ALS-U: highest brightness soft x-rays in just 200 m through an ultra-dense 9BA and extensive MOGA optimization

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U.S. DEPARTMENT OF ENERGY
Office of Science

BERKELEY LAB

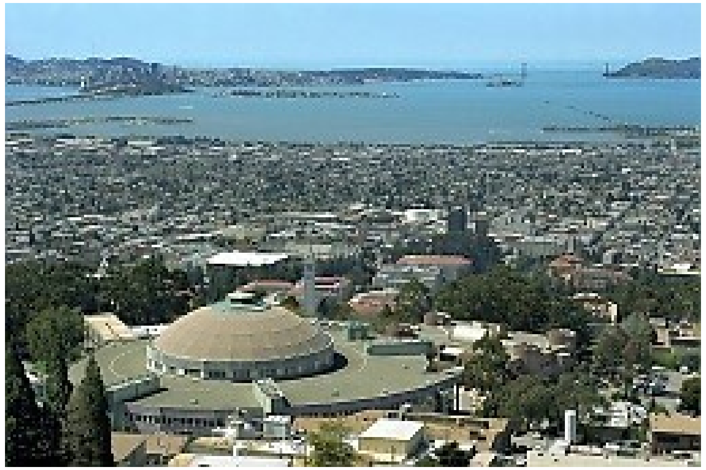
ALS-U
ADVANCED LIGHT SOURCE

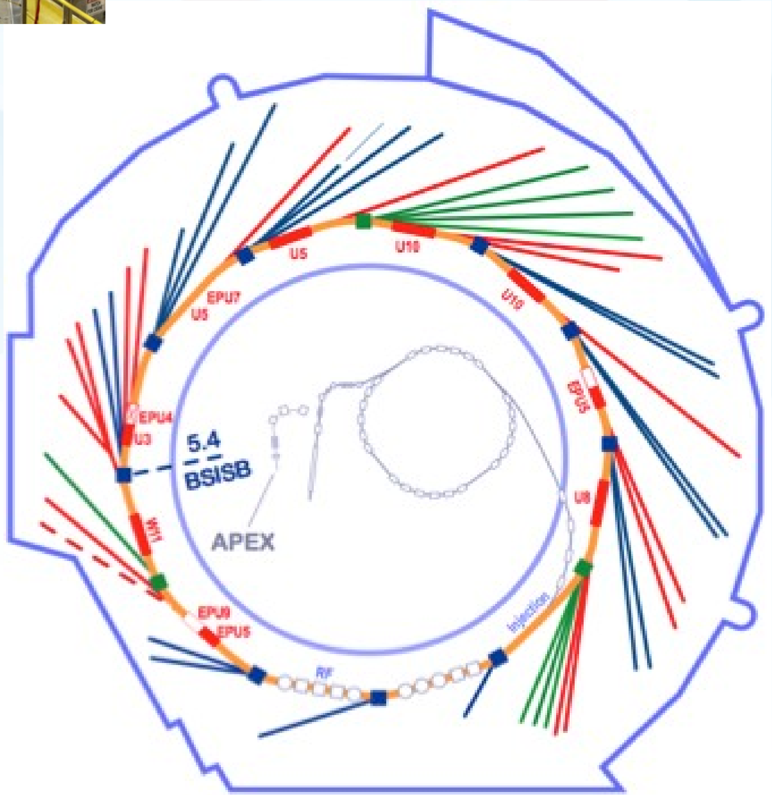
LEL 2022 |3rd Workshop on Low Emittance Lattice Design| June 26 – 29, 2002

Outline

- ALS-U project overview
- Lattice design and optimization
- Conclusions

Advanced Light Source (ALS)

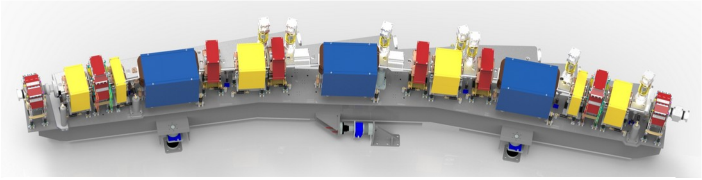


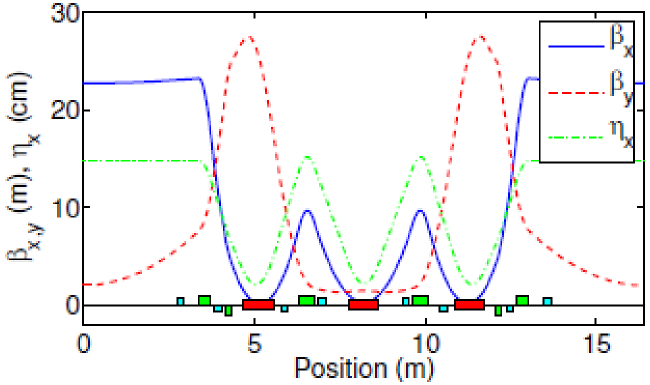


- One of the first 3rd generation light source has been in operation for ~30 years since 1993
- 1.9 GeV storage ring with ~200 meter circumference
- Optimized for soft x-rays however covers a wider spectrum – from IR to hard x-rays
- ~40 beamlines, mixture of bend, ID and superbend with over 2000 users each year

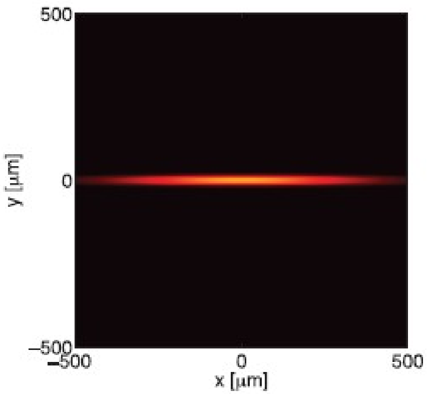
ALS-U will replace TBA lattice with 9BA lattice

