Optimization of Nonlinear Dynamics for ALS-U Lattices

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Outline

- Overview of ALS upgrade (ALS-U)
- ALS-U lattice design requirements
- Nonlinear dynamics optimization
- Conclusions

MBA Based Diffraction Limited Light Sources Become Reality


MAX-IV (Sweden), 3 GeV, 250 pm


Sirius (Brazil), 3 GeV, 280 pm

HEPS (China), 6 GeV, 60 pm


APS-U (US), 6 GeV, 65 pm


Spring-8-U (Japan), 6 GeV, 100 pm


ESRF-II (France), 6 GeV, 150 pm


SLS-2 (Switzerland), 2.4 GeV, 125 pm

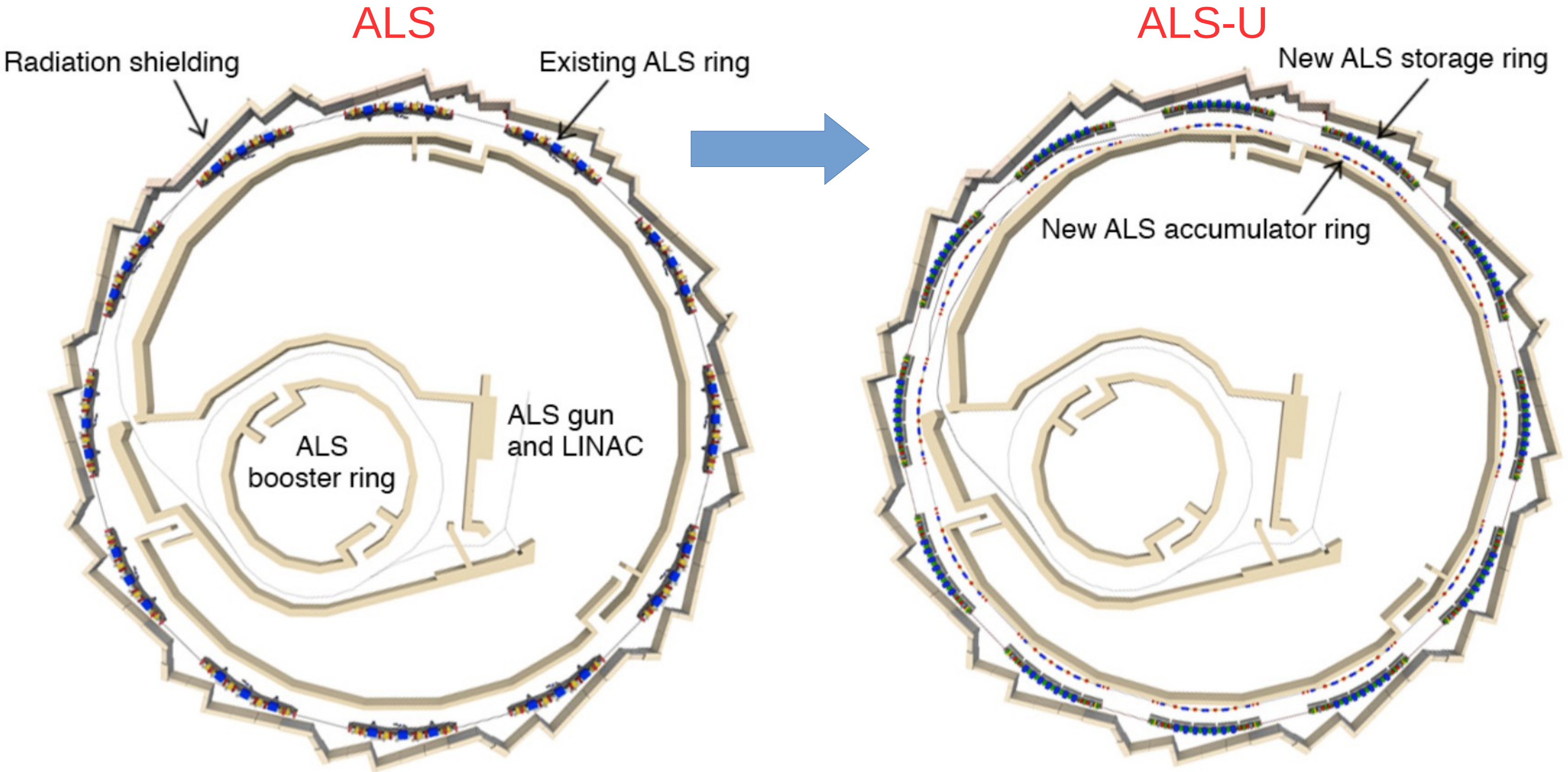

Soleil (France), 2.75 GeV, 500 pm


ALS-U Received CD-0 !

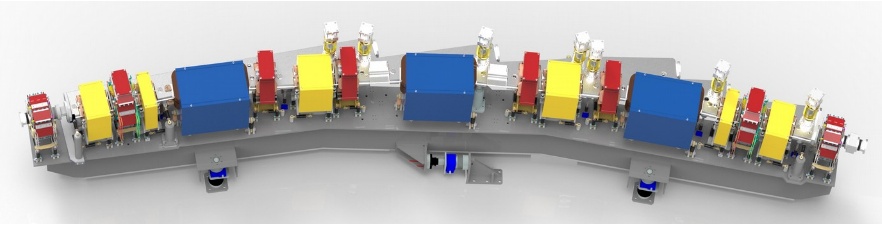
ALS-U (US), 2 GeV, 70 pm

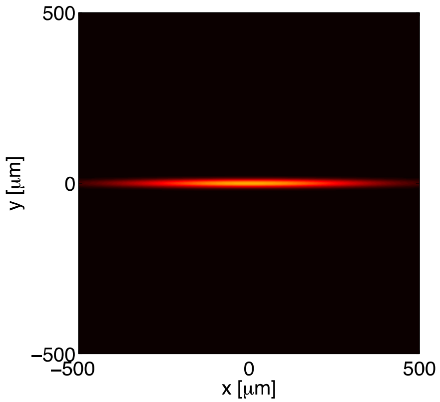
Scope of ALS-U

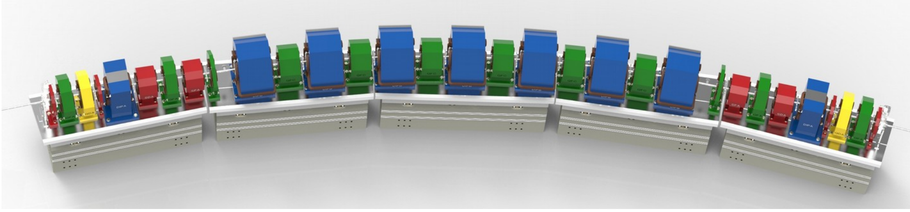
1. **Replacement** of the existing triple-bend achromat storage ring with a new, high-performance storage ring based on a multi-bend achromat.
2. **Addition** of a low-emittance, full-energy accumulator ring in the existing storage-ring tunnel to enable on-axis, swap-out injection using fast magnets.
3. **Upgrade** of the optics on existing beamlines and realignment or relocation of beamlines where necessary.
4. **Addition** of three new undulator beamlines that are optimized for novel science made possible by the beam's high coherent flux.

