Mechanical Design of ALS-U Swap-out Kicker Stripline Electrodes

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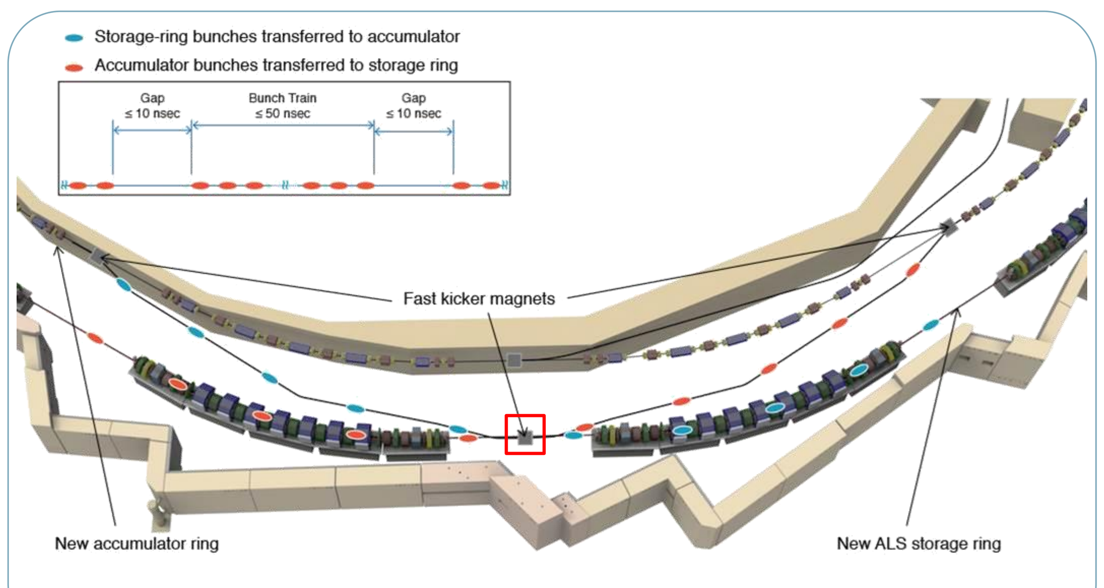
Introduction

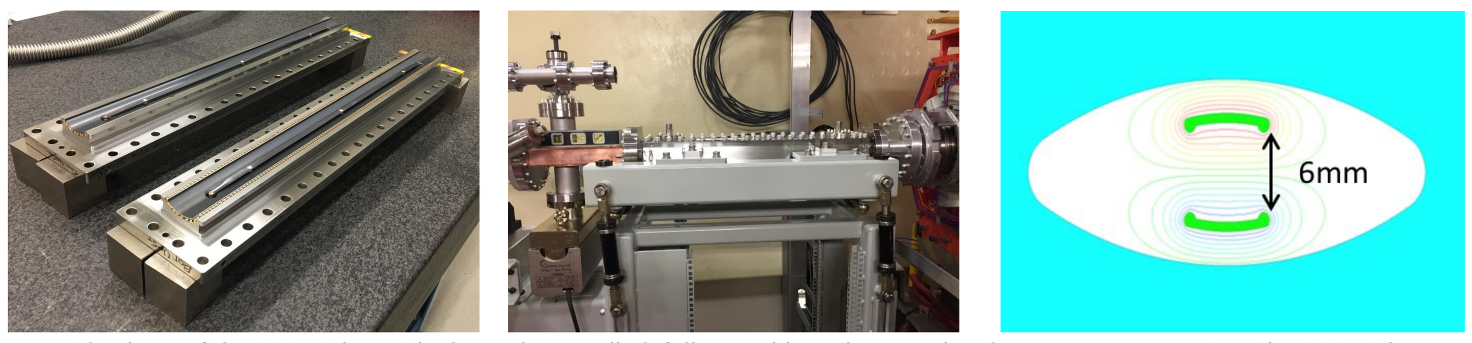
The Advanced Light Source is a Department of Energy-funded synchrotron facility that provides users from around the world access to the brightest beams of soft x-rays, together with hard x-rays and infrared, for scientific research and technology development in a wide range of disciplines. The ALS-Upgrade project will replace the existing storage ring and add a low-admittance accumulator ring to allow on-axis swap-out injection in order to lower emittance. A pulsed magnet system with an effective 10 ns rise/fall time and 50 ns flat top swaps electron bunches between the storage and accumulator rings without disturbing bunches circulating in the storage ring.



