FRXA01

Full Energy On-Demand Beam Injection from SACLA into the SPring-8 Storage Ring

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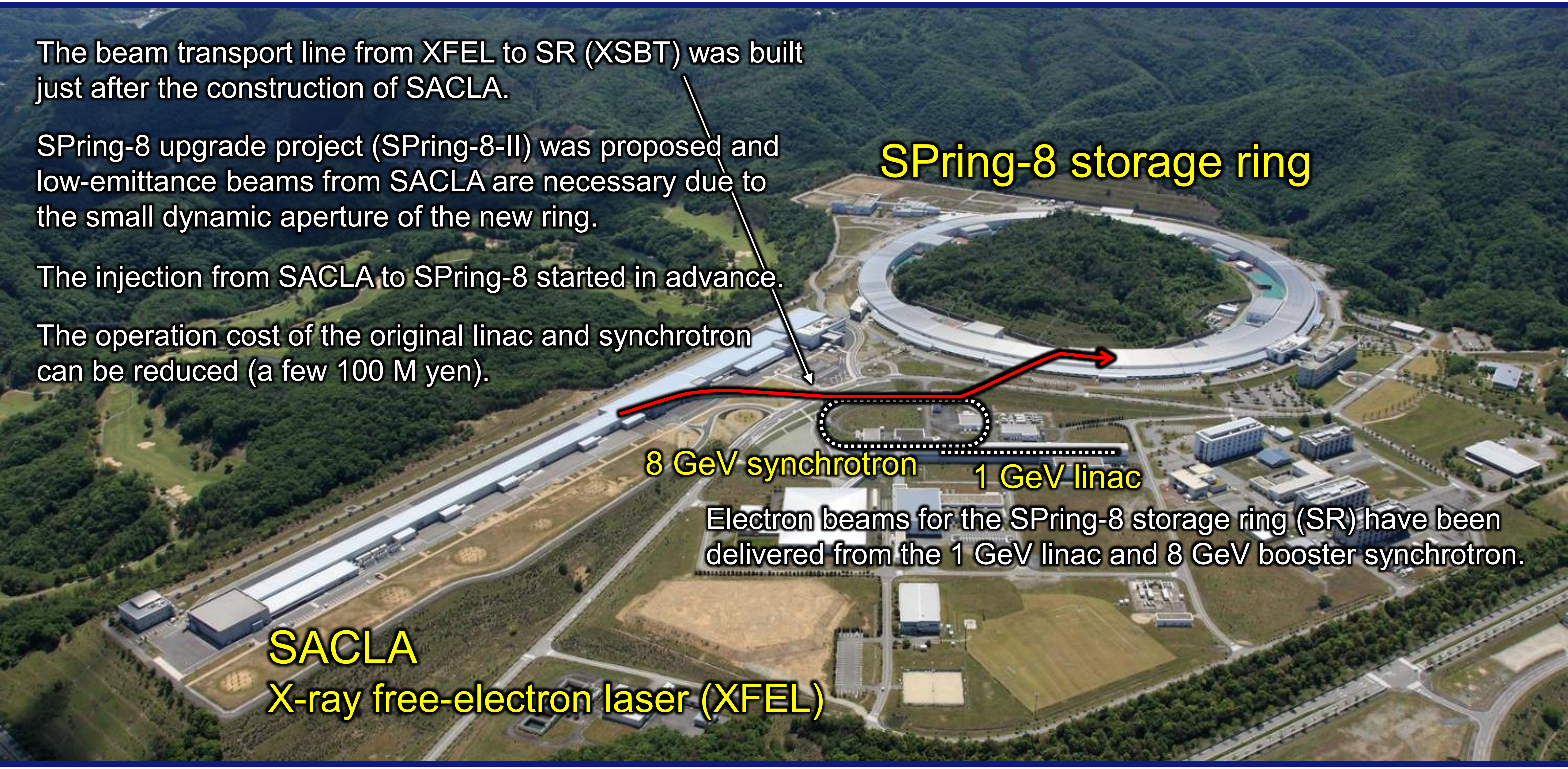
Introduction

The beam transport line from XFEL to SR (XSBT) was built just after the construction of SACLA.

SPring-8 upgrade project (SPring-8-II) was proposed and low-emittance beams from SACLA are necessary due to the small dynamic aperture of the new ring.

The injection from SACLA to SPring-8 started in advance.

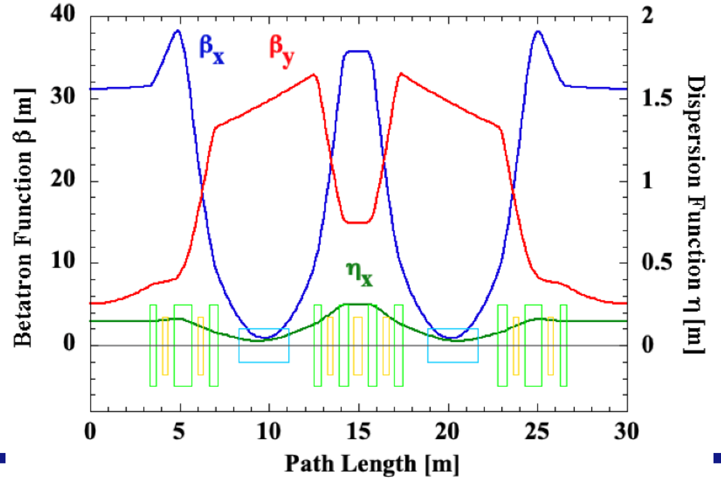
The operation cost of the original linac and synchrotron can be reduced (a few 100 M yen).

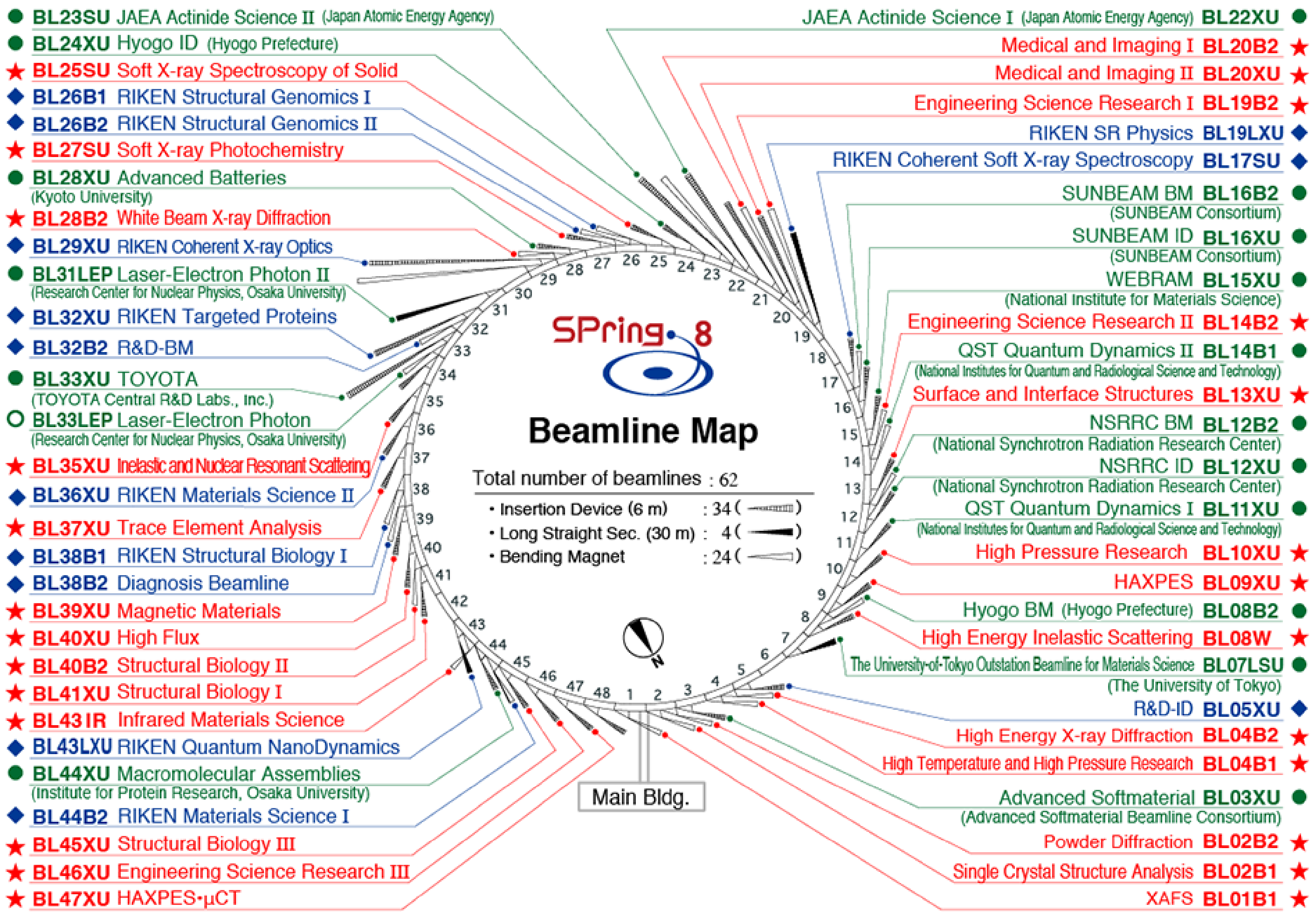


Electron beams for the SPring-8 storage ring (SR) have been delivered from the 1 GeV linac and 8 GeV booster synchrotron.

