On-Axis Swap-Out Injection At ALS-U

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2nd RULε Topical Workshop on Injection and Injection Systems
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BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

ALS-U ADVANCED LIGHT SOURCE

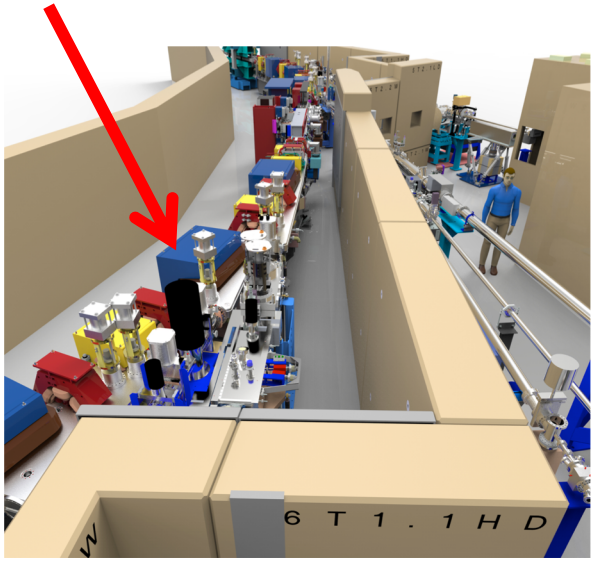
Outline

- ALS-U overview
  - Reasons behind swap-out injection choice.
- Operational issues in swap-out implementation
  - Timing issues, beam losses control, transfer lines, decoherence kicker.
- Technological aspects
  - Stripline kickers.
    - Beam impedance minimization.
    - Characteristic impedance matching.
    - Power dissipation.
  - Pulser
    - Design progress.
  - Attenuators
    - Wide band, high voltage.
- Conclusions

Scope of ALS-U

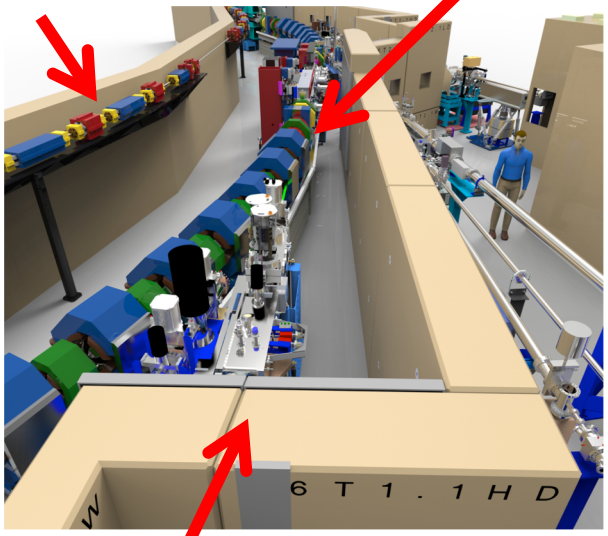
1. **Replacement** of the existing triple-bend achromat storage ring with a new, high-performance storage ring based on a multi-bend achromat.
2. **Addition** of a low-emittance, full-energy accumulator ring in the existing storage-ring tunnel to enable on-axis, swap-out injection using fast magnets.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

Existing ALS ring



New accumulator ring

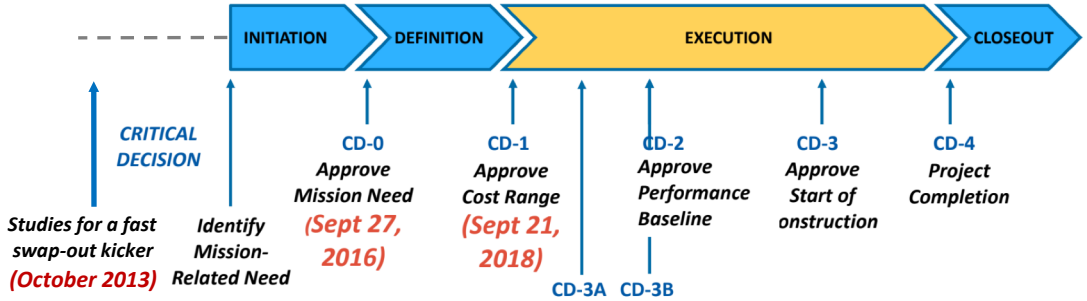
New ALS-U ring



Same ALS tunnel

Drivers Behind ALS-U Choice of Injection Scheme

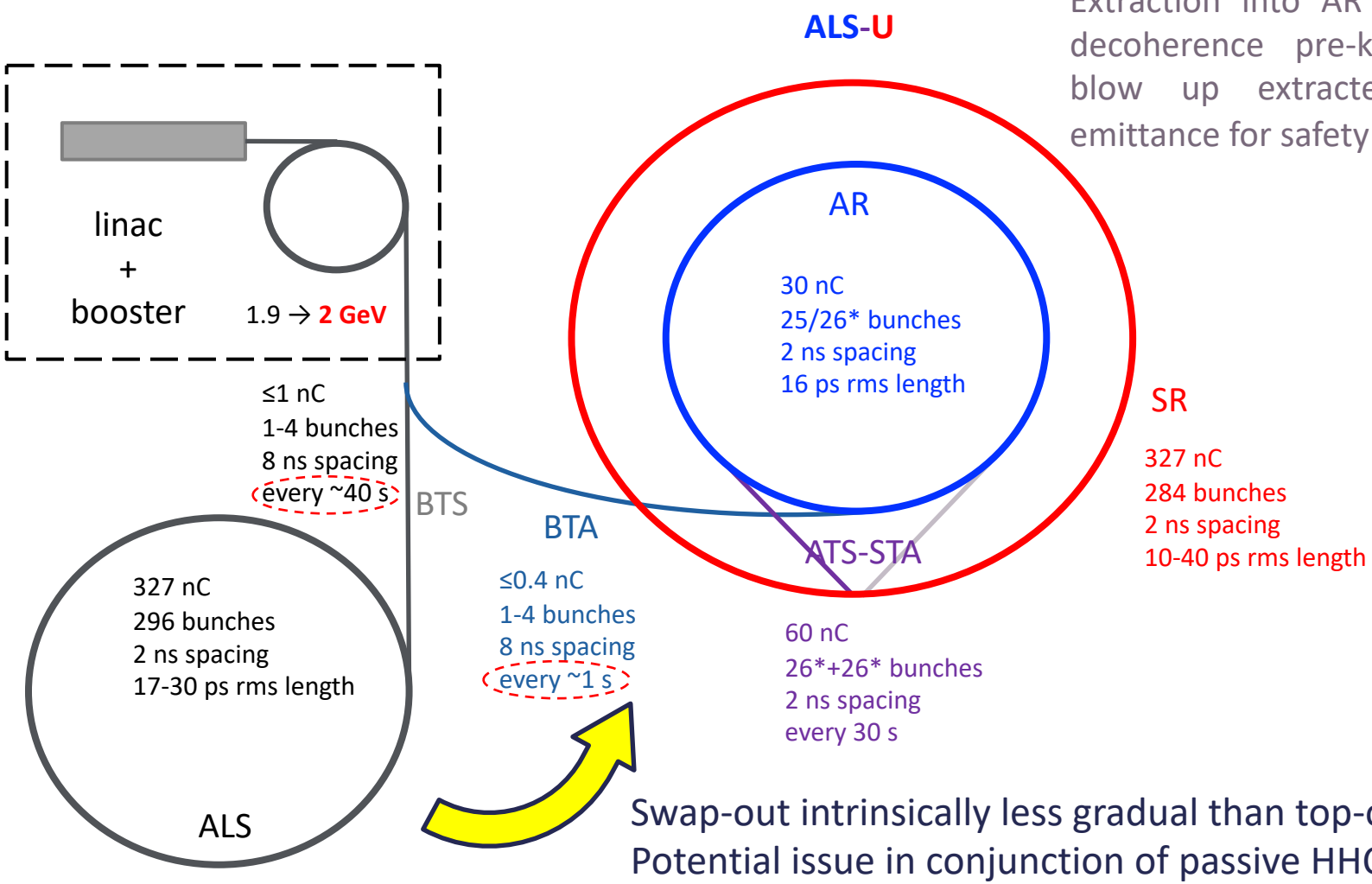
- Ultra-low emittance and new ID's with narrow horizontal gap go hand in hand with smaller dynamic aperture. Higher emittance injector.
  - Traditional off-axis accumulation not possible.
- Small ring, Touschek limited lifetime: almost all RF buckets have to be filled. Project decision to keep existing ALS 500 MHz RF system.
  - Less traditional longitudinal accumulation also not possible.
- Project decision to keep existing ALS injector.
  - Accumulator ring necessary to support swap-out of long trains.
- Development of a fast swap-out kicker was identified as a key enabling technology early in the project's life. Swap-out is not only fast kickers, though…



ALS-U Project Timeline

From Top-off To Swap-out

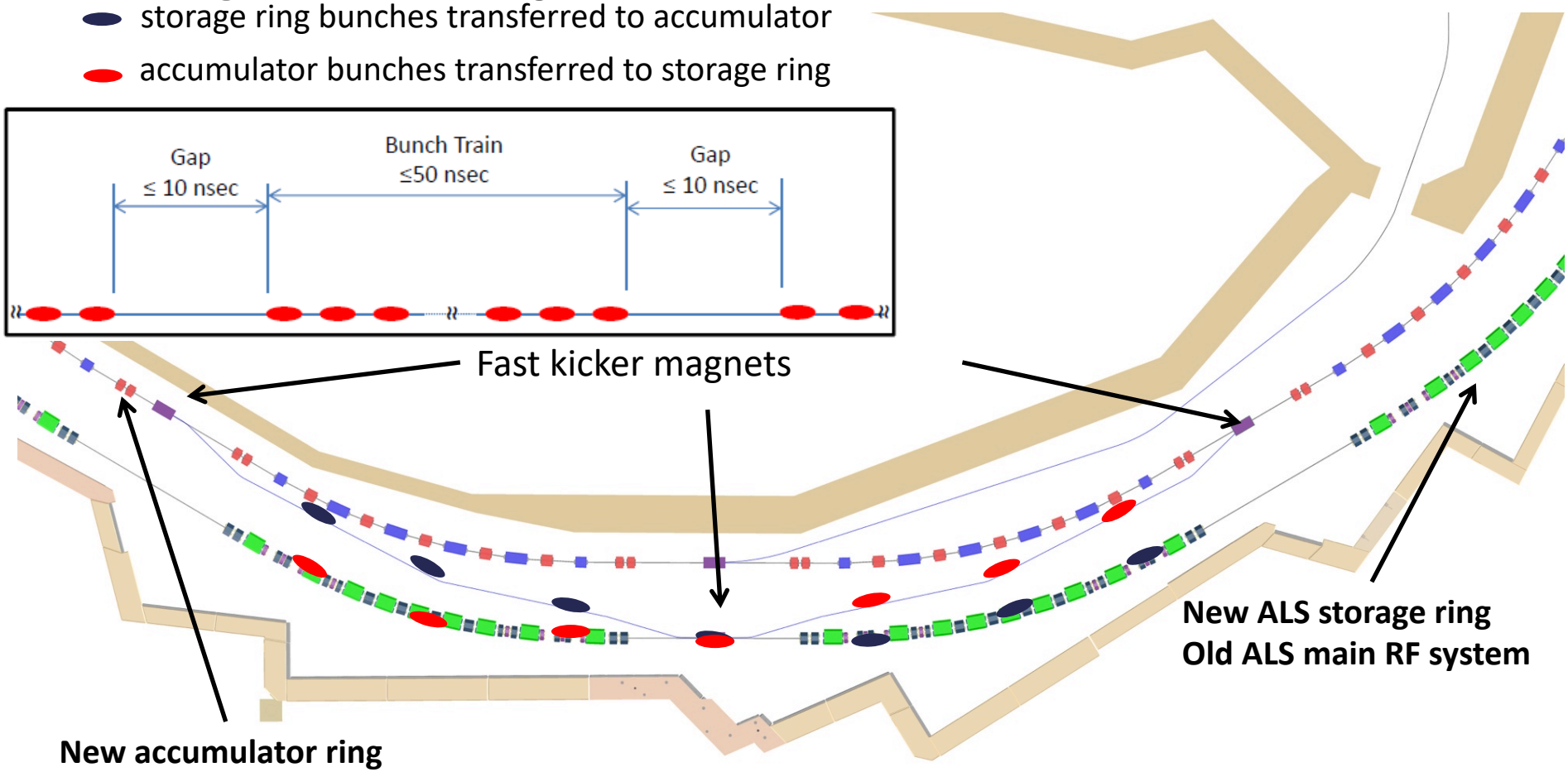
Extraction into AR requires decoherence pre-kicker to blow up extracted train emittance for safety reasons.



