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FAST KICKER AND PULSER R&D FOR THE HEPS ON-AXIS INJECTION SYSTEM*

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Abstract

The HEPS plans to adopt on-axis injection scheme because the dynamic aperture of machine is not large enough for off-axis injection for its baseline 7BA lattice design. A couple sets of superfast kicker and pulser of ±15kV amplitude, 15ns pulse bottom width are needed for bunch spacing of 10ns to minimize perturbation on adjacent bunches. To achieve these requirement, a multifaceted R&D program including the strip-line kicker and HV pulser, was initiated last 2 years. So far, the prototype development of a 750mm long strip-line kicker and a DSRD pulser was completed and the preliminary test results show they can meet the baseline requirement of the HEPS.

INTRODUCTION

The High Energy Photon Source (HEPS) proposed by Institute of High Energy Physics (IHEP), is a typical next generation synchrotron radiation photon source based on a low emittance ring of 6GeV, 60pmrad, 1296m. For its baseline 48 period 7BA (7-Bend-Achromat) lattice design, the dynamic aperture (DA) of machine is not large enough for off-axis injection and only on-axis injection scheme is possible [1-3].

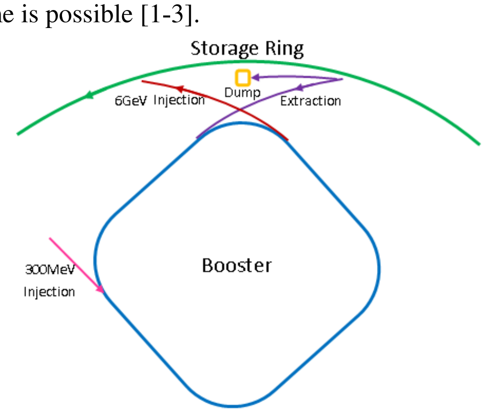

Figure 1: HEPS injection and extraction system layout.

On-axis swap out injection is one of candidate injection scheme, in which the booster acts as an accumulating ring. The injection and extraction system layout is showed in the Fig. 1. A target bunch in the storage ring will be extracted and injected back into the booster, merged with the bunch in the booster of full energy. After several times of radiation damping time, the higher charge bunch will be extracted from the booster and injected into the empty RF bucket of the storage ring. To minimize perturbation on adjacent bunches during on-axis swap out injection, a couple sets of superfast kicker and pulser are needed. It is a big challenge for HEPS. So, In HEPS-TF, a R&D program for HEPS, a strip-line kicker of 750mm long and its fast pulser of ±15kV amplitude, 15ns pulse bottom width for 10ns minimum bunch spacing of filling pattern are developed in these 2 years.

In on-axis swap out injection scheme, a single bunch has to be manipulated by a couple sets of fast kicker and its pulser. The pulse width of deflection action from the kickers should be less than twice of minimum bunch spacing. A dual-blade strip-line kicker, a kind of counter TEM travelling wave kicker is adopted. The pulse width of kick is contributed both by strip-line kicker and pulser [4-6]. Balance between the length of blades and electrical pulse width should be considered when design a fast kicker system. For 10ns of bunch spacing, the total kick pulse width has to less than 20ns. In our case, a 750mm long strip-line kicker occupied 5ns, and electrical pulse occupied 15ns. In order to achieved maximum deflection, 5ns flat top of electrical pulse is required for so long kicker and left 10ns is for rise and fall time of electrical pulse. Parameters for HEPS-TF injection kicker system are listed in Table 1.

Table 1: HEPS-TF Injection Kicker System Parameters

Parameters	Value
Beam energy(GeV)	6
Minimum bunch spacing(ns)	10
Kicker strength (mrad/m)	1
Length of strip-line kicker (mm)	750
Gap between the two blades (mm)	10
Good field region (mm)	±2.3 (x) ±1.0 (y)
Field uniformity	2%
Odd-mode impedance (Ω)	50±0.5
Even-mode impedance (Ω)	60±0.5
Kicker operation pulse voltage (kV)	±20
Degree of vacuum (Torr)	1×10^{-9}
Pulse rise time(10%-90%)(ns)	4
Pulse flat top(90%-90%)(ns)	5
Pulse fall time(90%-10%)(ns)	4
Amplitude of pulse (kV)	±15
Pulse flat-top reproducibility	<1%
Pulse residual voltage	<3%
Pulse repeat rate-CW (Hz)	50Hz
Pulse burst rate(Hz)	300
Jitter trigger to output-RMS(ns)	0.1

