Beam-Based Alignment, Undulator Stability, and Trajectory Control at *LCLS**

P. Emma, H. Loos, H.-D. Nuhn

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Santa Fe, NM, USA

***With input from:**

- ***DESY***
- ***PAL***
- ***PSI***
- ***SACLA***

The Need for Precise FEL Alignment

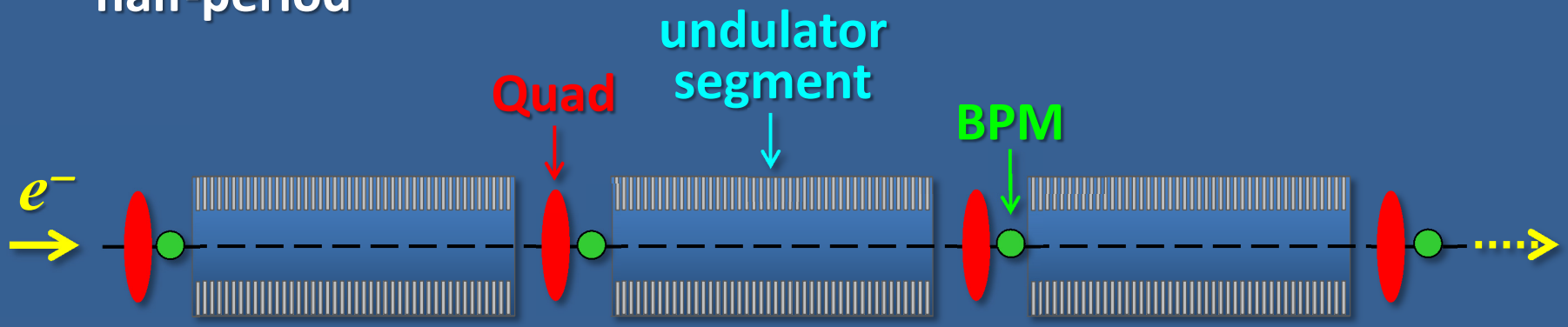
- **An FEL needs a high-brightness e^- beam**
- **In addition, it also needs a straight undulator trajectory**
- **But the micron-level tolerances are quite challenging**
- **So beam-based alignment (BBA) was developed…**

  P. Emma, R. Carr, H.-D. Nuhn, *Beam-based alignment for the LCLS FEL undulator*, NIM-A, Vol. **429**, June 1999, pg. 407-413.

  - Published 18 years ago
  - Demonstrated in 2009 and used for 8 years at ***LCLS*** (and elsewhere)
- **In addition, we touch on related issues…**
  - Undulator motion control
  - Tunnel temperature stability
  - Trajectory feedback loops
  - Alignment diagnostics
  - Automated beam corrections

BBA Assumes the Following

- FEL undulator has a FODO focusing lattice with one BPM, one quadrupole magnet, and one undulator segment per half-period

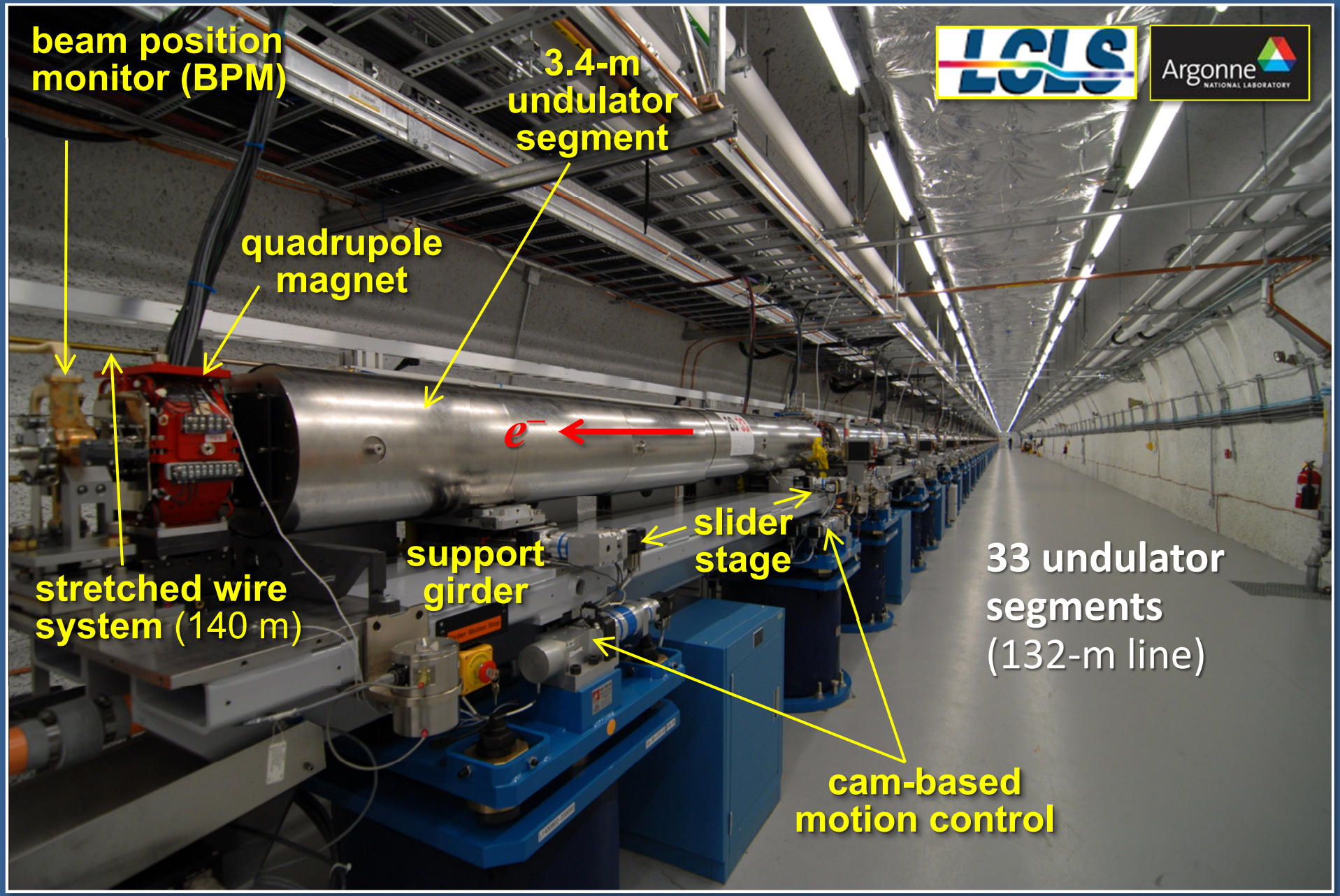


- The BPMs must resolve beam position (x & y) at 1-μm level
- The electron energy must be changeable over a large range*
- Quad magnets are moveable (x & y) through remote control

* or see ***SACLA*** method (ahead)

LCLS Undulator Beamline

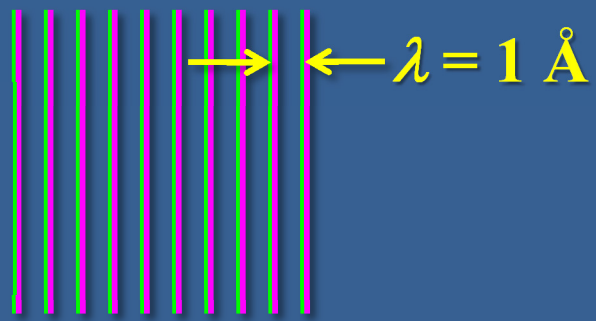
LCLS Undulator Beamline



Electron Trajectory Errors in an Undulator

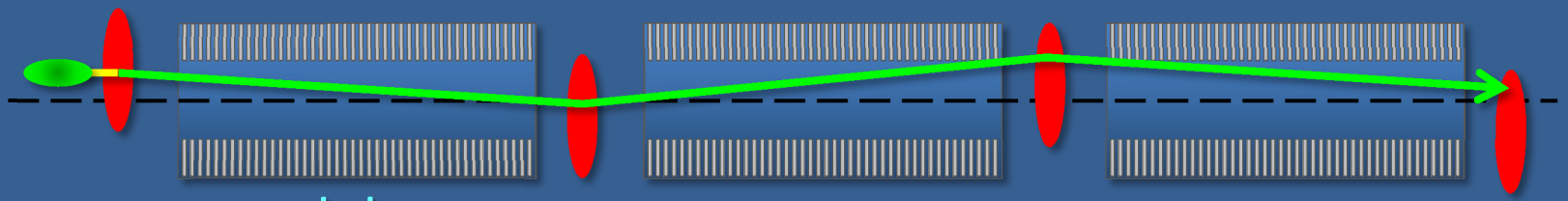
imperfect trajectory causes
e^-/photon phase errors…

e^- and photons
phase matched



FEL bunching

quadrupole
magnet



undulator
segment

Electron Trajectory Errors in an Undulator

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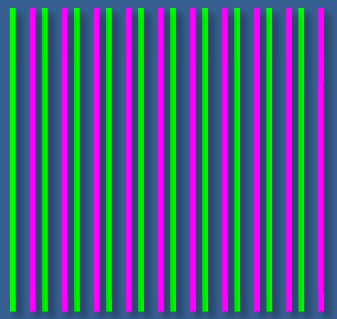
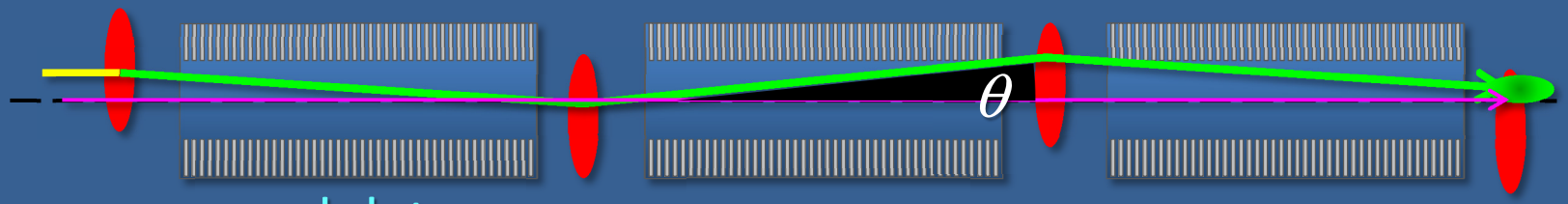


phase error
slips as θ^2

FEL bunching

quadrupole
magnet



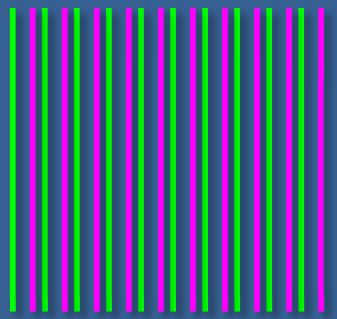
undulator
segment

$L \approx 5$ m

$\pi L \theta^2 \ll \lambda$

Electron Trajectory Errors in an Undulator

imperfect trajectory causes
e^-/photon phase errors…



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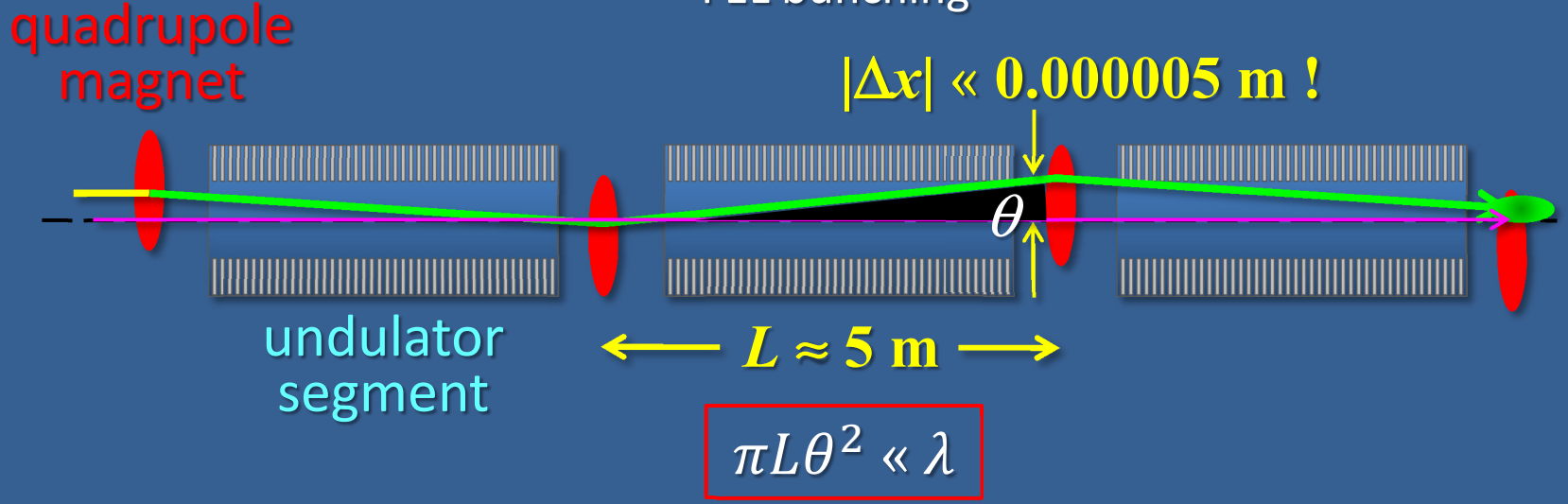


$$\pi L \theta^2 \ll \lambda$$

- **Trajectory straightness requirements are extremely tight**
- **Alignment requires an empirical *beam-based* method…**

