Strip-line Kickers and Fast Pulsers R&D at HEPS

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HEPS/HEPS-TF Injection System
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Outline

1. HEPS Injection and Injection Systems
2. Progress of R&D on Strip-line Kicker
3. Progress of R&D on Fast Pulser
4. Summary
HEPS Injection and Injection Systems
HEPS storage ring is a typical MBA LER, for it’s baseline lattice design, the Dynamic Aperture (DA) is not large enough for off-axial injection. Only on-axial injection schemes are possible.
Challenges for HEPS Injection System

- The baseline injection scheme for HEPS: On-axial swap-out injection
  - Dumping mode
  - Recycling mode (for high bunch charge mode)
    (booster acts as an accumulating ring)

- The other potential scheme: On-axial longitudinal accumulating injection by 3rd harmonic RF system (166/500MHz)

- For both on-axial injection systems, the biggest challenges:
  Super fast kicker and pulser.

**Swap-out injection mode**
- Electrical pulse <15ns

**Longitudinal injection mode**
- Electrical pulse <4ns
## Injection & Extraction Section Layout

- Compatibility of both on-axial injection schemes

### Main Design Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Injection</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight section length</td>
<td>m</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Kick angle</td>
<td>mrad</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Kick direction</td>
<td></td>
<td>Vertical</td>
<td>Vertical</td>
</tr>
<tr>
<td>Length of Strip-line kicker electrode</td>
<td>mm</td>
<td>300</td>
<td>750</td>
</tr>
<tr>
<td>Gap of Strip-line kicker electrode</td>
<td>mm</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Quantity of Strip-line kicker</td>
<td></td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Longitudinal space between strip-line kicker electrode</td>
<td>mm</td>
<td>&lt;30</td>
<td>&lt;75</td>
</tr>
<tr>
<td>Amplitude of electrical pulse</td>
<td>kV</td>
<td>±15</td>
<td>±15</td>
</tr>
<tr>
<td>Rise time of electrical pulse (10%-90%)</td>
<td>ns</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>Flat top of electrical pulse (90%)</td>
<td>ns</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Fall time of electrical pulse (90%-10%)</td>
<td>ns</td>
<td>1.5</td>
<td>4</td>
</tr>
</tbody>
</table>

**Diagram Details:**
- **Injection System Layout:**
  - 6m straight section
- **SR Injektion System Layout:**
  - Strip-line kickers
  - Lambertson + 10 × 300mm long kicker
- **7BA Curved Section:**
  - Lambertson septum
- **SR Extraction System Layout:**
  - 4 × 750mm long kicker + Lambertson
  - Strip-line kickers
- **Unit Information:**
  - Horizontal, vertical, and longitudinal positions.

**Side View:**
- Stored bunch orbit
- Injected bunch orbit
- Quads

**Operational Parameters:**
- Rise time (10%-90%)
- Flat top (90%)
- Fall time (90%-10%)
Progress of R&D on Strip-line Kicker
Injection strip-line kicker is a kind of encounter travelling wave kicker.
APS-U has been successful in Strip-line kicker design and its scheme looks best for us\[^{1}\][\(^{2}\)][\(^{3}\)]

**Pros of APS-U type Strip-line kicker**
- “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 feed-throughs.

**Figure 5:** The kicker installed in the BTX beamline.

**Figure 10:** Beam spot movement when kicker amplitude varies from 0 to 15kV.

**Figure 11:** Measured y-centroid position vs kicker amplitude.
2-D Geometry Model for Optimization

- The strip-line blades are decided by:
  - $a, b$ - axes of the center ellipse
  - \( \text{gap} = 5\text{mm} - \frac{1}{2} \text{distance between blades} \)
  - \( \text{blade} = 3\text{mm} - \text{thickness of blades} \)

- The outer body half shell consists of 2 half ellipses that defined by:
  - Center half: \( X_c, a_0, b_0 \)
  - Outer half: \( X_c, a_{00}, b_0 \)

