Stripline Kicker Development at ALS

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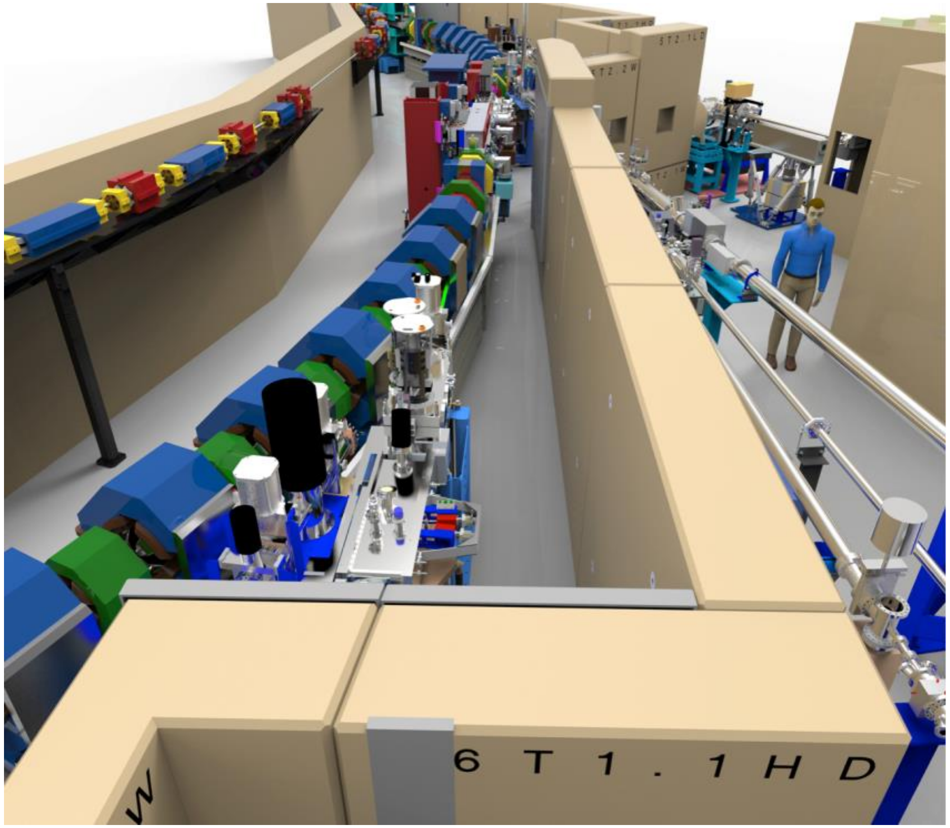
Advanced Low Emittance Rings Technology ALERT 2016

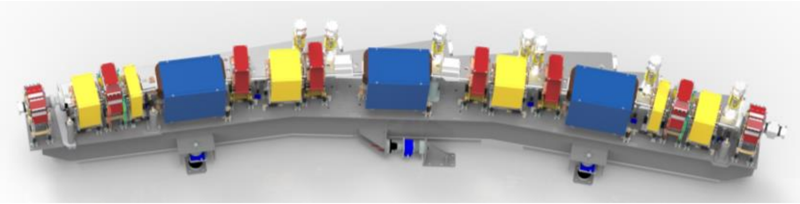
ALS-U ADVANCED LIGHT SOURCE

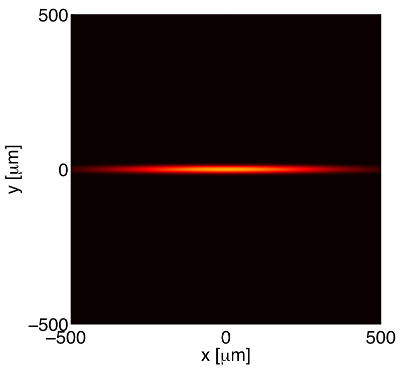
Outline

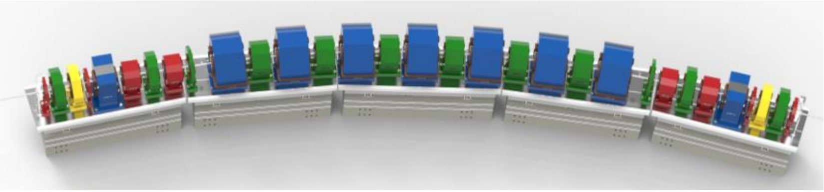
- Motivation
  - ALS-U / swap-out
- History
  - TFB/LFB
  - Pseudo-single bunch
- Recent Development
  - Pulser(s)
  - Stripline Kicker
  - Injection Studies
- Summary

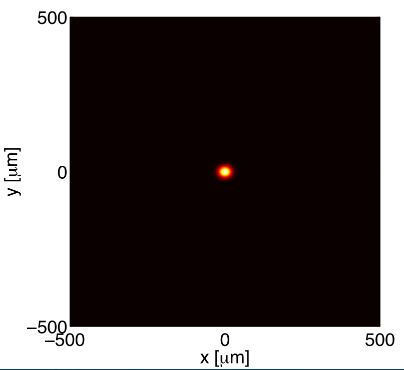


ALS and ALS-U in numbers





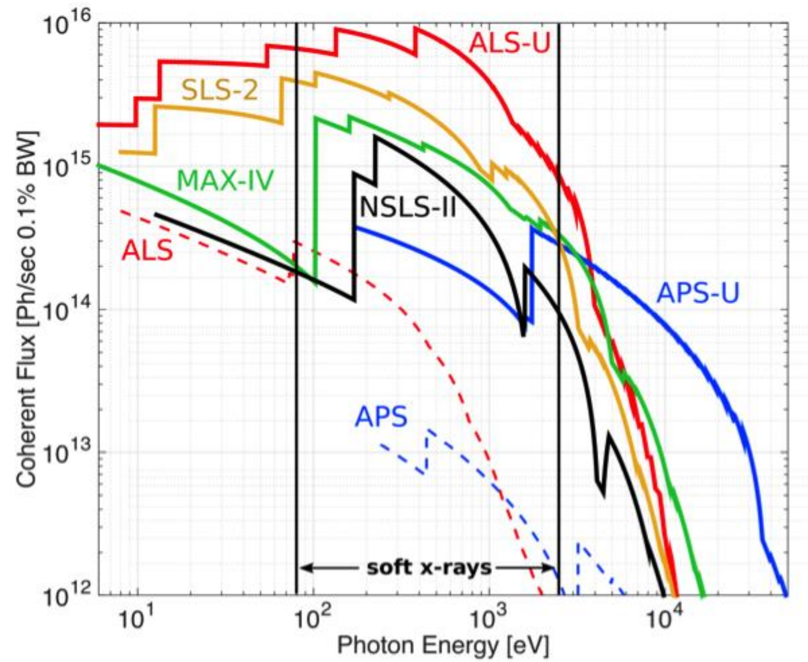


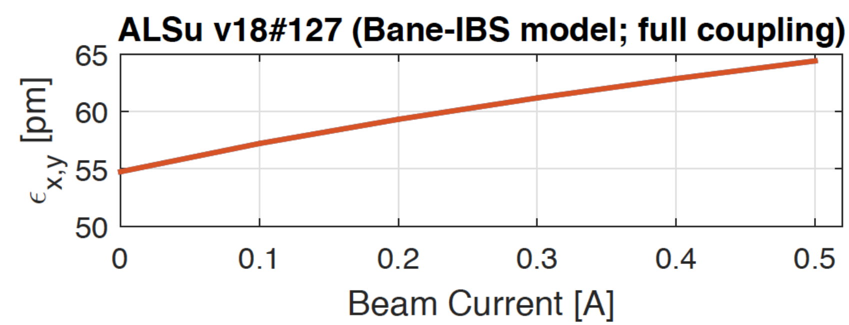


Parameter	Units	ALS	ALS-U
Electron energy	GeV	1.9	2.0
Horiz. emittance	pm	2000	~50
Vert. emittance	pm	30	~50
Beamsize @ ID center (σ_x/σ_y)	mm	251 / 9	<10 / <10
Beamsize @ bend (σ_x/σ_y)	mm	40 / 7	<5 / <7
bunch length (FWHM)	ps	60-70 (harmonic cavity)	120-200 (harmonic cavity)
RF frequency	MHz	500	500
Circumference	m	196.8	~196.5

Optimizing for soft x-rays

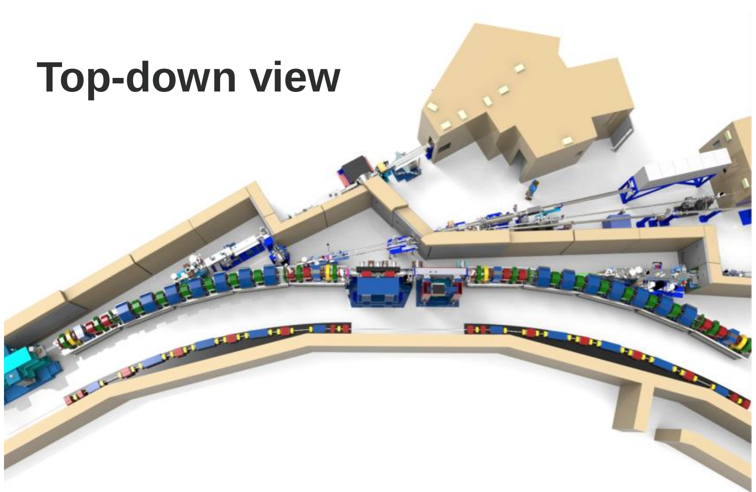
- Brightness peak in soft x-rays allows low electron beam energy (3 keV-2 GeV)
- Diffraction limited emittance moderate (2 keV-50pm) – reachable with 200m ring
- Vertical plane diffraction limited at same (‘large’) emittance - round beam
- Lower energy allows shorter focal lengths-more magnets, lower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

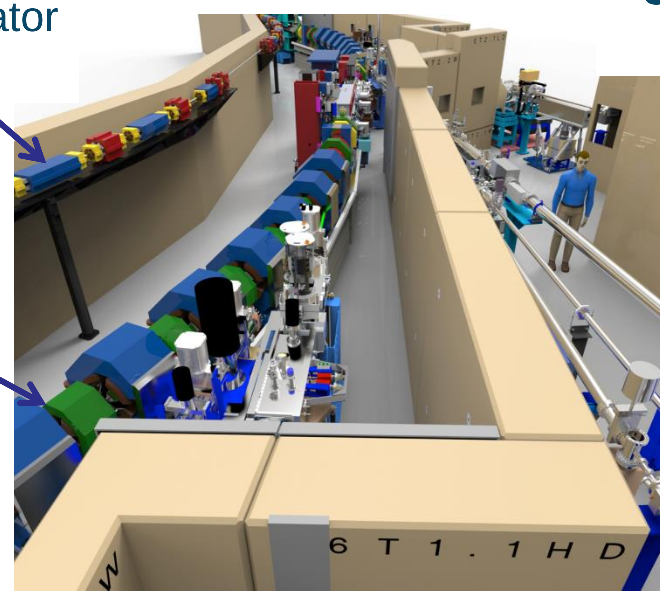




Scope of the ALS-U project

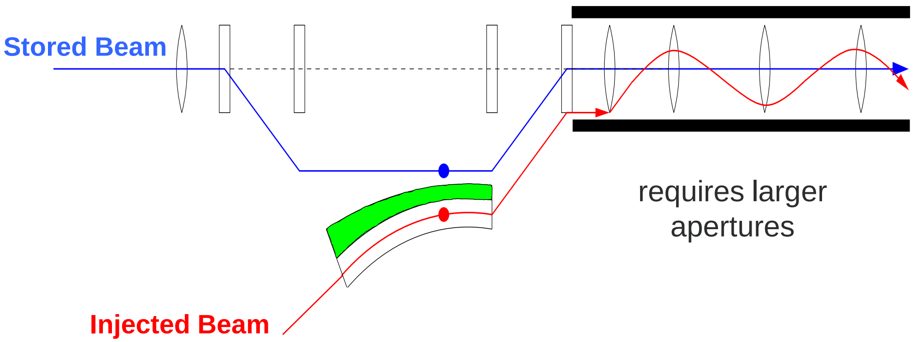
1. **Replacement** of the existing triple-bend achromat storage ring with a new, high-performance storage ring based on a multi-bend achromat.
2. **Addition** of a low-emittance, full-energy accumulator ring in the existing storage-ring tunnel to enable on-axis, swap-out injection using fast magnets.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





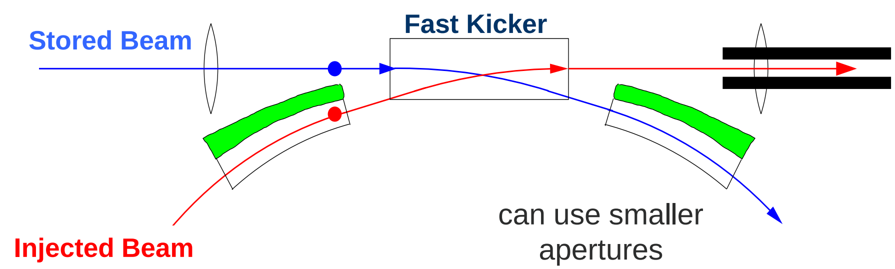
Swap-out with a full-energy accumulator

Traditional off-axis injection



On-axis swap-out injection

(initially proposed by M. Borland)



Swap-out enables:

