PROGRESS TOWARDS ELECTRON-BEAM FEEDBACK AT THE NANOMETRE LEVEL AT THE ACCELERATOR TEST FACILITY (ATF2) AT KEK

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Abstract

Ultra-low latency beam-based digital feedbacks have been developed by the Feedback On Nanosecond Timescales (FONT) Group and tested at the Accelerator Test Facility (ATF2) at KEK in a programme aimed at beam stabilisation at the nanometre level at the ATF2 final focus. Three prototypes were tested: 1) A feedback system based on high-resolution stripline BPMs was used to stabilise the beam orbit in the beamline region c. 50m upstream of the final focus. 2) Information from this system was used in a feed-forward mode to stabilise the beam locally at the final focus. 3) A final-focus local feedback system utilising cavity BPMs was deployed. In all three cases the degree of beam stabilisation was observed in high-precision cavity BPMs at the ATF2 interaction point. Latest results are reported on stabilising the beam position to approximately 50nm.

INTRODUCTION

A number of fast beam-based feedback systems are required at future single-pass beamlines such as the International Linear Collider (ILC) [1]. For example, at the interaction point (IP) a system operating on nanosecond timescales within each bunch train is required to compensate for residual vibration-induced jitter on the final-focus magnets by steering the electron and positron beams into collision. The deflection of the outgoing beam is measured by a beam position monitor (BPM) and a correcting kick applied to the incoming other beam. In addition, a pulse-to-pulse feedback system is envisaged for optimising the luminosity on timescales corresponding to 5 Hz.

The Feedback on Nanosecond Timescales (FONT) project has developed ILC prototype systems, incorporating digital feedback processors based on Field Programmable Gate Arrays (FPGAs), to provide feedback correction systems for sub-micron-level beam stabilisation at the KEK Accelerator Test Facility (ATF2) [2]. Previous results [3], [4] have demonstrated an upstream closed-loop feedback system that meets the ILC jitter correction and latency requirements. Earlier results demonstrating the propagation of the correction obtained using the upstream stripline BPM feedback system at ATF2 are reported in [5]. The ultimate aim is to attempt vertical beam stabilisation at the nanometre-level at the ATF2 IP [6]. An overview of the extraction and final focus beamlines at the ATF, showing the positions of the FONT5 system components in both the upstream and IP regions, is given in Fig. 1.

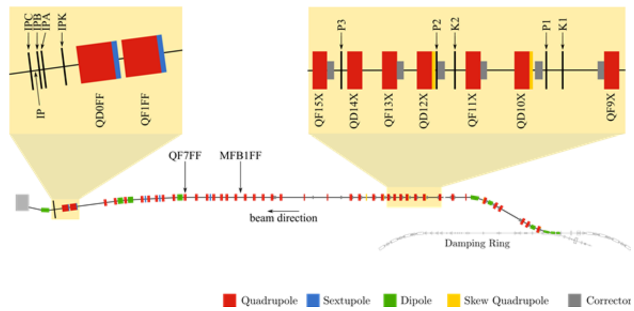

Figure 1: Layout [7] of the ATF extraction and final focus beamline with the FONT regions zoomed in.

We report here the latest developments and beam testing results from the FONT project using both the upstream stripline BPM system as well as near-IP cavity BPMs [8,9] to drive feedbacks for stabilising the beam at the IP.

UPSTREAM FEEDBACK SYSTEM

The upstream feedback system (Fig. 1) comprises 3 stripline BPMs and 2 stripline kickers. The design goal for this system is to stabilize the vertical beam position to the 1 µm level at the entrance to the final-focus system. This requires BPMs capable of resolving bunches separated in time by around 100 ns, and with a position resolution at the submicron level. For tests of the FONT5 system the ATF is operated in a mode whereby a train of two or three bunches is extracted from the damping ring and sent down the ATF2 beam line. The bunch separation is determined by the damping ring fill pattern and typically is chosen to be between 140 ns and either 154 ns (3-bunch mode) or 300 ns (2-bunch mode).

