

# Development of Stripline Kicker for APS

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This project aims toward characterizing a new ultra-fast stripline kicker for the Advanced Photon Source Upgrade (APS-U) to meet the requirement of extremely low beam emittance in the upgraded synchrotron. The project mainly consists of three parts in parallel: 1. Develop an analytic model of the stripline kicker. 2. Perform CST Microwave Studio simulations with solid models of the kicker. 3. Conduct real hands-on measurements on the kicker with network analyzer and Time-Domain Reflectometry (TDR). We want to study and compare how the impedance of the transverse kicker corresponds to spatial displacement of the two blade-like stripline conductors. We will also discuss what we will do for next steps.

## I. INTRODUCTION

The Advanced Photon Source (APS) is preparing for a significant upgrade for the accelerator and beamline facilities, in order to largely improve the brightness, coherence and stability of the storage ring x-ray beams. The Advanced Photon Source Upgrade (APS-U) storage ring will operate with a transverse electron beam size  $< 100$  pm, much less than the present value of 3.1 mm. This small beam size is not compatible with traditional techniques of injecting electrons into a storage ring which rely on multi-turn damping. To overcome this limitation we are developing a set of new 6-nanosecond rise-time, 6-nanosecond flattop and 6-7-nanosecond fall time stripline kickers to transfer the 6 GeV electron beam from the injector to stable orbits within the proposed storage ring.

The transverse strip-line kicker is mainly composed of two blade-like electrodes, four feed-throughs and an outer conductor (shown in picture). It is essentially a modified shielded twin-line transmission line system. As a transmission line, the system has its impedance. Our goal is to optimize the impedance of our device so that it matches the intrinsic 50 Ohm impedance of the coaxial transmission lines it is attached to. This is done to minimize the reflected wave amplitude at the interface between the stripline kicker and transmission line system, reducing the amplitude of the reflected wave mitigates against undesirable beam deflections and damage to the pulsers driving the entire systems of different impedance.

There are two operation modes for our transverse kicker: Even mode, with the same positive voltages on both blades, and odd mode, with opposite voltages on two blades. These names follow the symmetry of the electric field and the potential in the device. As we can see from the CST Microwave studio simulation, odd mode has odd symmetry and even mode has even symmetry, both with respect to the central plane. Each mode has its own characteristic impedance and the odd mode is used for deflecting the high energy electron beam

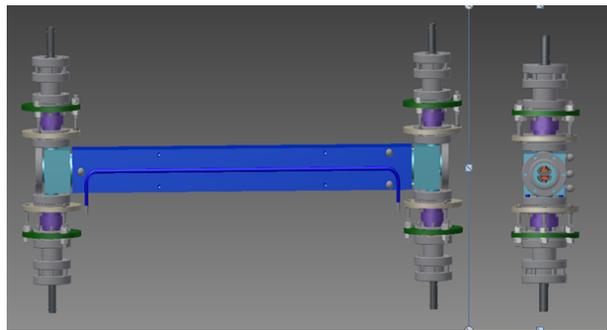


FIG. 1. 3D model of the stripline kicker made in Autodesk inventor. Front view and side view

A similar device has been fabricated and tested in anticipation of using it at the Damping Ring and Pre-damping ring of the Compact Linear Collider (CLIC). The transverse kicker at CLIC has a rise-time around 500ns and flat top around 900ns, and the damped beam has an horizontal emittance of 500nm and vertical emittance of 5nm. These parameters are far from the standards for APS-U. However, the device is still a very good reference for us.

In the following parts of this paper, we are going to present: (1) Theoretical and analytical model of our stripline kicker. (2) Simulation results from CST microwave studio. (3) Impedance variation in frequency domain from network analyzer measurements. (4) Positions of impedance discontinuity by Time Domain Reflectometry (TDR) analysis.

