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

T. Inagaki, H. Tanaka (RIKEN SPring-8 center),
C. Kondo, K. Fukami, S. Takano (JASRI),
K. Sato, H. Akikawa (Nohon Koshuha Co. Ltd.)

SPring-8 RIKEN SPring-8 Center JASRI NIKOHA

Work funded & supported by MEXT

MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

Outline

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

Motivation

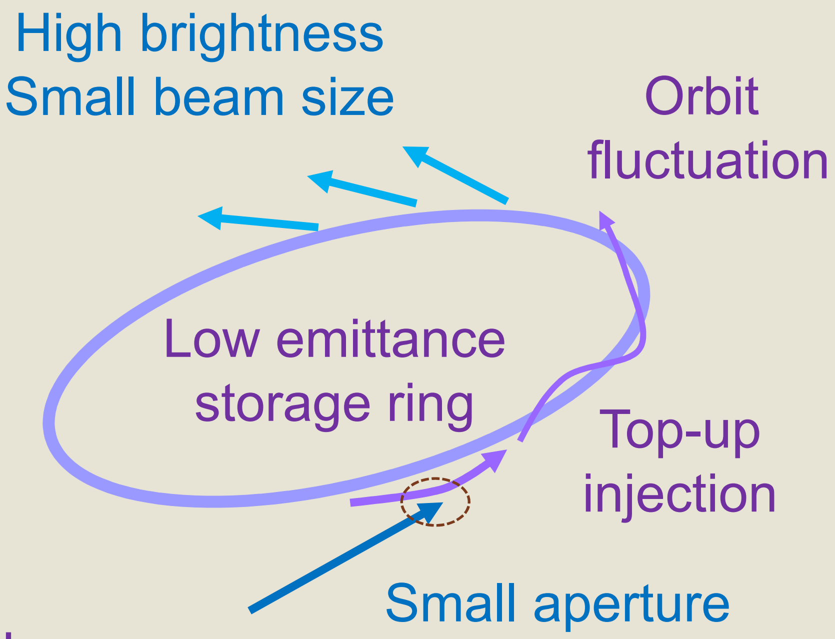
- Low emittance electron storage ring for higher brightness