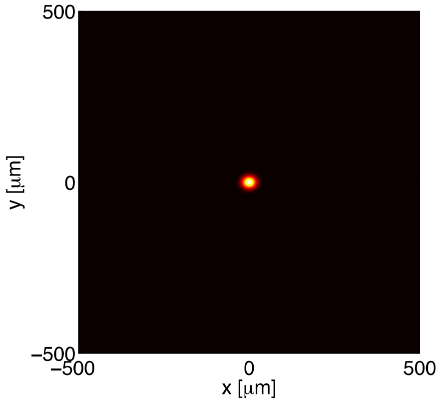


ALS and ALS-U in Numbers



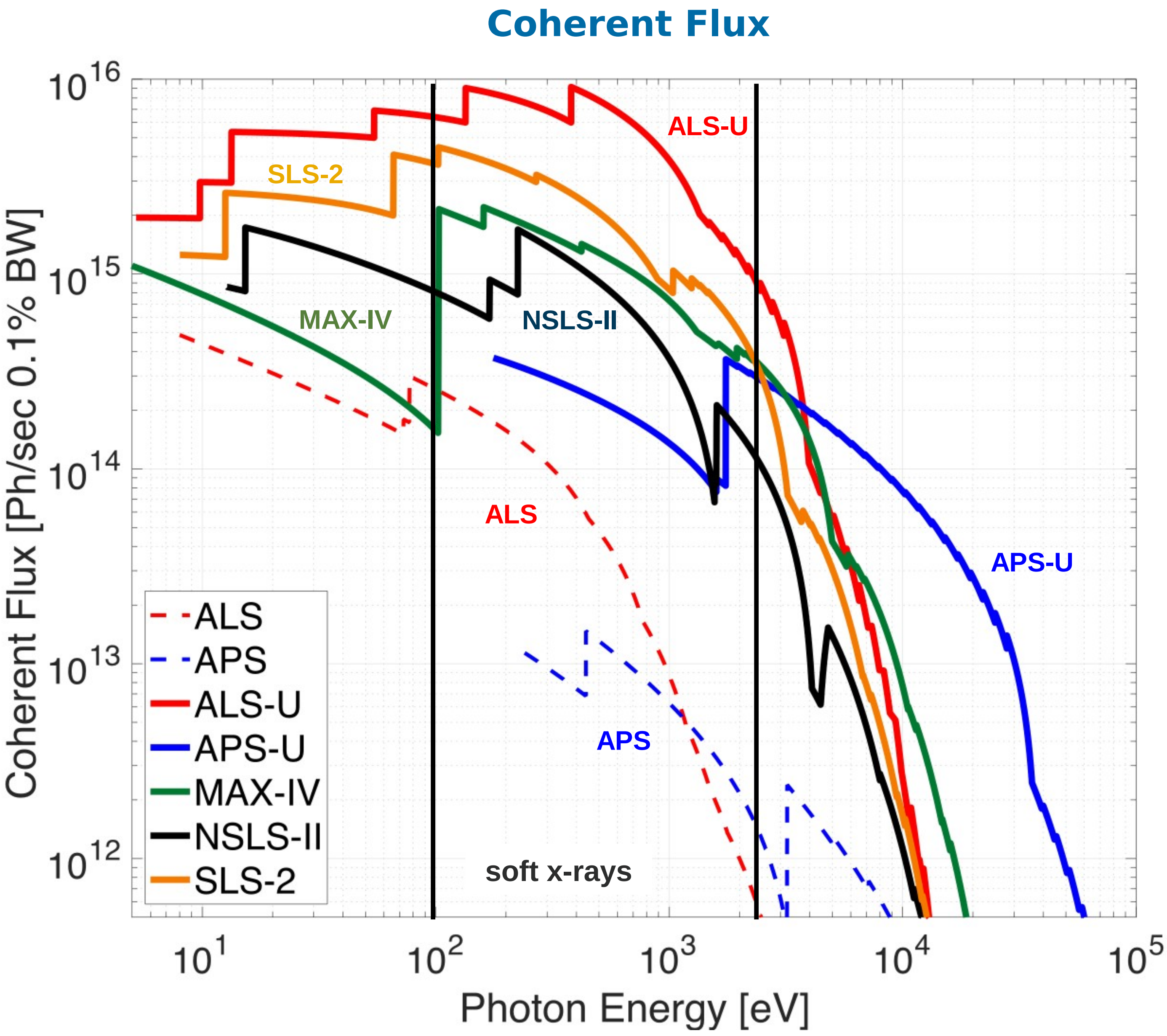






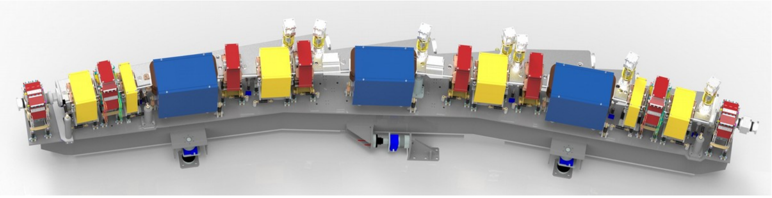
Parameter	Units	ALS	ALS-U
Electron energy	GeV	1.9	2.0
Horiz. emittance	pm	2000	<70 (stretch goal 50)
Vert. emittance	pm	30	<70 (stretch goal 50)
Beamsize @ ID center (σ_x/σ_y)	mm	251 / 9	<13 / <13
Beamsize @ bend (σ_x/σ_y)	mm	40 / 7	<5 / <7
bunch length (FWHM)	ps	60-70 (harmonic cavity)	100-200 (harmonic cavity)
RF frequency	MHz	500	500
Circumference	m	196.8	~196.5

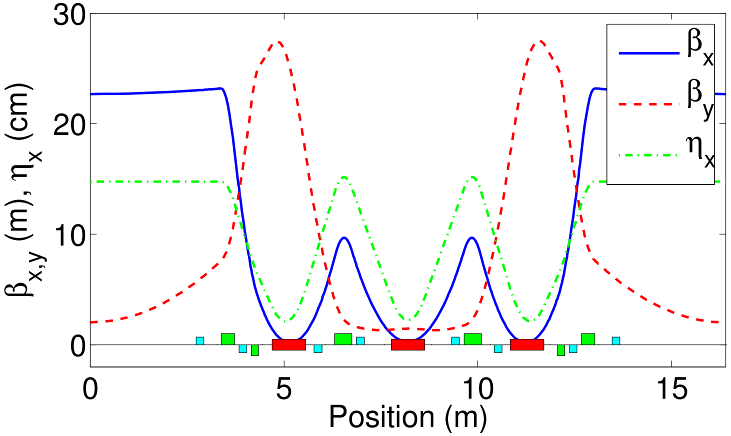
Optimizing for soft x-rays



Challenges of ALS-U lattice design

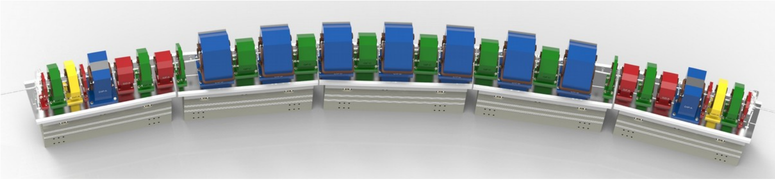
ALS today : triple-bend achromat

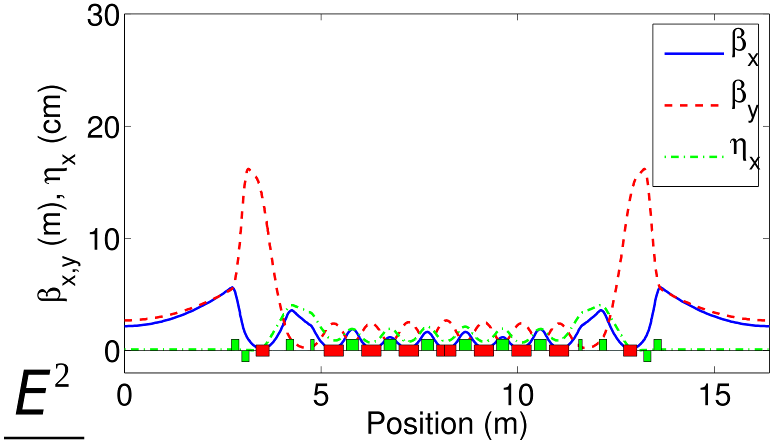




$\varepsilon_x \approx$ 2000 pm-rad at 1.9 GeV

ALS-U: multi-bend achromat





$\varepsilon_x <$ 70 pm-rad at 2.0 GeV

$$\varepsilon_x \approx \sigma_x \sigma_\theta \mu \frac{E^2}{N_D^3}$$

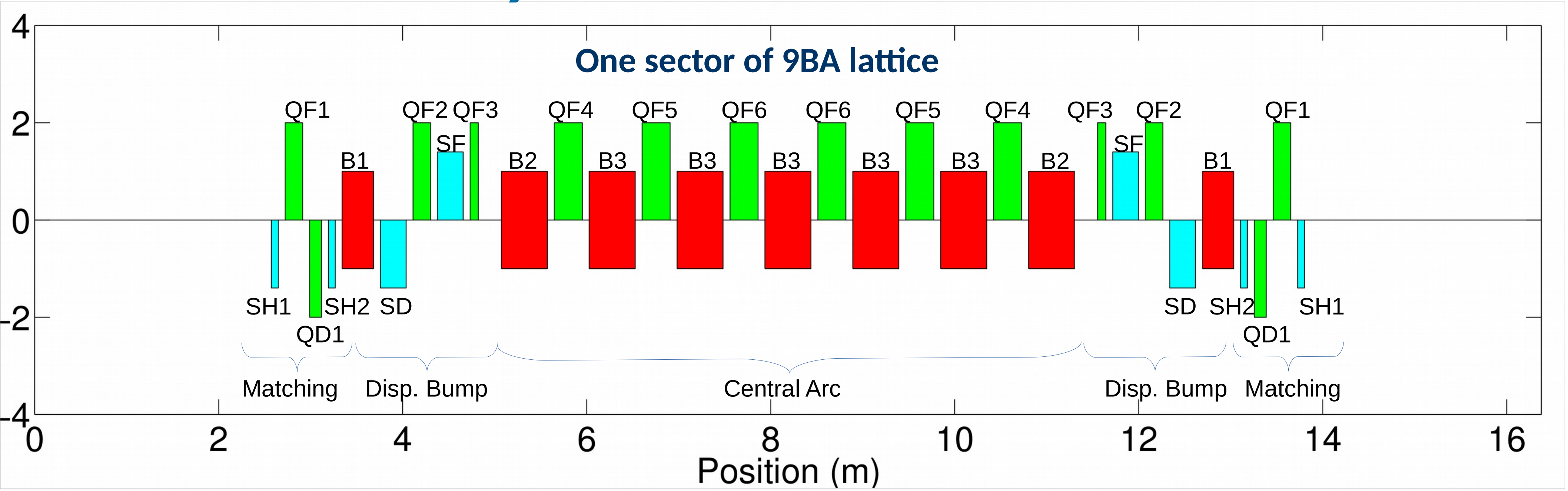
The quantities are linearly scaled with ~Nd:

	Beta At center	Maximum Dispersion	Natural Chromaticity	Maximum Qaud Grad.	Chromatic sext Grad.	Dynamic Aperture	Lifetime
ALS	~22 m	~15 cm	~30	~20 T/m	550 T/m^2	~15 mm	~7 hour
ALS-U	~2 m	~2 cm	~66	~105 T/m	5000T/m^2	~1 mm	~1 hour

Nd↑ → Small emittance
Small beta and dispersion → Strong Quad gradient → Strong chromaticity

→ Strong sextupole → Strong nonlinear effect → Difficult to optimize

9BA Lattice Layout for One of 12 Sectors



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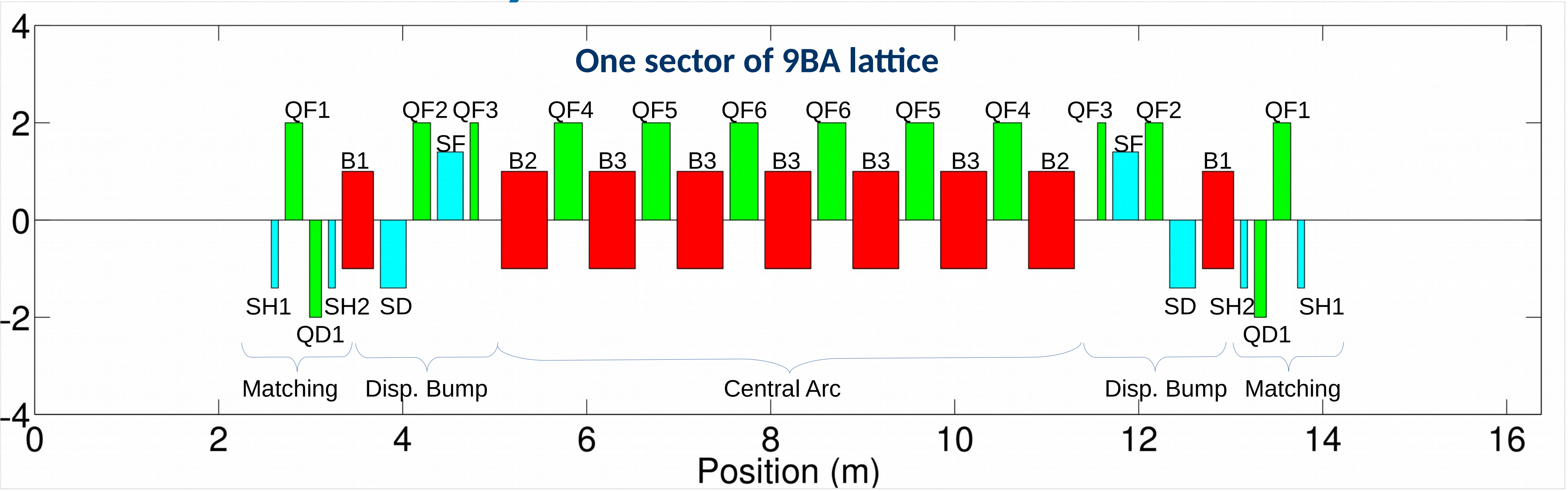

