Development of a solid-state pulse generator driving kicker magnets for a novel injection system of a low emittance storage ring

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Outline

• Motivation
• Design of kicker and pulse generator
• Development of the pulse generator
• Summary
Motivation

- **Low emittance electron storage ring** for higher brightness such as “Diffraction-limited light source”
- **Small beam size**
  - Orbit fluctuation should be reduced.
- **Short beam lifetime**
  - Top-up injection is indispensable.
- **Small dynamic aperture**
  - Precisely control the injection beam.
- **Stable and reliable beam injection scheme** was considered

SPring-8 → SPring-8-II  
ESRF-EBS  
APS upgrade  
TPS  
MAX-IV  
Sirius
Off-axis in-vacuum beam injection scheme

Windowless injection
Conserve high quality beam

PM-based DC septum
Stable, energy saving

In-vacuum pulse septum
Small amplitude of injection beam

Linear bump orbit
with identical kicker magnets

Solid-state pulse generator
Low jitter and precise amplitude control

Injection beam from LINAC

Differential pumping without window

 Permanent magnet-based DC septum

In-vacuum type pulse septum

Kicker

Stored beam

Quad.-pole

Linear bump orbit

Same amplitude and timing

Orbit perturbation is closed

Solid-state pulse generator

Solid-state pulse generator
**Strategy for the bump orbit stabilization**

- Pair of the kickers should be matched
  - Kick angle $\sim$ a few $\mu$rad
  - Field amplitude $<$ 0.1%
  - Timing $<$ sub ns

- Conventional pulser using thyratron
  - Large timing and voltage fluctuation.

- Solid-state switch
  - Stable and long lifetime

- Parallel drive
  - Definitely synchronized.
  - Fluctuation of the kick is canceled out.

- Amplitude of the two pulse generators are also matched ($\sim$0.1%) to reduce the trajectory offset.

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**Conventional system**

- Residual kick causes orbit fluctuation

**New system**

- Bump orbit is closed

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May 2, 2018, IPAC'18 (Vancouver), WEYGBF4, T. Inagaki, et. al.
Prototype kicker magnet for 3 GeV light source

- **Kicker magnet design**
  - Large kick angle (5.5 mrad)
    → High magnetic field (0.25 T).
  - Short pulse width (2.2 $\mu$s)
    → Frequency response up to 1 MHz
  - C-type, silicon-steel laminated core.
  - 2 turn for low inductance (4 $\mu$H)
    → High pulse current (2.2 kA)

<table>
<thead>
<tr>
<th>Kicker parameters (tentative)</th>
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<tbody>
<tr>
<td>Bump amplitude</td>
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<tr>
<td>Kick angle</td>
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<td>Pole length</td>
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<td>Gap width</td>
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<tr>
<td>Magnetic field</td>
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<tr>
<td>Pulse current</td>
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<td>Pulse width</td>
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<td>Inductance</td>
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</table>
Solid-state pulse generator design

- Capacitor discharge circuit (93 nF, 50 kV) for 2.2 kA, 2.2 μs pulse
- High precision HV charger 50 kV, 0.01% accuracy
- Solid-state HV switch 6.5 kV, 14 series
- Fast recovery diode array 1.2 kV, 80 series
- Regeneration circuit for better power efficiency.
- Variable inductor for current balance correction.

Circuit diagram

Design parameters
- Peak current (each) 2.2 kA
- Pulse width 2.2 μs
- Capacitance 93 nF
- Charging voltage 50 kV
- Parallel drive
  - Amplitude difference < 0.1%
  - Timing difference < 1 ns
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Originally developed for klystron modulator at SACLA
- Full-bridge 20 kHz inverter + HV transformer
- Digital PWM regulation of the inverter

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**Circuit diagram**

- HV-IGBT (Mitsubishi CM750HG-130R)
  - 6.5 kV, 750 Adc, Tr ~ 200 ns

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- Fast recovery diode array 1.2 kV, 80 series, 2 parallel
- Regeneration circuit for better power efficiency.
- Variable inductor for current balance correction.

Circuit diagram

Ultrafast recovery diode (CKE CKF12P100D1D) 1.2 kV, Trr ~ 135 ns

Design parameters

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- Pulse width 2.2 µs
- Capacitance 93 nF
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- **Regeneration circuit for better power efficiency.**
- Variable inductor for current balance correction.

Circuit diagram

Regeneration reactor

100 mH

Design parameters

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- Regeneration circuit for better power efficiency.
- **Variable inductor for current balance correction.**

**Design parameters**

- Peak current (each): 2.2 kA
- Pulse width: 2.2 μs
- Capacitance: 93 nF
- Charging voltage: 50 kV
- Parallel drive
- Amplitude difference < 0.1%
- Timing difference < 1 ns
Operation test results

• Checked items
  • Charging voltage accuracy, regeneration efficiency
  • Peak current and pulse width
  • Matching of the pulse currents
  • Instead of the kicker magnets, two air-core inductors driven in parallel.
Capacitor charging waveforms

- Charges to 50 kV within 100 ms. OK
- Voltage accuracy: ~ about 0.01% OK
- Regeneration: 75% of initial voltage OK
- Power efficiency: 56%. OK
Pulse current amplitude and pulse width

- Peak current: 2.2 kA for each coil  OK
- Pulse width: 3.3 μs  wider than design (2.2 μs)
- Same current passed to both inductors  OK
Current matching

• We used a differential amplifier to amplify the current residual.
• **Current difference: within ±0.2%** of the peak current, (including the measurement accuracy)
• Promising results for a common pulse generator as a parallel driver.
• We plan to improve the accuracy of the measurements and also the equality of the current pulses.

![Diagram showing current matching setup](image)

- Load inductor-1
- Load inductor-2
- Oscilloscope
- Differential amplifier

**Inductor-1 current (I₁)**: 830 A
**Inductor-2 current (I₂)**

Differential amplifier output (I₁ - I₂)

- ±0.8 A (±0.1%)
- ±1.6 A (±0.2%)
Improvement for shorter pulse width

- Pulse width: measured 3.3 $\mu$s, design 2.2 $\mu$s
- Internal inductance of the circuit is larger than expected.
- We measured a transient voltage at several points.
- We plan to modify the components and to shorten the pulse length.
  - **HV switch (IGBT)**
    - Replace to other fast thyristor switches.
  - **Diode array**
    - 80 series, 2 parallel → 4 parallel
  - **HV cable**
    - Shorten the cable length.
    - 2 cables in parallel
    - Low impedance return path (copper plate)
Summary

• Off-axis in-vacuum beam injection system is proposed.
• Kicker magnets driven by high-precision solid-state pulse generators to launch a closed linear bump orbit is the key to suppress the transient oscillation of stored beam.
• A prototype of the solid-state pulse generator for driving two kicker magnets in parallel was designed, assembled, and tested.
  • It generated half-sinusoidal pulse current of 2.2 kA for two dummy load inductors.
  • The current waveforms were matched within ±0.2%.
  • The pulse width was 1 μs wider than the design, which was due to the large inductance in the circuit.
• Promising results are obtained to achieve the identity of the two kicker magnets by using a common pulse generator as a parallel driver.

Remaining tasks

• Reduction of the inductance and shorten the pulse width.
• Fabrication of the kicker magnet prototype, and the combination test.