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It can be seen that as couple of nanoseconds pulse rise time, the whole system including a strip-line kicker, feedthroughs, pulsers, cables, connectors and terminators should be an ultra wide bandwidth (from DC-1GHz) TEM transmission system. However, several kV of high voltage and field quality requirement of kicker limit the TEM mode cut off frequency. That is the difficulties of on-axis injection superfast kicker system.

STRIP-LINE KICKER

The strip-line kicker R&D is always carried out around some key issues including ultra wide band, impedance, field quality, high voltage, beam wake field effect, vacuum and mechanical structure and fabrication.

Here, the impedance of strip-line is including the odd-mode (different mode) impedance and even-mode (common mode) impedance. Due to electromagnetic coupling between two blades close together, odd mode impedance must be less than even mode. Since the strip-line kicker is driven by a bipolar pulser, the odd mode impedance always optimized to 50Ω for impedance matching with pulser and transmission system. Beam induced signals on both blades are in common mode, so even mode impedance also prefers close to 50Ω to avoid round trip reflection.

In initial, our physics design followed the APS-U's strip-line kicker prototype which was test on its BTX beam line successfully [7-9]. "D" shaped blades are used to improve field-uniformity in the good field region. An ellipse outer body with vanes geometry is adopted to ease common-mode impedance-matching. Tapered end sections for matching impedance to the feedthroughs. Figure 2 shows a 750mm long strip-line kicker 3D model with 650mm main part in the middle and 50mm taper parts at both ends [10-12].

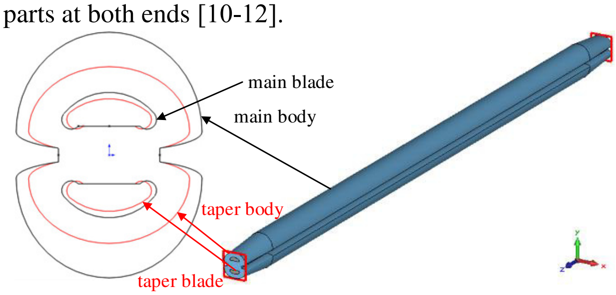

Figure 2: 3D strip-line kicker model.

Based on APS-U's design, further optimizations were done. First one is to extend the "vanes" to decouple 2 strip-lines, then achieve lower impedance mismatching in common-mode (Zeven<60.5 Ω), lower reflection(S11<-40db), lower beam power loss of 15% (loss factor=0.893V/pC, σ_z=3 mm).Further optimizations is to improve the taper parts and end covers, which can decrease 16% beam power loss.

The mechanical design of the strip-line kicker is driven by physics design, vacuum requirement, assembling, and fabrication techniques. Figure3 shows the final 3D mechanical assembling diagram. The strip-line kicker consists of 2 750mm long blades with tapered end, an out body with 2 transition parts at both ends, 2 special end covers connected to out body by sliver seal for vacuum and beryllium copper braid for electrical connection, and 4 commercial HV vacuum feedthroughs from FID GmbH which support the blades at both ends.

The kicker out body is split into 5 pieces to be machined by EDM. 3 pieces of middle main body are made from FOC and 2 pieces of transition parts are made from 316-L stainless steel to ease flange TIG welding. All 5 pieces of body with cooling water channels are assembled and brazed in a vacuum atmosphere.

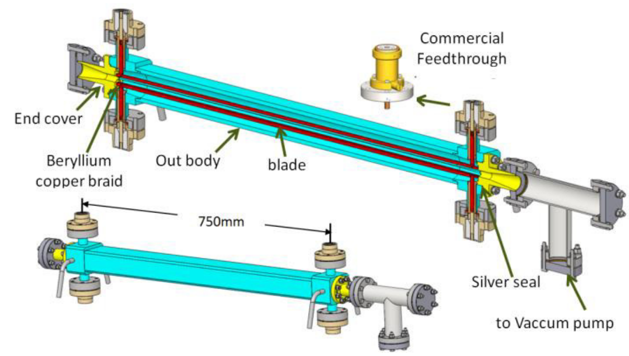

Figure 3: 3D mechanical assembling diagram of kicker.

