Multi-Objective Genetic Optimization for LCLSII X-ray

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- Summary

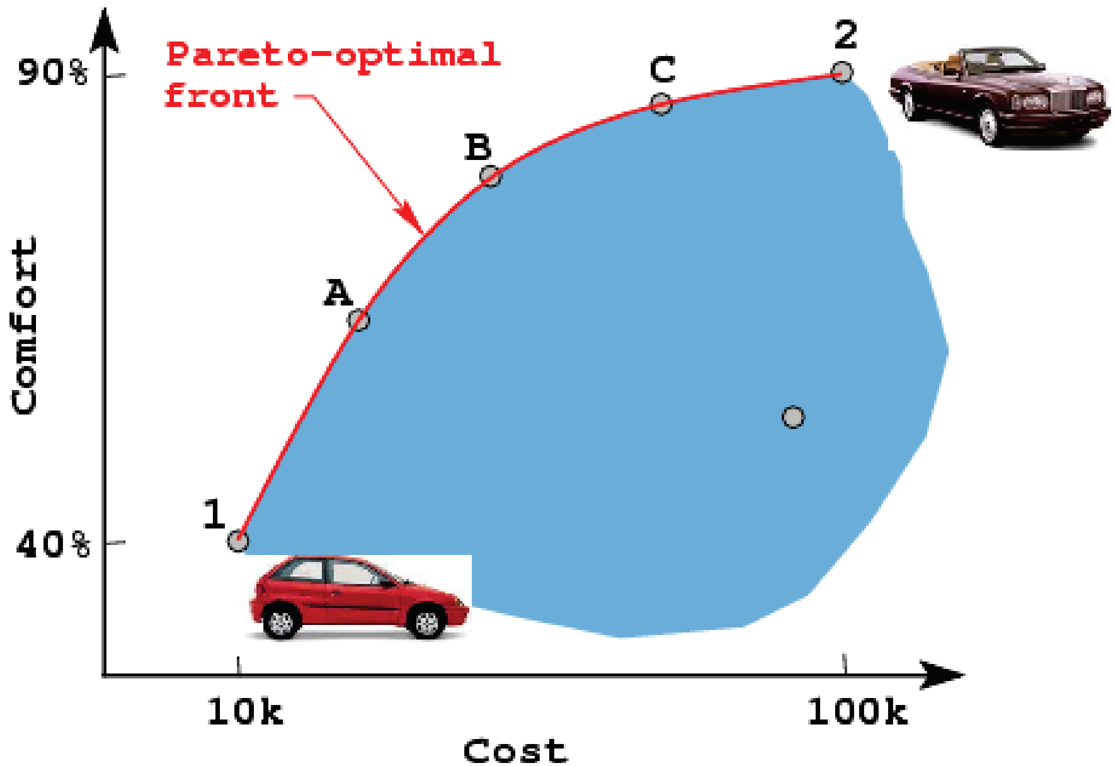
Motivation

- Optimize the beam (different charge) to minimize the energy spread, jitters (Current, energy, timing) and get flat top current profile for the core beam.
- MOGA is useful with complex system to find solutions where local maxima exist
- However, the optimization is not efficient and the computation for each run must be fast, we use LitracK

Introduction to MOGA

Multi-Objective Optimization:
Handling multiple conflicting objectives

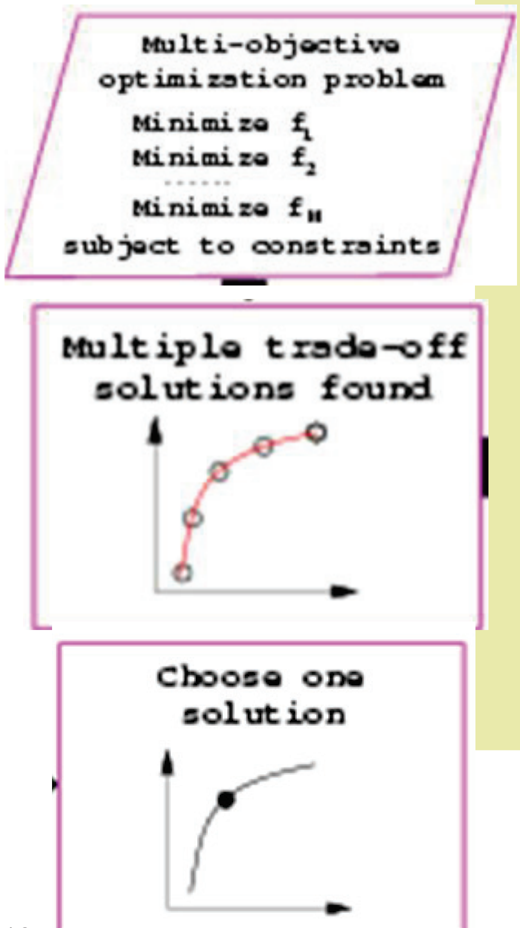
- We often face them



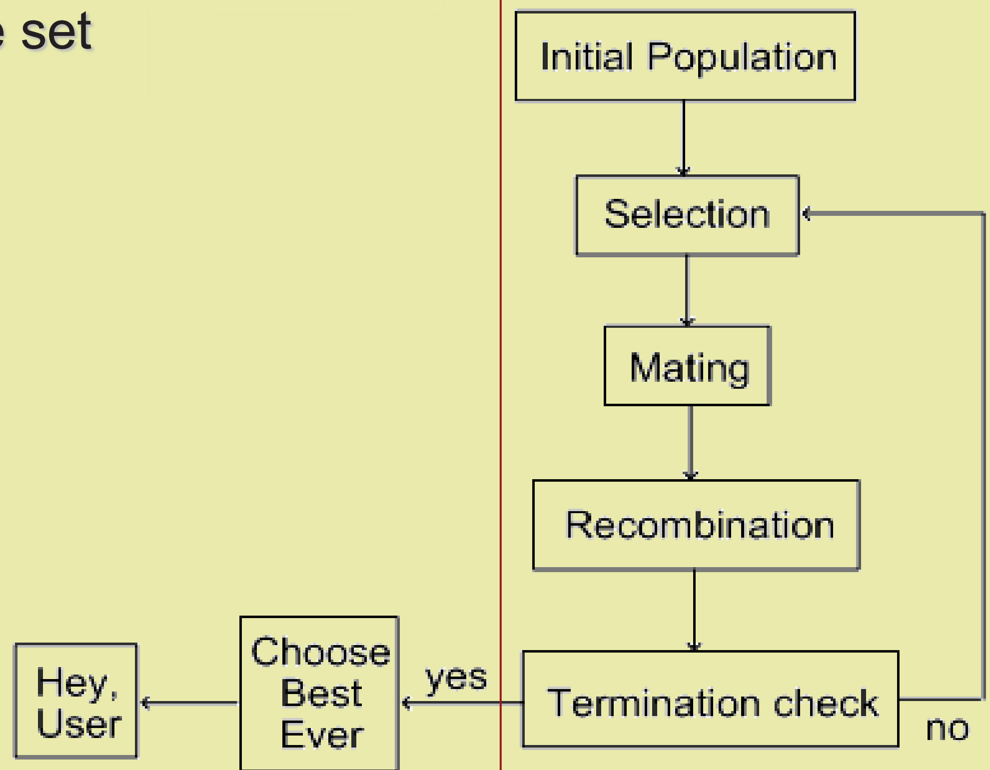
Genetic Algorithm to find the minimum/maximum