Swap-out intrinsically less gradual than top-off.
Potential issue in conjunction of passive HHC use:
Filling an empty SR will have to be done gradually, avoiding inducing large transients in the cavities.

Swap-out Injection Scheme

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



500 MHz main RF → h = 328:
9x 26-bunch trains + 2x 25-bunch trains,
all separated by 4-bucket gaps.

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

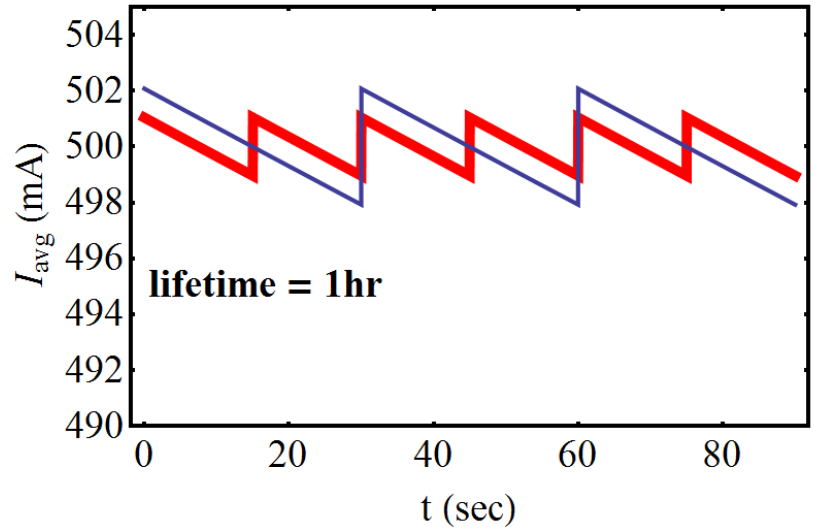
Beam Lifetime Dictates Frequency of Swap-out Cycles

- **Under unusual circumstances, ALS has sometime operated with ~1hr lifetime. Background losses not an issue for existing shielding**

- **≥1hr total lifetime goal achievable with**
  - Touschek $\tau \geq 1.4hr\ (harmonic\ cavities)$
  - Gas $\tau \geq 4hr\ (NEG\ coating)$

- **<1% (peak-to-peak) average-current variation target is achievable with swap-out injections every 30''**
  - ~15'' swap-out possible with existing injection system

Average current with swap-out every 15 and 30sec [for 1hr lifetime]



- Lifetime estimate (vacuum, Touschek) to be refined in the next Project phase
- Being able to understand/control losses locations is important.

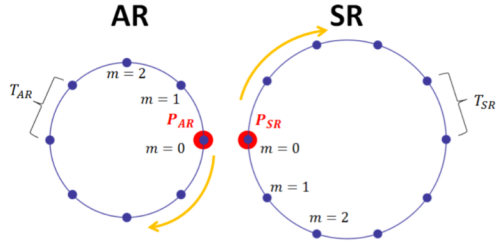
Top-off Injection Into Accumulator Is An Integral Part of the Swap-out Cycle

- Each train is recycled every 330 seconds.
  - Bunches need to be topped off with ~ 0.1 nC charge.
  - Occasionally, 1 bunch needs to be created anew (1.15 nC)
- The injector can easily produce 0.1 nC bunches, but only to up to 4 of them per injector cycle (1 Hz).
- Creating a 1.15 nC bunch in the Accumulator may instead require 2, or even 3 injection cycles.
- Injector bunches are separated by 4 RF buckets.
- There are two ways to top-off an entire train in 10 injection cycles (plus a couple more when a 25-bunch train has to become a 26-bunch train):
  - 4x 4-bunch injections + 4x 2-bunch injections + 2x 1-bunch injections.
  - 8x 3-bunch injections + 2x 1-bunch injections.
- When a 26-bunch train becomes a 25-bunch train the Accumulator feedback system will “clean” one bunch out.

Timing Issues In The ALS-U Swap-Out Injection

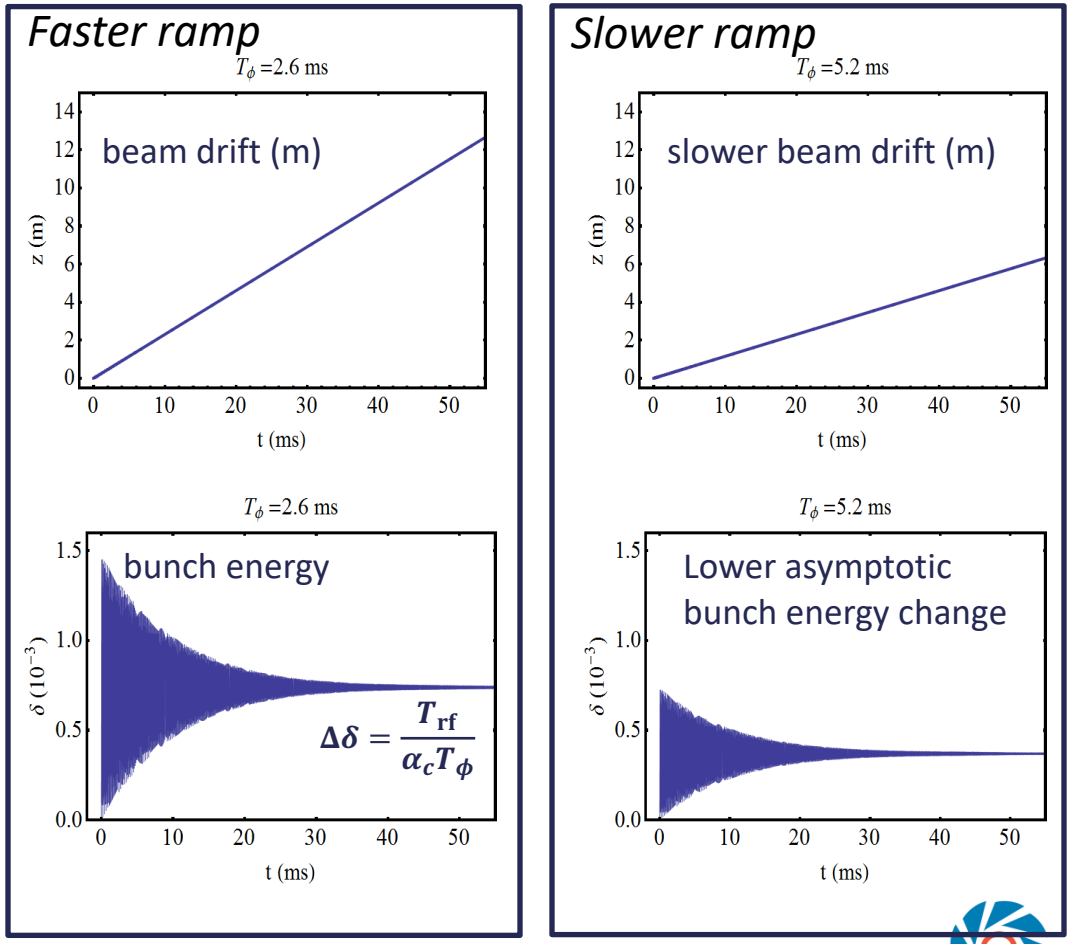
- Project level choices:
  - ALS RF system is re-utilized in the Storage Ring.
  - Existing ALS Injector kept and upgraded to 2 GeV.
  - Realignment of existing ALS beamlines kept to a bare minimum.
  - Accumulator Ring to use same tunnel. Has to be installed high on the inner wall.
- Consequences:
  - 9-bend lattice makes ring shorter: SR RF frequency goes up ~750 kHz (1/2 harmonic). Harmonic number remains h = 328.
  - Keeping the Accumulator at the same frequency identified as best option. Fitting to the inner wall means its harmonic number is 304. No easy way to change it to 303, or 305.
  - Injector much less flexible; has to remain at the lower ALS frequency.
- Storage and Accumulator Rings harmonic numbers not mutually prime.
  - "Phase agility" has to be implemented on the AR to be able to target every SR bucket.
- Injector and Accumulator Ring RF frequencies different by 750 kHz
  - Allow off-phase injection into AR: Max $\Delta\phi \approx 2.4^\circ$ (3-bunch), 3.5° (4-bunch).

“Phase Agile” RF System



- Phase control in AR RF system is necessary for flexibility to align any SR to any AR bucket for swap-out.
- ALS transitioned to fully digital low-level RF controls in 2018. New sytem provides necessary capability.
- Slow phase-ramp over to minimize beam energy variation.
- For $\Delta\delta < 0.5\times10^{-3}$, beam drift around a full turn will take about $t = \frac{T_0}{\alpha_c \Delta\delta} \simeq 1.2s$ (vs. $30s$ between swap-outs)
- Ongoing measurements to estimate differential variations between AR and SR circumferences
  - To be handled by AR lattice tuning

Linear RF phase ramp $\boldsymbol{\phi = \phi_0 - \frac{2\pi}{T_\phi} t}$

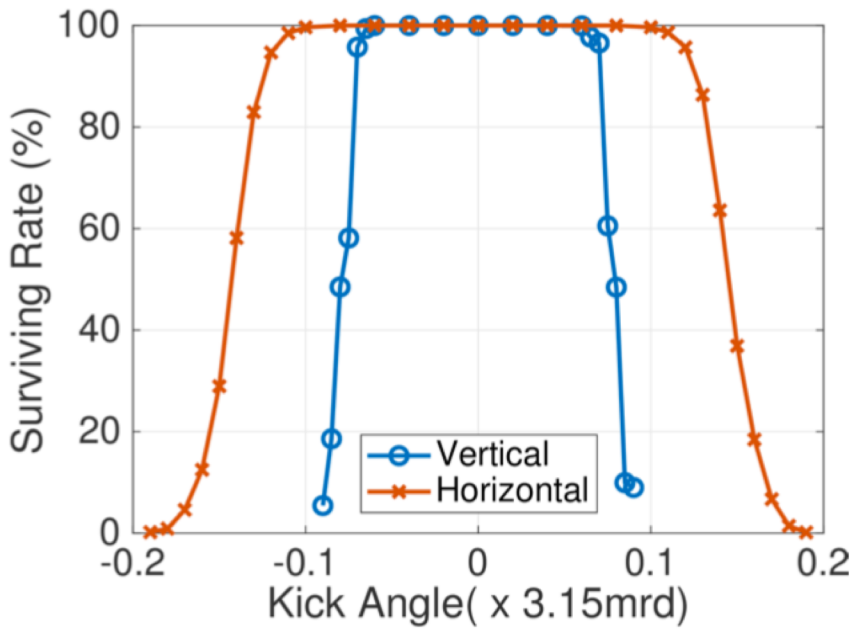


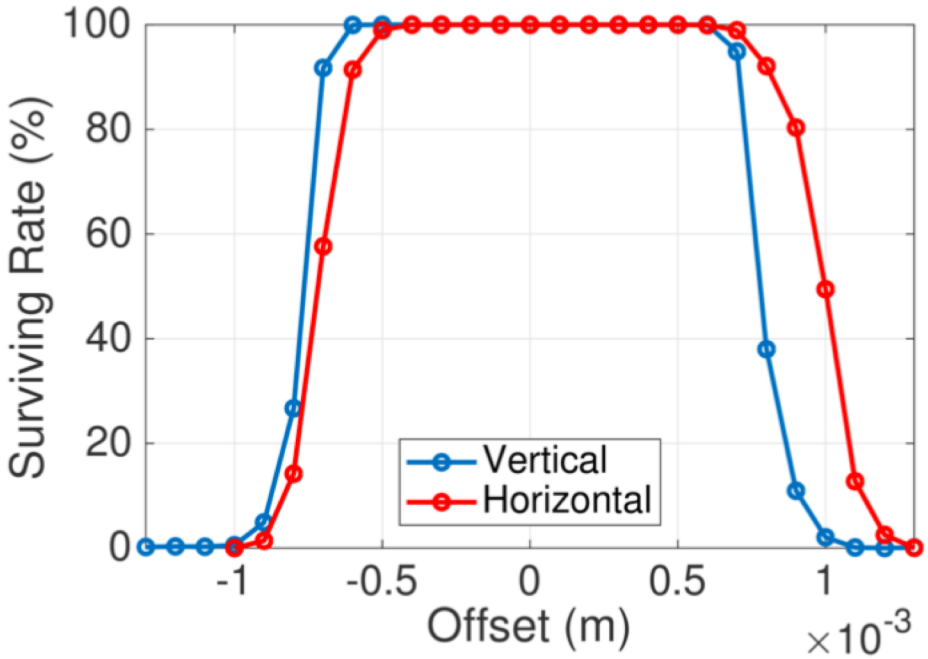
Beam Losses Issues in ALS-U Swap-out Injection

- ALS top-off designed to reach 90% efficiency. Occasionally operates as low as 50% efficiency.
  - Top-off event: up to 1.5 nC total charge every 40 seconds.
  - Losses as high as 0.75 nC/shot well tolerated.
- ALS-U swap-out cycle involves close to 60 nC every 30 seconds.
  - Swap-out ideally less lossy (circulating beam nominally unperturbed, full use of acceptance).
  - Swap-out into Accumulator should be virtually loss-free.
- To match ALS losses, ALS-U has to operate with close to 97% efficiency (AR to SR).
- Injection into Accumulator involves 2.5-3.5 nC within a 30 seconds period.
  - Can potentially match ALS losses by itself.