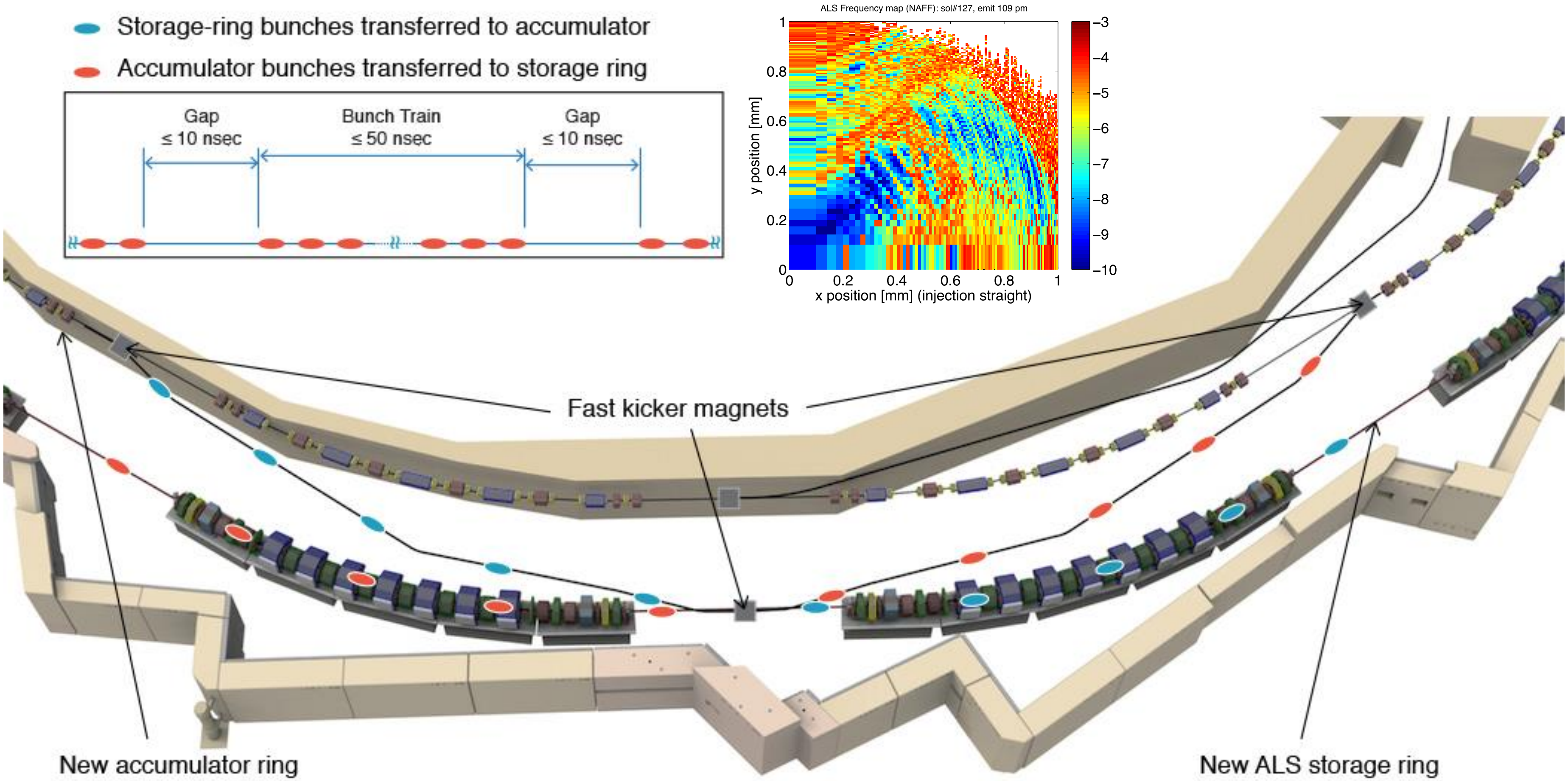
- Stronger-focusing MBA lattices with smaller dynamic apertures
- Round beams - more useful shape and reduced emittance growth
- Vacuum chambers with small round apertures → Improved undulator performance

Only ALS-U and APS-U plan to include swap-out

Swap-out with full energy accumulator enables:

- Bunch train swap-out and recovery of the stored beam current
  - Lower demand on the injector
  - Very small (~nm) injected emittance
  - More flexibility in fill patterns

Swapping accumulator and storage ring beams

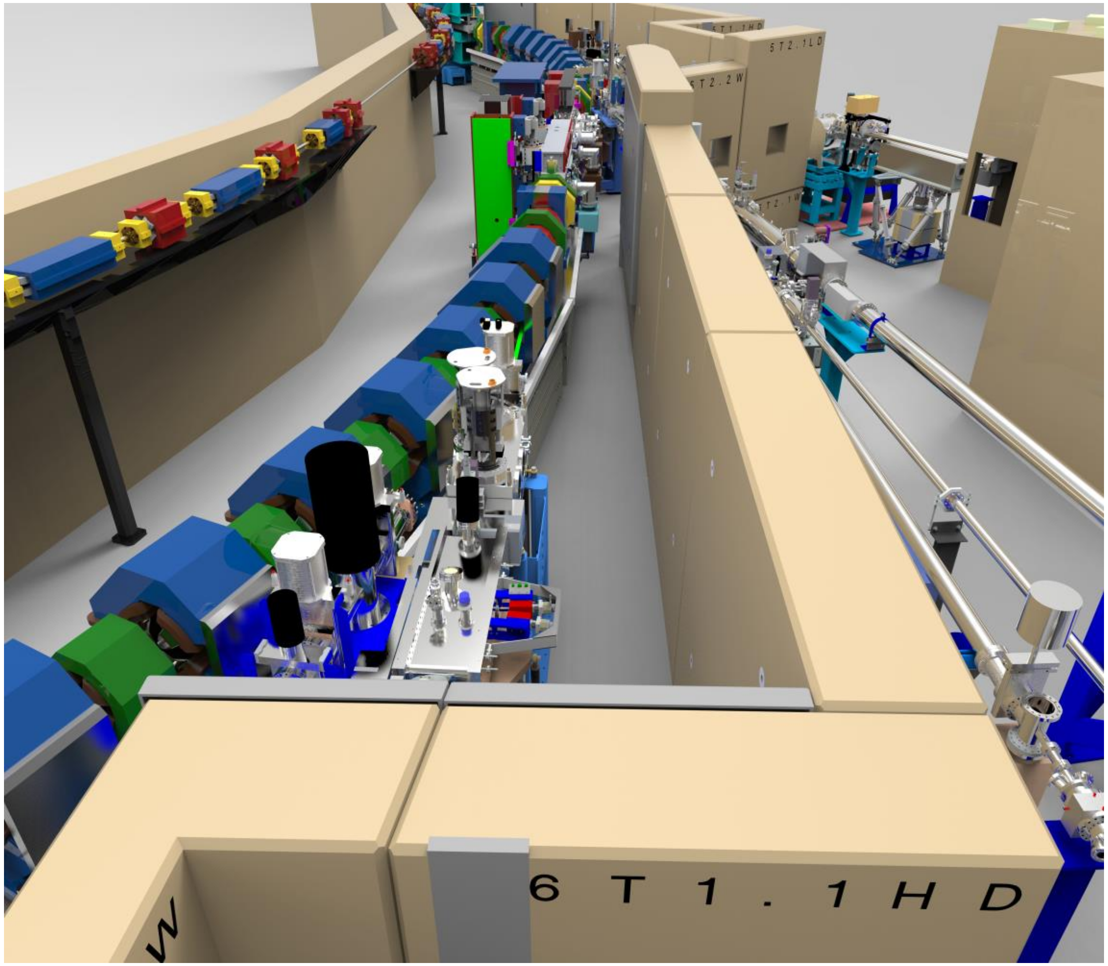


Swap-out injection was first proposed by M. Borland for possible APS upgrades

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)



ALS

BESAC Prioritization Process (2016)

SCIENTIFIC FACILITIES

Flagship accelerators bid for better beams

DOE considers wish list of upgrades to x-ray and neutron sources

By Robert F. Service

A scientific advisory panel for the United States Department of Energy (DOE) has begun weighing possible upgrades to four of the nation's top sources of high-energy x-rays and neutron beams. For years, the giant machines—two x-ray synchrotrons, an x-... lied on technology so cutting-edge that some doubted it would even work. But the LCLS succeeded in turning out ultrashort bursts of coherent x-rays—an advance that has already led to groundbreaking scientific developments in glimpsing the formation of chemical bonds and tracking the movements of electrons in complex materials. That success encouraged the development of more power-... them through powerful magnets that cause them to shed beams of x-rays that are less intense but have longer pulses than beams from FELs. The APS specializes in producing energetic "hard" x-rays, which are useful for nailing down the positions of individual atoms in samples; the ALS generates less energetic "soft" x-rays, which are better at identifying chemical elements.

Brighter prospects for beamlines

An advisory panel is weighing upgrades to four major U.S. scientific user facilities.

FACILITY	TYPE	COST (EST.)	NEW CAPABILITIES
Linac Coherent Light Source	X-ray FEL	$272 million	Doubles x-ray energy
Advanced Photon Source	Hard x-ray synchrotron	$734 million	Increases brightness 100x to 1000x
Advanced Light Source	Soft x-ray synchrotron	$300 million	Increases brightness 1000x
Spallation Neutron Source	Neutron accelerator		
-Proton power upgrade		$165 million	Doubles beam power
-Second target station		$1.3 billion	Adds new target station

Summary Table from BESAC Prioritization

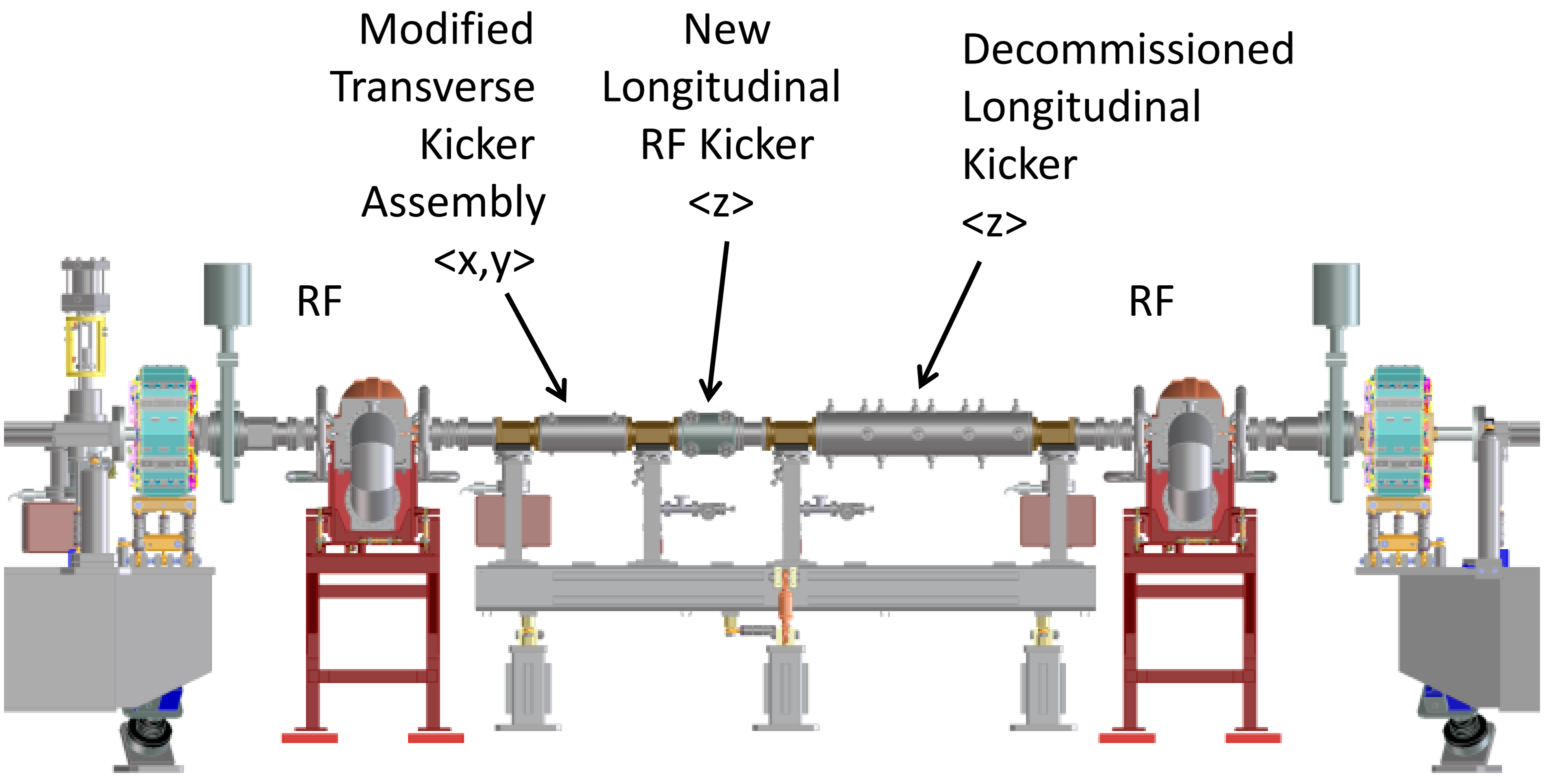
Summary Table of Assessment

Facility Upgrade	Criteria 1	Criteria 2
APS-U	Absolutely Central	Ready to initiate construction
ALS-U	Absolutely Central	Ready to initiate construction
LCLS II-HE	Absolutely Central	Ready to initiate construction
Proton Power Upgrade	Absolutely Central	Significant scientific/engineering challenges to resolve before initiating construction
SNS Second Target Station	Absolutely Central	Significant scientific/engineering challenges to resolve before initiating construction

U.S. DEPARTMENT OF ENERGY | Office of Science

Table taken from close-out presentation by John Hemminger (chair of BESAC and BESAC prioritization subpanel), presented to and accepted by BESAC on June 9, 2016.

