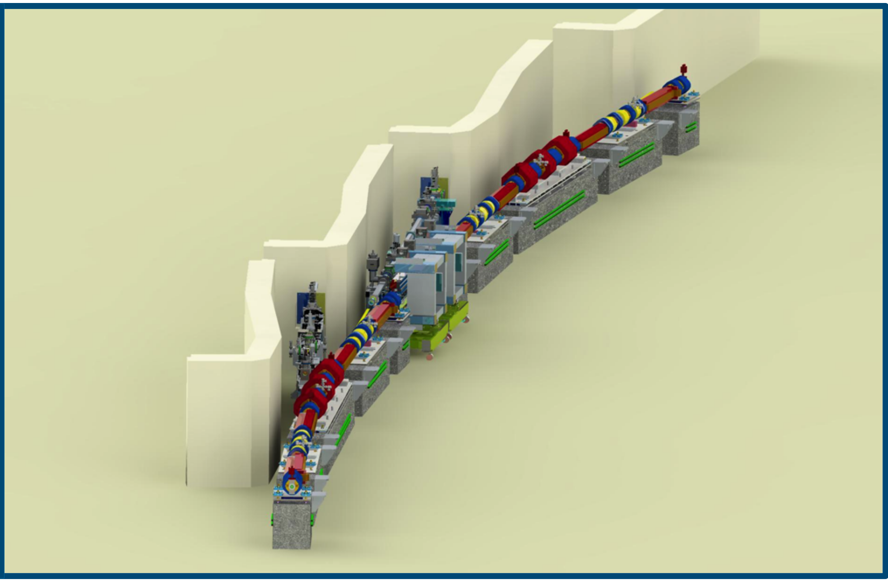
Comparison of five tracking based methods of optimizing nonlinear dynamics



Aimin Xiao presenting for **Yipeng Sun, Michael Borland**
Argonne National Laboratory

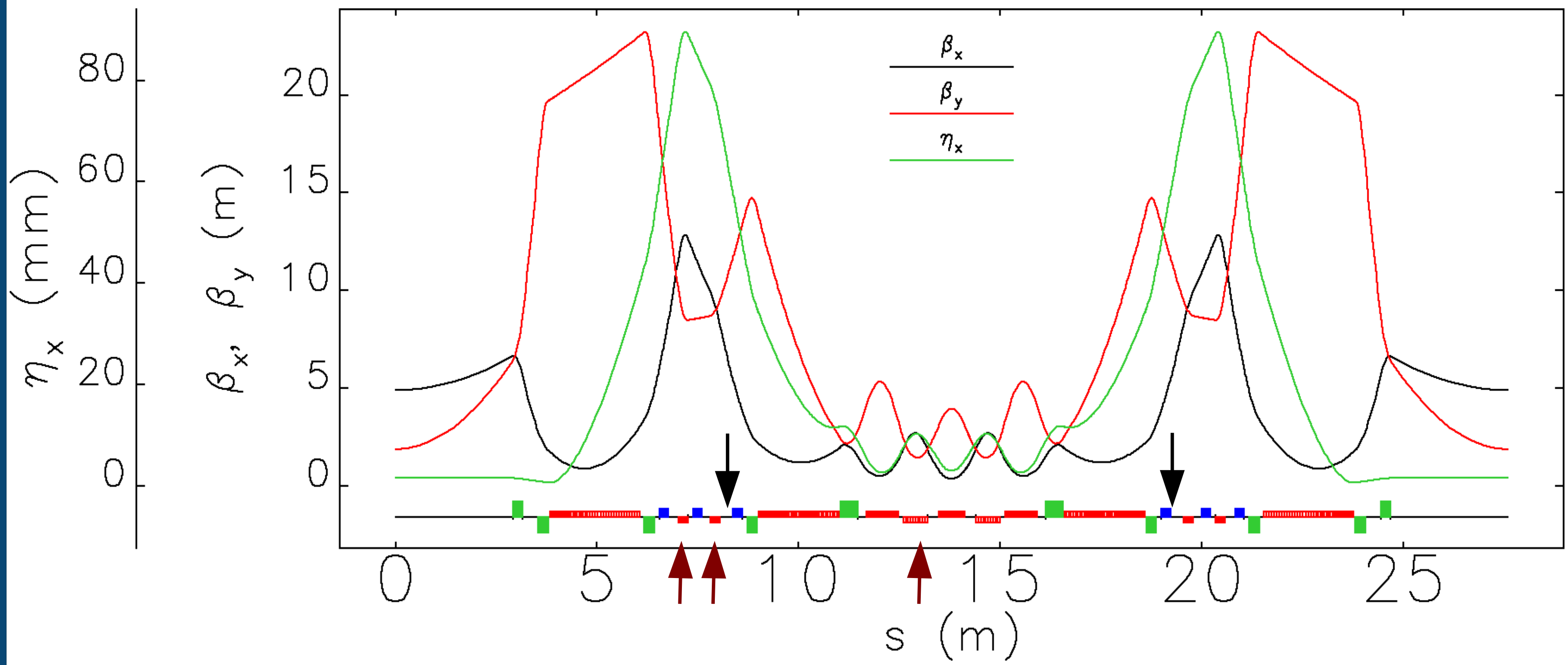
Thanks to APS-U physics team for discussions

ICFA Mini-Workshop on Dynamic Apertures of Circular Accelerators
November 01-03, 2017

Outline

- Overview of APS-U lattice
- Linear optics optimization
- Nonlinear optics optimization
  - Different algorithms and optimization targets
- Ensemble evaluation of performance robustness
- Benchmark studies at APS
- Conclusion

41-pm lattice with reverse bends



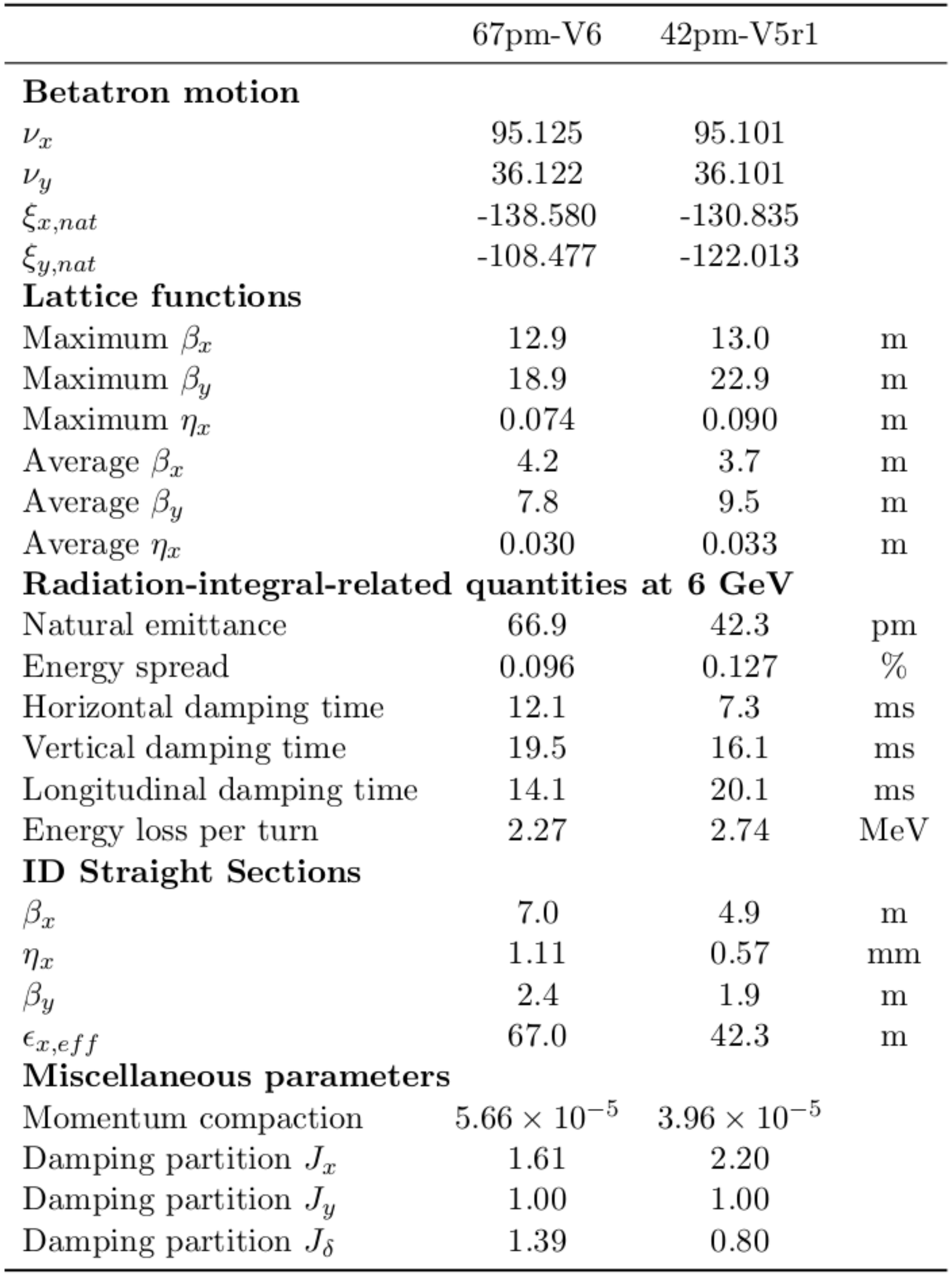
- Reverse bends in Q4, Q5, and Q8
- Emittance reduced from 67 pm to 41 pm
- Max η_x raised 74 mm to 90 mm: weaker sextupole magnets
- Black arrows mark two potential octupoles in existing 8-pole magnets

