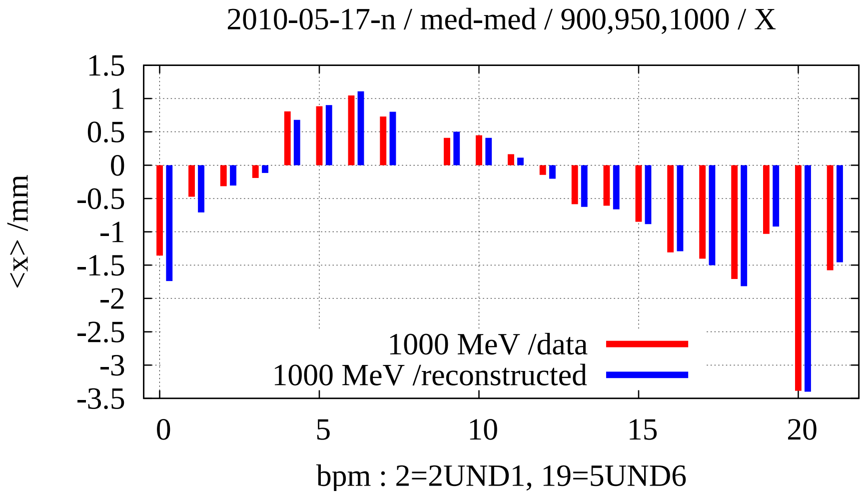


1050MeV looks weired ??! ⇒ redo in November → got no beam–time ⇒ redo in January

Measured and Reconstructed Orbits



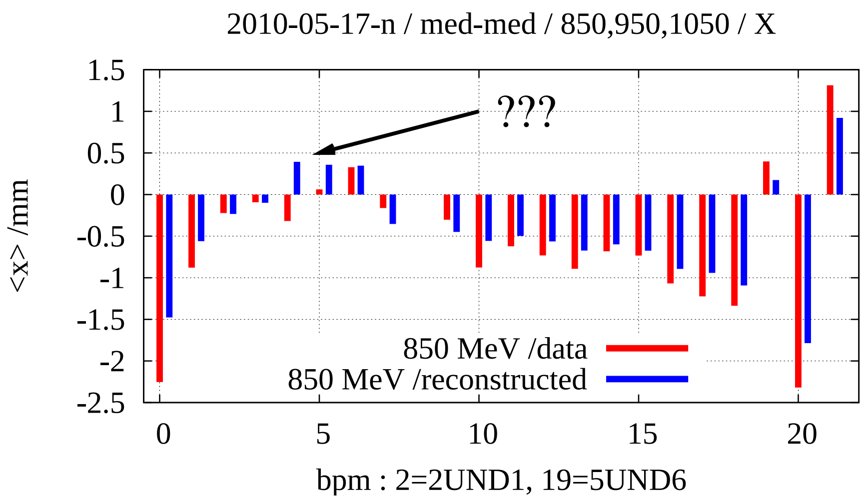


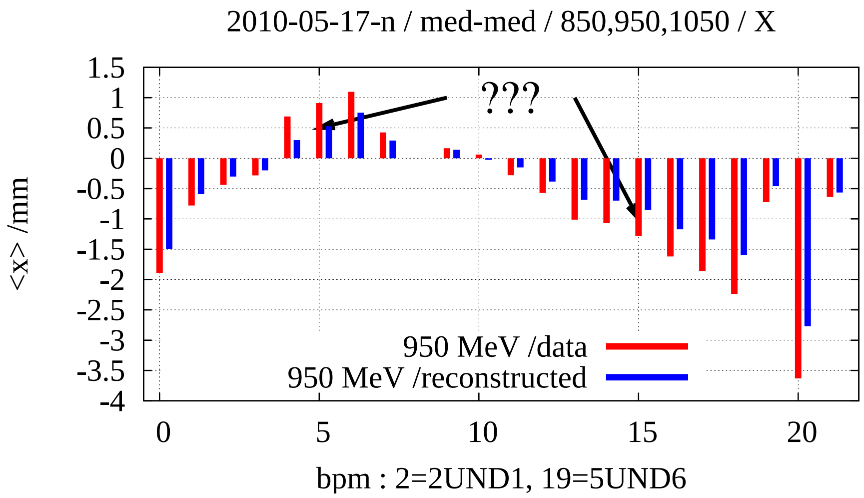


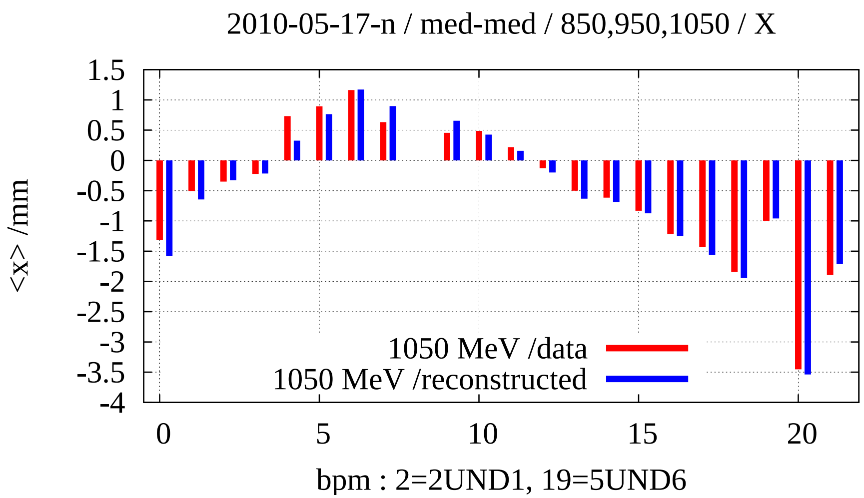
- Data set for small E–range (950±50) MeV.
- $w_i \propto 1/\mathrm{Var}_k(x_{i,k})$; worst 2 : $w \to 0$
- First to movers upstream undulator deselected.
- $\tau \approx 10^{-5}$ necessary :-(
- **However:**

  $\Rightarrow$ reasonably good agreement !

Measured and Reconstructed Orbits (2)







- Data set for large E–range (950±100)MeV.
- $w_i \propto 1/\mathrm{Var}_k(x_{i,k})$; worst 2 : $w \to 0$
- First to movers upstream undulator deselected.
- Subset at 1050MeV corrupted $\to$ not suff. many d.o.f.

$\Rightarrow$ **redo !** (and do better!)

SUMMARY :

- LCLS-BBA-Method allows for offset independent measurement at highest resolutions.

$\Rightarrow$ **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!

$\Leftarrow$ major bugs fixed

$\Leftarrow$ **Repeat measurement with adequate energy range !**