SPring-8 Storage Ring

Beam energy	8 GeV
Circumference	1436 m
Beam current	100 mA
Natural emittance	2.4 nm rad
Beam size (straight section)	H 316 μm / V 4.9 μm
Lattice	Double-bend (achromat)
The number of cells	44
Energy spread	0.11%
Betatron tune	H 41.14 / V 19.35
Acceleration frequency	508.58 MHz
Harmonic number	2436



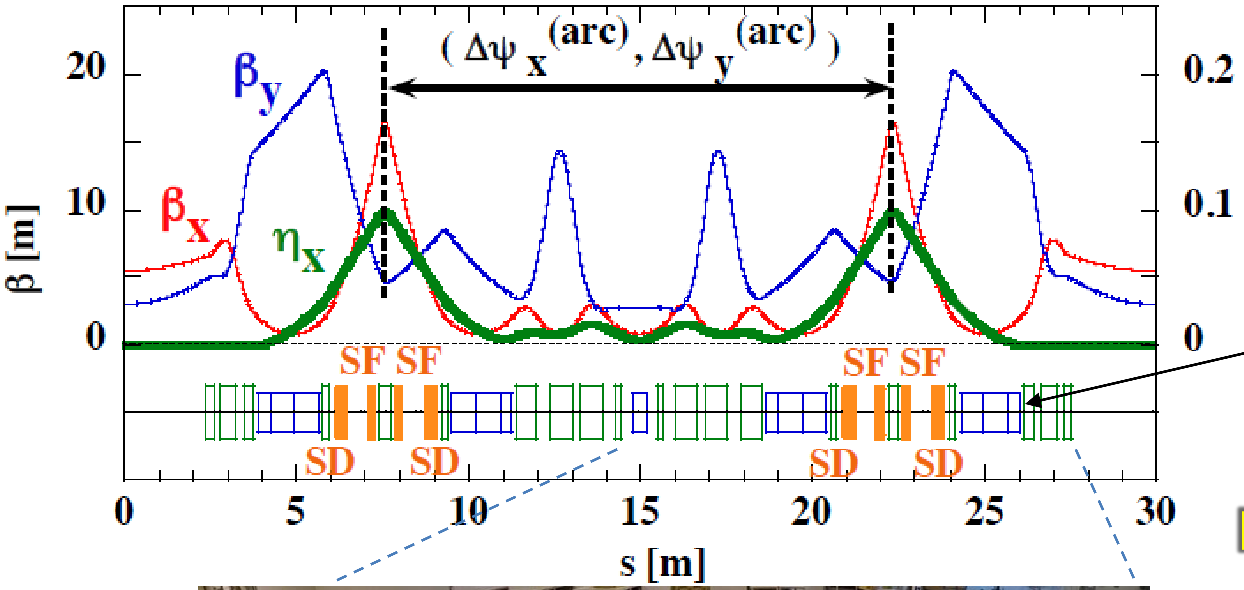


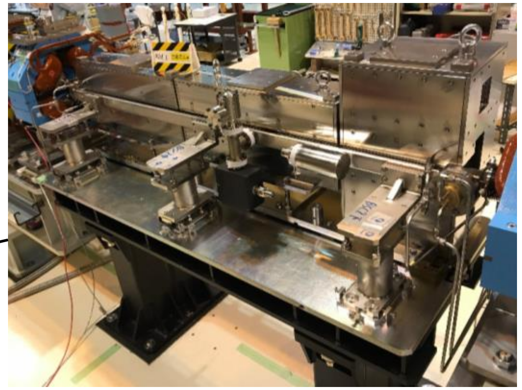
57 beamlines in operation

SPring-8 Upgrade

- Emittance: 2.4 nm rad → < 100 pm rad (still under optimization)
- Lattice: Double-bend Achromat (DBA) → 5-bend Achromat (5BA)
- Beam Energy: 8 GeV → 6 GeV
- SPring-8-II Conceptual Design Report, Nov. 2014, http://rsc.riken.jp/pdf/SPring-8-II.pdf
- Low-emittance beam (< 500 pm rad) is needed for injection. → Injected from SACLA

Linear Optics

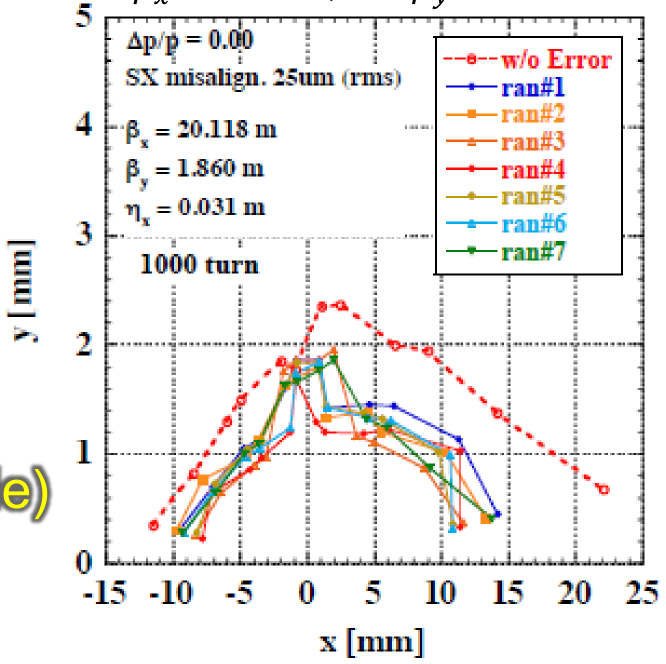




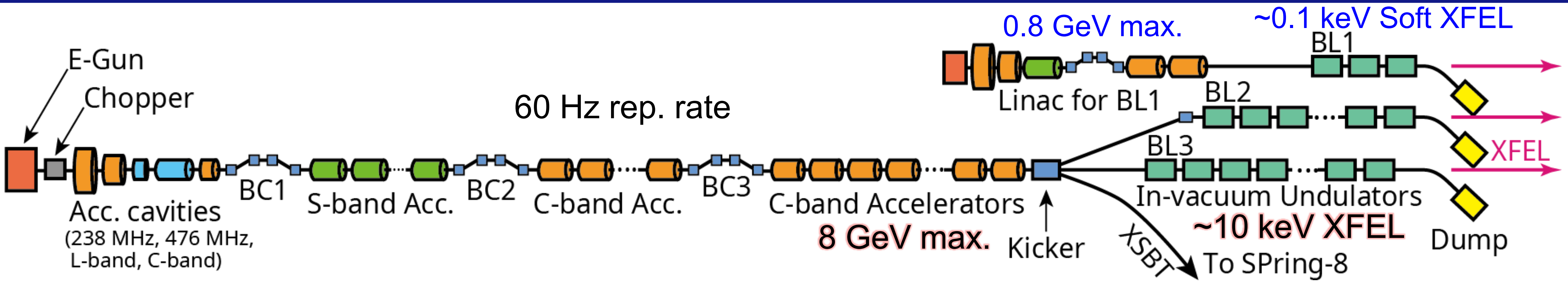
Permanent magnet (dipole)

Dynamic Aperture

$\beta_x = 20.1$ m, $\beta_y = 1.86$ m

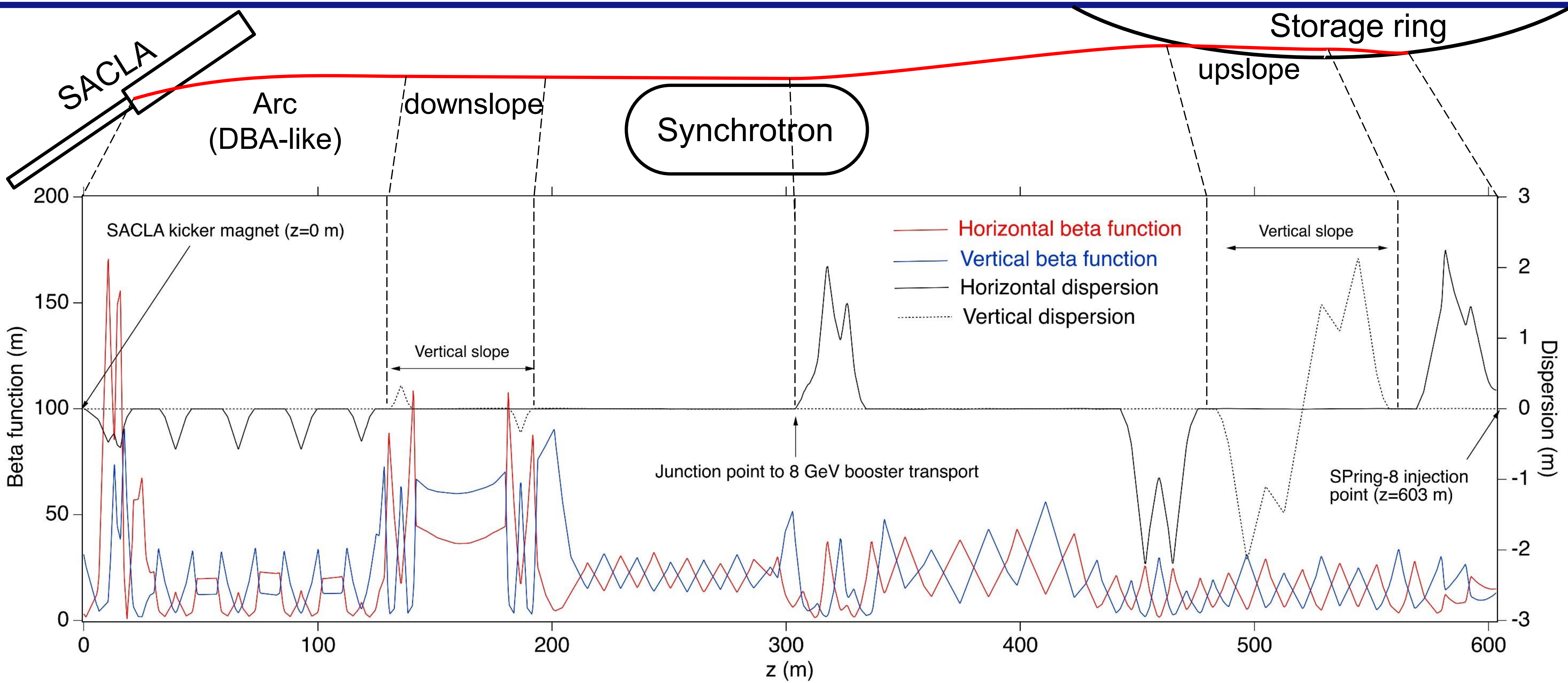


XFEL facility, SACLA



- A low-emittance beam is generated by 500 kV thermionic electron gun. (CeB_6)
- The bunch length is shortened by sub-harmonic acceleration cavities and three bunch compressors.
  - 1 ns, 1 A → ~10 fs, ~10 kA
- The beam is accelerated to 8 GeV (max) by C-band accelerators. (> 35 MV/m)
- XFEL is generated by in-vacuum undulators. ($\lambda_{\mathrm{u}} = 18\ \mathrm{mm}$)
  - ~0.8 mJ/pulse (10 keV)
- The beam route is switched by a kicker magnet.
  - BL2, BL3, and XSBT (XFEL to Storage ring Beam Transport line)
- Projected emittance: ~2 μm rad (normalized), ~130 pm rad (natural, 8 GeV).
  - Slice emittance: < 1 μm rad (normalized)