  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

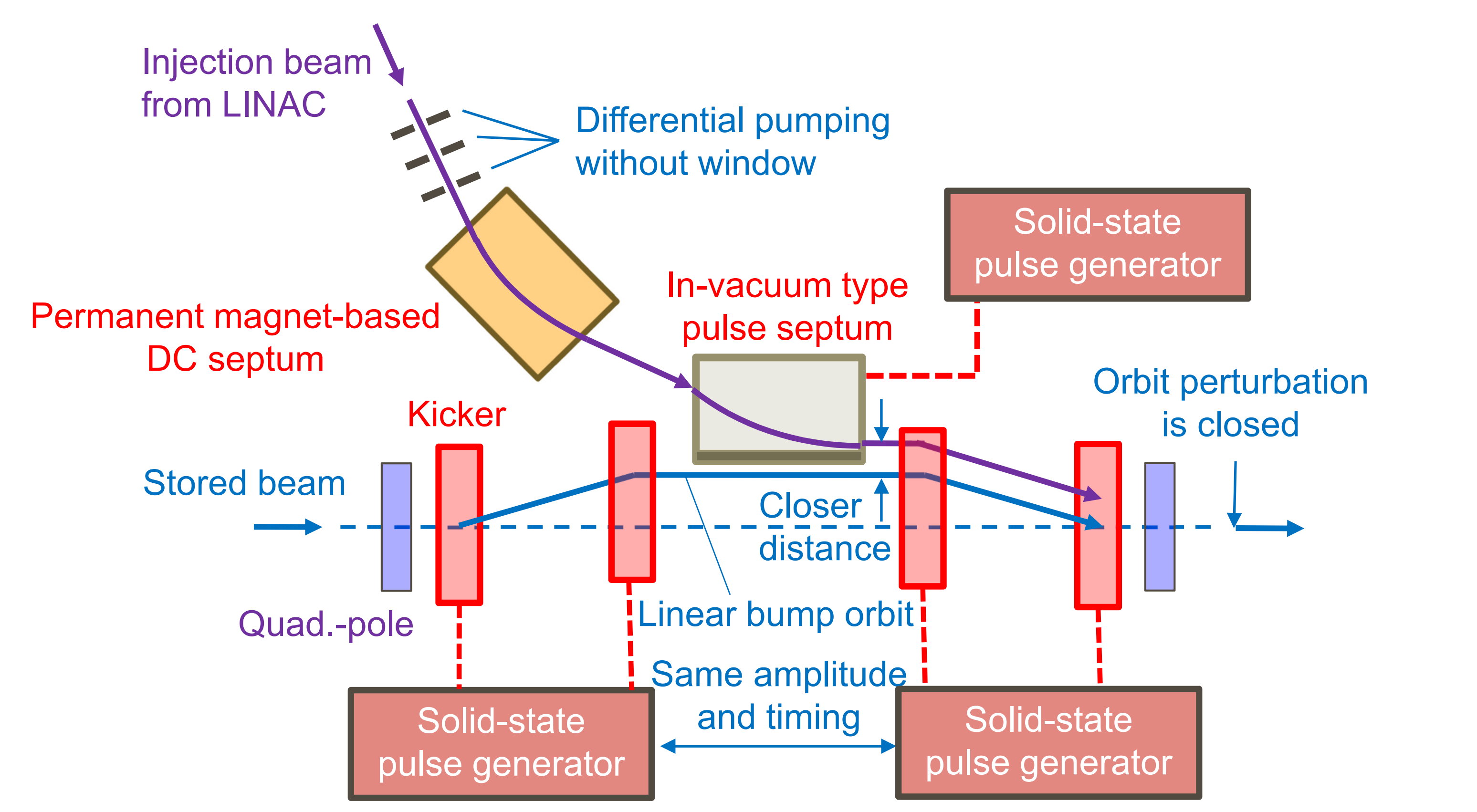
Sirius

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

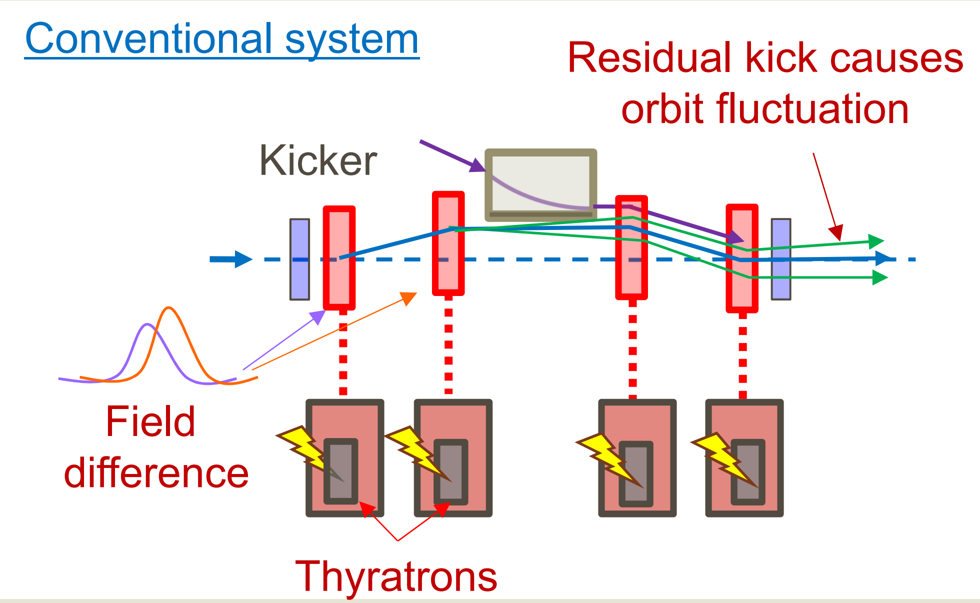


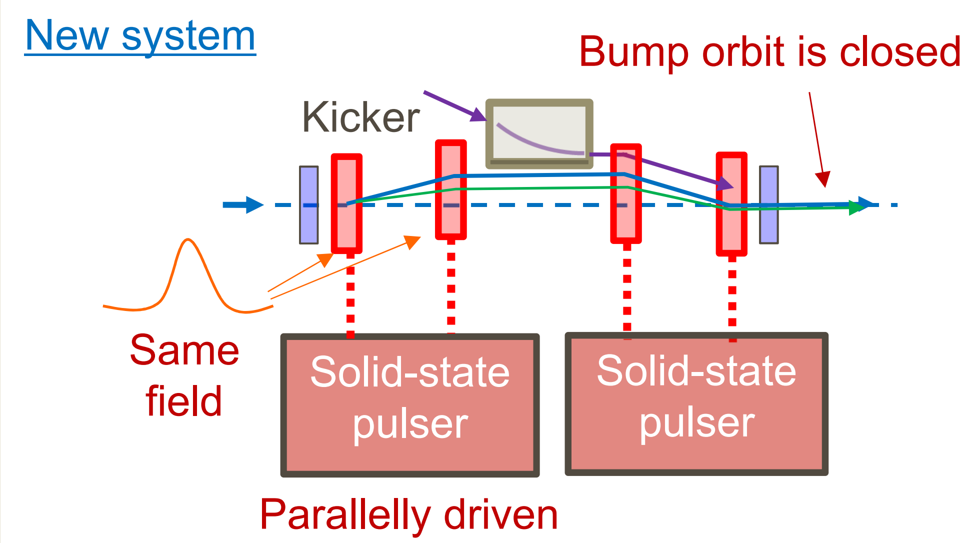
Linear bump orbit
with identical kicker magnets

Solid-state pulse generator
Low jitter and precise amplitude control

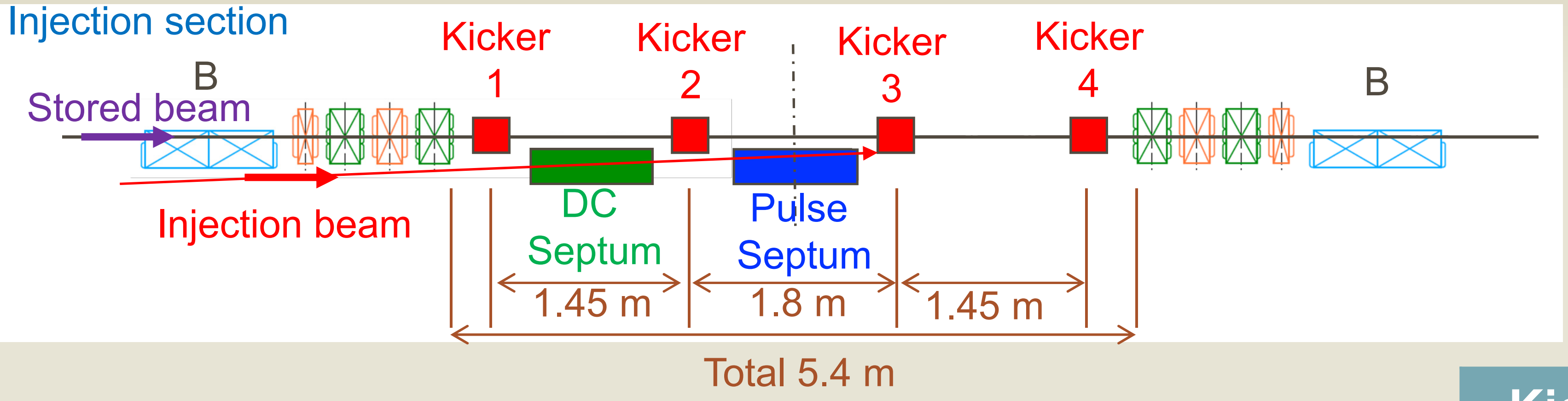
Strategy for the bump orbit stabilization

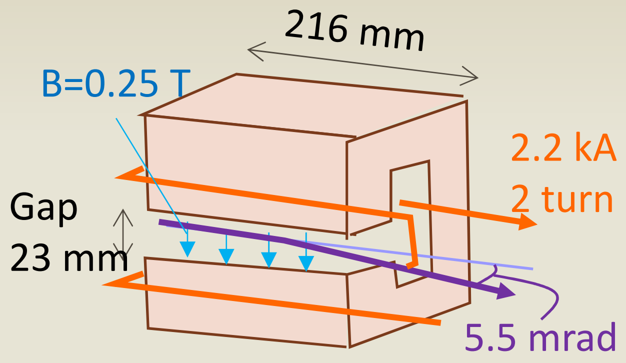
- Pair of the kickers should be matched
  - Kick angle ~ a few μrad
  - Field amplitude <0.1%
  - Timing < sub ns
- Conventional pulser using thyratron
  - Large timing and voltage fluctuation.
- Solid-state switch
  - Stable and long lifetime
- Parallel drive
  - Definitely synchronized.
  - Fluctuation of the kick is canceled out.
- Amplitude of the two pulse generators are also matched (~0.1%) to reduce the trajectory offset.





Prototype kicker magnet for 3 GeV light source



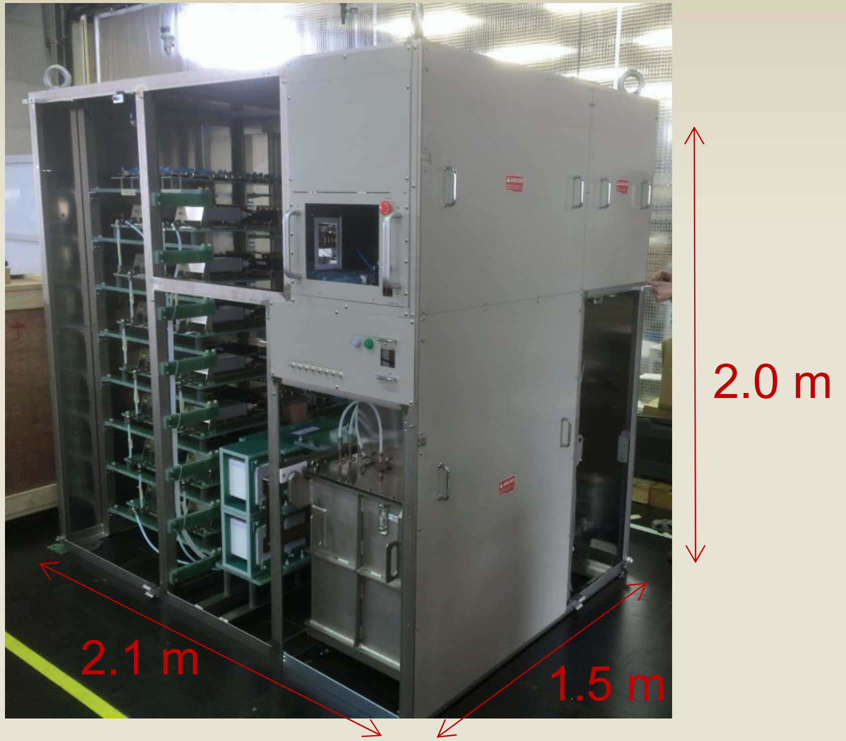


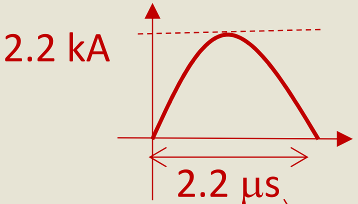
- Kicker magnet design
  - Large kick angle (5.5 mrad)
    - ⇒ High magnetic field (0.25 T).
  - Short pulse width (2.2 μs)
    - ⇒ Frequency response up to 1 MHz
  - C-type, silicon-steel laminated core.
  - 2 turn for low inductance (4 μH)
    - ⇒High pulse current (2.2 kA)

