FR1A06

Pulse-by-Pulse Beam Parameter Switching of High-Quality Beams for Multi-Beamline Operation at SACLA

H. Maesaka[1], T. Fukui[1], T. Hara[1], N. Hosoda[2], C. Kondo[1,2], S. Matsubara[2], T. Ohshima[1,2], M. Yamaga[2], Y. Otake[2], T. Hasegawa[3], O. Morimoto[3], Y. Tajiri[3], S. Tanaka[3], M. Yoshioka[3],

1: *RIKEN SPring-8 Center*

2: *Japan Synchrotron Radiation Research Institute (JASRI)*

3: *SPring-8 Service, Co. Ltd.*

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Outline

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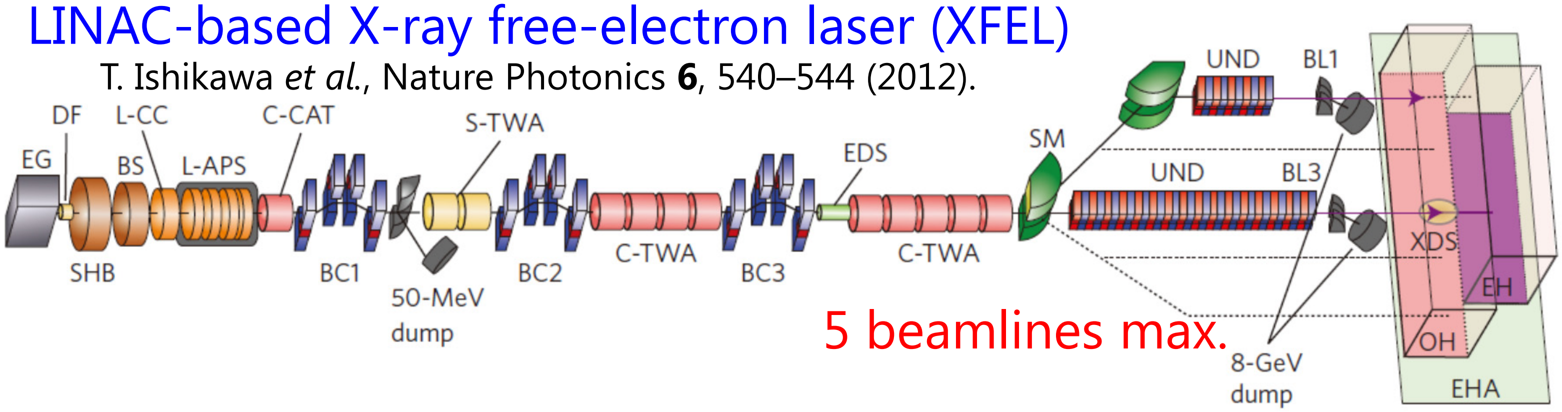
Demands for Multi-Beamline Operation of XFEL

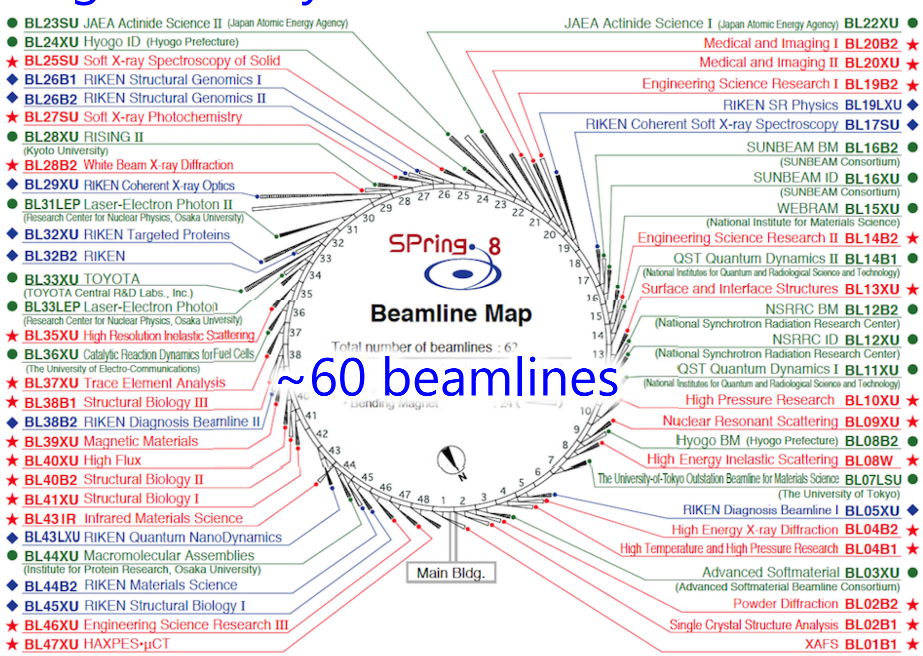
LINAC-based X-ray free-electron laser (XFEL)

T. Ishikawa *et al.*, Nature Photonics **6**, 540–544 (2012).



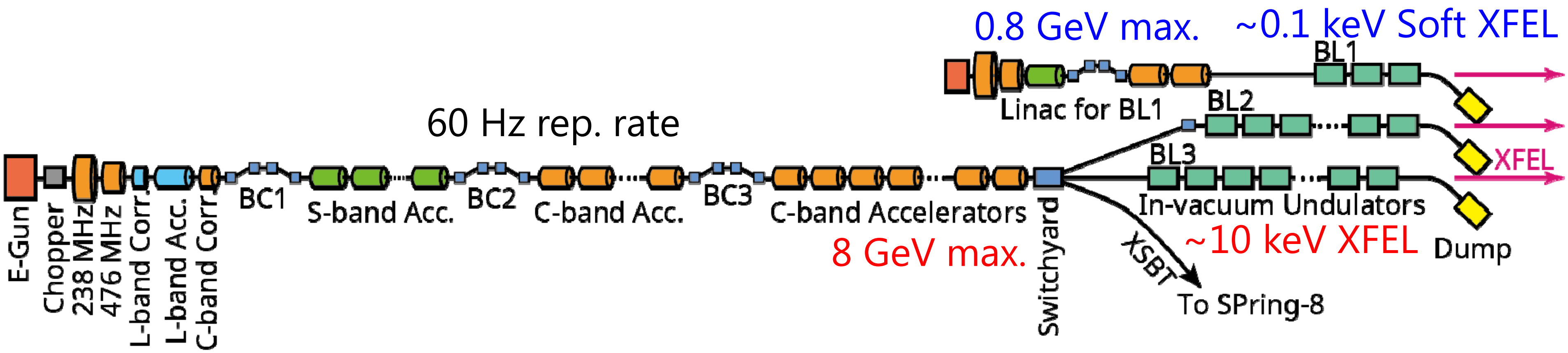
SACLA (2011)

Ring-based synchrotron radiation source



- The number of beamlines in a LINAC-based XFEL facility is much smaller than a ring-based light source.
- Increasing experimental opportunities of XFEL is quite important to maximize the scientific outcomes.

New Beamlines of SACLA



- New XFEL beamline, BL2, was constructed in 2014.
  - Kicker magnet was also installed to the switchyard to distribute a 60 Hz electron beam to BL2 and BL3 one after another.
    - T. Hara *et al.*, Phys. Rev. Accel. Beams **19**, 020703 (2016).

- SCSS test accelerator was moved to the upstream of BL1 in 2014.
  - Beam energy was upgraded to 0.8 GeV in 2016.
    - K. Togawa *et al.,* Proc. IPAC’17, TUOAA2, pp. 1209–1212.

- Beam transport line to the SPring-8 storage ring was also built to inject a low-emittance beam required in the SPring-8 upgrade project.
    - SPring-8-II Conceptual Design Report, Nov. 2014, `http://rsc.riken.jp/pdf/SPring-8-II.pdf`

