



Injection Kicker and Pulser Development for ALS-U

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U.S. DEPARTMENT OF
ENERGY

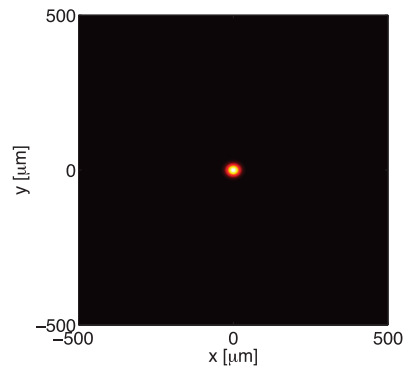
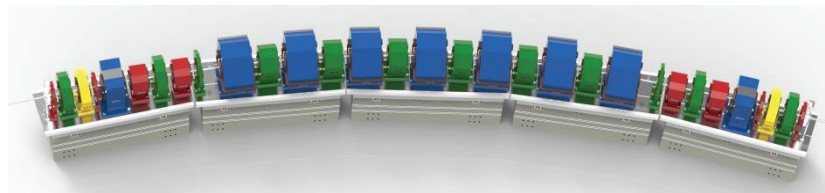
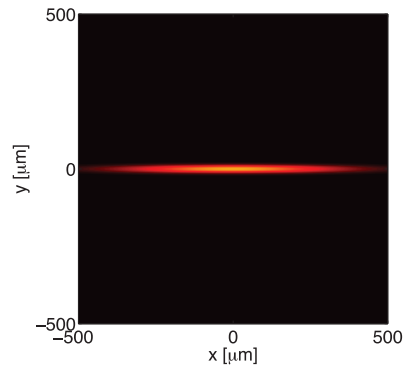
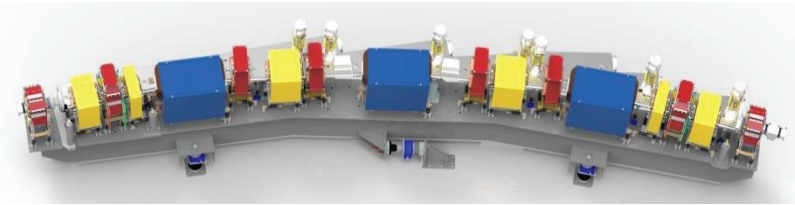
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Outline

- ALS-U overview
- On-axis swap-out injection
- Stripline kicker and pulser designs
 - with some discussion of the state-of-the-art
- Beam tests in the ALS storage ring
- Continuing R&D activities
- Conclusion

ALS to ALS-U

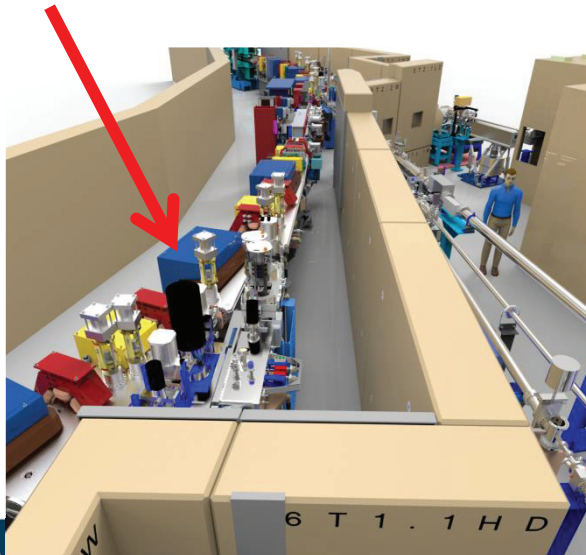


Parameter	Units	ALS	ALS-U
Electron energy	GeV	1.9	2.0
Beam current	mA	500	500
Horiz. emittance	pm-rad	2000	<75
Vert. emittance	pm-rad	30	<75
Beamsize @ ID center (σ_x/σ_y)	μm	251 / 9	<14 / <14
Beamsize @ bend (σ_x/σ_y)	μm	40 / 7	<7 / <10
bunch length (FWHM)	ps	60-70 (harmonic cavity)	120-200 (harmonic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

Scope of the ALS Upgrade (ALS-U)

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.

Existing ALS storage ring

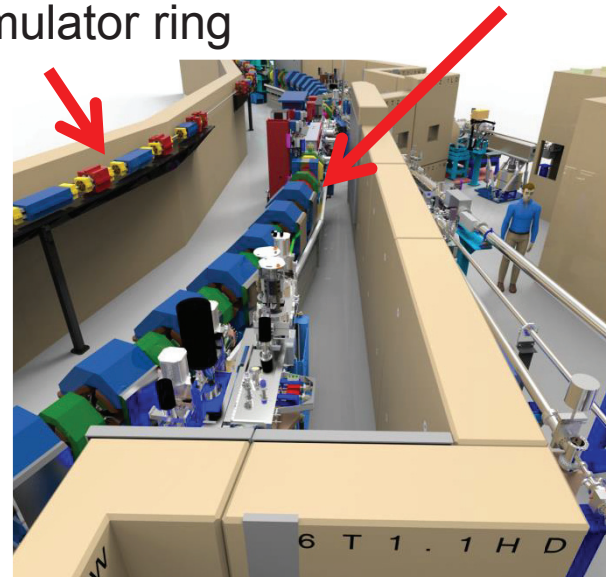


Single bunch top-off injection

New accumulator ring



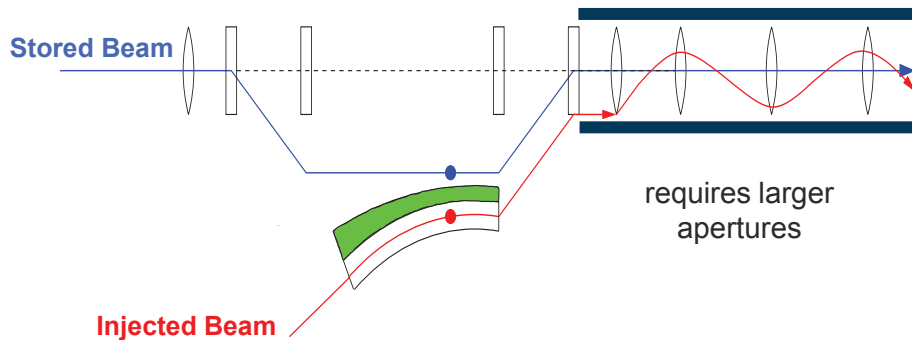
New storage ring



Swap-out injection

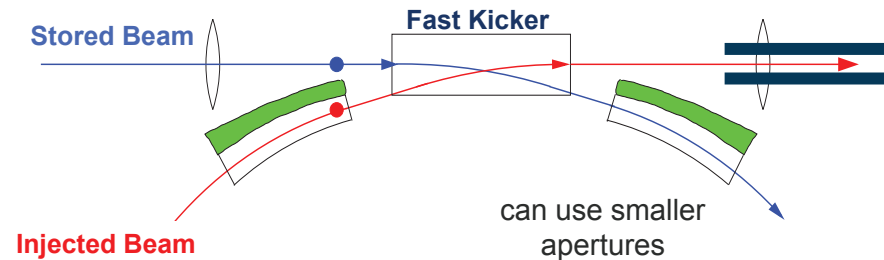
On-axis swap-out injection

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

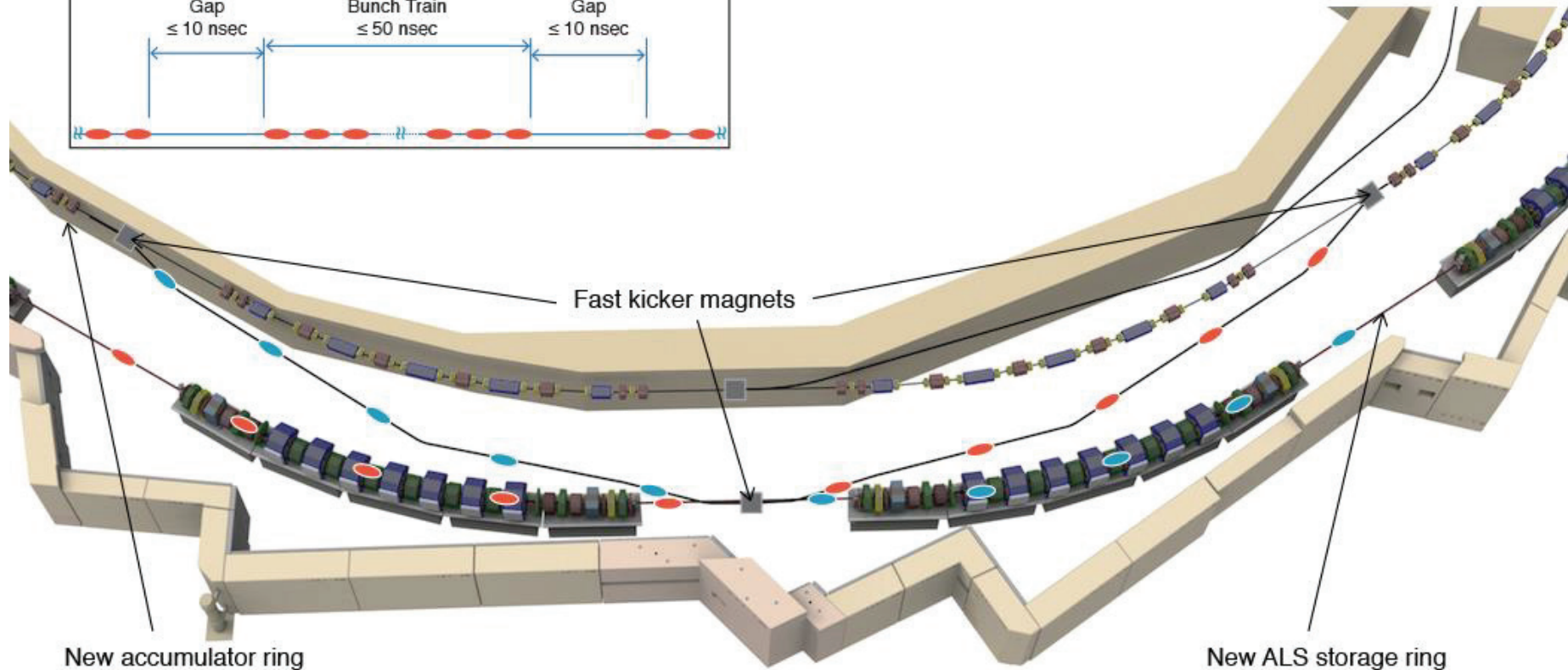
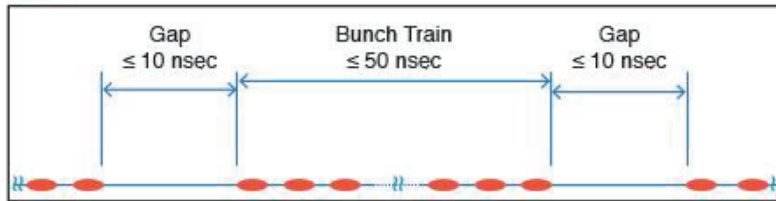
Swap-out with full energy accumulator enables:

