Low Emittance Rings Workshop – ESRF, Grenoble, Sep 15-17, 2015

Work towards a soft x-ray diffraction limited upgrade of the ALS (ALS-U)

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for the ALS-U team

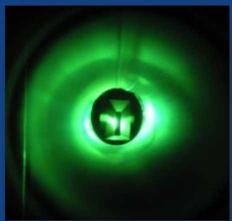
Advanced Light Source, Accelerator Technology and Applied Physics Division

Outline

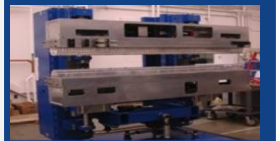
- Introduction
  - ALS / ALS-U
- Optimization for soft x-ray diffraction limit
- R+D Progress towards ALS-U
  - Baseline Lattice
  - Injection / Pulsed Magnets
  - Bunch Lengthening
  - NEG coating
- Pre Conceptual Design Work
  - Magnets, Layout, Photon Beamlines

Pioneering Accelerator and Beamline Upgrades have kept ALS as Soft X-Ray Leader for 20 Years

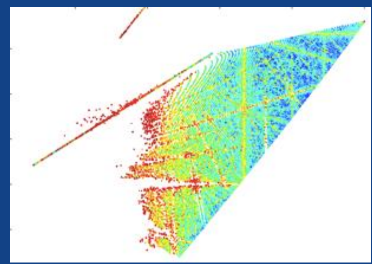
first ALS light



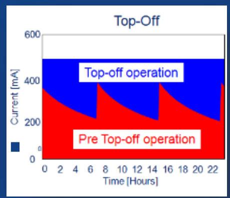
elliptically polarizing undulator



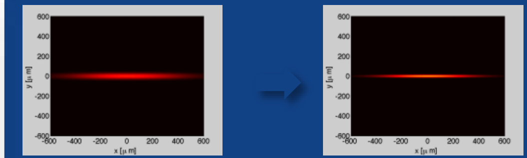
frequency maps



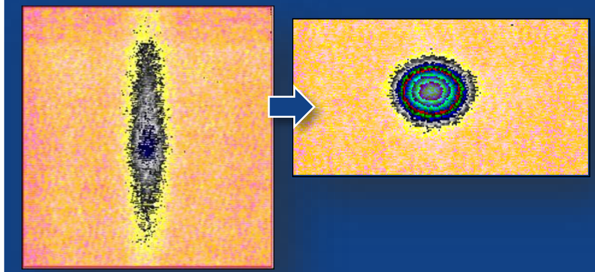
top-off at 500 mA



brightness upgrade
3x emittance reduction

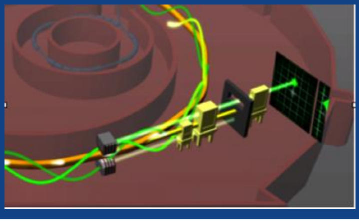


1993 2003 2013 2020s

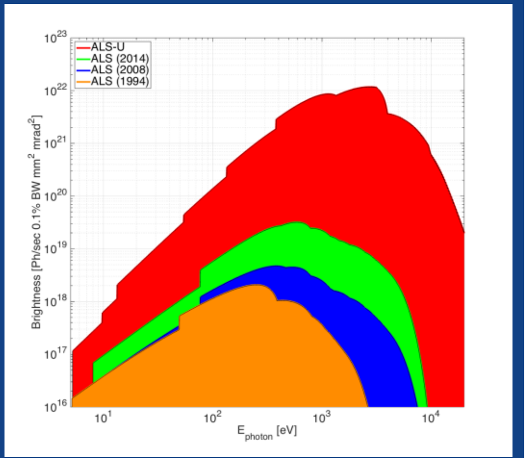


multi-bunch feedback for high-current and high-brightness

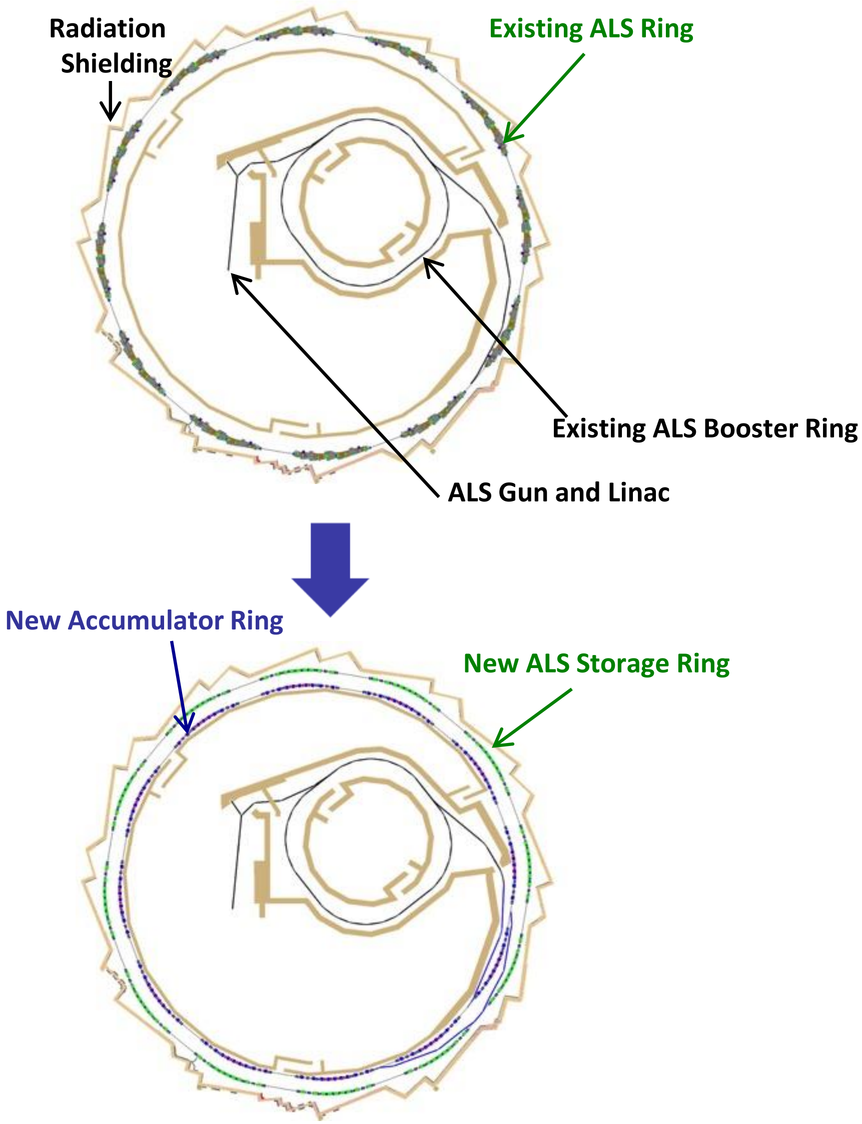
pseudo single bunches for pulses on demand



ready for generational leap: ALS-U



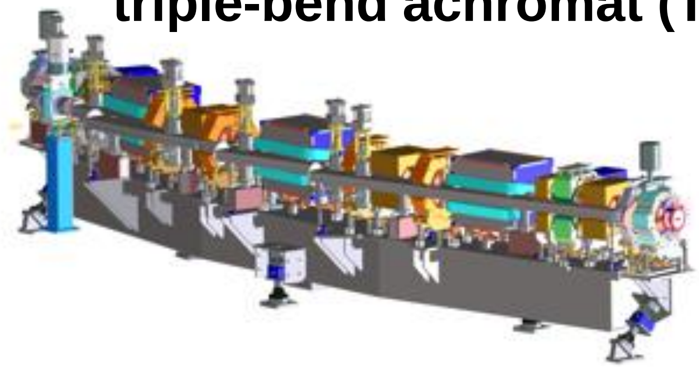
Introduction: ALS / ALS-U



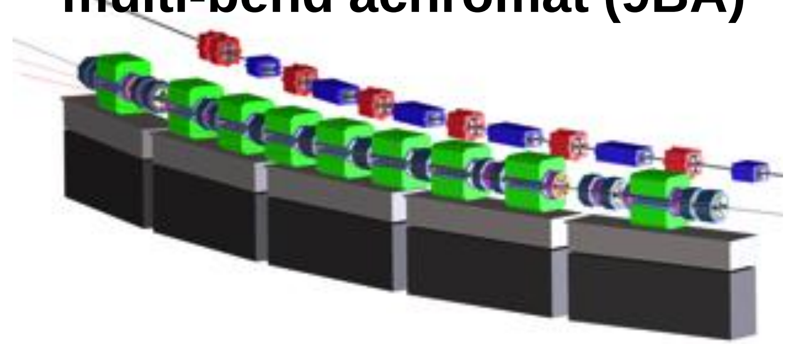
Parameter	Units	Current ALS	ALS-U
Electron Energy	GeV	1.9	1.9-2.2 (2.0 baseline)
Horiz. Emittance	pm rad	2000	~50
Vert. Emittance	pm rad	30	~50
Beamsize @ ID center (σ_x/σ_y)	μm	251 / 9	<10 / <10
Beamsize @ Bend (σ_x/σ_y)	μm	40 / 7	<5 / <7
Energy Spread	ΔE/E	9.7×10^{-4}	$<9 \times 10^{-4}$
Typical Bunch Length (FWHM)	ps	60-70 (harmonic cavity)	150-200 (harmonic cavity)
Circumference	m	196.8	~196.5
Bend Magnet Angle	degree	10	3.33

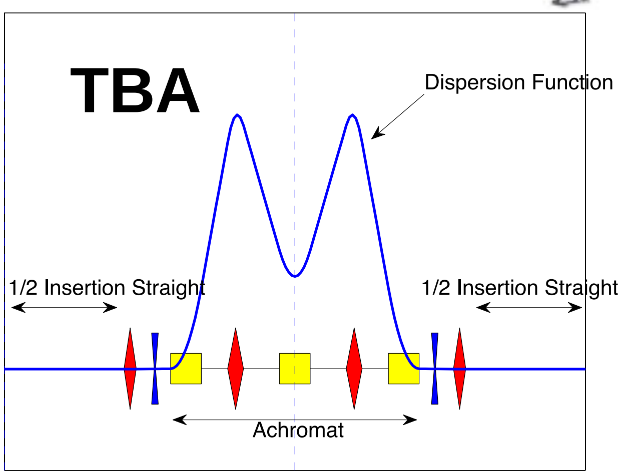
ALS-U uses compact 9BA to reach soft X-ray diffraction limit

ALS today
triple-bend achromat (TBA)



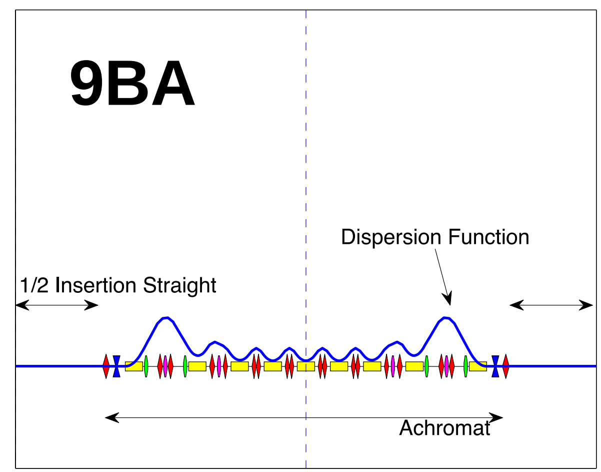
ALS-U
multi-bend achromat (9BA)





$$e_x = 2000\ \text{pm} \ @\ 1.9GeV$$

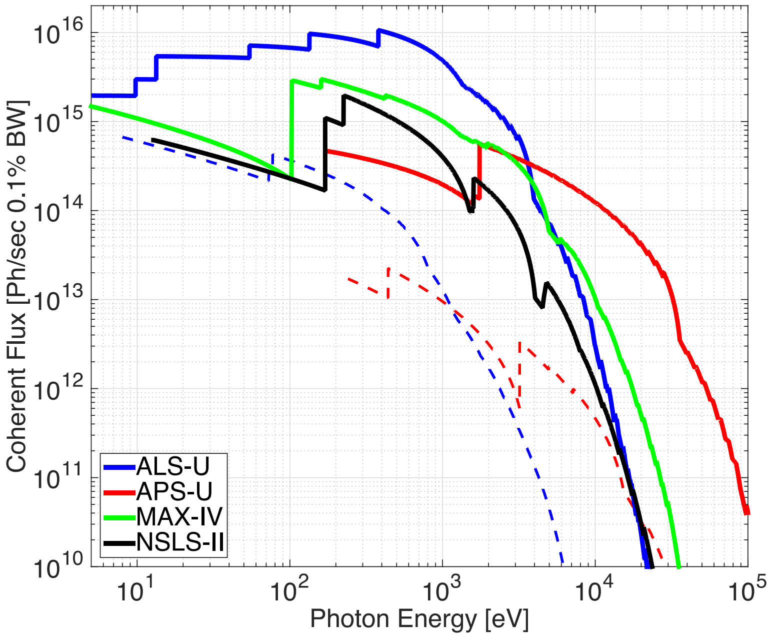
$$e_x = C_L \frac{E^2}{N_D^3}$$

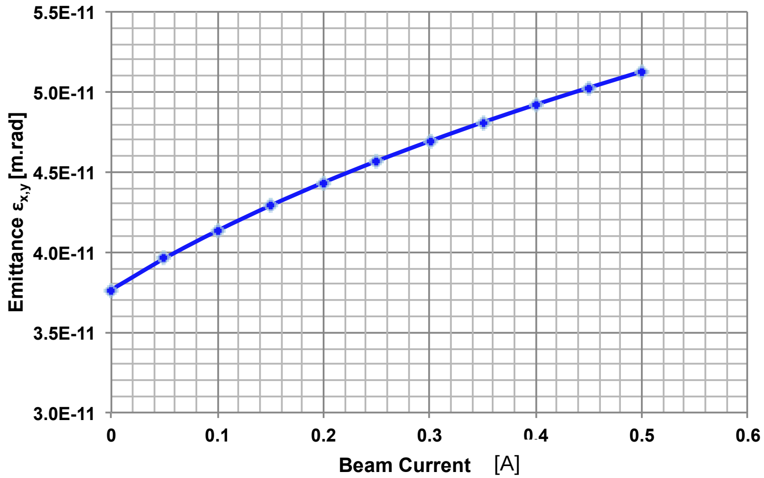


$$e_x = 52\ \text{pm} \ @\ 2.0GeV$$

Optimizing for soft x-rays

- Brightness peak in soft x-rays allows low electron beam energy (3 keV-2 GeV)
- Diffraction limited emittance moderate (2 keV-50pm) – reachable with 200m ring
- Vertical plane diffraction limited at same ('large') emittance - round beam
- Lower energy allows shorter focal lengths-more magnets, lower emittance
- Smaller ring-less unit cells-larger dispersion-weaker sextupoles
- Intrabeam scattering much worse-need to fill all buckets and lengthen bunches aggressively
- Heatload on optics smaller for lower beam energy

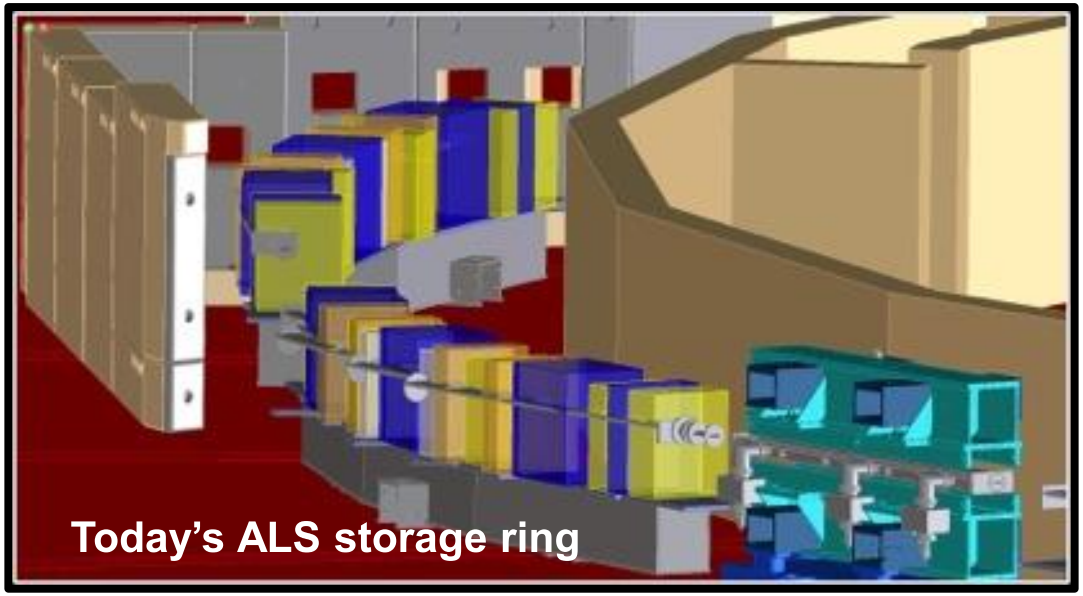


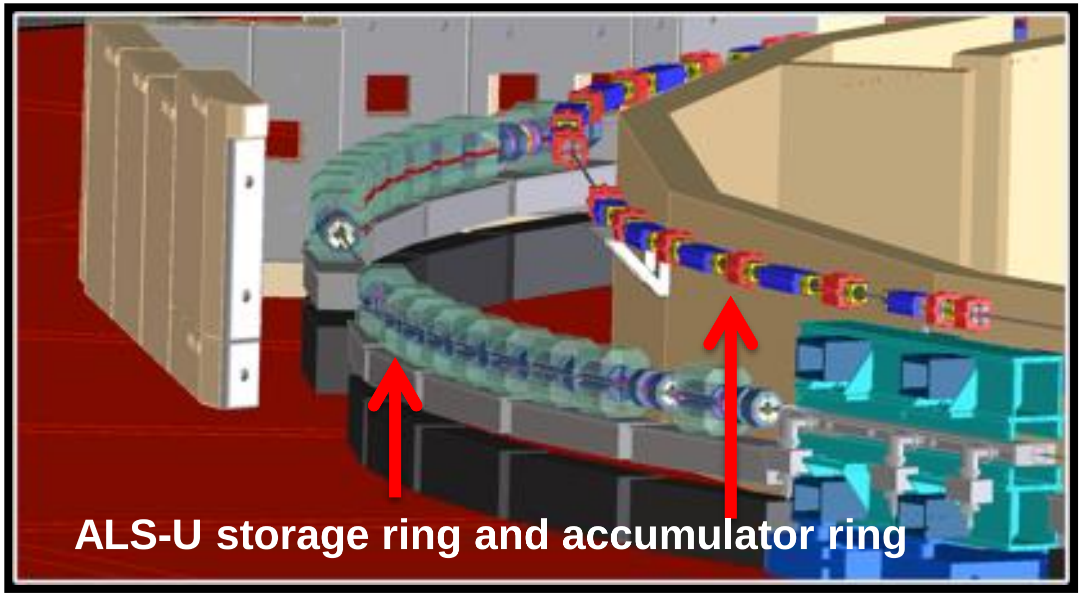


Use of Swap-Out Enables Generational Leap

On-axis swap-out injection:

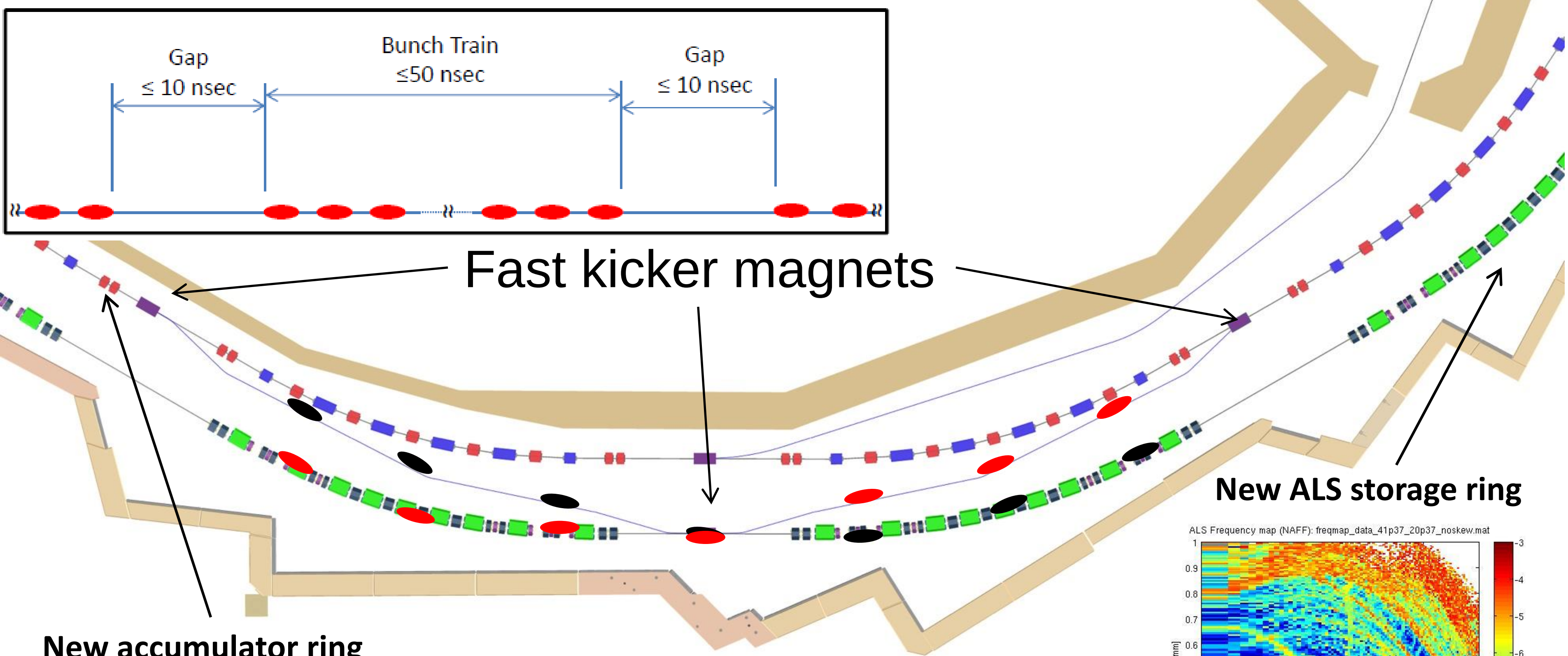
- **Further optimization of lattice** (smaller emittance)
- **Round beams** (more useful shape and reduced emittance growth)
- **Magnet field requirements relaxed** (cost benefit)
- **Vacuum chambers with small and round apertures** (better undulator performance)
- **Reduced injection losses** (better performance)

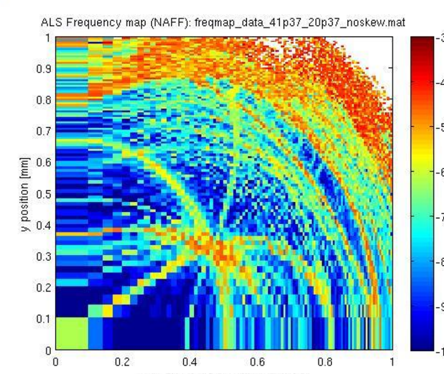




Swapping accumulator and storage ring beams

- storage ring bunches transferred to accumulator
- accumulator bunches transferred to storage ring

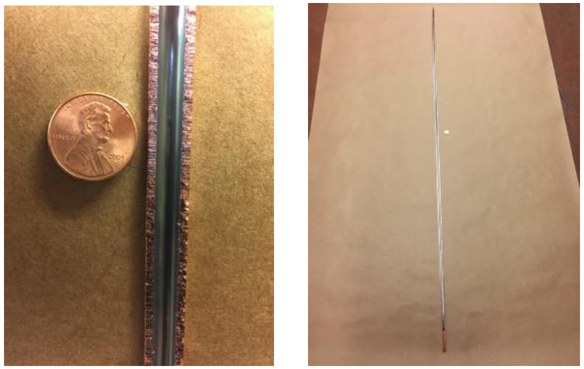




Swap-out injection was first proposed by M. Borland for possible APS upgrades

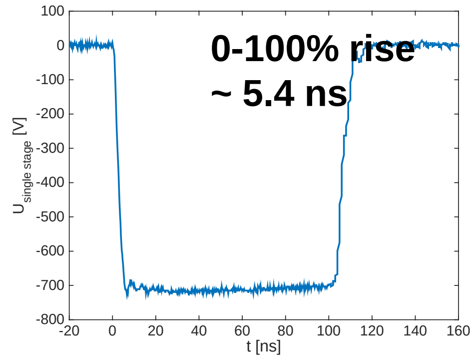
Examples of R+D Progress

Very small NEG coated vacuum chambers



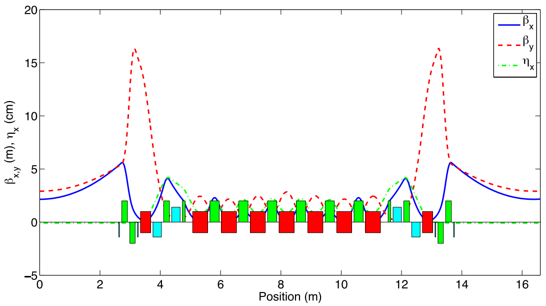
Coated 6 mm chamber (world record)

On-axis Injection – Fast pulsed magnets



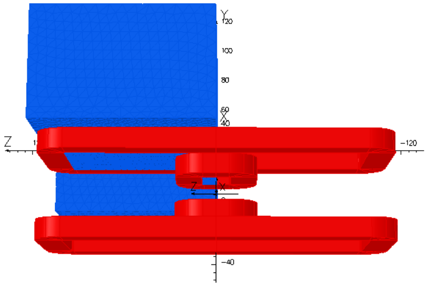
Adder achieves 5 ns rise (7 ns needed)

Optimization of Physics Design



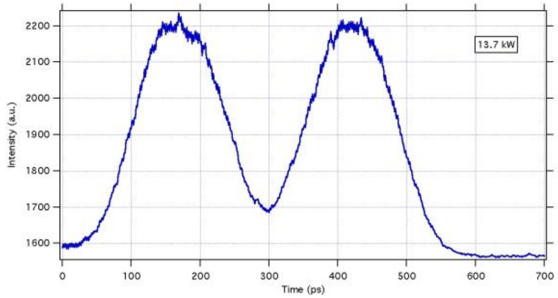
Released Baseline Lattice

Magnets – SR Production



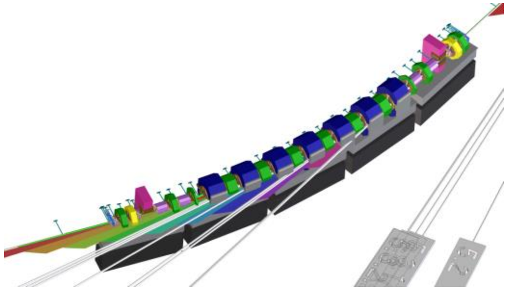
Evaluated Superbend options

Harmonic Cavities - Transients



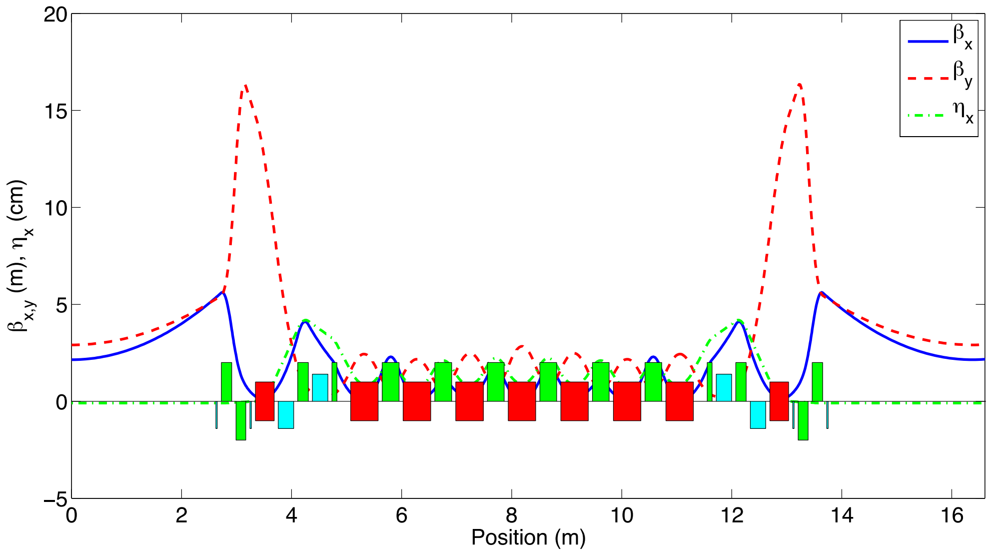
Achieved needed bunch lengthening with ALS-U bunch trains in ALS (3HC)

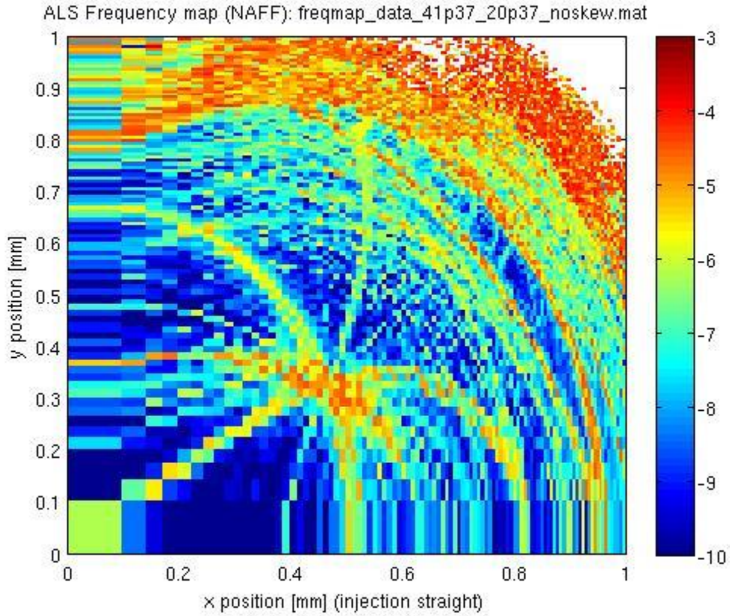
Engineering



Automated iteration between physics and CAD model

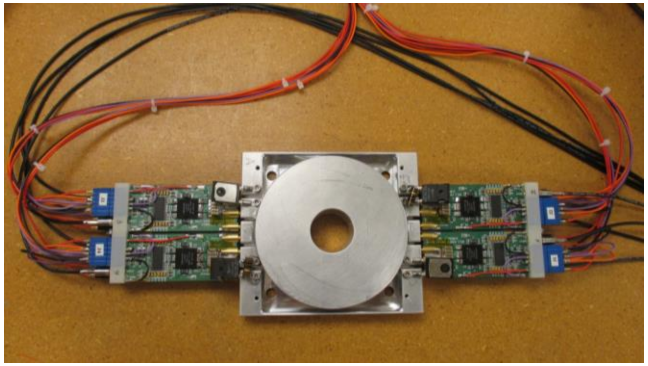
ALS-U Baseline Lattice

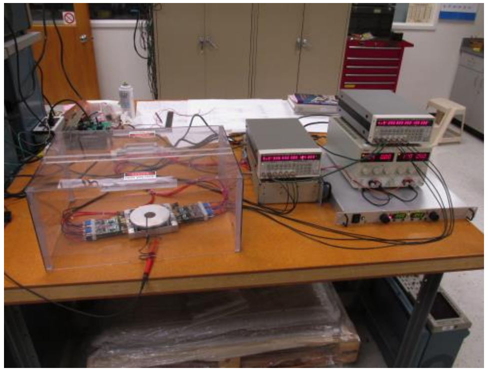


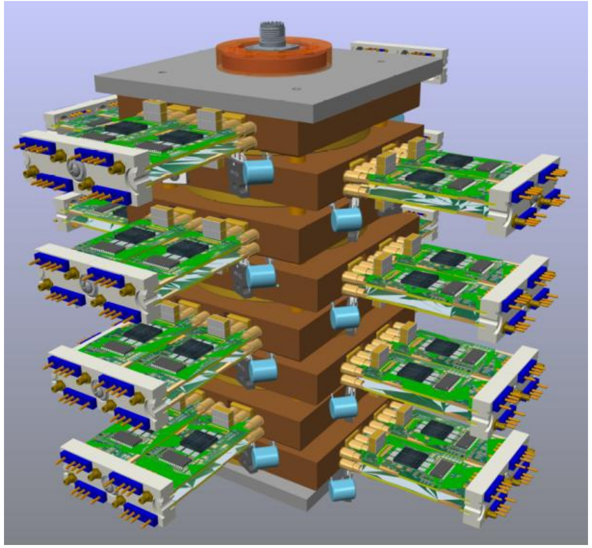


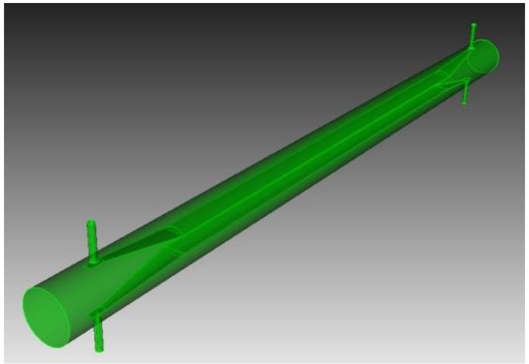
- ALS-U uses very compact 9BA
  - Low beam energy allows very high phase advance per cell
  - No longitudinal gradient dipoles, no octupoles, no half integer phase advance between sextupole sections
- Released baseline lattice, optimized with MOGA (linear+non-linear):
  - allows to study of engineering/layout/geometry questions
  - achieves basic design goals: Emittance, Dynamic Aperture, Momentum Aperture