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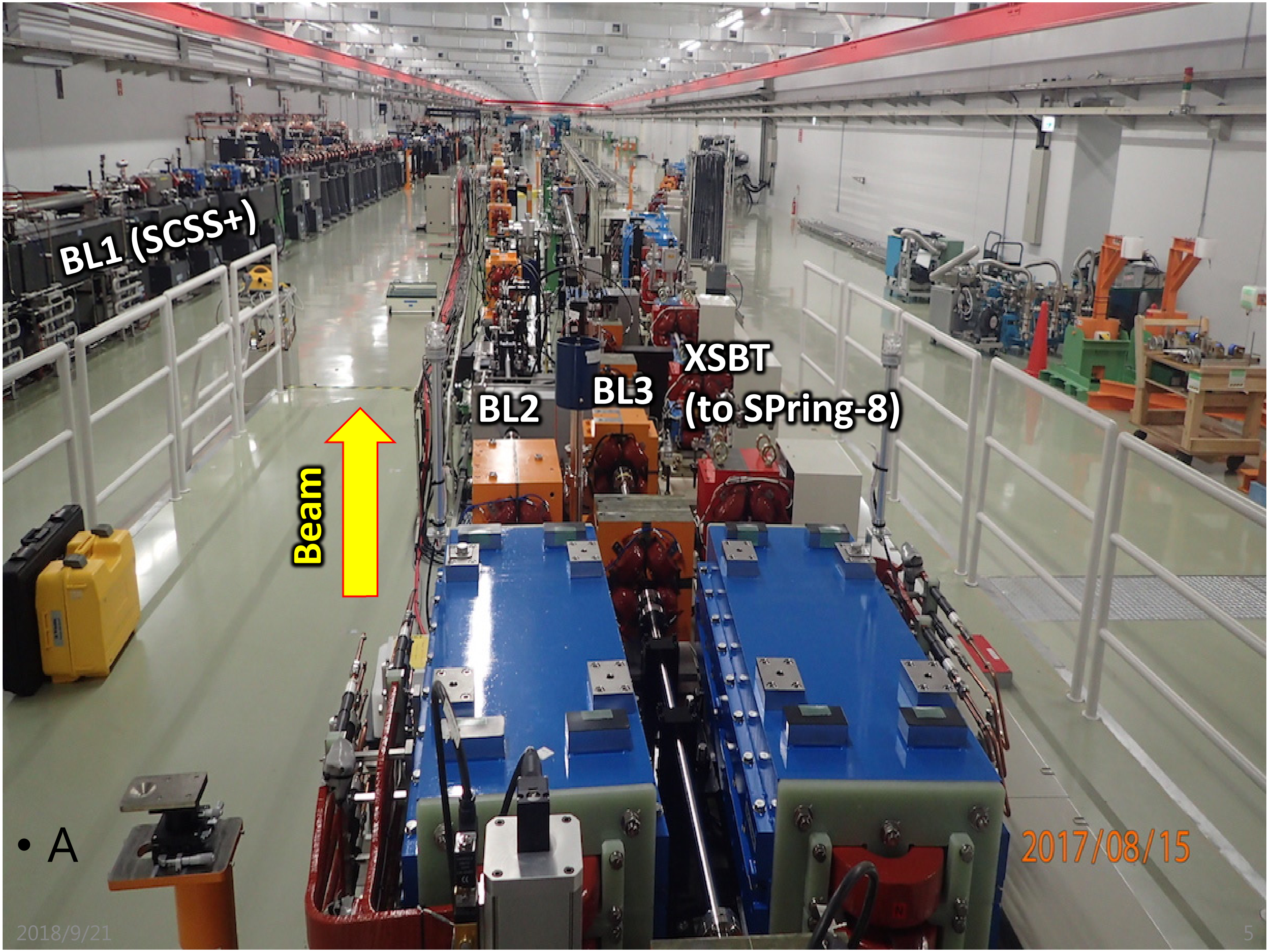
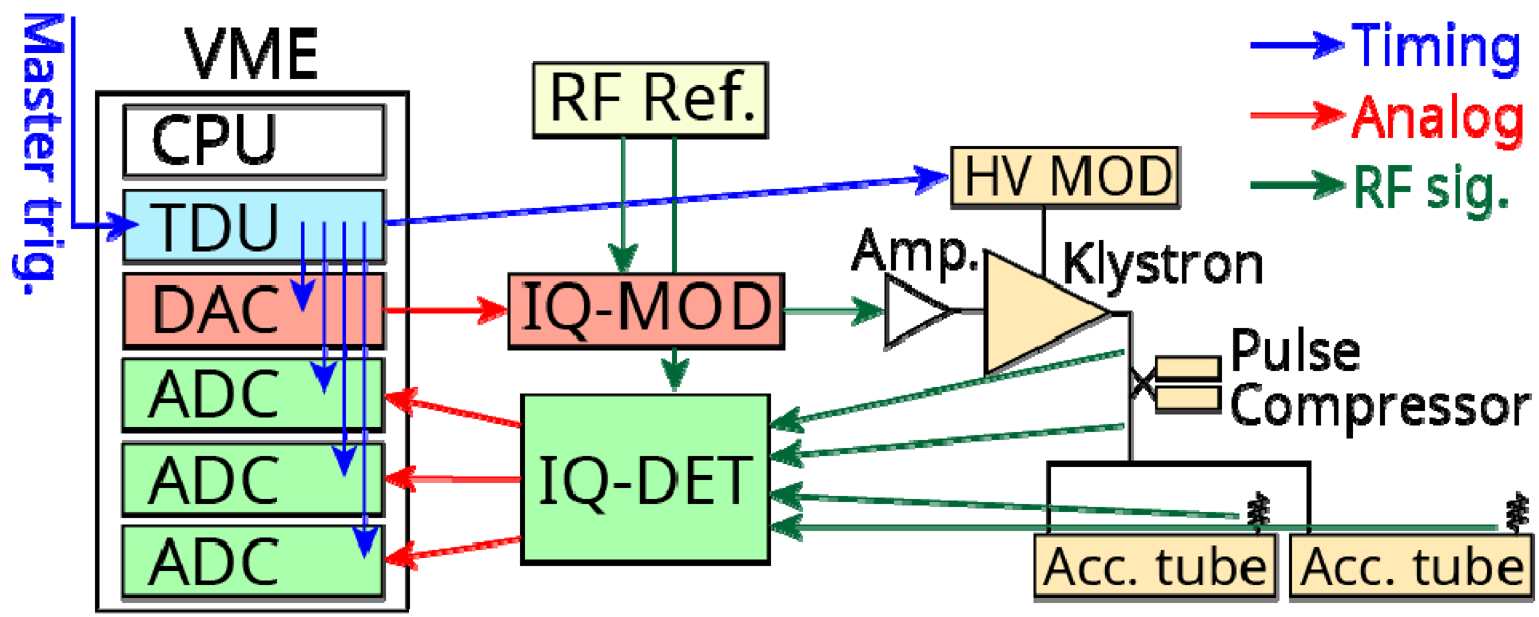


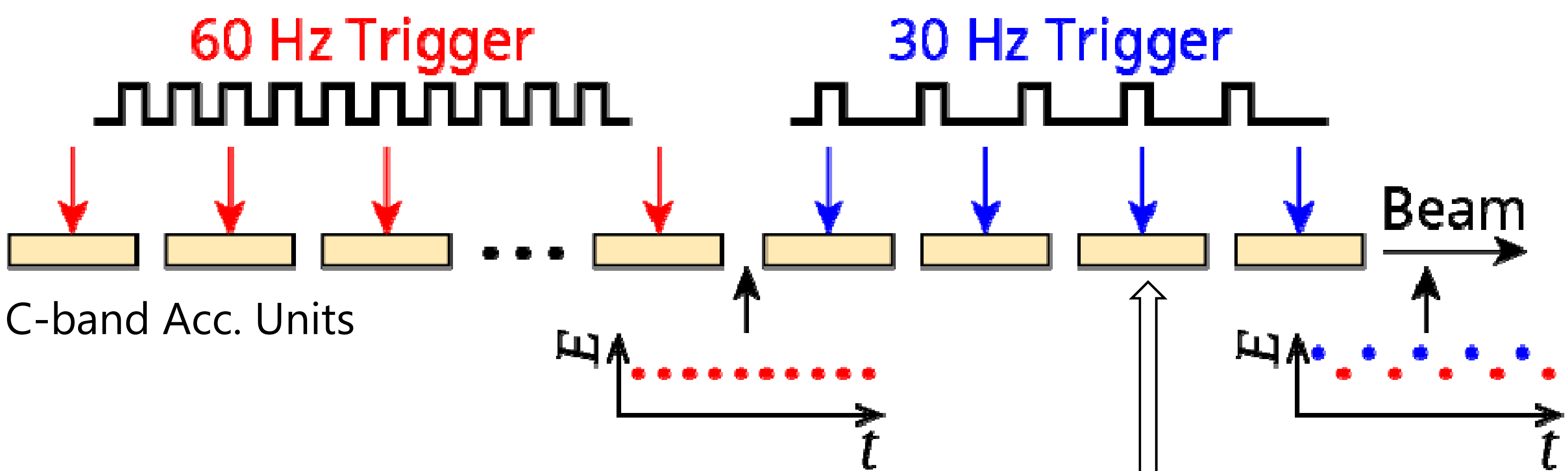
Timing and LLRF System for Each Accelerator Unit

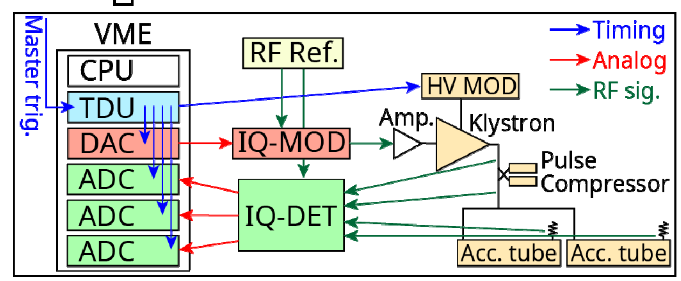


- Beam energy and bunch length are controlled by the timing and LLRF system pulse-by-pulse.
- Trigger signals are generated by a Trigger Delay Unit (TDU).
- RF signal is synthesized by an in-phase and quadrature modulator (IQ-MOD).
  - IQ baseband waveforms are generated by a 238 MSPS VME-DAC.
- RF signals from high-power RF component is detected by an IQ detector (IQ-DET).
  - IQ baseband waveforms are digitized by 238 MSPS VME-ADC.

