ALS-U Injector(s)

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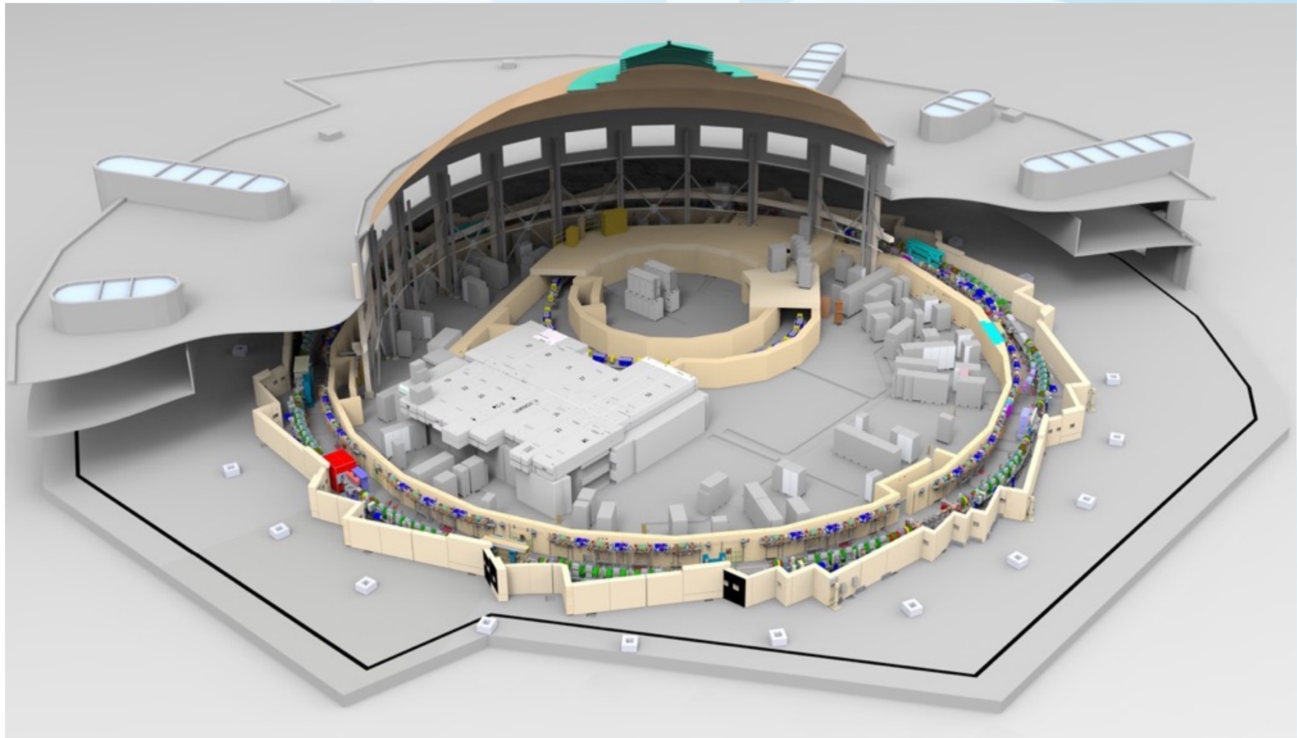
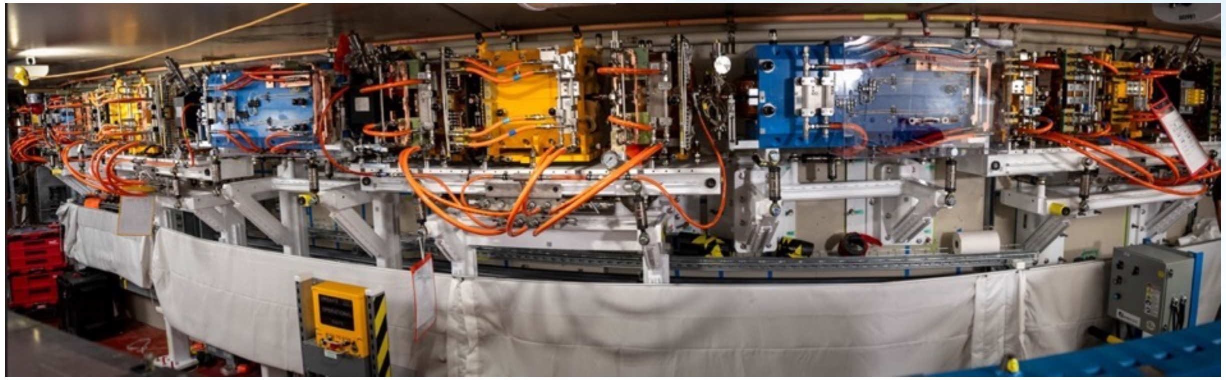
iFAST Injector Workshop, March 7, 2024

Outline

- Introduction: ALS-U
- Swap-Out Injection
- New accumulator + booster modifications
- R&D results on injection elements for swap-out
- Accumulator status (installation in progress)
- Summary





ALS-U Project

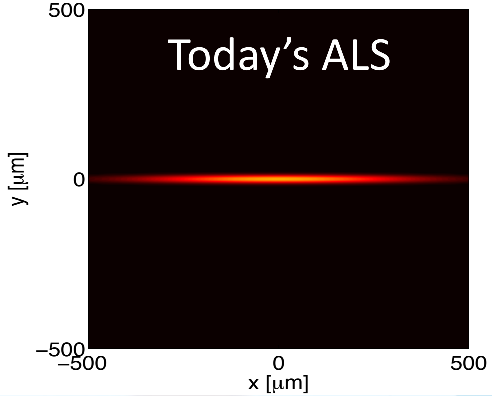
ALS-U will deliver a world-leading light source that provides users with bright, high-coherent-flux soft x-rays

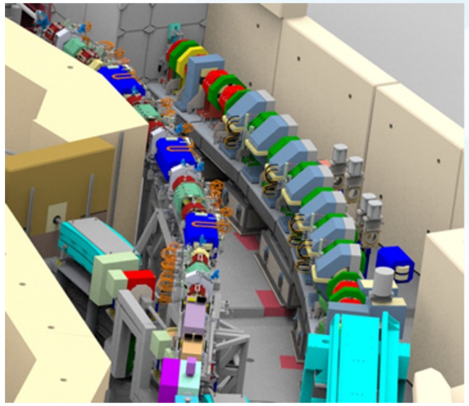
High-level Goals:

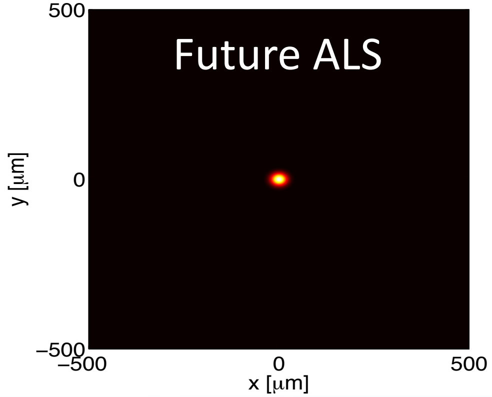
- Achieve an increase in brightness and coherent flux of soft x-rays (@1 keV) of at least 2 orders of magnitude beyond today's ALS capabilities
- Develop a set of experimental capabilities that will enable leadership in soft x-ray science
- Provide infrared and hard x-ray capabilities comparable to present-day ALS