ALS today : triple-bend achromat

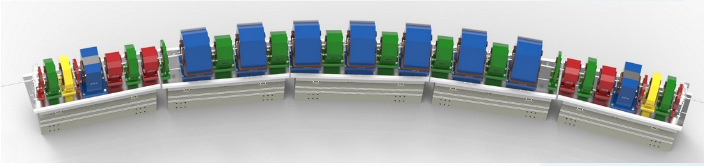


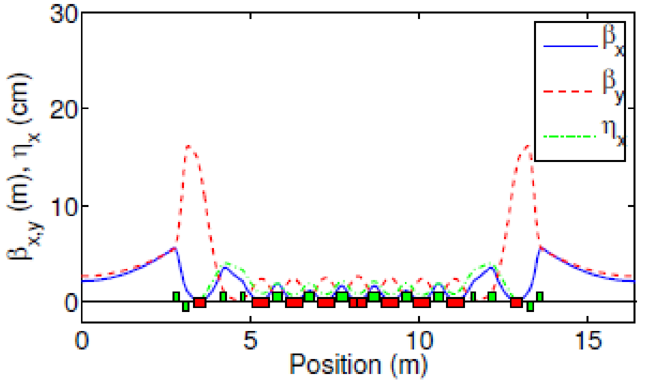


$\varepsilon_x \approx 2000$ pm-rad at 1.9 GeV

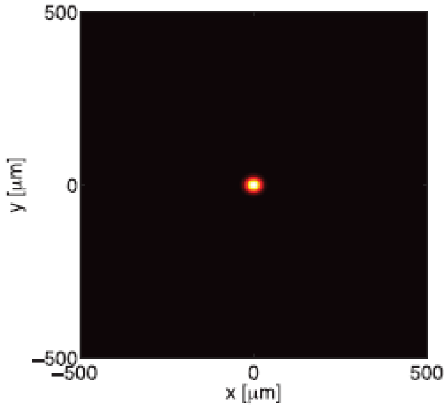


ALS-U: 9-bend achromat with reverse bends





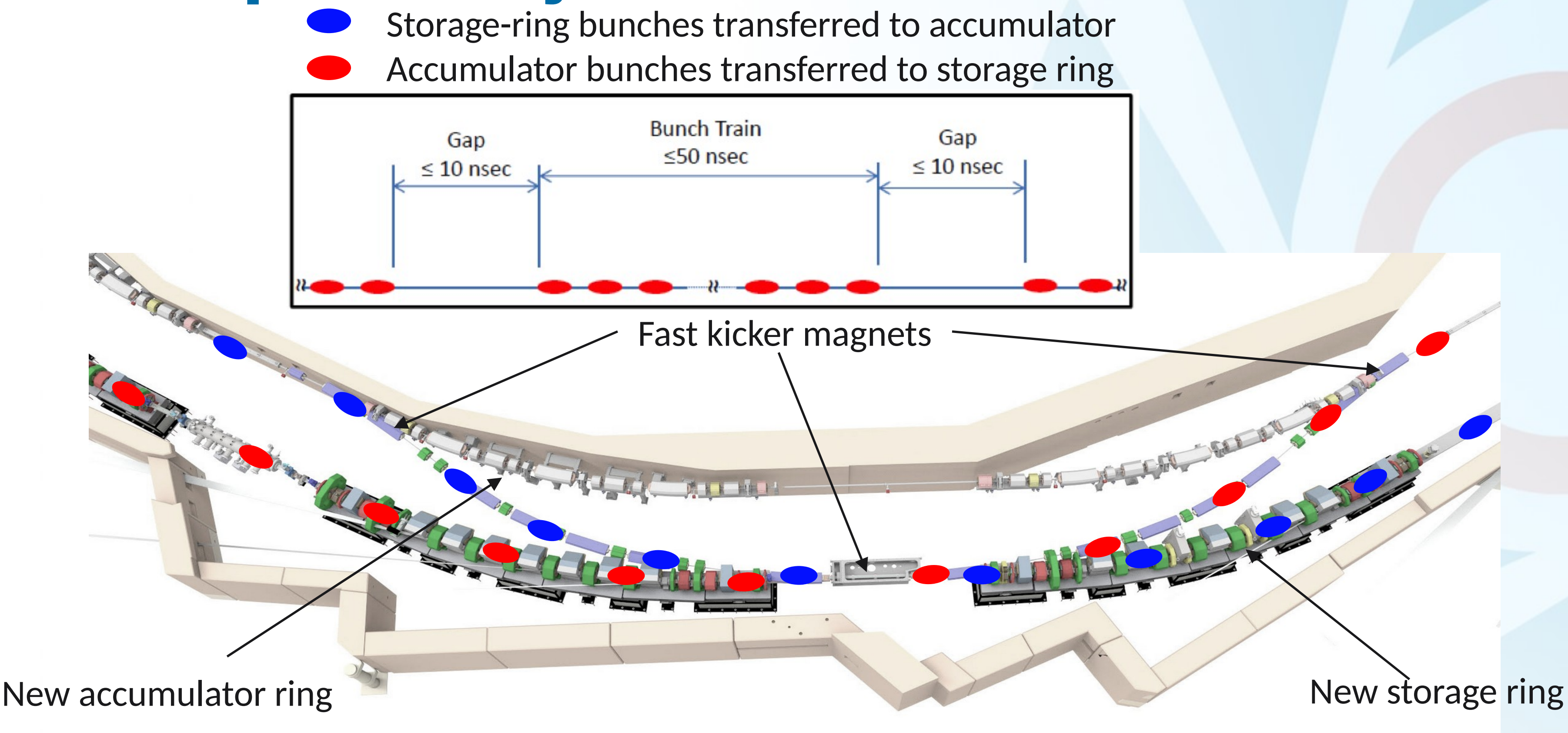
$\varepsilon_x < 75$ pm-rad at 2.0 GeV



ALS to ALS-U

Parameter	Units	ALS	ALS-U
Electron energy	GeV	1.9	2.0
Beam current	mA	500	500
Horiz. emittance	pm-rad	2000	<75
Vert. emittance	pm-rad	30	<75
Beamsize @ ID center (σ_x/σ_y)	μm	251 / 9	<14 / <14
Beamsize @ bend (σ_x/σ_y)	μm	40 / 7	<7 / <10
bunch length (FWHM)	ps	60-70 (harmonic cavity)	120-200 (harmonic cavity)
Circumference	m	196.8	~196.5

On-axis swap-out injection



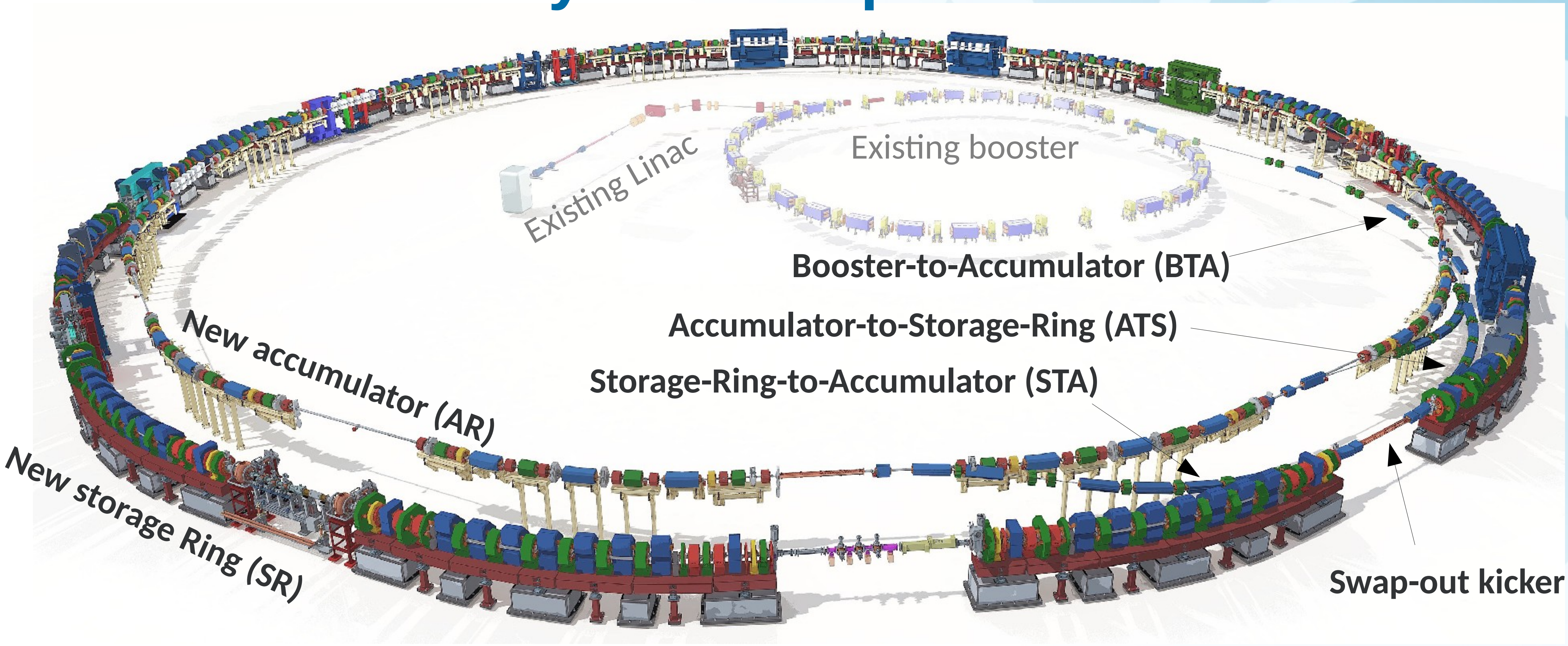
Swap-out enables

- MBA lattices with smaller dynamic apertures → higher brightness
- Small round apertures → improved undulator performance

Bunch train swap-out with beam recovery in accumulator

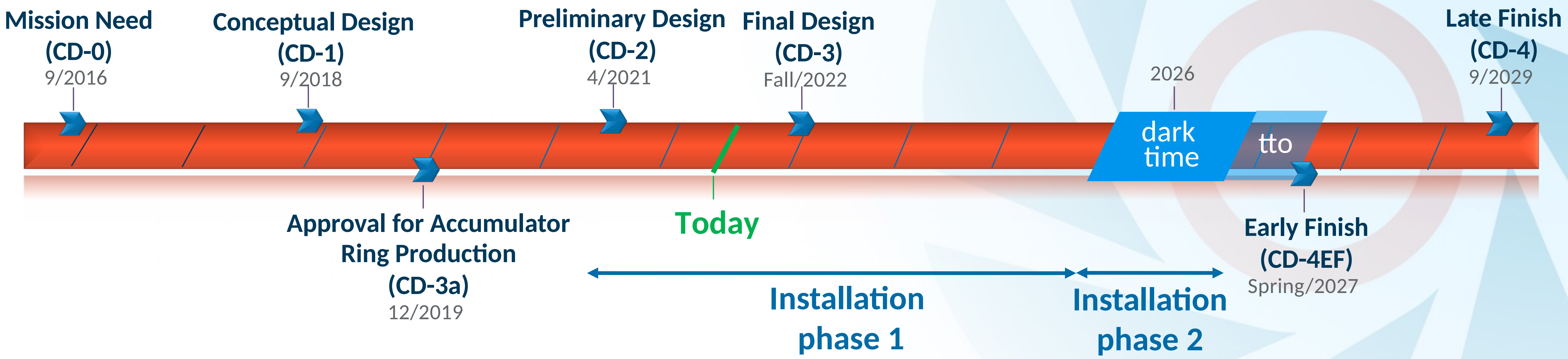
- Lower demand on the injector
- Very small (~nm) injected emittance

ALS-U accelerator system scope



Replacement of the existing triple-bend achromat storage ring with a new, high-performance storage ring based on a multi-bend achromat.
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.
Addition of 2 new undulators and refurbishment of existing undulators or undulator vacuum chambers where needed.

ALS-U project timeline

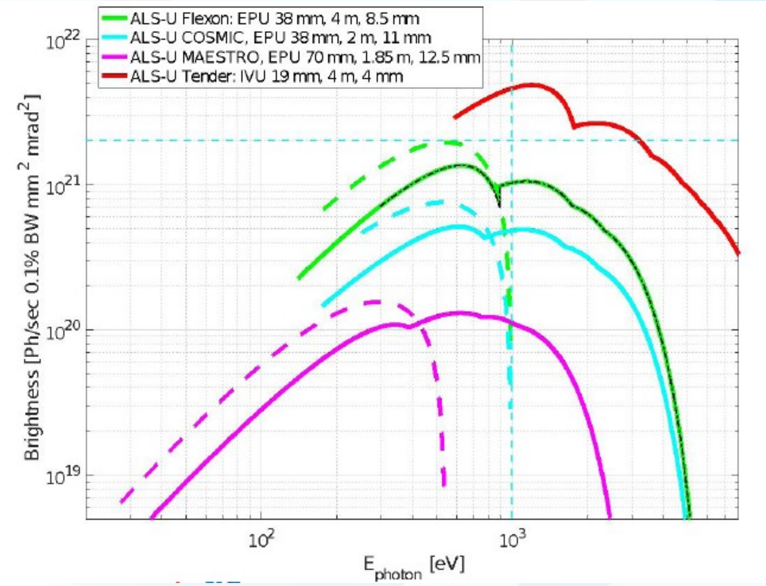


- CD-0 approval in Sept. 2016 and CD-1 in Sept. 2018
- Baselined CD-2 in April 2021 with CD-4 in Sept. 2029
- Currently completing the final design (CD-3) and plan to transition into the implementation phase this fall
- Dark Time is scheduled to be one year in 2026 followed by a 6-month transition to operations (tto) where beamlines are brought online
- Accumulator is procured early (CD-3a) in Dec. 2019
- Installation is separated into 2 phases: Tunnel prep and accumulator ring installation during phase 1; Replace the existing storage ring with a new ring and install new beamlines during phase 2

Storage ring lattice design and optimization

Project goal, constraints and design requirements

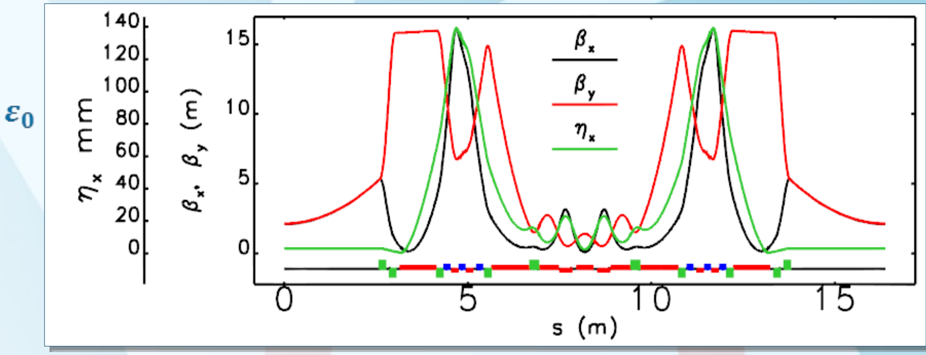
- **High-level project goals:**
  - Factor ~100 improvement of brightness @1keV photon energy over current ALS
  - Continuing support of super-bend beamlines
  - Continuing IR science program
- **Boundary conditions:**
  - Fit existing ALS site
  - Maintain the same no. and length of straight sections; avoid movement of existing ID beamlines
  - Leverage existing injection system (Linac, Booster) and other subsystems (RF infrastructure) as much as possible
- **Lattice design requirements**
  - A round beam with ~75 pm emittance and 2-3 m beta functions
  - A sufficient dynamics aperture (DA) for on-axis swap-out injection and long vacuum lifetime
  - A sufficient momentum aperture (MA) to achieve ~1 hour Touschek lifetime



