Beam Commissioning of the ALS-U Test Kicker

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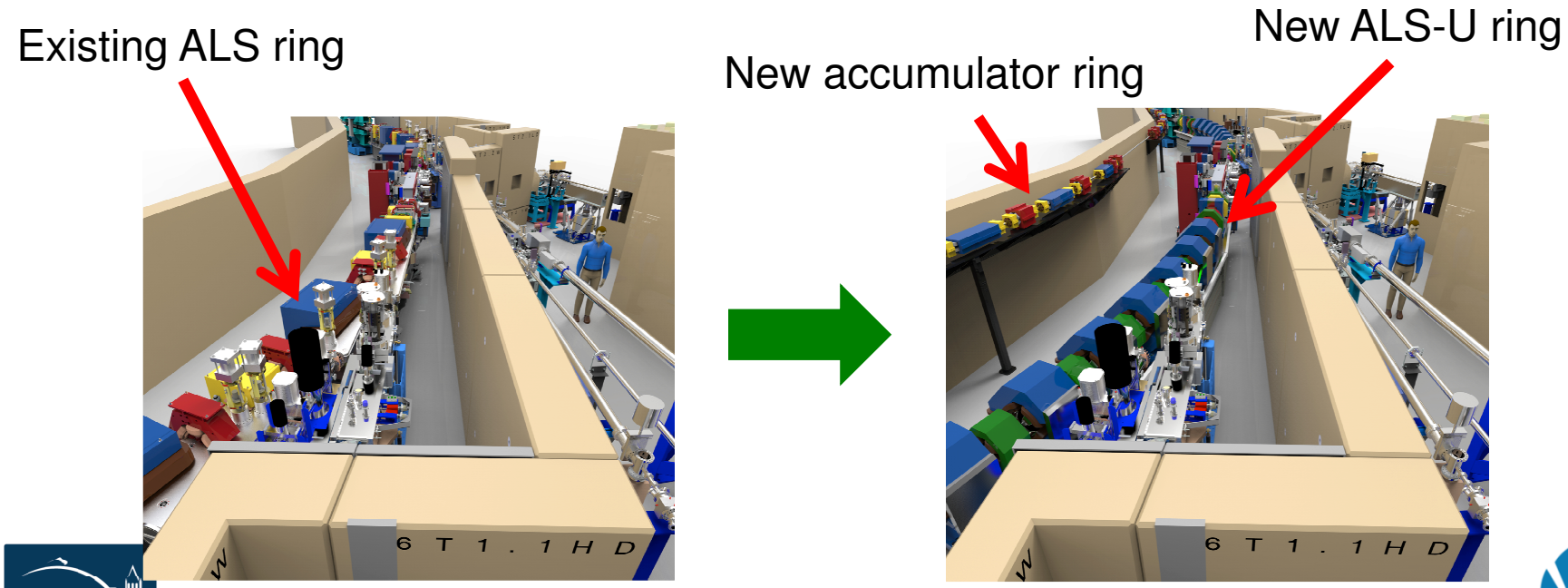
ALS-U ADVANCED LIGHT SOURCE

Outline

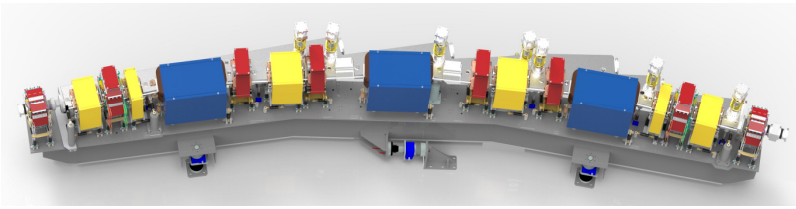
- Introduction: ALS-U Project and Swap-Out Injection.
- ALS-U Test Kicker at the ALS. Design and Motivation.
- Test Kicker Assembly and Bench Measurements.
- Test Kicker Operation With ALS Beam.

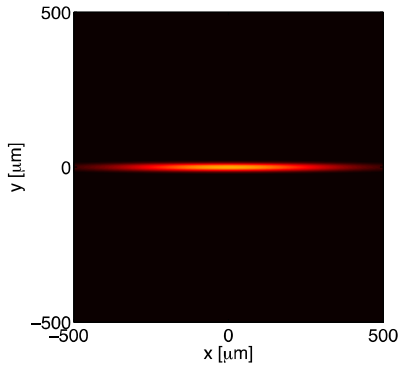
Scope of ALS Upgrade (ALS-U)

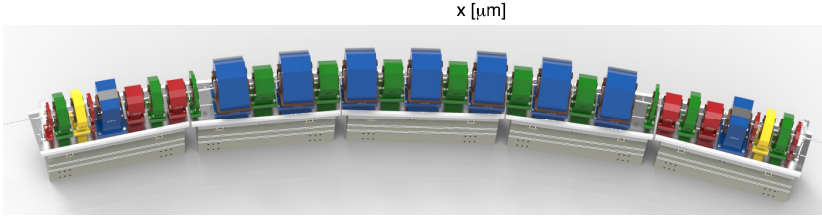
1. **Replacement** of the existing triple-bend achromat storage ring with a new, high-performance storage ring based on a multi-bend achromat.
2. **Addition** of a low-emittance, full-energy accumulator ring in the existing storage-ring tunnel to enable on-axis, swap-out injection using fast magnets.
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.

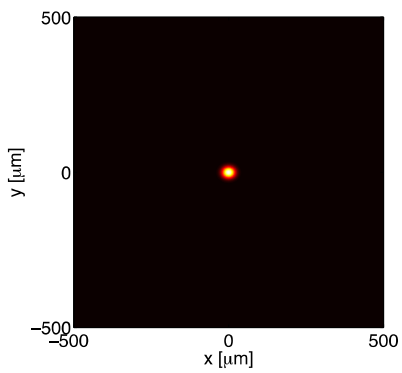


ALS and ALS-U in numbers









Parameter	Units	ALS	ALS-U
Electron energy	GeV	1.9	2.0
Horiz. emittance	pm	2000	<70 (stretch goal 50)
Vert. emittance	pm	30	<70 (stretch goal 50)
Beamsize @ ID center (σ_x/σ_y)	mm	251 / 9	<13 / <13
Beamsize @ bend (σ_x/σ_y)	mm	40 / 7	<5 / <7
bunch length (FWHM)	ps	60-70 (harmonic cavity)	100-200 (harmonic cavity)
RF frequency	MHz	500	500
Circumference	m	196.8	~196.5