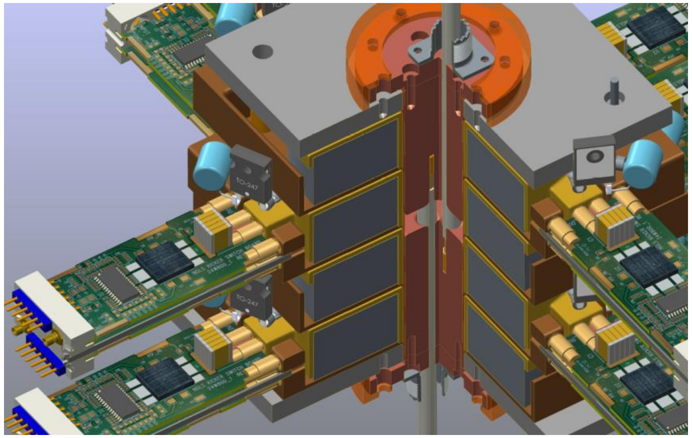
ALS-U R+D - Injection





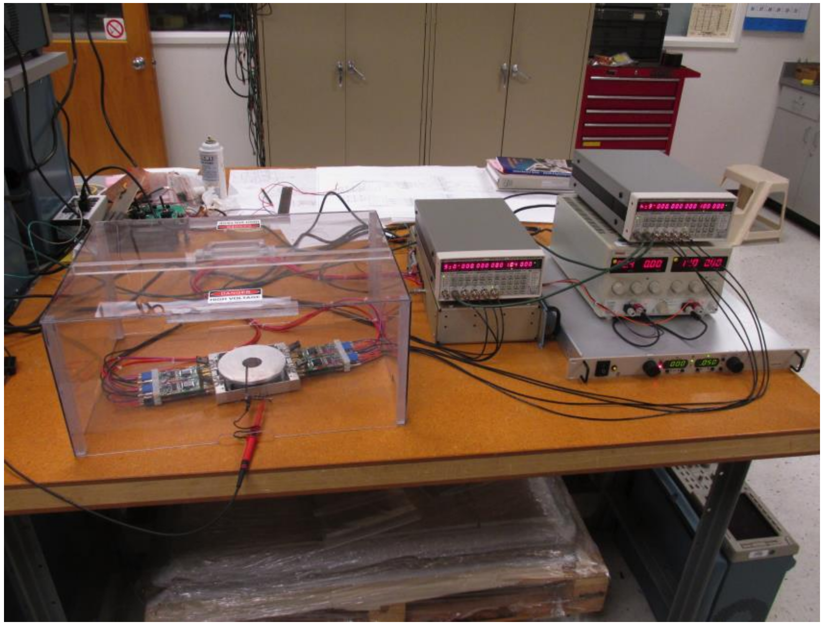


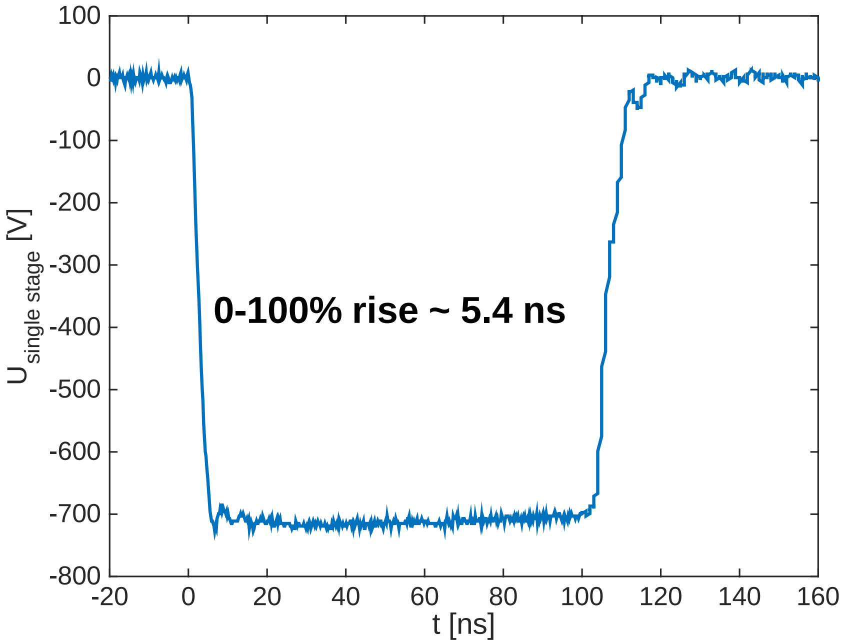




- Pulsed Magnets/Injection – Swap-out for ALS-U
  - Pursuing various pulser designs (inductive/transmission line adder)
  - Also evaluating capabilities of industry (Germany, USA/SBIR)
  - Very small aperture stripline kicker with tapered ends, 0.5 m modules

R+D Success - Injection



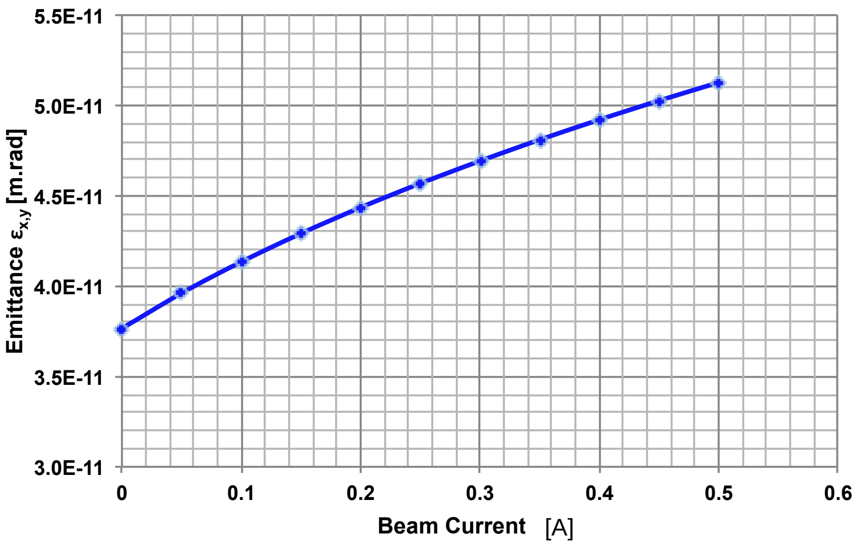


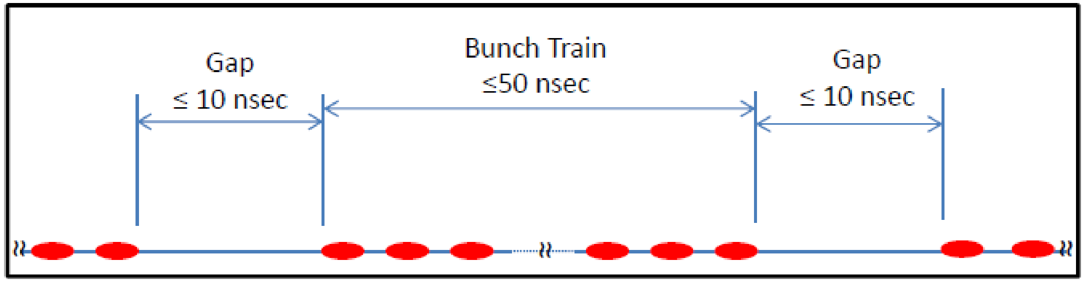
- **Single module with ALS-U parameters has been tested successfully** (<<10 ns rise/fall time)
  - Consistent with RF / THC design
  - Full pulser almost complete; test with beam in FY16

  See talk by Stefano de Santis for more details

ALS-U Bunch Lengthening

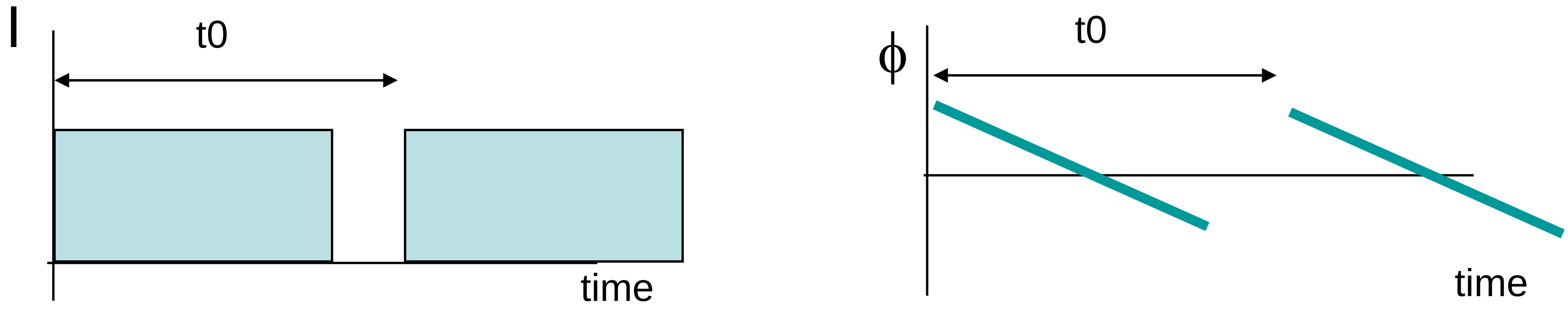
- Bunch lengthening factors of >=4 essential
- Has been demonstrated (s/c or low frequency RF) but difficult
- Fill pattern important
- Conducted beam tests on ALS to verify simulation codes and select baseline RF option (100/500 MHz, s/c vs n/c, active/passive)





Transient beam loading effects

Unequal filling (i.e. gaps, bunch charge variations) creates transient loading of main and harmonic RF systems, causing bunches to be at different RF phases (i.e. different arrival times) and have different bunch lengths

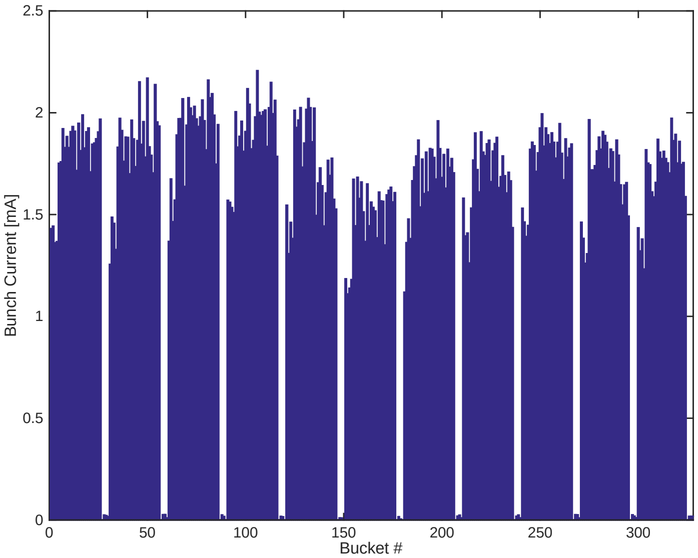


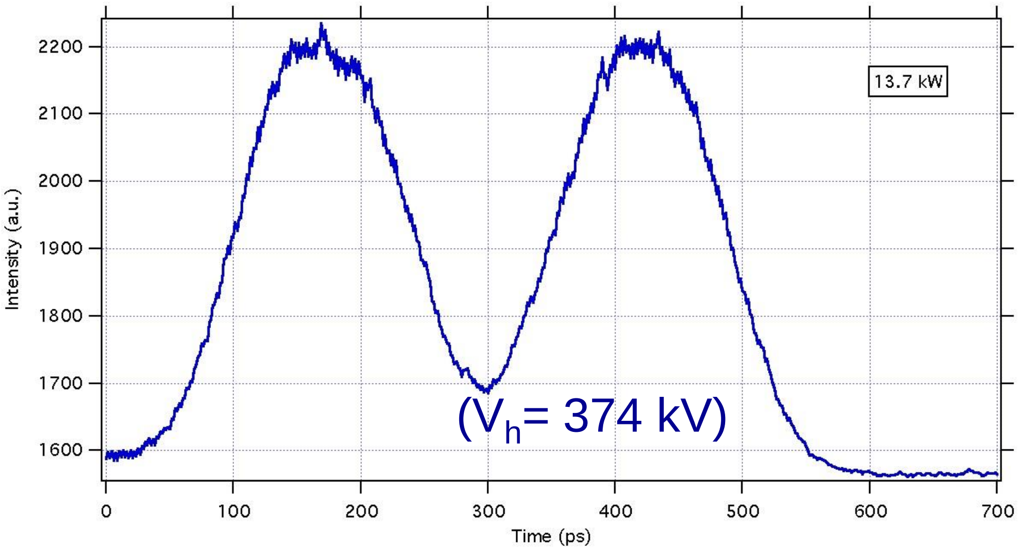
For the main RF only, this effect is small (few degrees). With the HCs, the effect is much larger (flat potential – self amplification). This affects both the lifetime improvement and operation of the multibunch feedback systems.

$$\Delta\phi = \frac{\Delta V}{V_{\rm rf}\cos\phi_1} = \frac{h\alpha\Delta V}{2\pi E Q_s^2},$$

The effect shows up in passive and active systems. Beam driving term is very large compared to external drive. Therefore needs careful study even for active systems.

R+D Success – Bunch Lengthening

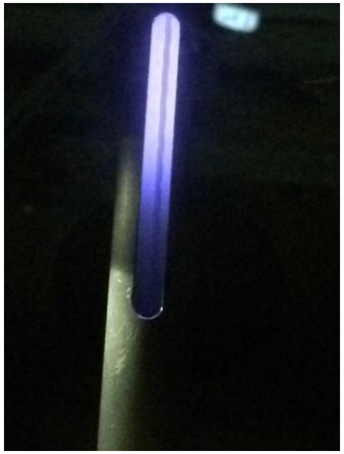


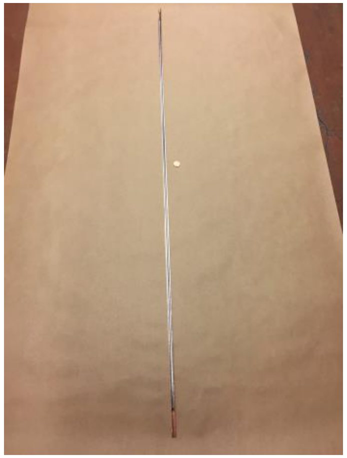
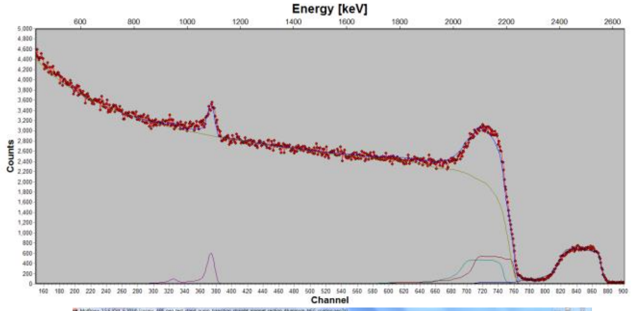


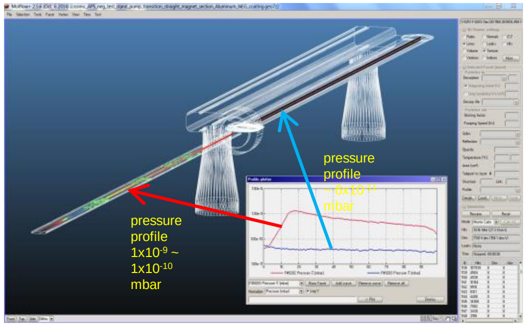
- **Large bunch lengthening factors (>4) essential (IBS), but not routinely achieved before**
- Extensive simulations (finite element, multi particle tracking)
- Measurements with ALS harmonic cavity system in parameter regimes close to ALS-U (fill pattern, lengthening factor) – **Achieved factor >4, retiring large risk.**

More details in talk by Stefano de Santis

R+D Success - Vacuum



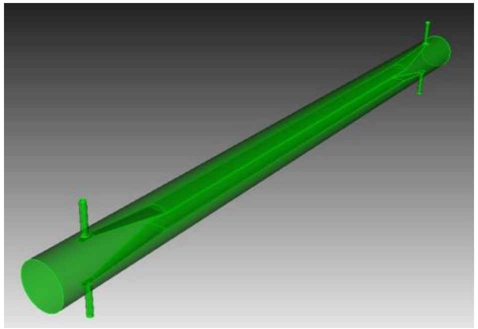



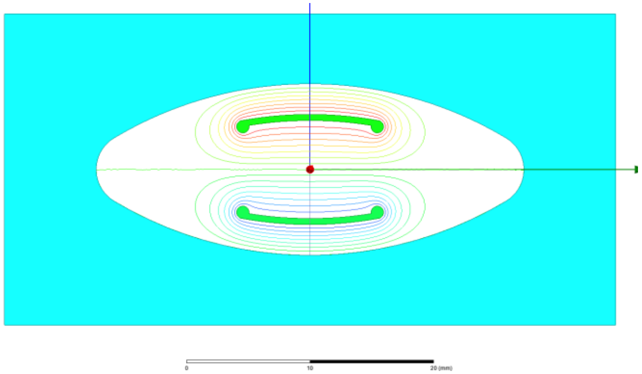


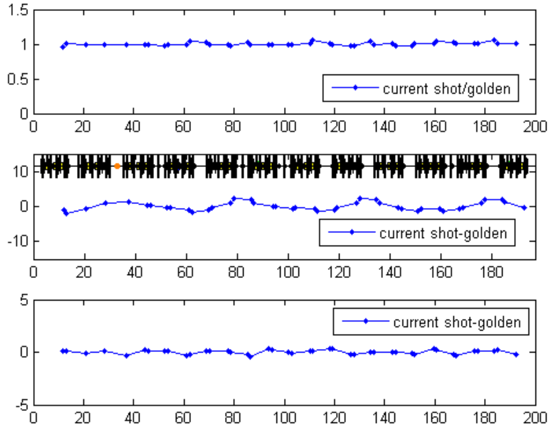
- Concentrating on small apertures and unusual shapes
  - Industry capabilities evaluated in parallel as part of COSMIC project.
- First small copper chamber (6 mm) NEG coated at LBNL, currently being characterized
  - As far as we know this is the **smallest chamber ever coated**
  - Also developing in-house knowledge to model dynamic vacuum systems