$\Leftarrow$ **Improve and establish standard procedure.**

* * * SPARES * * *

Dispersion–Free Steering

- Orbit (= dipole) kicks create (spurious) dispersion

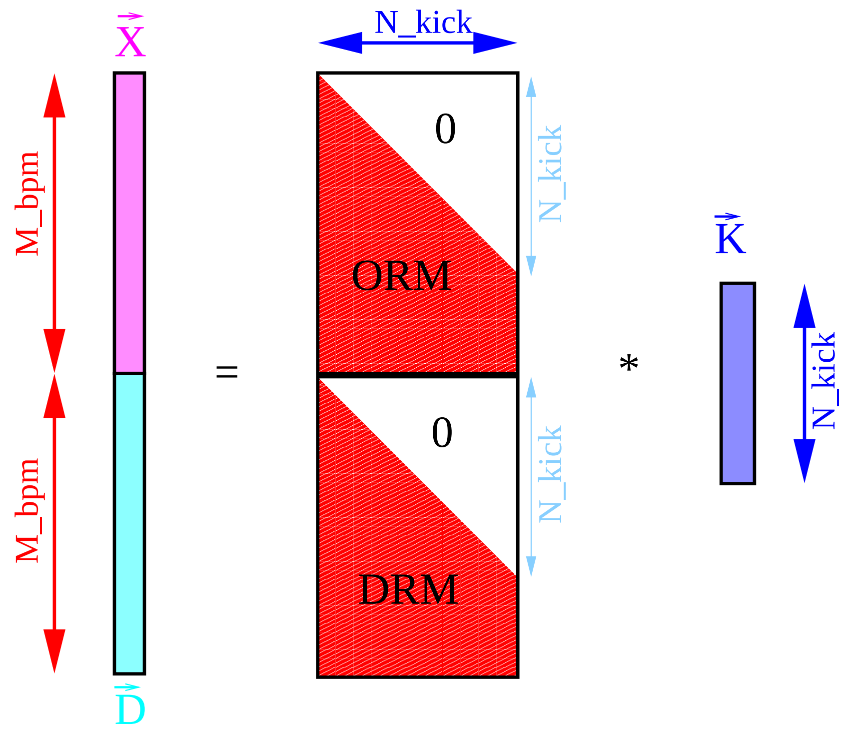
+ **given N perturbations (=correctors) $\{K_i\}_{1\le i\le N}$** and M **BPMs**

+ **yields** M **measured orbits** $\{X_i\}_{1\le i\le M}$

+ and M **measured dispersions** $\{D_i\}_{1\le i\le M}$

+ **measured** $\vec{X}$ ←**offset** + statistical fluctuations

+ **measured** $\vec{D}$ ←statistical fluctuations **only**



↗ causality in beam line : each upper right → 0

↗ $2M$ conditions for N corrector settings ⇒

↗ **overdetermined system** :
w/o errors → conditions linearly dependent
w/ errors → **least squares solution →SVD**

Dispersion–Free Steering (2)

- Introduce **weight** w
  (**0**$\rightarrow$ orbit-only, **1**$\rightarrow$ 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:

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

$\nearrow$ $\vec{\Xi} \in \mathbb{R}^{2M}$:= "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 $\rightarrow \vec{\Phi}_i$ with error $\rightarrow \vec{\Delta}_i$

