Beam Based Alignment in SASE Undulator Sections

“The LCLS–Method”

30.06.2010

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

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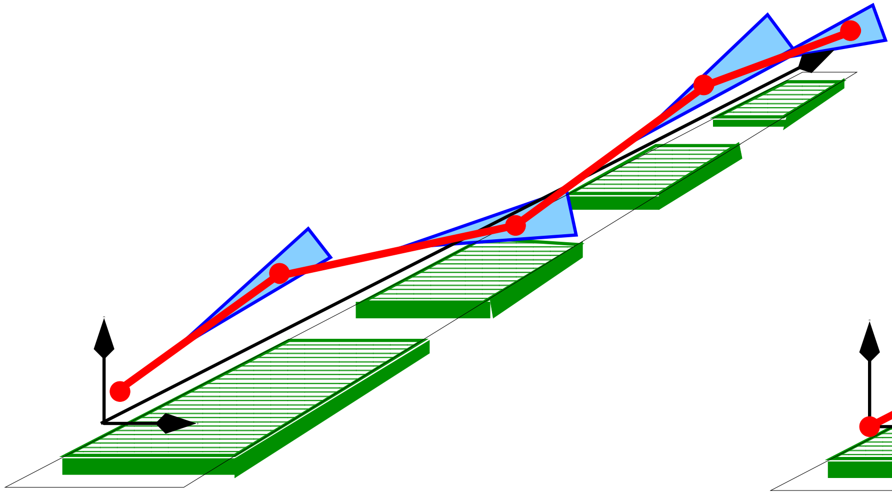
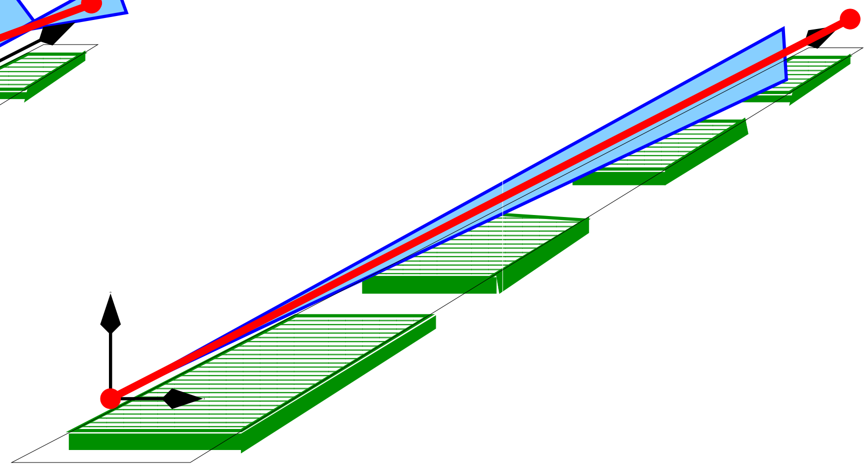
DESY

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

$\longrightarrow$ Beam orbit excursion in undulator $\ll$ rms beam envelope
  $\longrightarrow$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 :

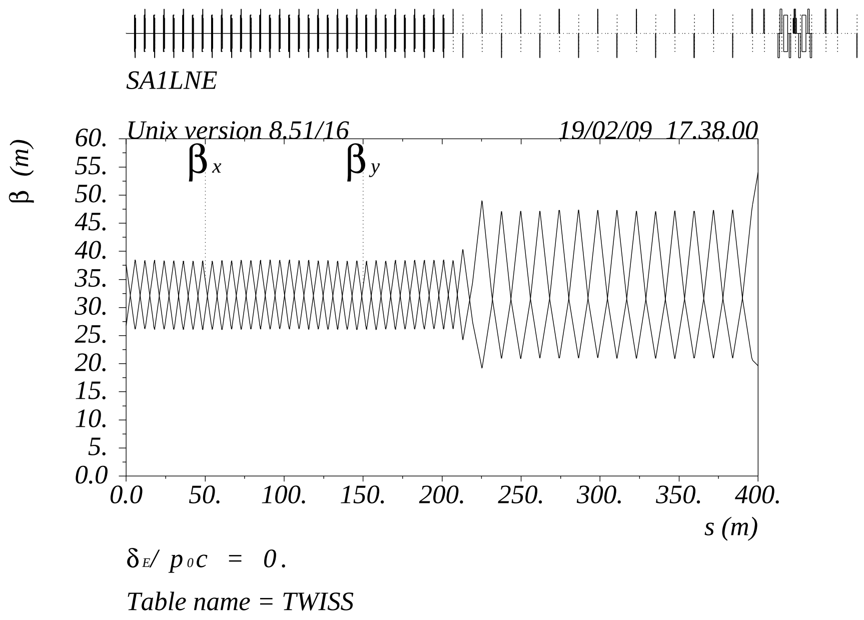
- Flat orbit

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

$\Rightarrow$ **potentially: “‘saturation”**

Example : XFEL Undulator SASE-1

SASE-1 and half of T4



- misaligned quads ⇒perturbed orbit
- initial quad misalignment & BPM offsets ≈ 300μm (**?**)

⇒ *beam–based–alignment* (=BBA) necessary

- in SASE-1 : high resolution cavity BPMs: res→ 1μm — 3μm
- **correctors≡quad movers**
- in T4 : most likely only: res→ 20μm — 50μm

- Target for orbit : **rms (over ∼20m) < 3μm**

⇒ BBA will be tricky (mainly due to large unknown offsets)

- Option–1 : try **Dispersion–Free Steering** (dispersion measurement only needs a difference orbit!)

Motivation : Accuracy/Resolution Issues

- XFEL :
  $\beta\gamma\epsilon \approx 1.0 \cdot 10^{-6} - 1.5 \cdot 10^{-6}$m;
  $\langle\beta\rangle_{\rm undu} \approx 30$m. $\Rightarrow$ $\sigma \approx 30 - 60\mu$m
  at 4GeV–17.5 (14?) GeV .
- BPM resolution in UNDULATOR section:
  $\sigma_X \approx 1\mu$m $\Rightarrow$ **OK**.
- 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**.

- **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 $\vec{\Delta} \in \mathbb{R}^M$

$\longrightarrow$ 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)

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

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

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

– **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 $0 = \sum_{i=1}^{M} \Delta_i$ & $0 = \sum_{i=1}^{M} s_i \Delta_i$

