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Automatic FEL Optimization at FERMI

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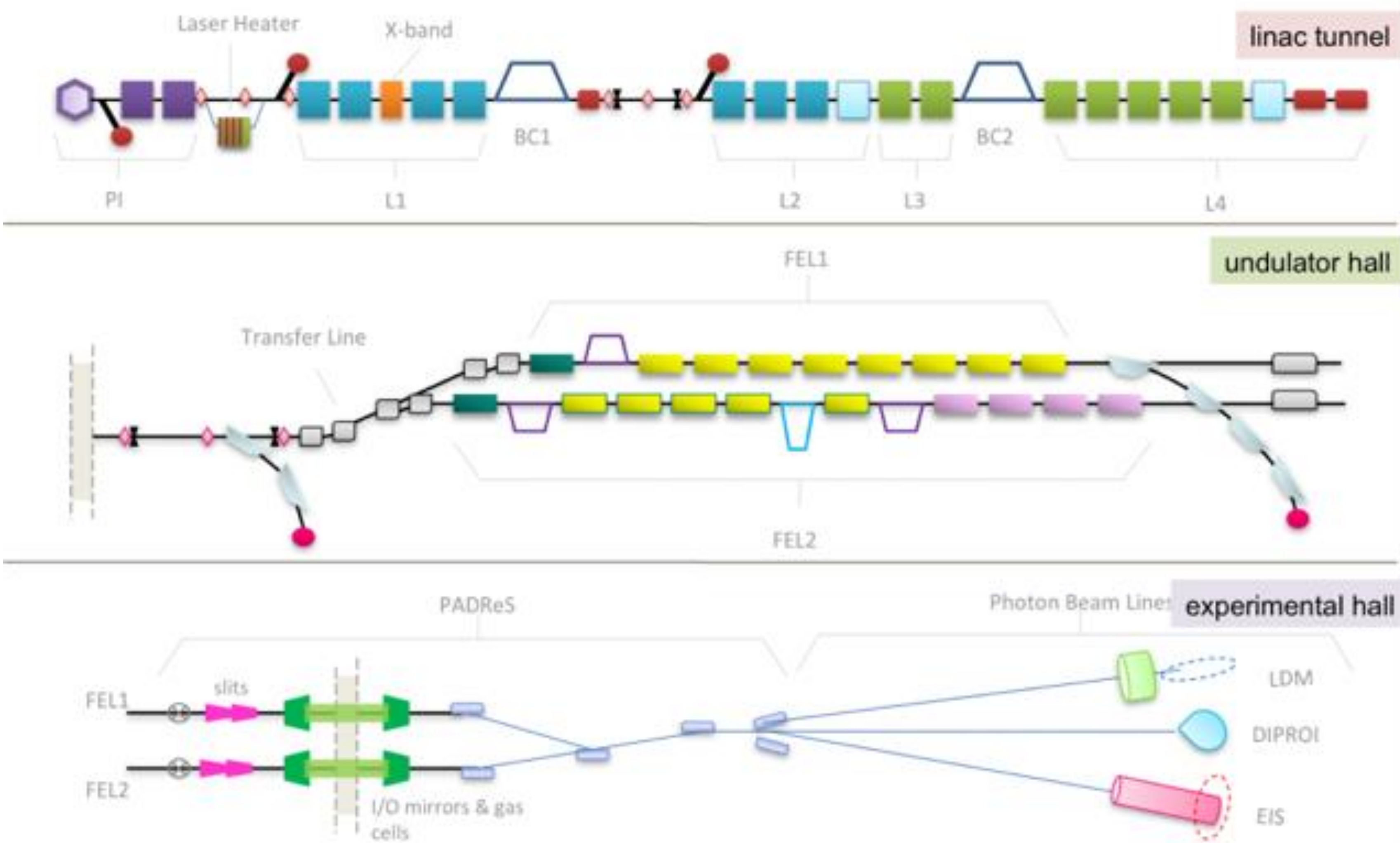
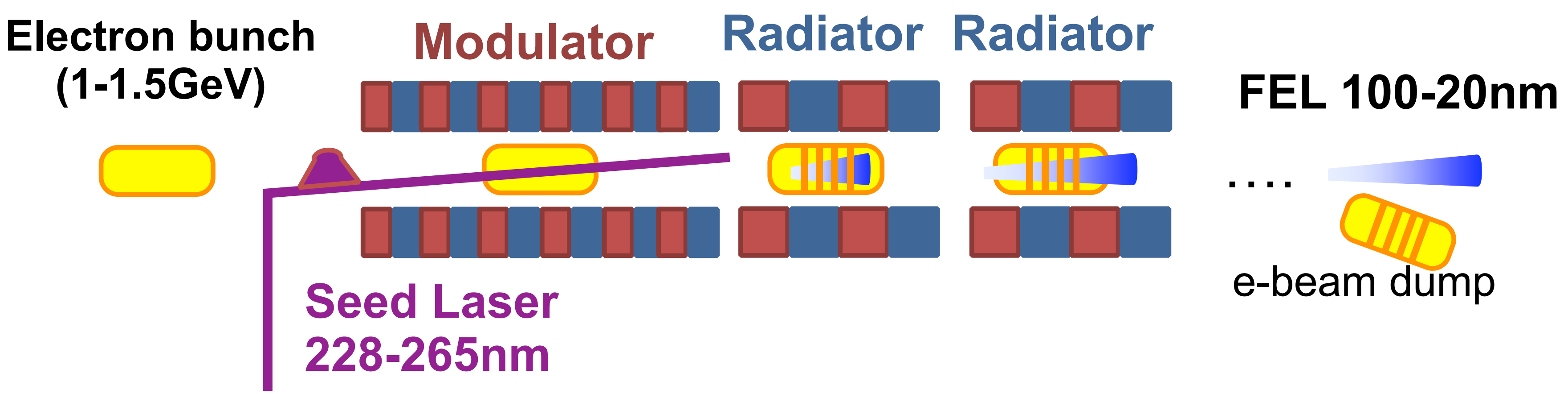
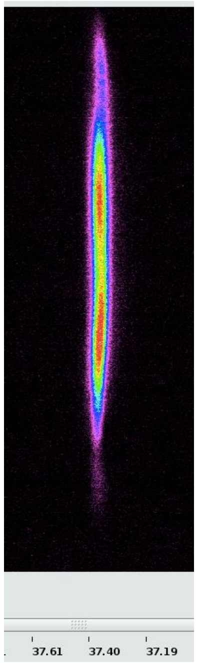
Machine layout (seeded Free Electron Laser)



