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First Results with a Surface Conversion H^- Ion Source Based on Helicon Wave Mode-Driven Plasma Discharge

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Abstract. The currently employed converter-type negative ion source at Los Alamos Neutron Science Center (LANSCE) is based on cesium enhanced surface production of H^- ion beams in a filament-driven discharge. The extracted H^- beam current is limited by the achievable plasma density, which depends primarily on the electron emission current from the filaments. The emission current can be increased by increasing the filament temperature but, unfortunately, this leads not only to shorter filament lifetime but also to an increase in metal evaporation from the filament, which degrades the performance of the H^- conversion surface. In order to overcome these limitations we have designed and tested a prototype of a surface conversion H^- ion source, based on excitation of helicon plasma wave mode with an external antenna. The source has been operated with and without cesium injection. An H^- beam current of over 12 mA has been transported through the low energy beam transport of the LANSCE ion source test stand. The results of these experiments and the effects of different source parameters on the extracted beam current are presented. The limitations of the source prototype are discussed and future improvements are proposed based on the experimental observations.

Keywords: Negative ion source, Helicon plasma discharge.

PACS: 29.25.Nj, 52.25.Jm

INTRODUCTION

The accelerator facilities at Los Alamos Neutron Science Center (LANSCE) consist of two injector systems (H^+ and H^-), 800 MeV linear accelerator, proton storage ring and experimental areas. The H^- ion beam, required for charge exchange injection into the proton storage ring, is currently produced with a filament-driven surface conversion ion source (see e.g. Ref. 1). The H^- ion source regularly produces beam currents of 16-18 mA at 6 % -12 % duty factor (60 – 120 Hz, ~1 ms pulses). The future scenarios for the LANSCE accelerator facility require improvements on the performance of the H^- ion source. Thus, a development program aiming at improvements on different ion source technologies has been initiated. The development strategy is comprised of several paths, namely (1) gradual improvement of the filament-driven surface conversion ion source (see R. Keller *et al.* in these proceedings), (2) development of helicon-driven (*rf*) surface conversion ion source, (3) collaboration with SNS ion source R&D team and (4) feasibility studies of other ion source concepts (e.g. ECR-driven surface conversion ion source). This article

focuses on the status and future prospects of the helicon-driven surface conversion ion source development at LANSCE.

Helicon plasma generators² are characterized by high plasma density, up to 10^{13} cm^{-3} , achieved with exceptionally good power efficiency. The use of helicon plasmas for negative ion production was proposed by Welton³. Efforts for combining a helicon plasma generator with an SNS-type H^- ion source have been carried out at Oak Ridge National Laboratory (see R.F. Welton *et al.* in these proceedings).

The focus of our efforts has been on developing a helicon-driven surface conversion ion source. The source is equipped with a biased converter electrode similar to the LANSCE filament-source. Replacing the filaments by an rf-antenna is expected to yield higher beam currents, due to increased plasma density, and longer source lifetime. A benefit of this approach (in contrast to the designs presented in References 3 and 4 is the “self-extraction” of the H^- ions from the converter electrode yielding a low emittance ion beam (typically less than 0.2π mmmrad, 95 % norm.-rms)¹. In addition, due to the “self-extraction” i.e. energetic H^- ions, the stripping losses of H^- in collisions with electrons are reduced significantly due to lower cross-sections. Compared to purely inductive rf-coupling, helicon discharge provides better stability at low neutral gas pressures (1-10 mTorr i.e. 0.13-1.3 Pa), which helps to minimize the losses of H^- in collisions with neutrals.