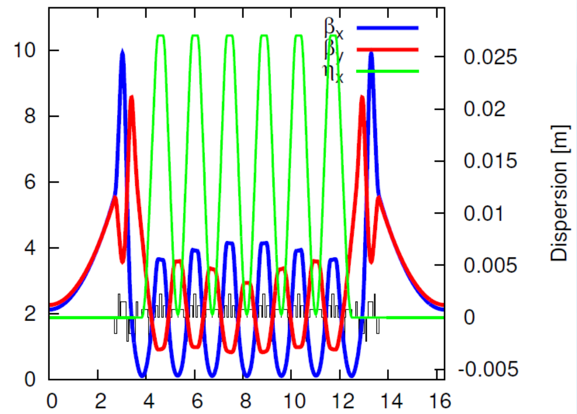
Lattice exploratory

- The target emittance could in principle be met by MBA with the number bend > 7
- 10BA lattice would require excessive field gradients to achieve emittance goal since magnet too short
- 8BA lattices in hybrid-like configuration were early on found promising but discarded because of insufficient MA and liftime
- 7BA lattices need high-field longitudinal-gradient magnets (+ reverse bending):
  - APS-U typed hybrid 7BA seem to have larger emittance than 9BA
  - Aggressive MAX-IV style 7BA could top brightness of 9BA, but many challenges in magnet technology for high-field combined function longitudinal gradient dipoles, vacuum design and strong sext
- 9BA lattices meet both emittance and dynamic requirements and chosen as our baseline lattice
  - The limited space prevents the ESRF type design with “-I” phase advance cancellation in the same sector
  - Rather, the phase advance cancellations are achieved across adjacent sectors

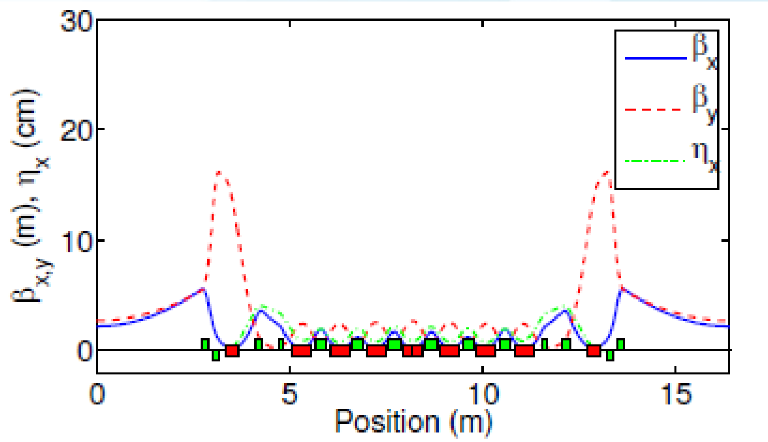
ESRF/APS-U Type 7BA lattice



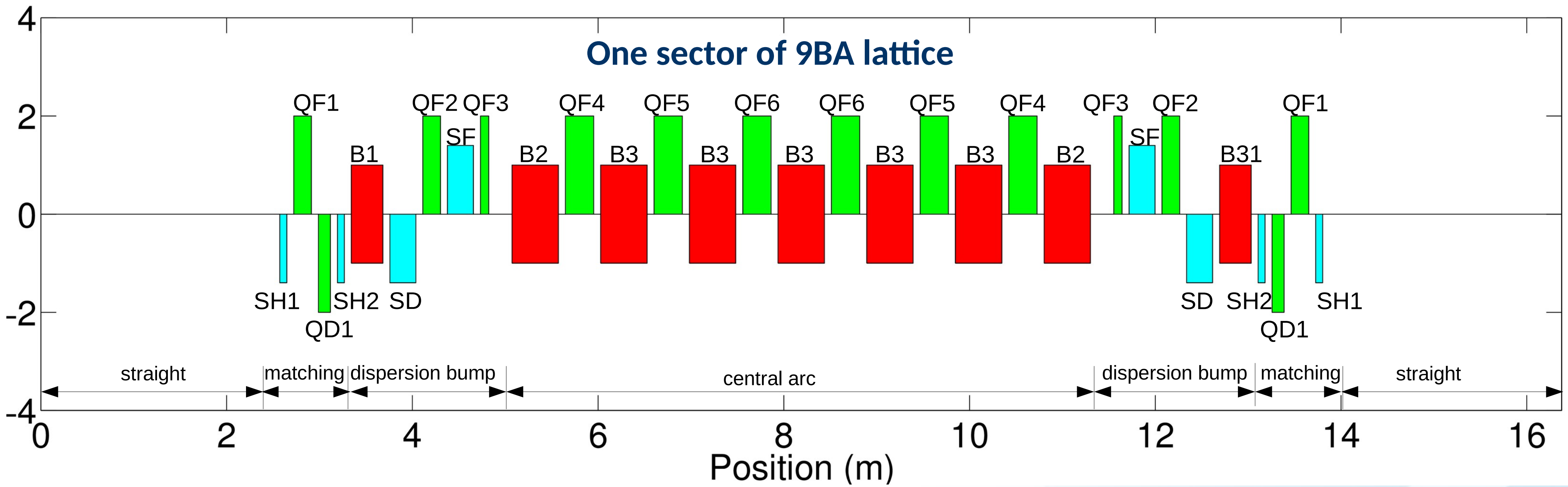
Max-IV type 7BA lattice



ALS-U 9BA lattice

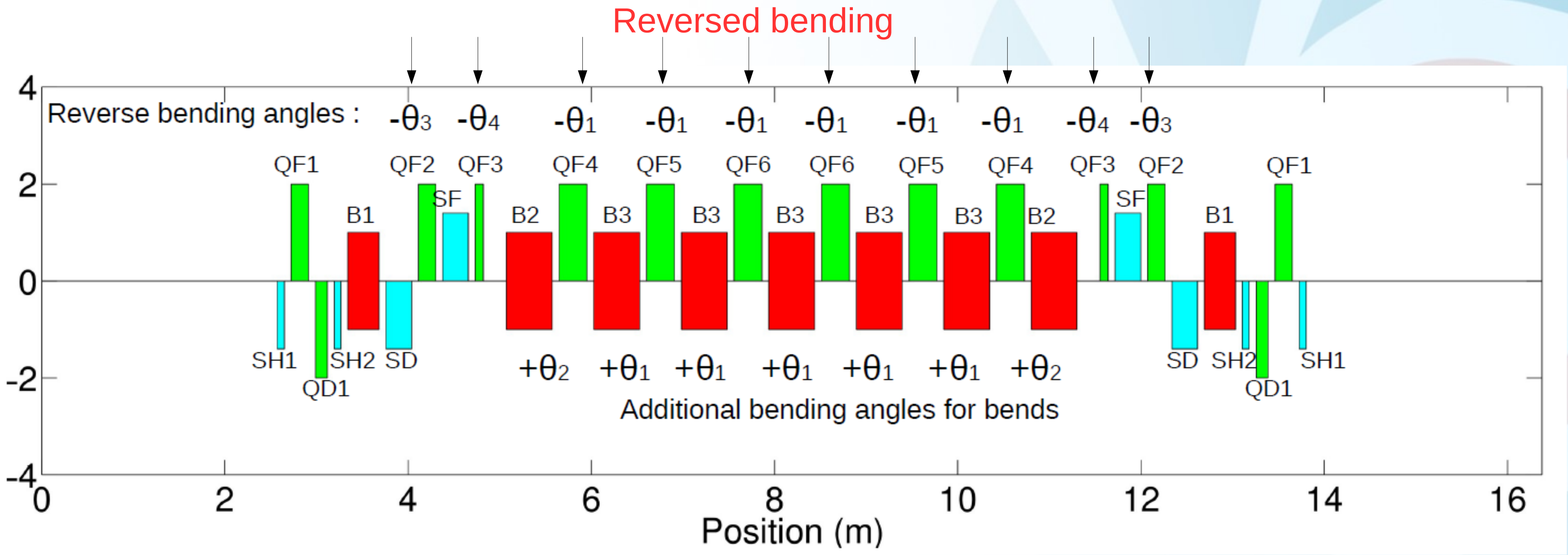


9BA lattice layout and constraints



- 12 fold symmetry exactly overlap with the existing ALS machine
- 9 combined-function bending magnets with uniform bending 3.33 deg
- Mirror symmetric 7 quad families, 2 chromatic and 2 harmonic sextupole families
- Space constraints
  - Align the straight to existing ID location
  - Length of the center straight is 5.145 m
  - Minimum spacing between magnets is 75 mm
- Magnet strength constraints
  - Quad gradient <105 T/m
  - Inner bend gradient 40 T/m <k1<47 T/m and outer bend gradient k1<20 T/m
  - Chromatic sextupole gradient k2 <7000 T/m^2 and harmonic sextupole gradient k2 <4000 T/m^2