Work on BES Accelerator R+D grant started

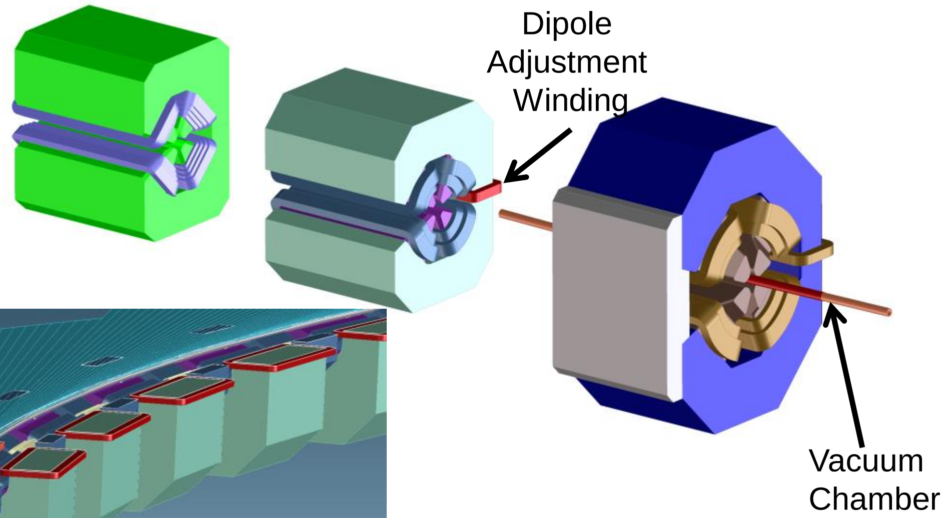
- Capitalizing on success of LDRD R+D program, as well as new beam instrumentation from recent ALS controls upgrade (complementary)
- On-axis swap-out injection studies for optimizing the performance of diffraction-limited storage rings:
  - minimizes the risk and uncertainty of swap-out injection, and
  - reduces the commissioning time by developing and testing beam-based methods to correct and optimize the accelerator during on-axis injection.
- Status:
  - Finalizing design of kicker
  - Testing early versions of software (first turn trajectory)

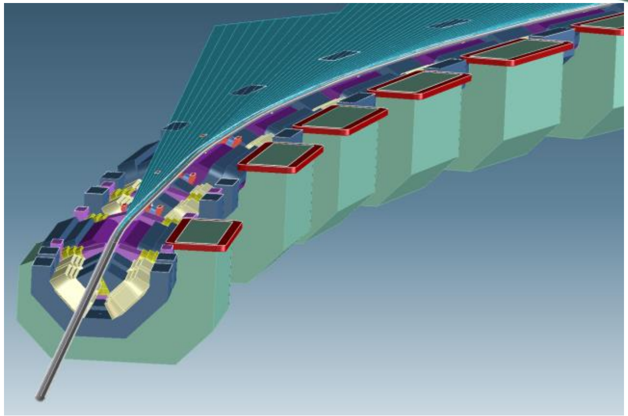


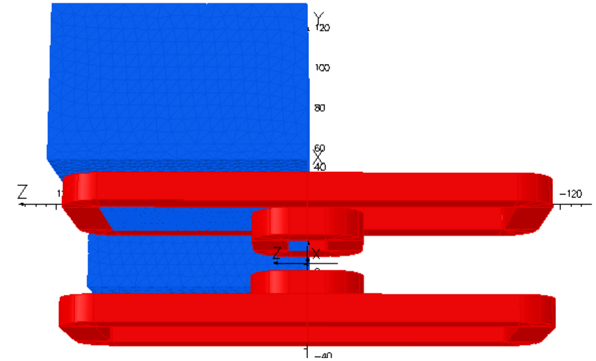


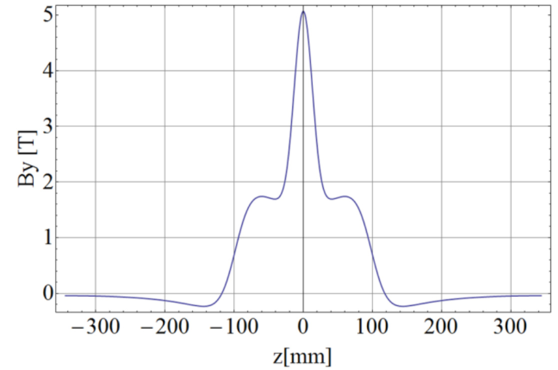


Magnet Design Progress



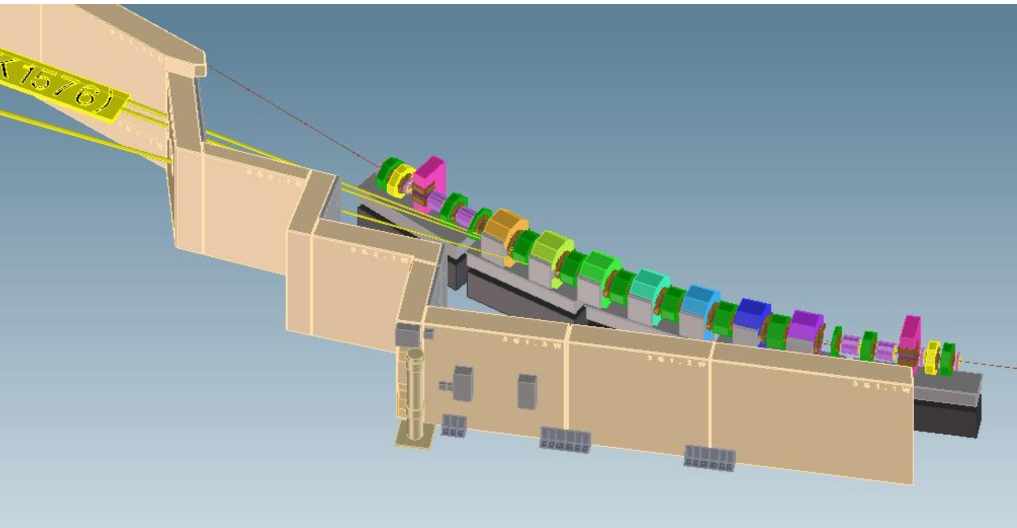


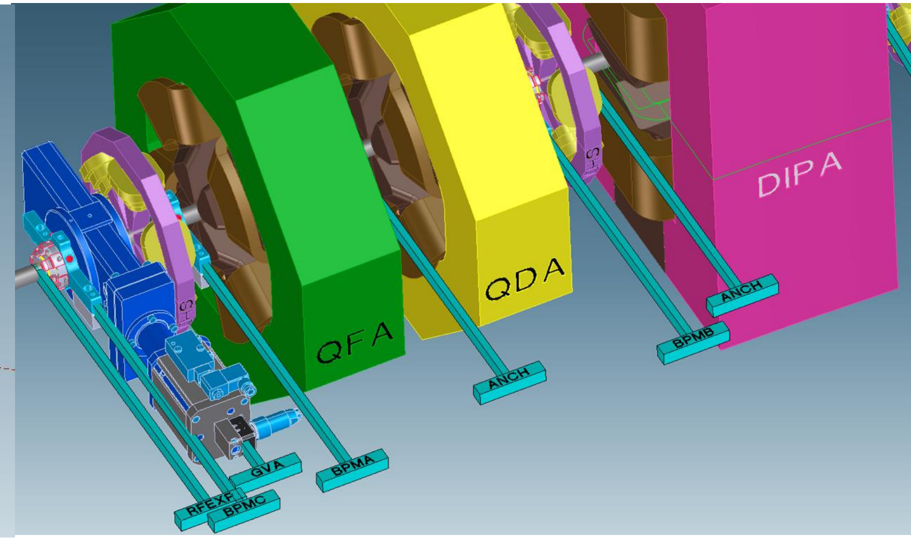


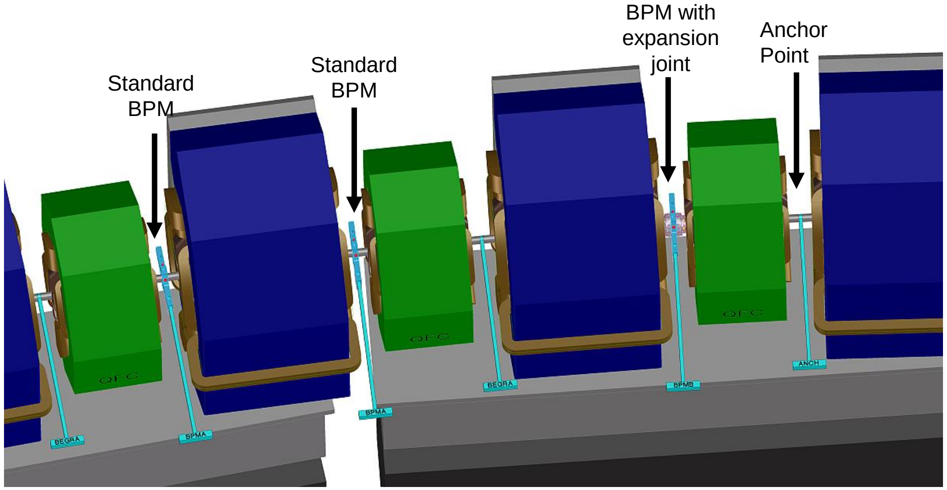


- Magnets, Radiation Production
  - Established feasibility of basic accelerator magnets (quadrupoles, gradient dipoles) – advanced materials and 3d pole shape
  - Studying various hard x-ray options (permanent magnet and s/c Superbends, 3PW, multiple field strengths)
  - Studying Insertion Devices for small/round chambers

Efficient Physics – Engineering Integration







Developed automated scripts to move from physics design to 3D CAD model

- Using Pre-conceptual designs for magnets
- Combining with sample designs for all necessary vacuum components

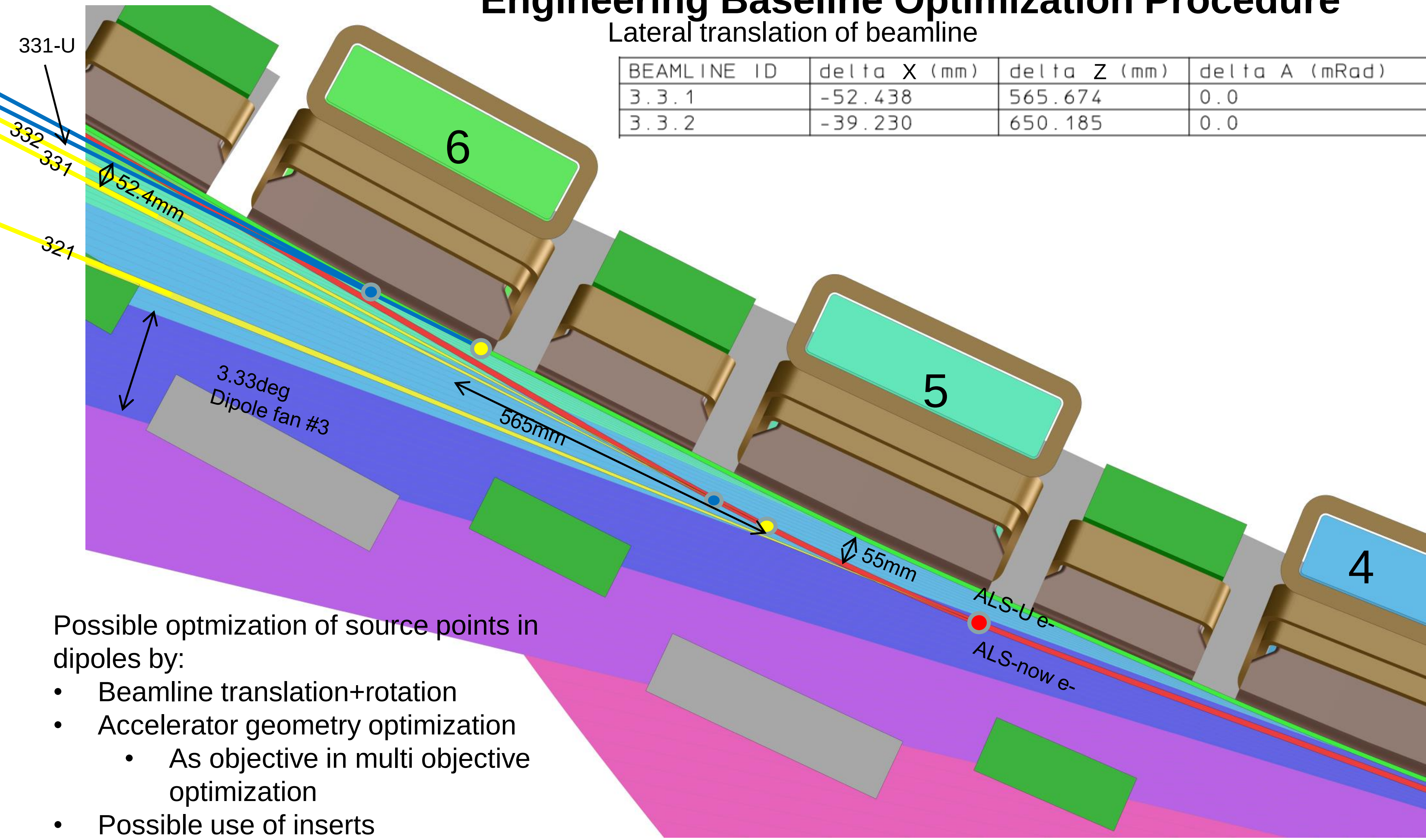
Allows evaluation of space constraints/interference and photon beamline needs

Evaluating best strategy for Source Point Shift

Engineering Baseline Optimization Procedure

Lateral translation of beamline

BEAMLINE ID	delta X (mm)	delta Z (mm)	delta A (mRad)
3.3.1	-52.438	565.674	0.0
3.3.2	-39.230	650.185	0.0



Possible optmization of source points in dipoles by:

- Beamline translation+rotation
- Accelerator geometry optimization
    - As objective in multi objective optimization
- Possible use of inserts

Summary

- ALS Accelerator has been successfully upgraded many times in 20+ years to remain world leading
- ALS-U proposal is LBNLs highest priority and aligns with BES goals (is responsive to BESAC reports)
  - R+D program is progressing well to reduce technical risks
  - Pre-conceptual design work is ongoing
- ALS-U will be the highest performance soft x-ray Storage Ring in the world

Acknowledgements

ALS-U already involves a sizeable and excellent team during the pre-conceptual phase

David Robin, Christoph Steier, Sergio Zimmermann, Jim Krupnick, Chuck Swenson, Ken Chow, Steve Virostek, Roger Falcone, Steve Kevan, Howard Padmore, Tony Warwick, Changchun Sun, Weishi Wan, Marco Venturini, Stefano De Santis, Tianhuan Luo, Simon Morton, Alastair MacDowell, Hiroshi Nishimura, Fernando Sannibale, John Byrd, Andre Anders, Rob Duarte, James Osborne, Chris Pappas, Will Waldron, Ken Baptiste, Erik Wallen, Greg Portmann, Arnaud Madur, Jin-Young Jung, Arnaud Allezy, Dan Colomb, Jacqueline Bell, Joe Wallig, Ed San Mateo, Eric Phillips, Thomas Oliver, James Nasiatka, Ryan Miyatkwa, Malcom Howells, Bill Ghiorso

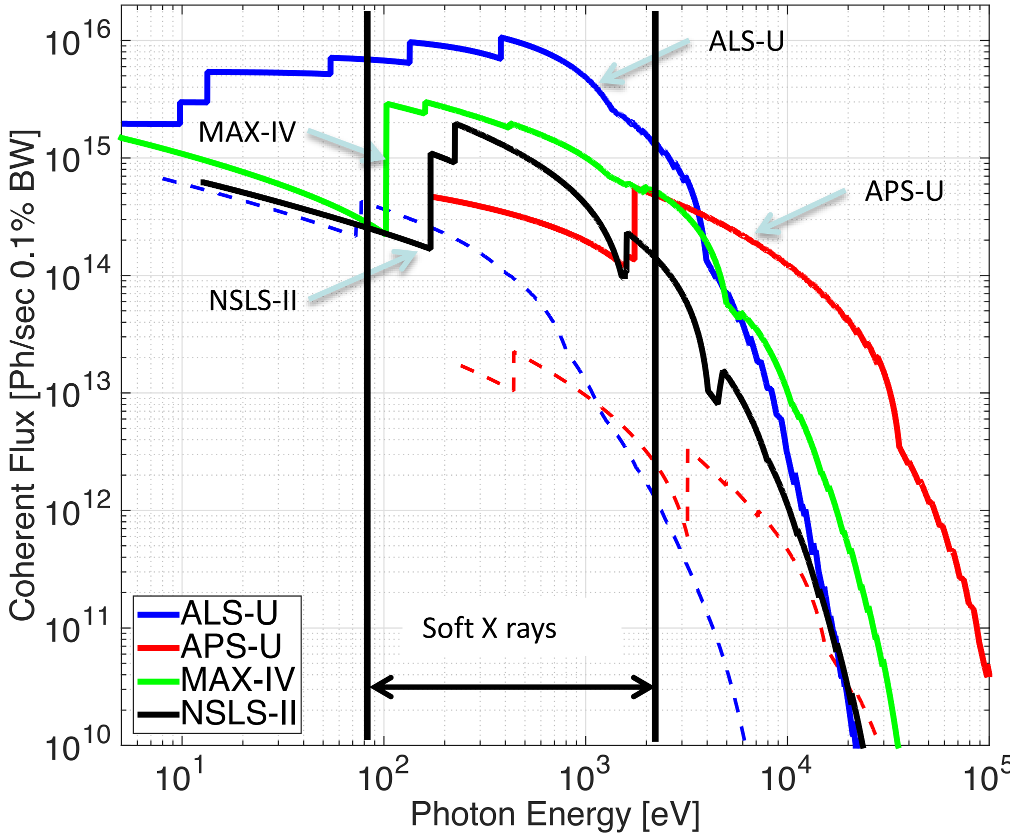
Backup Slides

ALS-U is Optimized for Soft X-Ray Science

- **Choices are made to optimize brightness for photon energy range:**
  - Electron beam energy
  - Undulator technology

