XFEL as a Low-Emittance Injector for a 4th-Generation Synchrotron Radiation Source

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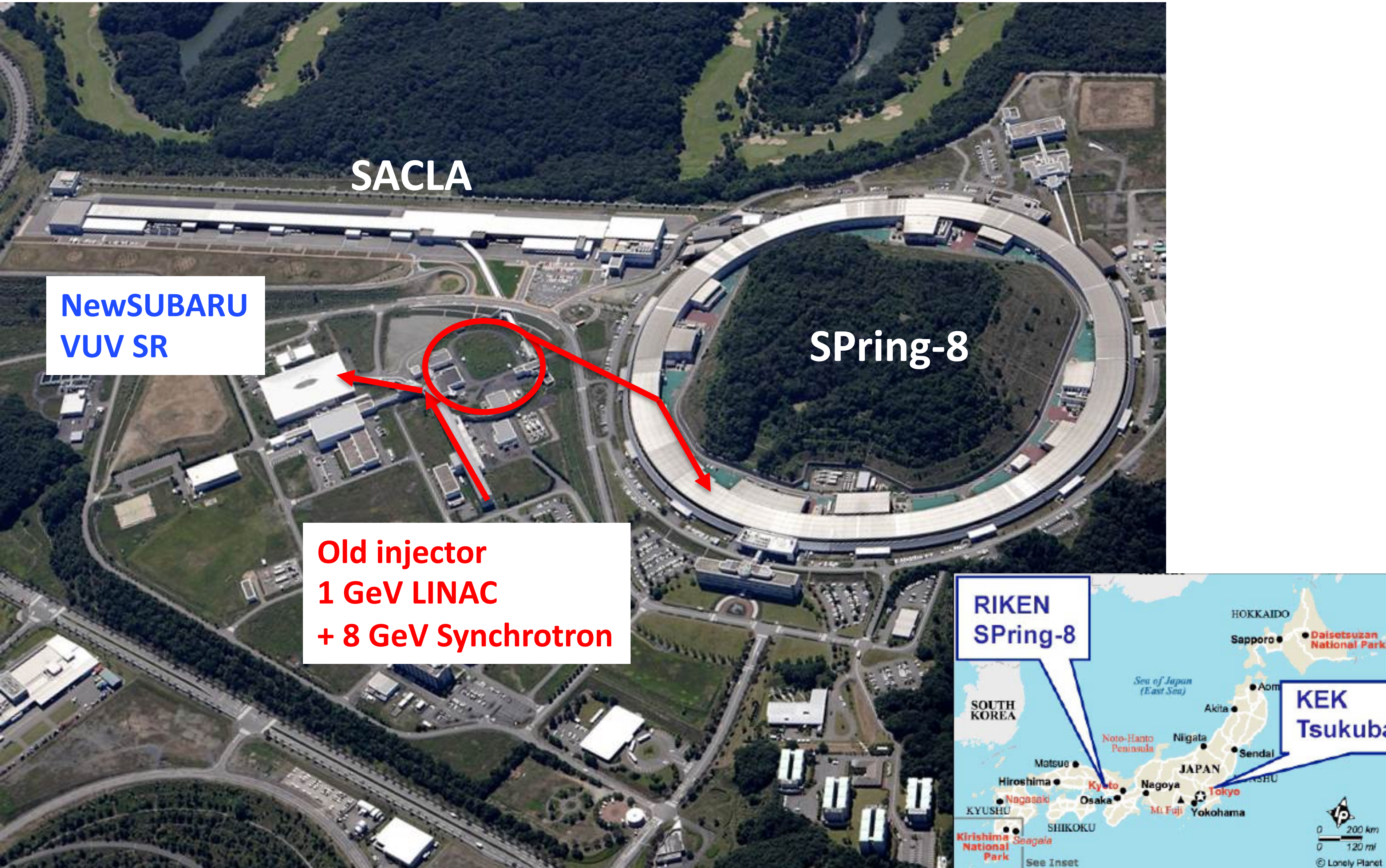
RIKEN SPring-8 Center

SPring-8 campus（～2020）



SPring-8 campus（2020～）

Beam injection to SPring-8 from SACLA

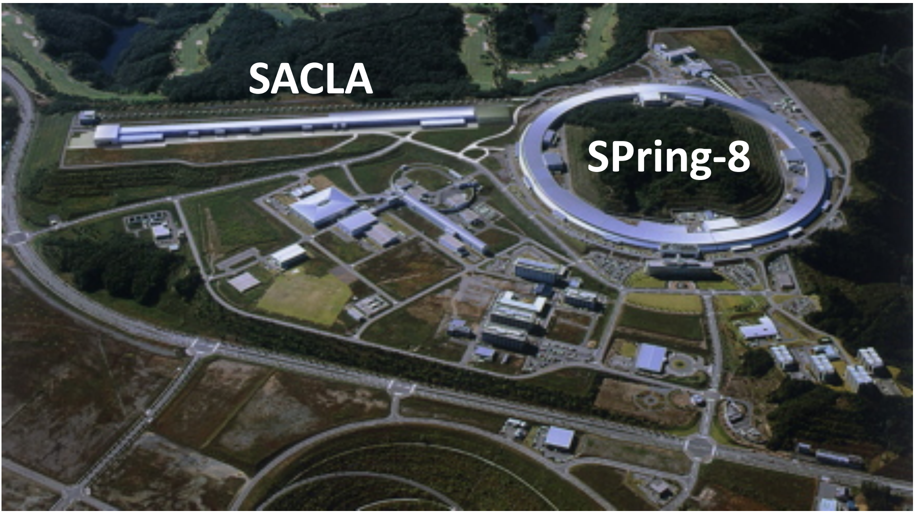
Motivations

- Low-emittance beam injection is need for SPring-8-II, that is a future upgrade project of SPring-8, due to its small transverse aperture.

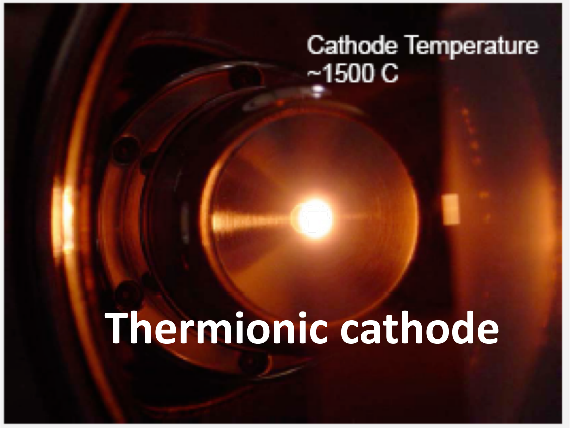
- Renewal cost of high-voltage substation for the old injector accelerators was huge.

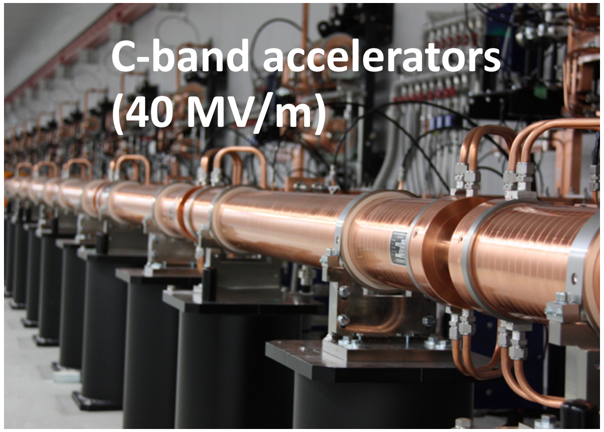
- SPring-8/SACLA declared a green facility. By shutting down the old injector accelerators, electricity consumption can be saved.