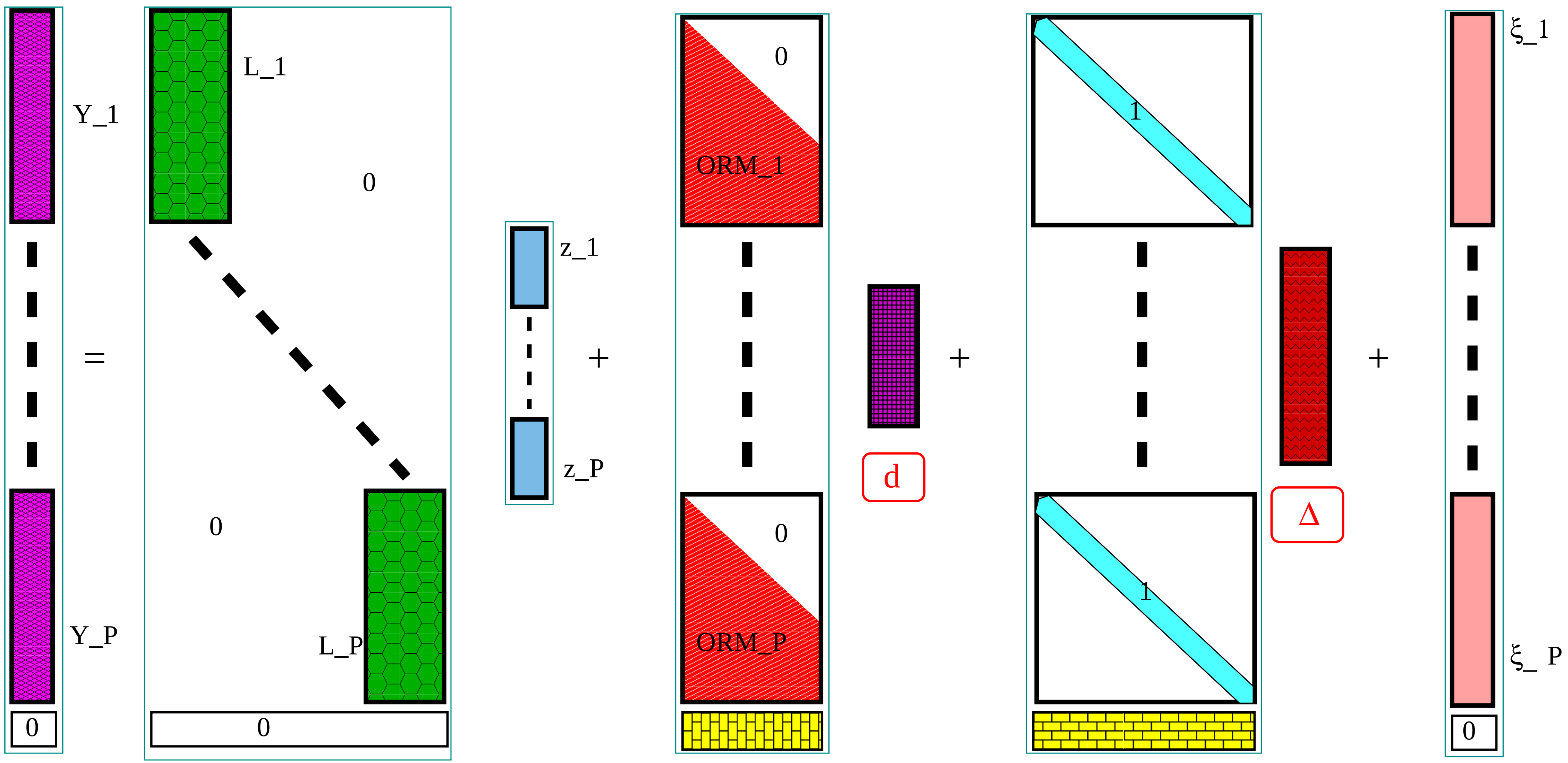
$\leftarrow \Delta_i = \Delta^{(0)} + \Delta^{(1)} s_i$

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

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

$\longrightarrow$ **$PM + 2$ constraints for $2P + N + M$ variables**

The LCLS Method (2)



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

$\rightarrow$ **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

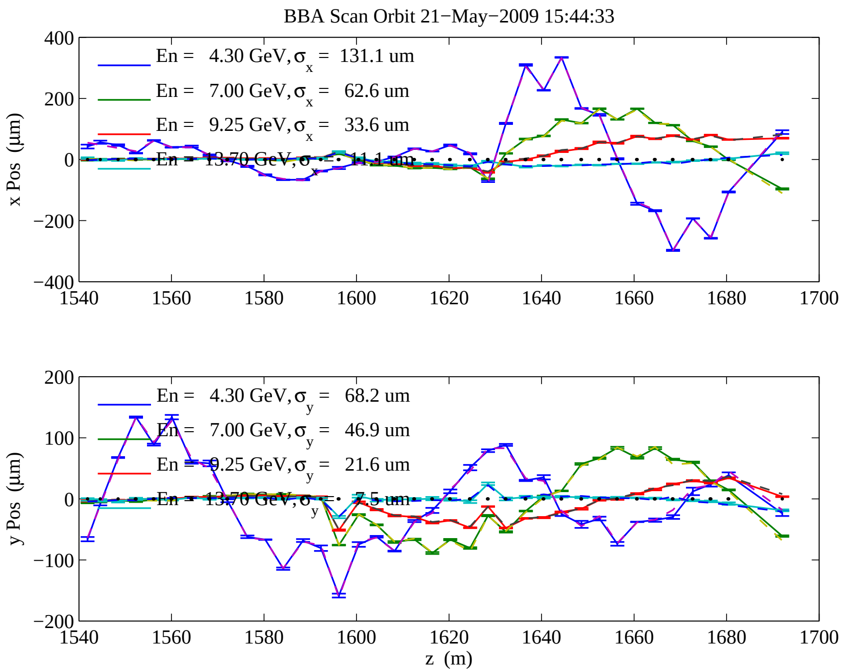
$\Rightarrow$ introduce various weights for various constraints $(w_i(k), \ldots)$

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)

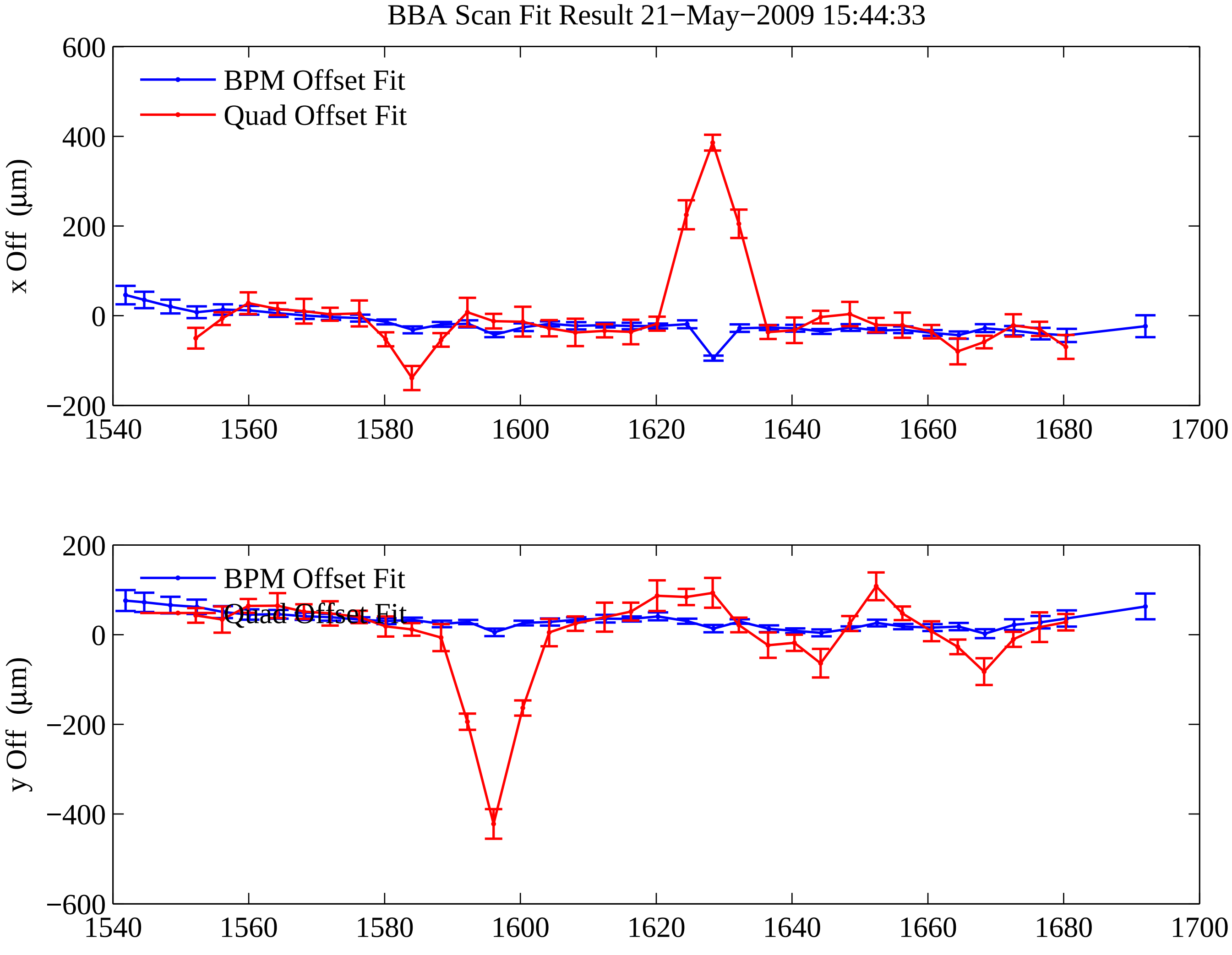
$\longrightarrow$ measure "up" $\longrightarrow$ correct $\longrightarrow$ measure "down" $\longrightarrow$ verify