3BA

Electron Beam Profile



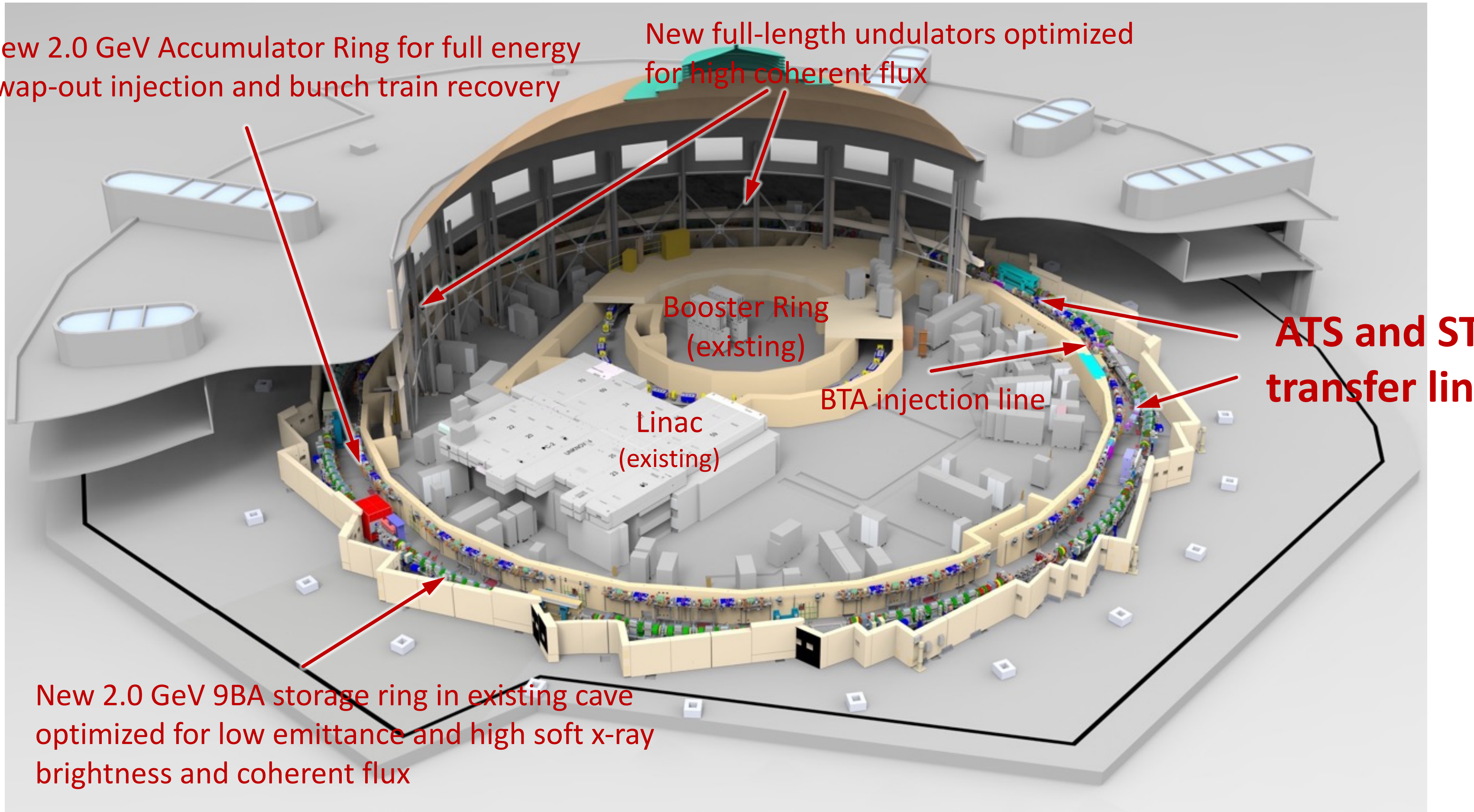


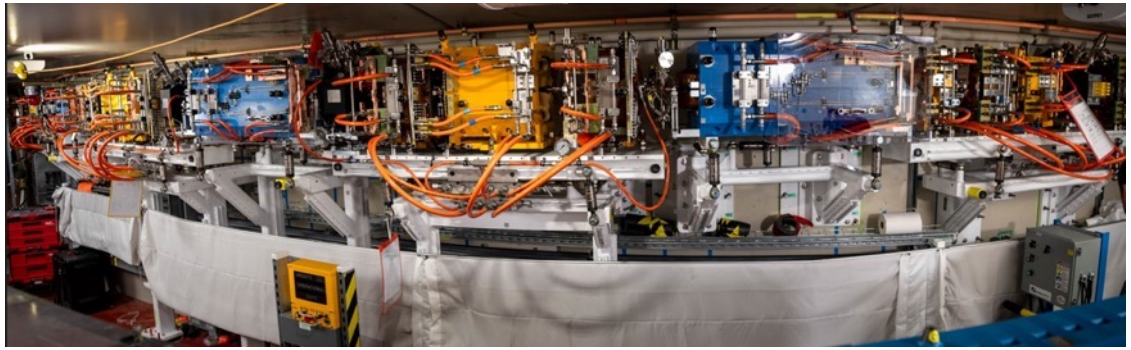


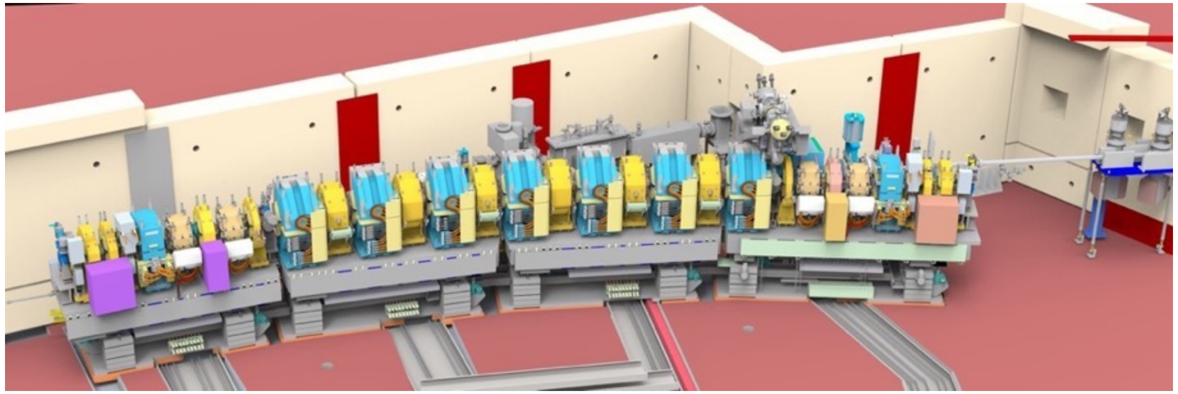
9BA

ALS-U Scope

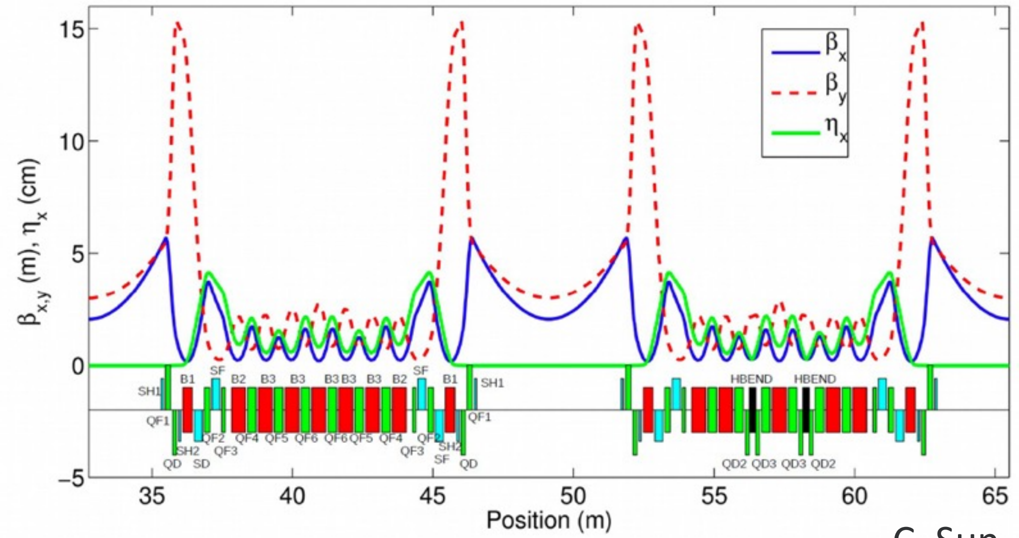
The Accumulator Ring is being installed and will be commissioned early in order to minimize the risk and duration of one-year dark period; Storage Ring, ATS+STA will be installed during dark period



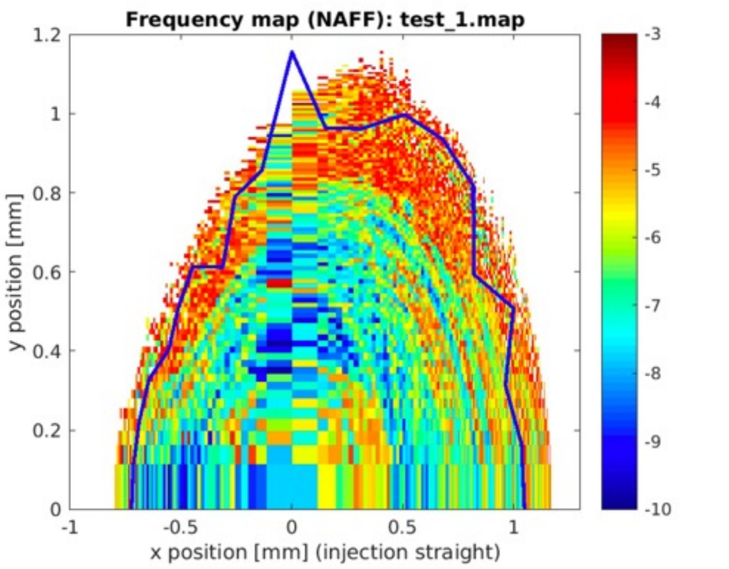


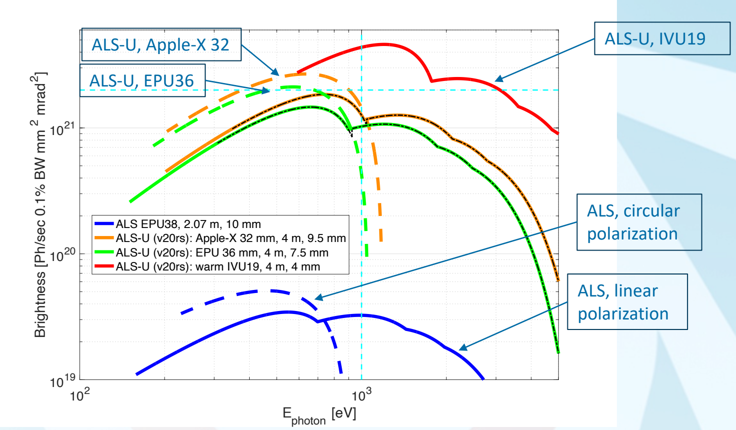


More than two order of magnitude brightness improvement, 69 pm emittance, diffraction limited to ~ 1.5 keV



C. Sun





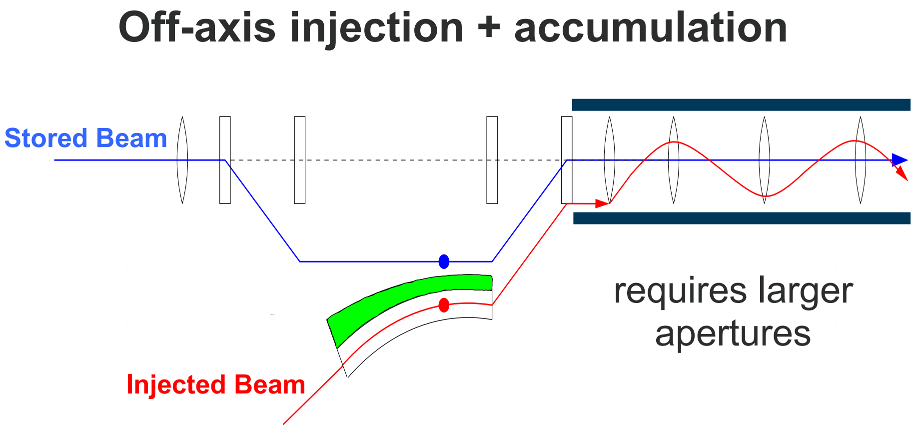
Storage Ring	Design
Energy	2.0 GeV
ε_x (full coupling)	69 pm
ε_y (full coupling)	69 pm
$\Delta p/p$	0.98×10^{-3}
$\sigma_{x/y}$ @ ID	12 µm/14 µm
$\sigma_{x/y}$ @ Bend sources	7 µm/10 µm
Bunch Length (FWHM)	110 ps
Current	500 mA
Lifetime	~1 h

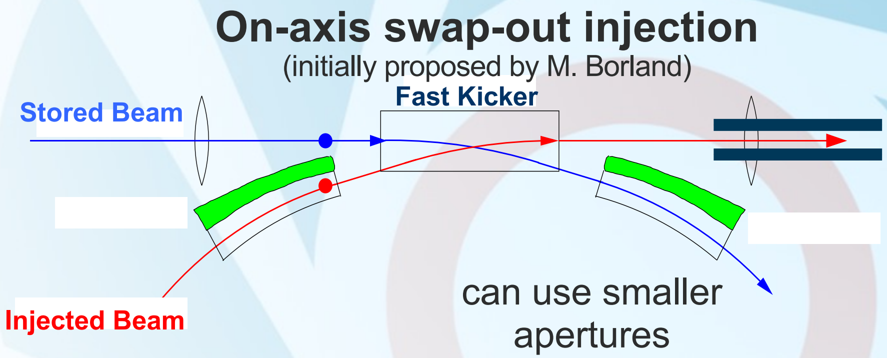
Improvements: Emittance, undulator length, undulator technology+gap, smaller β_x: **Overall: >100x @ 1 keV**

- 9 Bend achromat lattice with reverse bends and high field Hbends in 3 sectors for hard x-rays
- Small, optimized beta functions in straights
- ~2.5% dynamic momentum aperture in arcs
- On-axis injection (swap-out) needed

Swap-Out Injection

Performance enabling ALS-U feature – Bunch train swap-out

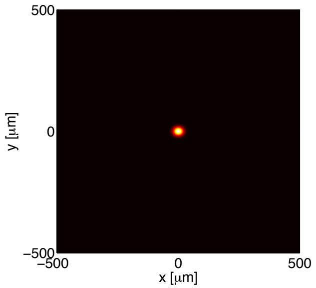




Swap-out enables:

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

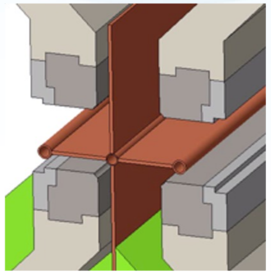
Allows lattices with stronger focusing + higher brightness