Step 1 : Find a set of Pareto-optimal solutions

Step 2 : Choose one from the set



Step 1



Standard procedure of a canonical genetic algorithm

Functional Decomposition

Convergence:

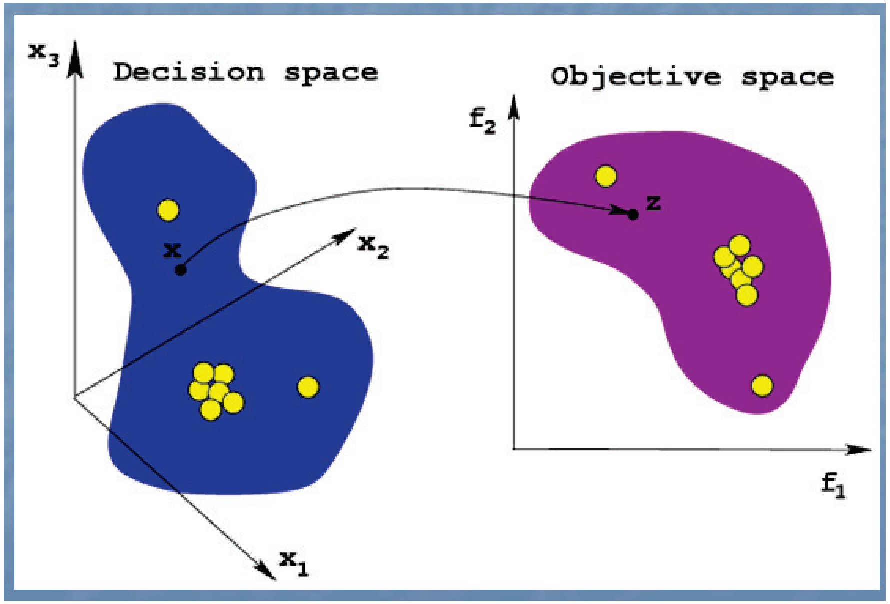
- Emphasize non-dominated solutions → Non-dominated sorting

Diversity:

- Prefer less-crowded solutions

Elite-preservation

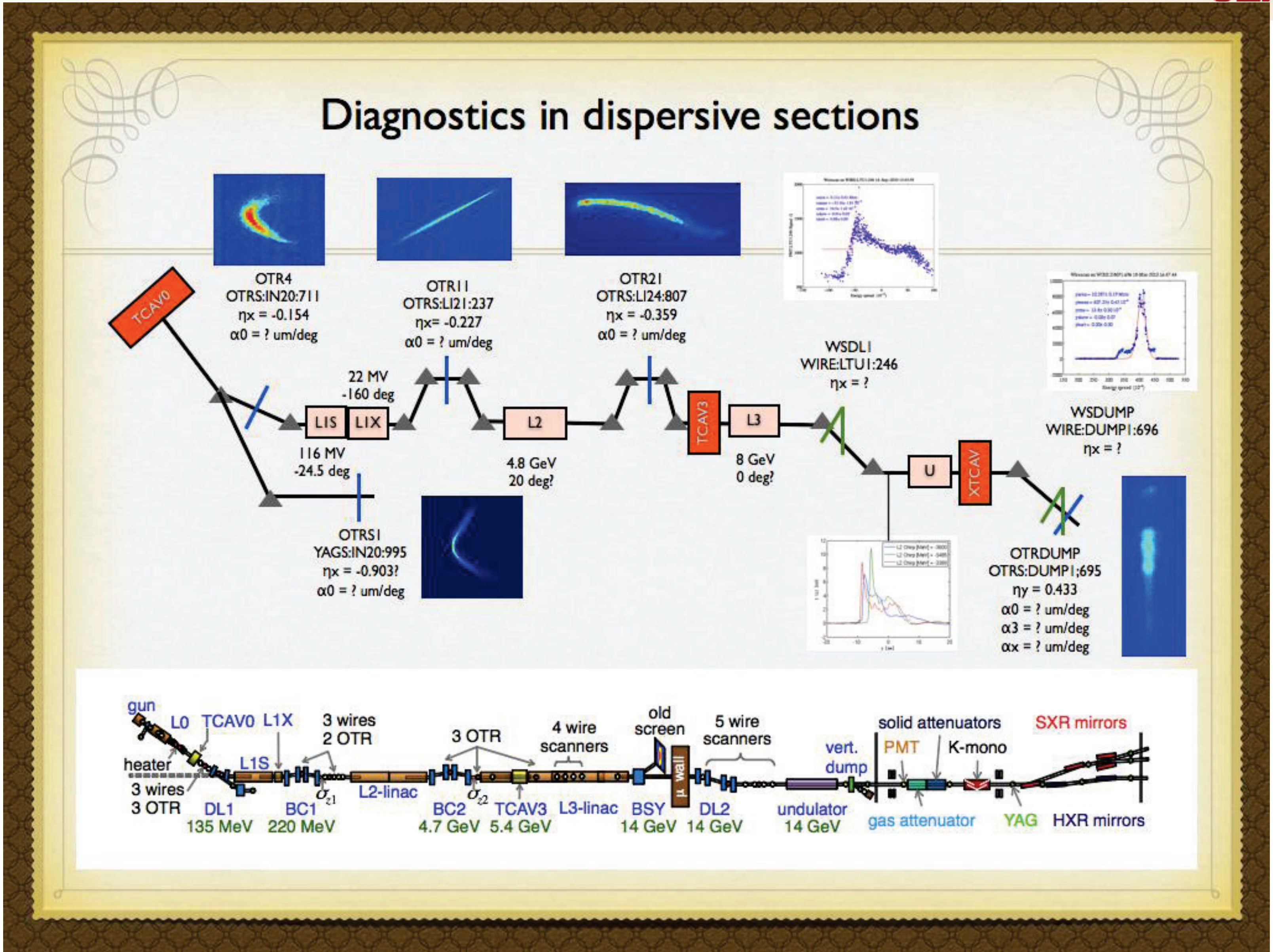
- For ensuring convergence properties



Benchmark with LCLS beam

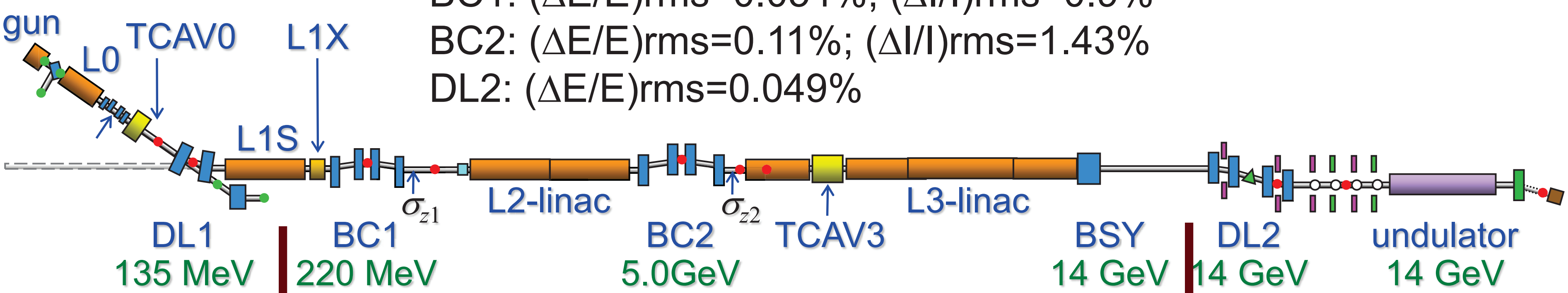
Phase space @150pC

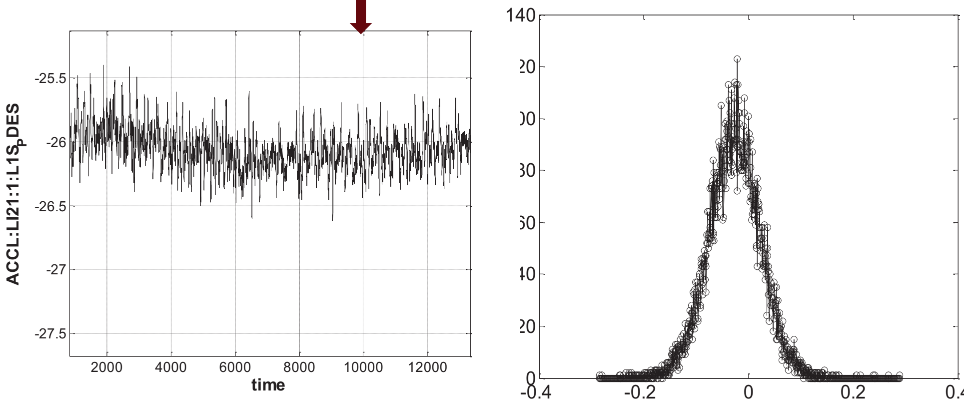
(James Welch)

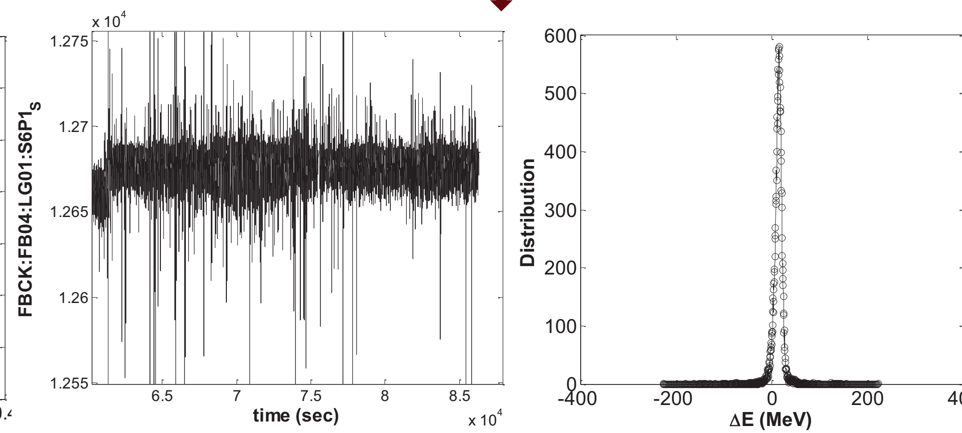


Jitters in LCLS (more at WEPSO10, F.-J. Decker)

BC1: $(\Delta E/E)_{rms}$=0.054%; $(\Delta I/I)_{rms}$=0.9%
BC2: $(\Delta E/E)_{rms}$=0.11%; $(\Delta I/I)_{rms}$=1.43%
DL2: $(\Delta E/E)_{rms}$=0.049%





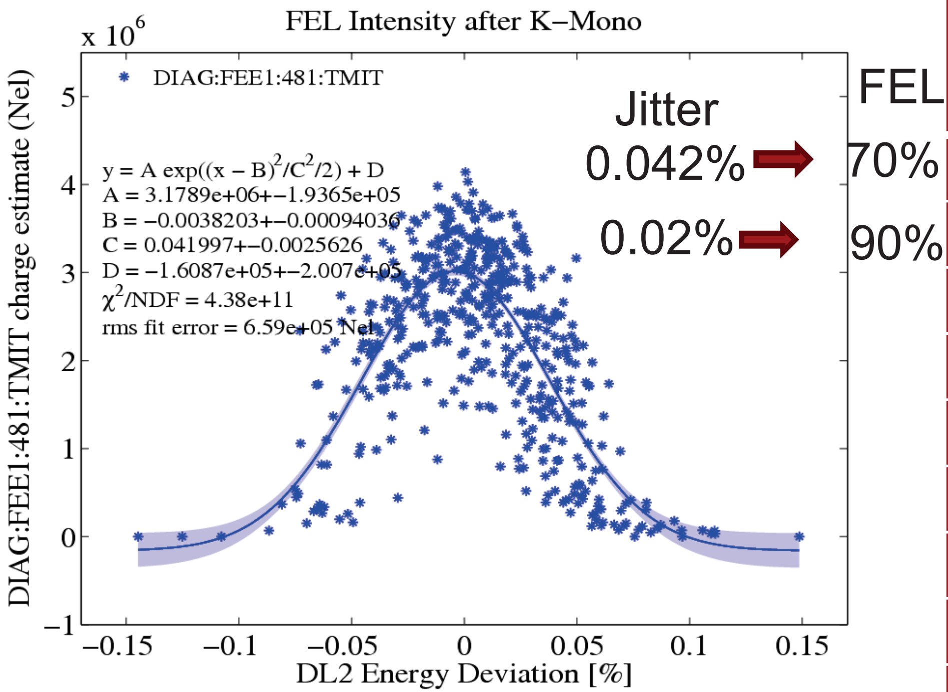


L1S phase,
$(\Delta\phi)_{rms}$=0.048°

DL2 Energy,
$(\Delta E/E)_{rms}$=0.049%

Improvement with MOGA

- The energy jitter is a concern in LCLS for SEEDED FEL
- The energy jitter can be reduced by a factor of 2 with MOGA



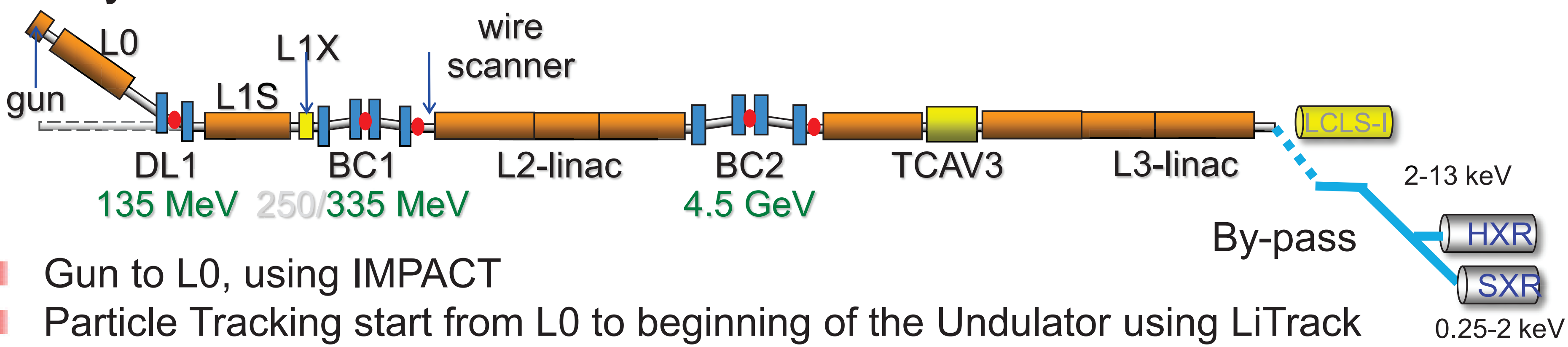
FEL intensity of a seeded beam after the K-monochromator versus DL2 energy. The sigma of the fitted Gaussian is 0.042%