Beam transport line from SACLA to SPring-8



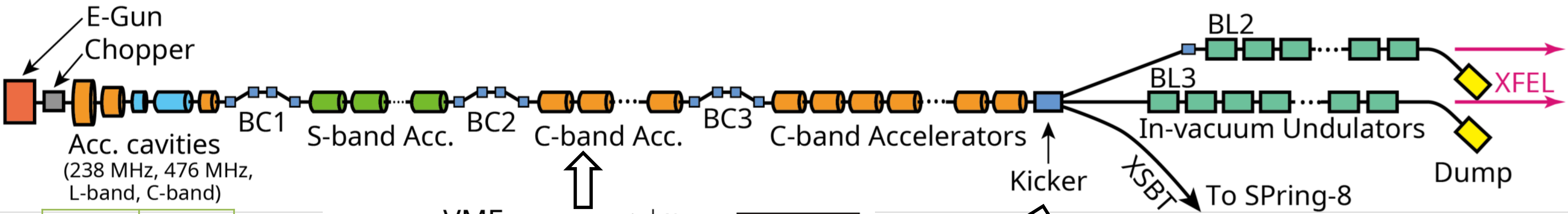
Beam monitors： BPM x 25, Screen x 43, CT x 7, Loss monitor x 1

Requirements for injection from SACLA

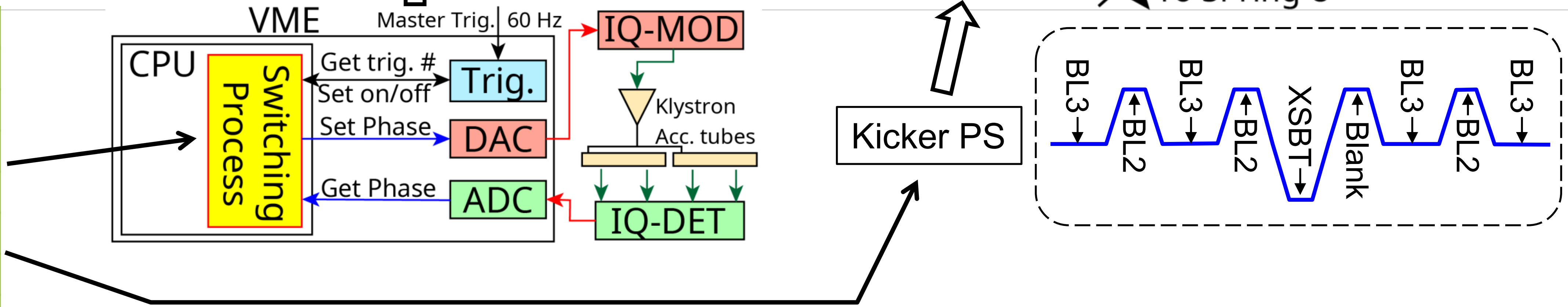
	SPring-8	SPring-8-II	XFEL
Beam Energy	8 GeV	6 GeV	4 – 8 GeV
Bunch Length	< 10 ps	< 10 ps	~10 fs
Peak Current	< 1 kA	< 1 kA	> 10 kA
Emittance	< 100 nm rad	< 500 pm rad	~100 pm rad
Rep. Rate	10 Hz (initial) < 0.1 Hz (top-up)	10 Hz (initial) < 0.1 Hz (top-up)	60 Hz max.
Beam Route	XSBT	XSBT	BL2, BL3
Sync. with SR	Yes	Yes	No

- Emittance after XSBT should be as small as possible.
  - Smaller peak current (< 1 kA) is better for SPring-8 to suppress emittance growth in XSBT due to coherent synchrotron radiation (CSR) effect.
- On-demand beam route and parameter switching.
  - Top-up injection in parallel with the XFEL operation.
- Synchronization of SACLA to SPring-8.
  - Within 6 ps std. (bunch length of SPring-8: ~10 ps std.)
- Sufficiently small satellite bunch.
  - SPring-8 bunch purity: $< 10^{-8}$ ($= Q_{\mathrm{satellite}}/Q_{\mathrm{main}}$)

On-demand beam route and parameter switching

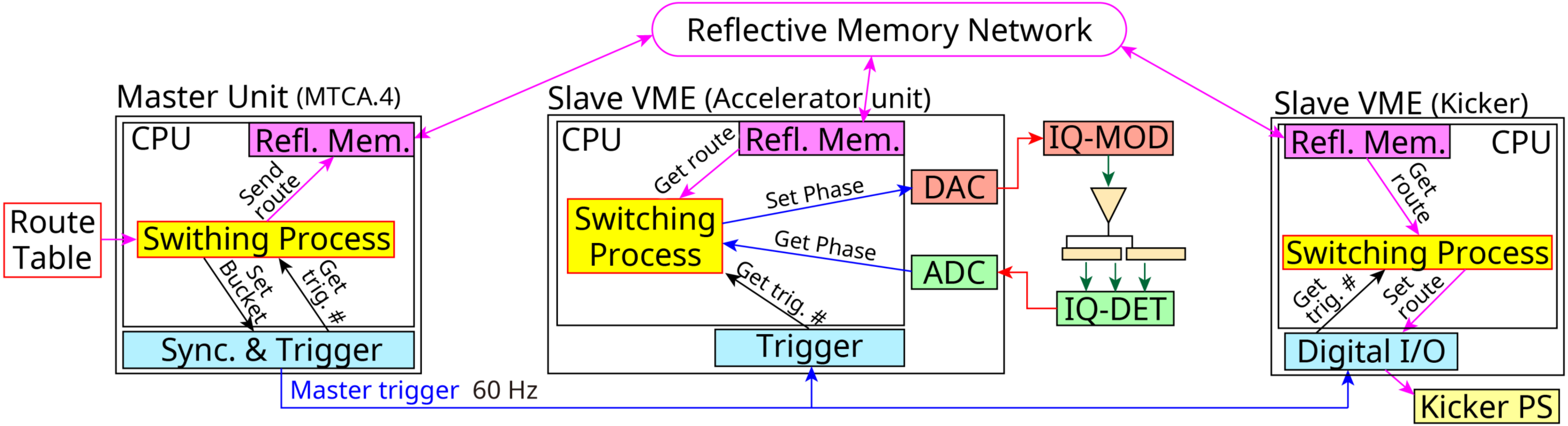


Trig. #	Route
0	BL3
1	BL2
2	BL3
3	BL2
4	XSBT
5	Blank
6	BL3
7	BL2
⋮	⋮



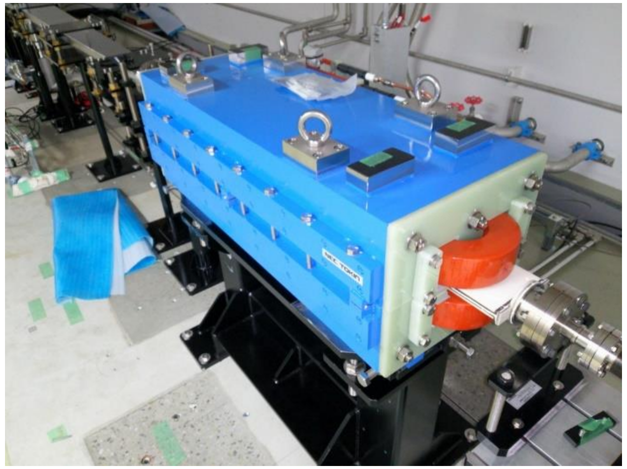
- We distribute beam route information and switch the beam route and parameters shot-to-shot.
  - Beam energy is changed by turning each accelerator unit on or off. (~120 MeV / C-band unit)
  - bunch length is changed by shifting the RF phase of the accelerator units before BC3.
- Electron beams for BL2, BL3, and XSBT are individually optimized. (Beam energy, bunch length, etc.)

Block diagram of the switching system



- We use a reflective memory network to distribute beam route data, since the route data must be updated in real-time.
  - The beam route table can be changed by operators on demand.
- Parameter switching for each accelerator component is implemented to a software process on a CPU module.
  - This process wait for the next trigger, read the next route data, and set parameters to each component.
- We evaluated the error rate of the parameter switching system.
  - Error rate was 1 x 10^{-7} level, which is well below the trip rate of high-power klystrons.

