Statistical optimization of FEL performance

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Motivation

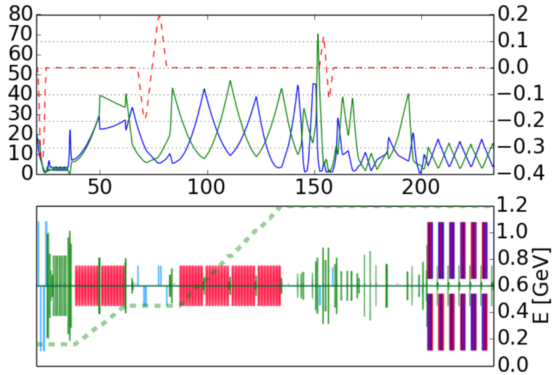
- Make sure we reach best FEL performance by comparing real performance to simulations and tuning to design parameters
- Simulations of statistical processes (like SASE) become less feasible with increasing accuracy. E.g. 1sec of XFEL operation (27000 runs) would need 100 days on a 1000 core cluster with reasonable accuracy and would add 10KEur to electricity bill
- Current procedure of tuning SASE at FLASH is lengthy and manual and would cost lots of money if extrapolated to XFEL.EU
- Self-driving cars and self-focusing cameras are around, so self-tuning light sources are clearly within reach
- Investing into advanced on-line optimization and tuning methods
- Name statistical optimization in analogy with statistical learning, i.e. when paramets or models are not known exactly
- First developments have been ongoing since early 2015 focusing on FLASH

Approaches

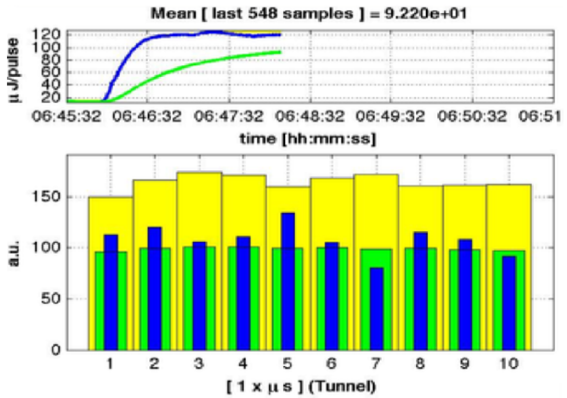
- In principle, with perfect diagnostics, applying alignment and optics corrections etc., should do the job
- This is however not the case in reality
- Instead, mimic what an operator is doing (tuning optics knobs and looking at SASE level), but using more advanced algorithms
- The problem is multidimensional and response functions to optics elements (e.g. steerers) may be bad. Linear theory is not applicable and nonlinear optimization may encounter local maxima.
- Strategy: split into sequences such as {V14, V7, H10,H12} -> {Q13SMATCH, Q14SMATCH, Q15SMATCH} -> {FODO QUADS} -> {intra-undulator orb. correctors} -> {RF phases and Voltages ACC23}
- Within each block apply a nonlinear optimization method (simplex) or a simple scan
- Find best possible sequence
- All optimization steps are subject to additional beam loss constraints (penalty between 0.0 and 0.7 alarm, forbidden to go above 0.7, where 0.7 is not a fixed number)

FEL optimization at FLASH

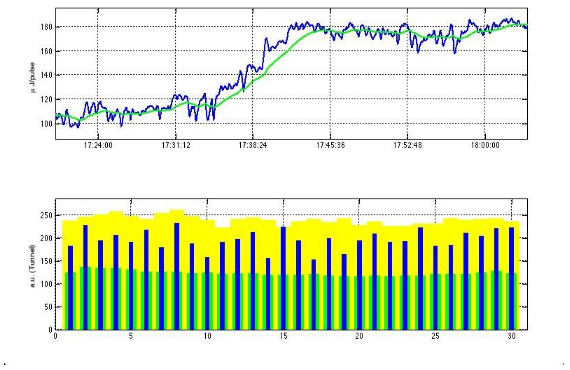
- Automatically adjusting transverse optics (launch steerers, intra-undulator steerers, matching quads, FODO strength) based on photon diagnostics (GMD, MCP, Spectrometer)
- Adjusting compression level using knobs for phases and voltages in BC modules
- It works (*I. Agapov et al., proc. IPAC 2015*)
- Tuning strategies adjustable and in principle self-learning (ongoing R&D, first in simulation)
- Python code, part of OCELOT, based on python DOOCS binding



FLASH OCELOT model
(used in tuning strategy simulator)