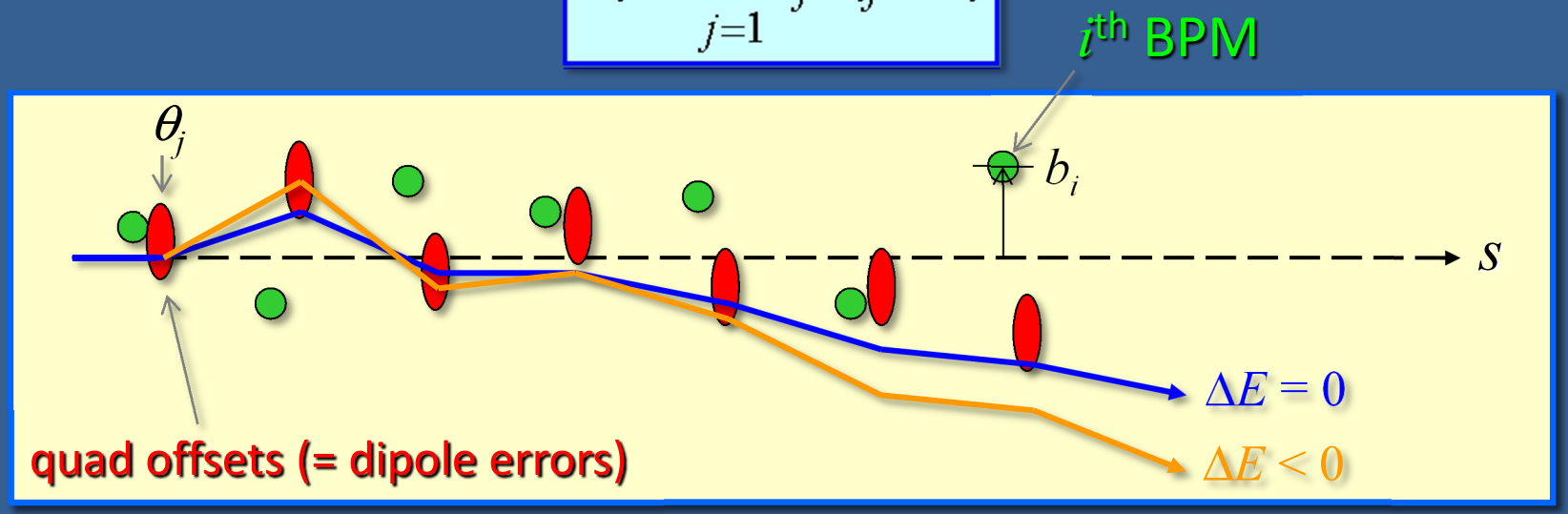
Beam-Based Alignment Procedure

- Read undulator BPMs (1-μm res.) for each of 3 or 4 e^- energy settings (*e.g.*, 4, 7, 9, & 14 GeV)
- Do **NOT** change anything in the undulator
- Form matrix and solve for quad & BPM offsets
- Add fit constraint to force mean offsets toward zero
- Apply quad. alignment corrections (motors) & adjust BPM offsets (software)
- Repeat 2-3 times (takes 2-3 hrs total at *SLAC*)
- Apply every 1-2 mo. (depends on environment)

The Method

- BPM readings, m_i, are sum of upstream kicks, θ_j, plus offsets, b_i

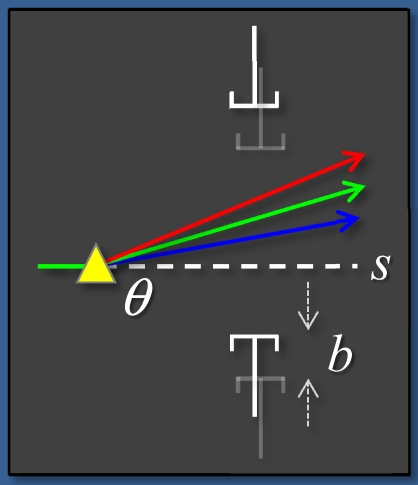
$$m_i = \sum_{j=1}^{i} \theta_j C_{ij} - b_i$$



- Kicks are sensitive to momentum, p_k, while offsets , b_i, are not

$$m_{ik} = \frac{1}{p_k} \sum_{j=1}^{i} e \Delta B_j \ell C_{ij}(p_k) - b_i$$

P. Emma, *et al.*, FEL'98, p. 407.

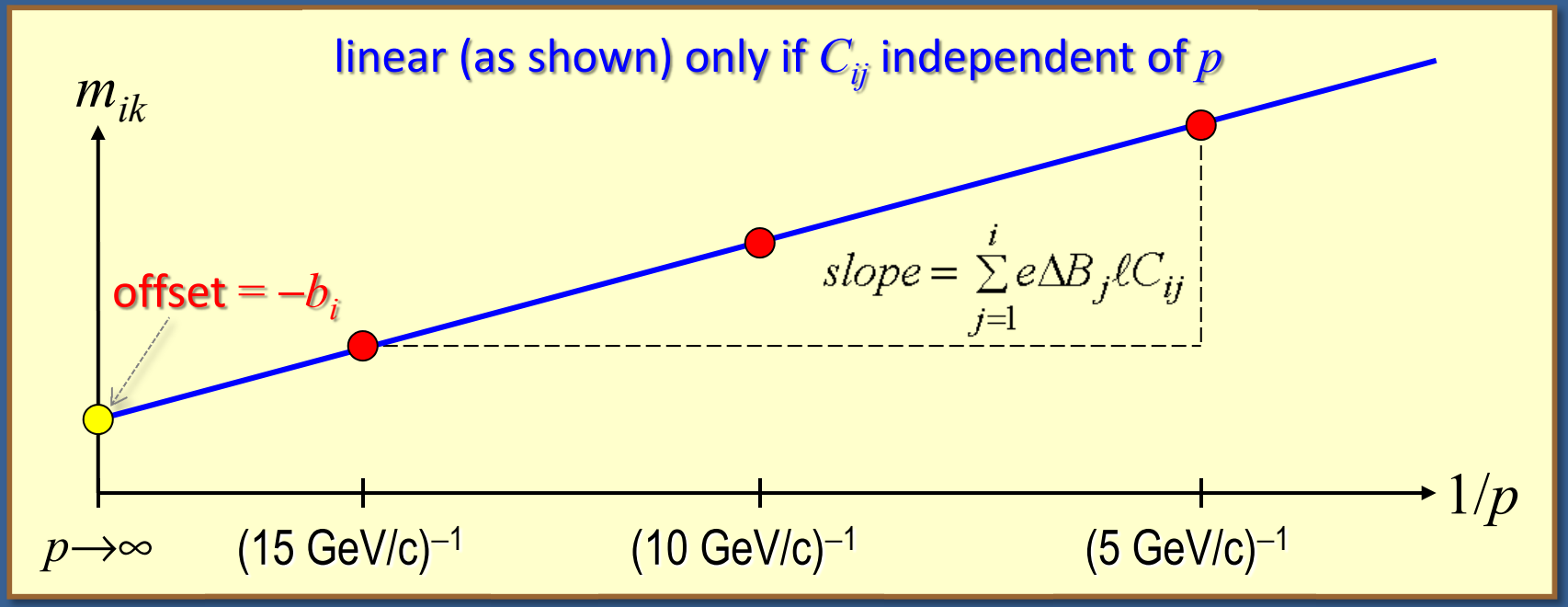


Simplified View

(BPM readback, m_{ik}, vs. $1/p_k$)

$$m_{ik} = \frac{1}{p_k} \sum_{j=1}^{i} e\Delta B_j \ell C_{ij}(p_k) - b_i$$

- As $p \rightarrow \infty$, BPM reading converges to its static offset, $-b$



- Rewrite transfer coefficients, C_{ij}, (thick lens quadrupole),

$$\frac{eC_{ij}}{p_k} = P_{ij}(k) \equiv \left[1 - Q_{11}^{j}(k)\right] R_{11}^{ji} - Q_{21}^{j}(k) R_{12}^{ji}$$

where $\boldsymbol{Q}^j$ is the transfer matrix across the j^{th} quad, and $\boldsymbol{R}^{ji}$ is the transfer matrix from j^{th} quad exit to i^{th} BPM, all evaluated at the k^{th} momentum setting, p_k .

- Then solve…

BPM readings at p_1

BPM readings at p_2

more at $p_{3,\,4,\,5\,\cdots}$ ↓

$$\begin{bmatrix} m_{11} \\ m_{21} \\ \vdots \\ m_{N1} \\ m_{12} \\ m_{22} \\ \vdots \\ m_{N2} \end{bmatrix} = \begin{bmatrix} -1 & 0 & \cdots & 0 & P_{11}(1) & 0 & \cdots & 0 \\ 0 & -1 & \cdots & 0 & P_{21}(1) & P_{22}(1) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & -1 & P_{N1}(1) & P_{N2}(1) & \cdots & P_{NN}(1) \\ -1 & 0 & \cdots & 0 & P_{11}(2) & 0 & \cdots & 0 \\ 0 & -1 & \cdots & 0 & P_{21}(2) & P_{22}(2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & -1 & P_{N1}(2) & P_{N2}(2) & \cdots & P_{NN}(2) \end{bmatrix} \cdot \begin{bmatrix} b_1 \\ b_1 \\ \vdots \\ b_N \\ \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \Delta x_N \end{bmatrix}$$

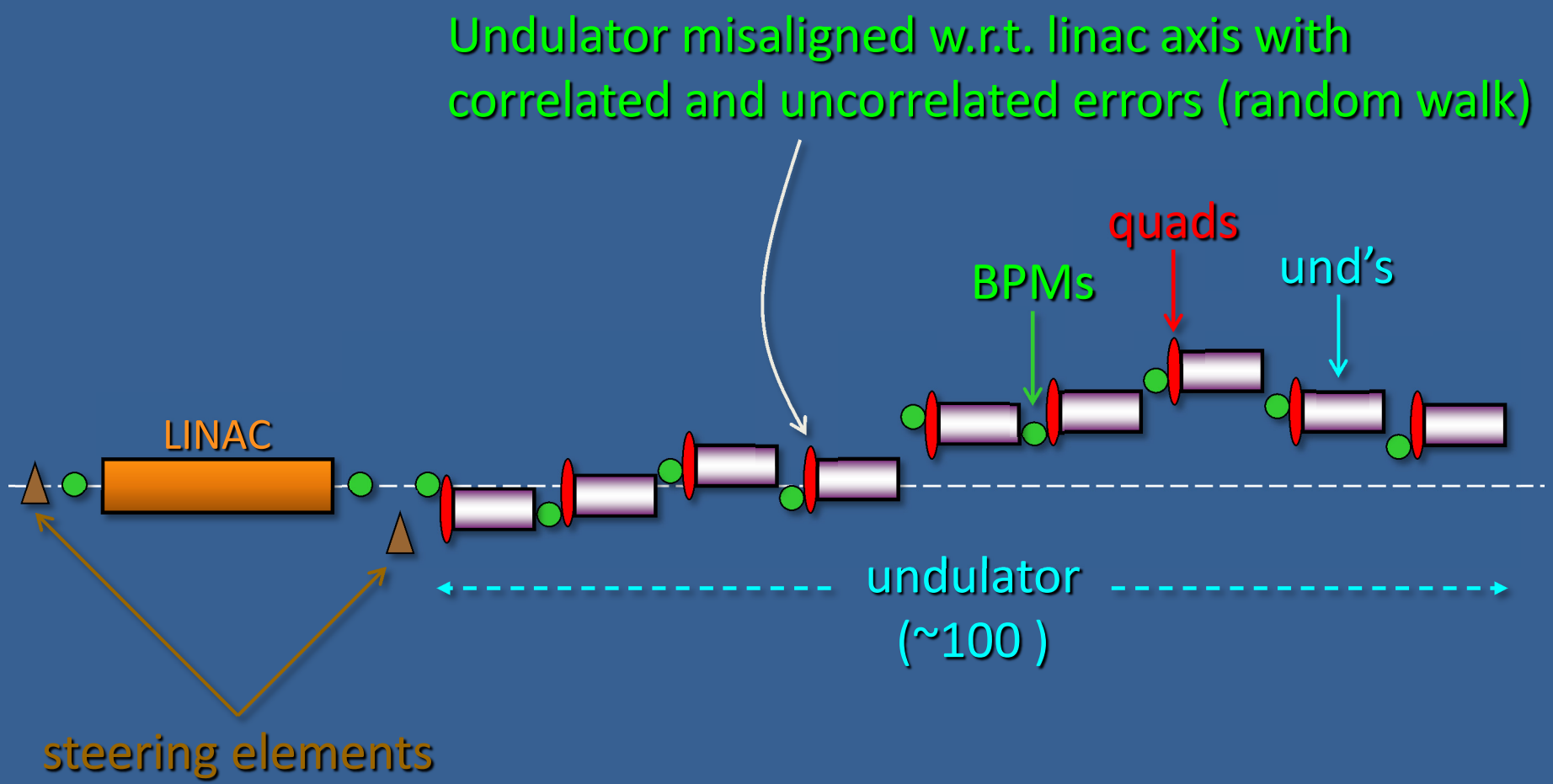
BPM offsets

quad offsets

known optical functions at each p_k

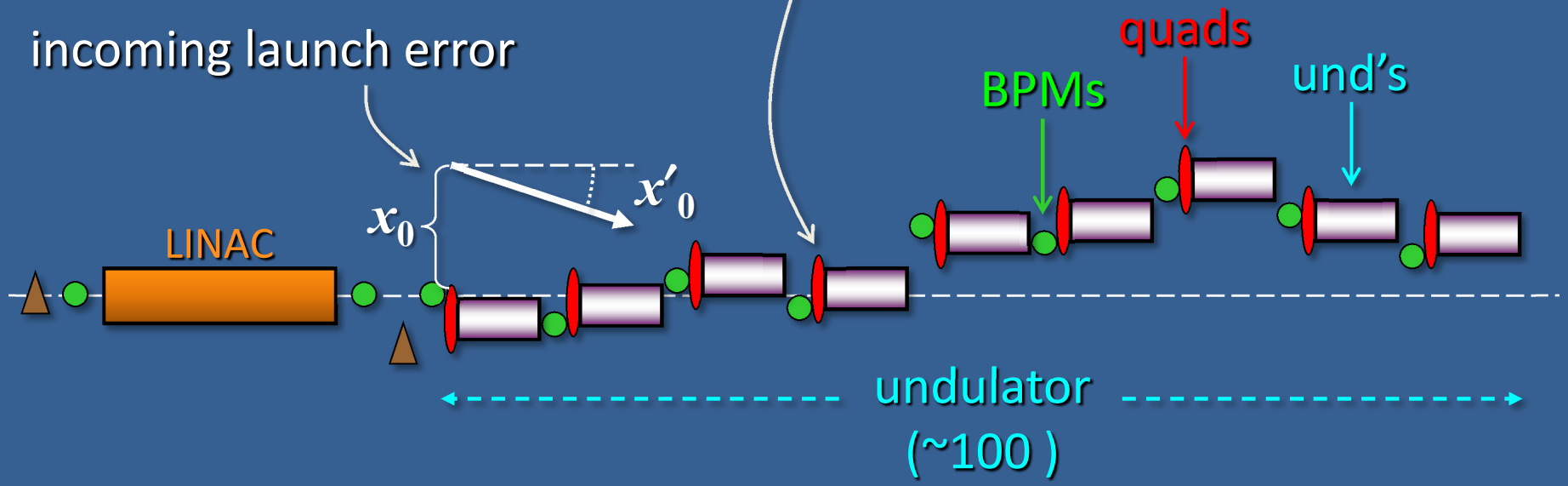
Undulator Before BBA

(cartoon)