Allows for **small (~6mm) round** apertures

S. Omolayo

Permits higher performance polarizing undulators

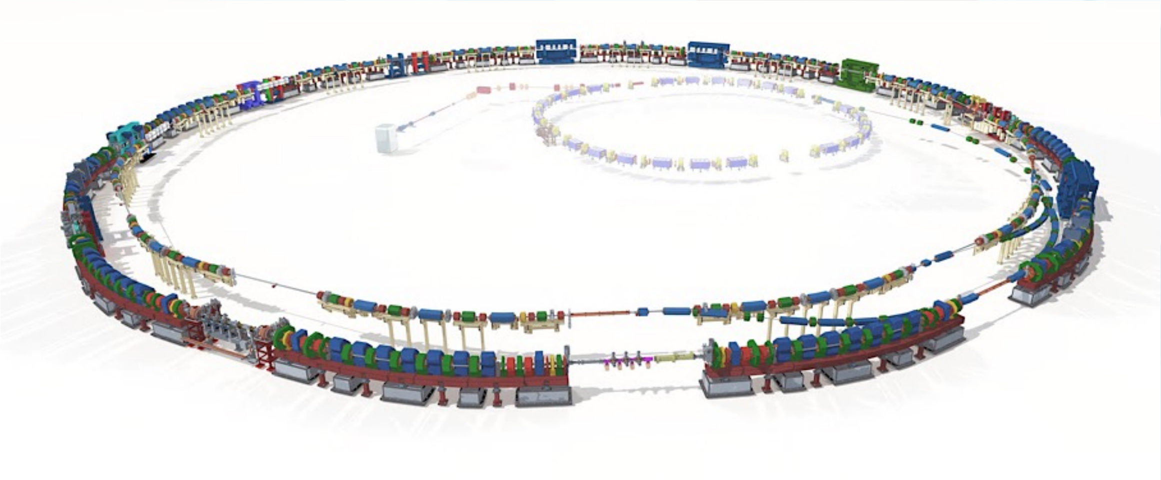


Delta/Apple-X undulator

E. Wallen

Injector Requirements for Swap-Out

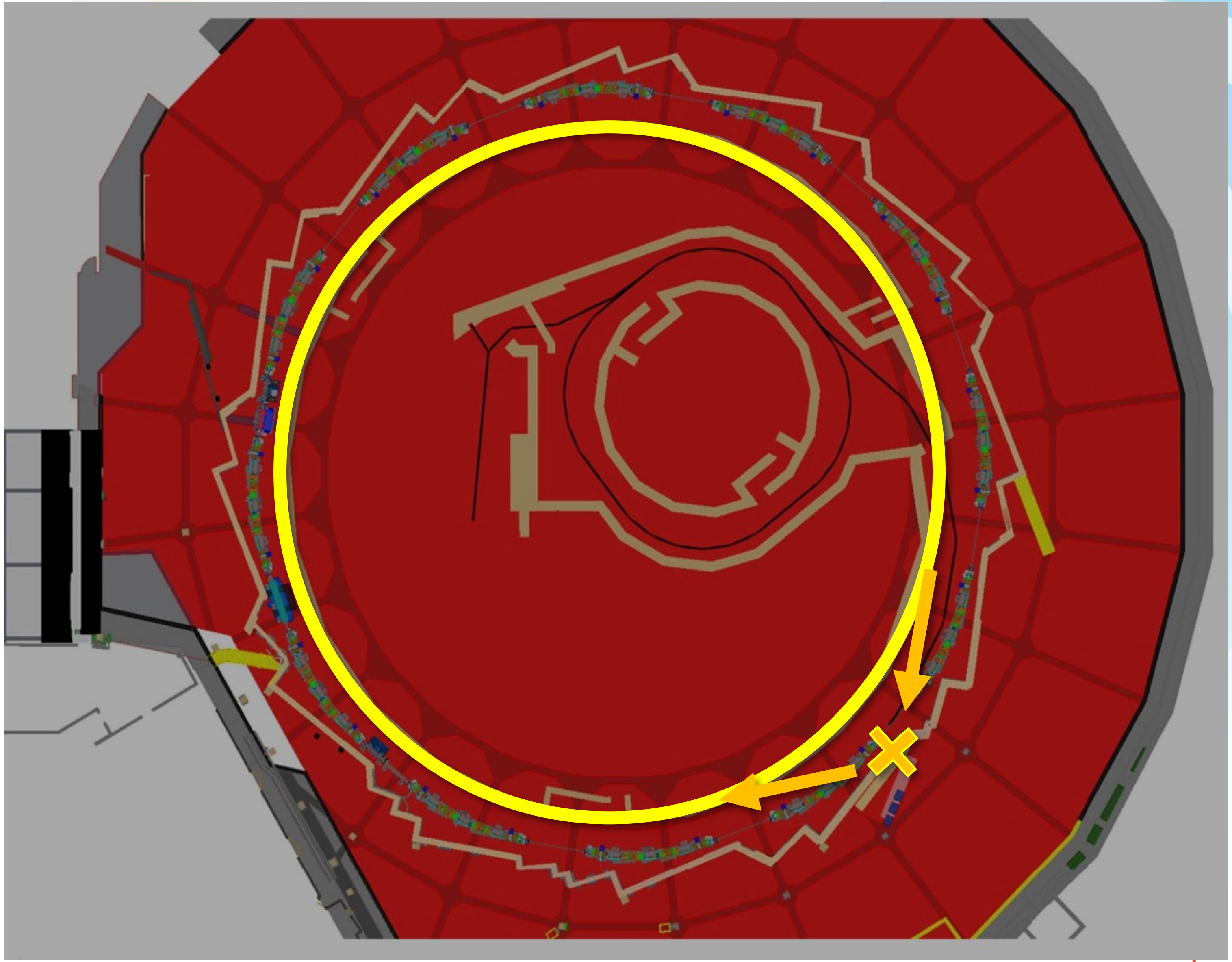
- Hard requirements:
  - Sufficient charge per bunch
  - Sufficiently small emittance
  - Stable pulse to pulse (charge, position, angle, energy, …)
- Desired
  - Cost + space optimized
  - Minimized beam losses – ALARA
  - Minimum perturbations on user photon beams - transients



- For ALS, booster is fairly small – hard to achieve sufficiently small emittance
- Booster also makes charge recovery from SR difficult
- Accumulator ring comes with inherent stability of a storage ring
- Selected full energy accumulator with bunch-train swap out

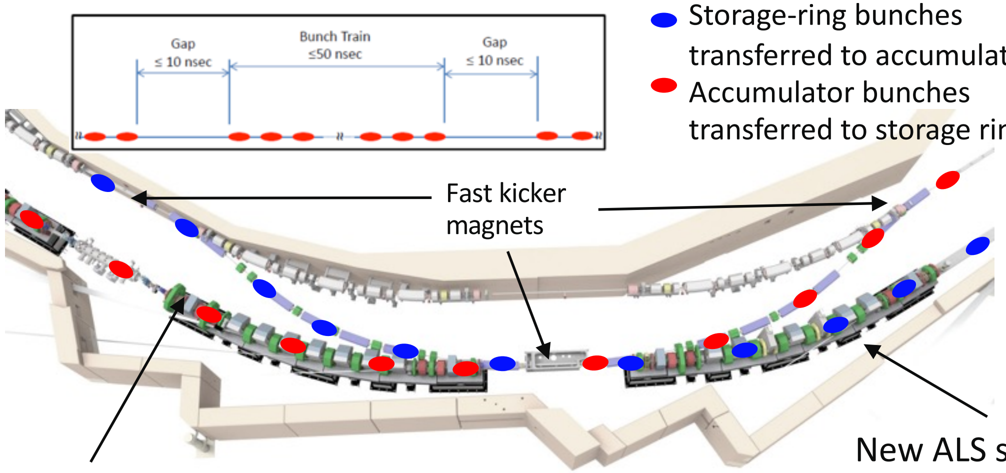
Accumulator location in SR tunnel is optimal solution

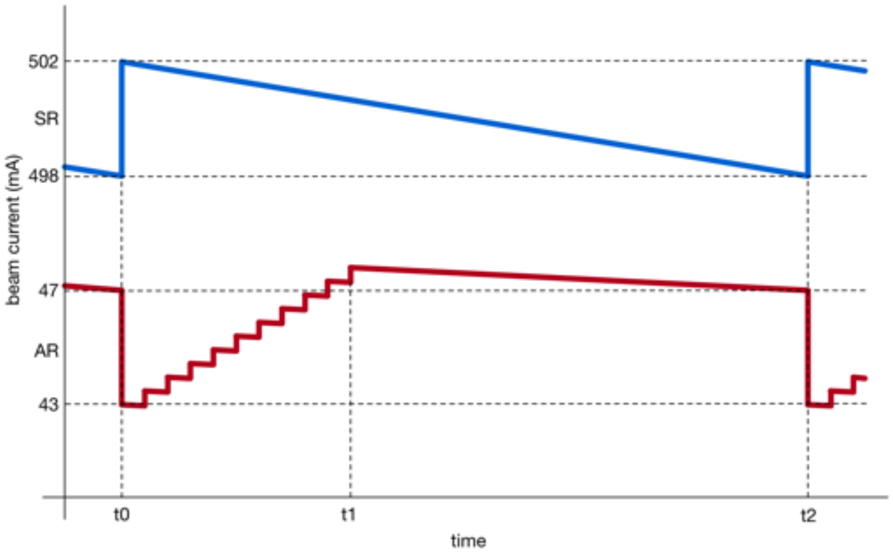
- **Advantages:**
  - Easing lattice design for $\varepsilon_0 \lesssim 2nm$
  - Much shorter transfer lines from/to Storage Ring
  - Minimal alteration of floor plan and shielding
    - Evaluated access issues with building code official and fire marshal
    - Finished study of seismic issue.
- **Potential Challenges:**
  - Somewhat crowded tunnel space
  - Supports are non-trivial
    - Both challenges were overcome in ALS-U design and accumulator construction



ALS-U Operation/Fill Modes

- Advantages of bunch train swap-out with recovery
  - minimizes number of lost/dumped electrons
  - reduces demands on injector
  - made swap-out-kicker development easier
- ALS-U expected lifetime ~1 h @ 500 mA
  - Need to replace 0.09 nC/s
  - Booster routinely delivers 1 nC/s
- Planned Swap-out Timing:
  - Between SR swap-out injections the AR train is filled from the BR in Top-Off mode.
  - AR injection between 1 and 4 BR bunches per shot, at up to 1Hz.
  - Do not need to top-off every bunch in single swap-out, could spread over multiple swap-out cycles if necessary
- To achieve 1% current stability, swap-out would need to happen every 36 seconds (500 mA)
  - User experience at ALS shows ALS minimum of 12 seconds between injections is acceptable
- Can maintain bunch-to-bunch current variation around 10%, similar to ALS