- Engineering constraints
  - ✓ Fit in the current ALS footprint, 196.5 m circumference
  - ✓ Distance between magnet is 0.075 m
  - ✓ Quad gradient <105 T/m ,
  - ✓ Inner bend gradient (geometric quad with offset) 40 T/m <k1<47 T/m
  - ✓ Outer bend gradient (geometric dipole) k1<20 T/m
  - ✓ Chromatic sextupole gradient k2 <7000 T/m^2
  - ✓ Harmonic sextupole gradient k2 <4000 T/m^2
- Physics Constraints
  - ✓ Maximum beta function < 30m
  - ✓ Equal fractional tunes for coupling resonance
  - ✓ Dispersion in the straight <1mm

ALS-U Lattice Design and Optimization

- Design goals
  - ✔ Low natural emittance (~100pm), low beta-functions in straight sections
  - ✔ Sufficient Dynamic Aperture (DA) to accept 2nm injected beam
  - ✔ Large Momentum Aperture (MA) for sufficiently long lifetime

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  - ✔Multi-objectives probem with often conflicting requirements
  - ✔Highly constrained by space, engineer and physics requirements

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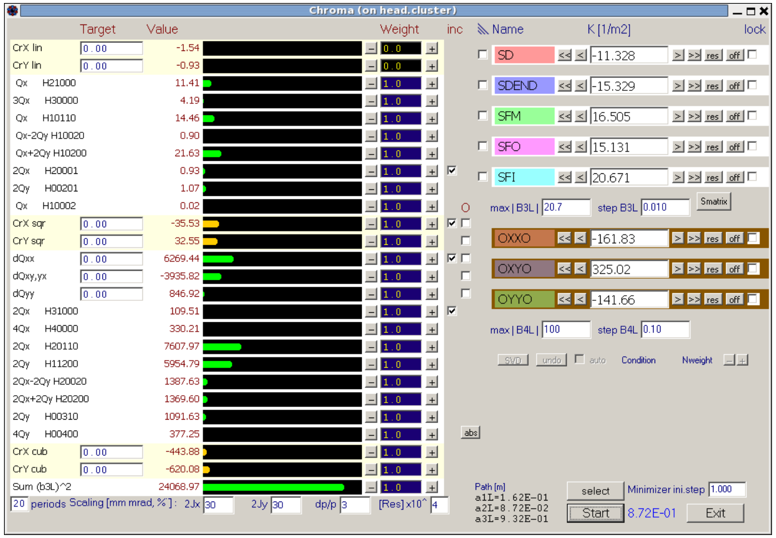
- Approaches:
  - ✔ Earlier attempts to first design linear lattice and then optimize the nonlinear dynamics by targeting non-linear tuneshifts (chromatic, geometric) and resonant terms were not very successful
  - ✔ Simultaneous optimization of linear and nonlinear properties of the lattice is necessary
  - ✔ Multi-Objective Genetic Algorithm (MOGA) is extensively used to optimize ALS-U lattice

Optimization of Nonlinear Dynamics

- Analytical Approach
  - ✔ Calculate resonance driving term (RDT), tune shift with amplitude and energy
  - ✔ Mimiziation of these calculated quantities
  - ✔ Fast approach and supports a larger number of knob tuning
  - ✔ Weights need to be assigned to individual quantities based on experience
  - ✔ Results might not be optimal
  - ✔ Must check and iterate with direct tracking



Chroma (on head.cluster)

	Target	Value	Weight	inc
CrX lin	0.00	-1.54	0.0	
CrY lin	0.00	-0.93	0.0	
Qx H21000		11.41	1.0	
3Qx H30000		4.19	1.0	
Qx H10110		14.46	1.0	
Qx-2Qy H10020		0.90	1.0	
Qx+2Qy H10200		21.63	1.0	
2Qx H20001		0.93	1.0	☑
2Qy H00201		1.07	1.0	
Qx H10002		0.02	1.0	O
CrX sqr	0.00	-35.53	1.0	☑ ☐
CrY sqr	0.00	32.55	1.0	☐
dQxx	0.00	6269.44	1.0	☑ ☐
dQxy,yx	0.00	-3935.82	1.0	☐
dQyy	0.00	846.92	1.0	☐
2Qx H31000		109.51	1.0	☑
4Qx H40000		330.21	1.0	
2Qx H20110		7607.97	1.0	
2Qy H11200		5954.79	1.0	
2Qx-2Qy H20020		1387.63	1.0	
2Qx+2Qy H20200		1369.60	1.0	
2Qy H00310		1091.63	1.0	
4Qy H00400		377.25	1.0	
CrX cub	0.00	-443.88	1.0	
CrY cub	0.00	-620.08	1.0	
Sum (b3L)^2		24068.97	1.0	

20 periods Scaling [mm mrad, %] : 2Jx 30 2Jy 30 dp/p 3 [Res] x10^ 4

	Name	K [1/m2]	lock
☐	SD	-11.328	☐
☐	SDEND	-15.329	☐
☐	SFM	16.505	☐
☐	SFO	15.131	☐
☐	SFI	20.671	☐

max | B3L | 20.7 step B3L 0.010

Name	K [1/m2]	lock
OXXO	-161.83	☐
OXYO	325.02	☐
OYYO	-141.66	☐

max | B4L | 100 step B4L 0.10

☐ auto Condition Nweight

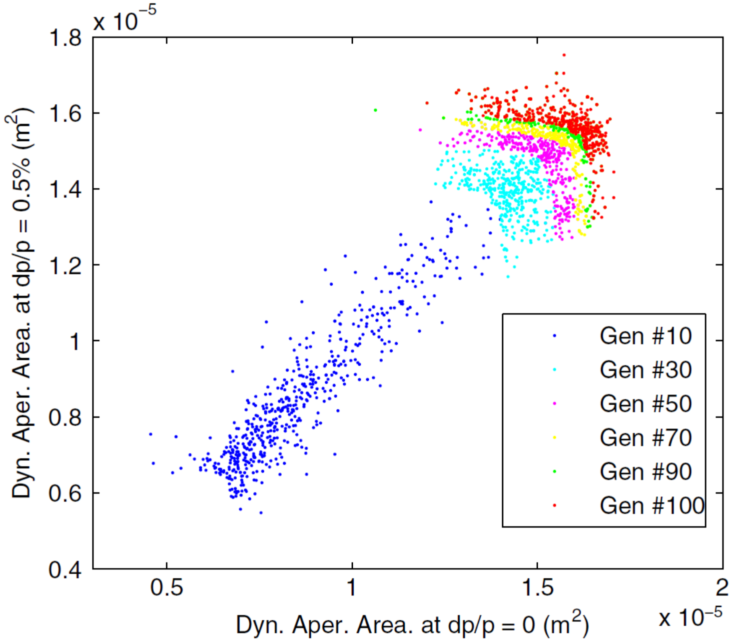
Path [m]
a1L=1.62E-01
a2L=8.72E-02
a3L=9.32E-01

Minimizer ini.step 1.000

8.72E-01

OPA code example for RDT minimization

- Direct Tracking Approach
  - ✔ Determine the quantities such as dynamic aperture, momentum aperture, lifetime and diffusion rate by tracking
  - ✔ Optimized these quantities using optimization algorithms
  - ✔ Tuning linear lattice as well as sextupoles and octupoles
  - ✔ A slow approach, need parallel computing for a large number of knob tuning
  - ✔ A global optimal with trade-off between multi-objectives could be found using Multi-Objective Genetic algorithm (MOGA)

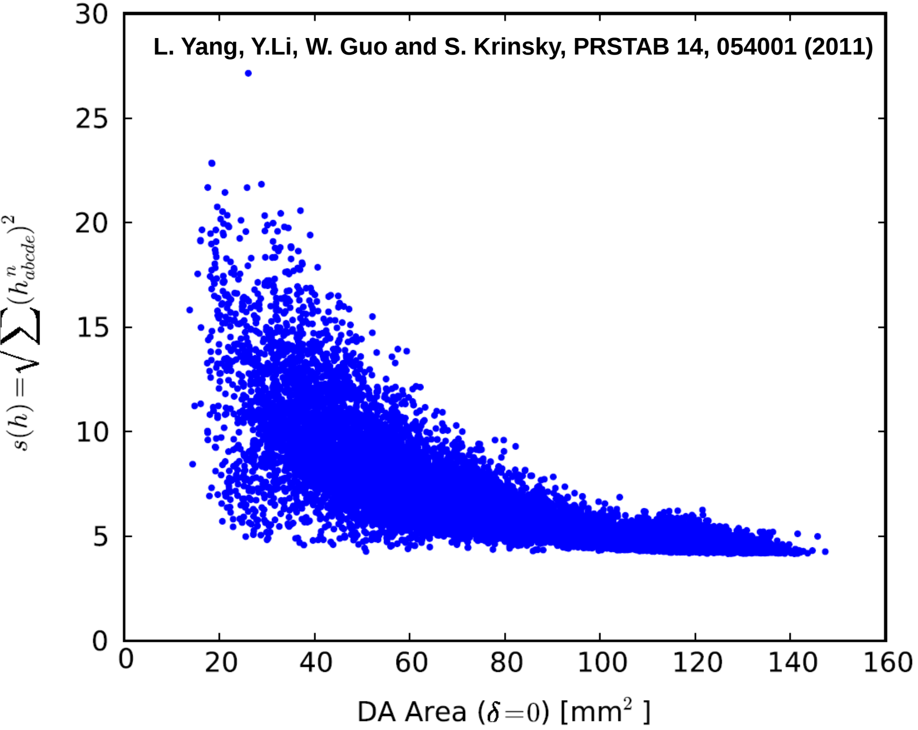


DA optimization example using MOGA for ALS lattice

Correlation of Nonlinear Quantities Determined by Both Analytical and Tracking Methods

Dynamic Aperture (DA)