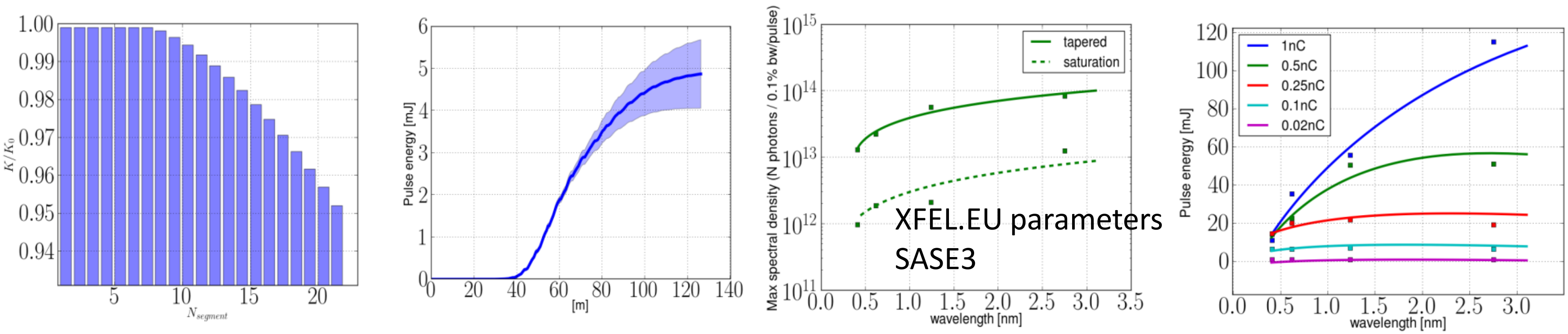
4-corrector tuning, 13nm, FLASH1



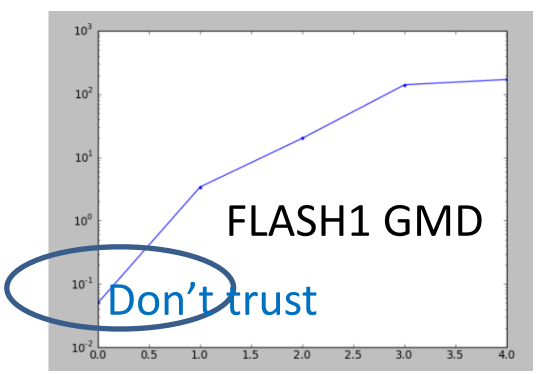
4-corrector + und. steerer + matching quad + FODO quad tuning, 17nm, FLASH1

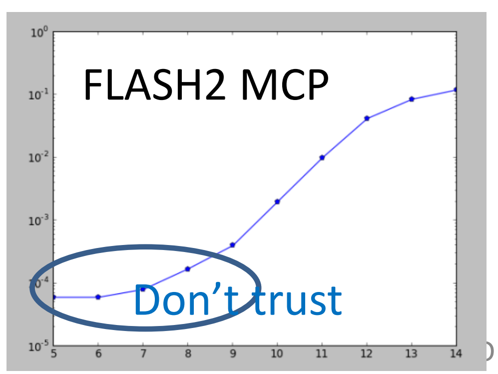
Tapering

- At XFEL.EU one could increase the peak power and spectral density up to 10 times for both hard and soft x-rays by reducing the K starting around saturation point (tapering)

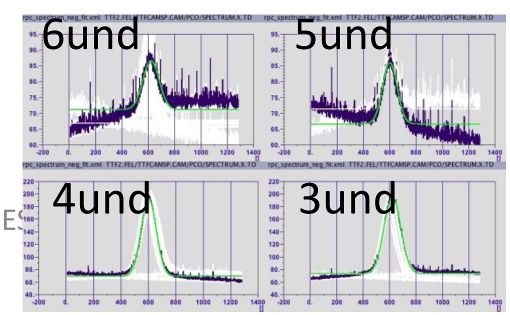


- Undulator gap opening takes time, need to be efficient in tuning
- Possible procedure in operation: determine saturation and scan a parametric knob
- Gain curve and saturation length measurement procedure done at FLASH





- Contrary to expectations, spectral width diagnostics at FLASH1 is a poor indication of saturation



Tapering optimization procedure

Procedure 1

- Close undulator n
- Close undulator n+1
- Fine-tune K(n+1) and phase shifter between two undulators for max power
- etc.
- From simulations, this does not lead to optimal tapering

Procedure 2

- Determine saturation length
- Apply tapering knob (quadratic or exponential)
- While applying tapering knob, keep orbit constant
- If necessary, fine-tune phase shifters (need almost perfect phase shifter vs. K settings)

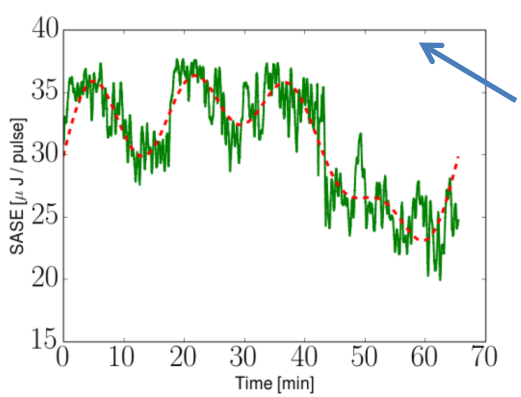
$$K(n) = K_{0i} + a_{0i}(n - n_i) + a_{1i}(n - n_i)^2, \quad n_i \leq n \leq n_{i+1}$$

$$K(n) = K_0, \quad n < n_0$$
$$K(n) = K_1 + a_0(n - n_0)^{a1}, \quad n \geq n_0$$