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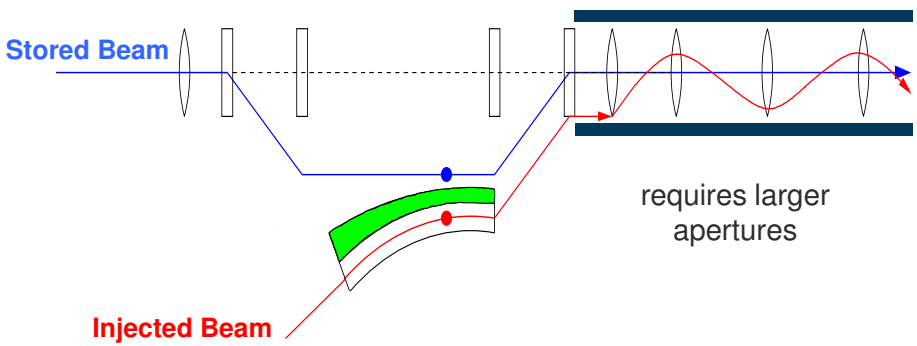
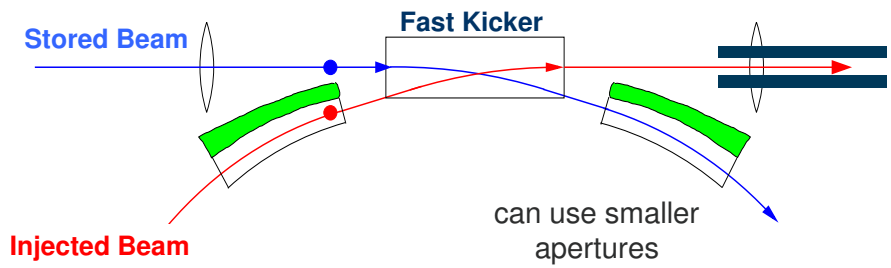
Background: Swap-out Injection

Traditional off-axis injection



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



Swap-out enables:

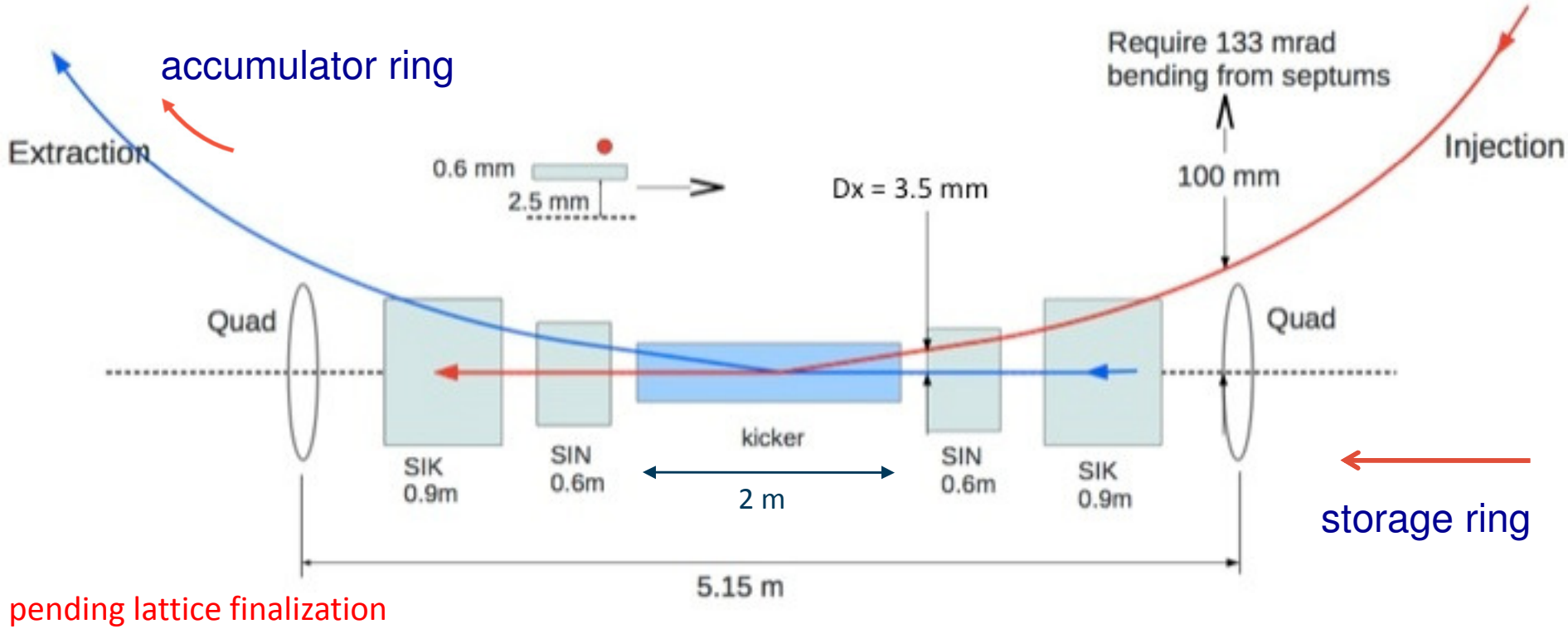
- Stronger-focusing MBA lattices with smaller dynamic apertures
- Round beams - more useful shape and reduced emittance growth
- Vacuum chambers with small round apertures → Improved undulator performance

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

ALS-U Kicker Requirements



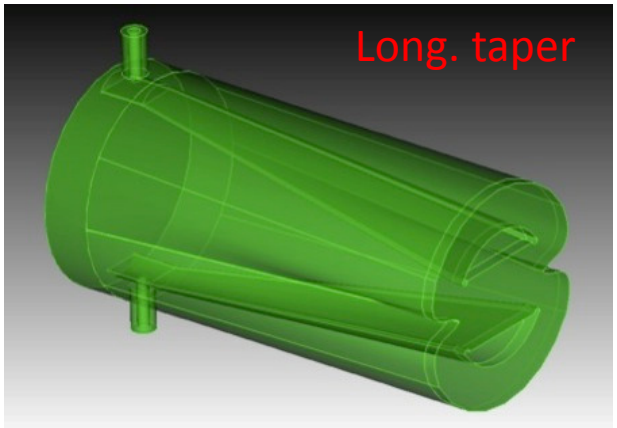
pending lattice finalization

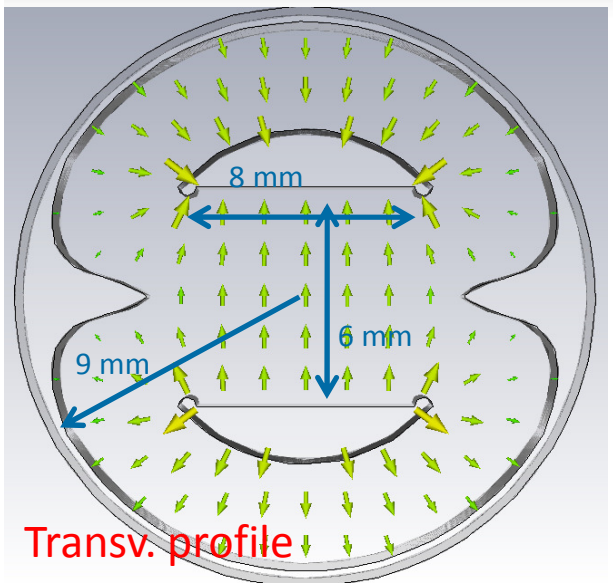
ALS-U Beam: 11 trains of 25/26 bunches. Gap Length: 10 ns