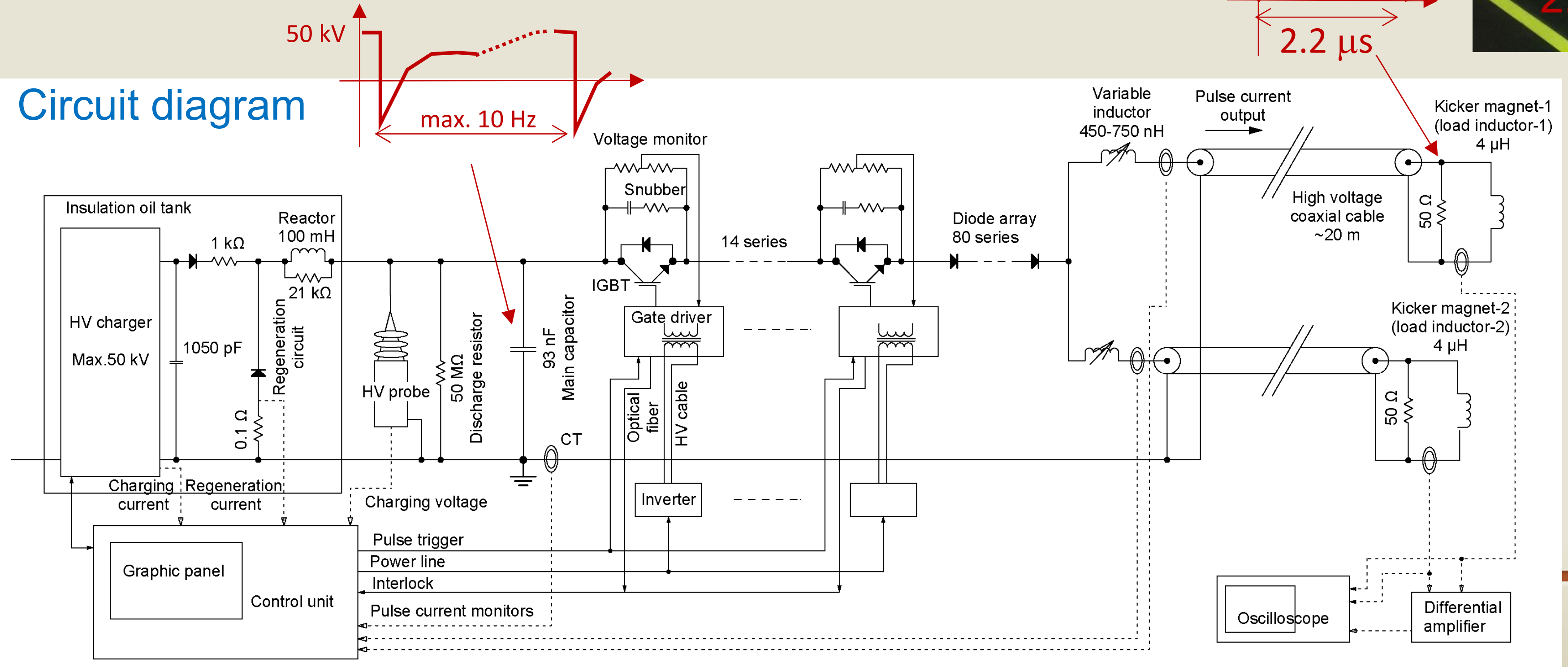
Kicker parameters (tentative)	
Bump amplitude	8 mm
Kick angle	5.5 mrad
Pole length	216 mm
Gap width	23 mm
Magnetic field	0.25 T
Pulse current	2.2 kA
Pulse width	2.2 μs
Inductance	4 μH

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.







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

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.

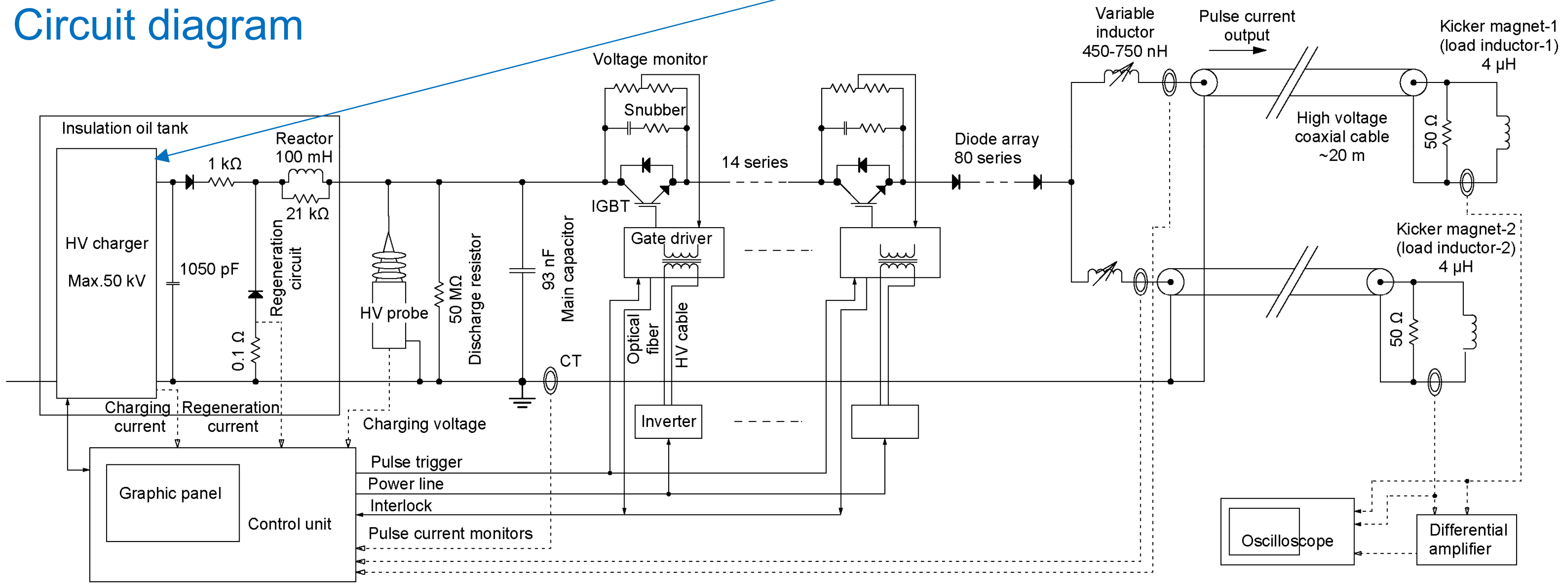
HV transformer

HV charger

Originally developed for klystron modulator at SACLA

- Full-bridge 20 kHz inverter + HV transformer
- Digital PWM regulation of the inverter

