TUNING THE LINAC WITH SUPERCONDUCTING RESONATOR USED AS A PHASE DETECTOR

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Abstract

The ANU Heavy Ion Facility is comprised of a 15 MV electrostatic accelerator and superconducting linac booster. The beam is double terminal stripped to provide high charge states at the entrance to the linac, which consists of twelve β=0.1 Split Loop Resonators (SLR). Each SLR needs to be individually tuned in phase and amplitude for optimum acceleration efficiency. The amplitude and phase of the superbuncher and time energy lens also have to be correctly set. The linac set up procedure developed at ANU utilises a beam profile monitor in the middle of a 180 degree achromat and a new technique based on a superconducting resonator operating in a beam bunch detection mode. Both techniques are used to derive a full set of phase distributions for quick and efficient setting up of the entire linac. Verification of the superconducting phase detector is accomplished during routine linac operations and is complemented by longitudinal phase space simulations. The new technique allows better resolution for setting the resonator acceleration phase and better sensitivity to accelerating current. In addition, it is faster to perform, independent of energy and atomic number of the incident beam and less sensitive to beam steering and de-focusing introduced by accelerating resonators.

INTRODUCTION

The ANU Heavy Ion Facility (HIAF) is comprised of a 15 MV electrostatic accelerator followed by a superconducting linac booster. A pulsed beam is obtained using a single frequency, single gap grid buncher operating at the 1/16th sub-harmonic of the linac frequency of 150 MHz and positioned at the low energy (LE) of the 14UD accelerator. The beam bunches have a typical pulse width of 1.5 ns FWHM with a bunching efficiency ~25%. The beam is further compressed to ~ 100 ps wide by the superconducting buncher made up of a β=v/c=0.1 Quarter Wave Resonator (QWR).

The setting of the bunching and acceleration phase of the resonators is achieved by two complemtary techniques. The first technique interprets a Beam Profile Monitor (BPM) trace in the middle of a 180 degree achromat [1, 2]. A special large bore BPM83 by National Electrostatic Corporation (NEC) is used for this procedure. The energy dispersion at this location allows observation of the beam energy affected by each successive resonator. The second technique employs a superconducting resonator to detect the arrival time of a beam bunch and it is described in this contribution.

This paper has been organised into three main sections. The first section outlines the general concept of the linac tuning procedure based on superconducting cavity as a phase detector at very low, sub-nA beam intensities. The second section presents key experimental results based on the new technique of utilising a superconducting phase detector to set up linac resonators for effective acceleration. Finally, the third section presents interpretation of linac tune results and defines limitations of the technique.

METHODS

Phase detection based on rf cavities similar to [3] has been developed for a low intensity tandem operating with a linac booster accelerator. The use of superconducting SLRs, normally employed for ion beam acceleration, to detect the arrival phase of the bunch results in very high sensitivity due to the very high shunt impedance when compared to room temperature resonators. The unloaded quality factor Q_0 of the electroplated SLRs used is just above 10^8, resulting in a very low frequency bandwidth of about Δf_{BW}=1 Hz at an eigenfrequency of 150 MHz. The simplest technique to minimise the effect of microphonics is overcoupling of the rf pick up port, which in turn results in a widening of the loaded bandwidth and a lower sensitivity. For example, in order to widen the loaded bandwidth to an acceptable band Δf_L=100 Hz, the coupling constant should be set to a value $\beta=\Delta f_L/\Delta f_{bw}+1=101$.

A HP Model 8405A Vector Voltmeter is the main building block of the experimental setup. The instrument has sensitivity of 100 μV full scale with phase resolution of 0.1°. The two probes are ac-coupled. Loading of the SLR is acceptable because of the high input impedance of the probes (0.1 MΩ shunted by 2.5 pF). The Vector Voltmeter measures the magnitude of a reference and resonator voltage and the difference in phase between the voltages. The SLR is overcoupled to a loading constant β~101 by driving its coupler to a predefined position with the stepper motor. The channel "A" probe is connected to output of linac master oscillator while the channel "B" probe is connected to the SLR inductive variable coupler. The phase recorder output provides a DC voltage proportional to phase in the range ±180 degrees. Both amplitude and phase outputs are routed to a data logger.