Bend Angle: 3.5 mrad
Total Kicker Length: 2 m
No. of Modules: 4
Pulse Voltage: 5.3 kV

Rise/Fall Time: ≤ 10 ns
Max. Pulse Length: 50 ns
Repetition Rate: ≈ 30 s

ALS-U Kicker Design: Stripline kicker + Inductive adder pulser

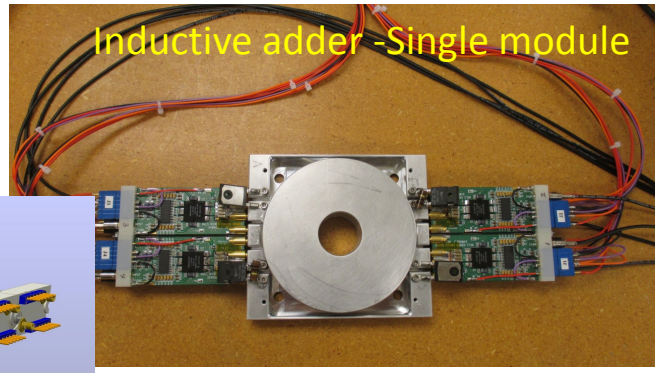


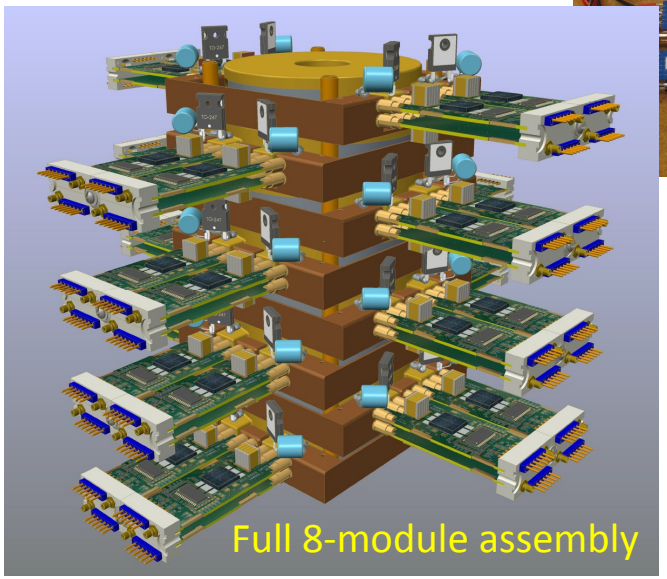


Four 0.5 m long tapered striplines. 6 mm minimum gap between striplines.

Midplane fenders to reduce characteristic impedance mismatch between odd and even mode down to 50 and 64 Ω (A. Krasnykh).

5.5 kV bipolar MOSFET inductive adder.





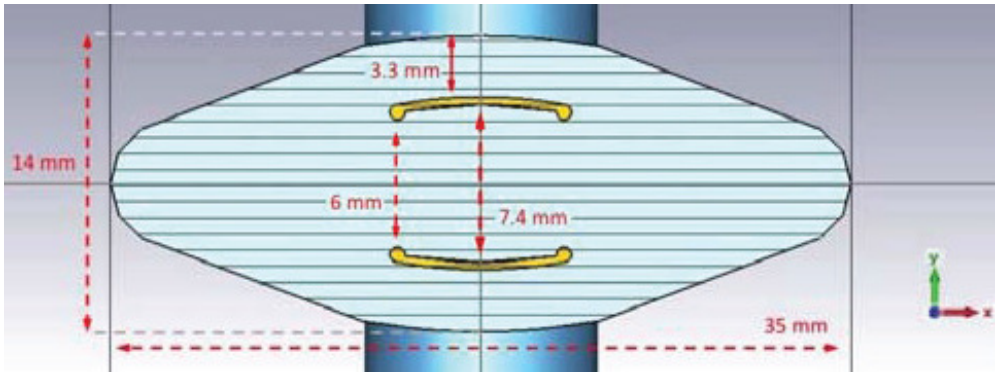
The ALS-U Test Kicker at the ALS

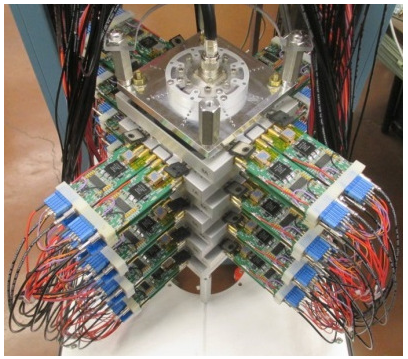
- Successful implementation of the swap-out kicker is a key element for the success of the ALS upgrade.
- Its design presents several challenges:
  - Electrodes in close proximity of the circulating beam (≤ 3 mm).
  - Small transverse dimensions amplify the effect of mechanical misalignments.
  - Rise/fall time in pulser output < 7 ns in order to fit in the 10 ns gap (due to propagation time in the kicker). Flat-top stability within ±1% at 5.3 kV.
  - Characteristic impedance matching in the kicker structure has to preserve pulser performance.
- We were able to take advantage of the similarities between ALS and ALS-U and test a technology demonstrator of the kicker with the ALS beam.