M. Borland et al. Proc. NA-PAC16 (2016).

Linear optics optimization

- Integer tunes scanned for best performance
  - Limited by minus I phase separation between sextupoles
- Linear lattice design iterates with other systems
  - Magnet design
  - Vacuum design
  - Beam instrumentation design
- Linear optics included in some MOGA optimization processes, using
  - Direct variation of gradients or
  - Variation of linear optics targets (e.g., emittance, fractional tunes, beta functions, phase separation)

High-level lattice comparison



	67pm-V6	42pm-V5r1	
Betatron motion			
ν_x	95.125	95.101	
ν_y	36.122	36.101	
$\xi_{x,nat}$	-138.580	-130.835	
$\xi_{y,nat}$	-108.477	-122.013	
Lattice functions			
Maximum β_x	12.9	13.0	m
Maximum β_y	18.9	22.9	m
Maximum η_x	0.074	0.090	m
Average β_x	4.2	3.7	m
Average β_y	7.8	9.5	m
Average η_x	0.030	0.033	m
Radiation-integral-related quantities at 6 GeV			
Natural emittance	66.9	42.3	pm
Energy spread	0.096	0.127	%
Horizontal damping time	12.1	7.3	ms
Vertical damping time	19.5	16.1	ms
Longitudinal damping time	14.1	20.1	ms
Energy loss per turn	2.27	2.74	MeV
ID Straight Sections			
β_x	7.0	4.9	m
η_x	1.11	0.57	mm
β_y	2.4	1.9	m
$\epsilon_{x,eff}$	67.0	42.3	m
Miscellaneous parameters			
Momentum compaction	5.66×10^{-5}	3.96×10^{-5}	
Damping partition J_x	1.61	2.20	
Damping partition J_y	1.00	1.00	
Damping partition J_δ	1.39	0.80	

Apertures and injected beam

- Physical apertures are much smaller than in our existing ring
  - Basic chamber has radius 10 mm in simulations
  - Photon absorbers have radius 8 mm
  - Insertion device chambers in three flavors
    - 2: Round with radius of 4 mm to allow helical SCUs
    - 8: Super-elliptical with a=4 mm, b=3 mm, n=6 to allow HGVPUs
    - 25: Elliptical with semi-axis of 10 mm and 3 mm
  - Collimation is still under study
    - Likely to be smaller than photon absorbers

$$\left|\frac{x}{a}\right|^n + \left|\frac{y}{b}\right|^n = 1$$

- Booster at 6 GeV, 100nm by 20nm emittance
- Vertical on-axis swap-out injection
- DA optimized to accept ±3σ from booster transversely

Nonlinear optics optimization[1,2]

[1] See citations in M. Borland, IPAC12, 1035.
[2] M. Borland, *et al*. J. Synch. Rad 21, 912-936 (2014).

- Optimization goals:
  - Large dynamic acceptance for injection efficiency
  - Large local momentum acceptance for Touschek lifetime
  - Desired positive chromaticity, motivated by 48-bunch mode
- Performance limited by
  - Smaller physical apertures
  - Strong focusing, large natural chromaticity
  - Smaller dispersion at sextupoles (than APS)
- Direct tracking optimization can include
  - Effects of likely errors
  - Effects of radiation damping and longitudinal motion
  - Vacuum chamber apertures
- Recently improved lifetime:
  - Control chromatic detuning
  - Inclusion of ID physical apertures
  - Explore different symmetry conditions for sextupoles

Exploration of different algorithms and optimization targets

Algorithms:

- MOGA: multi-objective genetic algorithm
- MPSO: modified particle swarm optimization (combines some features of GA)

Targets[1]:

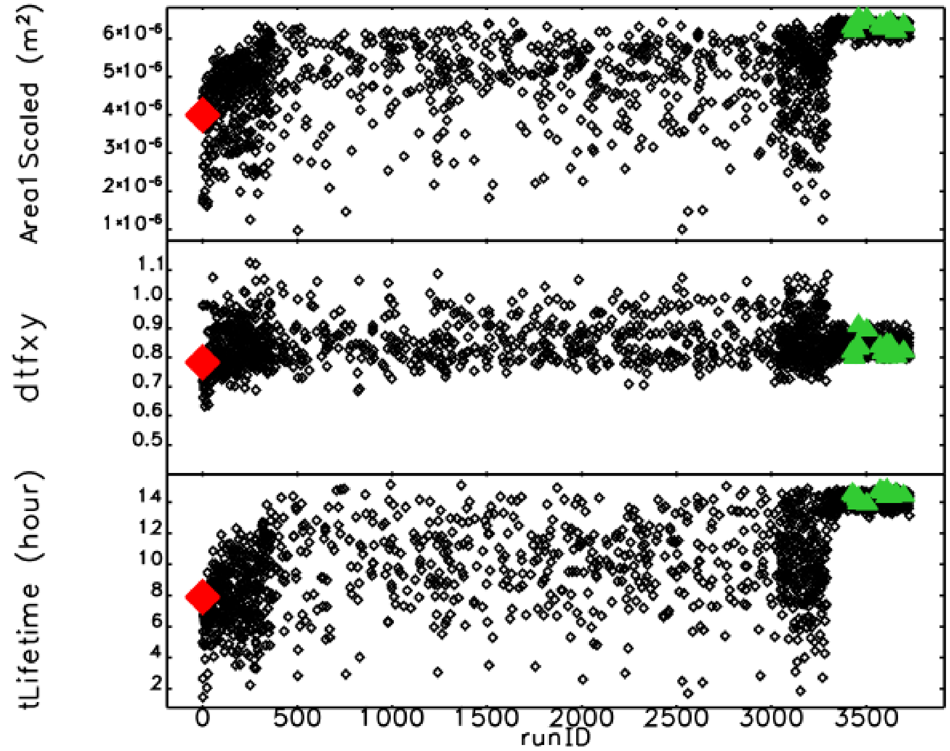
- **LMA**: objective of dynamic acceptance, local momentum acceptance and chromatic detuning (as above)
- **ANA**: objective of nonlinear chromaticity and driving/detuning terms
- **CSI**: objective of CS invariant distortion and chromatic detuning
- **DA**: objective of on- and off-momentum dynamic acceptance, and chromatic detuning
- **DET**: detuning of x-y grid (on and off momentum)

Knobs:

- Up to 12 families of sextupoles, w/ or w/o symmetry
- Same linear optics

[1] Y.-P. Sun et al., in NA-PAC16 (2016).

