

HIGH GRADIENT OPERATION OF 8-GeV C-BAND ACCELERATOR IN SACLA

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Abstract

In X-ray free electron laser facility, SACLA, C-band high gradient accelerator was employed in order to shorten the 8-GeV accelerator length. In total, 64 klystrons, 64 RF pulse compressors, and 128 accelerating structures are used in SACLA. Since the C-band accelerator generates high acceleration gradient (nominal 35 MV/m), associated with a high RF breakdown rate, reliability of the high power RF components and the reduction of the trip rate less than several trips per an hour are the key issues for the stable operation. At beginning of beam commissioning in 2011, the trip rate of the C-band accelerator was still high. Major causes of the trips were an RF breakdown in an accelerator cavity and an abnormal discharge in a thyatron tube. After the RF conditioning time of 700 hours, the RF breakdown rate was reduced to be 1/10 comparing with the beginning stage of the RF conditioning. Concerning the thyatron discharge, we confirmed most of the discharges do not influenced to the next pulse generated by a klystron modulator and it can be excluded from the trip items of an interlock system. We currently operate the accelerator with the beam energy as much as 8.5 GeV, and the acceleration gradient of 38 MV/m in average, with an acceptable trip rate of once per 20-30 minutes, which provides stable laser for XFEL user experiments. Availability of the C-band high gradient accelerator for compact accelerator is confirmed.

INTRODUCTION

SACLA (SPring-8 Angstrom Compact Free Electron Laser) [1] is a unique X-ray free electron laser (XFEL) facility, aiming to generate an X-ray laser with a compact electron accelerator and an in-vacuum undulator. The compactness is important to be able to construct within an available space in the SPring-8 campus, and for lower construction costs. In order to shorten the 8 GeV accelerator length, a C-band (5712 MHz) accelerator is employed. A higher frequency is chosen to produce a higher acceleration gradient. The nominal acceleration gradient is about 35 MV/m, which is twice higher than that of conventional S-band accelerators.

Figure 1 shows the configuration of the SACLA accelerator. For the energy from 400 MeV to 1.4 GeV, 12 C-band acceleration units accelerate an electron beam at -48 degree off crest phase, which provides an energy chirp for the following bunch compression chicane BC3. After BC3, the 52 C-band acceleration units accelerate the beam up to the target energy around 5 GeV to 8 GeV, dependent on a laser wavelength.

Since SACLA is the single-pass FEL facility, if only one unit out of 64 makes a trip (interlocked failure), it

surely changes the beam energy and makes a serious influence to the laser properties. For example, when each unit makes one trip per 3 days on average, the beam trip is almost hourly occurred in total. Therefore reduction of the trip rate is the crucial point for stable laser provision.

The beam commissioning was started in March 2011 and the first lasing at a 0.12 nm wavelength was achieved in June [1]. At that time the trip rate was high due to the insufficient conditioning time for RF components [2]. Major causes of these trips were RF breakdown (arcing) in cavities and abnormal discharge (pre-trigger) of thyratrons. Then we lowered the beam energy to 7 GeV, and a pulse repetition rate up to 10 pps, because the beam energy and the repetition rate were not so important for immediate beam commissioning. Instead, a high beam energy of over 8 GeV and low trip rate were required for user runs. Hence we spent much effort to reduce the trip rate. Careful RF conditioning effectively reduced the number of the RF breakdowns. Since March 2012, the SACLA accelerator is stably operated for the user experiments with the energy up to 8.5 GeV and the acceleration gradient of 38 MV/m in 10 pps.

C-BAND ACCELERATOR SYSTEM

Figure 2 shows the configuration of the C-band accelerator system. Two 1.8 m long accelerating structures are connected to a 50 MW pulse klystron with

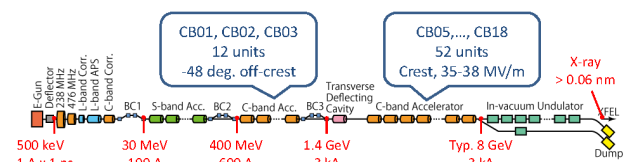


Figure 1: Configuration of the SACLA accelerator.