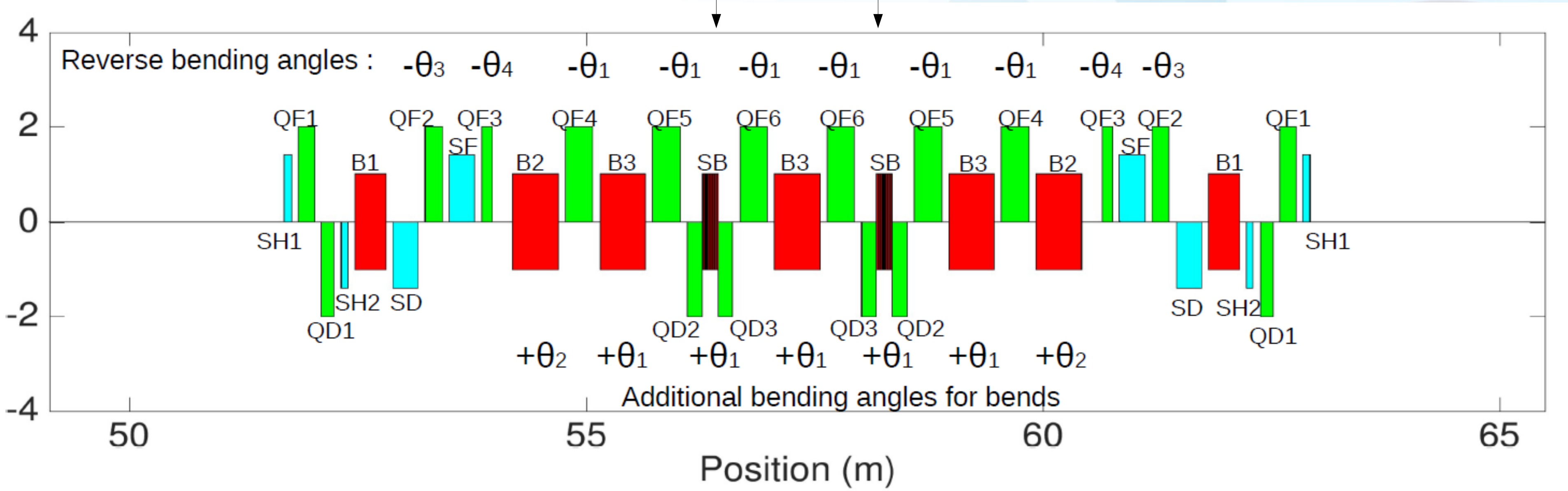
The SR lattice is further enhanced with reverse-bends



- Reverse bending is introduced to the lattice by offsetting quads QF2-QF6 by about few millimeters
- Less than 0.3 deg reverse bending angle is achieved for each quad
- Additional bending in bend magnet to set overall bending angle to 30 deg per sector
- The reverse bending angles are optimized with MOGA to achieve better lattice performance
- Reduce the natural emittance by about 20%, but without negative impacts on dynamics

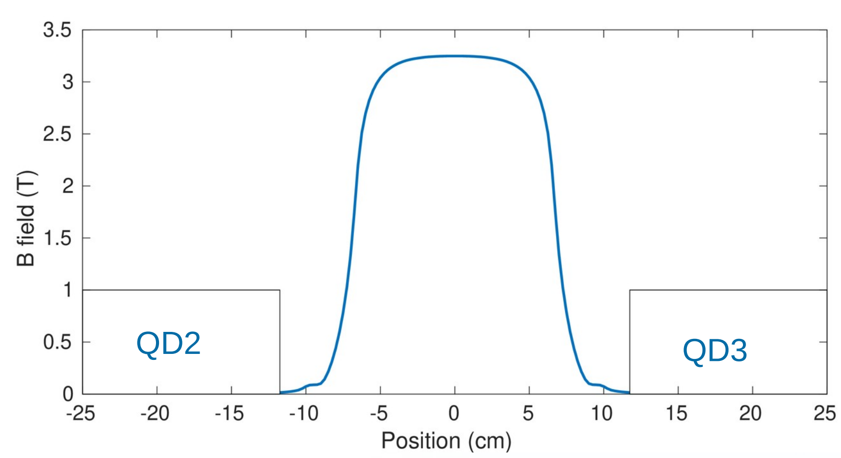
Hard-bends to continue supporting super-bend beam users

Hard bend sectors 4, 8 and 12



- Two normal bends in sectors 4, 8 and 12 are replaced with two 3.2T permanent magnets (hard-bend)
- Two thin quads on both sides of hard-bends to provide additional de-focusing
- The hard-bend sectors are matched to the normal bend sectors by tuning quad gradient
- Increase the natural emittance by ~18% and lifetime by ~10% however the DA stays the similar

Field profile of 3.2 T HBend



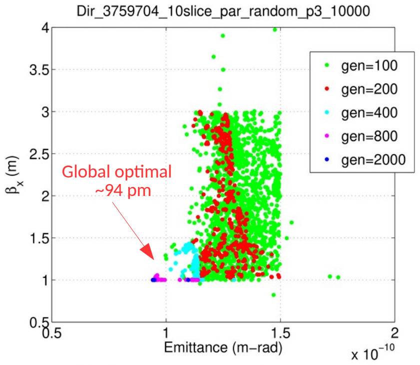
Lattice optimizations with MOGA

Linear Opt.

2 Objectives:
- Emittance
- Beta

9 Knobs:
- 9 quad gradient

To explore input parameter and objective spaces



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Linear Opt.

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9 Knobs:
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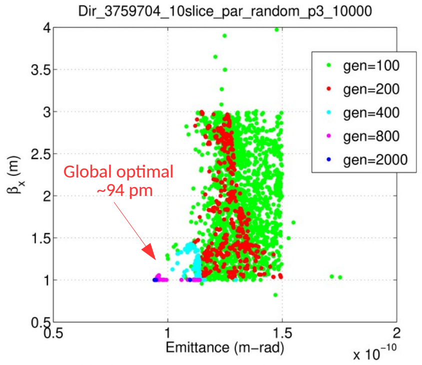
To explore input parameter and objective spaces

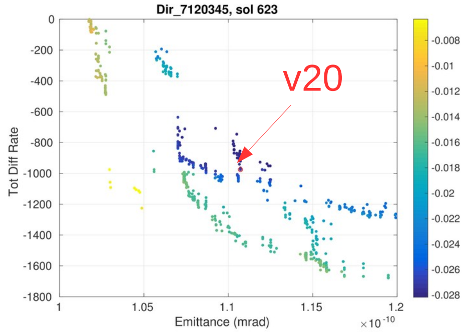
Linear & nonlinear opt.

3 Objectives:
- Emittance
- MA
- Total diffusion rate

11 Knobs:
- 9 quad gradient
- 2 harmonic sext.

Many runs were carried out; hyper-parameters and input parameter ranges are tuned





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11 Knobs:
- 9 quad gradient
- 2 harmonic sext.

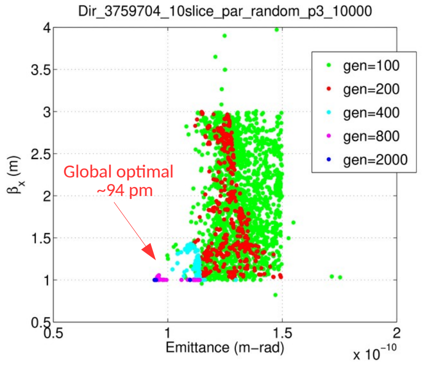
Many runs were carried out; hyper-parameters and input parameter ranges are tuned

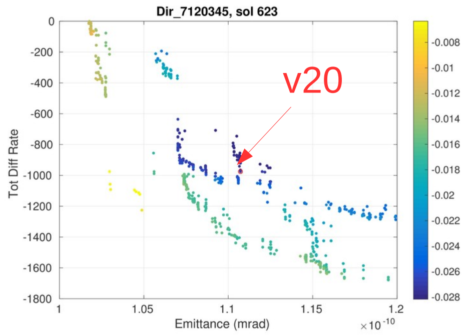
Linear & nonlinear Opt. with reverse bend

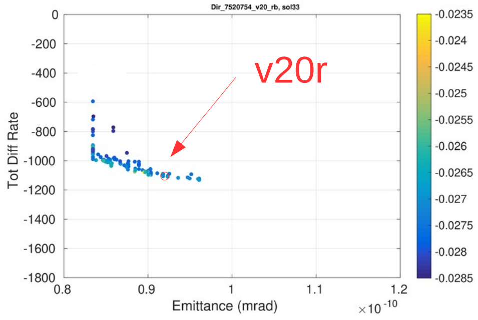
3 Objectives:
- Emittance
- MA
- Total diffusion rate

14 Knobs:
- 9 quad gradient
- 2 harmonic sext.
- 3 reverse bend ang.

Reduce emit by about 20% but similar DA

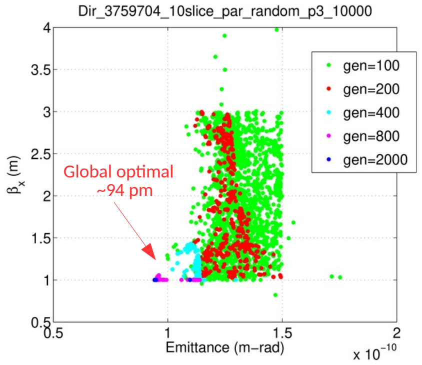


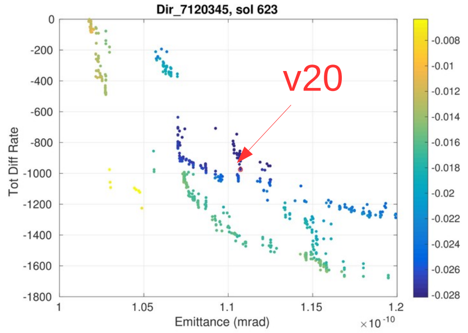


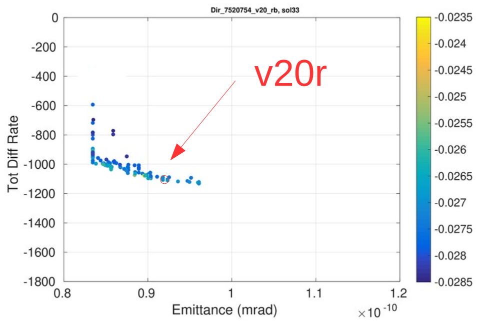


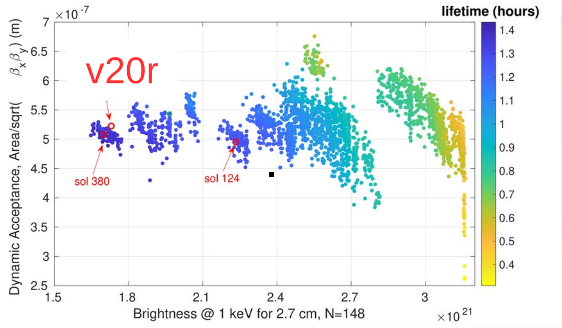
Lattice optimizations with MOGA

Linear Opt.	Linear & nonlinear opt.	Linear & nonlinear Opt. with reverse bend	Linear & nonlinear Opt. using alternative objectives
2 Objectives: • Emittance • Beta 9 Knobs: • 9 quad gradient To explore input parameter and objective spaces	3 Objectives: • Emittance • MA • Total diffusion rate 11 Knobs: • 9 quad gradient • 2 harmonic sext. Many runs were carried out; hyper-parameters and input parameter ranges are tuned	3 Objectives: • Emittance • MA • Total diffusion rate 14 Knobs: • 9 quad gradient • 2 harmonic sext. • 3 reverse bend ang. Reduce emit by about 20% but similar DA	3 Objectives: • Brightness • Lifetime • Dynamic acceptance 14 Knobs: • 9 quad gradient • 2 harmonic sext. • 3 reverse bend ang. Lifetime is further improved and lattice variants are identified