The linac tunes are arbitrated by estimating the beam transmission through the linac up to the target devices, the optimum energy gain, transverse dimension and pulse

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width at specified measurement locations. Different Faraday cups and removable apertures with nanoamp current metering capabilities have been used around the linac loop to measure beam transmission and losses. Transverse beam cross-section and its position have been defined with profile signal generation from a wire scanner or BPM. The energy of the beam injected into the linac is estimated via NMR field measurement of the energy analysing magnet, pre-calibrated with accuracy better than 0.1% by nuclear reaction techniques. The energy gain and changing ion beam rigidity introduced by the linac accelerating resonators is calculated by scaling the excitation current of the 180º achromat dipole. Determination of beam pulse timing characteristics with sub nanosecond time resolution is based on an X-ray detection system incorporating a BaF_2 scintillator crystal as described in [4]. The X-ray is produced by the bunched beam striking a removable Ta target. The computer program SPACE is used to trace a longitudinal phase ellipse through the linac. The original code was obtained from A. Frawley at Florida State University with modifications added at the ANU.

During linac tuning using superconducting SLR as a phase detector, three isotopes of Nickel $^{58,62,64}Ni^{+22}$ were accelerated with all beams used for a physics experiment. All beams were produced using a 4 μg/cm^2 carbon foil in the terminal of the 14UD, a second terminal carbon stripper foil 8 μg/cm^2 thick or the linac 12 μg/cm^2 carbon foil stripper. All cavities were tuned and locked at a nominal incident power of about 6 W per cavity and at coupling strength that the LHe plant and cryogen distribution system could sustain. The cavities were then turned off. The DC and pulsed beams were then tuned through the linac. Finally, the cavities were turned on and locked, one by one, without changing any settings in the RF control loops.

Figure 1 shows an example of the signal produced by a superconducting SLR overcoupled to the loading constant β~61 which corresponds to loading bandwidth of Δf_L=60 Hz. The $^{62}Ni^{+22}$ beam energy produced by terminal and linac stripping is 200 MeV, with a beam current of 2.5 nA. The signal is extracted from the coupler line and displayed on an oscilloscope together with the linac reference signal. The frequency of incoming ion bunches is 9.375 MHz, which is dictated by the frequency of the low-energy pulsing system. Therefore, the 150 MHz superconducting SLR will ring at the16th harmonic of the 9.375 MHz excitation signal.

The SLR's excitation signal is independent of the energy and atomic number of the incident ion and cross section of the passing beam bunch. The measured rms noise level in the oscilloscope electronic circuit, including resonator pick up, is typically U_{Nrms}~50 mV. An acceptable signal to noise ratio (SNR) should be higher than 1:1 or greater than 0 dB in order to isolate a desired signal U_S from noise floor U_N. The absolute minimum level of the oscilloscope resolved resonator pick up signal can be derived from the equation $SNR_{dB}=20\log_{10}(U_S/U_N)=0$ or U_S=50 mV. For 200 MeV $^{62}Ni^{+22}$ beam, the minimum resolved beam current is I_{OSCmin}= 2.5 nA x 50 mV/290 mV= 0.4 nA, where 290 mV is the peak-to-peak resonator pick up signal as shown in Fig. 1.

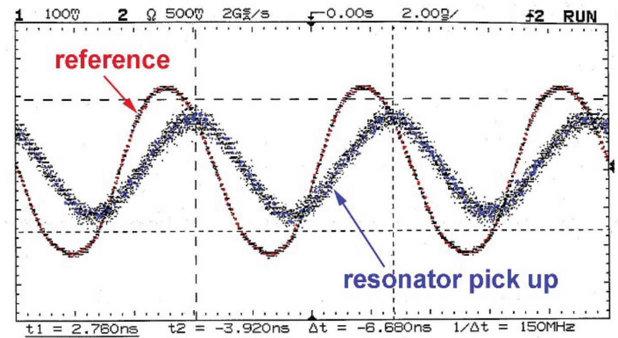

Figure 1: Example of SLR's rf field generated by pulsed beam passing through resonator. $^{62}Ni^{+22}$ beam energy produced by terminal and linac stripper is 200 MeV and beam current is 2.5 nA. The last 12th linac SLR is set as a phase detector. SLR is overcoupled to the loading constant β~61.