- **Features of ALS 2 GeV ring compared with higher energy ring:**
  - Larger beam current
  - More undulator periods for given photon energy
  - Lower heat load on beamline components

    ✓**ALS-U design results in:**
    Highest coherent soft x-ray flux



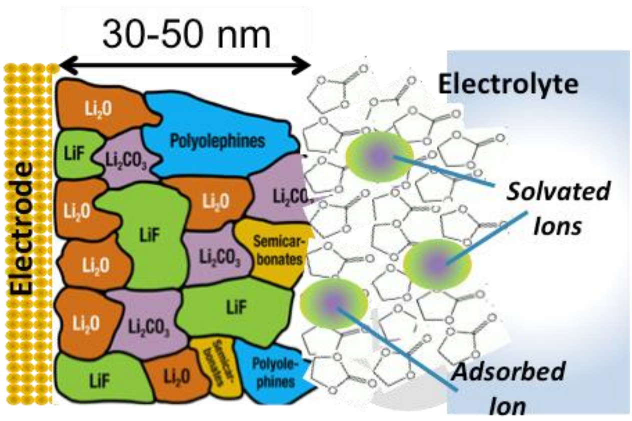
--- --- current ALS, APS

ALS-U Connects Nanoscale Landscapes to Function

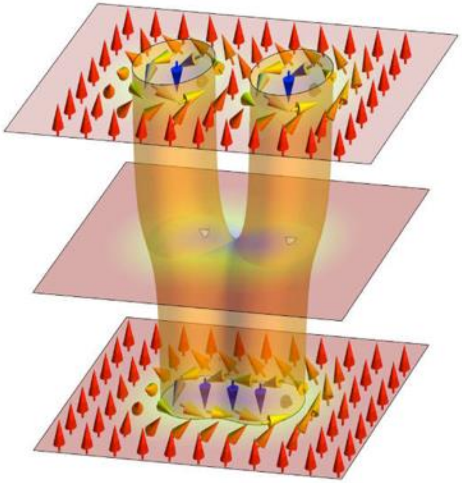
Measuring & directing nanoscale chemistry

Materials to enable low power processing

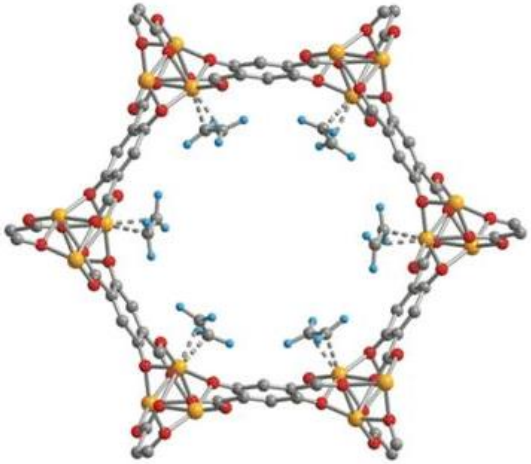
Global biological & environment challenges



Electrochemical landscape controls ion transport, SEI stability, cell lifetime



Magnetic landscape controls spin and skyrmion transport, processing



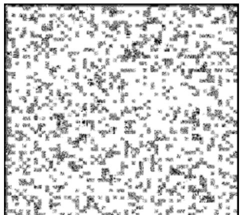
Chemical landscapes in MOFs controls catalysis, CO_2 capture

ALS-U tools will

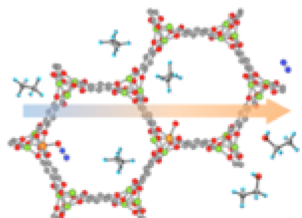
- - map *nanoscale landscapes* with chemical, electronic, magnetic contrast
- - probe *nanoscale motion* of mass, charge, spin, elementary excitations

Brightness allows capture of spontaneous nanoscale kinetics: approaching the h/k_BT timescale

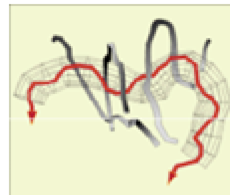
Nucleation kinetics



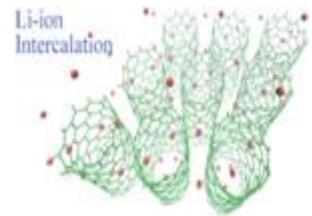
Selective Catalysis
10.1038/nchem.1956



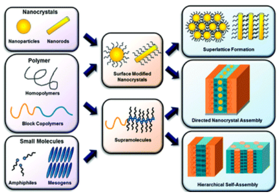
Polymer reptation



Intercalation kinetics,
10.1039/C0EE00473A



Self assembly

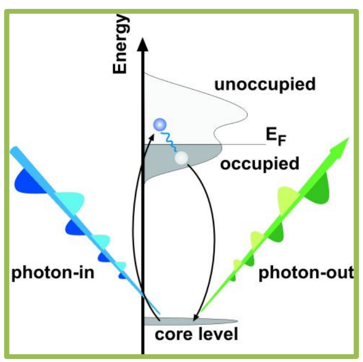


Energy Scale (eV): 10^{-1}, 10^{-3}, 10^{-5}, 10^{-7}, 10^{-9}, 10^{-11}, 10^{-13}, 10^{-15}, 10^{-18}

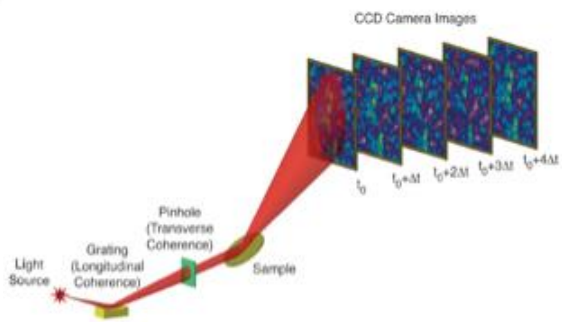
Time Scale (sec): 10^{-12}, 10^{-10}, 10^{-8}, 10^{-6}, 10^{-4}, 10^{-2}, 10^{0}, 10^{2}

now/ne

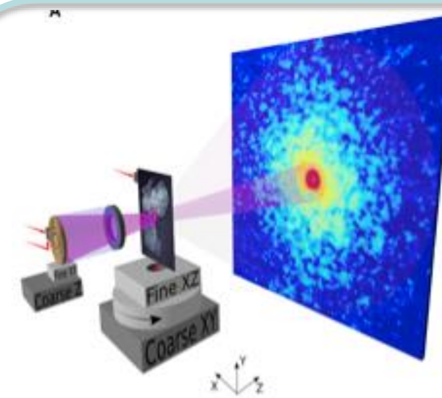
w RIXS FT-RIXS Fast XPCS XPCS movies movies/XPCS



Resonant Inelastic X-Ray Scattering: $S(q,\omega)$



X-ray Photon Correlation Spectroscopy: $S(q,t)$



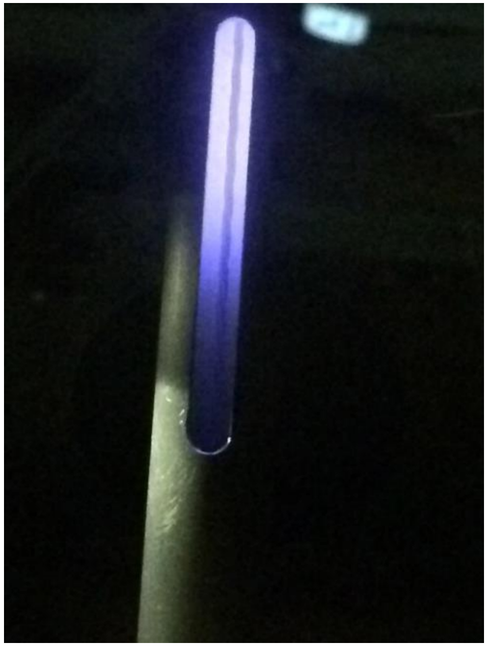
Time-resolved X-ray Microscopy: $G(r,t)$

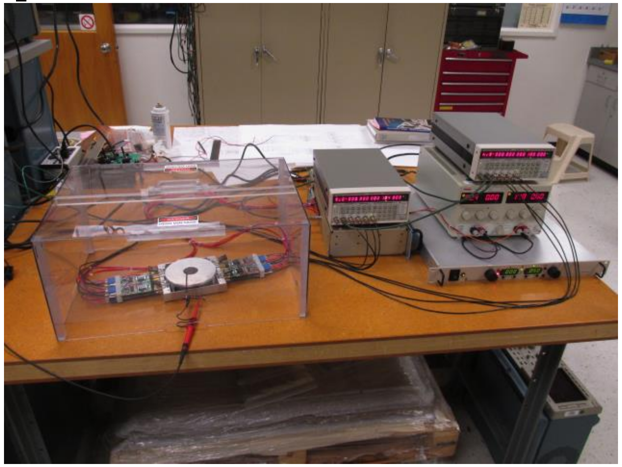
Goals for R+D program

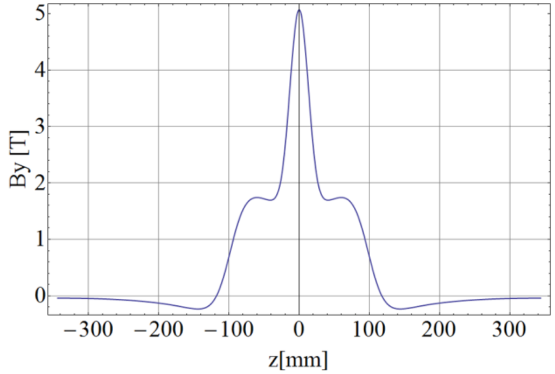
- Reduce technical risks + explore new technologies for performance advantage of soft x-ray DLSR
  - Concentrate on areas with highest technical risk
  - Approach: Demonstrate necessary technology at subsystem level or through advanced simulations
- Selection of R+D topics covers main areas of risk and opportunity:
  - Low emittance ➔ compact, **small aperture magnets** ➔ very small vacuum chamber diameter ➔ need for **NEG coating**
  - Low energy ring ➔ intrabeam scattering is severe ➔ **aggressive bunch lengthening** as well as filling as many buckets as possible ➔ **pulsers with very small rise and fall times**
  - Highest possible brightness ➔**need for optics that preserve coherent wavefronts**.
  - Small apertures (both planes) open new opportunities for **radiation production devices**.

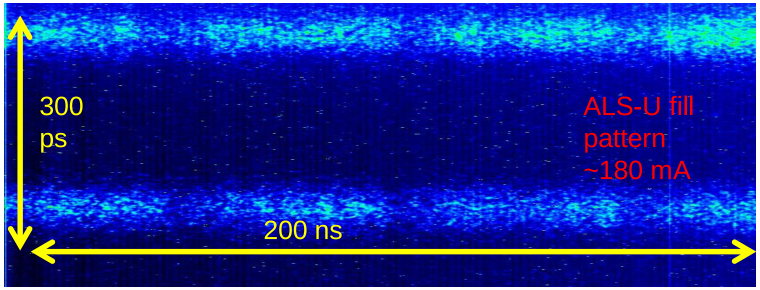
R+D Areas currently pursued

- Pulsed Magnets/Injection
- Vacuum System, small gap NEG coated chambers
- RF system, harmonic RF, transients, fill pattern
- Magnets, Radiation Production
- Optimization of Physics Design, Staging
- Emittance preserving photon optics





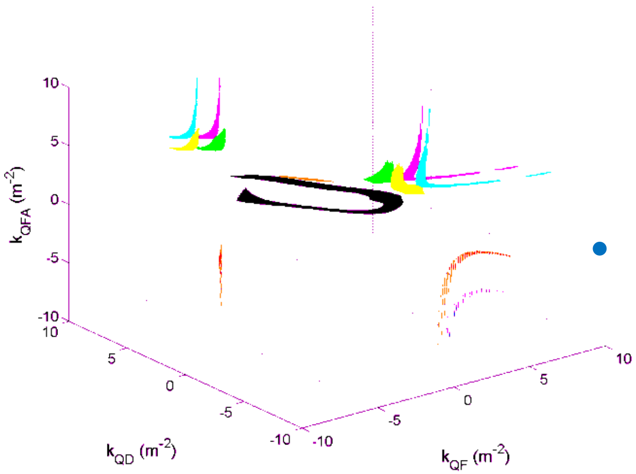


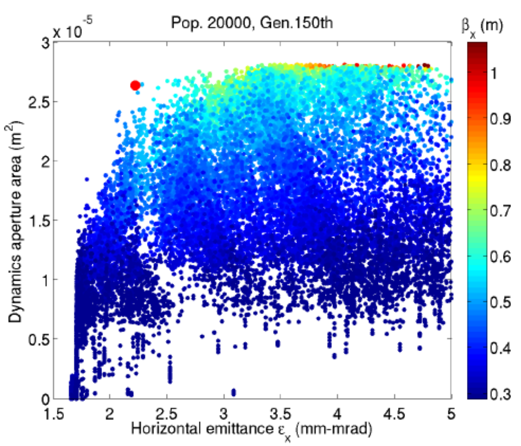


Risk Mitigation Through R&D

- **Risks that have been mitigated**
  - Fast pulsers with necessary parameters for swap-out can be built
  - NEG coating process has potential for smaller apertures than prior art
  - Bunch lengthening factors achievable with fill patterns for swap-out
  - Space in lattice is sufficient to enable small gap Superbends
  - Power density and vacuum pressures in arc chambers are OK
- **Risks that are in process of being mitigated – continuous progress**
  - Beam interaction of very small aperture stripline kickers
  - In-situ activation of NEG chambers in integrated vacuum/magnet systems
  - Required thermal distortion of coherence preserving optics
  - Beam-based correction commissioning strategies
  - Beam dynamics with super-bends in the lattice
  - Integration of many bend magnet beamlines in MBA lattice
  - Magnet-to-magnet cross-talk of closely spaced magnets

Lattice optimization



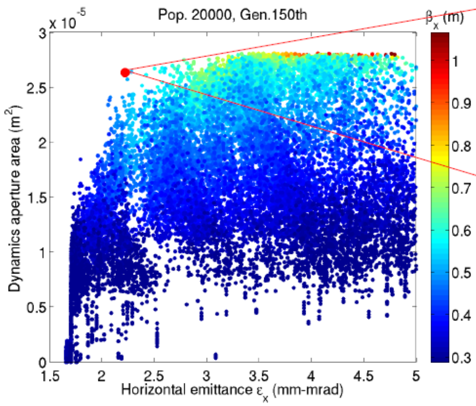


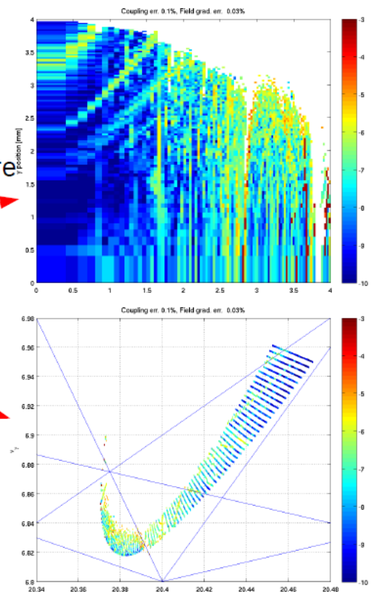
- **GLASS – Global Analysis of All Stable Solutions** D. Robin, et al. PRSTAB 11, 024002 (2008)
  - Tool to look for optimum lattice solution for highly periodic lattices (few parameters)
- **MOGA – Multi Objective Genetic Algorithms**
  L. Yang et. al, NIM A 609 (2009) 50-57
  - First accelerator use for photo injectors (Bazarov et al./Cornell)
  - Moderate computation time for larger dimensional parameter spaces
  - Integrated optimization of linear+nonlinear lattice
- **Frequency Maps (quantitative diffusion rates)**
  C. Steier, et al., 10.1016/j.nima.2010.11.077
  - In use for years for studies of global dynamics (simulation and measurement).
  - Can also be used as merit function (e.g. for MOGA)

Simultaneous Optimization of linear and nonlinear Lattice

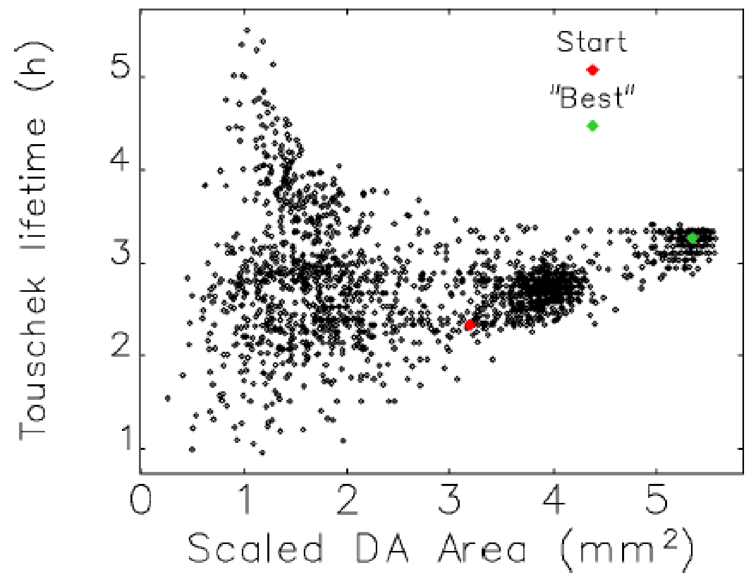
Linear and nonlinear properties of the lattice are optimized simultaneously using GA.

