SwissFEL Undulator section BBA and optimisation

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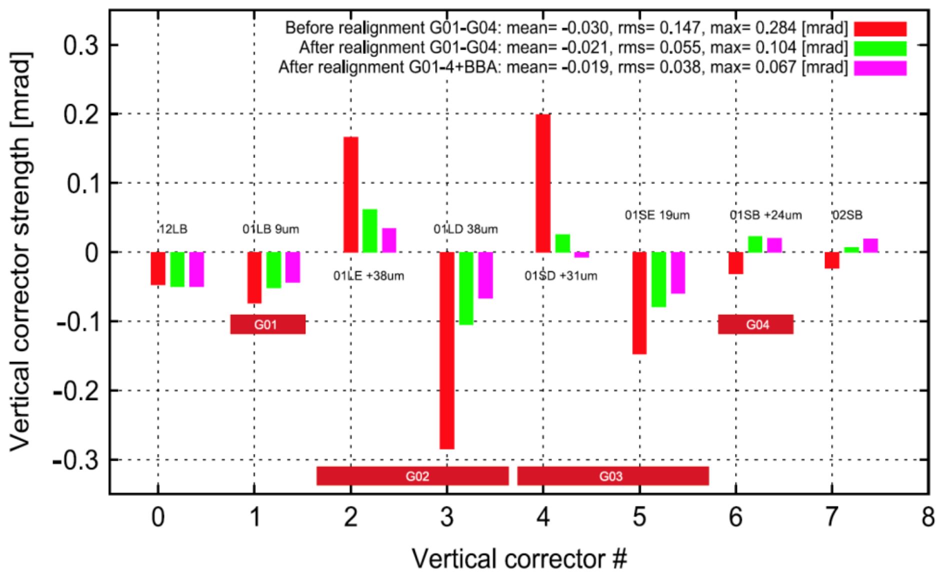
Introduction: Success story of Swiss Light Source (1/3)

- Vertical emittance tuning at SLS
  - ε_y~1 pm achieved for the first time*, which is similar to ILC/CLIC damping ring specification
  - Procedure:
    - Re-survey in the tunnel
    - Remote girder re-alignment
    - Systematic coupling and vertical dispersion correction
    - Random optimisation

* M. Aiba, M. Boge, N. Milas and A Streun, NIM-A, 694, pp.133-139 (2012)

Introduction: Success story of Swiss Light Source (2/3)

- Girder alignment with circulating beam + orbit feedback!
  - Remote alignment based on tunnel survey data
  - Immediate reduction in vertical corrector strengths: Before, after girder alignment and After Quad-BPM BBA



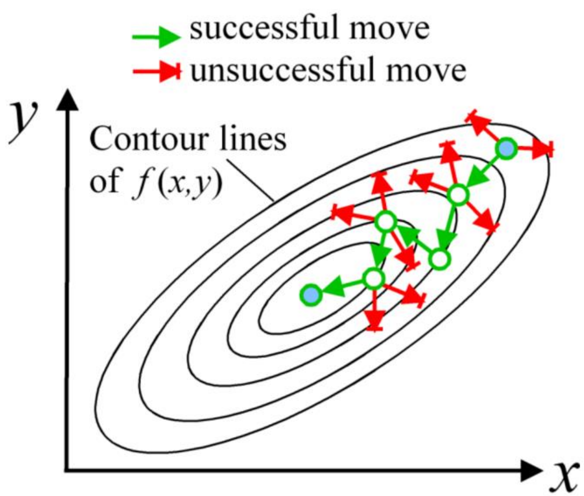
Corrector strength is as informative as BPM:

Necessity of corrector indicates existence of misalignments!