The resonator crossover phase occurs two times during the rf cycle when the rf field amplitude crosses zero value. The crossover phase information obtained from phase detection is used to accurately determine optimum acceleration phase of the resonator being tuned. During crossover search, the phase of the beam-induced signal with respect to the reference phase is influenced by variation of the transit time of the beam bunch due to energy gain/loss caused by accelerating resonator during its phase reference ramp. This might make the crossover determination uncertain. The comprehensive evaluation of this effect is outside the scope of this paper.

Nevertheless, there is a simple procedure to extract beam phase data from an SLR by combining output from phase detection measurements with BPM data. The approximate determination of the crossover phase of the QWRs and SLRs was achieved by interpreting the BPM trace in the middle of a 180 degree achromat. The energy dispersion at this location allowed observation of the energy of the beam as it was affected by each successive resonator. The crossover phase and its type, 0 or 180 degrees, was inferred by variation of the resonator phase from 0 to 360 degrees and briefly identifying phases with zero energy dispersion. After that, the measurement of the crossover phase is done at higher resolution with superconducting SLR operating in phase detection mode.

All linac tunes were undertaken for superconducting QWR superbuncher and eleven SLRs with a central frequency of 150 MHz. All resonators are driven by a self-excited loop with amplitude and phase locking. The last 12th linac resonator, 4.3, was used in bunch phase detection mode. The most challenging tunes are experienced with the superbuncher and first few linac resonators. This is due to relatively long distances (L>10 m) to the phase detector, enhancing the effect of beam steering by QWR and SLR. Figure 2 shows typical progression of phase shift of the signal measured with 12th SLR operating in bunch phase

ISBN 978-3-95450-178-6

detection mode with respect to master oscillator over one cycle tuning an arbitrary linac accelerating resonator.

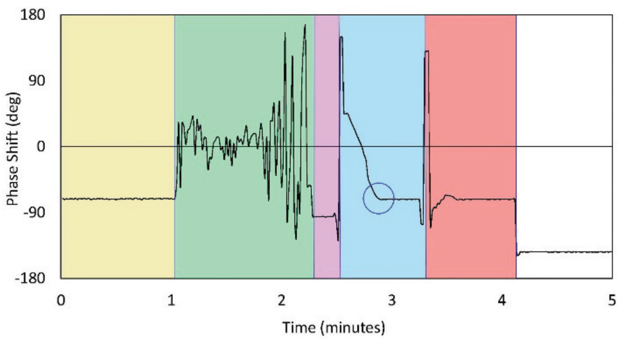

Figure 2: Variation of phase shift of the bunch-induced signal in the 12th linac SLR operating in bunch phase detection mode with respect to master oscillator over crossover search cycle. Each segment represents operation condition of SLR: constant stable phase of bunches arrive from upstream phase tuned cavity, (yellow area); cavity to be tuned is turned On unlocked (green); SLR is amplitude and phase locked (pink); crossover 1 search (blue) where area enclosed in circle corresponds to high resolution tune with SLR; crossover 2 check (light red) and accelerating phase set (no fill).

The stable bunch phase shown in Fig. 2 in a segment highlighted in yellow is produced by upstream phase tuned accelerating SLR. Unstable phase shift occurs when the next cavity under tune is turned on in self-excited loop and still unlocked (green area). Then the resonator is amplitude and phase locked at arbitrary reference phase resulting in stable phase shift measured by phase detection SLR (pink area). The coarse crossover search begins with the reference phase ramped over 360º range and observing both BPM trace and the phase detection resonator phase simultaneously (blue area). The crossover phase and its type, 0 (crossover 1) or 180 degrees (crossover 2), was inferred by briefly identifying phases with zero energy dispersion by observing a BPM trace,followed by high resolution measurement with superconducting SLR phase detector as shown in the blue area enclosed by a circle. The next step is to check the crossover 2 by advancing the reference phase by 180º (light red). Finally, the acceleration resonator phase is set to +72º with respect to the re-bunching crossover and -108º with respect to bunching crossover correspondingly (no fill area in Fig. 2).

RESULTS

Verification of the new technique was accomplished during routine linac tune when accelerating ions $^{64}Ni^{+22}$ from 200 MeV to final energy ~330 MeV. The beam was initially stripped to charge state Q_1=13 using a terminal stripper and the final charge state with Q_2=22 with the second linac stripper. All cavities were tuned and set for acceleration using standard BPM-based technique and the superconducting SLR phase detection technique discussed.