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

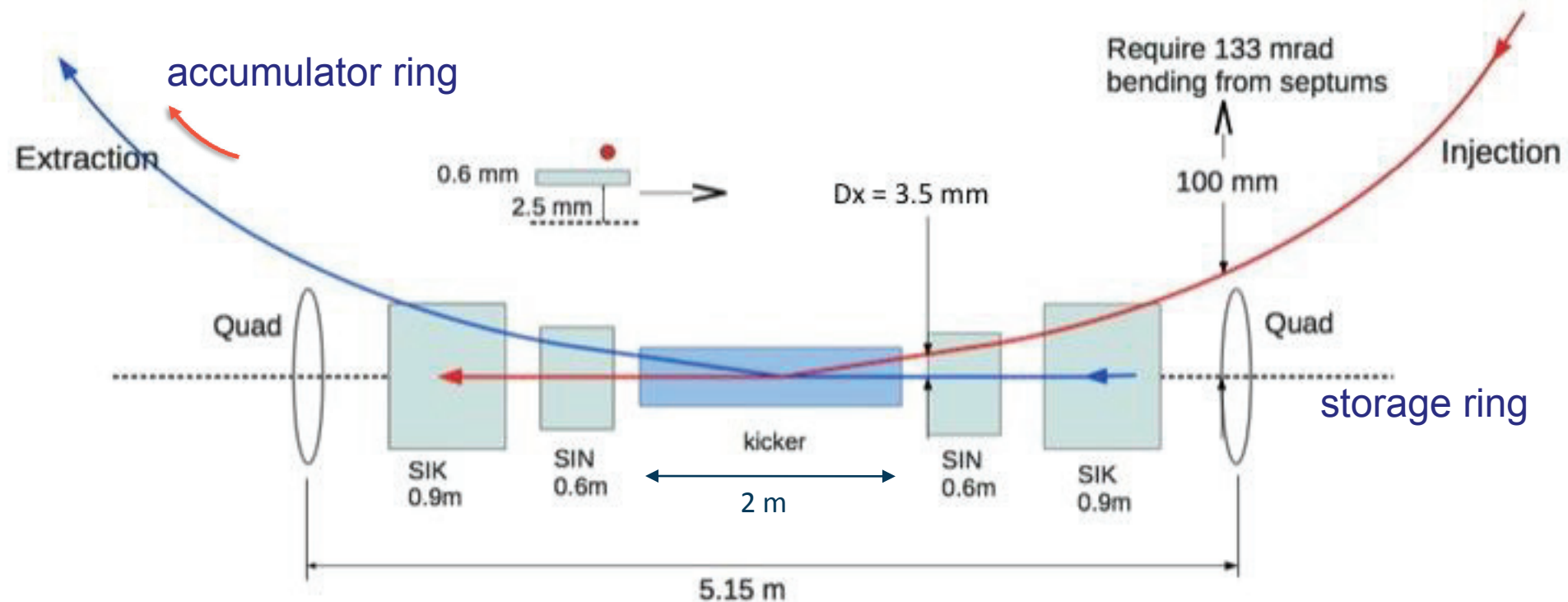
Swapping accumulator and storage ring bunch trains using fast kicker magnets

● Storage-ring bunches transferred to accumulator

● Accumulator bunches transferred to storage ring



ALS-U kicker requirements (storage ring)



ALS-U Beam: 11 trains of 25/26 bunches. Gap Length: 10 ns

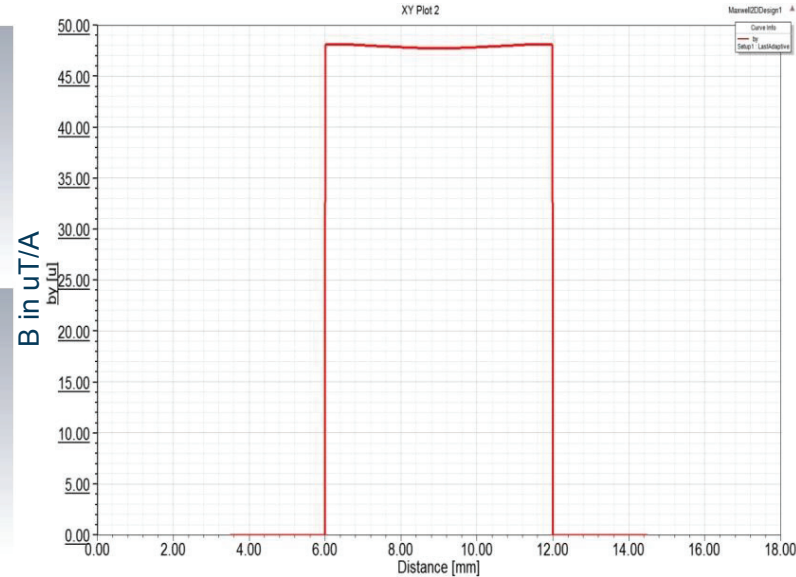
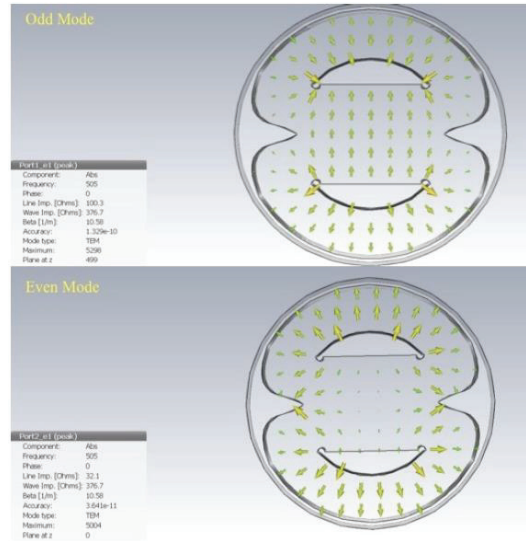
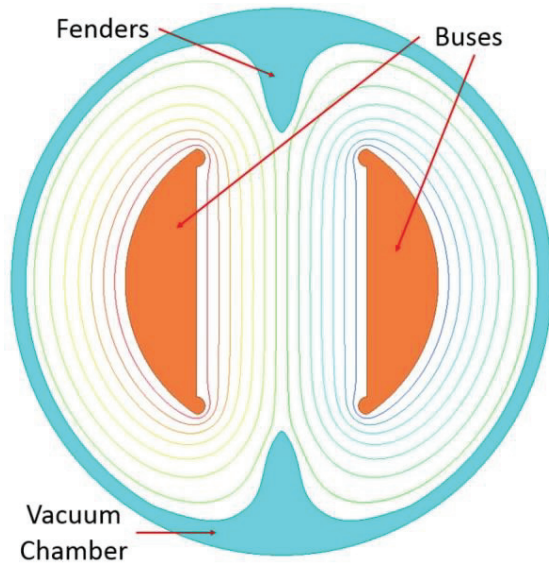
Bend Angle: 3.5 mrad
Total Kicker Length: 2 m
No. of Modules: 4
Electrode spacing: 6 mm

Rise/Fall Time: ≤ 10 ns
Pulse Width: 50 ns
Repetition Period: ~ 30 s

Fast kicker magnet technology

- Ferrite-loaded kickers are too slow unless broken up into an unreasonably large number of individually driven sections
- Stripline kickers can meet the requirements and advanced designs have been and are being developed for many applications (ILC, CLIC, APS-U, HEPS, ALS-U, LCLS-II,)
 - Impedance optimization (fenders, tapering, etc.)
 - Feedthroughs (HV, impedance)
 - Vacuum pumping
 - Thermal management
 - Fabrication techniques
- See TWISS Workshop 2017, Berlin