- Clean injection is a higher priority in ALS-U. Beam loss monitoring system planned to help diagnosing and tuning.

Beam Losses Source: Injection Jitter (from kicker field, or Accumulator orbit stability)



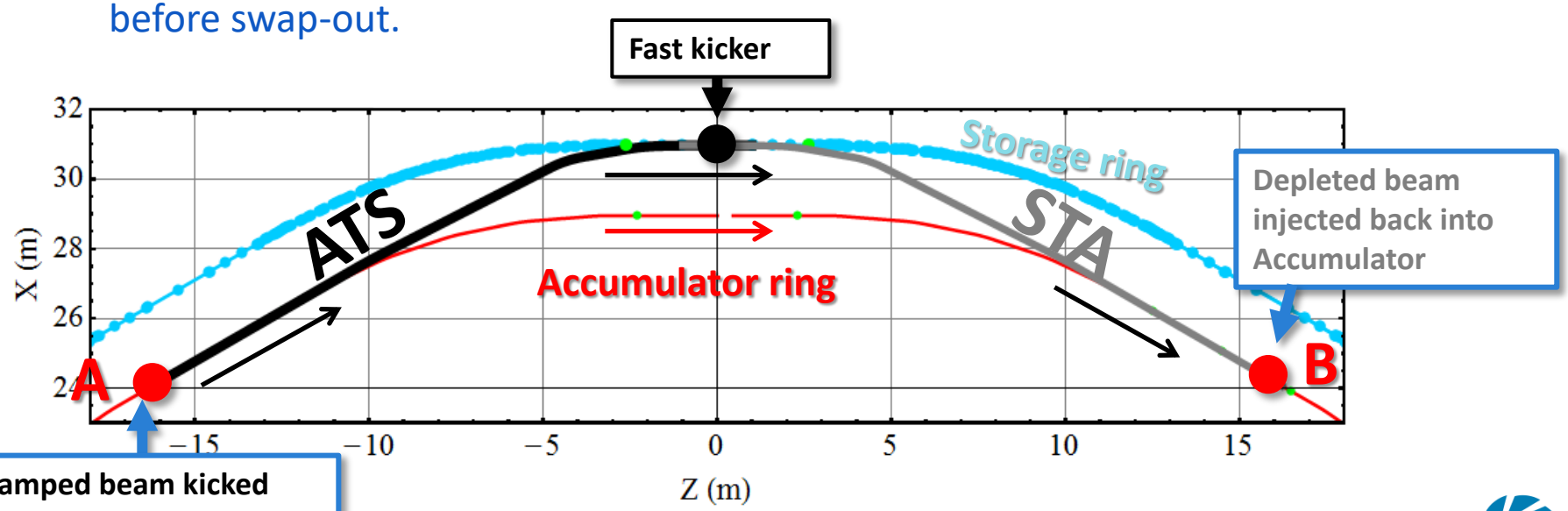


- 6D tracking with both radiation and cavity on
- Tracking 2000 particles for 30000 turns with different inject beam angles and offsets
- Linear errors, multipole errors, and physical aperture are included during the tracking

100% injection efficiency can be achieved with 10% perturbation on the nominal kick amplitude (3.15 mrad) in horizontal direction and 7% perturbation in vertical direction, and 0.5 mm offset in both directions, respectively.

Design of Swap-out Transfer Lines Is Revving Up

- **Requirements:**
  - Full 6D matching of lattice functions (Twiss, dispersion, linear coupling). Different elevation (~0.6m) between Storage and Accumulator rings
    - Rotated magnets , supports not trivial.
  - Path-length constraint for swap-out timing
    - Path-length difference between the Transfer-line route and Accumulator route from **A** to **B** should be $n\lambda_{RF}$
- **Challenges:**
  - Tight space, potential lay-out conflicts with Storage, Accumulator rings and the BTA transfer line
  - STA beam emittance to be blown up by pre-firing a decoherence kicker 100's ns before swap-out.



Swap-out kicker requirements and design

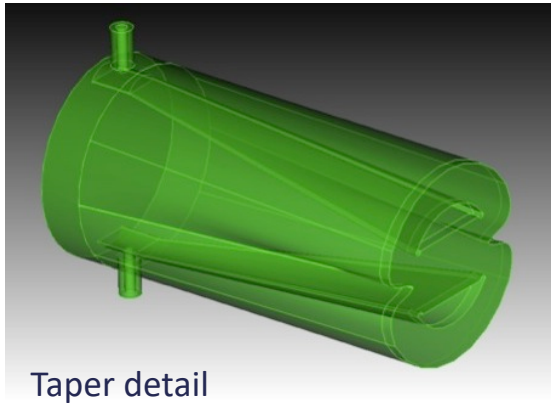
- Tapered striplines (3.6 cm taper)
  - Coupling impedance reduction at higher frequencies $f_{cut} \propto 1/L_{taper}$
  - Easier characteristic impedance matching feedthrough-stripline.
- Midplane fenders (A. Krasnykh)
  - Design for Z_{odd}=50Ω; reduce $Z_{even} \longrightarrow$50Ω with fenders.
  - Design for Z_{even}=50Ω; increase $Z_{odd} \longrightarrow$50Ω with external loads.

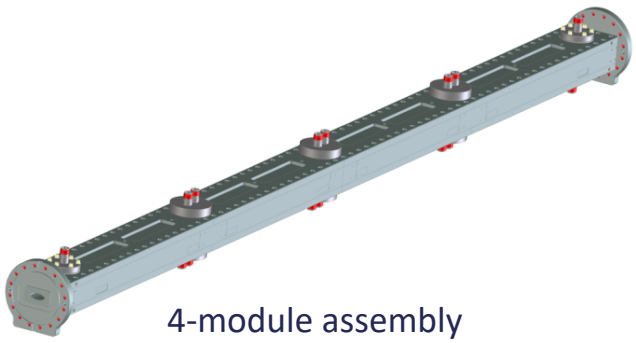
Assumes perfectly balanced striplines

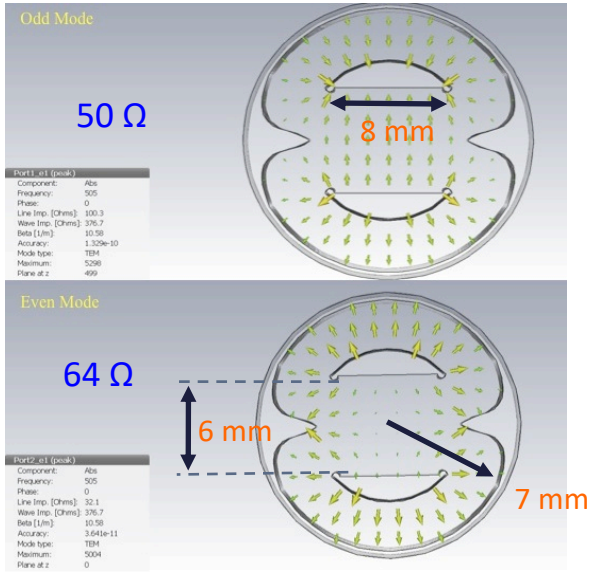
- 50 cm stripline length
  - Maximizes shunt impedance.
  - Reduce number of kicker modules.
  - 30 cm stripline impedance zeroes at n x 500 MHz.

Reduces loss factor, but not power dissipated on striplines

Total kick angle	3.5 mrad
Total kicker length	2 m
Rise/fall time	< 10 ns
Max. pulse voltage	6 kV
Kick frequency	1/30 s
Max. flat top ripple	±5%