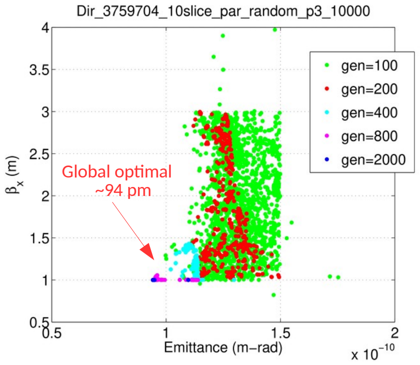


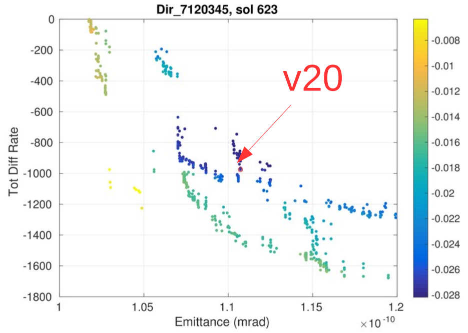


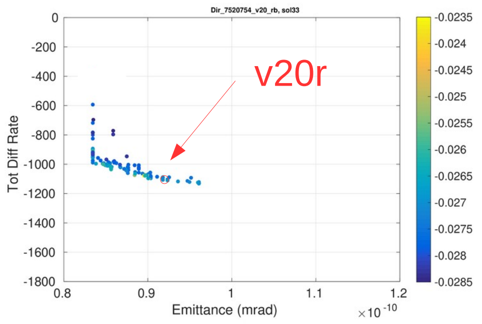


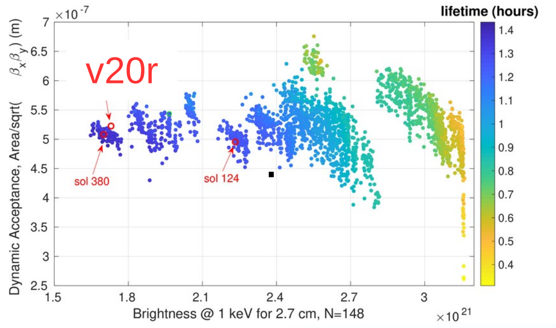
Lattice optimizations with MOGA

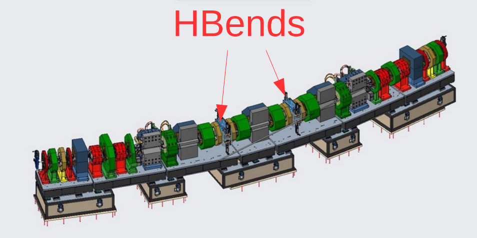
Linear Opt.	Linear & nonlinear opt.	Linear & nonlinear Opt. with reverse bend	Linear & nonlinear Opt. using alternative objectives	Introduce 3.2T HBend by matching
2 Objectives: • Emittance • Beta 9 Knobs: • 9 quad gradient To explore input parameter and objective spaces	3 Objectives: • Emittance • MA • Total diffusion rate 11 Knobs: • 9 quad gradient • 2 harmonic sext. Many runs were carried out; hyper-parameters and input parameter ranges are tuned	3 Objectives: • Emittance • MA • Total diffusion rate 14 Knobs: • 9 quad gradient • 2 harmonic sext. • 3 reverse bend ang. Reduce emit by about 20% but similar DA	3 Objectives: • Brightness • Lifetime • Dynamic acceptance 14 Knobs: • 9 quad gradient • 2 harmonic sext. • 3 reverse bend ang. Lifetime is further improved and lattice variants are identified	Matching Objectives: • Twiss functions • Phase advance between SFs 6 Knobs: • 5 quad gradient • 1 dipole gradient Increase natural emit by 18% and lifetime by 10% but similar DA



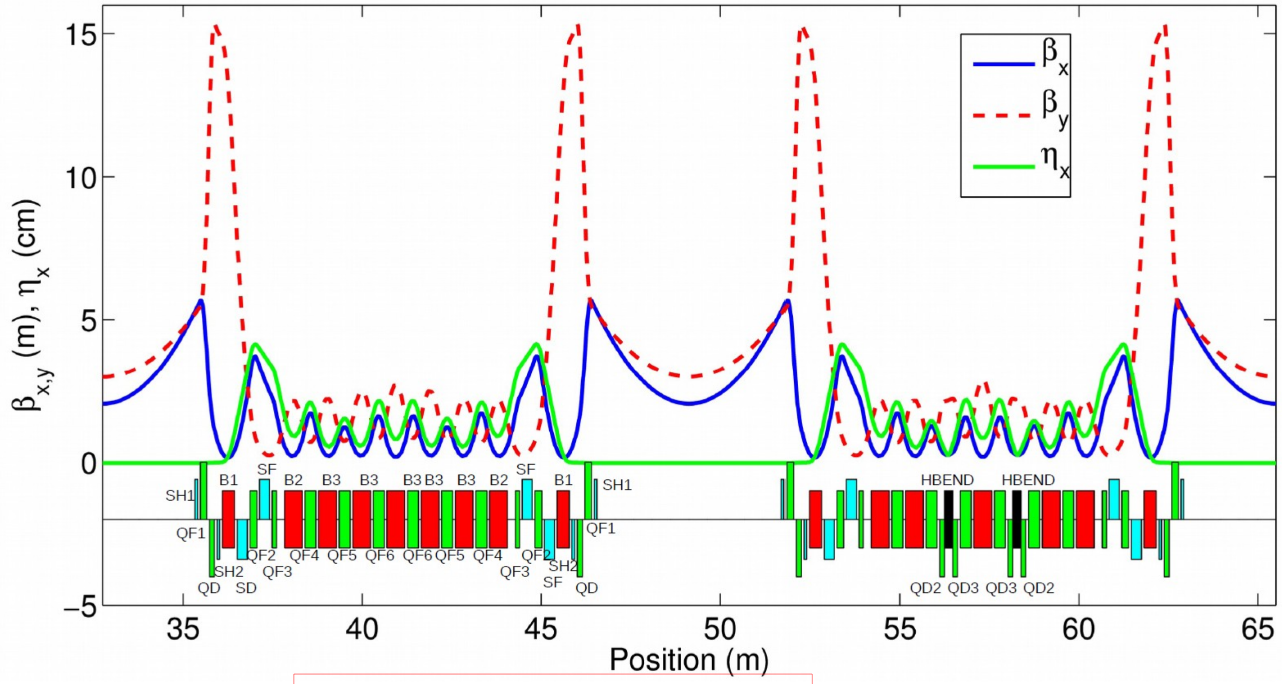


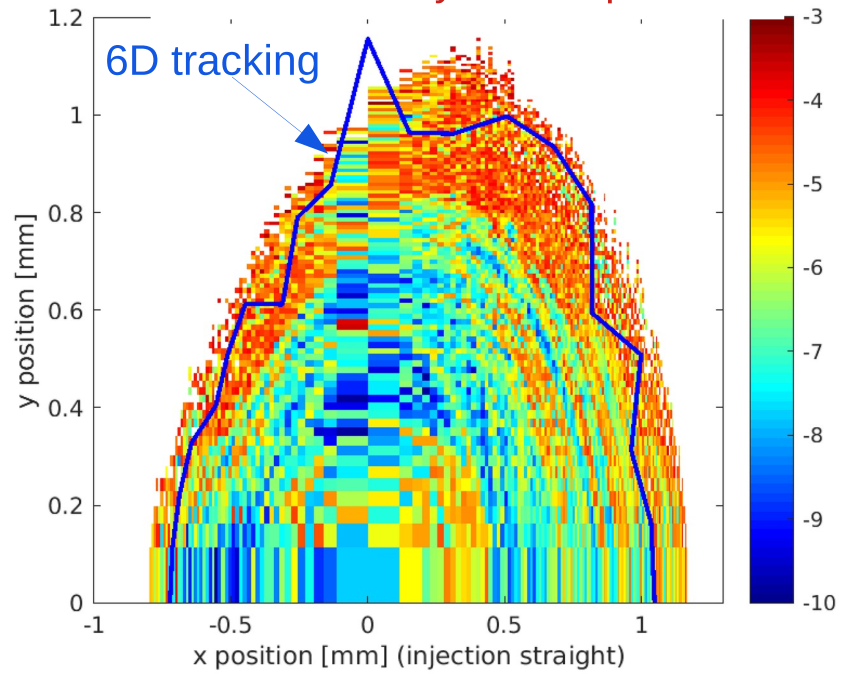


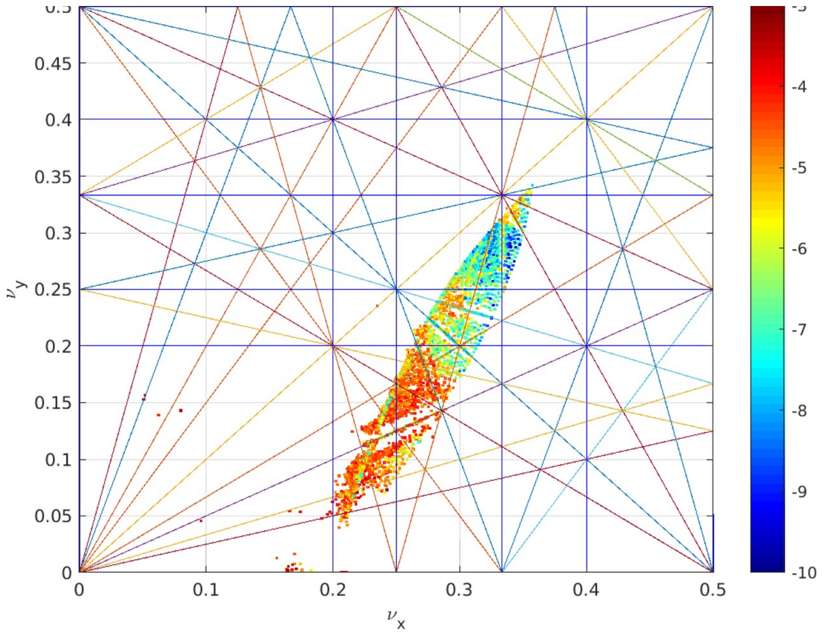




Properties of the baseline lattice SRv21







Betatron Tune	H	=	41.35818
	V	=	20.35340
Beta Function	H	=	2.04620
	V	=	2.99890
Chromaticity	H	=	-64.27565
	V	=	-64.76878
Energy Spread		=	1.02076E-03
Emittance		=	1.08334E-10