2D modeling of conceptual ALS-U stripline kicker

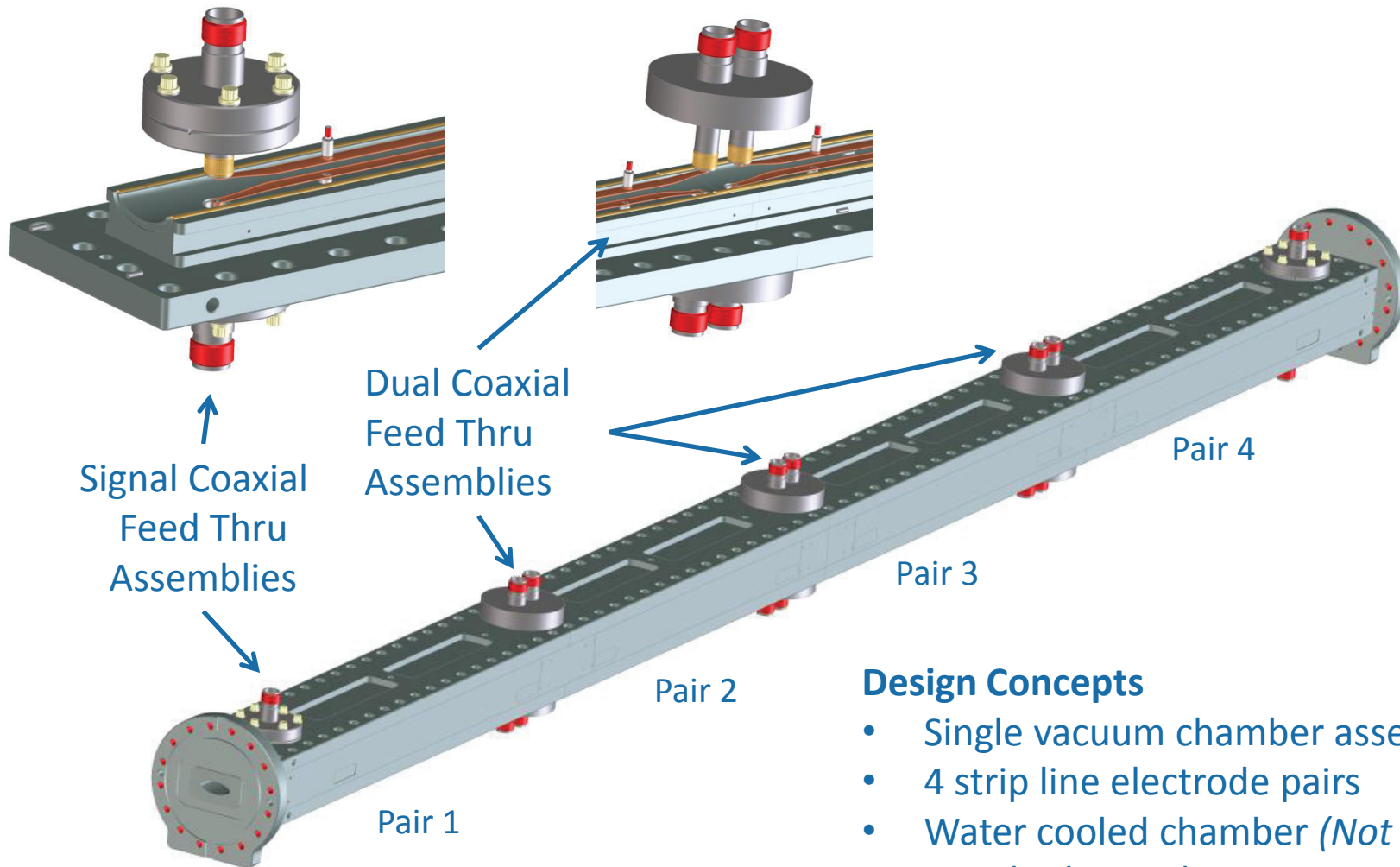


The fenders reduce the impedance mismatch between the even and odd modes

Characteristic impedances are
 $Z_{\text{odd}} = 50$ ohms and
 $Z_{\text{even}} = 64$ ohms

B field flatness
between the buses
(6mm separation)

Conceptual ALS-U kicker assembly design (note the elliptical chamber shown will actually be a round chamber)

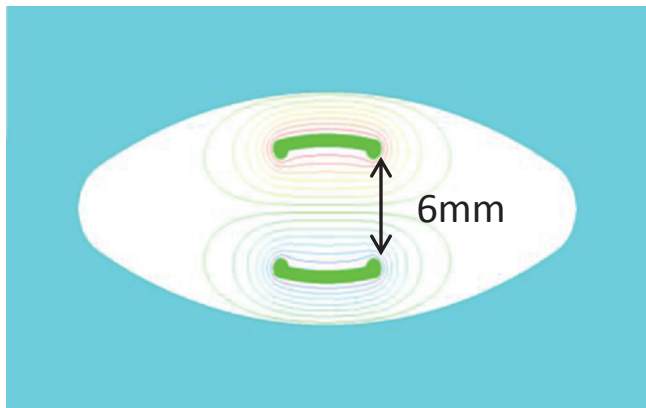


Design Concepts

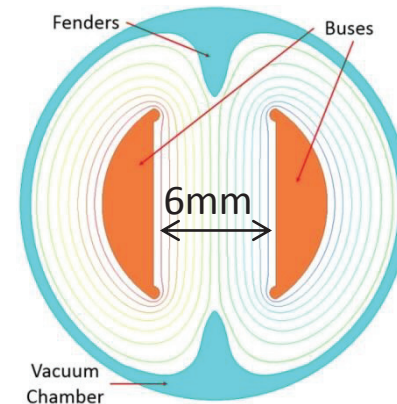
- Single vacuum chamber assembly
- 4 strip line electrode pairs
- Water cooled chamber (*Not shown*)
- Matched impedance structure
- Precision assembly

Prototype kicker design vs. ALS-U design

- The large ALS beam in the horizontal plane influenced the vacuum housing and electrode design for the prototype kicker
- “fenders” will be used in the ALS-U design to reduce the impedance mismatch between the even and odd modes
- Packaging details will be optimized for ALS-U as a result of the cylindrical geometry, limited space (space between striplines, number of striplines per vacuum chamber, etc.)



Prototype at ALS

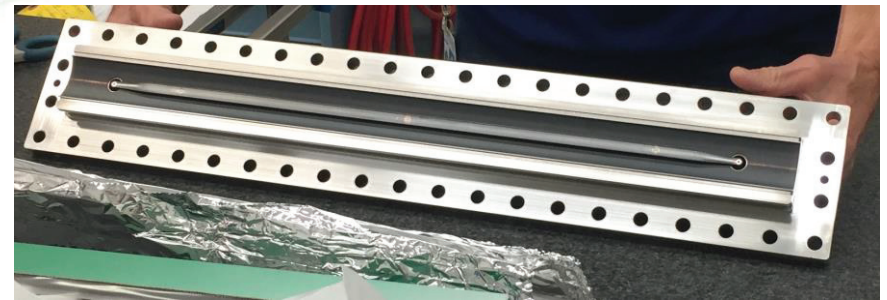
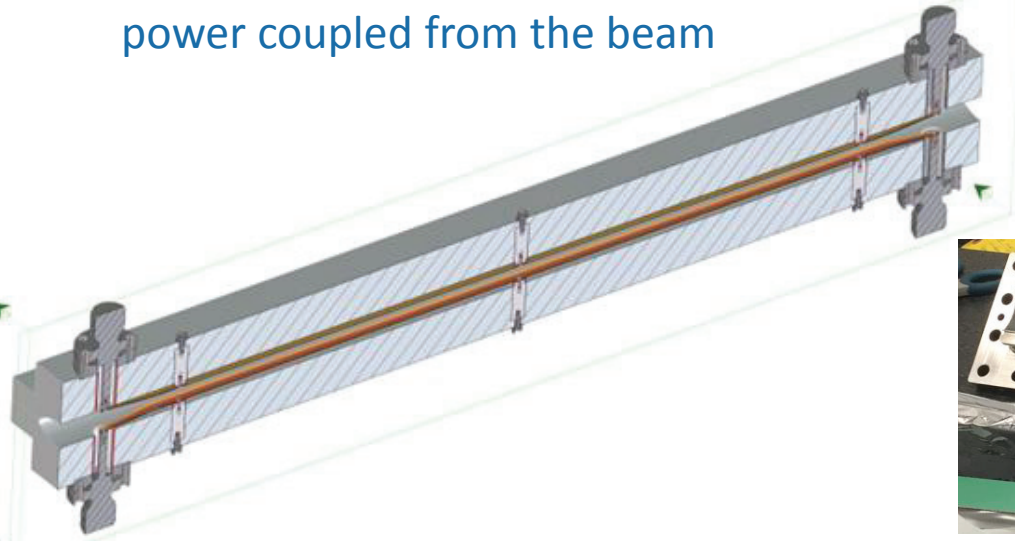


ALS-U (preliminary)

A stripline kicker design based on ALS-U parameters has been adapted for installation at ALS

- 50 ohm copper striplines supported by Macor posts and commercial HN feedthroughs
- High-emissivity (~ 0.6) sub-micron cupric oxide coating on chamber and electrodes to reduce temperature rise as a result of power coupled from the beam

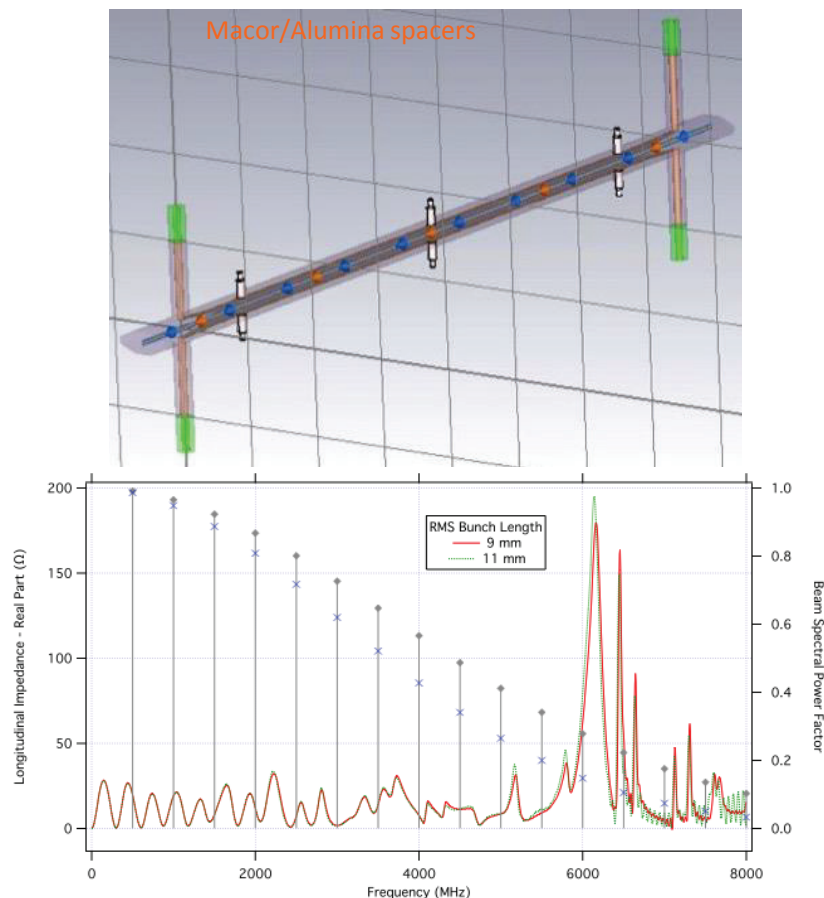
Beam Energy	2 GeV
Bend Angle	3.5 mrad
Distance Between Electrodes	6 mm
Total Magnet Length (4 modules)	2 m
Stripline Length	0.5 m
Stripline Impedance	50 ohms