History: Original ALS TFB / LFB Kickers

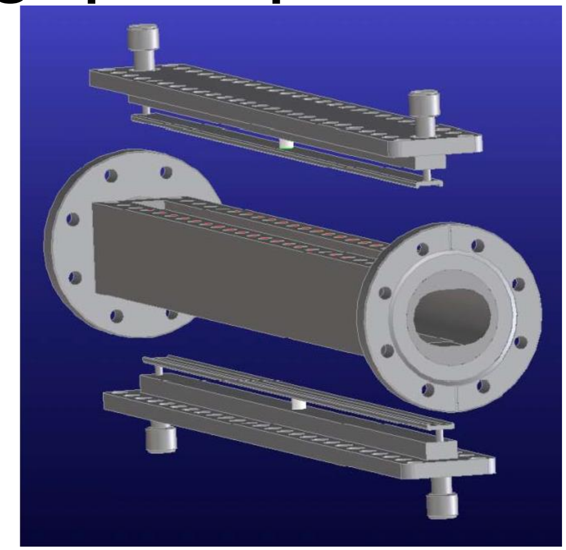


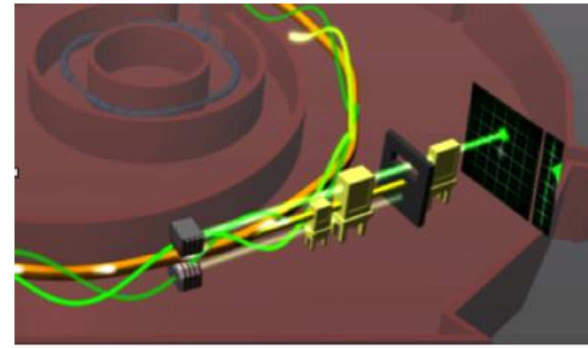
ALS/LBNL together with PEP-2/SLAC were pioneers of broadband multibunch feedback systems

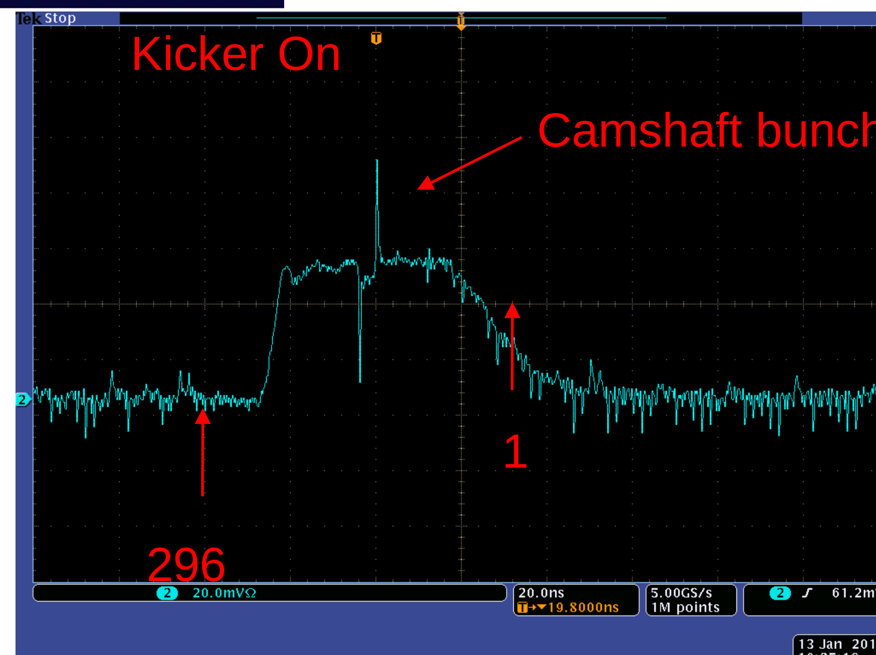
- Original systems (mid 1990s) used two (large aperture) transverse and one longitudinal stripline kicker for the 3 TFB/LFB systems
- Recently modified as part of effort to create space for one new undulator
    - Combined transverse kickers, replaced longitudinal one with cavity

First small gap stripline kicker at ALS

- 15 mm vertical gap between striplines
- Used in routine user operation: Pseudo Single Bunch Mode
- Up to 1.5 MHz repetition rate
- Currently +/- 1 kV
- About 60 ns pulse length
- Similar challenges for beam coupling impedance, HOMs, heating, feedthroughs, RF loads as planned systems for ALS-U







Subsequent to measurement on right, we moved the kicker pulse forward and placed the camshaft non-centered in gap, resulting in acceptably small disturbance of bunches at begin+end of train

Swap-out Injection R&D

Swap-out Injection Enables Performance Leap

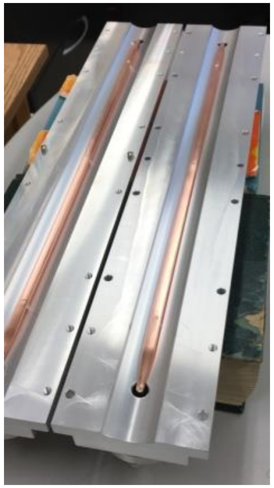
- it permits lattice optimization with reduced emittances;
- it allows round beams that minimize intra-beam scattering;
- it is compatible with higher performance undulators such as DELTA, vertical or bifilar helical devices.

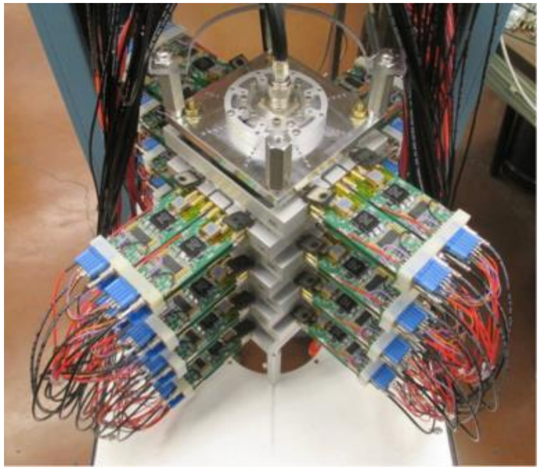
Significance and Impact

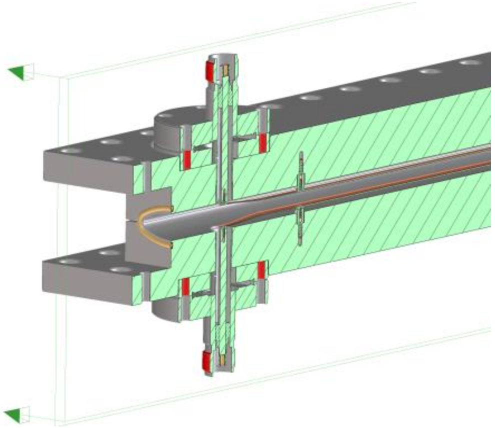
Swap-out injection is not in use at existing rings, because of its technical challenges. We are retiring the risks associated with the fast magnets and pulsers, and developing tools for fast beam-based commissioning, i.e. to allow for a short dark time.

Research Details

- Built inductive adder capable of producing pulses with necessary characteristics and stripline kicker to be tested in ALS in beginning of 2017.



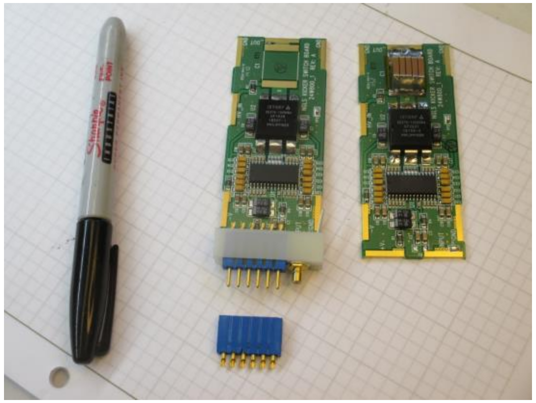


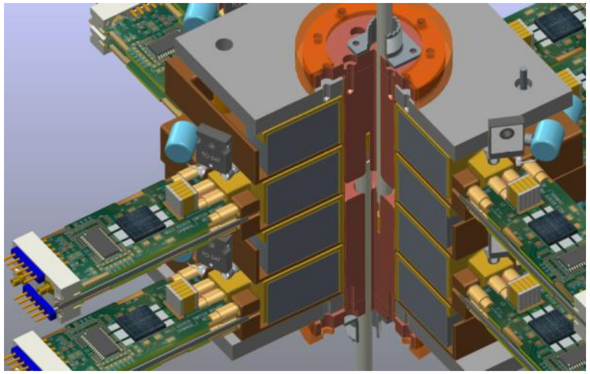


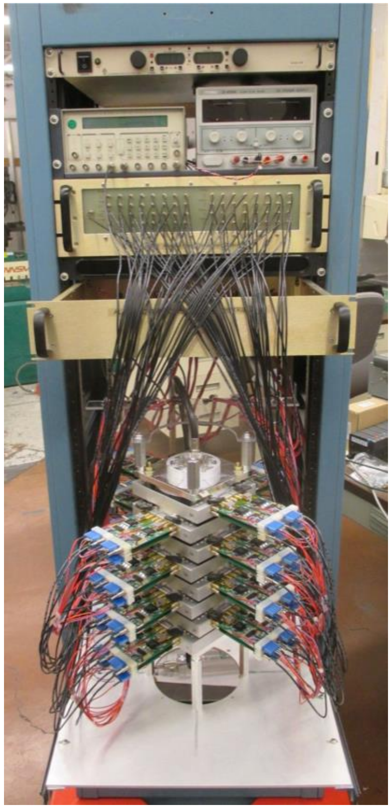
Left: Prototype Stripline kicker. Middle: Full inductive adder. Right: CAD model of stripline kicker to be installed in ALS for beam tests.

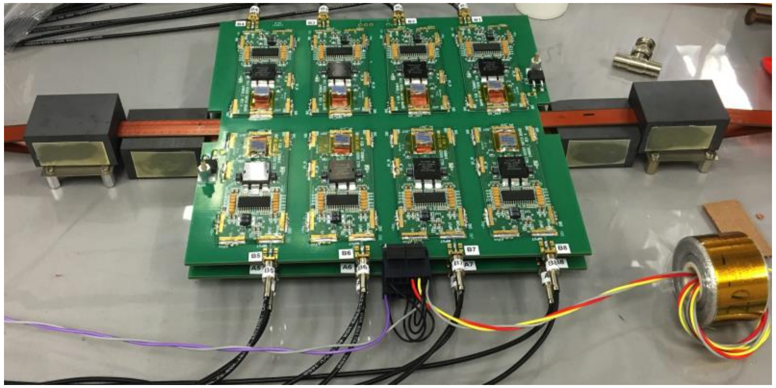
C. Steier, et al., Proc. IPAC 16, p. 2962, ISBN 978-3-95450-147-2

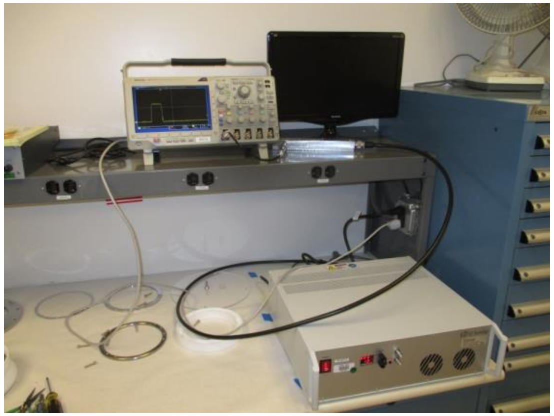
Pulsers for ALS-U Stripline Kickers









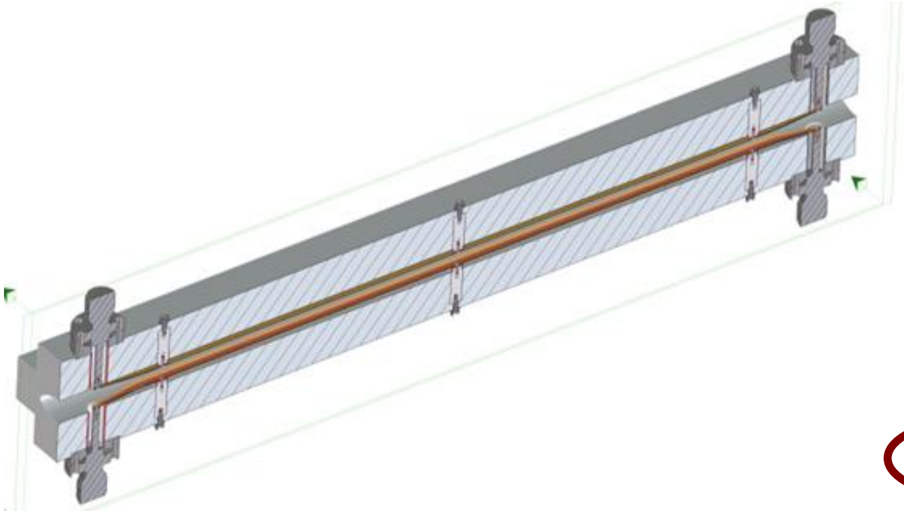


- Swap-out for ALS-U – different from prior NLC/ILC work
  - <7 ns rise/fall time, 50 ns flat top (bunch train swap out)
  - Pursuing various pulser designs (inductive/transmission line adder)
  - Also evaluating capabilities of industry (Germany, USA/SBIR)

Goals for Stripline Kicker + Pulser

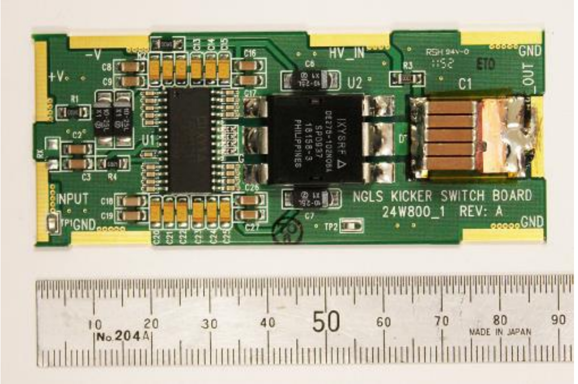
Beam Energy	2 GeV
Bend Angle	3.5 mrad
Distance Between Striplines	6 mm
Total Magnet Length (4 modules)	2 m
Stripline Length	0.5 m
Stripline Impedance	50 ohms