## II. MOTIVATION

APS is the pioneer of top-up injection, which means Injection into the storage ring while any photon shutter is open. This is done in order to improve x-ray beam position stability through constant heat load on X-ray optics, constant heat load on storage ring components

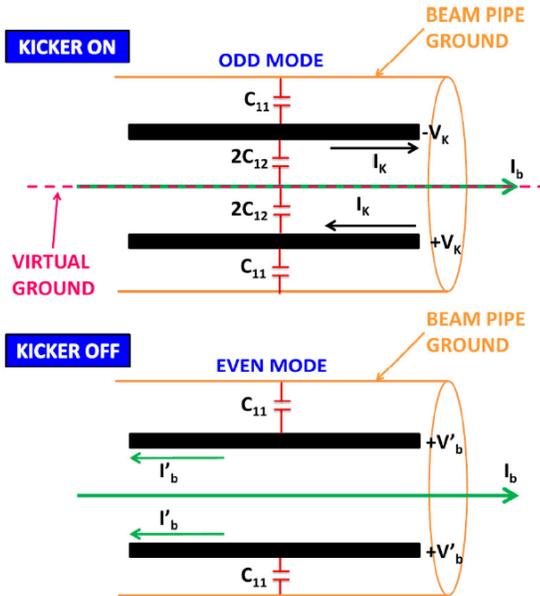


FIG. 2. Scheme of the two operation modes of the stripline kicker: odd mode (with opposite electrode voltage) and even mode (with same electrode voltage).

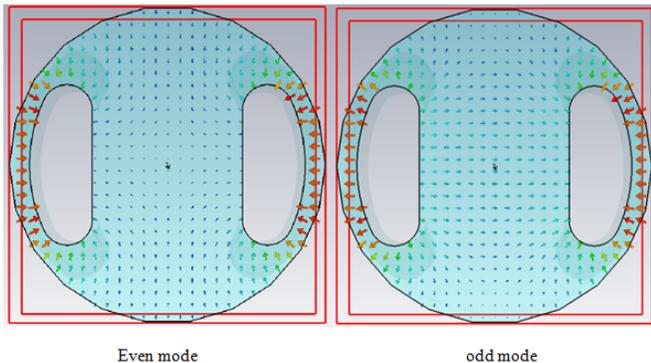


FIG. 3. Electric field line of the device when operating in even mode and odd mode. Simulated by CST microwave studio. Field strength increase from blue to red. We can see even mode shows even symmetry about central plane, while odd mode shows odd symmetry

and constant signal strength for beam position monitors. On the other hand, injection design for an ultra-low-emittance light source, such as the APS upgrade, is limited by strong non-linear effects due to the focusing force applied and the resultant strong sextupoles that make the dynamic aperture very small. Thus, only on-axis swap-out beam injection/extraction can be used. This means that there is not betatron oscillation and the target bunches must be extracted and injected without affecting the emittance and stability of the remaining stored beam, so the kicker field must be negligible at the next upstream or downstream bunches. So, the

duty cycle of the kicker must be extremely short. For APS-U, this is approximately 10 RF buckets at 500 MHz, which indicates 20ns. This is why we need to design an ultrafast kicker with a 6-nanosecond rise-time, 6-nanosecond flattop 6-7-nanosecond fall time and 30kV differential voltage to transfer the 6GeV electron beams.

The electromagnetic requirements on the device to maintain the transmission system as close as possible to  $50\Omega$ , in order to reduce reflected wave amplitude to avoid perturbing adjacent bunches with reflected waves and to eliminate excessive reflection back to the pulser to avoid damage and also to avoid dispersion and wave distortion of the pulse. In addition, we need to couple out the beam wakefield driven excitations of the kicker.

### III. THEORETICAL MODEL

To perform analytic calculations to understand the basic physics behind our measurements, we can model our kicker by a shielded dual conductor transmission line.

