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Operation of a Small-Gap Undulator on the NSLS X-ray Ring*

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Abstract

We report results of an on-going experiment being carried out in the X13 straight section of the NSLS X-ray Ring which explores the limits of the operation of small-gap undulators. In particular, we discuss the operation of a 16 mm period small-gap undulator. At an electron beam current of 300 mA the variable gap vacuum chamber has been closed to an inner aperture of 3.8 mm with no effect on the electron beam lifetime. Measurements of the output radiation spectrum at a magnet gap of 7.5 mm are described.

I. *Introduction*

The development of high-brightness synchrotron radiation sources has been advanced by the utilization of permanent magnet insertion devices, pioneered by Klaus Halbach [1]. Such permanent magnet devices provide high field strength, excellent field quality, and impressive reliability in a very economical manner. Here, our interest is in the implementation of short-period, small-gap undulators situated in low-beta insertions of a storage ring. In particular, we report results of an on-going experiment being carried out in the X13 straight section of the NSLS X-ray Ring, which explores the limits of the operation of small-gap devices.

The vertical magnetic field B_y in a pure-permanent-magnet undulator has an approximately sinusoidal dependence on the axial coordinate z,

$$B_y = B_u \sin 2\pi z/\lambda_u ,$$

where λ_u is the undulator period length. The peak field B_u depends exponentially on the full magnet gap G,

$$B_u \propto \exp\left(-\pi G/\lambda_u\right) .$$

From this it is clear that to achieve high magnetic field strength at short periods

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requires small magnet gap and hence small electron beam aperture. Placing the undulator at a location with small vertical betatron function permits long electron beam lifetimes with small vertical aperture. In the X-ray Ring the vertical beta function has a value of β_v=0.33m at the insertion center.

The motivation for desiring short-period undulators is also clear. The fundamental radiated wavelength λ_1 from an undulator is

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right),$$

where the field strength parameter K is given by

$$K = 0.93 \;\; B_u(T) \;\; \lambda_u(cm),$$

and γ is the electron energy in units of electron rest mass. One usually wants K to be of order unity to have high flux and reasonable tuning range. For a given electron energy, in order to obtain shorter radiated wavelength in the fundamental, the period length λ_u must be decreased. To maintain K near unity, it is then necessary to reduce the gap G.

Some potential limitations on the electron beam aperture, and hence the undulator gap, are Coulomb scattering lifetime, transverse impedance of the vacuum chamber, vacuum pressure in the low-conductance region of the small aperture chamber, and possible ion trapping in this region. We have successfully operated the X-ray Ring with a vertical beam aperture of only 3.8mm in the prototype small-gap undulator chamber, and obtained a high-brightness output radiation beam at 3 KeV in the fundamental from a pure-permanent-magnet undulator having a 16mm period length, operating at a full gap of 7.5 mm.

In what follows, a brief description of the small-gap undulator system is presented, followed by results from studies of the stored beam lifetime as a function of electron beam aperture. Finally, a measurement of the output radiation spectrum is described and presented.

II. *Description of Small-Gap Undulator System*

The NSLS Prototype Small-Gap Undulator (PSGU) is comprised of three major components: a variable-aperture vacuum chamber with drive system, a

pure-permanent-magnet small-period undulator with an independent drive system, and an elevator base stage, upon which all of the above components are supported. The design concept of the variable-aperture chamber has been described elsewhere [2], but is summarized using Fig. 1.