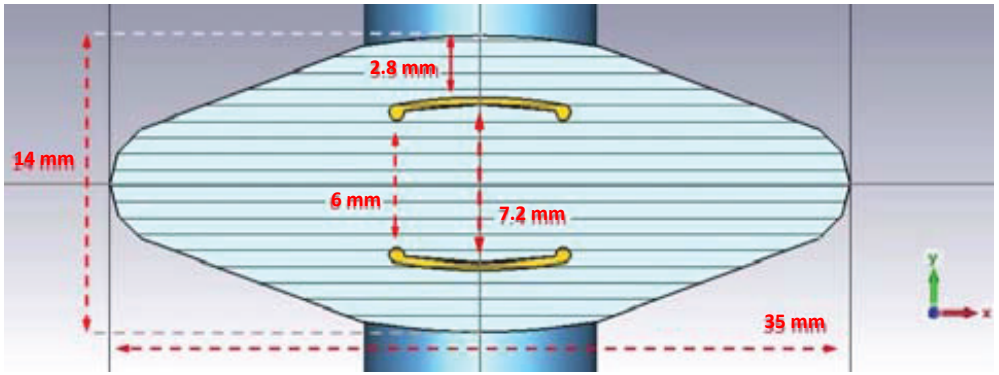


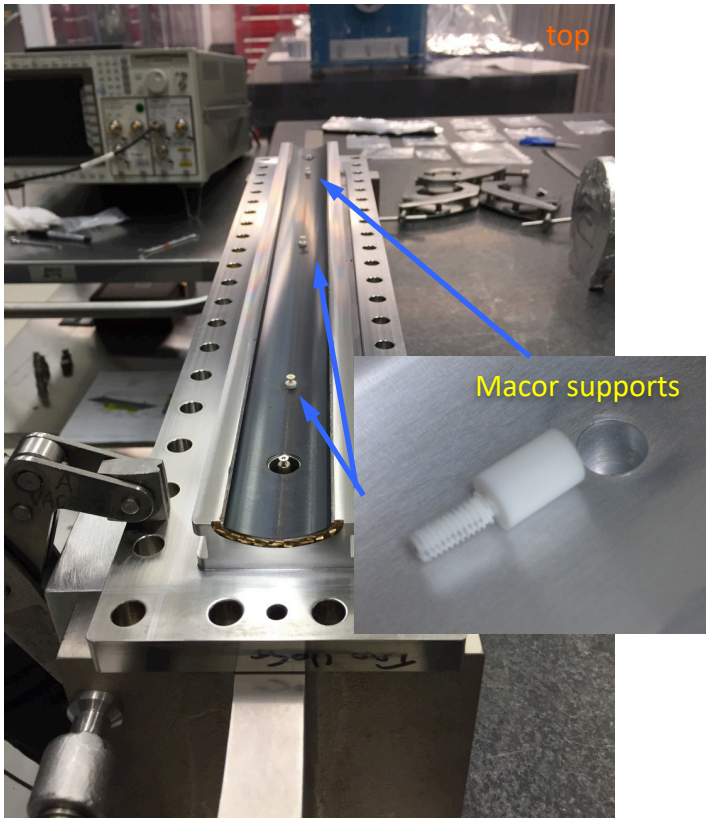


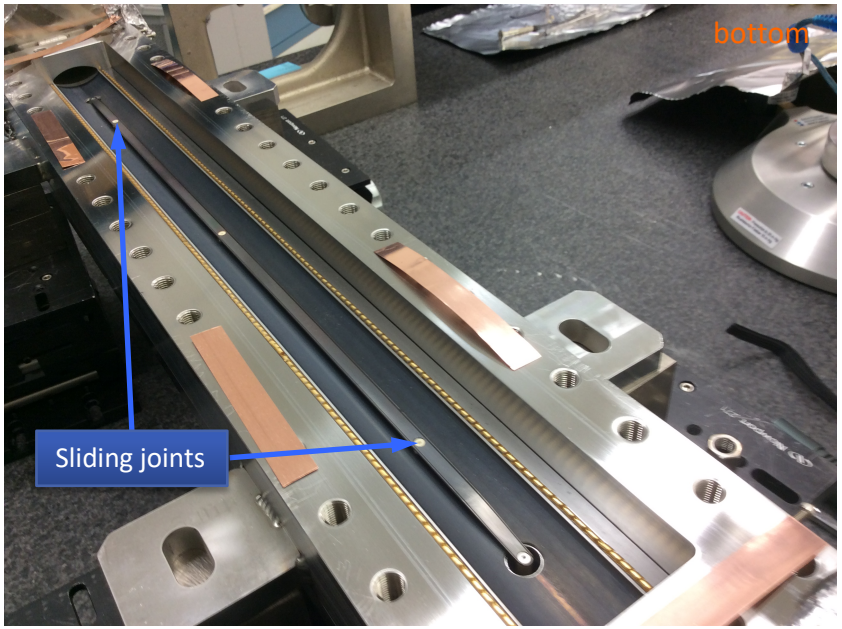


Shorter, weaker, version to be used as decoherence kicker

ALS-U Test Kicker



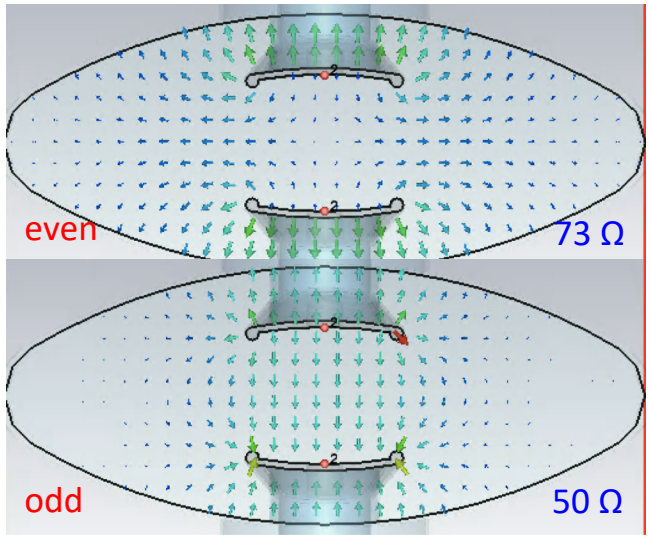




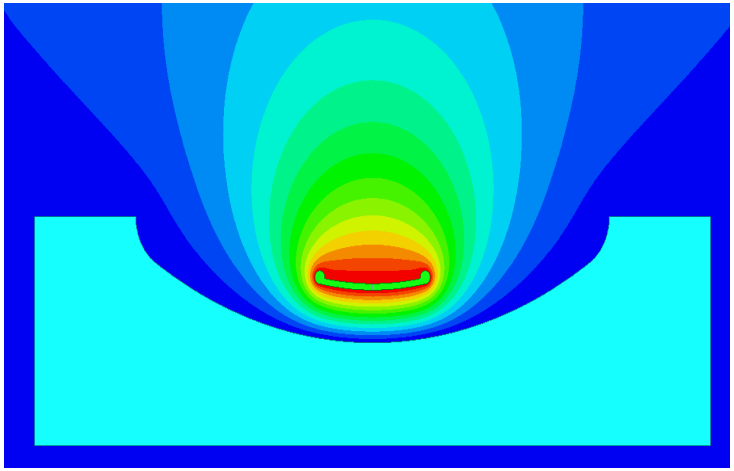
Cupric oxide deposition to increase thermal emissivity

0.5 m long stripline kicker, with **same aperture as ALS-U kicker modules**. Horizontal dimensions have to be much larger, fenders are not used. Cold test model also built.

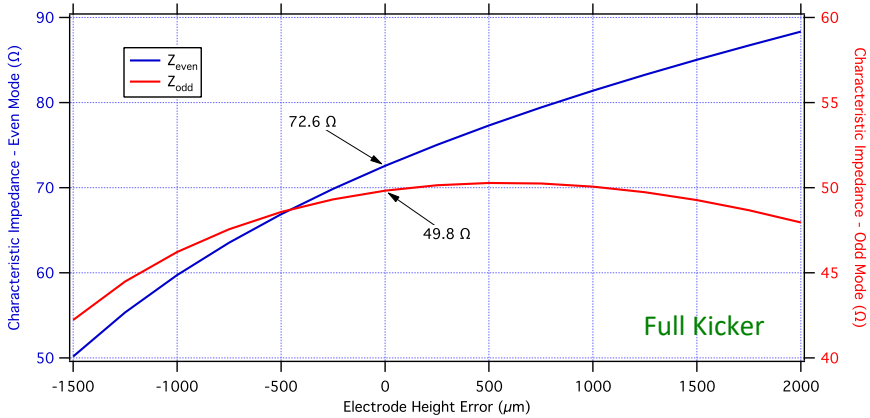
Characteristic Impedance Values For Half and Fully Assembled Kicker

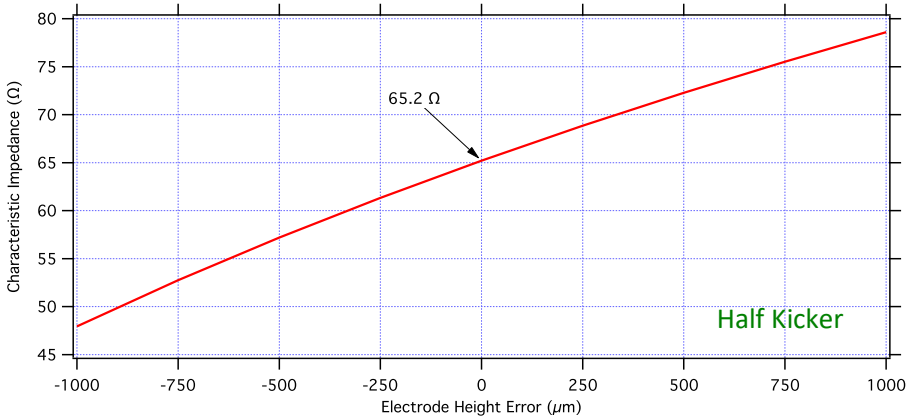


CST MICROWAVE STUDIO



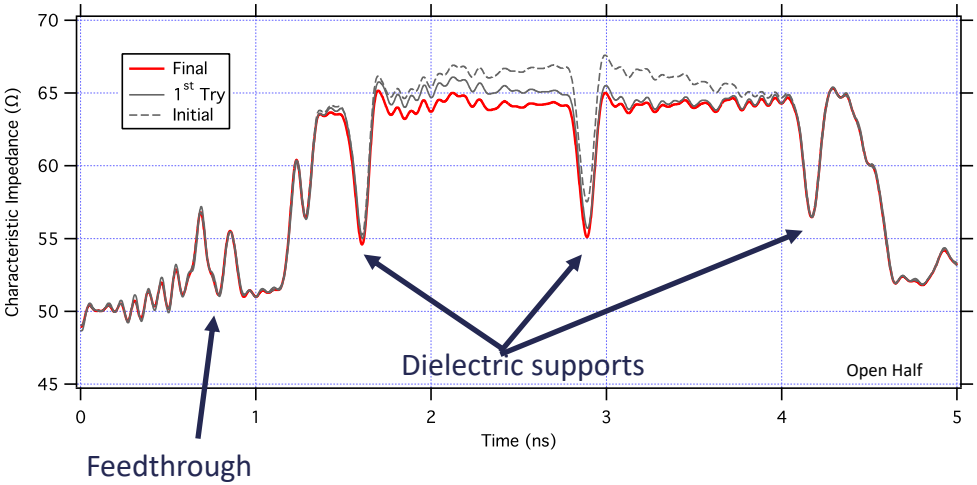
ANSYS MAXWELL

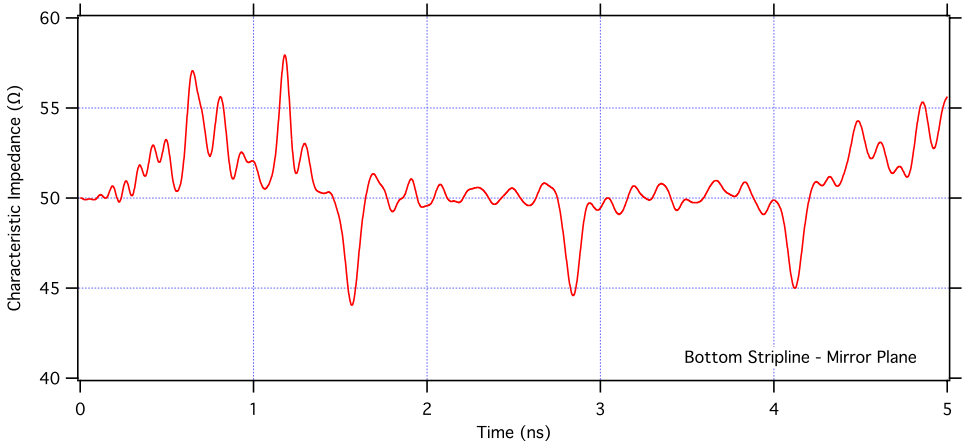




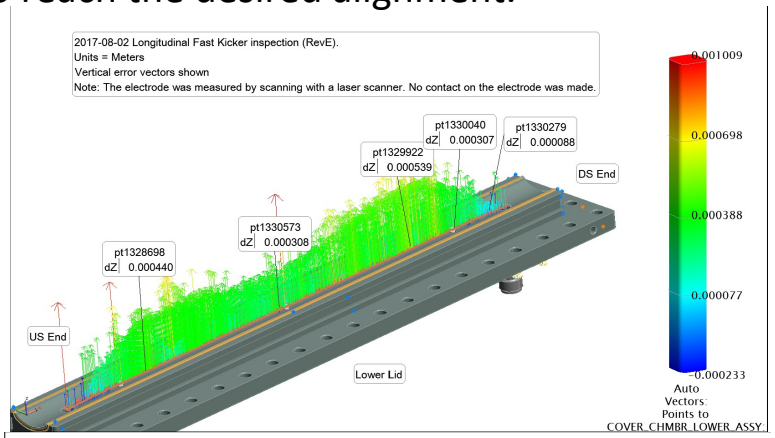
Characteristic impedance highly sensitive of electrode position

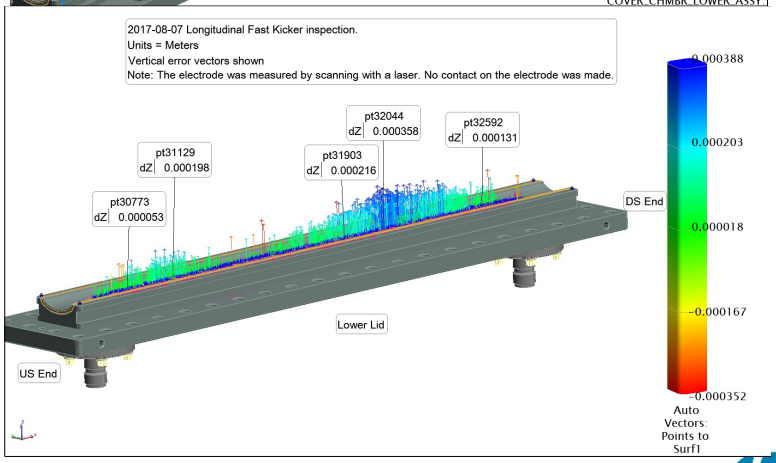
TDR Measurements (Kicker Open Halves)



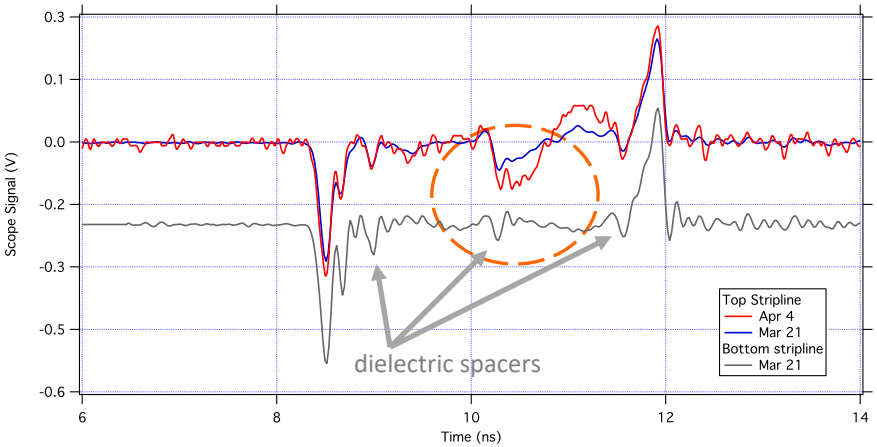


Stripline height can more easily be corrected in an open half kicker. TDR measurements (left), supplemented by laser scans (below), are used to reach the desired alignment.

