On-Demand Beam Route and RF Parameter Switching System for Time-Sharing of a Linac for X-ray Free-Electron Laser as an Injector to a 4th-Generation Synchrotron Radiation Source

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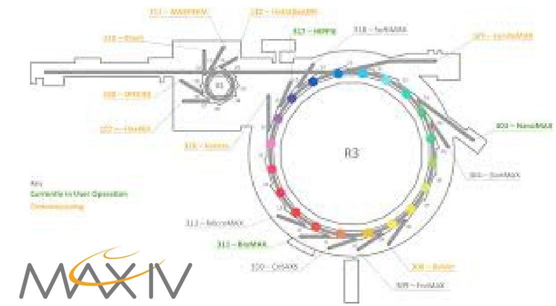
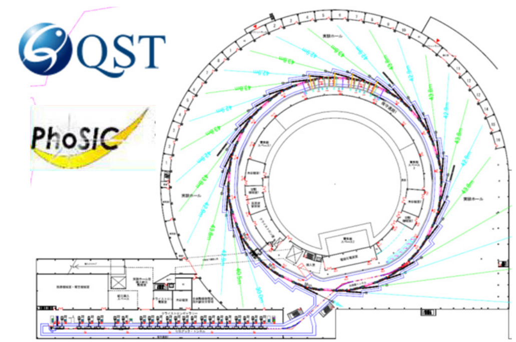
Outline

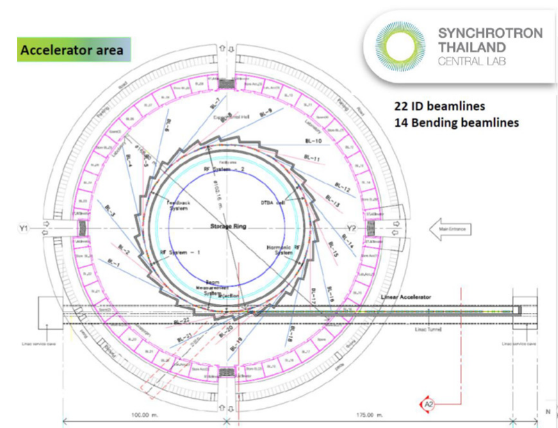
- Introduction
  - 4th generation ring-based light source with full-energy injector linac
  - SPring-8-II project
  - XFEL facility SACLA
  - Time-sharing of a linac for both XFEL and injector
- Current beam route and parameter switching system of SACLA
  - Parallel operation of two XFEL beamlines.
- On-demand beam route and parameter switching system
  - System design
  - Test results at a test bench and SACLA
- Summary and outlook

Introduction

- 4th generation ring-based light sources (4GLS) with multi-bend achromat lattice needs low-emittance injected beam.
  - Due to the narrow dynamic aperture.
- Some of the 4GLSs use full-energy linacs as injectors.
  - Injector linac can be a driver of X-ray free-electron laser (XFEL).
  - Mainly 3 GeV class facilities.
  - MAX IV, Tohoku Japan, Thailand, etc.
  - SPring-8-II is a typical 6 GeV class project with a full-energy linac (SACLA).

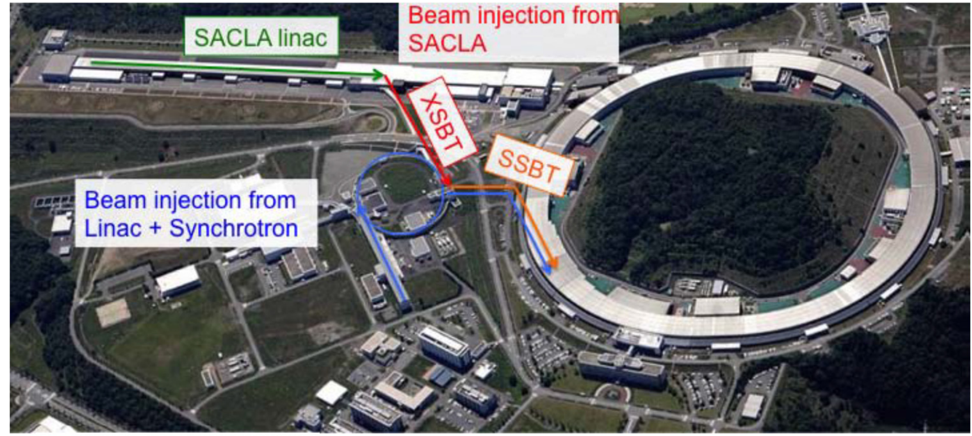


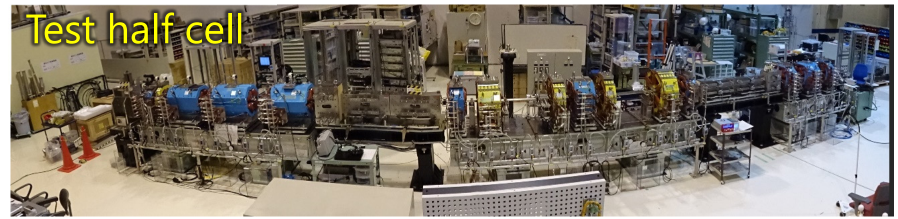




SPring-8-II Project

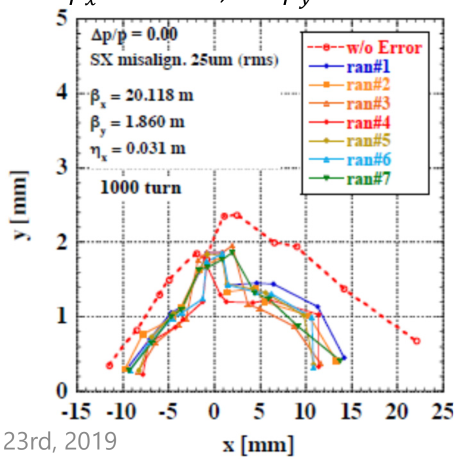
- Emittance: 2.4 nm rad → 140 pm rad (without radiation damping of undulators)
- Lattice: Double-bend Achromat (DBA) → 5-bend Achromat (5BA)
- Beam Energy: 8 GeV → 6 GeV
- SPring-8-II Conceptual Design Report, Nov. 2014, http://rsc.riken.jp/pdf/SPring-8-II.pdf
- Low-emittance beam (< 500 pm rad) is needed for injection. → Injected from SACLA