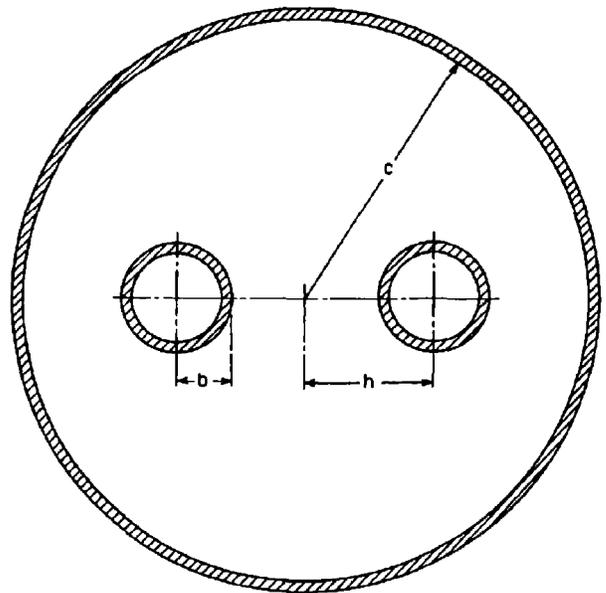


FIG. 4. Shielded dual conductor transmission line, with radius of outer conductor  $c$ , radius of both inner parallel conductors  $b$  and distance between the centers of inner conductors  $h$

The (odd mode) characteristic impedance of the transmission line is given by the formula:

$$Z_0 = \frac{\eta}{\pi} \left[ \ln(2\nu \frac{1-\sigma^2}{1+\sigma^2}) + \frac{1+4\nu^2}{16\nu^4} (1-4\sigma^2) \right] \quad (1)$$

Where we define  $\nu = \frac{h}{b}$  and  $\sigma = \frac{h}{c}$ , and  $\eta = \sqrt{\frac{\mu_0}{\epsilon_0}}$  is the intrinsic impedance of vacuum. This simplified model

is actually a good approximation of our system. We choose the parameters so that the cross section area of the inner conductors are the same as the the cross sections of the kicker blades:  $55.96\text{mm}^2$ . We choose center-to-center distance to be 12mm, and the adjust the outer conductor so that the impedance is about  $50\Omega$ . The outer radius we use is 11.5mm. We will see how it behaves comparing to the real device in following sections.

#### IV. SIMULATION SET-UP

We built two models in CST microwave studio: One shielded dual conductor transmission line exactly the same as the analytic model, and the other is close to the real transverse kicker.

The shielded dual conductor transmission line is made by subtracting two symmetric inner cylinders from the outer cylinder using the Boolean subtract command. The default material of Microwave studio is vacuum in the bulk and perfect conductor on the boundary, which is exactly the situation we need. So, we simply use the default material setting. The parameters are exactly the ones we used in the analytic calculation: 4.18mm inner radius, 12mm center-to-center distance and 11.5mm outer radius. The shielded dual conductor transmission line model is shown in Figure 5.

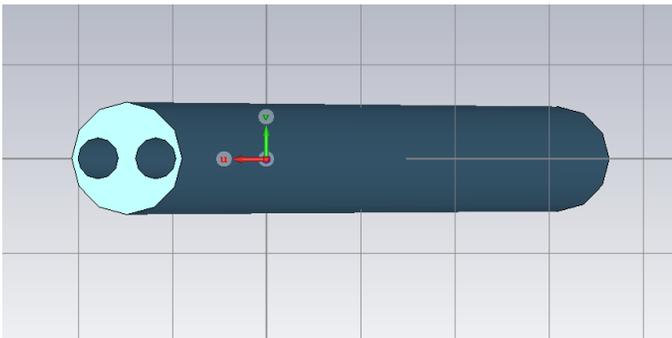


FIG. 5. Shielded dual conductor transmission line model made in CST Microwave studio

The second model is built in a similar but a little bit more complex manner. The outer conductor is modeled by adding up two symmetric elliptical cylinders with semi-major axis 11.2mm and semi-minor axis 7mm, so that is resembles the outer conductor of the transvers kicker. For the inner conductor, we imported the solid model of blades from Autodesk Inventor, and subtract the blades from the outer conductor. The default face-to-dace distance of the blades is 9mm.