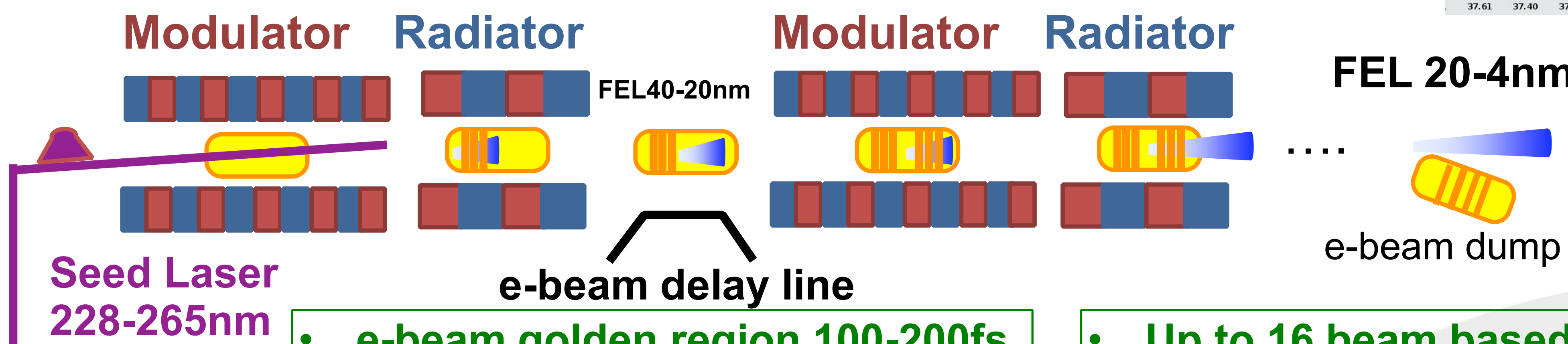
FEL-1 FEL-2 basic schemas

FEL-1





FEL-2



- e-beam golden region 100-200fs
- seed laser pulse 100 fs
- orbit stability within 10um rms