- 7 parameters: 3 Quads + 4 Sextupoles
- 7 constraints: stability, positive partition number, maximum beta and dispersion functions
- 3 objectives: emittance, betax and dynamics aperture





A trade-off between the dynamics and emittance is found.



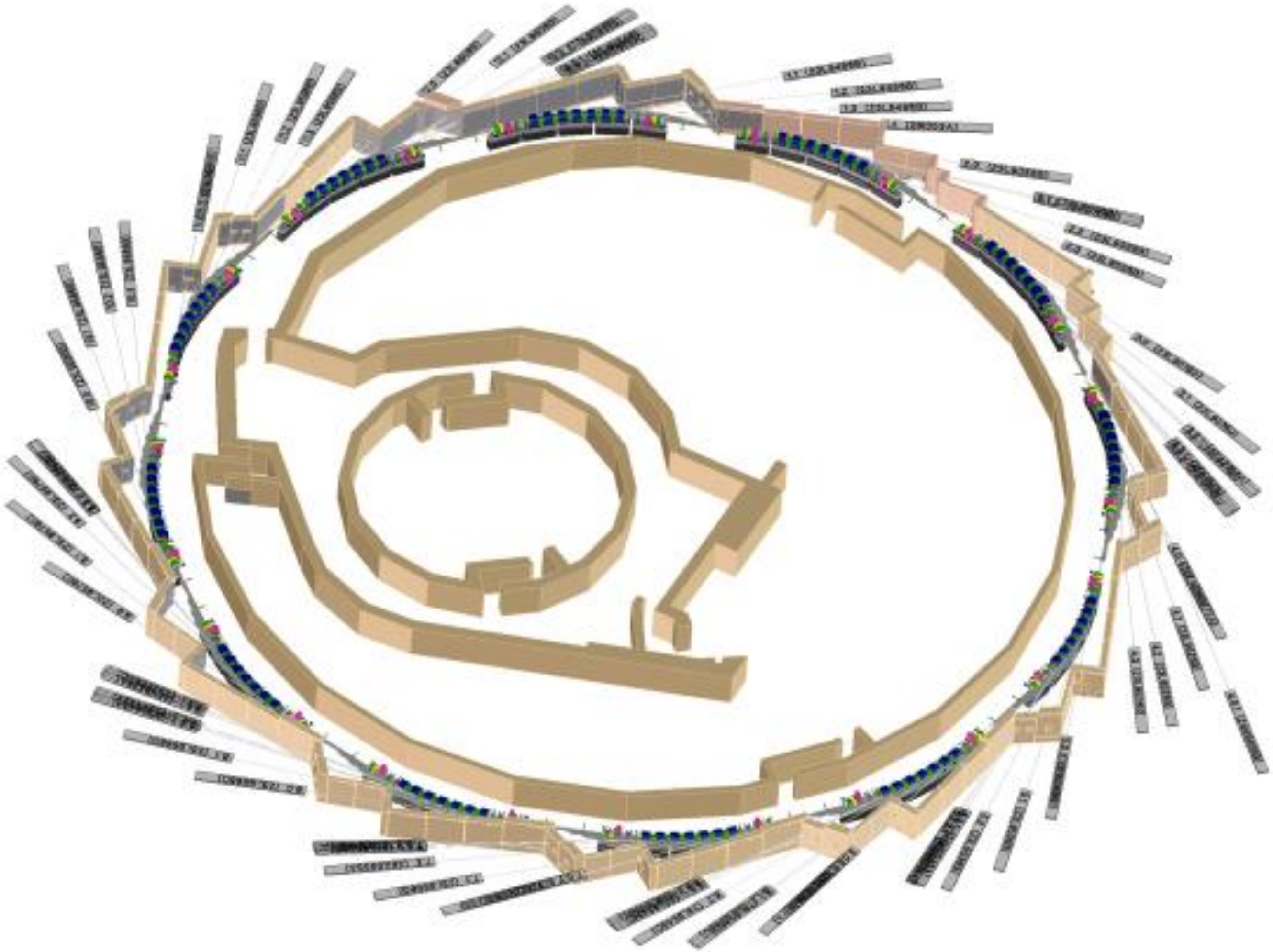
Normalized to $\beta_x=\beta_y=3$m

ALS, C. Sun

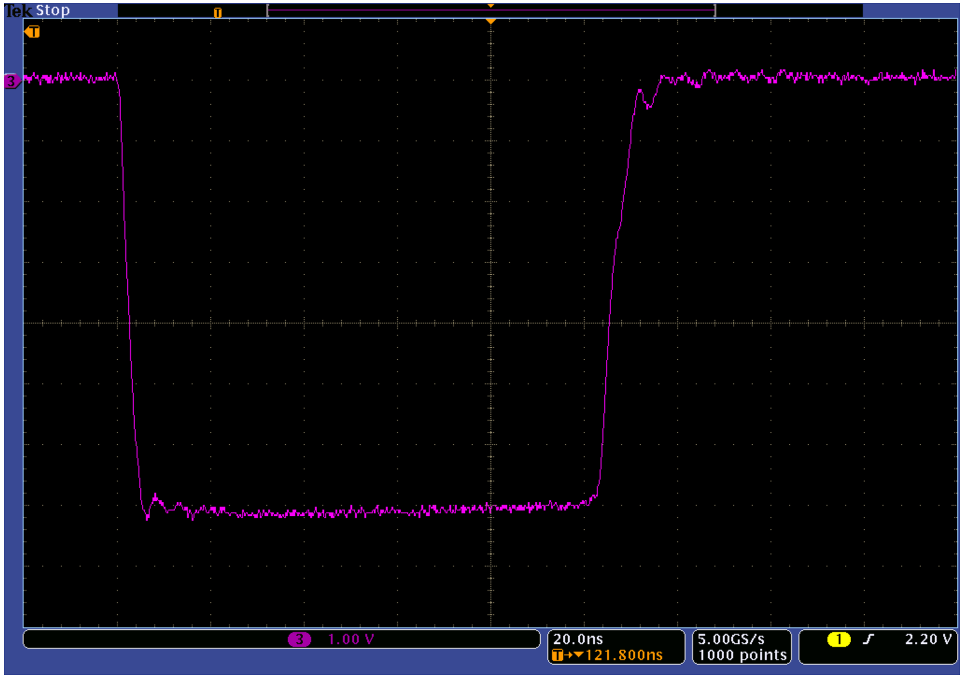
APS-U, M. Borland

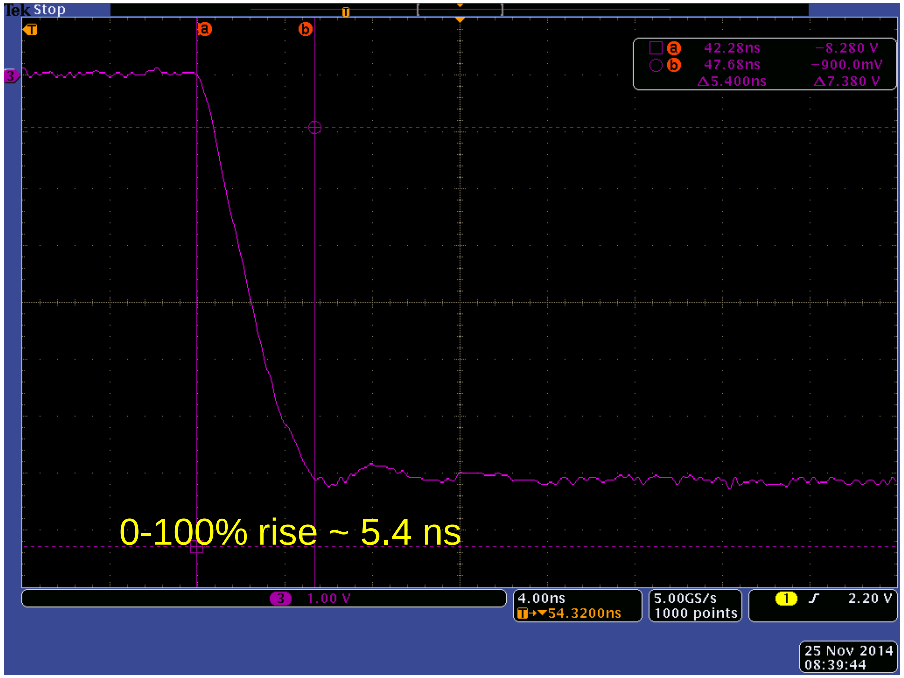
- Challenge: space of stable solutions vs. quadrupole gradients very sparse
- In general case not possible to just include quads as parameters, but rather lattice parameters + lattice fit

Establishing first baseline lattice



ALS-U R+D - Injection

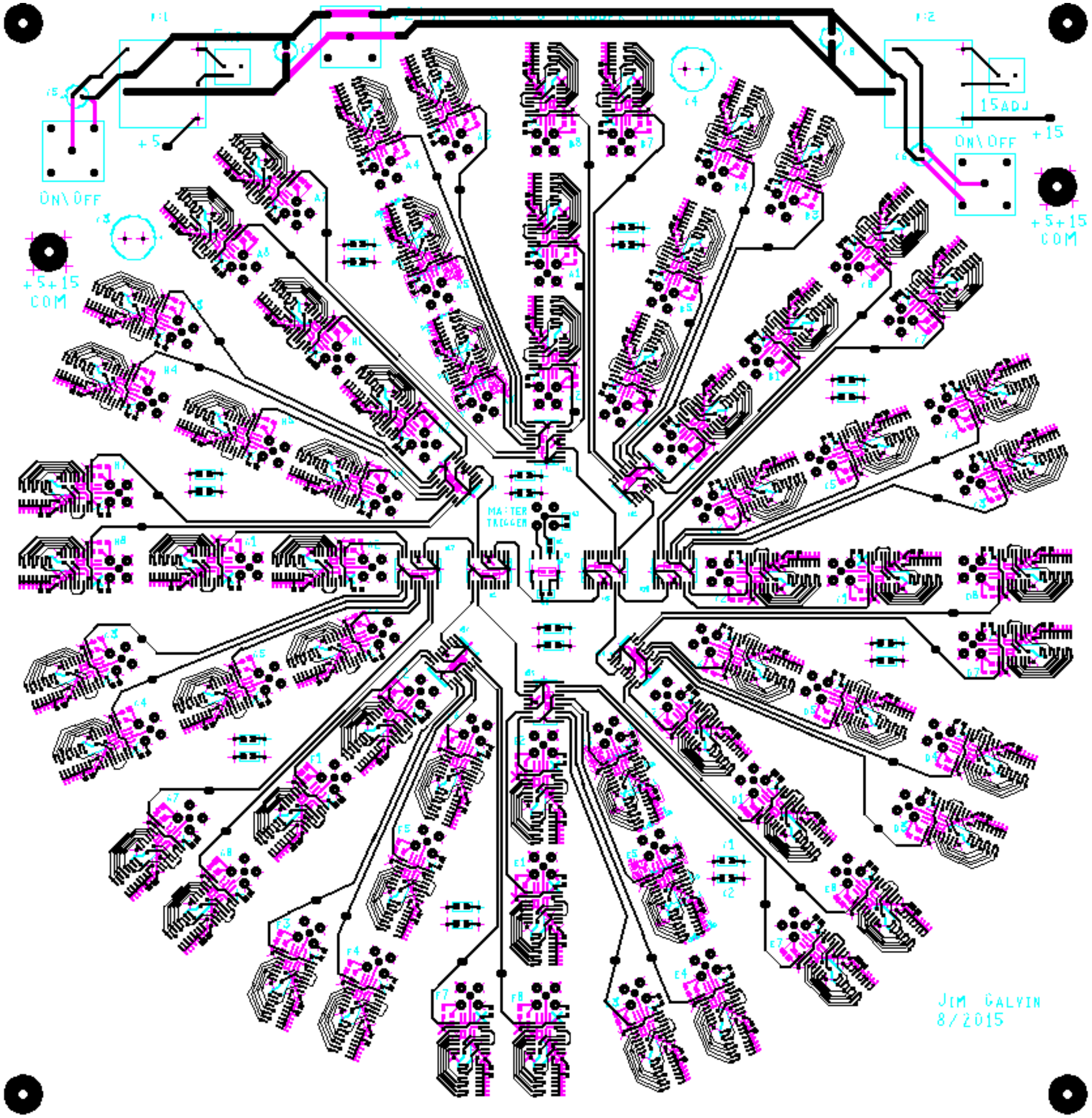




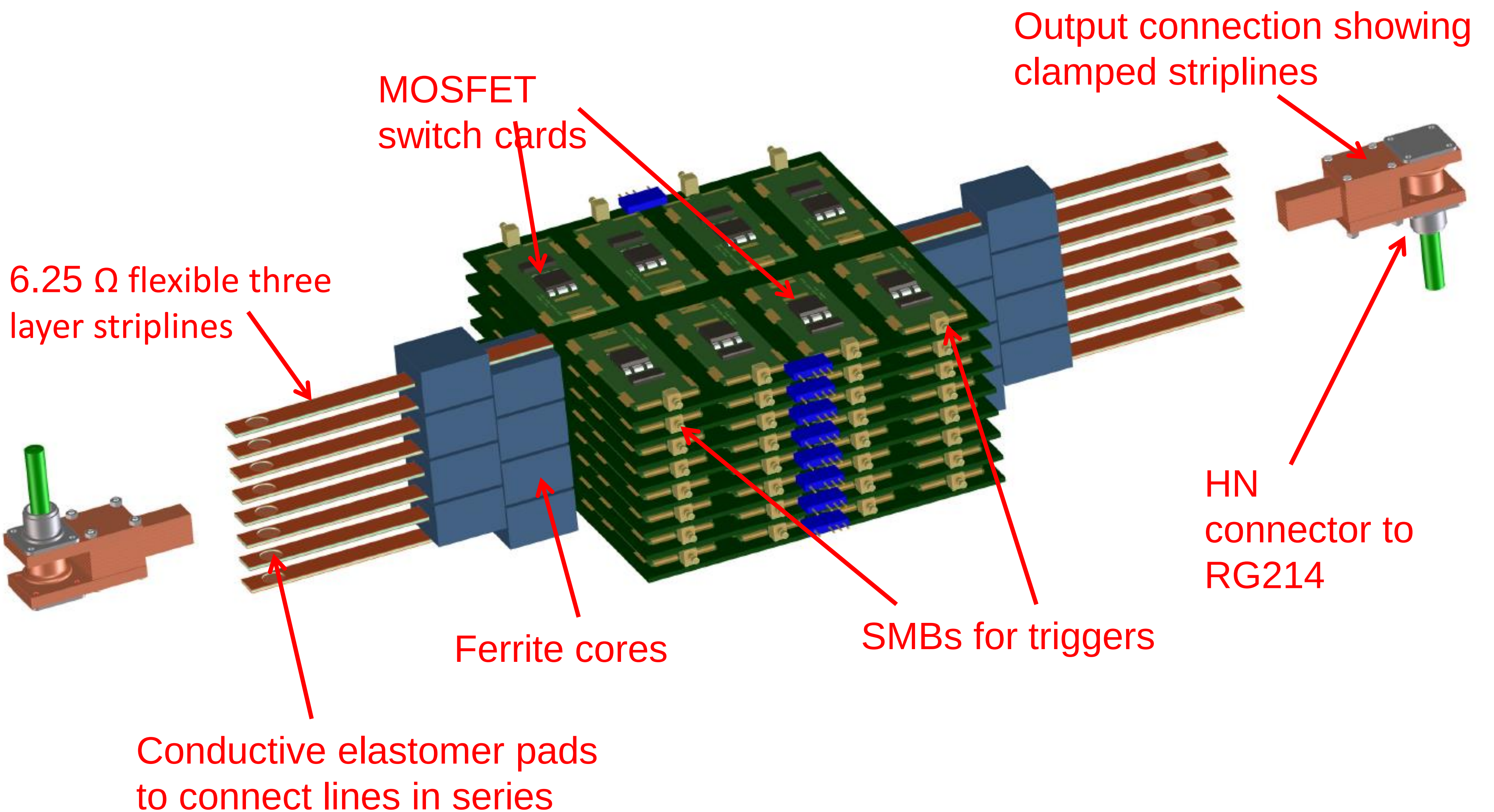
- Single module with ALS-U parameters tested (<10 ns rise/fall time)
  - consistent with ALS-U RF / THC design
- All modules (8 kV) summer, test with existing ALS kicker before end of year
- ALS-U kicker has long flat-top for bunch train swap out, but same technology can deliver short flat-tops.