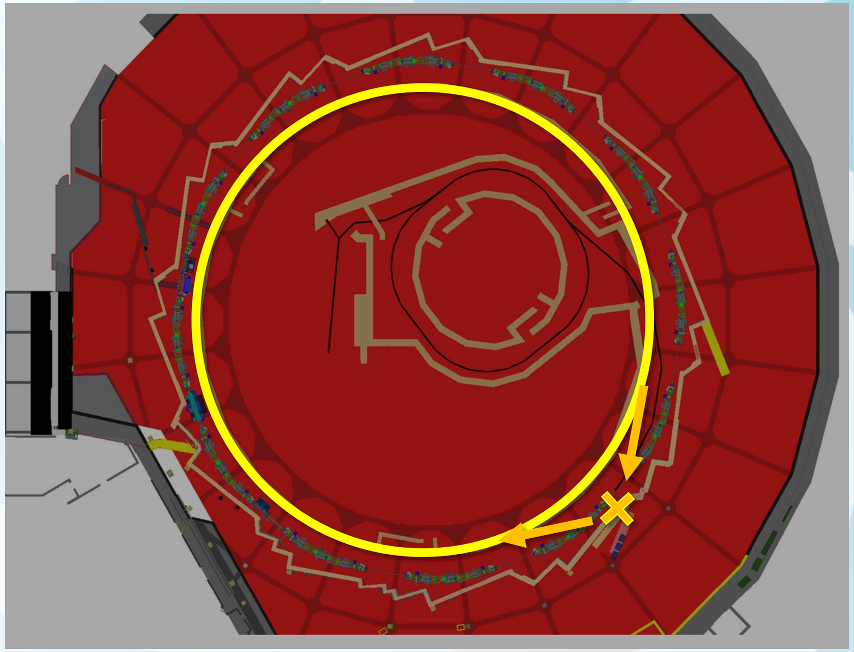




New Accumulator and Booster modifications

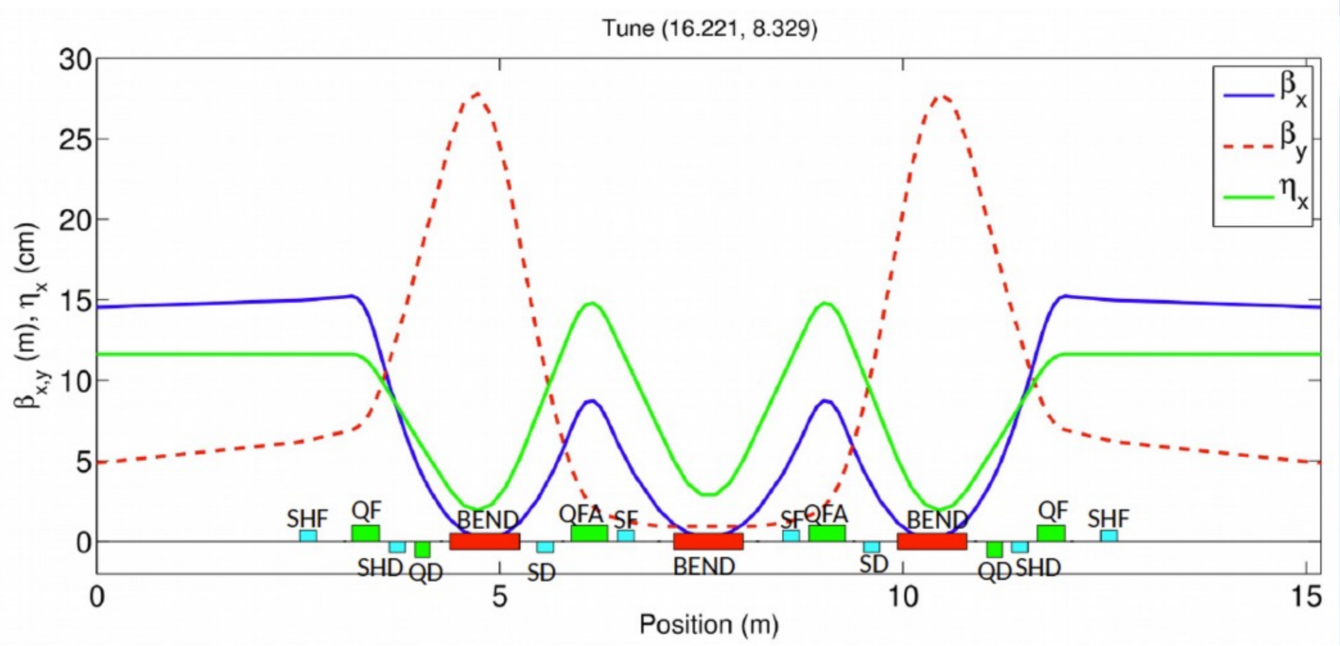
AR Parameters

- 1.8 nm emittance for ~100% injection efficiency into the SR
- <50 mA average current beam (1/11 of SR)
  - 1 train of 25 or 26-bunches
- Enables swap-out every ~30 s
  - Modest lifetime requirement for accumulator
- Top-off injection to replenish SR train in between swap outs
  - Accept (relatively large) beam from existing ALS gun/Linac/booster
  - >95% injection efficiency (from booster)
- Fit into ALS tunnel against inner shielding wall, leave serviceable corridor between AR and SR
- Small AR magnet apertures to minimize magnet size, weight
- AR has same rf frequency as the SR
  - AR circumference is "quantized" $C_{AR} = \frac{304}{328} \times C_{SR}$



Accumulator uses Triple-Bend-Achromat lattice

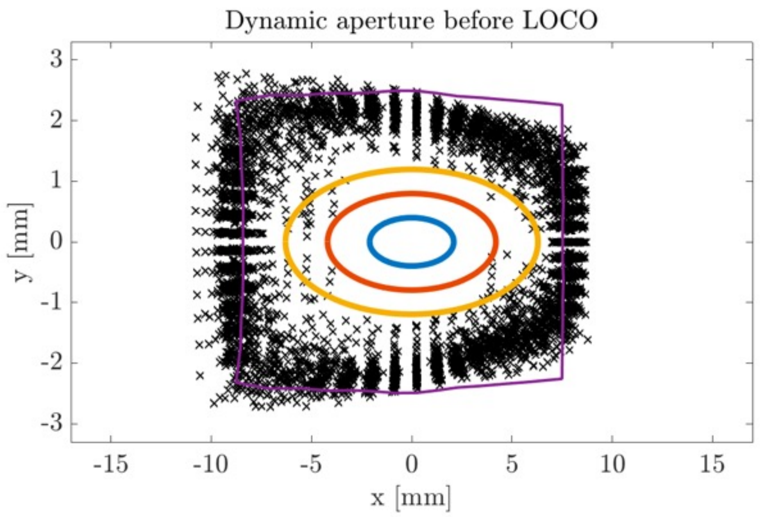
- Scaled-down and optimized version of ALS TBA (circumference ~14m shorter)
  - 12 sectors
- Lattice optimization done w/ genetic algorithm (MOGA)
  - 1.8 nm emittance
  - Finite dispersion in straights
- Straight magnetic-axis, combined-function bends
- Magnet apertures significantly narrower than in ALS
  - Optimizing weight, power consumption and cost

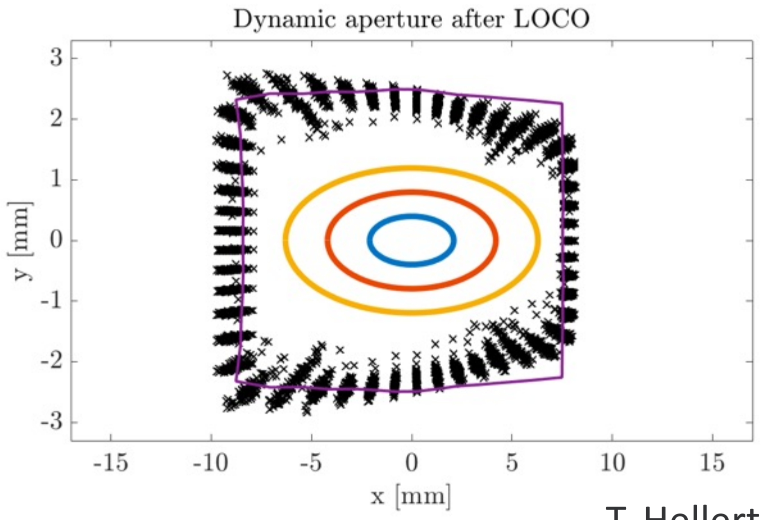


C. Sun

- 3 Bends (combined function, defocusing gradient)
- 3×2 Quadrupoles (QF,QFA, QD)
- 4×2 Sextupoles (w/ correctors)
  - 1 skew-quad corrector
  - 6 dipole correctors (two of them fast)
- 6 BPMs

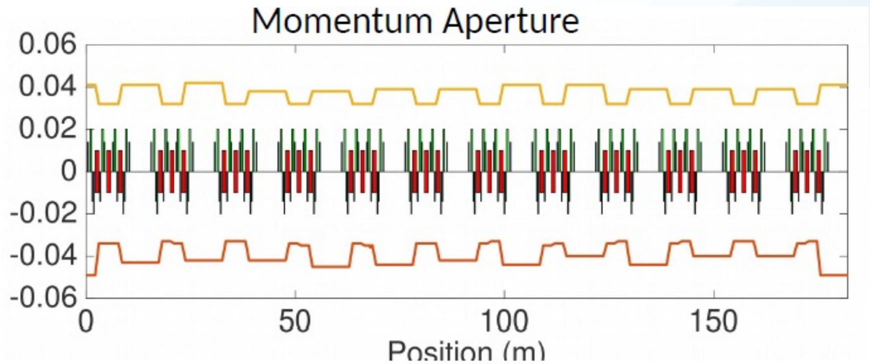
Extensive simulations determined magnet and other error tolerances





T. Hellert

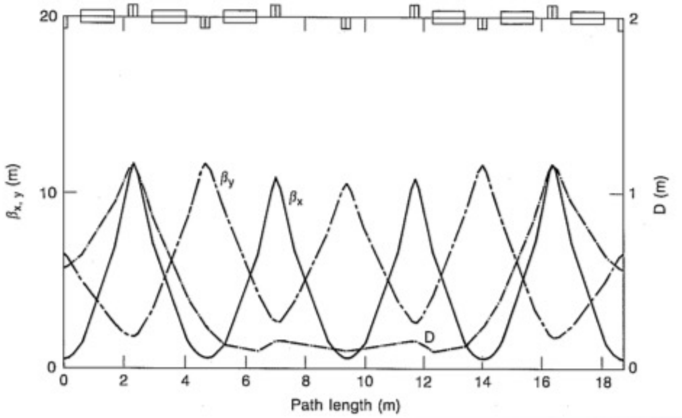
- Error Sources considered (using simulated commissioning toolkit – SC):
  - Systematic multipoles errors
  - Random multipole errors
  - Mechanical, assembly imperfections
  - Magnet misalignments
- Achieve dynamic and momentum aperture close to physical apertures – predict rapid commissioning
- Impact of differential circumference variations (AR/SR) is small

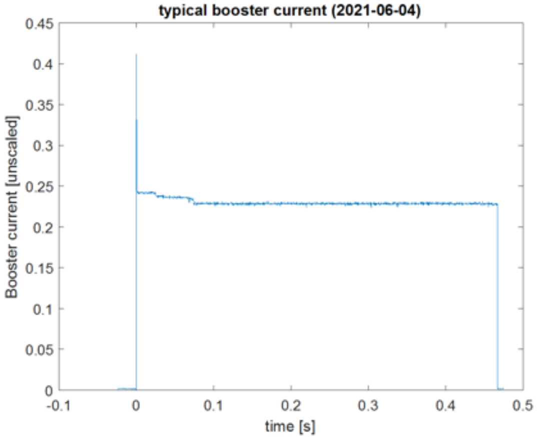


Dynamic Momentum Aperture with errors is larger than RF acceptance

Booster Upgrades

- Linac+Booster have previously been refurbished
  - Power supplies, controls, timing, vacuum instrumentation, …
- Accumulator (with bunch train recovery) relaxes requirements on injector
- Charge and emittance from Booster sufficient for ALS-U
- ALS-U upgrades are limited to expanding booster energy to 2.0 GeV
  - Dipole power supply
  - RF cavity power coupler