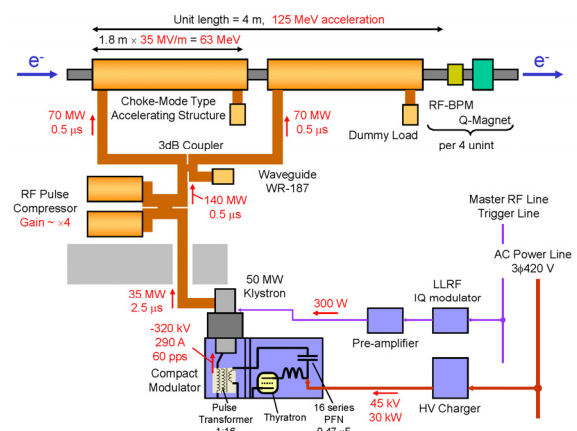


Figure 2: Configuration of the C-band accelerator system. Typical parameters for nominal operation are noted in red.

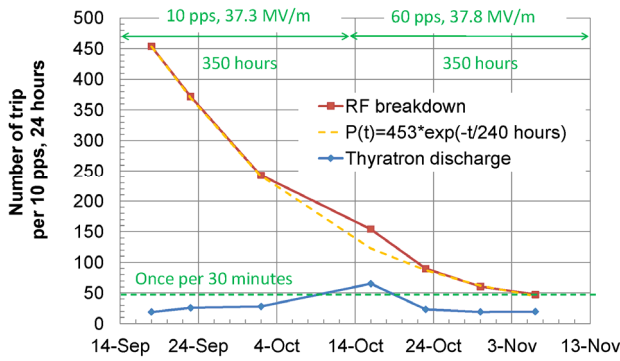


Figure 3: Number of the total trips of the 64 C-band acceleration units during the RF conditioning., due to the RF breakdown (red) and the thyatron’s discharge (blue). The yellow dashed line is the exponentially fitted curve of the RF breakdown rate.

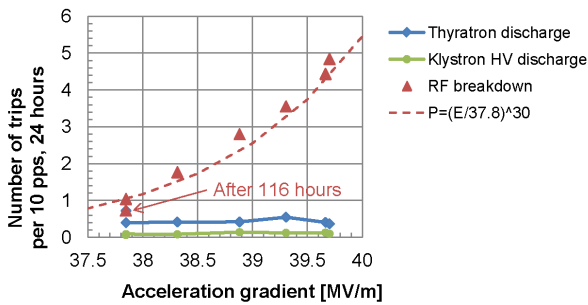


Figure 4: Trip rate of each C-band acceleration units, as the function of the acceleration gradient.

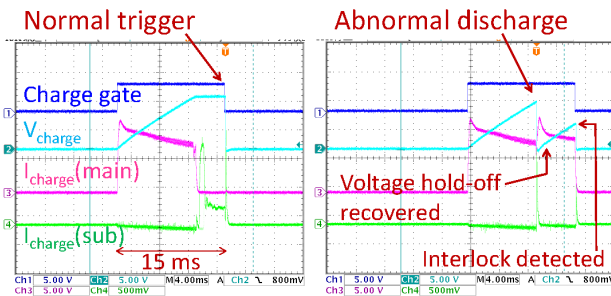


Figure 5: Typical waveforms of the charging cycle (left), and the waveforms of the abnormal discharge during the charging period (right). The charging voltage (V_{charge}) of the PFN capacitors was set at 45kV and the repetition rate was 10 pps in both waveforms.

