SASE SATURATION AT THE SCSS TEST ACCELERATOR RANGING FROM 50 nm TO 60 nm

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Abstract

The SCSS (SPring-8 Compact SASE Source) test accelerator was built in 2005 in order to demonstrate the SCSS concept, i.e., the accelerator design based on the three key technologies: thermionic gun, C-band linac and in-vacuum undulator. In June 2006, laser amplification was first observed at the wavelength of 49 nm, however, it was found that the laser intensity did not saturate at that time. After that, several improvements have been made to the accelerator components and operation procedures to achieve saturation: e.g., repair of the downstream undulator having a large multipole field error, and improvement of the RF parameter stability. In October 2007, SASE saturation was verified by a measurement of the radiation pulse energy as a function of the wavelength, which was an alternative method to the normal gain curve measurement. The electron beam performance was deduced by comparing the experimental results with FEL simulations to conclude that the beam performance did not deteriorate during the process of acceleration and bunch compression. This is an encouraging result toward realization of the X-ray FEL based on the SCSS concept.

INTRODUCTION

The x-ray free electron laser (XFEL) facility, which is under construction at the SPring-8 site, is based on three key accelerator technologies: a low emittance injector in conjunction with a single crystal thermionic gun, high gradient normalconducting C-band accelerators, and in-vacuum undulators with a short magnetic period. Combination of these technologies makes it possible to reduce the facility scale and thus the total cost of construction. This accelerator design is significantly different from other XFEL projects [1]-[2] and called the SPring-8 Compact SASE Source (SCSS) concept.

Prior to construction of the XFEL machine, a test accelerator was built in 2005 in the SPring-8 site in order to demonstrate the SCSS concept. After accelerator commissioning for several months, the first FEL amplification was observed in June 2006 at the wavelength of 49 nm [3] although saturation of the laser power was not observed at that time. In order to achieve saturation, accelerator performances have been carefully investigated and a lot of im-

provements have been made to the accelerator components and operation procedure.

During the accelerator commissioning after the improvements, a significant enhancement of the laser intensity was observed together with a reduction of the pulse energy fluctuation. Finally in October 2007, SASE saturation was verified, by measuring the radiation characteristics as functions of the undulator gap, i.e., the radiation wavelength.

In this paper, an overview of the SCSS test accelerator and its commissioning history are described together with several key improvements toward achievement of the SASE saturation. In addition, results of investigation to evaluate the electron beam performance from the FEL intensity measurement are reported.

OVERVIEW OF THE TEST ACCELERATOR

Although the facility scale of the test accelerator ($\sim$60 m) is much smaller than the XFEL facility ($\sim$700 m) under construction, it consists of accelerator components essential for the XFEL facility. Figure 1 shows a schematic view of the accelerator layout. The electron beam with a bunch length of 1 nsec is extracted from the 500-kV pulsed DC gun and the following deflector. The electron charge after the deflector is 1 nC and thus the current is 1 A. The 238-MHz pre-buncher applies an energy chirp to compress the electron beam to a bunch length of $\sim$20 psec by means of velocity bunching, and the 476-MHz booster increases the beam energy up to 1 MeV. The S-band linac increases the beam energy to 45 MeV and provides an energy chirp to compress the beam to a bunch length of $\sim$1 psec with a magnetic chicane (bunch compressor) just after the S-band linac. After the bunch compressor, the beam is accelerated up to 250 MeV with a couple of normal conducting C-band accelerator cavities with a field gradient of 35 MV/m.