HELICON-DRIVEN SURFACE CONVERSION ION SOURCE PROTOTYPE AND LANSCE ION SOURCE TEST STAND

A schematic of the helicon ion source prototype is presented in Figure 1. The mounting flange, extraction system, converter electrode and repeller electrode (magnetic + electrostatic) are identical to the parts used in the LANSCE filament source. The magnetic field required for the helicon wave mode excitation is created by a permanent magnet array in which the individual magnets are magnetized parallel to the source axis. The array consists of 18 rectangular magnets arranged in 6 rows. The 3-loop rf-antenna, wrapped around the plasma chamber (OD 75 mm, both PYREX and Al_2O_3 have been used), is placed in the fringe field of the permanent magnets. The strength of the magnetic field on the source axis, at the location of the antenna, is about 0.01 T. This configuration is suitable for excitation of the $m = 0$ helicon wave mode⁵. The RF-power with a frequency of 13.56 MHz is coupled into the plasma with the aid of a capacitive matching circuit consisting of shunt- and series-capacitors. The reflected/forward power fraction is typically 1-20 %. The position of the converter electrode, whose concave surface (127 mm radius of curvature) is designed to focus the ion beam through the outlet aperture, can be varied with respect to the antenna and the magnet array. Applying the (negative) converter voltage of 250-350 V facilitates ignition of the discharge and thus significantly simplifies the tuning efforts for the rf-matching. The permanent magnet ring embedded in the repeller electrode creates a magnetic field hump (0.02 T) near the outlet aperture of the source and reduces the amount of cold electrons leaking from the plasma into the extraction (through the $F = -\mu \nabla B$ force), which improves the e^-/H^- ratio of the extracted beam.

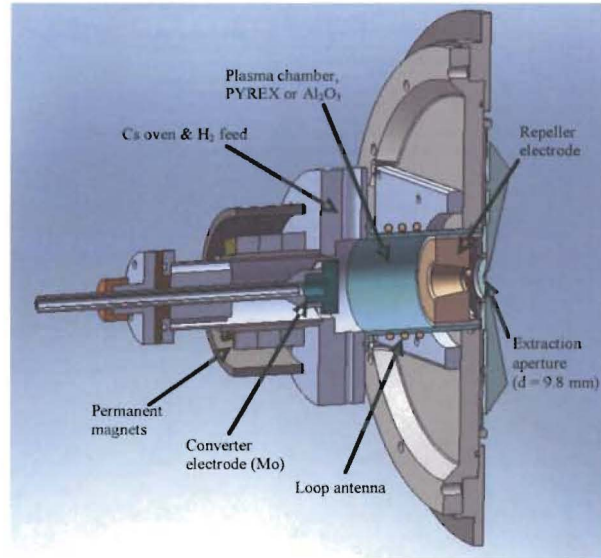


FIGURE 1. Schematic of the helicon ion source prototype.

The first cesiation experiments with the helicon source were performed using the cesium oven designed for the filament-driven sources (see Figure 2a). For the filament source the oven is typically loaded with 25 grams of cesium lasting up to 40 days (not limiting the source lifetime). The drawback of the oven design is that the hottest part of the assembly is the cesium reservoir instead of the shaft conducting cesium vapor into the plasma chamber. This causes uncontrolled bursts of cesium, as a result of cesium condensation on the inner surface of the shaft clogging the tube, and subsequent sudden release of cesium as the oven is brought up to operational temperatures (around 200 °C). In the case of the filament source this does not present a problem because the excess of cesium is deposited on the walls of the plasma chamber and affects the cesium balance of the source in a favorable manner since the source performance can be affected by controlling the wall temperature⁶ (see also Keller *et al.* in these proceedings). For the helicon source excessive amounts of cesium in the plasma chamber presents a major problem since it has an adverse effect on the rf-matching (reflected power increases dramatically). In order to improve the cesiation process of the helicon source, a new cesium oven (see Figure 2b) was designed and tested. In this oven design, utilizing two resistive heaters, the cesium reservoir is the coldest spot of the assembly. Thus, the consumption of cesium during the initial cesiation of the ion source is reduced and uncontrolled bursts of cesium are avoided. The oven was loaded with 1 gram cesium ampule for each experimental run described in this article. The ampule is cracked by bending the cesium reservoir. The duration of each run was 4-7 days (8-10 hours a day).