- Up to 16 beam based feedbacks running at the same time

Short / long term drifts

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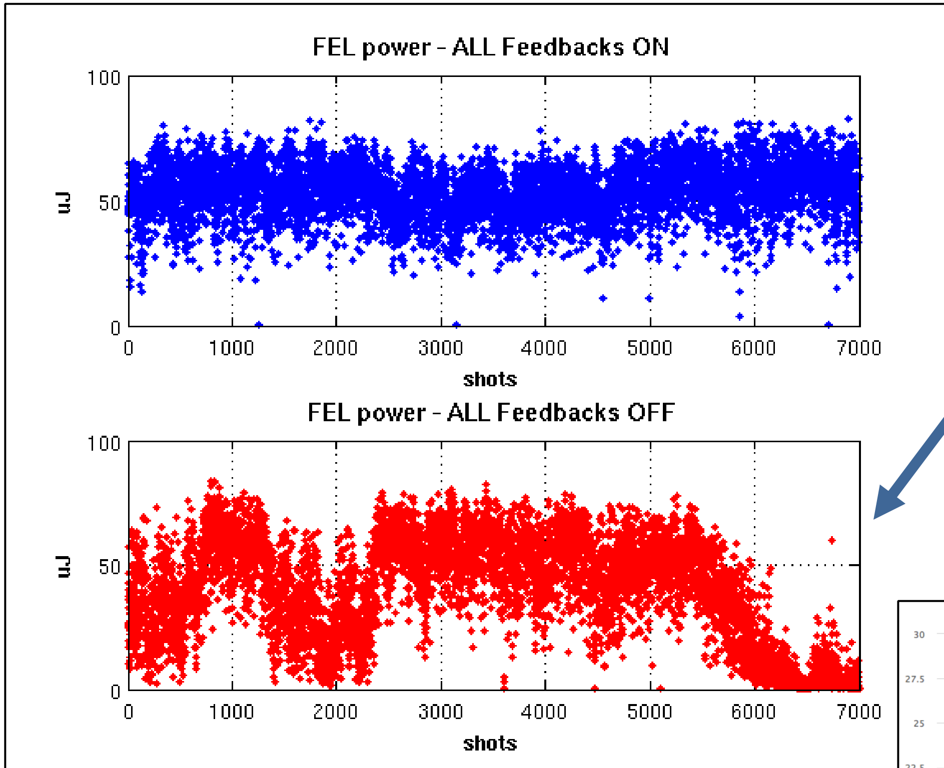