1 half of a disassembled kicker

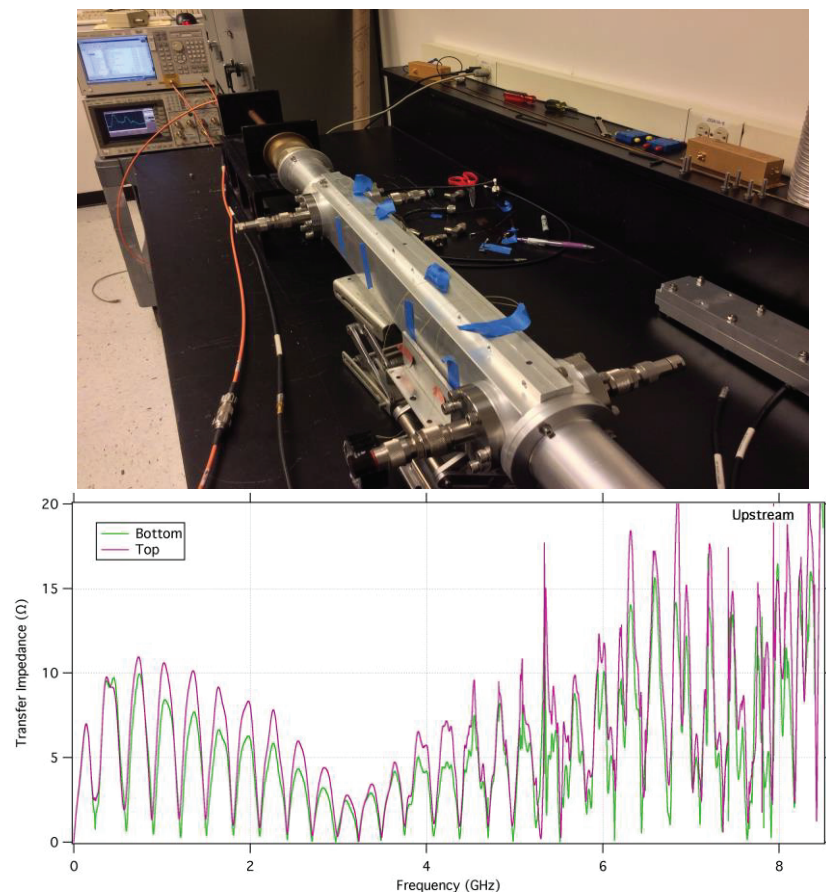
3D modeling of the stripline kicker and bench testing of the cold model

CST Particle Studio Simulations



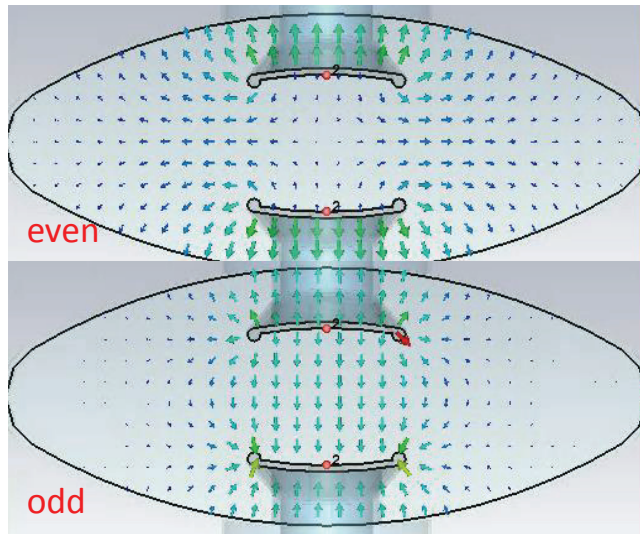
Longitudinal impedance, deposited beam power

Bench measurements on cold test model

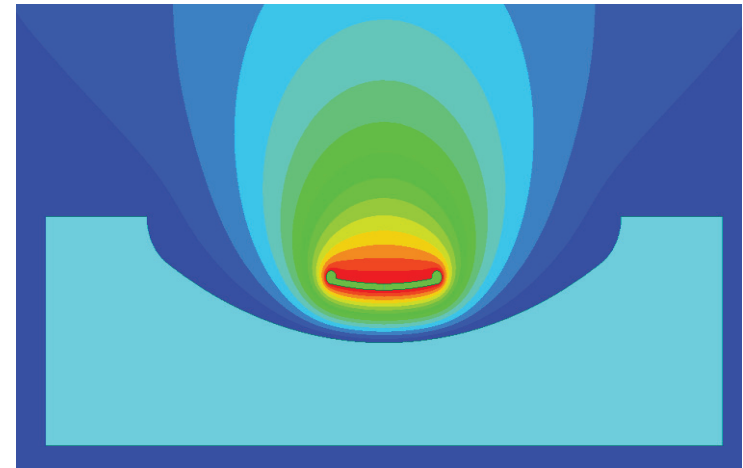


Pick-up impedance

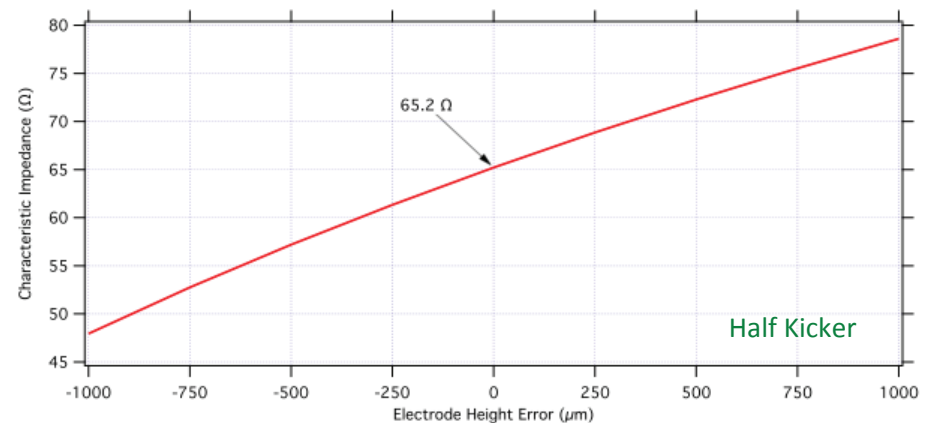
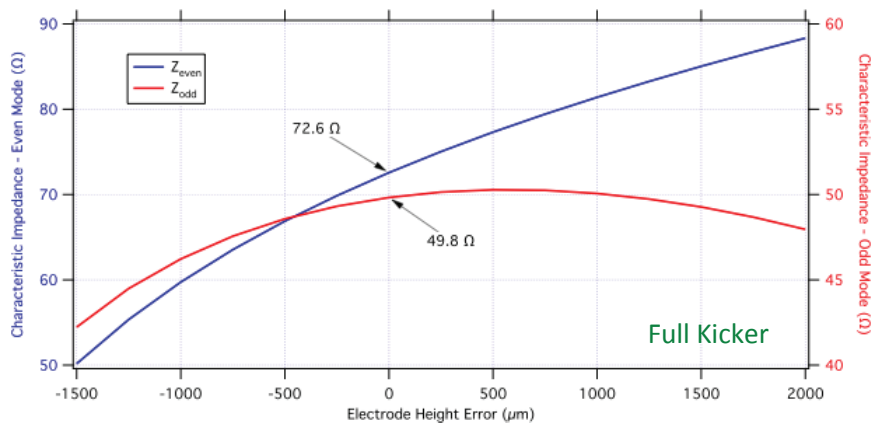
Characteristic impedance values for half and fully assembled kicker



CST MICROWAVE STUDIO

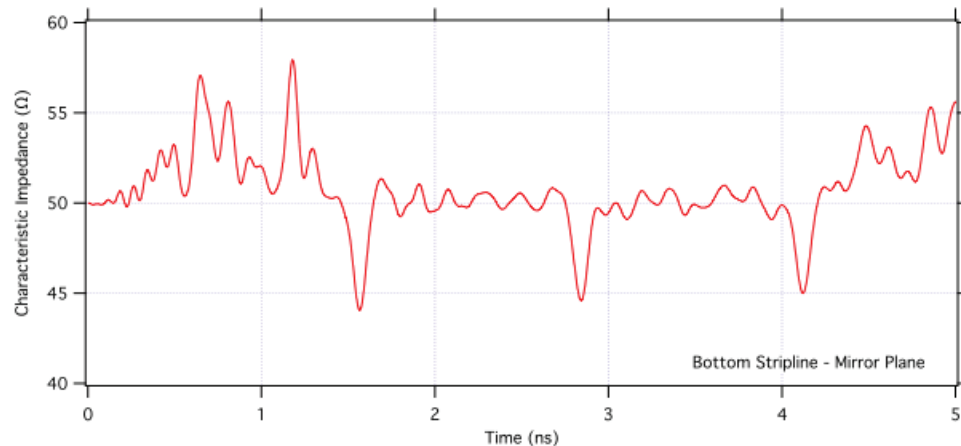
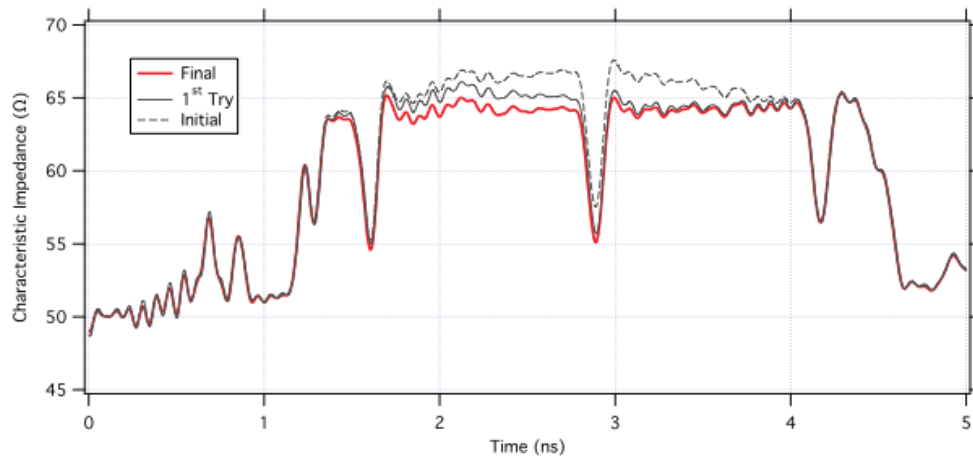