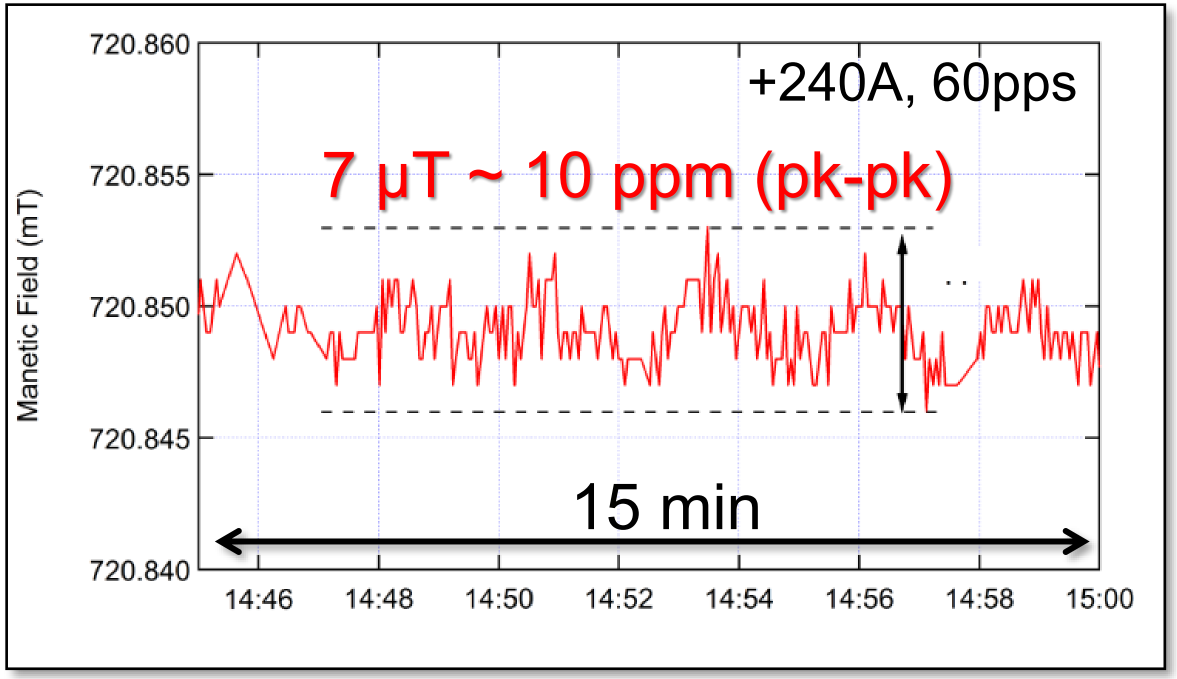
Kicker Magnet



Kicker magnet
（Yoke length 0.95 m, B_{max}=0.9 T）

Power supply（60 Hz, 1 kV-299 A）

Magnetic Field Stability



Measured by a gated NMR.

Full SiC MOS-FET modules
ROHM BSM120D12P2C005

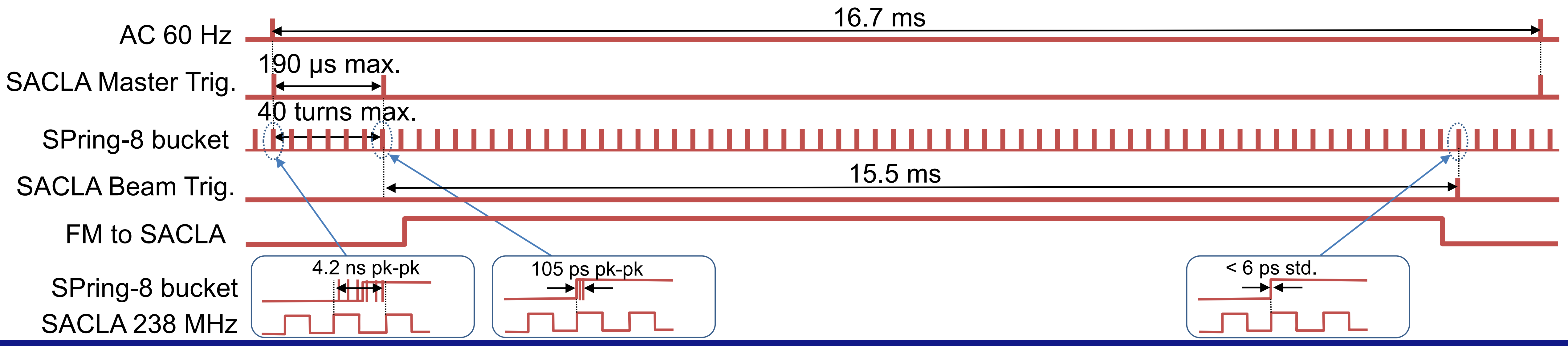
C. Kondo *et al.*, Rev. Sci. Instrum., **89**, 064704 (2018).

Synchronization of SACLA to SPring-8

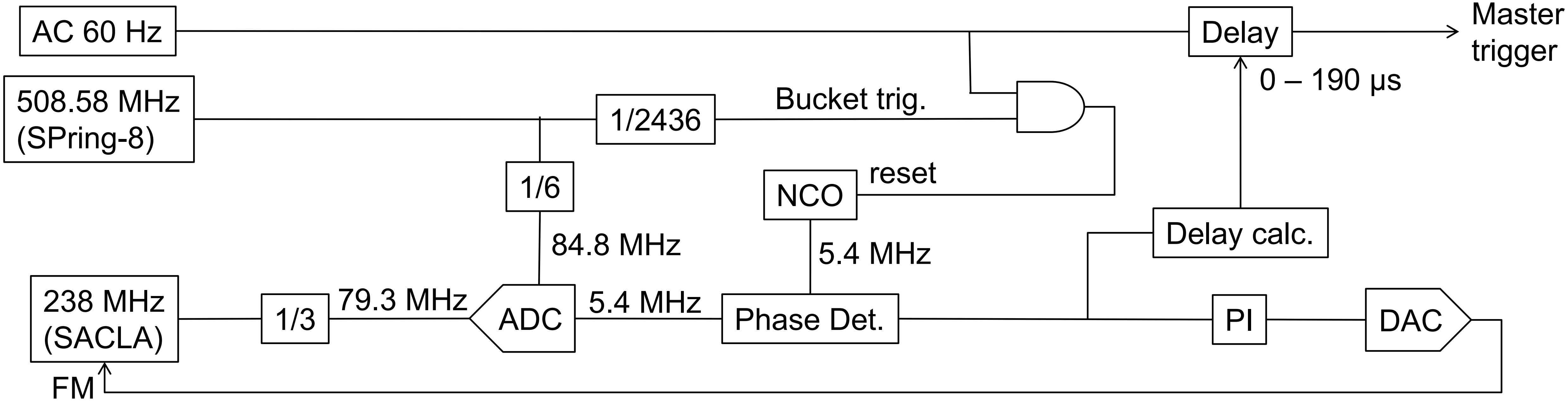
- The beam timing of SACLA must be precisely synchronized with the desired backet of SPring-8.
- The master clock of SACLA does not have a simple rational coefficient for the RF frequency of SPring-8.
  - SACLA: 238 MHz (= 5712 MHz / 24)
  - SPring-8: 508.58 MHz

  → We cannot use a conventional phase-locked loop (PLL) for synchronization.
- We apply frequency modulation (FM) to synchronize SACLA with SPring-8.
  - Timing jitter is ~4.2 ns (the priod of 238 MHz) without FM.
  - FM duration: ~15 ms → FM depth ~70 Hz of 238 MHz (~0.3 ppm)
- Since frequency fluctuation affects other electronics of SACLA, the FM depth should be as small as possible.
  - We found that the FM depth had to be 0.01 ppm level, which came from the frequency tolerance of mode-locked laser synchronized to SACLA.
  - If we wait for several turns (*N* turns maximum) until the smallest time difference, the timing jitter can be reduced to (4.2 ns) / *N*.
  - → We set *N* to 40 and the maximum timing jitter is ~105 ps [= (4.2 ns) / 40].
    Revolution period: 4.8 μs → maximum delay: 190 μs

T. Ohshima et al., IPAC'19 THPRB034.



Synchronization system



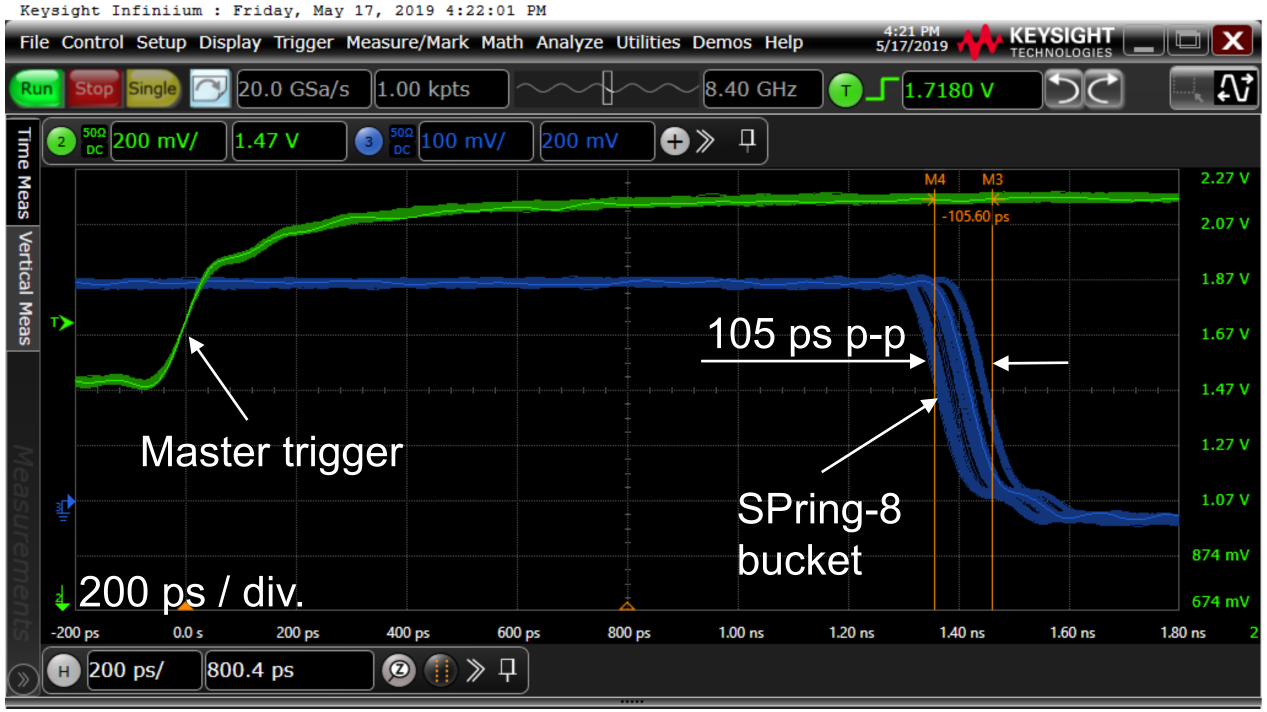
- The SACLA RF signal is digitized by the SPring-8 clock, and the phase difference is calculated.
- The master trigger signal is delayed according to the phase difference, so that the trigger timing falls into the 105 ps window.
- FM control with a PI feedback loop is applied to the SACLA master oscillator.
- These functions are implemented to a MTCA.4 digitizer AMC (Struck SIS8300L2) and a synchronization RTM.