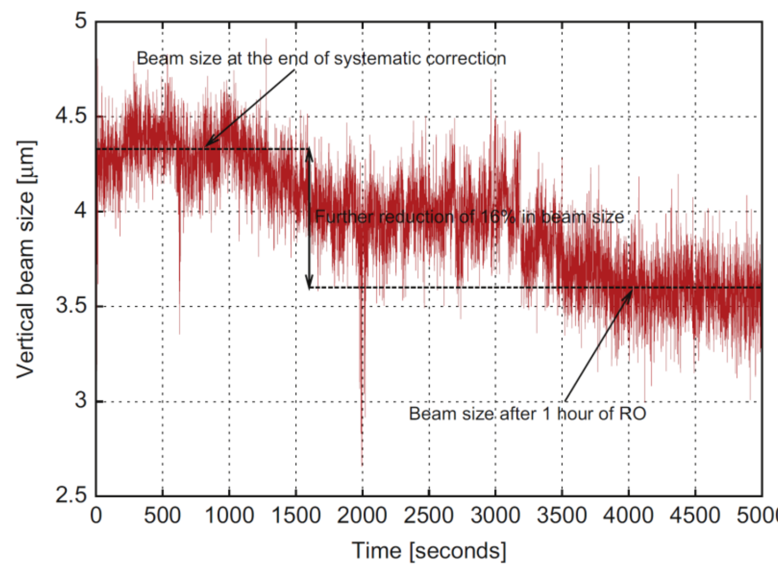
Introduction: Success story of Swiss Light Source (3/3)

- Random optimisation after all the systematic corrections

Example: 2 knobs (x,y)



SLS emittance tuning:
Figure of merit = Ver. Beam size
Knobs = 24 non-dispersive skew quads



1.3 pm
↓
0.9 pm!

Systematic corrections may never be perfect
due to measurement errors, knob errors (hysteresis) etc.
Random optimisation can cover these deficiencies!

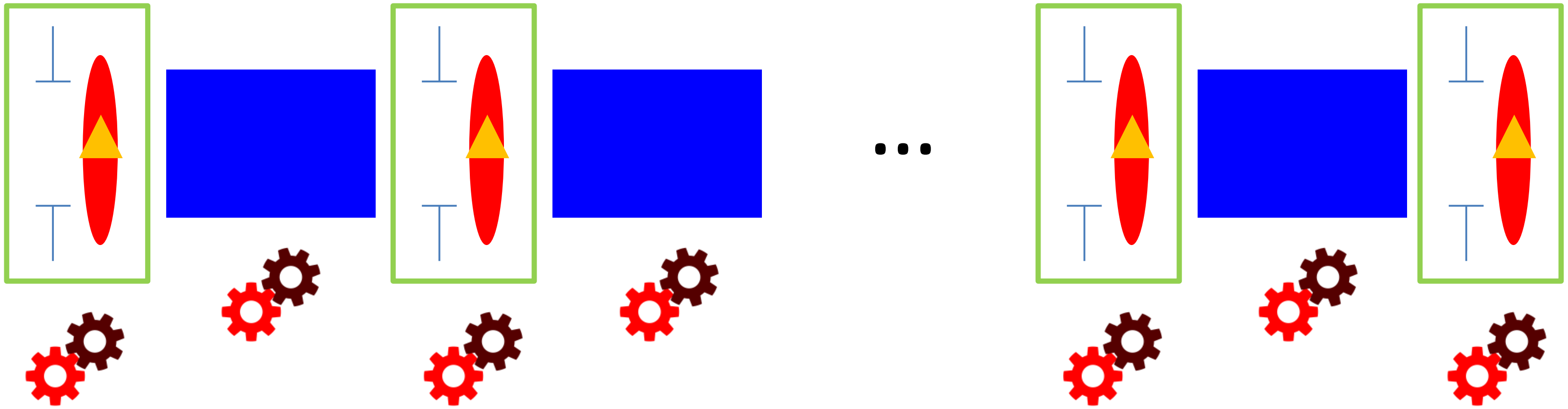
BBA of SwissFEL undulator section (1/6)