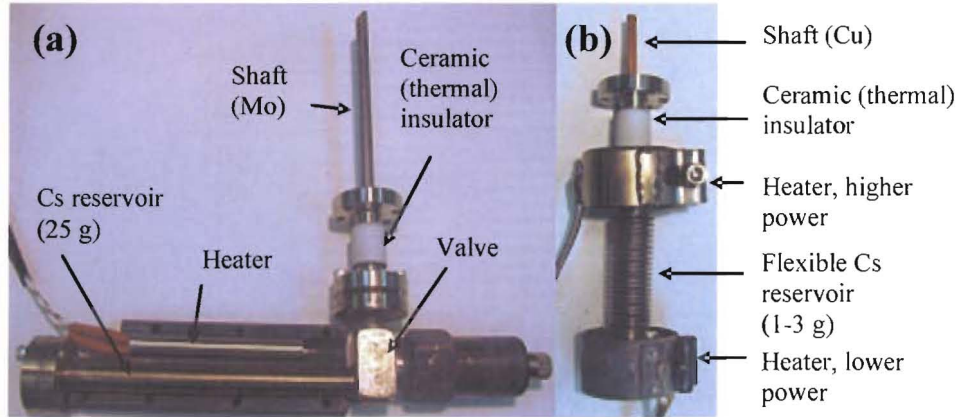


FIGURE 2. (a) The old Cesium oven for the filament-driven source and (b) The new Cesium oven for the helicon-driven source. The main parts of both oven designs are shown.

All measurements described in this article were performed at 80 keV extraction voltage on the LANSCE ion source test stand (ISTS) illustrated in Figure 3. The ISTS⁷ is a reproduction of the LANSCE H⁻ injector system. The beam current values reported in the following section were measured with a Faraday cup at the end of the LEBT corresponding to the injection point of the 670 keV column of the LANSCE H⁻ injector. The reported beam current values are not affected by residual electrons since the beam current was measured after the 4.5 degree bend. The diameter of the extraction aperture used in the measurements with the helicon-driven source is 9.8 mm, being identical to LANSCE filament sources.

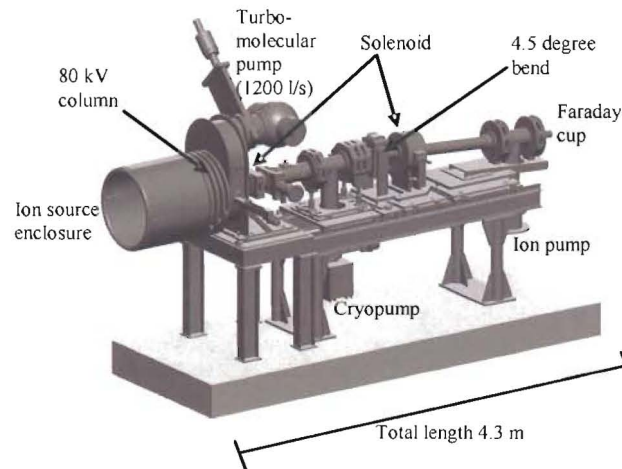


FIGURE 3. The configuration of the LANSCE ion source test stand (components used for the measurements in this article are highlighted).

EXPERIMENTAL RESULTS

The first beam extraction experiments with the prototype of the helicon-driven surface conversion ion source were performed without cesium injection⁸. An H⁻ beam current of 3.4 mA was achieved at 1 % duty factor. The LANSCE filament sources

typically produce 2-2.5 mA of H^- beam current in uncesiated conditions (at 6 – 12 % duty factor).

Recently the experiments with the helicon source have concentrated on operating the source with cesium. The effects of different source parameters (neutral gas pressure, rf-power and -matching) have been explored to gain experience on the cesium equilibrium in this source. The duty factor has been gradually increased up to 3.7 %. The development process is very time-consuming since drastic changes between source conditions between consecutive experimental runs must be avoided in order to ensure a systematic approach. Five experimental runs were performed at ISTS with the improved cesium oven. Each run takes about 3 weeks including source and cesium oven assembly (including outgassing), 4-7 days of experiments and clean-up of the cesiated source. The highest H^- beam currents achieved during each experiment are presented in Figure 4. So far, the highest obtained H^- beam current is 12.3 mA. The beam current was stable at the level of over 12 mA for 2 hours (the source parameters were deliberately changed after this). The highest transient current obtained so far is 16.1 mA lasting for few minutes. The e/H^- ratio of the extracted beam depends on the cesium conditions. Values (e/H^-) as low as 5 have been achieved.