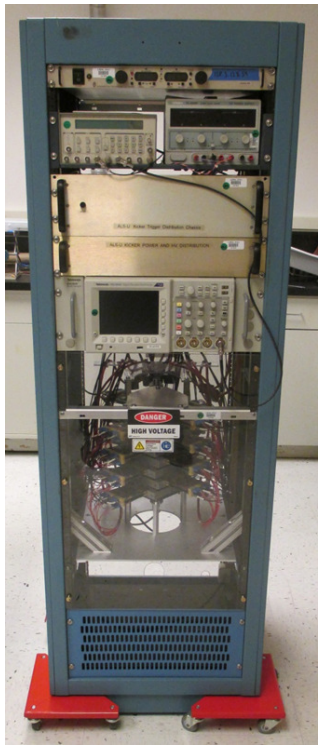
The ALS-U Test Kicker Timeline

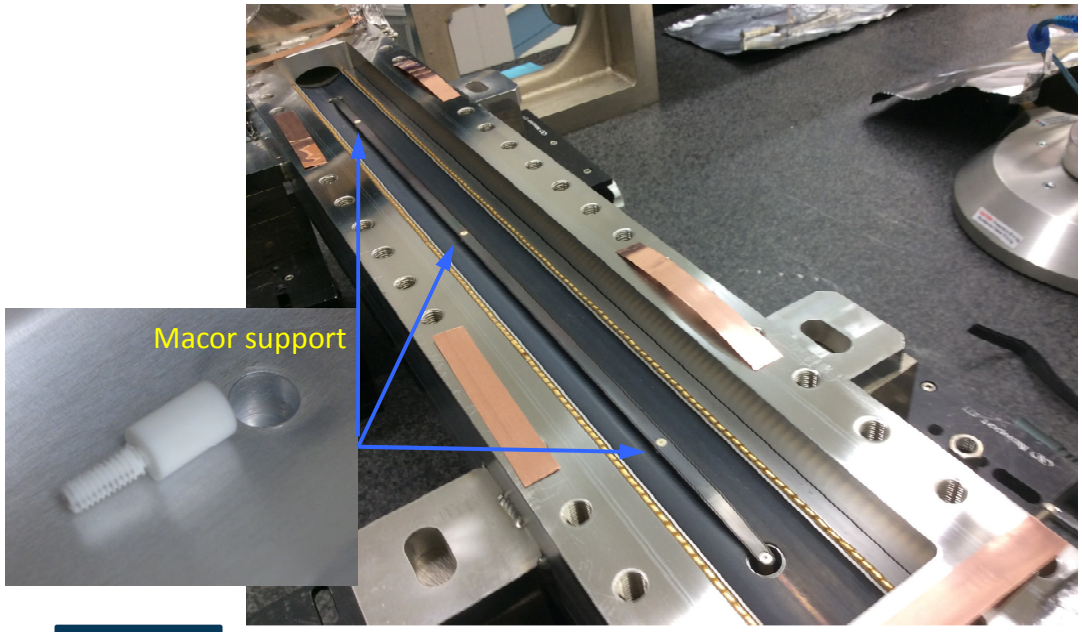
- Jan/Feb: kicker with original stripline version assembled and installed on the ALS.
- Mar: kicker tested with increasing beam current during the ALS restart, up to 500 mA, in passive mode.
- Mar: kicker and pulser tested with ALS beam.
- Mar 28th: due to operational mishap, full beam injected with harmonic cavities detuned. Shorter bunches and higher peak current briefly increased electrodes temperature before beam dump. Beam lifetime reduction observed and following measurement of reduced beam aperture and changes in beam induced signal in kicker, removal follows.
- Apr: TDR measurements and visual survey after kicker chamber can be opened evidenced sag in downstream half of top stripline, up to 2 mm away from nominal position.
- Aug: kicker with new stripline assembled and installed on the ALS.
- Sept: measurements with beam.

ALS-U Test Kicker









Cupric oxide deposition to increase thermal emissivity

0.5 m long stripline kicker, with same aperture as ALS-U modules and the inductive adder pulser prototype were installed in a ALS straight.
Horizontal dimensions have to be much larger, which why fenders are not used.
Cold test model also built.

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

(See my LER 2015 and 2016 presentations)

- 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

Measurements during assembly of actual kicker

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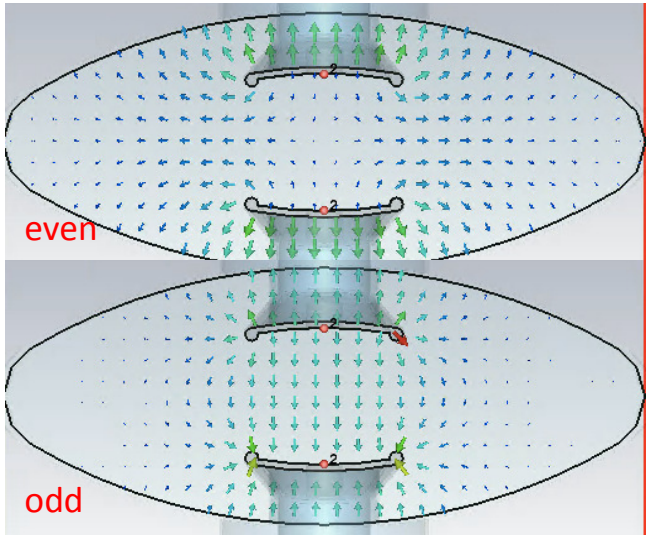
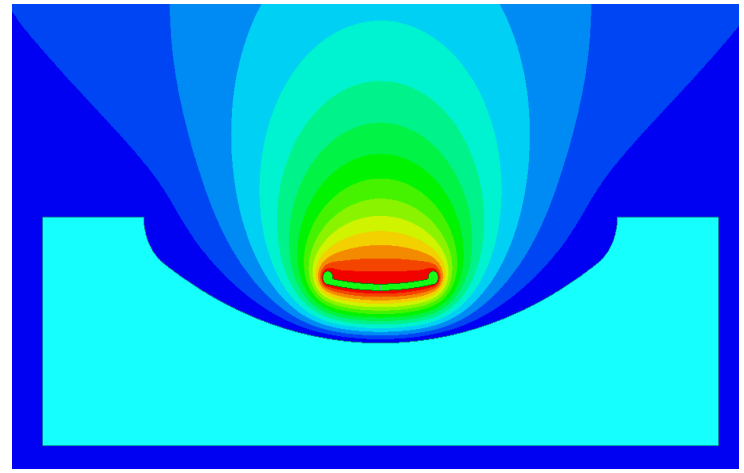
TDR Measurements As Kicker Diagnostics

- Good impedance matching is essential for proper kicker operation:
  - Deviations from the nominal 50 Ω odd mode characteristic impedance causes reflections of the deflecting pulse slowing its rise/fall time.
  - Changes of the 73 Ω even mode impedance along the kicker may increase its beam coupling impedance and therefore the amount of the deposited beam power to be dissipated.
- Due to the small transverse dimension impedance values are very sensitive to the electrodes position in the vacuum chamber.
  - Kicker chamber halves open: TDR measurements used to guide in proper positioning of each stripline electrode.
  - Kicker fully assembled: TDR measurements used to verify electrodes state at various stages (after assembly, baking, operations with beam)