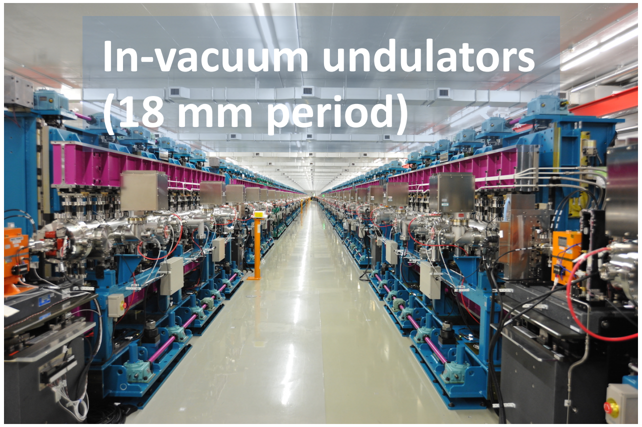
XFEL facility SACLA
(SPring-8 Angstrom Compact free-electron LAser)



2011	SACLA commissioning
2012	User operation with BL3
2014	BL2 in operation
	SCSS accelerator moved to BL1
2020	Beam injection to SPring-8



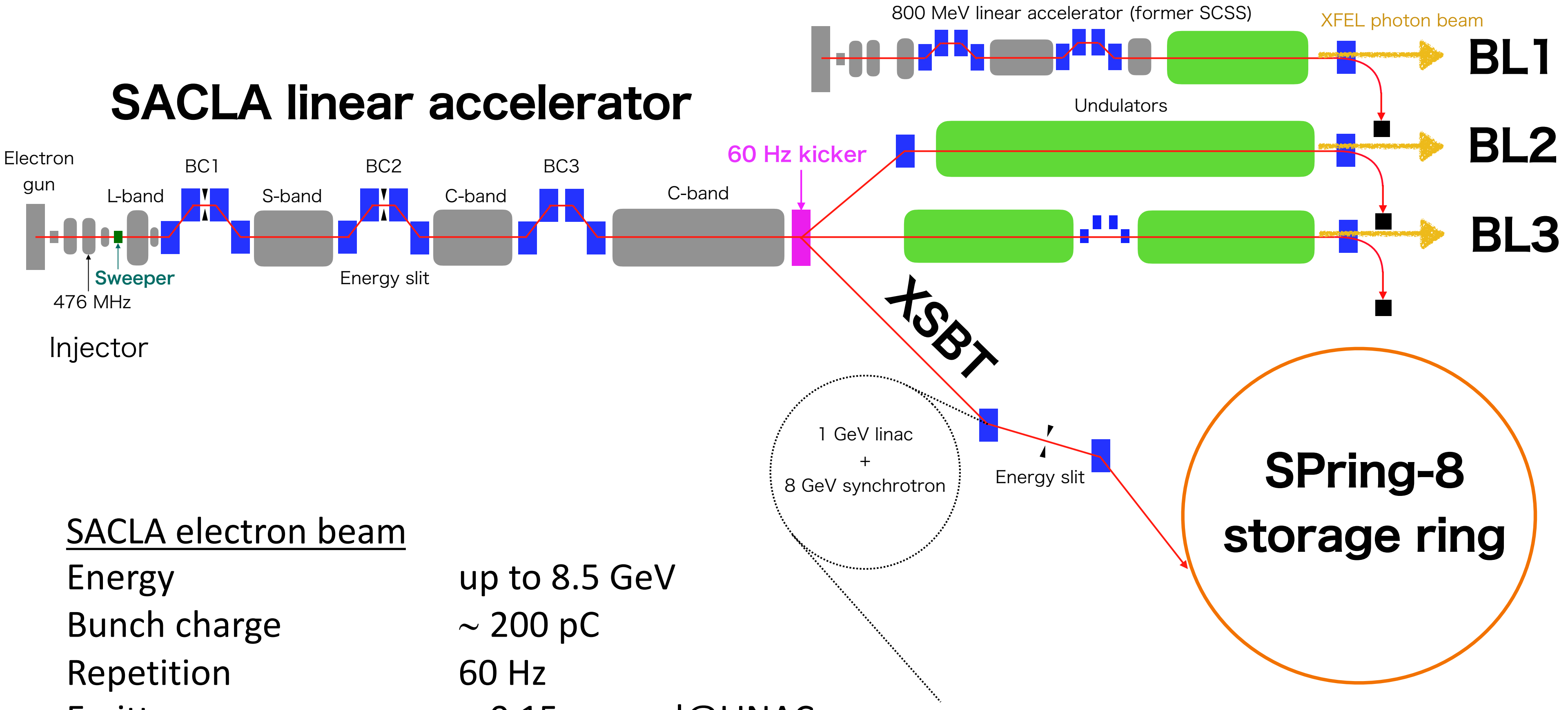




3 key technologies of SACLA

SACLA XFEL facility

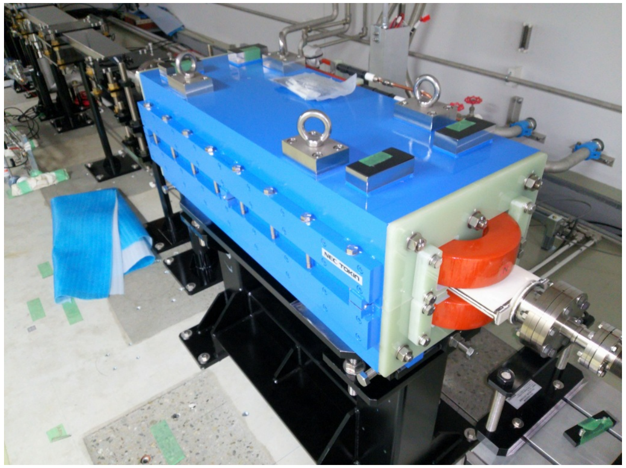
BL1: EUV and soft x-ray (20-150 eV)
BL2 and BL3: hard x-ray (4-15 keV)



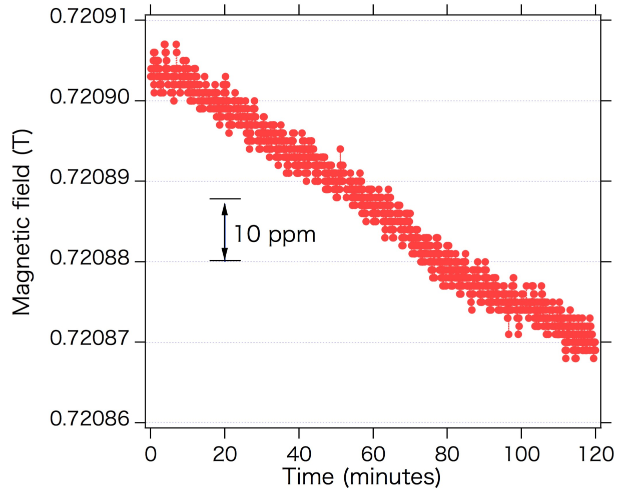
<u>SACLA electron beam</u>

Energy	up to 8.5 GeV
Bunch charge	~ 200 pC
Repetition	60 Hz
Emittance	~ 0.15 nm-rad@LINAC
	~ 1 nm-rad@injection point of SPring-8

Electron beam switchyard

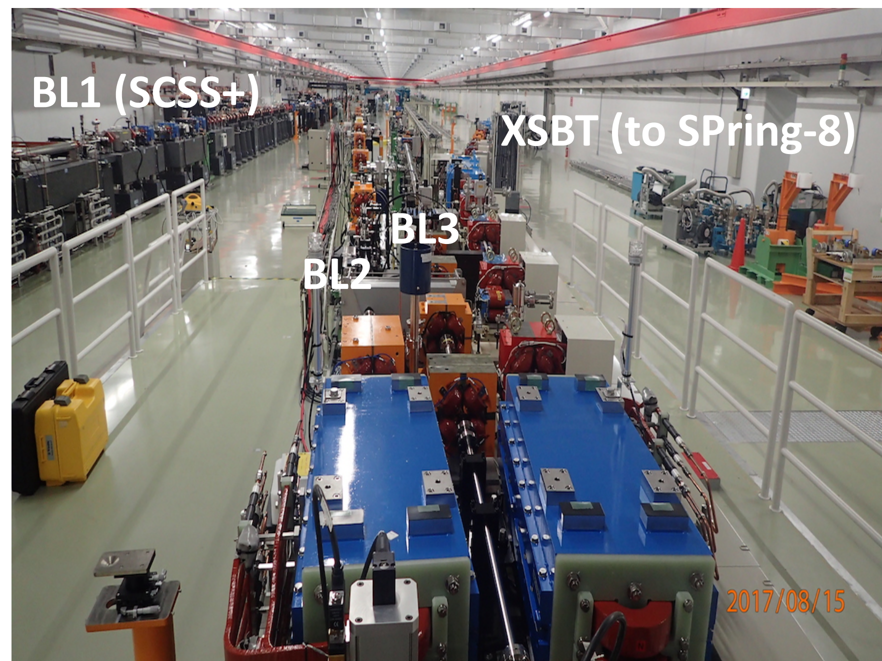


Kicker magnet
(Yoke length 0.95 m, B_{max}=0.9 T)



Stability of the kicker magnetic fields measured by a gated NMR.