ANSYS MAXWELL

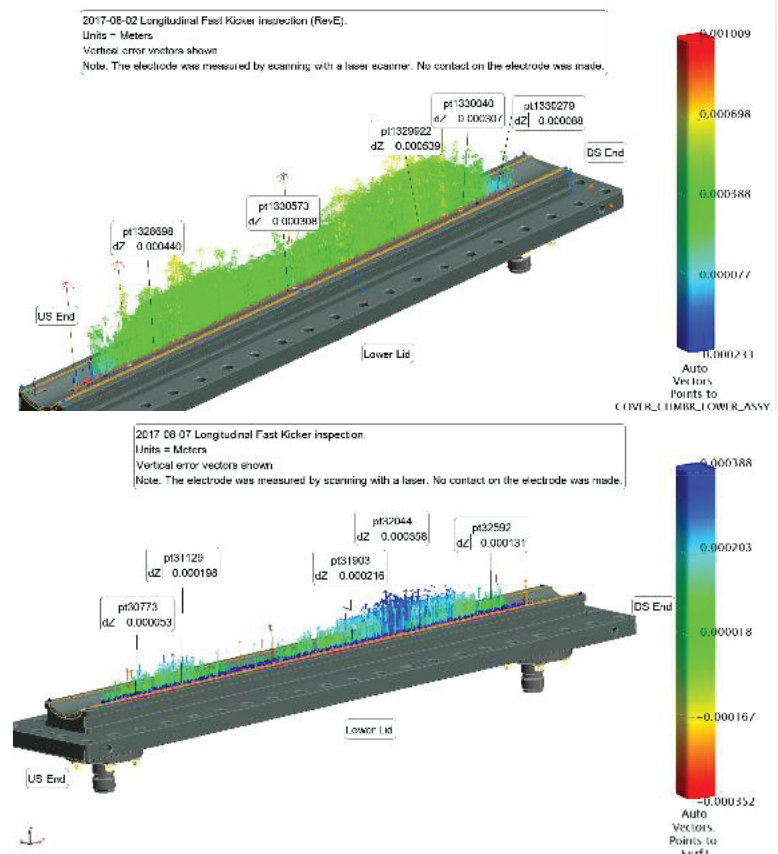


Characteristic impedance highly sensitive of electrode position

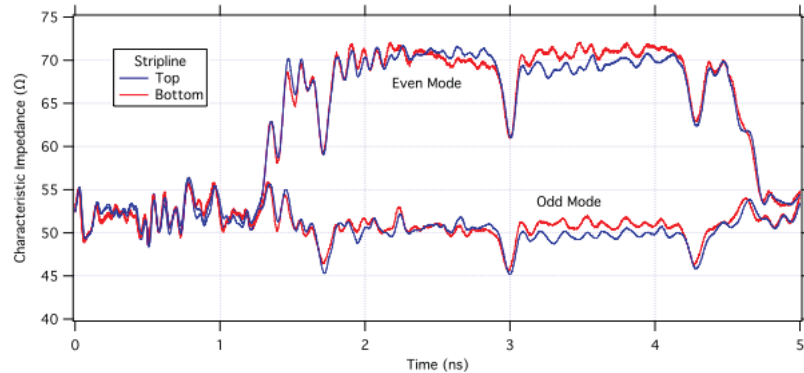
TDR measurements (kicker halves)



Stripline height can more easily be corrected in an open half kicker. TDR measurements (left), supplemented by laser scans (below), are used to reach the desired alignment.



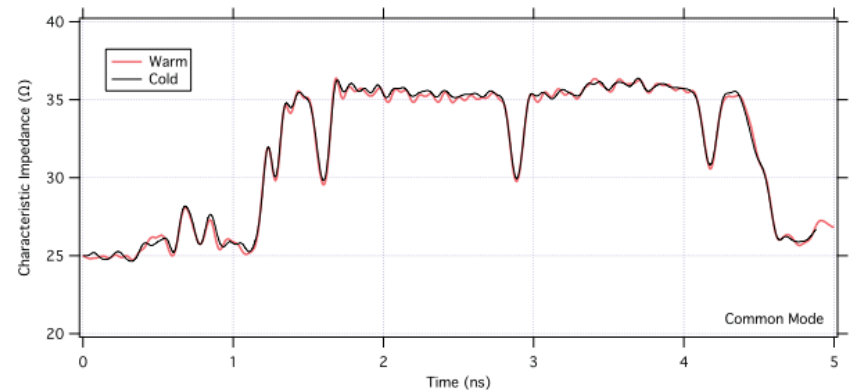
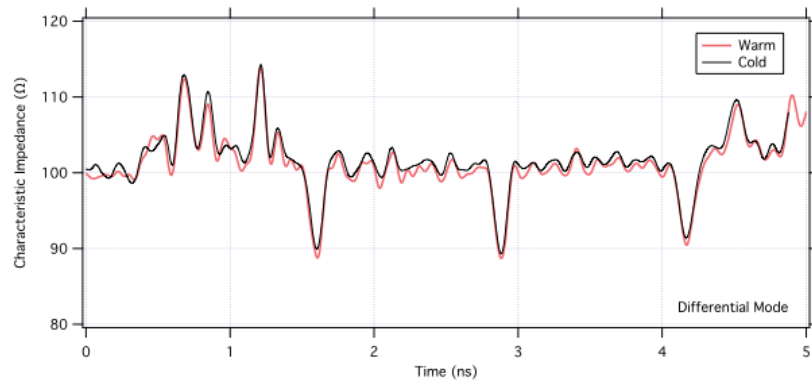
TDR measurements (full assembly)



After the kicker is fully assembled, we can measure even and odd mode impedances along the striplines (left). Measurements below show measurements of differential and common mode impedances after final assembly and during initial baking at 70 °C. Z_{diff} and Z_{comm} can be measured directly with a 2-channel TDR and are linked to the impedance of the individual striplines by:

$$Z_{diff} = Z_{odd1} + Z_{odd2}$$

$$Z_{comm} = Z_{even1}Z_{even2} / (Z_{even1} + Z_{even2})$$



Fast HV pulser technology

- MOSFET arrays
 - Behlke
 - Diversified Technologies (DTI)
- MOSFET-switched inductive voltage adders and transmission line adders
 - LLNL, LBNL, SLAC, UR/LLE, CERN, DTI, Sydor/Kentech, HEPS, ...
- Drift step recovery diodes and fast ionization devices
 - FID GmbH, Megaimpulse
 - SLAC/Ioffe/DTI (A. Krasnykh, FEL2017, TWIIS2017)
- Nonlinear transmission lines (electromagnetic shocklines)
 - SLAC (A. Krasnykh, FEL2017, TWIIS2017)

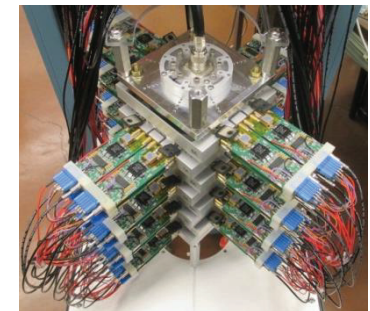
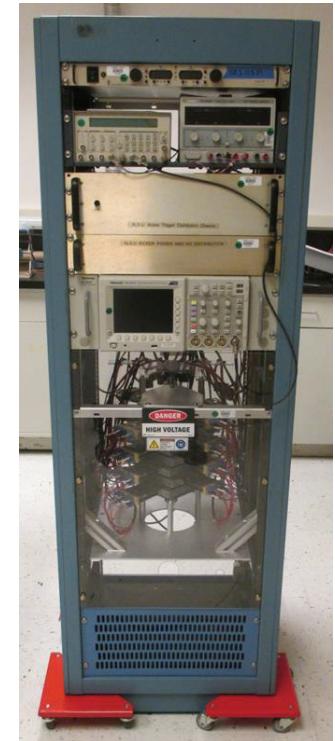
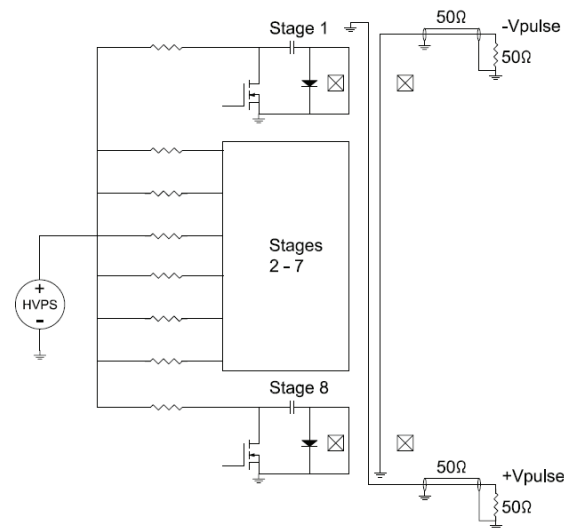
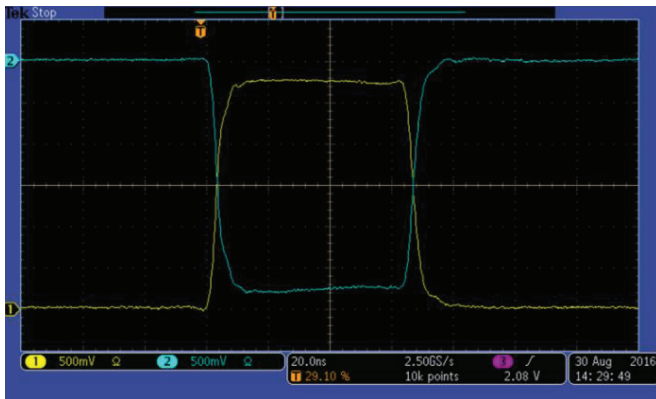
Experience with commercial HV pulser vendors has been good, but this is still a backup solution

- Several companies can likely meet or exceed the ALS-U performance requirements...but proprietary information can limit the ability of operations staff to maintain and repair the pulsers.
- FID GmbH delivered a unipolar pulser with proprietary semiconductor devices. The output waveform easily met the requirements and was tested to 6.5M pulses which is the equivalent of 6 years of ALS operation.
- Diversified Technologies demonstrated a unipolar inductive voltage adder made from commercially available MOSFETs and although the demonstration system did not meet the waveform requirements, the design clearly had the potential to do so with modifications.
- Sydor/Kentech has provided preliminary design concepts with commercially available MOSFETs in proprietary architectures which look promising.