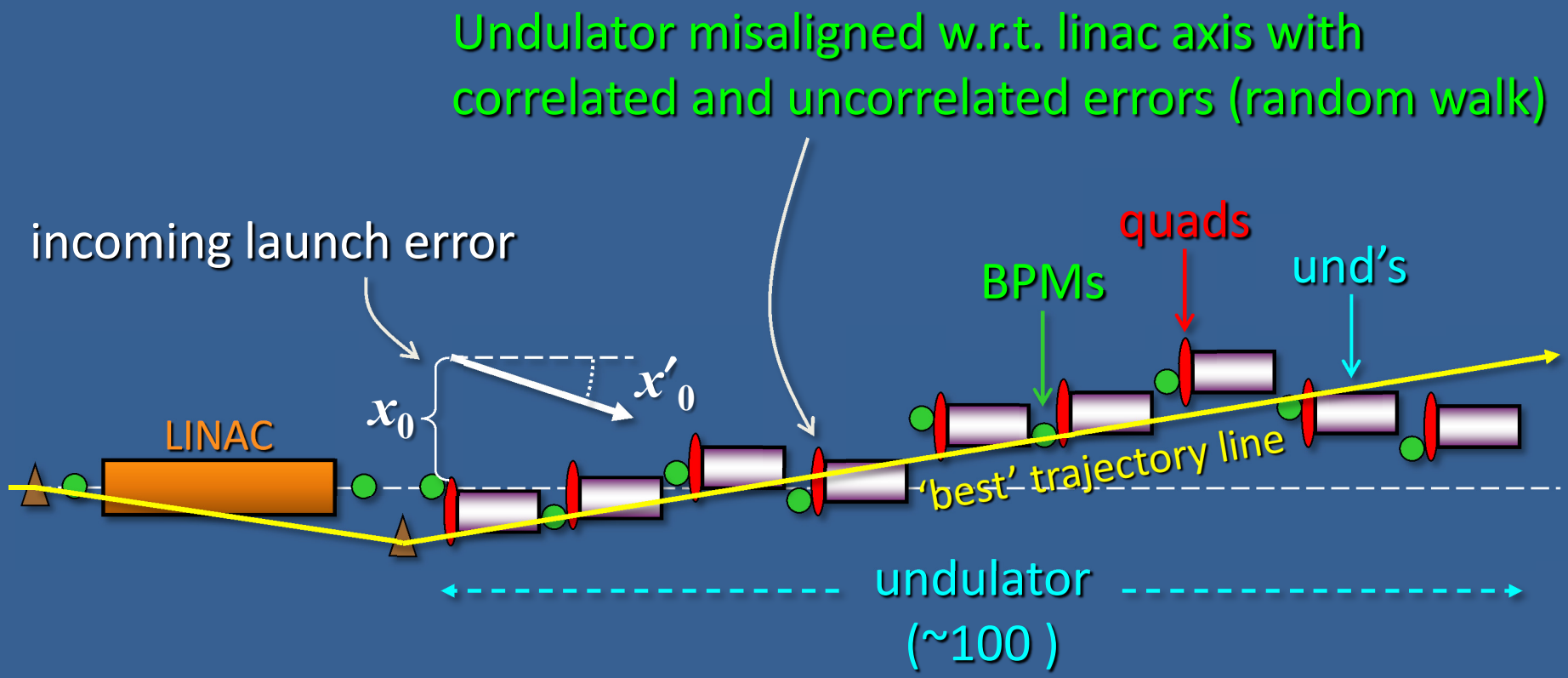


Undulator Before BBA
(cartoon)

Undulator misaligned w.r.t. linac axis with
correlated and uncorrelated errors (random walk)



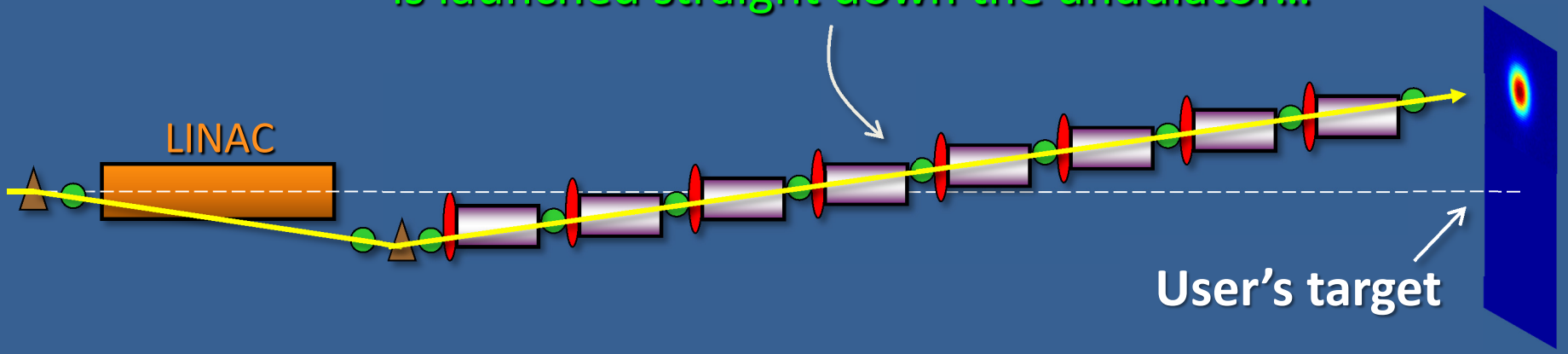
Undulator Before BBA
(cartoon)



Solution also minimizes final offsets, thereby choosing the 'best' trajectory line (minimizes final corrections).

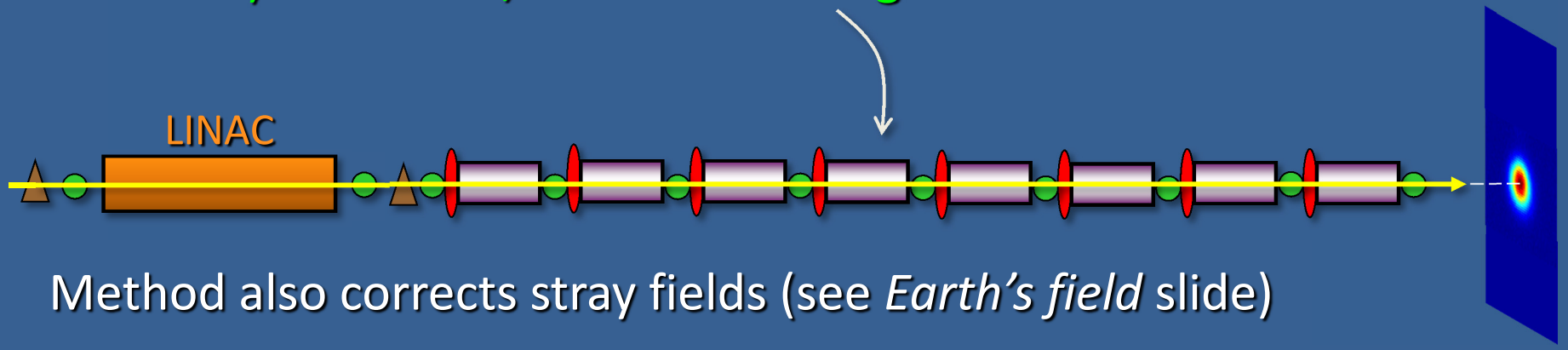
Undulator After BBA
(cartoon)

Alignment correction is applied and then beam is launched straight down the undulator…



Undulator After BBA
(cartoon)

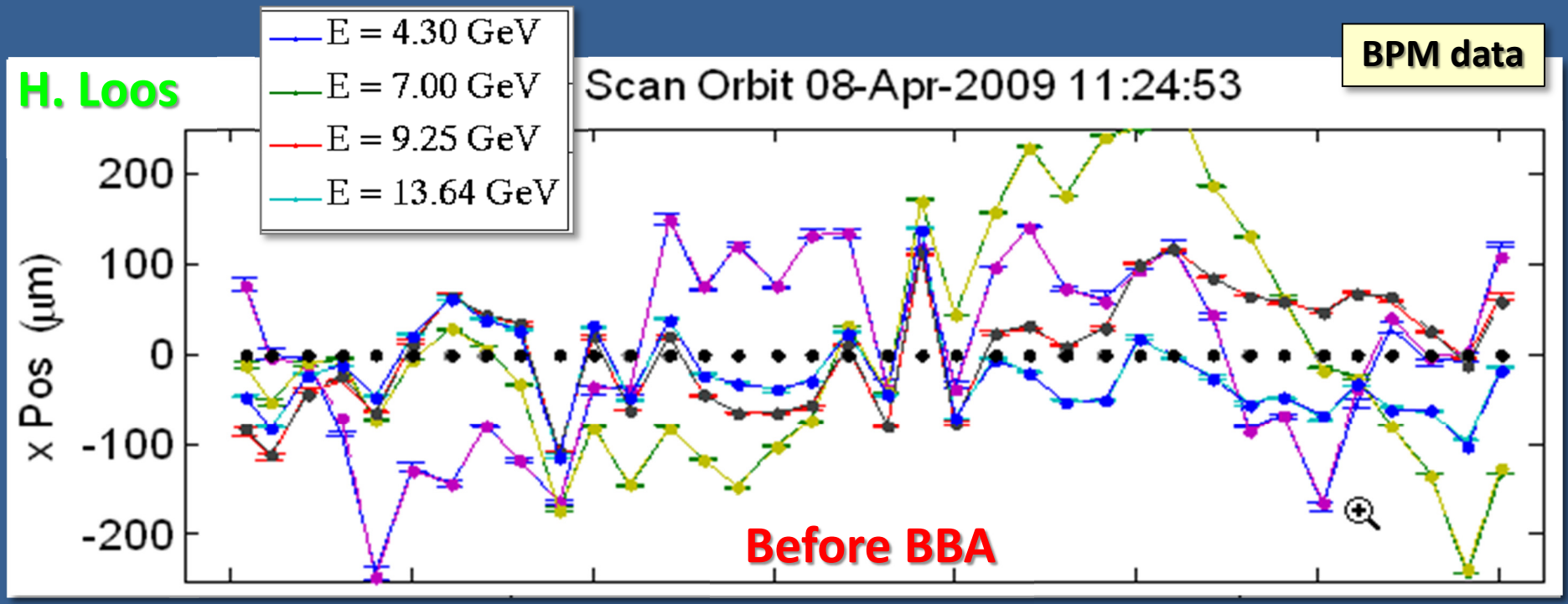
Pointing error removed by 'motoring' girders (und., quad, & BPM) as needed, and re-launching beam…



Method also corrects stray fields (see *Earth's field* slide)

Real BBA Applied at *LCLS* (33 BPMs & quads)

- Record undulator trajectory (BPMs) at 4 energies
- Scale all upstream (linac) magnets for each energy
- Do not change anything in the undulator (but adjust launch)
- Correct quad alignment (motors) and BPM offsets (software)



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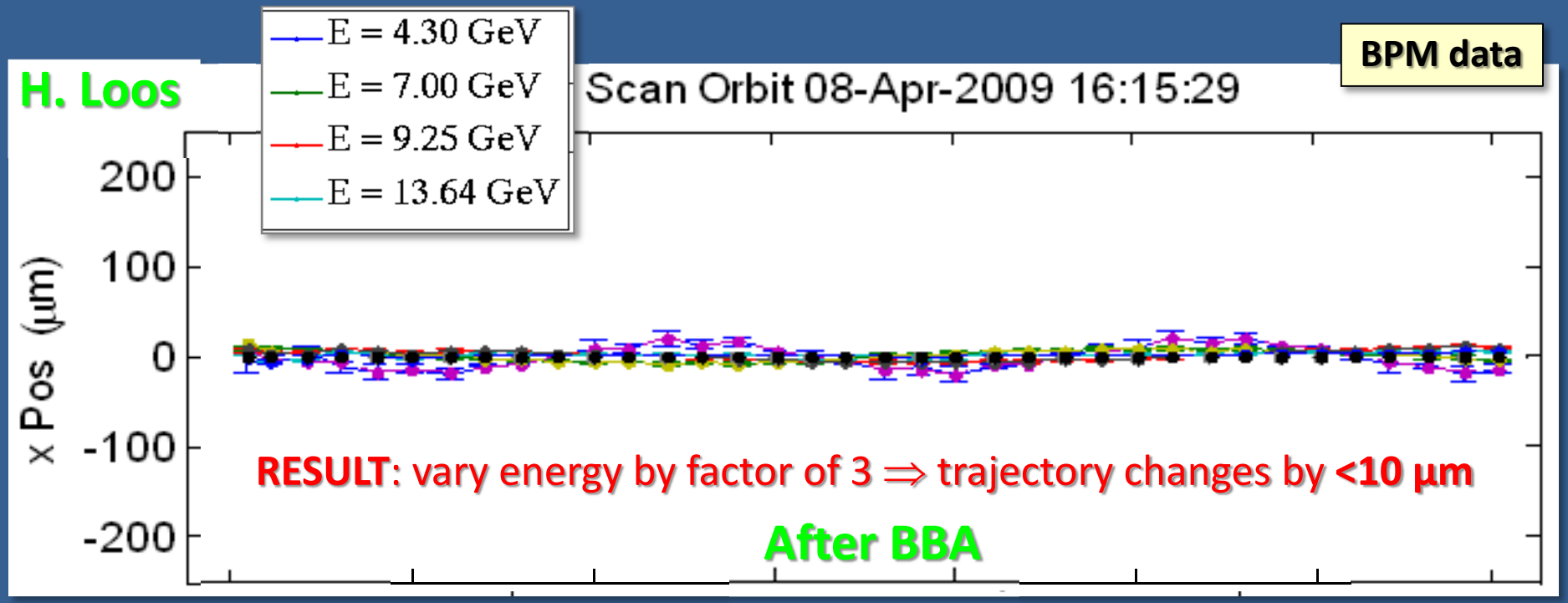
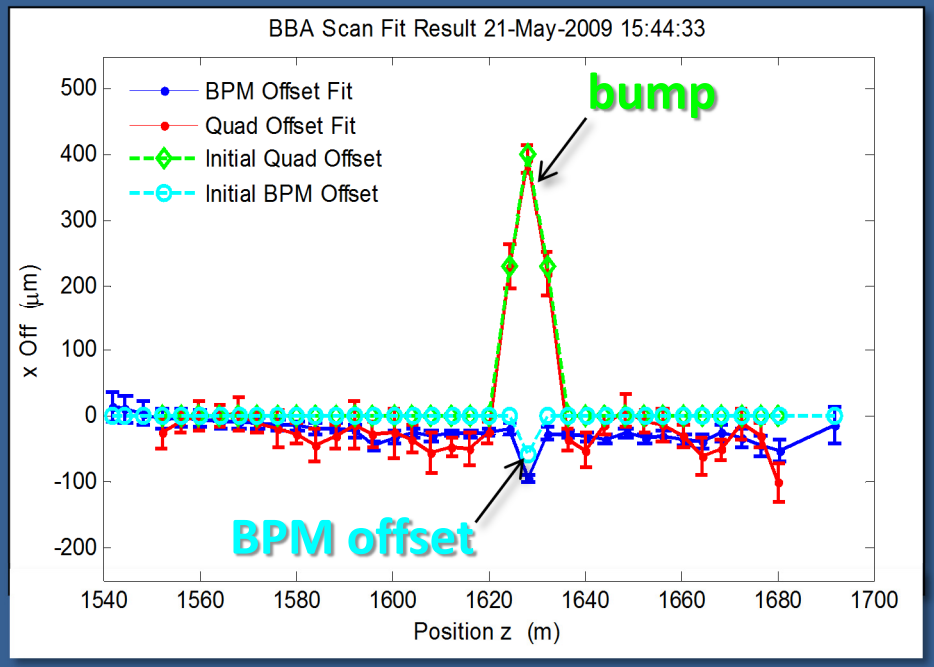
- Next iteration shows trend toward *dispersion-free* trajectory