an RF pulse compressor (SLED) system. For the nominal operation the output power of the klystron is about 35–40 MW with 2.5 μ s pulse width. The RF power is once stored to two high Q cavities of the SLED. When an RF phase is inverted by a phase switch keying (PSK) using an in-phase and quadrature (IQ) modulator [3] at 2 μ s point of the pulse, the stored RF power is extracted from the SLED cavities. The RF power is about 200 MW in peak, and 140 MW on average for the 300 ns filling time of the accelerating structure [2]. The RF power is fed into two accelerating structures ($R_{sh} \sim 54 M\Omega/m$ and $\tau \sim 0.53$) to

obtain a nominal acceleration gradient of 35 MV/m. Even though we designed the cavity wall thickness of 4 mm and round off the corner of iris with a radius of 2 mm, the maximum surface electrical field is about 100 MV/m. In order to sustain such a high RF field, the structure is made of pure oxygen-free-copper with HIP treatment, carefully machined and brazed with clean environment [4].

The klystron is driven by a compact 110-MW high-voltage pulse modulator, which equips a conventional line-type pulse forming network (PFN) circuit and a thyatron tube [5]. Capacitors constituting the PFN are charged by an inverter-type highly-precision HV charger. The charged voltage is precisely regulated within about 10 ppm (rms), which stabilizes the RF output phase and amplitude of the klystron within 100 ppm and 0.2 degree, respectively.

REDUCTION OF TRIP RATE

RF Conditioning

RF conditioning is the process to obtain a higher RF field in the cavity, which clean the cavity surface and reduce the number of the RF breakdown. By the summer of 2011, we performed the RF conditioning of more than 1,000 hours and realized to operate at an acceleration gradient of 35 MV/m [2]. In order to raise the acceleration gradient up to 38 MV/m, we performed the additional RF conditioning during the night time. Figure 3 shows the progress of trip rate reduction. The RF breakdown rate $P(t)$ is exponentially decreased with an elapsed time. The time constant of decrease of the RF breakdown rate is 240 hours. After an RF conditioning time of 2 months (700 hours), the RF breakdown rate was decreased to be 1/10 and it showed proved the possibility to obtain a high-energy electron beam up to 8.5 GeV.

In order to investigate the availability of further high acceleration gradient, we gradually raised the RF power and measured the trip rate. Figure 4 shows the trip rate depending on the acceleration gradient. We found the RF breakdown rate is proportional to the 30th power of the acceleration gradient (red dashed line in Figure 4). After a measurement time of 116 hours at a maximum acceleration gradient of 39.3 MV/m, the RF breakdown rate decreased to be 2/3 of the initial rate at the acceleration gradient of 37.8 MV/m. It proved the potential to obtain a higher acceleration gradient by further RF conditioning.

Thyatron Abnormal Discharge

Our thyatron is e2v CX-1836, which equips three control grids and is filled with deuterium gas. Figure 5 shows the waveform of a charging cycle. In normal operation, the thyatron is triggered after charging period of 15 ms. But it occasionally discharged during the charging period, without a trigger pulse. Then the interlock system detects insufficiency of a charging voltage and halts the next charging. This discharge phenomenon is known as the “pre-trigger” of the thyatron, but the rate of it is much higher than that of our

expectation. The rate seems independently of the charging voltage (see Figure 4), and was not reduced during the conditioning (see Figure 3). Therefore, it becomes a dominant reason of the interruption of the accelerator operation, especially at low energy (< 8 GeV). In normal operation, the thyatron conducts huge current (~ 5 kA) by generating plasma of the deuterium gas. After PFN capacitors are fully discharged, the plasma density drops within the nominal recovery time (~ 20 μ s) and the connection is closed [6]. We suppose the same recovery occur after the abnormal discharge. In the left figure of Figure 5, the charging voltage was raised again after the abnormal discharge occurred. It means the withstanding voltage is surely recovered and we need not to halt the next HV pulse.