Summary of operation conditions corresponding to linac tunes by both techniques is listed in the Table 1.

Table 1. Comparison of linac tunes based on two techniques: superconducting cavity as phase detector (SLR) and BPM.

			SLR		BPM	
SLR	E_{acc}, MV/m	β	ΔE, MeV	ϕ_{acc}, deg	ΔE, MeV	ϕ_{acc}, deg
1.1	2.78	0.085	12.01	-34.7	11.93	-36
1.2	3.08	0.088	13.67	-56.6	13.65	-57
1.3	2.99	0.090	13.52	122.2	13.44	121
2.1	2.45	0.092	11.22	16.1	11.29	17
2.2	2.44	0.095	11.26	75.9	11.14	74
2.3	2.66	0.097	12.33	-77.3	12.22	-79
3.1	2.41	0.099	11.19	-37.5	11.23	-37
3.2	2.49	0.101	11.56	158.2	11.68	160
3.3	2.27	0.102	10.53	-145.3	10.67	-143
4.1	1.85	0.104	8.54	-124.8	8.59	-124
4.2	1.88	0.105	8.66	6.1	8.56	4
4.3	1.85	0.107	8.49	4	8.56	5

Identification of resonators is as follows: 1.1, 1.2, 1.3, 2.1, …, 4.3 where the first number identifies one of the four module cryostat and the second number stands for one of the three SLRs housed in each module cryostat. Resonator 4.3 is used in bunch phase detection mode and is therefore tuned for acceleration using the BPM method. The energy gain, ΔE, introduced by the linac accelerating resonators is calculated by scaling the excitation current of a 180º achromat dipole. The average accelerating field, E_{acc}, is calculated from the formula E_{acc}= ΔE /($Q_2 L_{SLR}\cos(\phi) T_{(\beta)}$), where Q_2 is the ion beam charge state after the 2nd stripper; L_{SLR}=0.221 m is the active length of the SLR; ϕ = -18º is the resonator accelerating phase and transit time factor $T_{(\beta)}$=1 for ion with optimum velocity β=0.1. In the Table above, ϕ_{acc} is the set resonator accelerating phase in LLRF control system corresponding to ϕ = -18º which is +72º with respect to the re-bunching crossover and -108º with respect to bunching crossover.

The quality of the linac tune is judged on the following criteria: beam transmission through the linac and up to the target devices, the energy gain, transverse dimension and pulse width/energy spread in specified measurement locations. Figure 3 shows transformation of longitudinal phase space ellipses simulated with SPACE code through the injection section of the linac consisting of superbuncher and 90º achromatic bend up to the first linac SLR.The beam bunches used in SPACE simulations have a pulse width of 1.0 ns FWHM and calculated FWHM energy spread 127 keV as shown in Fig. 3 as an ellipse without fill. The beam is further compressed to <100 ps wide at the linac first resonator (yellow ellipse) by the superconducting buncher β=0.1 QWR operating at 0.4 MV/m and introducing energy gain to the incoming beam. The bunching action of superbuncher is shown as an ellipse with green fill in Fig. 3.

SPACE- simulated longitudinal phase ellipses through the linac resonators are shown in Fig. 4. The resonator accelerating fields and phases used in simulation are the same as listed in Table 1.

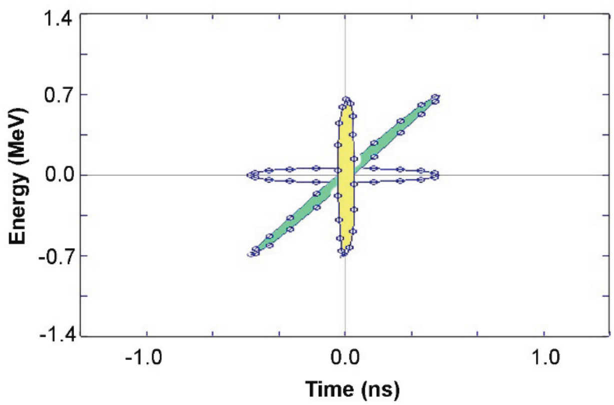

Figure 3: SPACE- simulated longitudinal phase ellipses through the superbuncher to the first linac SLR: a) terminal and linac double stripped beam injected to superbucher from 14UD operating with low energy pulsing system with calculated FWHM energy spread 127 keV and assumed time spread 1 ns (no fill ellipse); b) phase ellipse transformed by superbuncher QWR operating at 0.4 MV/m (green fill); c) beam arriving at the linac entrance to the first accelerating SLR positioned 6.98 m away from superbuncher (yellow fill).