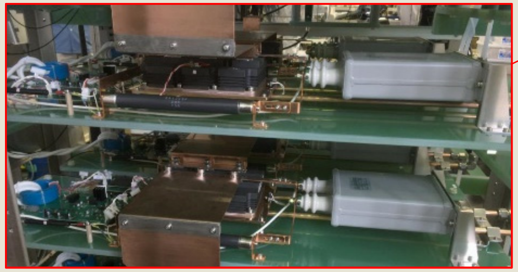
Circuit diagram



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

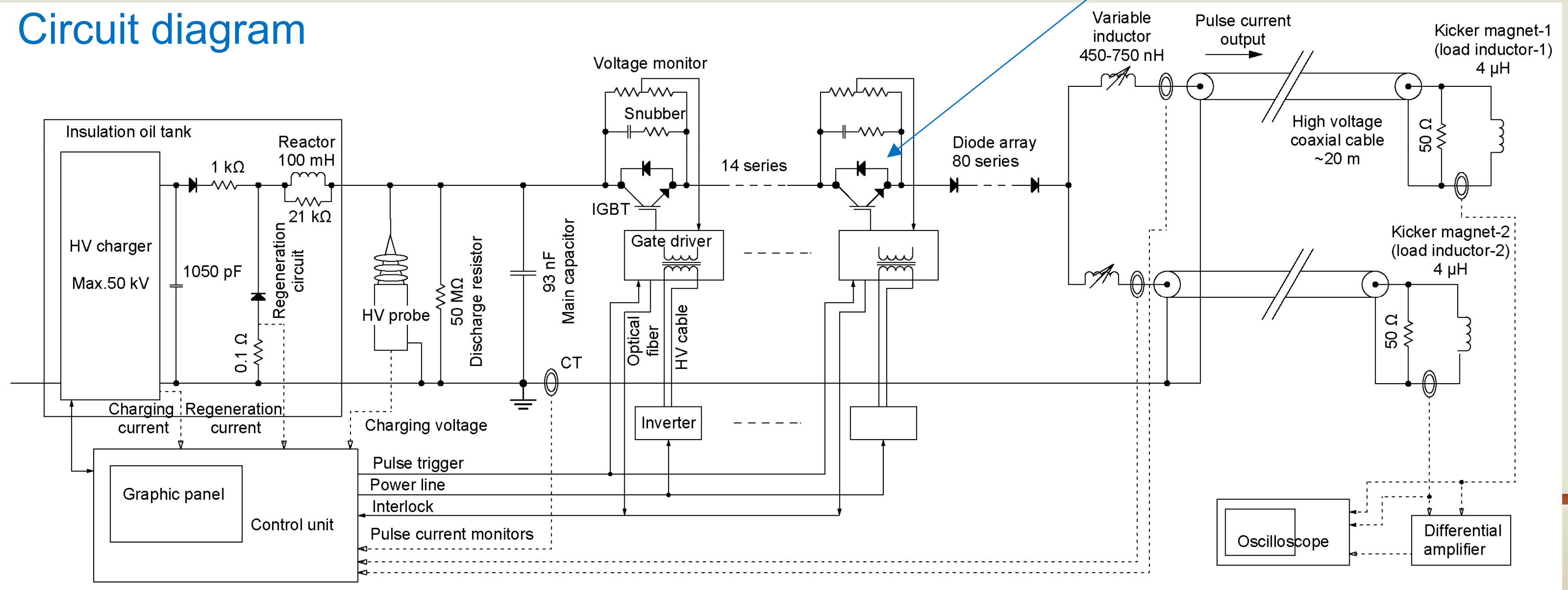
Solid-state pulse generator design

- 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.