- Goal:
  - Trajectory straightness of 2~3 μm! (at 5.8 GeV e-beam energy) over 13 undulator modules
- Procedure:
  - "Corrector based alignment", inspired by SLS experience, to align BPMs using electron beam*
  - Undulator alignment with "Alignment quad" using electron beam
  - Random optimisation using photon beam (laser pulse energy) as the optimization target

* cf. Photon-beam-based alignment, e.g. Fermi, SACLA
DFS-like electron-beam-based alignment, e.g. LCLS

BBA of SwissFEL undulator section (2/6)

- Aramis undulator section
  - Fully periodic with 13 undulators, ~60 m
  - Quad+Corrector and BPM between each undulator
  - Cavity BPM, resolution of 1 μm or higher
  - Undulators and Q+BPM units are both motorized

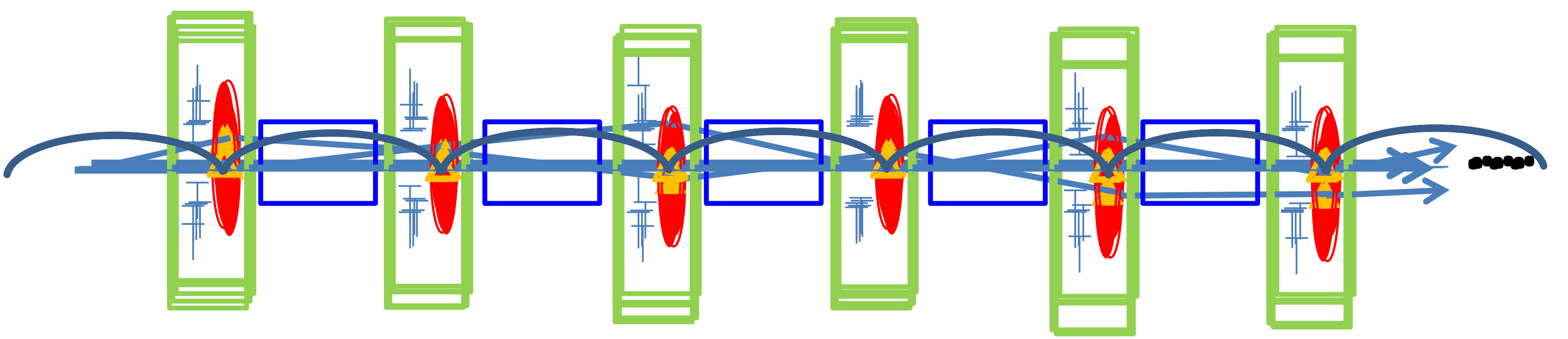


BBA of SwissFEL undulator section (3/6)