Variables	optimal	~operational
I_{pk} (kA)	3	3
ϕ_{L1} (degree)	-19.3	-26.1
V_{L1}(MV)	111	118
ϕ_{Lx} (degree)	-154	-160
V_{Lx}(MV)	22	22
ϕ_{L2} (degree)	-19	-38.7
V_{L2}(GV)	5.06	6.15
ϕ_{L3} (degree)	-10.3	0
V_{L3}(GV)	8.79	7.667
R_{56}@BC1(mm)	-45.5	-45.5
R_{56}@BC2(mm)	-51.3	-20.6
($\Delta I/I$) (%)	11	7
($\Delta E/E$) (%)	0.014	0.033

MOGA optimization of LCLSII

LCLSII Optimization

- Layout



- Gun to L0, using IMPACT
- Particle Tracking start from L0 to beginning of the Undulator using LiTrack
- Wake field is included

Variables:

- Phase and Voltage of L1,LX,L2,L3; R56@BC1; R56@BC2, …

Objectives

- Energy spread/energy chirp
- Jitters(energy, current, timing) due to RF Voltage, phase, Charge, Laser timing

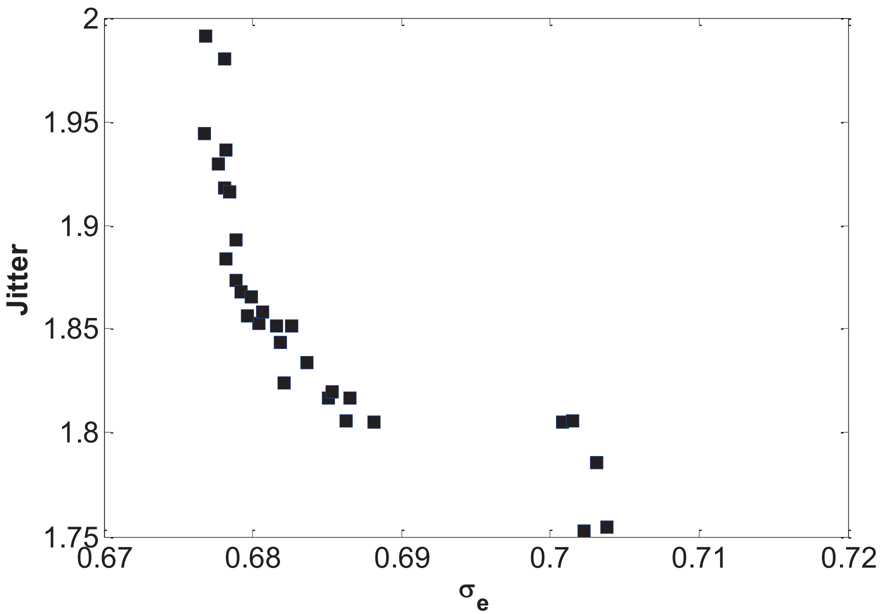
Constrains

- Peak current at the beginning of undulator (3kA/4kA)
- Energy at BC1(335MeV) & Energy at BC2(4.5GeV)
- Energy at the beginning of undulator (13.5GeV/10GeV)
- Nonlinear chirp correction, ….

Example of LCLSII

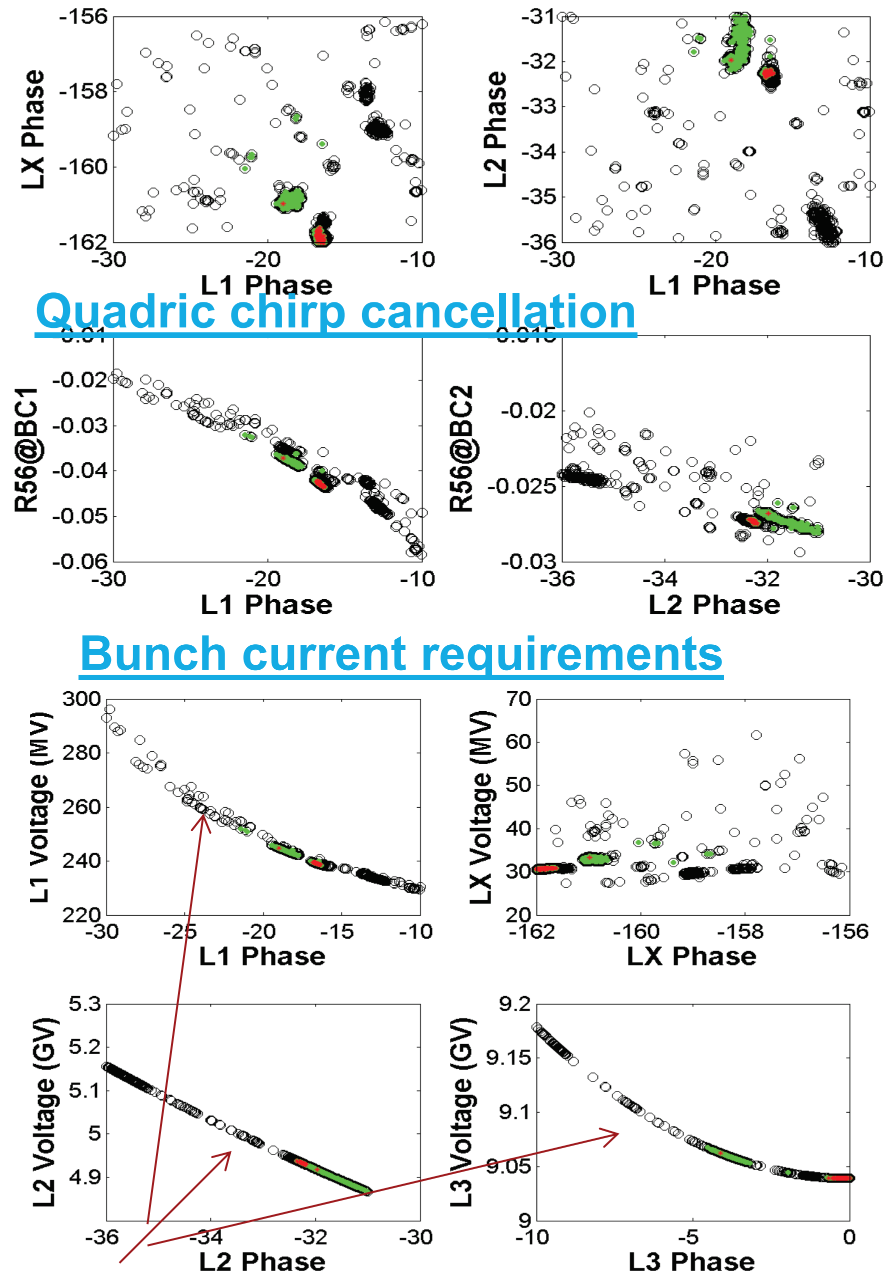
Two Objectives: jitter and energy spread

$$Obj_{senitivity} = \frac{\Delta I / I}{(\Delta I / I)_{rms}^{baseline}} W1 + \frac{\Delta E_i / E}{(\Delta E / E)_{rms}^{baseline}} W2 + \frac{\Delta \tau_i}{(\Delta \tau)_{rms}^{baseline}} W3$$



