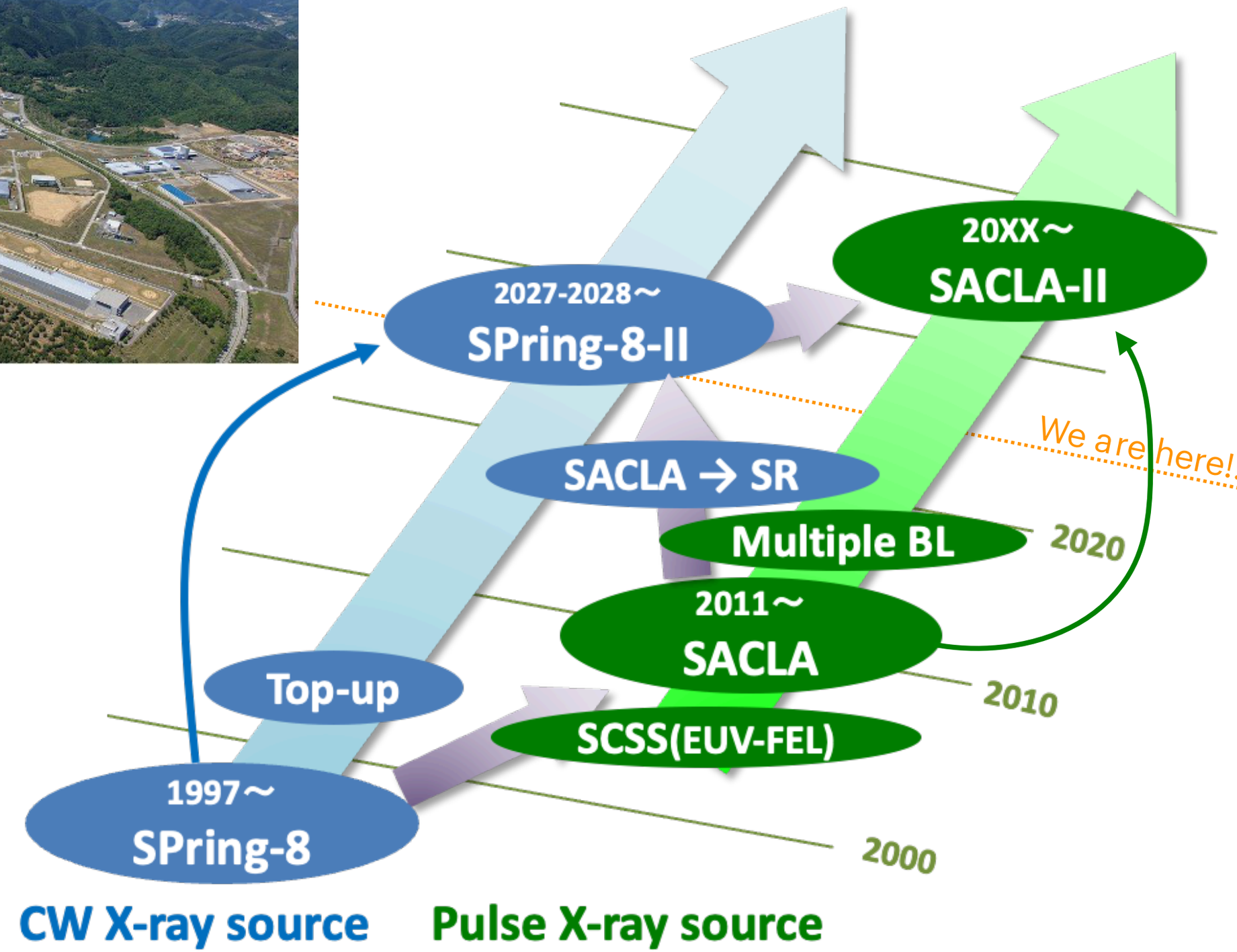
# Recent updates and prospects of SACLA (accelerator)

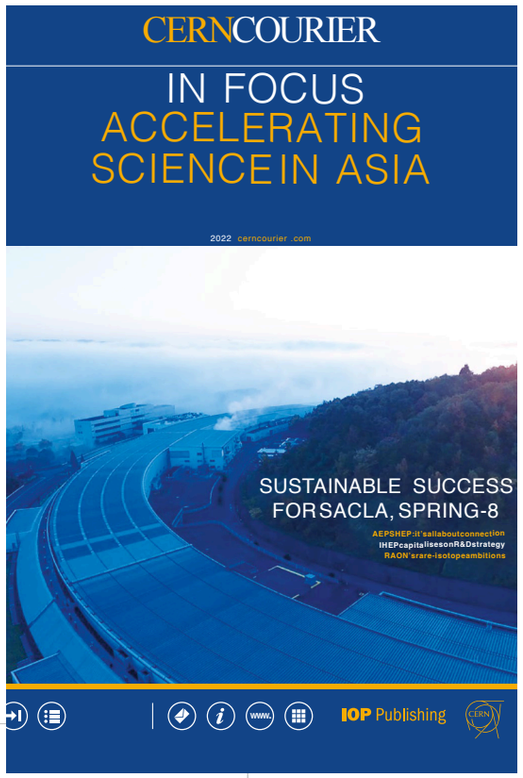
03/03/2025, SACLA Users' Meeting
Eito Iwai, on behalf of SACLA/SPring-8 staffs
JASRI/RIKEN SPring-8 Center

# Roadmap for accelerator upgrades in SPring-8

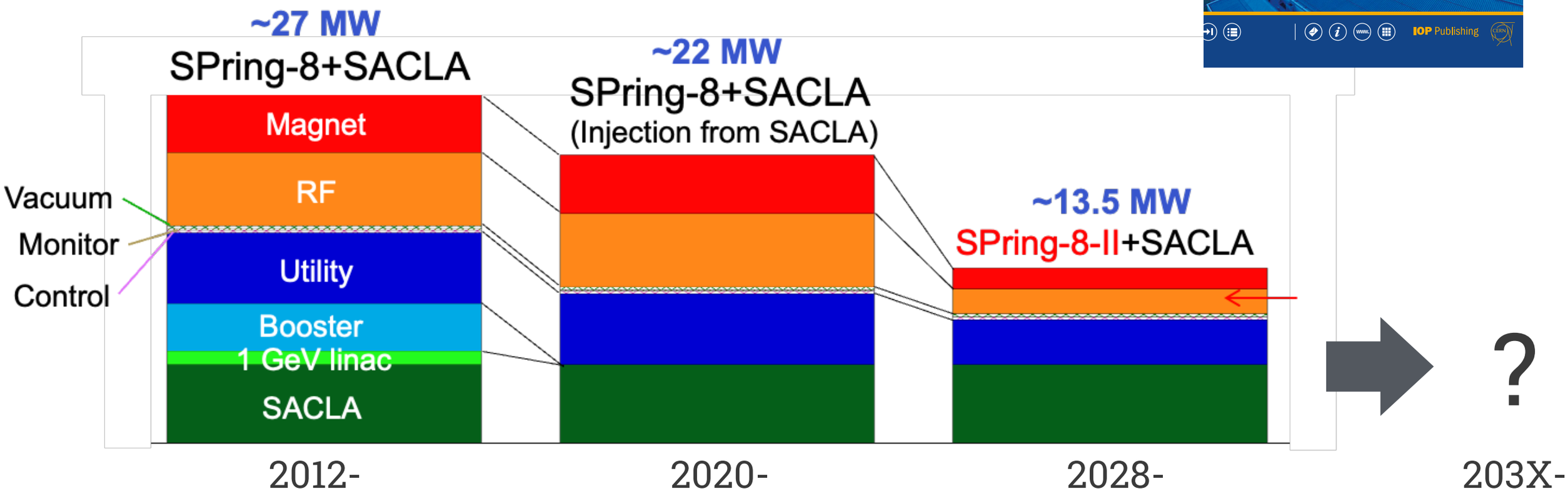


# Roadmap for accelerator upgrades in SPring-8

- Global strategy of SPring-8 campus
  → Green facility




- History of electrical power usage




➡ What is expected to be for the SACLA upgrade?

# Concepts of 'SACLA-II' upgrade

- High repetition rate XFEL: > x10
- While keeping electrical power consumption

- How?

➡ Introducing X-band technology for efficient beam acceleration

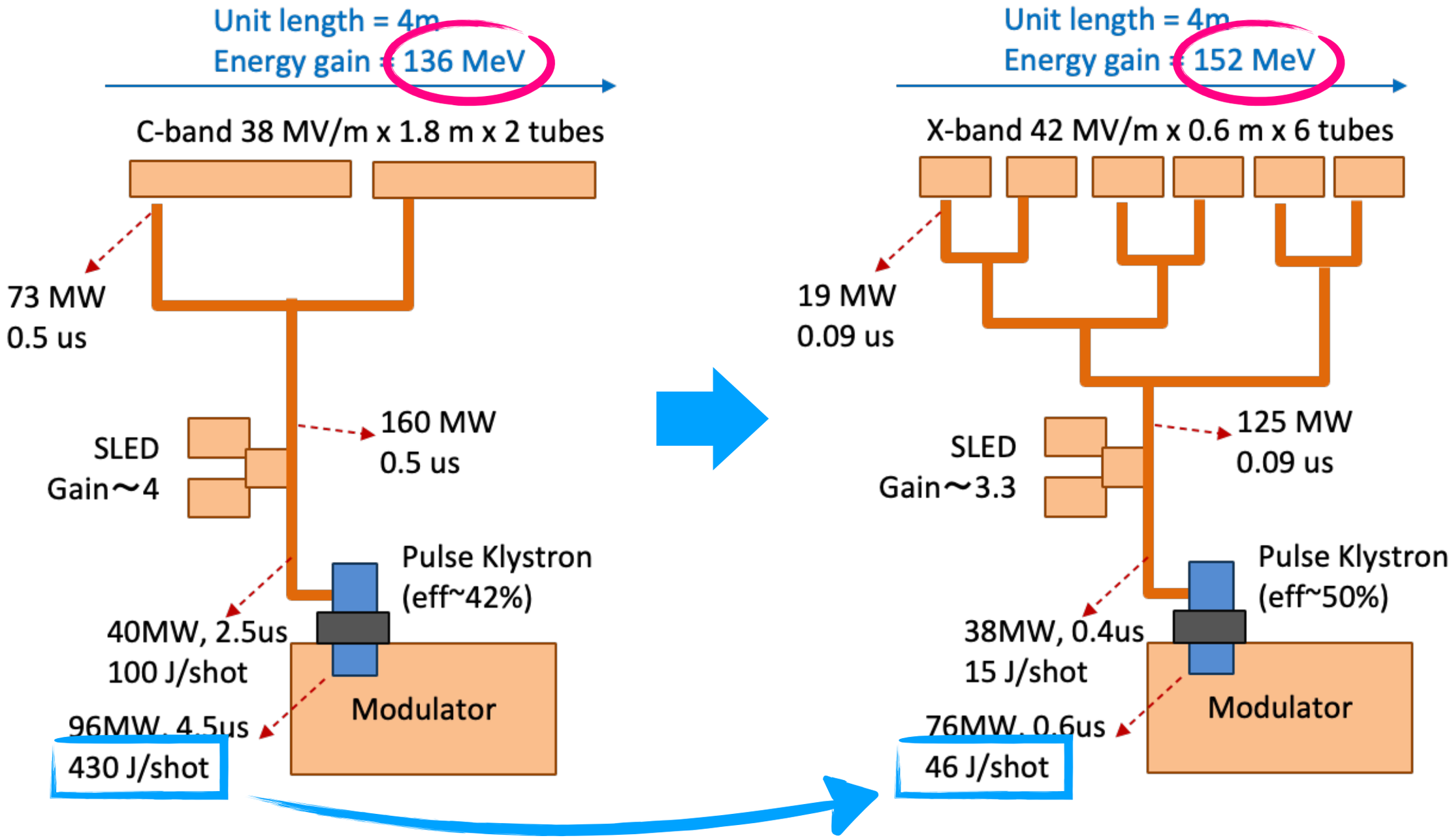
- Merit
  - Compact and smaller volume
  - Shorter filling time

  } → energy efficient

- Development items
  - Processing technology and corresponding cavity design
  - Stronger Wakefield effect
  - …

# Concept of the efficient RF acceleration

- SACLA: C-band (5.7GHz) RF unit
- SACLA-II: X-band (11.4GHz) unit

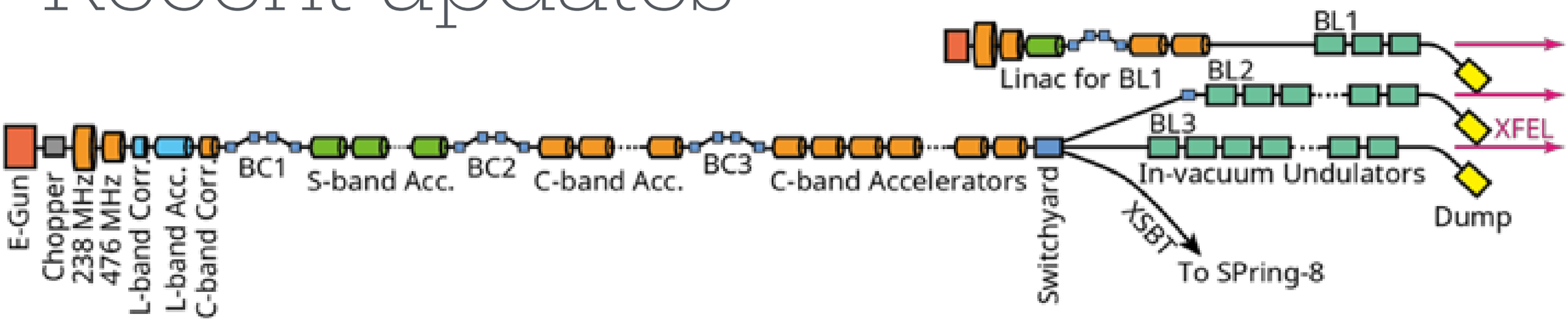



✓ x1/10 power consumption while keeping similar or better acceleration gradient
→ pulse repetition rate x10 w/ same power consumption

# Recent updates

- How are we going to realize the upgrade?

# Recent updates



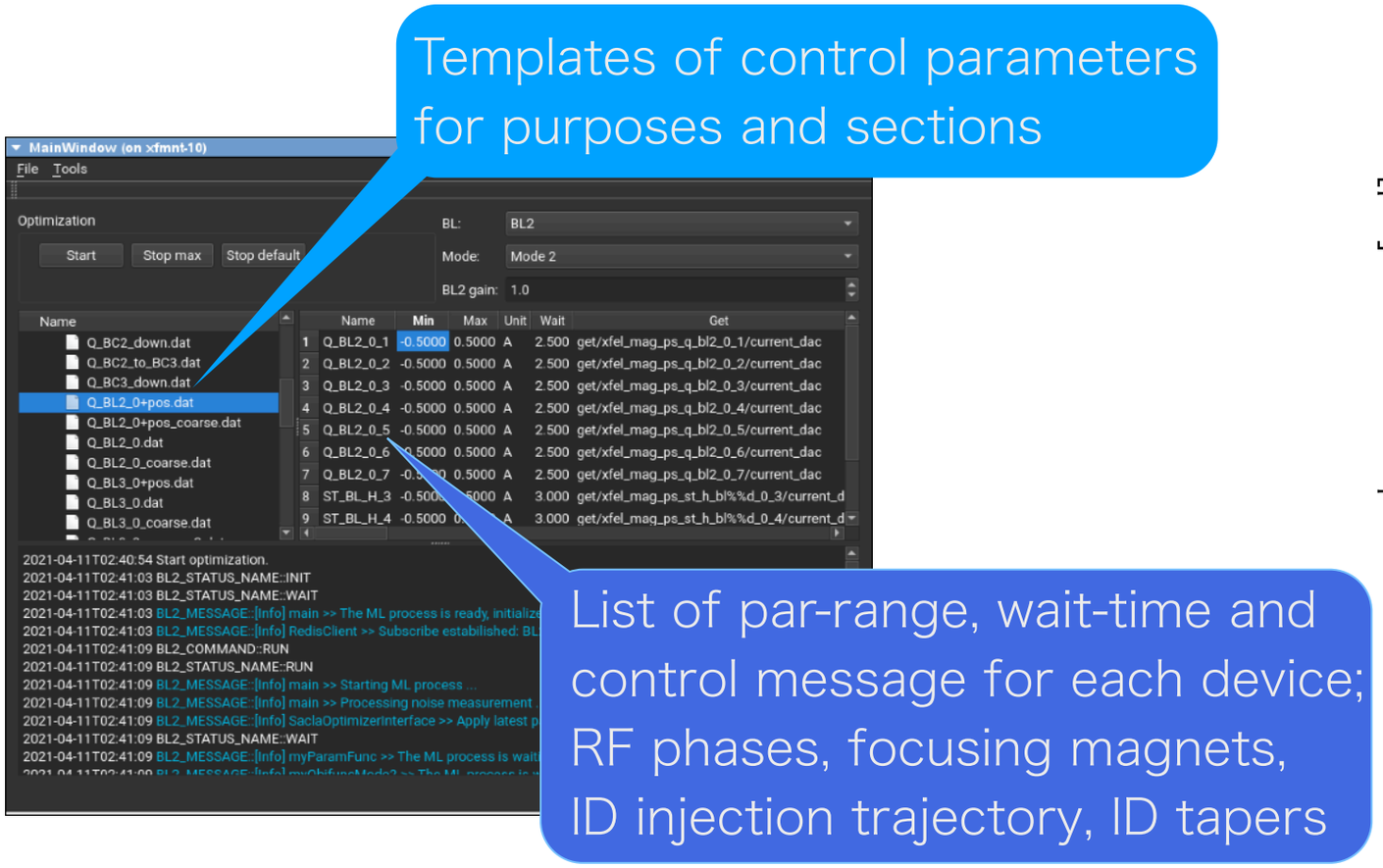

- Key system upgrades in past
  - Pulse-by-pulse switching operation (since 2017)
    - ✓Gun, all RF units and a kicker magnet are controlled on a pulse-by-pulse basis
  - Beam injection from SACLA to SPring-8 storage ring (since 2020)

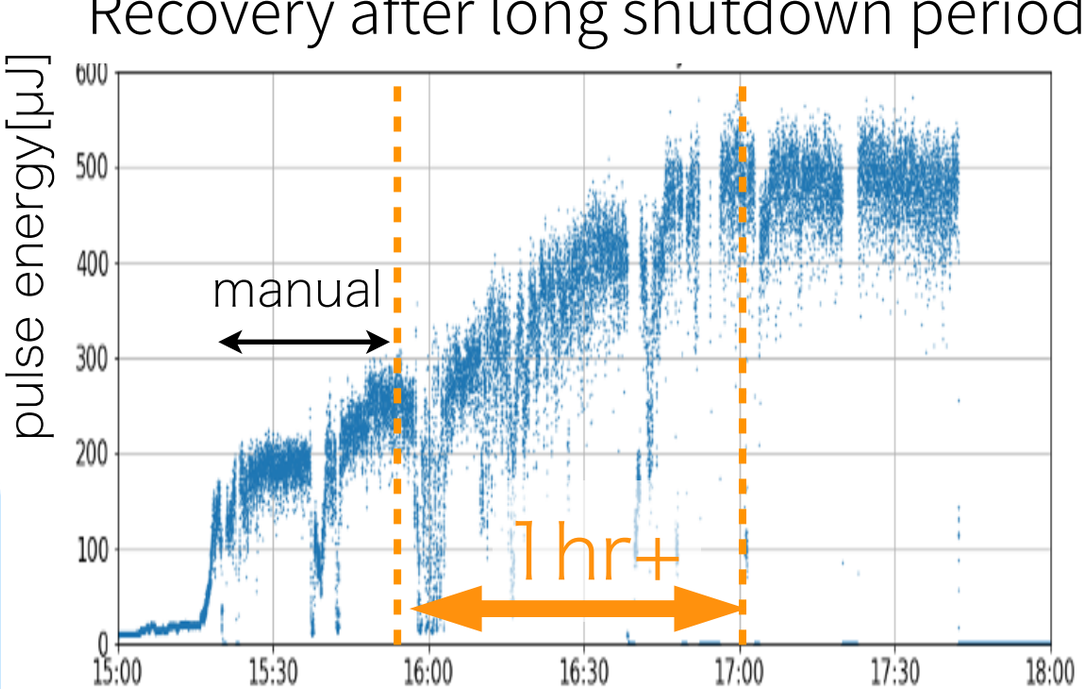
- Recent updates after starting beam injection from SACLA to SPring-8
  - Introduced AI-driven beam optimizer
  - Pulse-by-pulse control also for quadrupole magnets

➡ Improved tunability and flexibility for better XFEL performance

# Beam optimizer

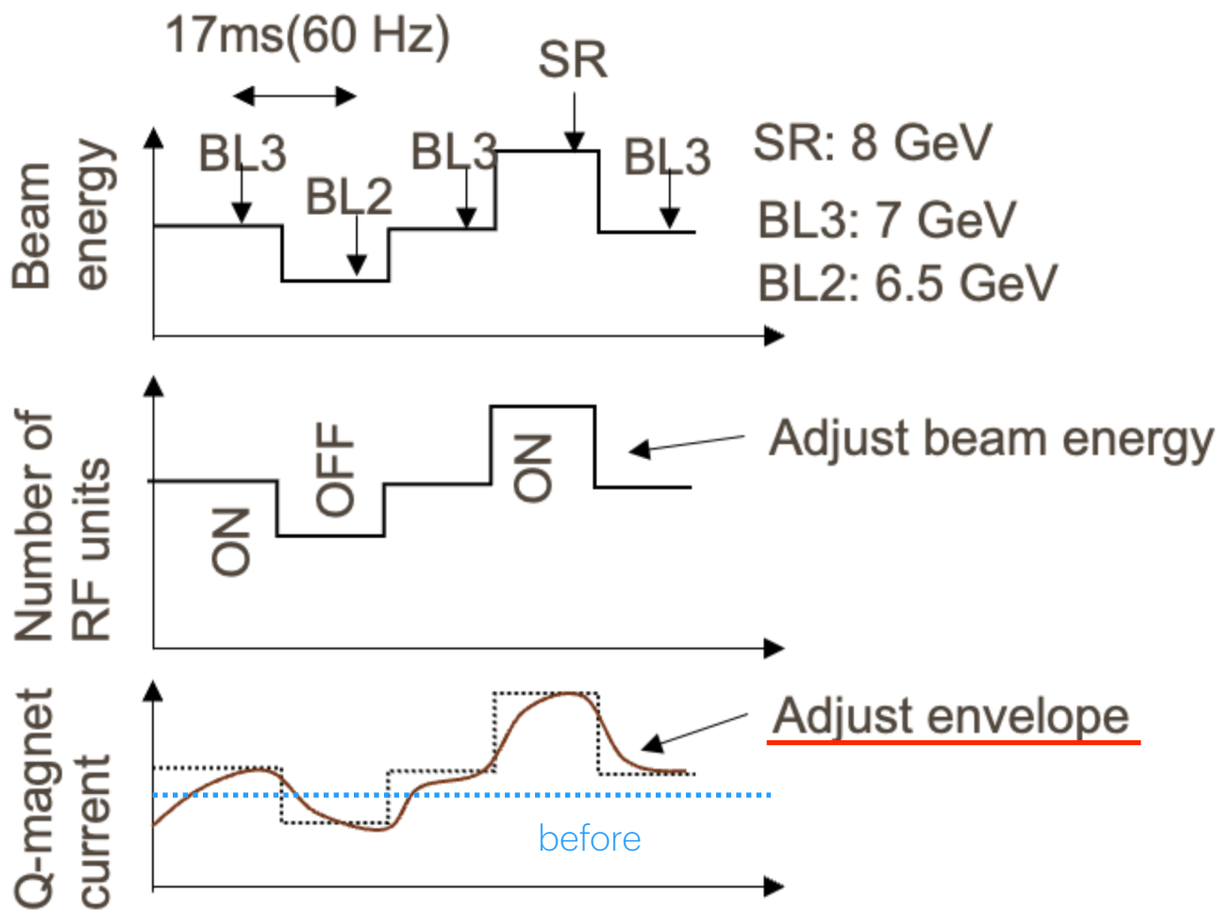
- Introduced AI-driven automated tuning system; beam optimizer
  - Operation becomes more complicated even though the tuning time becomes constrained
  - Fully utilize the improved tunability and flexibility for efficient tuning and better XFEL performance

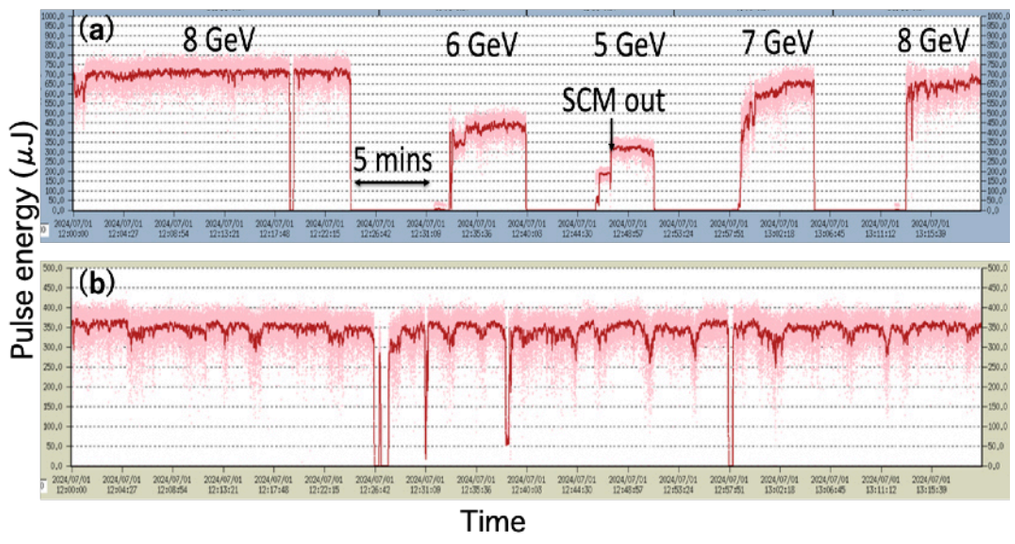


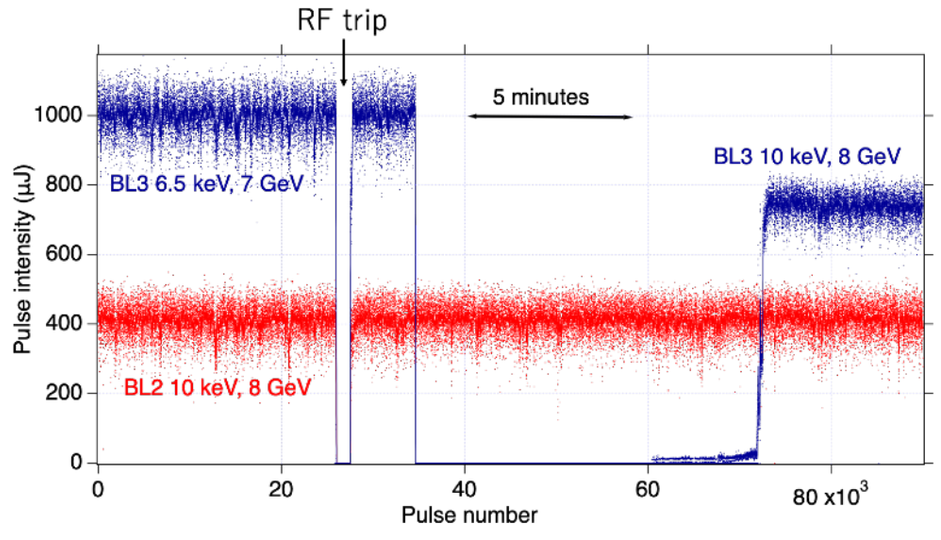



# Pulse-by-pulse control also for quadrupole magnets

- Quadrupole magnets had been common even though beam energies were different for each pulse
- Optimized beam envelope for different beam energies for each pulse



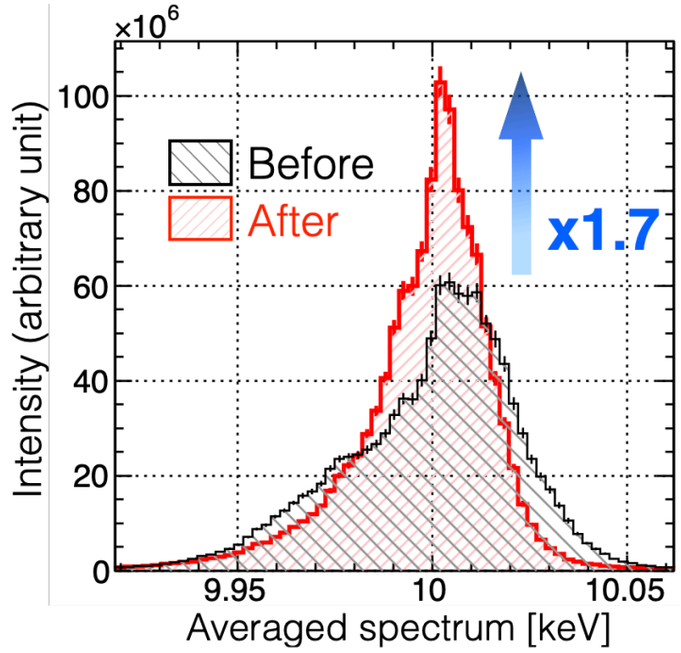



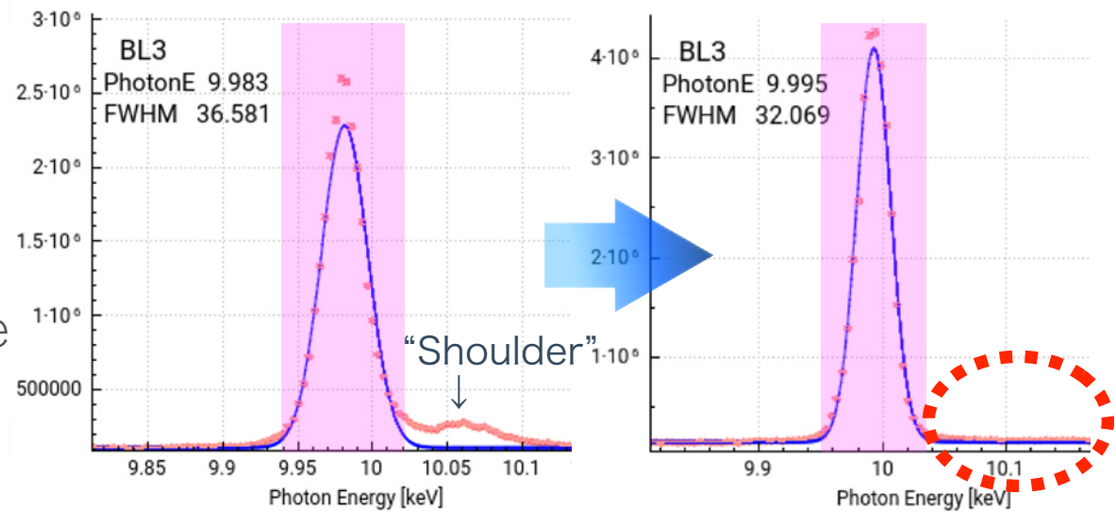
E. Iwai *et al.*: J. Synchrotron Rad. **30**, 1048 (2023)

# Various optimization

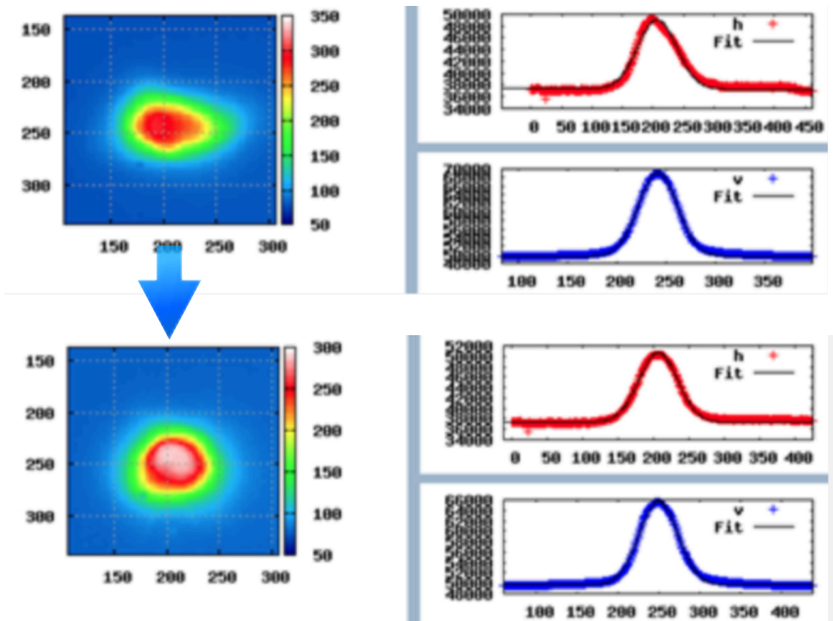
- Spectral brightness
  - A new spectrometer with enough resolution to measure shot-by-shot spectral-width online installed permanently (with great help of BL group)
  - Optimized for spectral brightness of central wavelength




- Spectral shape
  - Request from an user: “Suppress peak height in side-band less than 3 % of one of central wavelength”
  - A “shoulder” often remains in spectrum even after the spectral brightness optimization




- XFEL spatial profile
  - Request from another user: “Round spatial profile with single ‘core’”
  - Double (or sometimes multiple-) “cores” often appear in spatial profile



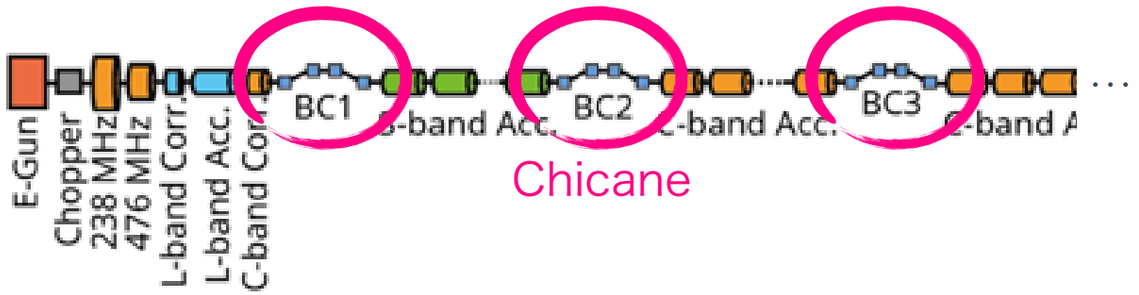
➡ Tailor-made XFEL

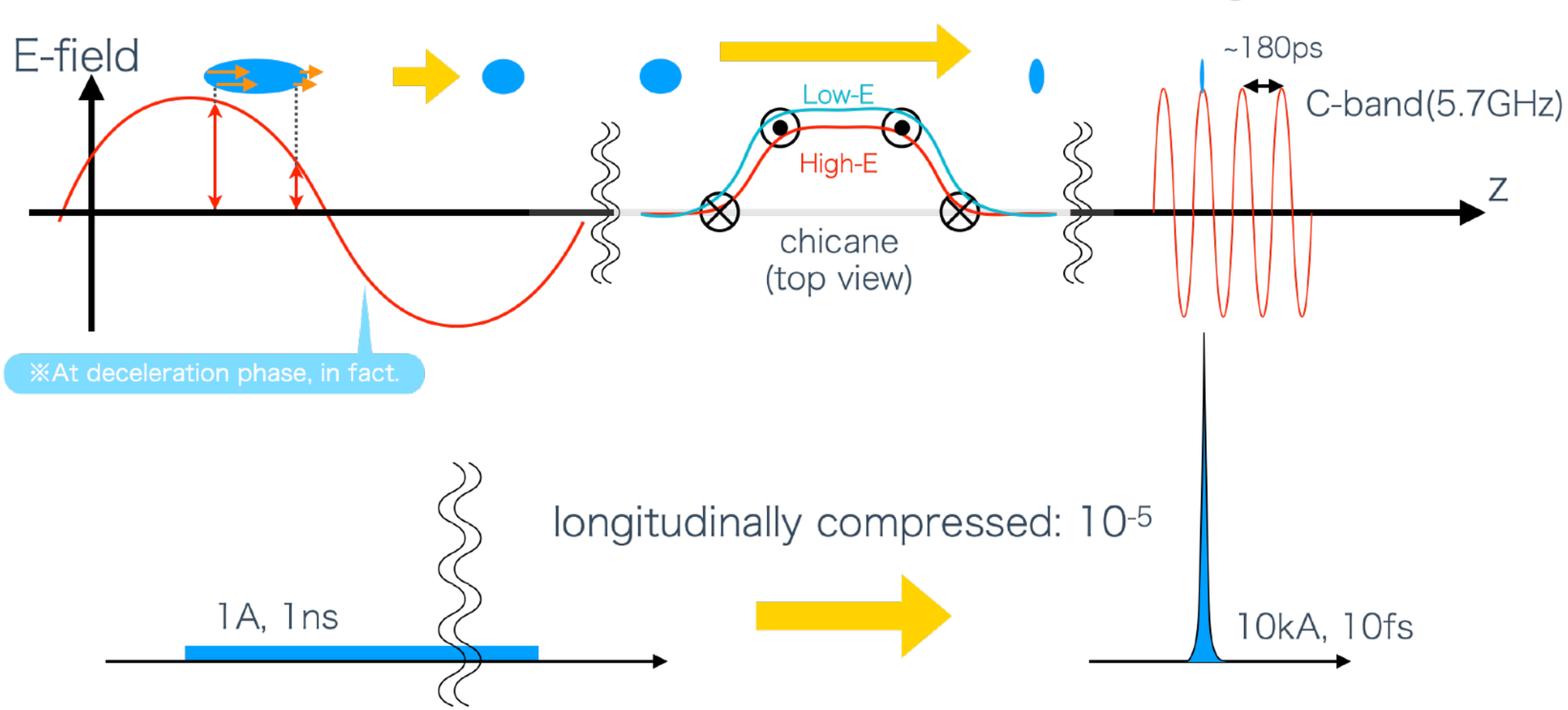
# Ongoing developments

- Short pulse XFEL
- X-band deflector

# Short pulse XFEL - Introduction -

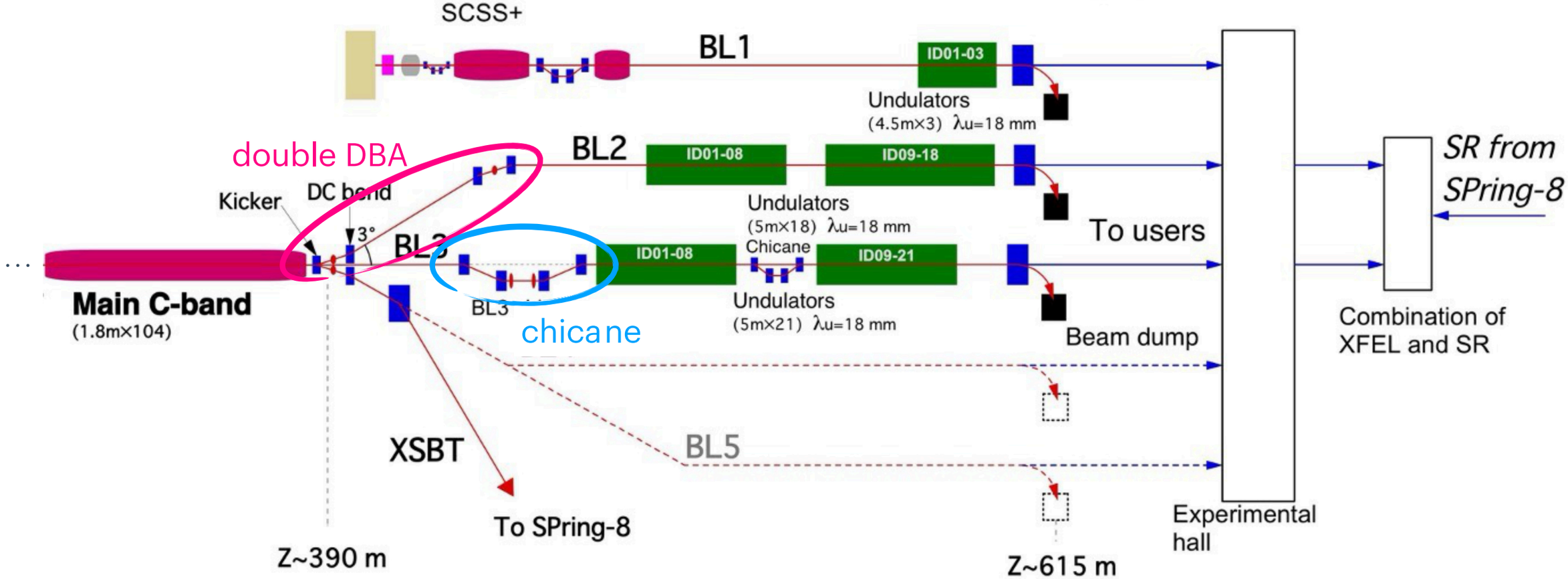
- 'Energy-chirp' and bunch compression
  - At the initial stage, electron bunch is placed off-crest phase to apply energy-chirp to the bunch
  - The energy-chirped bunch is compressed by velocity-bunching ($\beta$<1) and three chicanes ($\beta$~1)



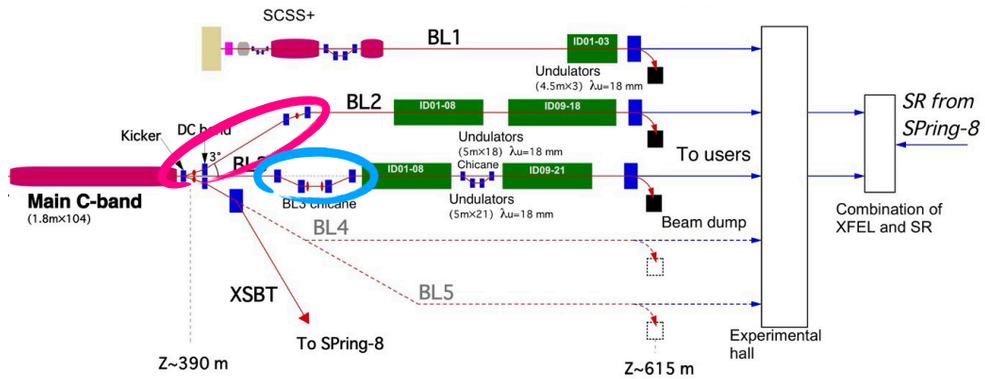



# Short pulse XFEL

- Non-negligible ‘reverse' energy-chirp was found, caused by Wakefield and space charge
- With the finite reverse energy-chirp, another chicane on BL3 is expected to decompress the bunch, while the double DBA (‘dog-leg’) on BL2 provides the opposite effect and is expected to further compress the bunch



# Demonstration test




- Electron bunch decompression at BL3:
  Compare electron bunch lengths with/without chicane

| | Electron bunch length fwhm [fs] |
|---|---|
| w/o chicane | 10.1 |
| w/ chicane | 13.1 |

(DCM+111, w/o norm, peak-base)

✓ Inserting a chicane makes electron bunch lengths longer by around ~ 3 fs

- XFEL pulse compression at BL2:
  Compare XFEL pulse lengths by changing parameter of the double DBA

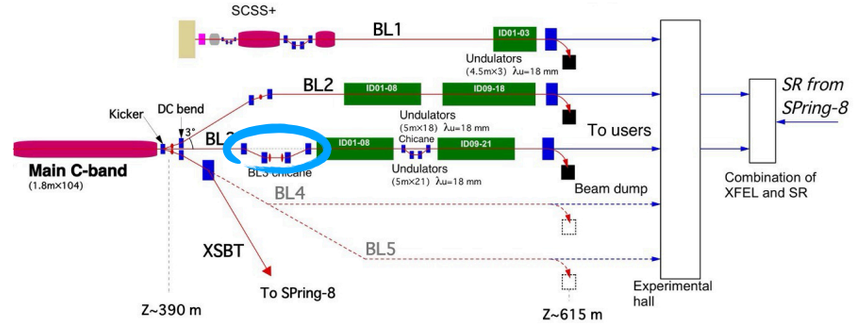
| Parameter: '$R_{56}$' [$\mu$m] | -14 | 31 | 111 | 156 | 215 |
|---|---|---|---|---|---|
| XFEL pulse length [fs] (Gauss) | 13 | 14 | 10 | 8.2 | 2.7 |

✓ Preliminary measurements show clear tendency of XFEL pulse length reduction with the '$R_{56}$' parameter

※ With collaborative help of BL group

# Future plan

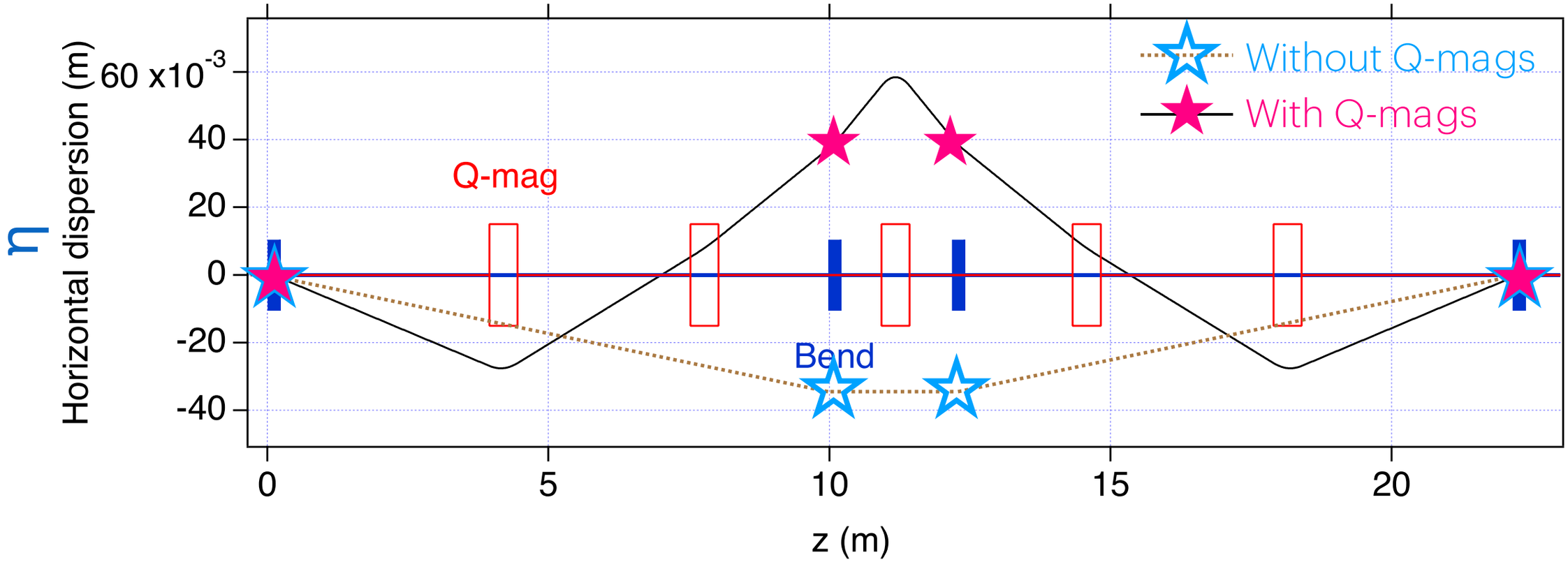
$R_{56} \sim \Sigma_B \eta_i$




- (de)compression power ~ $R_{56}$ ~ sum of dispersions($\eta$) at bending magnets
- Introduce series of quadrupole magnets to BL3 chicane to change the sign of horizontal dispersion

  ➡ Strong Q-mags (with the straight beam pass) are necessary

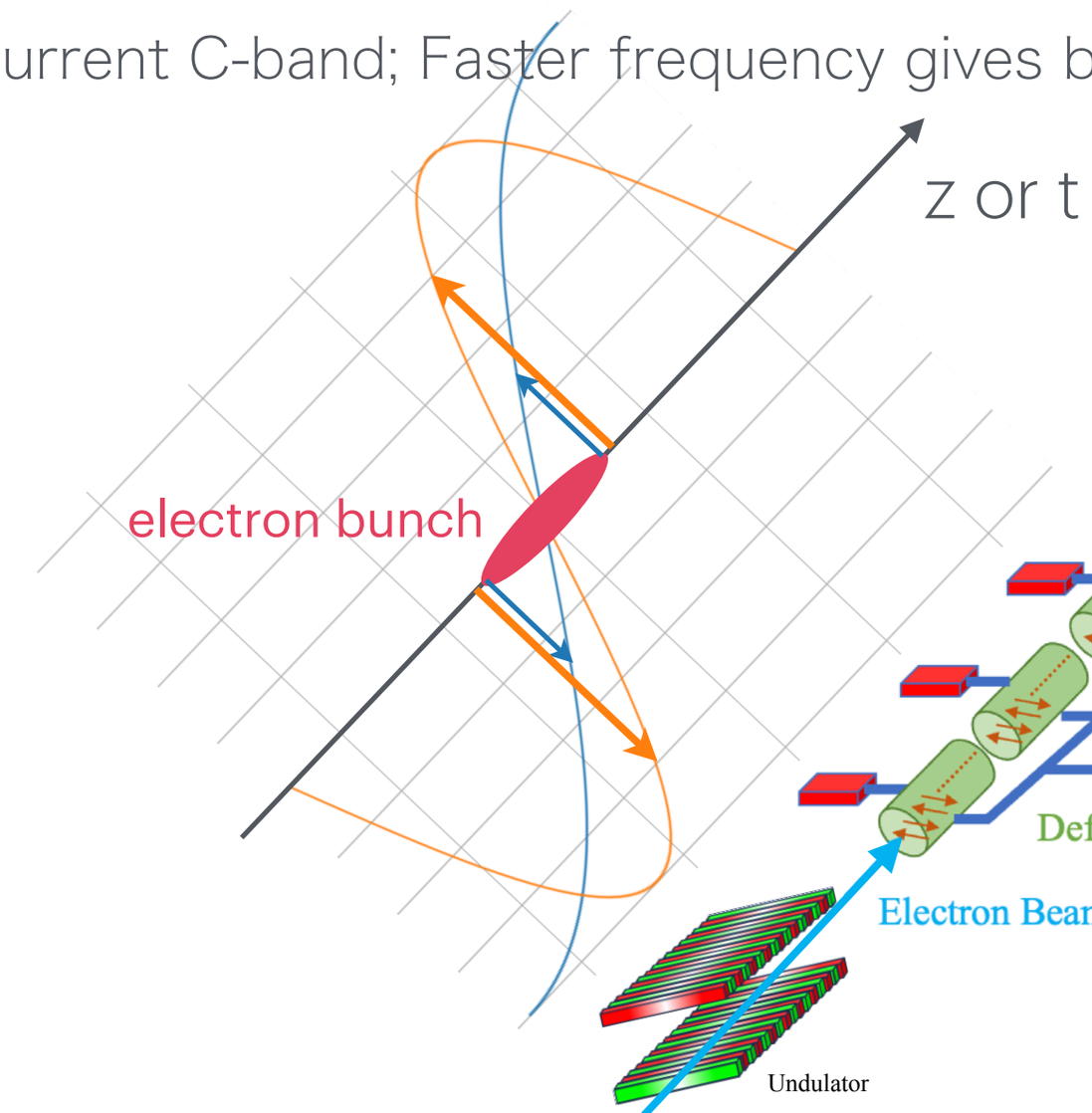
- Example of introducing 5 quadrupole magnets while chicane length is maintained the same as present

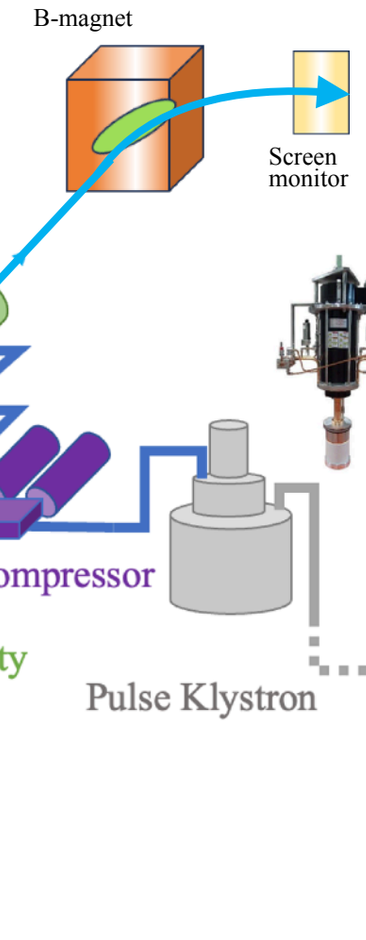


# Ongoing developments: X-band deflector

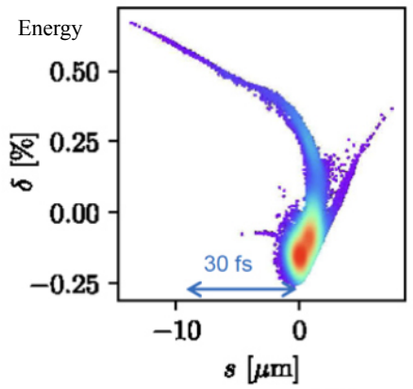
# X-band deflector

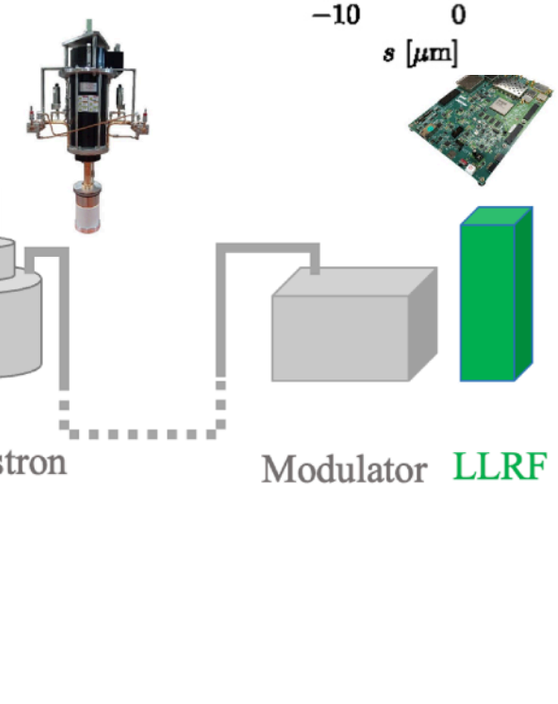
- ‘Deflector’: Horizontally kick the electron bunch according to arrival timing; can convert timing distribution to horizontal position distribution
  ➡ Observe bunch length online to optimize for short pulse XFEL
- Why ‘X-band’ ?
  Twice as current C-band; Faster frequency gives better resolution




H. Maesaka, et.al., PRAB 21, 050703 (2018)



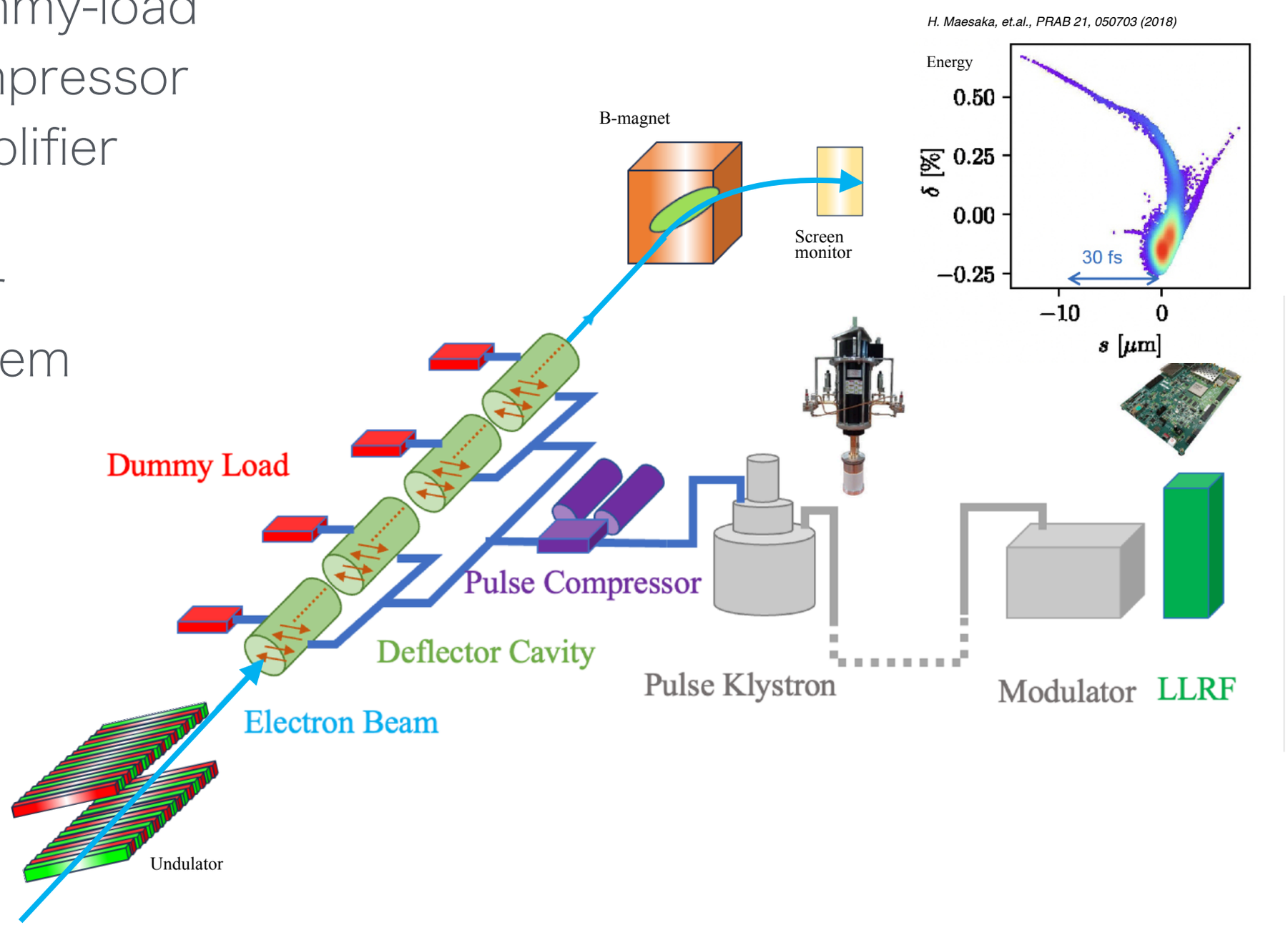




➡ Goal is to realize X-band deflector with a timing resolution of 1 fs
The observed bunch length information will be fully utilized by beam optimizer

# Developing items

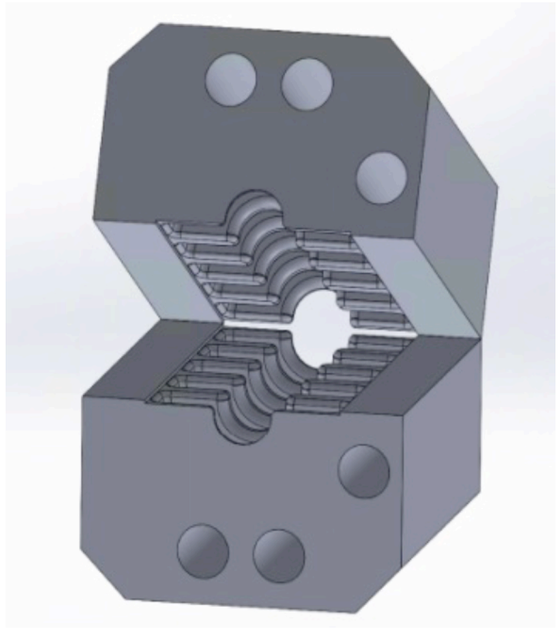
- X-band deflector cavity

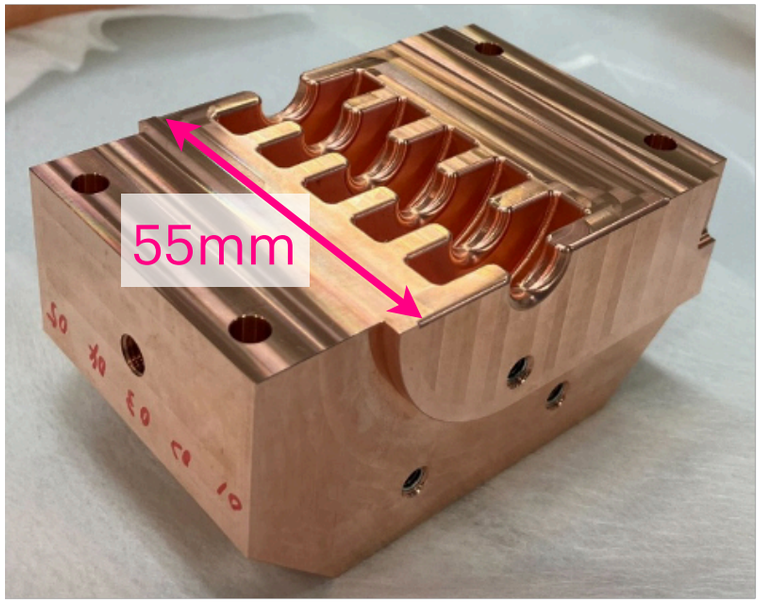
- X-band spiral dummy-load
- X-band pulse compressor
- X-band driver amplifier
- X-band klystron
- X-band modulator
- X-band LLRF system

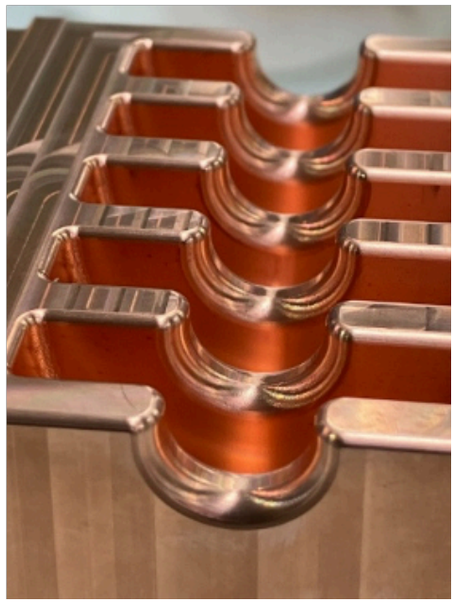


# Deflector cavity

- Introduced X-band: machining accuracy becomes more critical
- New scheme: longitudinally-split two halves ↔ conventional disk-loaded type
  ➡ Expect cost reduction; for future mass production
- The deflector consists of 4 cavities
  Each cavity consists of 3 of 30cm-long units
  Each unit consists of two halves
- Cold model was measured and tuned
- High-power prototype will be delivered before next summer
- The 1st (out of 4) cavity within next FY





Cold model (regular cell block)

# Schedule

| | FY2024 | FY2025 | FY2026 | FY2027 | FY2028 |
|---|---|---|---|---|---|
| **7-cell high-power protytype** | Manufacture (Fabricating, tuning, brazing) → | ↔ High power test | | | |
| **Other X-band related stuffs** | Manufacture → | | | | |
| **1st cavity** (out of 4) | | Manufacture ↔ | ↔ High power test | | |
| **2nd and 3rd cavity** | | | Manufacture ↔ | ↔ High power test | |
| **The last cavity** | | | | Manufacture ↔ | ↔ High power test |
| **‘X-band deflector’** | | | ☆ Partially install the 1st cavity?? | | ★ Fully installed and start operation |

# Concepts of 'SACLA-II' upgrade

- High repetition rate XFEL: > x10
- While keeping electrical power consumption

- How?

➡ Introduced X-band technology for efficient beam acceleration

- Merit
  - Compact and smaller volume
  - Shorter filling time

  } → energy efficient

- Development items
  - Processing technology and corresponding cavity design ← X-band deflector
  - Stronger Wakefield effect ← Short pulse XFEL
  - …

✓ Research on the key technology is already begun with short pulse XFEL and X-band deflector as ongoing practical application projects

# Summary

- Concept of the ‘SACLA-II’ upgrade
  - x10 repetition rate with same power consumption
    - Green and sustainable facility
  - X-band main linac
- Recent updates
  - Improved tunability and flexibility for better XFEL performance
    - Pulse-by-pulse control of quadrupole magnets
    - AI-driven beam optimizer
  - Short pulse XFEL
  - X-band deflector

➡Strategic and coherent R&D underway toward SACLA-II upgrades in 203x

# Thank you for your attention!