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

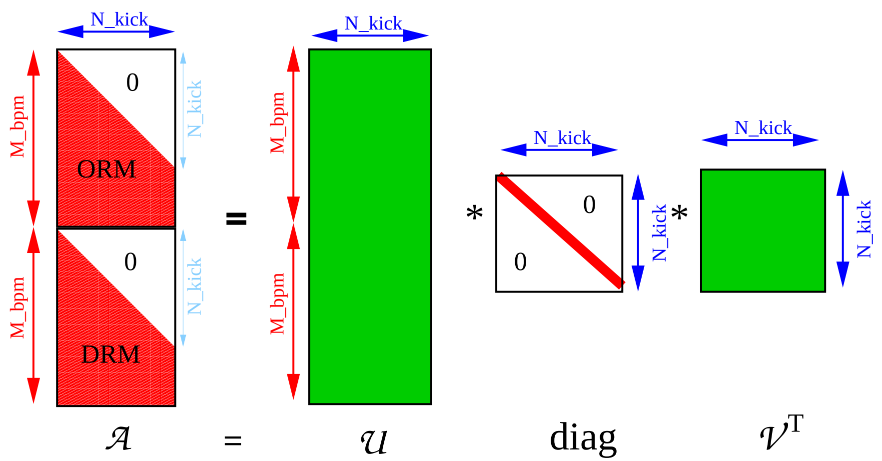
How to compute $\vec{\Phi}_i$?

- **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)
  $\Rightarrow \vec{\xi} \equiv \vec{\Xi} = \underline{\mathcal{A}}\vec{K}$ is fully redundant, i.e.
  $\exists \underline{\mathcal{A}}^* \in \mathbb{R}^{M \times 2N}$ 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

$\Rightarrow \ldots$

SVD + for DispFree Steering

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



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

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

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

- 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 $\sigma_i = 0$???**

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

$\Rightarrow$ yields least square solution !

- MORE GENERAL : *condition* of $\underline{\mathcal{A}}$: $\mathrm{cond}(\underline{\mathcal{A}}) := \frac{\max_i\{\sigma_i\}}{\min_{i,\sigma_i>0}\{\sigma_i\}}$

  $\longrightarrow$ large cond means that solutions $\vec{K}$ of linear system $\underline{\mathcal{A}}\,\vec{K} = \vec{\Xi}$ strongly depend on small variations ($\longleftarrow$errors!) of $\vec{\Xi}$

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

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

$\Rightarrow$ for **Dipersion–Free Steering :**

$\Leftrightarrow$ **use only highly correlated orbit/dispn modes !!!**

& ignore strongly contaminated orbit/dispn modes !!!

$\Rightarrow$ **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 $P = 2$, $\boxed{|E_2 - E_1| \ll E_1}$ $\Rightarrow \underline{\mathcal{L}}_2 \approx \underline{\mathcal{L}}_1$, $\underline{\mathcal{O}}_2 \approx \underline{\mathcal{O}}_1 + \frac{\Delta E}{E}\underline{\mathcal{D}}_1$
- 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 :
  $\vec{Y}_2 \approx \underline{\mathcal{L}}_1 \; \vec{z}_2 + \underline{\mathcal{O}}_1 \; \vec{d} + \frac{\Delta E}{E}\underline{\mathcal{D}}_1 \; \vec{d} + \vec{\Delta} + \vec{\xi}_2$

$\Rightarrow$ **Dispersive Difference Orbit** :
$\vec{Y}_2 - \vec{Y}_1 \approx \underline{\mathcal{L}}_1 \; (\vec{z}_2 - \vec{z}_1) + \frac{\Delta E}{E}\underline{\mathcal{D}}_1 \; \vec{d} + (\vec{\xi}_2 - \vec{\xi}_1)$

$\longrightarrow$ **Eliminates the offsets !!!!**

- If $\vec{z}_2 \approx \vec{z}_1$, then solving
  $w \, (\vec{Y}_1 = \underline{\mathcal{O}}_1 \; \vec{d})$ and
  $(1-w) \, ((\vec{Y}_2 - \vec{Y}_1)\frac{E}{\Delta E} = \underline{\mathcal{D}}_1 \; \vec{d})$ simultaneously for $\vec{d}$
  is exactly the well known dispersion–free steering algorithm with weight w !!!

Extending the LCLS Method for More Flexibility

$\Rightarrow$ introduce various weights for various constraints $(w_i(k), \ldots)$

Preliminary Commissioning Ideas / **Outline of MD**

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

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

  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 $\mathtt{F}_i$ per E_i**

⇐ **reproducible!!**

- **BBA measurement** :
  1. load & cycle into $\mathtt{F}_i$; 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 :

  $\text{BBA}_1 := (E_1 \to E_2 \to E_3 \to E_4 \ldots) \to$

  $\text{BBA}_2 := (\ldots E_4 \to E_3 \to E_2 \to E_1) \to$

  . . .