Y. Otake *et al.*, Phys. Rev. Accel. Beams, **19**, 022001 (2016).

Beam Energy Control

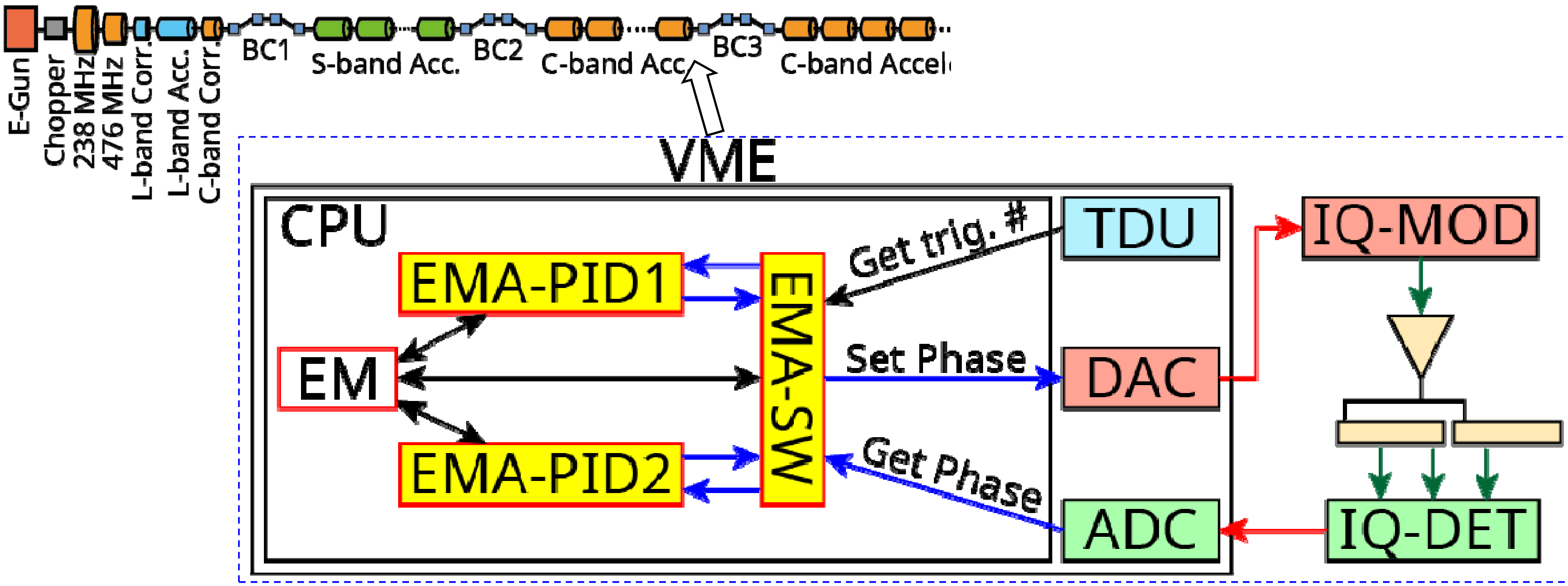




- Trigger rate of each accelerator unit can be changed by VME Trigger Delay Unit (TDU)
- Beam energy can be changed one after another.
- Acceleration voltage of each C-band unit: ~ 120 MeV
- Although the quadrupole strength in the accelerator is the same for both high and low energy beams, the beam envelop can be matched by quadrupoles after the switchyard.
- Two beams with the energy ratio of 1:2 could be appropriately accelerated and transported by the same quadrupole setting.

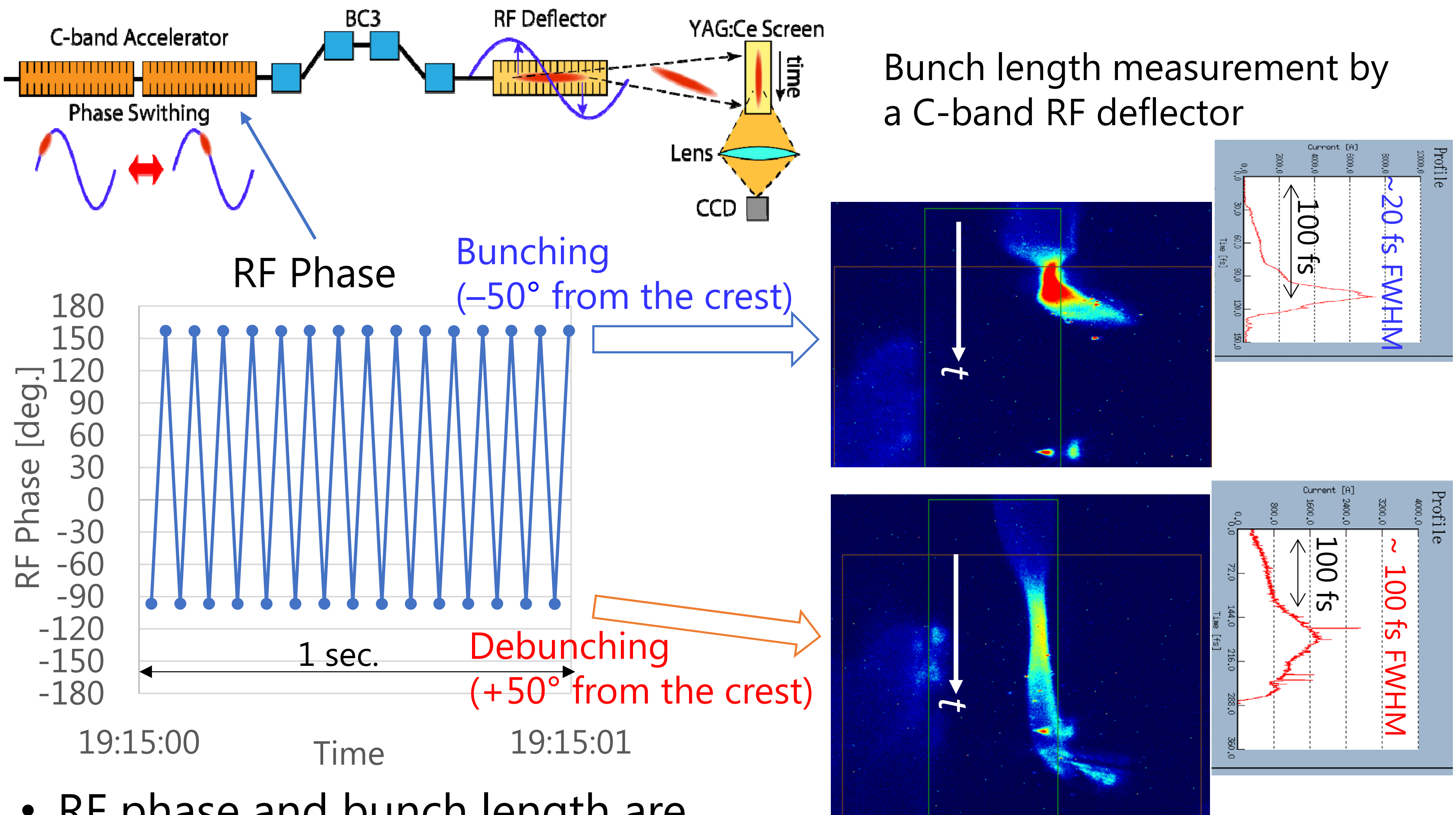
T. Hara *et al.*, Phys. Rev. ST Accel. Beams, **16**, 080701 (2013).