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

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

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

The LCLS Method (**Application (2)**)



(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 $\longrightarrow$ on crest.
  - 1–2 bunches.
- **Reliable RF controls.**
- **Stable machine (gun, magnets, RF).**
- **Working and well calibrated diagnostics** : wire–scanners, pyros, toroids, BLMs, BPMs (!!!)
- **Optics : macthing and controll** . . .

Preliminary Commisioning 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. . .),

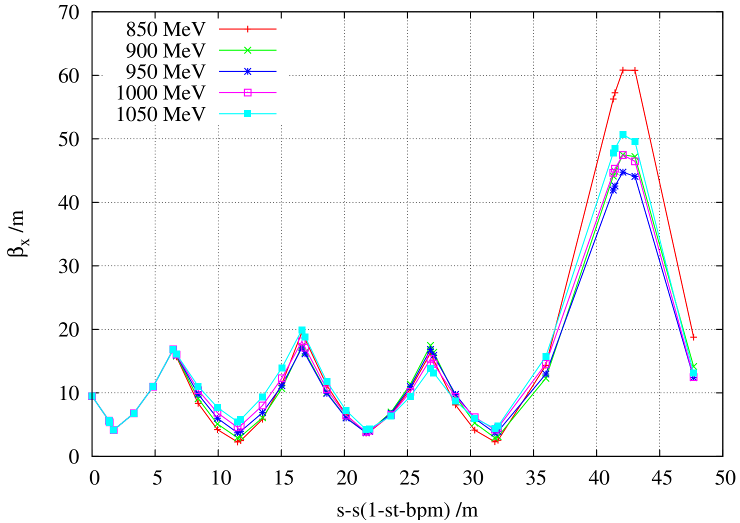
- Probably (at least initially) several iterations w/ ≈ 4 energies needed :

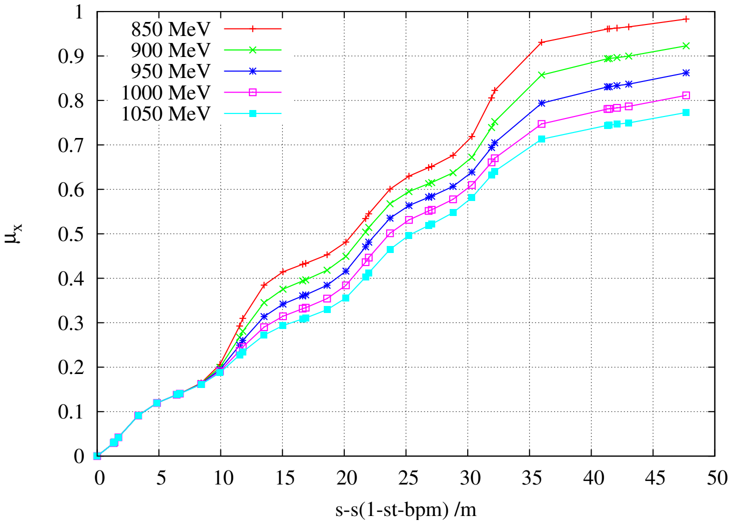
  $\text{BBA}_1 := (E_1 \to E_2 \to E_3 \to E_4 \ldots) \to$