Sync. RTM

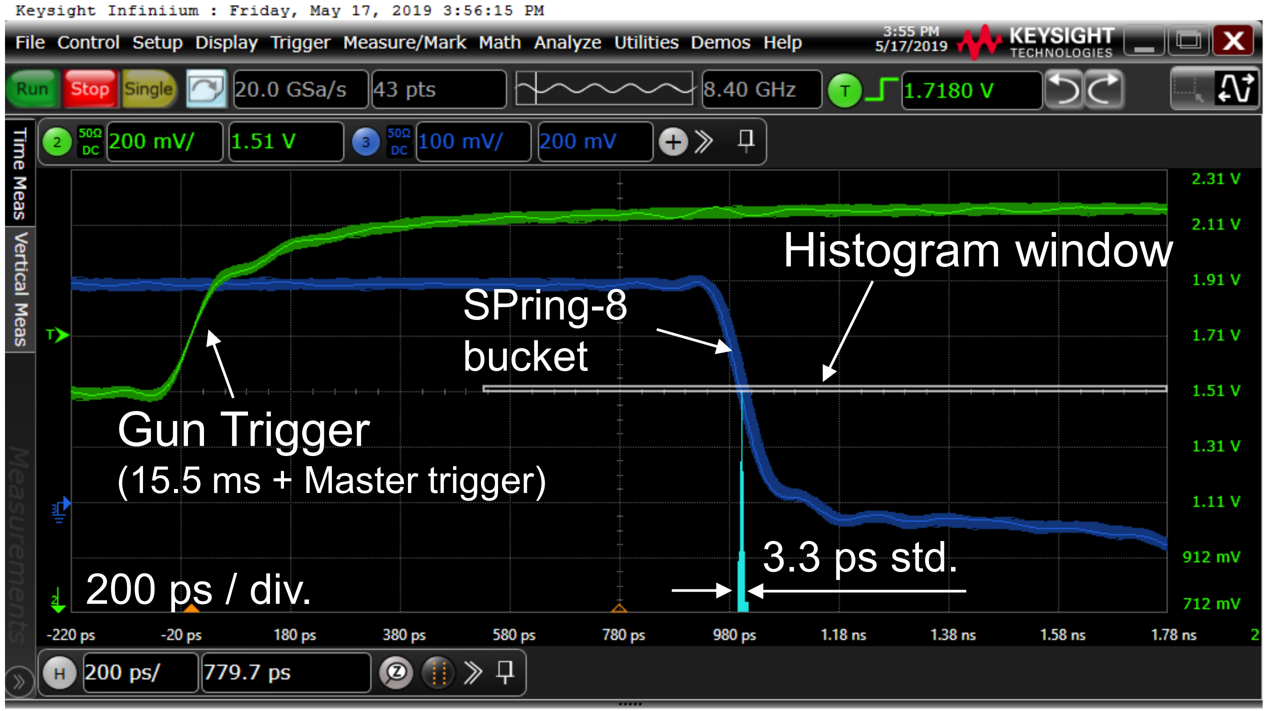
Digitizer AMC

Synchronization results

Before FM



After FM

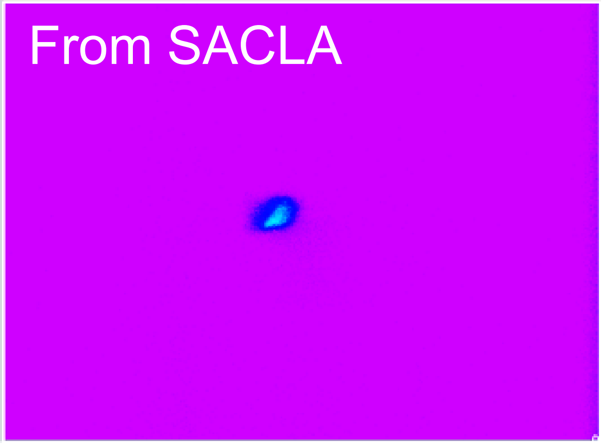


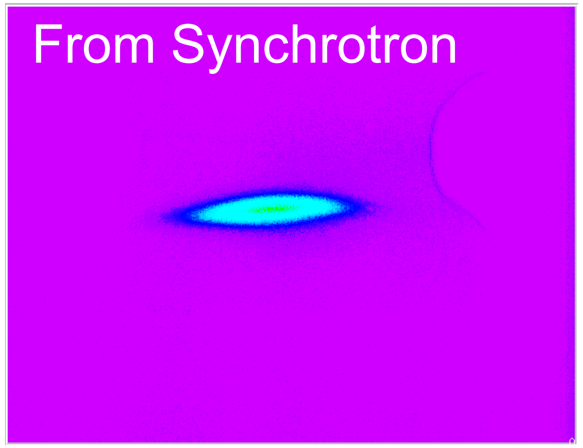
- The master trigger signal is synchronized within 105 ps to the SPring-8 bucket signal before the FM control.
  - The delay adjustment works well.
- The timing jitter is reduced to 3.3 ps std. after the FM control.
  - Enough for the beam injection.

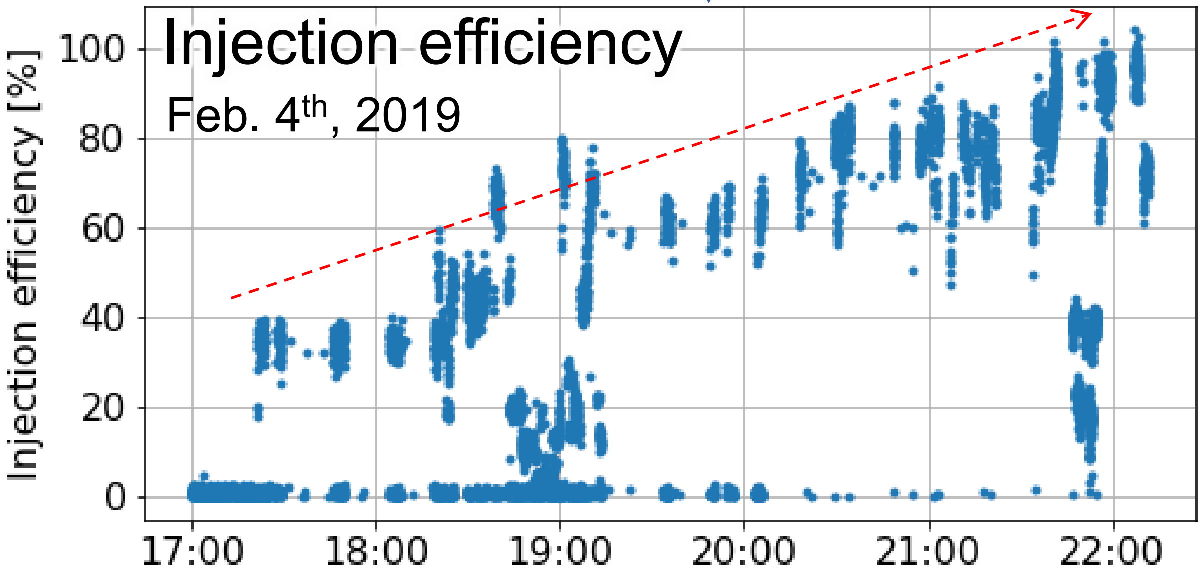
Beam commissioning

- Oct. 2018: Beam commissioning for SPring-8 injection started. (~1 shift [~8 hours] / month)
  - 1 Hz injection without XFEL.(long bunch)
- Dec. 2018: First storage of the beam from SACLA. (~10 μA / shot)
- Feb. 2019: More than 90% injection efficiency was achieved.
- Oct. 2019: First on-demand injection in parallel with XFEL operation.
  - Short bunch beam have been delivered to XSBT since then for easier operation.
- Nov. 2019: First 10 Hz injection and top-up operation with 100 mA.
- Feb. 2020: First user run with the SACLA beam.
- Sep. 2020: The default injector was switched to SACLA.
- Mar. 2021: Shutdown of the 8 GeV booster synchrotron and 1 GeV linac.