“LMA”: DA, LMA, chromatic detuning [1,2]



DA area (top)

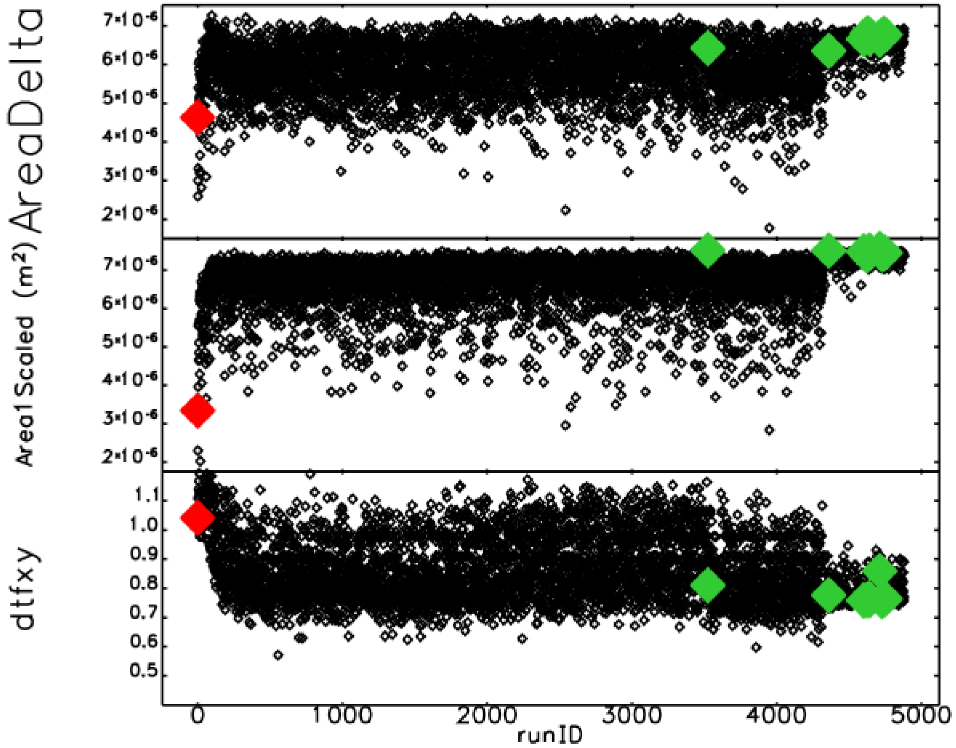
Chromatic detuning (middle)

Touschek lifetime (bottom)

- Nominal optimization method
- Need to track two synchrotron periods for LMA (~1000 turns)
- One case takes ~5 hours on 12 cores
- Effective and reliable

1. M. Borland et al. ANL/APS/LS-319, APS (2010).
2. M. Borland et al. J Synchrotron Radiation, 21:912 (2014).

“DA”: On- and off-momentum DA[1,2]



Off-momentum DA area (average of dp=±3%) (top)

On-momentum DA (middle)

Chromatic detuning (bottom)

- Preliminarily determines that fewer turns (<<1000 turns) needed for DA calculation
- Greatly reduces computing time needed
- Needs at least 500-1000 evaluations to converge

1. L. Yang et al. PRSTAB, 14:054001 (2011).
2. M. Ehrlichman. PRSTAB, 19:044001 (2016).

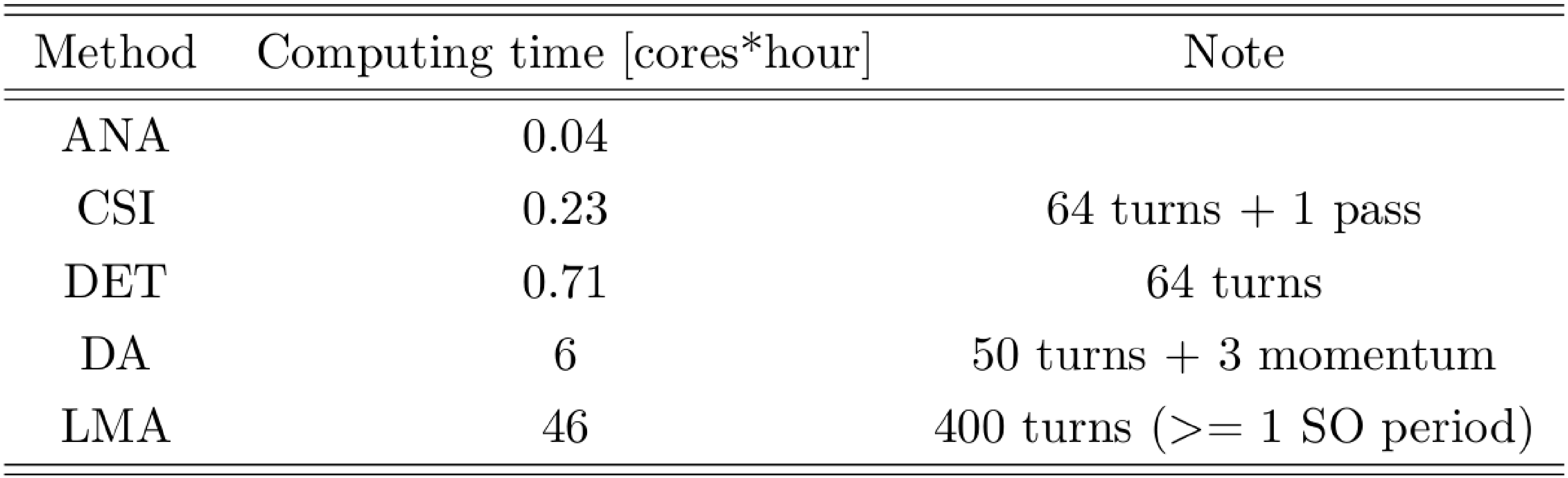
Other methods

In general, these methods take less computing time than **LMA** and **DA**

- **ANA**: objective of nonlinear chromaticity and driving/detuning terms[1]
  - Objectives targets selected from optimization results of other methods (LMA, DET...)
- **CSI**: objective of CS invariant distortion and chromatic detuning[2,3,4]
  - Track for one turn, or one super-cell
  - Different initial conditions of x-y space
- **DET:** objective of detuning of x-y grids, w/ or w/o energy offset

1. J. Bengtsson. SLS-TME-TA-1997-0009, SLS (1997).
2. B. Autin. M. Month et al., eds., Physics of Particle Accelerators, 288. American Institute of Physics (1987).
3. J. Hagel. CERN LEP-TH 86-22, CERN (1986).
4. Y. Li and L. Yu. TUPOB54, NA-PAC 2016.

Computing time



Method	Computing time [cores*hour]	Note
ANA	0.04	
CSI	0.23	64 turns + 1 pass
DET	0.71	64 turns
DA	6	50 turns + 3 momentum
LMA	46	400 turns (>= 1 SO period)