We modified the interlock system not to halt the operation by the single discharge event. When the second discharge occurred within one minutes, the interlock system halts the next charging for the machine protection. In June 2012, we tentatively modified 25 units. The trip rate of the modified unit is drastically reduced to be roughly 1/3 of the previous halt rate. The remaining 39 units were modified in this summer shut down period.

PRESENT OPERATIONAL STATUS

Thanks to these improvements, we have operated SACLA with beam energy of up to 8.5 GeV. So far the C-band accelerator has operated about 10,000 hours, without any serious troubles of high power RF components of 64 units.

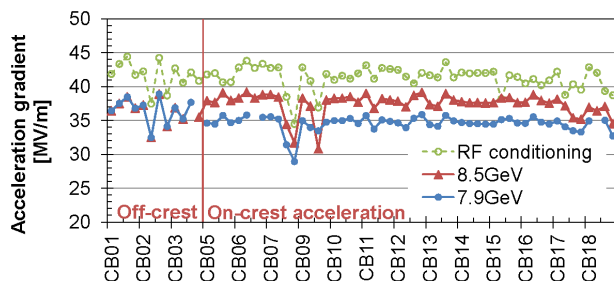


Figure 6: Typical acceleration gradients at each C-band unit in the cases of 8.5 GeV (red) and 7.9 GeV (blue). Maximum acceleration gradient values of individual RF units in the RF conditioning are also displayed (green).

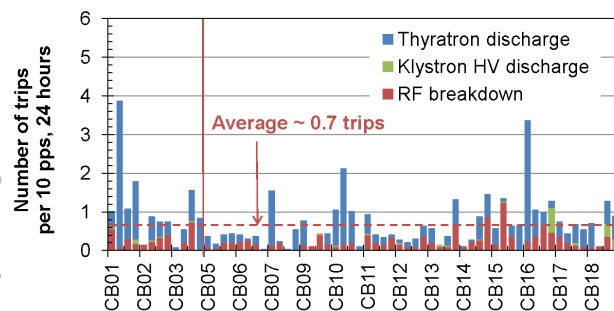


Figure 7: Trip rate of each C-band unit in July 2012. The acceleration gradient was set about 35 MV/m (7.9 GeV case of Figure 6).

Figure 6 shows the acceleration gradient of each C-band acceleration unit in two sets of typical beam energy. The averaged electrical gradient is about 38 MV/m and 35 MV/m for 8.5 GeV and 7.9 GeV, respectively. We have several standby units as a backup for troubles.

Figure 7 shows the trip rate of each unit in July. In average, the number of trips per one unit in 24 hours is 0.7 events and 1.1 events for 7.9 GeV and 8.5 GeV cases, respectively. The trip rate of the SACLA accelerator is the sum of the trip rate of the 64 units, which is once per 30 minutes for the 7.9 GeV case and once per 20 minutes for the 8.5 GeV case in 10 pps. These trip rates are still not sufficiently low to our requirement but an acceptable level for the user experiments. The trips are still dominantly caused by the thyatron discharges (65%). Since we modified the interlock systems of 39 units in this summer, we expect the trip rate will be highly reduced and we will increase the repetition rate to 20 pps or more.

SUMMARY

Since the C-band accelerator of SACLA generates high acceleration gradient as high as 35-38 MV/m, reliability of high power RF components and reduction of a trip rate are the key issues. The trip is dominantly due to an RF breakdown and an abnormal discharge of a thyatron tube. In order to reduce the number of RF breakdown, we performed an RF conditioning time of 700 hours. The RF breakdown rate was reduced to be 1/10 at an acceleration gradient of 38 MV/m. In order to reduce the number of a machine trip due to thyatron discharge, we modified the function of an interlock system. Thanks to these improvements, the trip rate was decreased and we were able to raise the beam energy. SACLA is currently operated at a beam energy of up to 8.5 GeV and an acceleration gradient of 38 MV/m, with an acceptable trip rate of once per 20-30 minutes in 10 pps. We confirmed the validity of the C-band high gradient acceleration for compact and stable XFEL facility.

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