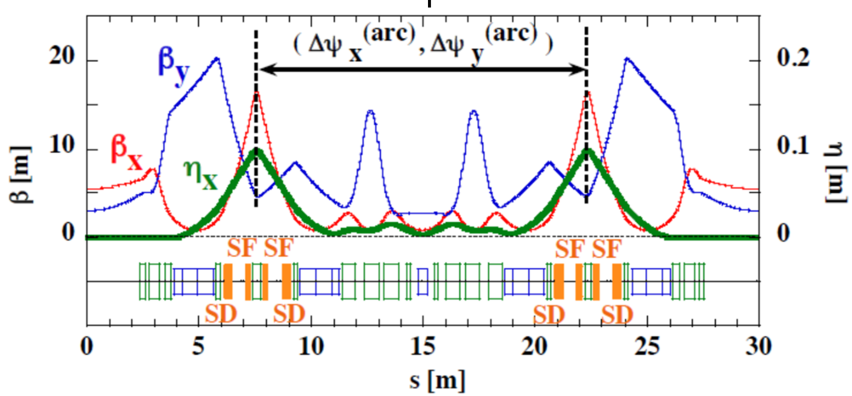


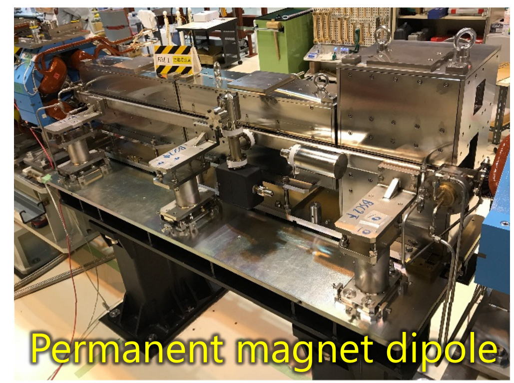
Dynamic Aperture

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

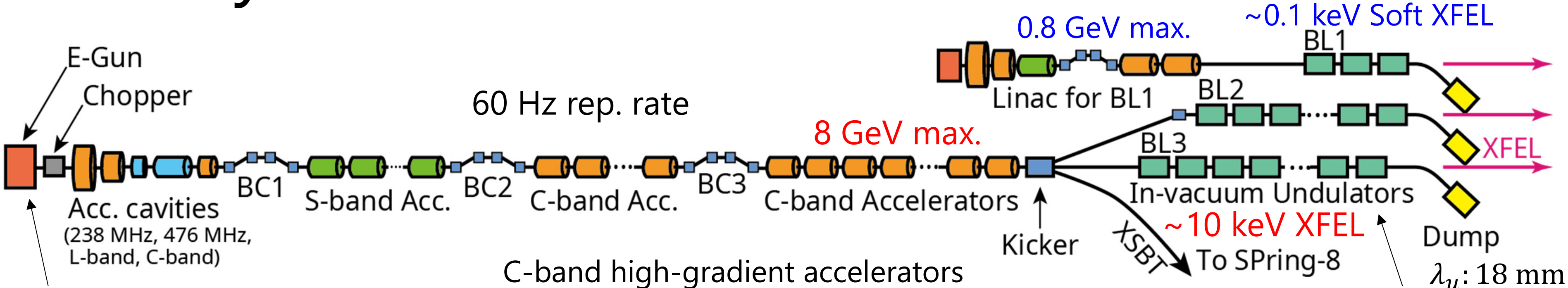


Linear Optics

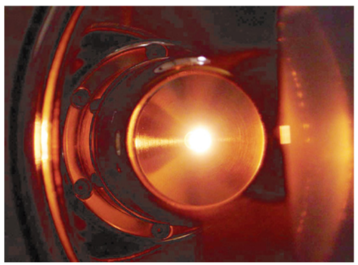




X-ray free-electron laser SACLA

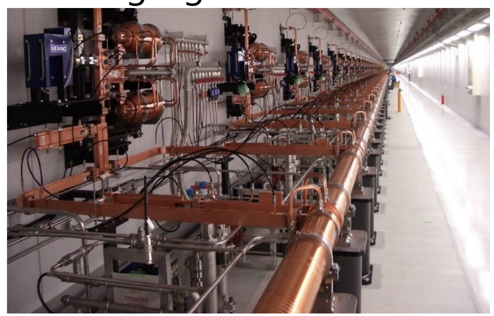


500 kV thermionic gun

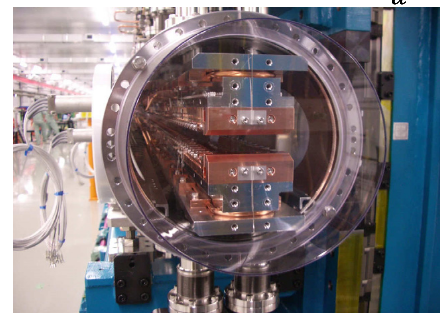


Norm. emittance
~ 1 mm mrad

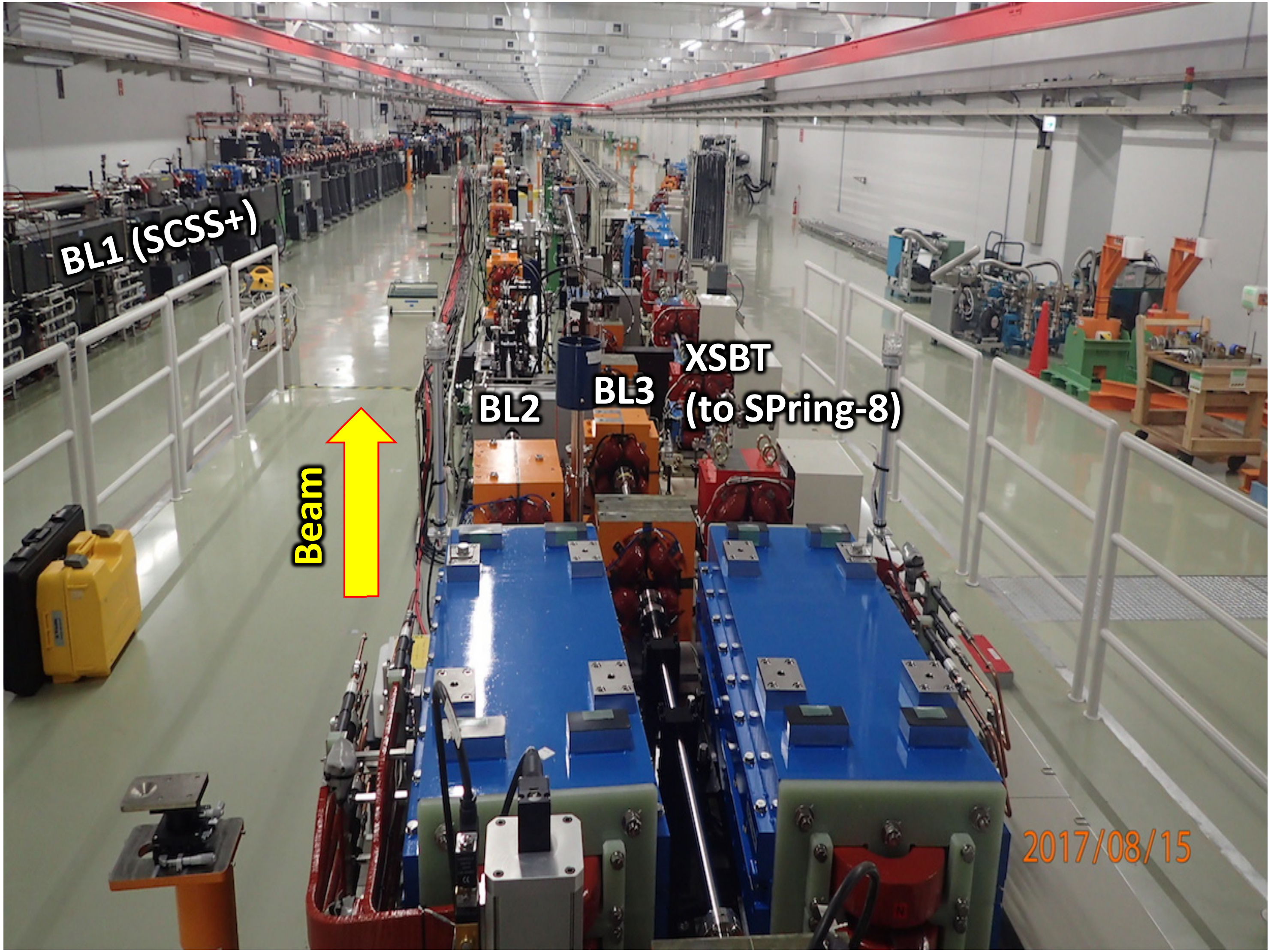
C-band high-gradient accelerators



> 35 MV/m



- Beam energy: 4 – 8 GeV
- Bunch length: ~10 fs
- Peak current: > 10 kA
- Norm. slice emittance: < 1 mm mrad