- New parameter:
  - \( \text{vane} (\geq<\text{b}) - \frac{1}{2} \text{distance between Vanes} \)
Based on APS-U’s design, further optimize was done

- Extend the vanes to decouple 2 strip-lines, then achieve:
  - lower impedance mismatching in common-mode (<60.5 Ω),
  - lower reflection (S11 < -40 db),
  - lower beam impedance (loss factor = 0.893 V/pC, ↓15%)

**Strip-line Kicker Design Improvement 1**

**Z-TDR**

**S11-dB**

**Longitudinal wake potential (σz = 3mm)**

**Real part of the longitudinal impedance vane<b**
Strip-line Kicker Design Improvement 2

- Improve the taper part to further decrease beam impedance; Power loss decrease 16%.

### Graphs

**Longitudinal wake field potential**

- **1D Results\Particle Beams\ParticleBeam1\Wake potential**

- **Longitudinal wake field potential**

- **Longitudinal impedance**

**Table 1**

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>① 0.855</td>
<td>228</td>
<td>2463</td>
</tr>
<tr>
<td>② 0.788</td>
<td>210</td>
<td>2270</td>
</tr>
<tr>
<td>③ 0.716</td>
<td>191</td>
<td>2063</td>
</tr>
</tbody>
</table>

### Equation

Power loss: \( P = kI_b^2n_b/f_{rev} \)
2-D Strip-line Optimization Result

### Main body cross section

#### Transition part at the end

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Main body (black)</th>
<th>Transition part (red)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{odd}$ / $\Omega$</td>
<td>49.81</td>
<td>50.00</td>
</tr>
<tr>
<td>$Z_{even}$ / $\Omega$</td>
<td>60.39</td>
<td>58.23</td>
</tr>
<tr>
<td>$E_{max}$ / (MV/m)</td>
<td>6.42</td>
<td>6.63</td>
</tr>
<tr>
<td>$E_{ave}$-gap / (MV/m)</td>
<td>2.99</td>
<td>3.00</td>
</tr>
<tr>
<td>$\Delta E/E$ gap / (%)</td>
<td>1.70</td>
<td>5.76</td>
</tr>
<tr>
<td>$Y$ (±1mm) / (%)</td>
<td>0.20</td>
<td>0.63</td>
</tr>
<tr>
<td>$Y$ (±5mm) / (%)</td>
<td>1.70</td>
<td>5.76</td>
</tr>
<tr>
<td>$X$ (±2.3mm) / (%)</td>
<td>1.45</td>
<td>4.39</td>
</tr>
</tbody>
</table>
Difference-mode Electric field

E = 6.42 MV/m for ±15 kV square wave input

Main body

E = 6.63 MV/m for ±15 kV square wave input

Transition part

1mm slice
3-D Model and RF Parameters

Square wave excitation $t_{\text{r}} = 10\text{ps}$
- TDR-Odd: $\sim 49.8$ $\Omega$
- TDR-Even: $\sim 60.0$ $\Omega$

Gaussian wave, 0~1 GHz,
- Reflection: $< -30$ dB,
- Insertion loss: $< 0.02\%$
E-field uniformity

- The field uniformity in the middle plane

Curves in the middle plane

±15 kV square wave input

- Integral E-field Along z

<table>
<thead>
<tr>
<th>x (±2.3 mm)</th>
<th>Y (±5 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (±2.3 mm) : &lt;1.5%</td>
<td>Y (±5 mm) : &lt;1.7%</td>
</tr>
</tbody>
</table>

x (-2.3~2.3 mm) at y=0, 1, 2, 3, 4

y (-4~4 mm) at x=0, 1.1, 1.7, 2.3
750mm Strip-line with Perfect Feedthrough Model

Steel-1010 $\sigma = 6.993 \times 10^6$ S/m

Cu (pure) $\sigma = 5.96 \times 10^7$ S/m

Steel-1010 $\sigma = 6.993 \times 10^6$ S/m

Cu (annealed) $\sigma = 5.8 \times 10^7$ S/m

Coaxial Feedthrough (air line, 50Ω):
Do=16 mm, Di=7 mm

$E = 17.1$ MV/m for 15 kV square wave input

Pulse setting: $t_r + t_{\text{top}} + t_f = 1.5 + 1 + 1.5 = 4$ ns.
Voltage at $t_{\text{top}}$ is 15 kV
RF Parameters