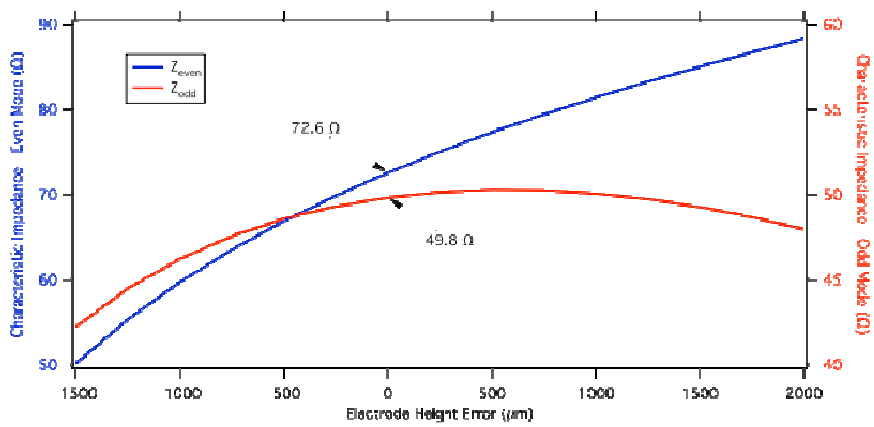
Characteristic Impedance Values For Half and Fully Assembled Kicker

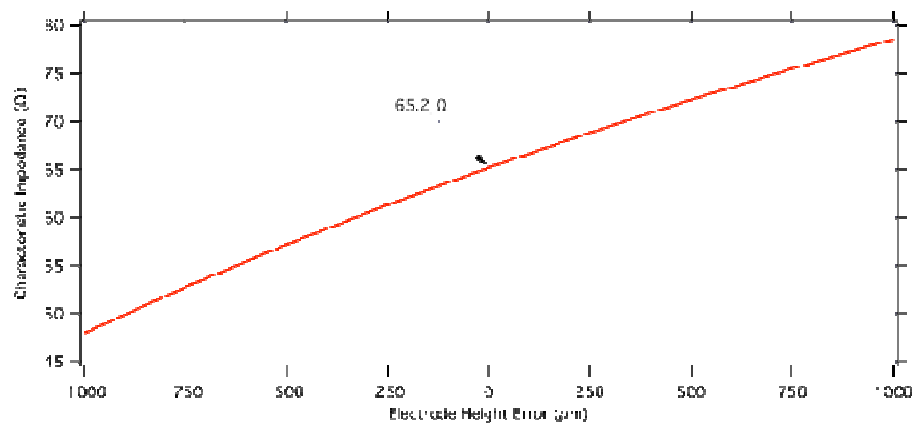


CST MICROWAVE STUDIO



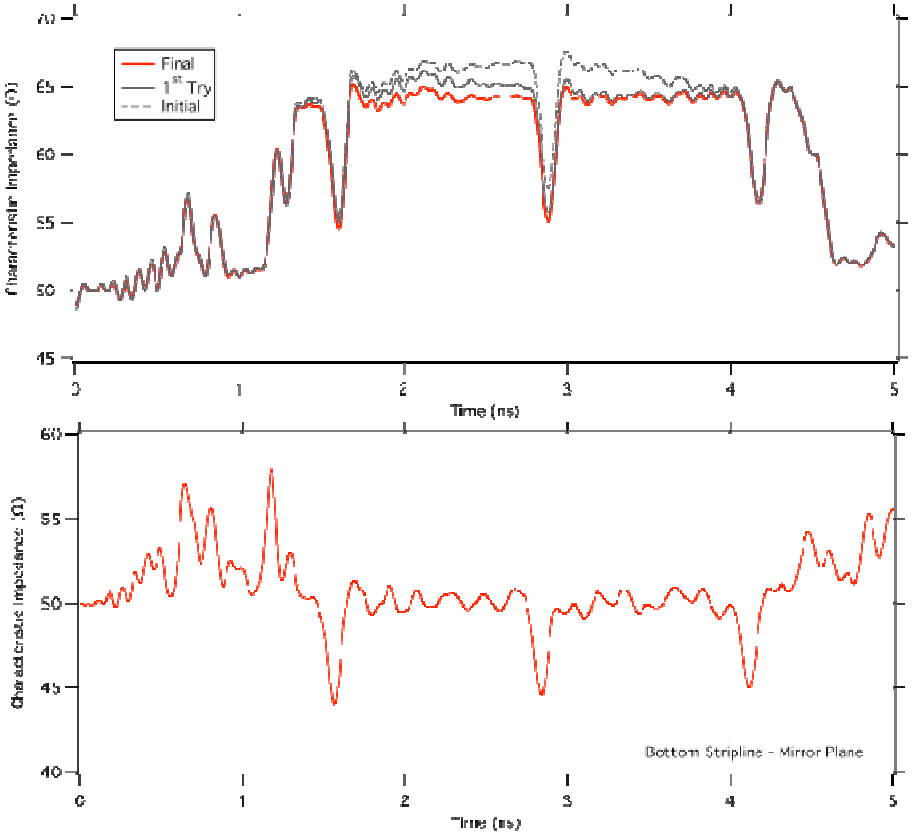
ANSYS MAXWELL



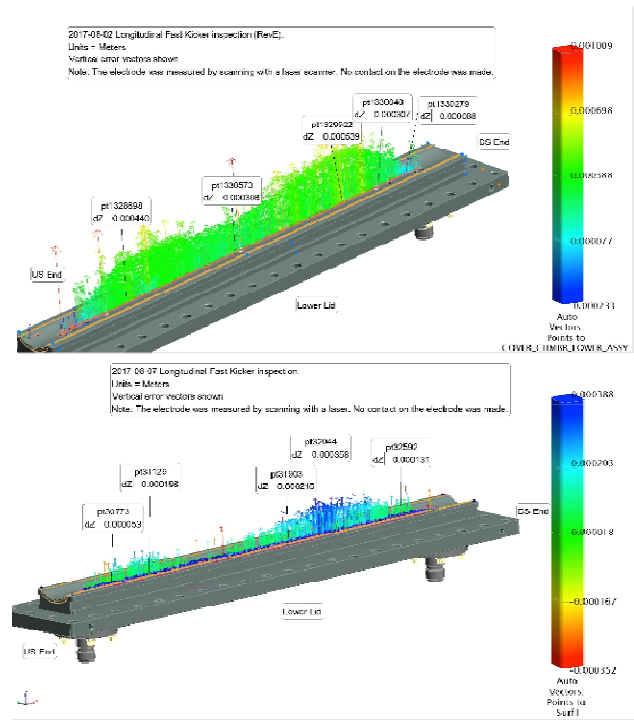


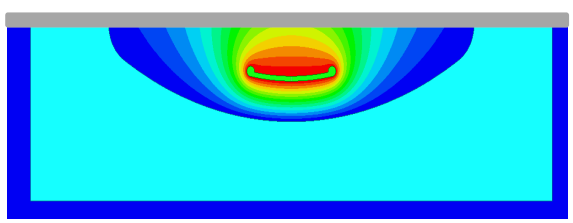
Characteristic impedance highly sensitive of electrode position