SiC power supply (60 Hz, 1 kV-299 A)



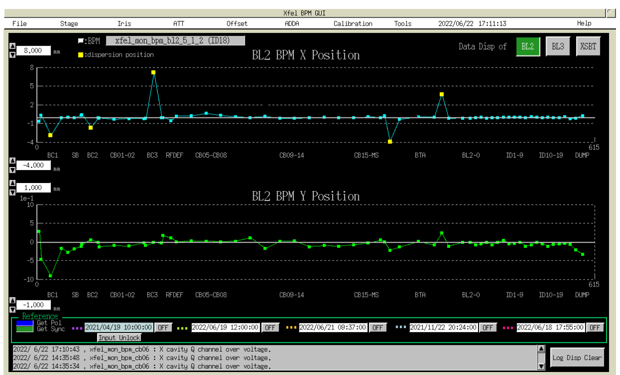
Beam injection to SPring-8 from SACLA

Issues

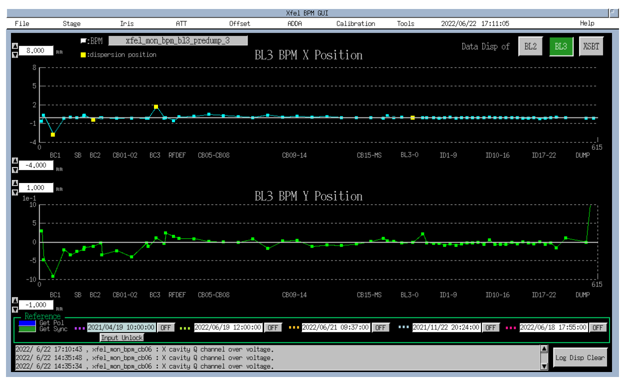
- Must keep XFEL user operation while injecting the beam.
- Beam injection and XFEL tuning should be independently performed.
- Injection beam energy is fixed at 8 GeV, while the energies of XFEL beamlines are changed depending on XFEL user experiments.
- Reference clock frequencies of SACLA (238 MHz) and SPring-8 (508.58 MHz) are not related by an integer multiple.

3 virtual accelerators

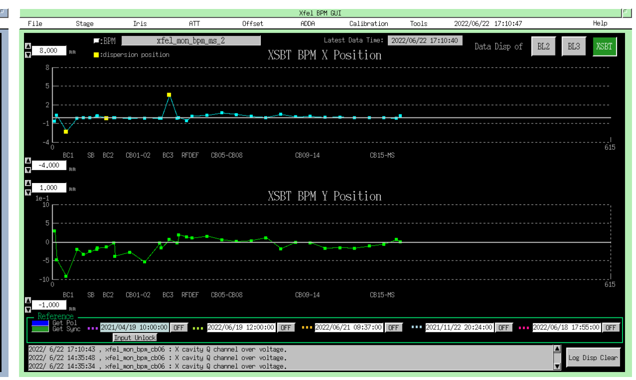
- Independent setting of RF parameters for three destinations.
- A 16 bit tag containing bunch destination is attached to each electron bunch.
- Measured data are saved with the bunch tag and handled separably by destination, for example a beam energy FB on individual destination possible.
- 7 pulsed quadrupoles are installed this year and another 14 quadrupoles next year to facilitate transverse beam envelop matching.



XFEL BL2



XFEL BL3

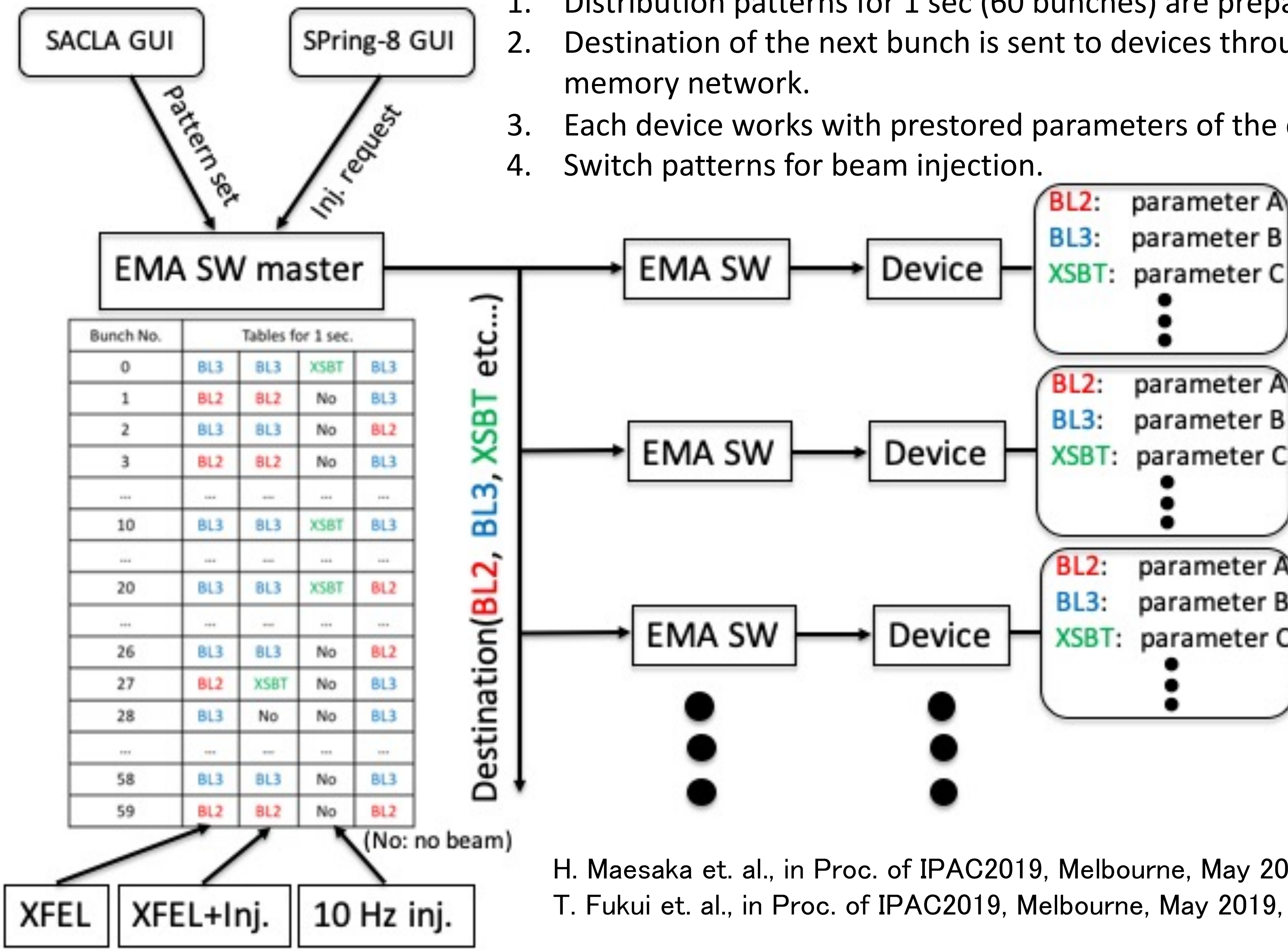


XSBT

Electron beam orbits measured and displayed by destination.

Beam parameter control

1. Distribution patterns for 1 sec (60 bunches) are prepared in a table.
2. Destination of the next bunch is sent to devices through a reflective memory network.
3. Each device works with prestored parameters of the destination.
4. Switch patterns for beam injection.