Near equal fractional tune

~2-3m beta function at straight

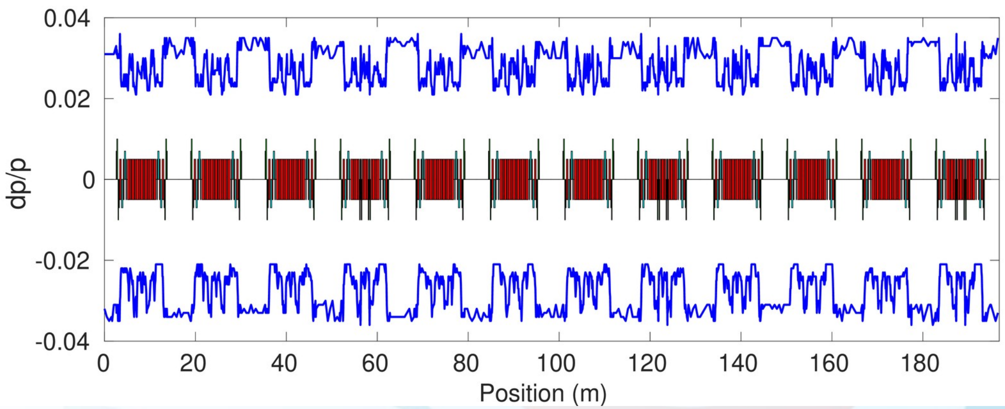
108 pm natural emit
~70 pm for round beam

- After the MOGA run, the fractional tunes are matched to the level of 10^{-4} difference to generate a round beam with a nominal skew error setting

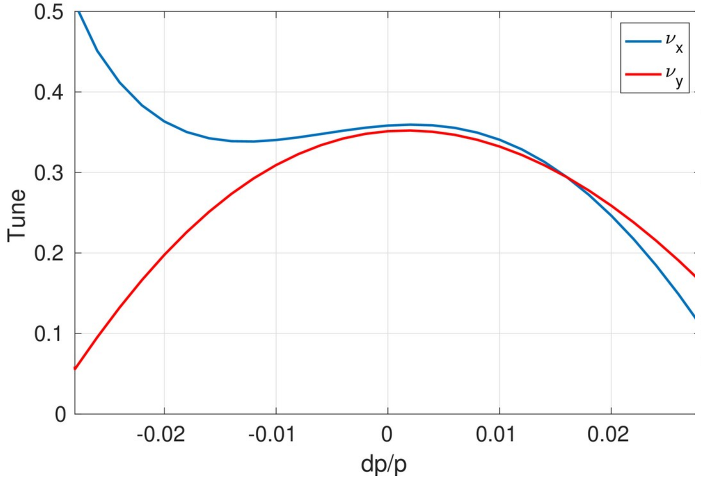
Momentum aperture, tune footprint and lifetime

- 6D tracking for 25000 turns with linear quad gradient and skew errors, physical apertures and collimators included
- About 3% MA in straights and 2.2% in arcs
- MA is limited by the integer tune in the vertical direction, and by both integer and half integer tune in the horizontal direction
- ~1.3 hours Touscheck lifetime with harmonic cavity (HC)

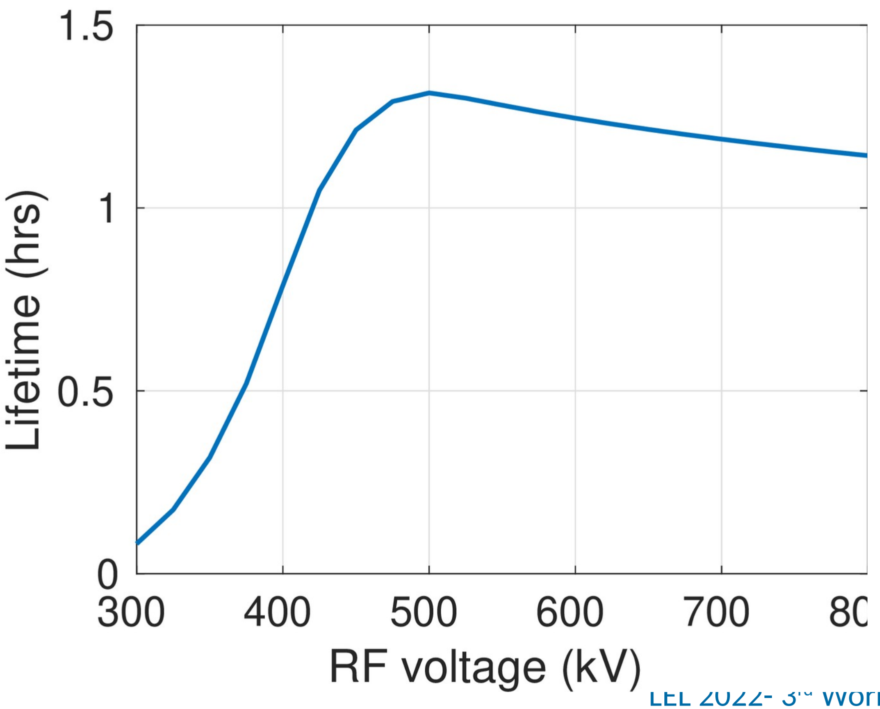
Momentum Aperture (MA)