Stripline BPMs (Fig. 2) were used due to their inherently fast, broadband response and capability to resolve bunches with the required time resolution. In the FONT5 system only the vertical plane of the BPMs is routinely instrumented (Fig. 3) with an analogue processor (Fig. 4), which functions [7] so as to deliver the stripline pickoff-pair difference and sum signals in a form that can be easily recorded by the digitizer for calculation of the position-dependent, beam charge-independent ratio of the two. Ten processors were built and are used in beam operations at ATF2. A single BPM processor can be used to process the beam position data in either the horizontal or vertical plane; from here on only the vertical plane is considered.

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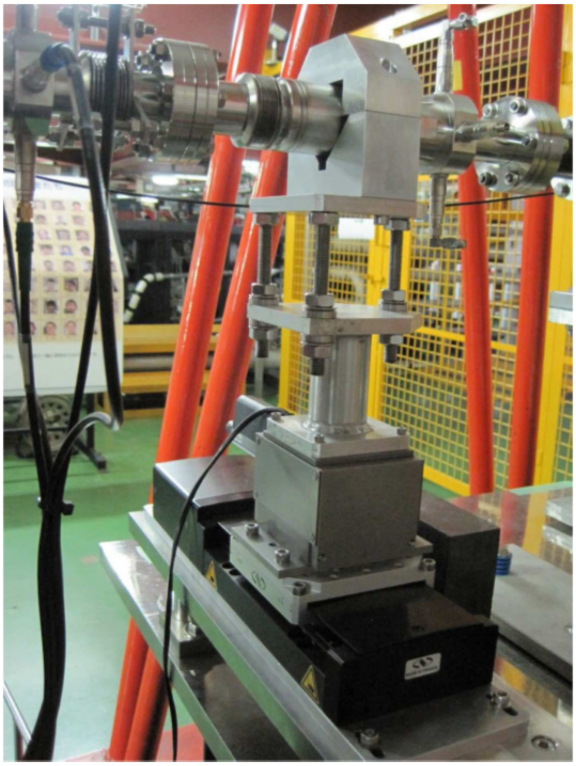

Figure 2: Photograph of FONT5 stripline BPM P3 and its mover in the ATF2 beam line.

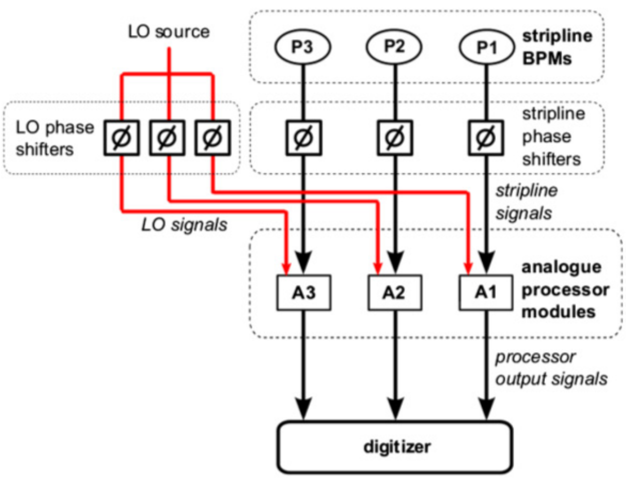

Figure 3: Schematic of the BPM system. For each BPM, a phase shifter is used on one of the stripline signals to adjust the relative path lengths of the two input signals at the BPM processor, and another phase shifter is used to adjust the phase of the LO signal at each processor.

Analogue Processor Latency

The latency of the processor is defined to be the time interval between the arrival of the stripline signals at the inputs and the peak of the signals at the outputs. One of the principal design goals was that the latency should be low, while providing baseband output pulses that are amenable to convenient digitization. The latency was measured by using a test bench to provide realistic beam-proxy input signals and observing on an oscilloscope the arrival time of the processed output signal (Fig. 6). Subtracting from this the time of arrival at the oscilloscope of the input when the processor is bypassed, the processor latency before the amplifier stage was found to be 10.4+-0.1 ns, and 15.6+-0.1 ns including the amplifier stage (Fig. 4).

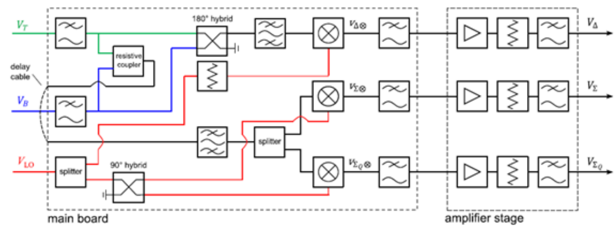

Figure 4: Schematic diagram illustrating the structure of the FONT5 analogue processor.