TDR Measurements (Kicker Halves)



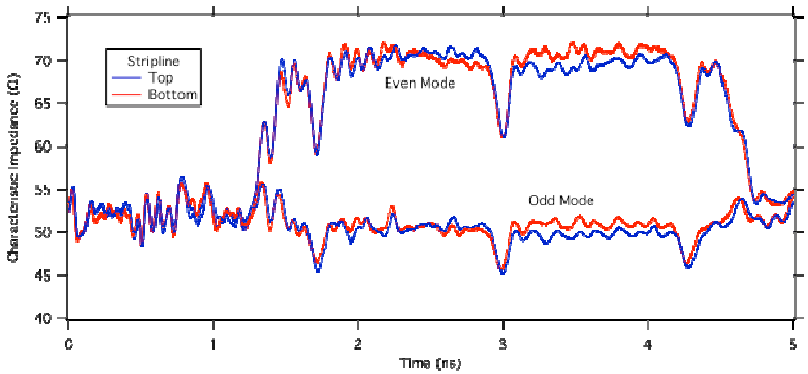
Stripline height can more easily be corrected in an open half kicker. TDR measurements (left), supplemented by laser scans (below), are used to reach de desired alignment.





The kicker half can quickly be closed by a metal plane (left) and an impedance equivalent to the full kicker's odd mode measured (left and above)

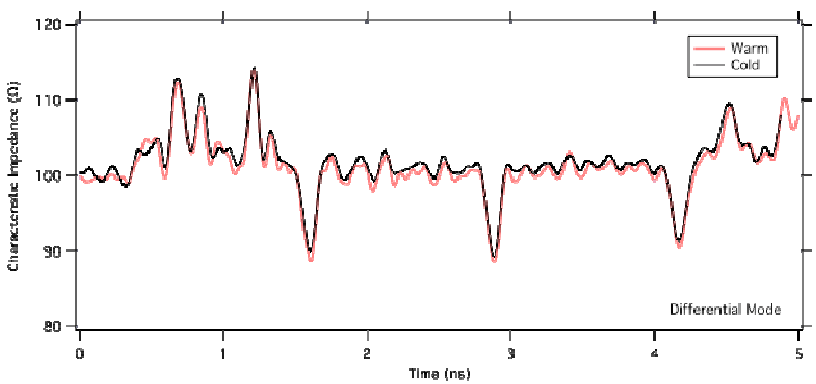
TDR Measurements (Full Assembly)

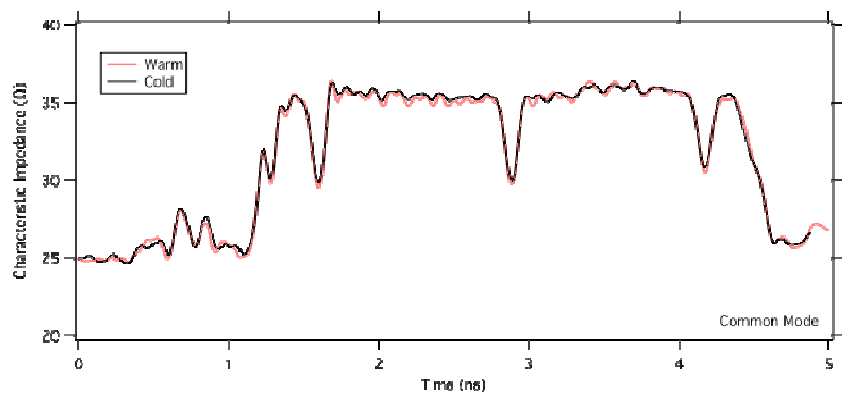


After the kicker is fully assembled, we can measure even and odd mode impedances along the striplines (left). Measurements below show measurements of differential and common mode impedances after final assembly and during initial baking at 70 °C. Z_{diff} and Z_{comm} can be measured directly with a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