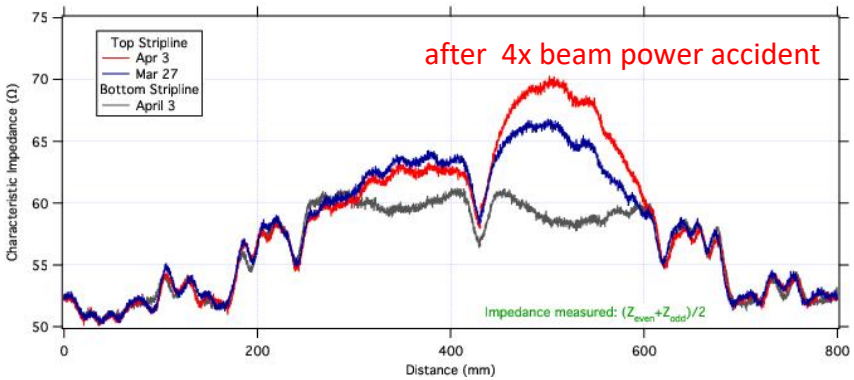




Diagnostics based on beam signals and TDR measurements during operational intervals (original stripline: Mar-Apr '17)



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.

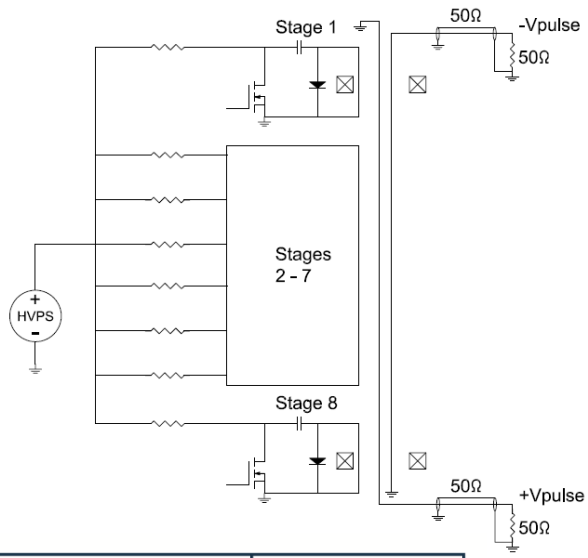
This kicker operated within specs until a mishap caused excessive beam power to be absorbed (HHC cavities detuned at full current).

In normal beam conditions power dissipation below 4 W/stripline, in line with 2.5 W value estimated by CST Particle Studio simulations.

New stripline installed in Sept. 2017 has operated flawlessly. Beam power interlock added, HHC tuning procedure revised.

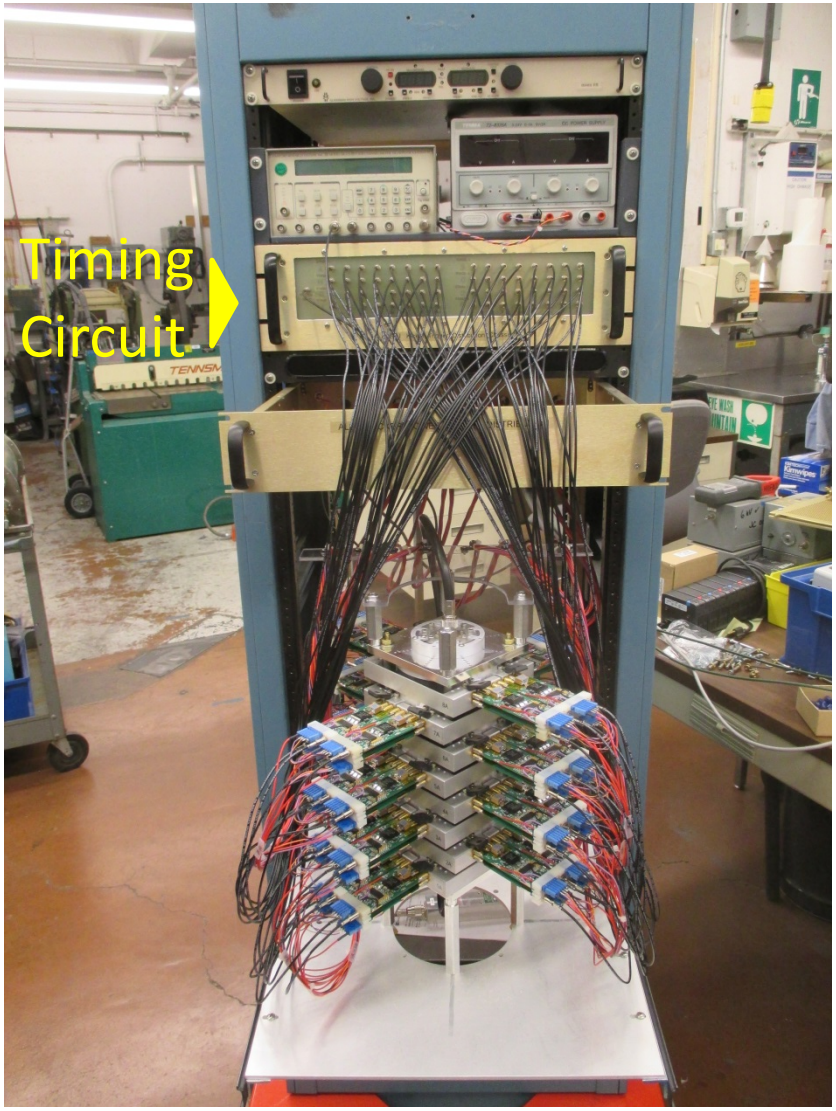
Bipolar inductive voltage adders (IVA's) are the baseline pulser approach for driving the stripline kickers

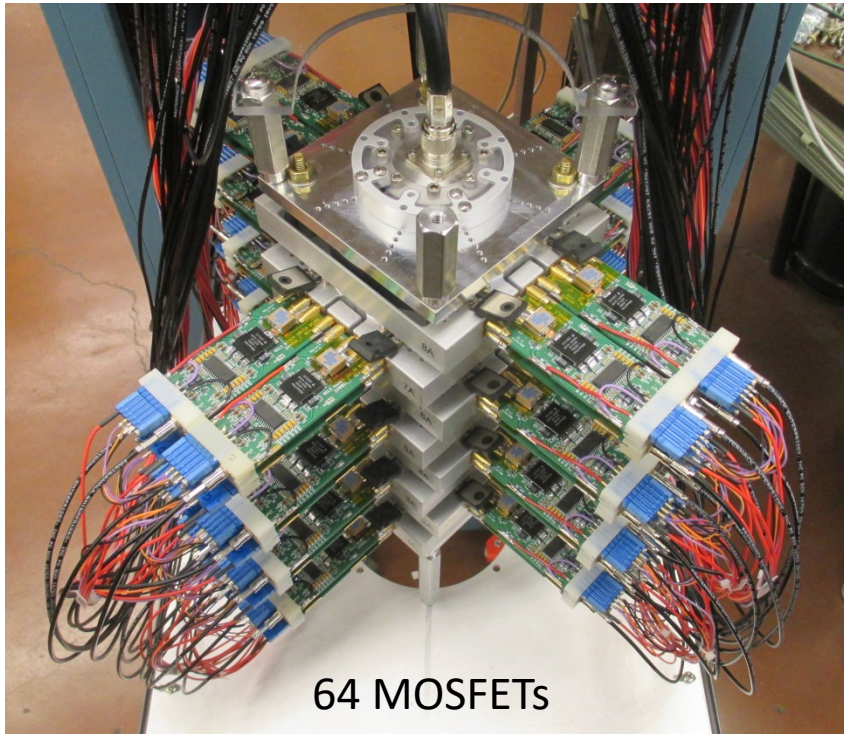
- Similar to systems at LLNL, SLAC, LLE, CERN, etc.
- MOSFETs
- Adjustable pulse width
- Simplified timing synchronization
- Minimum number of pulsers
- Readily available commercial components

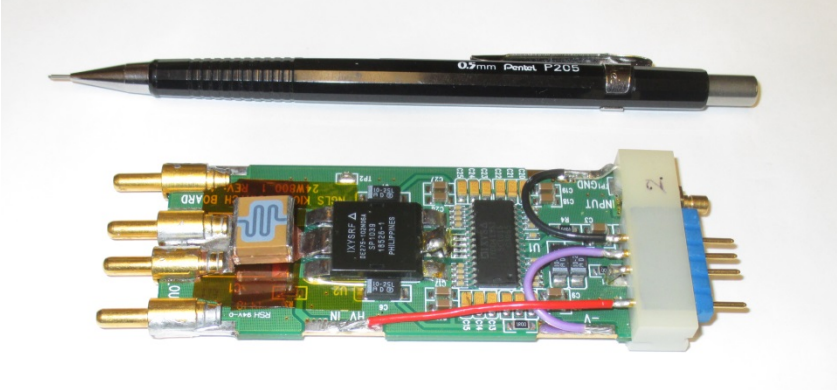


Load Impedance (2 parallel 50 ohms)	25 ohms
Stripline Voltage	+/- 5.25 kV
Stripline Current	+/- 105 A
Rise/Fall Time (5-95%)	7 ns
Flattop (95-95%)	50 ns
Flattop Ripple	+/- 1%
Repetition Rate	<0.1 Hz

ALS Test 8-stage bipolar inductive voltage adder using high voltage MOSFETs

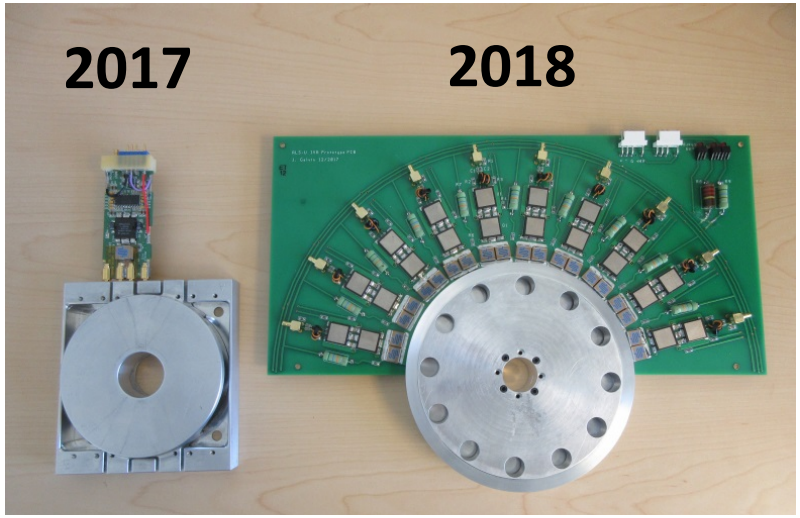


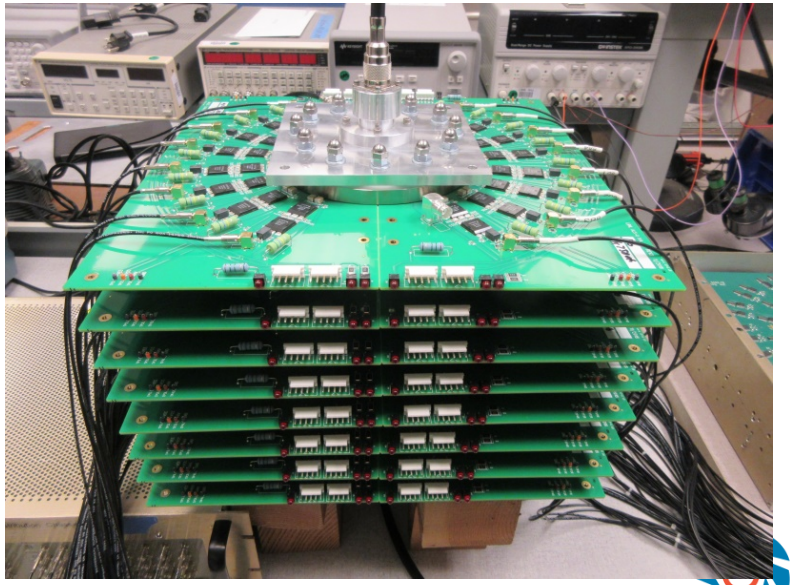


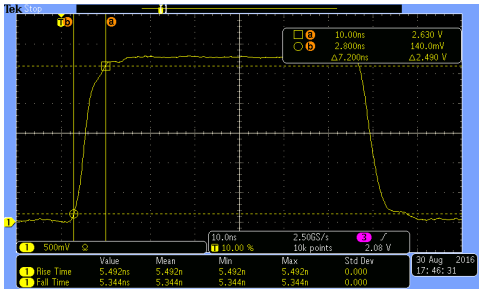


We are continuing to develop the inductive voltage adder for shorter rise/fall time

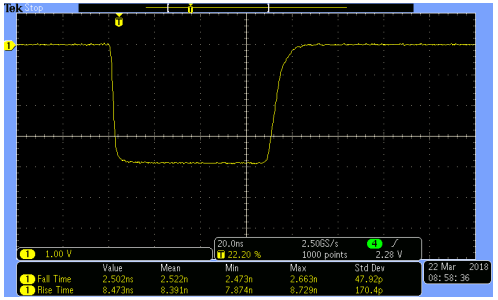
- Adopted a LLNL core housing design
  - Lower inductance than the first prototype
  - Informal LLNL collaboration
- New MOSFET PC board
  - Updates gate driver IC
  - Adds more parallel MOSFETs to lower current/device, decrease inductance, and allow heavier loading
  - Adds LED-based diagnostics
- Plan is to demonstrate test the full system with beam by Spring 2019.