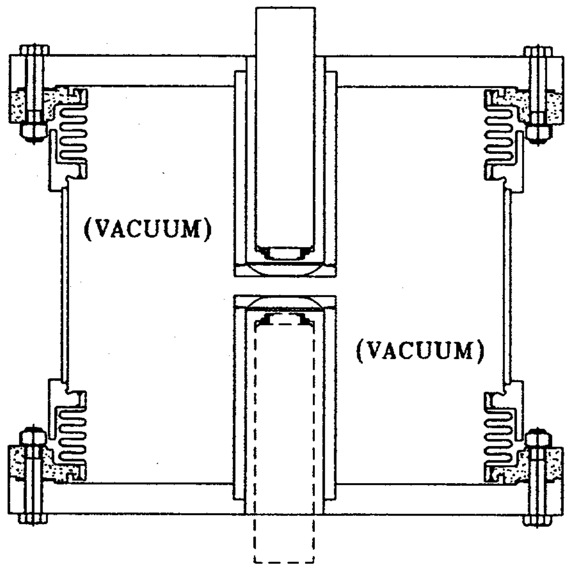

Figure 1 Cross section of the Prototype Small-Gap Undulator (PSGU) vacuum chamber, as seen along the stored beam direction. Deep wells from the top and bottom flanges extend toward the electron beam. Bellows permit the wells to be moved closer together, or apart. The regions of the wells nearest the electron beam are thinned to 1 mm and the undulator magnet arrays are inserted into the wells, up to the thinned region. The chamber is about 460 mm in diameter.

The figure presents a cross section of the vacuum chamber, as seen along the stored beam direction. Deep wells, from the top and bottom flanges, extend towards the stored beam and can be moved closer together or apart by means of top and bottom bellows. The central section of the chamber, between the bellows, is fastened through legs to the elevator base stage below, while actuators attached between the two flanges control the electron beam aperture. The portions of the wells near the stored beam are thinned to 1 mm, and the magnet arrays of the undulator are inserted into the wells, up near the thinned region. The chamber is cylindrical, about 460 mm in diameter, with its axis oriented vertically. At present, the electron beam aperture is variable between

14 mm and 3.8 mm, and the small-aperture region is 104 mm wide and 390 mm long.

The PSGU undulator magnet is 320 mm long, with a 16 mm period. It uses NdFeB magnets in a high-performance 6 block/period version of the Halbach pure-permanent-magnet design (see Fig. 2).

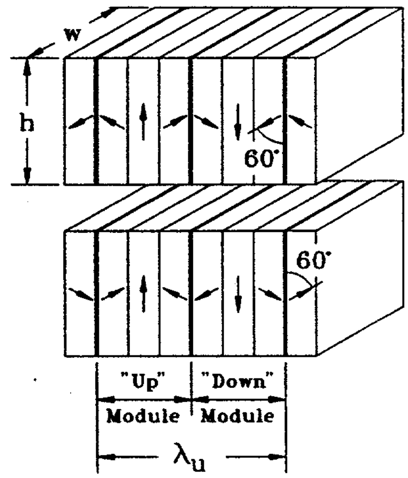

Figure 2 Schematic of the six block/period pure-permanent-magnet structure used in the PSGU undulator.

Its construction and magnetic field mapping are presented in detail elsewhere [3], but the mapping results are summarized in Table 1 and Fig. 3.

Table 1. PSGU Integrated Multipoles

Multipole	Goals	Measured	Units
Dipole	100	7	G•cm
Skew Dipole	100	-20	G•cm
Quadrupole	10	-5	gauss
Skew Quadrupole	100	-18††	gauss
Sextupole	50	-37	G/cm
Skew Sextupole	50	-30††	G/cm

†† Values determined using $\Delta x=\pm 2$ mm. All others: ±4 mm.

The magnet gap was fixed at 6 mm for these measurements, which is the design goal for actual use of the undulator. At this gap, a peak field of 0.623 Tesla was obtained.

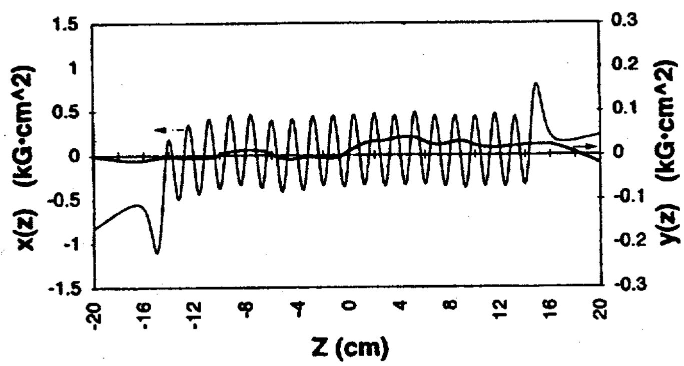

Figure 3 The x and y trajectories in the completed PSGU undulator, at a magnet gap of 6 mm. Note the different scales for x and y.