- XFEL photon energy: 4 – 20 keV
- XFEL pulse energy: > 500 μJ (10 keV)
- Rep. rate: 60 Hz max.
- Total length: ~ 700 m


BL1 (SCSS+)
Beam
BL2
BL3
XSBT
(to SPring-8)
2017/08/15

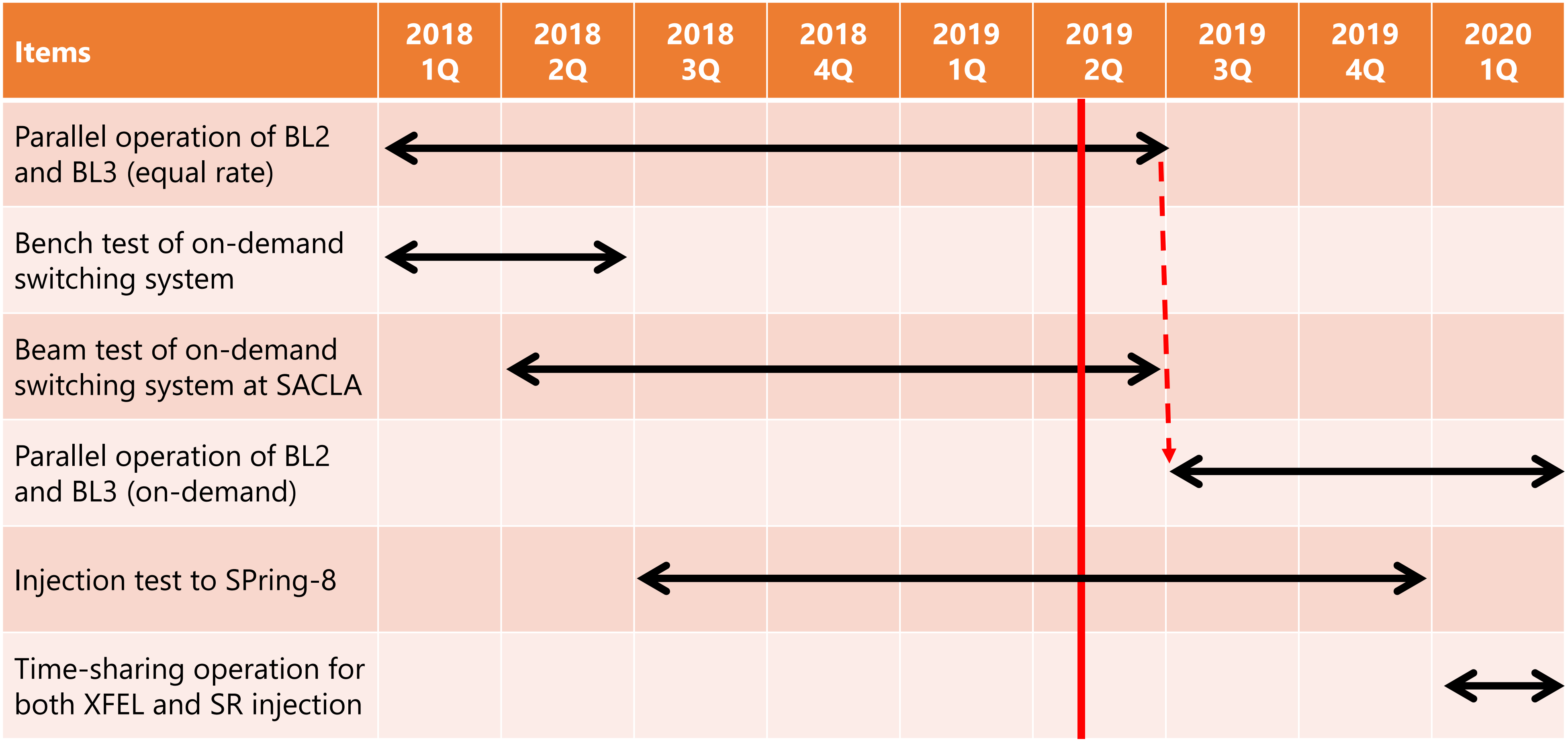
XFEL v.s. Injection to SPring-8(-II)

	XFEL	**SPring-8**	**SPring-8-II**
Beam energy	4 – 8 GeV	8 GeV	6 GeV
Bunch length	< ~ 10 fs	> 100 fs	> 100 fs
Peak current	> 10 kA	< ~ 1 kA	< ~ 1 kA
Rep. rate	60 Hz max.	10 Hz (initial) < 0.1 Hz (top-up)	10 Hz (initial) < 0.1 Hz (top-up)
Beam route	BL2, BL3	XSBT	XSBT
SR Sync.	No	Yes	Yes

On-demand beam route and parameter switching system is necessary.