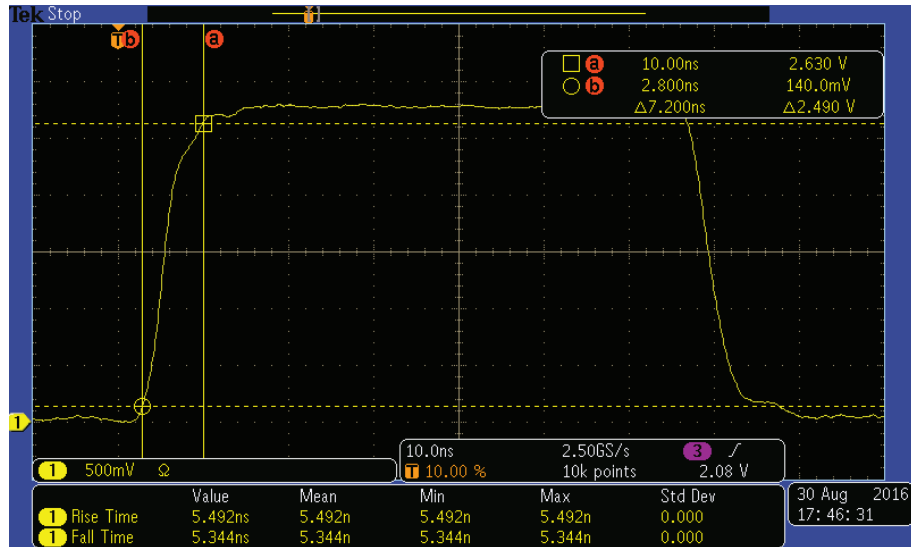
The stripline kicker pulser is based on a bipolar inductive voltage adder (IVA)

- Similar to systems at LLNL, SLAC, LLE, CERN, etc.
- MOSFET solid-state switches
- Adjustable pulsewidth
- Simplified timing synchronization
- Minimum number of pulsers
- Commercial options have been demonstrated as a backup solution

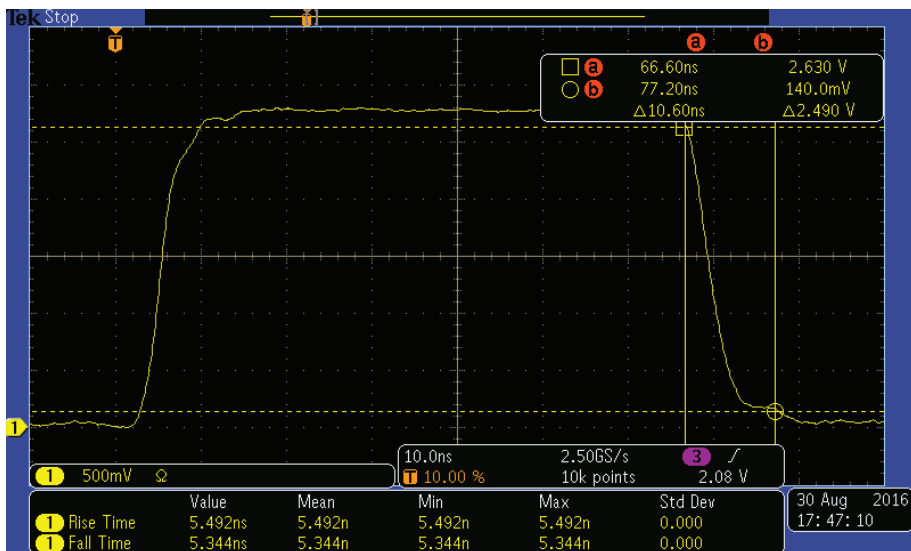
Load Impedance (2 parallel 50 ohms)	25 ohms
Stripline Voltage	+/- 5.25 kV
Stripline Current	+/- 105 A
Rise/Fall Time (5-95%)	7 ns
Flattop (95-95%)	50 ns
Flattop Ripple	+/- 1%
Repetition Rate	<0.1 Hz



Stripline kicker pulser voltage waveforms (5.5kV for Vch=750V)



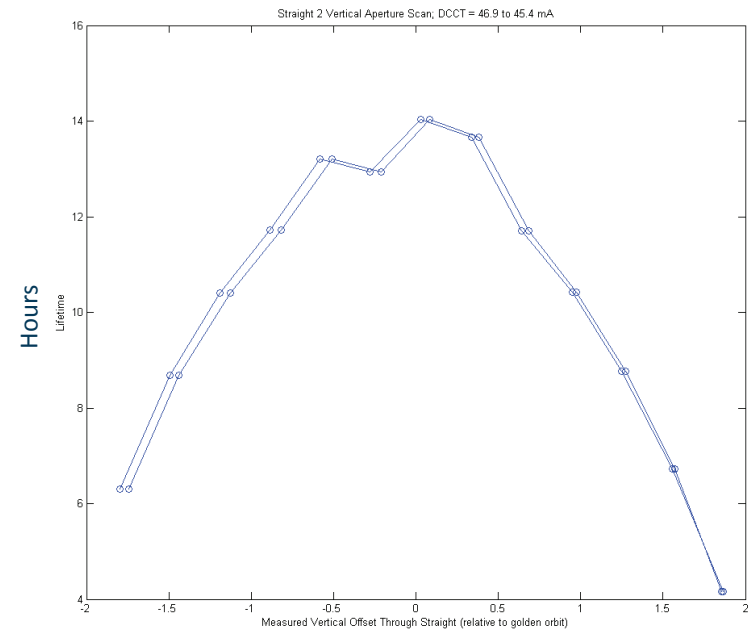
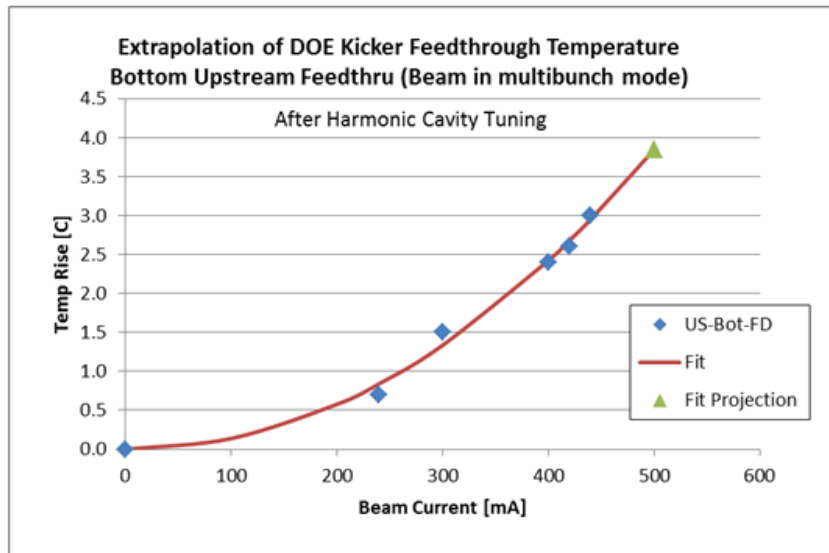
5-95% rise time = 7.2ns



95-5% fall time = 10.6ns

More work is required to understand the limitations and improve the fall time

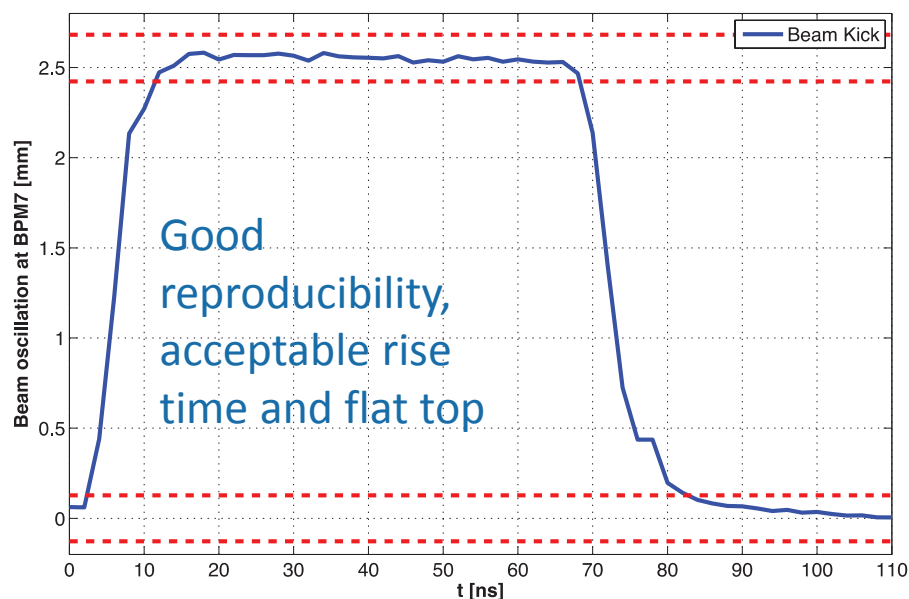
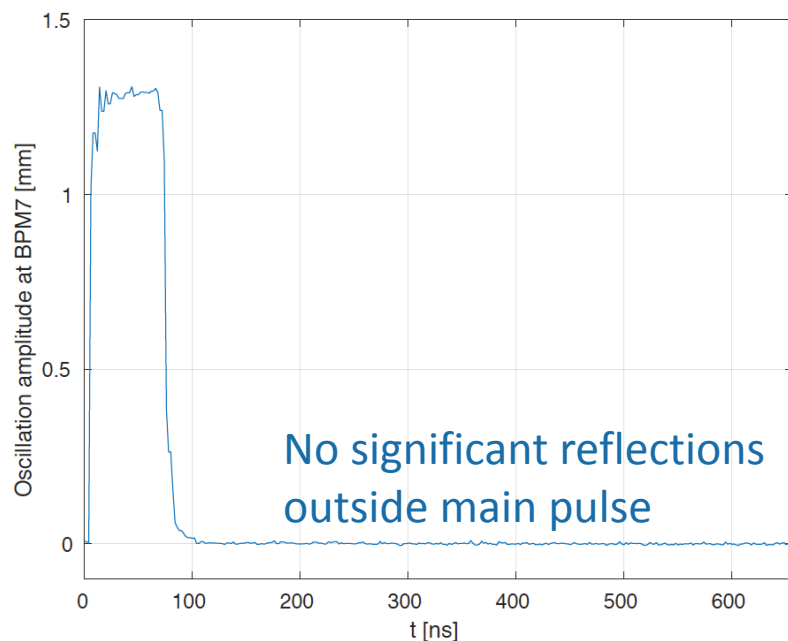
Initial checkout of system with beam at ALS: monitoring temperatures, aperture, and impedance