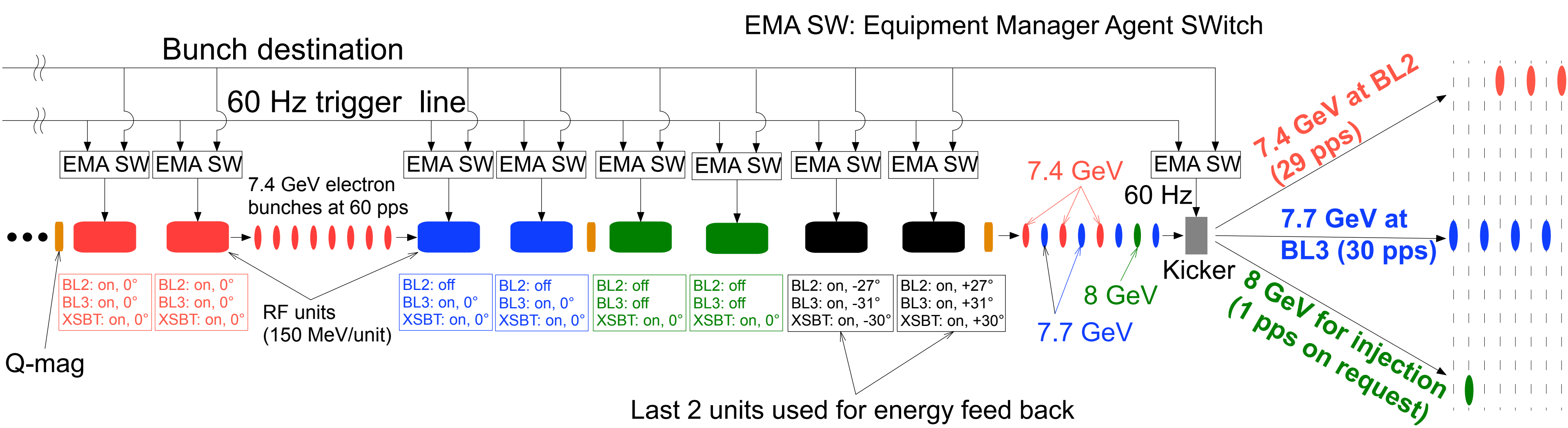


Bunch No.	Tables for 1 sec.			
0	BL3	BL3	XSBT	BL3
1	BL2	BL2	No	BL3
2	BL3	BL3	No	BL2
3	BL2	BL2	No	BL3
...	...	...	...	...
10	BL3	BL3	XSBT	BL3
...	...	...	...	...
20	BL3	BL3	XSBT	BL2
...	...	...	...	...
26	BL3	BL3	No	BL2
27	BL2	XSBT	No	BL3
28	BL3	No	No	BL3
...	...	...	...	...
58	BL3	BL3	No	BL3
59	BL2	BL2	No	BL2

H. Maesaka et. al., in Proc. of IPAC2019, Melbourne, May 2019, 3427 (2019).
T. Fukui et. al., in Proc. of IPAC2019, Melbourne, May 2019, 2529 (2019).

Bunch-by-bunch energy control

- Injection beam energy is fixed at 8 GeV, while the beam energies of BL2 and BL3 are frequently changed depending on user experiments.

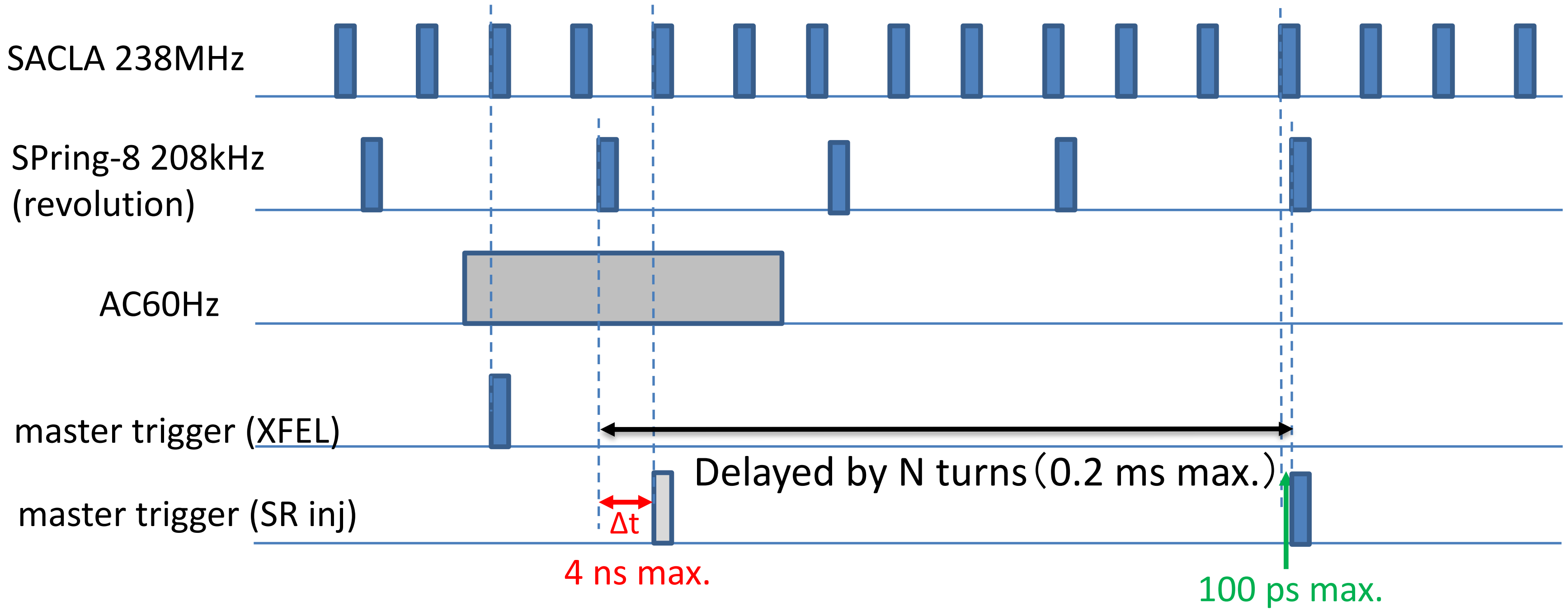


The number of RF cavities and their phases are changed bunch by bunch to satisfy the requirements of three destinations.

T. Hara et al., Phys. Rev. Accel. Beams **16,** 080701 (2016).

Synchronization of the two accelerators

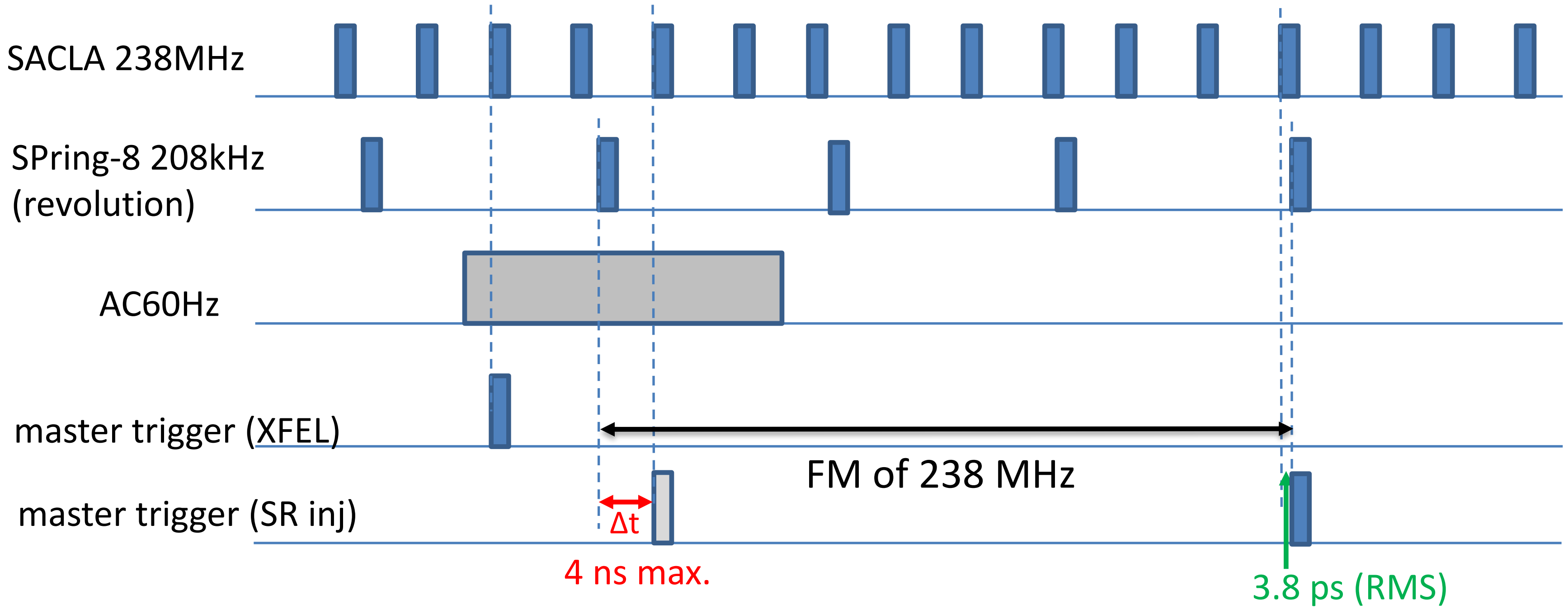
- The electron bunch of SACLA is synchronized to 238 MHz and 60 Hz (power line).
- Revolution frequency of SPring-8 is 208 kHz (508 MHz reference clock).
- The time difference up to 4 ns occurs between SACLA and RF bucket of SPring-8.
- Delay injection for N revolutions to have the minimum time difference (< 100 ps).