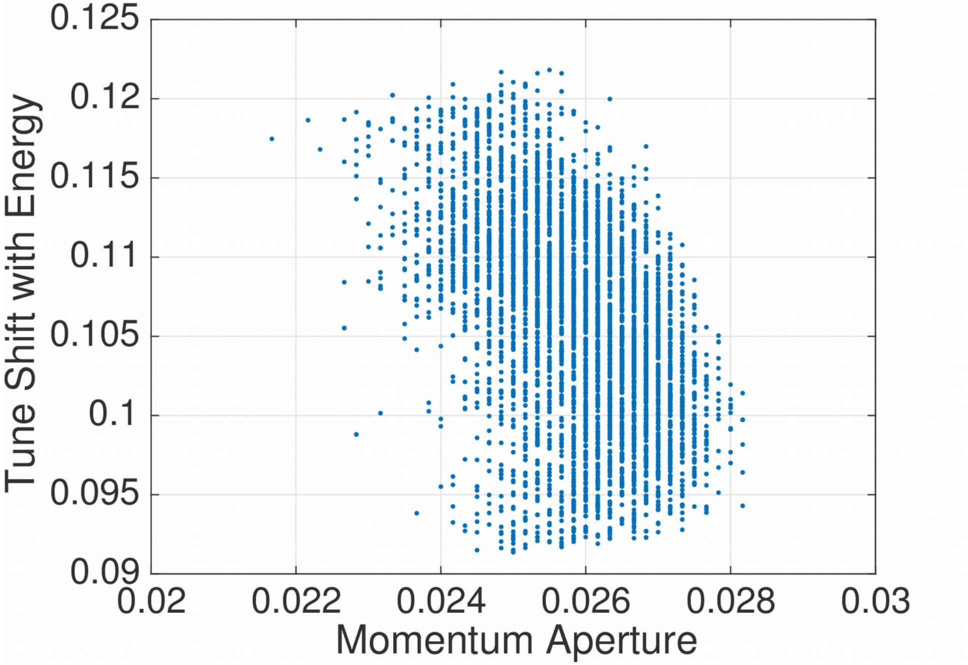
By analytical calculation



By direct tracking

Momentum Aperture (MA)

By analytical calculation

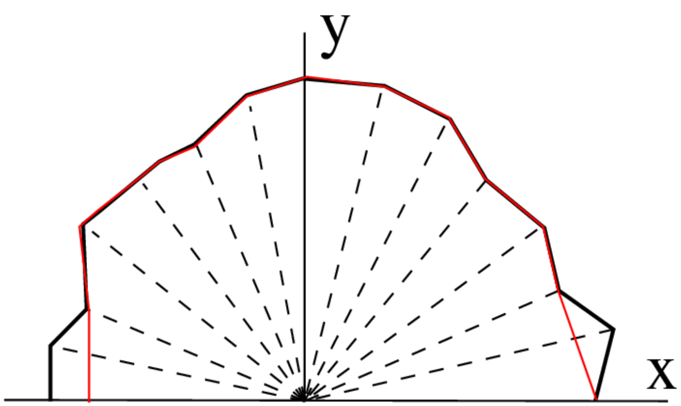


By direct tracking

- Large DA (MA) requires small RDTs (Tuneshift with energy), however small RDTs (Tuneshift with energy) do not always imply good DA (MA)
- Therefore, DA(MA) determined by tracking should be used a primary objectives to optimize nonlinear dynamics in order to find global optimal
- However, RDTs (Tuneshift with energy) could be used as constraints or secondary objectives in the optimizer to improve the speed of convergence

DA Area vs Total Diffusion Rate

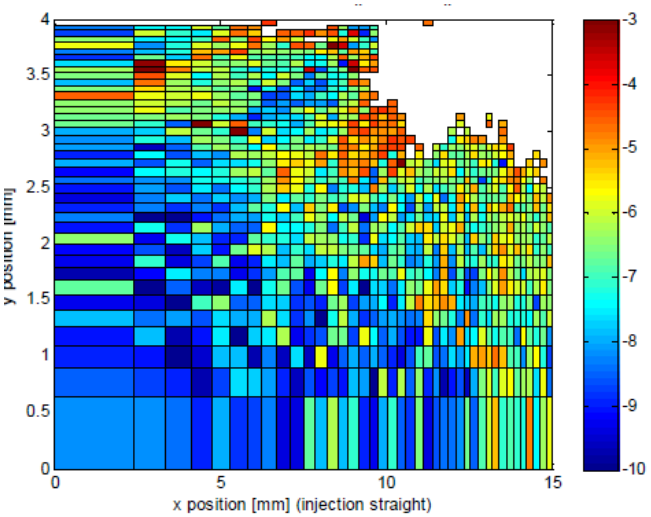
- Dynamics aperture area *[M. Borland, Elegant V 23.1]*
    - 21 lines, and 11 steps for each line
    - 4 interval splitting to refine the boundary
    - 4D trackding for 1000 turns
    - Boundary is clipped to avoid the island



- Total diffusion rate *[C. Steier and W. Wan, IPAC 2010]*
    - Frequency Map Analysis
    - 21 by 21 non-uniform grid search
    - 4D tracking for 512 turns for each grid.
    - Diffusion rate is calculated according to

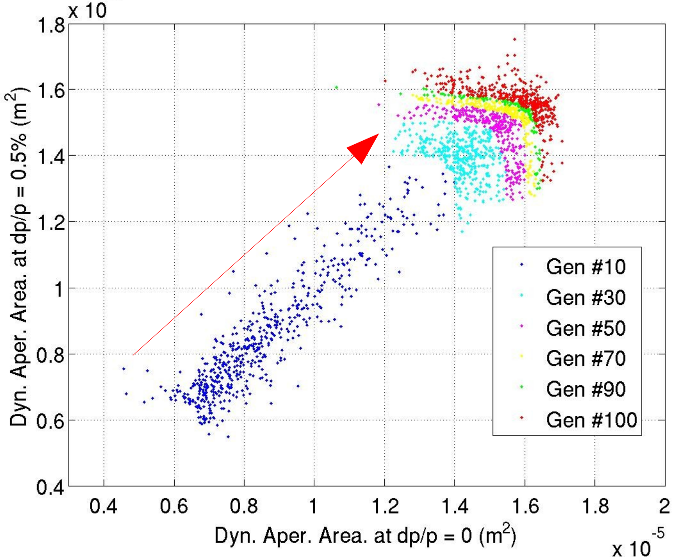
$$d = \log\left(\frac{\sqrt{(\nu_{x,1}-\nu_{x,2})^2+(\nu_{y,1}-\nu_{y,2})^2}}{N}\right)$$

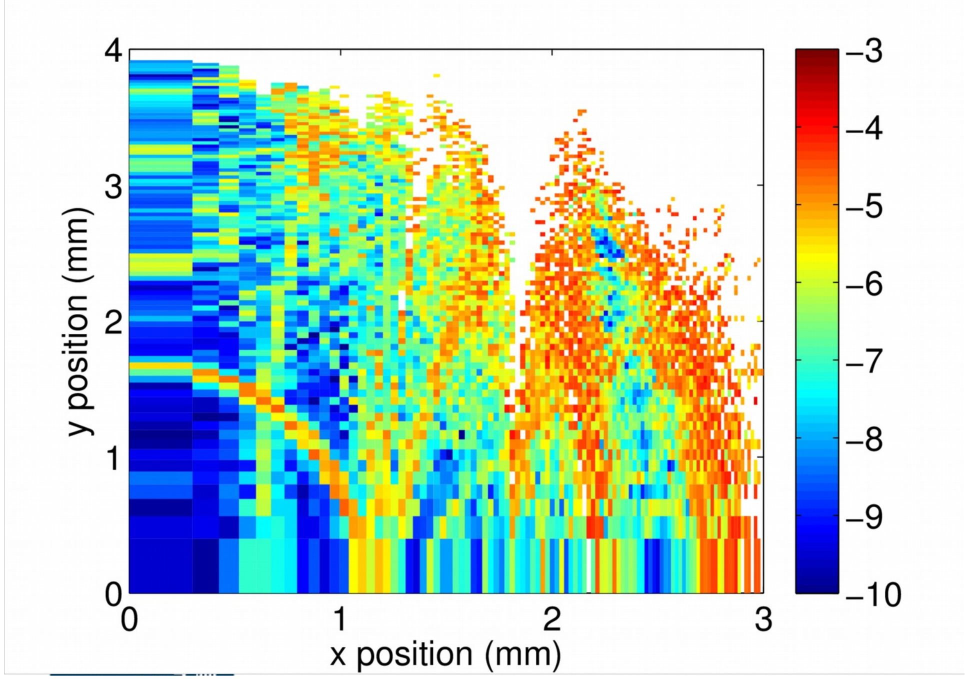
-
    - Diffusion rate is assigned to -3 for lost particle
    - Boundary is clipped to avoid the island
    - Summation of the diffusion rate over all the clipped grids.



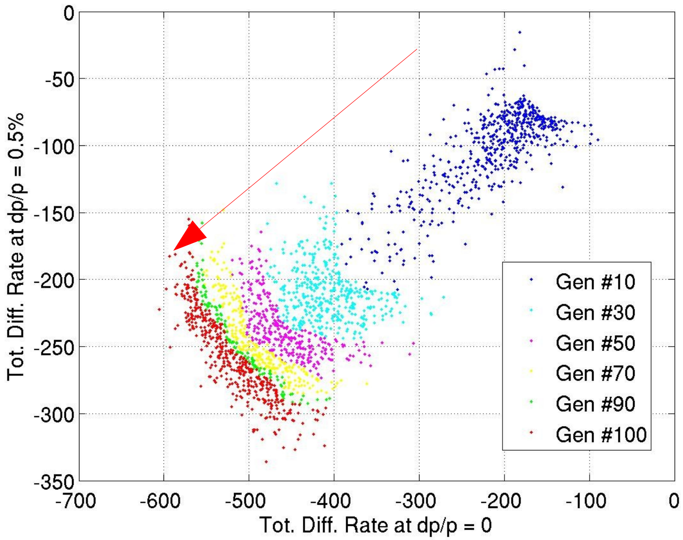
Dynamic Aperture (DA)