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

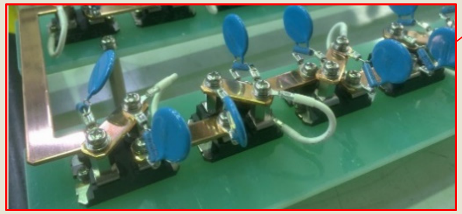
Circuit diagram



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

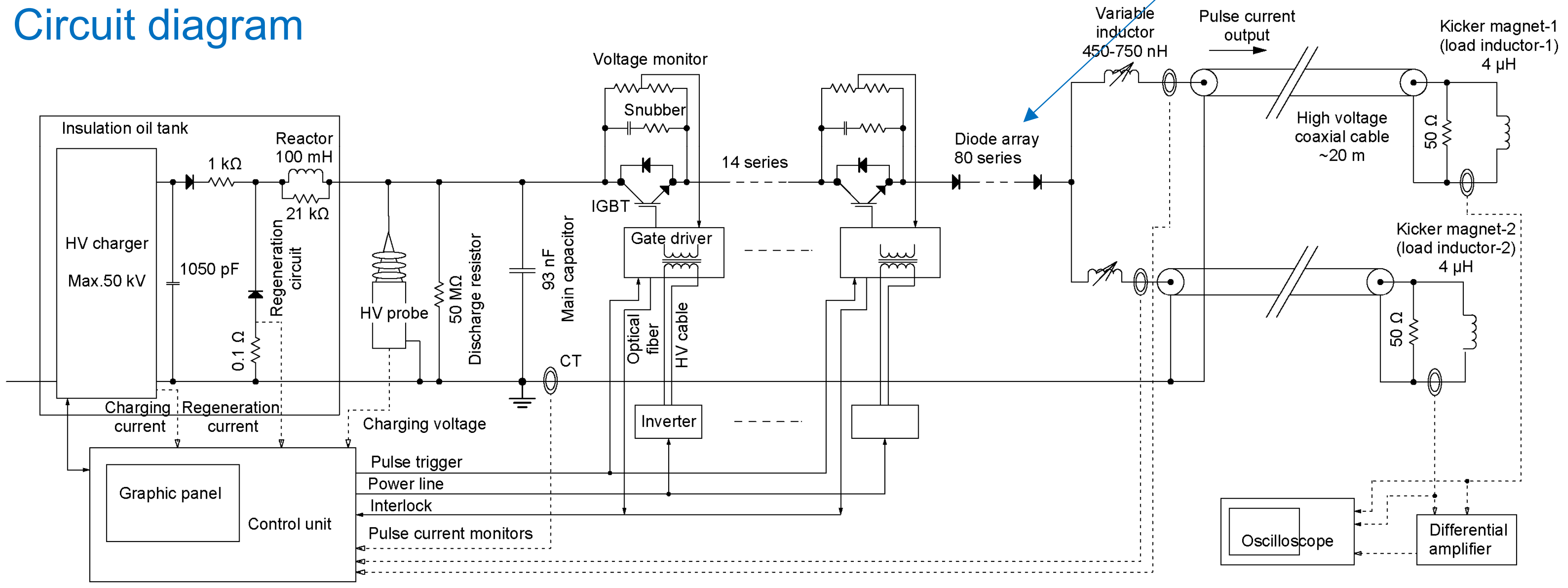
Solid-state pulse generator design

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



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

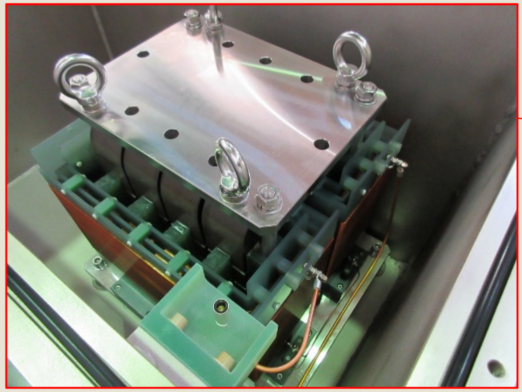
Circuit diagram



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

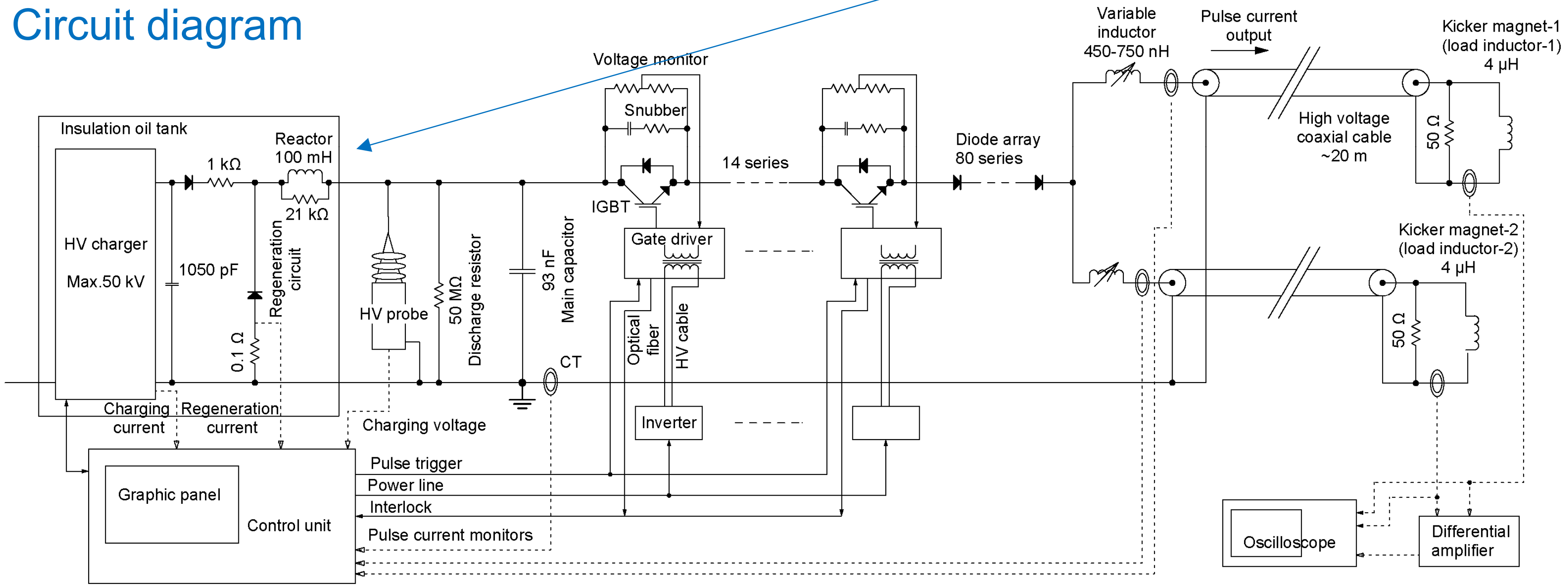
Solid-state pulse generator design

- 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.



Regeneration reactor
100 mH

Circuit diagram



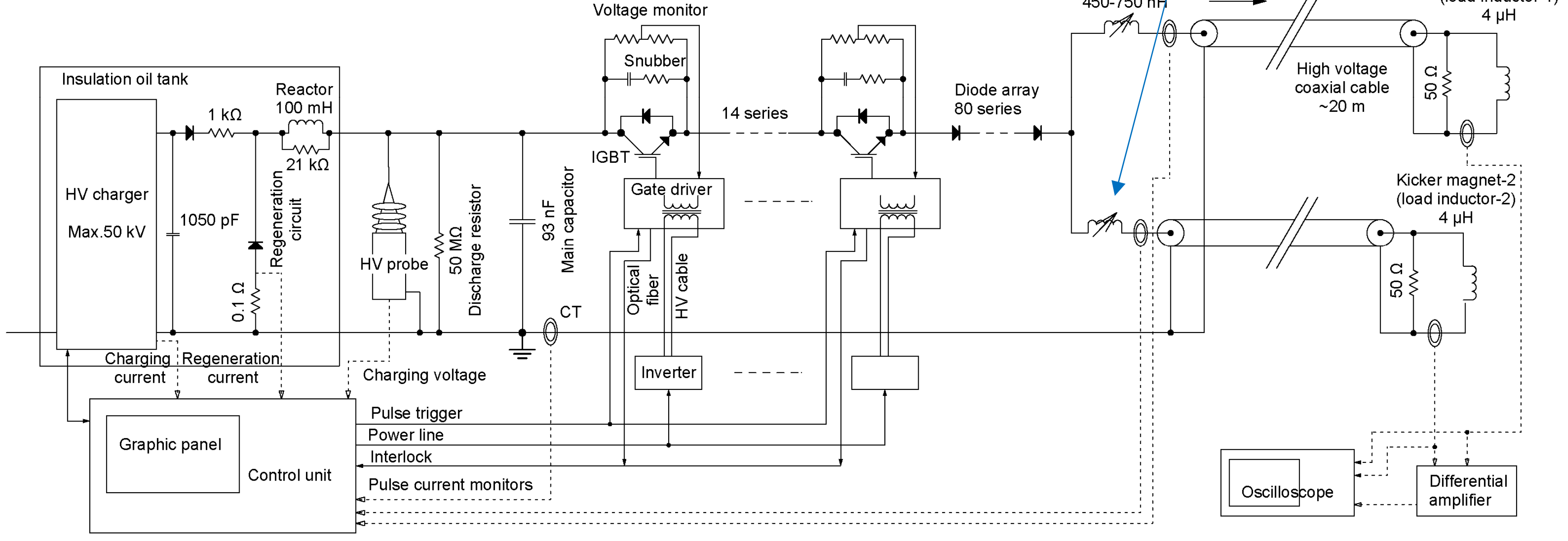
Design parameters	
Peak current (each)	2.2 kA
Pulse width	2.2 μs
Capacitance	93 nF
Charging voltage	50 kV
Parallel drive	
Amplitude difference	< 0.1%
Timing difference	< 1 ns