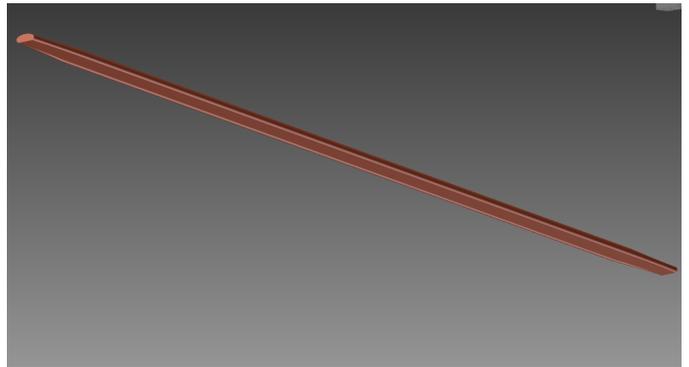


FIG. 6. Blade conductor model made in Autodesk Inventor, which is then imported into CST Microwave Studio

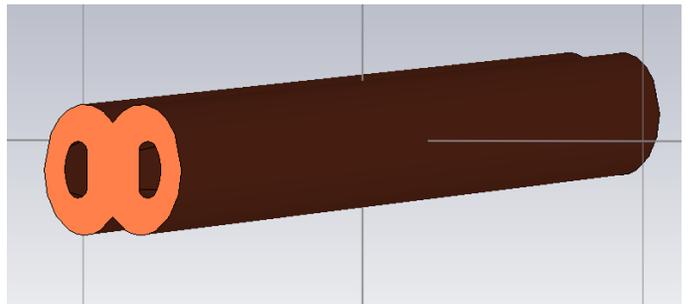


FIG. 7. Transverse kicker model made in CST Microwave studio. The inner conductors are made by the blade model above from Autodesk Inventor.

#### V. NETWORK ANALYZER MEASUREMENT

The set-up of the measurement is simple: connect two ports of the transvers kicker to the two ports the network analyzer. (Shown in figure 8)



FIG. 8. Lab set-up of network analyzer measurements.

What is non-trivial is to adjust the blade position. As shown in the figure, each blade is controlled by three screws on each side. The screw in the middle moves the blade vertically while the other two moves the blade both vertically and horizontally. The distance between two blades are fixed using three metal fixtures of different sizes



FIG. 9. Fixtures of different diameters used to fix the distance between the blades. Diameters are 6mm, 9mm and 12mm from left to right

However, even though we only want to change the vertical position of the blades, we still need to adjust the other two screws as the distance a single screw can move is limited. When one screw hits the end, the control plate is overly tilted so that it is stuck by the other two screws and cannot move further. In addition, tilting the plate too much may also short the inner and outer conductors, which has happened for several times and significantly interfered with the network analyzer measurement. In addition, we should notice that the two sides of the blades are coupled. Sometimes adjusting horizontal position of one end could significantly affect the horizontal position of the other end that has already been adjusted. So, we need to check the other side of the kicker each time after we make any adjustment.

The network analyzer is set in impedance magnitude mode with center frequency 352MHz, which is the synchrotron frequency) and span 20MHz. The network analyzer shows the impedance change corresponding to frequency change. We set marker at both the point at 352MHz and the point where impedance equals to 50Hz, to find the working impedance and the optimal working frequency. However we need to be careful that sometime the cables can have resonance in the frequency range that we are interested in. In these cases, the results are largely affected. One of the method to get rid of the resonance is to cut the cable to an appropriate lengths,