- Corrector-based BPM alignment

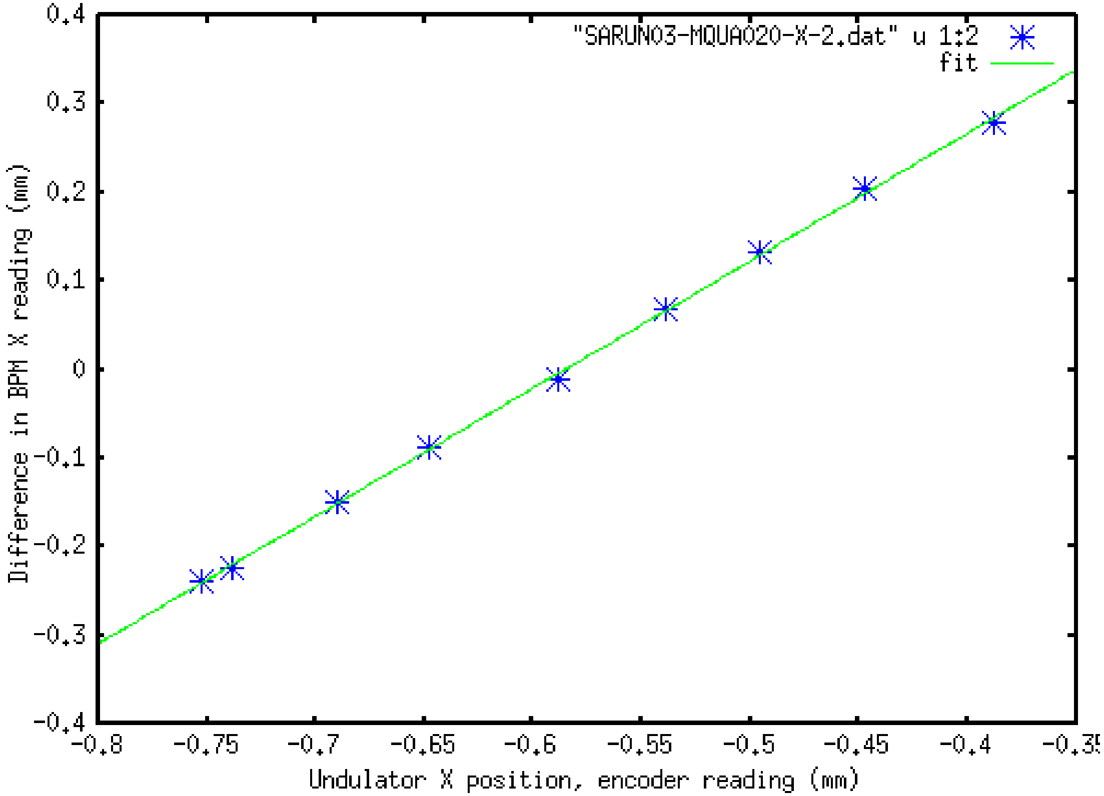
the deviation of corrector strength w.r.t. the average value

to take into account periodic/uniform field error (e.g. geomagnetism)



BBA of SwissFEL undulator section (4/6)

- Undulator alignment using “Alignment quad”



Undulator centre in the horizontal plane was found to be around -0.58 mm.
Note that the encoder has its own reference and -0.58 mm is not alignmemt error.

BBA of SwissFEL undulator section (5/6)

- First BBA in October, 2017 (Beam energy ~1.8 GeV)
  - 16th, evening
    - Quad-BPM relative alignment (3~4 hours)
    - BPM BBA (10 min)
  - 17th-18th
    - Beam setup, preparing for lasing
  - 18th, evening
    - Undulator alignment (~8 hours)
  - 19th
    - Beam setup for lasing → 17 μJ photon pulse energy
  - 19th, evening
    - Random optimisation: BPM offsets (soft Epics channels) were varied, with a trajectory feedback loop running, to maximise photon pulse energy (1~2 hours) → 37 μJ
    - Phase shifter adjustment(1~2 hours) → 50 μJ (Gain curve saturated)

Within ~16 hours (0.5+1+0.5 shifts), the first undulator section BBA was done. Note that the time consuming parts (Q-BPM alignment, Undulator alignment) are basically "one-time operation" or at least valid for long time once done.

BBA of SwissFEL undulator section (6/6)

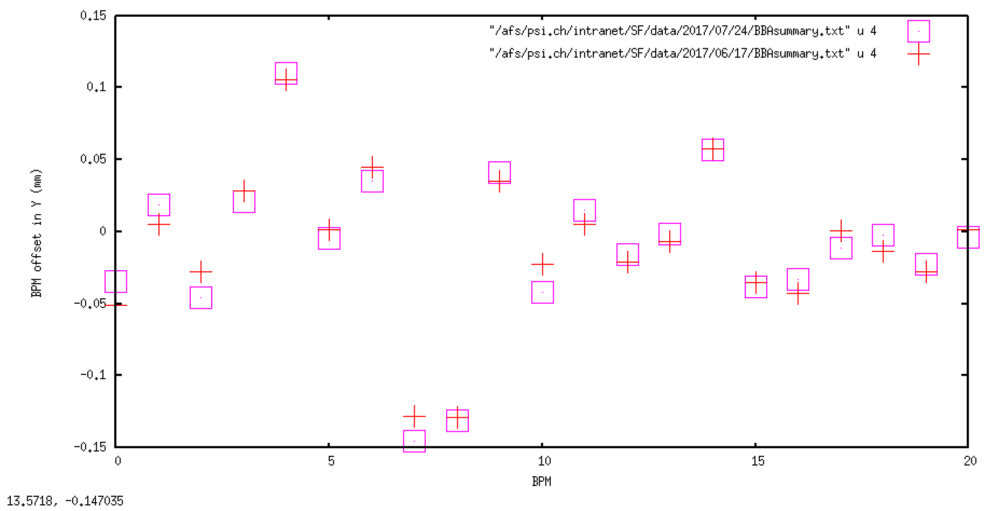
- Precision of systematic BBA
  - Found from the trajectory change through Random optimisation