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

  $\ldots$

Set up for FLASH-BBA MD End of May 2010



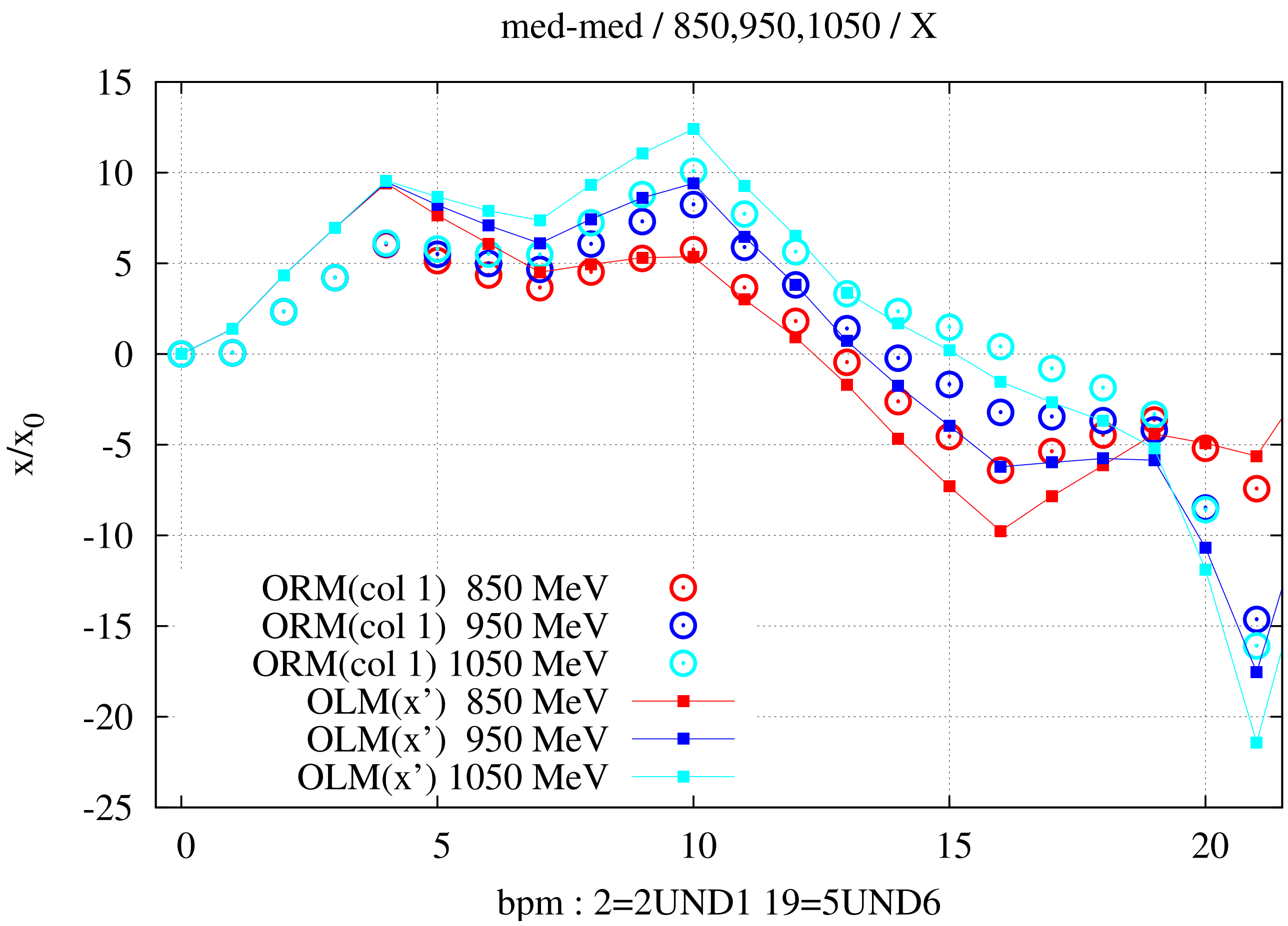


- Standard optics ("Med–Med") established during commissioning.
- Reference energy for k_1 values in "Med–Med" : 950 MeV.
- Don't be too brave . . .
  $\Rightarrow E$ **range only** ± 100 **MeV**
  $\rightarrow$850, 900, 950, 1000, 1050 MeV.

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

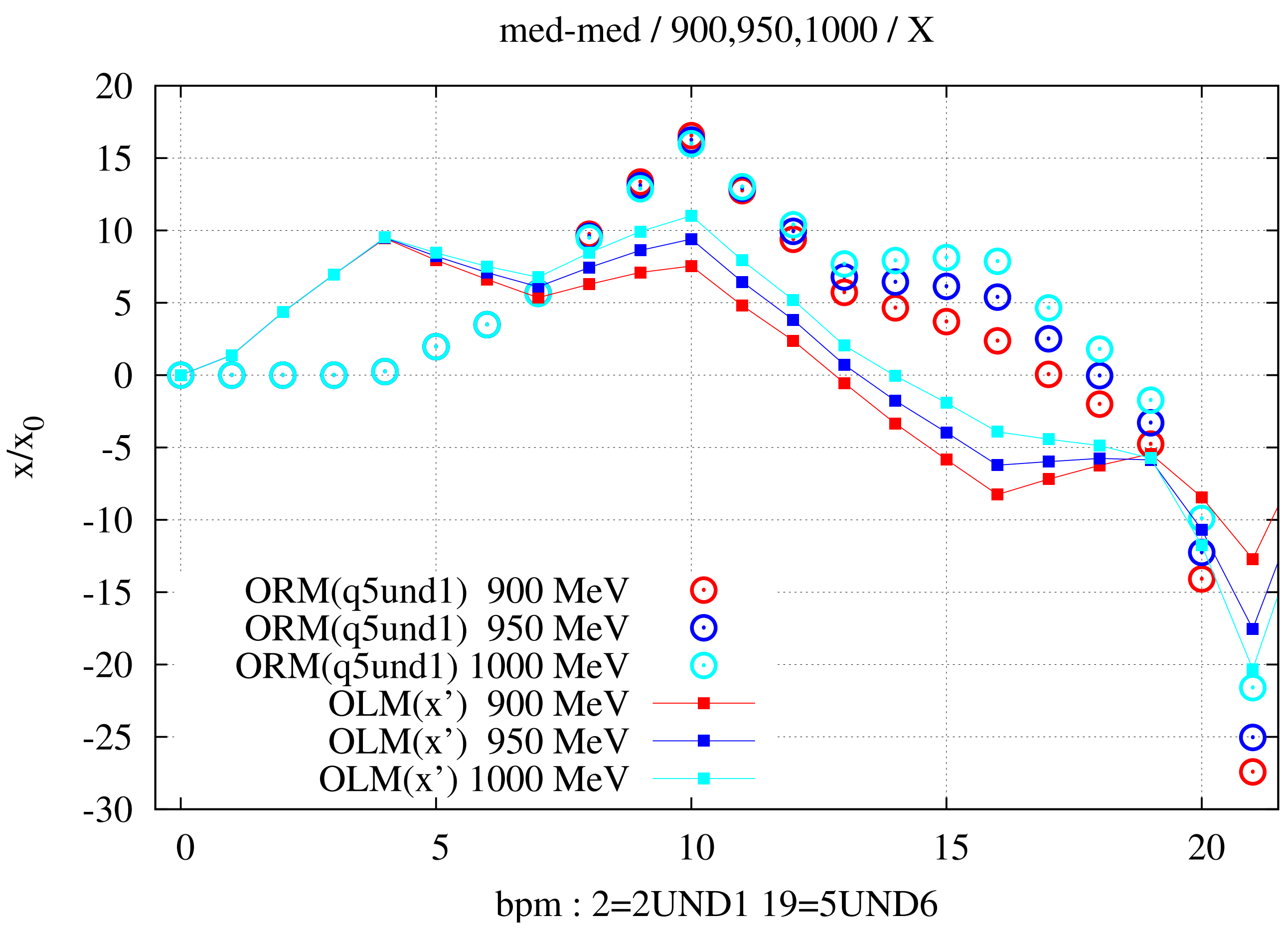
Set up for FLASH-BBA MD End of May 2010 (2)