Bunch Length Control



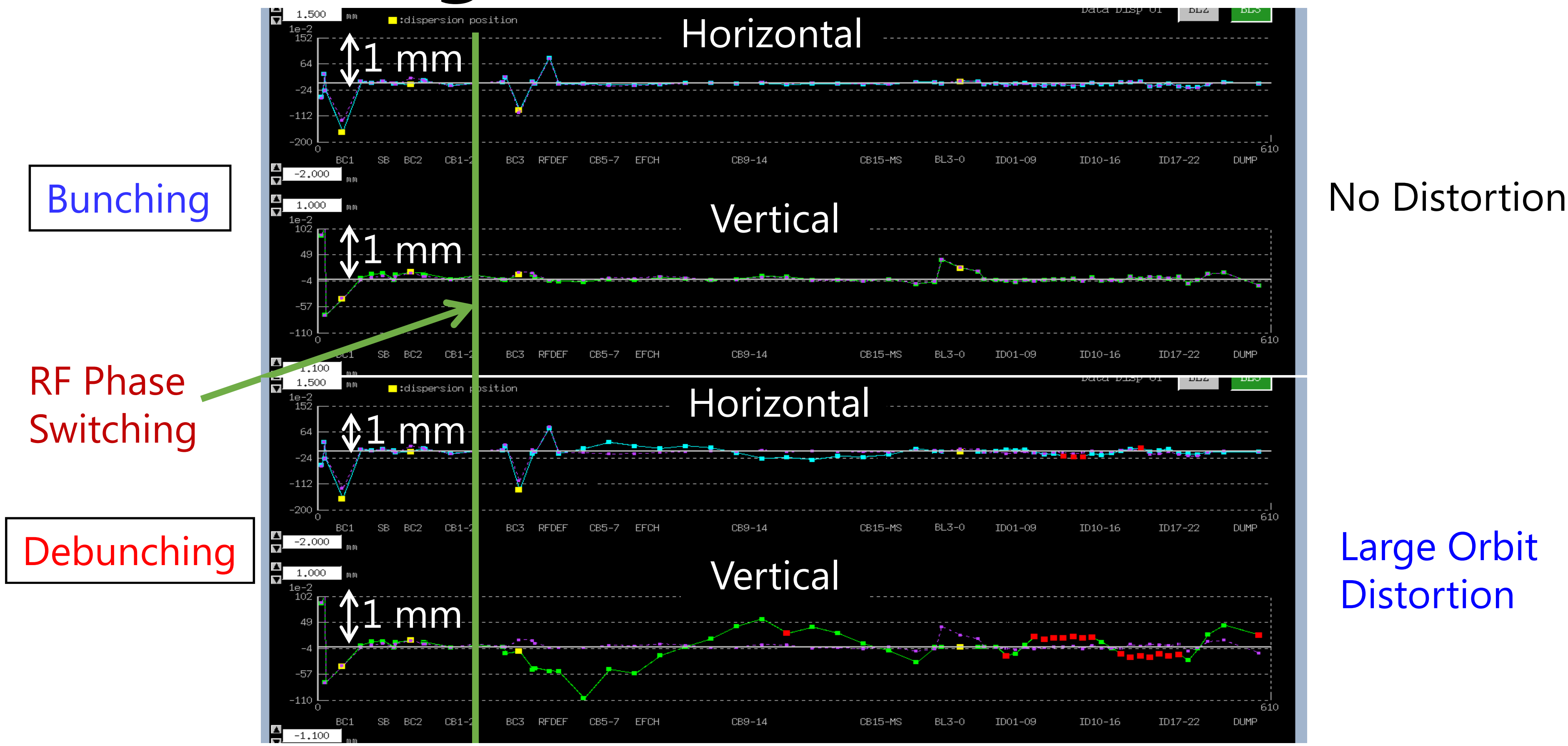
- Bunch length is controlled by adjusting RF phases of accelerator units before BC3.
- We developed software on the VME-CPU to change the rf phase pulse-by-pulse.
  - Firmware of VME-DAC and ADC cannot change the RF parameter pulse-by-pulse.
- MADOCA control system in SACLA [T. Fukui *et al.*, Proc. ICALEPCS'17, FRAPL03, pp. 1995–1999.]
  - VME modules are controlled by an Equipment Manager (EM) process.
  - Some EM agent (EMA) processes can be executed for real-time controls.
- Pulse-by-pulse RF parameter control function is implemented to the 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.

Demonstration of Pulse-by-Pulse Bunch Length Control



- RF phase and bunch length are appropriately changed one after another.

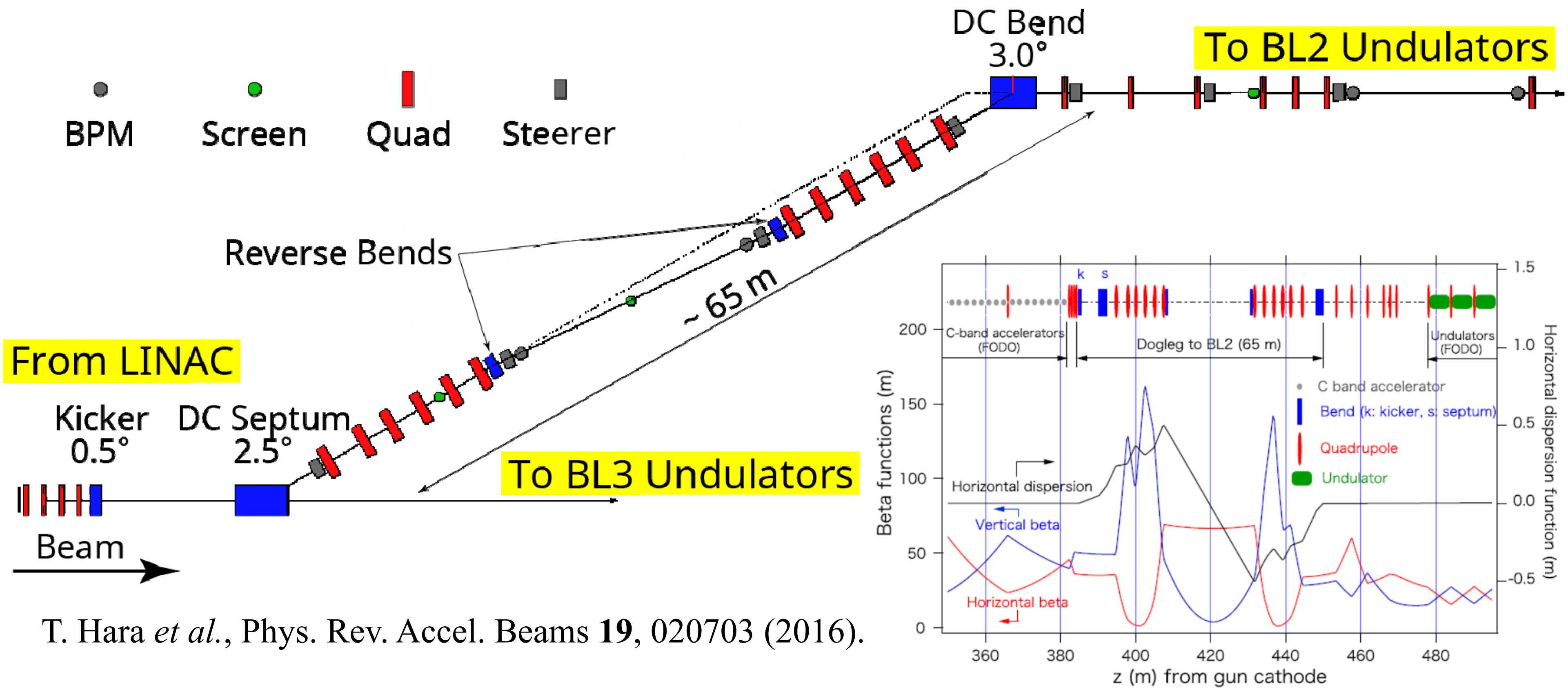
Orbit Distortion due to Focusing of the Acc. Tube



- Beam is deflected by the accelerator with the debunching phase.
  - Due to the phase-dependent focusing effect of an accelerator tube [*].
  - Beam orbit is displaced from the center of the accelerator.
- Precise alignment is necessary for changing the bunch length substantially.

[*] H. Maesaka *et al.*, Proc. FEL'13, TUPSO46, pp. 329–333.

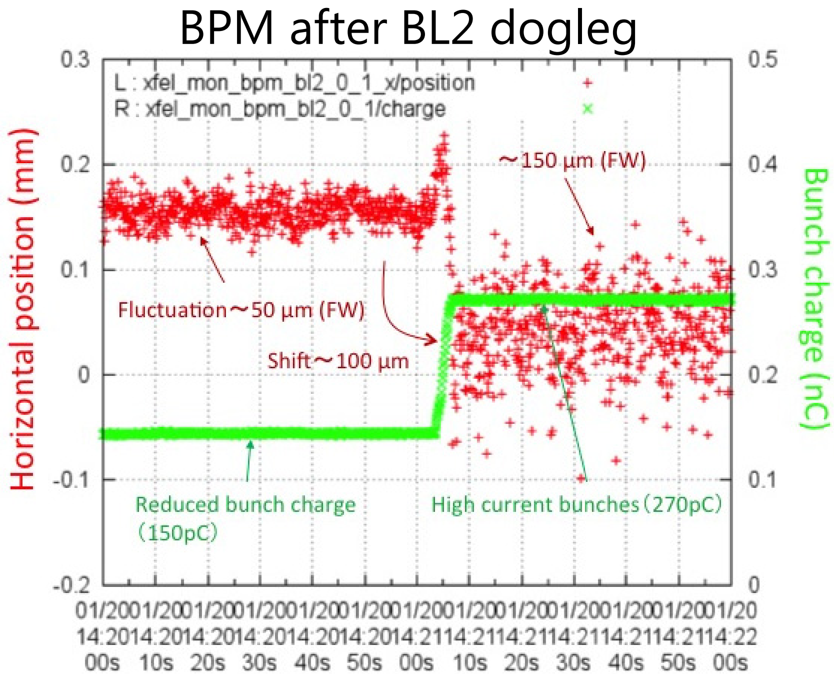
BL2 Dogleg (initial design)