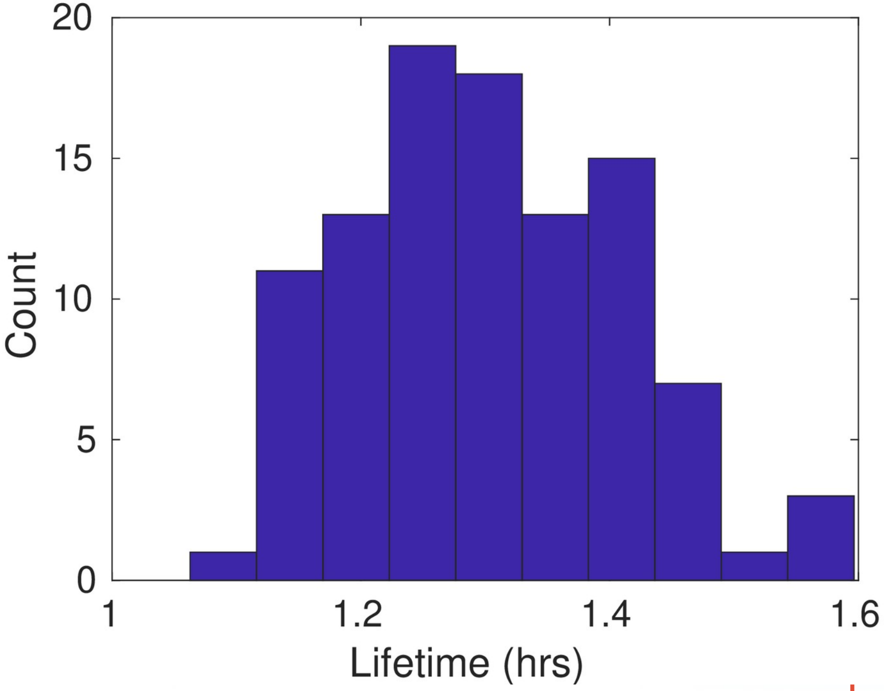
Tune shift vs Energy



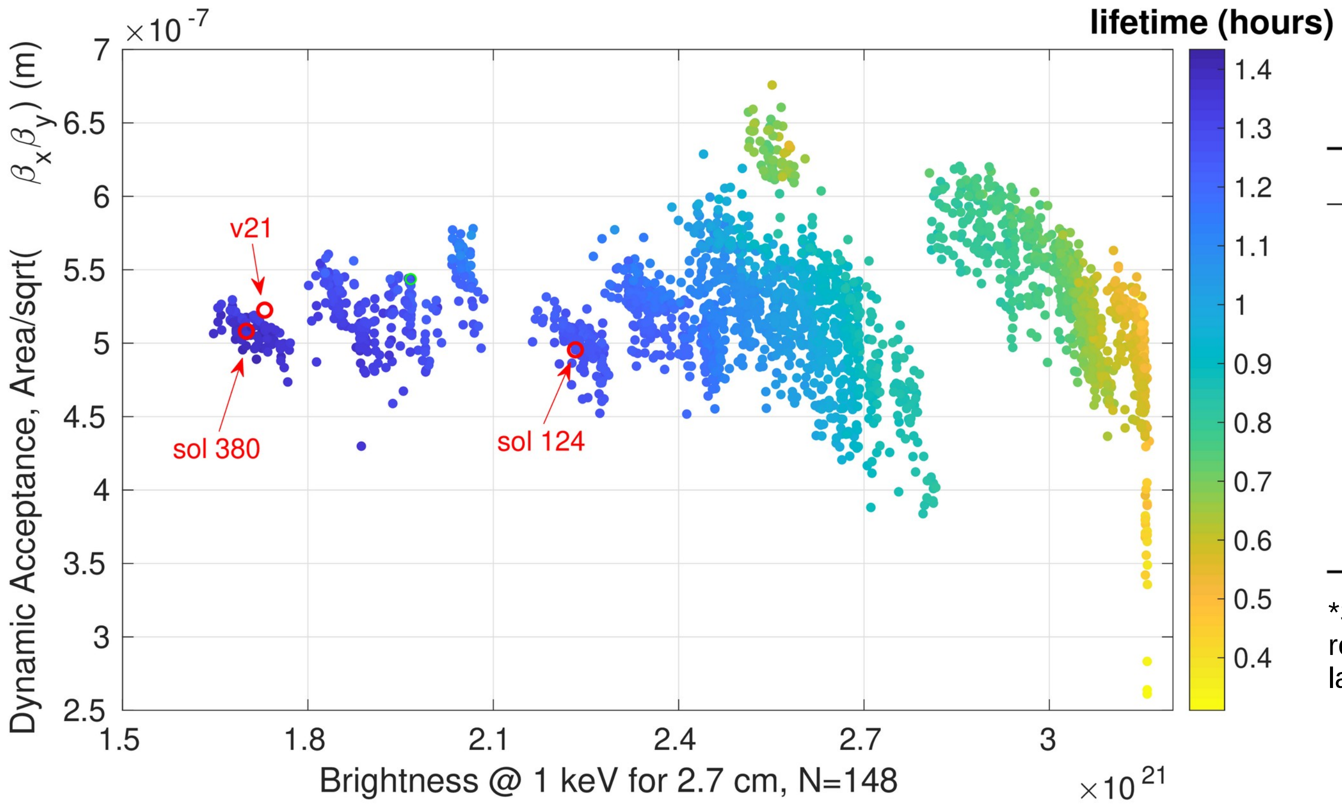
Lifetime vs RF voltage



Lifetime distribution with 100 random seed errors



Further optimization with brightness, dynamic acceptance & lifetime



Summary of lattice variants

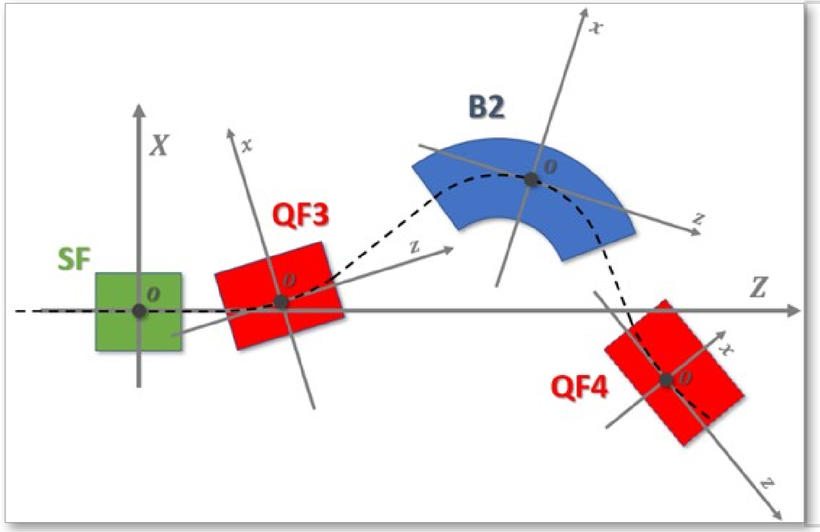
Name	v20r	Sol380	Sol124
Hor. Tunes	41.358	41.384	41.391
Ver. Tunes	20.353	20.392	22.397
Nat. Emittance (pm)	91.8	92.3	88.1
Rms emittance, round beam (pm)	62.0	62.4	59.6
Part. numbers $J_x/J_y/J_z$	2.08/1.00/0.92	2.08/1.00/0.92	2.13/1.00/0.87
Hor. Beta in straigth (m)	2.05	2.33	2.00
Ver. Beta in straigth (m)	3.00	2.93	1.74
Hor. Nat. Chrom.	-64.3	-65.8	-65.6
Ver. Nat. Chrom.	-64.8	-65.0	-73.6

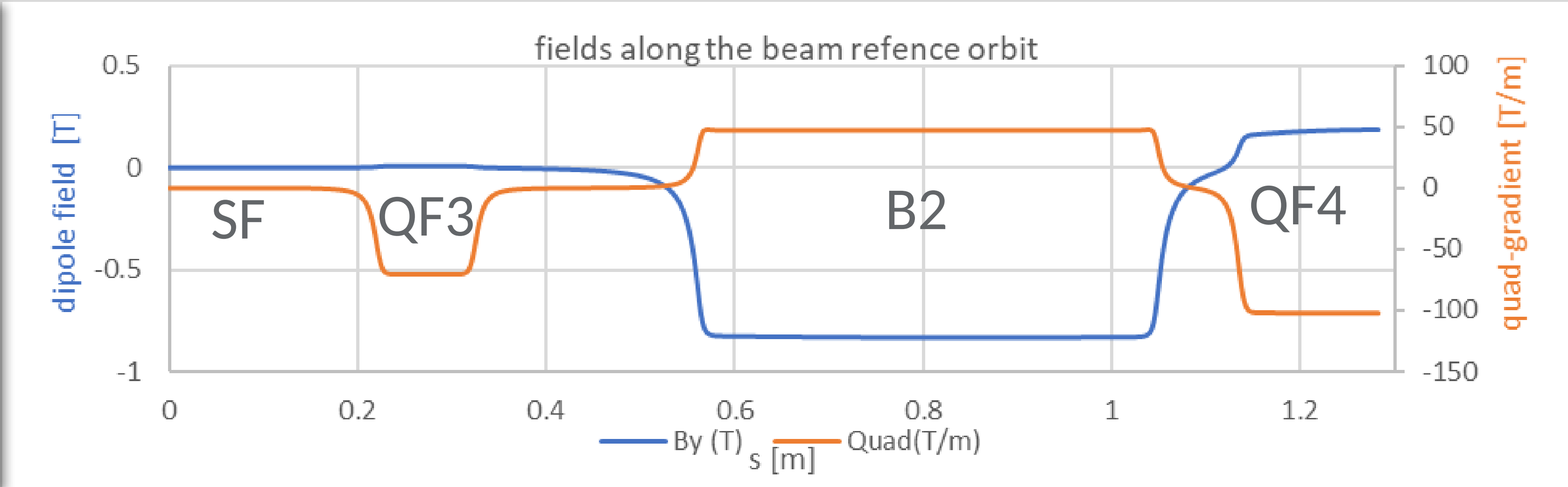
*Sol380 and 124 lattices do not include the hard bends and therefore the more relevant comparison is with lattice v20r which is essentially the version of the baseline lattice without hard bends

- Further MOGA optimization by directly targeting brightness, dynamic acceptance and lifetime
- Identify some other lattice variants with smaller beta function (sol124) or longer lifetime (sol380)
- However, the Touschek lifetime advantages disappear when including realistic errors and ID perturbations for these lattice variants
- Our baseline lattice v21 has the best performance overall

Improve magnet modeling by encompassing multiple adjacent magnet at once

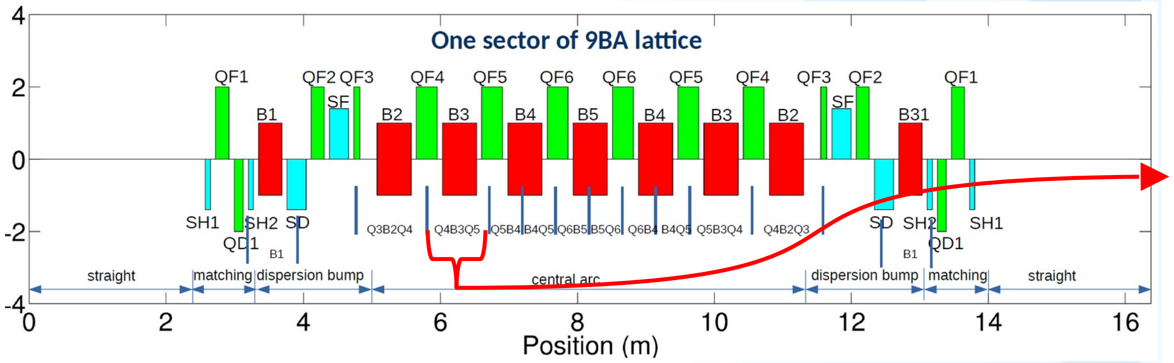
- Improved 3D magnetic-field calculations have been repeated by considering whole sets of adjacent magnets at once (e.g. SF-QF3-B2-QF4)
- The magnets' coil current and radial offset (main-bends and reverse-bending quads) are adjusted to meet the physics specifications for the integrated bending, focusing, and sextupole fields.
  - This requires a lengthy iterative process because of magnetic coupling between the magnets
- Field integrals are calculated along the reference obit (which is re-evaluated each time the fields are adjusted)

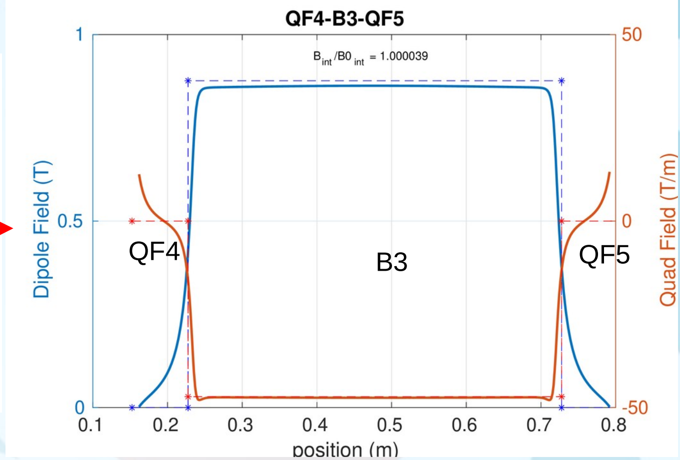




Impact of linear fringe field and cross talk on beam dynamics is small

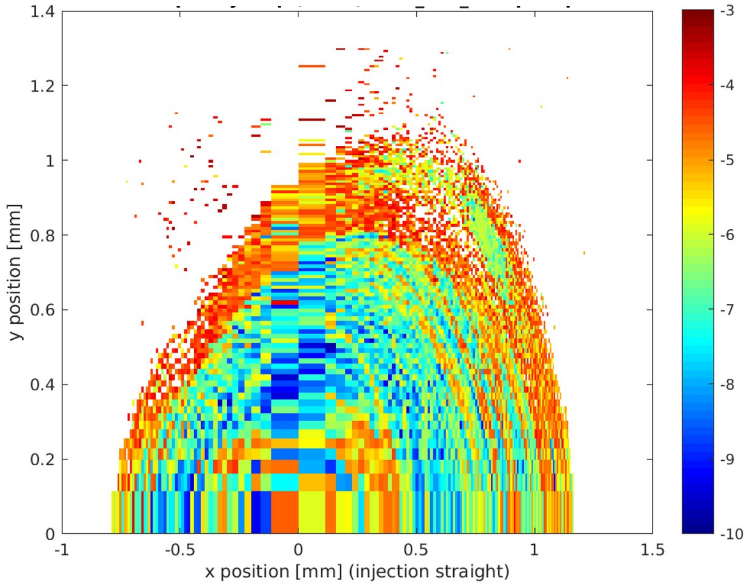
- Linear fringe field and cross-talk effects are studied by replacing the hard edge model of the magnets as soft edge models according to their integrated 3D field maps