Effects from last upstream quads and launch almost indistinguishable



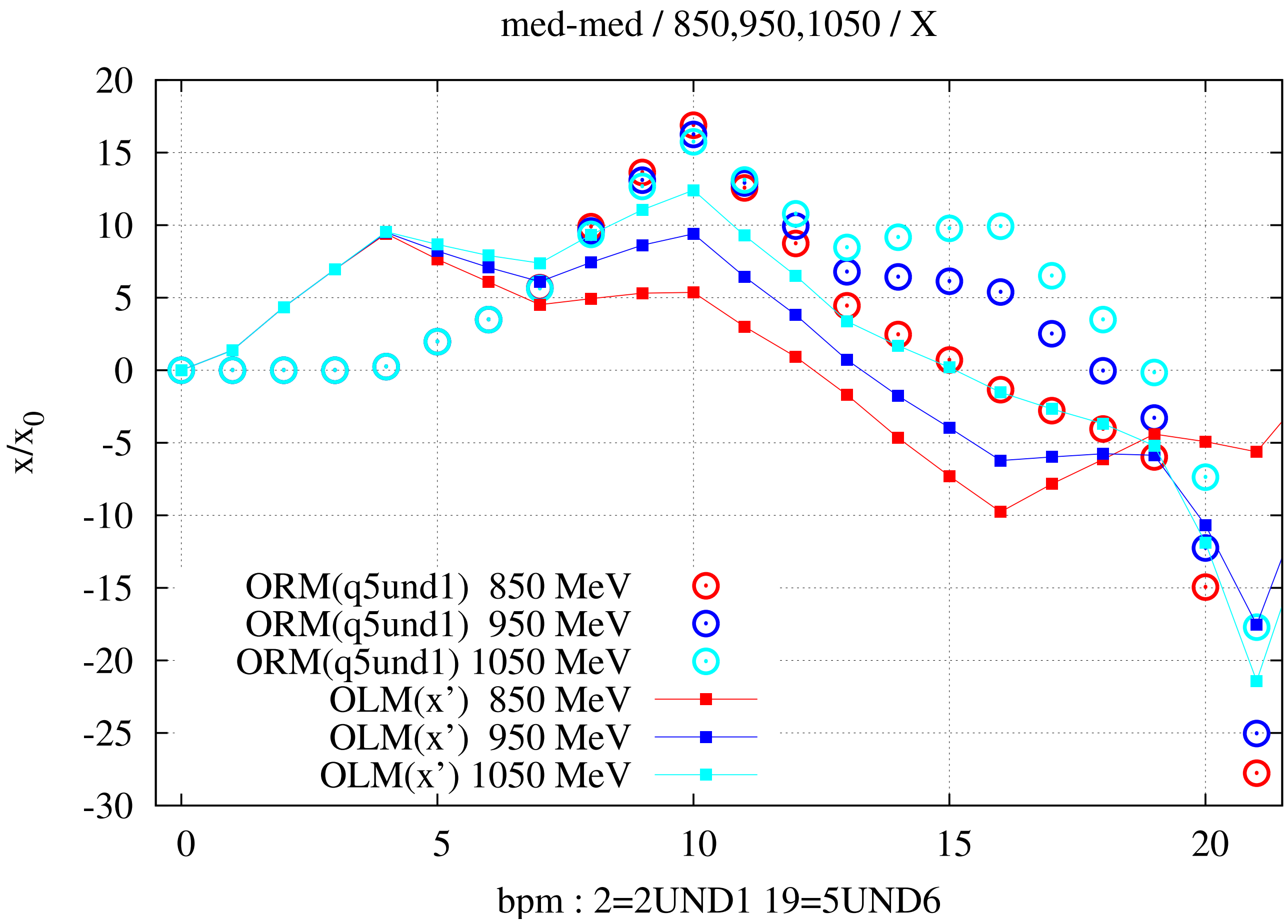
Set up for FLASH-BBA MD End of May 2010 (3)

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

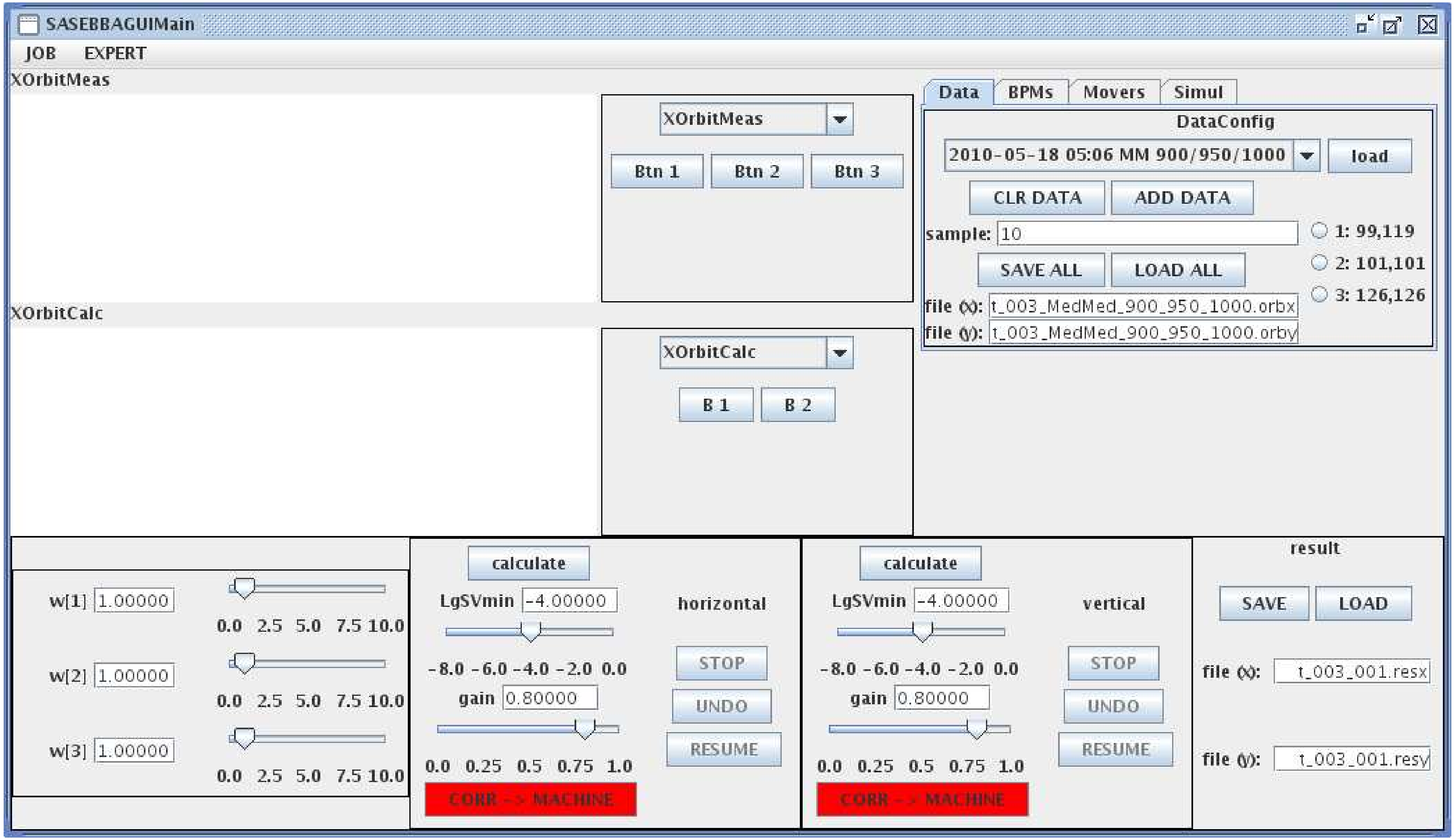


Set up for FLASH-BBA MD End of May 2010 (4)

850, 950, 1050 MeV : looks better



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



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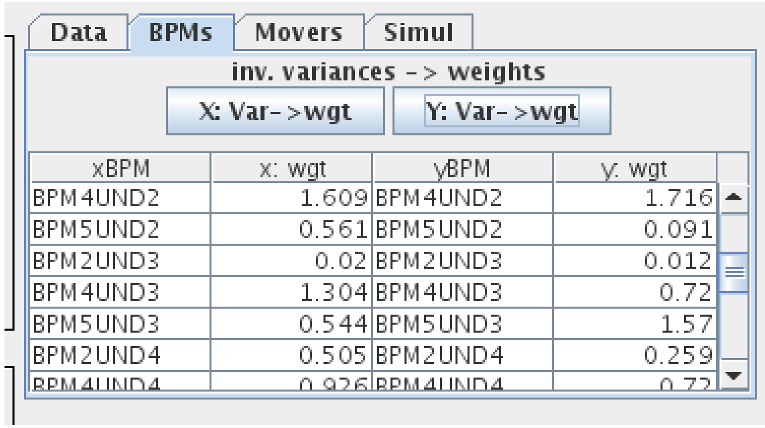
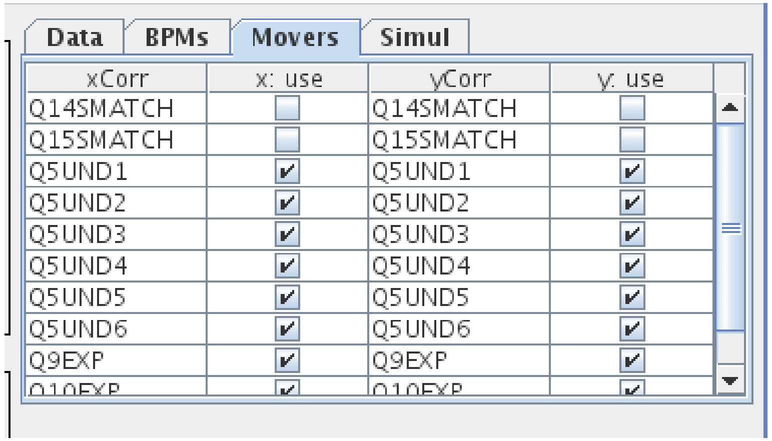