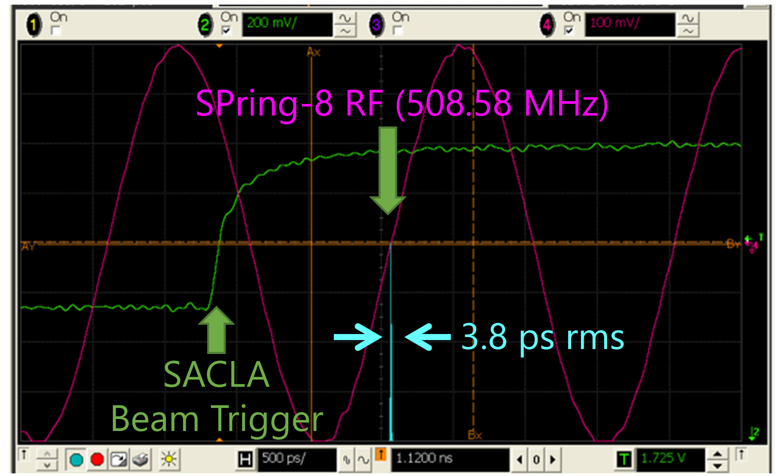
Synchronization of SACLA to SPring-8 is also needed.

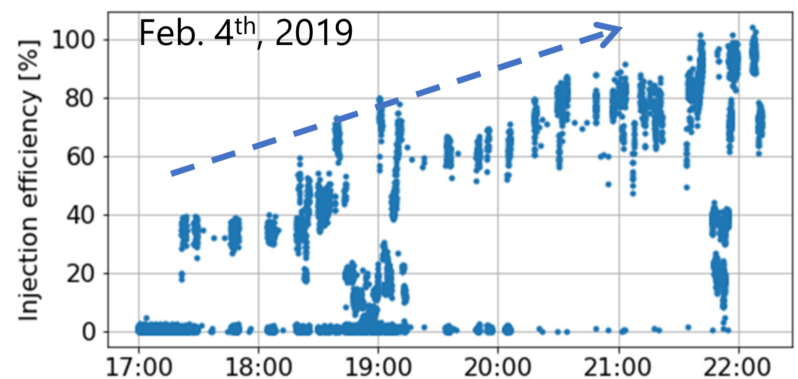
Timeline


Items
2018 1Q
2018 2Q
2018 3Q
2018 4Q
2019 1Q
2019 2Q
2019 3Q
2019 4Q
2020 1Q
Parallel operation of BL2 and BL3 (equal rate)
Bench test of on-demand switching system
Beam test of on-demand switching system at SACLA
Parallel operation of BL2 and BL3 (on-demand)
Injection test to SPring-8
Time-sharing operation for both XFEL and SR injection

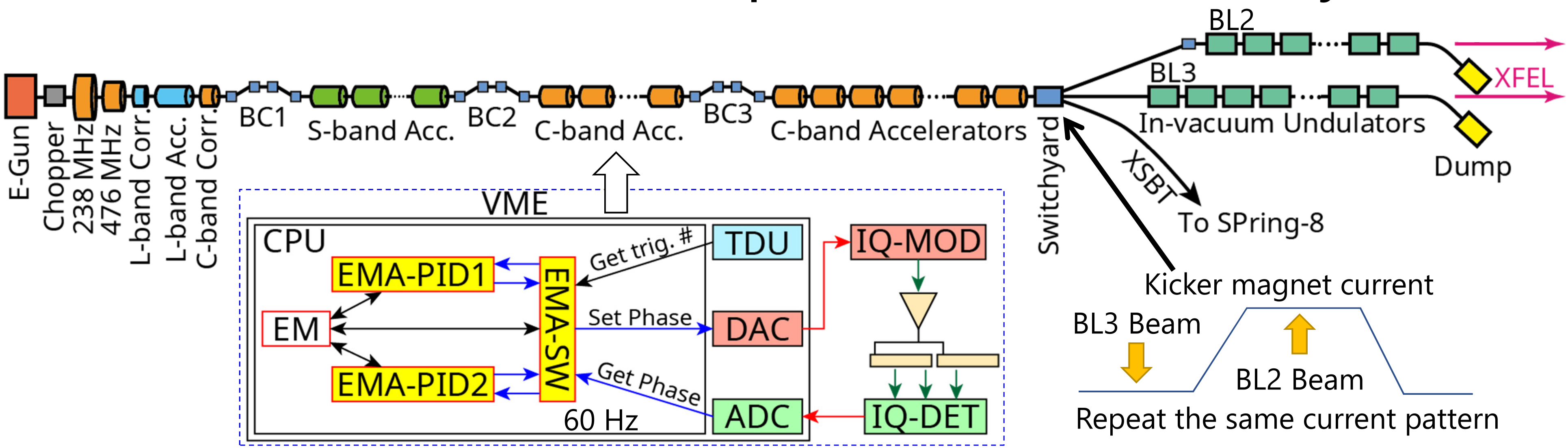
Beam injection from SACLA to SPring-8

- We developed a synchronization system of SACLA with SPring-8.
  - Detect time difference between the SPring-8 RF bucket and the SACLA master clock.
  - Apply frequency modulation to the SACLA master oscillator so as to synchronize with SPring-8.
  - 3.8 ps rms precision.
  - T. Ohshima *et al.*, “Timing Synchronization System for Beam Injection from the SACLA Linac to the SPring-8 Storage Ring”, THPRB034.
- Machine study for the beam injection from SACLA to SPring-8 started in October 2018.
  - ~ 1 shift/month
- More than 90% injection efficiency achieved in February 2019.





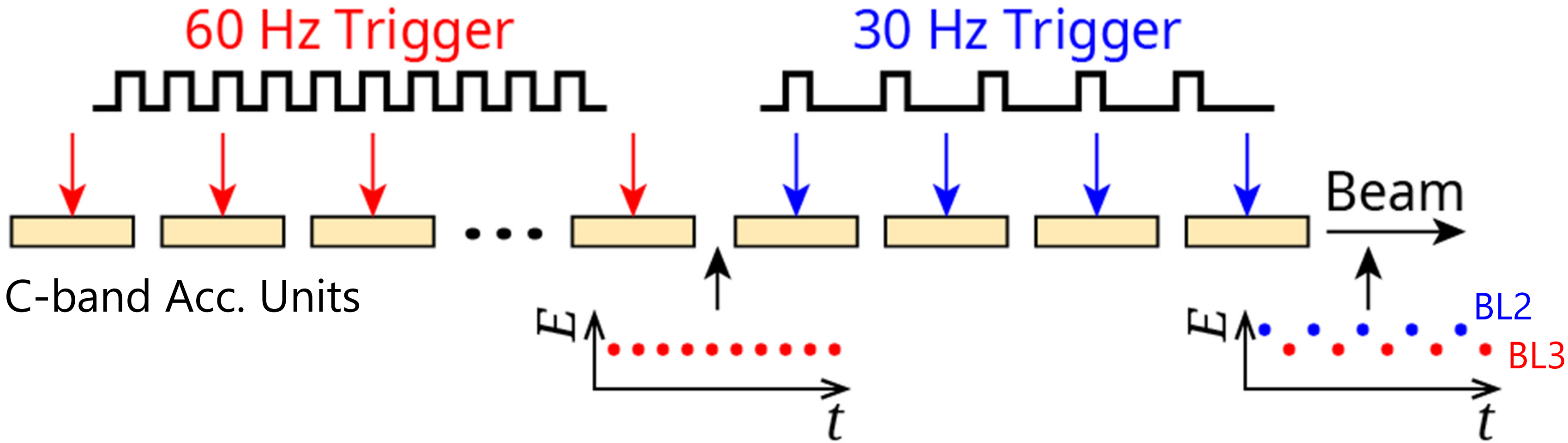
Current beam route and parameter control system



- Beam route, bunch length and beam energy can be switched in equal-rate one after another.
  - BL2 30Hz, BL3 30Hz
- Bunch length is controlled by changing RF phases of accelerator units before BC3.
  - We developed software on the VME-CPU to change the rf phase shot-to-shot.
- Shot-to-shot RF parameter control function is implemented to EMA processes.
  - EMA-SW: Access to VME modules and sort the data for each beam route.
  - EMA-PID1 and -PID2: Calculate set values to DAC by a PID algorithm.
- Kicker magnet just repeats the same current pattern.