The columns with heading "ϕ_{acc}= -18 degrees" corresponds to tune with all resonators set to accelerating phase -18º. Heading "$\phi_{3.1}$= +18 degrees" is the case when the phase of first resonator in the third cryostat is advanced by 36º with respect to the accelerating phase while setting all remaining resonators at -18º. The bottom row shows phase ellipses simulated at 6.43 m from the linac exit (ellipse with no fill) and 16.3 m (ellipse with green fill).

The pulsed beam width was measured with the set up based on BaF_2 detector positioned at distance of 16.3 m away from the linac. The pulse width is extracted from spectra shown in Fig. 5 with MCDWIN software for the FAST ComTec MCA-3 ADC card.

The estimated FWHM pulse width for different conditions is as follows: 1.25 ns for beam injected in superbuncher (blue dots in Fig. 5; 0.78 ns for beam compressed by superbuncher at nominal field for time focus at linac entry (brown dots) and 0.83 ns for beam accelerated to ~333 MeV (black dots).

Table 2 summarises the main outcomes of the linac tunes with SLR and BPM techniques. In the Table, E_{tot} is the measured output energy of boosted beam exiting the linac. ΔE_{SPACE} and $\Delta\tau_{SPACE}$ are SPACE-calculated energy spread and time width of the beam bunch at the distance 16.3 m away from the linac exit. $\Delta\tau_{FWHM}$ is the measured bunch width at the same distance. Ion beam transmission is defined as the ratio of beam current measured with a Faraday cup at the linac entrance to the cup positioned after the TEL, 16.1 m from the linac exit. I_{min} is the minimum beam current injected to the linac that is still within the sensitivity range of selected tuning technique.

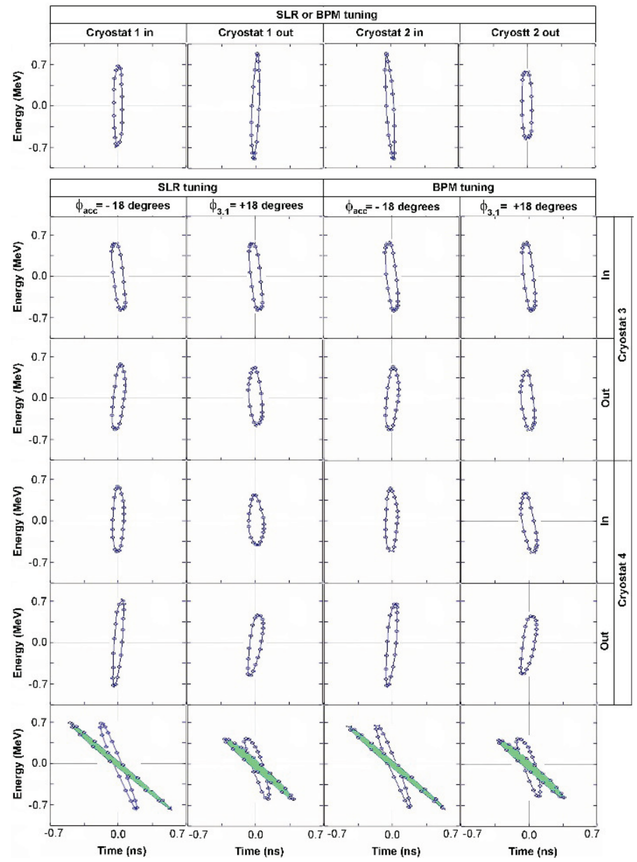

Figure 4: SPACE- simulated longitudinal phase ellipses through the linac resonators corresponding different tuning conditions as listed in Table 1: A. First row represents acceleration through the first two linac cryostats tuned by either SLR or BPM technique producing similar result; B. Columns below the first row contain data assuming SLR or BPM tuning techniques. C. The bottom row displays phase ellipses simulated at two distances from the linac exit: 6.43 m (ellipse with no fill) and 16.3 m (ellipse with green fill).