Comparison of beam profiles

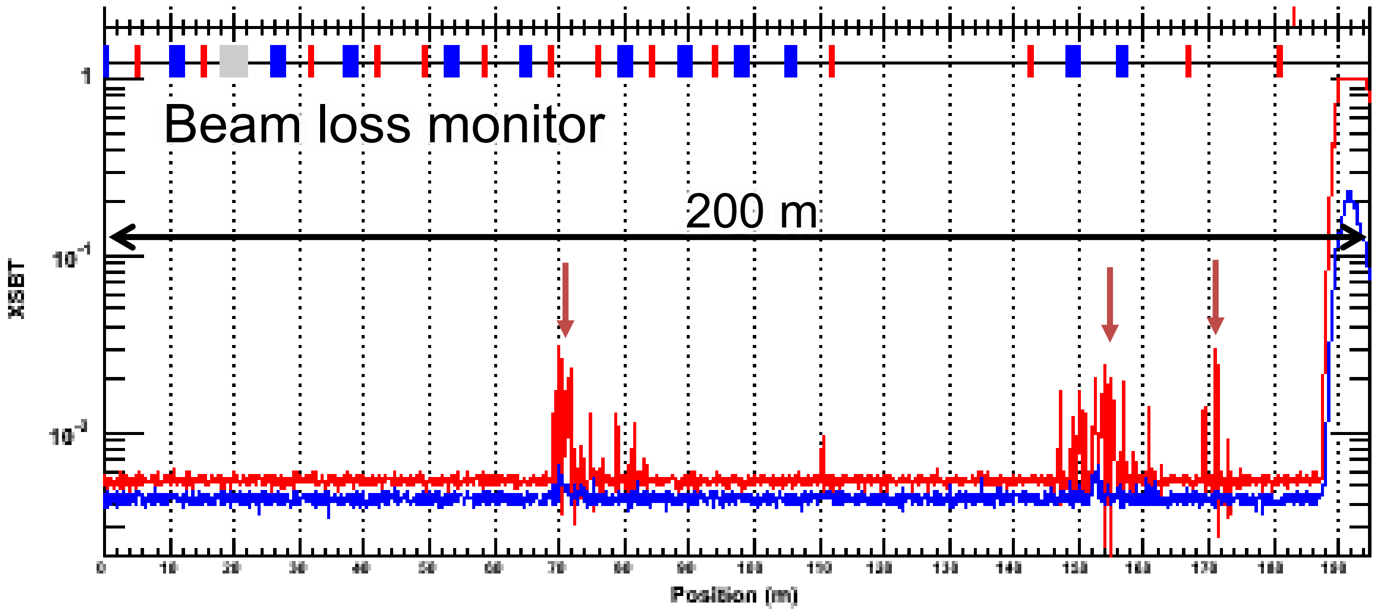


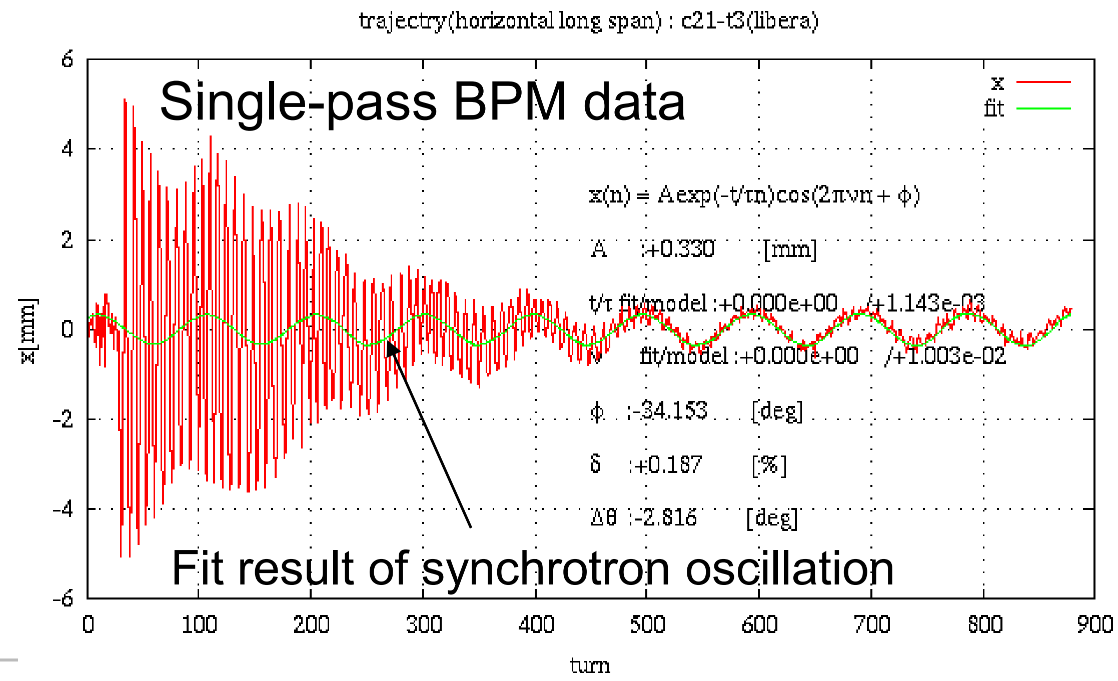




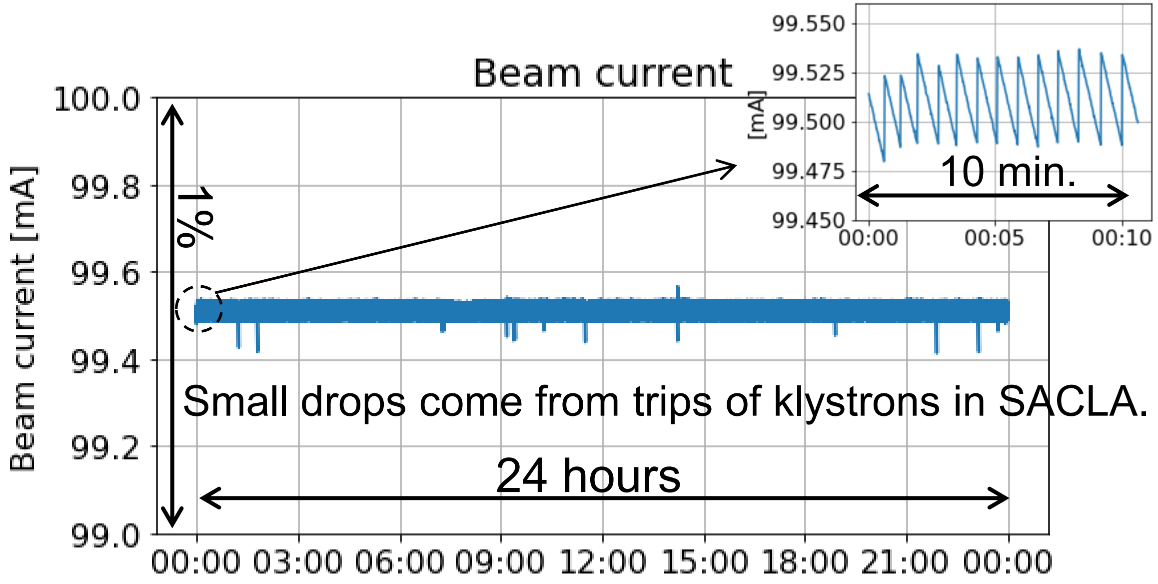
Beam monitors

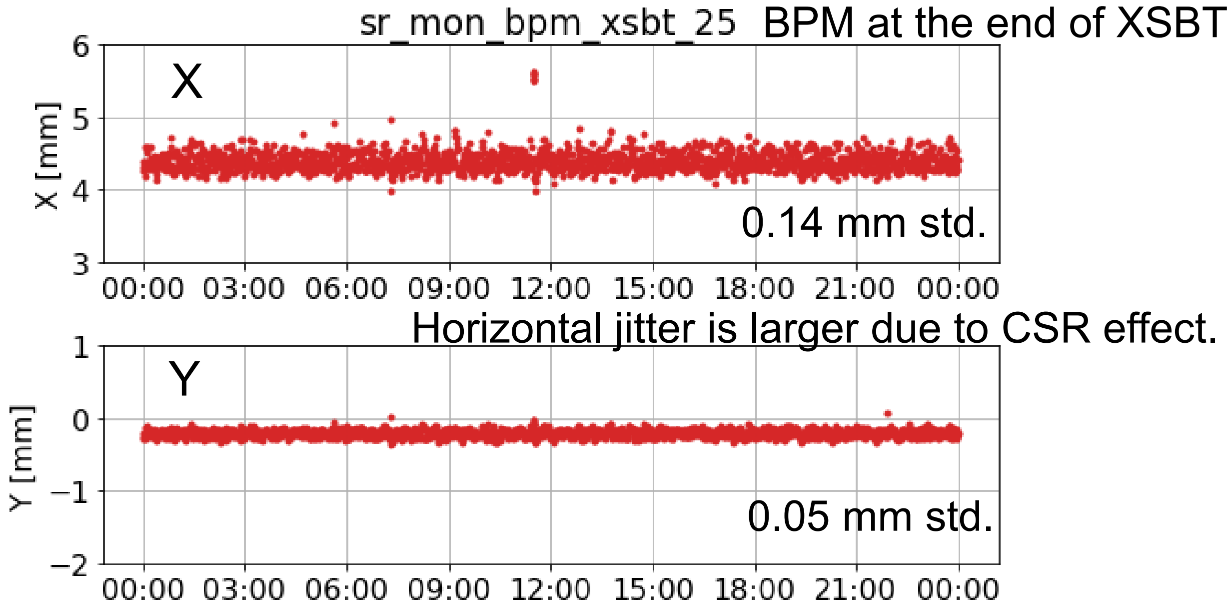
- BPMs and screen monitors are used for monitoring beam orbit and envelop.
- The injection efficiency is evaluated from a CT in XSBT and a DCCT in the SR.
- Beam loss monitor is also utilized for loss-less transmission.
  - The loss monitor detects Cherenkov light emitted in an optical fiber along the beamline.
- Beam energy and timing was tuned by using single-pass BPM data in the SR.
  - Synchrotron oscillation of the injected beam is minimized.