Test BBA with Intentional Orbit Bump

- Start with well aligned undulator (after BBA)…
- Install orbit bump (green) and BPM offset (cyan)



Run BBA as test case

H. Loos

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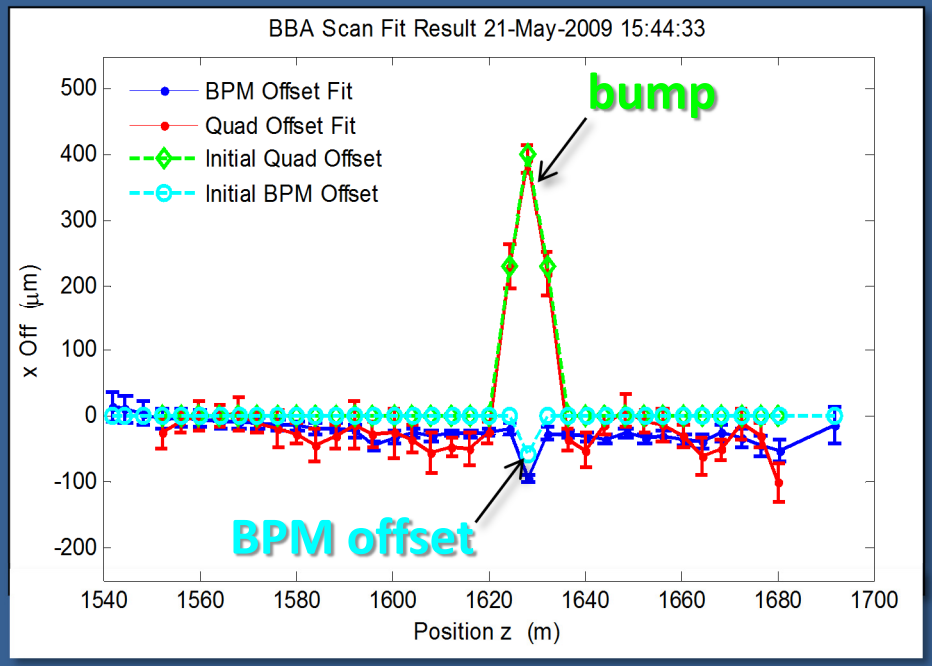
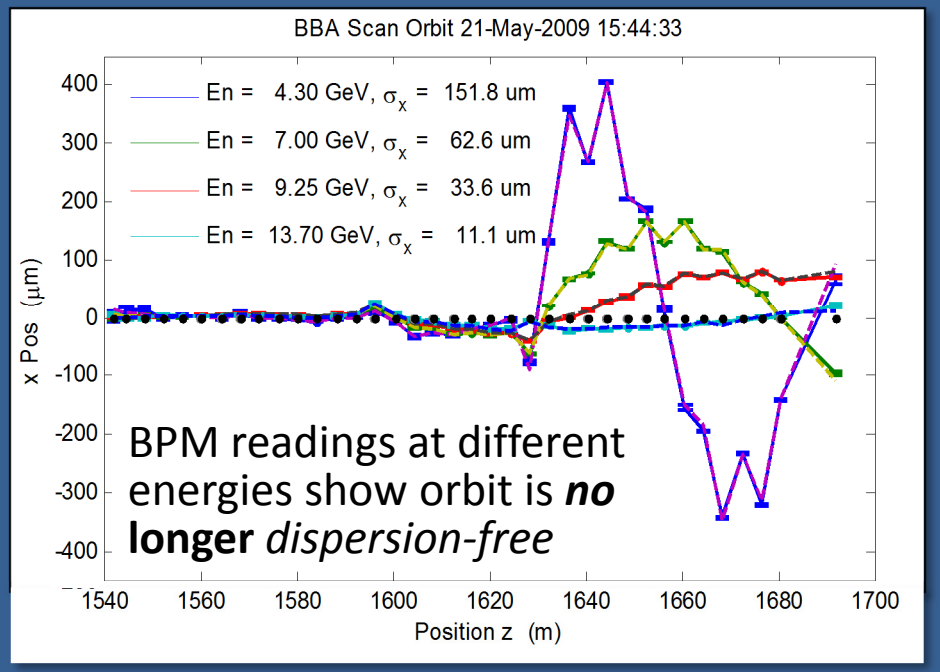


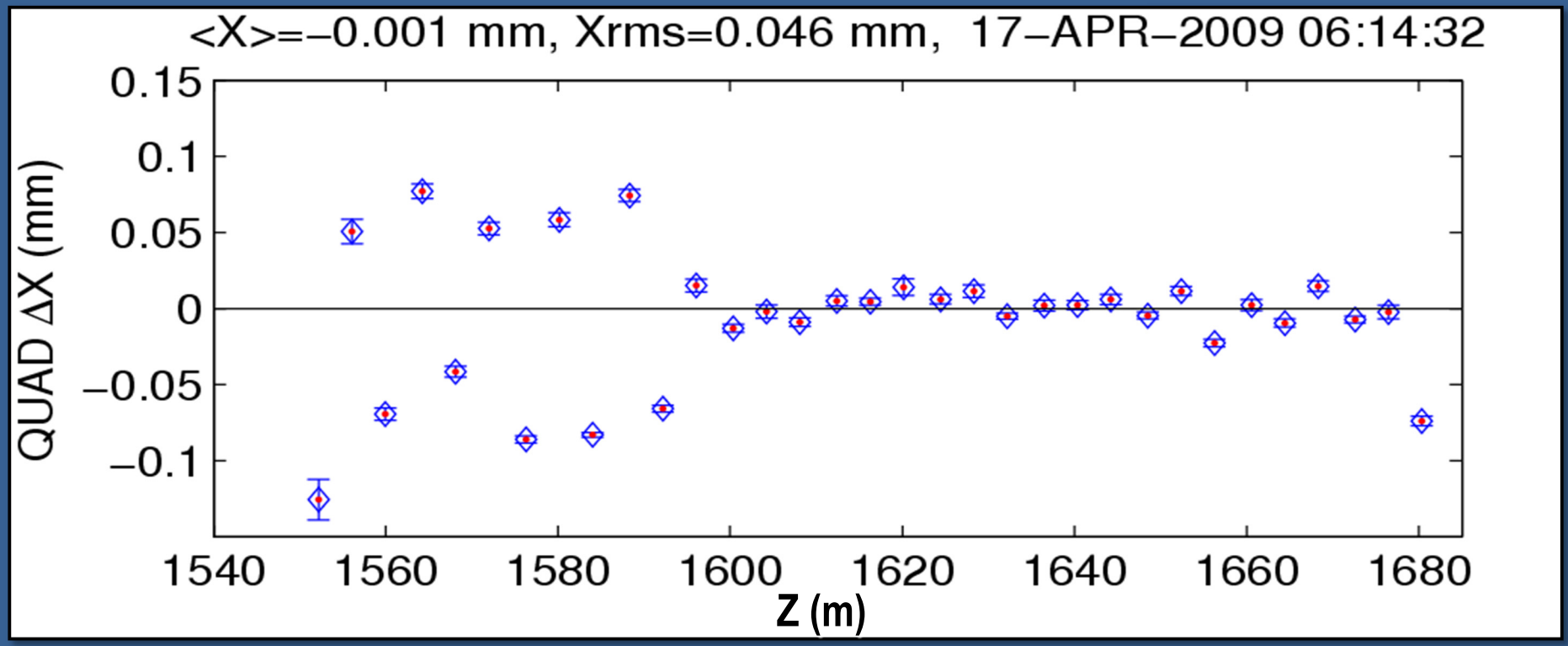


- BBA finds bump (red) and BPM offset (blue) – above

H. Loos

Effect of Earth's Magnetic Field

- Run BBA and apply corrections
- Now vary each quad gradient by 30% sequentially
- Record induced quad kick on trailing BPMs
- Calculate quad offsets (with respect to beam)



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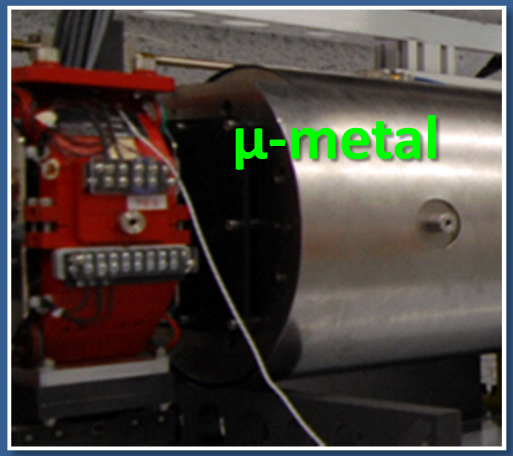

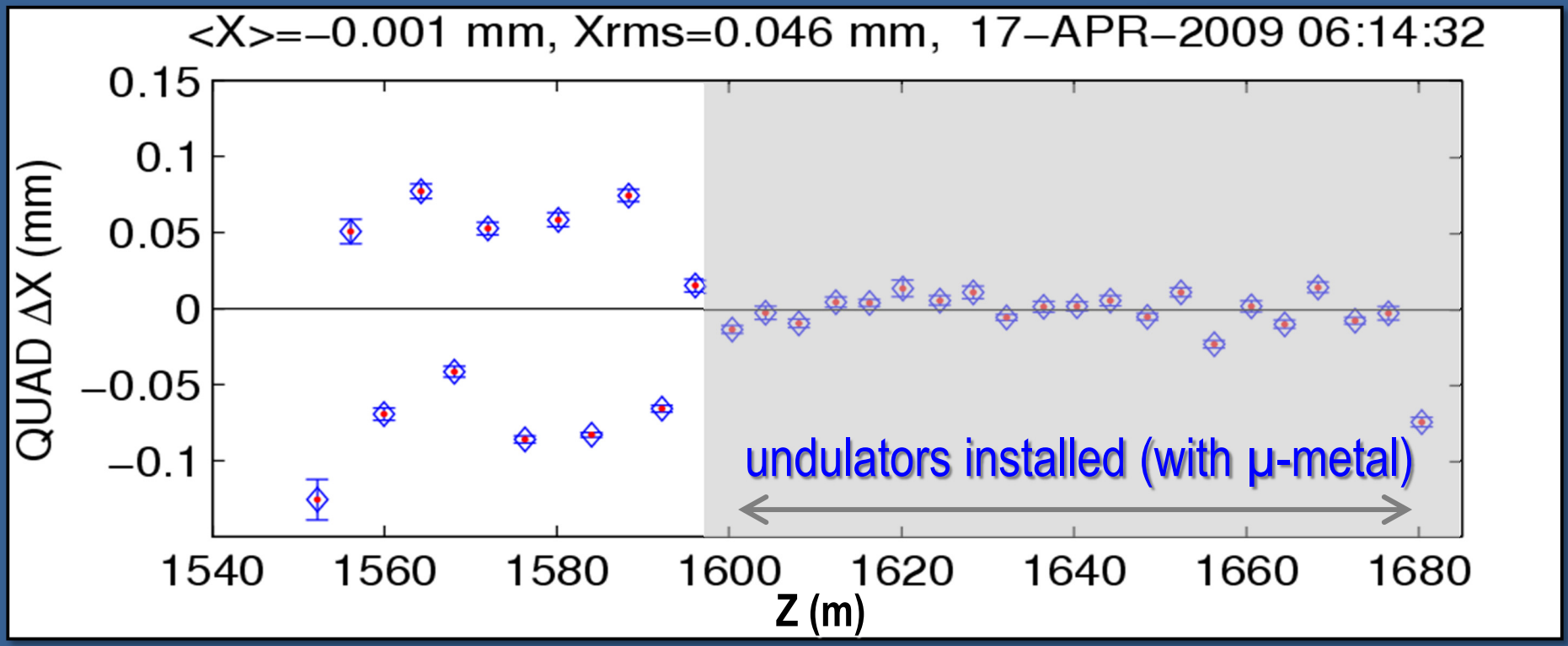

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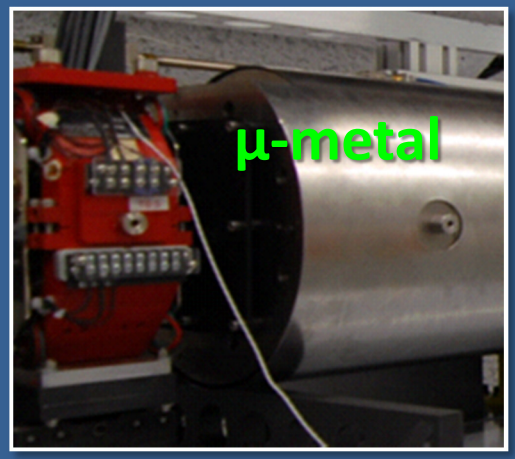