Location of the Swap-out Kicker in the Storage Ring shown by red box.

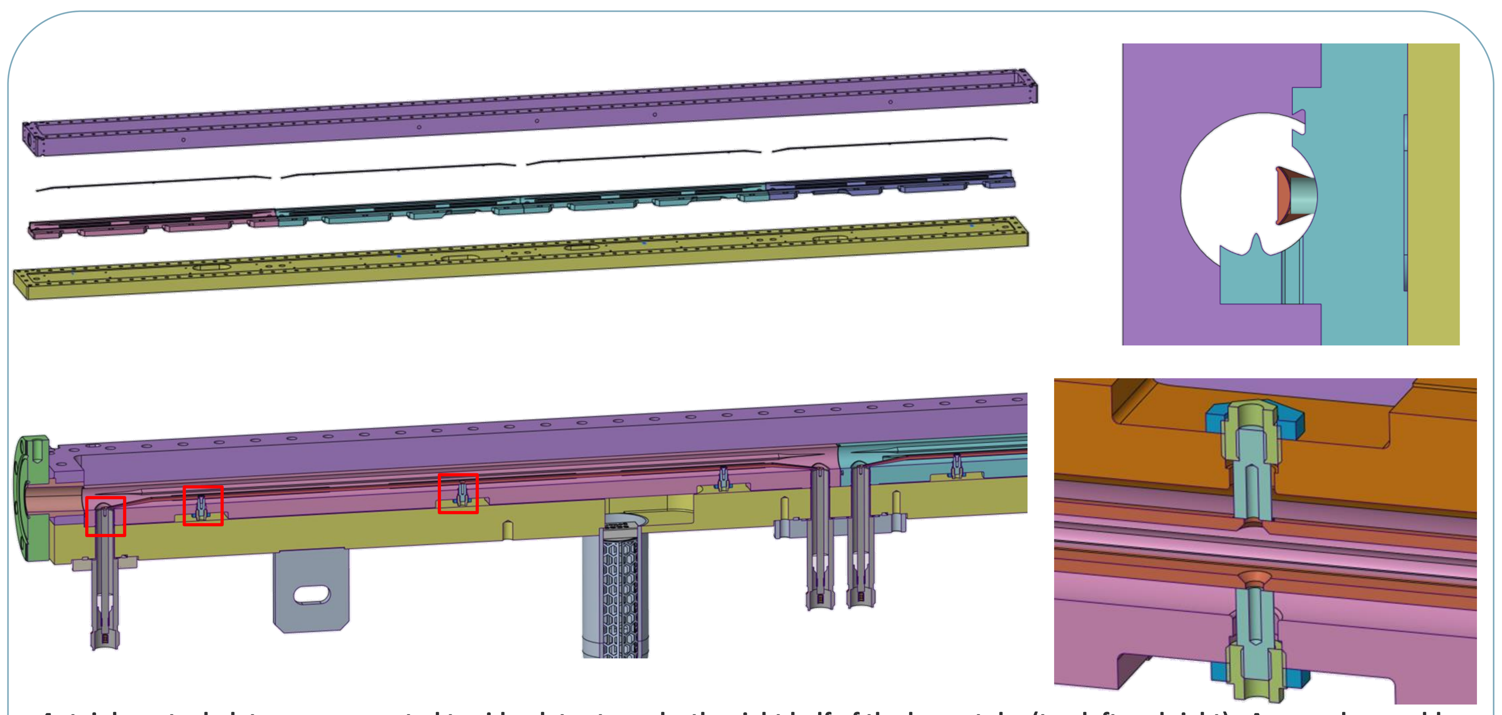
Kicker Layout and Assembly

A design study examined the rise/fall time requirements and available ~2 meters of space in the storage ring lattice and determined that a stripline kicker segmented into 4 x 475 mm long electrode pairs with a separation of 6 mm was the strongest candidate solution. A single electrode pair research and development prototype was designed, built, installed and successfully tested on the existing ALS storage ring. Side plates and a chamber body of stainless steel compressed aluminum wire to form the vacuum chamber. Electrical feedthroughs with copper central posts attached to the ends of the electrodes with 3 adjustable height ceramic posts act as insulated alignment features along each electrode.



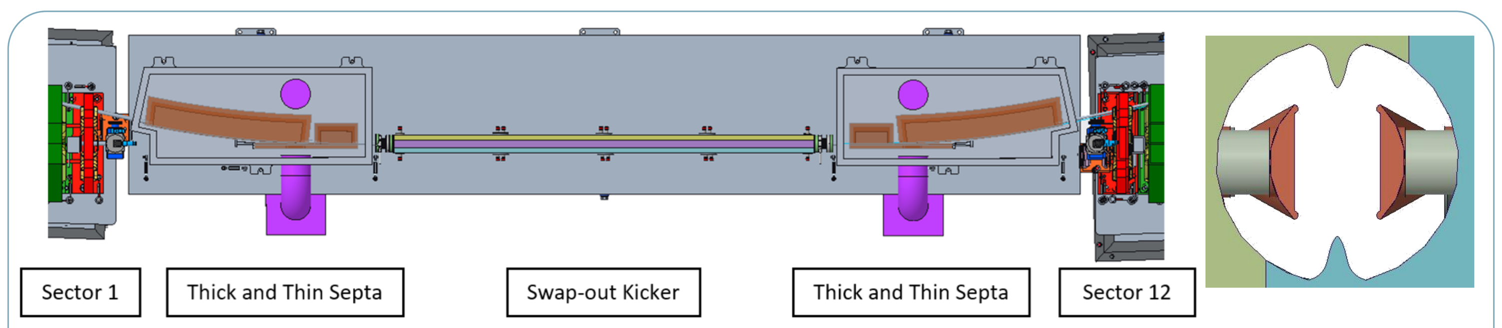
The two side plates of the R&D Kicker with electrodes installed, full assembly in the tunnel and aperture cross section. The R&D Kicker was a vertically kicking beam to avoid wider stored ALS beam size, while the ALS-U will be horizontally kicking with electrodes rotated 90 degrees.

The ALS-U design utilizes these features and incorporates 4 Vacuum ports along the length of the body are connected to 2 antechamber volumes that connect to the beam path through slots optimized to balance vacuum conductance and beam impedance.



4 stainless steel plates are connected to side plates to make the right half of the beam tube (top left and right). A second assembly of plates forms the left half of the beam tube. Electrodes are connected to feedthroughs and adjustable height ceramic posts (lower images). The ceramic posts sit in a Nitronic 70 bushing which is raised and lowered using threads in the beam tube plate, while a nut on the OD of the Nitronic bushing locks the posts position after adjustment. A countersink on the electrode where it mates to the central ceramic post acts as an anchor while slotted counterbores at the other posts act as sliding joints.