Computing time needed for each method
Measured using APS weed all.q cluster

Solutions from different methods

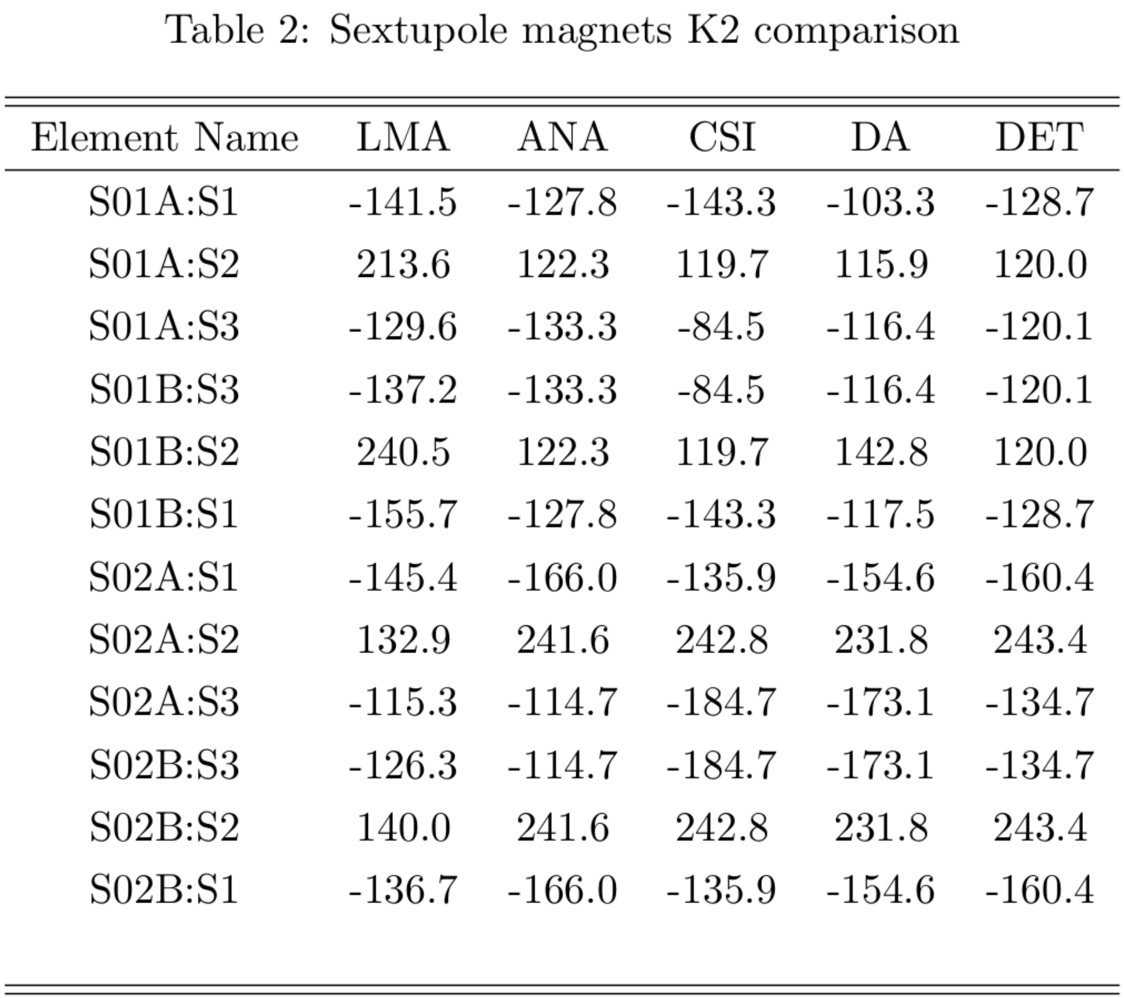


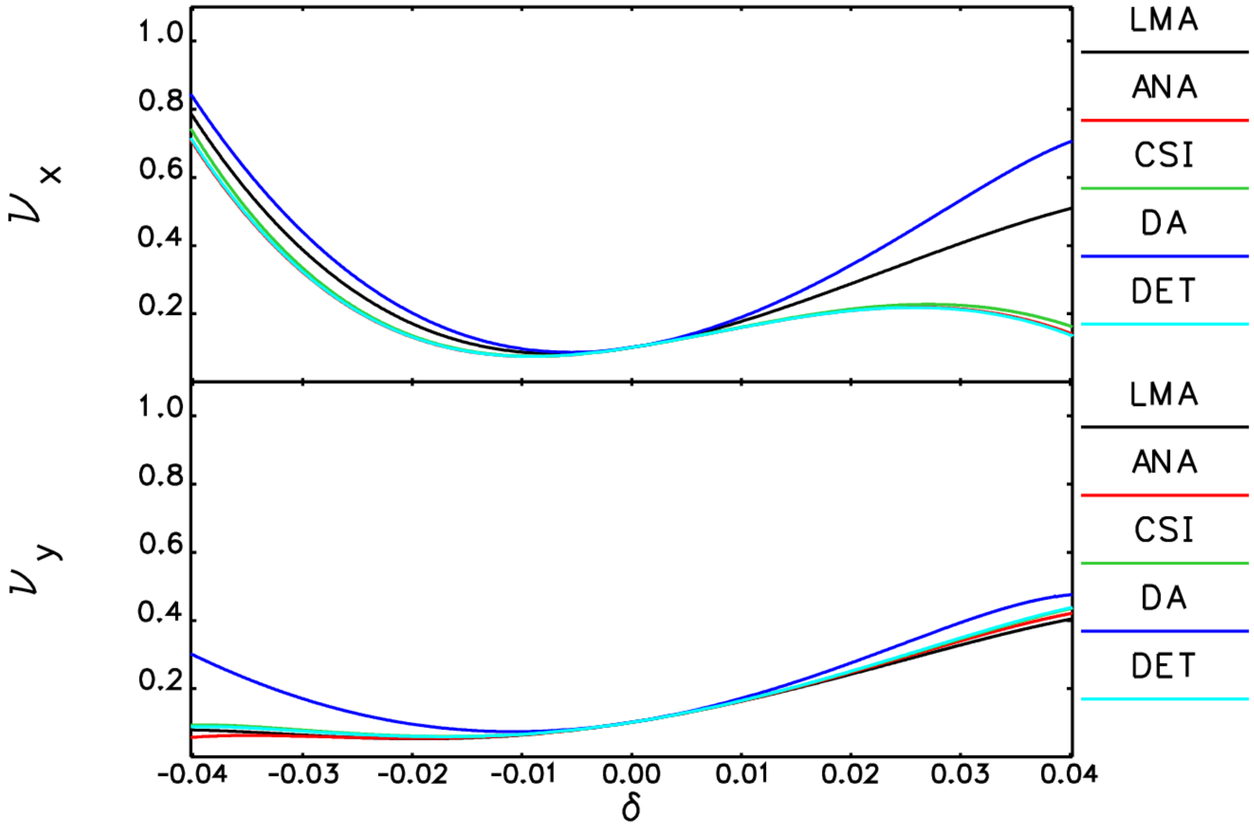
Table 2: Sextupole magnets K2 comparison

Element Name	LMA	ANA	CSI	DA	DET
S01A:S1	-141.5	-127.8	-143.3	-103.3	-128.7
S01A:S2	213.6	122.3	119.7	115.9	120.0
S01A:S3	-129.6	-133.3	-84.5	-116.4	-120.1
S01B:S3	-137.2	-133.3	-84.5	-116.4	-120.1
S01B:S2	240.5	122.3	119.7	142.8	120.0
S01B:S1	-155.7	-127.8	-143.3	-117.5	-128.7
S02A:S1	-145.4	-166.0	-135.9	-154.6	-160.4
S02A:S2	132.9	241.6	242.8	231.8	243.4
S02A:S3	-115.3	-114.7	-184.7	-173.1	-134.7
S02B:S3	-126.3	-114.7	-184.7	-173.1	-134.7
S02B:S2	140.0	241.6	242.8	231.8	243.4
S02B:S1	-136.7	-166.0	-135.9	-154.6	-160.4