- Thermal management for normal operation works well, no excessive heating observed in chamber or feedthroughs (air-cooled)
- Alignment well centered, clear beam aperture
- No HOMs observed in signals from kickers
- No significant change in TMCI thresholds, potential well distortion

Beam deflection tests at ALS

- Kicker integrated with ALS timing system
- Tested at reduced ($\sim 50\%$) voltage to keep measurement time manageable (not kick out beam)
- Need to understand and improve the fall time



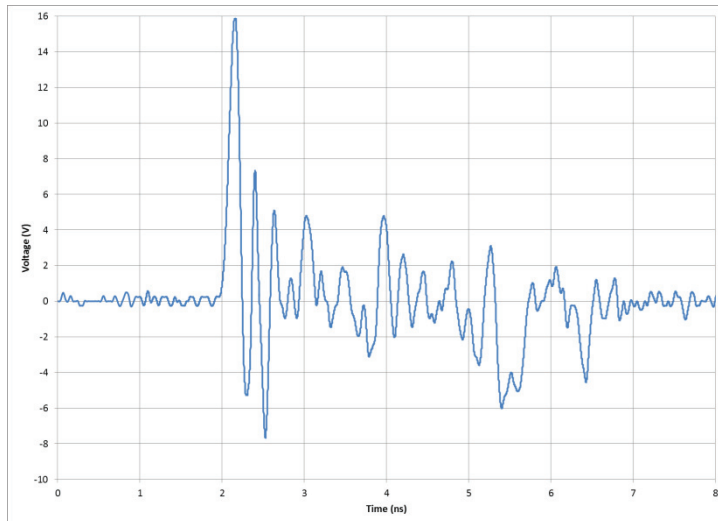
The kicker had to be removed and the electrode design had to be improved to accommodate a higher temperature rise

- TDR and beam-induced signal measurements confirmed that the kicker electrode design was acceptable for normal ALS beam conditions when there is bunch lengthening with a harmonic cavity
- When the harmonic cavity was detuned and the bunches were short, excessive power coupled to a kicker electrode and it deformed by $\sim 2\text{mm}$
- Modifications to reduce the impact of beam heating
 - Thicker electrodes and improved processing and handling
 - Expansion joints with larger range (from 0.22mm to 0.6mm)
 - Added diagnostics and interlocks
- Beam power loss (500mA) – into electrodes, chamber, cables, feedthroughs, and terminations (majority of power should be dissipated in the termination loads)
 - ALS without bunch lengthening: 243W (5mm RMS bunch length) – detailed model
 - ALS with bunch lengthening: 84W (9mm RMS bunch length) – detailed model
 - ALS-U with bunch lengthening: 28W (9mm RMS bunch length) – much simpler model, likely to be low

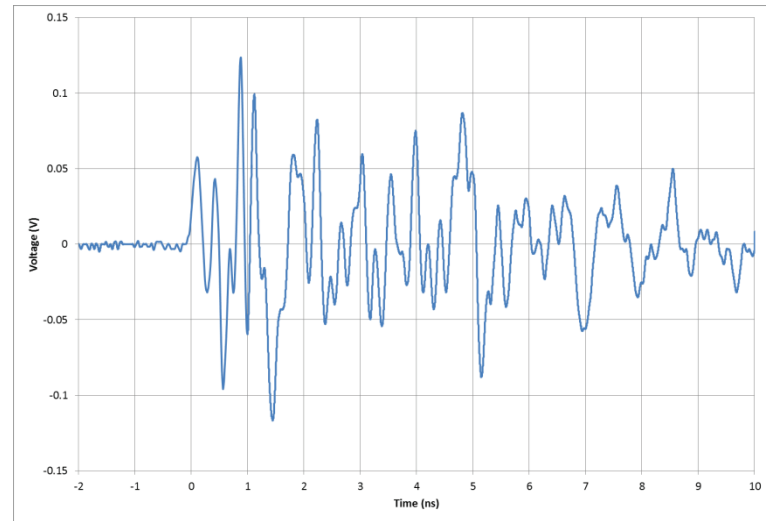


Testing at ALS in single bunch mode at 2mA with the pulser connected

- What are the amplitude of beam-induced signals that the pulser will see for 2mA single bunch mode?
 - 16V peak signals at the pulser-end of the drive cable when terminated into 50ohms
 - 120mV peak signals at a primary when pulser is connected (expected effect of secondary-to-primary coupling, core losses and permeability, MOSFET output capacitance, clamping diode capacitance, etc.)



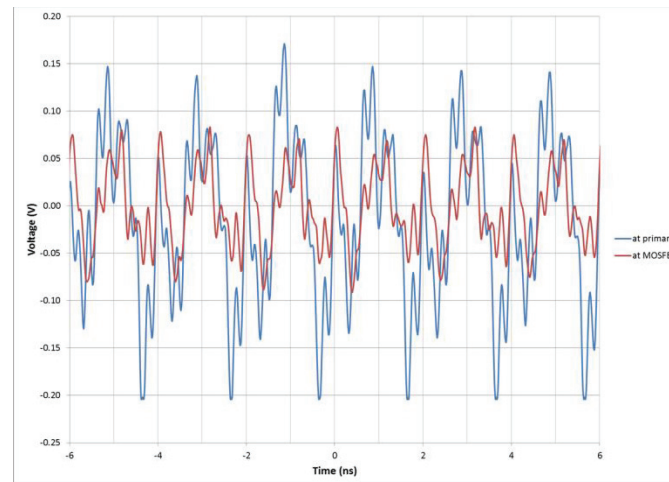
End of drive cable when pulser not connected



On a primary when pulser is connected

Testing at ALS in multibunch mode at 500mA with pulser connected

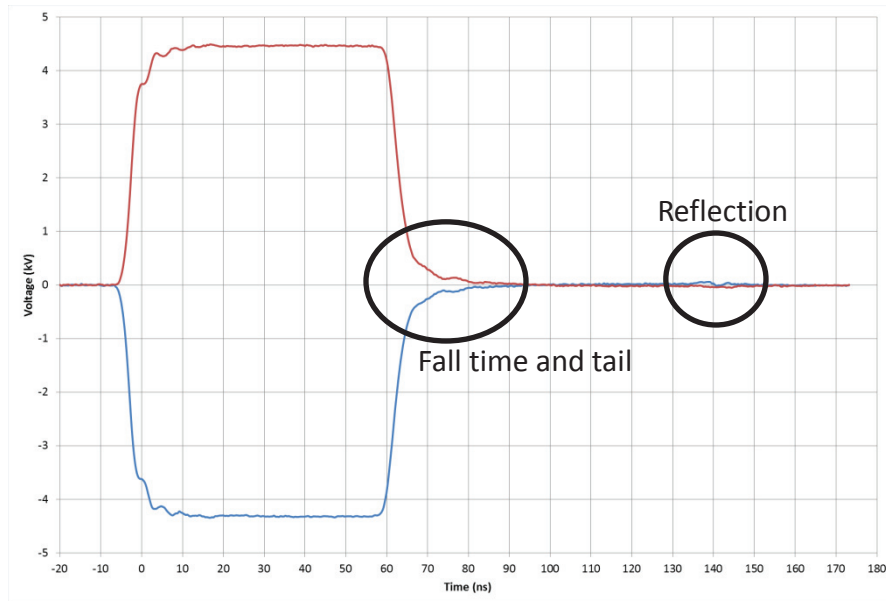
- Are the beam-induced signal levels in the stripline kicker electrodes high enough in peak voltage or average power to damage the kicker pulser?
 - Peak voltages on the primary and on the MOSFET vary depending on stage and MOSFET board and scope trigger timing, but are very low and insignificant ($\leq 200\text{mV}$ peak for 500mA multibunch mode)
 - No measurable temperature rise of any IVA components



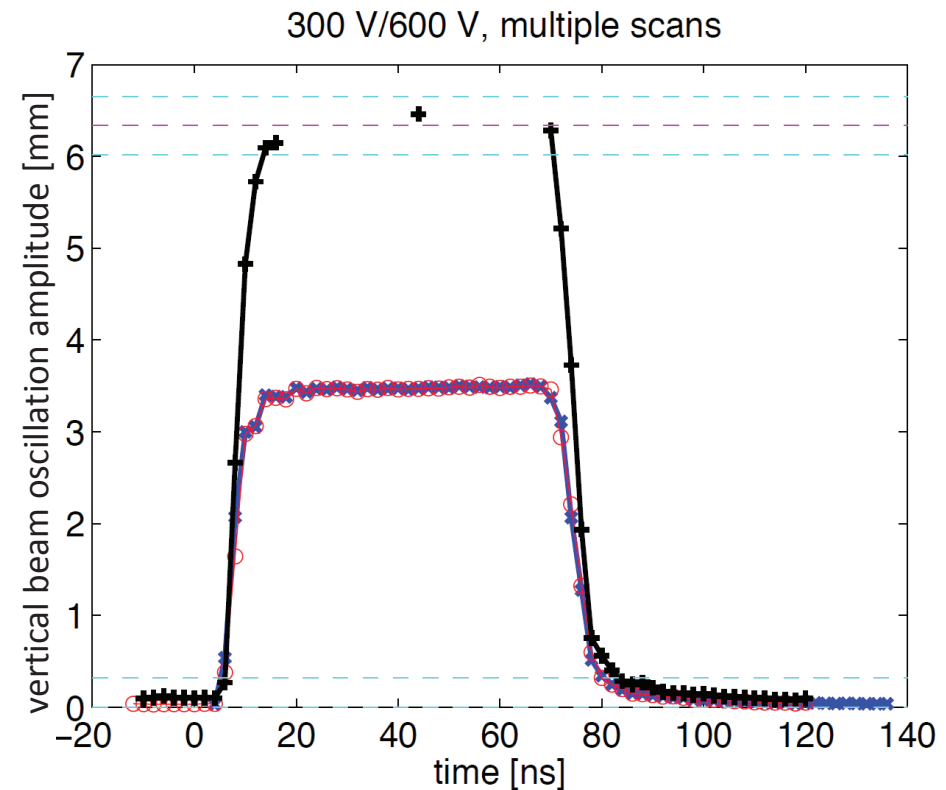
- Do we introduce any multibunch instabilities as a result of possible reflections at the pulser coming back through the kicker?
 - No additional measurable multibunch instabilities

Beam deflection tests at ALS

- Operated the pulser at $\sim 40\%$ and $\sim 80\%$ of ALS-U requirement
 - Characterized the long “tail” which is kicker pulser amplitude dependent
 - Some reflections seen from the termination
 - Some differences in attenuators for positive and negative pulses
 - Good repeatability