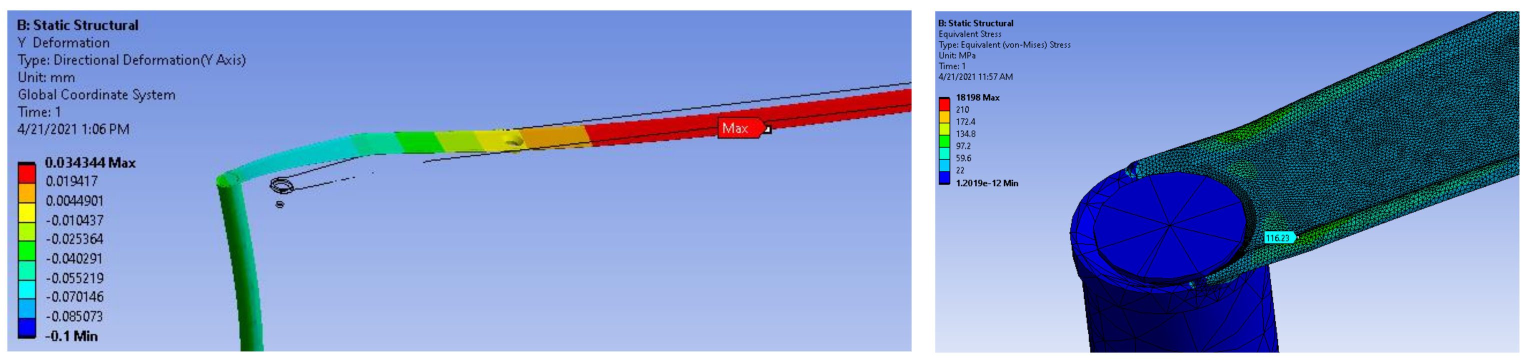
The placement of the kicker in the storage ring is a balance of stay clears to transfer lines, minimizing electrode spacing, electrode heating and alignment tolerance. Synchrotron light from the upstream arc sector can strike the electrodes with enough power that photon absorbers were considered between electrode pairs to shadow each 0.475 m section or upstream of the entire kicker to shadow the whole device. The former was non-workable due to the resulting increase in the length of the device if the absorbers had proper aperture transitions. Consideration of various electrode to electrode separations, and offsets to the stored beam revealed that an increase of electrode spacing from 6 mm to 9 mm or more would be required for a single absorber to mask the whole device.



The layout of the Swap-out straight for the ALS-U Storage Ring and cross section of the Swap-out Kicker showing the electrode orientation. A photon absorber located in between the Swap-out Kicker and Septa box would need to be positioned less than 1 mm offset from the stored beam to block synchrotron light from striking the kicker's electrodes.

Thermal Requirements and Modeling

Thermal expansion defines much of the mechanical design of the electrodes. Beam induced heating and synchrotron light strike are the main sources of heat deposited on the electrodes. Excessive heating of electrodes can cause thermal expansion beyond what the support posts and copper feedthroughs can accommodate. The electrode uses the center hole as an anchor point with a screw in the electrode and shoulder screw at the other two ceramic posts accommodating expansion and the copper posts flexing. To keep the stress from flexing the posts < %100 of yield strength, the diameter (4.85 mm) and length (60 mm) of the beams was customized and the maximum deflection/ thermal expansion set at 0.25 mm. This resulted in %85 stress of yield strength in the posts and acceptable deflections and stress in the electrodes as well.



The electrodes are designed to expand 0.25 mm towards the copper feedthroughs. The electrode deflects up towards the beam near the feedthrough and away from the beam on the opposite side of the ceramic support. Stress in the electrode is <30% of the Ultimate Tensile Strength for molybdenum.

To conservatively estimate the temperature rise in the electrodes conduction through the ceramic posts and copper feedthroughs was neglected and thermal radiation between the electrodes and chamber body was the only path considered. Solving the thermal radiation equation for the electrode temperature based off of incident power *P*, chamber temperature *T*, area of thermal radiation *A*, emissivity of chamber and electrode Ɛ, and the Boltzmann constant σ.

$$T_{electrode} = \sqrt[4]{\frac{P}{A} * \left[\frac{1}{\varepsilon_{electrode}} + \frac{1}{\varepsilon_{chamber}} - 1\right] * \frac{1}{\sigma} + T_{chamber}^{4}}$$