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.**

Variable inductor
450-750 nH

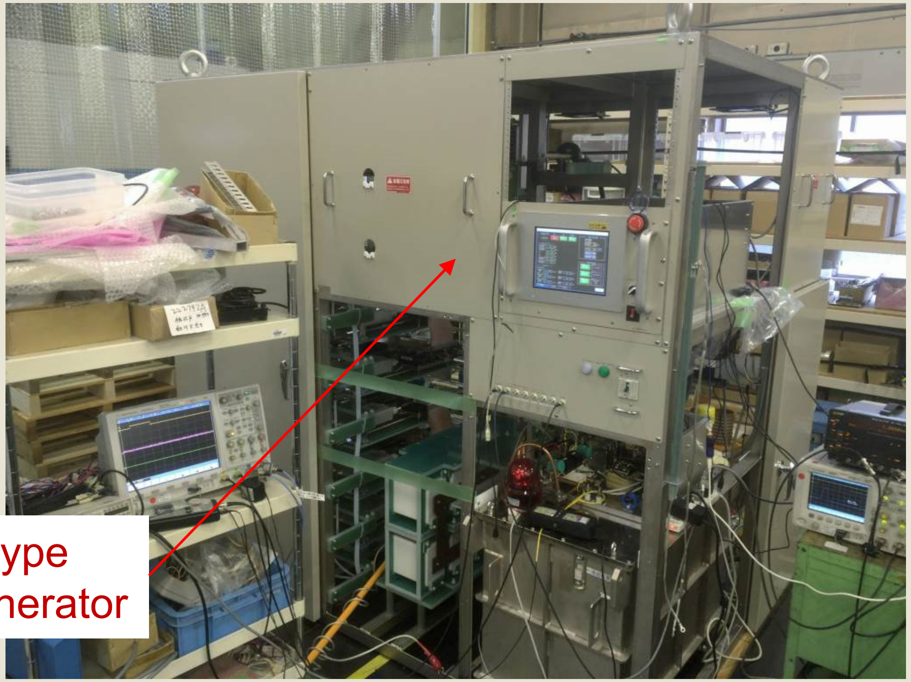
Circuit diagram

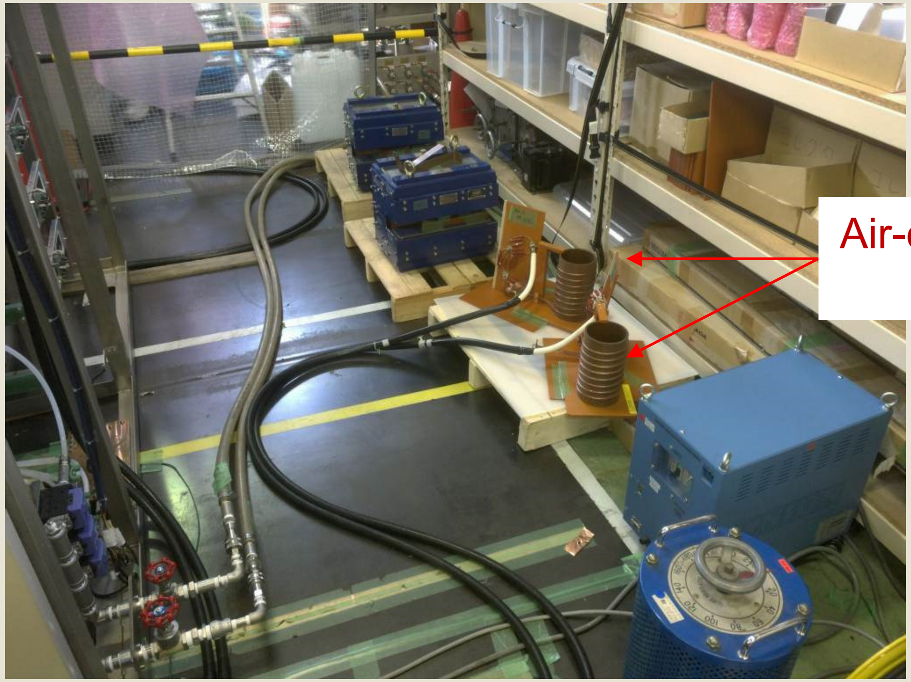


Design parameters	
Peak current (each)	2.2 kA
Pulse width	2.2 μs
Capacitance	93 nF
Charging voltage	50 kV
Parallel drive	
Amplitude difference	< 0.1%
Timing difference	< 1 ns

Operation test results

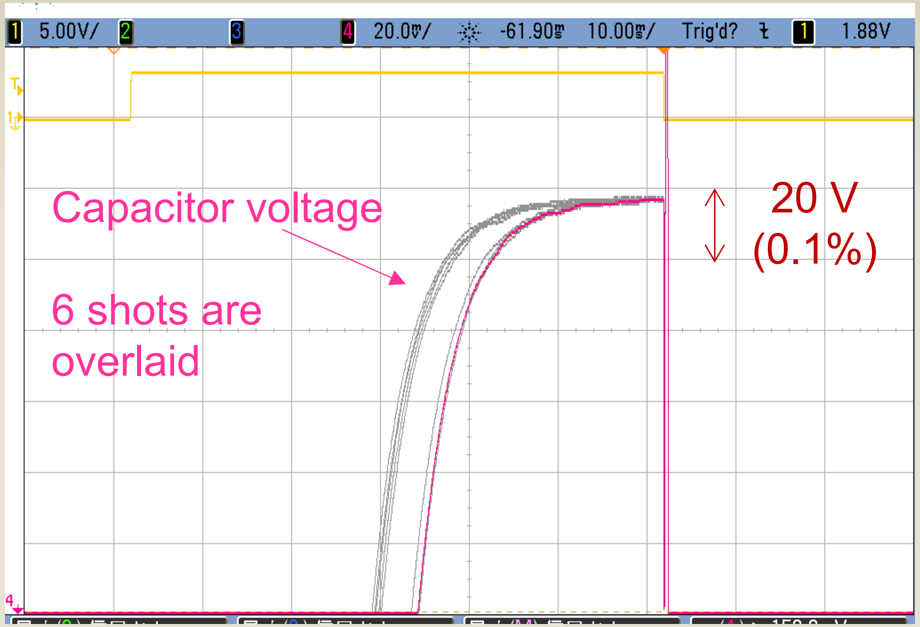
- Checked items
  - Charging voltage accuracy, regeneration efficiency
  - Peak current and pulse width
  - Matching of the pulse currents
- Instead of the kicker magnets, two air-core inductors driven in parallel.