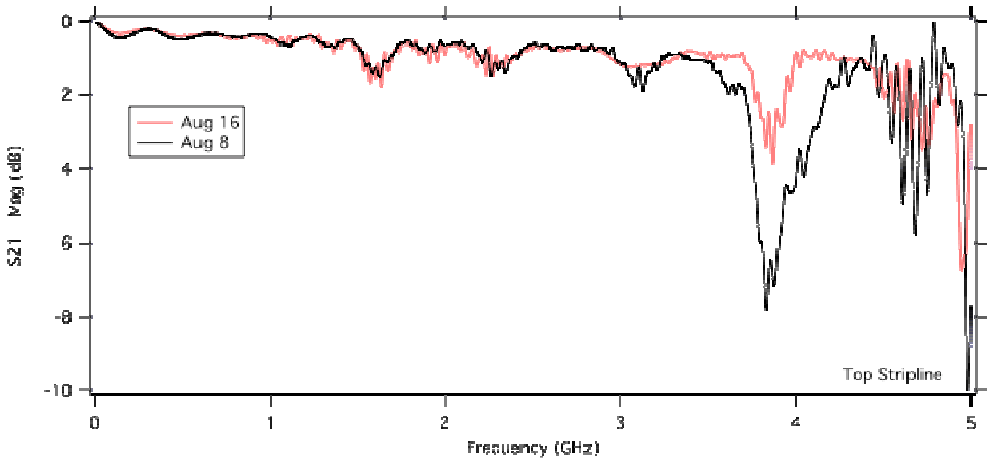
$$Z_{diff} = Z_{odd1} + Z_{odd2}$$

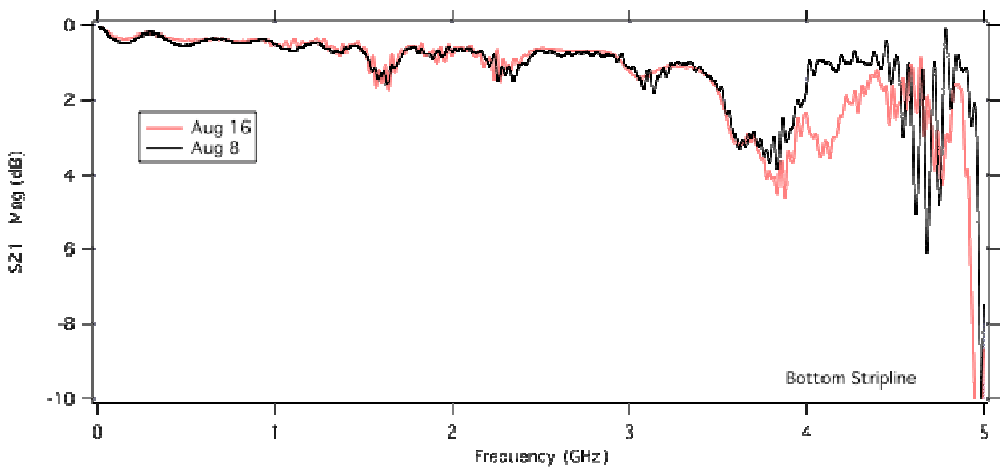
$$Z_{comm} = Z_{even1} Z_{even2} / (Z_{even1} + Z_{even2})$$





NWA Measurements (Full Assembly)





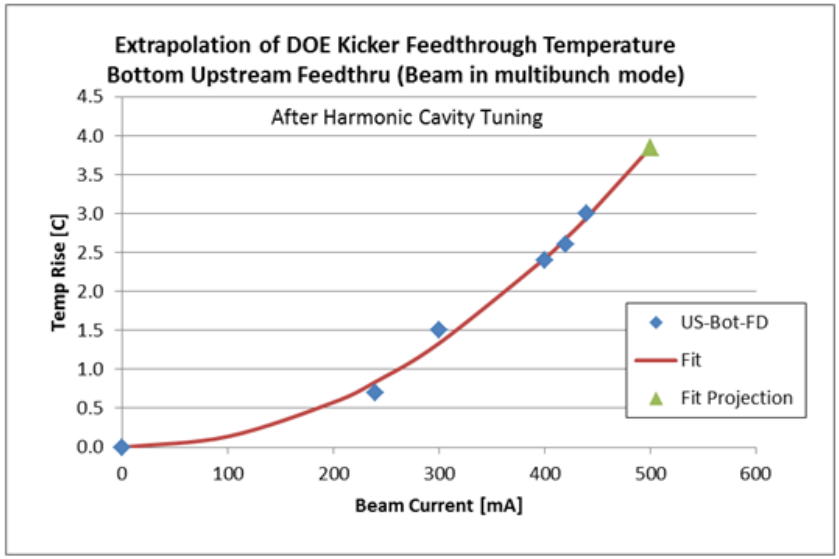
Network analizer measurements are also performed on the assembled kicker to identify possible defects with a high frequency response.

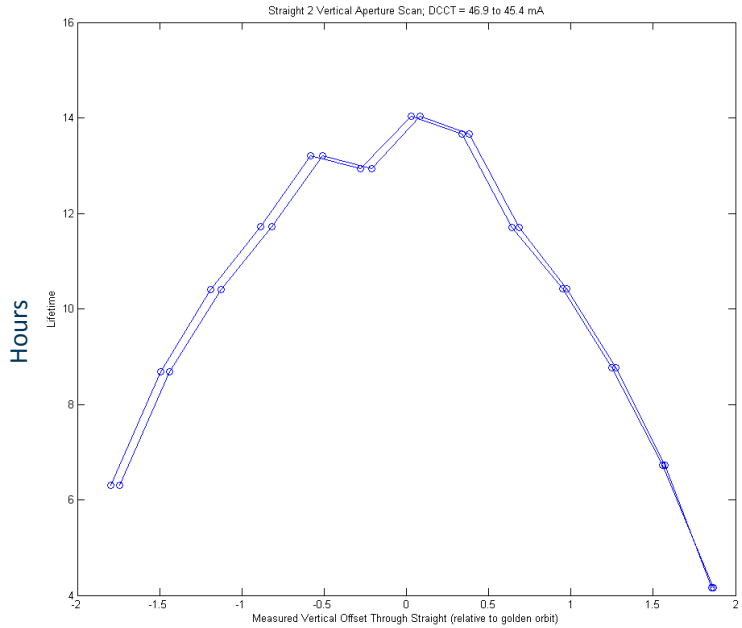
Beampipe cutoff is around 5 GHz.

The peak just below 4 GHz corresponds to an absorption peak in the Ceramaseal feedthroughs (see my LER 2016 presentation).

The origin of the differences between the two sets of measurements is unclear. However, the kicker had been assembled on August 8th with a large offset due to a failing TDR module and one of the cables used in the measurements was found to be defective a few days later.

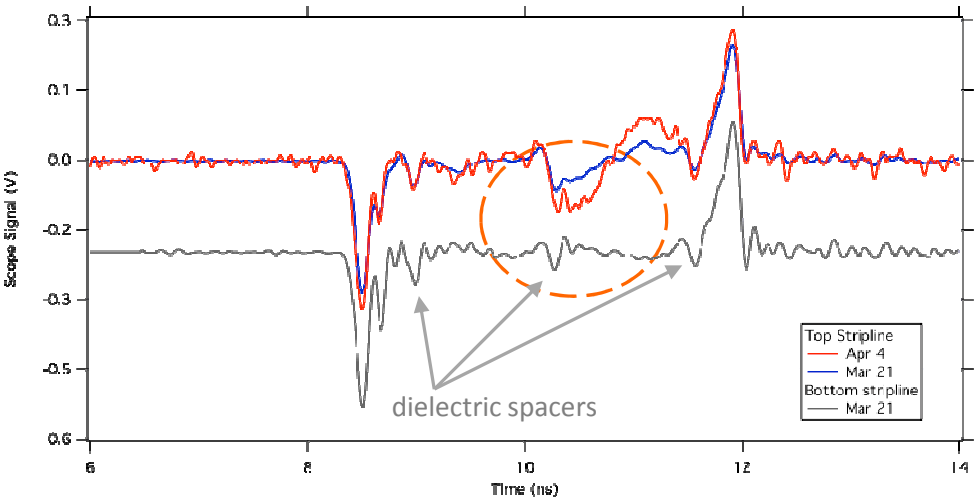
Stripline kicker experience at ALS: monitoring temperatures and beam aperture.