Measure Δt and calculate an optimum delay (the number of revolutions N)
to get the minimum time difference (Δt < 100 ps).

Synchronization of the two accelerators

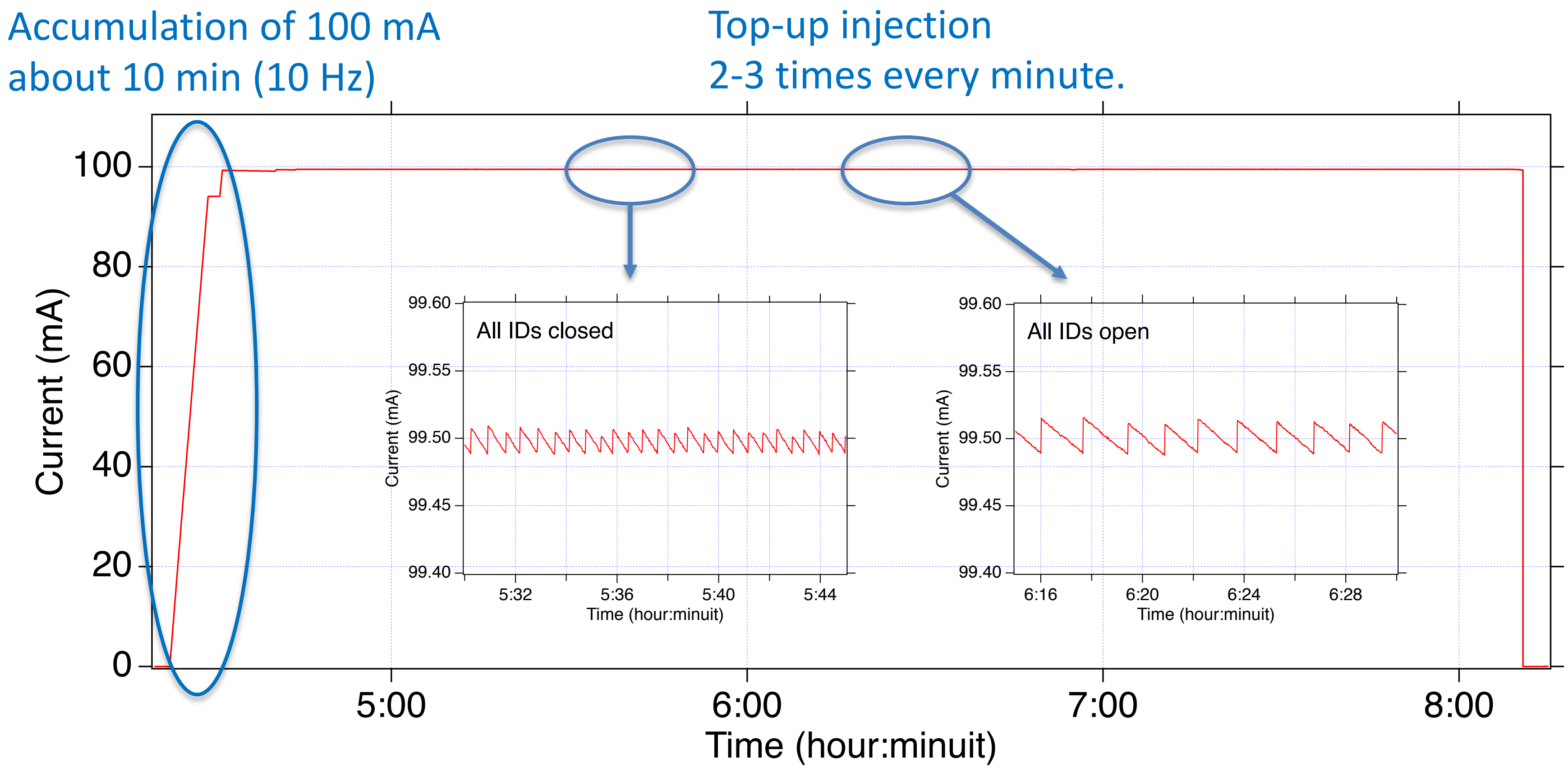
- To further reduce the time difference, frequency modulation is applied to 238 MHz of SACLA during the delay time.
- Finally the two accelerators are synchronized within 3.8 ps (rms).



T. Ohshima et. al., in Proc. of IPAC2019, Melbourne, May 2019, 3882 (2019).

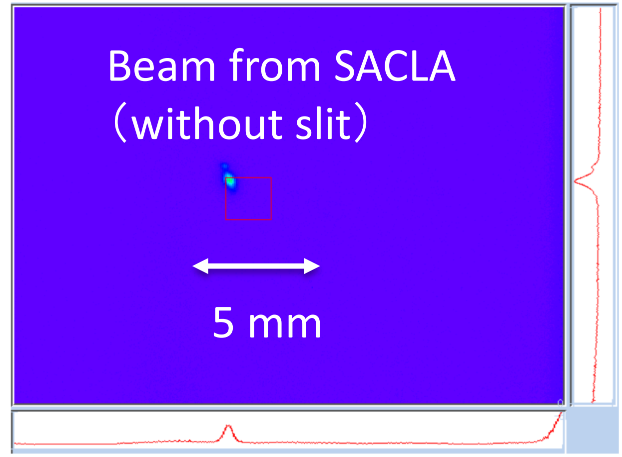
Beam injection to SPring-8

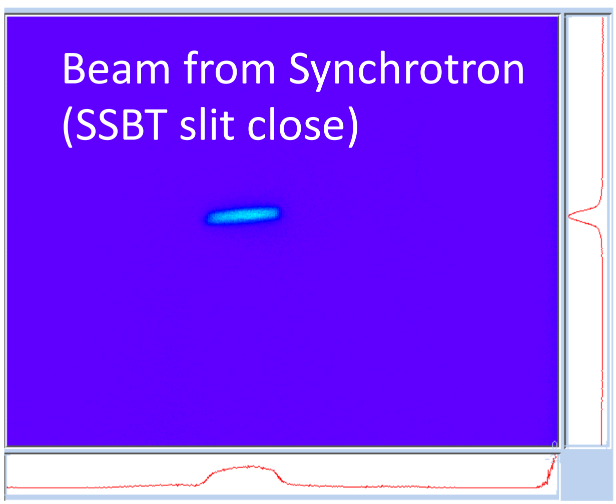
- Accumulation to 100 mA takes about 10 minutes with 10 Hz injection (XFEL operation interrupted).
- During top-up injection, the electron beam is injected when SACLA receive the request from SPring-8 (performed in parallel with XFEL operation).