Mod. 2017 –Full kicker

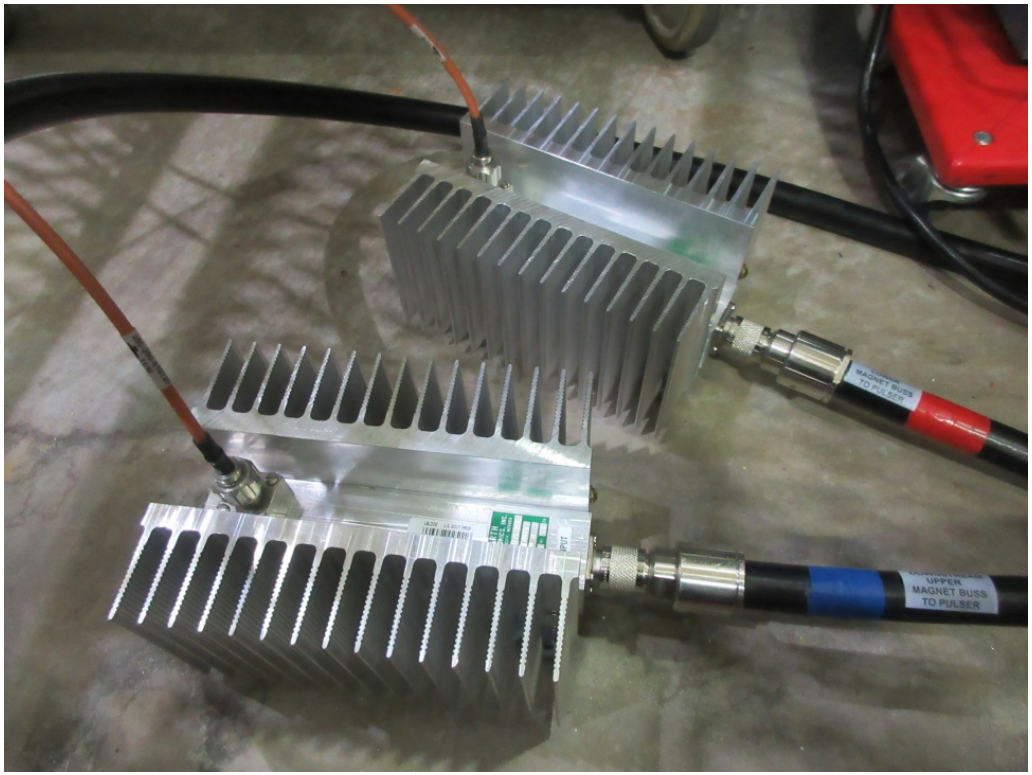


Mod. 2018 –Single stage

Barth custom developed 20W attenuators to meet the ALS-U requirements.

Absorb high voltage pulses after stripline transit and beam induced voltage.

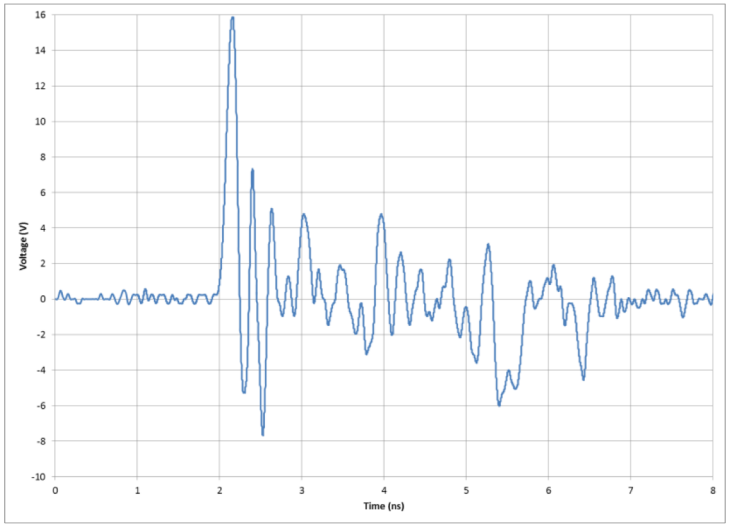
- 26dB attenuator (20x)
- Can handle the 5-6kV, 50ns pulses (HN connectors)
- 20W (for the ~10W beam induced signal power)
- ~5GHz BW
- Currently installed at ALS



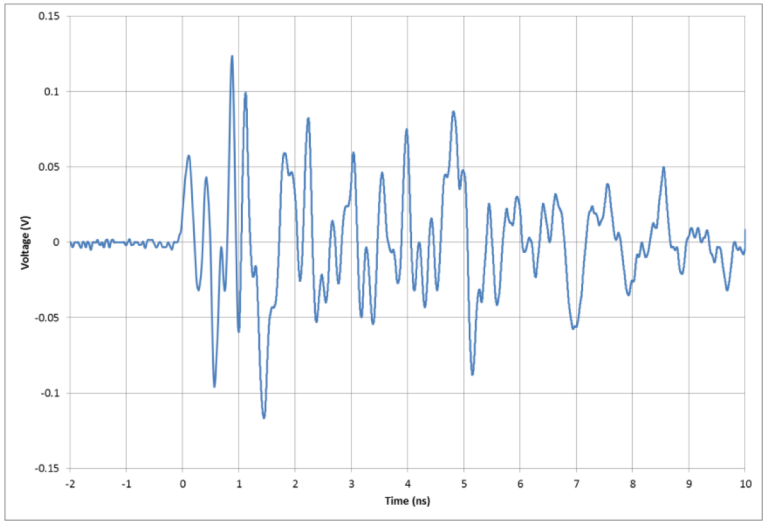
This takes care of the upstream ports termination

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. Long HV cables a natural low-pass filter.
  - 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

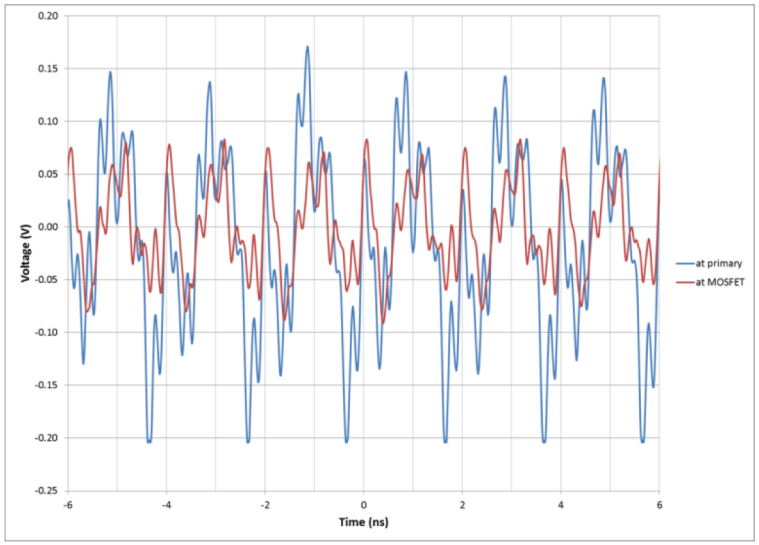


On a primary when pulser is connected

Odd/even mode and other impedance mismatches generate beam power at the downstream (i.e. pulser) ports

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 (≤200mV peak for 500mA multibunch mode)
  - No measurable temperature rise of any IVA components



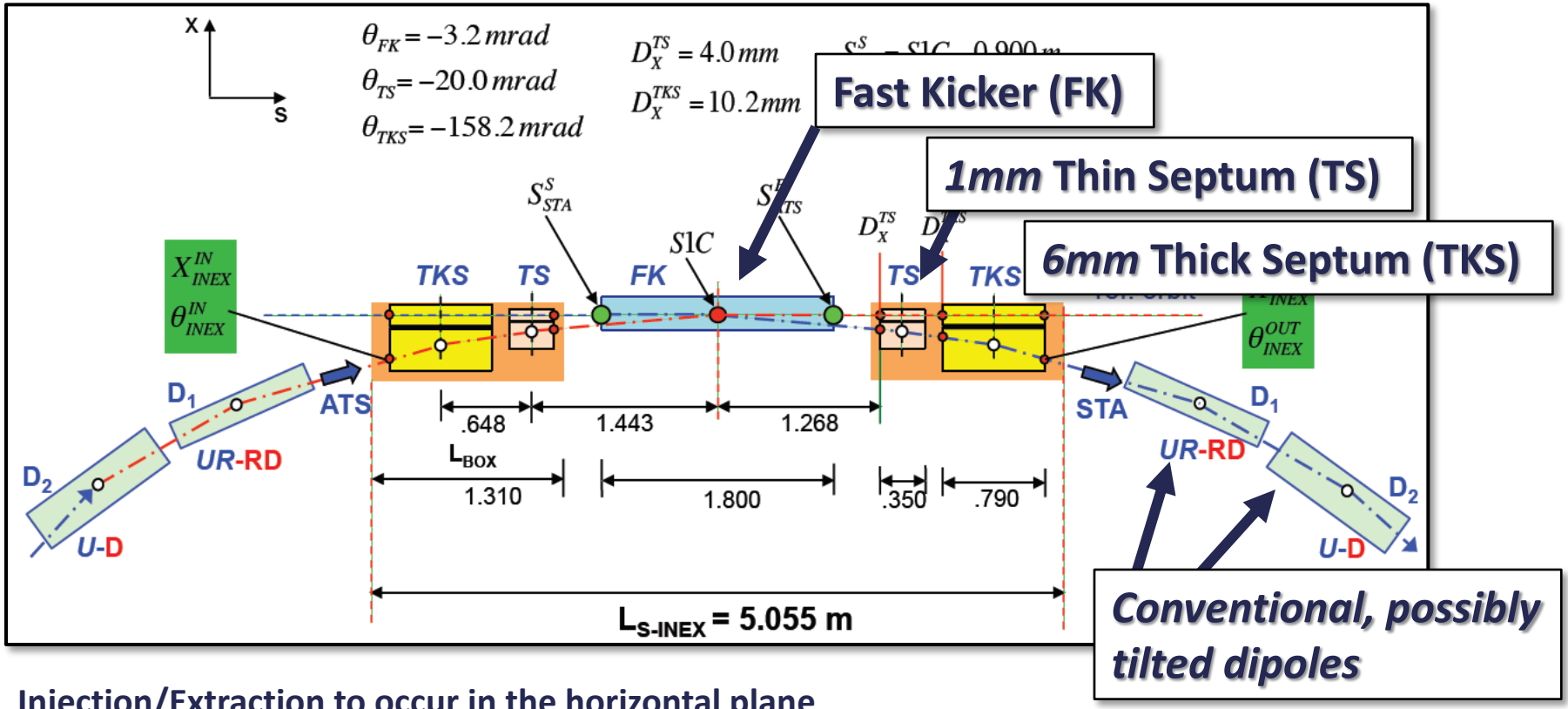
- Do we introduce any multibunch instabilities as a result of possible reflections at the pulser coming back through the kicker?
  - No additional measurable multibunch instabilities