Up to 12 families of sextupoles, w/ or w/o symmetry

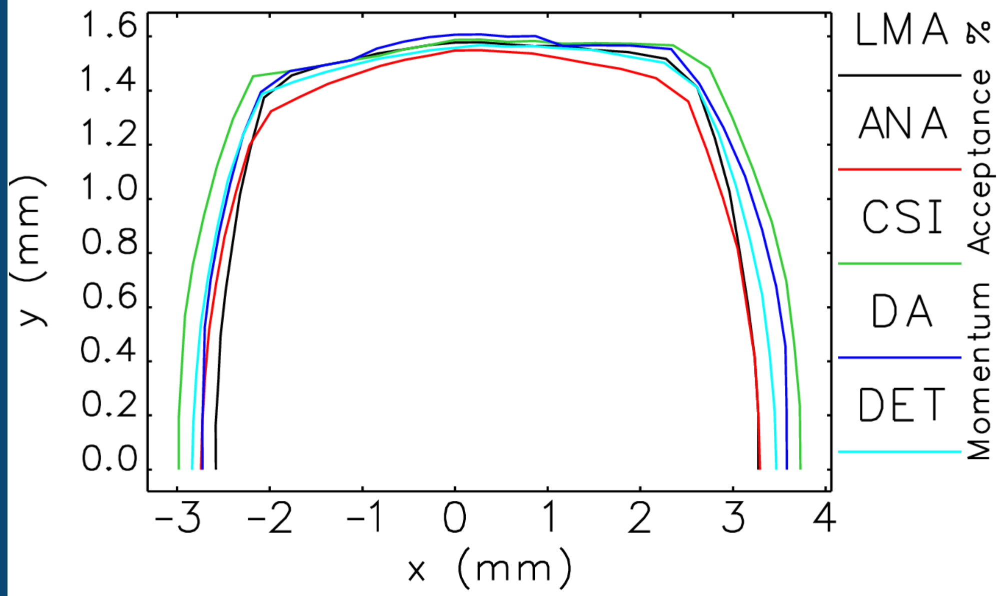
Same linear optics

Chromatic detuning in latest 41-pm lattice

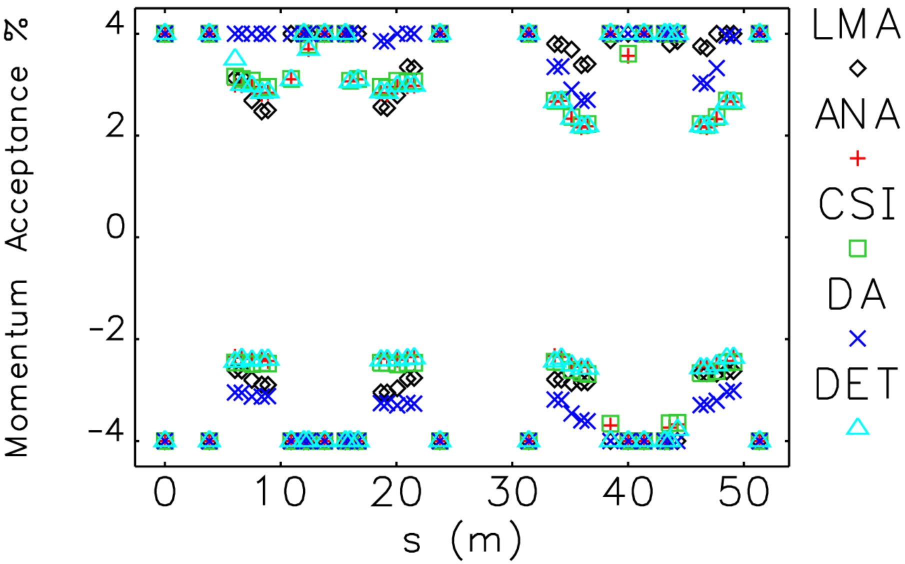


- LMA: objective of dynamic acceptance, chromatic detuning and local momentum acceptance
- ANA: objective of nonlinear chromaticity and driving/detuning terms
- CSI: objective of CS invariant distortion and chromatic detuning
- DA: objective of on- and off-momentum dynamic acceptance, and chromatic detuning
- DET: objective of detuning of x-y grids, w/ or w/o energy offset

Performance without errors



Dynamic acceptance

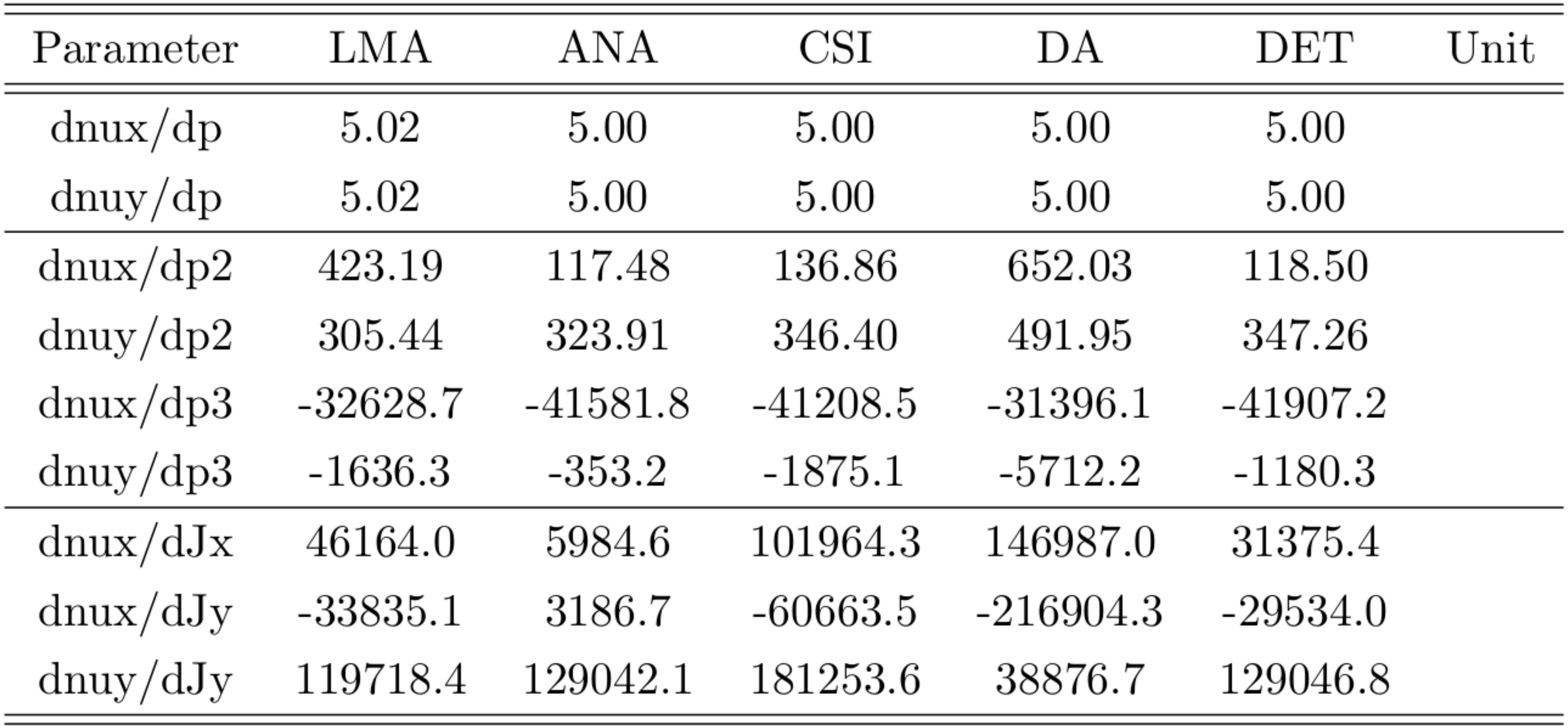


Local momentum acceptance

These methods provide:

- Different dynamic acceptance
- Different local momentum acceptance
- **LMA, DA** and **CSI** are similar; **ANA** and **DET** slightly worse
- This conclusion does not hold for evaluation with errors

Comparison



Parameter	LMA	ANA	CSI	DA	DET	Unit
dnux/dp	5.02	5.00	5.00	5.00	5.00	
dnuy/dp	5.02	5.00	5.00	5.00	5.00	
dnux/dp2	423.19	117.48	136.86	652.03	118.50	
dnuy/dp2	305.44	323.91	346.40	491.95	347.26	
dnux/dp3	-32628.7	-41581.8	-41208.5	-31396.1	-41907.2	
dnuy/dp3	-1636.3	-353.2	-1875.1	-5712.2	-1180.3	
dnux/dJx	46164.0	5984.6	101964.3	146987.0	31375.4	
dnux/dJy	-33835.1	3186.7	-60663.5	-216904.3	-29534.0	
dnuy/dJy	119718.4	129042.1	181253.6	38876.7	129046.8	