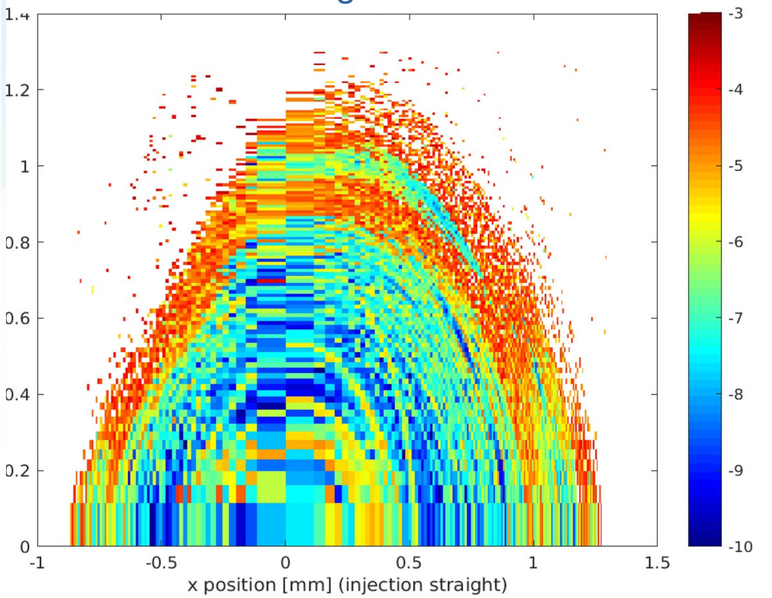
- Tunes and DA are slightly different from the baseline after replacing the hard-edge model with the soft-edge model
- The circumference stays the similar attributing to the cross-talk adjustment
- DA are recovered after the tune corrections

Baseline hard-edge model



ν_x= 41.3582; ν_y= 20.3533
C=196.508904

Soft edge model



ν_x = 41.3590; ν_y= 20.3537
C = 196.508904

Conclusions

- The SR baseline lattice (SRv21) based on 9BA with reverse-bends and hard-ends has been fully optimized
- The baseline lattice has been evaluated and results meet the design requirements
- Different lattice variants within the hardware capability of the baseline lattice has been explored

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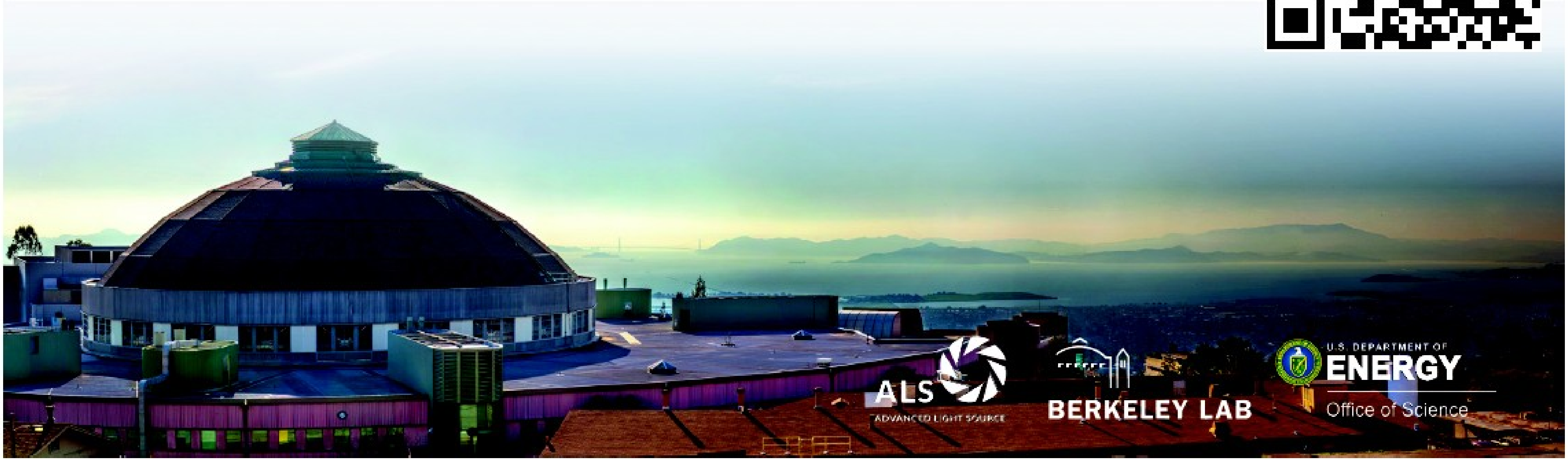
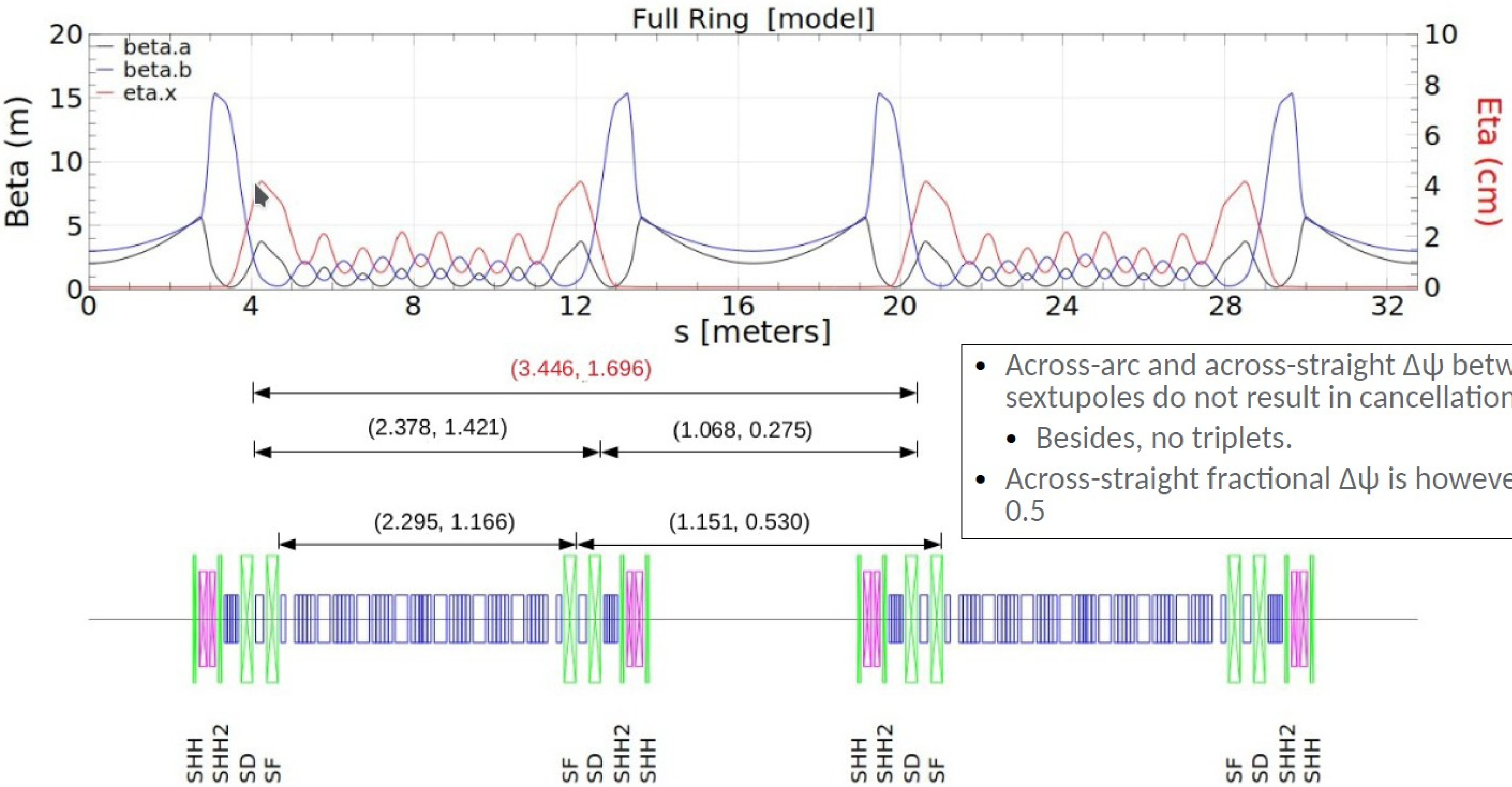


Thank You!

Backup

Per-sector phase advance explains lattice behavior



- Across-arc and across-straight Δψ between sextupoles do not result in cancellations
  - Besides, no triplets.
- Across-straight fractional Δψ is however close to 0.5

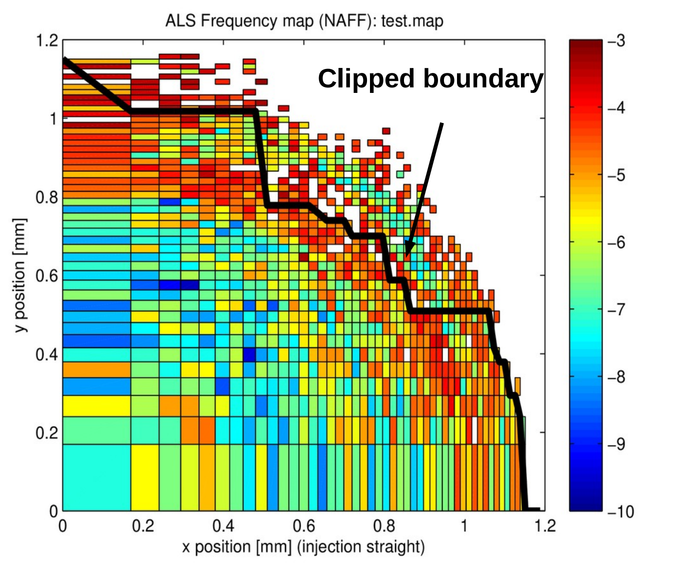
Courtesy of M. Ehrlichman

Dynamic Aperture (DA)

- Total Diffusion Rate
  - Total Diff. Rate calculation is based on Freqmap technique
  - 21 by 21 non-uniform grid, 4D tracking for N=512 turns
  - Tune calculated for first 256 and second 256 turns
  - Diffusion rate is calculated according to

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

  - Region is clipped to exclude unstable regions and islands
  - Tot. Diff Rate is given by the summation of the diffusion rat all grids inside the stable region
  - Faster and allow to optimize the resonance structure



- Dynamic Acceptance (normalized dynamic aperture)
  - 21 line, and 11 steps for each line
  - 2 step-back iterations to refine the boundary
  - 6D tracking for several thousand turns with radiation and cavity on
  - Region is clipped to exclude unstable regions and island
  - Dynamic acceptance is the normalized (by beta functions) area enclosed by the boundary