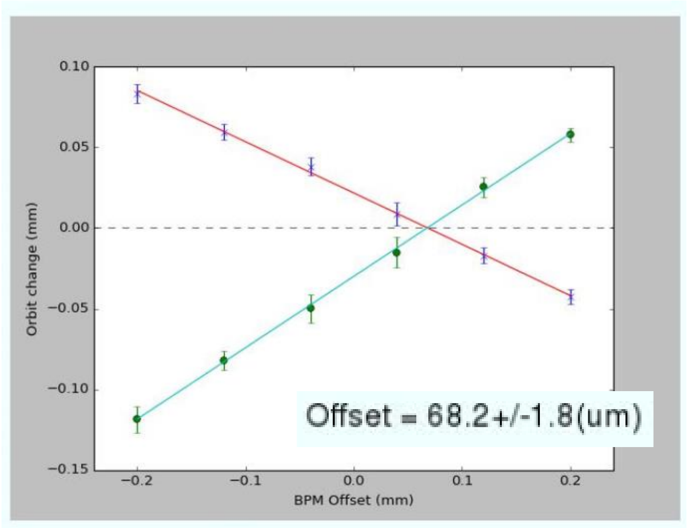
Energy (GeV)	1.8	2.45	5.8
Horizontal (μm)	19.1	16.4	**5.9~6.9**
Vertical (μm)	20.4	11.2	**4.7~6.3**

Precision for 5.8 GeV beam is scaled
from the results of 1.8 GeV and 2.45 GeV beams

Very good precision (as expected from simulation, see backup slide) was achieved.
Once lasing with detectable pulse energy can be obtained, Random optimisation (or any other algorithm) can realise almost perfect orbit at the end.