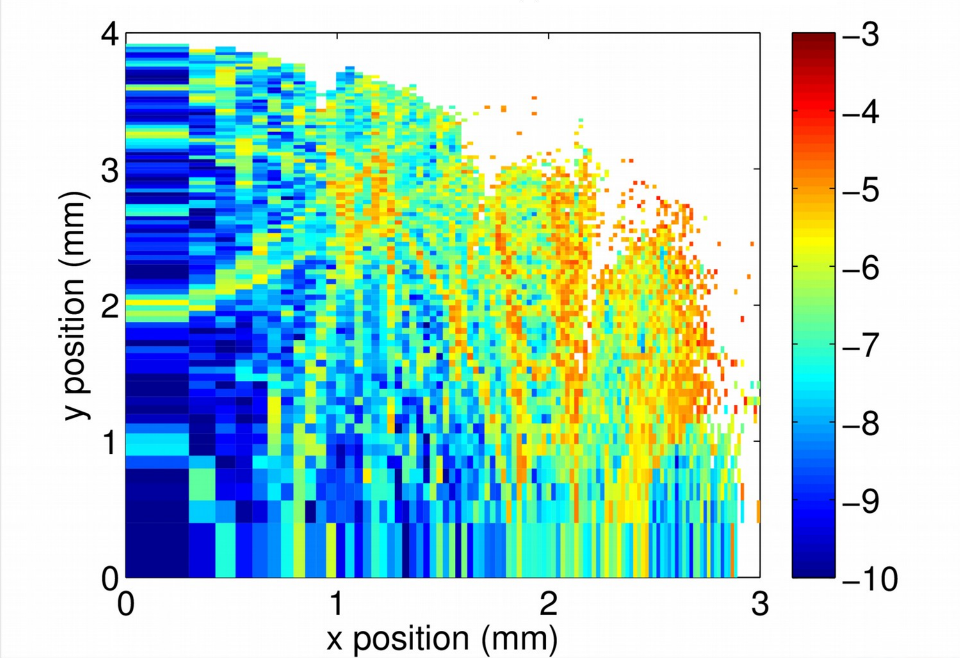
DA area as optimization objective





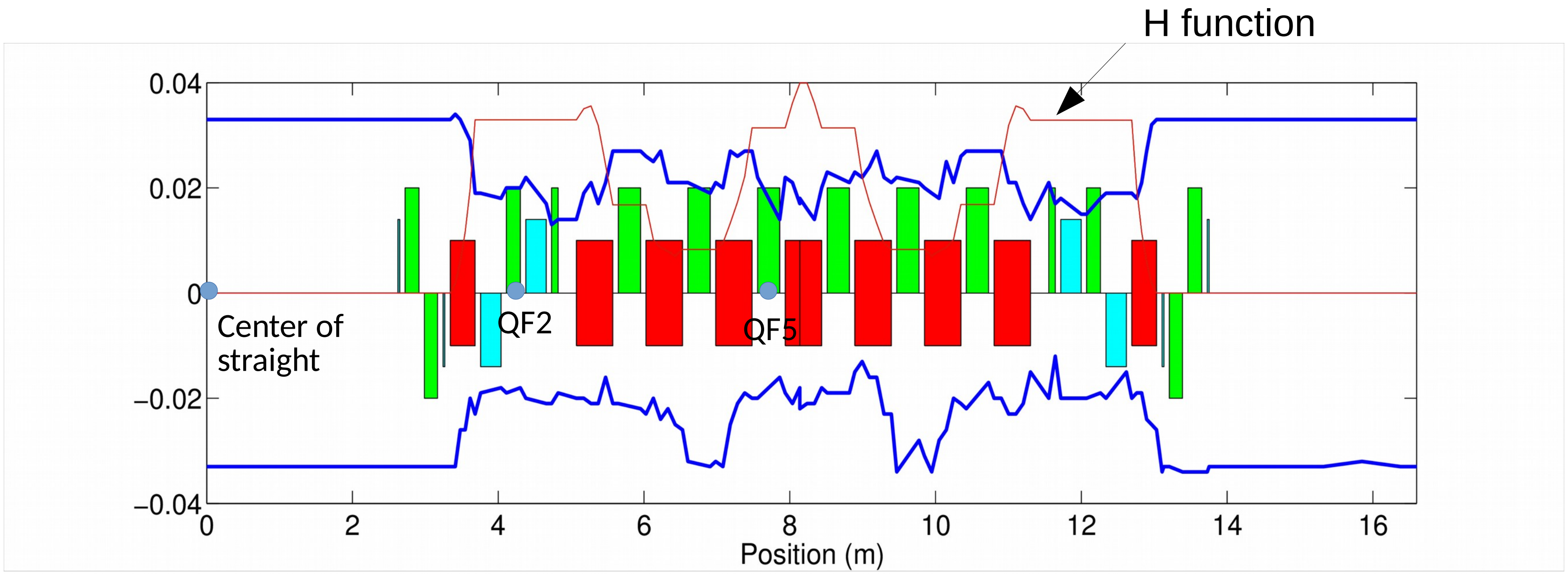
Total diffusion rate as optimization objective





Our previous study shows that lattice optimized with tot. diff. rate as an objective has better nonlinear performance

Momentum Aperture (MA)



- It is timing consuming to evaluate MA for the whole ring in the optimizer
- Instead, we use the average of MAs at several locations as an objective
  - ✓ 6D tracking with both radiation and cavity on
  - ✓ Tracking particle for 1000 turns (2 turns of synchrotron oscillation)
  - ✓ Skew and gradient errors are included in the lattice

Tracy, MOGA and Parallelization

- Tracy
  - ✓ Tracy is a single particle tracking library developed at ALS and has both matrix or symplectic tracking methods.
  - ✓ It has evolved into different variants and used in many laboratories
  - ✓ Most recent developments to improve its computing speed, flexibility, and its compatibility with parallel computing techniques (openMP).

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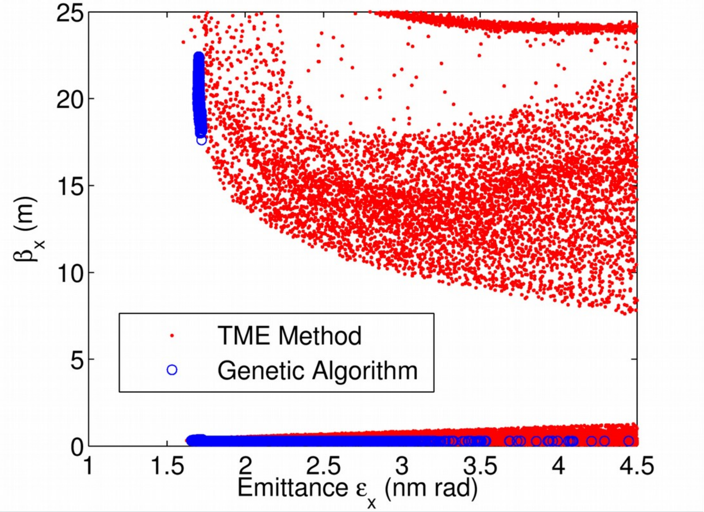
- MOGA
  - Multi-Objective Genetic Algorithm (MOGA) NSGA-II (Nondominated Sorting Genetic Algorithm II) is a widely used method to design and optimize accelerator components.
  - MOGA has been integrated to Tracy to optimize ALS and ALS-U lattices using parallel computing technique.

MOGA optimization example for ALS brightness upgrade with two objectives



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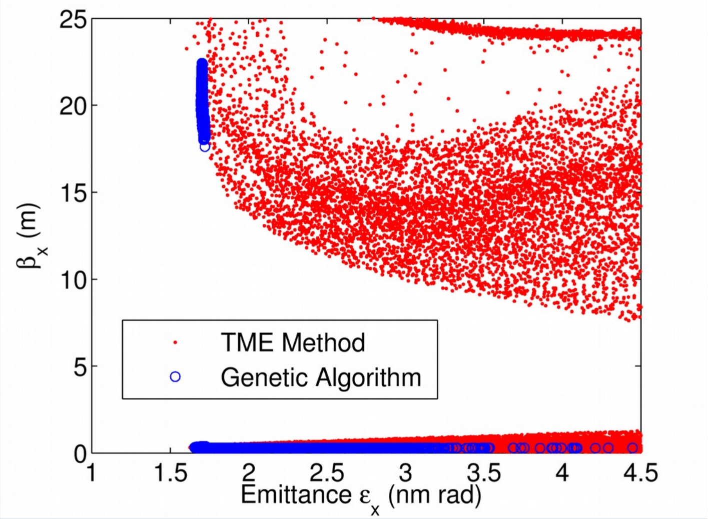

- Parallelization
  - ✔ Hybrid Open MPI/openMP is implemented in MOGA
  - ✔ MPI is used to parallelize the generation evaluations
  - ✔ OpenMP is used to parallelize DA and MA evaluations

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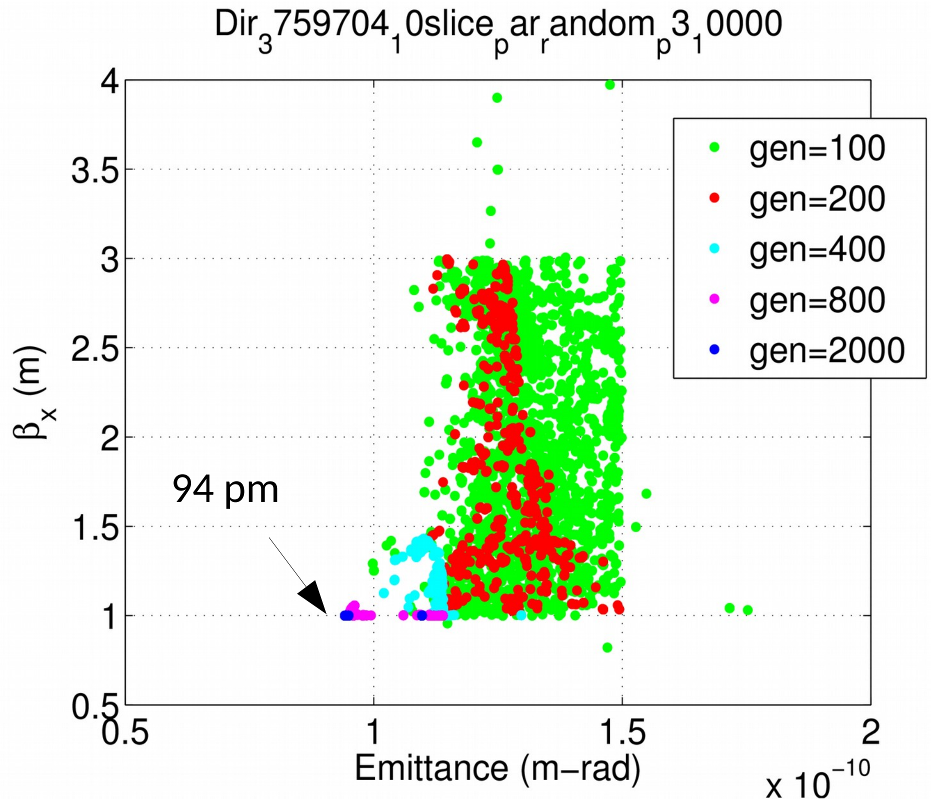
Optimization Strategy with MOGA