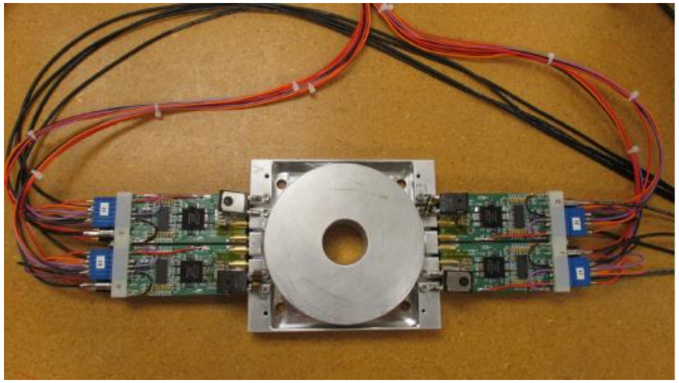
Load Impedance (2 parallel 50 ohms)	25 ohms
Stripline Voltage	+/- 5.25 kV
Stripline Current	+/-105 A
Rise/Fall Time (1-99%)	7 ns
Flattop (99-99%)	50 ns
Flattop Ripple	+/- 1%
Repetition Rate	<0.1 Hz

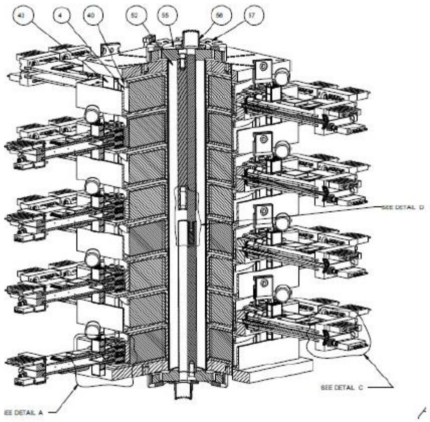


These are goals to improve transparency. Hard requirements are 5% / 95%

Inductive Adder Design Details

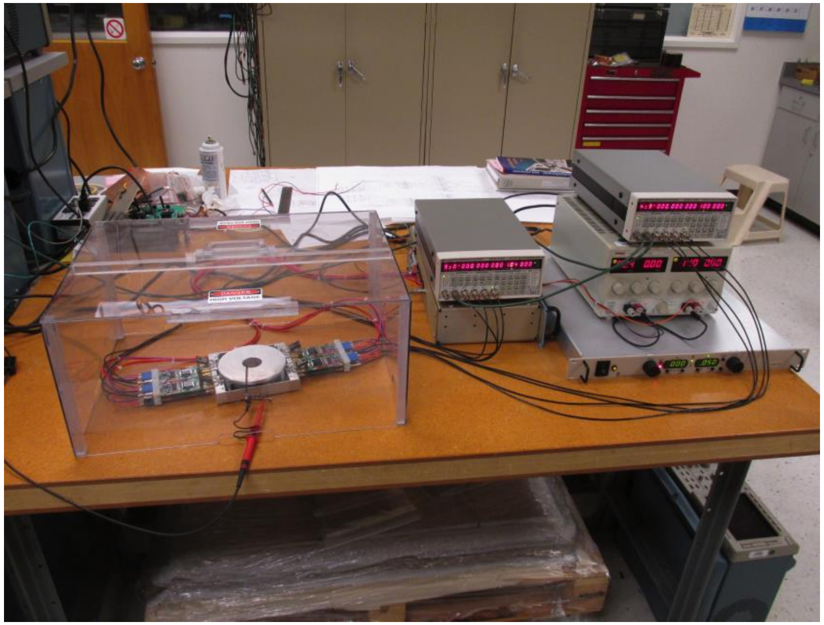


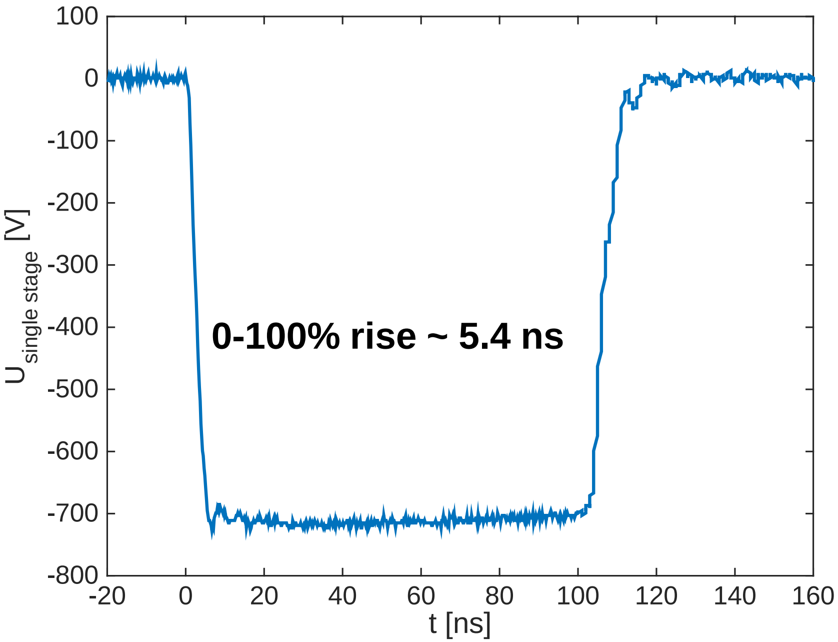




- Similar systems exist at LLNL, SLAC, University of Rochester, CERN, and others
  - 8 parallel boards per stage (210A / 8 = 26.25A per MOSFET)
  - 8 stages (656V / stage) : charge to ~750V to cover switch and stray losses
  - Equivalent load for each stage = 656V / 210A = 3.12 ohms
  - Equivalent load for each MOSFET board = 656V / 26.25A = 25ohms
  - Core: CMD5005 NiZn ferrite (OD=4.5”, ID=1.5”, 1” height)
  - Flexible stalk construction to vary the impedance (20-50ohms)
  - Output connector: custom feedthrough (modified UHF connector)
  - Output cable: RG-214
  - Input connector to kicker magnet: HN

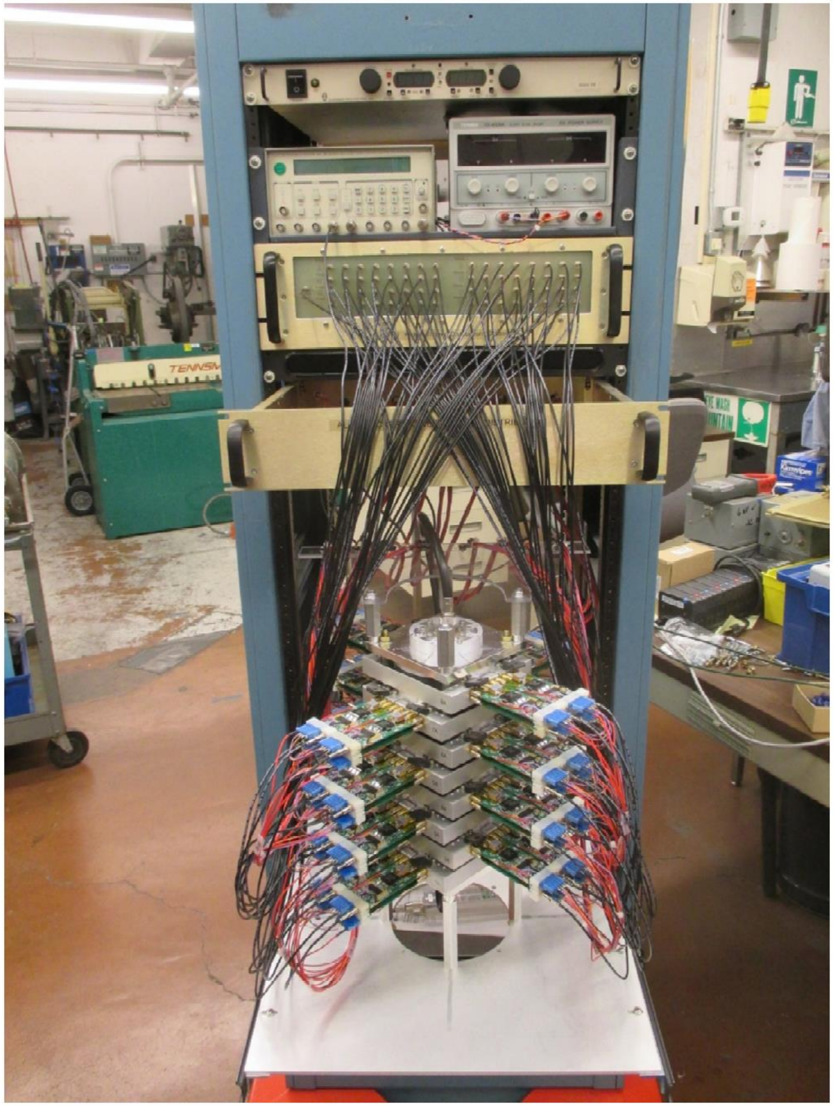
Single Stage Results

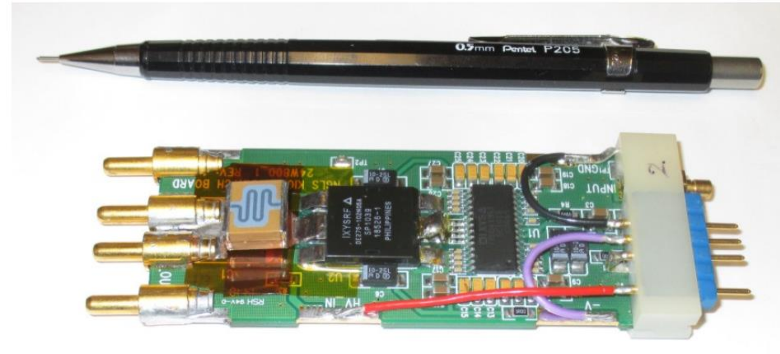


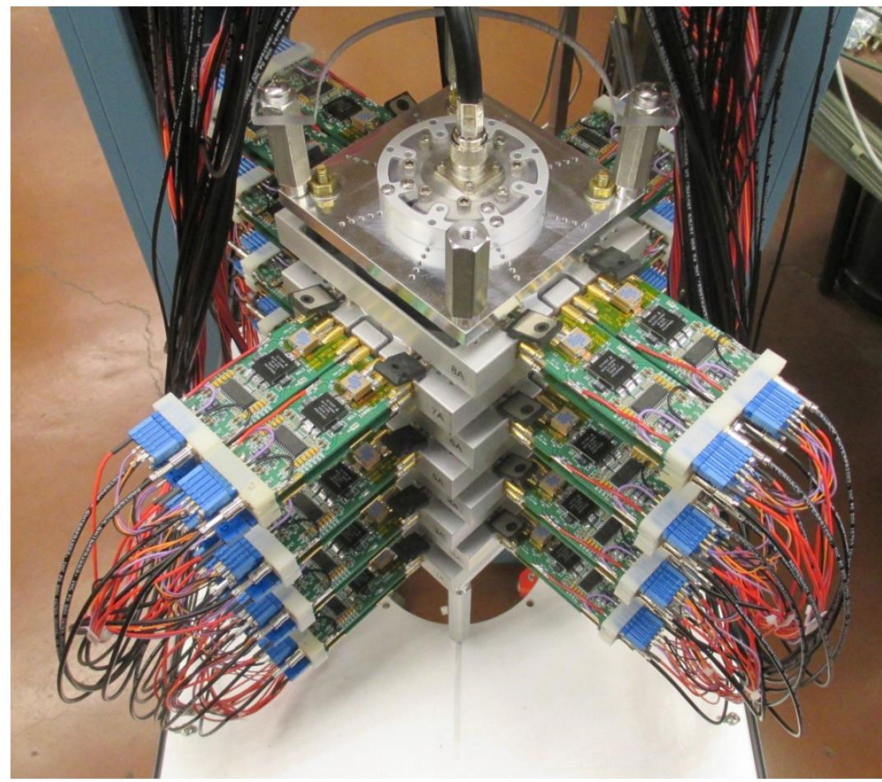


- **Single module with ALS-U parameters has been tested successfully** (<10 ns rise/fall time)
  - Consistent with RF / harmonic cavity design and planned fill patterns
  - Full pulser complete and tested at full voltage; test with beam in FY17

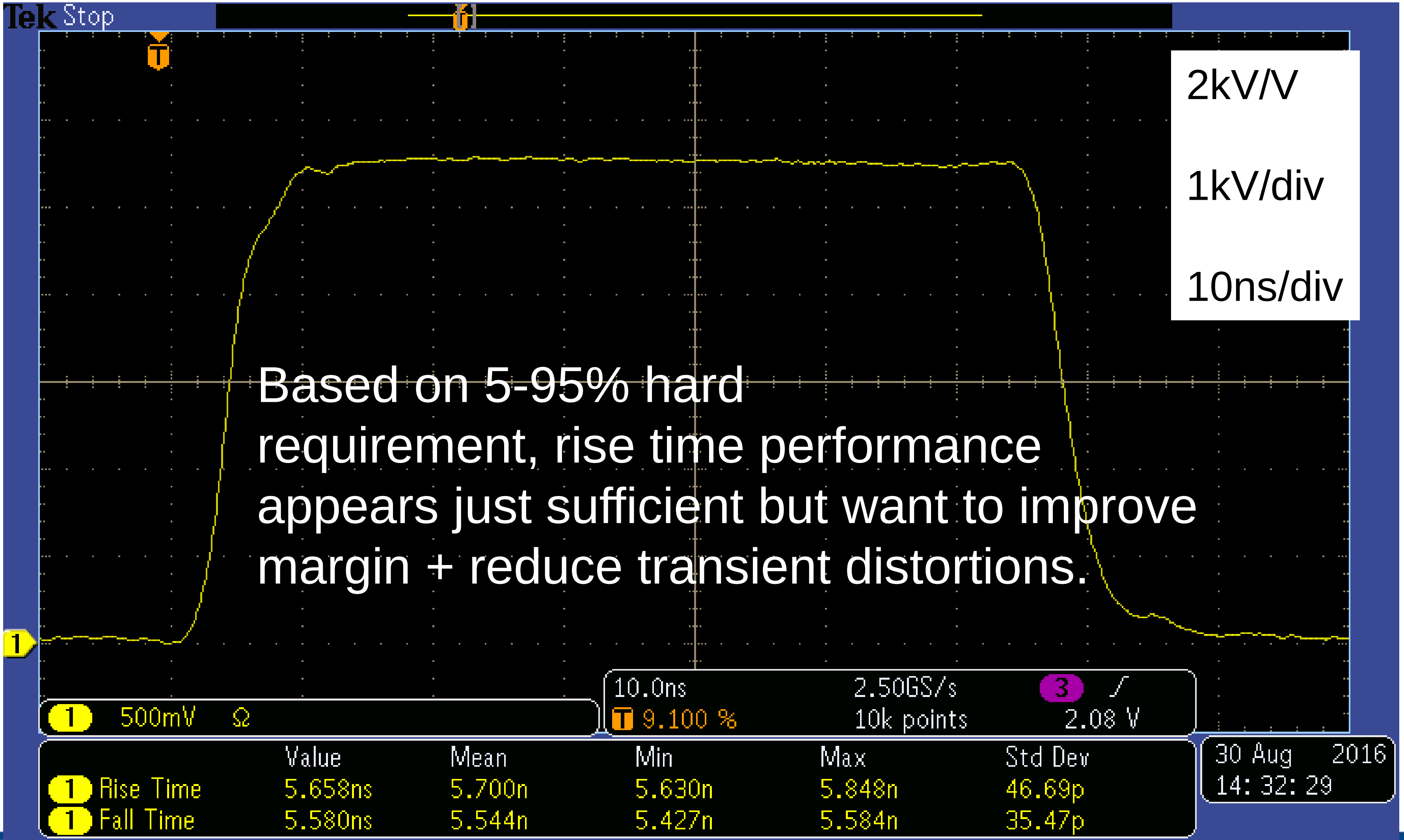
Fully assembled Inductive Adder







Testing Inductive Adder above nominal Voltage (5.5kV for Vch=750V)