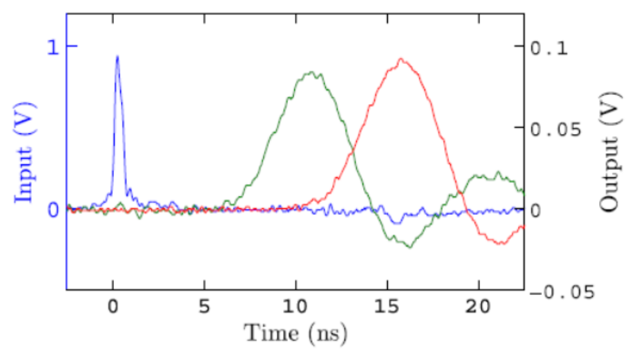

Figure 5: Input beam proxy signal (blue, left-hand scale) and processor output difference signal before the amplifier stage (green, right-hand scale, with factor 5 multiplication), and after the amplifier stage (red, right-hand scale), vs time (ns). The amplifier stage delays the output signal by an additional 5.2 ns.

Digitisation

The BPM processor outputs are digitised by the FONT5 custom digital feedback processor board (Fig. 6). The board has nine analogue signal input channels digitised using ADCs with a maximum conversion rate of 400Ms/s

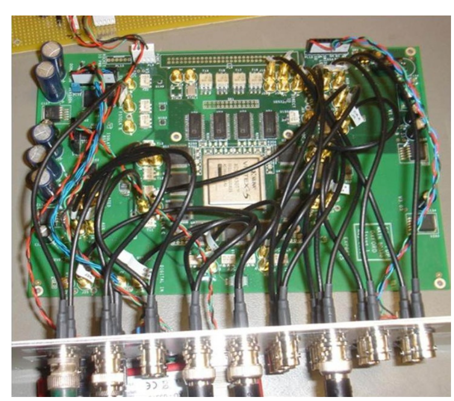

Figure 6: FONT5 digital feedback board.

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and two analogue output channels formed using DACs, which can be clocked at up to 210 MHz. The digital signal processing is based on a Xilinx Virtex5 FPGA. The FPGA is clocked with a 357 MHz source derived from the ATF master oscillator and hence locked to the beam. The ADCs are clocked at 357 MHz.

BPM Performance

The range of linear response is defined to be the range over which the system responds linearly to a change in beam position. A nonlinear response is expected if the input signal to a mixer (Fig. 4) is large enough to cause its output to saturate. Saturation will be avoided if the mixer RF input signal level is small compared with the design LO input signal level, ~7 dBm. For optimum resolution, the stripline BPM signals can be attenuated to ensure that for the nominal beam charge (~1 nC) the sum-channel signal level is comfortably below the mixer saturation point. The processor output is then expected to be linear for $|y| \lesssim 400$ µm, in agreement with corresponding measurements [7].

The resolution of the system is determined by comparing the beam position measured in one BPM with the position predicted at that BPM on the basis of the beam positions measured in the other two BPMs. Assuming that the three BPMs have the same resolution, σ, these residuals yield a resolution estimate, for a centred beam with a bunch charge of approximately 1 nC, of σ = 291+-10 nm [7] which is world leading in terms of the position resolution obtained in stripline BPMs in single-pass beam mode. Such a level of performance is achieved routinely in beam operations. For comparison, a global least-squares fit can be performed to explicitly minimize σ. For the same data set this yields a value for the resolution of 262+-11 nm. As this method removes any correlated components of the BPM position data, and also allows for variation in the individual BPM scale factors, this result represents the minimum possible resolution that could, in principle, be attained, if for example any residual correlated effects were accounted for. In contrast, the value obtained using the beam line model better represents the actual minimum sensitivity attainable in a given position measurement. The value attained with the least-squares fit is consistent with that expected from the measured system noise.