Conclusions and Acknowledgments

- Implementation of swap-out injection involves several aspects of the machine design.
  - ALS-U takes advantage of existing ALS subsystems and facilities, but that generates some additional design constraints.
  - Some aspects not yet analyzed to completion. On-going work has to fit in Project's schedule.
- Fast kickers remain a challenging technical issue.
  - ALS-U situation more benign than higher energy machines in some respects.
  - Useful experience from ALS test kicker. Feedthroughs wideband characteristic impedance and even/odd mode impedance matching not too critical. TDR measurements helpful in kicker assembly and diagnosing after installation.
  - While commercial pulser solutions exist, in-house design allows thorough testing and customization. Results obtained so far very close to fully satisfying requirements.
  - Supplier able to develop necessary high-voltage, high-bandwidth loads in order to kick at full beam current.
- Contributions by: T. Luo, C. Pappas, C. Steier, C. Sun, C. Swenson, M. Venturini, W. Waldron

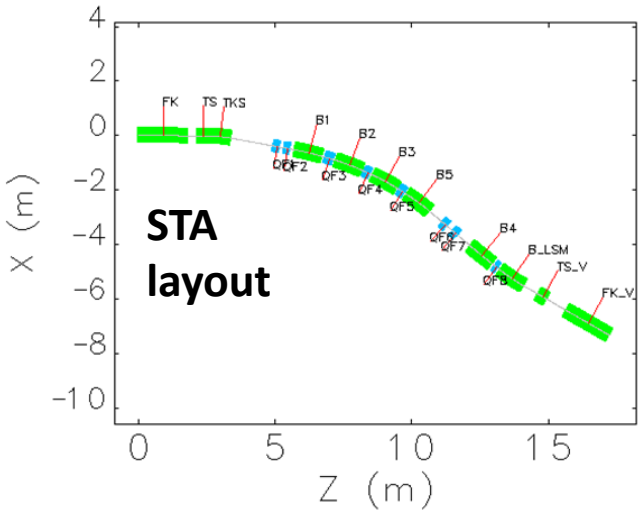
Backup Slides

Conceptual design of Storage-Ring injection/extraction sector with fast kicker

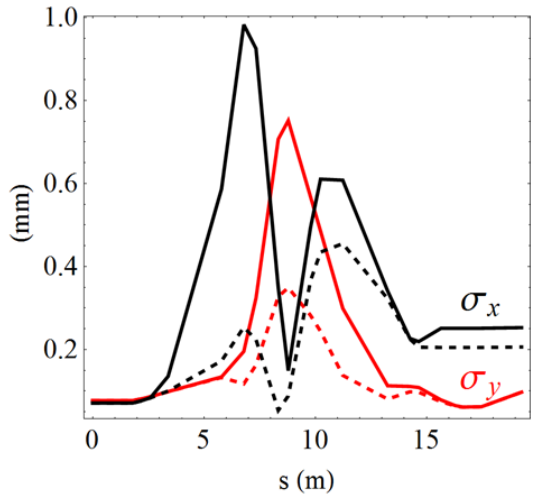


- Injection/Extraction to occur in the horizontal plane
- Pulsed septa scaled from existing devices in ALS
- Min. separation between stored and injected/extracted beams at thin septa is 4mm
- Optimum partition of stay-clear spaces between the two sides of the thin septa?

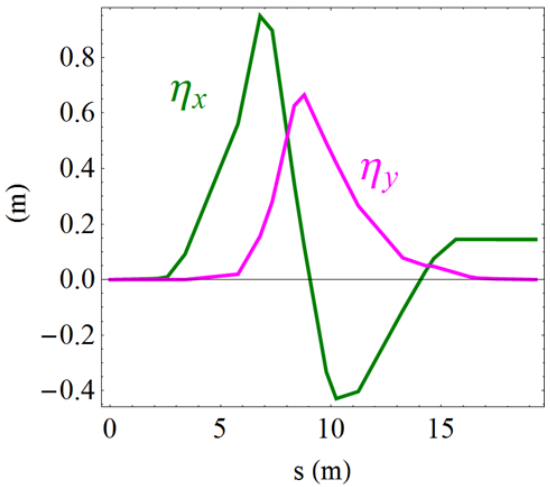
A preliminary design for the STA/ATS transfer lines shows feasibility



rms sizes



Dispersion

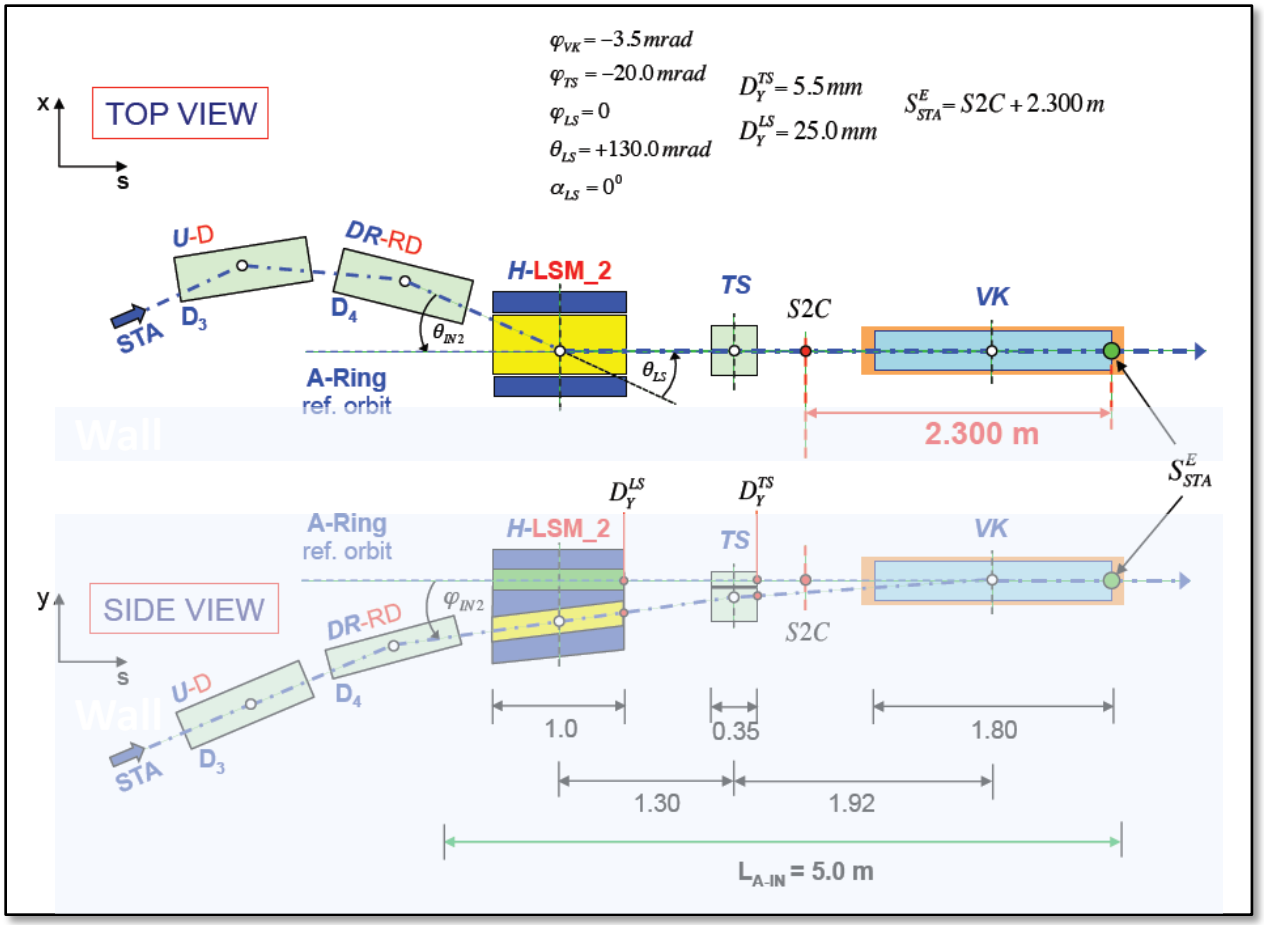


- Fairly large magnet-count needed to meet all requirements
- Most dipoles, quads are rotated; magnet supports may not be trivial
- More work needed (conflicts between magnets, identify need for special magnet designs …)
- Room for further optimization (reduce magnet count?)

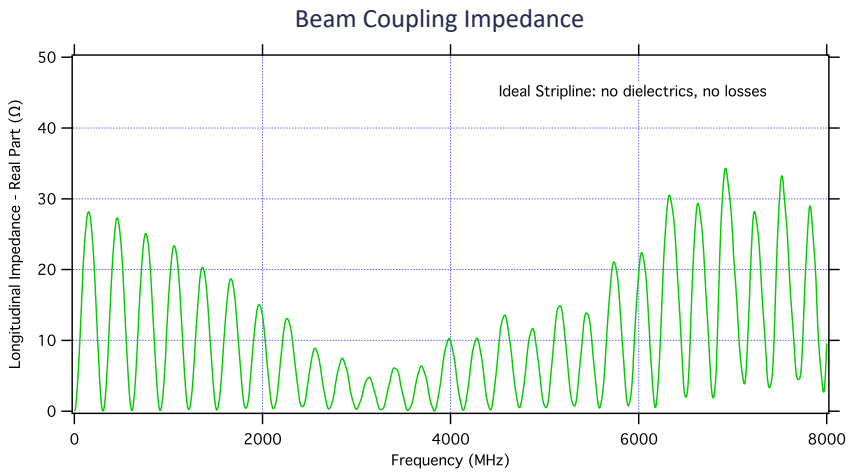
STA/ATS Injection into Accumulator from Storage R. involves Lambertson, Thin Septum, Fast(-ish) Kicker

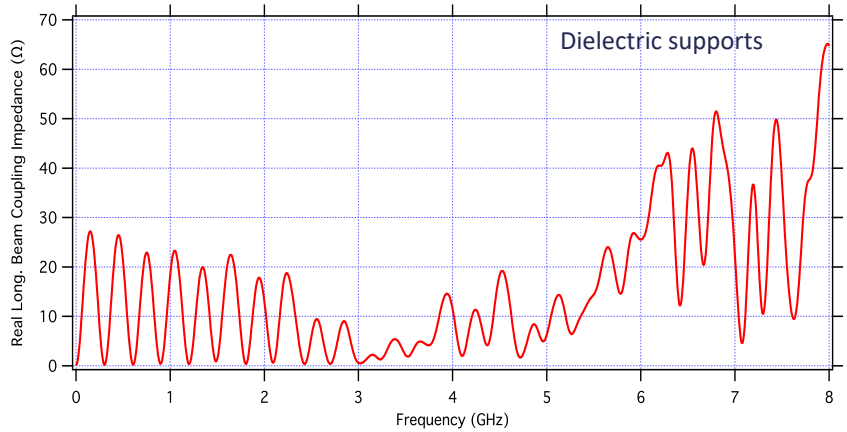
- FK in AR same as FK in SR (for simplicity)
  - But rotated by 90deg
- FK and Thin Septum to bend vertically
- Lambertson to bend horizontally