Issues at FLASH

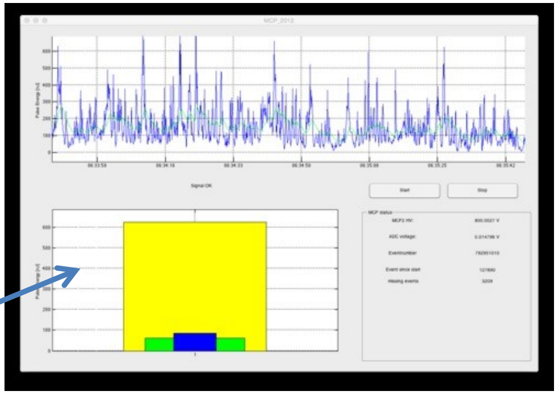
Following improvements are desirable:

- Diagnostic is important (e.g. at FLASH: BPM alignment wrt. undulator magnetic center probably worse than 1mm; xuv spectrometer often off-line; e-beam length measurement calibration unknown (to me); photon pulse energy measurement ok but some detector calibrations unknown; non-destructive e-beam size diagnostics would be great)
- Starting with well-matched orbit and optics makes convergence fast: Matching optics, closing dispersion etc. as the first step is essential
- Optics matching in linac turns out to be important (especially in BC) to minimize emittance degradation (see e.g. *Di Mitri and Cornacchia, NIM A 735 (2014) 60-65*)
- Machine stability has to be reasonable to start with (especially bad for sflash due to laser).



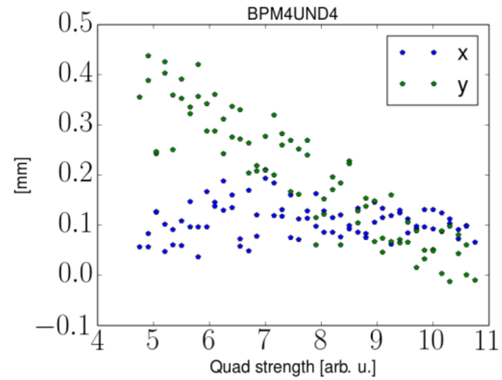
FLASH1 SASE oscillations and drift. Drift on few sec time scale is especially bad for automatic optimizer

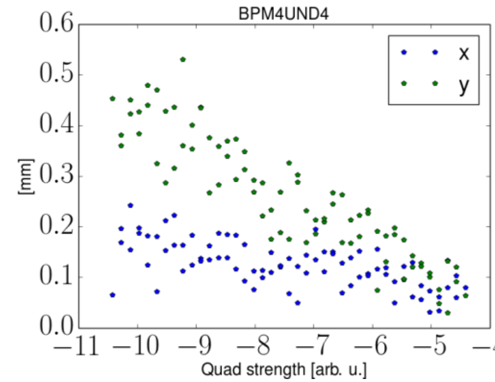
SFLASH signal
Spikes 500 units,
pedestal 100 units



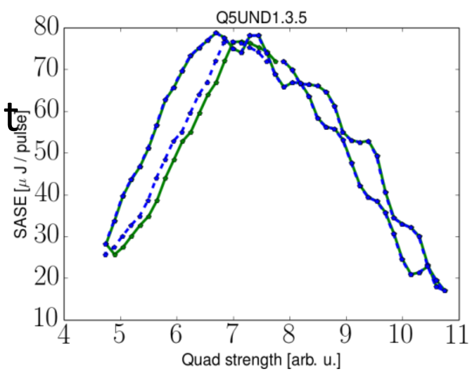
Issues at FLASH (contd.)

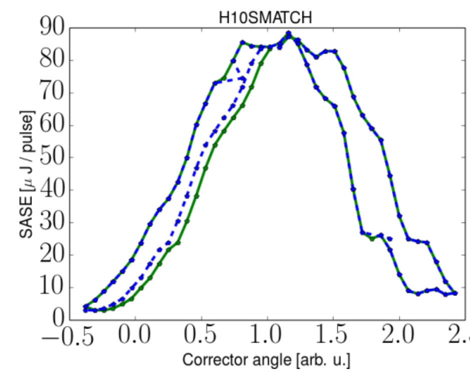
Misalignment is significant





Response functions subject to drift.
When the drift is too large, simplex won't always work, need to resort to scans + smoothing which is slower





Next steps

- End prototyping, software to be deployed at FLASH by end 2015
- A little bit more testing with beam
- Focus on efficiency:
  - XFEL has more components and some approaches may prove slow.
  Flight simulator is used to study tuning strategies.
  - Tuning strategies can be subject to evolutionary methods (simple example: randomly try different sequences such as {rf, orbit, fodo}, {rf, orbit, rf, fodo}, etc.) and eliminate those with poor performance
  - More advanced statistical and machine learning methods are under study.
  For example, Bayesian methods to deal with ill-posedness of finding the best correction or a source of error with limited diagnostics. Feasibility tbc.