xBPM	x: wgt	yBPM	y: wgt
BPM4UND2	1.609	BPM4UND2	1.716
BPM5UND2	0.561	BPM5UND2	0.091
BPM2UND3	0.02	BPM2UND3	0.012
BPM4UND3	1.304	BPM4UND3	0.72
BPM5UND3	0.544	BPM5UND3	1.57
BPM2UND4	0.505	BPM2UND4	0.259
BPM4UND4	0.926	BPM4UND4	0.72

← Weights can be assigned to BPMs

← e.g. $w_i \propto 1/\mathrm{Var}(x_i)$



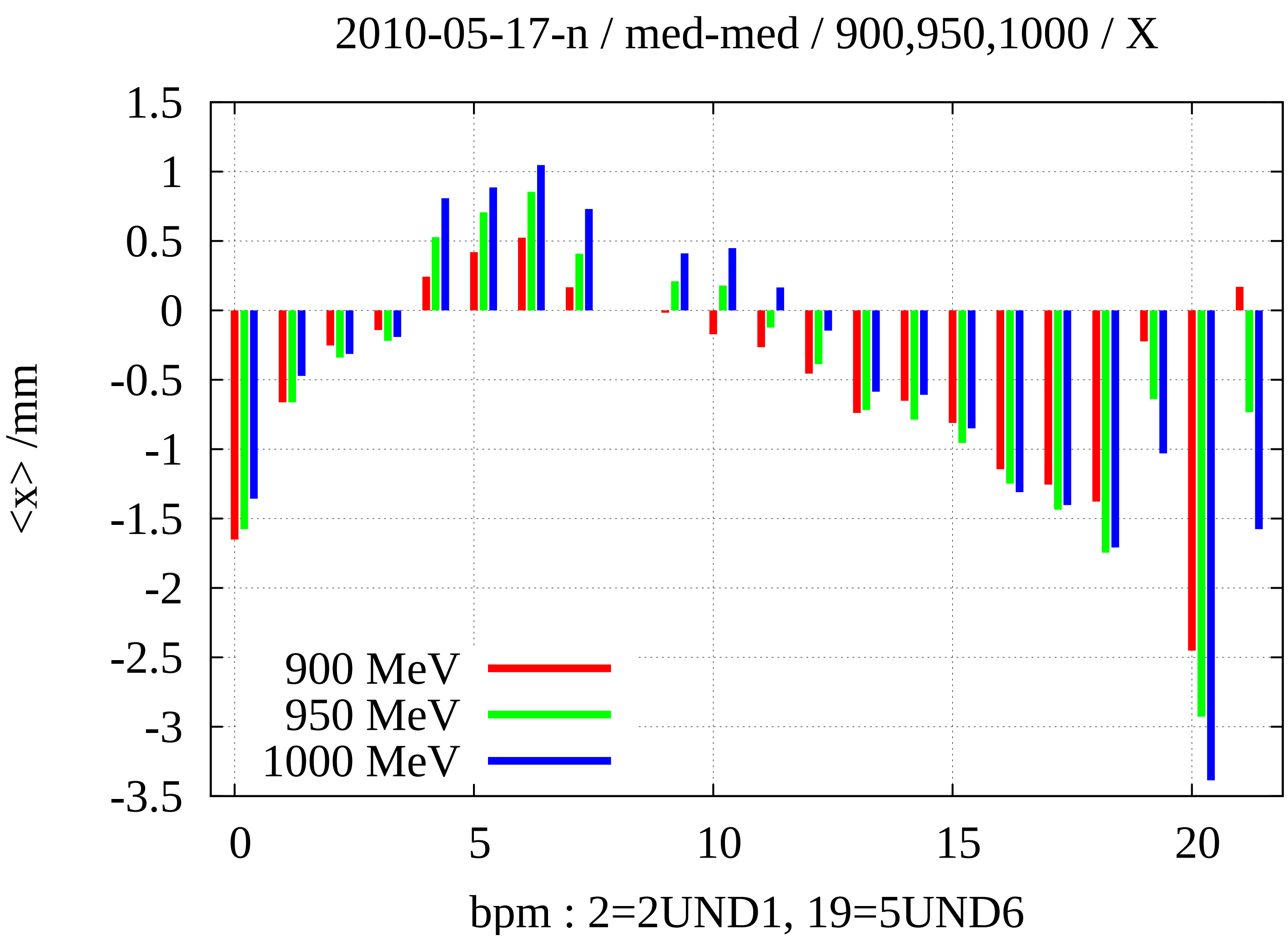
xCorr	x: use	yCorr	y: use
Q14SMATCH	☐	Q14SMATCH	☐
Q15SMATCH	☐	Q15SMATCH	☐
Q5UND1	☑	Q5UND1	☑
Q5UND2	☑	Q5UND2	☑
Q5UND3	☑	Q5UND3	☑
Q5UND4	☑	Q5UND4	☑
Q5UND5	☑	Q5UND5	☑
Q5UND6	☑	Q5UND6	☑
Q9EXP	☑	Q9EXP	☑
Q10EXP	☑	Q10EXP	☑