Upstream Feedback System Performance

Fig. 7 shows the vertical position of bunches 1 and 2 recorded in the feedback input BPMs, P2 and P3, as well as in the downstream BPM MFB1FF (see Fig. 1), which acts as an independent witness of the beam correction by the feedback loop. By construction bunch 1 is not corrected, but provides the input position information for the correction of bunch 2. The feedback reduced the vertical beam jitter from an r.m.s. deviation of 1.9um to 0.5um (P2) and from 1.7um to 0.6um (P3), representing a jitter reduction by a factor of slightly more than 3. The jitter at BPM MFB1FF, roughly 30m downstream, was reduced by the same factor, from 26um to c. 8um, thus demonstrating no detectable additional sources of beam jitter between P3 and MFB1FF.

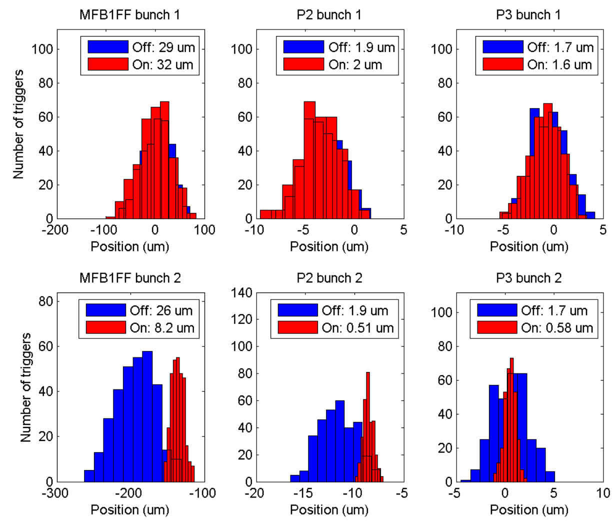

Figure 7: Distribution of vertical beam position measured in BPM (left to right) MFB1FF, P2 and P3 for bunch 1 (top row) and bunch 2 (bottom row) with feedback off (blue) and on (red) respectively.

A detailed simulation of the ATF2 beamline was used [8] to model the tracking of the vertical beam position from the measured inputs at P2 and P3 to the downstream locations of MFB1FF and the IP. The simulation reproduced accurately the measured position distribution at MFB1FF [8]. The implied jitter reduction at the IP was from c. 9.5nm to c. 3.6nm. Hence the upstream stripline-based feedback system is capable of delivering beam stabilisation at the IP at the few nanometre level. Though the beam position near the IP can be monitored using the local cavity BPMs (see Fig. 1), as described in the next section their resolution is not yet sufficient to be able to resolve beam jitter at the nanometre level, so that the predicted degree of beam stabilisation cannot yet be verified.

IP FEEDBACK SYSTEM

The IP feedback system (Fig. 8) comprises a C-band cavity BPM (IPB) [8,9] and a short stripline kicker (IPK). The final focus magnets (QF1FF, QD0FF) can be used to steer the beam by introducing a position offset or to move the x and y beam waists longitudinally along the beamline. The offset of the QF7FF magnet can be used to change the pitch of the beam trajectory through the IP region.

Determining the position of the beam at IPB requires both the dipole mode signal of IPB and the monopole mode signal of a reference cavity (Ref). The cavities were designed such that the y-port frequency of both signals is 6.426 GHz [8]. The signals are down-mixed to baseband using a two-stage down-mixer [10], as follows. The first stage down-mixer (M1) takes the 6.426 GHz reference

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and IPB signals and mixes each with an external, common 5.712 GHz local oscillator (LO) to produce down-mixed signals at 714 MHz. The second stage down-mixer (M2) mixes the IPB 714 MHz signal using the reference 714 MHz as LO, giving two baseband signals: I (IPB and reference mixed in phase) and Q (IPB and reference mixed in quadrature). The I and Q signals are subsequently digitised in the FONT5 digital board and normalised by the beam bunch charge; the charge is deduced from the amplitude of the reference cavity signal. The charge-normalised I and Q signals are calibrated against known beam position offsets (by moving the beam using QD0FF), allowing the IPB vertical beam position to be known in terms of a linear combination of charge-normalised I and Q.