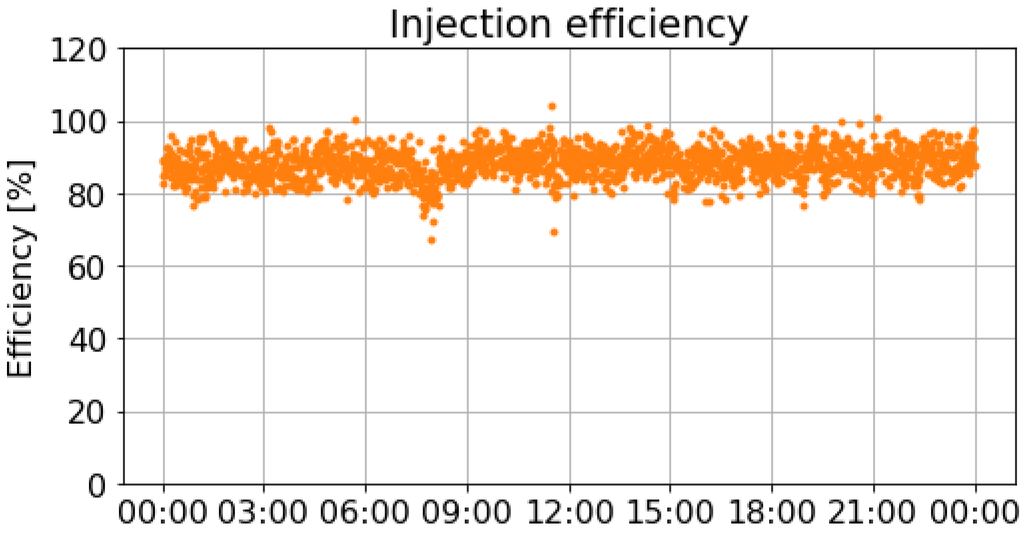


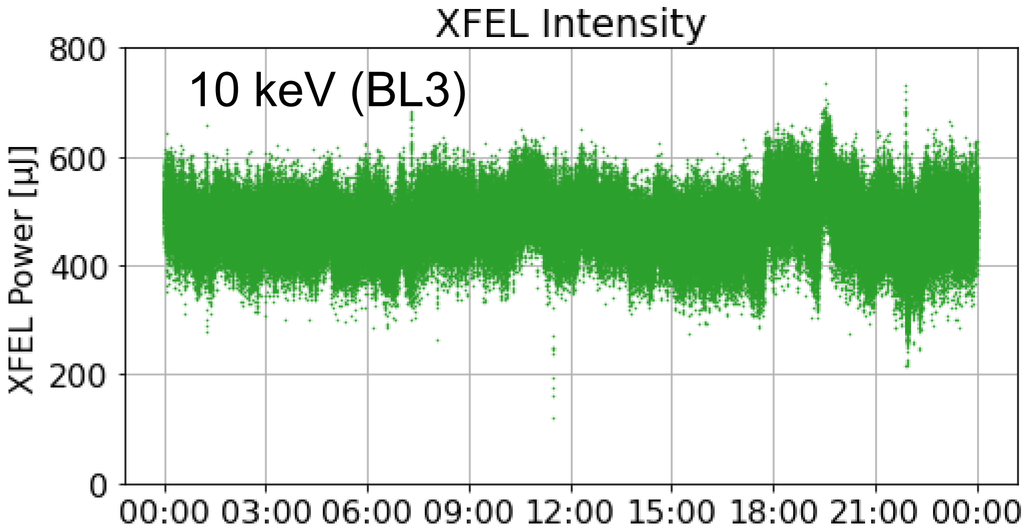


Stability (Top-up injection in parallel with XFEL)



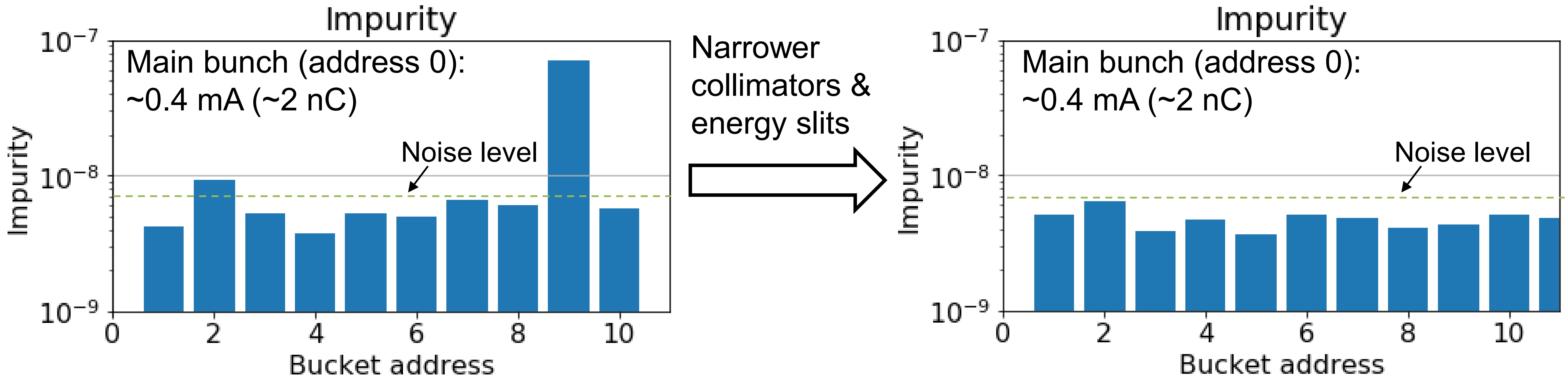






Bunch purity

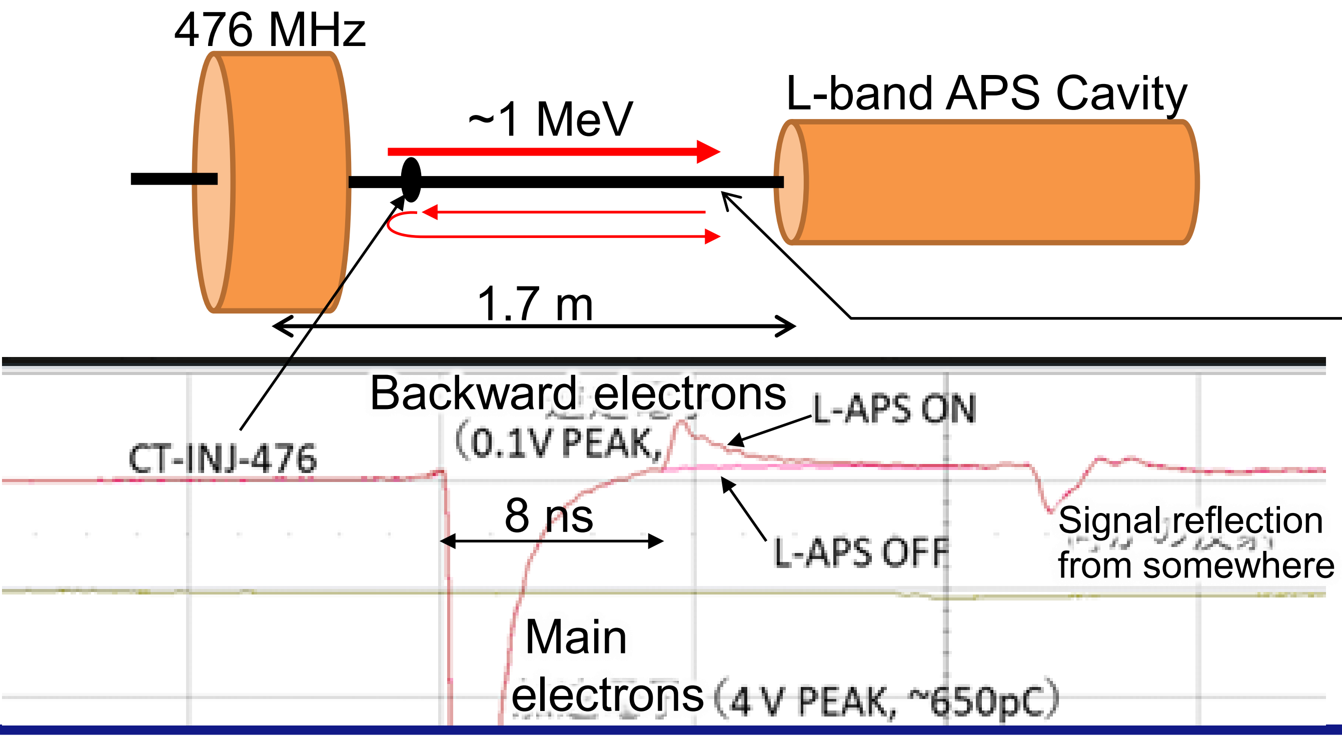
- Bunch purity is important for time-resolved experiments at SPring-8.
  - Requirement is typically < 1 x 10^{-8}
- We observed large impurity at address 9. (~18 ns from the main bunch)
  - Address 2 also shows significant impurity.
- If we closed collimators and energy slits from BC1 to BC3 as narrow as possible, the impurity was reduced to the noise level.
  - The source of satellite electrons was thought to be the low-energy section of SACLA.