← Knobs (quads/movers) can be disabled

← e.g. those which compete with initial conditions

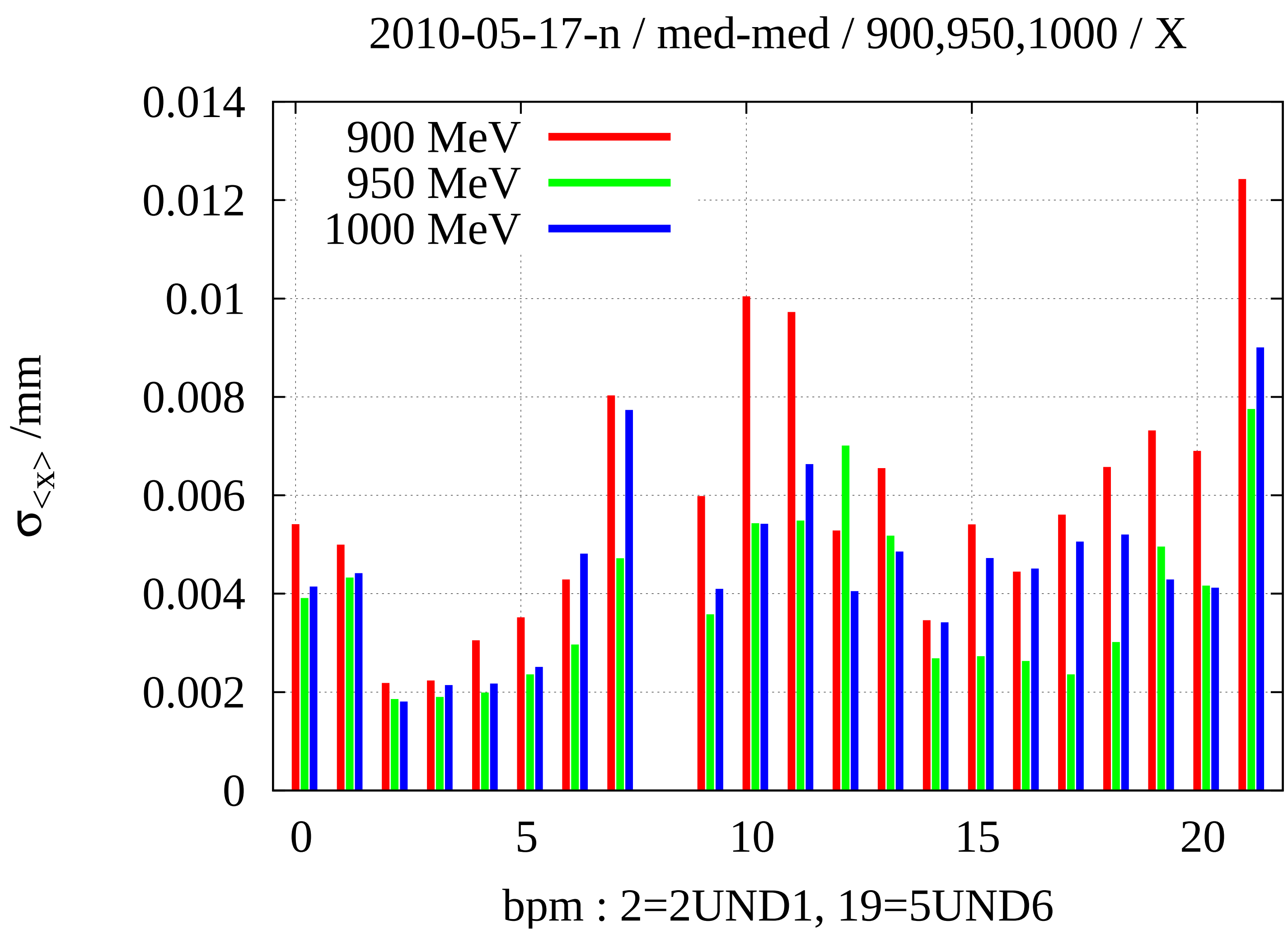
Preliminary FLASH Data

worst two BPMs deselected

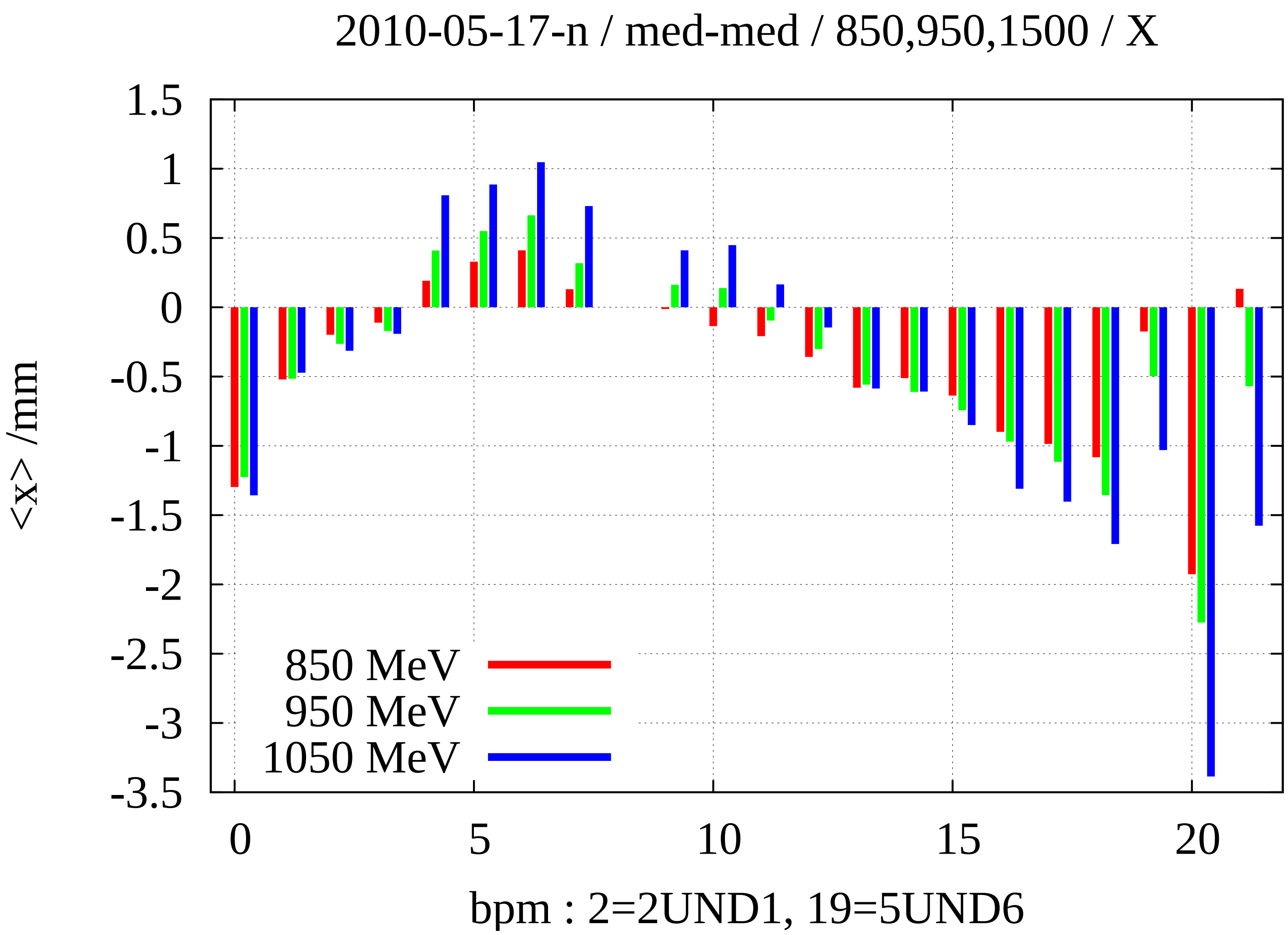


Preliminary FLASH Data (2)