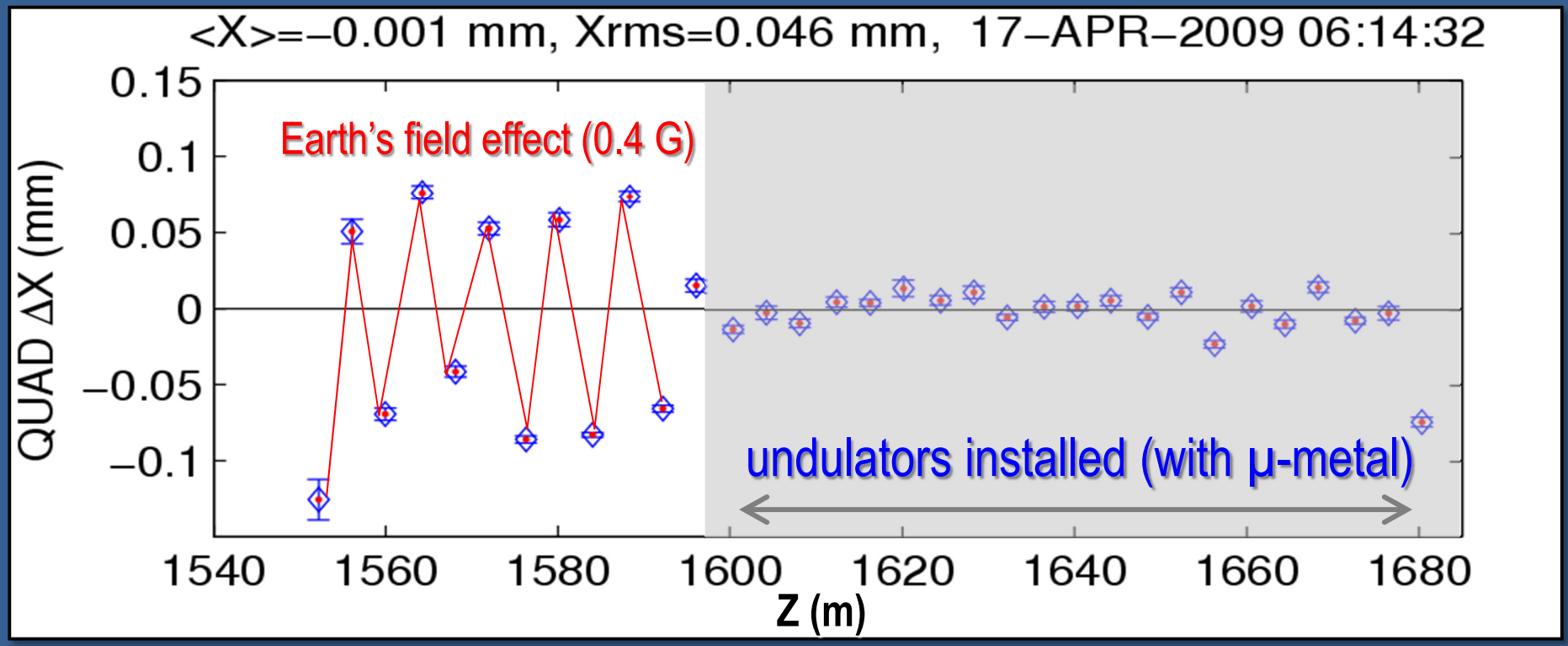

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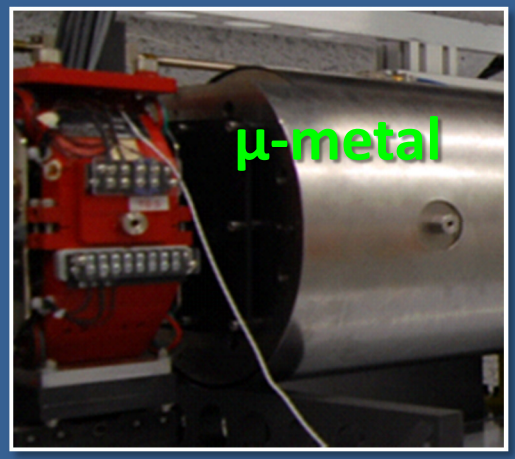
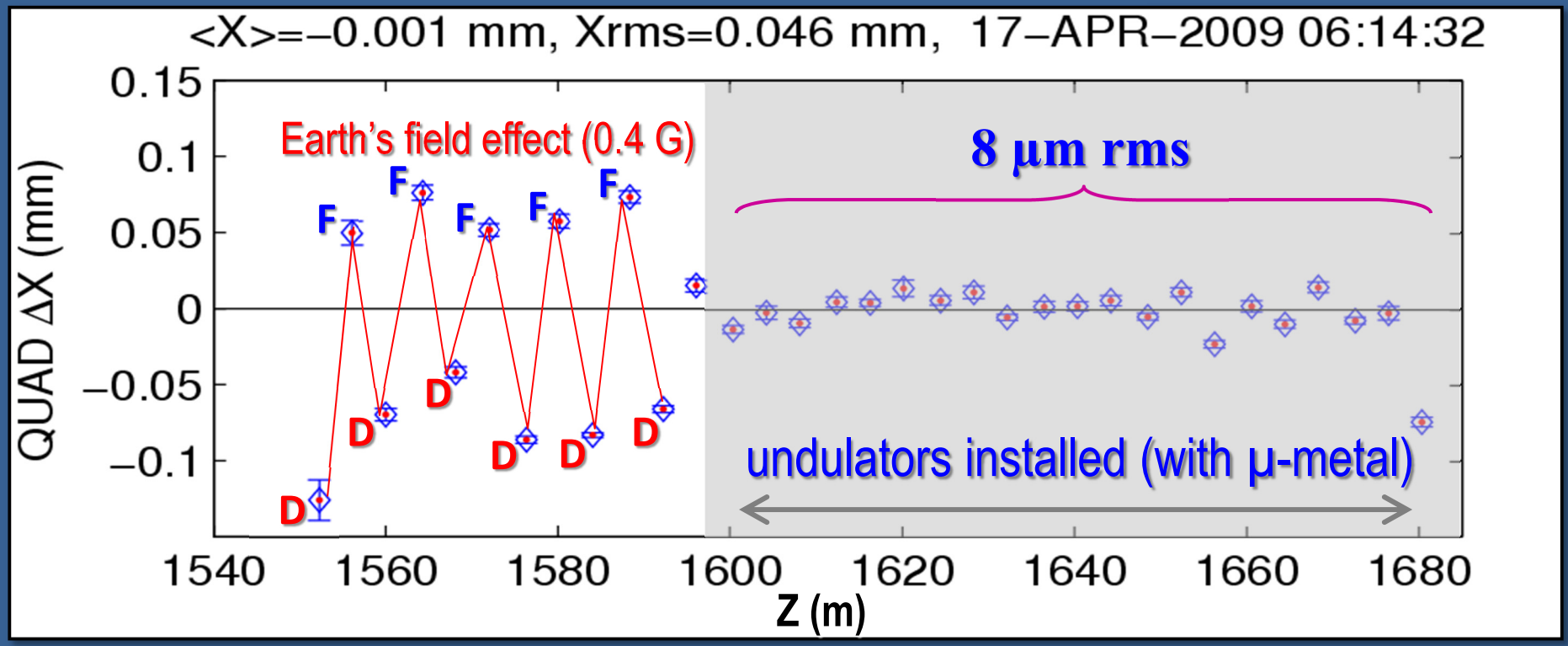
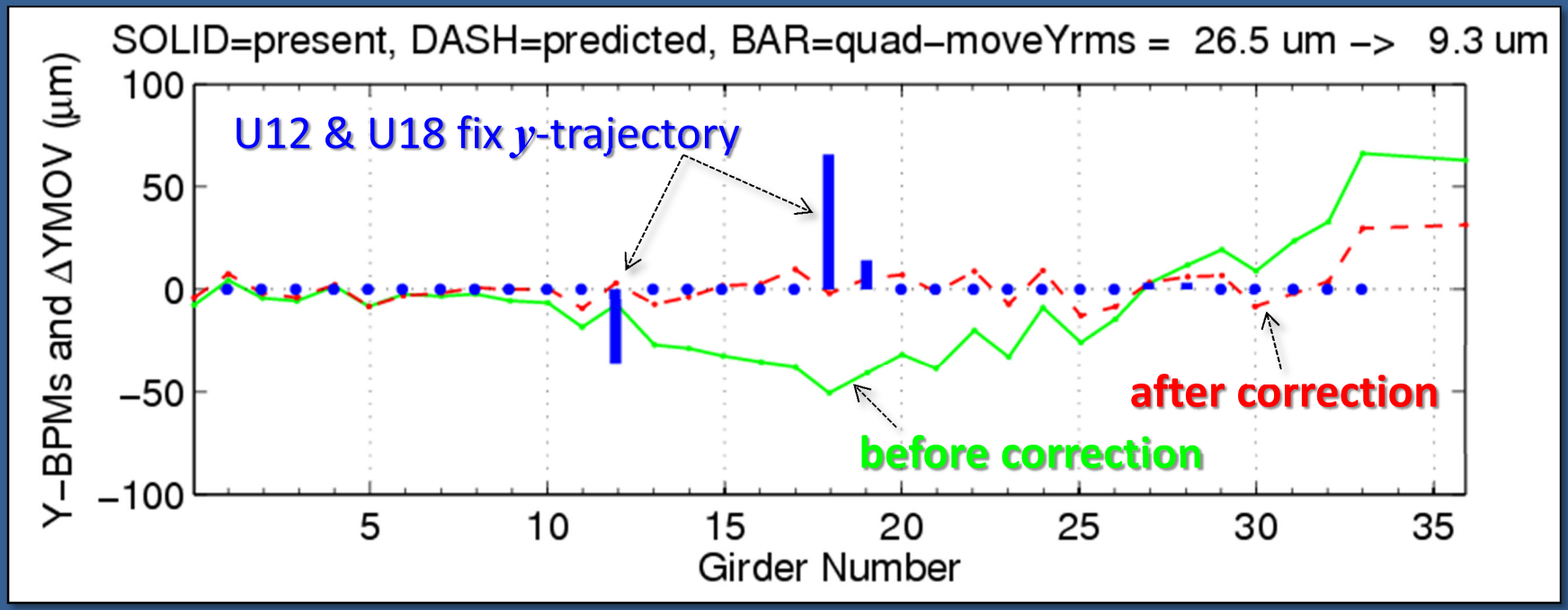




Occasional Undulator Trajectory Steering

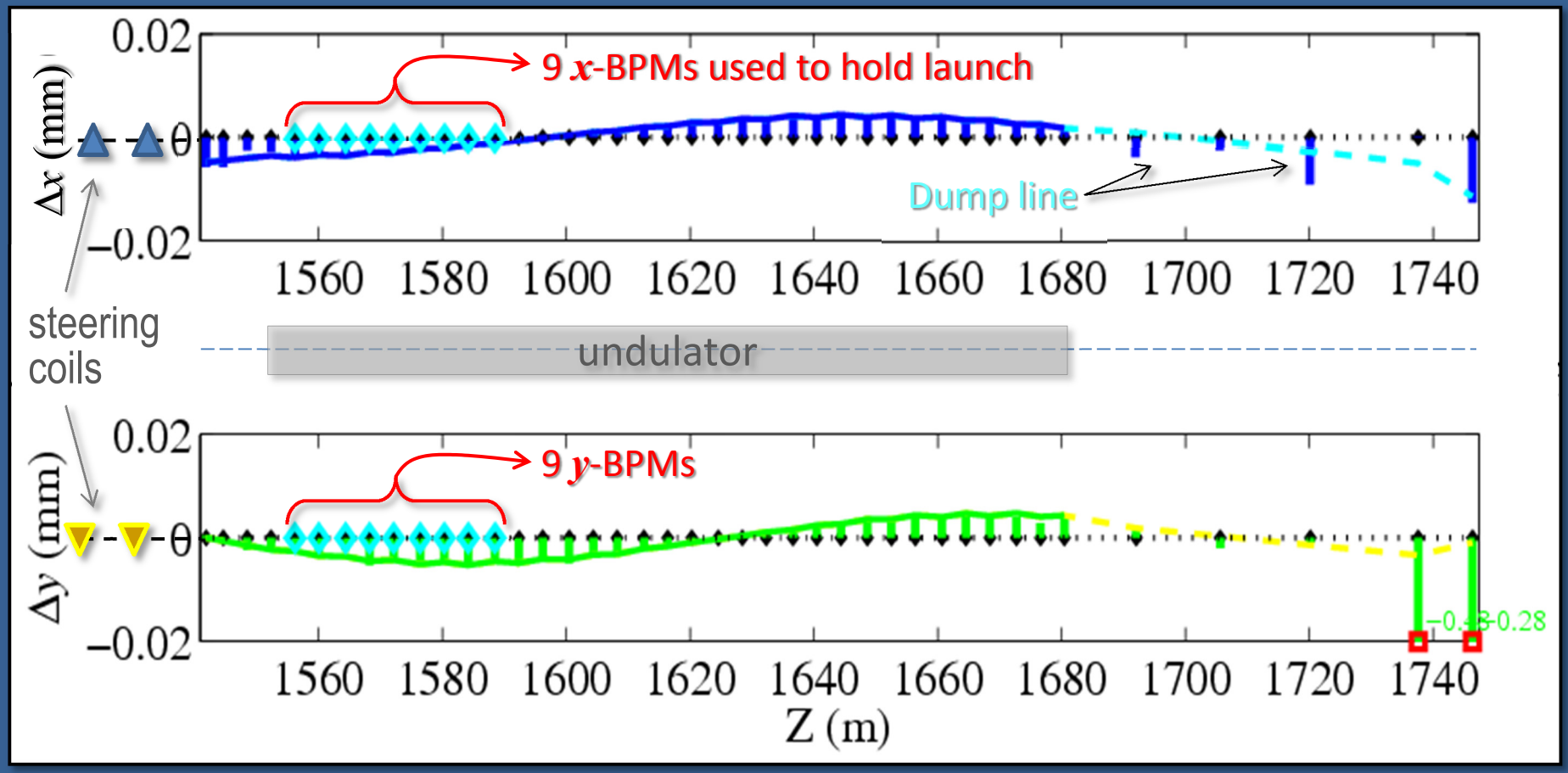
- As orbit degrades (1-3 wks), we add small corrections
- Steering BPMs back to *exactly zero* can reduce FEL gain, since BPM offsets can change
- Instead, apply correction as best 2 or 3 quad displacements



- Or use SVD steering

Trajectory Feedback Loop at Start of Undulator

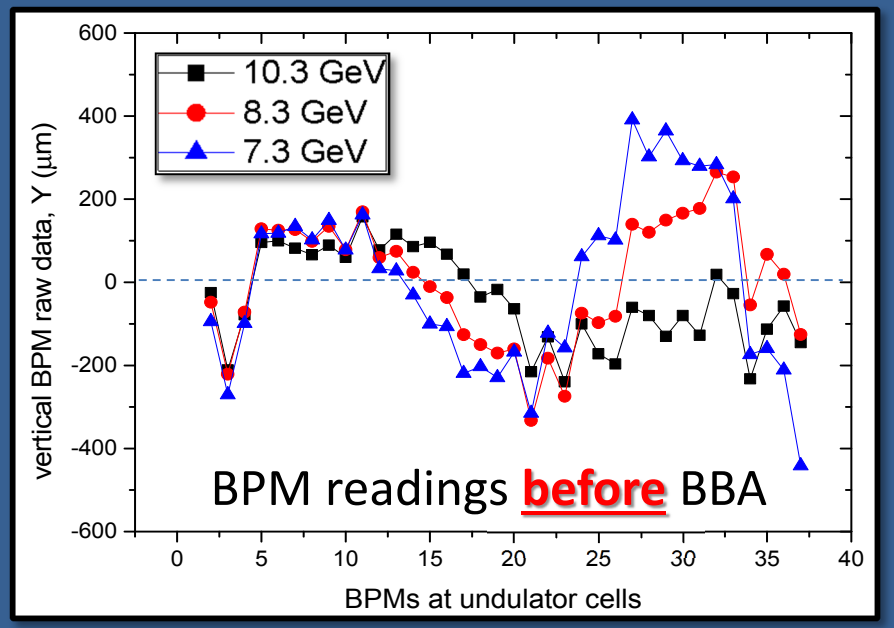
- Uses undulator BPMs and upstream steering coils
- Maintains incoming launch in x and y
- Typically controls slow drift, not fast jitter (< 1 Hz)

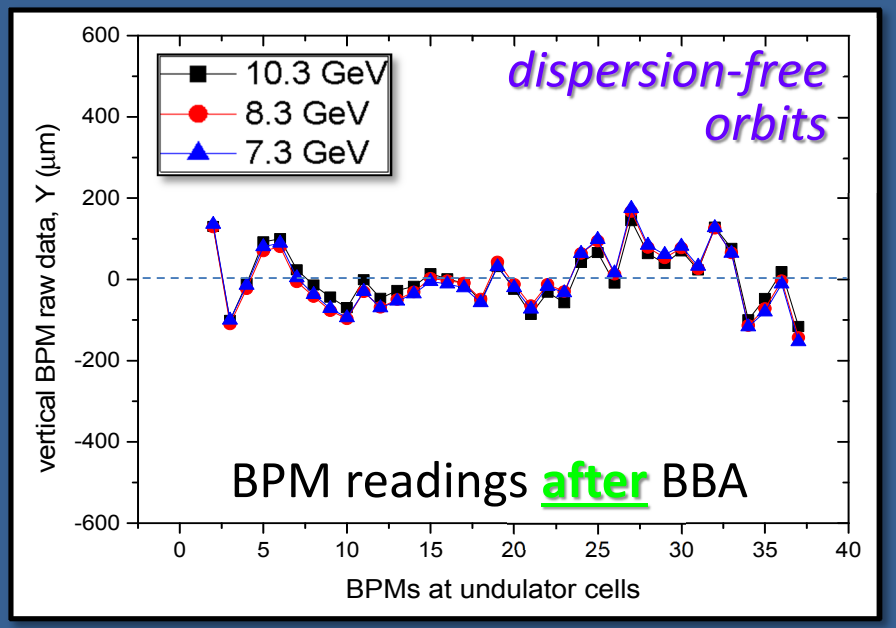


BBA at *Eu-XFEL*

Yuhui Li (*DESY*)