The chicane after the C-band linac is to eliminate the beam halo and to introduce the laser beam for seeding experiments or alignment of beam position monitors (BPMs) in the undulator section. The electron beam is finally injected to the undulator, which is composed of 2 in-vacuum undulators with the magnetic length of 4.5 m and magnetic period of 15 mm. The typical charge of the electron beam at the undulator entrance is $\sim$0.3 nC. The SASE radiation produced in the undulator is then transported to the diagnostics section while the electron beam is vertically de-
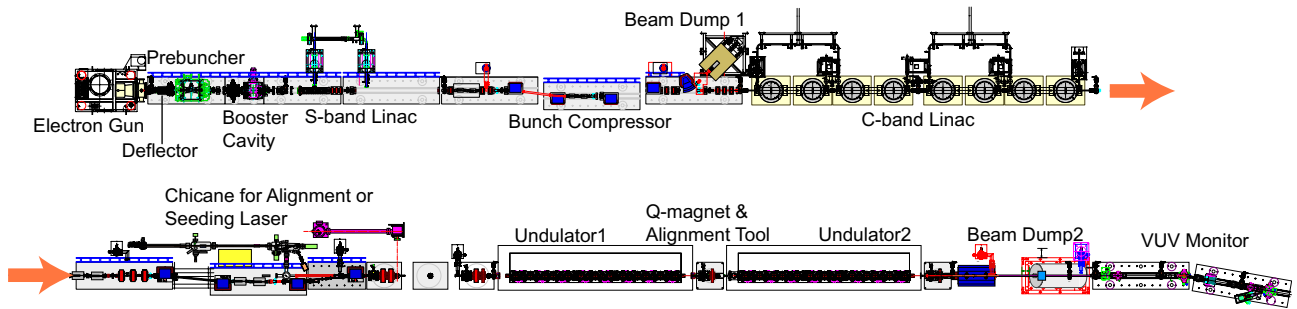
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Figure 1: Layout of the SCSS test accelerator.

flected by a dipole magnet and transported to the beam dump.

COMMISSIONING HISTORY

Figure 2 shows the time table of the accelerator commissioning of the SCSS test accelerator. The civil construction was finished in August 2005, and installation of the accelerator components started in September. The RF aging started in October and accelerator commissioning started in November. The 1st light from the undulator (spontaneous emission) was observed on 30th November. The electron energy at that time was 66 MeV and the wavelength was 480 nm.

Installation of the remaining accelerator components started in January 2006, and fine tuning of accelerator components, such as optimization of RF parameters and (projected) emittance measurement with the Q-scan method, started in April to aim at observation of FEL amplification with the electron energy of 250 MeV. The first symptom of the FEL amplification was verified on 20th June, as spectral narrowing at the wavelength of 49 nm. Then the radiation intensity was measured as a function of the bunch charge and the nonlinear dependence, being the proof of the laser amplification, was verified. In addition, the spatial coherence, which was evaluated by means of a double-slit method, was found to be much better than the spontaneous radiation. From these experimental results, it was found that the electron beam parameters would be close to those expected from the accelerator design, and that the FEL intensity should reach saturation just with the two undulator segments. It should be noted, however, that the laser intensity did not saturate in terms of the averaged pulse energy and shot-by-shot fluctuation, even after careful accelerator tuning.

After achievement of the FEL amplification, the accelerator tuning was devoted to seeding experiments at the electron energy of 150 MeV and the wavelength of 160 nm. A first result of seeding was obtained in December 2006, which was followed by investigation to improve the laser stability and characterization of the seeded FEL radiation [4]-[5].

In 2007, a lot of improvements have been made to the accelerator components toward realization of SASE saturation, which will be reported in the next section. Accelerator tuning aiming at SASE saturation started again in September 2007. After careful optimization of the electron trajectory and beam envelope matching in the undulator section, it was found that the laser intensity was enhanced by one or more orders of magnitude compared to that observed in 2006, and the fluctuation of the pulse energy was found to be around 10%. By measuring the averaged pulse energy and shot-by-shot fluctuation as a function of the radiation wavelength, it was verified that the laser intensity saturated in the wavelength region between 50 nm and 60 nm. The detail of this topic is discussed later in this paper.

IMPROVEMENTS TOWARD SASE SATURATION

A lot of improvements to the accelerator components and operation procedure have been made toward SASE saturation in the SCSS test accelerator. In this section, the details of these improvements are described except the topic on the stabilization of the injector RF system, which are already reported in [6] in detail.