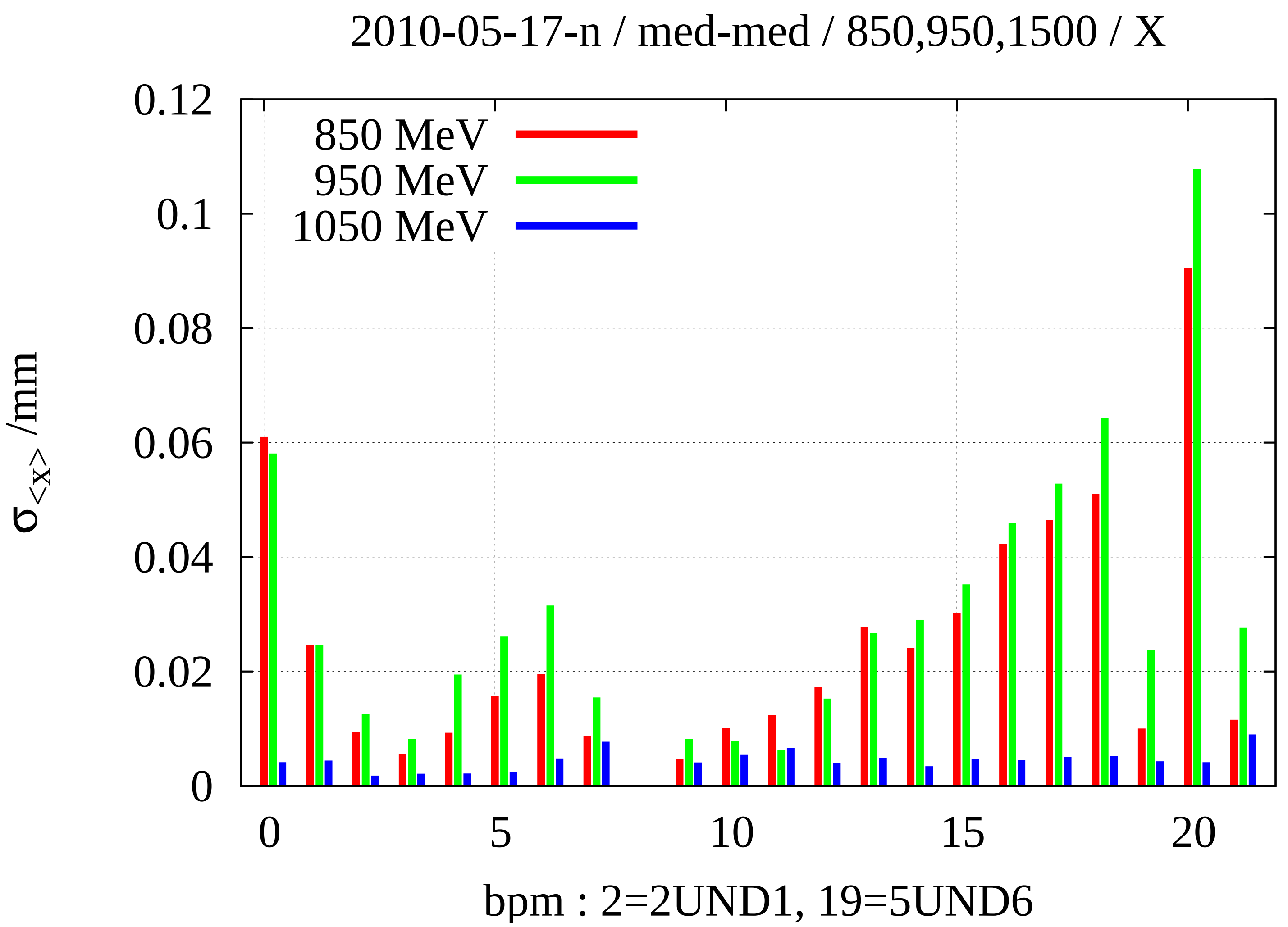
worst two BPMs deselected



Preliminary FLASH Data (3)



Preliminary FLASH Data (4)



1050MeV looks weired ??! + still some bug in evaluation routine :-(:-(:-(

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 : prototype (`java`) $\exists$ . . .
- 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 :

- Evaluation of preliminary set of measurements not consistently finished

$\Leftarrow$ fix bugs, check for consistency

- **Repeat measurement with adequate energy range !**
- **Improve and establish standard procedure.**

* * * SPARES * * *

Dispersion–Free Steering

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

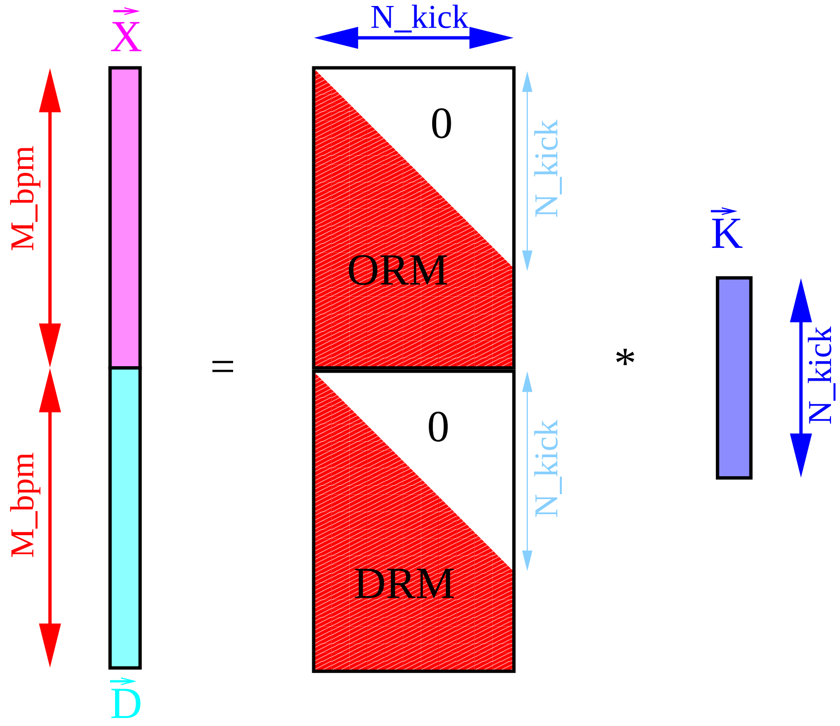
+ **given N perturbations (=correctors) $\{K_i\}_{1\leq i\leq N}$** and M **BPMs**

+ **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 → 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**→ 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 →$\vec{\Delta}_i$

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

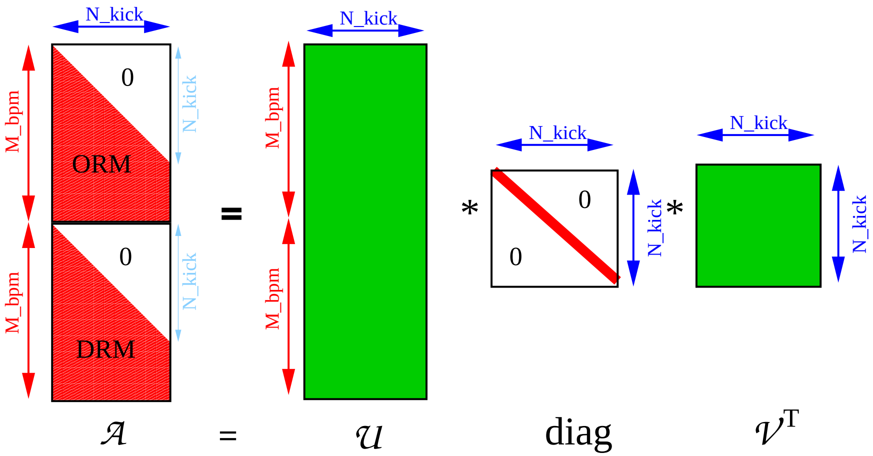
How to compute $\vec{\Phi}_i$?

- **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)
  $\Rightarrow \vec{\xi} \equiv \vec{\Xi} = \underline{\mathcal{A}}\vec{K}$ 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

⇒ ...

SVD + for DispFree Steering

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



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

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

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

- if system is **underdetermined** $\Rightarrow$solution of $\vec{\Xi} = \underline{\mathcal{A}}\ \vec{K}$ is $\vec{K} \in \vec{K}_{\mathrm{part}} + \mathrm{kern}(\underline{\mathcal{A}})$

$\Rightarrow$ 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 stronlgy contaminated orbit/dispn modes !!!

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