Odd-mode S-parameters

Even-mode S-parameters

TDR impedance

1 differential mode
2 common mode
Beam Impedance and Wake

- The worst case: longitudinal injection period in high charge mode ($\sigma_z=3\text{mm}, 14.4\text{nc}$)
- the power loss at each kicker is 2.1kW ;
- In longitudinal injection mode, If the injection time is 1/600 of running time , and the beam length is 3cm in normal operation, the average power loss should be decreased to 81W.

$$P_{ave} = \frac{P_{loss,1} \cdot t_1 + P_{loss,2} \cdot t_2}{t_1 + t_2}$$

| Sigz=3mm | 0.716 | 191 | 2063 | -0.03 | 313.5 |
| Sigz=3cm | 0.027 | 7.2 | 78 | 1.05 | 120.6 |
| Sigz=3mm+3cm | - | 7.5 | 81.3 | - | - |
In high charge mode, beam power loss dissipation is 233.3W at blades, 288.5W at outer body, 321.6W at upstream port and 419.3W at downstream port.

The sum of power loss dissipation is little less than the result from loss factor, because some power flows out from beam pipes at both ends.

Beam parameters:
\( \sigma_z = 3\text{mm}, \\ n_b = 648, \\ \text{Charge} = 1.334\text{nC} \\ \ y_{\text{offset}} = 0 \)
Induced Voltage and E-field excited by Beam

- Gaussian beam
- $\sigma_z = 3\text{mm}$
- Charge = 14.4 nC
- Offset = 0 mm

In worst case:
- Max. beam induced voltage on Feedthrough < 3990 V
- Peak E field on the copper blade is 19.4 MV/m
- Peak E field on the vacuum tank is 13.4 MV/m

Induced Voltage on Feedthroughs

Max electric field on face
First PoP Kicker Fabrication

- PoP kicker is to prove the fabrication technique and design simulation

**Computer Numerical Control (CNC) machining**

**Blade machining**

**Electrical discharge machining (EDM)**

**Out-body machining**

**Hydrogen Furnace braze**

**Assembled vacuum tank of kicker before brazing**

**Out-body Welding**

- Solder wire
- Copper main part
- Steel transition part
- Welding Seam
PoP Kicker assembly test

Network Analyzer: Keysight E5071C

Differential mode
Odd mode TDR: $Z_{\text{diff}}/2=51.2 \, \Omega$

Common mode
Even mode TDR: $Z_{\text{com}}\times2=59.7 \, \Omega$
PoP Kicker TDR Test Results

- The measurement and simulation results agreed well.
  - Very big mismatch in the feedthrough part.

Step signal rising time: 35 ps
750mm-long Strip-line Kicker prototype

- Final prototype kicker design is done, and it is being fabricated in the factory
Strip-line Blades and Out body

CNC machining

EDM machining

TIG welding

Out body assembling

Vacuum leak test after brazing

Vacuum out water leakage issue is to be solved
Next plans

- Cold Test after assembling next month: TDR, HV test
- Beam test at BEPCII Linac next year
300mm-long Compact Kicker Consideration

- For longitudinal injection, we need 10 sets of shorter strip-line kickers (300mm-long).
- In 750mm-long kicker design, the gap between adjacent kickers is 100mm. The same structure is not fit for 300mm-long kicker because 10 sets of shorter kickers could not install in limited space (3.3m).
- A new compact design has been considered. The gap between adjacent kickers blade is <10mm.
5-cell module kicker Structure

- The prototype is under design and plan to deliver to factory next month

- 300mm strip-line blade without taper (cold extrusion or CNC machining)
- out-body Split to 4ps to machine(CNC)
- 5 kickers in each module
Progress of R&D on Fast Pulser
Commercial Pulser

- 4ns kicker pulser for longitudinal injection (@166+500MHz RF) is hard for us to be made at home now.
- Fortunately, the FID commercial pulser can meet our requirements.