Final generation solutions

- Small jitter zone
- Small energy spread zone

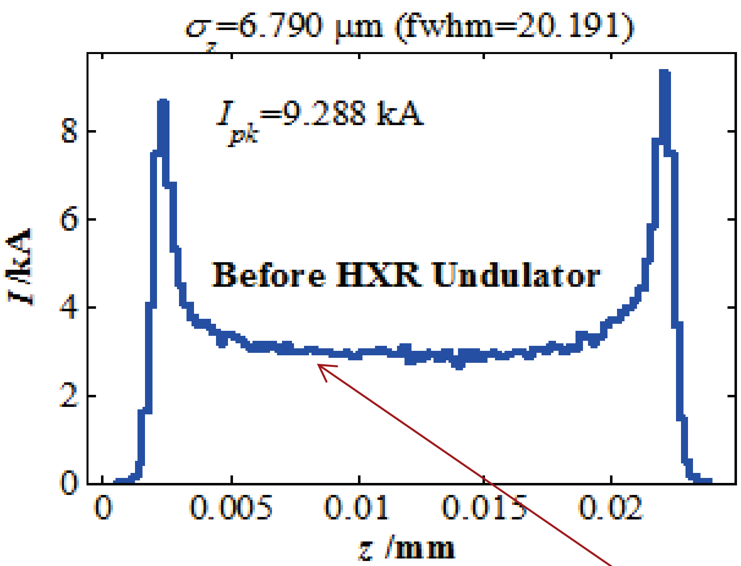


Constrains from energy: ΔE=V cos(φ)

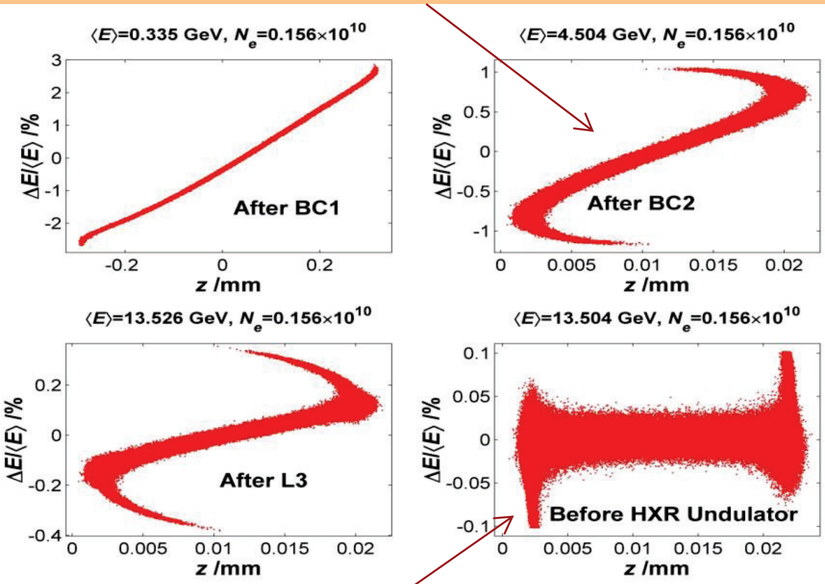
250pC HXR, current and phase space

ϕ_{L1}	ϕ_{Lx}	ϕ_{L2}	R56@BC1	R56@BC2
25.6	164.6	37.5	-29.8mm	-21.5mm

A proper energy chirp is required after BC2 in order to conceal the wake field effect



Flat top

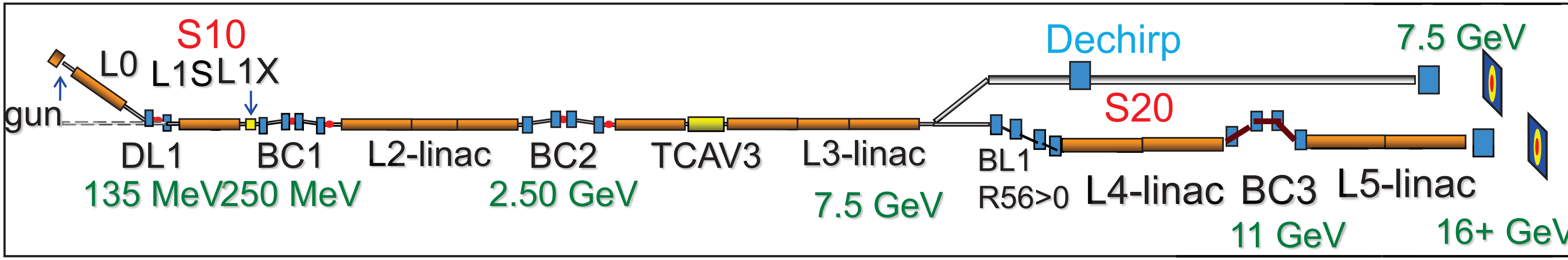


Zero chirp

LCLSII+
Two beam energy machine with 360Hz repetition rate

LCLSII+, 360HZ, TWO BEAM ENERGIES

- Layout

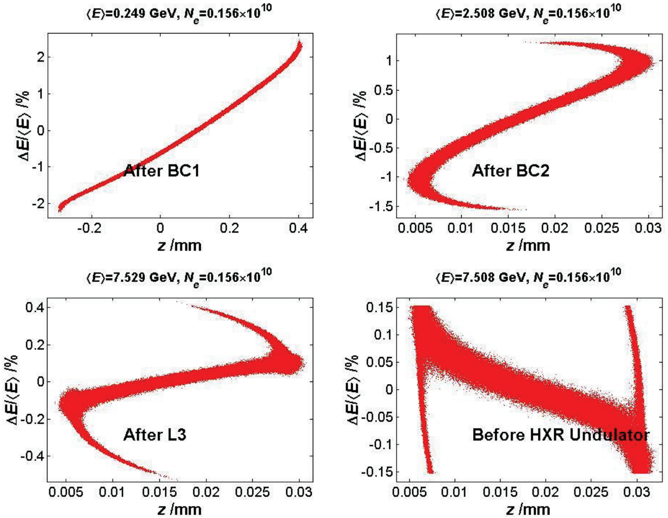


LCLSII **LCLSI**

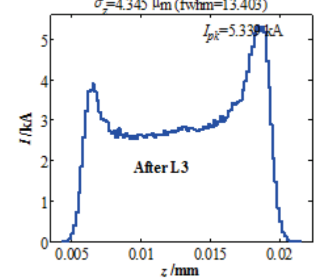
- The repetition rate increases from 120Hz to 360Hz (reducing accelerating gradient)
- LCLSI and II work together to provide two beam energy simultaneously
- De-chirper for low energy beam as an option (if necessary)
- Replace the LCLSI BC1 as a bunch lengthener(BL) (R56>0) to increase the energy chirp;