EM: Equip Manager
EMA: Equip Manager Agent

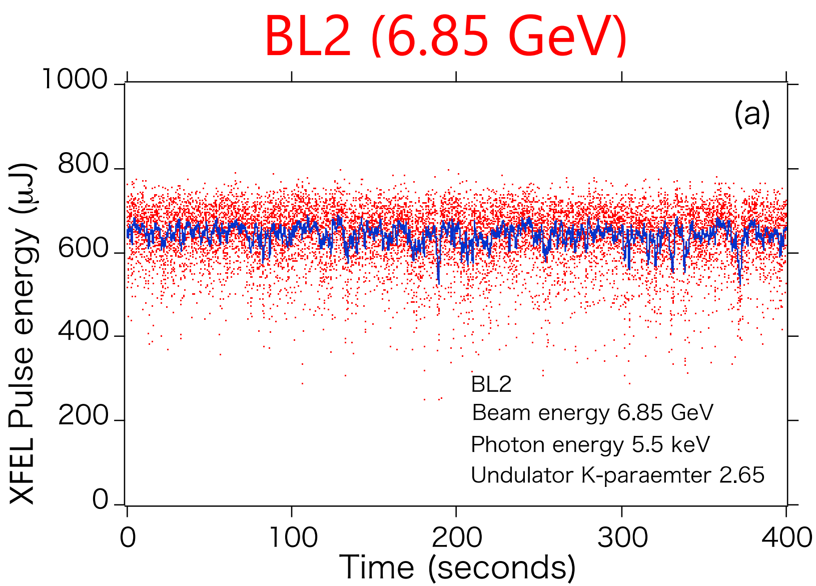
Current beam energy control scheme

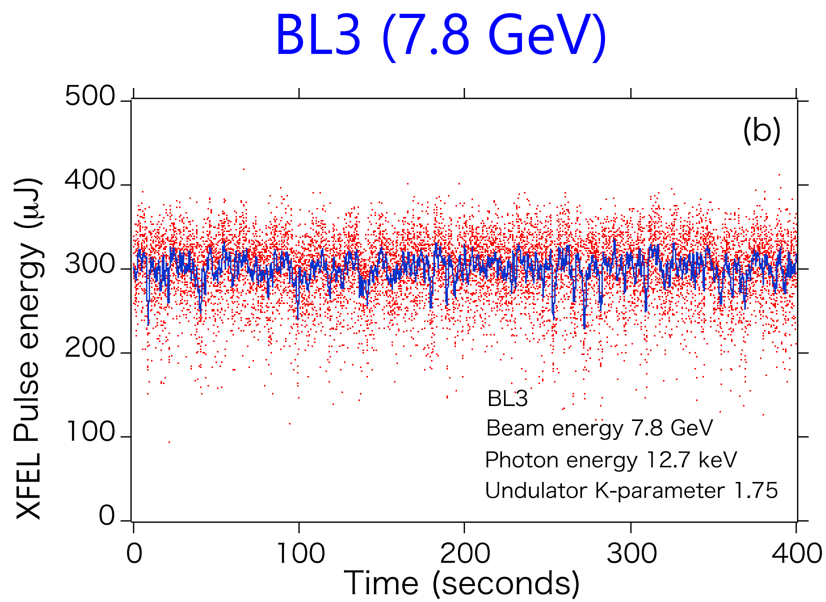


- Trigger rate of each accelerator unit can be changed by VME Trigger module.
  - No real-time software process is used for beam energy control.
- Acceleration voltage of each C-band unit: ~ 120 MeV
- Although the quadrupole strength in the accelerator is the same for both high and low energy beams, the beam envelop can be matched by quadrupoles after the switchyard.

T. Hara *et al.*, Phys. Rev. ST Accel. Beams, **16**, 080701 (2013).

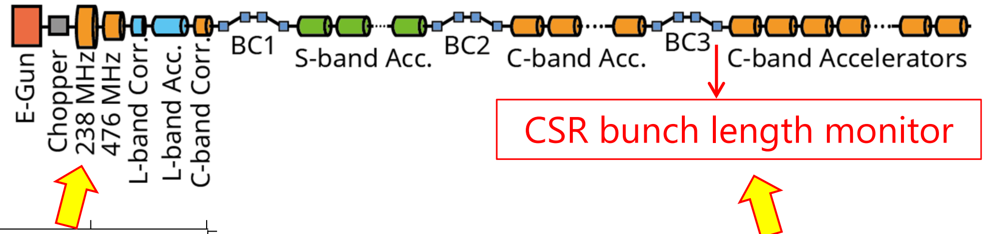
Parallel operation of two XFEL beamlines