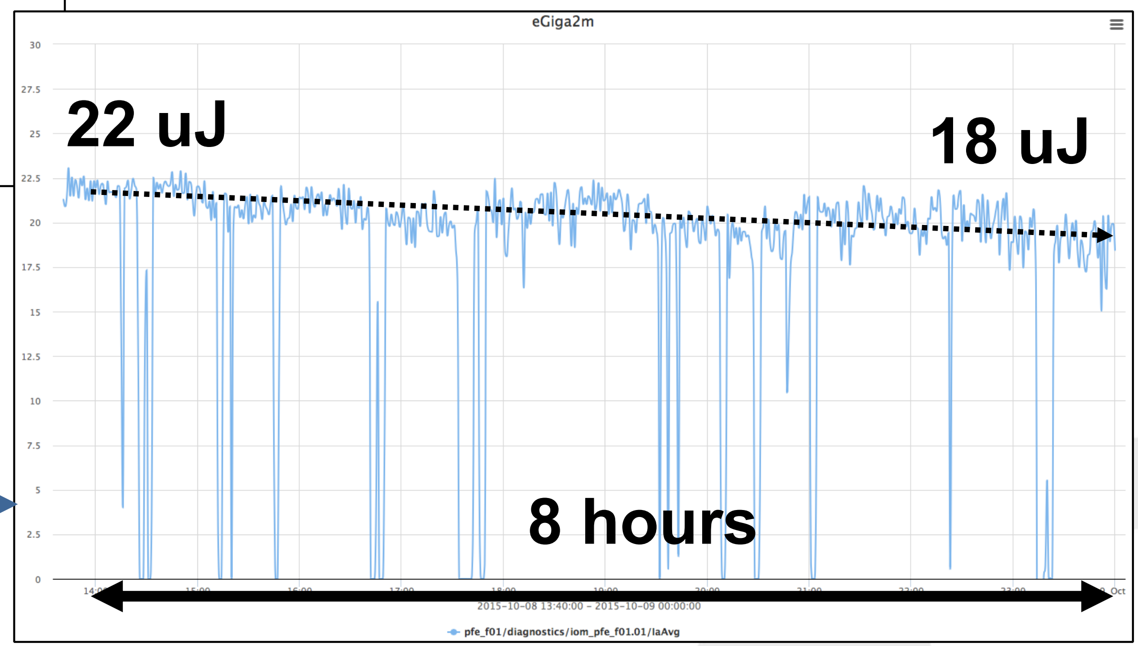
10min

Short term drift

- **Without beam based feedbacks the FEL power drops to 0 in a few minutes**

Long term drift

- **All feedbacks ON**
- **Lost 20% of FEL power in 8 hours**



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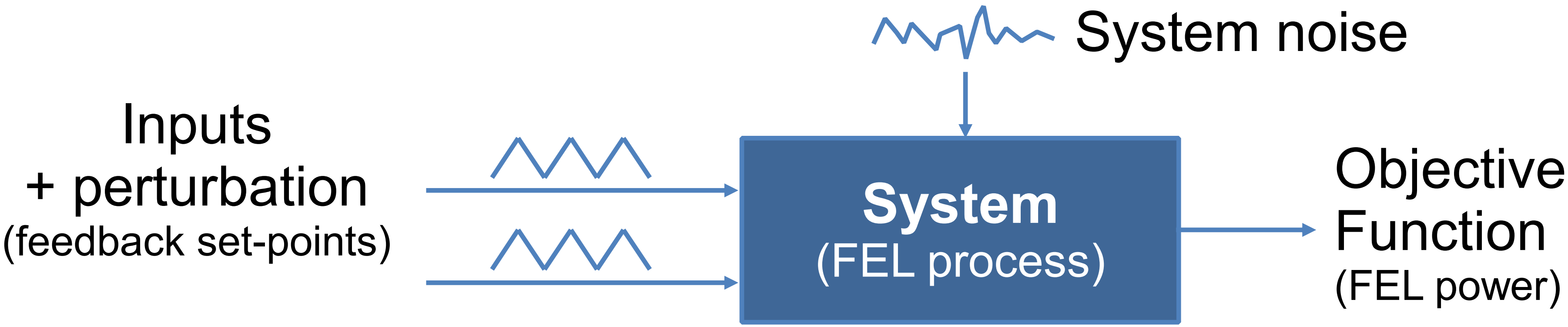
Short / long term drifts

FEL performance decay causes:

- **systematic causes**: FEL wavelength change (scans)
  - Improve machine physics models
  - Add feedforward / feedback systems
- **unpredictable causes**: thermal drifts (0.01° C), faults, mishandling, degradation of components….
  - Improve thermal stability
  - Improve diagnostics
  - ………

Stochastic optimization



Pros

- simple
- model-less

Cons

- doesn't assure global optimum
- convergence scales badly with the number of inputs
- no stop rule
- may perturb the system

Possible algorithms:

- stochastic approximation
- simultaneous perturbation
- random search
- simulated annealing
- evolutionary algorithms (genetic)
- …….

Optimization of electron and laser beam trajectories

Algorithm description

- Collect **N trajectories** and the corresponding ***objective function*** that has to be maximized (ex: FEL output power…)
- Sort the trajectories according to the objective function value in descending order
- Calculate a "**golden**" trajectory by averaging the first M trajectories (M usually 10% of N)
- Calculate the "**mean**" trajectory by averaging the remaining N-M-P trajectories where P is the number of the **worst** trajectories (P usually 10% of N)
- Sum the difference between the golden and the mean trajectory to the trajectory feedback set-point
- Go back to the first step

$x^{(1,1)}$……….$X^{(1,n)}$ $F_{1(\mathbf{MAX})}$	**Golden Trajectory**
$x^{(2,1)}$……….$X^{(2,n)}$ F_2	
…………………………………….	
$x^{(M,1)}$……….$X^{(M,n)}$ F_M	
$x^{(M+1,1)}$…….$X^{(M+1,n)}$ F_{M+1}	**Mean Trajectory**
$x^{(M+2,1)}$…….$X^{(M+2,n)}$ F_{M+2}	
…………………………………….	
…………………………………….	
…………………………………….	
…………………………………….	
$x^{(N-P,1)}$……..$X^{(N-P,n)}$ F_{N-P}	
$x^{(N-P+1,1)}$…..$X^{(N-P+1,n)}$ F_{N-P+1}	**Worst Trajectories**
…………………………………….	
$x^{(N,1)}$……..$X^{(N,n)}$ $F_{N(\mathbf{MIN})}$	