- Same BBA procedure as *LCLS*
- *E* = 10.3, 8.3, and 7.3 GeV
- Used ~5 times so far since May
- Allows 0.2-nm FEL lasing

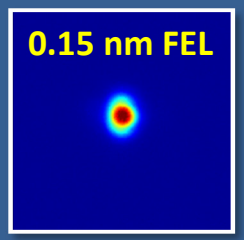




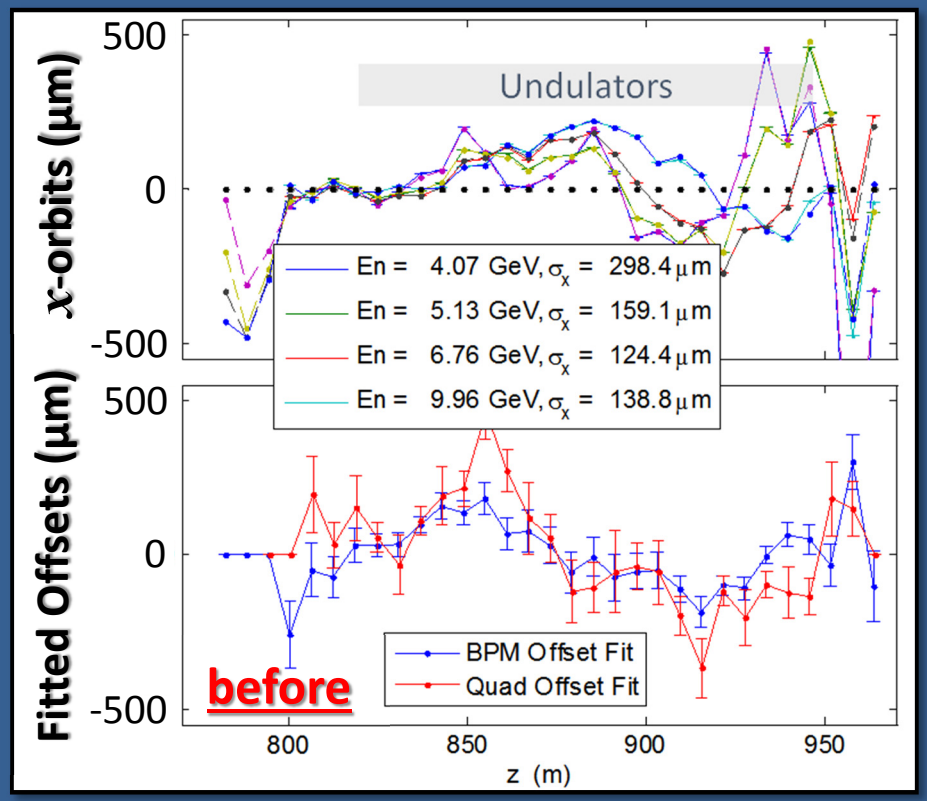
BBA at *PAL-XFEL*

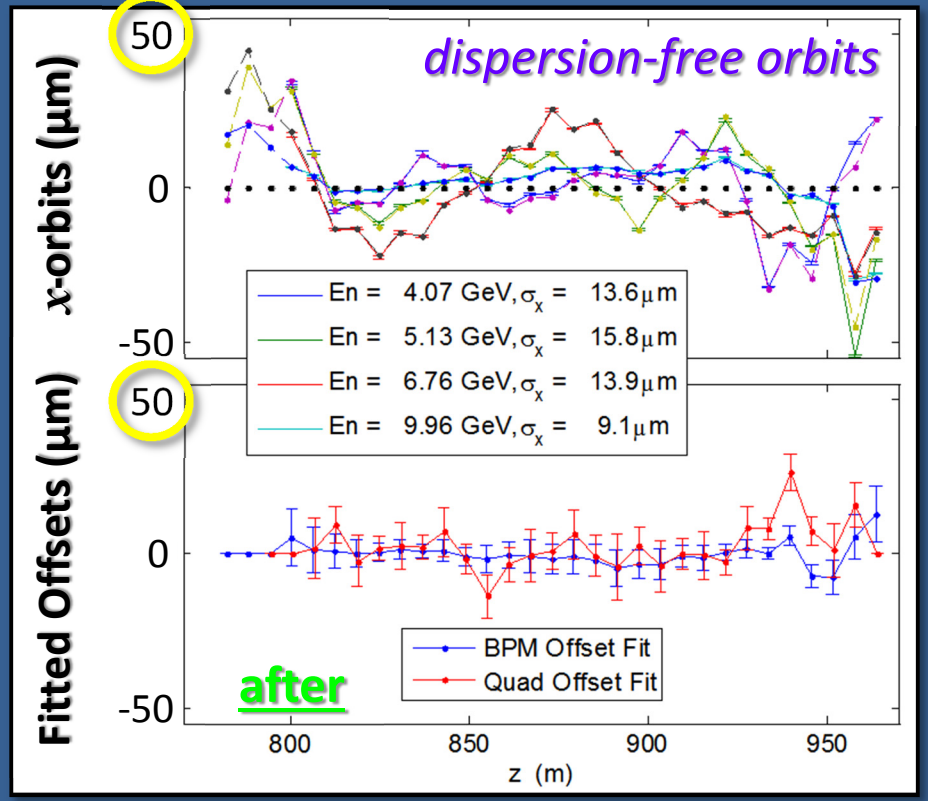
H. Loos,
H.-S. Kang

- Same BBA procedure as *LCLS*
- Both Hard & Soft X-ray FELs
- E = 4-10 GeV (2-3 at SXR)
- Variable gap undulators
- Initial BBA with gaps open
- BBA reduces ΔE orbits by 10



PAL POHANG ACCELERATOR LABORATORY

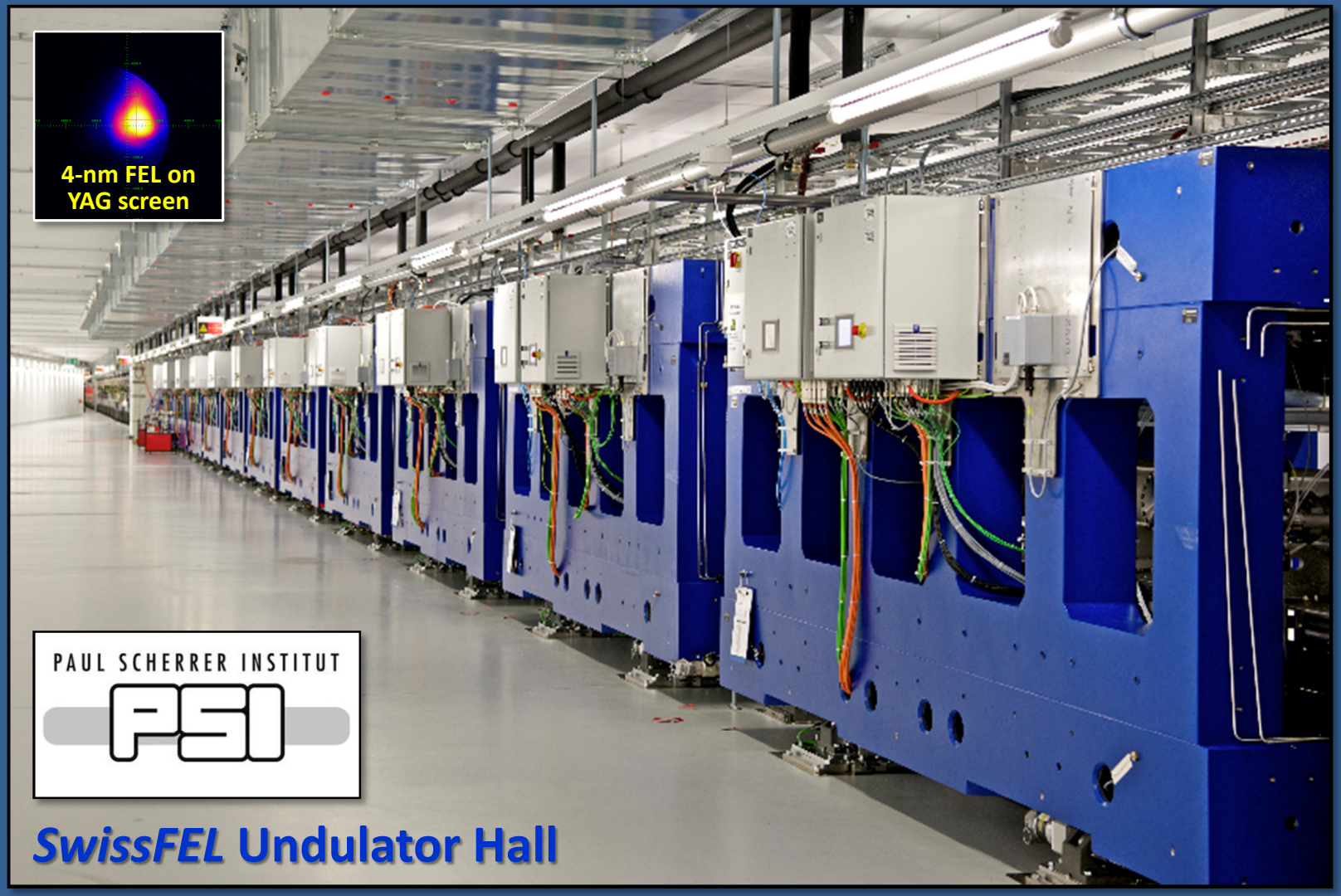




No BBA yet at *SwissFEL*

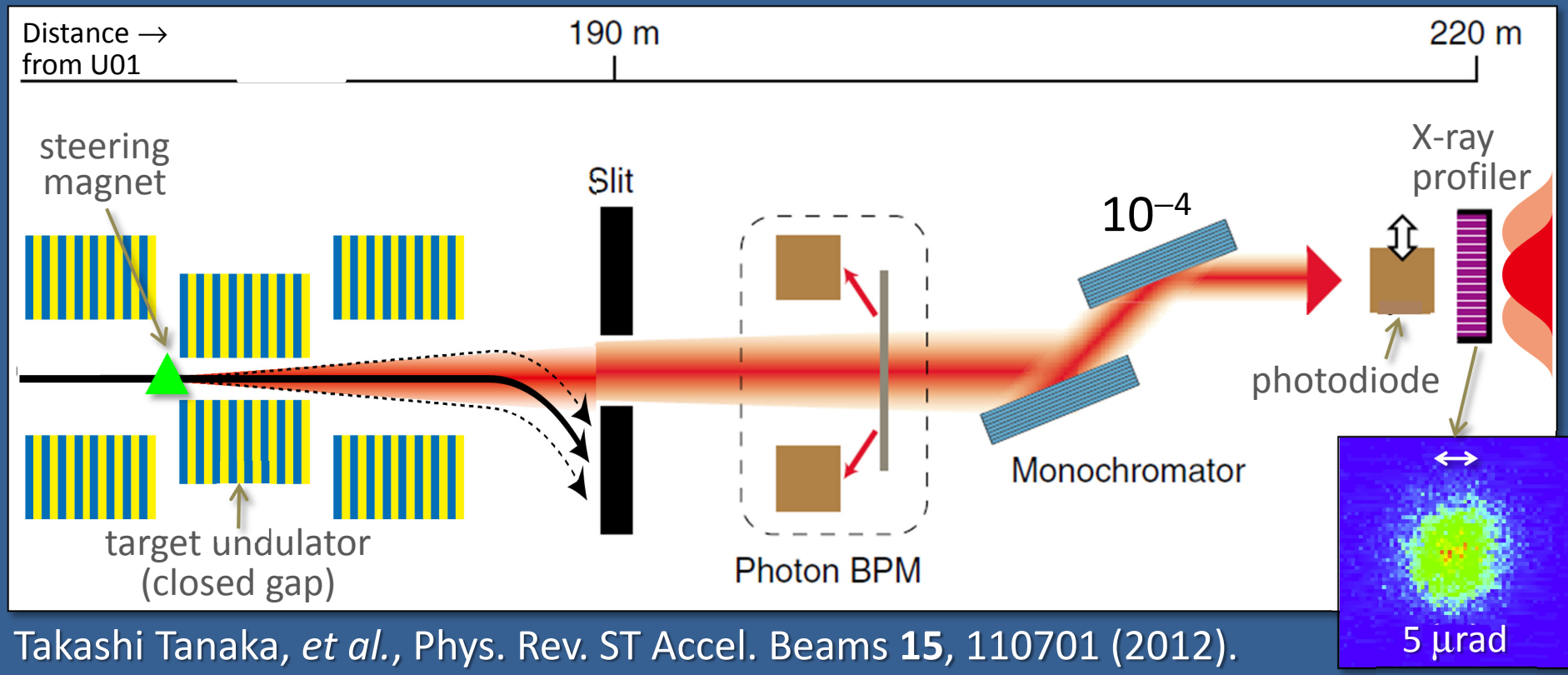
H. Braun

No systematic BBA yet, but lasing observed at 4 nm



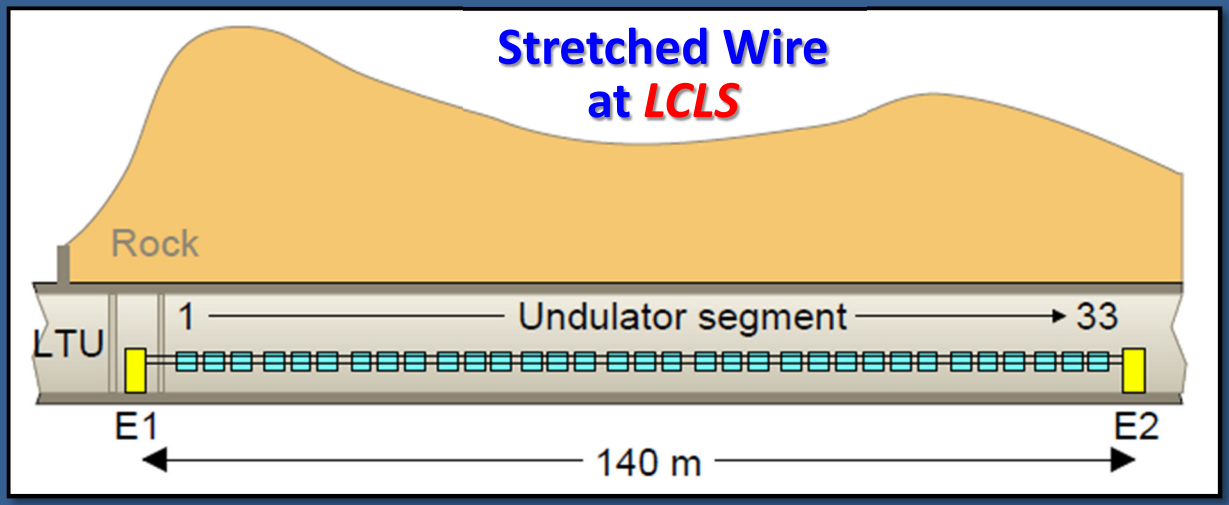
BBA at *SACLA* – a different approach

- Use spont. radiation profile from one undulator at a time
- Filter light through 10^{-4} monochromator
- Steer e^- trajectory to place spont. beam on screen ref. point
- Repeat for each und. segment
- Used each few weeks initially – now 6 months