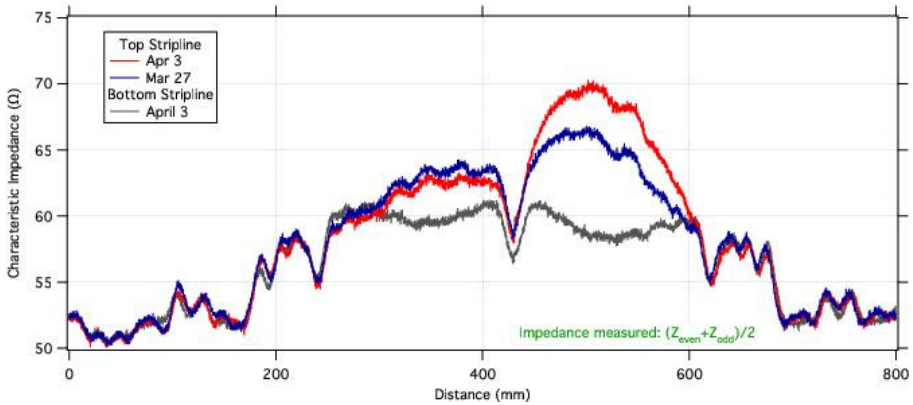




- After the kicker has been installed on the ALS, a first family of measurements directly monitors the well-being of both kicker and ALS beam, by observing temperatures on the kicker body and by vertical aperture scans.
- Thermal management for normal operation works well, no excessive heating observed
  - Feedthroughs are air-cooled
- Alignment well centered, clear beam aperture as designed

Diagnostics based on beam signals and TDR measurements during operational intervals





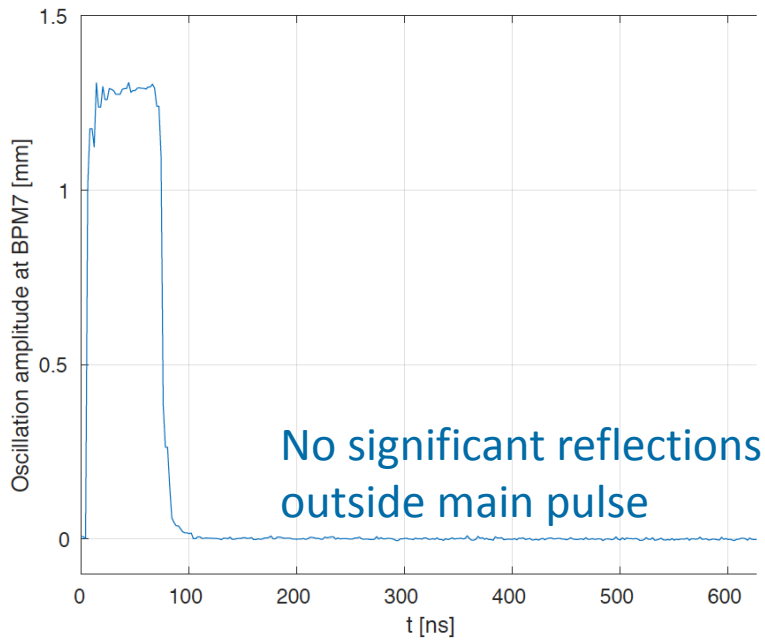
On-line diagnostic: 8 GHz bandwidth scope analyzes beam-induced signals. Response in the top stripline shows increasing impedance mismatch due to electrode deformation right of the center spacer.

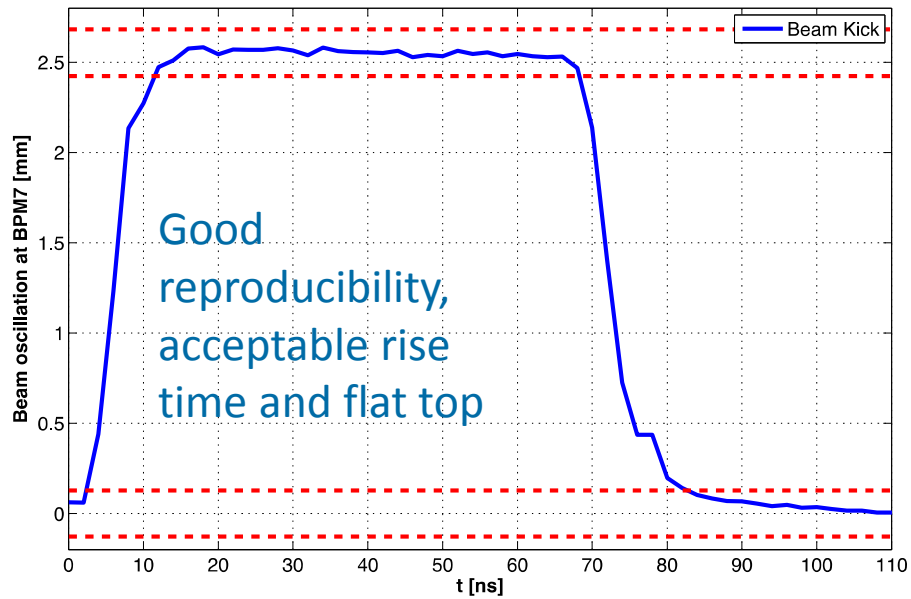
Off-line diagnostic: Requires ring access; not possible during beam operations. TDR measurement of stripline characteristic impedance. From this data a more quantitative assessment of the electrode displacement is possible.

Even this kicker operated within specs until a mishap caused excessive beam power to be absorbed (HHC cavities detuned at full current).

Successful deflection of ALS bunches achieved.

- Kicker integrated with ALS timing system – worked out of box
- Shown is a test at reduced (~50%) voltage to keep measurement time manageable (not kick out beam)
- Full voltage demonstraded in bench measurements.





- Results are consistent with expectations, fulfill almost all requirements (but no margin, yet)

The original design of the stripline kicker electrodes has been 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 where there is beam 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 ~2mm
- Modifications to reduce the impact of beam heating
  - Robust electrodes and improved processing
  - 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 estimated by CST simulations
  - ALS without bunch lengthening: 243W (5mm RMS bunch length) – detailed model from CAD
  - ALS with bunch lengthening: 84W (9mm RMS bunch length) – detailed model from CAD
  - ALS-U with bunch lengthening: 28W (9mm RMS bunch length) – much simpler model, likely to be low
- New kicker installed and ready to be commissioned in early September !

Conclusion

- A stripline kicker and pulser, which are key components to enable on-axis swap-out injection, have been demonstrated for ALS-U parameters. In addition, the integrated system was installed and demonstrated with beam in the ALS storage ring.

- After modifications to the electrodes to improve immunity to short-bunch fault conditions at ALS, the stripline kicker will be re-installed in the ALS storage ring in August. Commissioning to begin in September.

- Microwave measurements techniques have been extremely helpful in aiding the mechanical assembly of the kicker, monitor its correct operations and detect impeding faults.