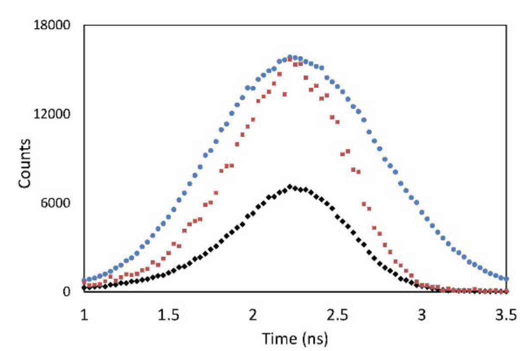

Figure 5: Pulsed beam timing characteristics measured with the pulse monitoring system at a distance of 16.3 m away from the linac exit: beam produced by low energy bunching system (blue dots); beam compressed by superbuncher at nominal field for time focus at linac entry (brown squares) and beam accelerated to ~333 MeV with tune corresponding to 2nd column in Fig. 4 (black diamonds).

ISBN 978-3-95450-178-6

Table 2. Summary of Linac Tunes with SLR and BPM Techniques

	E_{tot}, MeV	ΔE_{SPACE}, MeV	$\Delta\tau_{SPACE}$, ns	$\Delta\tau_{FWHM}$, ns	Ion beam transmission, %	I_{min}, nA
SLR ϕ_{acc}= -18 °	332.5	1.51	1.04	1.12	82	0.8
SLR $\phi_{3.1}$=+18 °	332.5	1.12	0.7	0.83	92	0.6
BPM ϕ_{acc}= -18°	332.4	1.46	1.0	1.1	86	1.6
BPM $\phi_{3.1}$=+18°	332.3	1.03	0.68	0.79	93	1.4

DISCUSSION

The acceleration phase for each accelerating cavity is set at –18 degrees with respect to the maximum acceleration phase for phase stability. Over-bunching is sometimes observed, which is evidenced by a wide BPM trace equivalent to a higher energy spread and poor transmission as shown in Fig. 4. To counteract this, the acceleration phase is set to +18 degrees in the selected resonator when it leads to an improvement in beam profile. Typically this is necessary in the first resonator of third cryostat SLR (3.1).

The SLR tuning technique allows better resolution for resonator acceleration phase setting ϕ_{acc} and better sensitivity to accelerating current when compared to the BPM technique. However, the high precision ϕ_{acc} setting does not results in higher beam energy gain or transmission as shown in Table 2. Therefore, the main application of the SLR technique is for tuning beams of ultra-low, sub-nanoamp, intensities.

For both SLR and BPM methods, "ϕ_{acc}= -18 degrees" tune results in a longitudinal phase ellipse with smaller semi-minor axis and longer semi-major axis when compared to "$\phi_{3.1}$= +18 degrees", while the total area of the phase ellipse remains constant (see Fig. 4 and Table 2). Moreover, "ϕ_{acc}= -18 degrees" tune results in worse beam transmission, which suggests that such operation causes beam emittance growth due to non-linear effects and consequently higher beam loss in the achromatic bend due to increased energy spread.

Finally, "$\phi_{3.1}$= +18 degrees" tune results in similar beam quality and final energy for both SLR and BPM tunes. Nevertheless, the SLR technique is quicker and more robust because it is not dependent on energy and atomic number of the incident beam and is also less sensitive to beam steering introduced by accelerating resonators.

Superconducting SLR phase detection transforms the accelerating cavity into a beam phase detector or two cavities into a beam energy detector [3], which is less sensitive to beam defocusing with energy change and provides good accuracy when determining bunch time of arrival. This new development improved operational capabilities, resulting in the substantial enhancement in the linac performance.

ACKNOWLEDGEMENT

This work has been supported by Australian Federal Government Superscience/EIF funding under the NCRIS mechanism. We wish to express our appreciation to RSPE's Nuclear Physics staff members T. Kibedi, A.Muirhead, T. Tunnigley, J. Heighway, J. Bockwinkel, and L. Lariosa for their skill and diligence during cryogenic plant and linac operations.

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