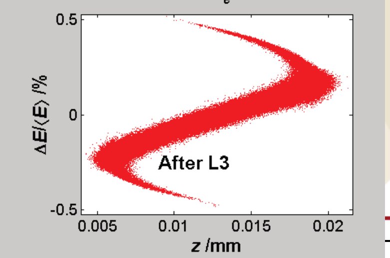
Difference compared with LCLS/LCLSII

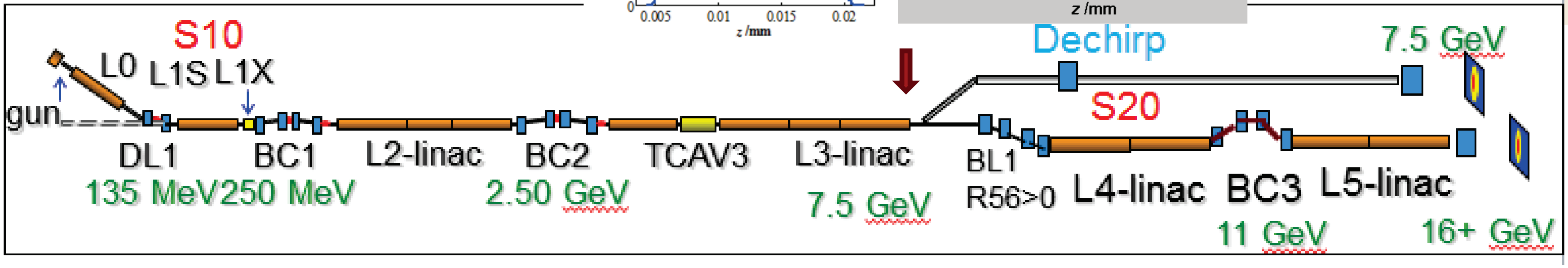
- The **accelerating gradient** is **lower** for 360Hz than the 120Hz case → Small energy chirp provided by the RF
  - High energy beam see **Longer** (double) **RF structure** → Stronger wake effect (de-chirp effect)



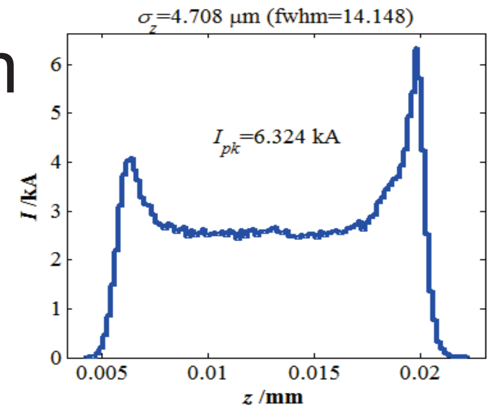
150pC (LCLSII+)

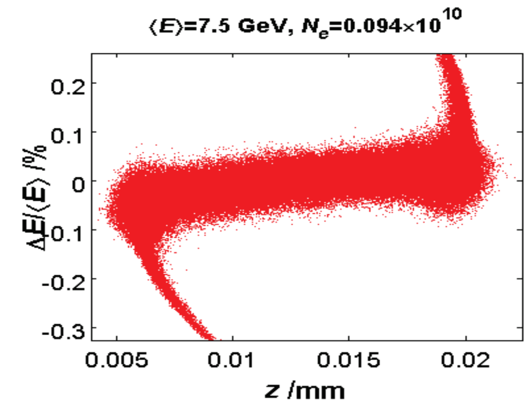






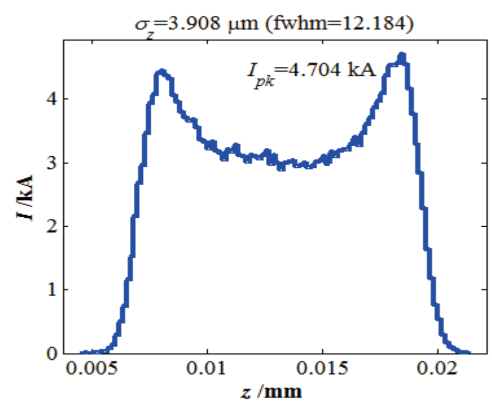
Low energy beam

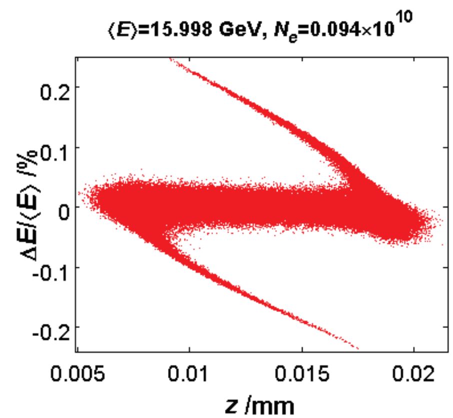




- R56@BL=+3.5mm
- R56@BC3=-7.5mm

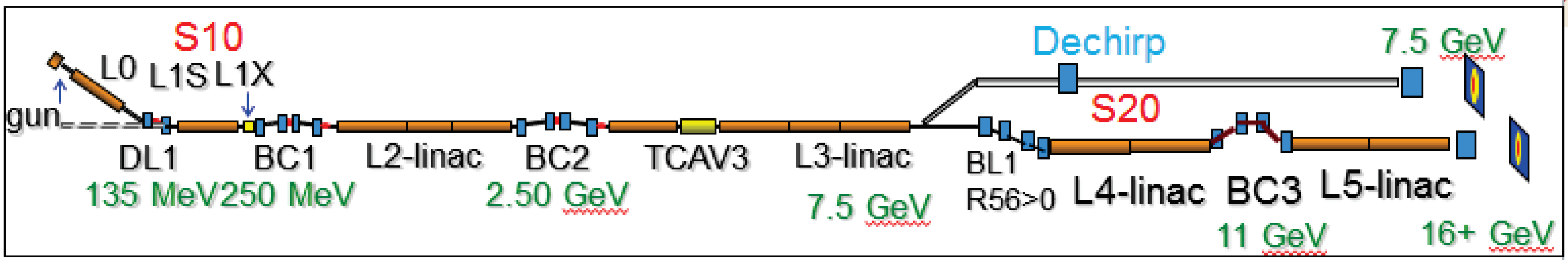
High energy beam



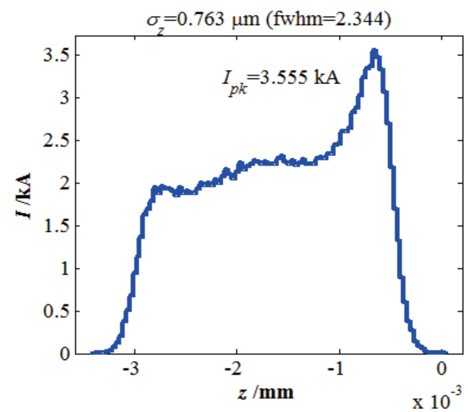


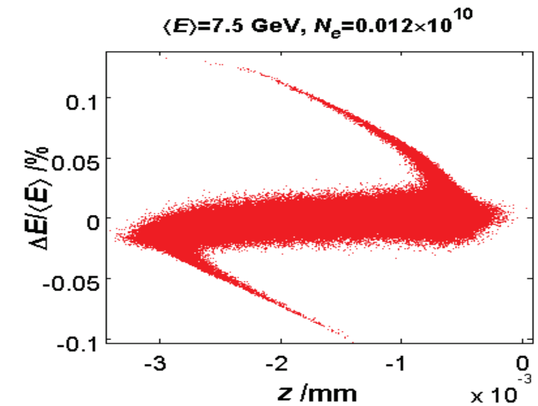
- The bunch lengthening section provides adjustable chirp and reduces the collective effect