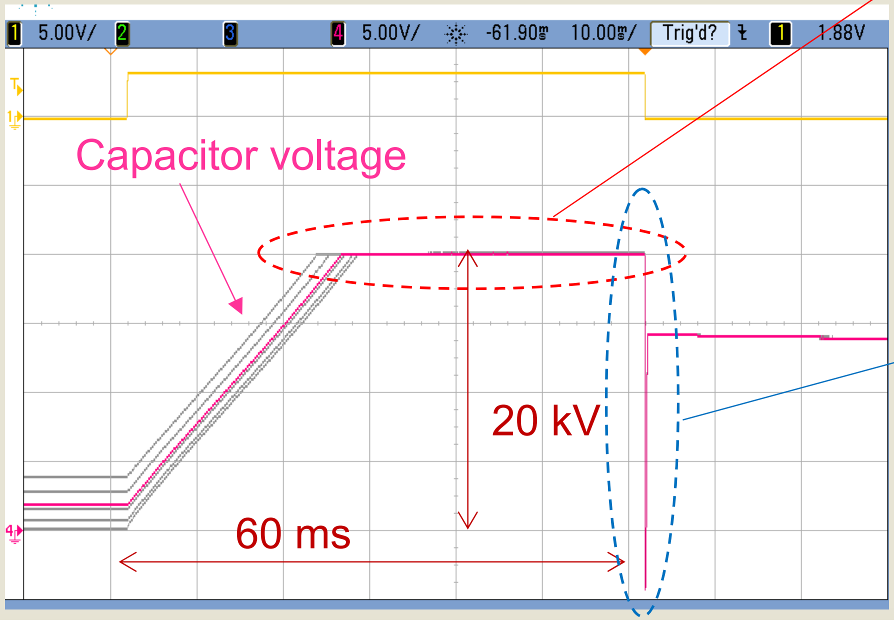


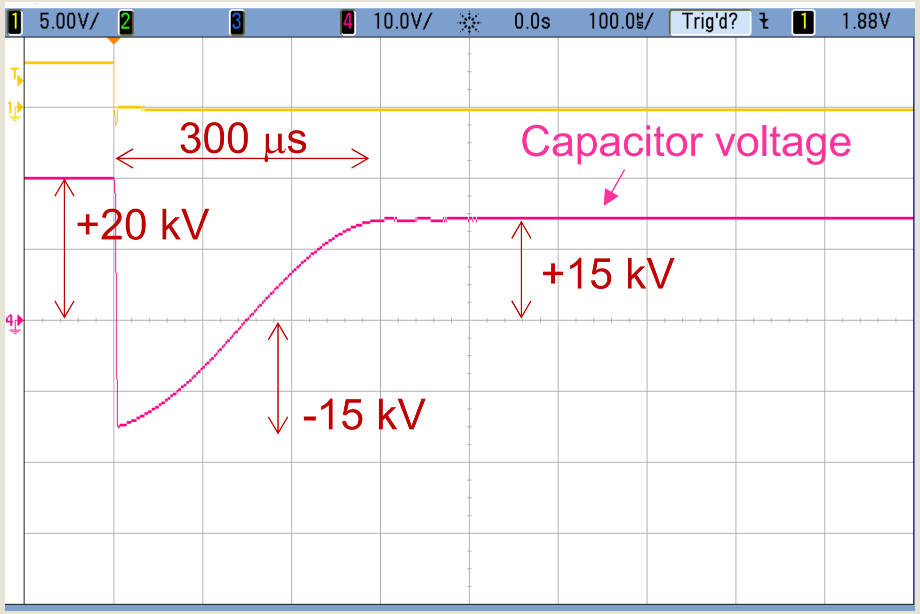


Capacitor charging waveforms

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

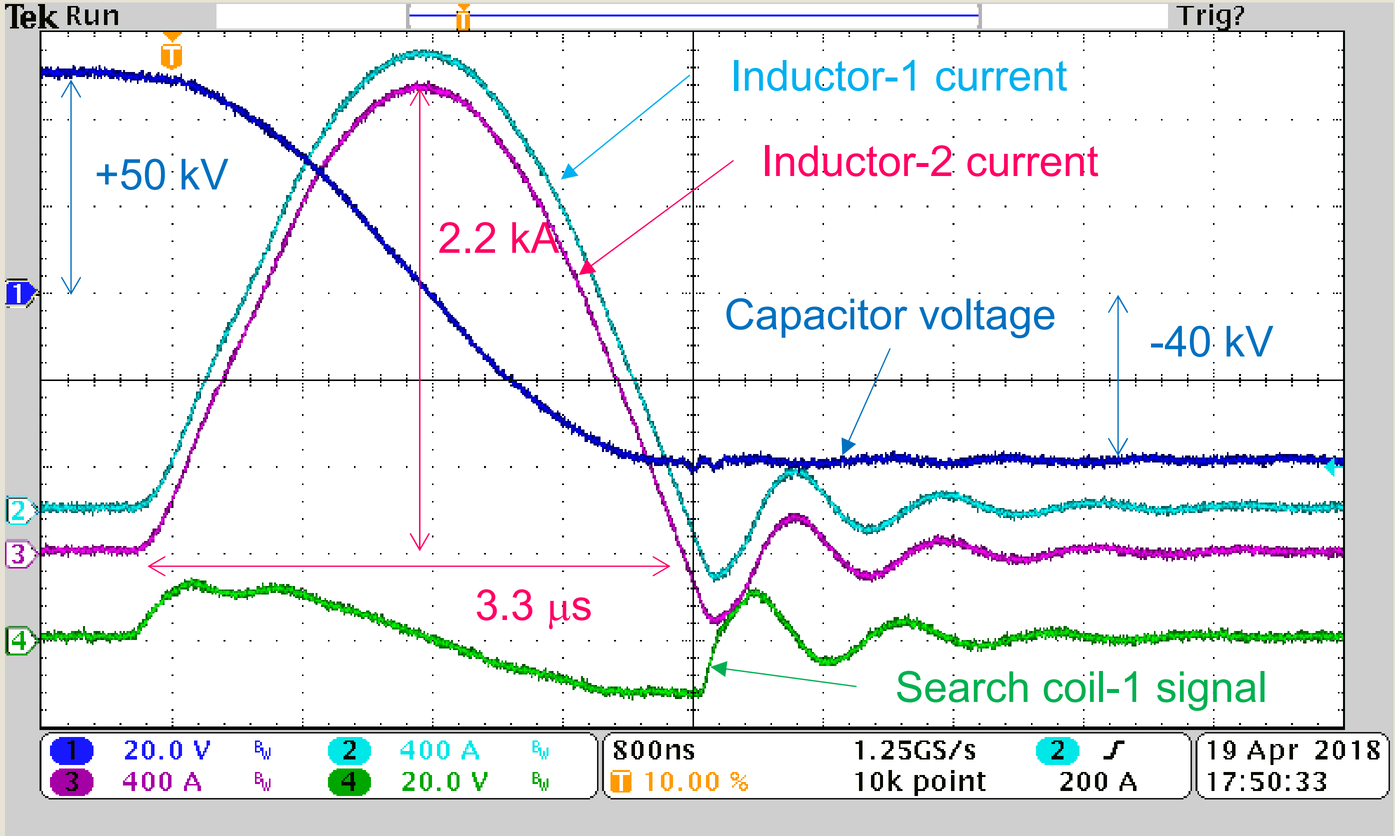






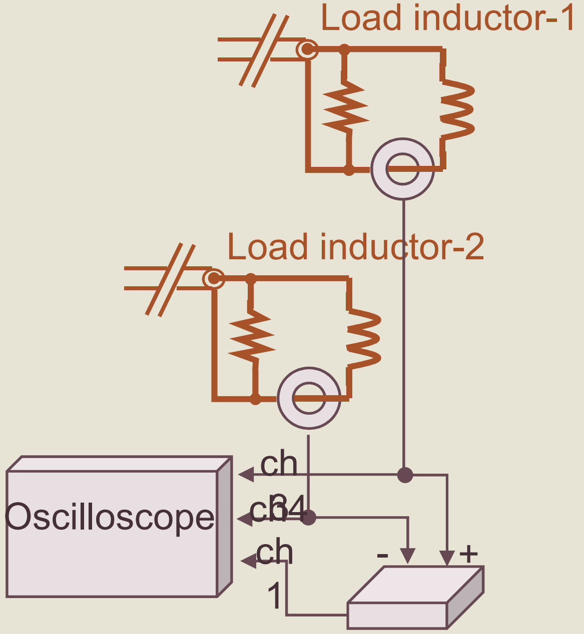
Pulse current amplitude and pulse width

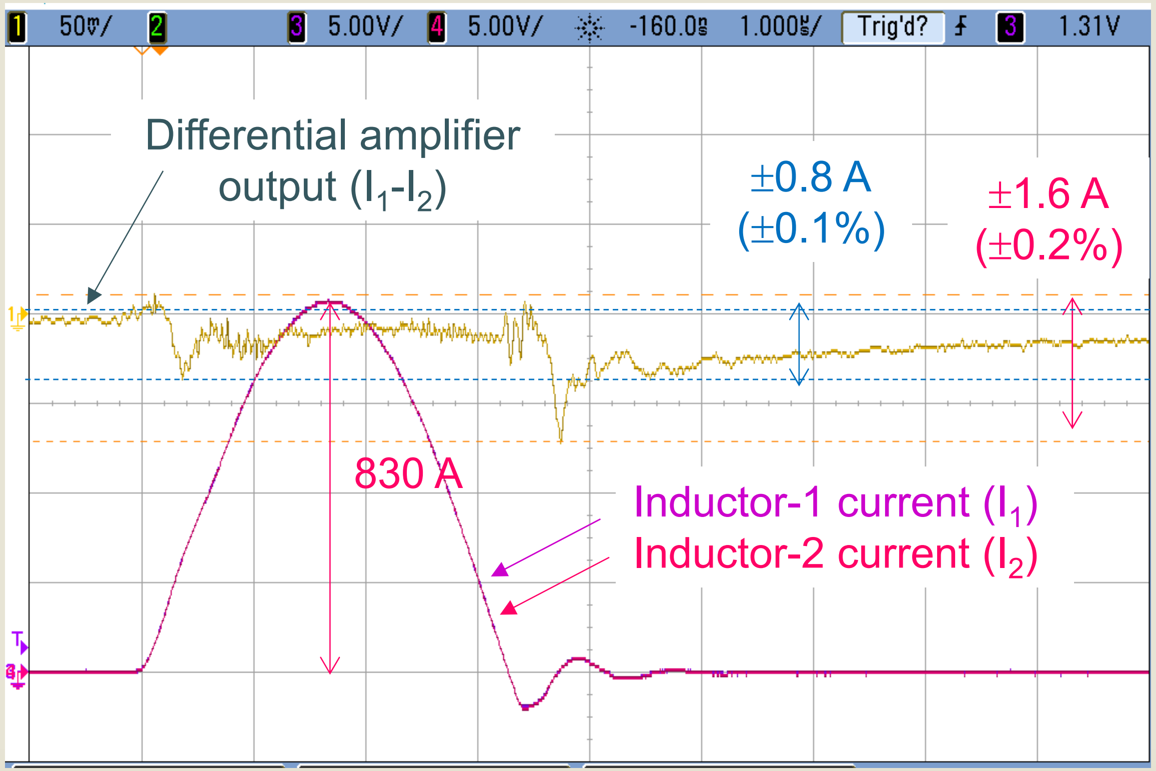
- Peak current: 2.2 kA for each coil   OK
- Pulse width: 3.3 μs   wider than design (2.2 μs)