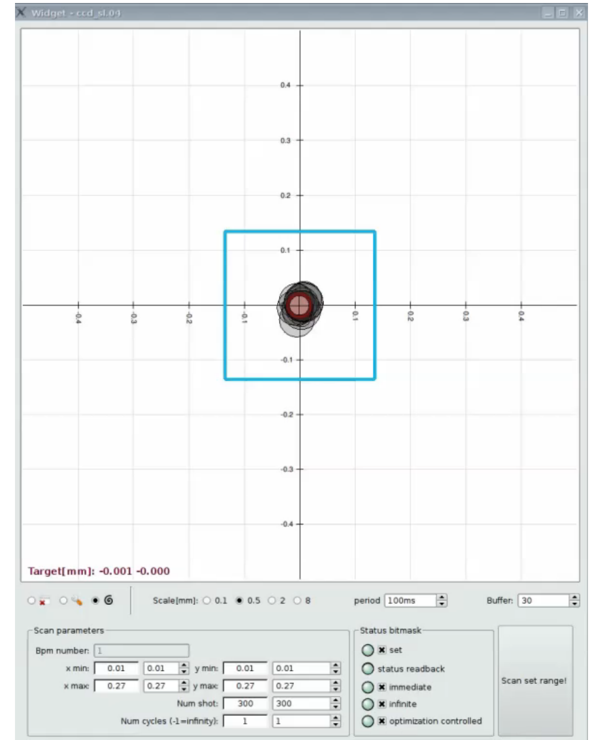
Optimization tool: operating modes

Active mode: trajectory feedback performs on each beam position monitor a 2D spiral scan, desynchronized from the others.

- **PROS:**
  - increments correlation between feedback setpoints and objective function (ex. *FEL intensity*)
- **CONS:**
  - perturbs the FEL output

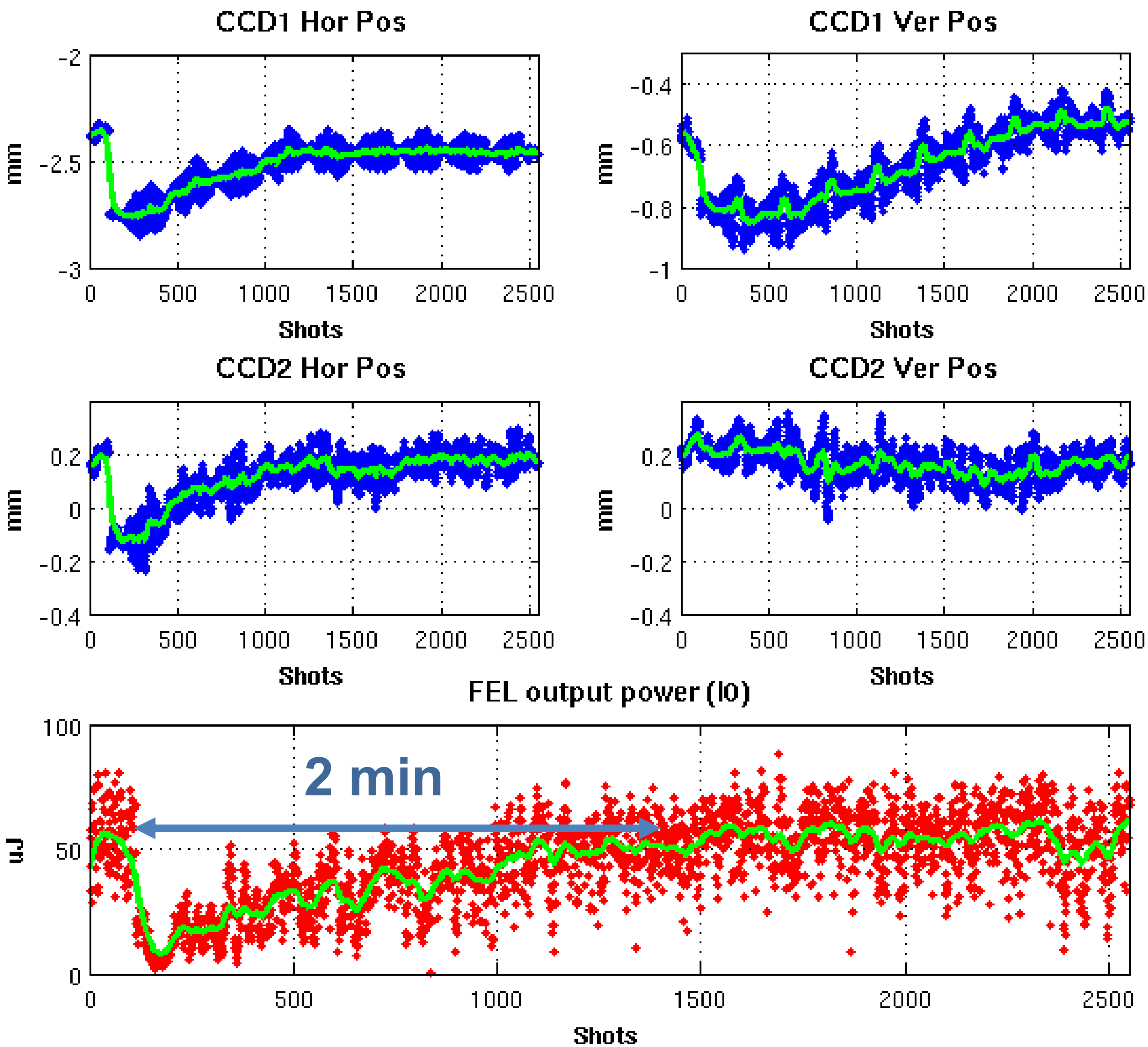
Passive mode: take advantage of the beam noise to "explore" the system inputs