Two fabrication process of 750mm long 3mm thick D shape blade were tried. The blades machined from FOC by CNC are so picky about materials hardness. The 316-L stainless steel blades with copper coating are rather easy to be made by cold extrusion and local CNC machining. It is concerned that the field uniformity of kicker can get worse because the deflection of both kinds of blades is a little large, about 0.9mm.

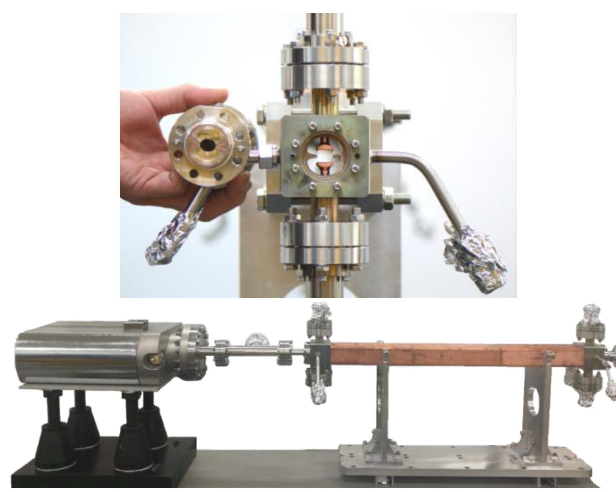

Figure 4: 750mm long strip-line kicker prototype.

As shown in the Fig. 4 the 750mm long strip-line kicker prototype passed vacuum leakage test smoothly after assembling. Then, the vacuum degree at the end of the kicker near the ion pumper gradually reaches 2×10^{-9} Torr after baking. But on the other end of kicker, the vacuum degree is only 2×10^{-8} Torr. The result of RF parameter test by the network analyser shows that the

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vacuum baking process does not have adverse effect the kicker assembling.

Figure 5 and Figure 6 show respectively S parameters and Time-Domain Reflectmeter (TDR) measurement results of kicker prototype. Compared with the simulation which uses a perfect feedthrough model, the results agree well and can meet our requirement. More further TDR test show that besides the feedthroughs, the other worst mismatching point are located at the RG217 cable connectors which is fitting for FID feedthroughs, attenuators and pulser.

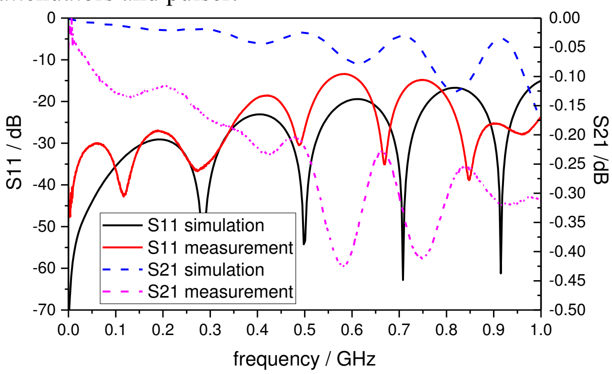

Figure 5: Testing and simulation S parameters.

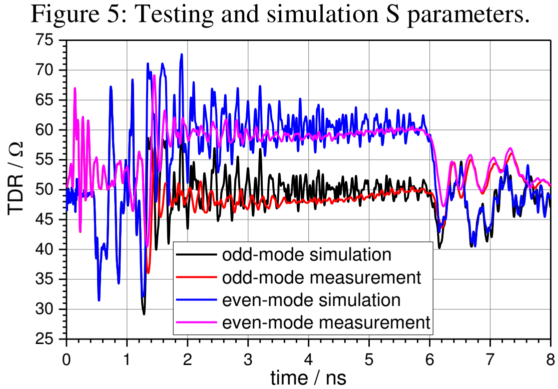

Figure 6: Testing and simulation TDR.