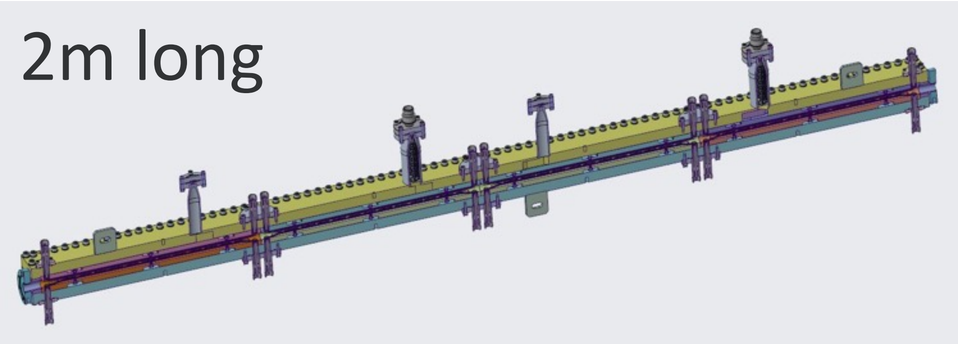


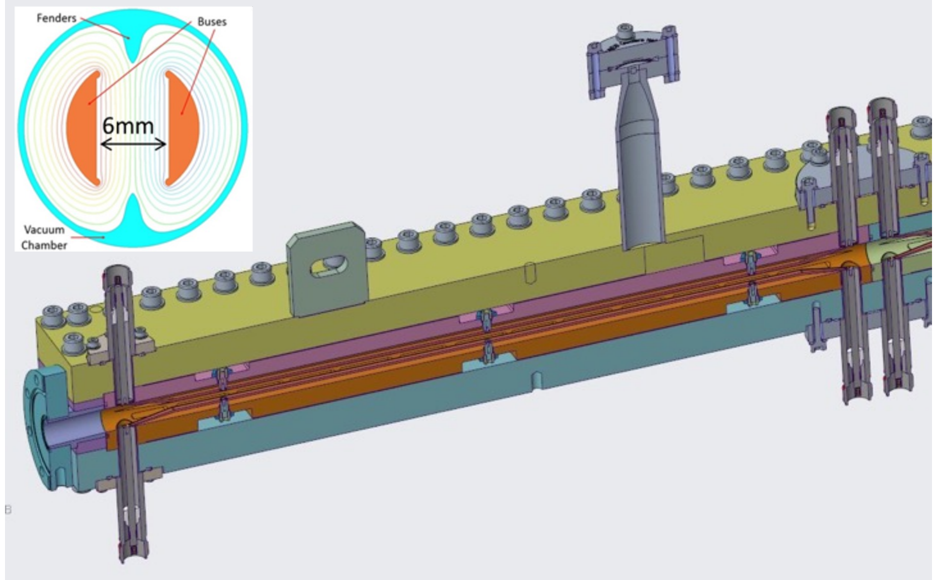


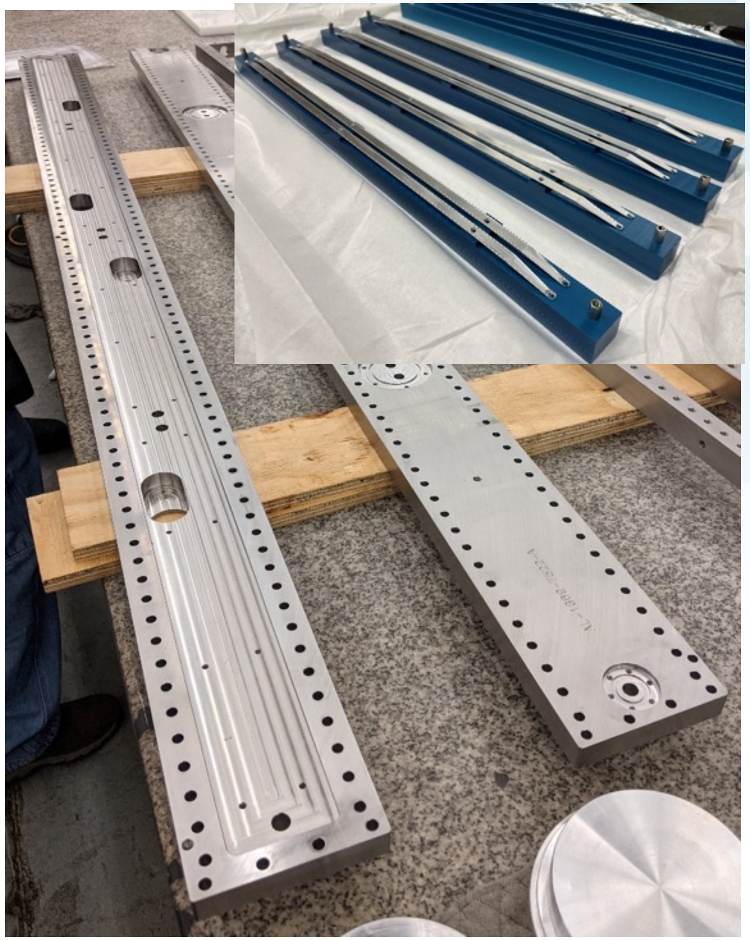
R&D results

Swap-out kicker concept was demonstrated at ALS with beam, full-scale prototype is currently in fabrication

W. Waldron

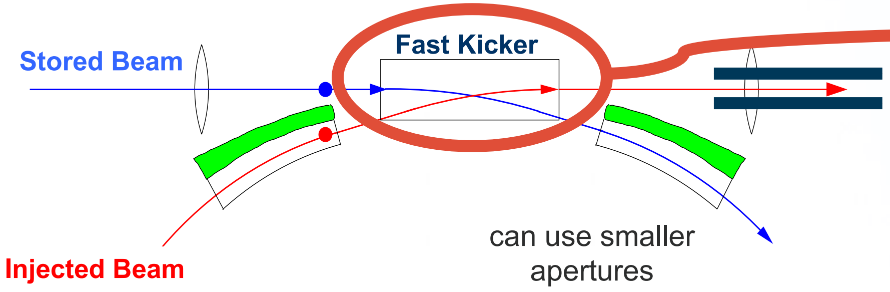


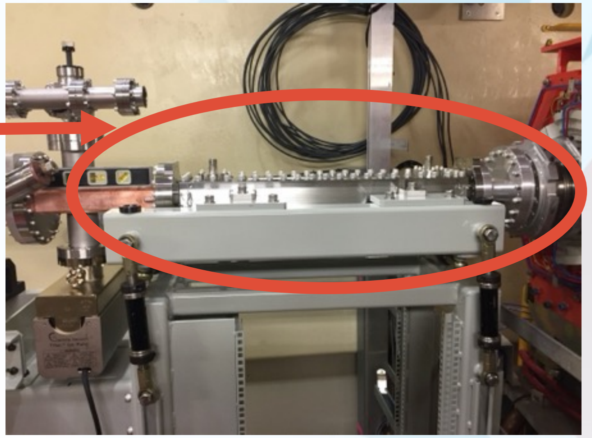


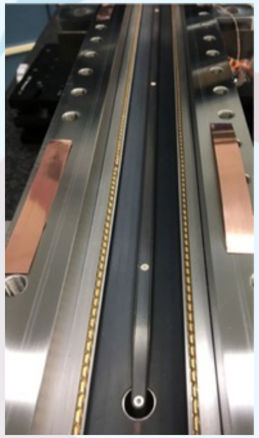


R&D pulser and stripline kicker beam tested over full year in ALS

On-axis swap-out injection
(initially proposed by M. Borland)



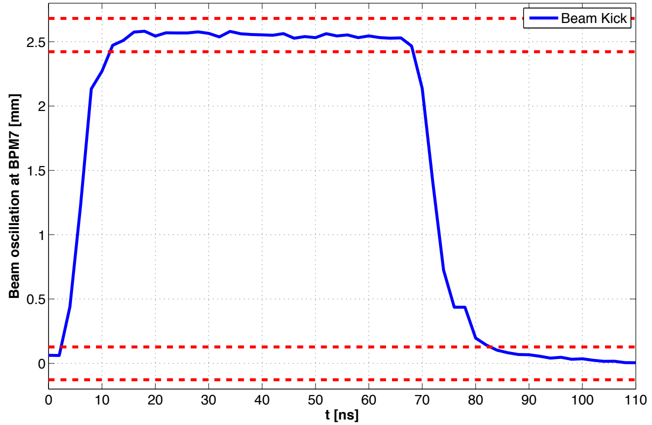


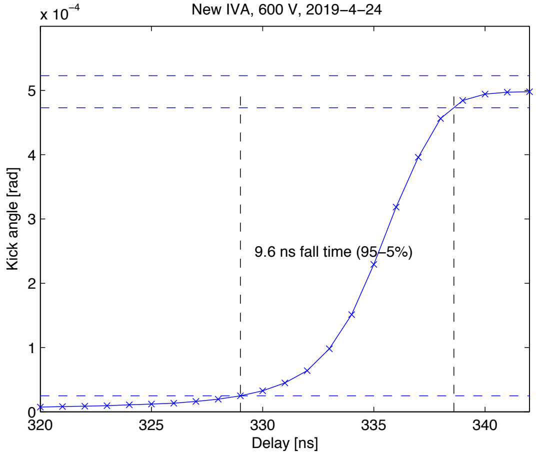


C. Swenson, C. Pappas, S. De Santis, C. Steier

W. Waldron

- In house design for kicker and pulser
- Beam based characterization of rise/fall-time and reproducibility





Successful swap-out technology demonstration on ALS:

- 6 mm full (vertical) gap stripline kicker installed in ALS in 2017
  - In user operations for several years
- Verified impedance and thermal design
- Kicked single bunch, mapping the time structure and reproducibility of pulser

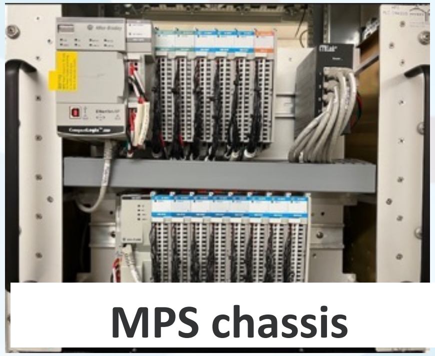
Accumulator progress

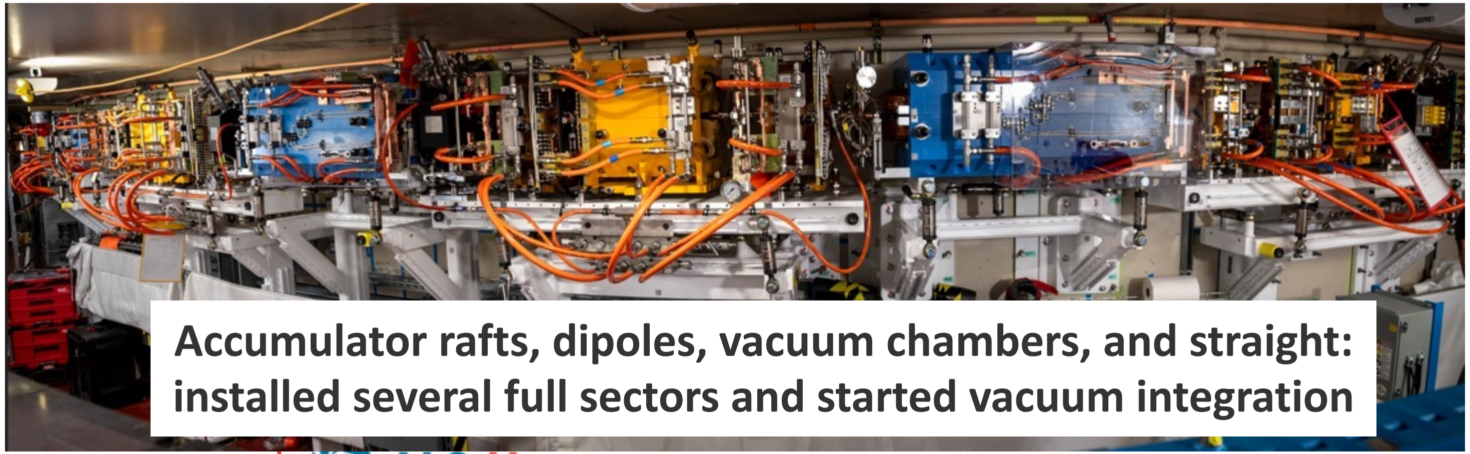
Accumulator Manufacturing and Installation

- Design work is complete, integration and installation plan are mature
- Received majority of mechanical hardware (for example vacuum, magnets, supports fully received)
- Prestaging output close to target rate, handoffs to removal and installation work well, good collaboration for installation support
- Starting electrical installations (rack baseplates, RF HPA); AR AC distribution was previously installed
- Completed full project cycle: Design, Integration, Manufacturing, Testing, Assembly, Installation Support -> basis of SR plan
- Integrated testing and commissioning planned for 2025