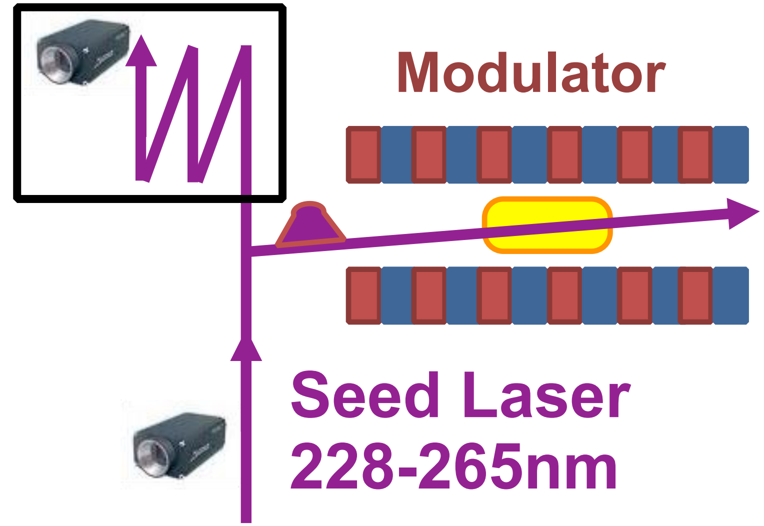
- **PROS:**
  - doesn't perturb the FEL output during optimization procedure
- **CONS:**
  - noise level could be insufficient to get a good correlation with FEL intensity signal



Continuous/Timed mode: run optimization continuously or over a fixed period of time. In **Timed mode:** the spiral decreases its amplitude in time *(simulated annealing)*.

Optimization tool: seed laser alignment (2 CCDs, 4 variables)





Moved three out of four feedback set-points which keeps the seed laser transversally aligned with electron bunch