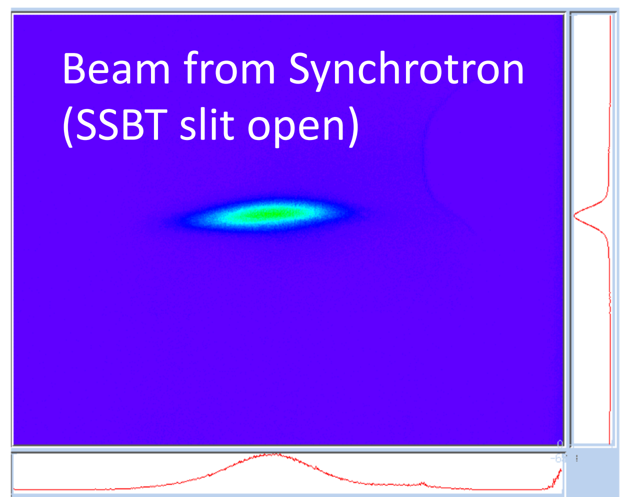


Improvement of beam quality

- Estimated emittance is ~1 nm-rad, that is well below the requirement for SPring-8-II (~10 nm-rad).
- Emittance of an old 8 GeV synchrotron was ~200 nm-rad.



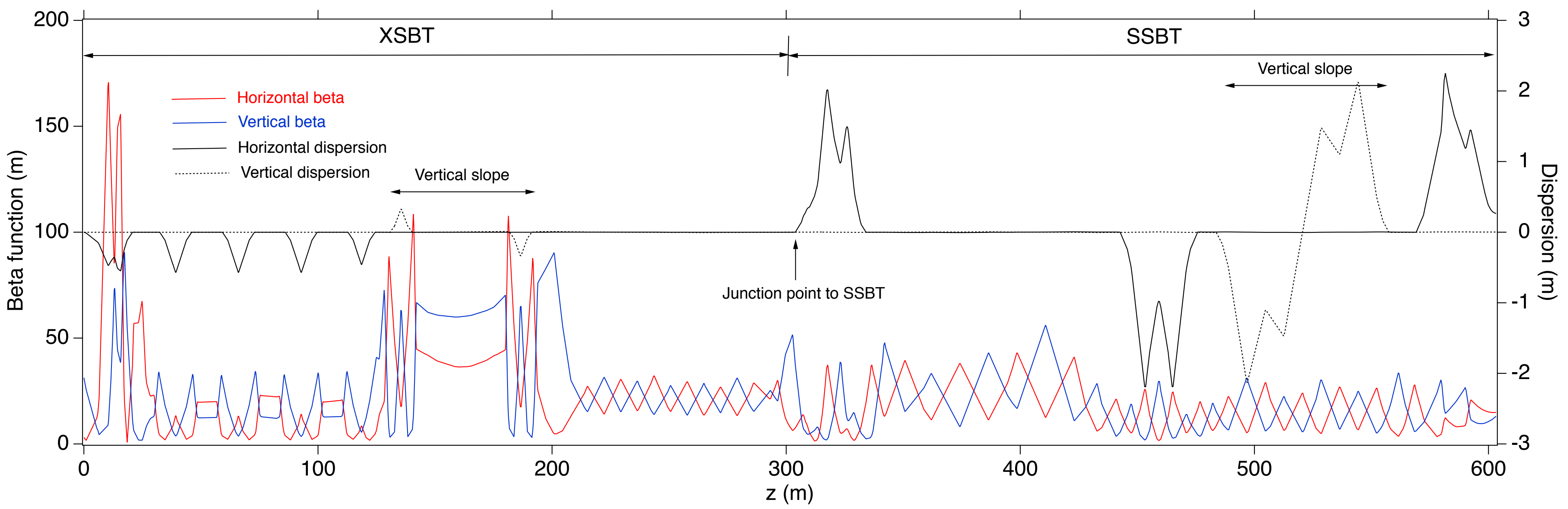




Beam profiles observed at the injection point of the SPring-8 storage ring.

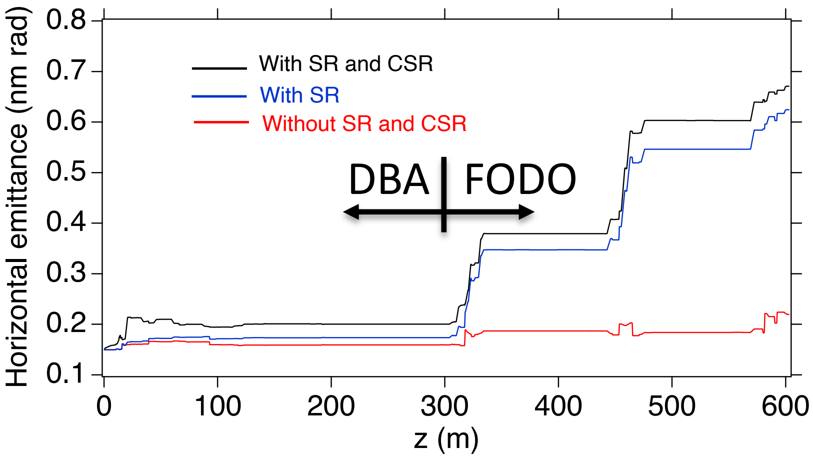
Beam transport to SPring-8 (XSBT)

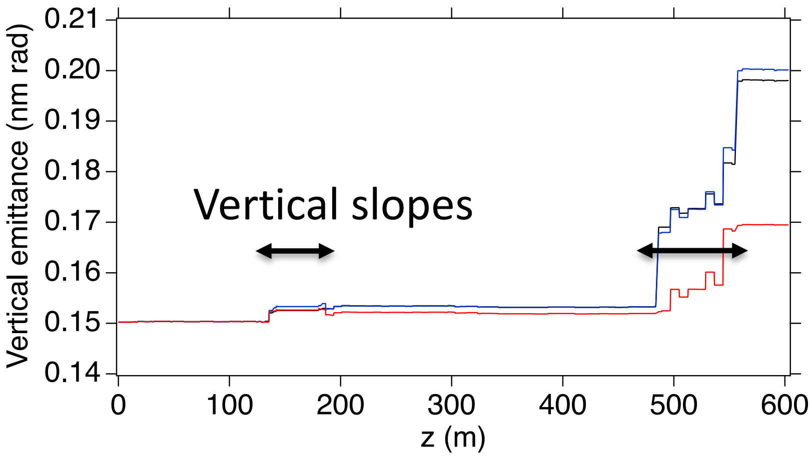
- XSBT (XFEL to Storage ring Beam Transport) is about 600 m long.
- First half of XSBT (300 m), connecting SACLA to an old synchrotron, was newly constructed with a DBA lattice.
- Last half of XSBT, connecting the old synchrotron to the SPring-8 storage ring, is the reuse of an old injection line with a FODO lattice.



Emittance growth at the transport line

Calculated by Elegant.





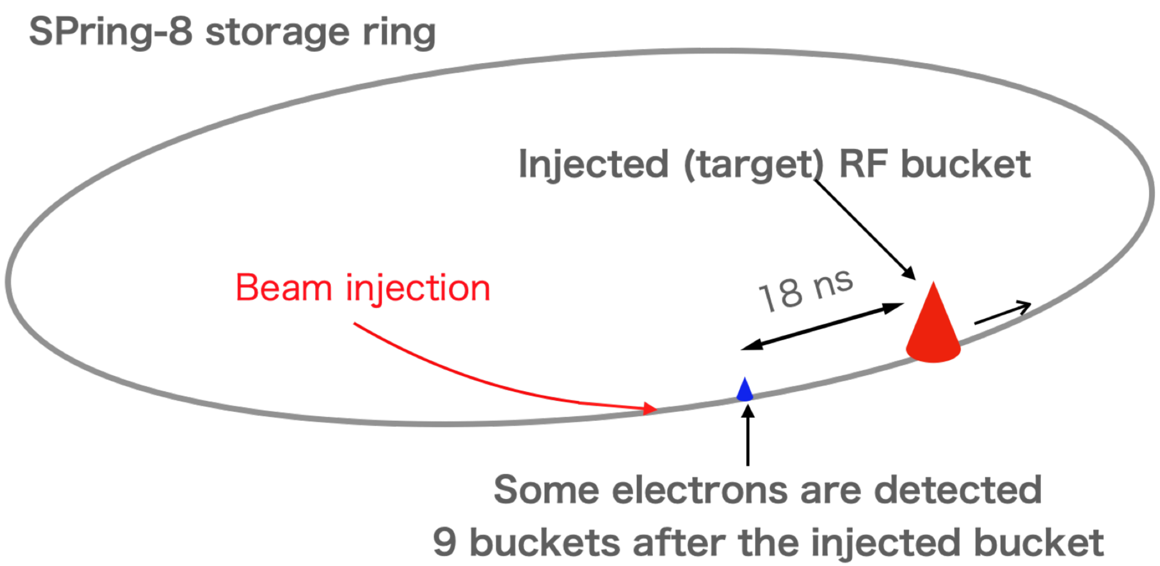
$$\Delta\epsilon_{x,y} = \frac{55 r_e \hbar \gamma^5}{48\sqrt{3} m_e c} \int \frac{\mathcal{H}_{x,y}(z)}{\rho_{x,y}^3(z)} dz \quad >> \quad \Delta\epsilon_{x,y} \cong -\frac{2 r_e \gamma^3}{3} \int \frac{\epsilon_{x,y}(z)}{\rho_{x,y}^2(z)} dz$$

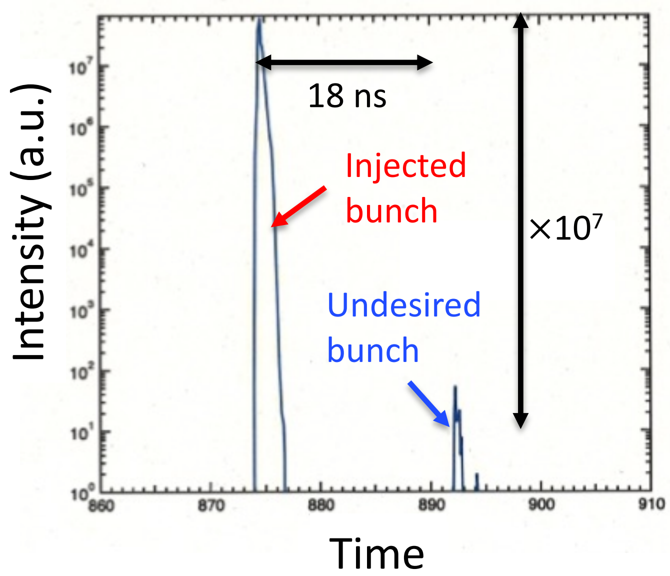
Quantum excitation **Radiation damping**

- Since the electron bunch is lengthened quickly at the first bend, emittance growth caused by CSR is limited.
- Main source of the emittance growth is quantum excitation of synchrotron radiation.
- Due to very small emittance (0.15 nm-rad), radiation damping is negligible.
- Second-order dispersions also degrade emittance.

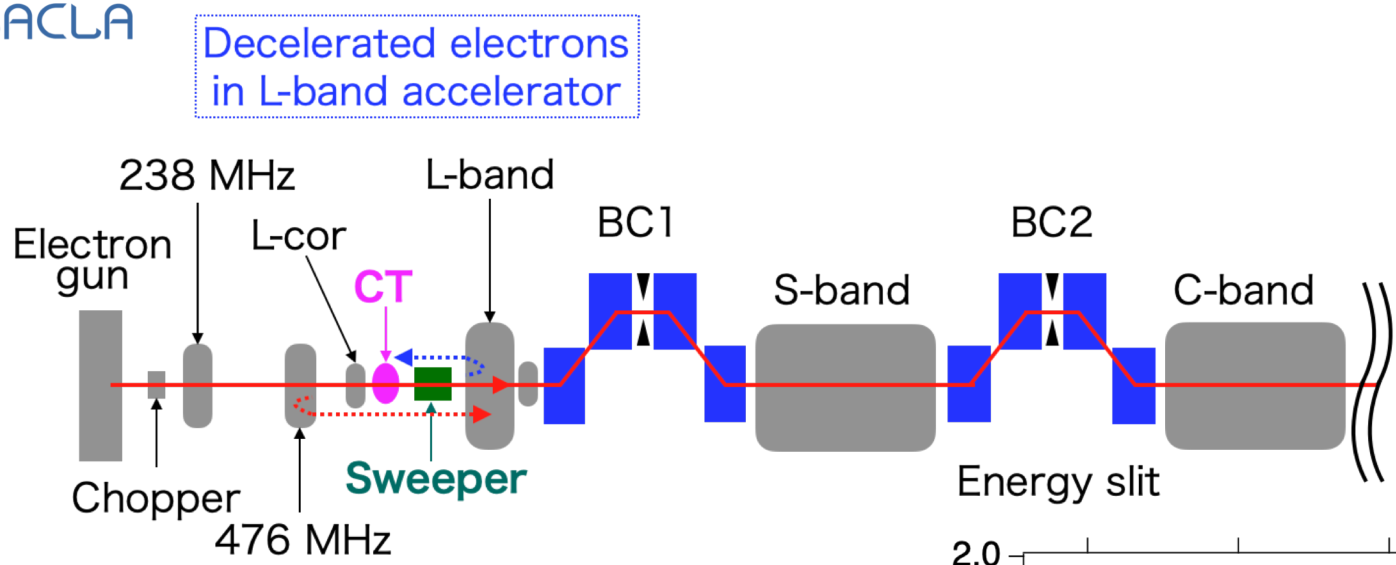
Bunch purity

- Electron bunch charge purity (contrast) of 10^{-8}~10^{-10} is routinely requested at SPring-8 for time-resolved experiments, such as nuclear resonance scattering, to reduce background noise.
- In the beam injection from SACLA, a small number of electrons are detected at 9 buckets (18 ns) after the injected main RF bucket.
- These undesired electrons have a long life time and accumulate to 10^{-7} after one night of top-up injection.



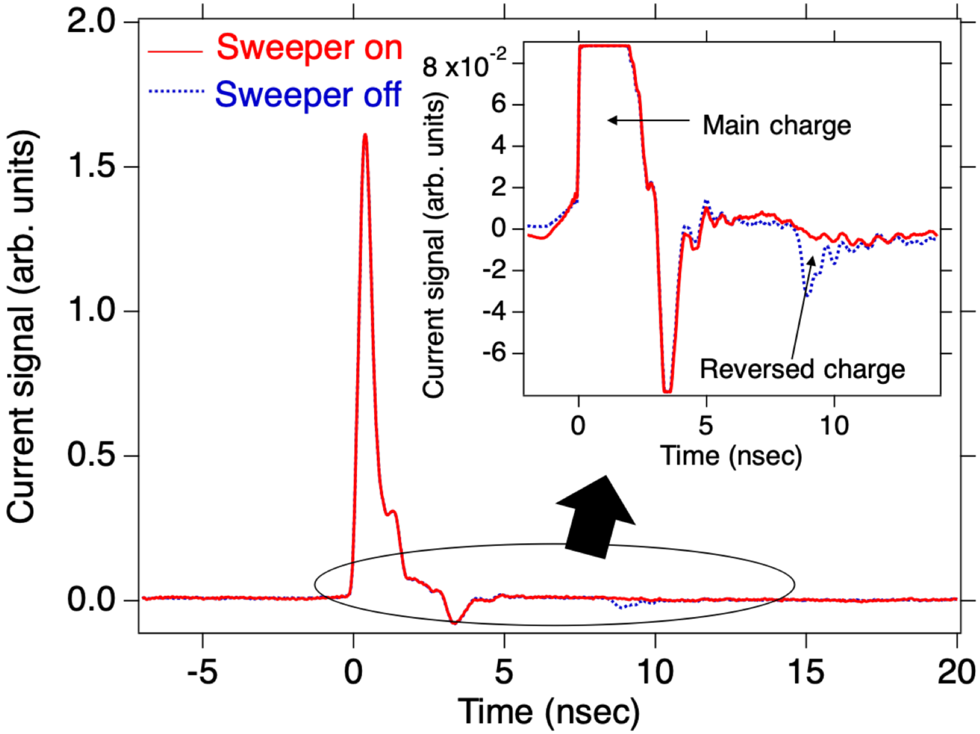


Bunch purity



Some electrons make a round trip between an L-band accelerator and a 476 MHz cavity, and then accelerated with a delay of 18 ns.

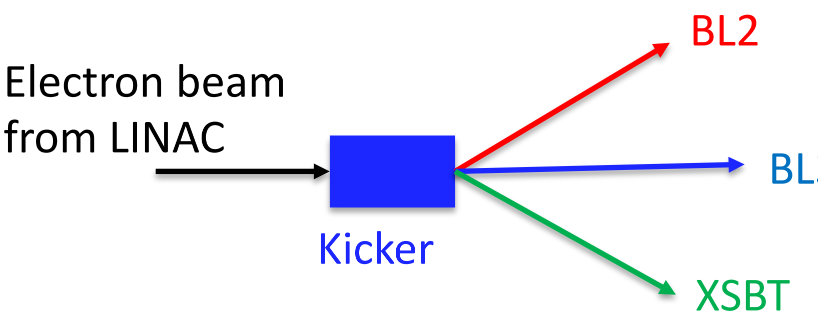
CT signal



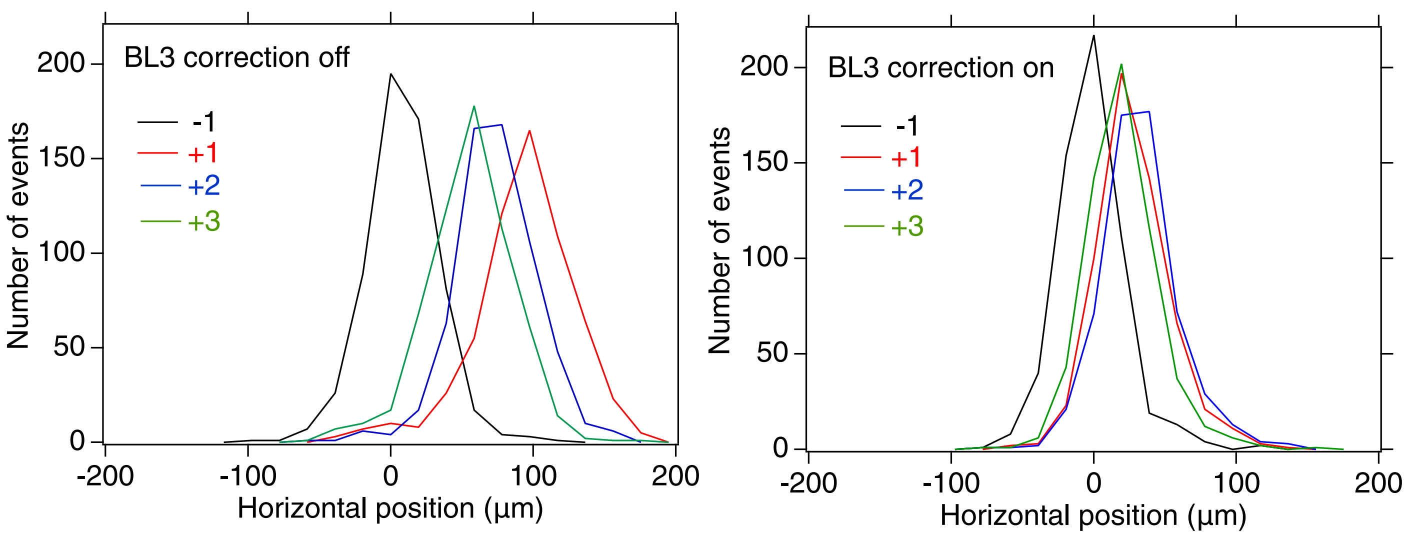
Hysteresis correction

Beam switching pattern for one second (60 pulses)

0	1	2	…	25	26	27	28	29	30	31	32	…	58	59
BL3	BL2	BL3	…	BL2	BL3	XS BT	No (1)	BL2 (2)	BL3 (3)	BL2	BL3	…	BL3	BL2



(1) Blank pulse (no beam).
(2) Fine adjustment of kicker current for BL2.
(3) Fine adjustment of kicker current for BL3.



Histograms of XFEL photon beam positions observed at 40 m downstream of the BL3 undulator end.
Beam size is ~300 μm (FWHM).

Summary

- XFEL linear accelerator of SACLA has been successfully used as a low-emittance full-energy injector of the SPring-8 storage ring.
- Electricity consumption has been reduced by 20~30 %.
- The beam injection from SACLA has been completed as a part of the SPring-8 upgrade project "SPring-8-II".

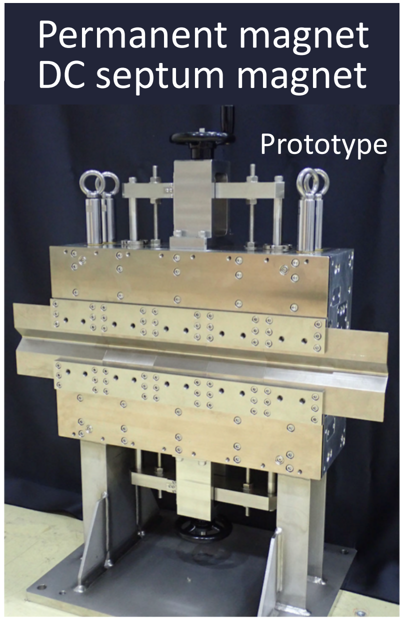
- Aiming 50 pm-rad with damping in user operations.
- Full energy injection from SACLA linac for green facility (already done).
- 4 long straights (2 for damping wigglers, 1 for FEL study).
- Shutdown for 1+ year around 2026~2028.

	SPring-8-II	Present SPring-8
Lattice	5 bend achromat	2 bend non-achromat
E	6 GeV	8 GeV
C	1435.44 m	1435.95 m
ε_{nat}	0.108 nmrad	2.4 nmrad
ν_x / ν_y	108.10 / 45.28	41.14 / 19.35
ξ_x / ξ_y	-154 / -149	-117 / -47
β_x / β_y @ ID	8.2 m / 2.8 m	31.2m / 5.0m
α	4.14e-5	1.60e-4
$\sigma_{\Delta p/p}$	0.097 %	0.109 %
U_0	2.6 MeV/turn	8.9 MeV/turn

K. Soutome et al., Proc. of IPAC22, p.477 (2022).

Hardware developments for SPring-8-II

- Permanent magnet based bending magnets.
- Transparent injection (kickers, power supplies, ceramic vacuum chambers).
- Compact in-vacuum undulator with magnetic-force cancellation.

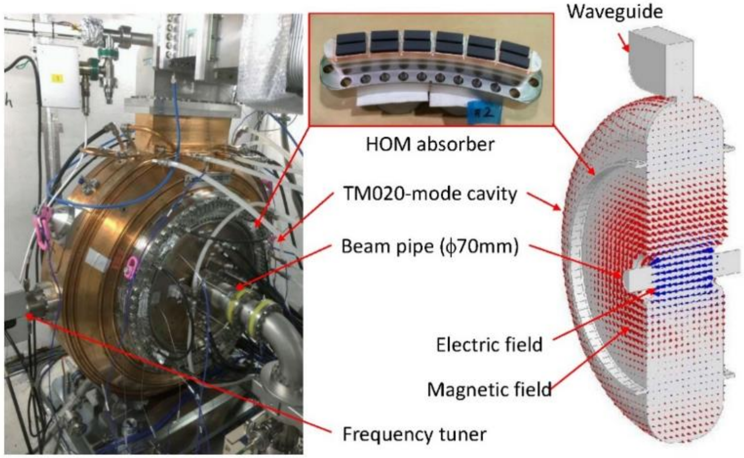


T. Taniuchi et al.,
PRAB 23, 012401 (2020).

Most developments for SPring-8-II have been applied for Japan 3 GeV ring (NanoTerasu) under construction.

- Electromagnets (quadrupoles, sextupoles, others).
- Stainless steel vacuum chambers with copper coating.
- MTCA.4 based beam position monitor (also running at present SPring-8).
- TM020-mode RF cavity with inner HOM dampers.
- Electron beam dampers with beam shaker*.

Performance test will start soon on the real running machine.



* T. Hiraiwa et al., PRAB 24, 114001 (2021).