2kV/V

1kV/div

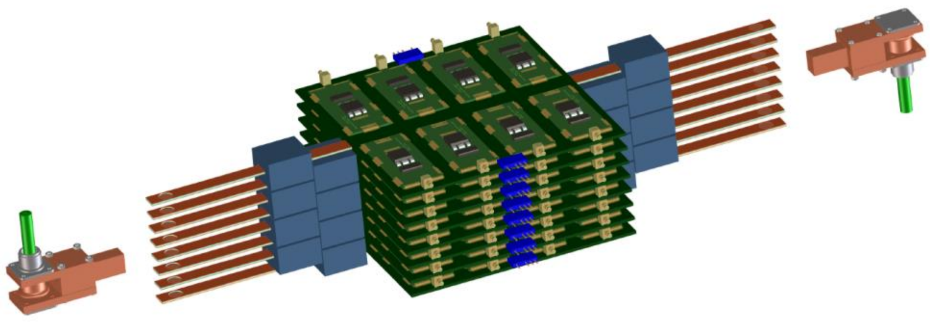
10ns/div

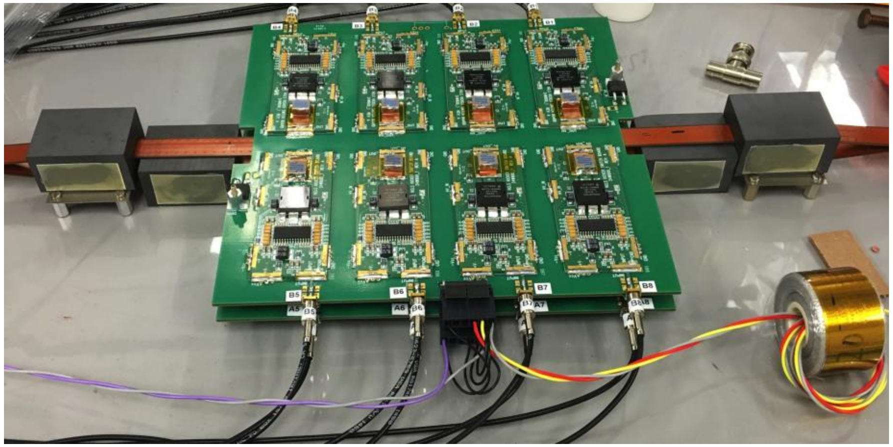
Based on 5-95% hard requirement, rise time performance appears just sufficient but want to improve margin + reduce transient distortions.

Next Steps

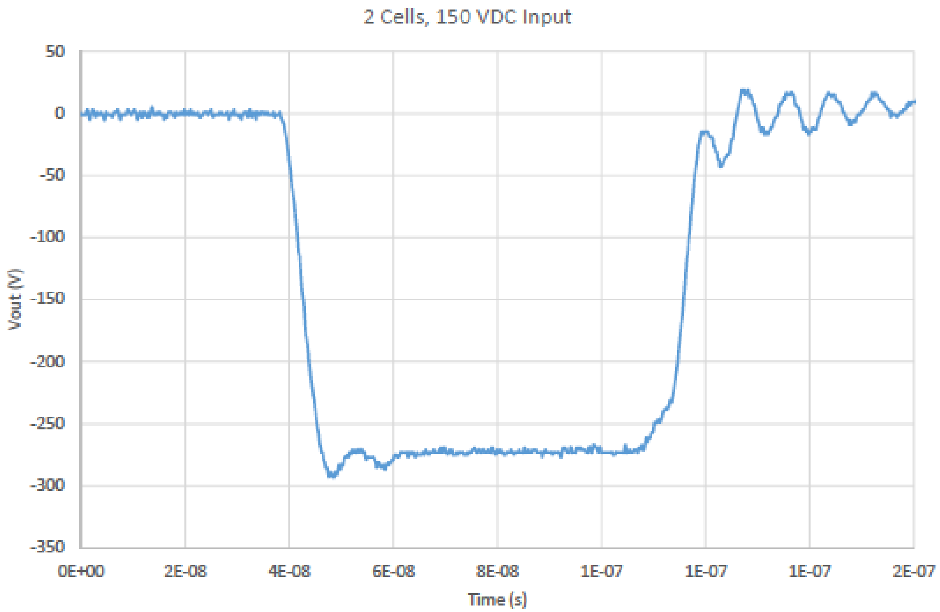
- Keep operating the IVA
  - Stagger stage timing – not expected to be a significant effect on rise/fall time based on the short transit time of the structure
  - Add parallel resistive or inductive load on each stage to look at the effect on the rise/fall time
  - Finish analysis of rise/fall time as a function of output V and I
  - Finish analysis of the rise/fall time as a function of stalk impedance
  - Evaluate "best" voltage waveform with respect to effects on beam
- Test evaluation MOSFET/driver boards and then lay out a 8-10 MOSFET/driver board
- Test a prototype IVA stage with the new core housing based on a modified LLNL design and the updated MOSFET/driver board
- Start to package the existing IVA for operation at ALS (cabling improvements, controls interface, etc.)

Transmission Line Adder

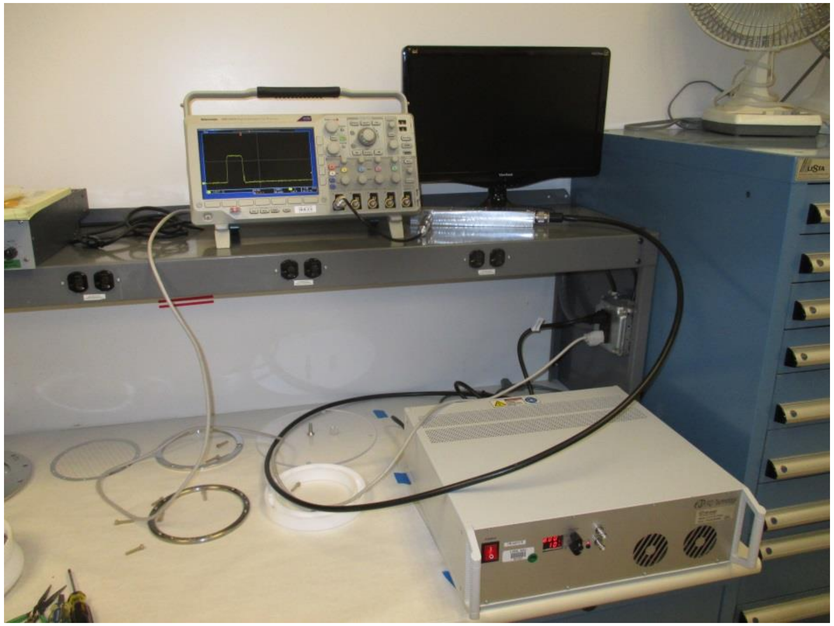


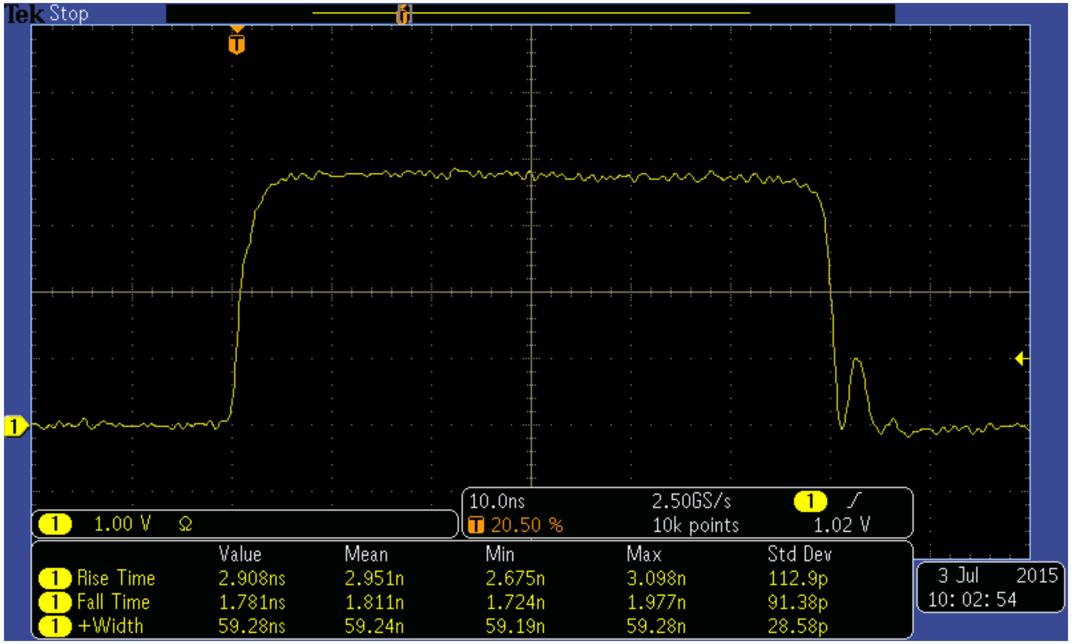


- Alternative approach, using same LBNL driver boards as inductive adder
- Flexible PCB boards with integrated transmission lines
- Very early in testing, only two stages combined so far
  - Rise+fall times OK (but only 2 stages), but significant ringing



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

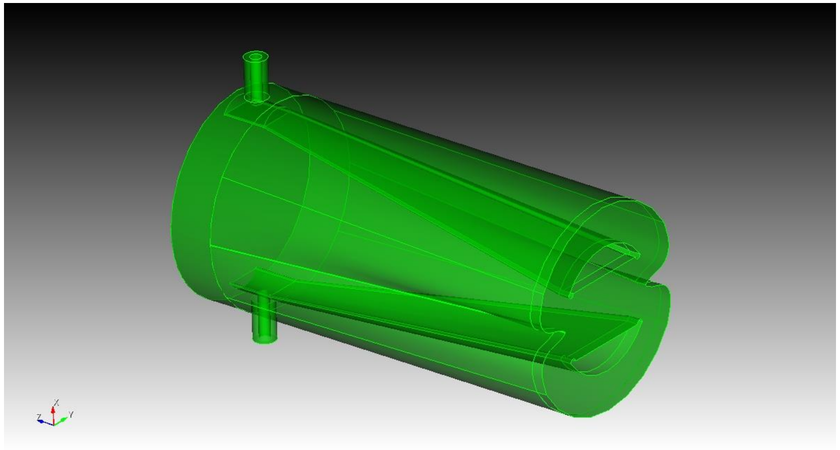


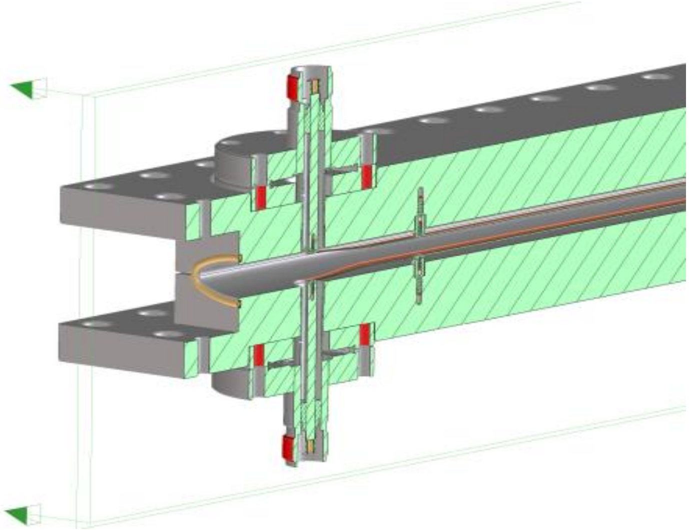


- Overcame some initial reliability problems
- Ringing at tail end of waveform is very reproducible, it is borderline acceptable, but not desirable (transient distortion of following bunches)