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>5 kV</th>
<th>10 kV</th>
<th>15 kV</th>
<th>20 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative Channel</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td>Positive Channel</td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>5 kV</th>
<th>10 kV</th>
<th>15 kV</th>
<th>20 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time 10-90%</td>
<td>600 ps</td>
<td>600 ps</td>
<td>600 ps</td>
<td>750 ps</td>
</tr>
<tr>
<td>Rise time 5-95%</td>
<td>600 ps</td>
<td>1 ns</td>
<td>1 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td>Flat top at 90%</td>
<td>1 ns</td>
<td>1 ns</td>
<td>1 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td>Pulse width at 5%</td>
<td>2.5 ns</td>
<td>3 ns</td>
<td>3 ns</td>
<td>3.5 ns</td>
</tr>
</tbody>
</table>
On the other hand, HEPS-TF’s task is to R&D an 8ns pulser for swap-out injection (baseline)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of Channel</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Max Output Voltage</td>
<td>kV</td>
<td>± 15</td>
</tr>
<tr>
<td>Max Output Current</td>
<td>A</td>
<td>300</td>
</tr>
<tr>
<td>Resistor Load</td>
<td>Ω</td>
<td>50</td>
</tr>
<tr>
<td>Pulse Rise Time (10%-90%)</td>
<td>ns</td>
<td>2</td>
</tr>
<tr>
<td>Pulse Fall Time (90%-10%)</td>
<td>ns</td>
<td>2</td>
</tr>
<tr>
<td>Pulse Flat-top Width (90%)</td>
<td>ns</td>
<td>4</td>
</tr>
<tr>
<td>Pulse Flat-top Variation</td>
<td>-</td>
<td>≤1%</td>
</tr>
<tr>
<td>Pulse Flat-top Reproducibility</td>
<td>-</td>
<td>≤1%</td>
</tr>
<tr>
<td>Pulse Tail Amplitude</td>
<td>-</td>
<td>≤3%</td>
</tr>
<tr>
<td>Pulse Rep Rate (CW)</td>
<td>Hz</td>
<td>50</td>
</tr>
<tr>
<td>Pulse Burst Rate (100ms once in every 500ms)</td>
<td>Hz</td>
<td>300</td>
</tr>
<tr>
<td>Jitter Trigger to Output</td>
<td>ns</td>
<td>0.1</td>
</tr>
<tr>
<td>Jitter Channel to Channel (rms)</td>
<td>ns</td>
<td>0.1</td>
</tr>
<tr>
<td>Skew Between Channels</td>
<td>ns</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Fast Pulser Design Consideration

The potential technologies for HV ns-fast pulser:

- RF-MOSFET based adder
  - Inductive adder
  - Transmission line adder
  - Marx generator
  - Series stacking
  - Hybrid Adder
- Co-axial magnetic switch compressor (shock wave transmission line)
- DSRD based PFL(Pulse Form Line) modulator
- Other switch: FID, SOS, SAS

Two solutions was considered for HEPS-TF:

- Hybrid adder (inductive adder+transmission line adder) based on RF-MOSFET
- PFL(Pulse Form Line) modulator based on DSRD
1. RF-MOSFET Pulser

- It is hard to produce a short pulse (<4ns) only by commercial RF-MOSFETs and driver (IXYS DE-series MOSFET: DE275-102N06A, Tr=2ns, Min.PW=8ns; Behlke MOSFET Module: HTS-50-08-UF, Tr=1.2ns, Min.PW=5ns)

- Pulsed power stacking is necessary for pulse of 15kV into 50Ω

  (IXYS DE-series MOSFET: Voltage rate=1kV;
  HTS-50-08-UF: Voltage rate=5kV)

U=220V, PRF=1kHz, RL=4Ω, 10X attenuation
Front edge (10%-90%) = 2.15ns
Rear edge (10%-90%) = 2.8ns
Width of pulse (FWHM) ≈ 8.2ns

IXZ631DF12N100  X 150 (6pcX25stage) = 15kV into 50Ω

25-stage adder (inductive or TLT) simulation
Hybrid Adder Based on MOSFET

- Inductive adder with many stages would lead to slow down front edge of output pulse due to transmission line effect (TLE).