64 Channel Trigger PC Board Layout

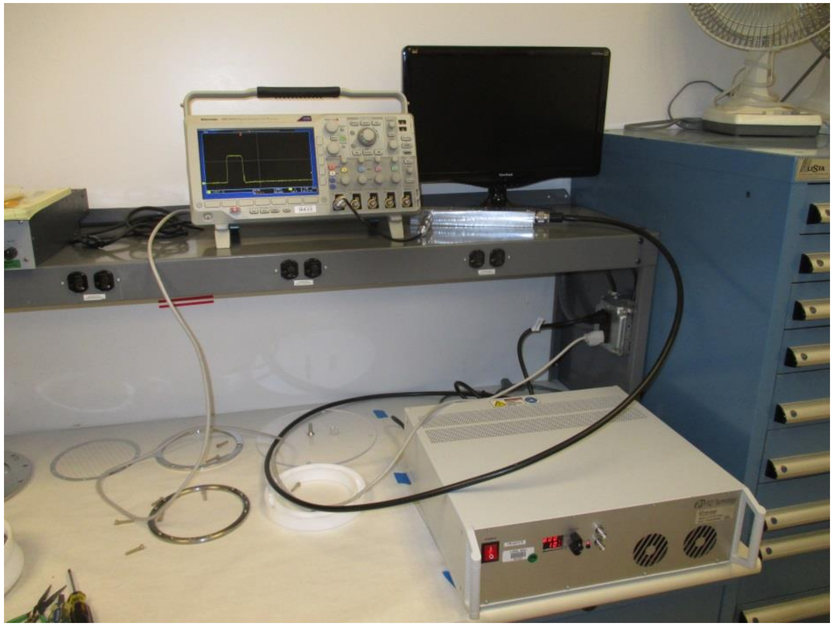
- 1 to 64 fanout
- 250ps resolution on individual channel timing adjustment

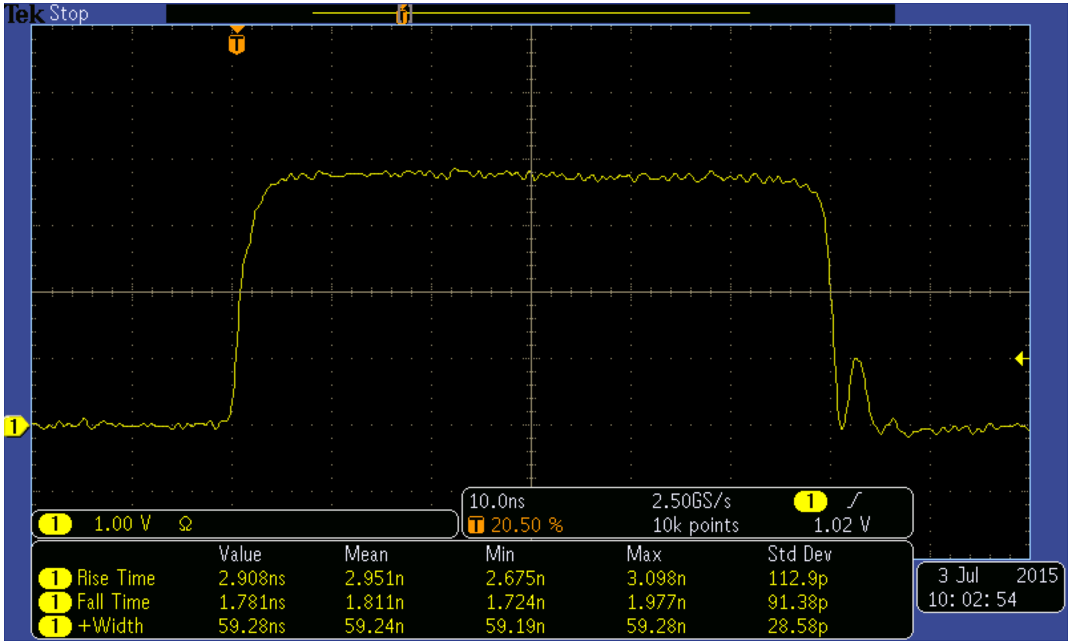


Alternative Pulser – Transmission Line Adder



Lifetime test on commercial pulser: 6.5 million shots at 7.5kV (equivalent to ~6 years of ALS-U operation)





- Overcame some initial reliability problems
- Ringing at tail end of waveform is very reproducible, it is borderline acceptable, but not desirable (transient distortion of following bunches)

Motivation for Harmonic RF

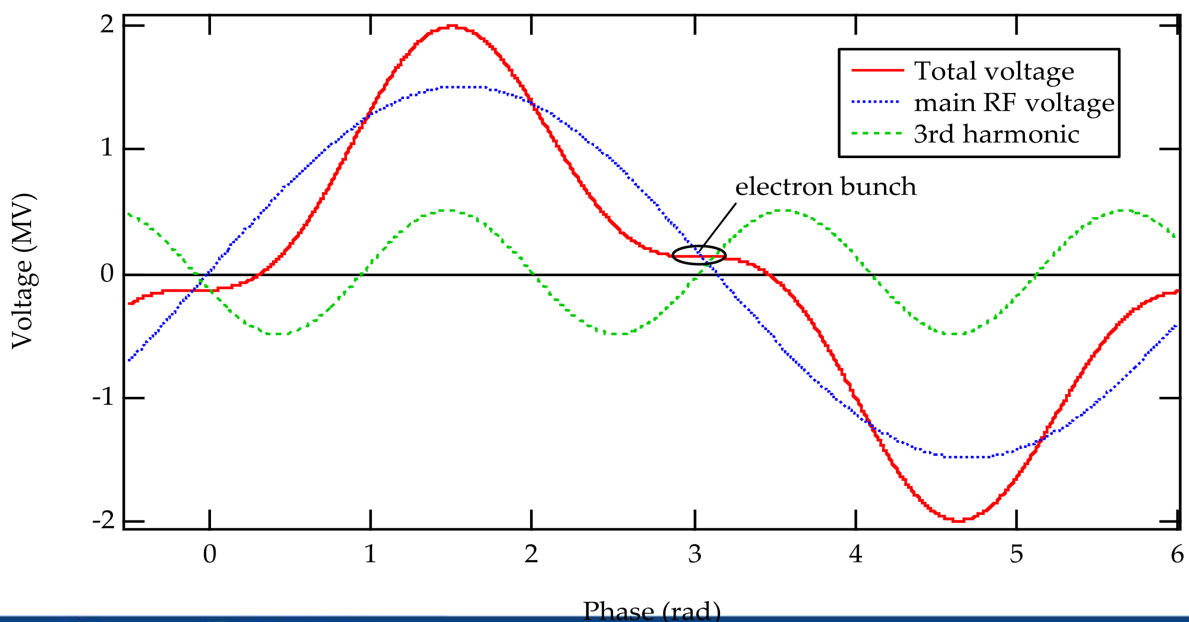
- Improve short Touschek lifetime by reducing bunch density. Most low-energy rings have implemented or considered 3HCs.
- Flattening of potential well induces large synchrotron frequency spread, providing large Landau damping.

- New: Modern lattice designs with much smaller horizontal emittance result in strong intrabeam scattering, which can be mitigate with lower bunch density. If Touschek form factor is beyond minimum, this also improves lifetime.
- Usually less important: Smaller peak current reduces heating induced in impedance sources (HOM loads, …)
- Options exist with regards to frequency, relative amplitude, technology.

Physics of harmonic RF systems

- Typical storage ring RF systems typically provide beam power and enough longitudinal focusing to give desired bunch length.
- By adding harmonic voltage(s), we can shape the bunch longitudinally, useful for a variety of applications.

$$V(z) = V_{rf}\left[\sin\left(\frac{\omega_{rf}}{c}z + \phi_s\right) + \sum_{n=1}^{\infty} k_n \sin\left(n\frac{\omega_{rf}}{c}z + n\phi_{hn}\right)\right]$$



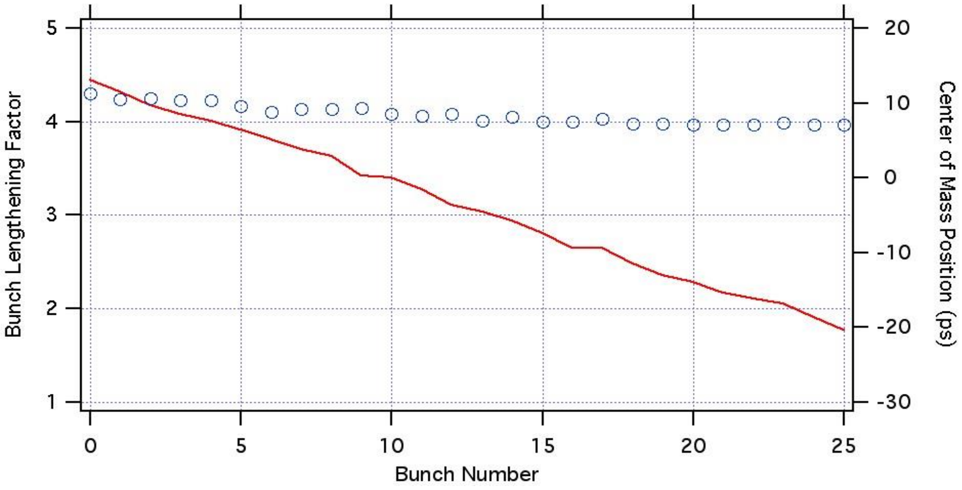
Focusing is cancelled at the bunch center

$$k_{\mathrm{opt}} = \frac{V_{h,\mathrm{opt}}}{V_{\mathrm{rf}}} = \sqrt{\frac{1}{n^2} - \frac{(U_0/V_{\mathrm{rf}})^2}{n^2-1}},$$

$$\sin(n\phi_{h,\mathrm{opt}}) = \frac{-U_0}{V_{h,\mathrm{opt}}(n^2-1)}.$$

For large overvoltage, k_{opt}~1/n and optimum phase is close to 90 deg.

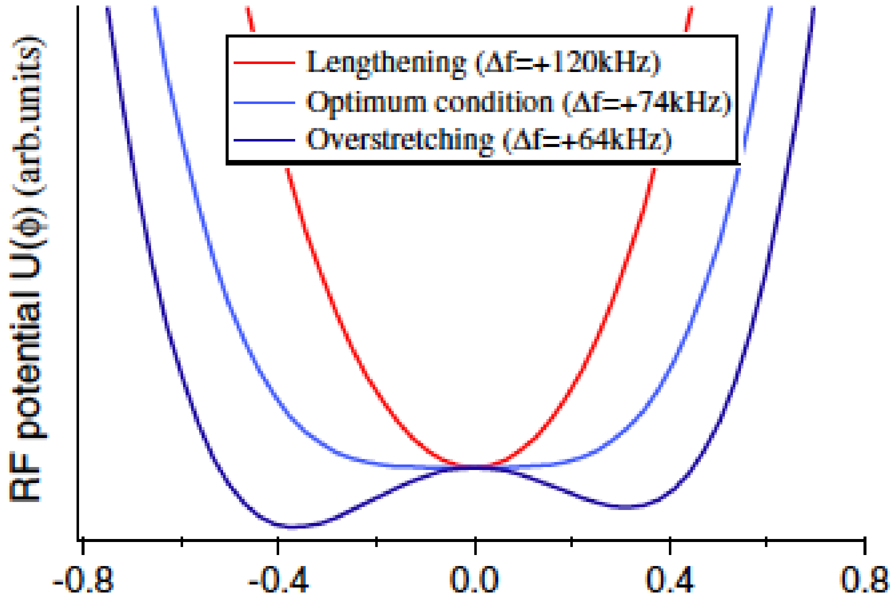
ALS-U Transient Simulations



- Simulations with old igor code became unstable for large bunch lengthening – not surprising
- Need true (parallel) multiparticle code
- Decided to try Mbtrack (Nagaoka, Soleil)
- Some challenges (Robinson damping of main cavities, …)
- But finally received good results, predicting the ALS RF/HC cavity system should be able to reach bunch lengthening factors of >= 4 with ALS-U type fill patterns
- Transients in that case can be measured

Overstretching – Double Bucket

- Increasing the harmonic voltage past a flat potential well creates multiple fixed points in the RF bucket.



Penco and Svandrlik PRSTAB 9, 044401 (2006)

FIG. 14. (Color) Potential well distortion in lengthening mode, at optimum condition (flattened) and in overstretching regime, calculated for $I_{beam} = 315$ mA by using formula (5).

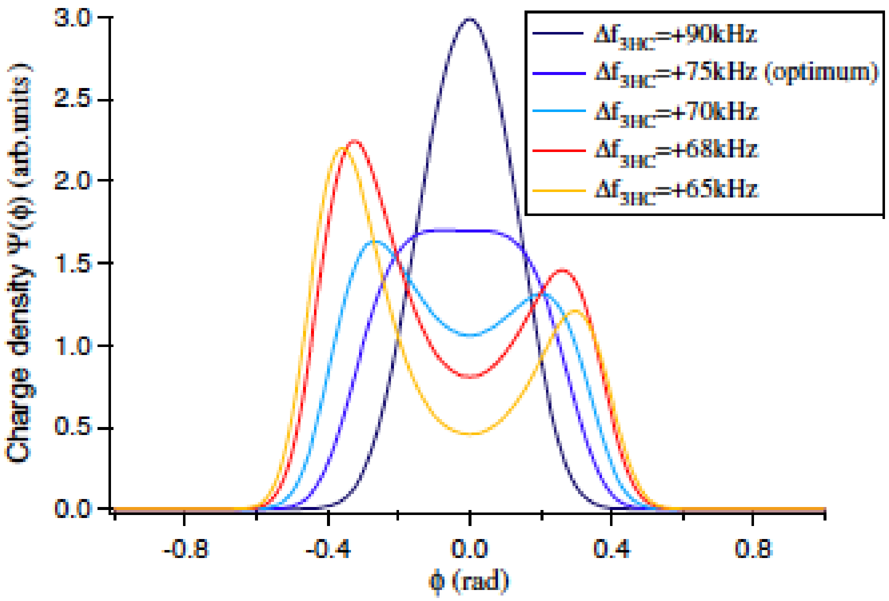
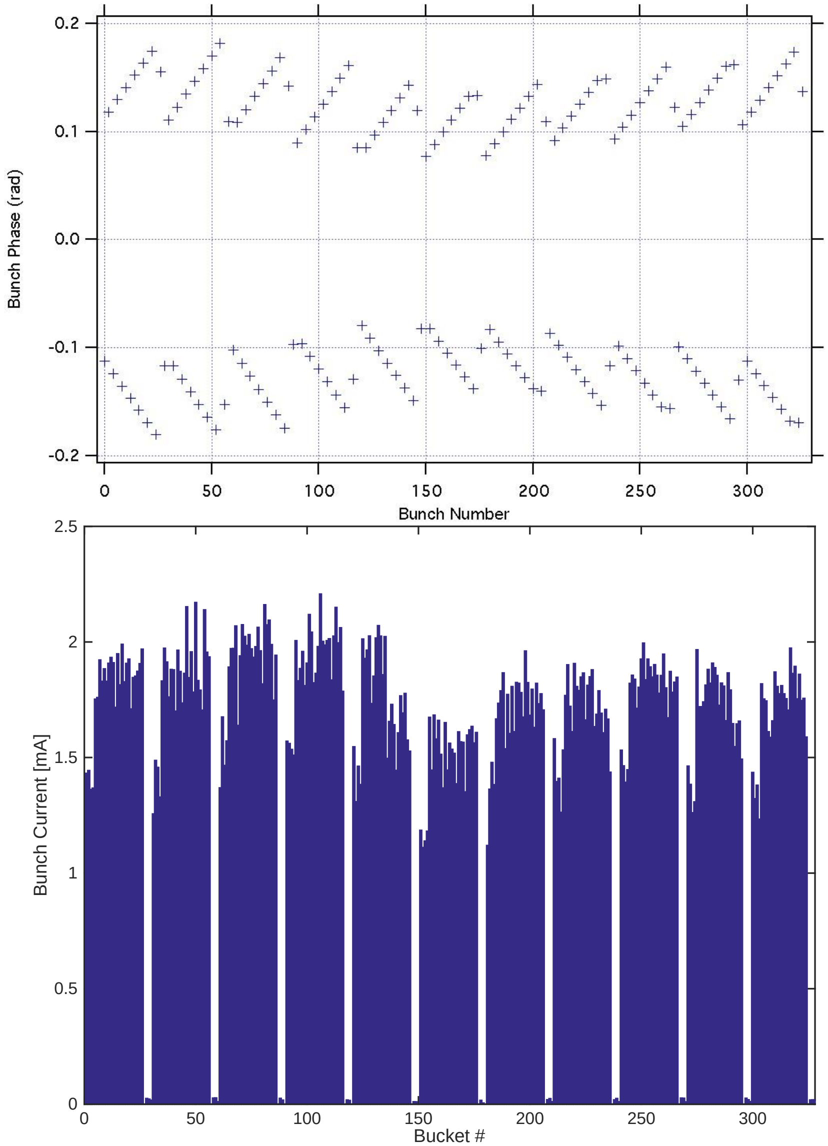


FIG. 15. (Color) Nominal charge density in the bunch in function of the 3HC detuning, calculated in uniform filling and at 315 mA by using formula (9).

