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# STUDIES ON HIGH REPETITION RATE OPERATION OF SACLA WITH X-BAND NORMAL CONDUCTING ACCELERATOR

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*Abstract*

The next upgrade plan for the XFEL facility SACLA is to increase the repetition rate of the accelerator, which is currently 60 Hz, by one order of magnitude to 1 kHz maintaining the performance of the current SASE and electricity usage. To improve the power efficiency, we choose X-band as the radio frequency (RF) of the main accelerator instead of current C-band. A basic design and optimization of the accelerator are undergoing. As a testbed, we plan to introduce an X-band transverse deflector cavity to measure the temporal distribution of the electron beam downstream of the undulator. The development of equipment such as pulse compressors, dummy loads, low-level RF control, which are common to the systems for high repetition, has begun.

## INTRODUCTION

The RIKEN SPring-8 Center and JASRI operate SPring-8, the 3rd generation synchrotron radiation facility, and SACLA, an X-ray free electron laser facility, providing synchrotron radiation for many scientific experiments. The upgrade project "SPring-8-II" is underway to replace the entire storage ring and obtain X-ray radiation with 100 times higher brilliance by 2029 [1]. SACLA has already been in operation for 13 years since 2011 [2]. We consider an upgrade in the 2030s, along with the replacement of aging equipment [3]. In this upgrade program SACLA-II, the increase in light intensity, the expansion of the wavelength range, and the increase in pulse repetition rate are being considered, which are strongly requested by users. To increase the light intensity, improvements to the electron gun and bunch compression section are being considered. To expand the wavelength range and increase the pulse repetition rate, part of the C-band (5.7 GHz) main accelerator is being replaced by an X-band (11.4 GHz) accelerator.

For higher pulse repetition rates, superconducting RF cavities are also being used in XFEL [4-6]. However, the use of sup erconducting cavities requires a large amount of liquid helium and huge cryo-plants to cool them, as well as investments almost equivalent to building a new facility, such as extending the accelerator length and strengthening radiation shielding. On the other hand, in many experiments using XFEL, MHz pulse repetition rates are not necessary, and repetition rates of 1 kHz are often sufficient.

We therefore aim to increase the power efficiency of the normal conducting accelerator by one order of magnitude and increase the pulse repetition rate to 600 Hz - 1 kHz, more than ten times the current 60 Hz, without increasing power usage. This will enable high-repetition XFEL with the current building, power, and cooling facilities. The acceleration energy can be increased by increasing the width of the RF pulses, which will enable the wavelength range to be extended to the higher energy side.

The SACLA-II project is studying each item with the aim of building a prototype in 2029. It also plans to introduce an X-band deflector cavity downstream of the BL3 undulator around 2027, combined with operational tests of X-band RF. These are currently being designed and prototype tested [7].

## SYSTEM DESIGN

### *Accelerator Configuration*

The layout of SACLA is shown in Fig. 1. In the compact 400 m long accelerator section, a 1 ns, 1 A low-emittance electron beam generated by a $CeB_6$ thermal cathode electron gun [8] is compressed to 10 fs and 10 kA in a buncher cavity [9] and three bunch compressors (BCs), and accelerated up to 8 GeV in a high gradient C-band accelerator [10]. The electron beam, generated and accelerated at a 60 Hz repetition rate, is distributed by high-precision kicker magnets [11] to two XFEL beamlines, BL2 and BL3, and the injection into the SPring-8 storage ring [12]. In BL1, the accelerator that was originally used as the SCSS prototype accelerator [13] has been relocated and its energy increased to 800 MeV and used for user experiments as an EUV-FEL facility [14].

In the upgrade program SACLA-II, part of the downstream C-band accelerator will be replaced by an X-band accelerator. As described in the next chapter, the X-band accelerator can provide an average acceleration gradient of 42 MV/m even at a 600 Hz repetition rate, thus providing a margin of acceleration energy. On the other hand, the remaining C-band accelerators and the S-band accelerators are planned to remove the pulse compressor and operate at short pulse RF to increase the repetition rate. As this change lowers the acceleration gradient to about half of the current level, we plan to compensate for the energy with the high-gradient X-band accelerator and obtain more than 8 GeV energy at the exit of the accelerator. If the repetition rate of the X-band accelerator is reduced to 200 Hz and the RF pulse width is increased, the acceleration gradient can be increased to 48 MV/m. The energy of the electron beam could be increased to 10 GeV to produce shorter wavelength XFELs.

As SACLA is currently also used as an injector of SPring-8, it is difficult to make a large-scale replacement work with a long shutdown period. Therefore, the X-band accelerator will consist of a unit with a total length of 4 m, same as the current C-band accelerator, and will be replaced by several units every shutdown period. In this way, the replacement can be carried out while the operation of SPring-8 and SACLA continues.

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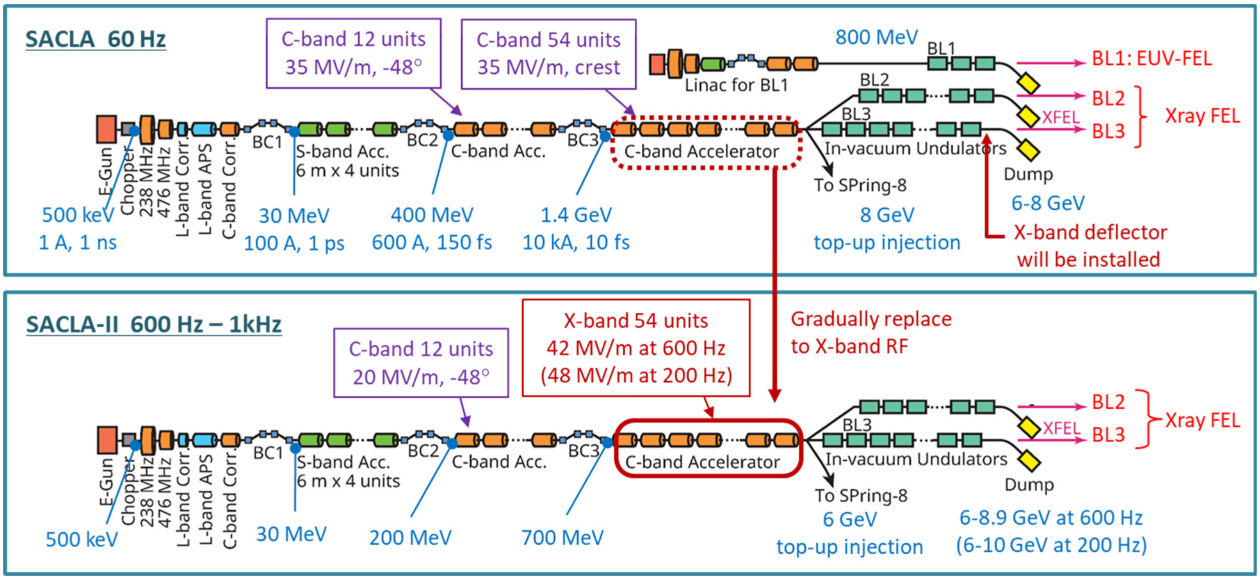


Figure 1: Layout of the current SACLA accelerator system and the future upgrade plan "SACLA-II".

## *X-band RF System*

A diagram of the X-band RF system currently being considered is shown in Fig. 2. As described in the previous section, the unit length is set to be 4 m, the same as for the C-band, with a design of six 0.6 m long accelerating tubes driven by one or two klystrons.

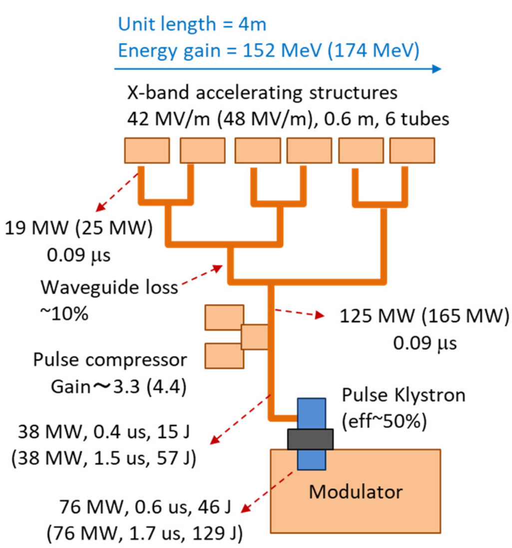


Figure 2: Diagram of the X-band RF system. Values in brackets ( ) are for long pulse mode.

The accelerating structure is designed as the scale of the C-band disk-loaded type structure [15] used in the SACLA-BL1 accelerator [14]. This structure has a 19% higher shunt impedance than the choke-mode type structure [10] currently used in the SACLA main accelerator. Table 1 shows the parameters. According to the scaling law of reference [16], two 1.8 m long C-band accelerating tubes can be replaced by six 600 mm X-band accelerating tubes if the attenuation parameter τ are scaled to the same degree.

To obtain the same acceleration gradient ($E_{accel}$), the input RF power ($P_{feed}$) to the accelerating tubes would be about 1/4 peak power and 1/3 filling time width ($t_F$). The RF energy required to obtain the same acceleration energy ($V_{accel}$) is inversely proportional to the square of the frequency, which is 1/4 for this case. By setting the parameters of the pulse compressor appropriately, the 400 ns, 38 MW klystron output can be compressed to 90 ns, 125 MW of power, which is fed to six accelerating tubes to generate an accelerating electric field of 42 MV/m. The accelerating field can also be increased to 48 MV/m by extending the RF pulse width to 1.5 µs.

Table 1: Comparison of the accelerating structure, C-band hoke-mode type [10] used at SACLA, C-band disk-loaded type (normal) [15] used at SACLA-BL1, and the X-band accelerating structure.

| Parameters | C-band Choke | C-band Normal | X-band Normal |
|---|---|---|---|
| Frequency GHz] | 5.712 | 5.712 | 11.424 |
| Structure type | TM01 mode, constant gradient | | |
| Phase advance | 3π/4 | 2π/3 | 2π/3 |
| $R_{shunt}$ [MΩ/m] | 54 | 64 | 91 |
| Length [m] | 1.8 | 1.8 | 0.6 |
| $t_F$ [ns] | 300 | 270 | 90 |
| Attenuation τ | 0.53 | 0.54 | 0.51 |
| $P_{feed}$ [MW] | 76 | 76 | 19 |
| $E_{accel}$ [MV/m] | 38 | 42 | 42 |
| $V_{accel}$ [MeV] | 69 | 76 | 25 |
| $P_{feed}*t_F/V_{accel}$ [J/GeV] | 330 | 270 | 67 |

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The efficiency of klystrons and pulsed power modulators is one of the most important development items for high repetition rates. A commercially available klystron with a power output of 20 MW, power efficiency of 41%, and a maximum repetition rate of 400 Hz has been manufactured by Canon [17]. They are also working with CERN to develop more efficient klystrons [18]. We will consider the possibility of other methods of increasing efficiency, such as multi-beam design. About the pulsed power modulators, it is essential to speed up the rise and fall of the high-voltage pulses and shorten the time width of the high-voltage pulses. Conventional modulators based on the pulse-forming network (PFN) circuit method slow down the pulse due to the leakage inductance and distributed capacitance of the pulse transformer, so we consider using a Marx generator or a linear transformer driver (LTD) that does not use a pulse transformer. The goal is to reduce the power used to less than 50 J per shot through a series of such developments. The current SACLA uses about 500 J per shot, so it will be possible to increase the repetition rate by a factor of 10 with the same power consumption. By further increasing the power efficiency, the final goal is to operate at a repetition rate of 1 kHz.

## X-BAND TRANSVERSE DEFLECTOR SYSTEM FOR SACLA-BL3

As well as the development and pilot operation of X-band RF components, we plan to install an X-band transverse deflector system to downstream of the BL3 undulator at SACLA, as shown in Fig. 3. The deflector cavity excites HEM11-mode RF with transverse electric and magnetic fields. The electron beam is injected near its zero phase to sweep horizontally in time (T), together with the vertical energy (E) dispersion by the bending magnet. The E-T phase spatial distribution is measured on a screen monitor. Similar deflector cavities (TCAV) have been used in LCLS [19] and many accelerator facilities, but with different cavity types and RF modes. Our design is based on the C-band deflector cavity [20] installed downstream of BC3 at SACLA. We consider a manufacturing method in which the cavity is formed from two blocks upper and lower, and formed by machining  for the cost reduction. A prototype of the cavity will be manufactured this year and a high-power test is planned for next year. Pulse compressors and dummy loads are being developed that can also be used in SACLA-II. These components will be built this year and high-power tests will be conducted next year [7].

The klystron with 20 MW output power [17] was purchased, and the conventional PFN-type modulator from SACLA [10] was modified for the X-band klystron. As the X-band RF is highly attenuated in the waveguide, the klystron was placed in the undulator hall near the cavity and connected to the modulator PFN section on the outside of the shielding chamber by high-voltage coaxial cables. An amplifier with a high-power GaN transistor was fabricated for the klystron's driver amplifier. For the low-level RF system that generates the RF pulse modulation, amplitude and phase control, and also measures the monitor RF signal, an on-board digital control system using RFSoC is being developed. These instruments are planned to be manufactured by 2026, fully tested on the test stand, and installed at SACLA in 2027. The development and operating experience of these instruments is planned to be fed back into the fabrication of the X-band components at SACLA-II.

## CONCLUSION

As a future upgrade of SACLA, we plan to increase the repetition rate by a factor of 10 or more for the same power usage, by replacing the C-band accelerator with X-band and improving the power efficiency of the klystron and pulsed power modulator. For the development and field testing of this key X-band accelerator technology, a transverse deflector system is planned to be installed downstream of the BL3 undulator. The design and development of the cavity, pulse compressor, dummy load, driver amplifier, and low-level RF control system is underway. High-power tests are planned for next year.

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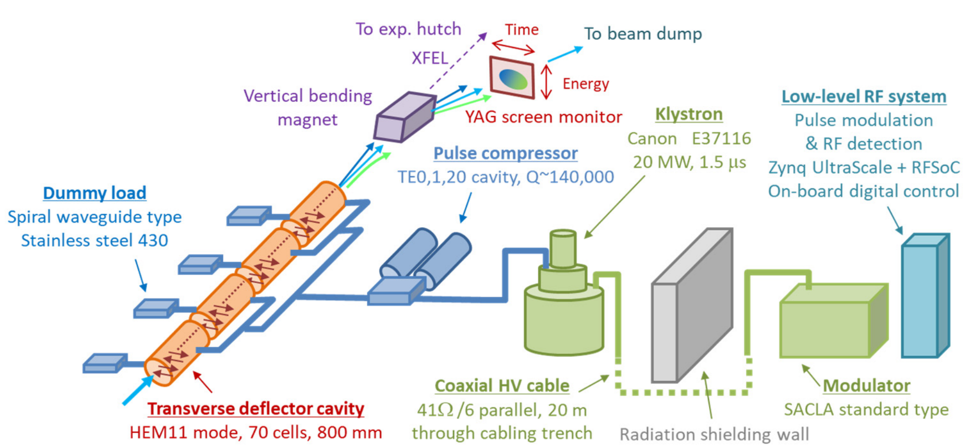


Figure 3: Schematic of the transverse deflector system for SACLA.

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