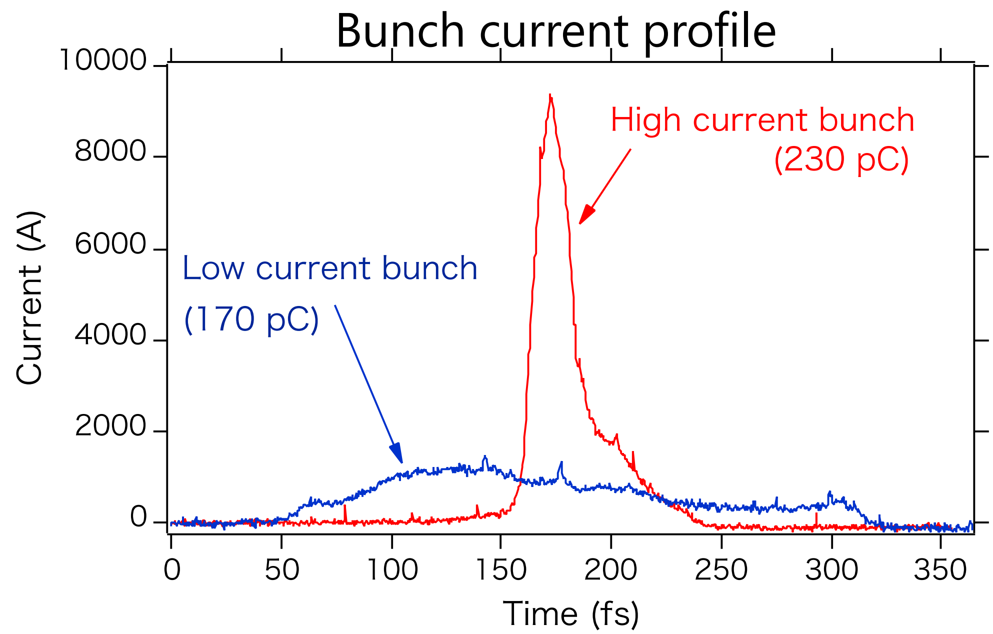


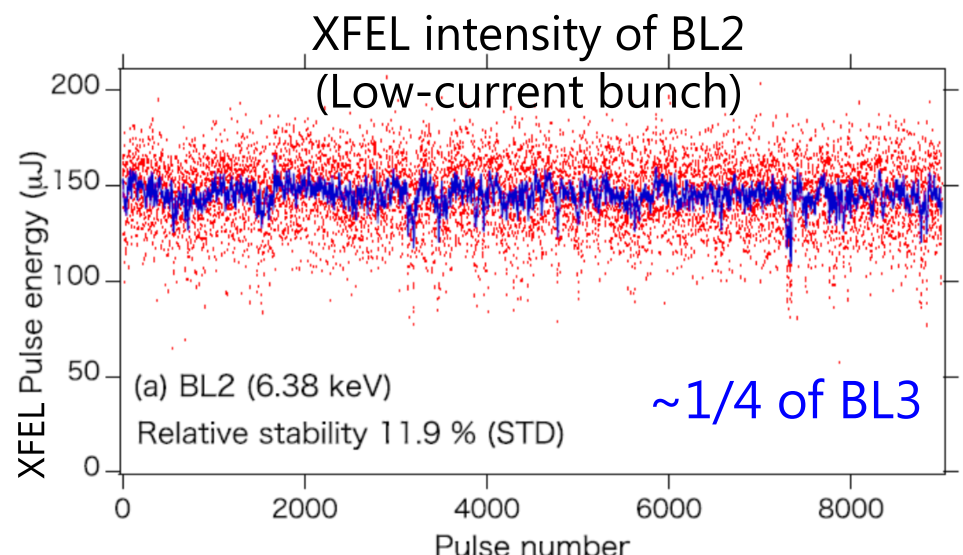
T. Hara *et al.*, Phys. Rev. Accel. Beams **19**, 020703 (2016).

- Deflection angles of the dogleg are +3° and –3°.
- Achromat and isochronous ($R_{56} = 0$) beam optics.
- Deflection angle of the kicker (0.5°) was made as small as possible to ensure orbit stability.

CSR Effects at the BL2 Dogleg



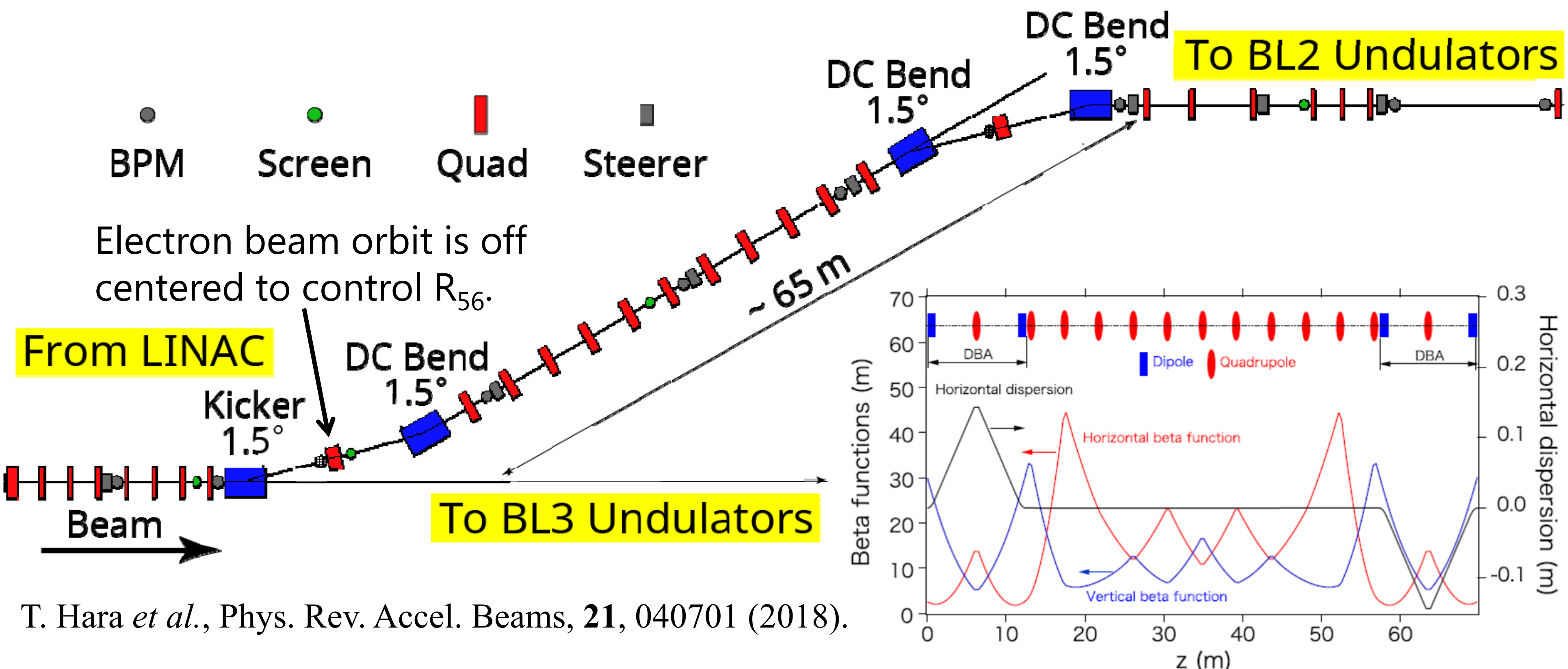




- Beam position of a high-current bunch showed large jitter after the BL2 dogleg.
  - Due to CSR effects.
- Although CSR effects can be suppressed for a low-current bunch, the XFEL intensity is limited to ~1/4 of BL3.

T. Hara *et al.*, Phys. Rev. Accel. Beams **19**, 020703 (2016).

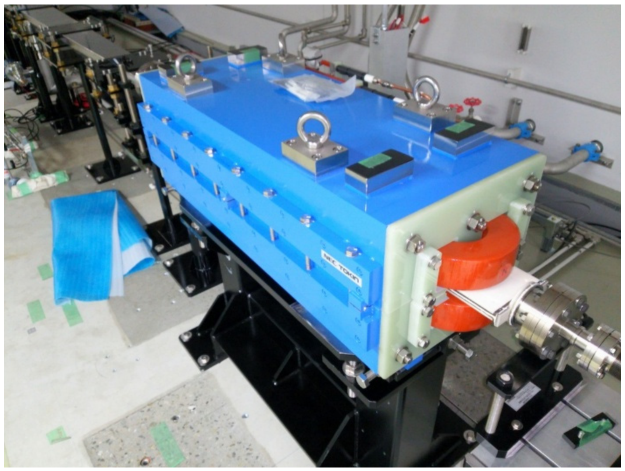
New BL2 Dogleg to Cancel CSR Effects



T. Hara *et al.*, Phys. Rev. Accel. Beams, **21**, 040701 (2018).

- Use two double-bend achromat (DBA) by four identical bending magnets (1.5° each).
- Horizontal phase advance between the DBAs is set to π.
- Even if the beam is deflected by CSR at the first DBA bends, it is kicked back at the second DBA with the same angle.
- Isochronous optics ($R_{56} = 0$) to avoid bunch lengthening.