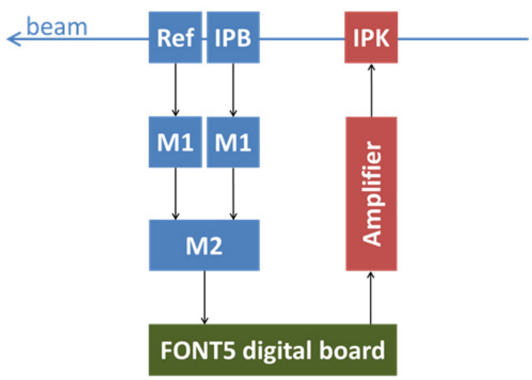

Figure 8: Schematic of IP feedback system showing the cavity BPM (IPB), reference cavity (Ref), first and second down-mixer stages (M1 and M2), FONT5 digital board, amplifier and kicker (IPK).

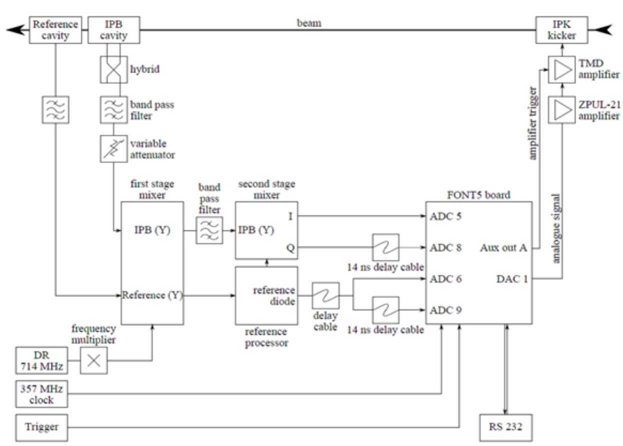

Figure 9: Schematic of operation of IP feedback system.

IP Feedback System Performance

We report the results of beam tests of the FONT5 system in the 2014 running period; earlier tests were reported in [11,12]. A detailed schematic of the hardware configuration is shown in Fig. 9.

The ATF was set up to provide two bunches per pulse of beam extracted from the damping ring, with a bunch separation of 274.4 ns. This separation was found typically to provide a high degree of measured vertical spatial correlation between the two bunches. The feedback tests therefore involve measuring the vertical position of bunch one and correcting the vertical position of bunch two. The system was typically operated in an 'interleaved' mode, whereby the feedback correction was toggled on and off on alternate machine pulses; the feedback 'off' pulses thereby provide a continual 'pedestal' measure of the uncorrected beam position. For the purpose of recording data with BPM IPB the longitudinal location of the beam waist in the IP region was adjusted by varying the strengths of the two final focus magnets QF1FF and QD0FF. For the results reported here the beam waist was typically set near the position of IPB.

The IP feedback system latency was measured and found to be 134 ns; however this could be reduced if, for example, a greater effort was made to optimise cable lengths. The performance of the feedback system was measured using IPB. Figure 10 shows the vertical position of bunch two recorded in IPB. The IP feedback reduced the vertical beam jitter from an r.m.s. deviation of 410 nm to 67 nm. The time-sequence of the data from the same run is shown in Fig. 11.

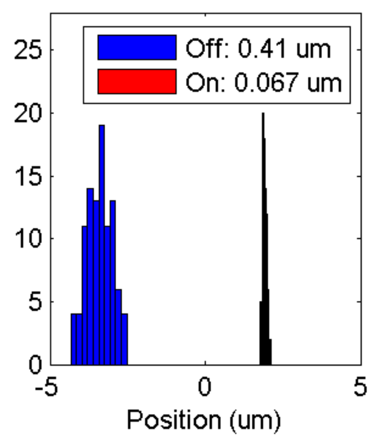

Figure 10: Distribution of the vertical position of bunch two in IPB with (red) and without (blue) application of the IP feedback correction.