Alignment precision – some numbers





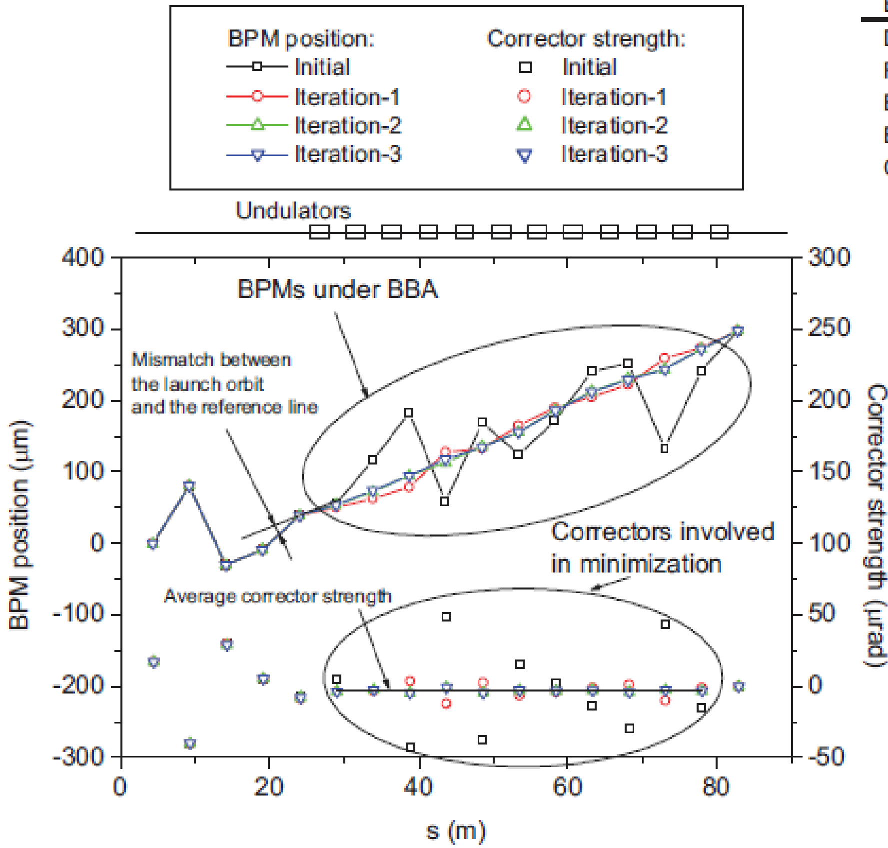
- Left: (Injector) BPM-Quad offsets, measured in June and July 2017
  - No significant change over time
  - RMS offset of 53 μm (Precision of Fiducialisation+Survey)
- A large vertical misalignment (~300 μm) in one of Quad-BPM pairs was found from BBA and fixed in the tunnel (re-alignment)
- Right: Typical offset measurement result
  - Typical statistical error is a few μm

Summary

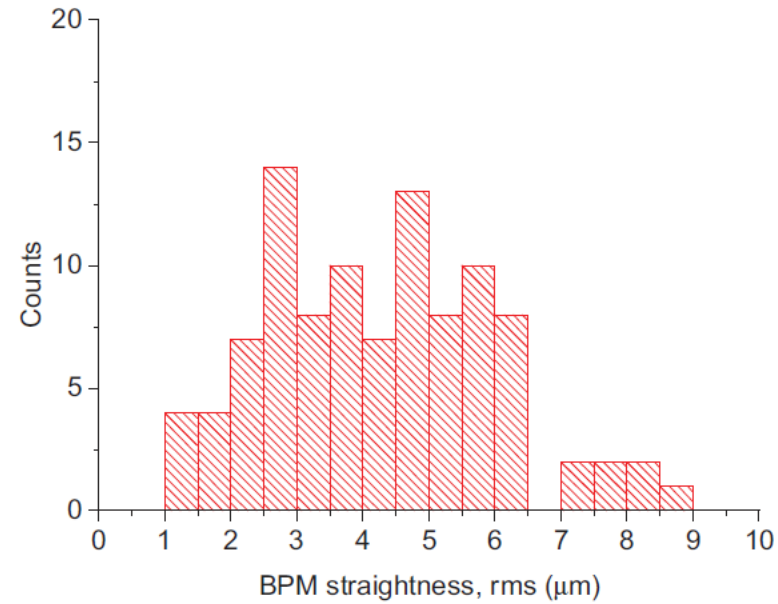
- SwissFEL undulator section BBA
  - Unique approach “Corrector-based alignment” was applied to align inter-undulator BPMs
  - Undulator alignment using “Alignment quad” was successful
  - Empirical optimisation is quite useful for delicate machine tunings, for instance μm-level BBA