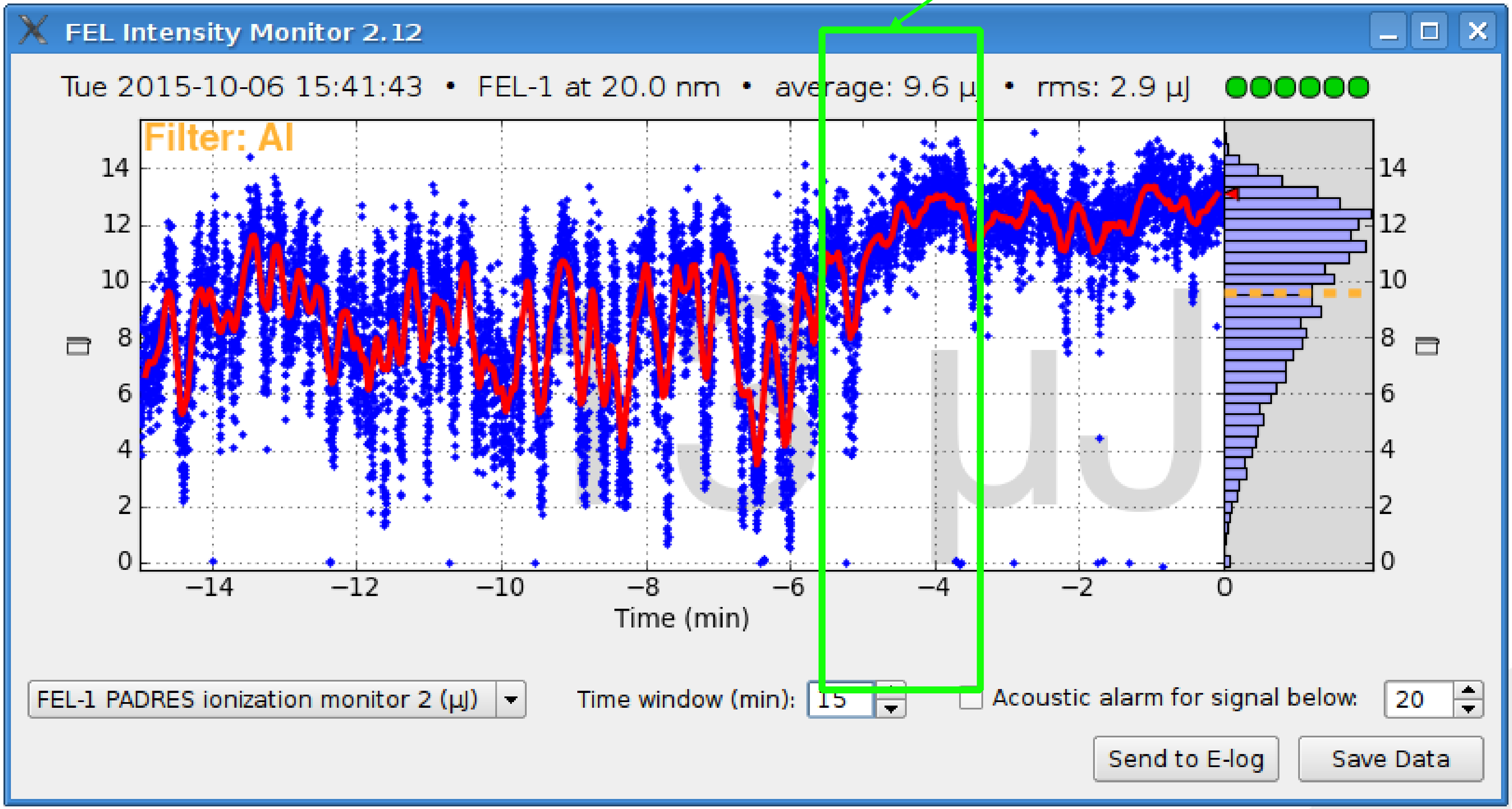
- **Drop** of FEL intensity from **50** to almost **0** μJ
- Automatic optimization **restores** the original beam positions on the CCDs and the FEL output power

Optimization tool: seed laser alignment (real case)

Optimization of the seed laser trajectory

- **Objective function:** FEL intensity measured by a gas monitor
- **Active mode**