- Same current passed to both inductors OK



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.

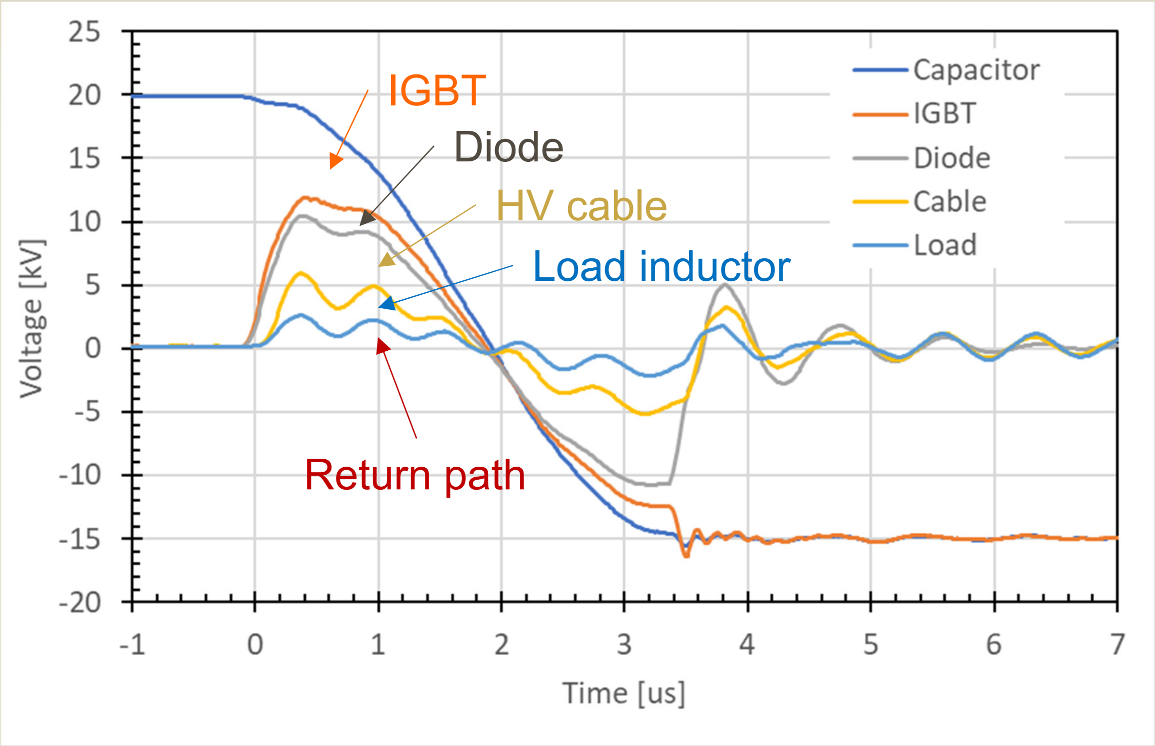


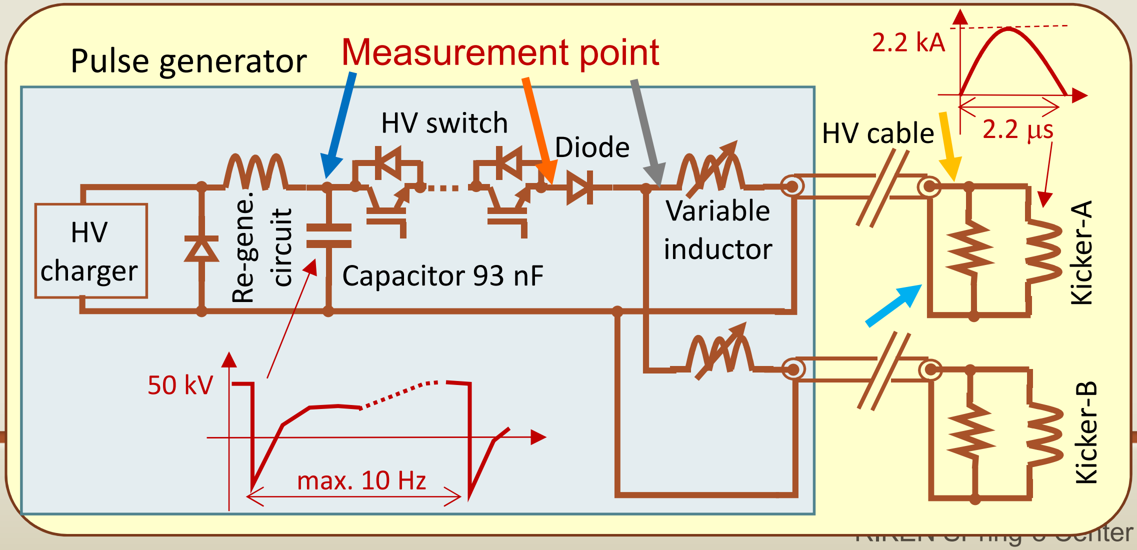


Improvement for shorter pulse width

- Pulse width: measured 3.3 μs, design 2.2 μs
- 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)

Charging voltage = 20 kV





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.