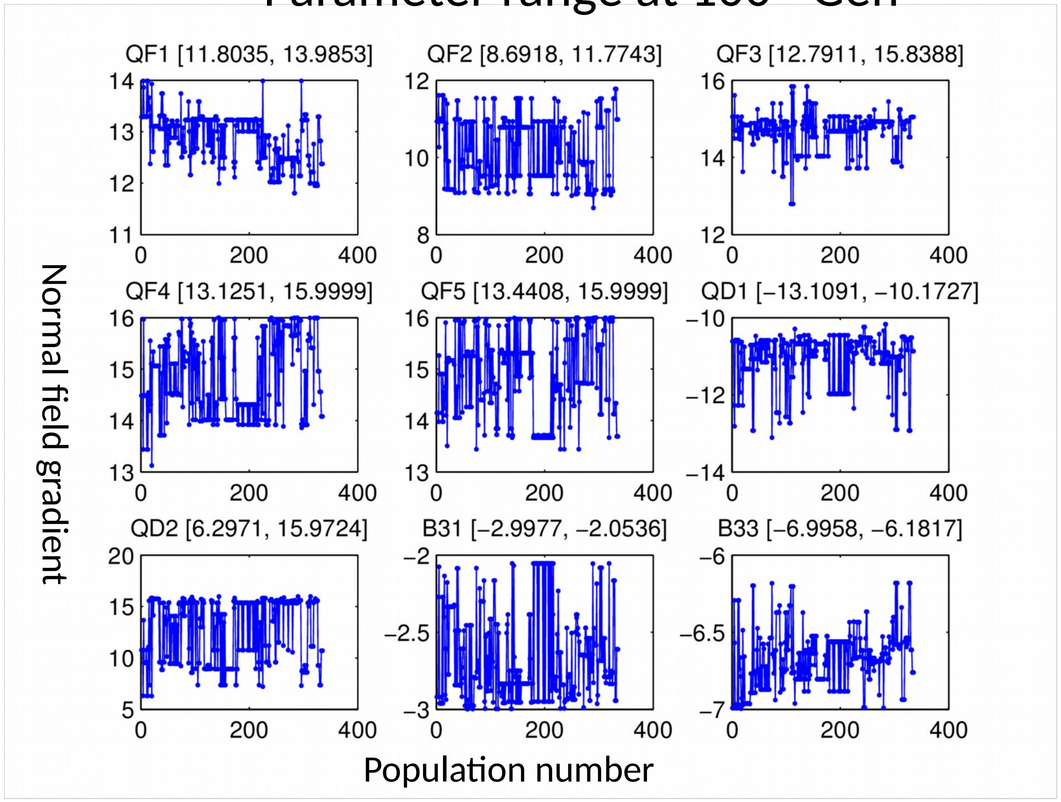
- Evaluations of the nonlinear objectives momentum and dynamic apertures are time consuming
- We were unable to find a good and fully converged solutions in a reasonable time when we optimized the linear and nonlinear properties starting from random initial population lattices in the first attempt

- Starting with good initial solutions will help to improve the convergence
- We carry out the MOGA optimization in two stages.
  - ✓ First, a fast linear optimization is carried out to explore the input parameter space
  - ✓ Then, linear and nonlinear properties are optimized simultaneously with the parameters input from linear optimization
- The linear and nonlinear optimizations are carried out in several steps. For each step, we modified the search rang of the parameters and genetic optimization parameters

Linear Optimization for 9BA Lattice

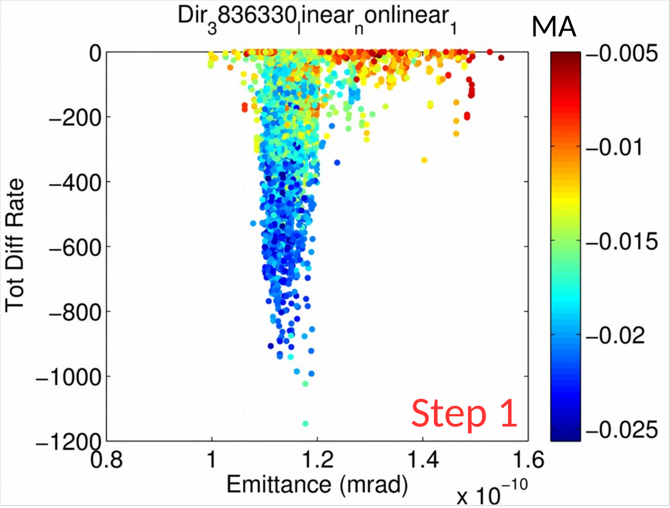


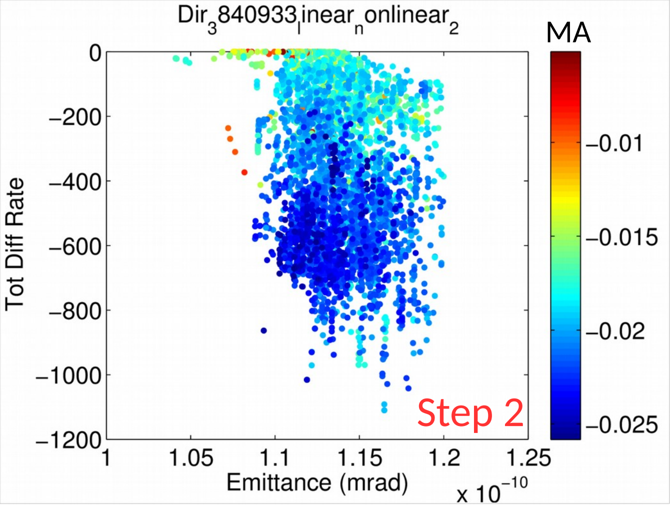
Parameter range at 100th Gen

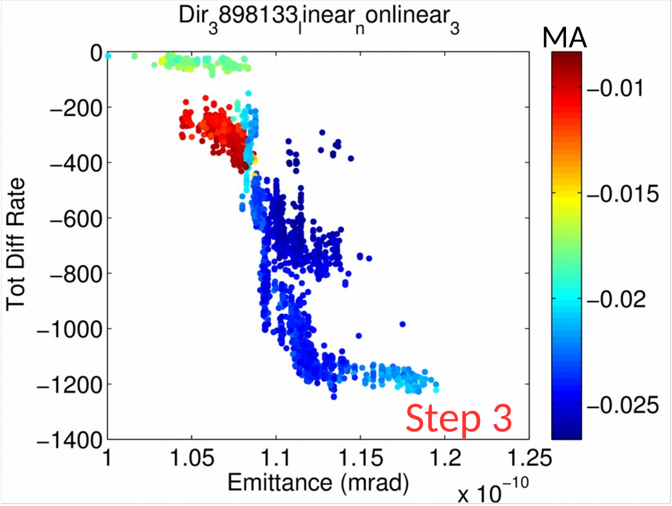


- A fast optimization, take several hours and could find true global optimal
- Two objectives: natural emittance is minimized and beta functions at the center of straight are minimized to 1 meter
- Initial populations are uniformly and randomly sampled in the parameter space
- The boundary conditions on beta function (<3m) and emittance (<150 pm) are also applied to concentrate the search and speed up the optimization
- No lattice errors are included
- The parameter space at 100th generation is analyzed and used for linear and nonlinear optimization in the next step

Linear and Nonlinear Optimizations

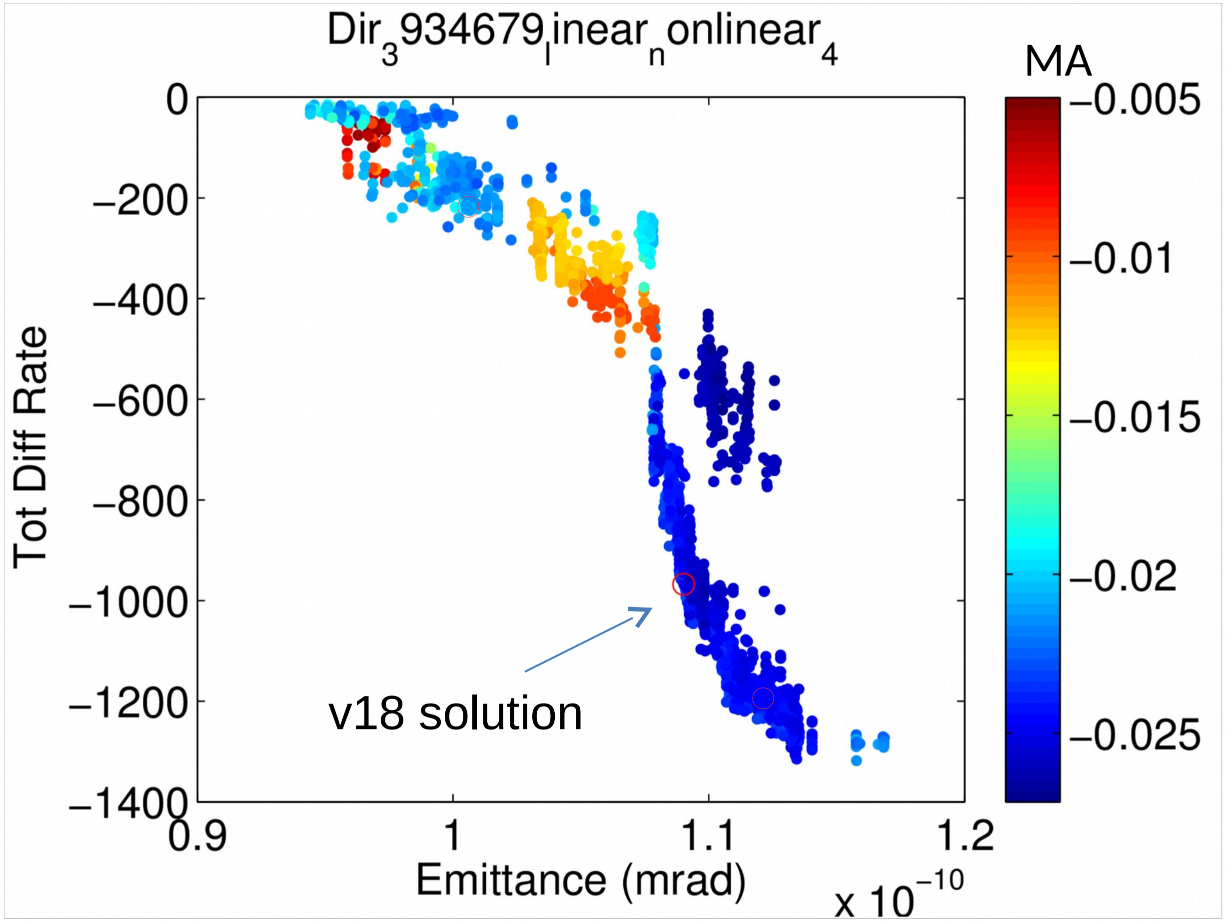






- A slow optimization process, could take several days or weeks
- 3 objectives: emittance, total diffusion rate and momentum aperture
- 11 knobs: 9 quad gradients and 2 harmonic sextupoles. Chromaticity is fitted to 1
- Relative skew quad error and quad gradient error are included
- Several optimization steps are carried out. For each step, the search rang of the parameters and the genetic parameters are modified to have spread search and fast convergent speed