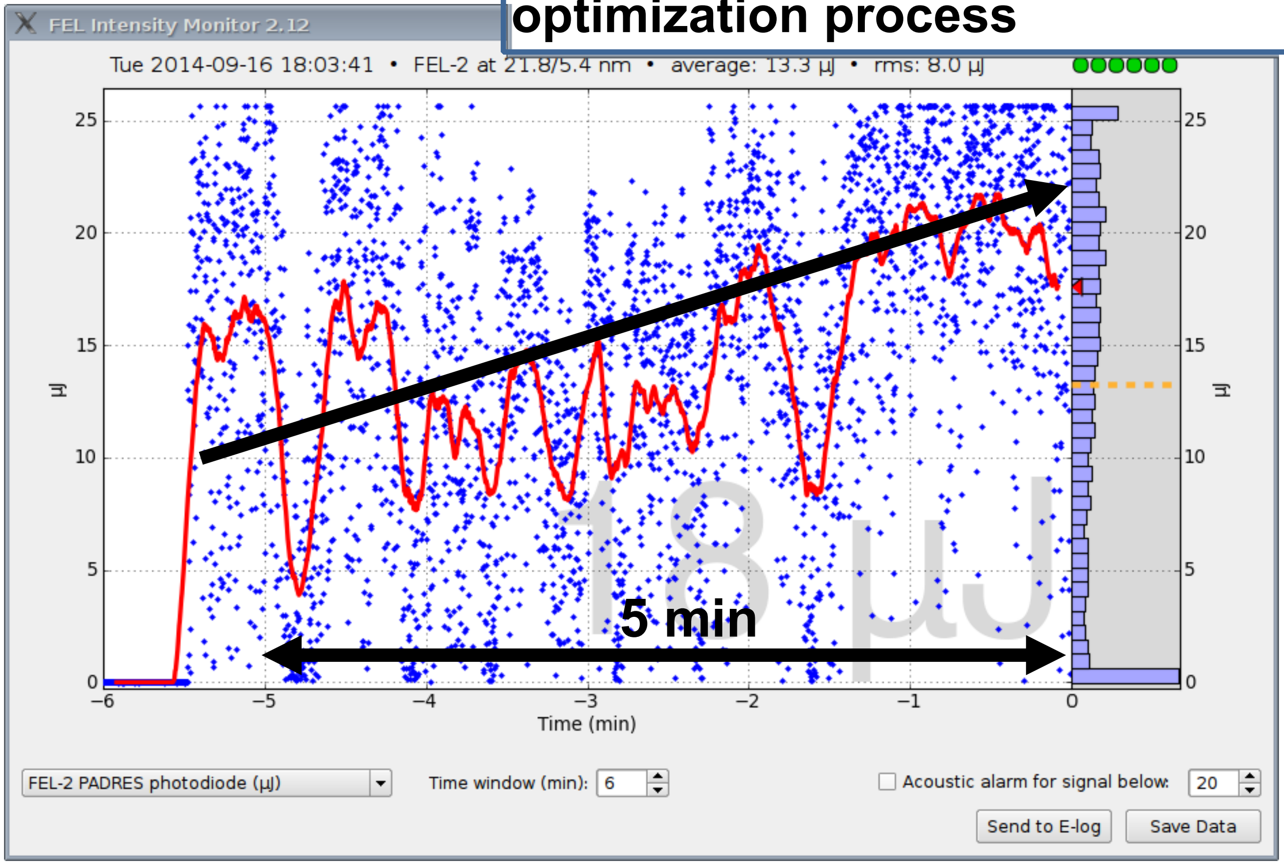
Optimization loop running



Optimization tool: FEL-2 alignment (15 beam position monitors, 30 variables)

Photodiode

Increase of the FEL intensity during the optimization process



Optimization of the intra-undulator trajectory

- **Objective function:** FEL-2 intensity measured by a photodiode and a CCD
- **Passive mode**
- FEL signal from **20 µJ** to **30 µJ** (5.4 nm)

Optimization triggering / Feedback monitoring

feedback_correlator

*** TARGET ***
Correlations with
srv-padres-srf:20000/pfe_f01/diagnostics/iom_pfe_f01.01: GetI

*** FEEDBACKS SENSORS ***
sl/diagnostics/ccd_sl.07: GetVerPos 0.297486
sl/diagnostics/ccd_sl.05: GetVerPos 0.223745
bc01/diagnostics/cblm_pyro_bc01.01: GetBunchLength 0.189015
sl/diagnostics/ccd_sl.04: GetHorPos 0.177866
l03/diagnostics/rtbpm_l03.01: GetHorPos 0.167193
l02/diagnostics/rtbpm_l02.04: GetHorPos 0.161606
l02/diagnostics/rtbpm_l02.03: GetHorPos 0.158425
sfel01/diagnostics/cbpm_sfel01.01: GetHorPos 0.157985
sfel01/diagnostics/rtbpm_sfel01.01: GetHorPos 0.157157
l03/diagnostics/rtbpm_l03.02: GetVerPos 0.144015

*** FEEDBACKS ACTUATORS ***
iufel01/power_supply/pscv_iufel01.04: GetCurrent 0.413885
sl/piezo/tiptilt_sl.02: GetVoltageVer 0.411332
kg05/mod/llrf_kg05.01: Getcav_amp_set 0.367692
kg03/mod/llrf_kg03.01: Getcav_amp_set 0.366240
sfel01/power_supply/pscv_sfel01.04: GetCurrent 0.310594
sfel01/power_supply/pscv_sfel01.06: GetCurrent 0.304641
kg04/mod/llrf_kg04.01: Getcav_phase_set 0.293048
iufel01/power_supply/pscv_iufel01.05: GetCurrent 0.285349
l03/power_supply/pscv_l03.01: GetCurrent 0.282975
sl/piezo/tiptilt_sl.03: GetVoltageHor 0.250698

- **Correlates (Pearson)** continuously shot to shot data of sensors and actuators included in the feedbacks (214 variables) with a objective function (ex. FEL power)
- **Sorts** actuators/sensor in descending order according the correlation value
- **Identifies** which actuators/sensors to use for the optimization

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Conclusions

Achievements

- **Optimization algorithms used routinely during machine operations**
  - **seed laser trajectory**
  - **electron beam trajectory**
- **Found method (by correlation analysis) to identify the correct optimization procedure**

To do list

- **To extend the optimization procedure to other subsystem (temporal alignment between seed laser and electron beam)**
- **Completely automatic optimization (replace human intervention)**
  - **noise detection -> optimization procedure**

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Thank you!