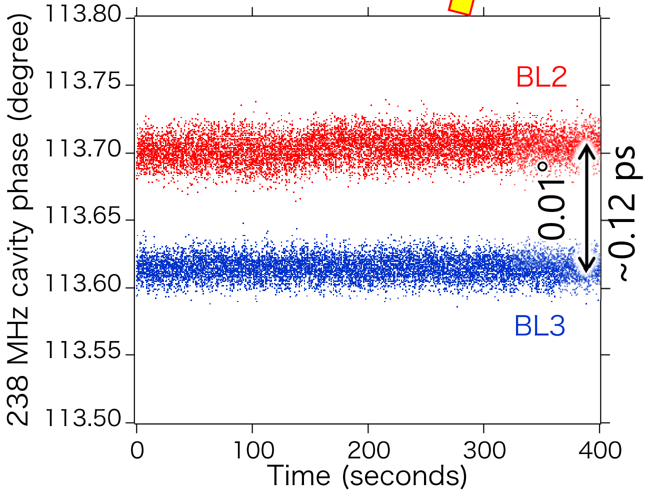


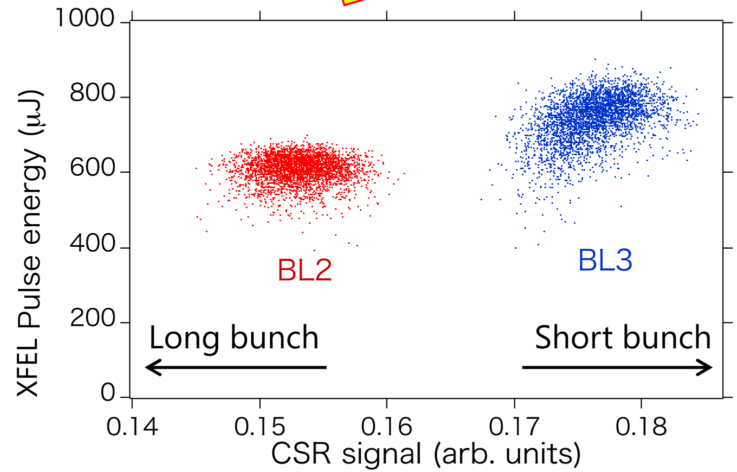


- Low-energy beams (6.85 GeV) are transported to BL2 and high-energy beams (7.8 GeV) to BL3.
- Photon energies are more than twice different between BL2 (5.5 keV) and BL3 (12.7 keV).

Beam Parameters for Each Beamline





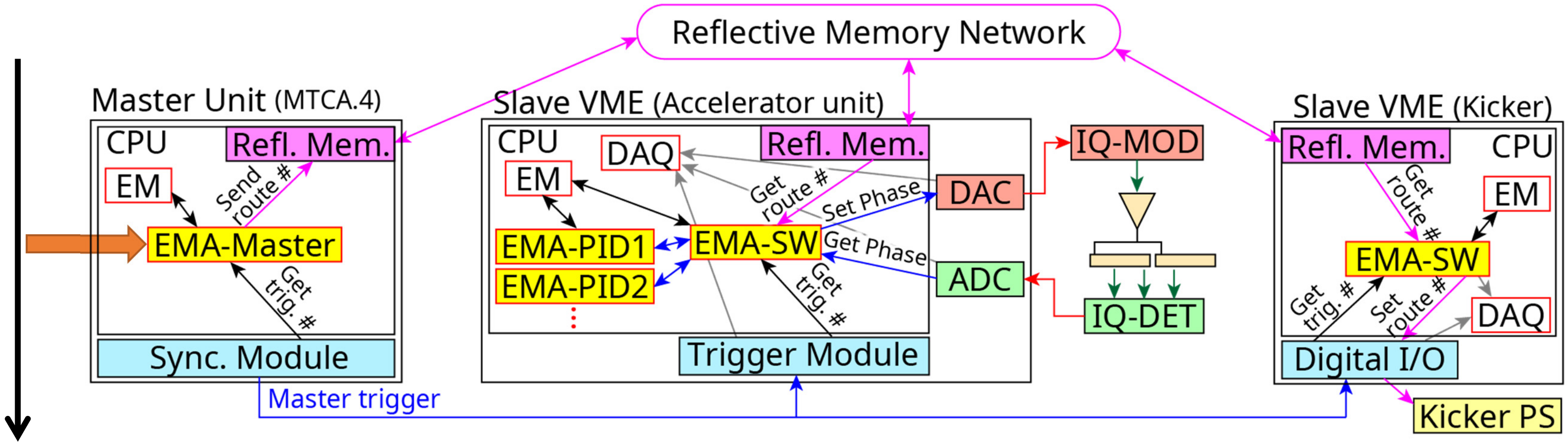


- 60 Hz electron bunches are alternately delivered to BL2 and BL3.
  - Beam energy: 7.8 GeV (same for both beamlines)
  - Photon energy: 10 keV
  - Bunch length: ~10 fs FWHM
- RF phase of each accelerator unit is appropriately changed by the shot-to-shot RF parameter switching software.

On-demand Switching System

- The beam route should be switched to XSBT only at an injection request.
- Beam injection frequency of SPring-8 is < 0.1 Hz during the top-up operation.

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



- To reduce cost and work load, we decided to use a software-based system with smallest hardware modification.
- Beam route information is distributed shot-to-shot by using a reflective memory network.
- Trigger and RF parameter for each accelerator unit and the current of the kicker magnet etc. are switched according to the route information.
- Route number, RF parameters and the master trigger number are recorded by an event-synchronized data-acquisition (DAQ) system shot-to-shot.

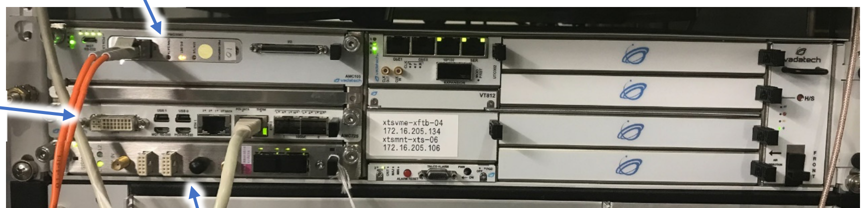
Equipment for on-demand switching

Master unit (MTCA.4)

Reflective memory

Front

CPU



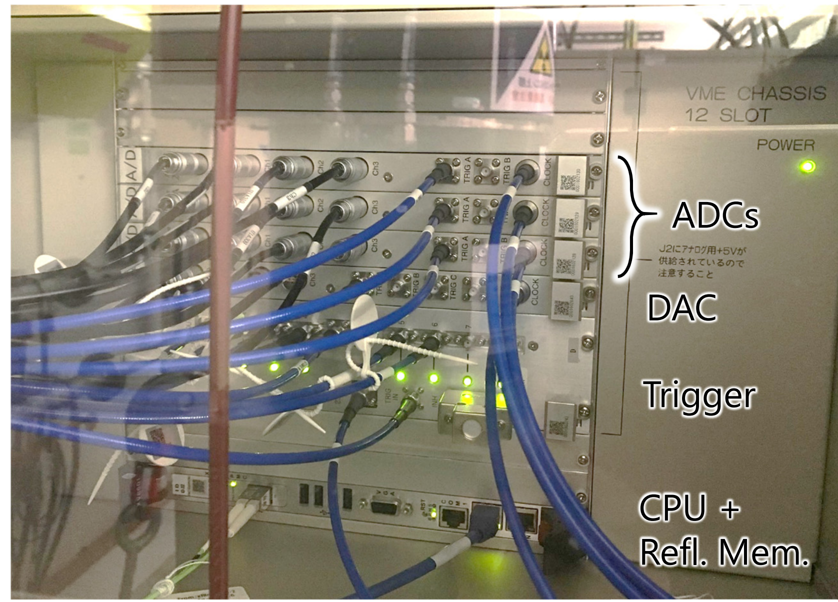
Digitizer for sync. with SP8

Rear

RTM for sync.