Repair of the Undulator Magnet

The undulator of the SCSS test accelerator consists of two identical segments and the FEL gain in each segment should be the same in principle. However, it was found that the FEL gain in the 2nd undulator (downstream, U2) was much lower than that of the 1st undulator (upstream, U1). To be specific, no FEL amplification was observed with U2 alone, while significant FEL gain was obtained with U1, and the spectral bandwidth of spontaneous radiation from U2 was about 3 times broader than that from U1. This means that the magnetic performance of U2 was much worse than U1. Indeed, magnetic measurements showed that the r.m.s. phase error of U2 was about 10 degree, being three times larger than that of U1 (3 degree). This is because we were not able to take enough time to correct the phase error for U2 due to a tight schedule of construction. It should be noted, however, that the phase error of 10
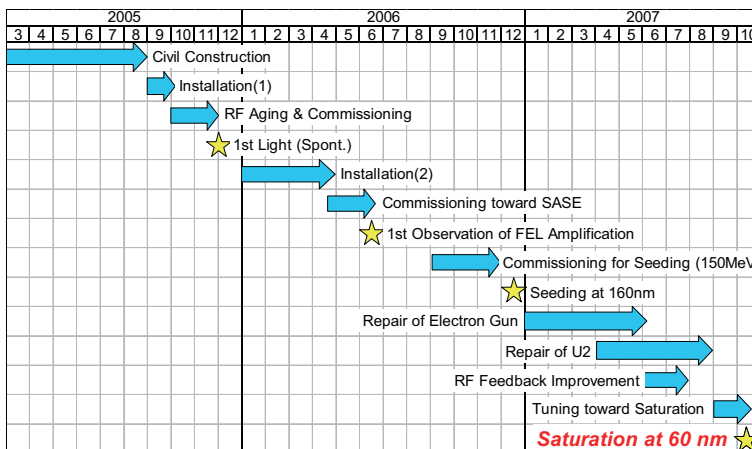
Figure 2: Time table of the SCSS test accelerator commissioning.

degree is not so large, especially for the fundamental radiation, as to be the main cause of the gain degradation and spectral broadening described above.

Besides the gain degradation, it was found that the transverse electron beam profile after U2 was distorted and inclined. This means that U2 had significant multipole error components. In fact, field integral measurements with a flipping coil system indicated that the magnetic field of U2 contained a strong skew quadrupole component. In the case of an undulator to be installed in the storage ring, the multipole components are always eliminated carefully. In construction of U2, we skipped this process because it was to be installed in the linear accelerator. However, we realized during the accelerator commissioning that the influence of the skew components on the beam dynamics was unexpectedly large due to the low electron energy and that the multipole components should be reduced as well as the storage ring.
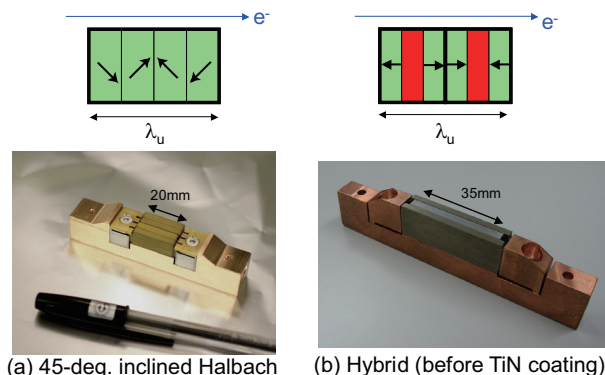

Figure 3: Magnet modules of U2 (a) before and (b) after the modification. Note that the hybrid magnet module is not yet coated with TiN, which is necessary to be used in in-vacuum undulators.

In principle, the multipole components can be corrected by flipping the magnet blocks horizontally or vertically, however, the multipole strength of U2 was too large to be

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corrected by the normal procedure. This is attributable to the design of the magnet blocks of U2, which is shown in Fig. 3 (a). In this design, four magnet blocks are assembled into a single holder (magnet module) and the magnetization axis is inclined by 45 degree compared to the normal Halbach configuration. This is to keep the symmetry of the magnet module and the flexibility of magnetic correction procedures for the phase and multipole error reduction [7]. From the viewpoint of magnet production, however, the inclined magnetization axis can cause a significant angular error and the resultant magnetic field performance can be unsatisfactory as found in U2. Therefore we have modified the magnet design as shown in Fig. 3 (b). This is the normal hybrid configuration adopted in a lot of SPring-8 in-vacuum undulators but not in the original U2 design due to difficulty in assembling. This problem was solved by a careful optimization of the shape and dimension of the magnet blocks, pole pieces, and clamping screws.