The kicker prototype high voltage test was carried out at vacuum condition. A pulser of ±20kV amplitude , 4ns pulse width from FID GmbH was applied to the kicker. Figure 7 is the HV test setup and Fig. 8 is the testing pulse waveform. The rise time (10%-90%) of kicker pulse is less than 929ps and fall time (90%-10%) is less than 1.8ns. It shows that the complete kicker which is inserted into the transmission system, contributes about 250ps of slowdown at pulse front edge.

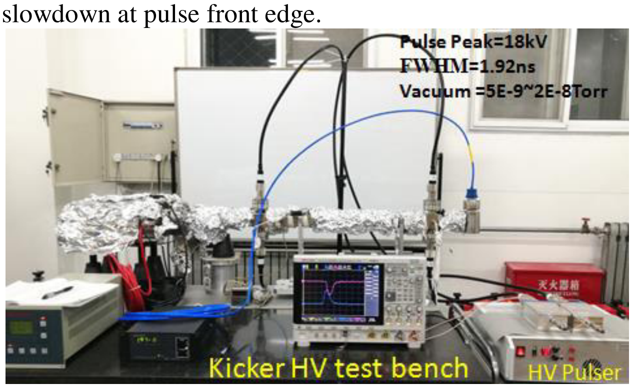

Figure 7: Kicker prototype HV test set up.

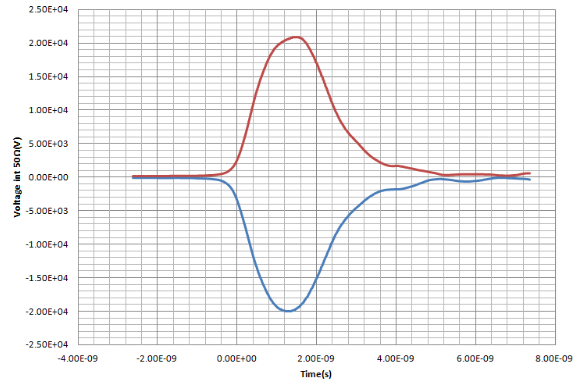

Figure 8: Kicker prototype HV test waveform.

HIGH VOLTAGE FAST PULSER

The specifications of strip-line kicker pulser for HEPS-TF are listed in the Table 1. For such HV ns-fast pulser, there are a couple of potential technologies based on certain fast switch including RF-MOSFET, DSRD, FID, PCSS, avalanche transistor, magnetic switch etc. [10]

The switch speed of RF-MOSFET in theory is less than 1ns. However, limited by trigger current, stray inductance of switching loop and trigger circuit, the typical switch speed of commercial RF-MOSFET is about 2~5ns, and the minimum pulse width is large than 6ns. Due to rather low power rate, the pulsed power stacking technologies are essential for single chip MOSFET. Typical stacking topologies are including series stacking, inductive adder, transmission line adder, Marx generator, or hybrid adder [13]. As for a 15kV/300A pulser, it used to need 150 piece of MOSFET (IXZ631DF12N100) in the stacking structure. [10]

The DSRD (Drift Step Recovery Diode) [14] is a special semiconductor diode which can open several hundred ampere of current in sub-nanosecond. So, a DSRD pulser is good choice for HEPS-TF kicker driver. In these 2 years, we are still focusing on DSRD pulser R&D.

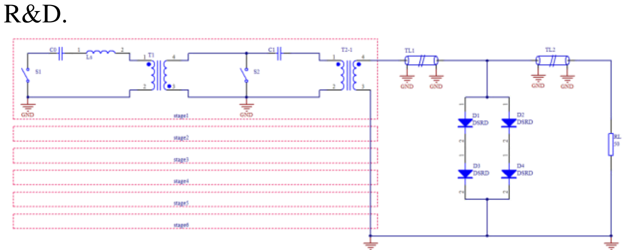
Figure 9: DSRD pulser schematic.

A novel practical DSRD pumping circuit was developed based on the circuit from SLAC [15-16]. An inductive adder with 2 switches was induced as a DSRD pumper. Figure 9 is the schematic of DSRD pulser with a 6-stage inductive adder. Advantages of using inductive adder are to avoid isolated switch driver and high voltage components. For pulse width of 5ns, a 0.5m long coaxial cable is used as Pulse Formation Line (PFL).