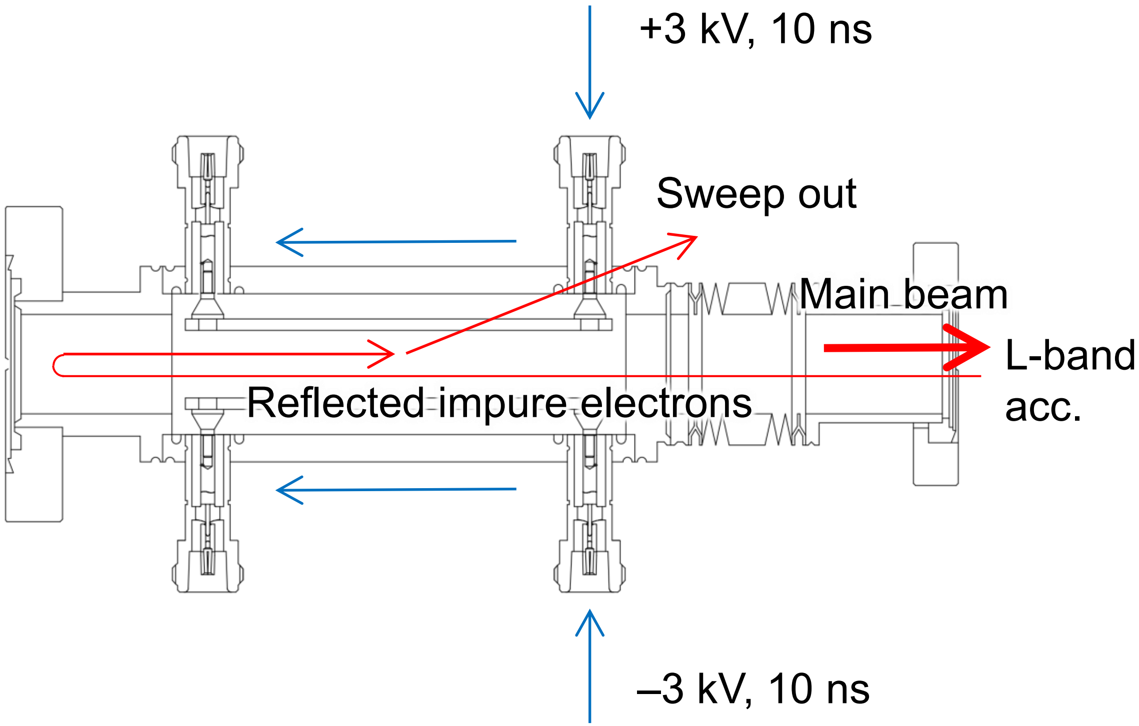


Bunch Purity Monitor: K. Tamura and T. Aoki, Proc. 1st Annual Meeting of Particle Accelerator Society of Japan, p.581 (2004).

Backward electrons at low-energy section

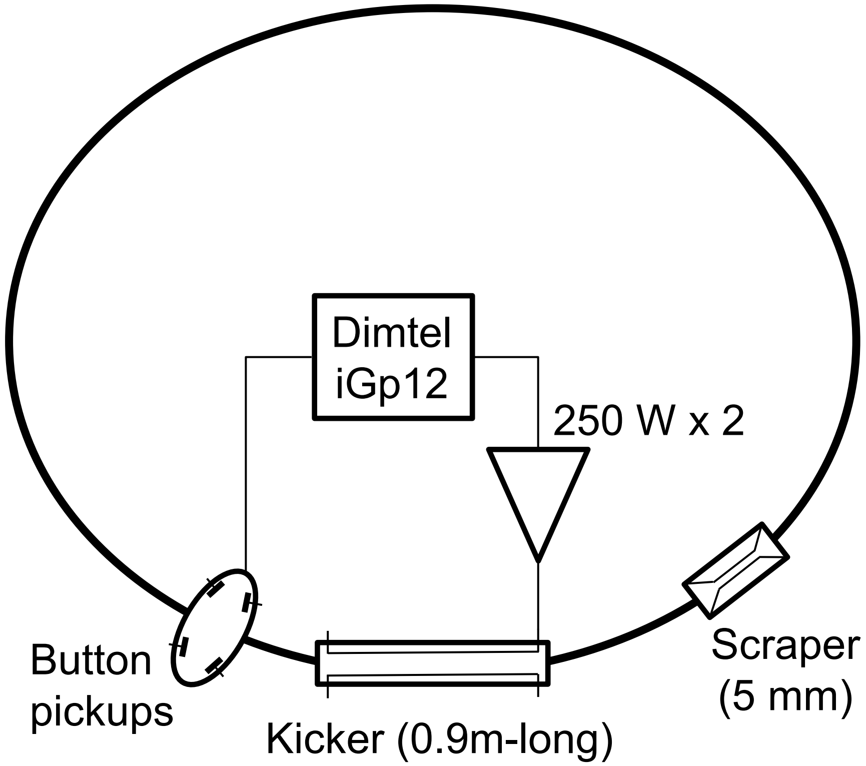
- Impurity at address 9 needs the electron delay of 18 ns, which is too long for normal acceleration process.
- We considered that some of the electrons were reversely accelerated at the entrance of an accelerating structure and accelerated again by an upstream accelerator.
- Backward electrons were detected by a CT between the 476 MHz cavity and the L-band cavity.
  - Re-acceleration of electrons was also confirmed by 1D tracking simulation.
- We installed a high-voltage sweeper for the reflected electrons.
  - The impurity at address 9 was reduced to approximately 1/10.

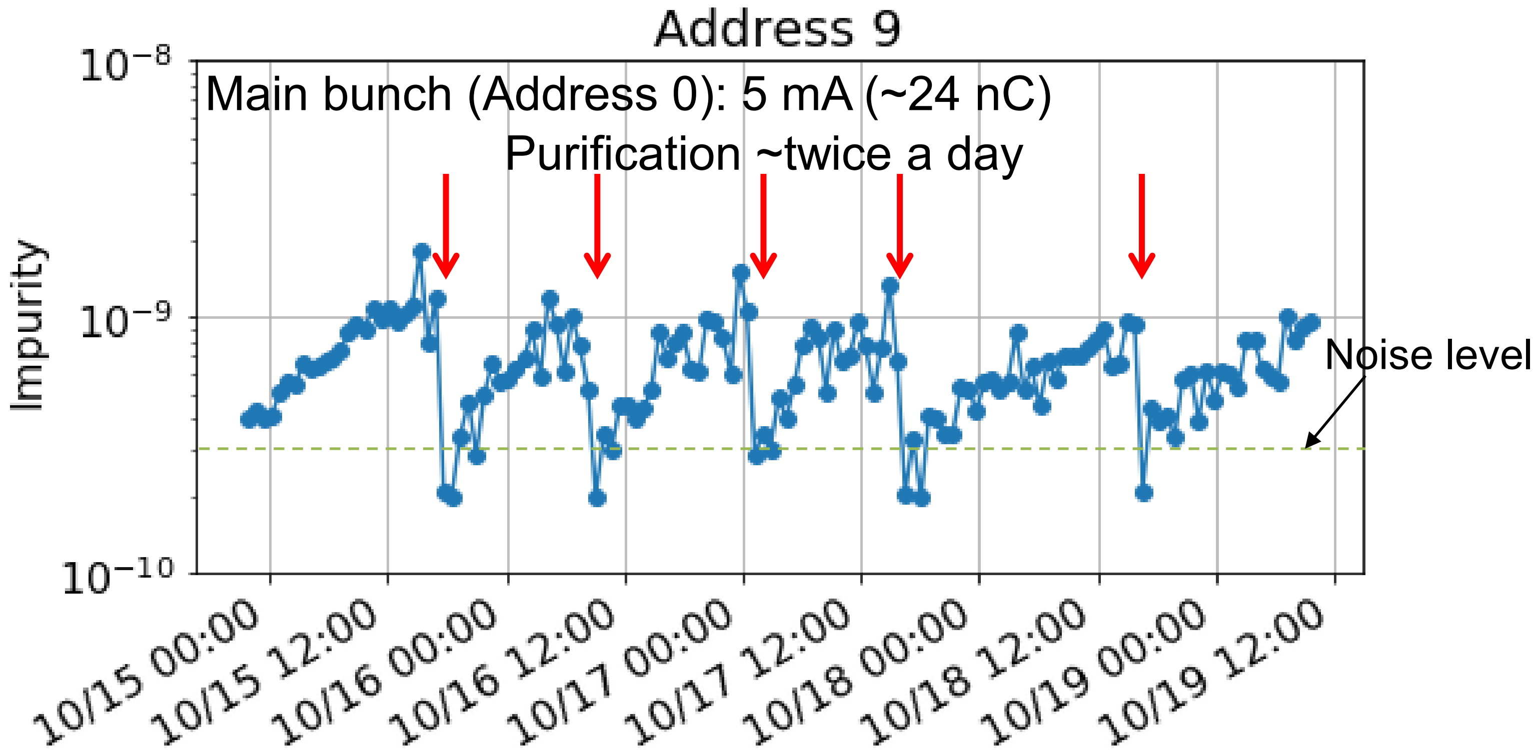




Bunch purification

- Impurity at address 9 slowly increased during a user run.
- We installed a bunch purification system to SPring-8, similar setup as a bunch-by-bunch feedback system.
  - Vertical betatron oscillation is excited to a satellite bunch and impure electrons are removed by a vertical scraper (5mm-gap).





Summary

- SPring-8-II requires low-emittance electron beam from SACLA.
- The injection from SACLA is also beneficial for current SPring-8.
  - The shutdown of the original 8 GeV booster synchrotron and 1 GeV linac saves energy consumption and operation cost.
- We developed an on-demand switching system of beam route and parameters to realize top-up injection in parallel with XFEL operation.
  - Beam energy, bunch length, kicker magnet, etc.
- A precise timing synchronization system between SACLA and SPring-8 was also developed.
- We succeeded in stable beam injection from SACLA to SPring-8 after one-year beam commissioning.
- Although some bunch purity degradations were found at first, the purity was improved by suppressing satellite electrons from SACLA and by removing impure electrons in the SR.
- The beam injector for SPring-8 was switched to the SACLA linac in Sep. 2020.