Trajectory Optimization

In order to avoid gain degradation, the electron trajectory in the undulator line should be as straight as possible both in the vertical and horizontal directions. This means that the parameters of several components in the undulator line should be optimized. Because the FEL gain is quite sensitive to the trajectory straightness, the FEL intensity monitored with a photo diode installed in the diagnostics beamline is used as a probe for optimization. Due to natural focusing in the undulator magnetic field, the optimization procedures in the vertical and horizontal directions are different.

Horizontal   In the horizontal direction, the coil current of the steering magnet installed between the two undulator segments is the only parameter to be optimized (Fig. 4 (a)). If there is a single kick error beyond the critical angle [8] at the drift section, the gain is degraded considerably. The coil current was optimized to reduce the kick error by monitoring the FEL intensity signal.

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Vertical   Because of the strong focusing in the vertical direction in the undulator, the electron beam is deflected if it is injected with a vertical slope and/or offset with respect to the axis of the magnetic center of the undulator, as shown in Fig. 4. In order to correct these errors, we have to sweep two parameters unlike the horizontal direction. In principle, any sets of steering magnets are available to correct the slope and offset, as far as they are installed before the undulator. However, the optimization is not straightforward due to other components such as the quadrupole magnets installed between the undulator and the steering magnets.

An alternative way is to optimize the undulator height and the steering magnet just before the undulator so that the slope and offset are effectively eliminated. In optimization of the steering current and height of U1, the gap of U2 was opened in order to eliminate the effects due to U2. Then, it was closed to determine the steering current and height of U2.
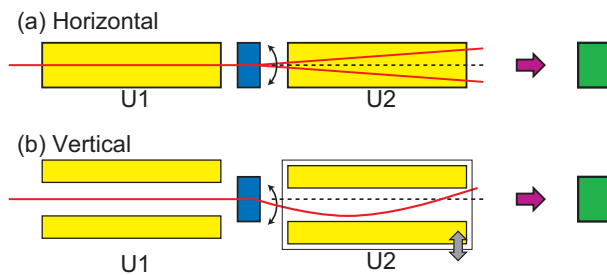

Figure 4: Trajectory correction procedure in the (a) horizontal and (b) vertical directions.

Envelope Matching

Since the FEL gain is dependent on the betatron functions in the undulator, the envelope matching or optimization of the focusing magnets is important. It should be noted, however, that the transverse beam profile measured with an optical transition radiation (OTR) monitor installed in the undulator line is the profile averaged over the whole electron bunch, and does not represent the profile of the lasing part. Thus it is not possible to optimize the focusing magnets by means of OTR monitors. Instead, we used the FEL intensity signal as a probe to investigate the response of each focusing magnet as well as the trajectory optimization, and found empirically several magnetic lenses and quadrupole magnets, to which the FEL intensity signal is quite sensitive. By tuning these parameters precisely, we succeeded in enhancement of the FEL gain by a factor of 2 to 5.

OBSERVATION OF SASE SATURATION

After the improvements described in the previous sections, the FEL intensity signal measured at the wavelength of 60 nm increased by one or more orders of magnitude and

was found to be close to that of the saturation power calculated from the beam parameters expected from the accelerator design. Furthermore the pulse energy fluctuation was found to be around 10 %, which was much less than that before the improvements. From these results, the SASE power seemed to saturate.

In order to verify SASE saturation, it is most straightforward to measure the gain curve, i.e., the radiation power P as a function of the undulator length z, which, within the framework of the linear FEL theory, is given by