Electronics racks at off-site storage


PS Rack


MPS chassis


Accumulator rafts, dipoles, vacuum chambers, and straight: installed several full sectors and started vacuum integration

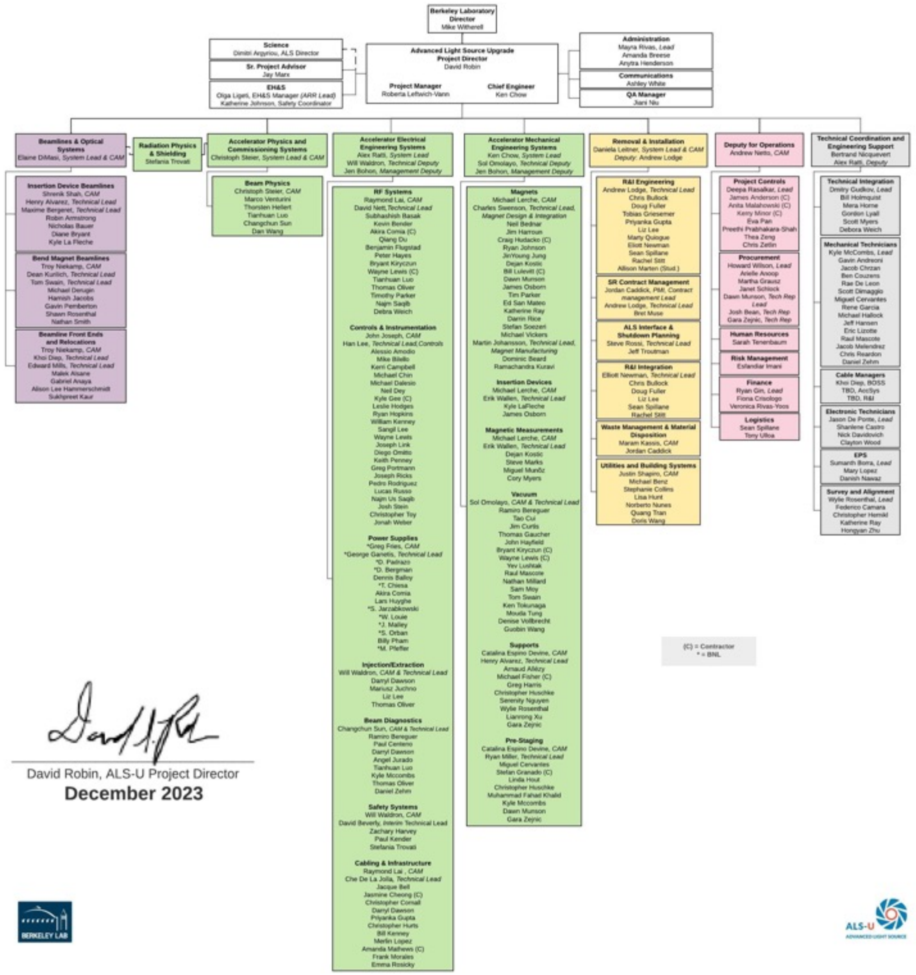

RF Cavities


RF HPA

Summary

- ALS-U will reach diffraction limit for soft x-rays (69 pm emittance)
- Lattice optimization aided by choice of on-axis swap-out injection
- Swap-out needed injector upgrades – optimum choice was full energy accumulator with bunch train swap-out
- Accumulator manufacturing and installation is well advanced, commissioning in 2025
- ALS-U upgrade will be complete afterwards during one year darktime starting in 2026

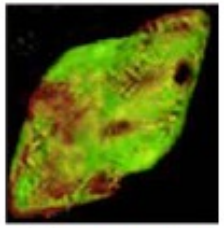
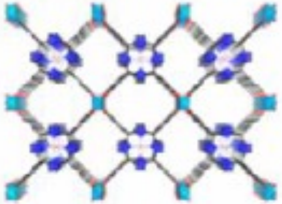
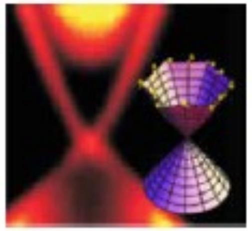
Acknowledgements



- ALS-U is very large project, but for the topics of this talk:
- Leads for swap-out R&D:
  - Will Waldron, Stefano de Santis, Chuck Swenson, Christoph Steier
- Accumulator Design:
  - Physics Lead(s): Marco Venturini, Christoph Steier
  - Mechanical: Steve Virostek
  - Electrical: Will Waldron

Backup Slides

Science Case for ALS-U

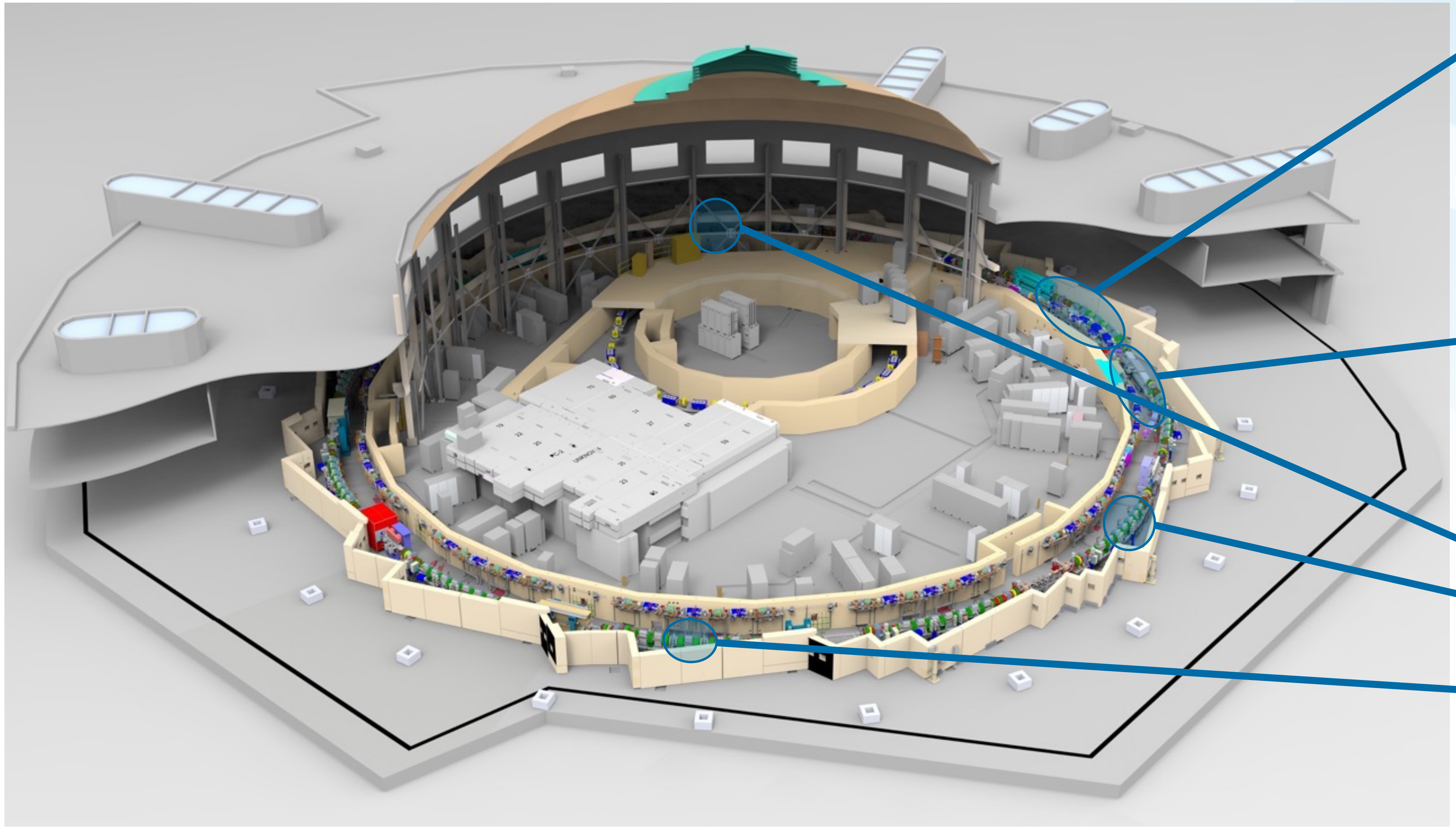
TRANSFORMATIVE OPPORTUNITY	EXAMPLE APPLICATION	POTENTIAL SOCIETAL BENEFITS
Understanding the critical roles of heterogeneity	 Charge motion	Energy storage, carbon sequestration, low-power computing
Mastering hierarchical architectures	 Controlling chemistry	Chemical catalytic reactors, solor fuel production, water purification
Harnessing coherence in light and matter	 Topological spin and quantum matter	Untralow-power computing, new classes of sensors, spin-based devices

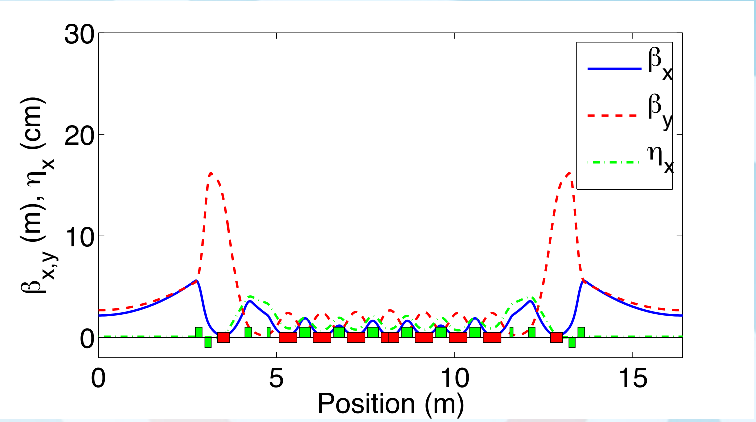
- **Soft x-ray light**, which has the appropriate energy to interact strongly with the electrons that determine the *chemical*, *electronic*, and *magnetic* properties of materials, and

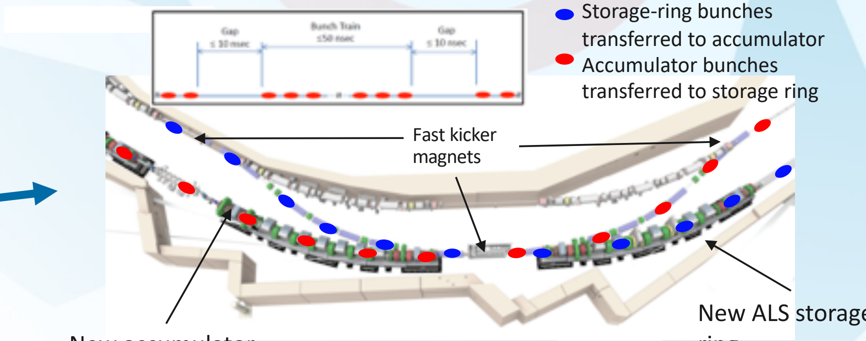
- **High coherent flux delivered in a nearly continuous wave**, which is necessary to resolve *nanometer-scale* features and interactions and which allows *real-time observation* of chemical processes as they evolve and materials as they function.