Final Pareto Front of Linear and Nonlinear Optimization



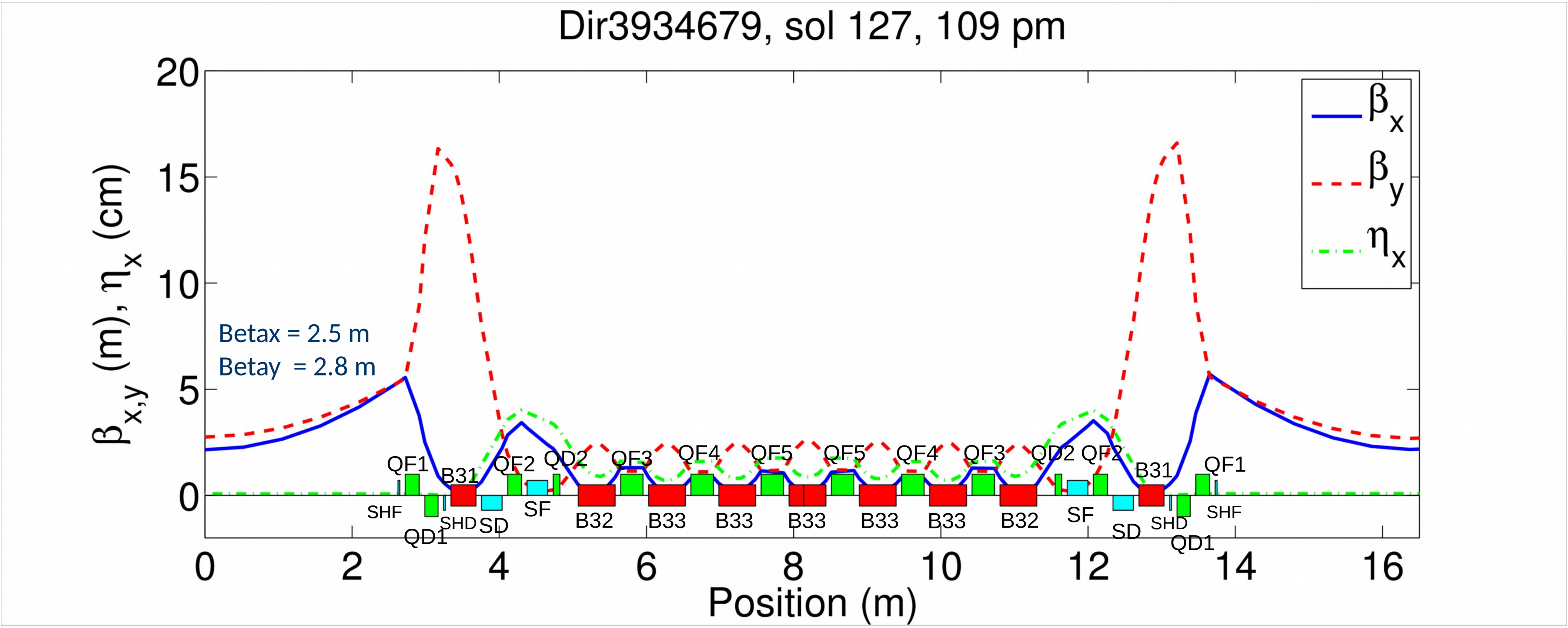
- Optimization is terminated when a converged solution front is observed
- Several solutions picked from the Pareto front are analyzed
- The solution named v18 has better overall performances

Parameter List of 9BA v18 Lattice

```
   PARAMETER LIST OF RING  (Dir_3934679,sol 127 )
______________________________________________________

Energy    [GeV]    =    2.00000
Circumf.  [m]      =  196.50000
Rev. Time [nsec]  =  655.45345
Rev. Freq.[MHz]   =    1.52566
Betatron Tune H  =   41.38011
               V  =   20.38958
Mom. Compaction   =    2.67674E-04
Chromaticity   H  =  -64.90647
               V  =  -67.62903
Synch.Integral 1  =    0.05260
             2  =    0.80753
             3  =    0.10704
             4  =   -0.69883
             5  =    0.00003
Damp.Partition H  =    1.86539
             V  =    1.00000
             E  =    1.13461
Rad. Loss [KeV]   =  181.91
Energy Spread     =    8.28121E-04
Emittance          =   1.09024E-10
Rad. Damping   H  =    7.726328
               V  =   14.412610
               E  =   12.702691
```

9BA v18 lattice



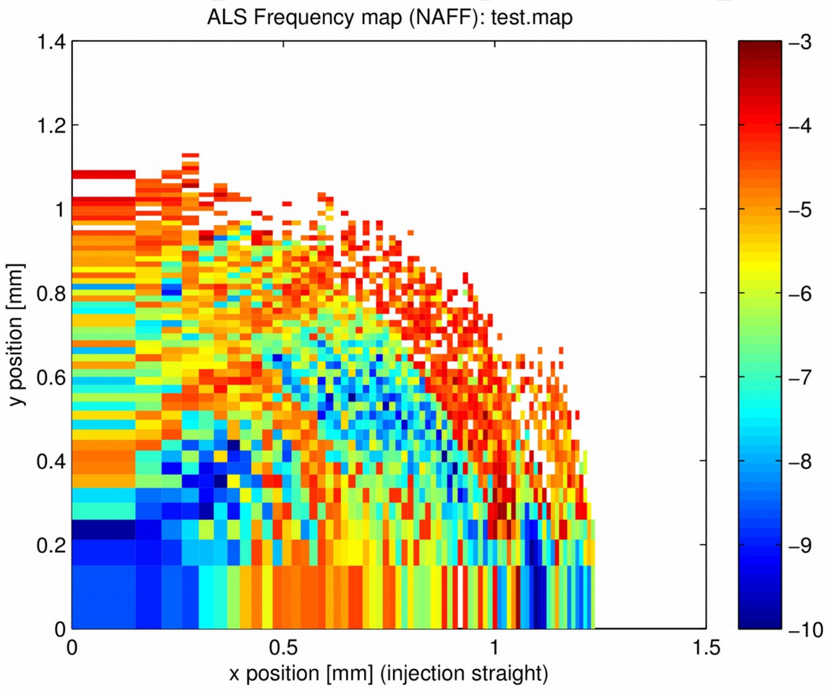
Betax = 2.5 m

Betay = 2.8 m

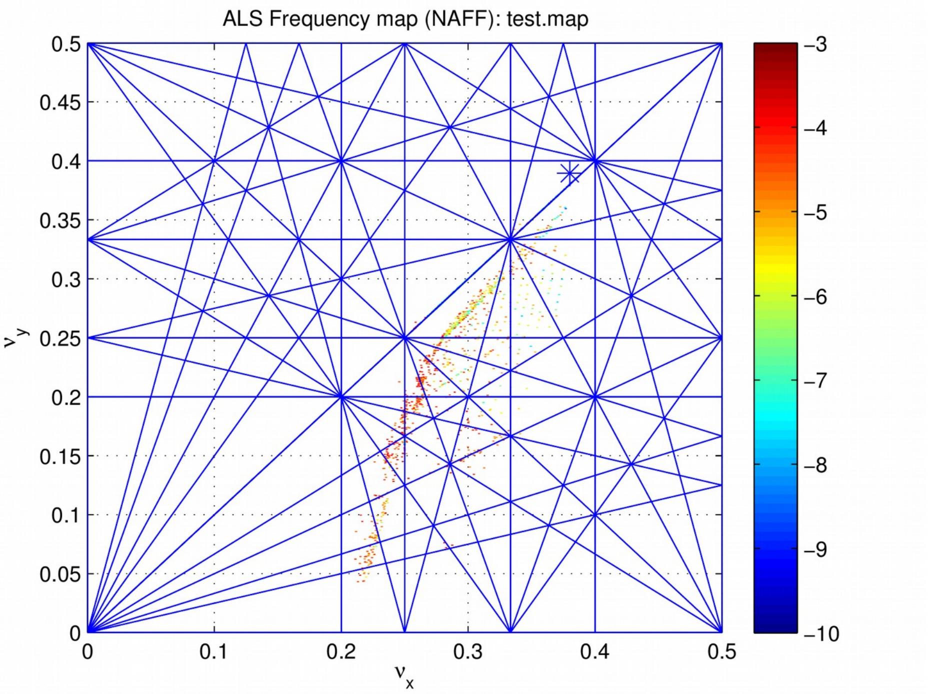
V18	QF1	QF2	QF3	QF4	QF5	QD1	QD2	B31k	B32K	B33K	SHF*	SHD	SF	SD
Grad. K (/brho)	12.542	10.113	15.309	15.870	15.606	-10.182	14.021	-2.8937	-6.9999	-6.9999	100.104	-1508.80	801.06	-658.494
Length (m)	01.9	0.19	0.305	0.305	0.305	0.180	0.09	0.34	0.5	0.5	0.025	0.025	0.28	0.28
Bend (deg)								3.3333	3.3333	3.3333				

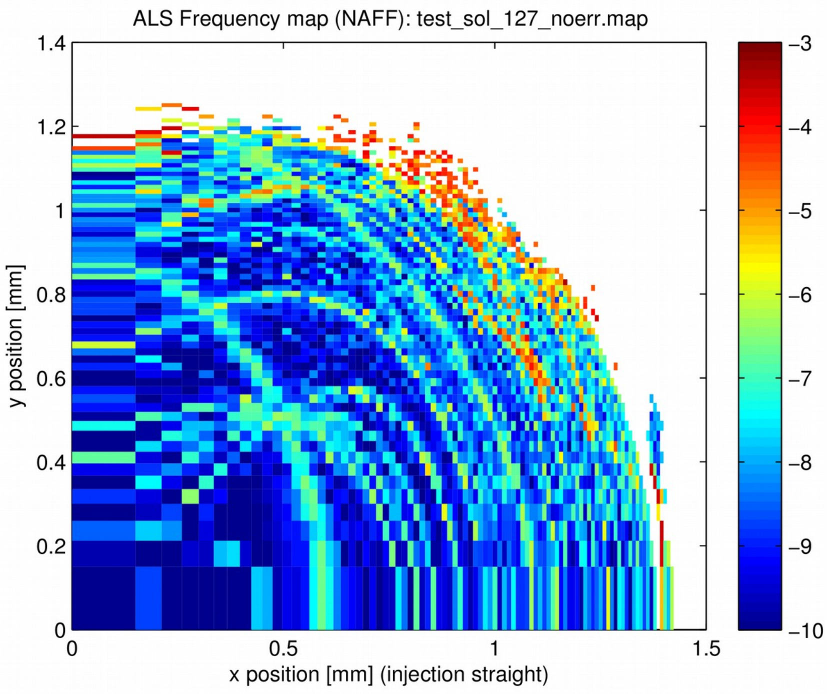
Gradients K defined here are normalized gradient by magnetic rigidity Brho at 2GeV. For quad, K = B'/Brho, and for sextupole K = B''/Brho.