$$P = P_0 \exp(z L_g^{-1}),$$

where P_0 is the effective input power and L_g is the gain length. The parameter z can be changed by opening the gap of several undulator segments or effectively by kicking out the electron beam by steering magnets. In the case of the SCSS test accelerator, however, both methods are not available: there are just 2 undulator segments and it is not easy to generate a magnetic field strong enough to kick out the beam.
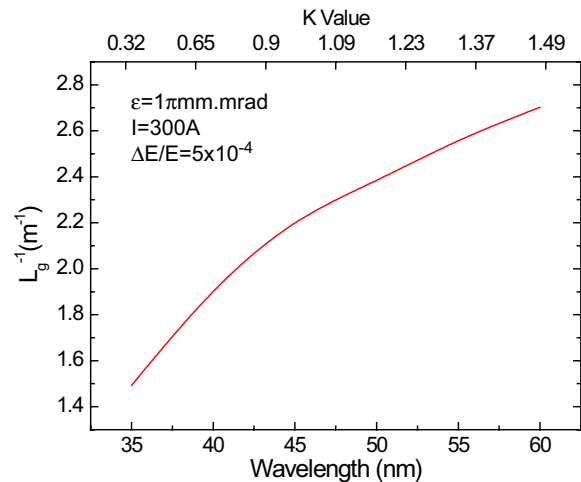

Figure 5: Inverse of the gain length as a function of the wavelength. The undulator K parameter is indicated in the upper abscissa.

Instead of z, we changed the parameter L_g by closing the undulator gap and thus changing the radiation wavelength. Figure 5 shows L_g^{-1} plotted as a function of the wavelength and the undulator K parameter, which is calculated with the beam parameters indicated in the figure. It is expected that the radiation power grows exponentially as the wavelength, and reaches saturation at a certain wavelength.

Based on the above concept, we measured the radiation pulse energy as a function of the wavelength. Figure 6 shows the measurement results in terms of the pulse energy averaged over 30 shots as a function of the wavelength. In addition, the shot-by-shot fluctuation of the pulse energy (r.m.s) is also plotted. The pulse energy was found to grow exponentially in the wavelength region shorter than 40 nm, while the growth rate became drastically low in the wavelength region longer than 50 nm. What was more clear was

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the pulse energy fluctuation. At the wavelength of 30 nm, the fluctuation was less than 10%, which means that the radiation process was spontaneous and no laser amplification took place. For longer wavelength, the fluctuation became larger and reached 40% at the wavelength of 40 nm. Clearly, the laser amplification based on SASE took place in this wavelength region. At the wavelength longer than 50 nm, the fluctuation was found to be small and around 10%. From these results, we can conclude that the SASE process reached saturation at the wavelength region longer than 50 nm.
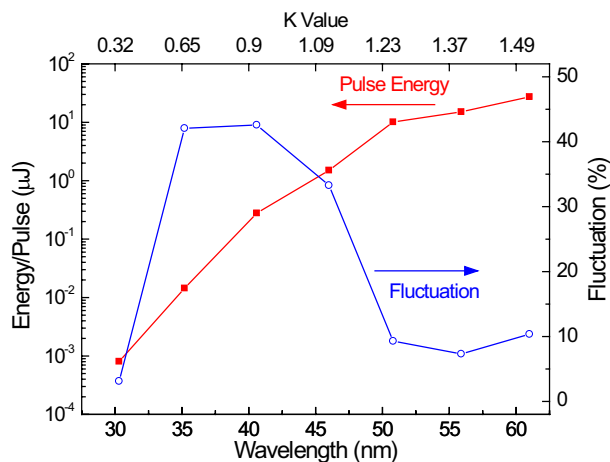

Figure 6: Pulse energy averaged over 30 shots and r.m.s. fluctuation as functions of the radiation wavelength.

After the above measurement to verify SASE saturation, we have measured the stability of the FEL beam at the wavelength of 60 nm in terms of the long-term drift and the pointing stability, and found that the variation of the laser power was about 10% for 1 hour, and that the pointing stability was better than 5%, which was measured at the position 10 m from the undulator exit.

EVALUATION OF ELECTRON BEAM PERFORMANCES

The achievement of SASE saturation in the SCSS test accelerator is an important step toward the realization of X-ray FEL based on the SCSS concept. It should be noted, however, that requirements on the beam parameters are more severe for shorter wavelengths. Thus it is important to investigate quantitatively the performances of the electron beam, especially the sliced beam parameters but not the projected ones.