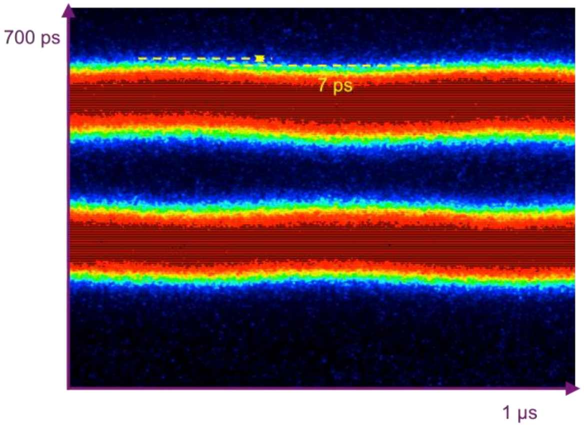
Unclear how practical useful – peak current starts to increase again, potentially very transients with gaps …

ALS measurement (ALS-U pattern)

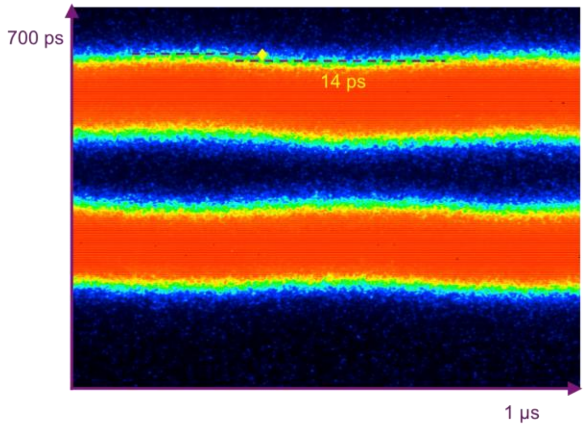


- Challenge: Harmonic number of ALS is 328, cannot be evenly divided in desired number of trains (only 8 or 41 possible) – might reconsider
- Tentative approach: Use 11 trains, most with 26 bunches and 4 bucket gap, two with 25/4. 500 mA total.
- Main RF is 1.25 MV in two cavities.
- 3rd HRF is up to 375 kV in 3 cavities.
- Simulations say that transients should still stay small enough to reach >= 4 lengthening factors

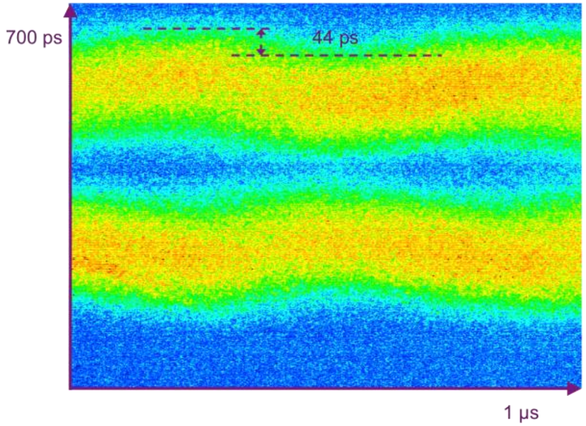
ALS(-U) - 3rd HC Measurements



(V_h= 175 kV)



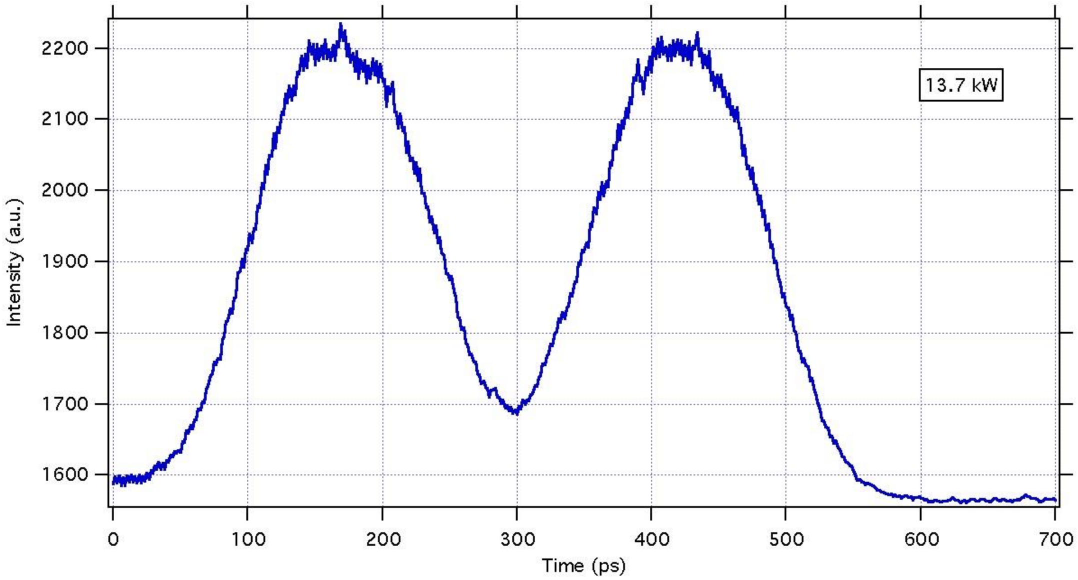
(V_h= 259 kV)



(V_h= 374 kV)

- Phase transient increases quickly (exponentially) with harmonic voltage (traces above are with saturated streak camera)
- Even close to optimum bunch lengthening, transient of approximate 11 train fill pattern remains acceptable
- Reasonable agreement with simulation code (mbtrack) predictions
- Interestingly found that variation in bunch train charge seemed to have bigger effect
  - Evening fill pattern with only systematic gaps left, reduced transients

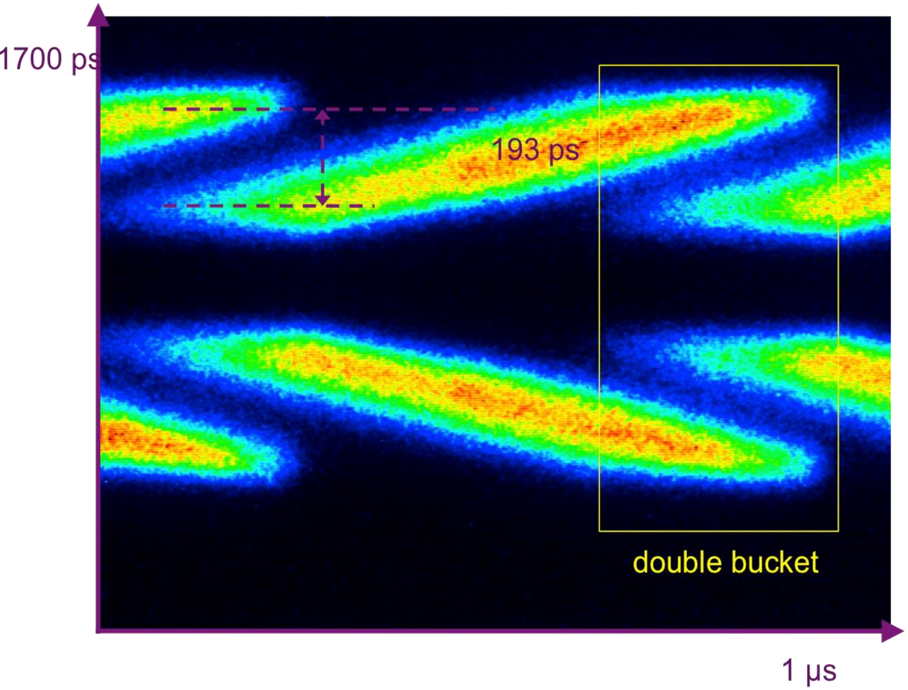
ALS(-U) - 3rd HC Measurements

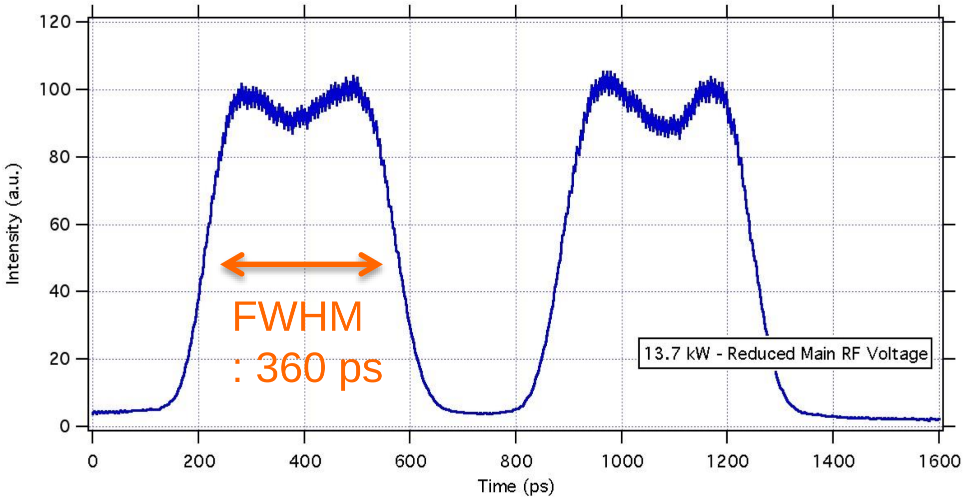


(V_h= 374 kV)

- Zero current bunch length of ALS in low emittance lattice is approximately 34 ps FWHM
- Measured bunch length at 374 kV harmonic voltage (1.25 MV main RF voltage) is 150 ps FWHM (factor > 4.4).
- Consistent with lifetime measurements
  - Total lifetime 11 h in this case, about 6 h in normal user mode, <4 h without harmonic cavities, Vacuum lifetime 30 h @ 500 mA, normal collimator settings
  - Corresponding estimated Touschek lifetimes 18, 7.2, 4.5 h

Saw onset of double bucket

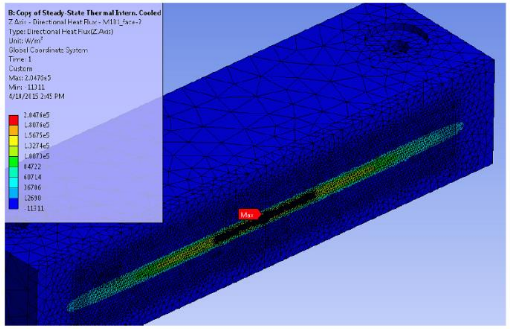


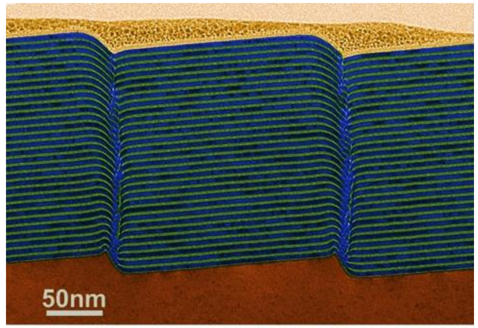


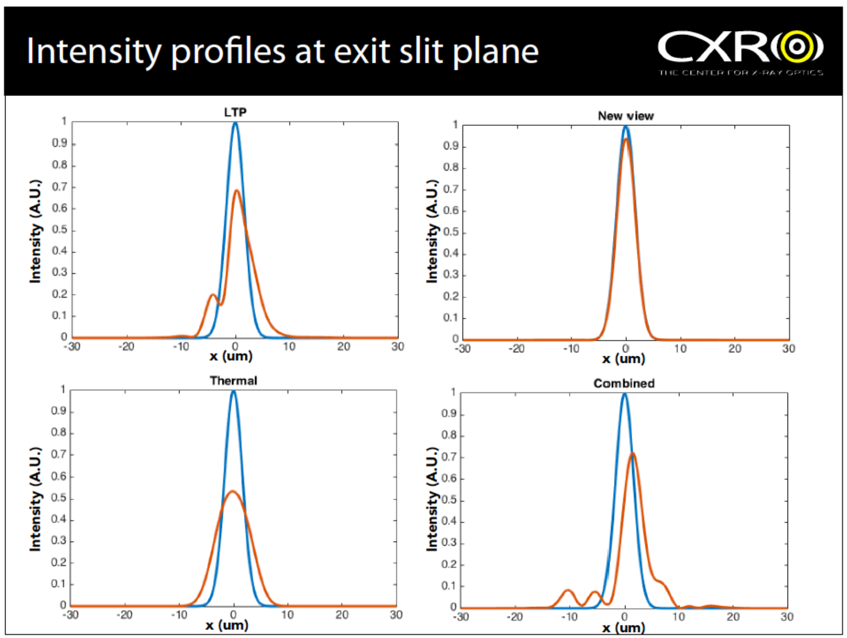
Caution: Streak Camera might be partially saturated.

- When reducing main RF voltage to 1.1 MV (with harmonic RF still at 374 kV), saw double bucket structures and very large bunch lengthening
- However, this is not a stable state – saw synchronous phase on LFB flip quickly, beam eventually went unstable

X-ray Optics Development



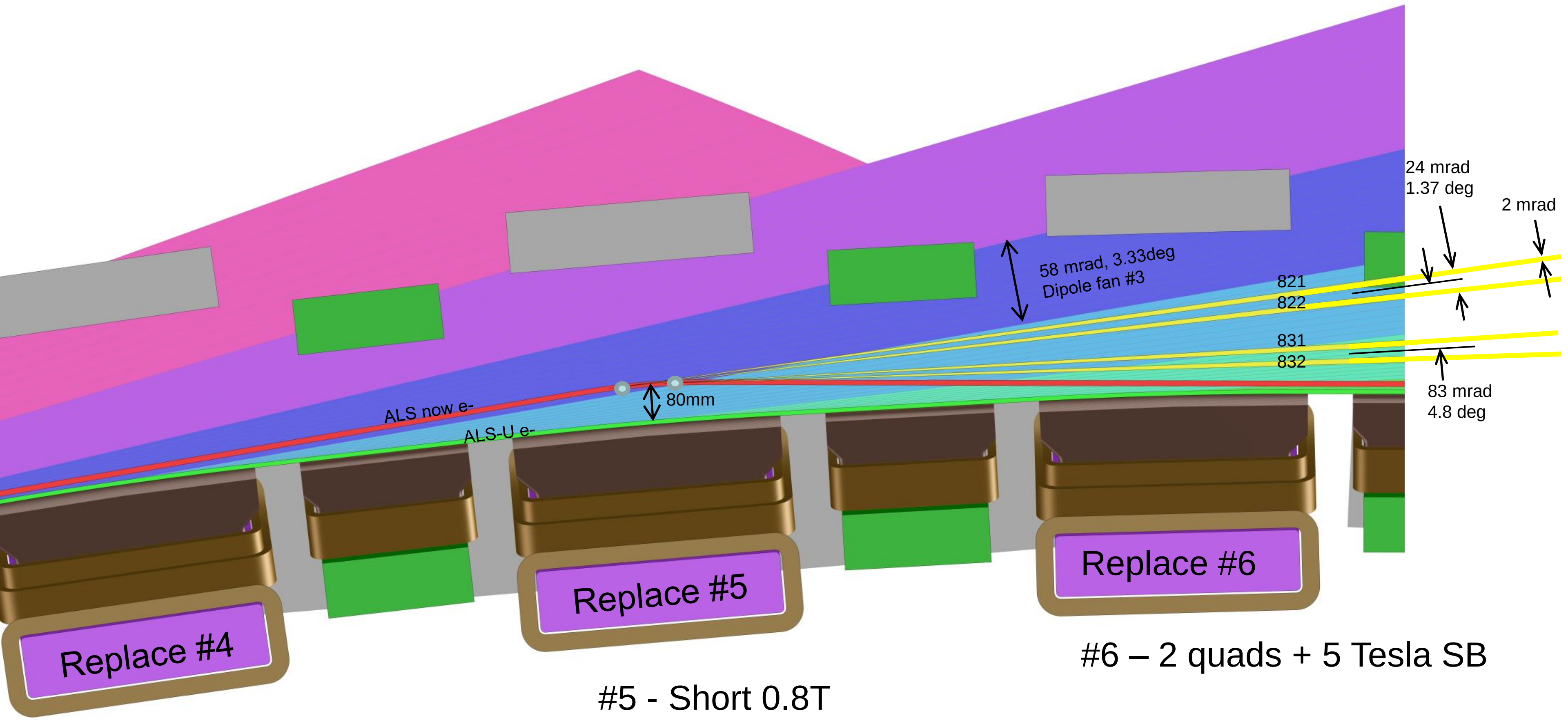




- Challenge to preserve photon brightness/coherent wavefronts horizontally+vertically:
  - Surface quality
  - Thermal distortions
- Work integrated as part of LDRD
  - Team of ALS/ENG/CXRO/ATAP
- Advanced simulation tools
- Studying different cooling schemes, including LN cooled Si
  - Will include hardware tests
- No show-stoppers identified, but much more work needed

Superbend Sector 8 – 2 Superbend source points

Separation of 8.2 source pair from 8.3 source pair = 4.8 deg > 3.3 deg fan from single dipole
- forces 2 separate superbend sources



#6 – 2 quads + 5 Tesla SB

#5 - Short 0.8T

#4 - 2 quads + 5 Tesla SB