Stripline Kicker

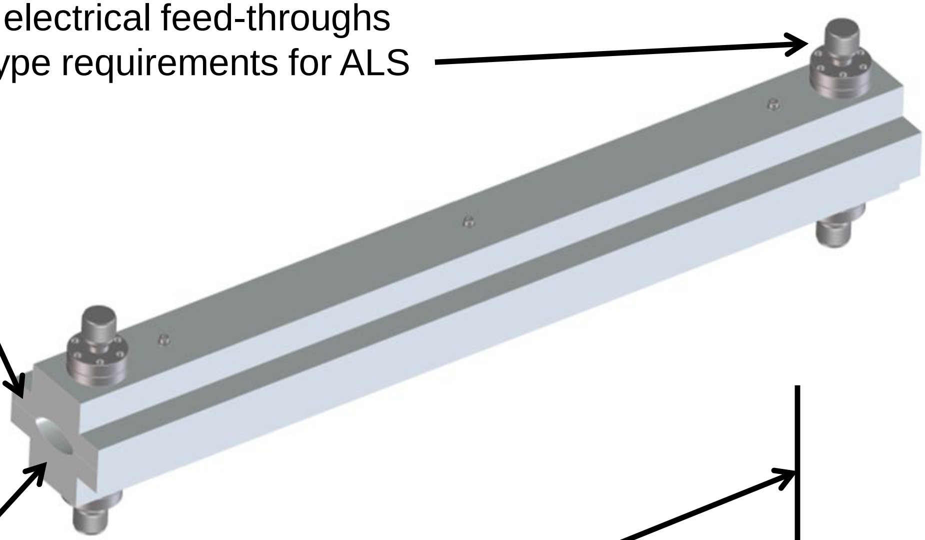
- Building 6 mm gap stripline kicker for test in ALS
- ALS test unit is different from ALS-U design because of aperture differences
  - same electrode gap+kick, no fenders, worse impedance matching for beam driven mode
- Will be a conservative test for ALS-U
- Vacuum design similar to existing 15 mm ALS stripline





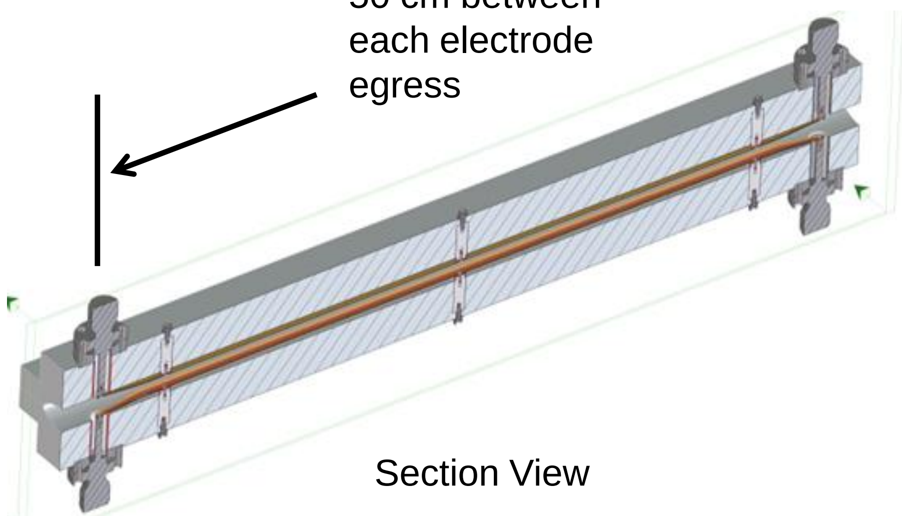
Finished Design of ALS Fast Kicker

Housing and electrical feed-throughs match prototype requirements for ALS installation.

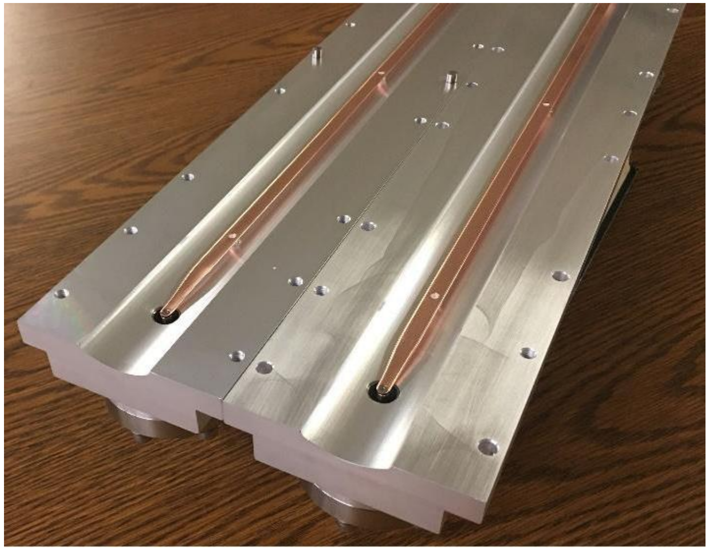


14 x 35 mm chamber aperture

50 cm between each electrode egress

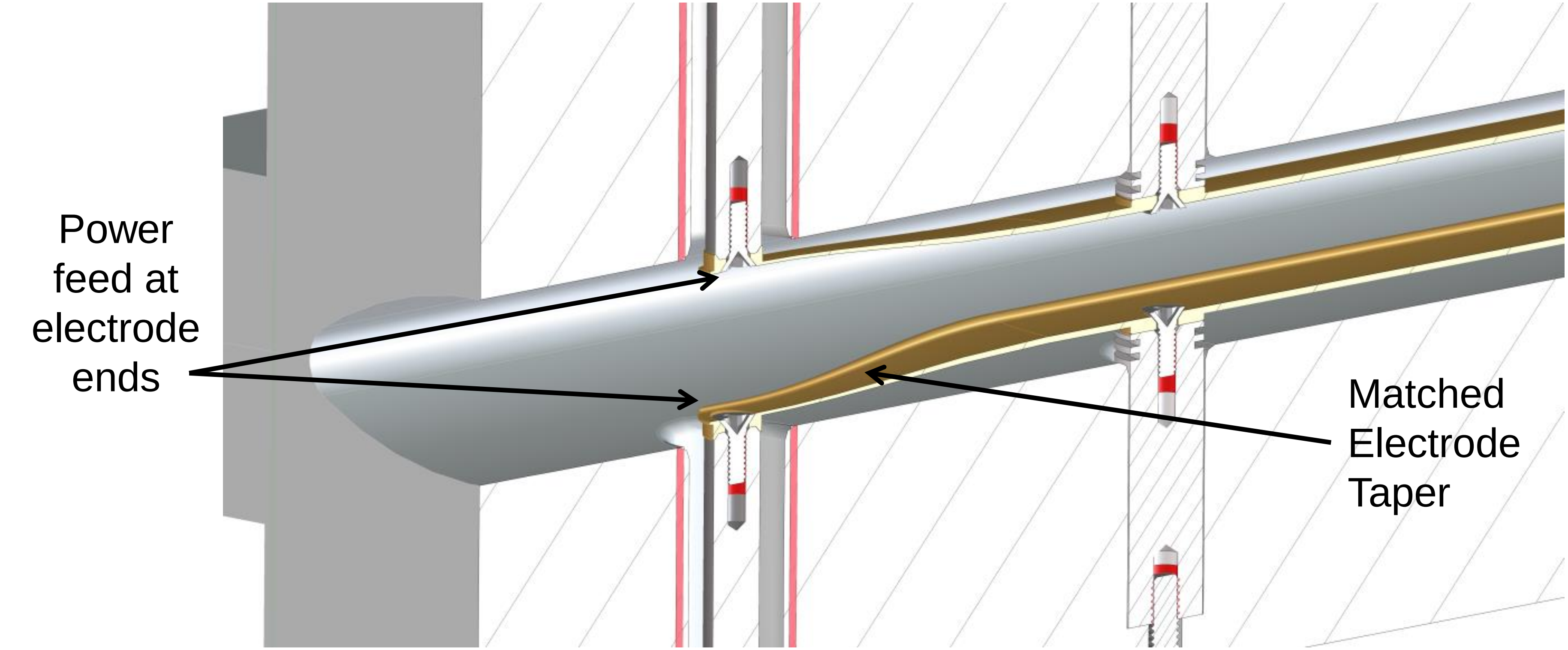


Section View

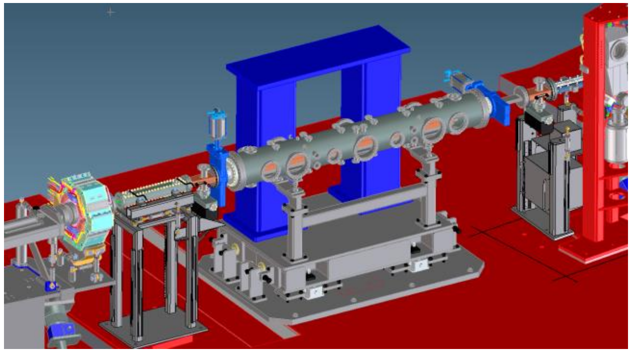


- Currently conducting multiple measurements on cold model:
- TDR, longitudinal+transverse impedance, field response with full pulser

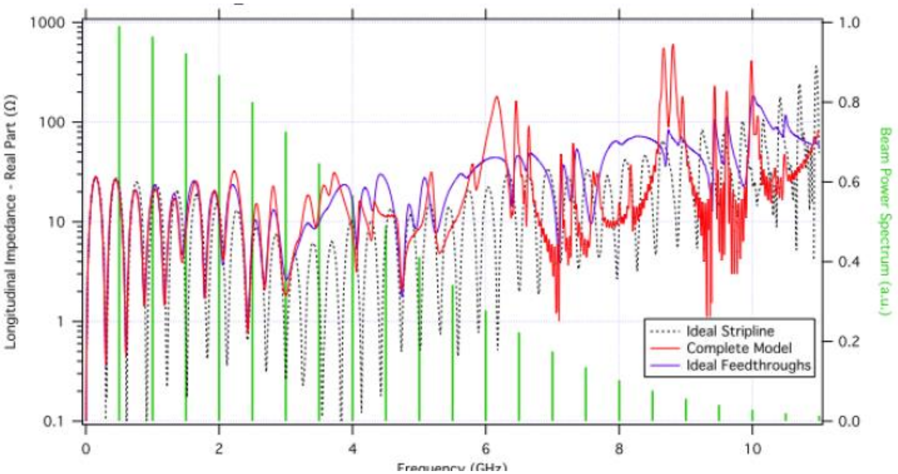
Shaped Electrodes Minimize Impedance

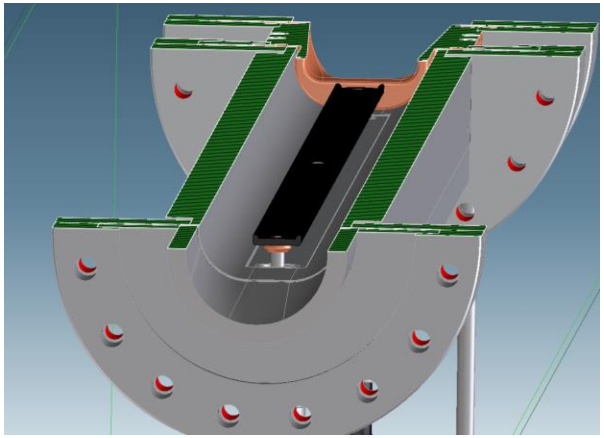


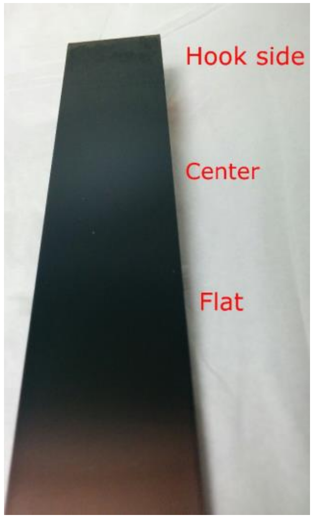
- Found space for stripline kicker and nonlinear injection kicker as part of rebuild of one straight for new undulator
- Finished all hardware designs (stands, absorbers, cable trays, …)



Thermal Management / Emissivity

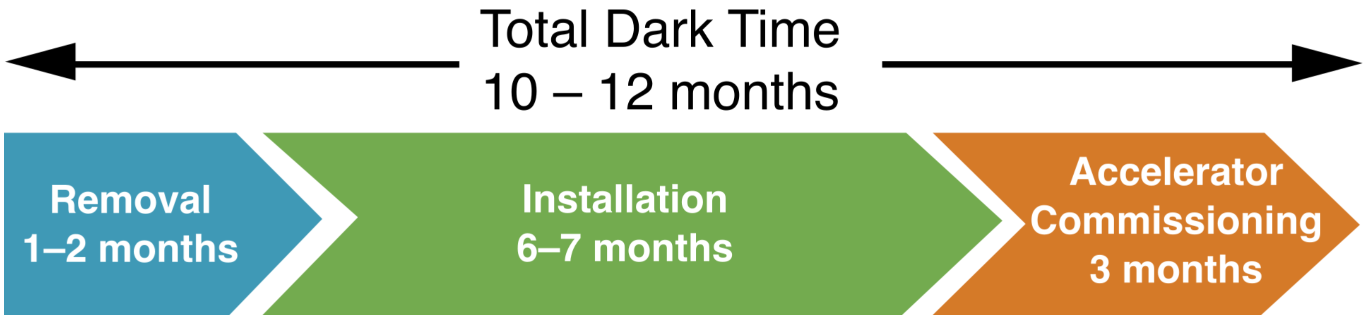






- Stripline taper optimization not as efficient to lower beam coupling impedance for flat ALS geometry as for round ALS-U geometry
- Estimated power deposited for full ALS beam is up to 3 W per stripline
- Concern for most conservative assumption about feedthrough and ceramic post heat conduction
- Revisited technique used before for original 15 mm ALS stripline: CuO coating (submicron) with plasma deposition – Emissivity above 0.5 achieved – this will provide temperature safety margin of >2
  - Also darken stainless kicker body (chemically) – impact on impedance negligible

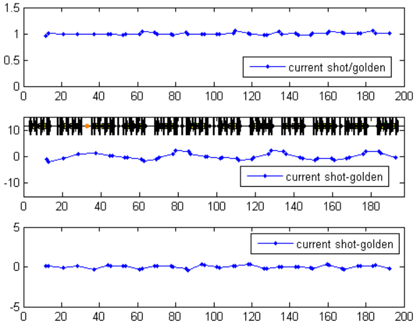
Interruption of science program is less than 1 year