Baseline is mature and stable, and reaches soft x-ray diffraction limit up to 1.5 keV

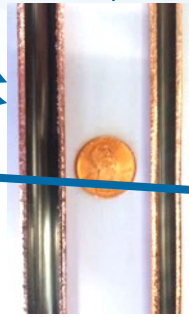
Major design choices have remained throughout R&D and design phases – 9 bend achromat, bunch trains swap out, accumulator, HBends



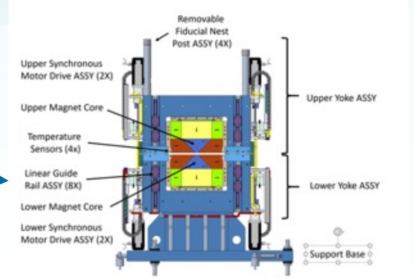




Bunch train swap-out using demonstrated kicker/pulser technology



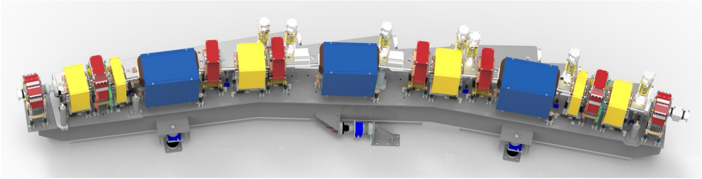
Small aperture NEG coating

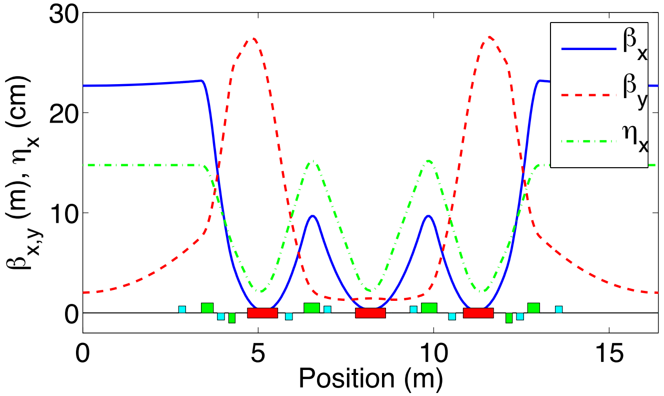


High Field PM bend magnets

Nine-bend achromat lattice reaches the soft x-ray diffraction limit up to 1.5 keV

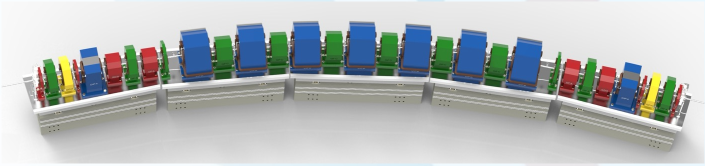
ALS today: triple-bend achromat

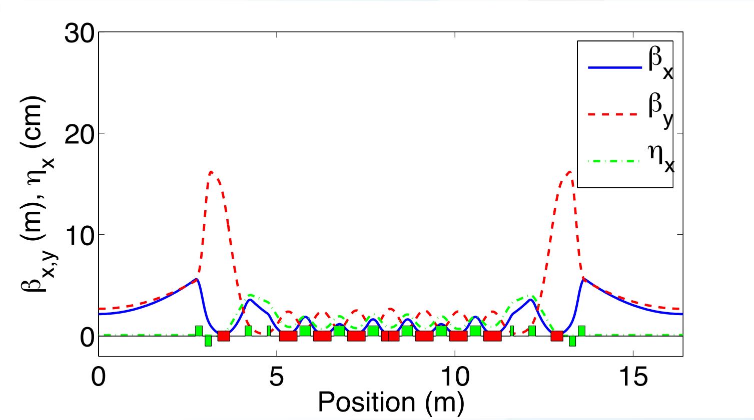




$\varepsilon_x \approx 2000$ pm rad at $1.9 GeV$

ALS-U: nine-bend achromat with reverse bends





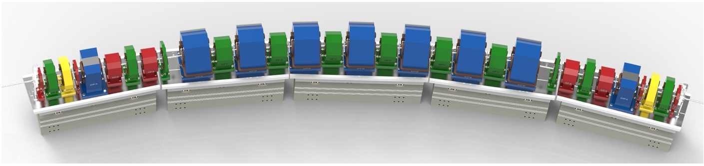
$\varepsilon_x < 75$ pm rad at $2.0 GeV$

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

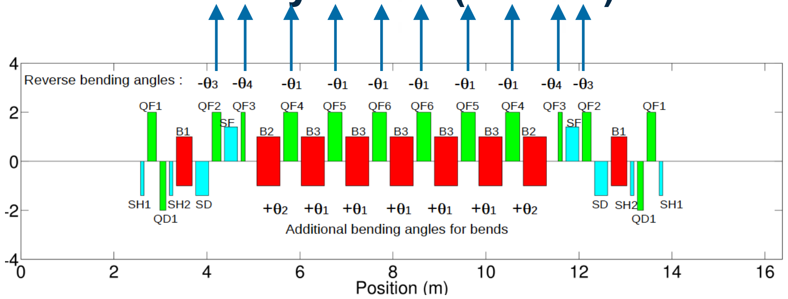
Large increase in coherent fraction due to lower emittance and smaller β-functions

Performance enhancing lattice features: Reverse bends & high-field bend magnets

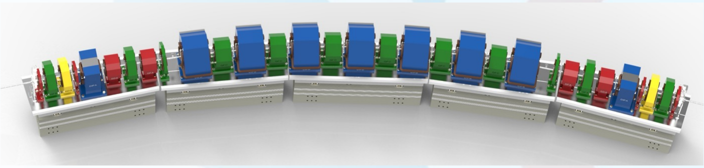
Reverse Bends



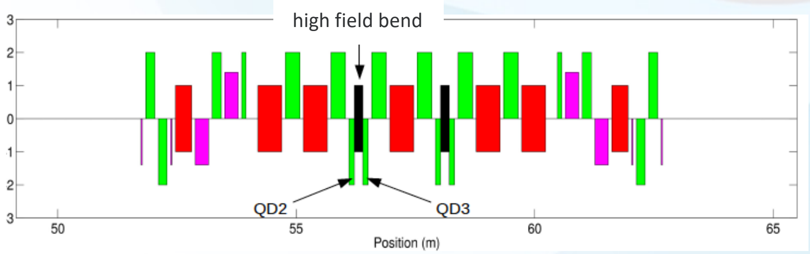
10 focusing quadrupoles per sector radially offset (~1 mm)



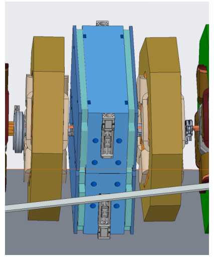
High Field Bend Magnets

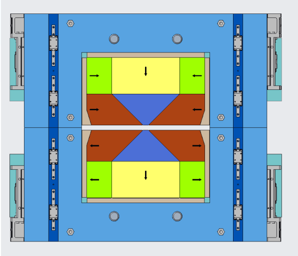


3 of 12 Sectors



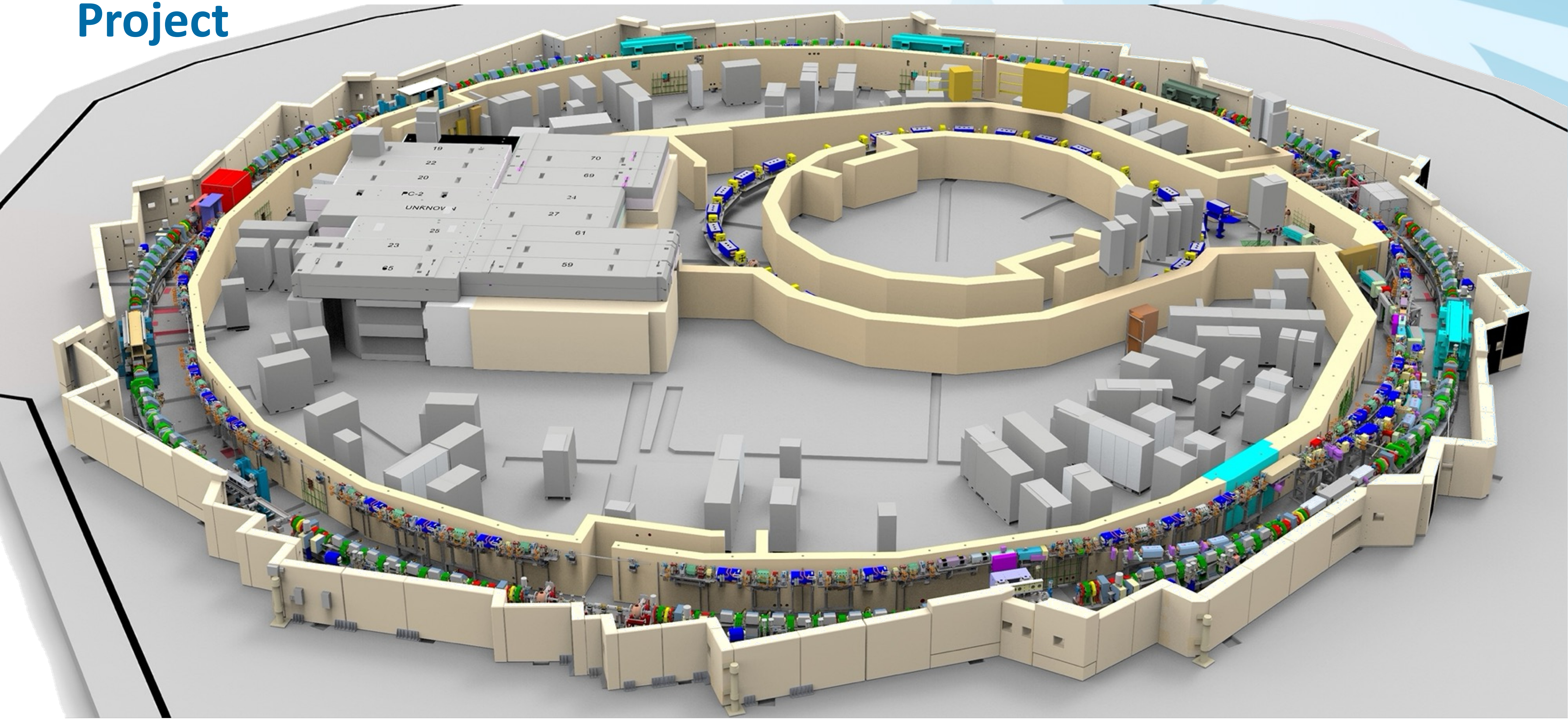
2 magnets each





- Reverse bends further reduce emittance
  - ~1 mm offset of 10 QF per sector
- High Field Bend Magnets allow generation of hard x-rays on intermediate energy ring
  - 3.2 T Permanent Magnet dipoles