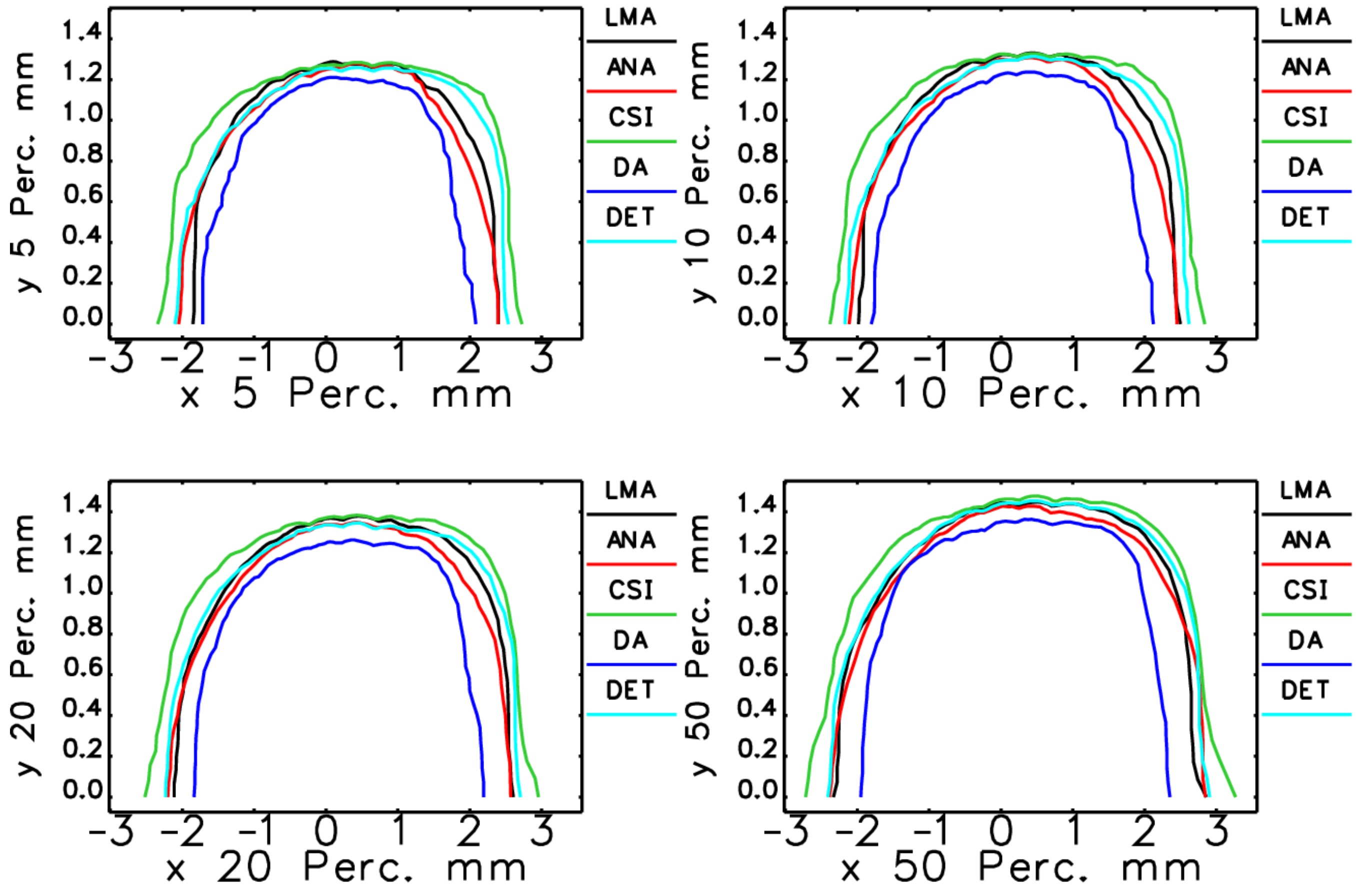
Different chromaticities and linear detuning terms

Ensemble evaluation procedure

- After MOGA optimization, perform commissioning simulations (with Vadim Sajaev's scripts[1])
  - Magnet strength and tilt errors
  - Misalignment and BPM errors; corrector errors
  - All configurations show similar success rate
- Ensemble evaluation to check the solution using results of commissioning simulations
  - Random and systematic multipoles; steering multipoles
  - Narrow IDs and harmonic cavity
  - These give ~100 dynamic acceptance (DA) and local momentum acceptance (LMA) results
  - Simplified methods for Touschek lifetime calculations with ideal 4th harmonic cavity

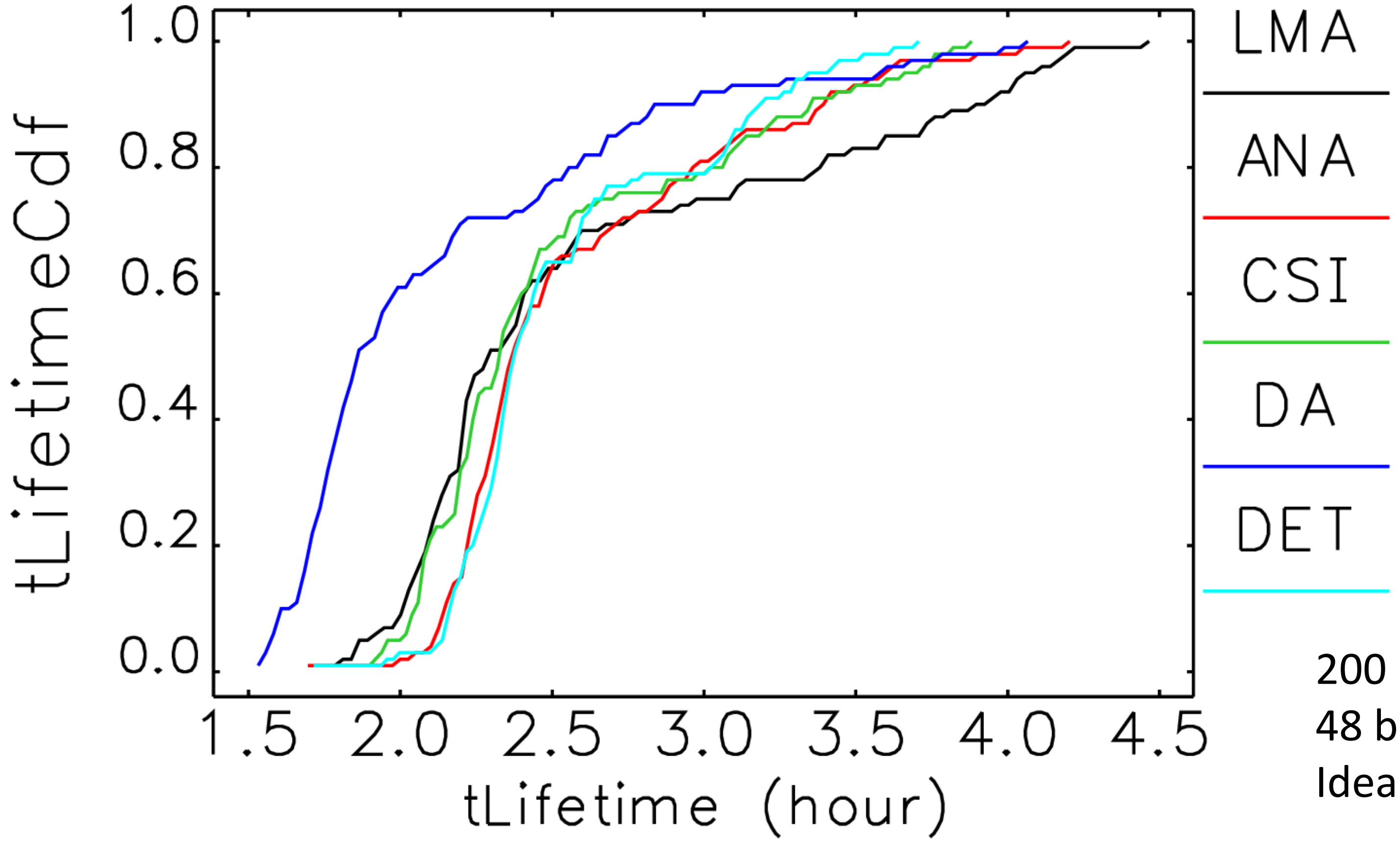
1: V. Sajaev, IPAC15, 533 (2015).

DA from ensemble evaluations



- Similar/larger DA than previous lattice version
- **CSI** and **DET** give larger dynamic acceptance
- **LMA** and **ANA** are similar
- Detailed injection simulation still to be done