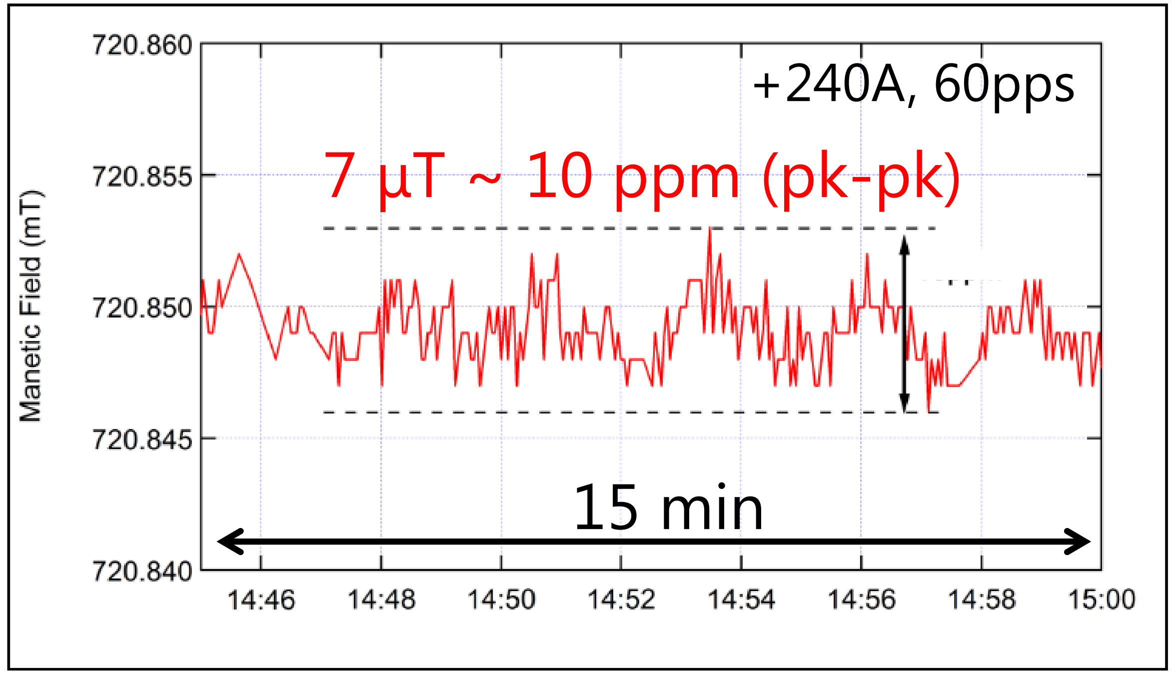
New Kicker Magnet



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.

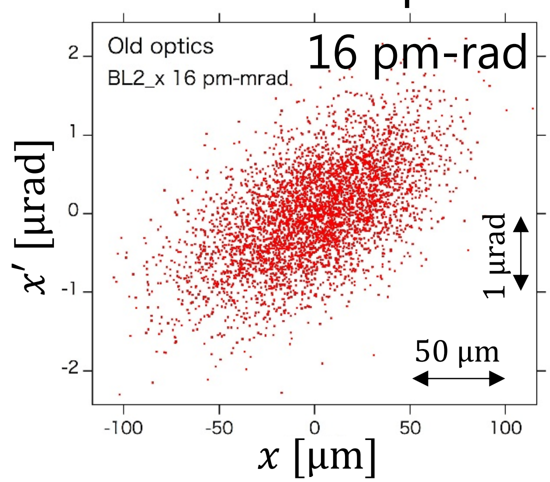
Full SiC MOS-FET modules
ROHM BSM120D12P2C005

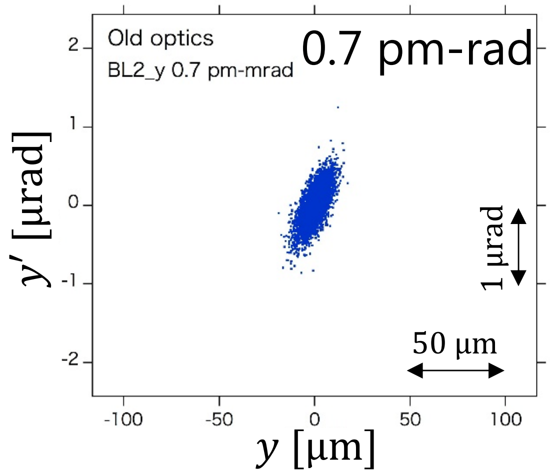
C. Kondo *et al.*, Rev. Sci. Instrum., **89**, 064704 (2018).

Mitigation of CSR Effects

Phase-space distributions of the pointing jitter after the BL2 dogleg

Old beam optics





Beam energy: 7.9 GeV
Peak current: ~10 kA

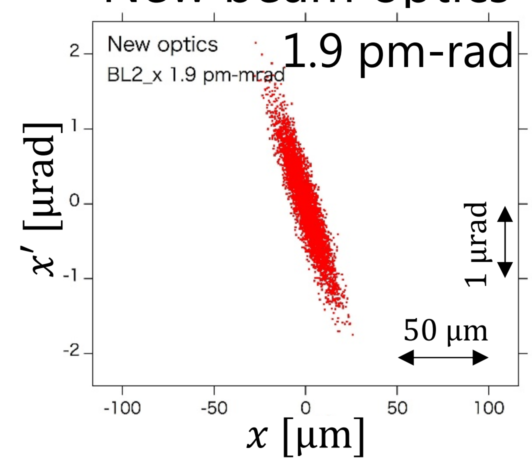
Horizontal pointing jitter

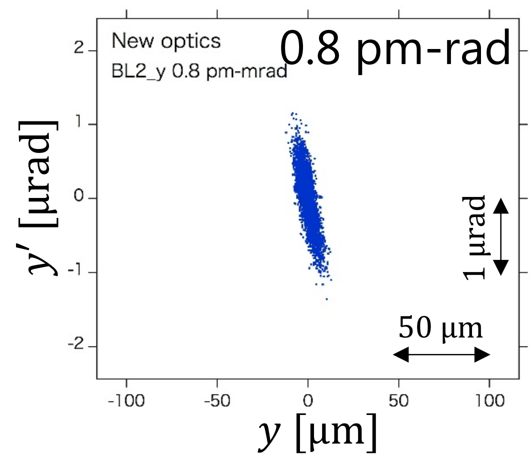
(BL3: 0.8 pm-rad)

Vertical pointing jitter

(BL3: 0.5 pm-rad)