The whole pulser is design as 50Ω coaxial structure, as shown in Figure 10, including a 6-stage inductive adder pumper, PFL, DSRD assembly, transmission line (strip-

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line kicker), and terminal attenuation. Such structure is good to produce a clean waveform of pulse. The structure of DSRD assembly is very important to minimize residual voltage during DSRD pumping period.

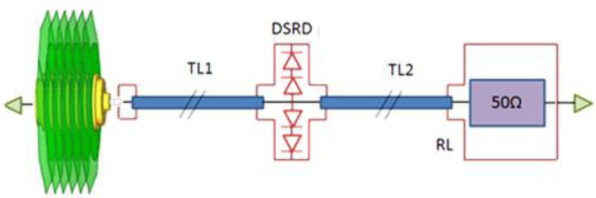

Figure 10: DSRD pulser structure.

The DSRD pulser prototype has been done and the photo and testing pulse waveform is show in Figure11. At the condition of 450V of charging voltage, the pulser can produce a pulse with amplitude of ±15kV into 50Ω, front edge (10%-90%) of 2.6ns, rear edge (90%-10%) of 3.5ns, FWHM of 7.4ns. The residual voltage pre pulse is a little large, and some improvements are being tried.

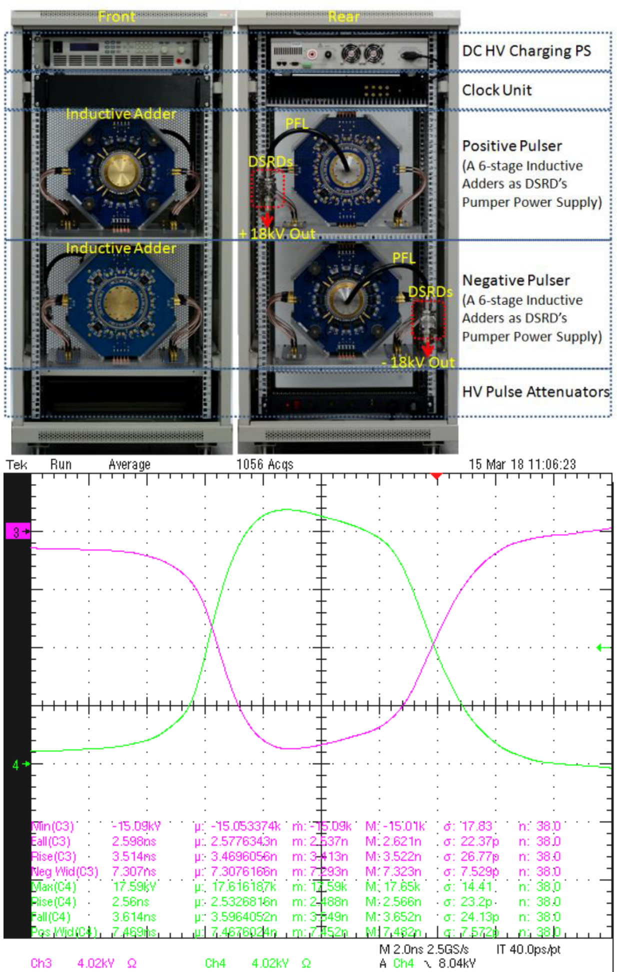

Figure 11: DSRD pulser prototype and testing result.

CONCLUSION AND NEXT PLAN

Fast kicker and pulser R&D for HEPS-TF have been carried out in these 2 years. A 750mm long strip-line kicker prototype was designed, fabricated and tested in the laboratory. The test results show the prototype can meet the initial requirements. A beam test plan on the BEPCII linac is considered. Another prototype R&D of 300mm long strip-line kicker is ongoing.

The high voltage fast pulser R&D is focusing on the DSRD technology. A ±15kV DSRD pulser prototype is completed. The preliminary test results show that the most specifications reach the requirement of HEPS-TF. The next plan for pulser R&D is to improve the residual voltage pre pulse as possible.

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