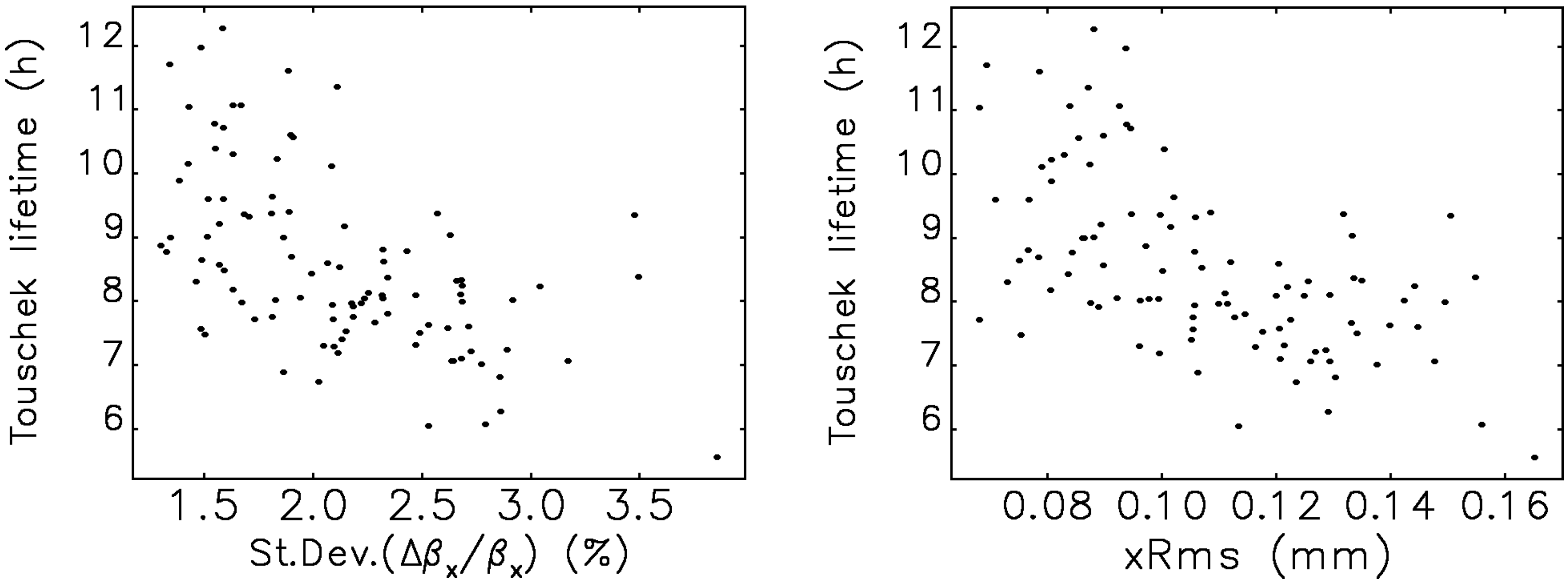
Touschek lifetime from ensemble evaluations



200 mA
48 bunches
Ideal harmonic cavity

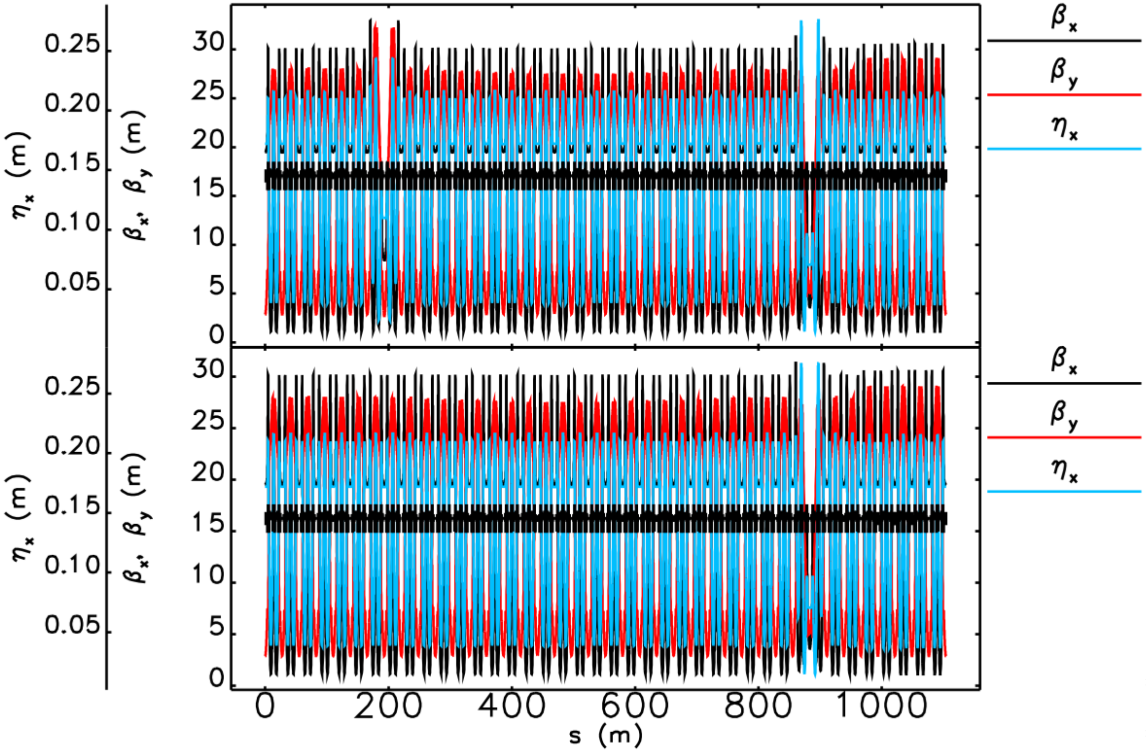
- **LMA** still most reliable; **DET** and **ANA, CSI** give similar lifetime
- **DA** lower lifetime

Analysis of performance variation for 67pm V6 lattice



- Looking for explanation of performance variation in ensemble evaluation
- See correlations with Touschek lifetime (324 bunch mode)
  - Horizontal beta beat, dispersion beat, rms x orbit (r=-0.57)
  - Vertical beta beat (r=-0.53)
- Correlations with DA are weaker
- Improved orbit and lattice correction should be pursued to improve lifetime

Benchmark Studies at APS



APS, 40 DBA cells, 3 nm

Bottom: Reduced horizontal beam lattice at 32-ID, **UBOP**

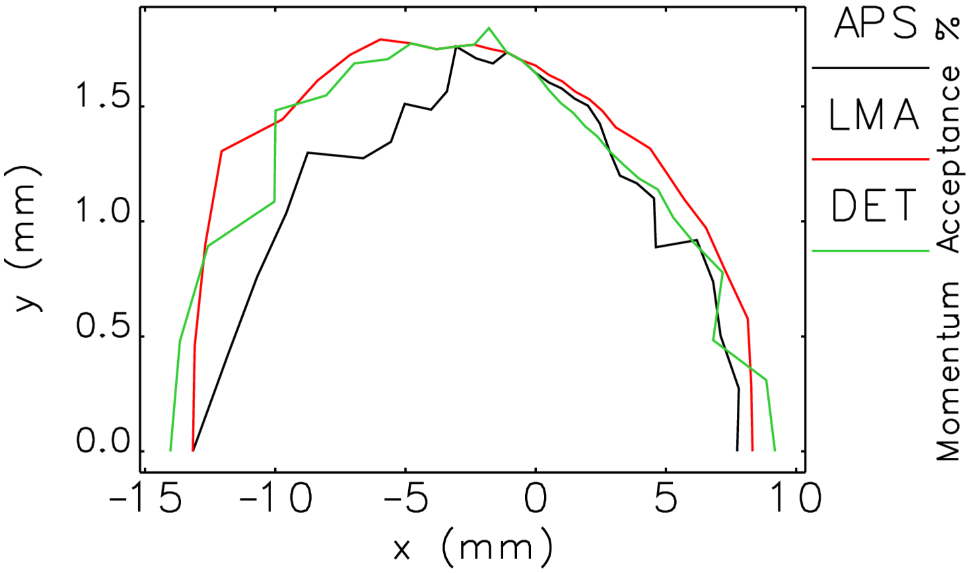
Top: plus RHB at 7-ID for HSCU, **HSCU***

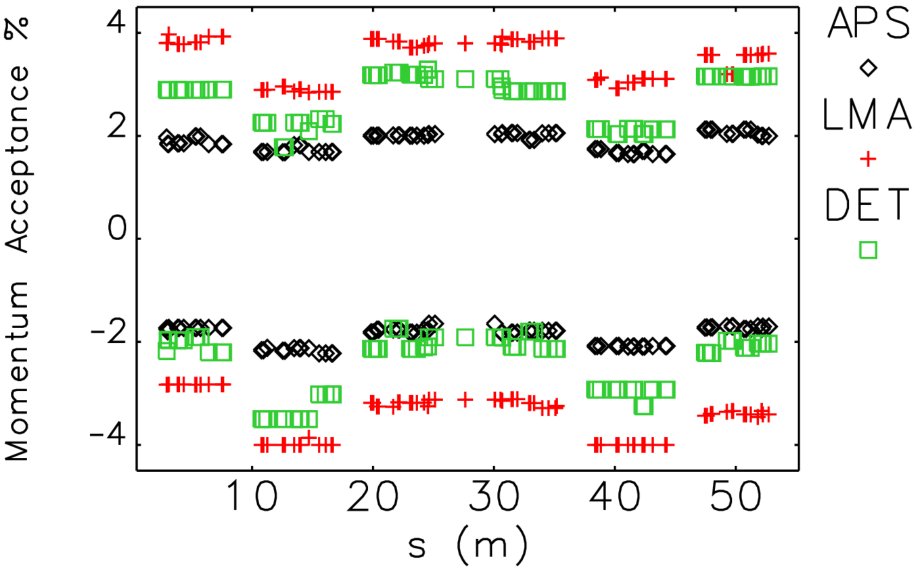
*Yipeng Sun et al, AOP-TN-2016-034

*Vadim Sajaev et al., in NAPAC16

- **LMA** method benchmarked several times, consistently improve APS machine performance (injection efficiency and lifetime)
- Recently preliminarily compared **LMA** and **DET**
  - 21 families of sextupoles (S4 and S5 for narrow ID-4)