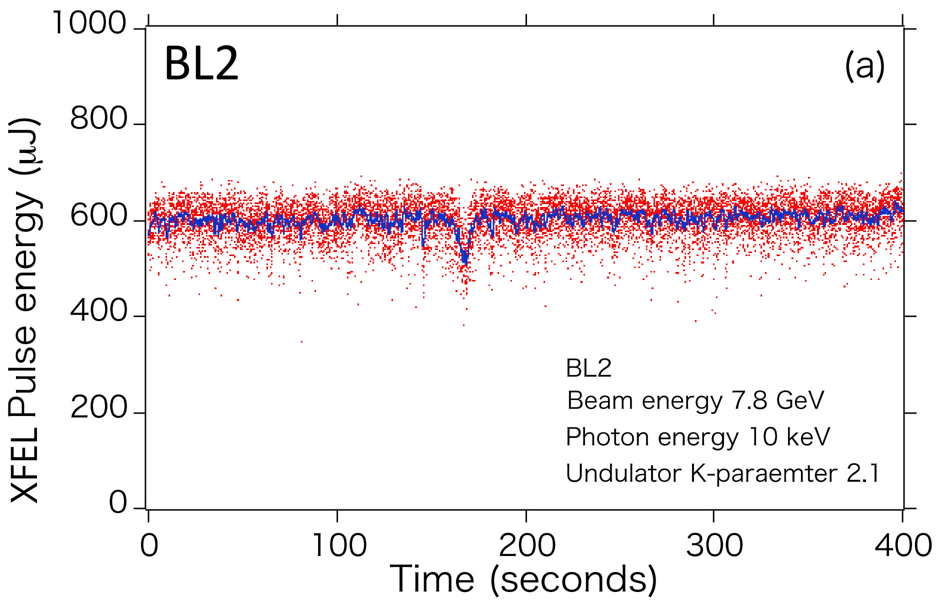
New beam optics

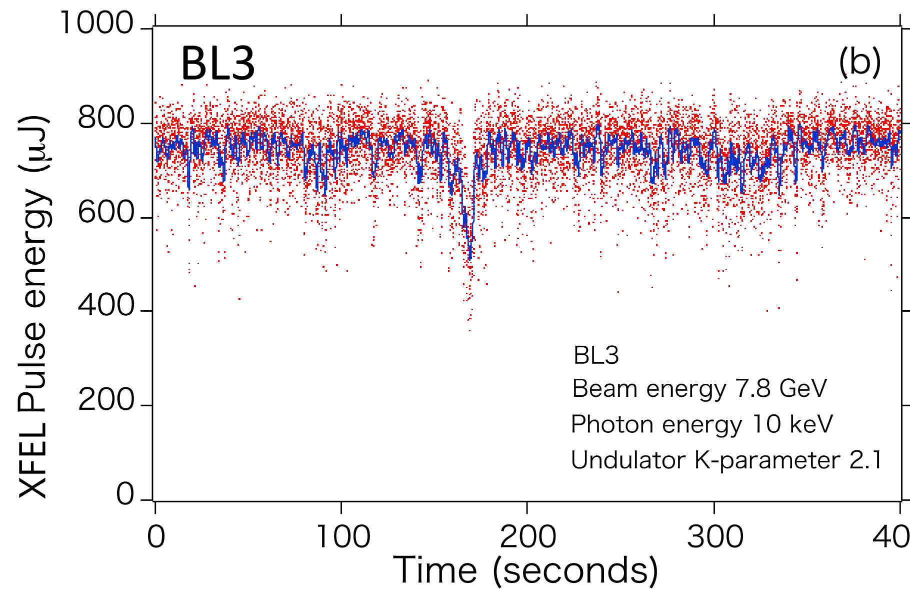




- Horizontal orbit stability is improved by an order of magnitude.
- 10 kA bunches are stably transported to BL2 through the dogleg.

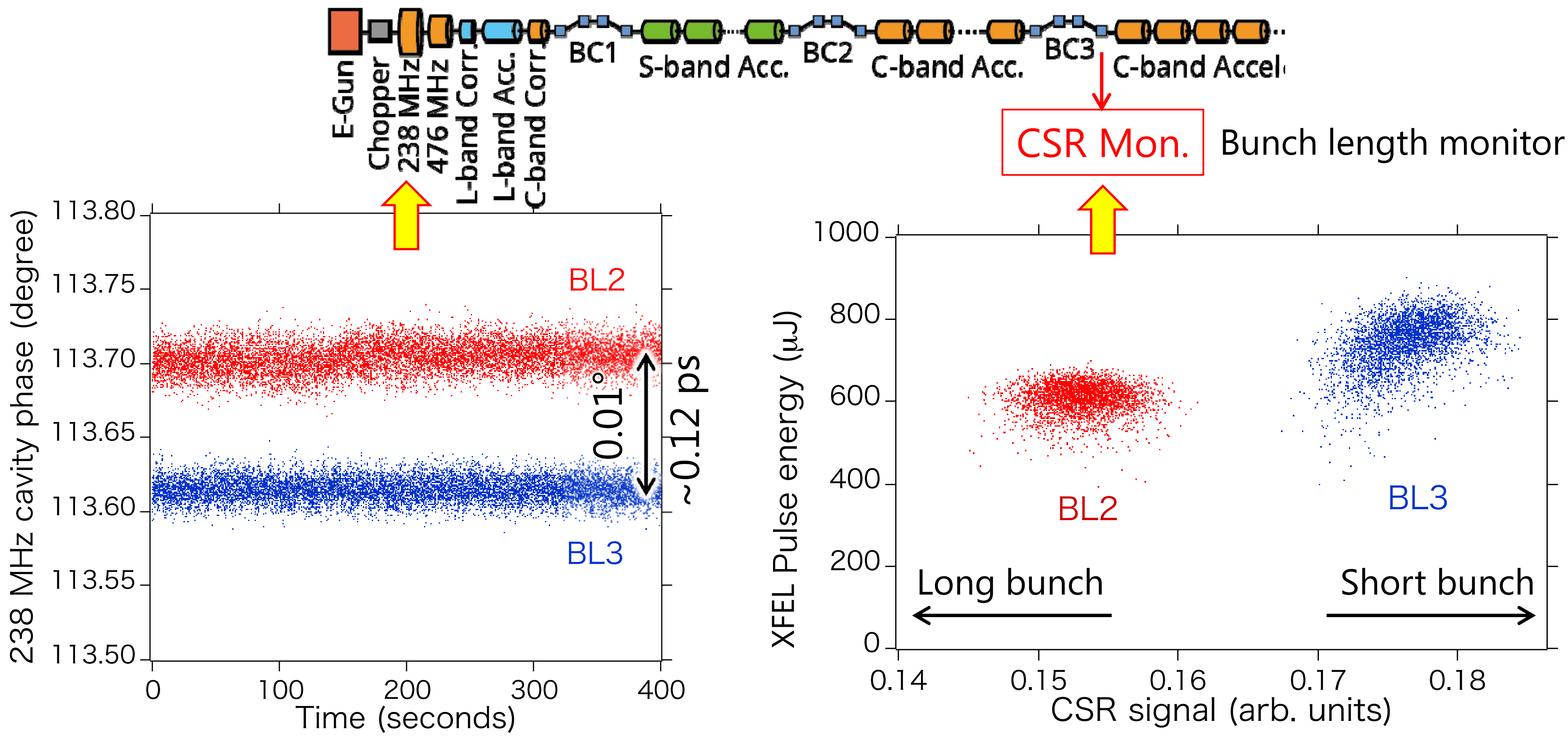
XFEL Performance of Modified BL2





- 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
- Bunch length is optimized for each beamline by the pulse-by-pulse RF parameter switching software.
- XFEL intensity is comparable to each other.

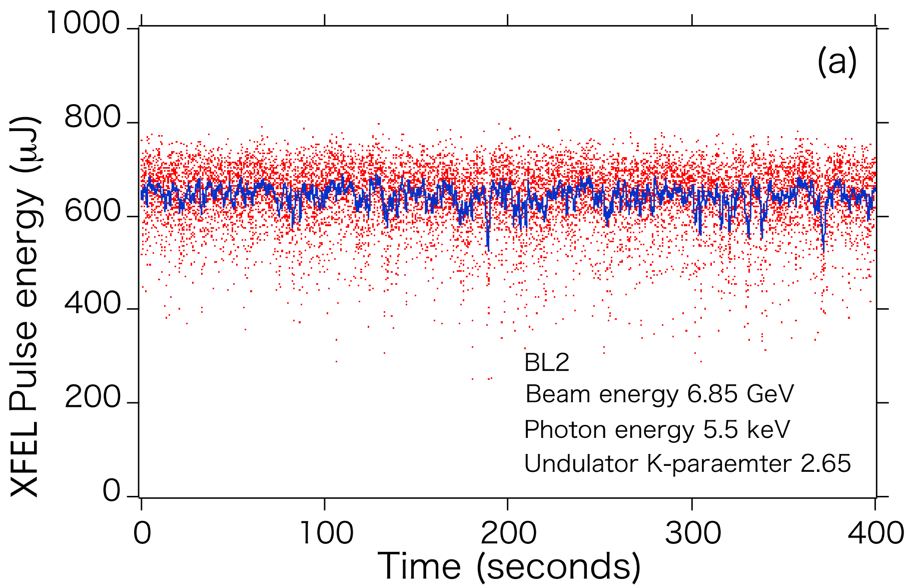
Beam Parameters for Each Beamline



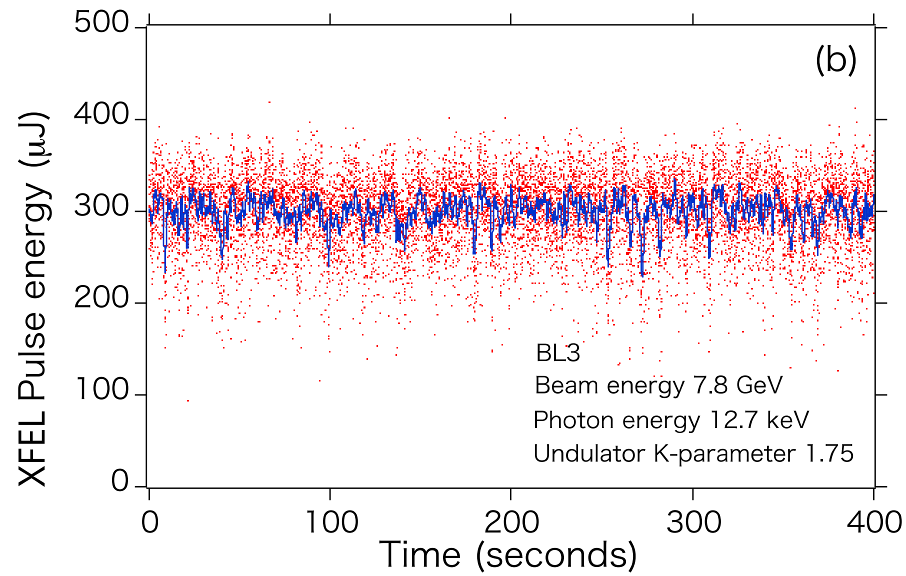
- 60 Hz electron bunches are alternately delivered to BL2 and BL3.
  - Beam energy: 7.8 GeV (same for both beamlines)
  - Photon energy: 10 keV
  - Bunch length: ~10 fs FWHM
- RF phase of each accelerator unit is appropriately changed by the pulse-by-pulse RF parameter switching software.
- Bunch length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