The sliced beam parameters can be measured directly by means of a transverse deflection cavity, which has not been installed in the SCSS test accelerator. Instead, we first measured the current profile with an RF zero phasing method [9]. Next, we performed FEL simulations with the measured current profile taken into account, in order to compare with the experimental results and deduce the

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beam parameters. The 3-D FEL simulation code SIM-PLEX [10], developed at the SPring-8, has been used for the simulations. In each simulation, we have assumed that the normalized sliced emittance (ε) and r.m.s. energy spread (σ_E/E) are kept constant over the whole bunch. In order to be consistent with the experiments, we repeated FEL simulations 30 times with the same conditions except the input seed for the random-number generator. Figure 7 shows the results of simulations in terms of the pulse energy at the undulator exit averaged over the 30 sets of simulations, for three different values of ε with an assumption that $\sigma_E/E = 5\times10^{-4}$.
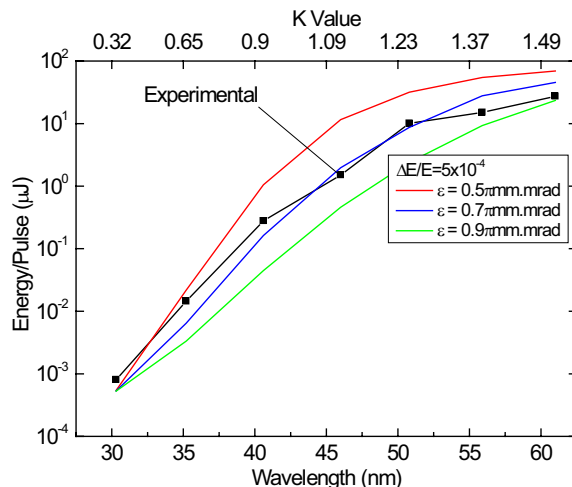

Figure 7: Comparison of the experimental results with simulations.

It has been found that FEL simulations with $(\varepsilon, \sigma_E/E) = (0.7, 5\times10^{-4})$ are in good agreement with the experimental results. Because the FEL gain length is dependent both on ε and σ_E/E, it is not possible to determine uniquely the two parameters only by the simulations. Instead, we can look for a relation between the two parameters that are consistent with the experimental results. The gain length L_g at the wavelength of 60 nm, calculated with the above beam parameters by means of the universal scaling function [11], was found to be around 0.4 m. It is possible to calculate ε as a function of σ_E/E that gives the gain length of 0.4 m, which is plotted in Fig. 8.

The dashed line shows the value of ε previously measured just after the electron gun by the double-slit method [12]. Because ε of the electron beam at the undulator entrance cannot be better than this value, and σ_E/E cannot be lower than 0, we can conclude that (1) σ_E/E is at least better than 6×10^{-4} and (2) ε is at least better than 0.8πmm.mrad. The second conclusion suggests that the beam emittance does not deteriorate significantly during the multi-stage bunch compression process, which is an encouraging result toward realization of the XFEL facility based on the SCSS concept.
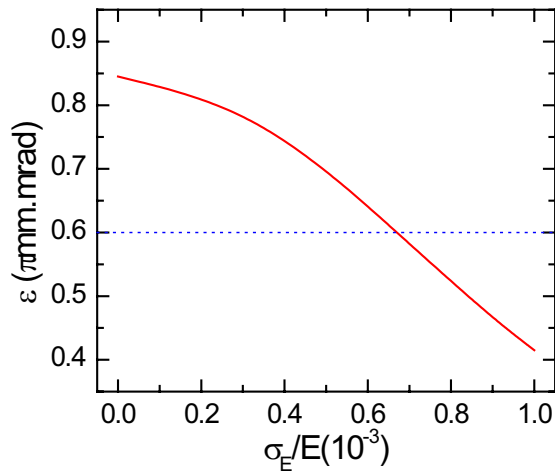
Figure 8: Relation between ε and σ_E/E to give the gain length of 0.4 m.

SUMMARY

The SCSS test accelerator was built in 2005 in order to demonstrate the SCSS concept, and has been operated for about 3 years. As described in this paper, SASE saturation was achieved in 2007 after several improvements to the accelerator components and fine accelerator tuning. The beam parameters deduced from the comparison between the experimental and FEL simulation results have been found to be very promising. After the accelerator commissioning dedicated to improve the FEL performance, user experiments in the SCSS test accelerator have been started in October 2007. The experiments have been carried out in success thanks to the stable operation of the accelerator, and several results have been already obtained and published [13].

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