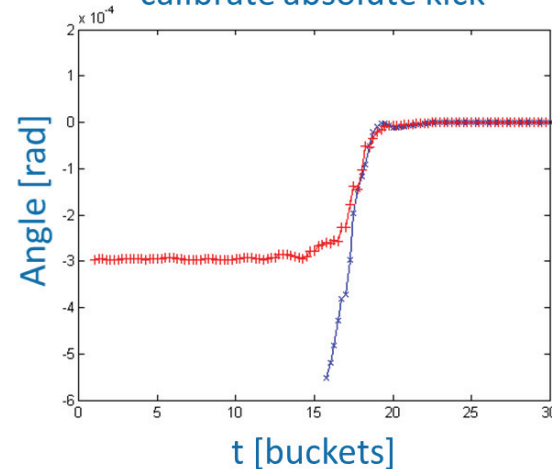
Pulser waveforms for 600V charge voltage



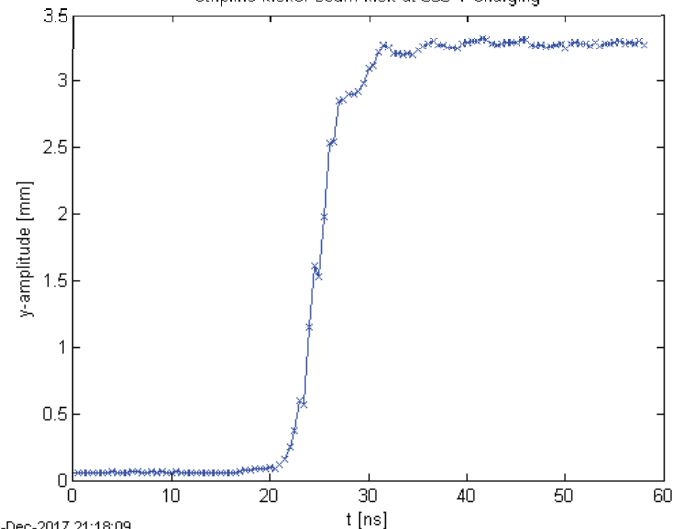
Latest results from testing with beam at ALS

- Mapped rising and falling slope for 2.3kV pulser output with 500ps resolution and used turn-by-turn BPM data to quantify the kick amplitude (within the error bars of our calculated deflection).
- ~200ps timing jitter and (thermal?) timing drift of similar magnitude were visible.
- Could see a low-level pre-pulse and the long tail which had been seen in previous tests.
- Also tested at 5kV pulser output (highest voltage so far with beam at ALS). Beam gets kicked out before aligning with the flat-top.

Use of 44 new BPMs to
calibrate absolute kick



stripline kicker beam kick at 300 V charging



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Various aspects of the design have been investigated with modeling and hardware tests

- 2D modeling
 - Stripline impedances
 - Peak electric fields (HV breakdown)
 - Electromagnetic fields (kick amplitude)
- 3D modeling
 - Feedthrough impedance
 - Tapered end effects
 - Effects of ceramic supports on impedance and losses
 - Simulated beam interaction
- Cold model testing
 - TDR measurements for detailed impedance analysis of actual hardware which includes real feedthroughs and fabrication tolerances
- System testing in ALS storage ring
 - High voltage operation
 - Thermal cycling
 - Vacuum performance
 - Deflection of beam
 - Power coupled from beam
 - Effects of cables and terminations
 - Diagnostics

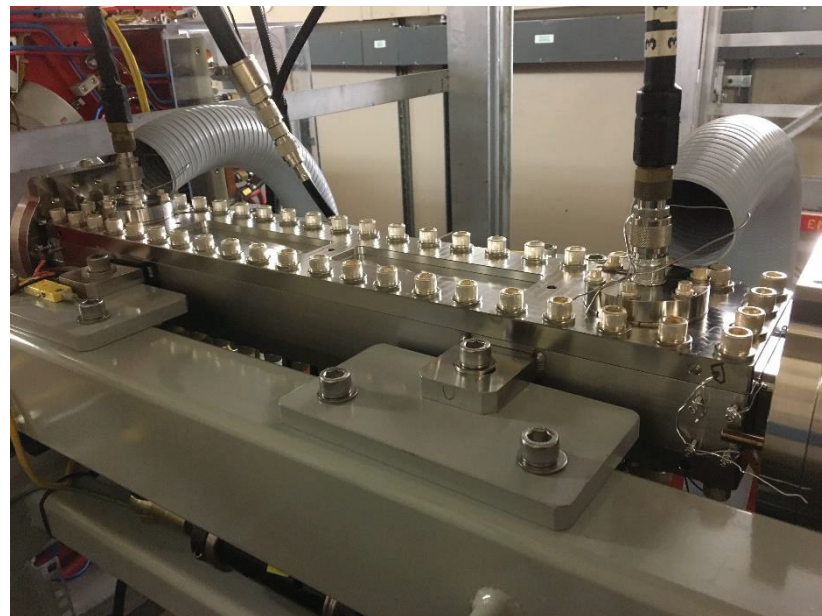
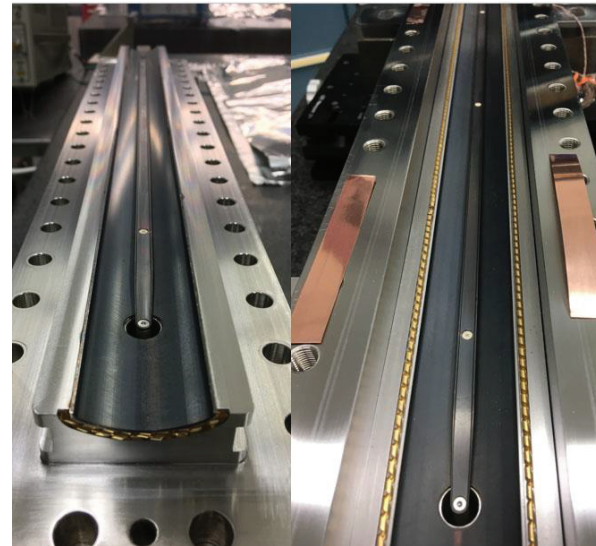
What we have learned from the prototype kicker effort:

- Commercial HV feedthroughs are acceptable (bandwidth)
- Benefits and process for building and diagnosing a cold model
- How to support electrodes with Macor posts and measure electrode position (laser scan, FaroArm) and alignment (shimming)
- RF measurements (TDR, Network Analyzer) to verify impedance at various stages of assembly
- Electrode and chamber coating process (high emissivity [~ 0.6] sub-micron cupric oxide with plasma sputtering)
- Beam-induced signal power is significant and must be managed (modifications to the kicker electrodes, implementing RF power interlock, custom terminations/attenuators, etc.)



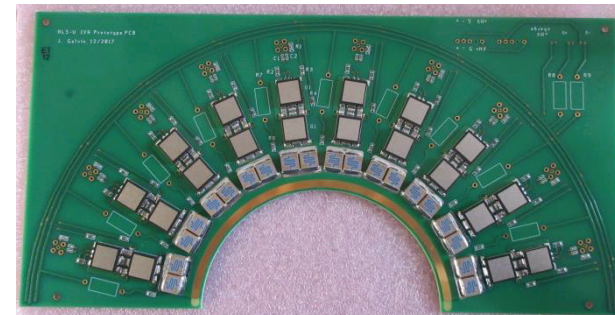
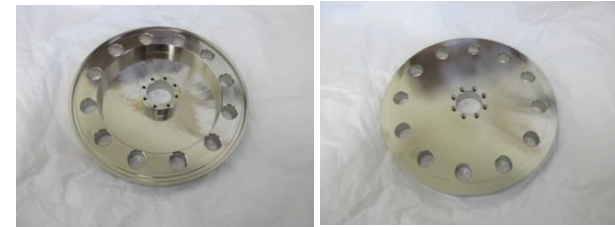
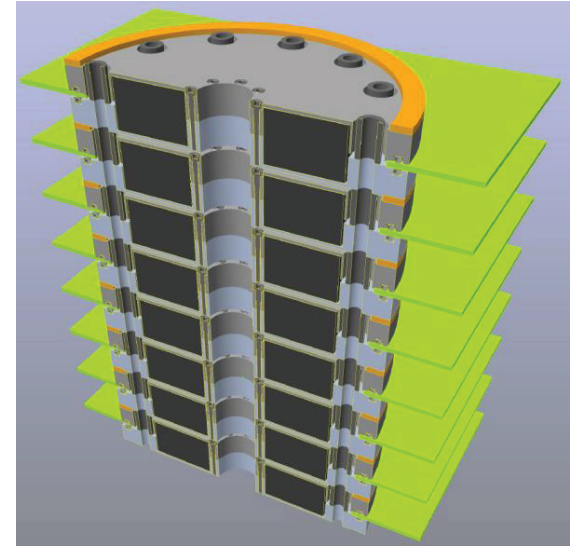
Continuing R&D on the stripline kicker

- Optimize packaging (number of magnets within a vacuum enclosure)
- RF modeling
- Coating development and thermal management
- Electrode fabrication and support
- Integration with injected beam (tolerance, offsets)



Continuing R&D on the pulser

- Understand the fall time details of the prototype system at ALS (pulser characteristics, reflections, etc.) with higher resolution beam deflection measurements, more TDR measurements, and configuration changes
- Understand the details of where beam-induced signal power is dissipated
- Improve the rise/fall time performance with a lower inductance design (components for next design iteration are being tested now)
- Develop a high voltage and high bandwidth termination that can dissipate the average power of the beam-induced signals (Custom Barth design is being tested now)
- Develop an RF power interlock on beam-induced signals that is compatible with the final system configuration (simultaneous signal monitoring and required interlock functionality)



Conclusion

- Stripline kickers and inductive voltage adders are key components to enable on-axis swap-out injection in the ALS-U conceptual design.
- A demonstration system was installed and tested successfully with beam in the ALS storage ring.
- R&D will continue to improve the following:
 - Rise/fall time of the inductive voltage adder
 - Average power handling of the kicker terminations
 - Interlock system to monitor power on the stripline electrodes
 - Kicker mechanical packaging and fabrication techniques
- The demonstration kicker which has been in the storage ring since August 2017 will remain for continued development of the external systems and for further physics studies.