Backup slides

Simulation*

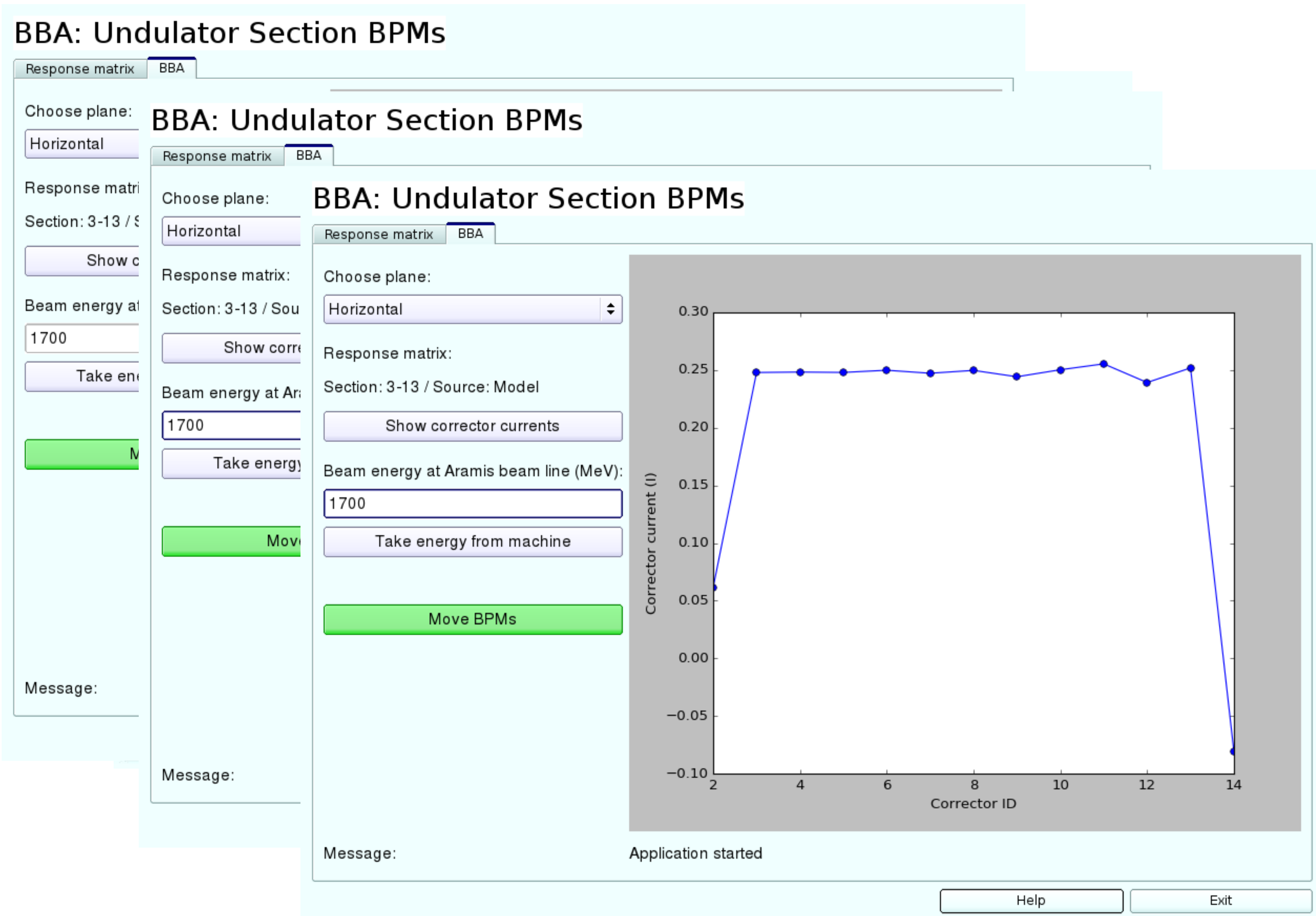


Error source	Value	Remarks
DC dipolar kick	~3 μrad/unit	~1/3 of the geomagnetism
Random dipolar kick	±1 μrad (U)	At both ends of undulator
BPM noise	1 μm rms (G)	
BPM-Quad misalignment	±5 μm (U)	
Corrector str. error	50 nrad rms (G)	



* M. Aiba and M. Boge, Proc. of FEL, pp.293-296 (2012)

Flattening corrector strength



FEL pointing

- Pointing of FEL is controled by moving the entire undulator section as a "single block"
- Example – The undulator section points slightly down in the vertical plane: