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SACLA X-RAY FEL BASED ON C-BAND TECHNOLOGY* (GERSCH BUDKER PRIZE LECTURE)

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Abstract

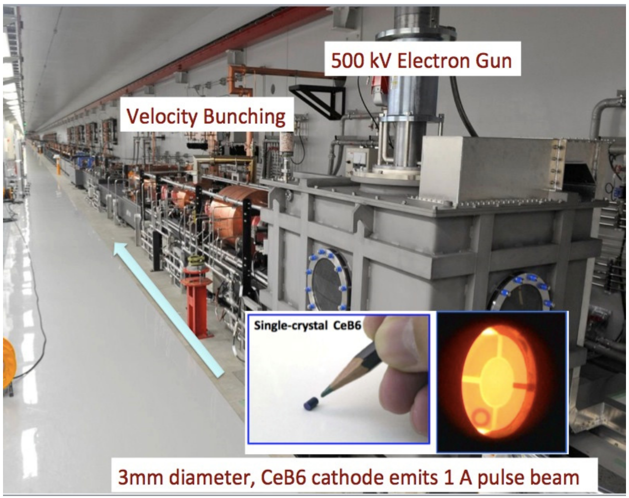
C-band linear accelerator technology was initially developed at e+e- linear collider R&D during years of 1996~2000 guided by the author at KEK [1-6], followed by SCSS project [7-10] at RIKEN/SPring-8 (2001~2005), where we demonstrated high gradient operation of C-band accelerator. After this demonstration, 400 m long 8 GeV C-band accelerator was build at SPrin-8 site during 2006~2010 as the main linac to drive X-ray FEL facility: XFEL/SPring-8, later named as SACLA [11-15]. After 1,700 hours of high power conditioning, the maximum acceleration gradient reached to 38 MV/m. The machine trip rate for each acceleration unit at nominal operation conditions is as low as once per day at gradient 35 MV/m and repetition cycle at 30 pps. The measured stabilities of phase and amplitude of the rf field were 0.03 degree and 0.01% in standard deviation, respectively. They were sufficient for the future upgrade of FEL seedings. The first lasing was achieved in 2011, since then the C-band accelerator has been keeping running in full time operation, and demonstrating fairly stable performance under continuous operation for 20,000 hours. The author took 20 years from the first proposal of the C-band accelerator to this end.

INTRODUCTION

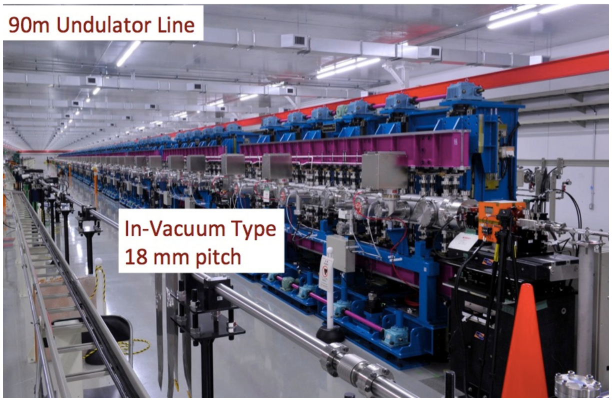
The X-ray FEL facility SACLA: SPring-8 Angstrom Compact free-electron Laser has been constructed at SPring-8 Japan, and started providing coherent X-ray beam for users since 2012 [14]. This is the world second X-ray FEL after LCLS SLAC, which started operation in 2009. Both are based on SASE FEL, radiating coherent intense short-pulse X-ray in Angstrom wavelength. SAC-SACLA uses SCSS concept [7,10]: unique combination of (1) normal-conducting high-gradient C-band accelerator and (2) in-vacuum short-period undulator and (3) low emittance thermionic electron source. These technologies were developed at SCSS R&D (2001~2006) at SPring-8 prior to SACLA. Prof. Hideo Kitamura and Dr. Takashi Tanaka developed the in-vacuum undulator. Dr. Yuji Otake and Dr. Hirokazu Maekasaka developed C-band LLRF system, which provide precise timing and rf-signals into whole system. The author chose the thermionic cathode followed by velocity bunching scheme. Dr. Kazuaki Togawa mainly contributed to the electron source R&D [8].

I will focus on C-band main linear accelerator in this prize lecture.

(a) SACLA 700 m long FEL facility was constructed at SPring-8 site and providing beam since 2012.



(b) Low emittance beam is generated by thermionic cathode, followed by velocity bunching and chicanes.



(c) In-vacuum undulator has been employed.

Figure 1: SACLA facility and its inside.

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Figure 2: C-band high-gradient accelerator in 400 m tunnel. Total 128 accelerating structures have been installed to accelerate beams up to 8 GeV. Eight S-band accelerating structures are used in the injector part .

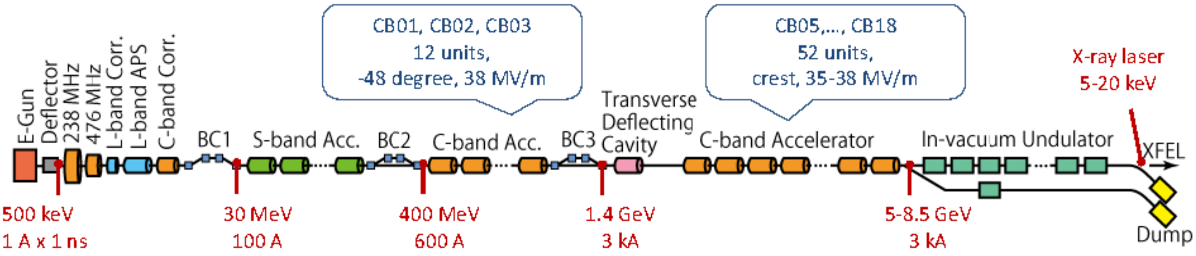

Figure 3: Schematic configuration of the SACLA accelerator, where 64 units of C-band system are used. Each unit consist of two accelerating structures, one klystron and modulator. Within active length of 230 m, C-band is able to provide 8.7 GeV energy gain in maximum. Injector complex uses sub-harmonic frequencies in order to perform velocity bunching, which was developed at SCSS [9].

C-BAND CHOICE

The author proposed C-band linear accelerator technology as the main linac in the future e^+e^- linear collider in 1992 and 1995 [1, 2]. This was a personal conclusion after one-year sabbatical stay in Frascati Laboratory in Rome (1990-91), where I performed various thought experiments on machine designs for the linear collider construction. During the sabbatical year I also found an idea to measure the nano-meter size of beam at the interaction point in the colliders by using a laser interferometer [16]. Five years later, the international collaboration team demonstrated creation of 60 nm spot at FFTB project, where the beam spot size was measured with this idea [17]. This demonstration proved feasibility of nano-meter focusing required at interaction point in the future e^+e^- linear collider, from which scepticism on the linear collision concept has been diminished.

During the thought experiments of machine construction for the e^+e^- linear collider, I took the first priority as lowering construction cost of the machine, and also reducing R&D items required, while keeping high reliability. The size of the project is huge; the number of required components is so large, for example, it requires a few thousand klystrons and modulators in the 500 GeV centre-of-mass energy linear collider, therefore each component has to be very reliable and low cost.

First, I eliminated the super-conducting technology from my thought experiment because of its complexity and higher machine cost and also less experience on high-gradient acceleration. I thought it would require many years of R&Ds to establish reliable technology, as a result, the concept of linear collider itself would lose a chance to contribute to high-energy physics competitively to proton experiments using circular colliders.

From the point of view of accelerator structure efficiency, a higher frequency is desirable, since the shunt impedance scales with the driving frequency as

$$r \propto \omega^{1/2}. \tag{1}$$

where r is the shunt impedance per unit length. In steady-state condition, the available accelerating gradient is

$$E_a = \sqrt{r(1-e^{-2\tau})P_{in}/L} \quad , \tag{2}$$

where τ is the attenuation constant, P_{in} is the input power to the structure, L is the structure length. For example at X-band, the shunt impedance becomes twice as high as S-band, which means we can get the same accelerating gradient with half of the rf input power.

In case of single bunch or short bunch operation, i.e., pulse duration of rf input power is close to the rf filling-time of the structure, we have to evaluate the system performance with the integrated pulse energy in each pulse mode operation. The filling-time of the structure is

$$t_F \propto \frac{2Q}{\omega}\tau \propto \omega^{-3/2} \; , \tag{3}$$

where Q is the quality factor, τ is the attenuation constant of the structure, which is usually chosen close to 0.5. We see that the filling time becomes shorter at higher frequencies. Typically, it is 900 nsec at S-band, 300 nsec at C-band and 100 nsec at X-band. Assuming a pulse compression ration of 5 in the pulse compressor, and including the beam pulse length, the pulse length at the klystron output becomes 9 µsec at S-band, 3 µsec at C-band and 800 nsec at X-band. From the point of view of pulse power supply technology for klystron, 3~10 µsec (C or S-band) is suitable for the conventional line-type modulator using PFN (Pulse Forming Network) with reasonable power efficiency. This type of modulator has been widely used in electron linear accelerator; its technology has been well established.

From Equations (2) and (3), we have rf pulse energy filled into the structure as follows.

$$W_{RF} = P_{in}\cdot t_F = \frac{\tau}{(1-e^{-2\tau})}\frac{2E_a^2 L}{\omega r/Q} \propto \frac{E_a^2}{\omega r/Q} L \propto \omega^{-2}E_a^2 L \tag{4}$$

We have to note that, impedance parameter is r/Q, not r. r/Q represents geometric efficiency, which scales as $r/Q \propto \omega$. At C-band r/Q becomes twice higher than S-band. By the way, we employ the choke-mode structure in our C-band system in order to cure the multi-bunch instability. It has more volume than the simple disk-loaded structure, therefore it stores more energy, as the results, r/Q drops about 10%. This is the cost we pay more electricity consumption in C-band system for this benefit of the multi-bunch capability. In the entire accelerator facility, it becomes negligibly small, since we spent extra power on magnets, cooling water pump, air conditioners and chillers.

Equation 4 represents the stored energy inside the structure, while 30% of input power is lost as resistive loss on the copper wall. It is clear that the stored energy simply proportional to its volume, i.e., product of length and cross-sectional area, which scales as $V \propto D^2 L \propto \omega^{-2}$, and it becomes quickly smaller at higher frequency as shown in Fig. 4.

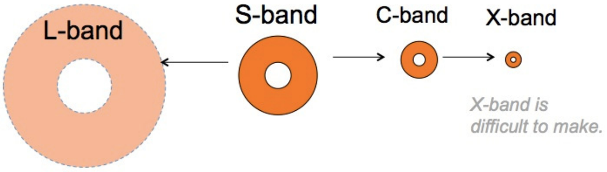

Figure 4: Frequency scaling of the accelerating structure.

Diameter and cross-sectional area scale as $D \propto \lambda \propto \omega^{-1}$, $S \propto \omega^{-2}$, respectively.

We see that rf pulse energy filled into the structure per unit length scales as $W_{RF}/L \propto \omega^{-2}E_a^2$, and at higher frequency, rf pulse energy required to fill the structure becomes quickly smaller. This is the main reason for choosing higher frequency than traditional S-band frequency. If we use C-band, we can obtain twice higher accelerating gradient with the same amount of rf pulse energy filled in the accelerating structure per unit length.

We have to note that the structure length scales as $L = v_g t_F \propto \omega^{-1.5}$. Typically, it is 3 m at S-band. If we keep the same group velocity, the optimum structure length at C-band becomes 1 m. This is too short, since we have to fabricate a large number of accelerating structures as many as three times than S-band. Each accelerating structure needs the input and output couplers, thus production cost becomes quite higher. In our design we made structure length as L = 1.8 m. If we try to make structure length even longer, the group velocity becomes higher, which requires larger iris aperture, thus the shunt-impedance r/Q drops.

While higher frequency is desirable for lowering the required rf pulse energy, engineering of high-power rf sources becomes rather difficult at higher frequency. Especially, the higher frequency klystron has several technical problems. It requires the driving beam to be focused into smaller diameter. In order to avoid collision to the drift-tube aperture, size of the cathode in the electron gun has be designed smaller, thus the beam current becomes low, as a result, higher voltage has to be applied on the electron gun to maintain the same amount of beam power (beam perveance value becomes smaller). It causes higher risk of high-voltage breakdown in the electron gun and the output cavity. If the beam focusing is wrongly designed or fabrication of focusing magnet has certain error, a part of the beam will collide to the drift-tube wall and triggers high-voltage breakdowns in high-voltage gaps at the gun region and the output cavity. In a worst case, meltdown of the copper drift-tube could be happened. These symptoms limit available maximum available power from the practical klystron tubes. Roughly speaking, the output rf pulse energy from the pulse klystron scales as

$$P \cdot t \propto \omega^{-2} \tag{5}$$

Toshiba E-3712 tube can produce: 80 MW x 4 µs = 320 Joules/pulse at S-band, which scales to 80 Joules/pulse at C-band. I chose C-band klystron parameter as 50 MW x

2.5 μsec = 125 Joules/pulse, which is still 50% higher than scaling law. To keep safety margin, we employed three-cell traveling output structure, which reduces 30% rf voltage across the output gap.

Together with higher voltage request on driving beam of klystron and shorter pulse width due to short filling time at higher frequency, extensive R&Ds are required on klystron power supply at higher frequency. C-band system can rely on conventional power supply, because the required voltage and pulse width are moderate value.

There are additional problems in higher frequency accelerators; dimensional tolerance of accelerating structure associated from the higher wake-filed impedance becomes tighter, which makes the fabrication cost higher and required production period longer. The alignment tolerance of structure in transverse direction scales as

$$\Delta y \propto \left(\frac{dW_T}{ds}\right)^{-1} \propto a^4 \propto \omega^{-4} \tag{6}$$

where a is the beam hole radius, W_T is the single bunch wake function. We see that alignment tolerance becomes very tight at higher frequency. At C-band, alignment tolerance is 30 um for 1.6 nC charge in the linear collider. In case of X-ray FEL, bunch charge is lower, therefore structure aliment can be tolerated.

By taking into account all these effects, I concluded C-band would be the best choice. The C-band frequency is 5712 MHz, which is twice higher frequency than the conventional S-band (2856 MHz). I assumed 35 MV/m as the nominal accelerating gradient, which is roughly twice higher gradient in the conventional S-band accelerators.

C-BAND ACCELERATOR AT SACLA

C-band Accelerator Unit [12]

As shown in Fig. 3, in SACLA facility, 64 C-band units are used to accelerate beam to 8 GeV. Each unit consists of two accelerating structures, one klystron, one modulator and associated LLRF system. Figure 5 shows one unit of the C-band accelerator installed in SACLA. The power flow is as follows. Inverter power supply takes wall plug power from 3ϕ 400 V AC, by rectifying, it stores 600 V DC in capacitor bank. IGBT switches the DC voltage at 20 kHz, convert into AC, followed by step-up transformer, 50 kV DC is generated along series multi-stage rectifying circuits in the secondary windings. It feeds current into PFN capacitor inside the modulator. After the charging voltage reaches close to the target value near 50 kV, a small inverter power supply parallel connected to PFN start to keep the charging voltage at target value with ultra-high precision within 10 ppm error level. By external trigger, the thyratron tube turns ON, the PFN generates 25 kV x 5000 A x 5 μs pulse, which is fed into primary windings in the pulse transformer. High voltage pulse of 350 kV, 310 A is generated in the secondary, which supply beam power to the C-band klystron. RF input signal around 200 Watt level is fed into the klystron input cavity, amplified by 60 dB gain on the beam, the three-cell output structure generates 50 MW x 2.5 μs rf power. The PFN circuitry and the klystron tube are housed in a metal-enclosure filled with insulation oil, thus EM noise emission is fairly low [13].

The output power from the klystron is sent to the accelerator tunnel along a penetrating waveguide through shielding wall. The rf pulse compressor stores it power temporally, then emits into compressed short-pulse after

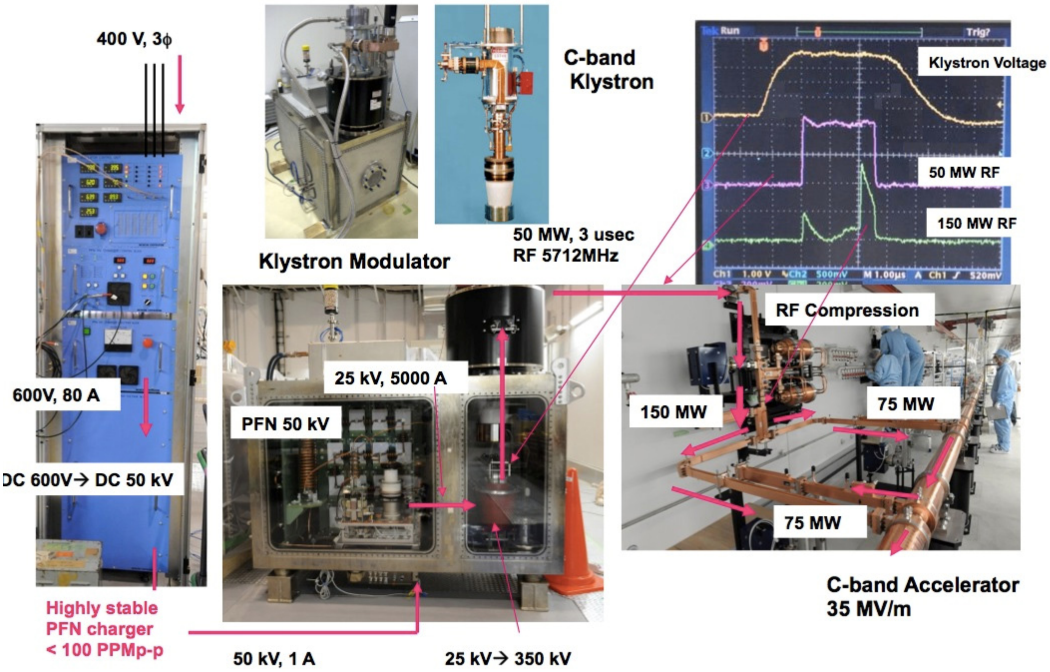

Figure 5: One unit of C-band accelerator system.

temporally, then emits into compressed short-pulse after flipping the input rf phase to the klystron. With five times compression, the peak rf power reaches to 150 MW. By splitting two waveguides, 75 MW peak power is fed into accelerating structure, and generates 35 MV/m accelerating field. After traveling wave reaches to the output coupler; it takes 300 nsec from the input coupler, the single bunch beam passes through the structure. It takes only 12 nsec for the electron bunch passing through two accelerating structures in one unit of C-band system, which is much shorter than the filling time.

C-band Klystron [3]

Figure 6 shows 50 MW C-band klystron, which was developed by C-band R&D at KEK. It uses three-cell traveling-wave output structure, which makes surface field gradient lower, and avoids back streaming electrons at saturation condition. This tube is now available from TOSHIBA Co. as commercial product; its catalog number is E3746, later E3748.

Figure 6: 50 MW C-band Pulse Klystron.

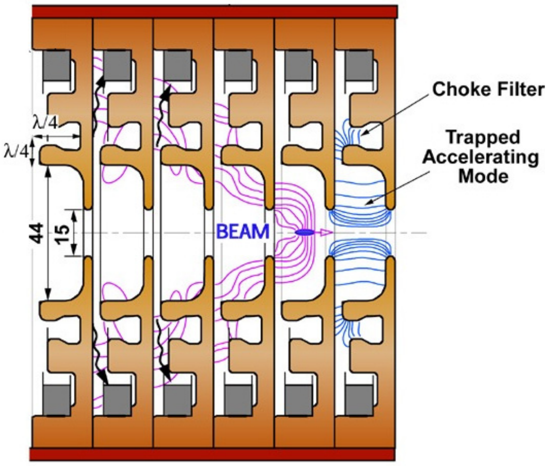

Figure 7: C-band choke-mode type acceleration structure.

Accelerating Structure [12,18,19]

Table 1 summarises the C-band accelerating structure installed in SACLA. It should be emphasized that in order to lower the surface field gradient at iris tip, disk thickness was made much thicker than simple scaled value from S-band, while it lowers the shunt-impedance.

Figure 7 shows schematic illustration of the choke-mode cavity structure. In each accelerating cell, ring-shaped SiC ring is loaded, which absorbs wakefield power from the beam and damps the HOM modes. Only the accelerating TM010-like mode is trapped within disk-loaded structure by means of notch-filtering action by the choke-structure. This structure will contribute future upgrade for multi-bunch operation of SACLA.

Table 1: C-band Accelerating Structure

C-band frequency	5712.00 MHz
Accelerating Structure	Quasi-CG-structure
Type of structure	Choke-mode cavity with SiC-loaded.
Structure Length	1791 mm
Number of cells	89 + 2 coupler cells
Phase advance per cell	$3\pi/4$
Cell Dimension	$2a = 17.3 \sim 13.6$ mm $2b = 45.7 \sim 44.0$ mm $D = 19.68$ mm Disk thick ness ***t* = 4 mm**
Shunt-impedance r	49.3~60 MΩ/m
Shunt-impedance r/Q	4.8 ~ 6.0 kΩ/m
Quality factor	10700 measured
Group Velocity	0.031~0.013
Attenuation Constant τ	0.53
Filling Time	296 nsec
Nominal Energy Gain	63 MeV at 35 MV/m

OPERATIONAL EXPERIENCE [15]

The rf conditioning required roughly 1000-hour operation at a designed acceleration gradient of 35 MV/m to achieve an acceptable trip rate of once per day at 10 pps repetition. The first lasing was achieved in June 2011 in this condition.

Until today, 64 C-band acceleration units have been operated for about 20,000 hours, without any serious problems concerning the high-power rf components. Small problem is remaining on thyratron tube; randomly happening sparks, which is the main source of machine trip.

Figure 8 shows the acceleration gradient of the individual C-band acceleration units for two sets of typical beam energies. The averaged acceleration gradients are set at 38 MV/m and 35 MV/m for the electron beam energies of 8.5 GeV and 7.9 GeV, respectively.

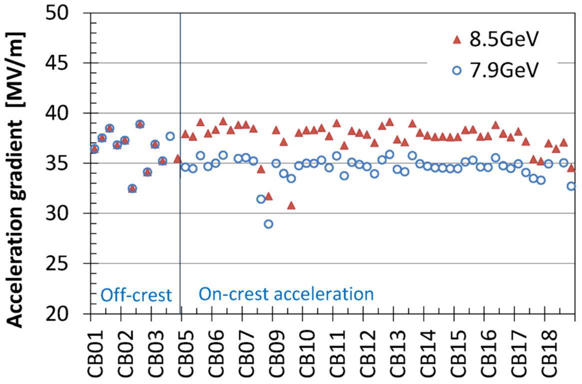

Figure 8: Typical acceleration gradients at C-band unit in the cases of 8.5 GeV (red triangle) and 7.9 GeV (blue circle).

SUMMARY

Since 2011, 8 GeV C-band accelerator is routinely operating at SACLA X-ray laser in SPring-8 Japan with accelerating gradient higher than the design value of 35 MV/m.

C-band accelerator is so reliable, which will be suitable for full energy injector for light sources with top-up operation; 3 GeV beam is available within 100 m long tunnel. European S-band is 2998.5 MHz, which is 142.5 MHz higher than US S-band (2856 MHz). Combination of 5712 MHz C-band (= 2856 MHz x 2) with European S-band is also possible with proper design of frequency mixing and injector timing control.

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