In order to study the feedback operation a scan was performed of the beam waist longitudinal position around the nominal centre of IPB by varying the current in the QD0FF magnet (Fig. 1). As the focal point is moved longitudinally away from the centre of IPB, the vertical beam jitter measured in IPB increases (Fig. 12b). Also, due to their slightly different incoming beam trajectories, this scan had the effect of changing the vertical position of bunch 2 w.r.t. bunch 1 (Fig. 12a). Both changes allow a test of the feedback performance. The range of vertical position change of bunch 2 was roughly +-4 um w.r.t. nominal centre, and the incoming beam jitter varied up to about 400 nm. Figure 13b shows that the feedback reduced the incoming beam jitter at all scan points. The expected bunch 2 feedback-on jitter can be computed

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using the feedback-off jitter and bunch 1-2 position correlation measurements; this is shown in Fig. 12b, and agrees remarkably well with the measured bunch 2 jitter.

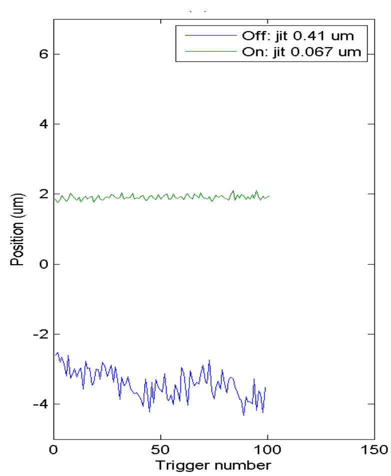

Figure 11: Time-sequence of the vertical position of bunch two in IPB with (green) and without (blue) application of the IP feedback correction.

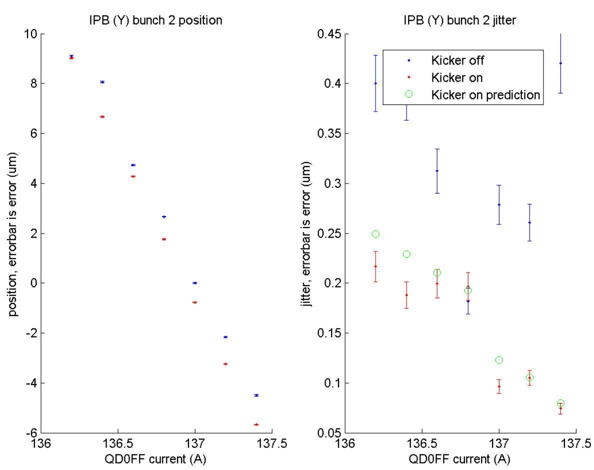

Figure 12: Bunch two mean position (a, left) and position jitter (b, right) with (red) and without (blue) application of the IP feedback correction. The green circles in (b) represent the predicted performance (see text).

Assuming that the FB performance is currently limited by the resolution of the cavity BPMs employed, the best position jitter stabilisation achieved, 67 nm, implies a BPM resolution of around 50 nm. This is consistent with direct estimates of the resolution determined using the system of three C-band BPMs at the ATF2 IP [8]. This is also consistent with fine scans of the longitudinal beam waist position at IPB, which yield a minimum measured beam jitter of around 50 nm (Fig. 13).

CONCLUSIONS

Beam stabilisation at the ATF2 IP using both stripline and cavity BPMs has been demonstrated. Vertical beam position stabilisation was achieved at the level of 0.5um in the upstream system, corresponding to an implied 3nm stabilisation at the IP. Local IP feedback was used to stabilise the beam directly to the level of 67nm. Work is ongoing to improve the resolution of the cavity BPMs near the IP from the currently measured value of c. 50nm in order to obtain improved results.

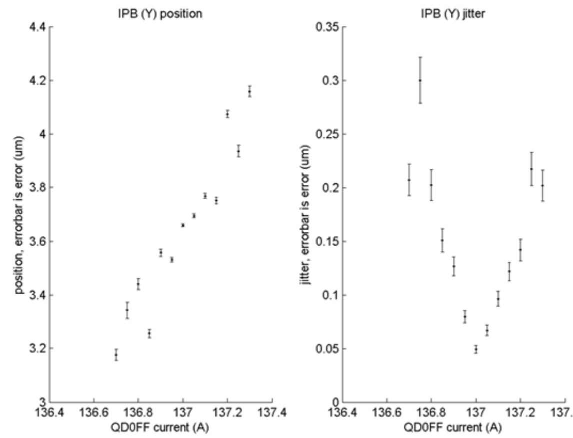

Figure 13: Bunch two mean position (a, left) and position jitter (b, right) vs. QD0FF current.

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