20pC (LCLSII+)

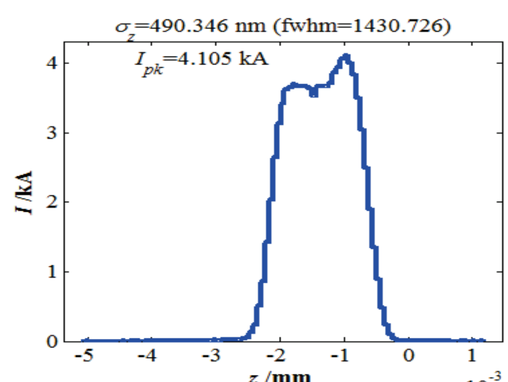


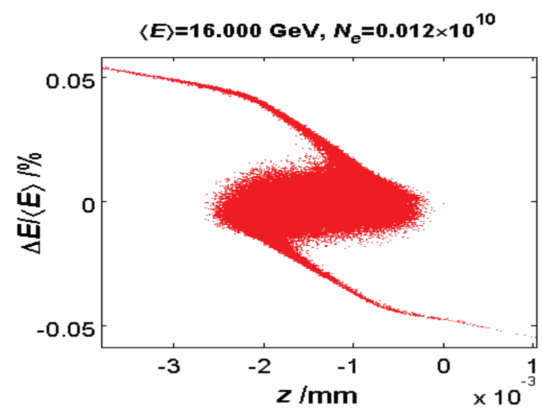
Low energy beam





High energy beam





- R56@BL=+2.5mm
- R56@BC3=-6mm

Summary

- MOGA optimization provides a very useful tool to find good configurations (RF phase and Voltage, BCs) with minimized jitters and energy spread (energy chirp).

- Deferent operating modes are optimized for LCLS, LCLSII and LCLSII+.
  - The energy jitter can be reduced by a factor 2 for LCLS
  - LCLSII+ with two beam energies and 360Hz repetition rate is very attractive to provide large flexibilities:
    - bunch charge (20-250pC), energy (7~16+ GeV),
    - peak current (>3kA) and energy chirp (zero or slightly positive).

Future work

SLAC

S2E simulation ---Integrated optimization, challenge in computation

- Injector: Impact
- Linac: Elegant (Litrack) → Further optimize *injector*; *Emittance*, and FEL
- Undulator (FEL): Genesis

Computer: NERSC

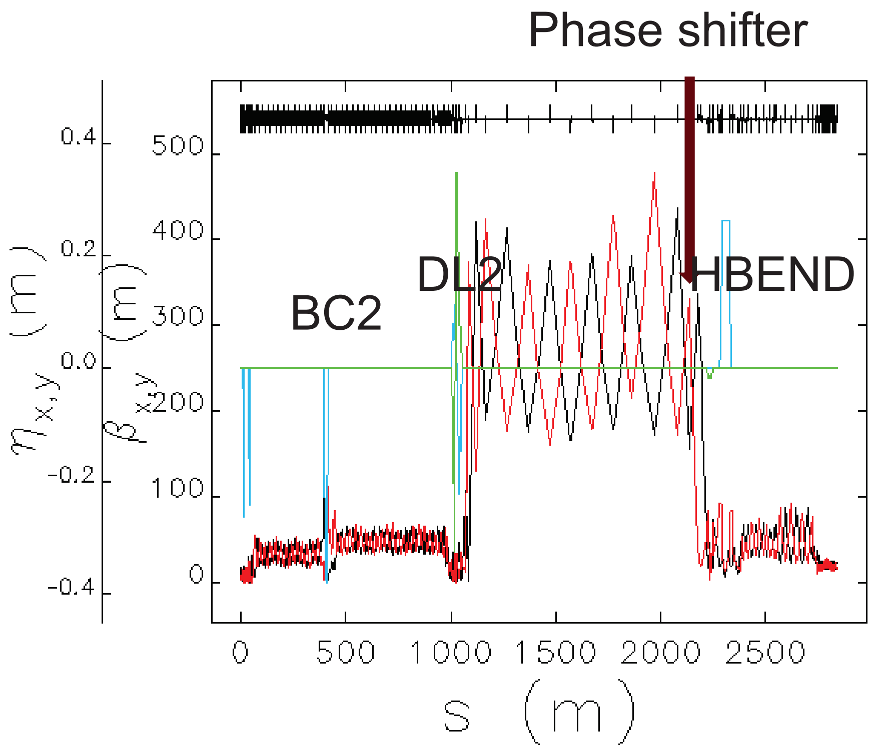
Acknowledgments:

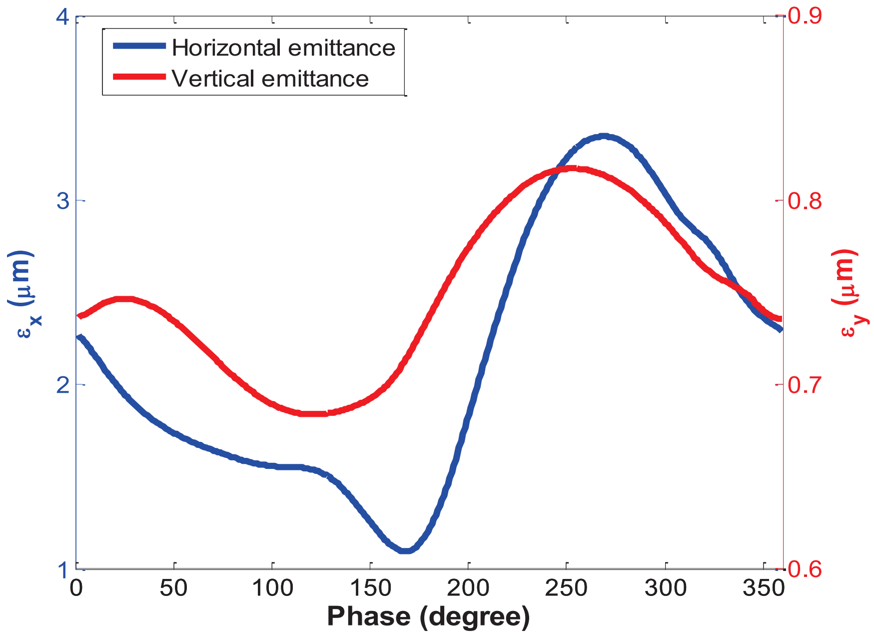
F. Zhou, M. Woodley, Y. Nosochkov, J. Wu, Y. Ding, Z. Huang, F.J. Decker, A. Krasnykh, J. Welch, J. Turner, T. Maxwell and LCLS Operation team