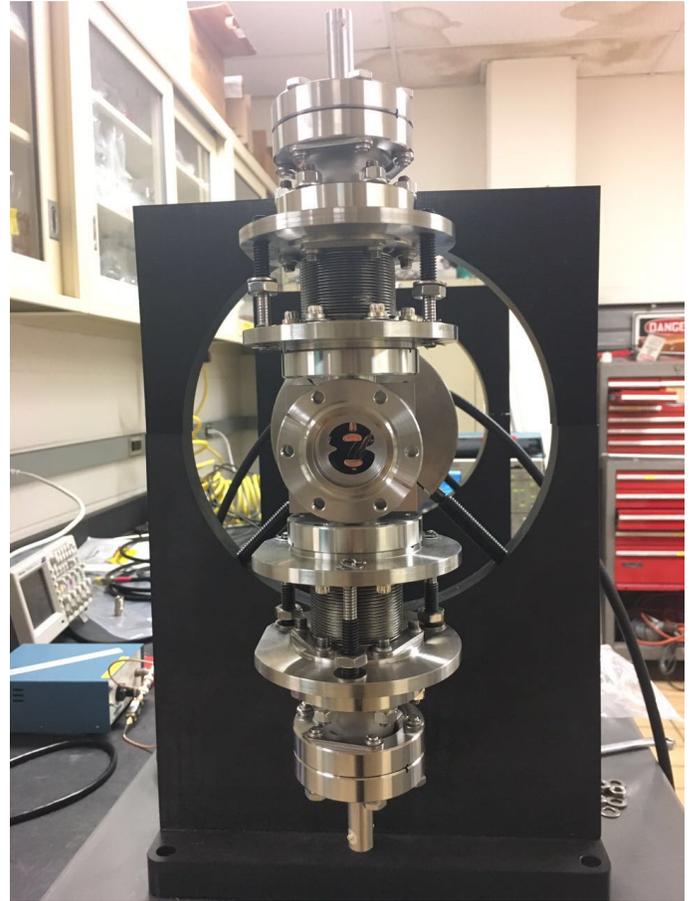


FIG. 10. Rear side view of the transverse kicker. The blades are controlled by screws and we use hex keys to adjust the position of the blades

or to connect another piece of cable so that we can avoid the resonant peak in our frequency range.

## VI. COMPARISON OF ANALYTIC SOLUTION, SIMULATION AND MEASUREMENTS

Figure11 shows the comparison of analytical solution, both shielded dual conductor simulation and blade model simulation and the real measurement. Simulation1 corresponds to shielded dual conductor simulation, while simulation2 corresponds to blade model simulation.

We can find that the system is resistant to small perturbations in blade positions, but when the position offset becomes larger, the impedance change is much faster. In both analytic result and simulation of shielded dual line, we can see that the change is not monotonous. This is due to the transition from blade-blade capacitance dominance to blade-shield capacitance. The impedance change in real measurement is unexpectedly but desirably smaller than the analytical and simulation result. Thus

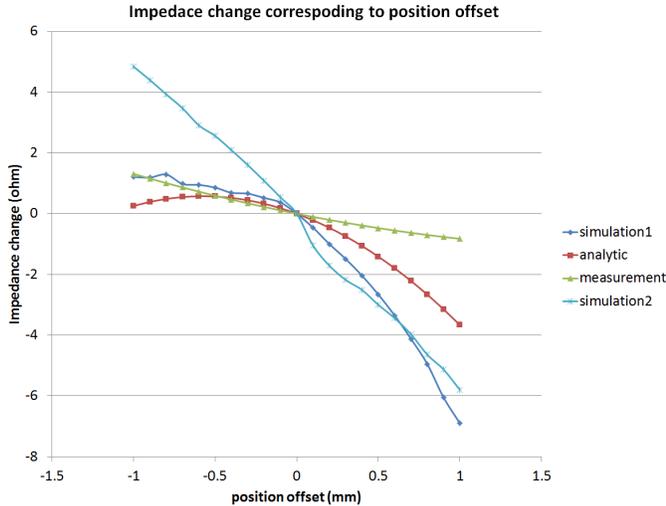


FIG. 11. Comparison of results from analytical solution, both shielded dual conductor simulation (simulation1) and blade model simulation (simulation2) and the real measurement

at this point, we can have a general conclusion that our device is resistant to small perturbations.

## VII. TIME DOMAIN REFLECTOMETRY

Time Domain Reflectometry (TDR) is a measurement technique used to determine the characteristics of transmission lines by observing reflected waveforms. By employing TDR, we can examine where the impedance discontinuities are in our device and how large they are.