The material selection for the electrodes was made due to high heat loads. The maximum total power deposited on an electrode is 4 watts, 3.2 watts of synchrotron light strike and 0.8 watts of beam induced heating. Experience from the ALS R&D prototype demonstrated stainless steel chamber and copper electrode emissivities of 0.5-0.6. Work done at SLAC on the TEM kicker electrodes [1] showed that molybdenum could be oxidized to enable effective radiative cooling and technical note 4206 by the National Advisory Committee showed emissivity results for molybdenum between 0.5-0.8 [2]. The candidate electrode materials were compared at different incident powers and with emissivities of 0.5 at the low end of results measured at LBNL and other reported results. Molybdenum satisfied the requirement to accommodate 0.25 mm of expansion at 5 watts, above the 4 watts requirements, while copper could only handle less than 1 watt (highlighted in blue).

Power, Temperature and Expansion for .5 and .5 ε materials			
Power (W)	Electrode Temperature (C)	Copper Expansion (mm)	Molybdenum Expansion (mm)
0.1	9	0.038	0.011
0.5	40	0.162	0.048
0.75	56	0.226	0.066
1	70	0.281	0.083
3	147	0.593	0.174
4	174	0.702	0.206
5	197	0.795	0.234
6	217	0.877	0.258
8	252	1.017	0.299
10	281	1.134	0.334

The previous heating analysis explored steady state conditions and not transient cases. Experience from the R&D kicker showed that increased electrode heating from bunch length shortening made an accelerator interlock necessary when the third harmonic cavity loses tuning a requirement. Additionally, storage ring beam offsets up to +/- 1 mm for steady state operation are being investigated to understand limits of steady state conditions that can be accommodated and transients.

Coatings and Prototyping

Past developments and new work have demonstrated emissive coatings capable of satisfying the thermal requirements. The main chamber body pieces are all 304 stainless steel, chosen for its mechanical and magnetic properties and compatibility with ultra high vacuum. Surfaces of the chamber that face the electrodes are blackened by an alkaline oxidizing process defined by MIL-DTL-13924 Class 4 by a commercial vendor. The R&D electrodes were copper and coated at LBNL by cathodic arc deposition of copper oxide, and the molybdenum coated by baking it in atmosphere at 538ºC for 1.5 hours with a 2 hour ramp up and 3 hour ramp down. Measurements performed by Jacob Jonsson at LBNL showed 0.59 and 0.69 emissivities of molybdenum with a polish 16 Ra and as cut by wire EDM.

Prototyping efforts making quarter and full scale prototypes at LBNL's main shop have been successful. The rough shape of the electrode is cut using wire EDM, the profiled on a CNC, and finished with hand polishing. Measurement of the initial prototype on a CMM showed profile tolerances better than 100 microns in most location with one deviation of the backside of the electrode reaching 112 microns.

Coated 1" diameter coupon on left and full scale prototype electrode on right. Electrode is cut by wire EDM and then profiled in a CNC. Improvements in CNC programming have reduced tool marks and other witness marks in production of electrodes.

Conclusion and Future Work

The design of the electrodes of the ALS-U Swap-out Kicker are key to enabling on-axis swap-out injection. Experience from the mechanical design of the ALS R&D stripline kicker combined study of the ALS-U requirements, the work of other labs and prototyping at LBNL have pushed the progress of the ALS-U design. All components of a full scale prototype are being constructed with assembly planned for the fall of 2021, with 8 prototype electrodes already completed. Testing and assembly of these components will give feedback to continue improving the design. Thanks to all the collaborators at LBNL and other lab's in the progress of this design.

Citations

1. A. Krasnykh, B. Hettel, J. Seeman. "Design and R&D on TEM-based Kicker Systems at SLAC". SLAC-PUB-17099. SLAC Linear Accelerator Laboratory. 2018.
2. W. Wade. "Measurements of Total Hemispherical Emissivity of Various Oxidized Metals at High Temperature". Technical Note 4206. National Advisory Committee for Aeronautics. 1958.

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