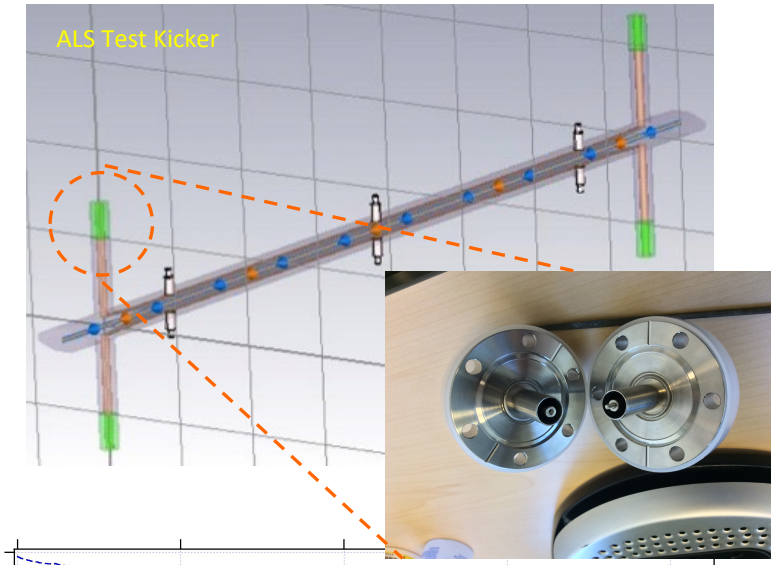
Schematic of STA line

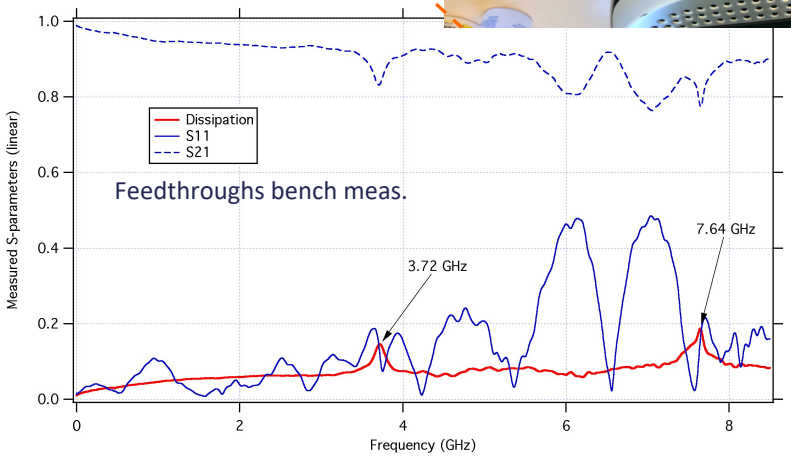


Limits of Computer Simulations



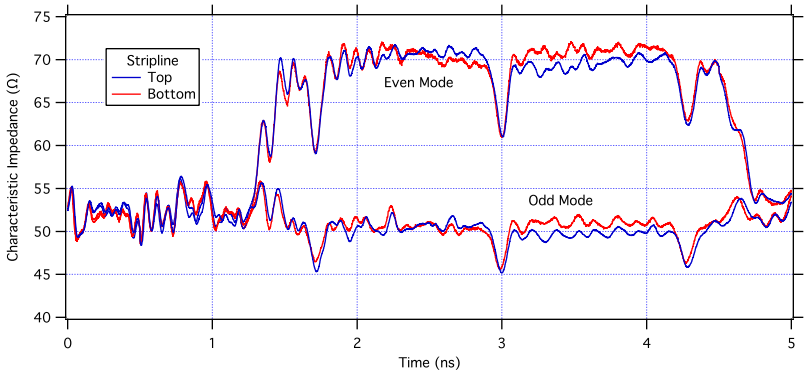






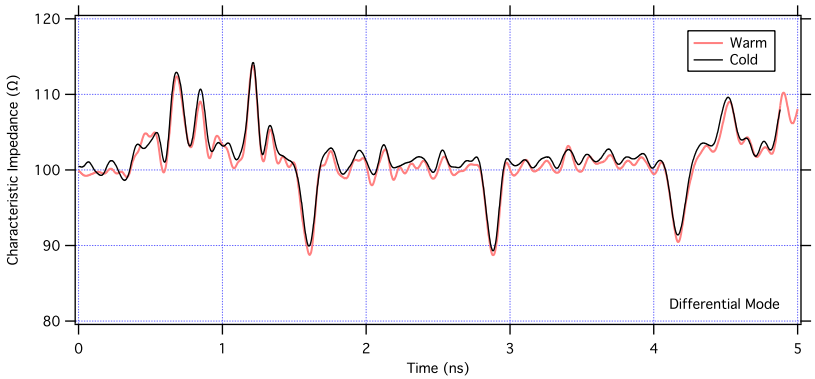
Feedthroughs modelling extremely complex. They can cause a stripline to deviate considerably from its theoretical behavior.

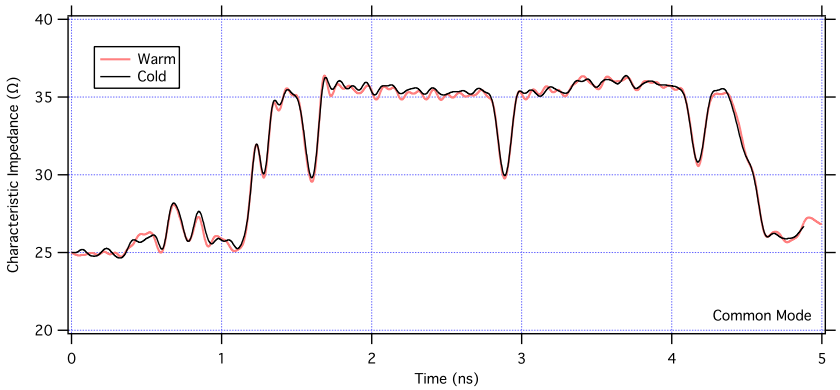
TDR Measurements (Full Assembly)



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:

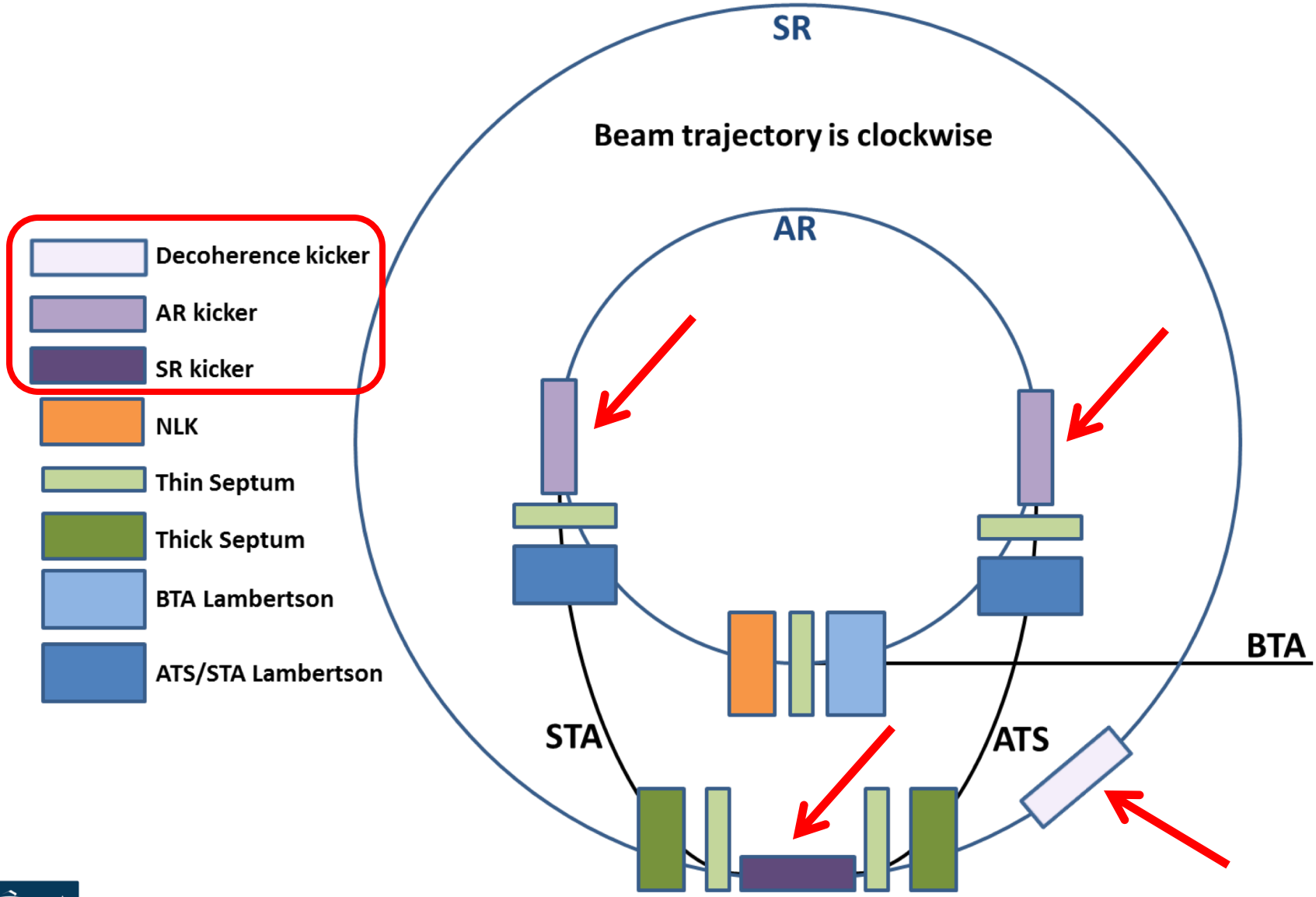
$$Z_{diff} = Z_{odd1} + Z_{odd2}$$
$$Z_{comm} = Z_{even1} Z_{even2} / (Z_{even1} + Z_{even2})$$



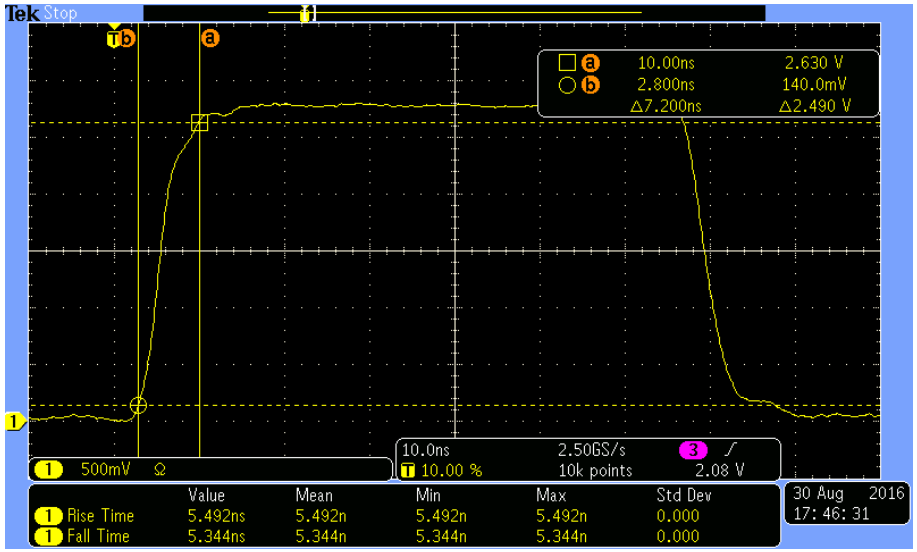


Measurements during and after baking

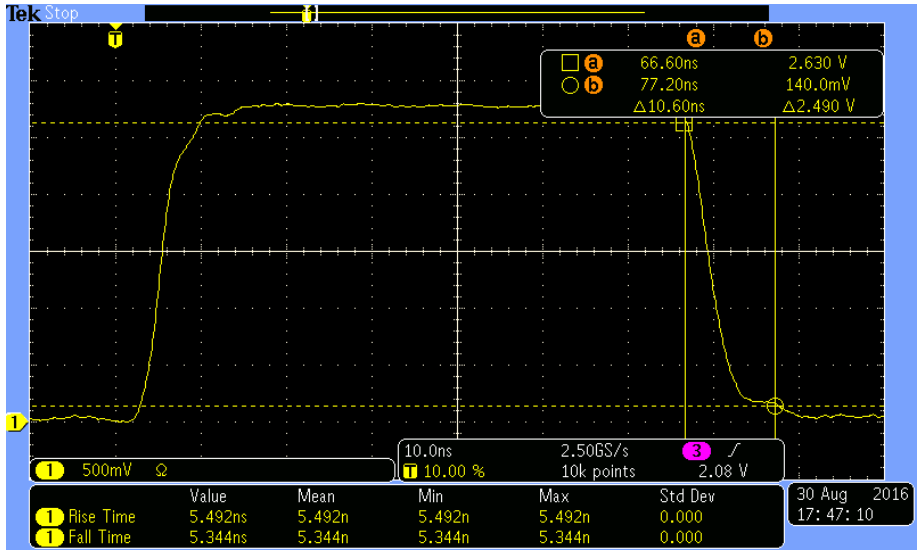
There are 4 stripline kickers that need pulsers



Stripline kicker pulser voltage waveforms (2017 Model)



5-95% rise time = 7.2ns



95-5% fall time = 10.6ns

More work is required to improve the fall time

Preliminary results of the new MOSFET board with Vcharge=400V into 4.9ohms and 2.6ohms