ALS-U Integrated CAD model includes all mechanical scope of Project



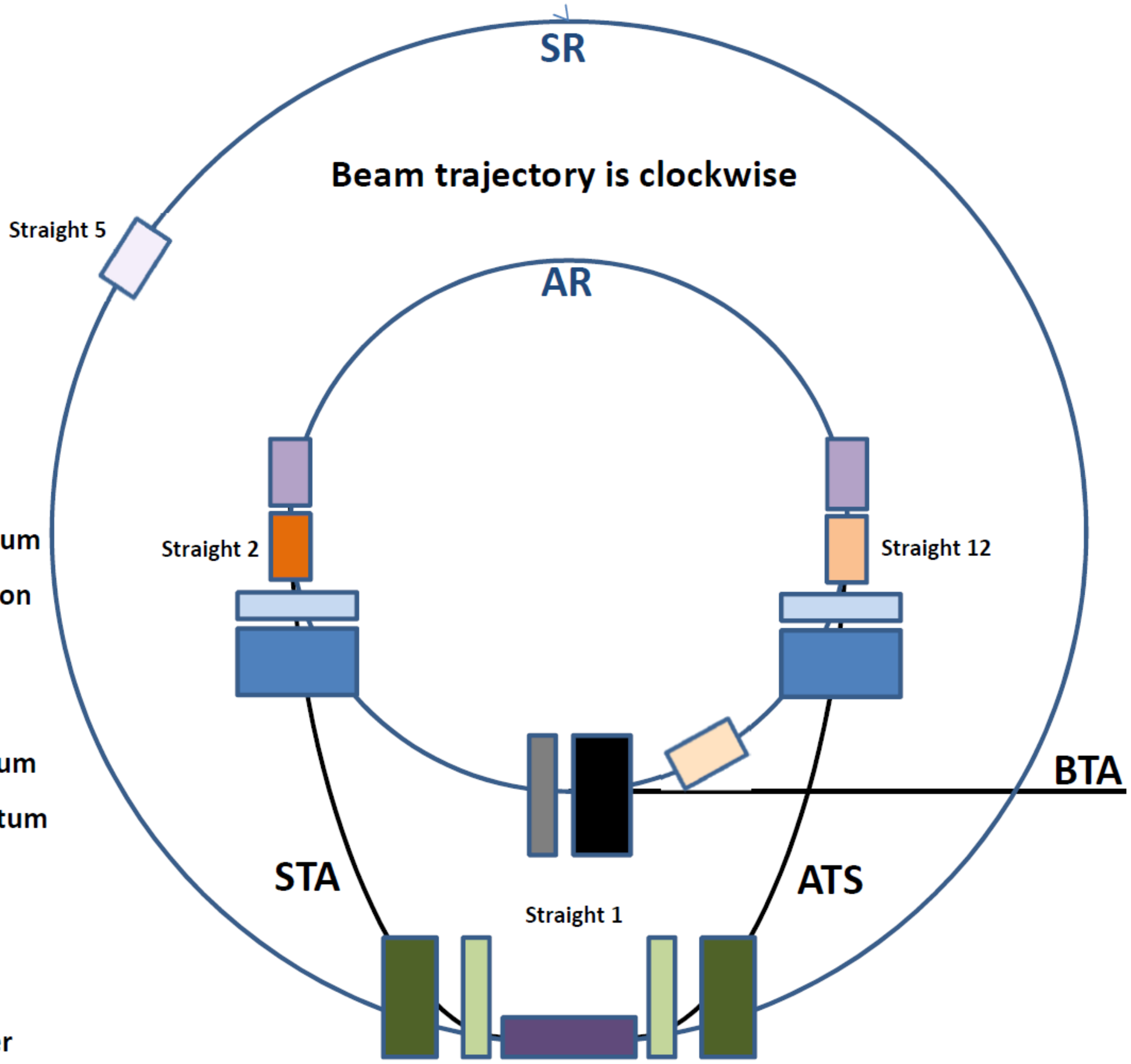
Injection / Extraction

AR
(commissioning)

- BTA Pre-kicker 1
- BTA Pre-kicker 2
- BTA Primary Kicker
- BTA Thin Septum
- BTA Thick Septum

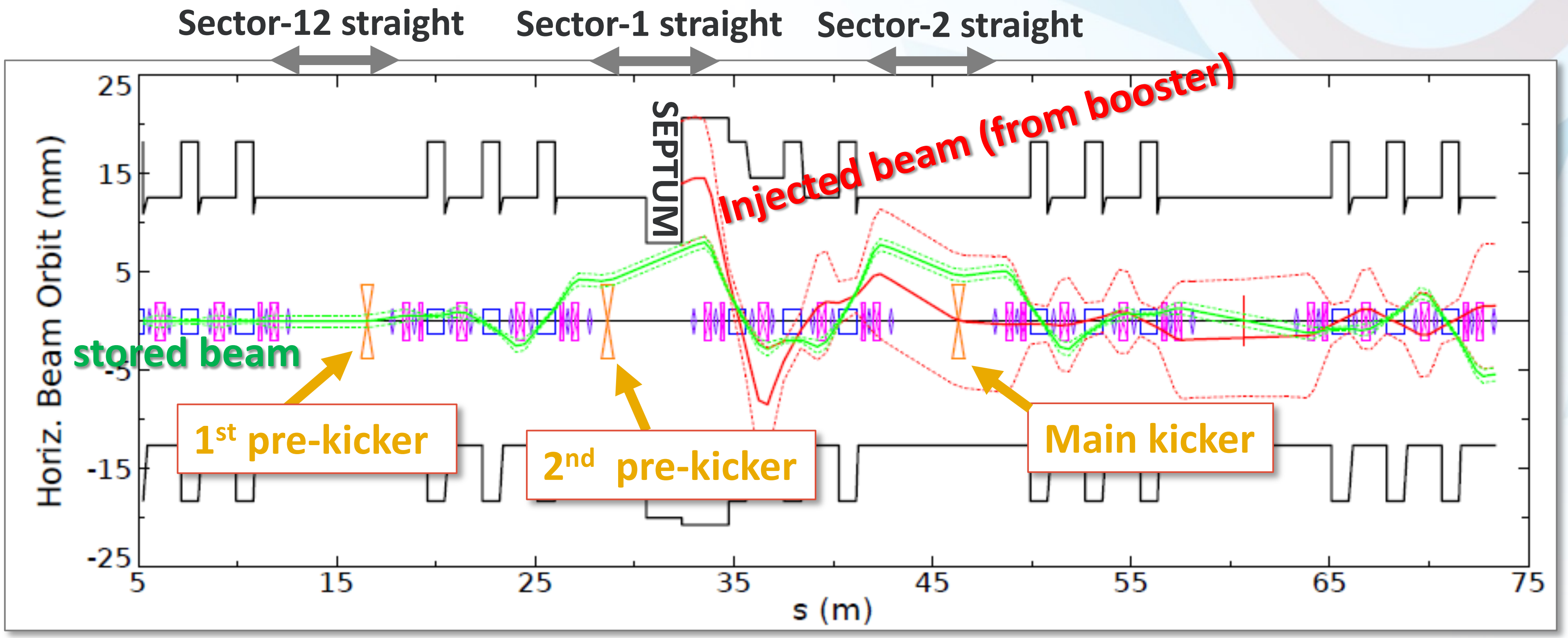
SR

- AR ATS/STA kicker
- AR ATS/STA Thin Septum
- AR ATS/STA Lambertson
- SR ATS/STA Thin Septum
- SR ATS/STA Thick Septum
- SR Swap-out kicker
- SR Decoherence kicker



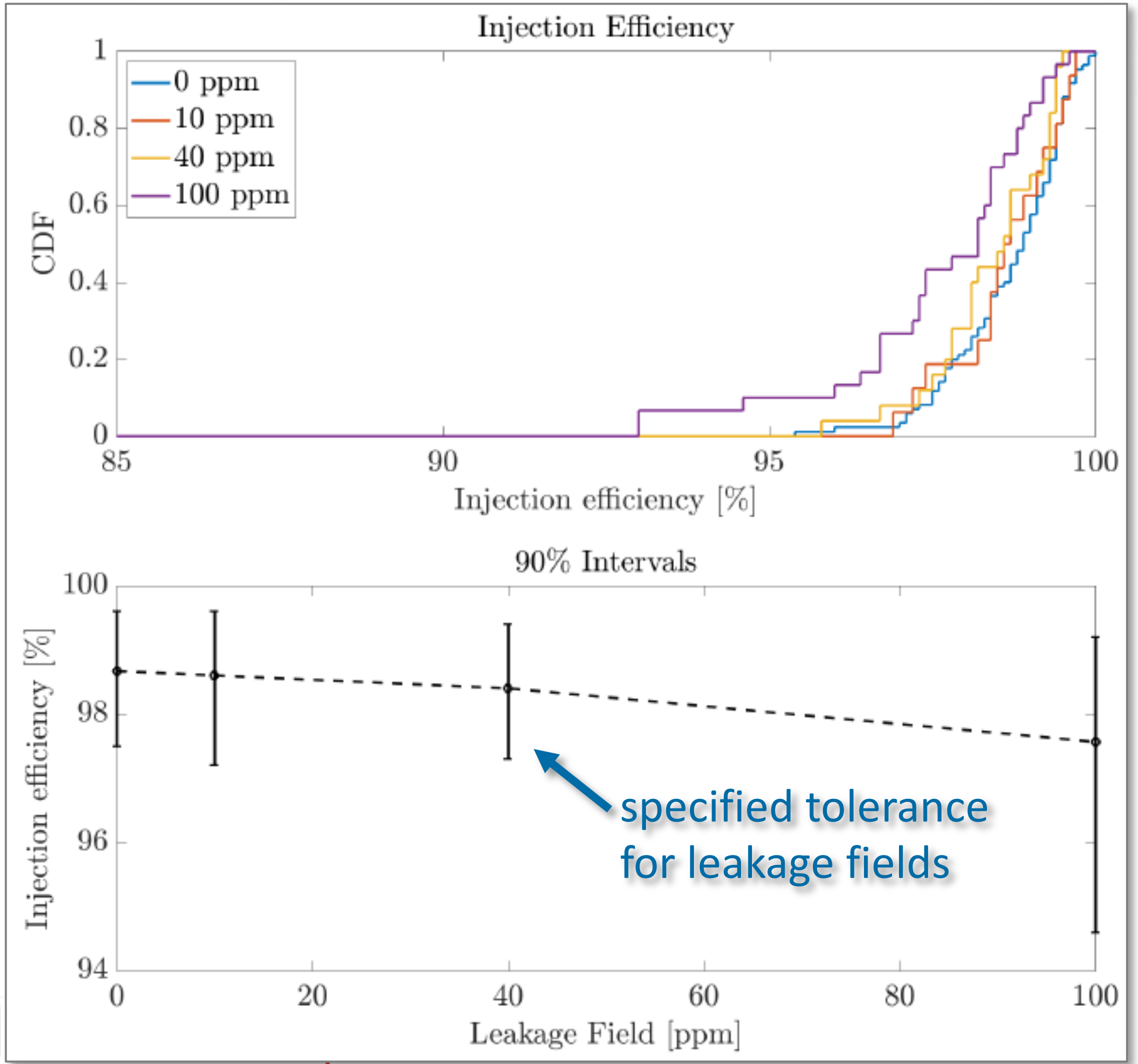
Injection from the Booster (top-off) is based on a three pulsed-dipole kicker (3DK) scheme

- Kickers are placed in three separate sectors (12, 1, and 2)
  - 1st and 2nd pre-kickers only affect the stored beam. The main kicker deflects both stored and injected beam.
  - Pulsed thin + thick septum in sector 1 straight
- For best injection efficiency the stored beam is left with a small, finite oscillation-amplitude past the main kicker



Simulations show injection efficiency > 95% over all lattice error realizations

Study of tolerance to thin-septum leakage fields (on top of all other error sources)



- 3DK optimally set (by scan) based on lattice error realization
  - No losses on the stored beam
- These simulation do not include 3-4% possible additional degradation due to collective effects
  - Likely to be less once wakes are included in full 3DK setting optimization
- With additional losses through BTA (BTA magnet errors, beam jitter) injection efficiency estimated to above 90% for the largest majority of error realizations

ALS-U Summary

Scope:

- New 2-GeV, high-brightness storage ring fed by a new full-energy accumulator ring and transfer lines in the existing ALS storage-ring tunnel
- 2 new full-length undulators
- Suite of 2 new and 2 upgraded world-leading undulator beamlines
- High-field bends and realignment of bend-magnet beamlines
- Seismic and shielding upgrades of SR tunnel

Cost:

- TPC of $590M (CD-2 approval 4/2021)

Schedule:

- CD-3A approved 12/2019 for the early installation and commissioning of the accumulator ring and BTA prior to dark time
- CD-2 approved 4/2021
- CD-3 approved 11/2022
- AR commissioning starts late 2025
- Dark Period is FY26 (start 6/2026)
- Early finish is early FY28 , >1 year of float to late finish