Frequency Map

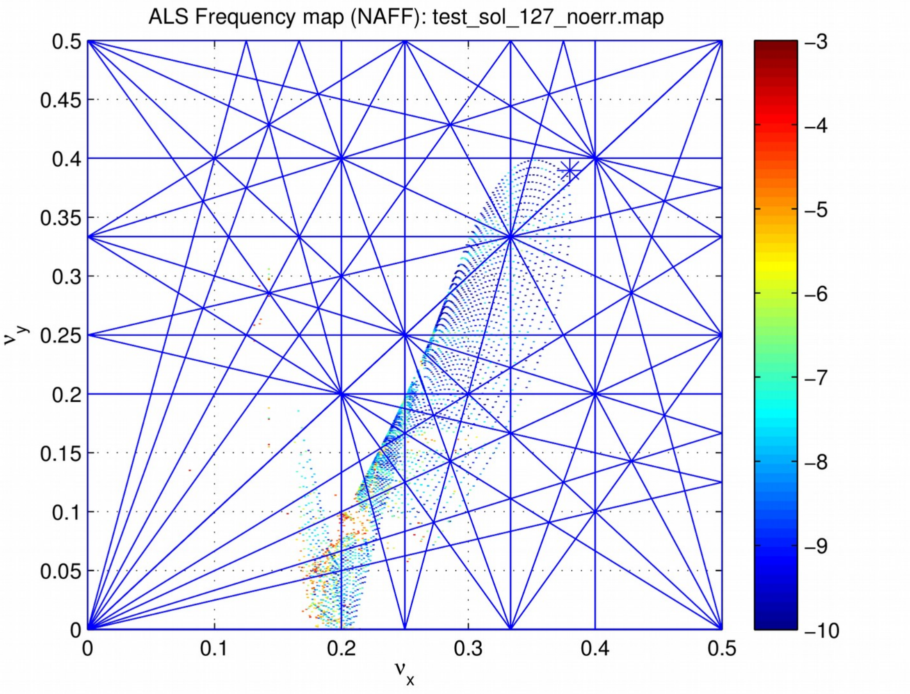

ALS Frequency map (NAFF): test.map

With errors

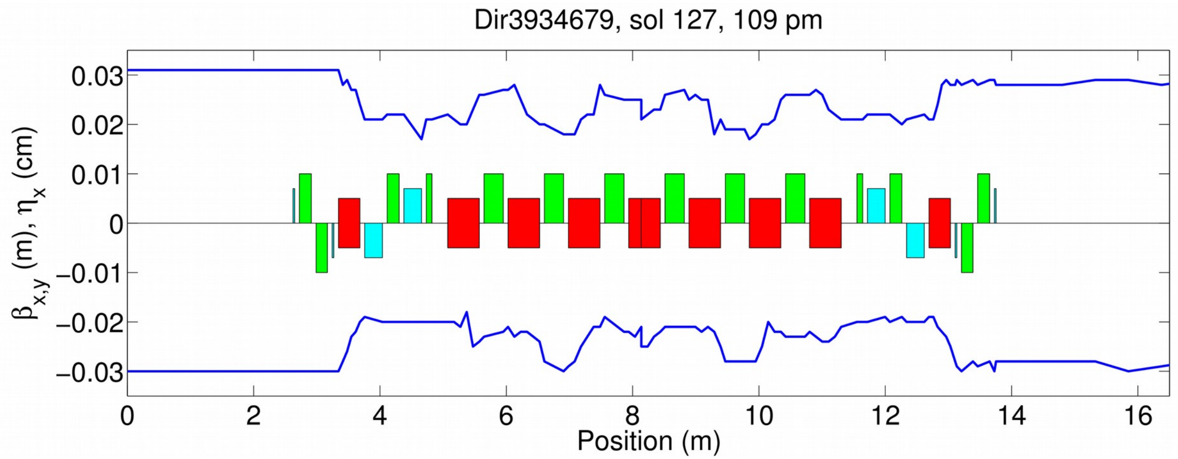

ALS Frequency map (NAFF): test.map


ALS Frequency map (NAFF): test_sol_127_noerr.map

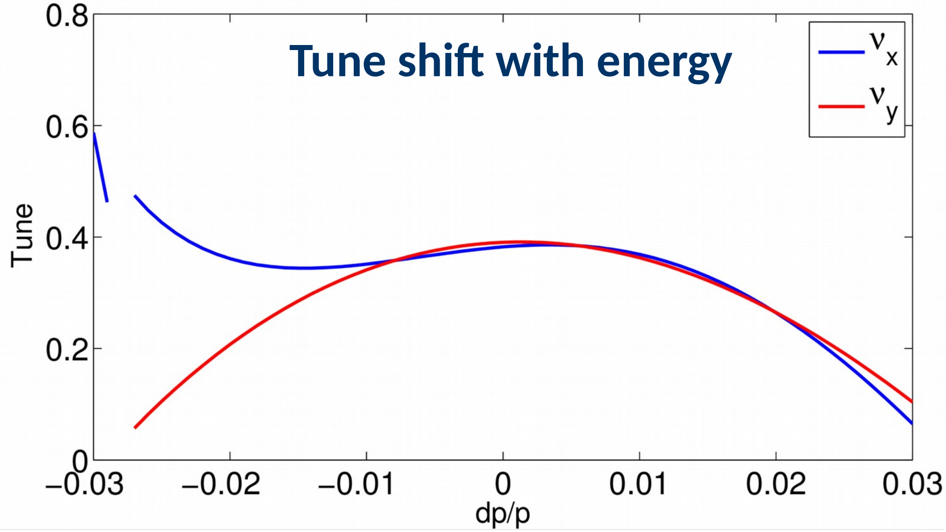
Without errors


ALS Frequency map (NAFF): test_sol_127_noerr.map

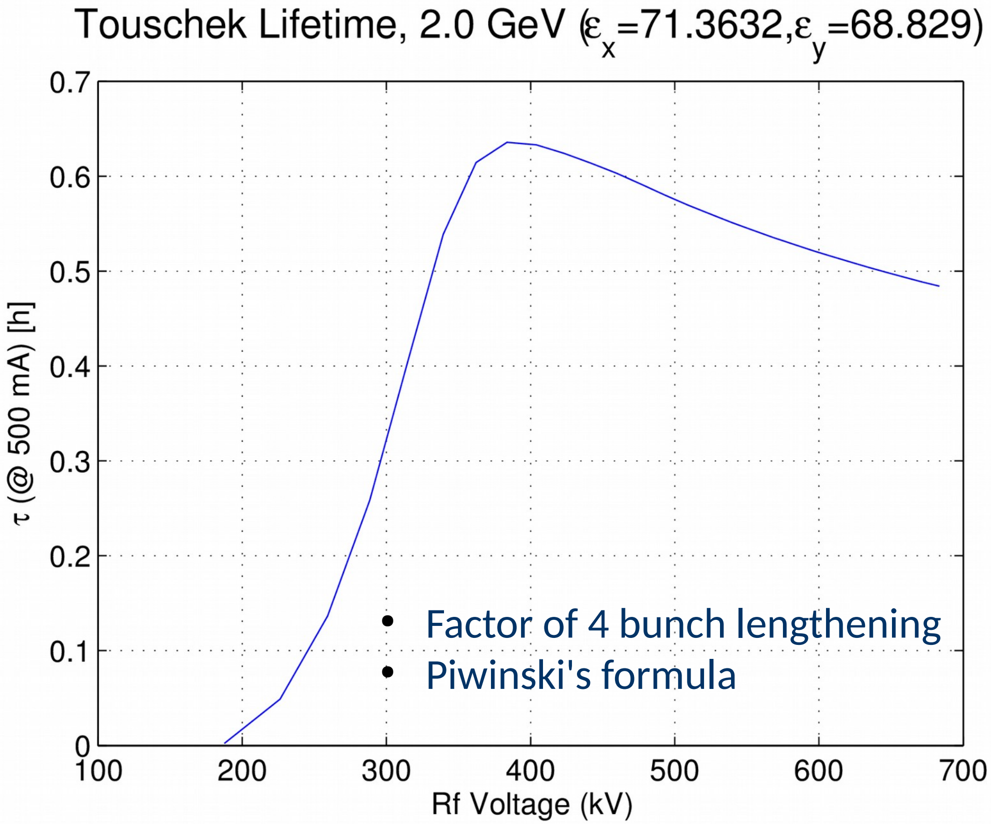
Momentum Aperture and Lifetime



- 6D tracking with cavity and radiation on
- Tracking for several dynamic time
- Skew quad and quad gradient errors are include
- RF voltage 650 kV and RF acceptance >3.7%



Tune shift with energy



- Factor of 4 bunch lengthening
- Piwinski's formula

Conclusions

- ALS-U received CD-0. We are actively working on the lattice design and optimization.
- MOGA has been extensively used to optimize ALS-U lattices, including 8BA, 9BA, super-bend and reverse bending lattices
- 9BA lattice is chosen as the current baseline design, which has dynamic aperture about 1 mm and lifetime about 1 hour
- Continue to explore lattice choices and improve the DA and MA