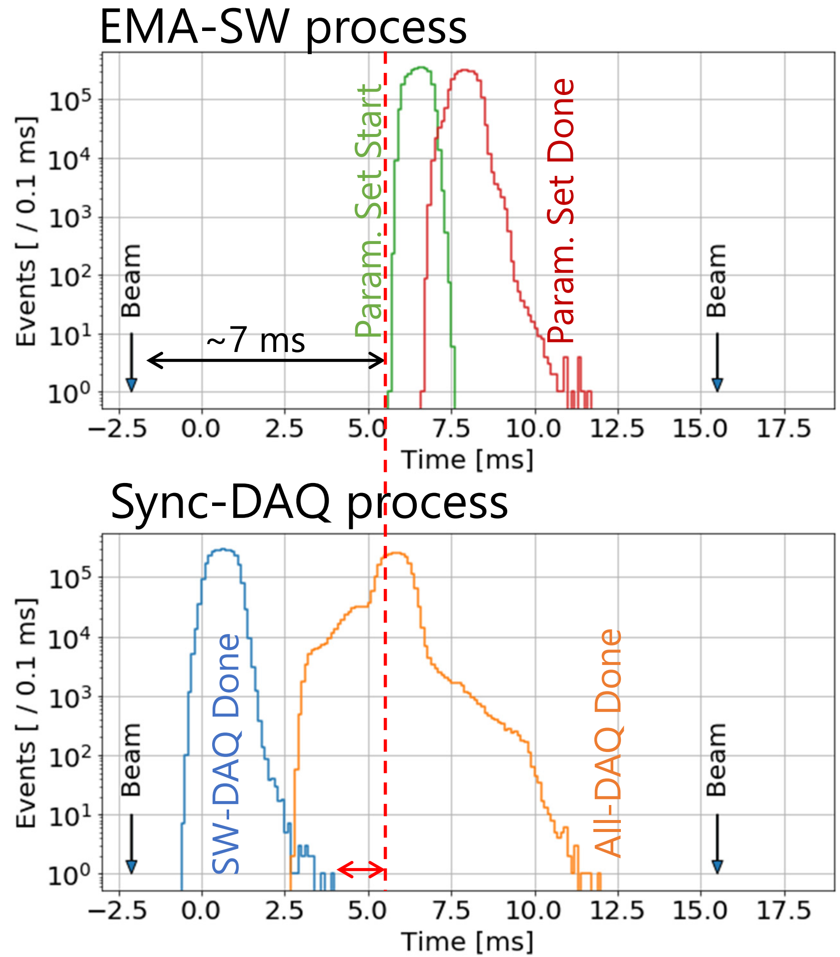
Reflective memory hub

Slave VME



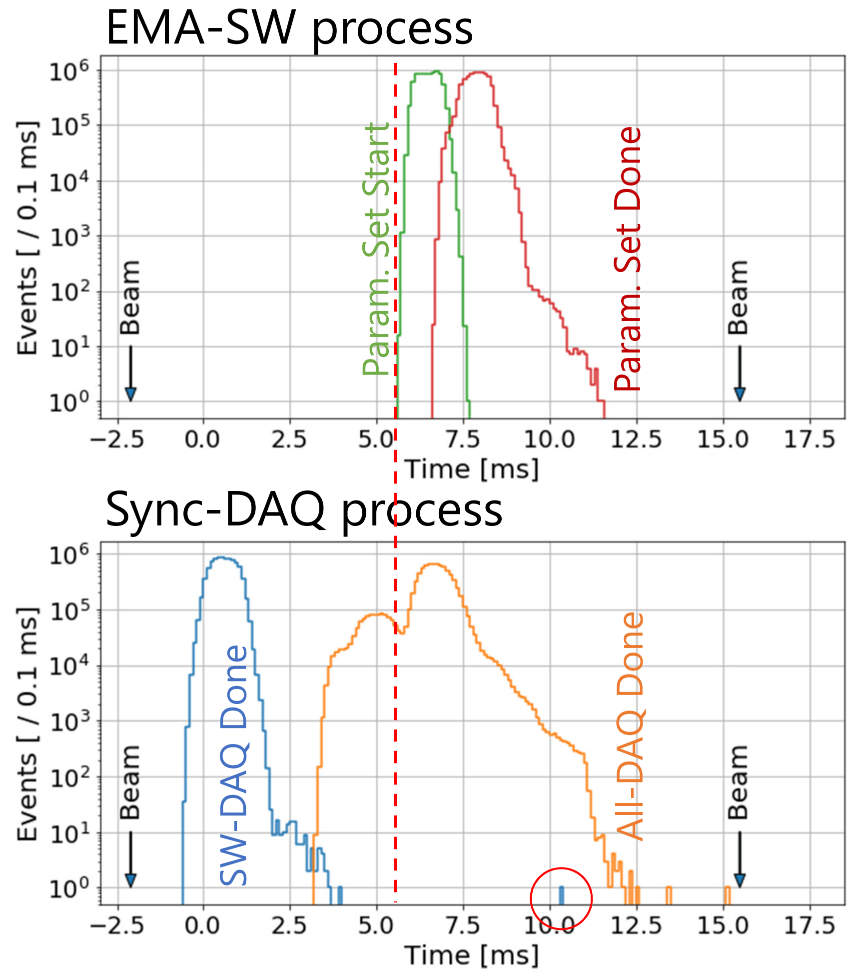
Evaluation at test bench

- Setup: 1 Master unit and 1 Slave unit.
- 60 Hz operation with several beam routes.
- More than 100 hours.
- EMA-SW process
  - EMA-SW starts parameter setting about 7 ms after the previous beam.
  - Parameter setting is finished well before the next beam.
- Sync-DAQ process
  - Sync-DAQ starts data taking just after the previous beam.
  - Data related to parameter switching are taken first before the parameter setting.
    - If DAQ is delayed, data for the next beam is taken wrongly.
  - DAQ of the other data is finished before the next beam.
- All the tasks are completed in time.
  - Failure rate $< 1 \times 10^{-7}$ /shot /unit