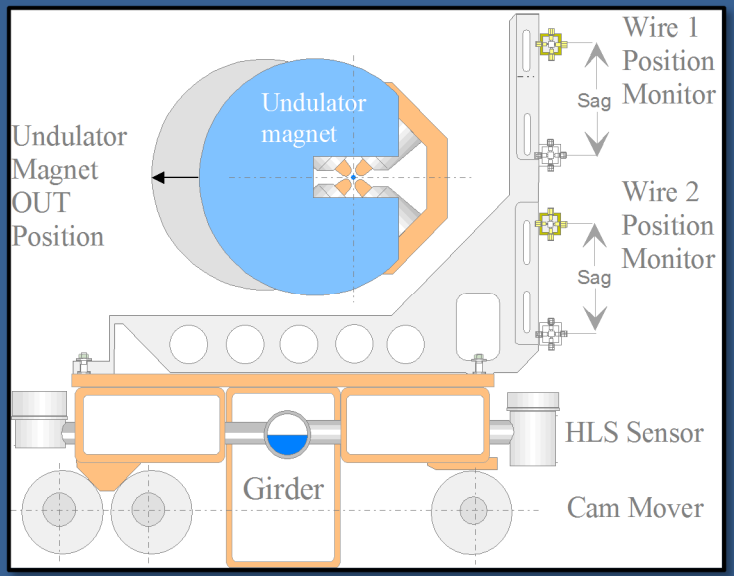
Takashi Tanaka, *et al.*, Phys. Rev. ST Accel. Beams **15**, 110701 (2012).

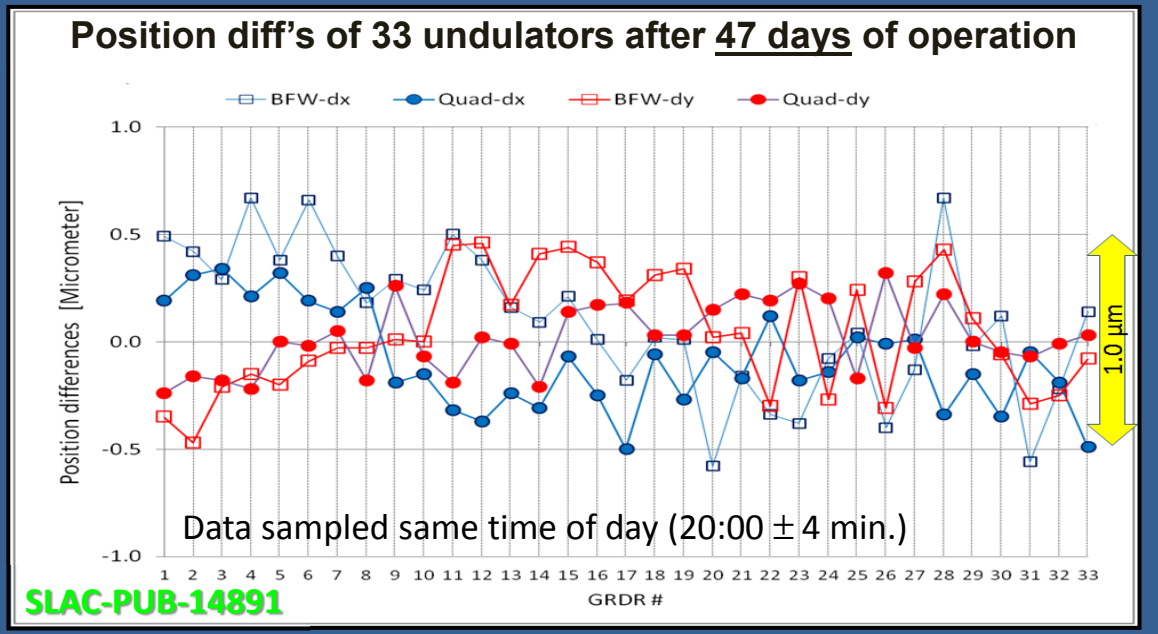
Undulator Alignment Monitors



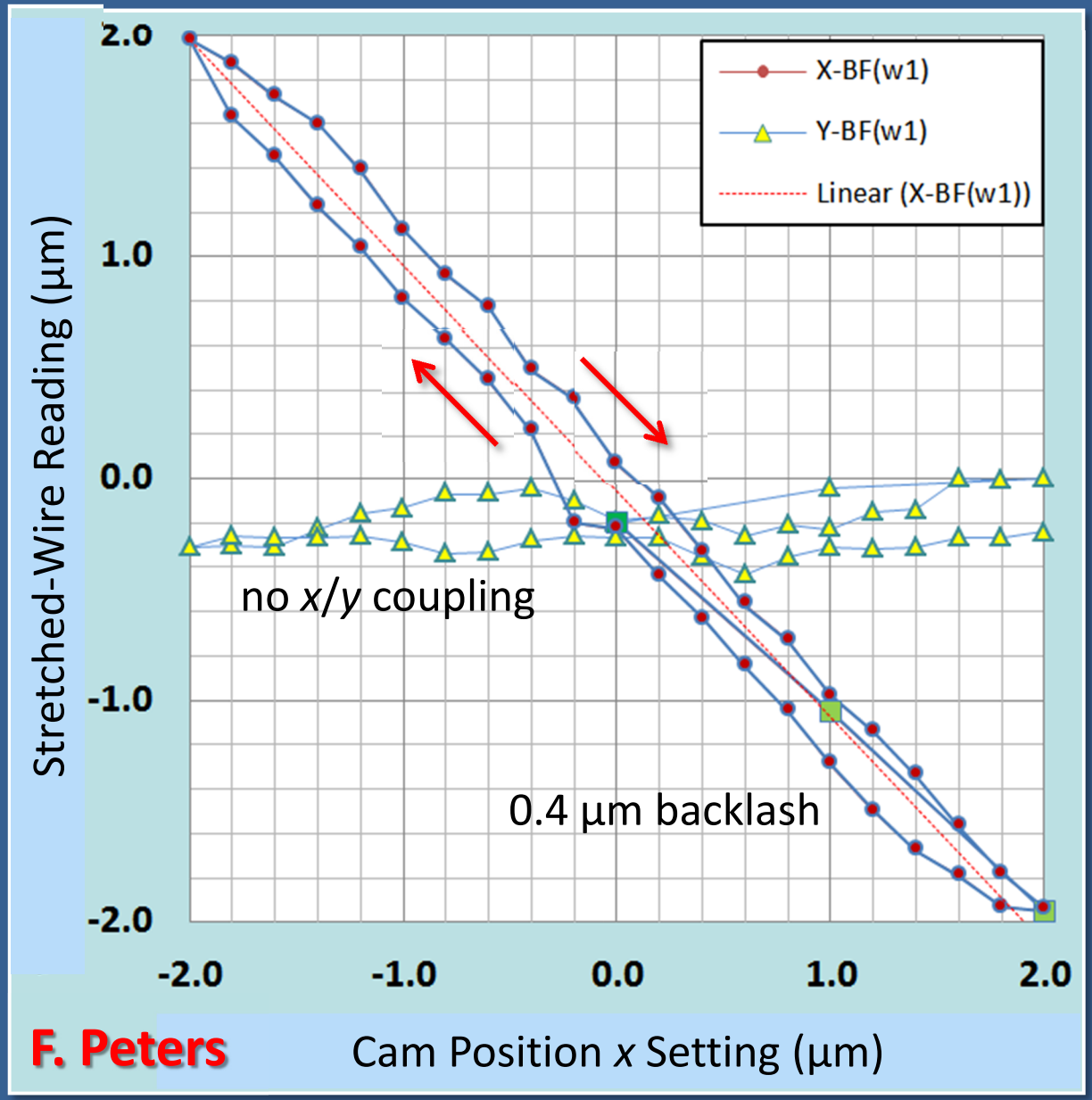
Measures x, y, pitch, yaw and roll of each of 33 quad magnets with respect to stretched wire (16-cm sag)

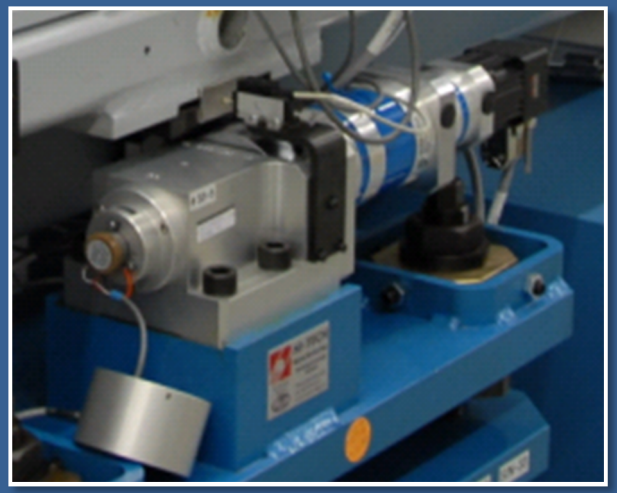
F. Peters, G. Gassner





Precision of Undulator Motion Control

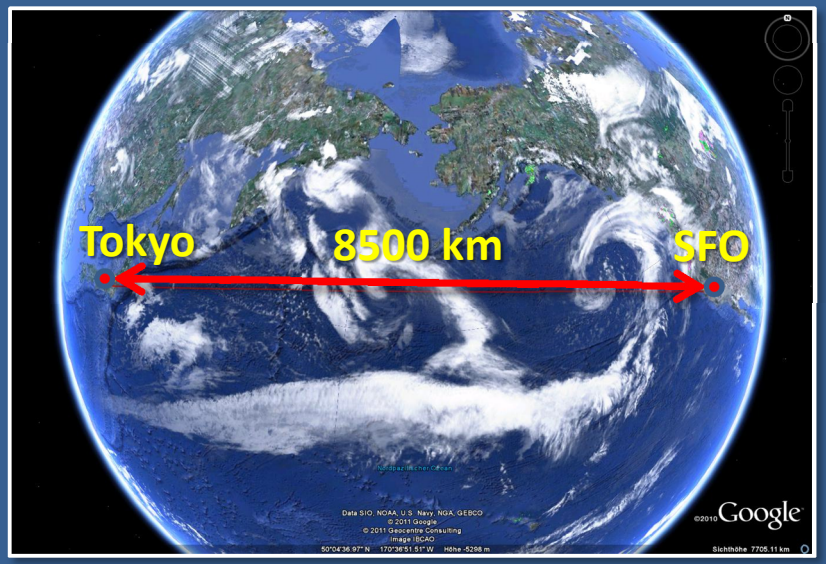




Cam Movers

F. Peters

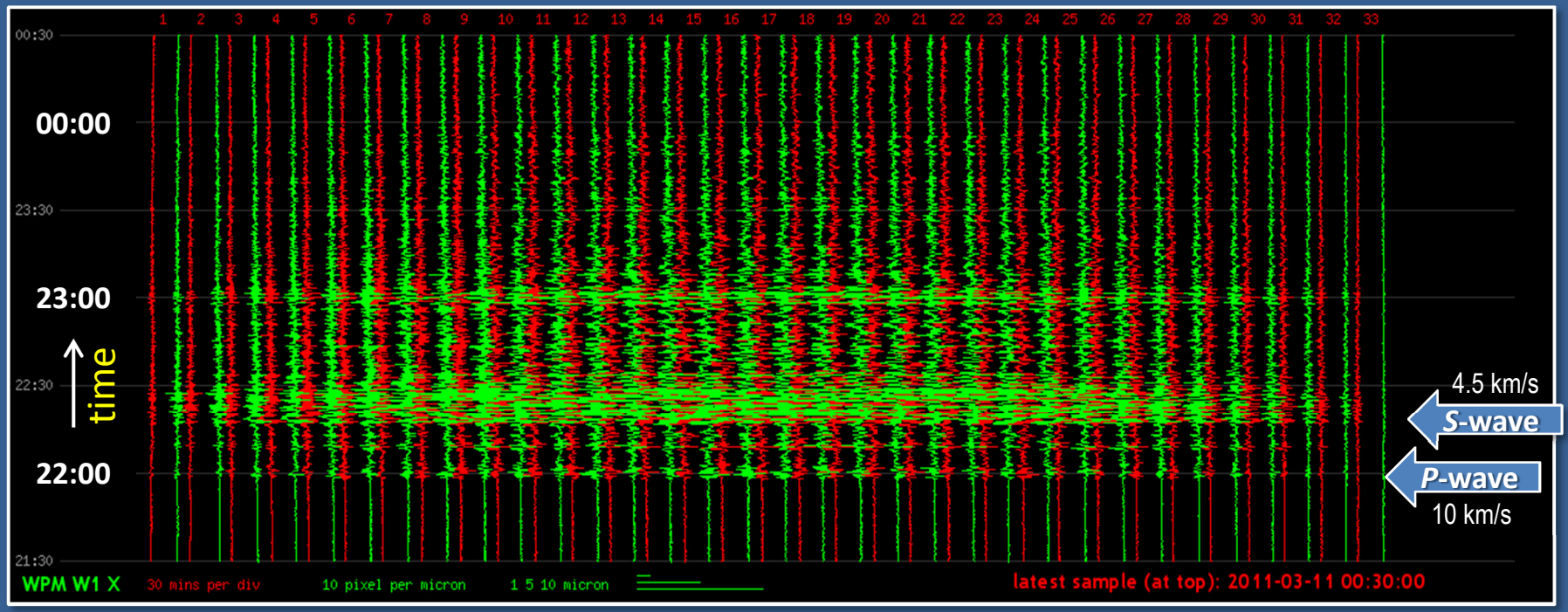
8.9 Earthquake in Japan (March 10, 2011, PST)