Benchmark Studies at APS, simulations





Dynamic acceptance

Local momentum acceptance

DET solution shows ~2mm wider DA in x

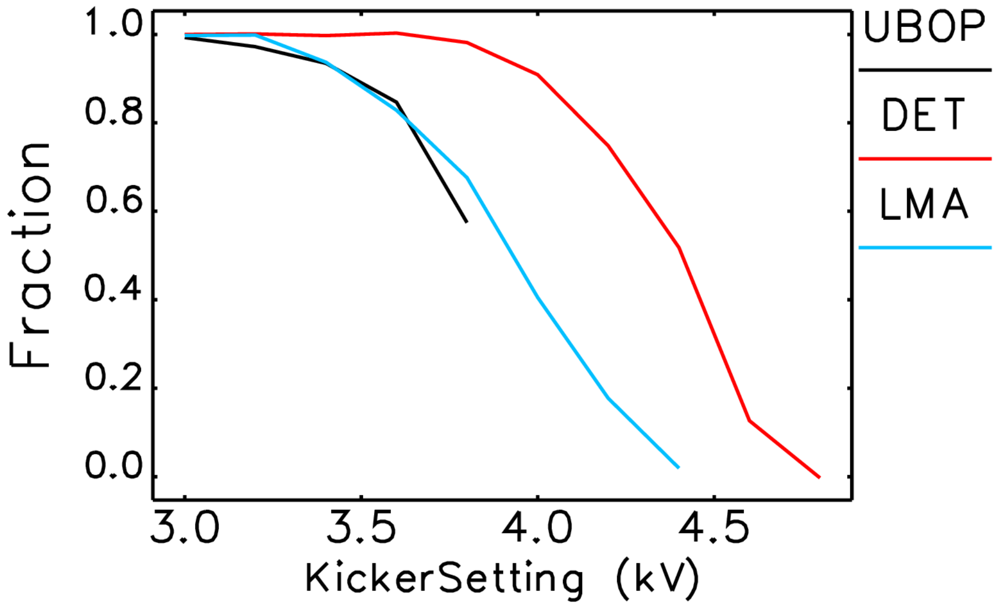
LMA solution shows larger momentum apertures

Note: LMA solution was picked with highest lifetime, and smaller DA

Benchmark Studies at APS, measurements

Case	Inj. Eff.	Lifetime [h]
UBOP + K2(UBOP)	87%	69
HSCU + K2(UBOP)	85%	58
HSCU + K2(**LMA**)	87%	73
HSCU + K2(**DET**)	92%	66

Injection efficiency and lifetime (1.3% coupling, 102 mA in 324 bunches, 9.5 MV RF, chromaticity of 3 in both planes).



LMA solution was picked with highest lifetime, and smaller DA

Both LMA and DET solutions improve APS performance

*Vadim Sajaev, Yipeng Sun, Apr 18, 2017

Online machine-based optimization APS

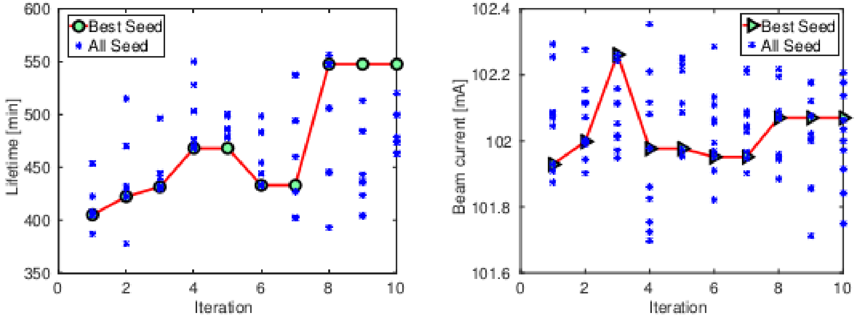


Figure 5: Topup mode, lifetime (left) and beam current (right) at each iteration. A total of 10 iterations, and 10 seeds for each iteration. Starting point is optimized sextupoles from MOGA simulation [7,15] on the medium chromaticity lattice ($\xi = 6$).

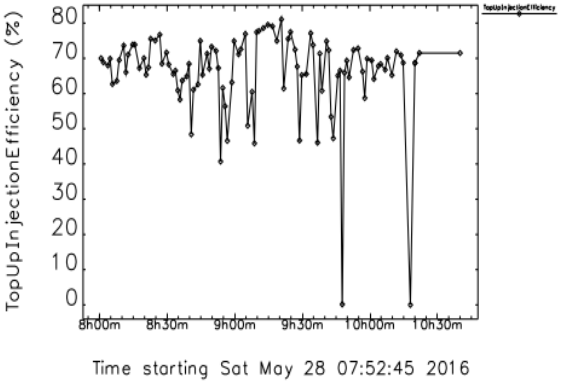


Figure 7: Top up injection efficiency during optimization.

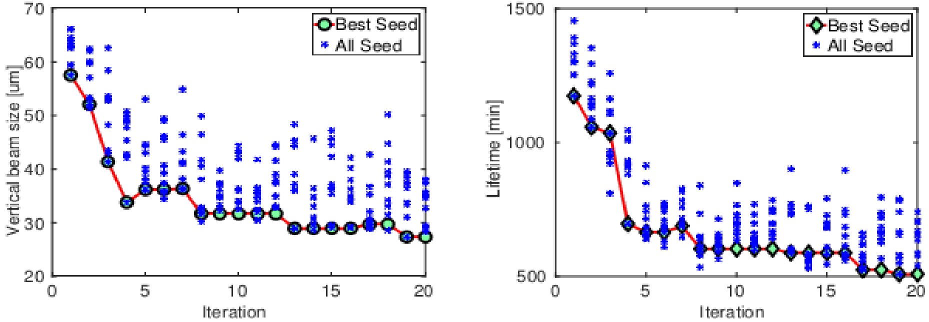


Figure 8: Vertical beam size (at sector 35 pinhole location) (left) and lifetime (right) at each iteration. A total of 20 iterations, and 10 seeds for each iteration. Starting point is 0 strength skew quads.

Parameter	MOGA	LOCO
σ_x @s35 pinhole	104.7	103.9
σ_y @s35 pinhole	24.6	22.3
Beam current [mA]	63	95
Lifetime [min]	320	300
ξ_x/ξ_y (measured)	6.34/6.27	4.23/3.28
RF gap voltage [MV]	9.415	9.410

Y.-P. Sun et al., in NA-PAC2016

Partial List of On-going and Planned Work

- Iterate with vacuum and magnet engineering design
- New optimization algorithms and setup development
  - Include off-m beta beating (in **ANA**)
  - Include optics beating from 100 commissioning/ensemble seeds (for faster methods)
  - ReMOGA for **LMA** (try to improve the worst seed)
- Octupole fields in the 8-pole corrector magnets (4 per sector); previous studies demonstrated improvements
- Continue bench-marking efforts for single-particle dynamics models using existing APS

Conclusions

- Both linear and nonlinear optics optimized for APS-U 41-pm lattice
- Different algorithms and optimization targets implemented for nonlinear optics optimizations
  - Some are much faster than original optimization approach using **LMA**
  - Explored different solutions spaces
  - Comparable performance
- There are some indications that improved orbit and lattice correction will allow increasing the lifetime of APS-U
- APS applications improved machine performance
  - Simulation based optimization
  - Online machine based optimization

Acknowledgements

- Early version of H7BA lattice used file provided by ESRF.
- Many of the simulations used the Blues cluster at Argonne's Laboratory Computing Resources Center
- Vadim Sajaev for providing commissioning scripts
- M. Ehrlichman for triggering our interest in the DA method; and Y. Li for introducing us to the square matrix method
- APS-U Beam physics team provided frequent feedback and advice