The first step is to make measurement with pulse generator and oscilloscope to capture the incident and reflected waveform. Figure 12 shows the oscilloscope image.

Then we can calculate the position of the discontinuity and the magnitude of the discontinuity impedance. The formula to calculate the impedance magnitude is given by:

$$Z = Z_0 \frac{V_R + V_I}{V_R - V_I} \quad (2)$$

Where  $Z_0$  is the characteristic of the transmission line,  $V_I$  is the incident voltage amplitude and  $V_R$  is the reflected voltage amplitude. And the position of discontinuity is given by:

$$D = \frac{vT}{2} \quad (3)$$

Where  $v$  is the propagation speed in the transmission line, which is  $\frac{2}{3}$  speed of light in the cable and speed of

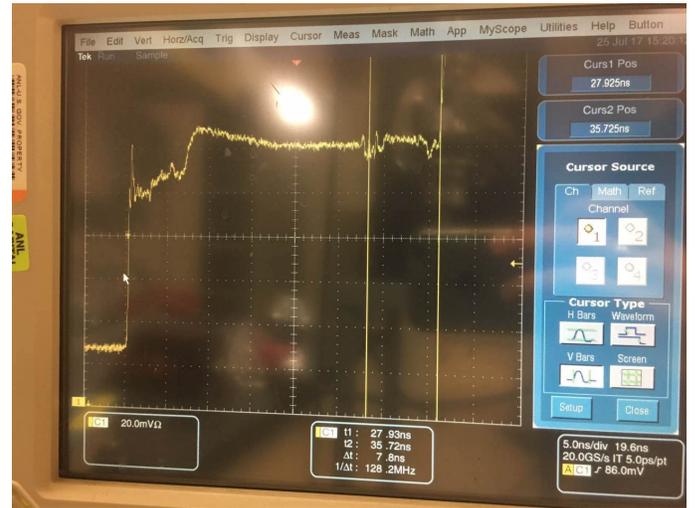


FIG. 12. Oscilloscope waveform from Tektronics oscilloscope. The steps on the image are what we need to calculate the impedance discontinuity position and magnitude

light in the transverse kicker, and  $T$  is the time interval measured by the oscilloscope. The impedance discontinuity and corresponding position is shown in Figure 13.

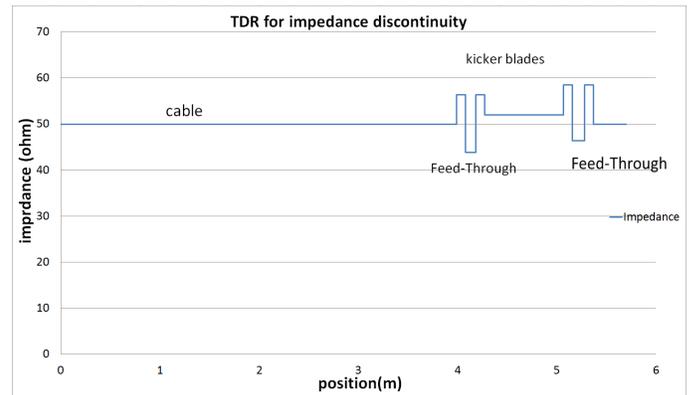


FIG. 13. Impedance discontinuity position and magnitude calculated from TDR measurement result given by the oscilloscope

From the figure, we can identify that there are two approximately symmetric impedance continuity of about  $42\Omega$  caused by the two feed-throughs. The impedance of the transverse kicker given by TDR is  $52\Omega$ . There is not noticeable changes in waveform when we adjust the position of the blades.

## VIII. CONCLUSION AND FUTURE STEPS

At this point, we have examined that our transverse kicker is symmetric, and is resistant to small perturbations in blade positions in the cases where two blades

are parallel. Unfortunately, due to the shutdown of most electric work at Argonne National Laboratory, we were not able to proceed to the measurements of the cases

with angular offsets at this moment. So our next step is to examine the effect of angular offset on the impedance of our device.

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