The undulator magnet beams are mounted to an independent drive system which presently enables magnet gaps between 7.35 mm and 26 mm within the wells of the PSGU vacuum chamber.

Using these parameters, the predicted performance of the undulator is summarized in Fig. 4 using a "tuning curve". This is a plot of the central-cone photon flux vs. photon energy for the whole range of possible magnet gaps. First, second, and third harmonics are illustrated as separate curves. Any single magnet gap corresponds to only three points, one on each curve. For example, the prediction for the 7.35 mm gap is indicated where the curves change from solid to dashed. The second harmonic curve is only roughly estimated, by doubling the flux expected in the third harmonic . The solid portion of the curve illustrates the capabilities of PSGU at the present time. However, we plan to re-work the vacuum chamber and the magnet drive in the near future to permit a minimum operational aperture of about 2mm and perhaps a magnet gap of as small as 5 mm. If the 5 mm magnet gap can be achieved, the dashed extension of the tuning curve results.

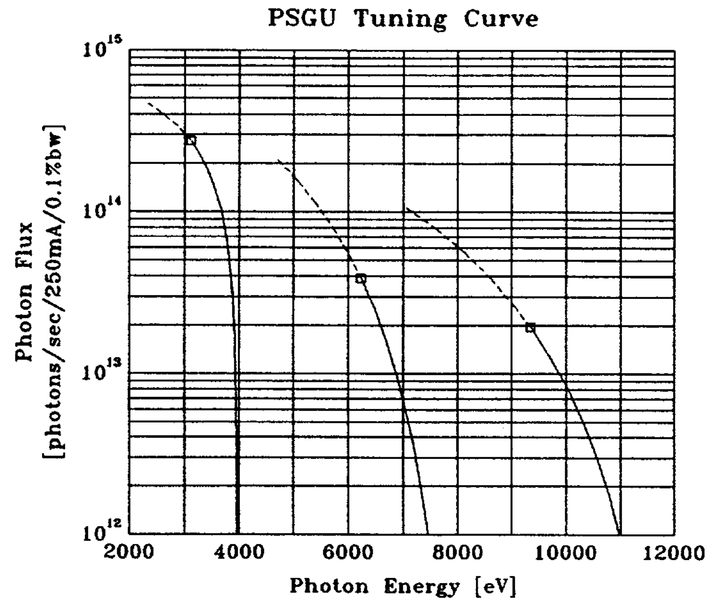

Figure 4 PSGU theoretical tuning curve, illustrating the first, second and third harmonics. The second harmonic curve is only a rough estimate, obtained by doubling the values for the third harmonic. The solid curves illustrate the present range of PSGU, to a minimum magnet gap of 7.35mm. If the minimum gap can be decreased to 5 mm, the dashed extension of the curves results.

The elevator base-stage provides mounting fixtures for the chamber and its drive, and the undulator magnet and its drive. In addition, it provides a ± 3 mm vertical translation of the chamber and magnet assemblies about nominal beam height.

III. Studies of Beam Lifetime vs. Electron Beam Aperture:

A. 4-jaw Scraper:

While design and fabrication of PSGU components were still on-going, an existing 4-jaw scraper assembly was refurbished and installed in the X-ray Ring, near the location intended for PSGU.

By measuring beam lifetime as a function of the electron beam aperture (determined by the scraper blades), we hoped to verify our estimates of the existing storage ring limiting aperture and thereby obtain a preview of the best-case operational aperture for PSGU. The vertical blades of the scraper were located about 150 mm upstream of the X13 straight section centerline (β_v=0.4m), while the extreme ends of the small-aperture region in PSGU are about 200 mm from the straight centerline, upstream and downstream. The 4 scraper blades were uncooled copper, 5 mm thick, two horizontal and two vertical, each on individually-controlled actuators. Only a single blade was used at a time.

Data were taken by moving one blade of the scraper in small steps and measuring the beam lifetime which resulted. The DC current transformer is usually used to measure lifetimes during normal operations shifts, but for these studies its time-response was too slow, and sometimes became oscillatory. Instead, lifetimes were calculated by the change in amplitude of a stripline sum signal over time, which was monitored at 53 MHZ using a spectrum analyzer. Fig. 5 presents one set of results.