Thank You

Cancellation of emittance growth by CSR in LCLSII

- A phase advance shifter is place before the HBEND.
- We scan the phase shift, there is a maximum horizontal emittance of 3.4 μm and a minimum one of 1.09 μm at 167.5°.
- Further minimization can be done by optimizing the betatron function at BC2





Cancellation of the transverse emittance growth due to CSR

- D. Douglas, Thomas Jefferson National Accelerator Facility Report No. JLAB-TN-98-012, 1998. (theory)
- Rui Li and ya. S. Derbenev, JLAB-TN-02-054 (theory)
- S. Di Mitri, M. Cornacchia and S. Spampinati, PRL 109, 244801 (2013). (experiment)
- ....

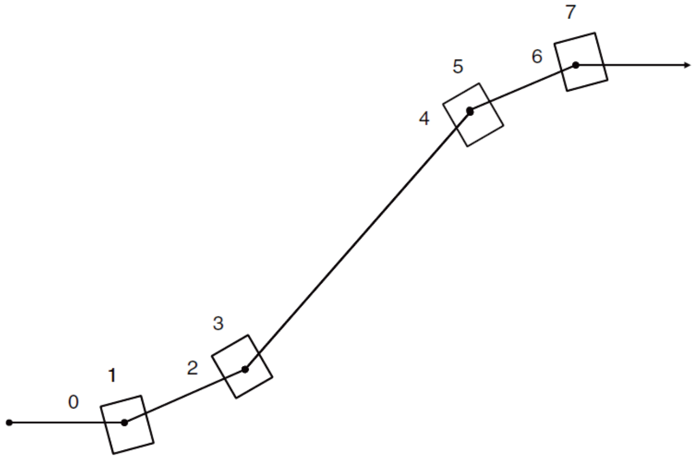
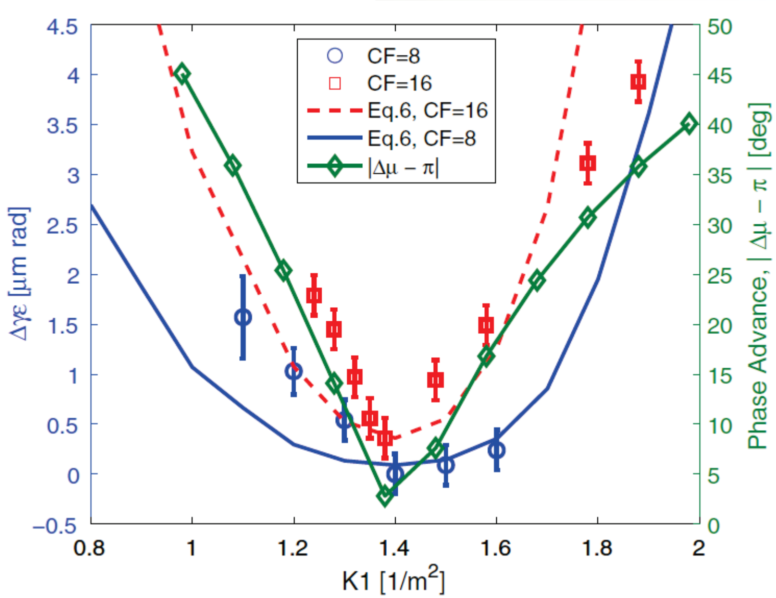
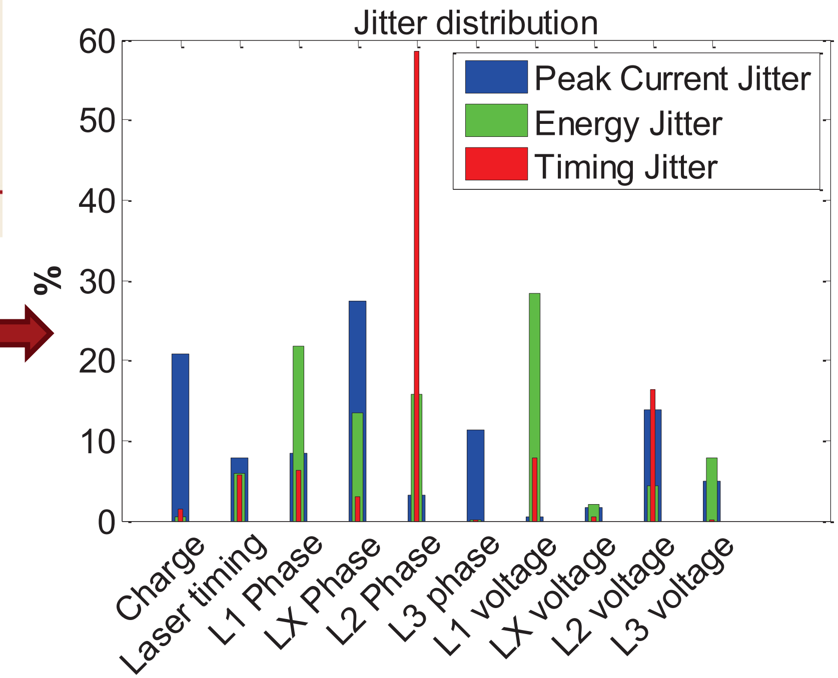


FIG. 1. The FERMI Spreader (not to scale). The design optics gives a betatron phase advance of π in the bending plane between two consecutive dipoles. There are quadrupoles between the dipoles (not shown here).



Detailed contributions

Dominant energy jitters sources in operation mode:
L1 phase and Voltage, X-band phase, L2 Phase



Comparison of two configurations

	Symbol	errors	ΔE/E (%) Optimal	ΔE/E (%)operation	Ratio oper/opti
Relative Bunch Charge	$\Delta Q/Q$	0.67%	-0.00044	-0.00039	
Driven Laser timing error	$\Delta\tau$	0.067ps	-0.000243	-0.00451	
L1 RF Phase error	$\Delta\varphi_1$	0.05°	-0.004776	-0.0167	3.4966
LX RF Phase error	$\Delta\varphi_x$	0.21°	-0.005218	-0.01036	1.9854
L2 RF Phase error	$\Delta\varphi_2$	0.023°	0.005050	0.01222	2.4198
L3 RF phase error	$\Delta\varphi_3$	0.023°	-0.000009	0.00005	
L1 RF relative voltage error	$\Delta V/V_1$	0.05%	-0.008729	-0.0219	2.5089
LX RF relative voltage error	$\Delta V/V_x$	0.02%	0.000584	0.001502	
L2 RF relative voltage error	$\Delta V/V_2$	0.009%	0.003185	0.003365	1.0565
L3 RF relative voltage error	$\Delta V/V_3$	0.01%	0.006348	0.00604	0.9515
Total Jitter	$\sqrt{\sum (\Delta r_i)^2}$		***0.014***	***0.033***	