Quake seen with stretched wire system at *LCLS*

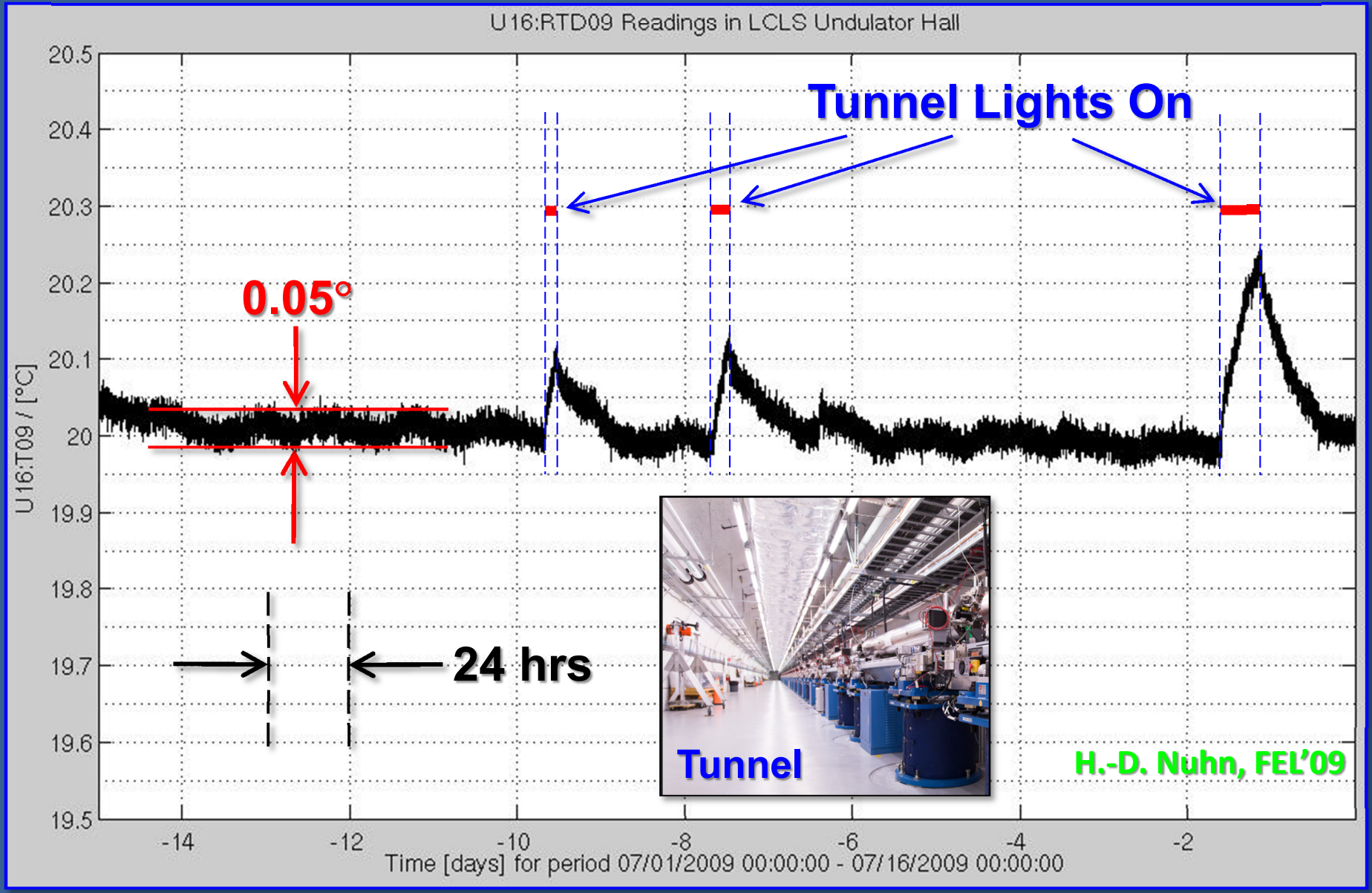
F. Peters

Below: Horizontal oscillations of 140-m wires, with arrival of ***P***- and ***S***-waves indicated.



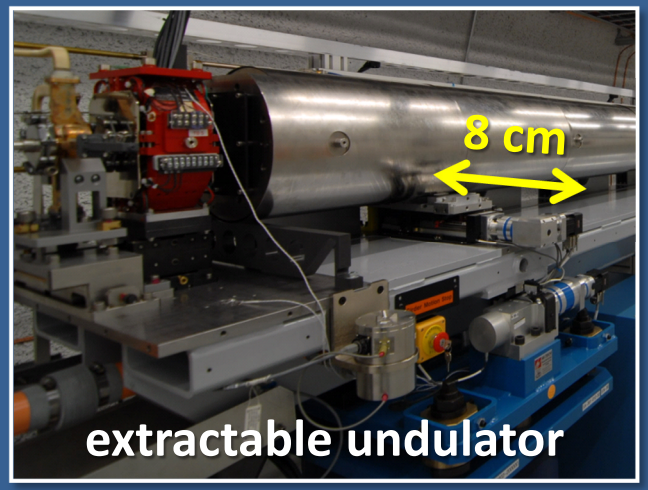
Undulator Tunnel Temperature Over 2 Weeks

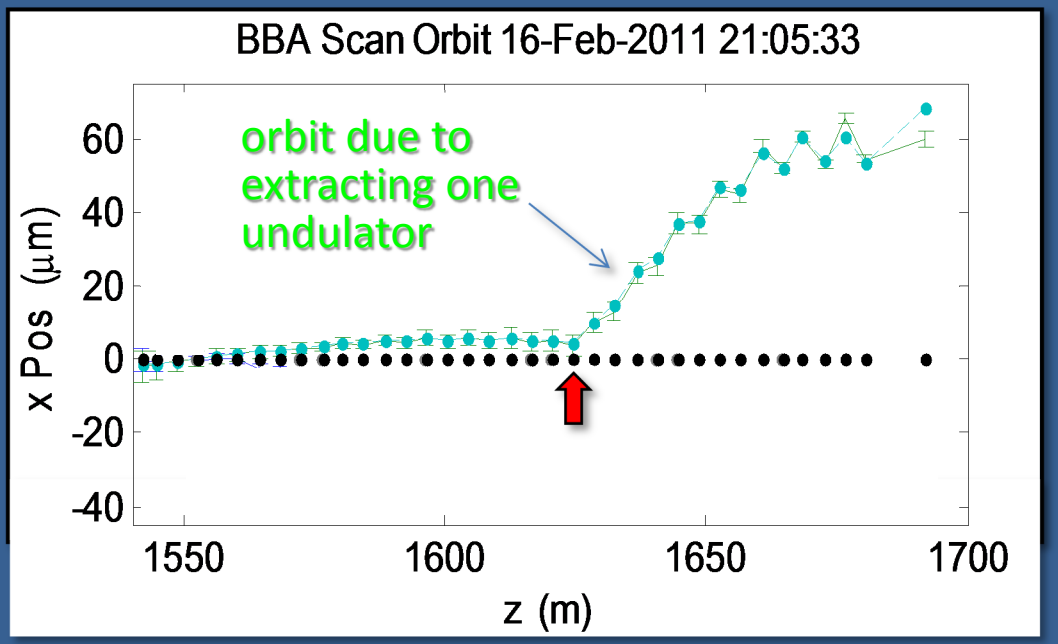
(stable to **0.05 degC** over 24 hrs)

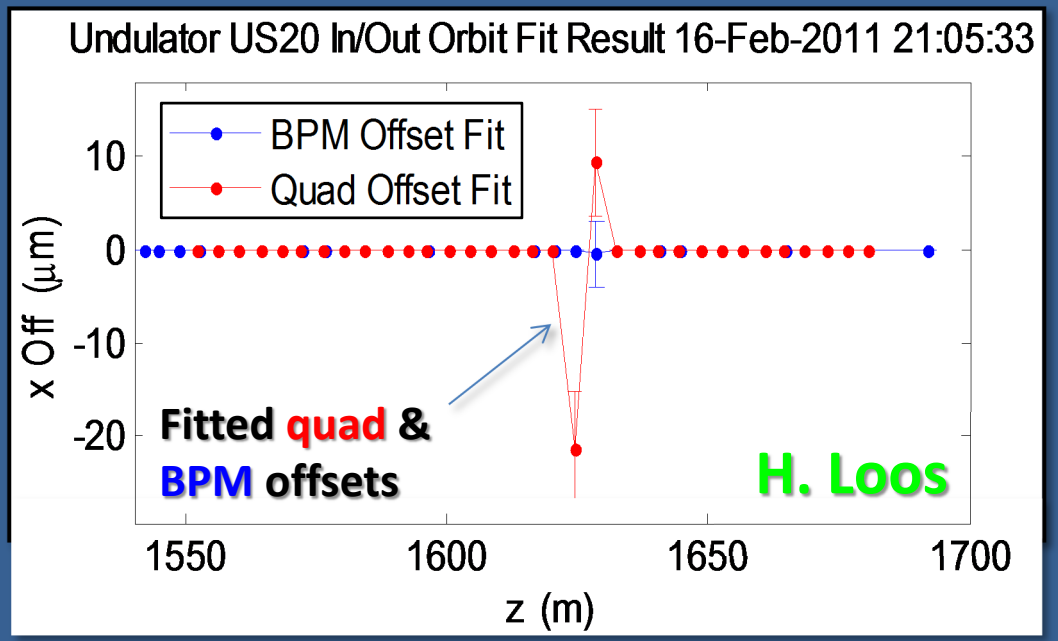


Dynamic Trajectory Correction

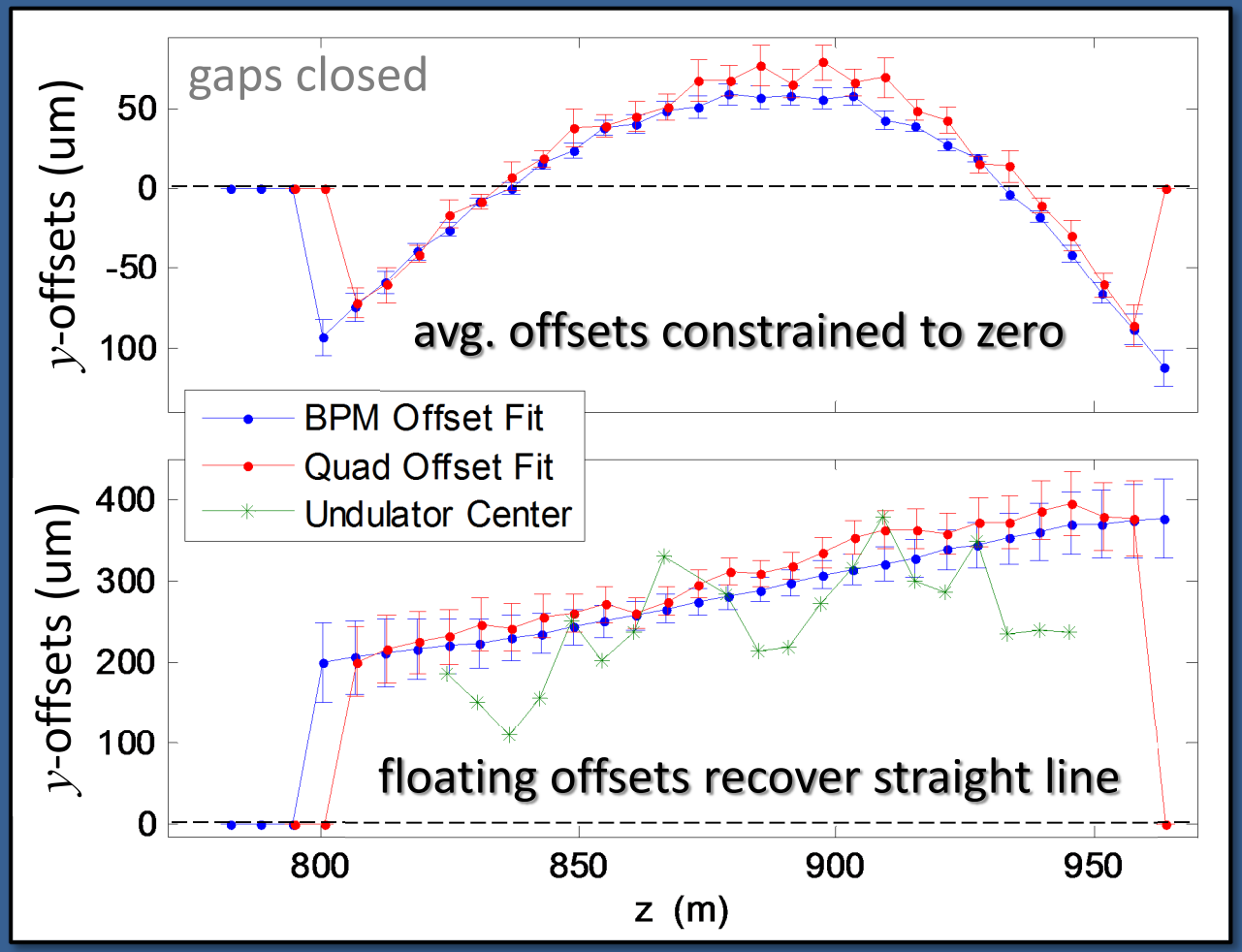
- Extracting one und. segment (8 cm) can kick the orbit due to:
  - off-axis field integrals,
  - Earth's field,
  - shifted load
- To compensate, we fit the diff-orbit to 2 local quad offsets, and a BPM offset.
- This is applied automatically by the control system using x and y steering coils.







Large Undulator Offsets Cause Bowing



- After *open-gap* BBA, repeat with gaps closed
- Fitted y-offsets show 150-µm bow*
- 'Floating' BPM offsets recover straight line
- Fit results move BPMs and quads to und. gap centers (measured by und. radiation analysis)
- An issue for large und. offsets that can be compensated

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* Undulator offset-kicks scale as $1/p^2$, rather than $1/p$.

H. Loos

More Practical Details on BBA

- Initial beam launch into undulator cannot be controlled well enough, hence becomes fit parameter for each individual energy
- Kick of *last* quadrupole cannot be measured well (too few BPMs after und.) – exclude this offset from fit
- Offset of *first* quadrupole has same effect as a change in launch angle – exclude from fit
- Measured orbits are invariant to shifting both BPM and quad offsets by a straight line (except when large und. offsets)
- Need to either force *first* and *last* BPM offsets to zero, or add fit constraint to force mean BPM offsets to zero

H. Loos

Summary

- BBA, using energy changes and BPM readings, has been quite successful at 3 different FEL labs (maybe 4)
- BBA with x-rays is used at *SACLA* with good success
- The *SACLA* method appears to be simple, but requires a monochromator and a high resolution x-ray profiler
- The energy-scan method requires good BPMs and sometimes tricky manipulations to change the e^- energy
- For hard x-ray FELs, some form of BBA is indispensable
- Many ideas and diagnostics are also available to monitor and maintain this critical alignment

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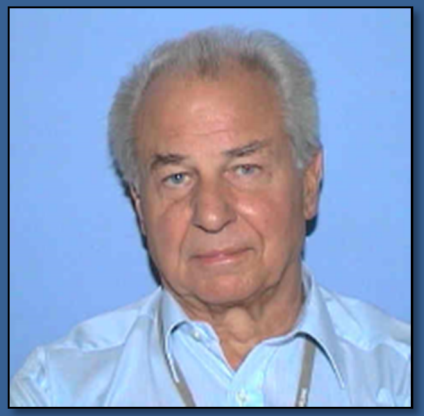
End



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- Henrik Loos
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