- **Accelerator Commissioning (3 months)**
  - Similar to the experience at other facilities over the last 15 years
  - Developing fast, automated, beam-based commissioning techniques now
  - >50% of beamlines will be ready at end of accelerator commissioning
  - The remainder of beamlines will be ready within 6 months of the end of accelerator commissioning

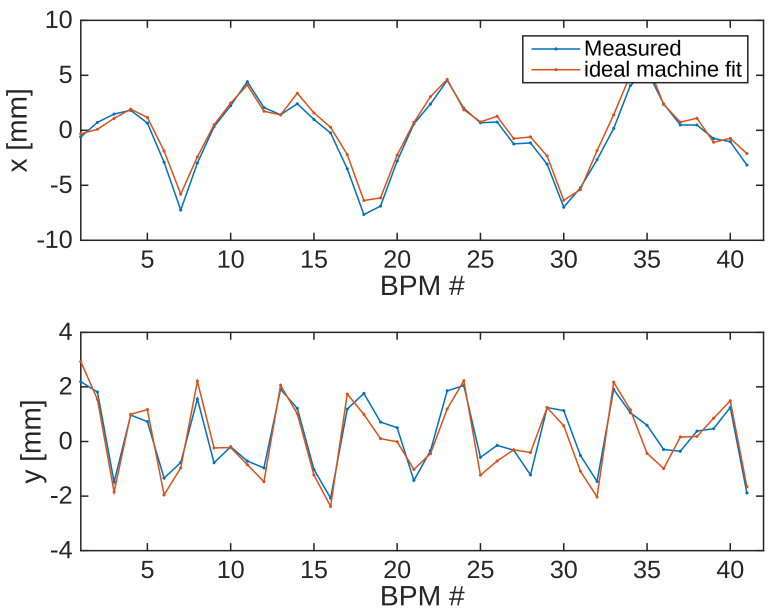
Developing Beam Based Correction techniques to speed commissioning

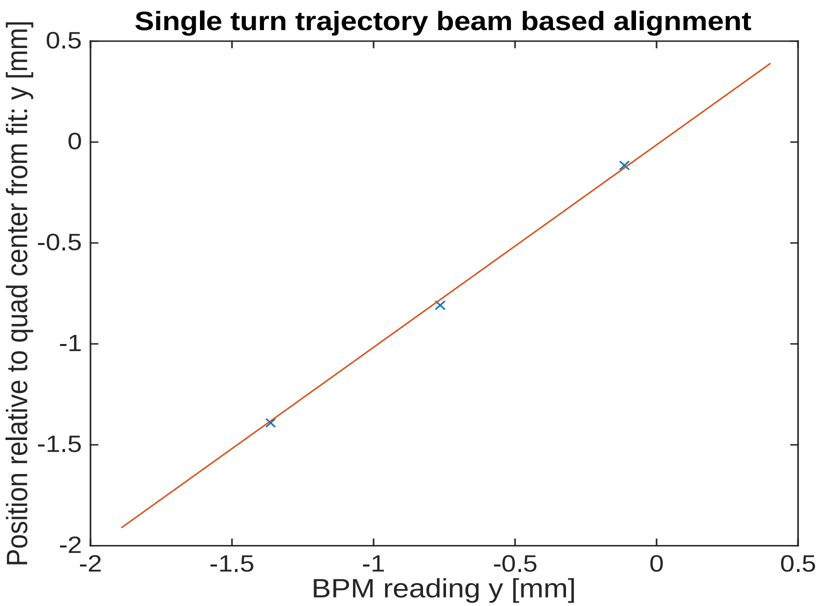
- Motivation:
  - Automated commissioning software can reduce commissioning time and reduce commissioning risk
  - Can also allow to relax requirements on magnets, BPMs, alignment (reducing cost)
  - Enabling technology is new Beam Position Monitors with much higher turn-by-turn resolution
- Software:
  - Implementation in Matlab based on MML (standard at ALS, Spear-3, and 20+ light sources world-wide)
  - Goals:
    - Demonstrated necessary BPM resolution (done)
    - Orbit correction based on first turn data (done)
    - Beam-based alignment based on first turn data (done)
    - Gradient and skew-gradient determination based on first/few-turn data (started – tune)
    - Sextupole symmetry correction based on few-turn data



Beam based alignment using turn-by-turn BPMs

- Demonstrated trajectory correction and ability to do better than 100 micron accuracy beam-based alignment without requiring stored beam.





Intentionally offset first turn trajectory of injected beam in the ALS and trajectory fits using the ideal machine model.

Beam based alignment measurement using only first turn trajectory measurements. Result agrees within 50 microns with stored beam measurements.

Successful initial tests of automated commissioning

Motivation:

- Traditional **manual** machine commissioning is slow and will be more challenging for the smaller dynamic aperture MBAs.
- New BPMs and algorithms offer the opportunity to largely automate and shorten the time to commissioning

Experimental test setup:

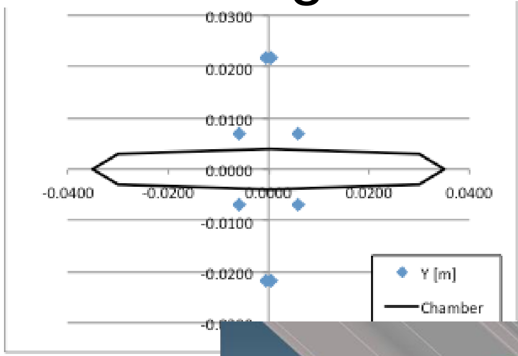
- Developed trajectory response matrix and correction code
  - Configurable number of turns, correctors, and singular values.
- Test example with all correctors off – beam makes only one turn due to a single badly aligned sextupole

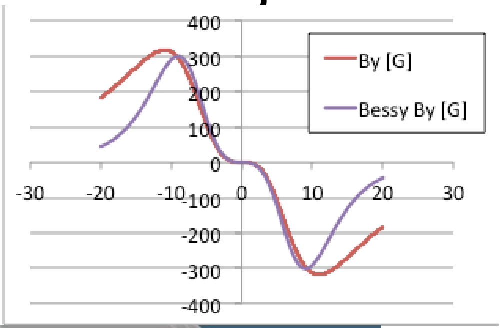
Result of test:

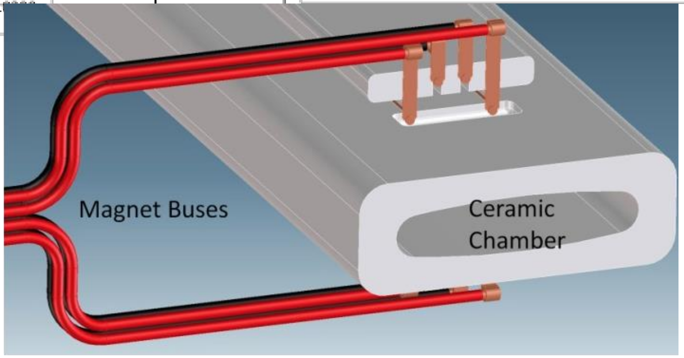
- **Correction sufficient after 3 injection shots to store beam!**
  - Residual closed orbit error about 1 mm peak

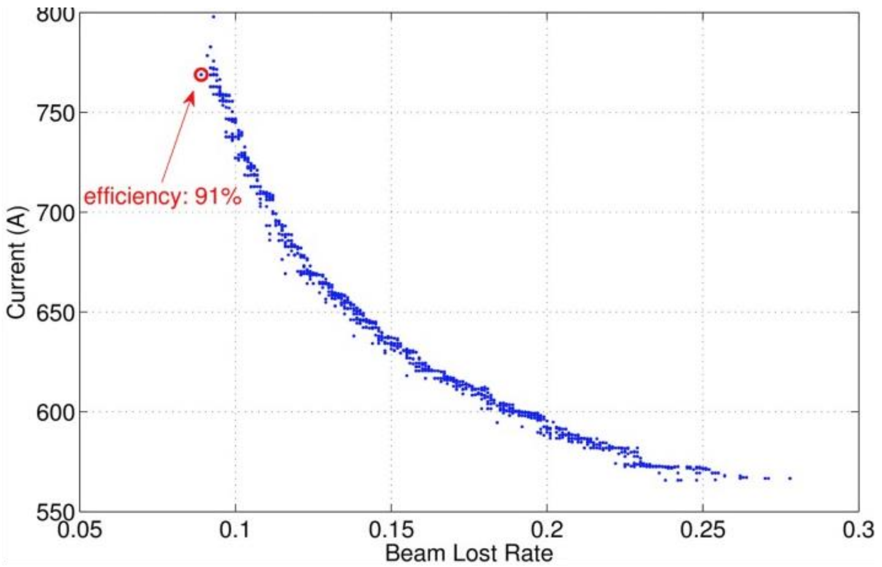
Nonlinear Injection Kicker

- We are also developing a nonlinear injection kicker
  - Planned to be installed in January next to 6 mm stripline kicker
  - Started design from earlier BESSY effort
  - Application is both ALS and ALS-U accumulator
- Kicker / conductor geometry optimized by MOGA integrated with full injection efficiency calculation









Summary

- ALS has long experience with stripline kickers
  - LFB / TFB (2 x transverse, 1 x longitudinal)
  - Pseudo single bunch (user operations, 15 mm gap)

- On-axis swap-out injection is key feature of ALS-U, enabling highest brightness and small (round) undulator gaps

- Development program for pulsers (3 variations) and small gap stripline kicker (6 mm gap) well under way
  - Also working on commissioning algorithms for on-axis injection

We are looking forward to beam test of 6 mm gap stripline in February 2017

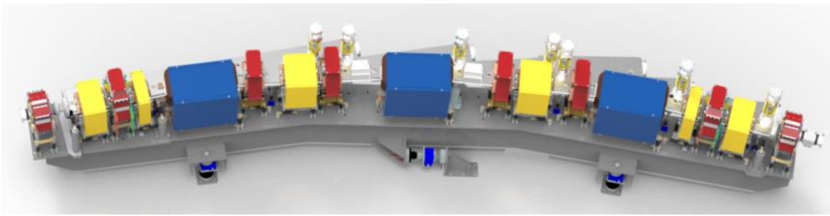
Acknowledgements

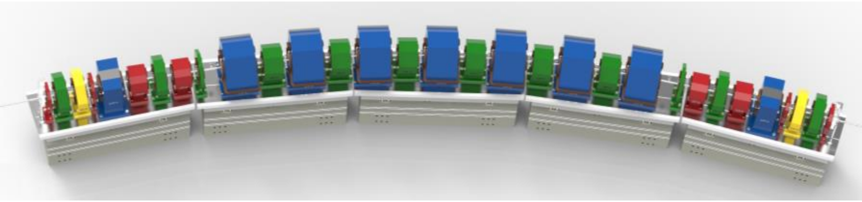
- Will Waldron, Chris Pappas (Pulsers and electrical design)
- Stefano de Santis (Impedance, Bench Measurements)
- Chuck Swenson (Magnetics, Mechanical, Vacuum)
- Thomas Oliver, Andre Anders (Vacuum, Coating)
- Greg Portmann (BPMs, MML)
- Changchun Sun, David Robin, Marco Venturini (Accelerator Physics, Pseudo Single Bunch, NLK, …)
- Slawek Kwiatkowski, Walter Barry (prior stripline kickers)
- Ed San Mateo, Mark Coleman (Mechanical Design)
- Jim Galvin, Bill Ghiorso, Jacque Bell (technical help)

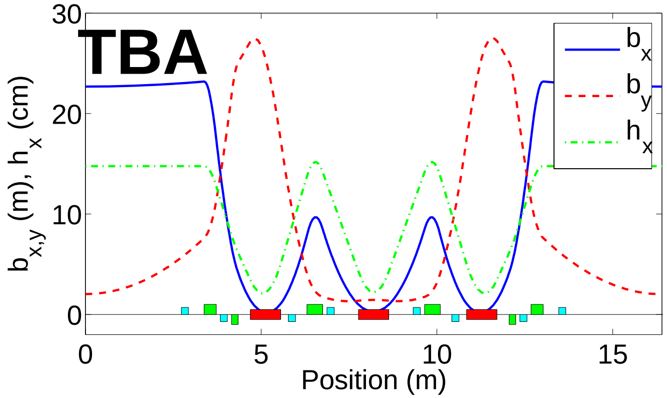
BACKUP SLIDES

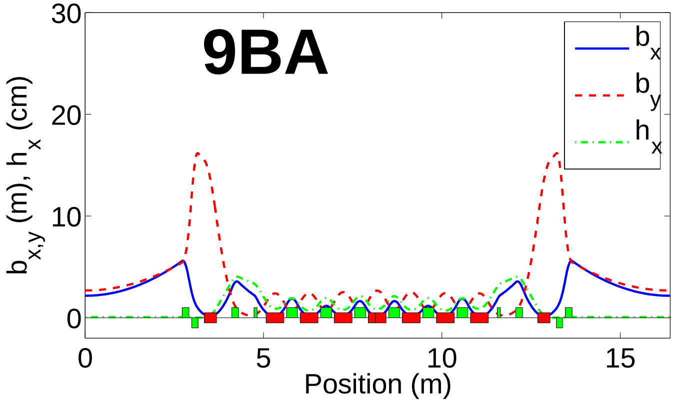
ALS-U uses compact 9BA to reach soft X-ray diffraction limit

ALS today triple-bend achromat (TBA)	ALS-U multi-bend achromat (9BA)