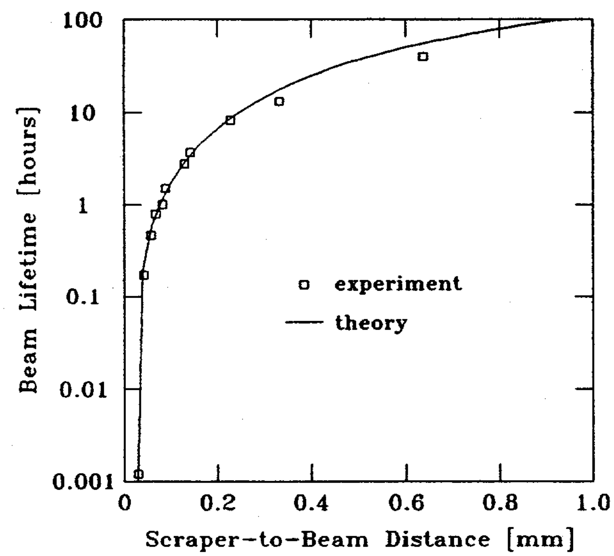

Figure 5 Vertical scraper results: initial stored beam of 21 mA at 2.584 GeV, 25 bunches, small-vertical-beam-size optics. These results suggest that a full electron beam aperture of about 2 mm might be imposed at this location without degradation of beam lifetime.

The initial stored beam was 21 mA at 2.584 GeV, in 25 bunches and used a small-vertical-beam-size optics [4]. (These optics have since become the normal-operation condition.) The theory curve [5] contains four contributions: the quantum lifetime, the nuclear Coulomb scattering lifetime for both horizontal and vertical apertures, and the nuclear bremsstrahlung lifetime. Of these, only the quantum and the Coulomb components depend on the vertical beam aperture. By decomposing the total lifetime into its components, one finds that Coulomb scattering dominates for lifetimes above 0.1 hour, but below this the quantum lifetime dominates. The theoretical curve is fit to the data using a number of adjustable parameters. The experimental points are offset along the abscissa by a constant (185 μm), which reflects the lack of absolute position calibration of the scraper blade. The storage ring pressure is adjusted in the formulas for best fit in the 10-to-0.1-hour region (0.15 n torr), and the vertical beam size is similarly adjusted for best fit around 0.1 hour and below (σ_y=7μm). Of these adjustable parameters, the resulting ring pressure seems somewhat too low, but the other parameters seem reasonable. The observed ring lifetime with all scraper blades fully withdrawn (≥ 19 mm from the beam) was 100 hours or more. This suggests that the full ring lifetime is attained at a half aperture of about 1 mm, as seen in Fig.5 or full aperture of about 2 mm. Such a result is about half the minimum aperture expected from scaling the aperture at the β-max by the square-root of the beta function, and implies that PSGU might operate down to a 2.5mm aperture without lifetime degradation.

B. PSGU Vacuum Chamber

The implications of the 4-jaw scraper results held true for the operation of the PSGU variable-gap vacuum chamber. When centered on the electron beam and closed to the minimum aperture of 3.8 mm, no change in the storage ring lifetime was observed. This was true not only for low beam currents, but also for 300 mA at 2.584 GeV, which is above the limits for present normal operations. No instabiity from vacuum chamber impedance was observed, confirming expectations from theory [6] and impedance measurements [7]. When the undulator magnet was then closed to a gap of 7.5 mm, with both local and global feedback systems disengaged, no change in the electron beam orbit was observed, which is consistent with the integrated multipole field goals listed in Table 1.

To reduce the electron beam aperture below 3.8 mm, the small-aperture region was offset from its initial position (centered on the electron beam) by use of the elevator base stage. The results appear in Fig. 6. The stored beam conditions were essentially the same as for the scraper results presented in Fig. 5. The theory curve was generated as in the previous case, but offset to match the data, and reflected about the 0 mm position. The adjustable parameters required were 0.3 ntorr for the pressure and σ_y=8.5µm, similar to the values obtained from the scraper measurements. As before, the quantum lifetime dominates the theory curve for lifetimes below 0.1 hours; otherwise, the Coulomb scattering lifetime is dominant. The lifetime with the aperture centered on the electron beam was about 61 hours, as can be seen from Fig. 6. Interpretation of these results takes a little more care. It seems clear that an offset of the aperture is possible before any lifetime degradation is seen; offsets between 0.5 mm and 1.0 mm seem reasonable. If we use 0.5 mm as an example, this means that the