- Transmission line adder can eliminate the TLE, but it is not easy to get commercial low-impedance transmission line; So, a hybrid adder was proposed.

3×10 stage inductive adder + 3×5kV inductive adder prototype built in 2011
2. DSRD Based PFL Modulator R&D

- Opening in sub-ns
- Got samples: K005 from the vendor in china ($i_p \geq 300A$, $V_p = 10kV$)

(A. Benwell, SLAC, A 5KV, 3MHz Solid-state Modulator Based on the DSRD Switch for an Ultra-fast Beam Kicker)
±15kV DSRD Pulser Circuit Design

- A 6-stage inductive adder for DSRD pumper circuit; Its advantages are free HV components and isolated driver (<1kV); need much fewer components
- 4 DSRDs(2 parallel, 2 series) switching 600A into 50 Ω; It is independent to the pumper
- 0.5m long PFL(TL1) for $p_w=5\text{ns}$
The whole pulser is designed as a 50Ω coaxial structure, including:

- Pumper circuit (6-stage inductive adder based MOSFET)
- PFL and Transmission line
- DSRD assembly
- Terminal attenuation
6-stage Pumper DSRD Pulser

6-stage Inductive adder

Pogo pin

Resonance Transformer (Ferrite)

Cooling & shielding plane

Coaxial Transformer (Nanocrystalline core)
Pumper P.S. PCB Design and Assembling

Top layer

Bottom layer
First PCB Assembling and Test

- Single stage pumper, PFL=0.3m
- Input DC HV=450V
- Attenuator: 30dB+20dB, 50Ω
- Output pulse:
  - Pulse Amplitude=3.1kV
  - Pulse Width(FWHM)=4.9ns

Voltage step during pumping caused by DSRD loop stray inductance, shunt resistance, T-BNC-connector

DSRD pumping current

Output Pulse voltage into 50Ω
DSRD housing improvement

1pc DSRD + shunter

1pc DSRD

2pcs DSRD in parallel

4pcs DSRD

- 407V(<4.9%)

-8.25kV

4pcs DSRD

140V(<1.5%)

540V(<5.7%)

-9.44kV

test at 3 stages, Input DC HV=450V
Latest 3-stage Circuit Testing

- 3 stage pumper
- 2Pcs DSRD in parallel, 0.5m PFL
- Input DC HV=450V
- Attenuator: 30dB+20dB, 50Ω
- Output pulse:
  - Pulse Amplitude=9.5kV
  - Pulse Width (FWHM)=7.5ns

3-stage testing is so far so good, and 6-stage full-power prototype is going to be tested after new DSRD housing, HV cable, connector, and attenuator is available next month.
Due to small DA, only On-axial swap-out injection and longitudinal injection based on ultra-fast kicker system are possible for HEPS. So, the task of HEPS-TF is to R&D a set of strip-line kicker system.

A 750mm-long strip-line kicker is being fabricated. A 300mm-long compact strip-line kicker design is ongoing.

For kicker pulser, MOSFET-based hybrid adder and DSRD-based PFL modulator are both potential approach for 8ns pulser.

Limited by switch speed, MOSFET-based adder is difficult to get a shorter pulse (PW<5~8ns).

A DSRD PFL modulator with a special 6-stage inductive adder pumper was designed. A half prototype was tested successfully and R&D is ongoing.


[3] C. Yao,... Preliminary Test Results of a Prototype Fast Kicker for APS MBA Upgrade

[4] A. Benwell1, SLAC, A 5KV, 3MHz Solid-state Modulator Based on theDSRD Switch for an Ultra-fast Beam Kicker
Thanks for your attentions!