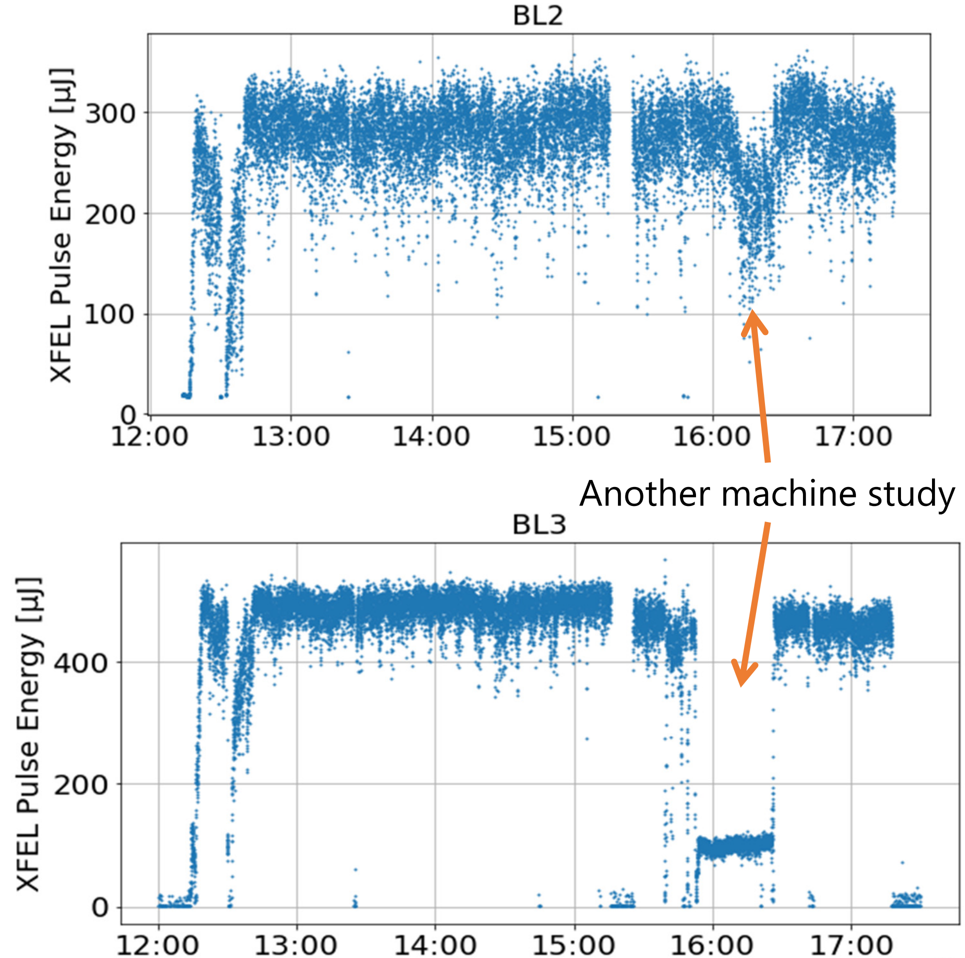
Test at the BL1 linac

- Setup: 1 Master unit and 4 Slave units.
- 60 Hz operation with several beam routes.
- More than 40 hours.
- All the EMA-SW processes worked in time.
- Sync-DAQ process
  - One delayed event of data taking related to parameter switching.
    - Data after parameter setting was recorded.
- Failure rate $\sim 1 \times 10^{-7}$ /shot /unit
  - Significantly smaller than the other faults, such as a trip of the HV power supply for a klystron.
- EMA-SW itself was confirmed to be OK by other data.



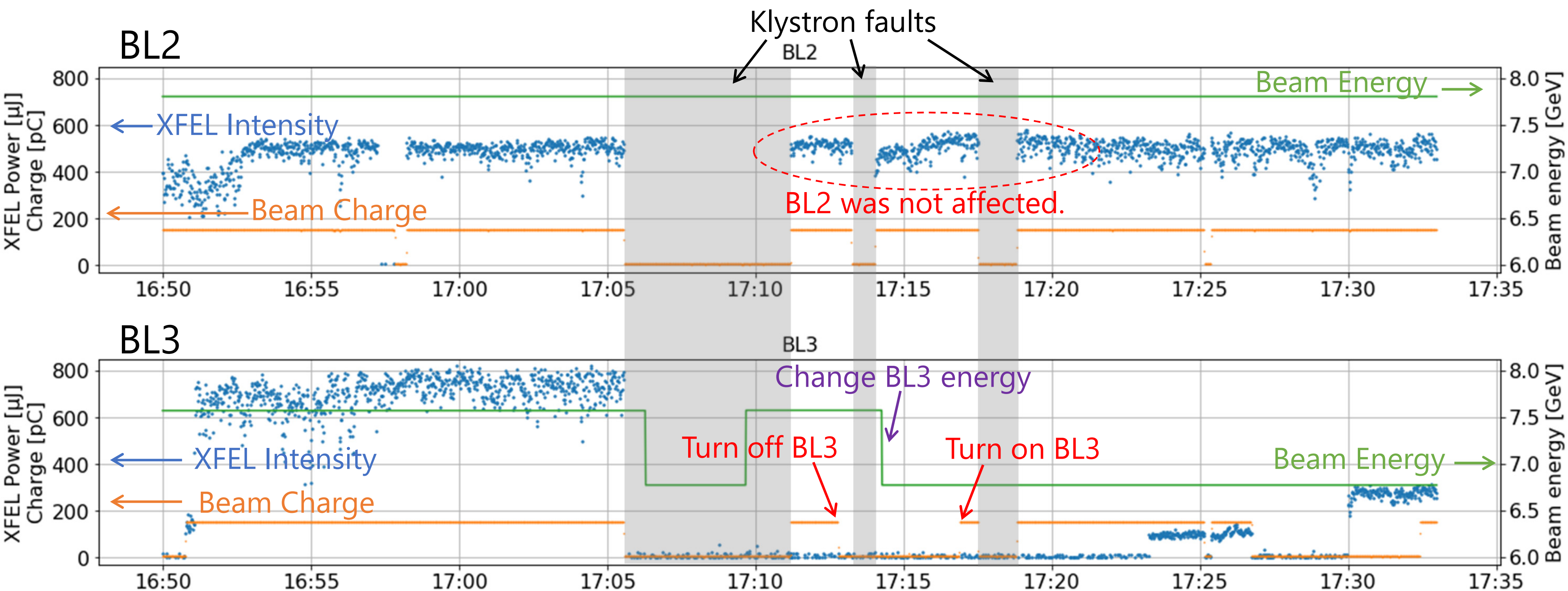
Beam test at SACLA

- Reflective memory modules and on-demand switching software were installed to 40 accelerator units out of 76.
- 60 Hz operation
  - BL2: 30 Hz, BL3: 30 Hz
- Tested for 5 hours.
- XFEL are stably generated for both beamlines.
- No error was observed.
- Error rate $< 2.5 \times 10^{-8}$ /shot /unit
- On-demand switching system worked well with a large setup.



Beam Energy Control

- The beam energy of one beamline should be changed without affecting the other beamlines.
- We changed the beam energy of BL3 without stopping the operation of BL2.



Summary and Outlook

- Some of the 4GLS projects have full-energy injector linac, which can drive XFEL.
- We developed an on-demand beam route and rf parameter switching system to share the SACLA linac for the XFEL beamlines and the injection to SPring-8(-II).
  - Reflective memory network for route data distribution.
  - Software-based system for parameter setting process.
- This system was tested at the test bench, the BL1 linac, and the SACLA main linac.
- Error rate was $< 2.5 \times 10^{-8}$ /shot /unit at SACLA linac.
  - Negligible compared to other failure causes.
- This system will be extended to all the accelerator units in SACLA.
- Beam injection experiments from SACLA to SPring-8 have been performed since last year.
- The first user operation of SPring-8 injected from SACLA is scheduled in the next year.