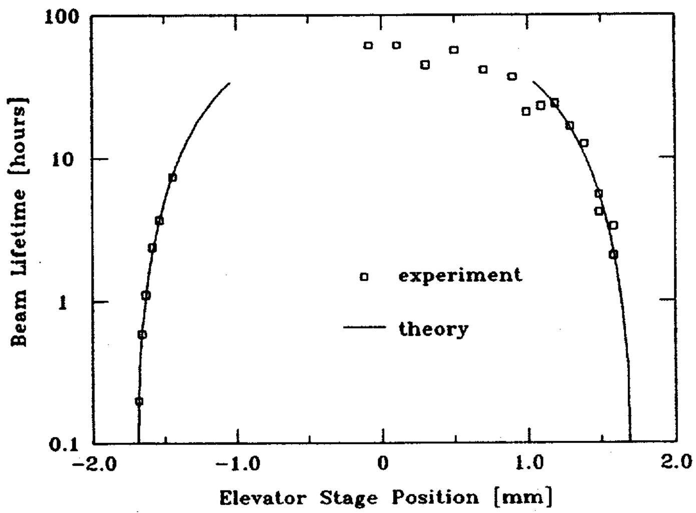

Figure 6 Results of vertical translation of the PSGU minimum aperture (3.8mm). Initial stored beam of 30 mA at 2.584 GeV, 25 bunches, small-vertical-beam-size optics. These results suggest that a minimum aperture 1 to 2 mm still smaller might be used without lifetime degradation.

minimum half aperture may be decreased by 0.5 mm, or a full aperture reduction of 1.0 mm, from 3.8 mm to 2.8 mm. While this neglects the effects of possible ion trapping or other instabilities which may not be well represented in this offset geometry, it suggests that a full aperture of between 2.7 mm and 1.7 mm may be plausible. This strongly motivates a re-work of the vacuum chamber to achieve such apertures while centered on the electron beam.

IV. *Measurement of Undulator Radiation:*

Following installation of the PSGU magnet and drive system, the X13 beamline was modified and a simple single-crystal x-ray spectrometer was installed to measure the radiation spectrum. The result appears in Fig. 7. The ultrahigh vacuum portion of the beamline was terminated with a 127 μm thick Be window, about 17 m from the undulator. The spectrometer was attached downstream of this window and consists of a 330 mm long flight path and a 450 mm diameter tank containing an entrance slit and a small $\theta/2\theta$ goniometer system. A Si(lll) crystal was mounted on the θ axis, while a small, windowless ion chamber was attached to the 2θ arm. The slit was set to 1 mm vertical, which limited the radiation passed to a fraction of the central cone of the undulator output. The tank and flight path were filled either with He or N_2.

When He filled the spectrometer, the undulator fundamental radiation could reach the crystal and be diffracted into the ion chamber, where sufficient photon absorption in the He produced a measurable signal. For the higher harmonics, however, the He absorption was so low, that the ion chamber response was very weak. A different result occurred when the spectrometer was filled with N_2. Here, the *fundamental* was adsorbed in N_2 before reaching the crystal, while the *harmonics*, reached the crystal and produced sufficient photon absorption in the ion chamber to obtain a measurable signal. Therefore, combining the two spectra obtained with He or N_2 in the spectrometer permitted both the fundamental and harmonics to be measured.

To obtain an absolute energy calibration, a thin Ni foil was attached over the end of the flight path, where it joined the spectrometer tank. A short spectrum was taken which included the Ni K absorption feature, at (8.333 KeV) and was used to correct the other spectra.