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

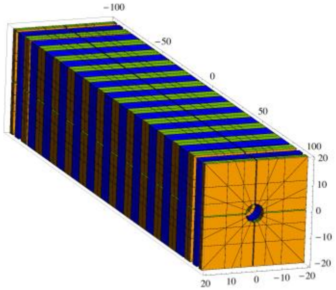
$$e_x = C_L \frac{E^2}{N_D^3}$$

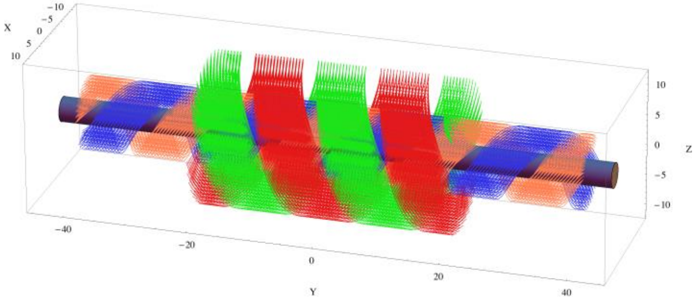
$e_x = 52\ \text{pm}\ @\ 2.0 GeV$

ALS-U Insertion Devices

4 undulators are included in base project:

- Will require polarization control
- Wide energy range
- Will make use of very small vertical and horizontal gaps possible in ALS-U
- Several ID concepts are under investigation



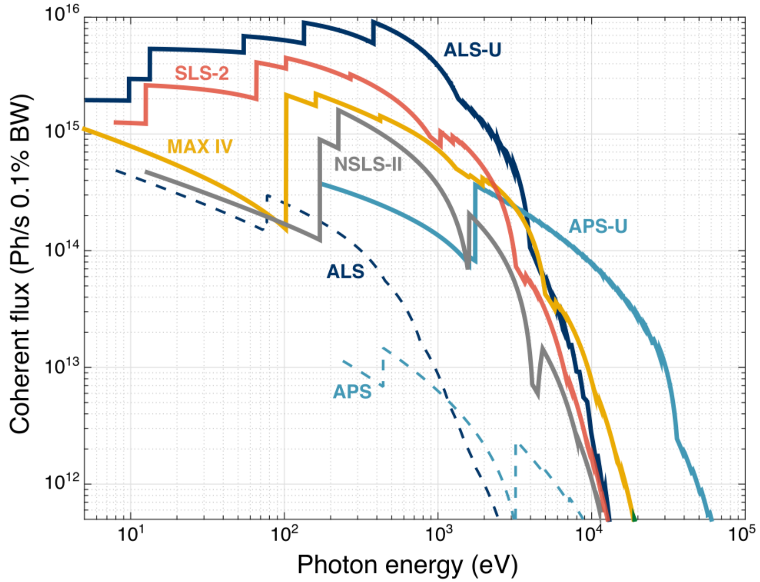


Optimized EPU, Delta, Superconducting double helical, etc.

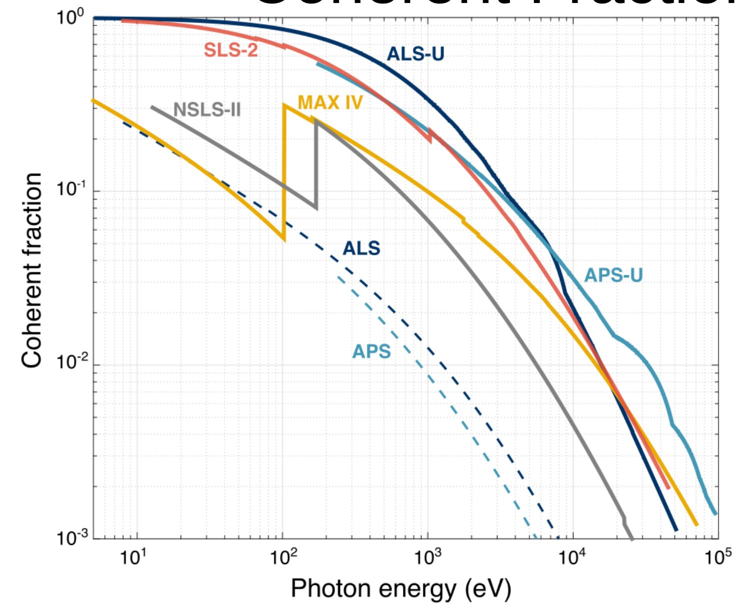
- Theoretical performance assessment is just starting
- Considering the use of multiple periods in EPU and superconducting-helical cases
  - Multiple periods offer optimized performance and significant power reduction at low energies which can significantly simplify front-end, mirror cooling, and BL design

ALS-U provides highest coherent fraction for soft x-rays

Coherent Flux



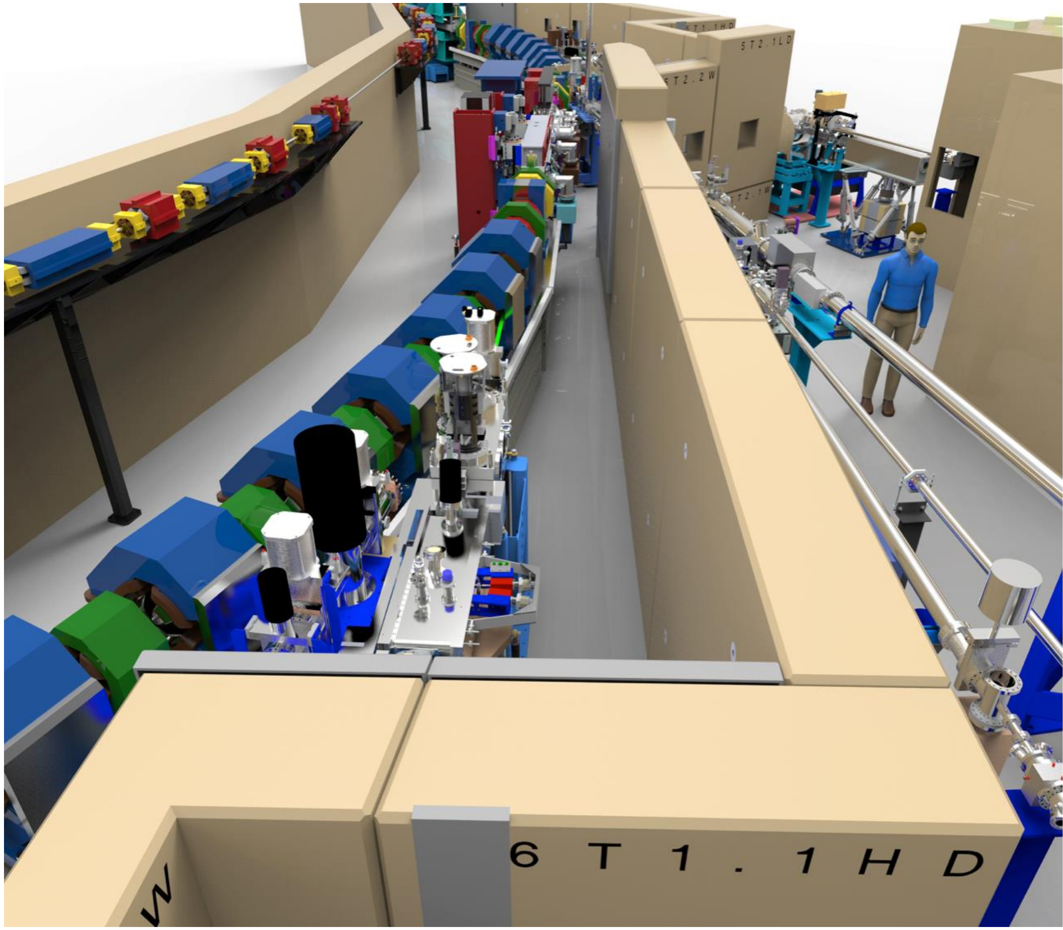
Coherent Fraction



Facility	Country	Status	Beam energy (GeV)	Coherent flux [10^{13} photons/(s×0.1% BW)] @ 60 eV (Li edge)	@ 284 eV (C edge)	@ 937 eV (Cu edge)	@ 2.47 keV (S edge)
ALS-U	US	Planning	2.0	690	710	420	88
SLS-2*	Switzerland	Planning	2.4	210	310	90	30
MAX IV	Sweden	Commissioning	3.0	26**	160	78	34
NSLS-II	US	Operating	3.0	21	140	39	10
APS-U	US	Design	6.0	N/A	30	14	28
Sirius	Brazil	Construction	3.0	80	95	12	21
ALS	US	Operating	1.9	17	11	1.0	0.05
APS	US	Operating	7.0	N/A	1.0	0.7	0.13
SPEAR3	US	Operating	3.0	2	1.7	0.3	0.30

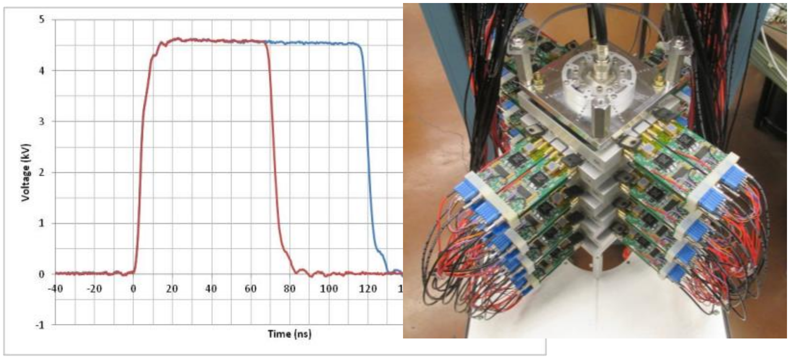
ALS-U Parameter Table

Beam energy	2 GeV
Emittance (horizontal/vertical)	~50 pm-rad
Circumference	~196.5 m
Tune (ν_x/ν_y)	41.38 / 20.39
Natural chromaticity (*x/y*)	-65 / -68
Momentum compaction factor	2.7×10^{-4}
Energy spread	8×10^{-4}
Damping time ($\zeta_x/\zeta_y/\zeta_l$)	8/15/13 ms
Twiss parameters and beam size	
Dipole bending angle	3.3333°
Straight-section length	5.25 m
β_x / β_y / η_x / η_y at insertion-device	≲3 / ≲3 / 0 /
Beam size at insertion-device	≲10 μm
β_x / β_y / η_x / η_y at bend source point	0.5 / 1.5 /
Beam size at bend source point (σ_x	≲5 / ≲8 μm
RF parameter	
Energy loss per turn (bare lattice)	182 keV
Energy loss per turn (with insertion	275 keV
Beam current	500 mA
Main RF frequency	500 MHz
Harmonic number	328
Natural bunch length σ_z (no potential-well distortion, no IBS, no harmonic cavities)	11 ps
Synchrotron tune (without harmonic cavities)	0.002
Bunch-lengthening factor	4–6
Main RF cavity	
Number of cavities	1
Shunt impedance	9 MΩ
Maximum voltage	≲0.75 MV
Third-harmonic cavity	
Technology	Normal
Operation mode	Passive
Number of cavities	3
Quality factor (*Q*)	21,000
R/Q	30



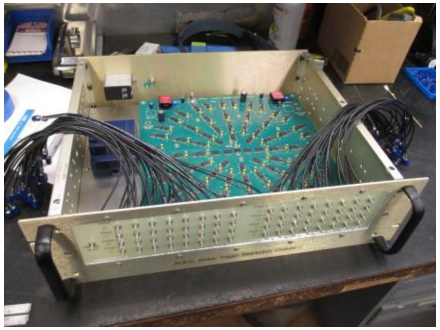
Example of ALS-U R+D: Injection

Inductive adder design, assembly, test



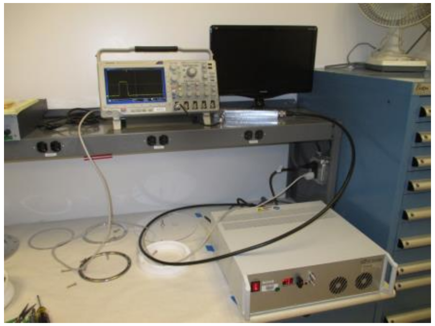
Full adder **tested above nominal voltage**, working on further rise time improvements

Pulser Timing + Synchronization



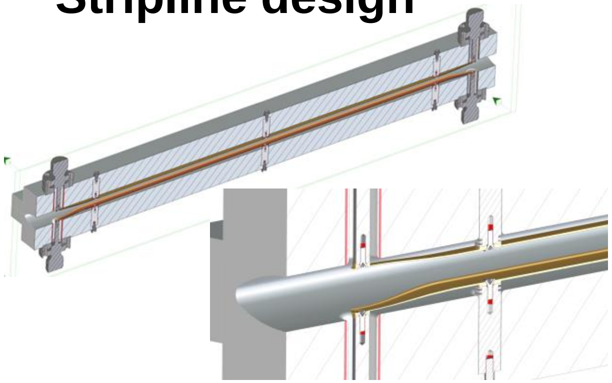
Trigger distribution tested, working on PLC controlled version

Commercial alternative



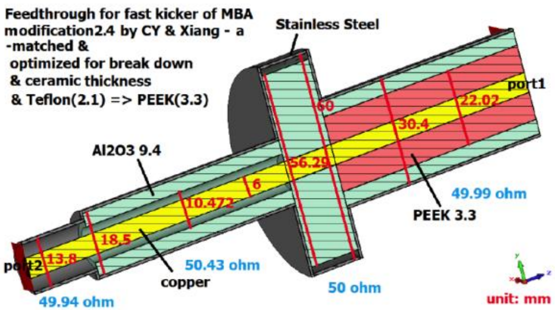
Evaluated capabilities of Industry – viable fallback solution

Stripline design



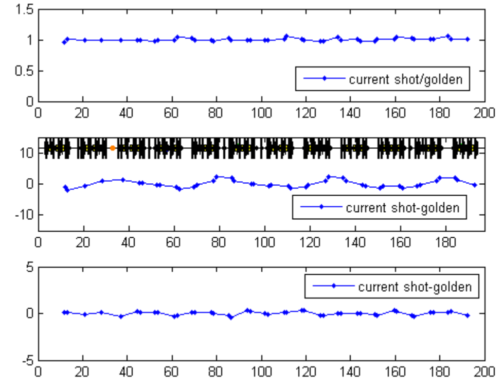
Prototype design finished (ALS),
Optimized for small beam impedance
Started Production

HV Feedthroughs



Working on improved solution compared to ones used at ALS (working with APS, industry)

Accelerator Physics



Developing+testing tools for beam based correction algorithms