Multi-Energy Operation

BL2 (6.85 GeV)



BL3 (7.8 GeV)

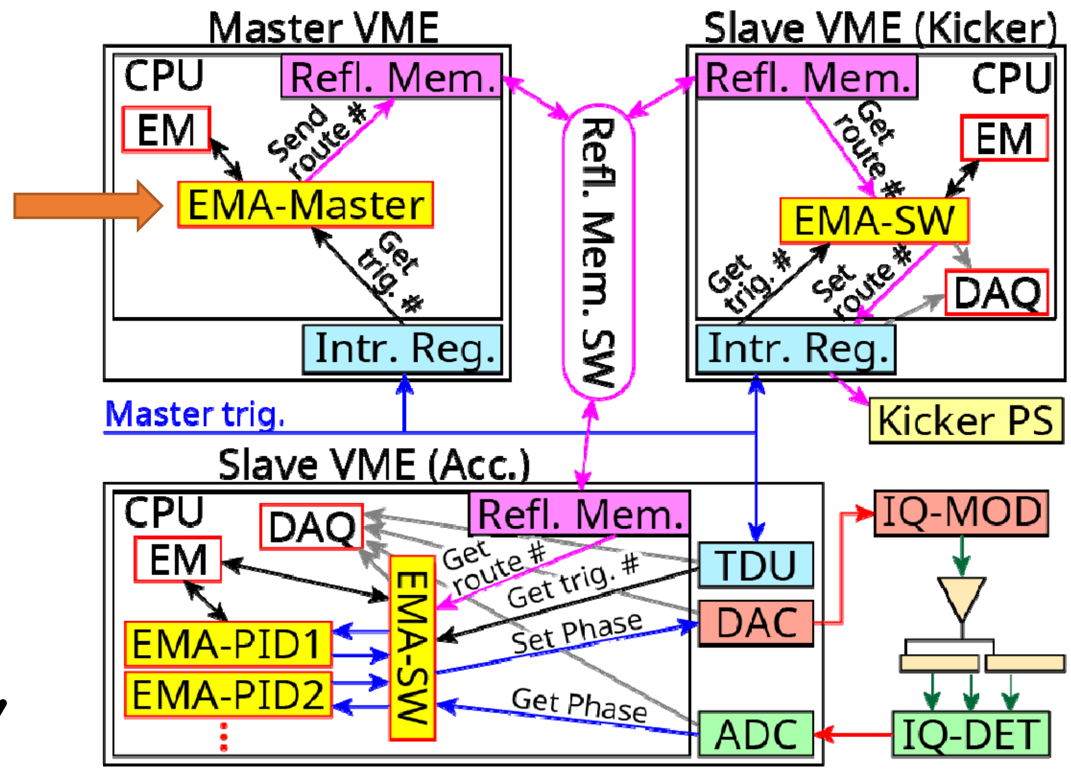


- Low-energy beams (6.85 GeV) are transported to BL2 and high-energy beams (7.8 GeV) to BL3.
- Photon energies are more than twice different between BL2 (5.5 keV) and BL3 (12.7 keV).

On-demand Switching System

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

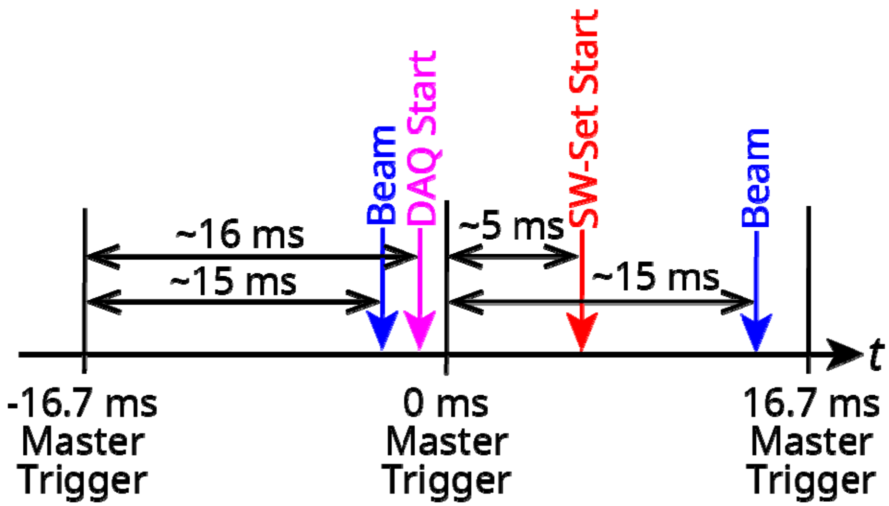
Trig. #	Route
0	BL3
1	BL2
2	BL3
3	BL2
4	BL3
5	BL2
6	XSBT
7	BL2
8	BL3
9	BL2

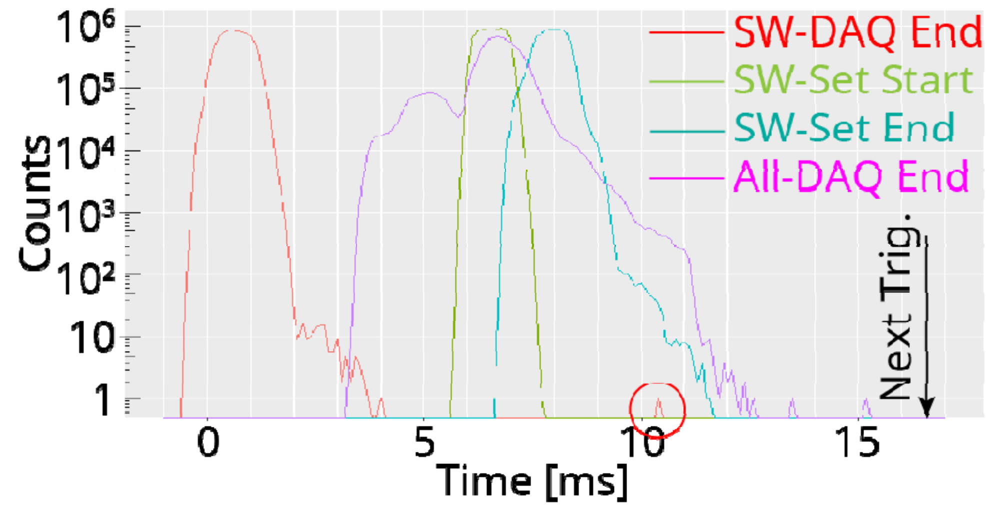


- Beam route information is distributed pulse-by-pulse by using a reflective memory network.
  - Mezzanine card on the VME-CPU.
- Trigger and RF parameter for each accelerator unit, the current of the kicker magnet etc. are switched according to the route information.
- Route number, RF parameters and the master trigger number are recorded by an event-synchronized data-acquisition (DAQ) system [*] pulse-by-pulse.

[*] M. Yamaga *et al.*, Proc. ICALEPCS’09, TUB003, pp.69–

Performance Test of On-demand Parameter Switching at BL1 LINAC





- Sequence of the on-demand switching system
  1. DAQ takes the data related to the route and rf parameter switching (SW-DAQ).
  2. DAQ starts taking the other data (All-DAQ) just after SW-DAQ.
  3. EMA-SW gets the route information and sets the trigger and rf parameter 5 ms after the master trigger (SW-Set).
- Setup: One master VME and four slave VMEs.
- Failure in parameter switching was not found for more than 40 hours.
- Only one inconsistency in the data was found.
  - Due to a delay of SW-DAQ and not to be the delay of EMA-SW itself.
- Error rate: 1×10^{-7} per pulse
  - Smaller than the other failures, such as a trip of the HV-PS for a klystron.

Summary

- New XFEL beamline, BL2, was constructed to increase opportunities for user experiments.
  - DC bending magnet was replaced with a kicker magnet.
- We developed a pulse-by-pulse beam route and RF parameter switching system to provide the optimized electron beam to each XFEL beamline.
  - Beam energy and bunch length are successfully optimized for each beamline.
- XFEL performance of BL2 was comparable to BL3.
  - After the modification of the BL2 dogleg to mitigate CSR effects.
- We are developing an on-demand beam route and RF parameter switching system needed for beam injection to SPring-8.
  - Sufficiently small failure rate of 1×10^{-7} per pulse.
  - On-demand switching system will be available in the next year.