The experimental data presented in Fig. 7 were taken at 26 mA at 2.584 GeV, with PSGU set to an inner aperture of 3.8 mm and a magnet gap of 7.5 mm (K=0.716). The current was kept low to prevent overheating of the Be window. The theory curve was obtained from the URGENT code [8], by specifying the basic undulator and storage ring parameters, the undulator K-parameter, and the location and size of the spectrometer slit. The processing of the experimental data involved almost no adjustable parameters. The absorption of the Be window and of the spectrometer gas (either He or N_2) was removed, and the absolute efficiency of the ion chamber was calculated using absorption coefficients and the chamber dimensions. Finally, the bandwidth of the Si(lll) analyzer was included. There was a significant scattered background from the analyzer crystal in the detected signal, especially in the case with He gas. Only in the He data, a constant background was subtracted to bring the lowest part of the curve back to zero. In Fig. 7, the short vertical line in the experiment curve at about 4.6 KeV is the splice point between the data taken with He gas (to lower energies) and that taken with N_2 gas (higher energies). The departure of the

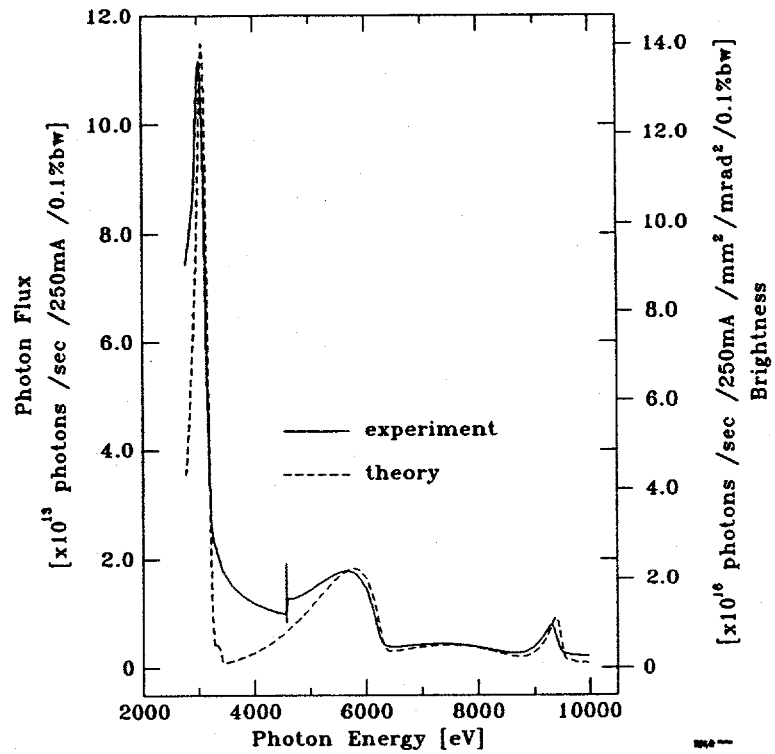

Figure 7 Spectrum measured for the PSGU undulator for a magnet gap of 7.5 mm, K=0.716, at 2.584 GeV, 26 mA, with an inner aperture of 3.8 mm. The theory curve was obtained using the URGENT [8] code.

experiment from the theory in this region may well be due to the scattered background, in the case of the He data, and to the influence of the Si(333) reflection, which produces a peak in the apparent position of the fundamental from the third harmonic. This peak is erroneously blown up to gigantic proportions when the absorption correction is applied, and its tail is still influencing the rising edge of the second harmonic. Despite these complications, the agreement with the theory is rather good. The data may suggest that the K parameter is somewhat greater than 0.716, since the peaks of first, second, and third harmonics all seem to be at slightly lower photon energies than predicted by the theory.

V. Concluding Remarks

We have successfully operated a small-gap undulator with a full vertical electron beam aperture of only 3.8mm, with no degradation of beam lifetime. Measurements carried out using the elevator stage strongly suggest that successful operation will be possible for a vertical beam aperture less than 3mm. In order to verify this, we plan to rework the PSGU vacuum chamber in December, 1994 to permit a minimum-attainable aperture of 2mm. Also, consideration will be given to reducing the present clearance between the magnet and chamber. In this manner we believe we will be able to achieve the design goal of a 6mm magnet gap.

In the longer term there is the very exciting opportunity to build a device utilizing an in-vacuum undulator magnet, along the lines of the work at KEK [9]. This would permit the operation of an undulator having first harmonic radiation at 5 KeV, with a period length of 10mm and a field strength parameter K. 0.7. Alternatively, a device with the present 16 mm period but 1 m long could be operated at a 5 mm gap for a K of nearly 1.2.

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