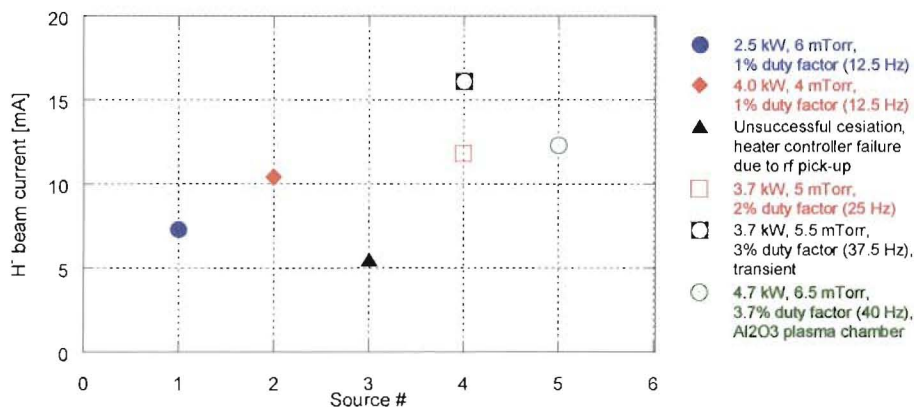


FIGURE 4. The performance of the LANSCE helicon ion source up-to-date (August 2008).

During the experiments we have observed the following trends affecting the H^- output of the helicon source:

1. Increasing the rf-power at constant neutral gas pressure corresponds to an increase of the H^- beam current. A clear “jump” is typically observed at 1.0-1.8 kW corresponding to the shift from purely inductive coupling into the $m = 0$ helicon mode. However, increasing the rf-power typically forces us to increase the neutral gas pressure in order to keep the reflected power under the limiting value set by the rf-amplifier (max 5 kW forward / 1 kW reflected). The cesium feed rate needs to be increased with increasing rf-power in order to maintain optimal cesium coverage on the converter electrode. This is due increasing plasma density and converter current resulting to higher sputtering rate of cesium from the converter. Converter currents up to 10 A have been measured at 5 kW of forward power (for the filament source the maximum is typically 2.5-3.0 A).

2. Decreasing the neutral gas pressure at constant rf-power corresponds to an increase of the H^- beam current. This is due to reduced stripping losses of the H^- beam

traveling through the plasma. Reducing the neutral gas pressure causes the converter current to decrease and consequently cesium feed rate needs to be lowered. Reducing the neutral pressure below 4 mTorr causes the reflected rf-power to exceed the limit of the amplifier because ignition of the discharge in the beginning of each rf-pulse becomes unreliable. Signs of severe neutral starvation have not been observed when the source has been operated at pressures above 4 mTorr. In practice this means that the droop of the H^- beam current within the discharge pulse (865 μs in these experiments) is less than 10 %.

3. The feed rate of cesium affects the matching of the rf-power. Injecting cesium at high rate helps to ignite the plasma at low neutral H_2 pressures but it also causes the reflected power to increase and does not correspond to optimized surface conditions.

DISCUSSION AND FUTURE IMPROVEMENTS

The results obtained with the helicon-driven surface conversion ion source are very promising. However, in its present form the source is not reliable enough for long-term operations. The extracted H^- beam current is restricted mainly by the neutral gas pressure (4-7 mTorr at sufficient rf-power levels) causing stripping losses. These losses could be mitigated by reducing the distance between the converter and the outlet of the source. However, as Figure 5 showing the fraction of surviving H^- ions as a function of distance from the converter under different neutral gas pressures demonstrates, it is more desirable to reduce neutral gas pressure. In fact, in pressure range exceeding 1 mTorr the dominating reaction causing H^- losses is neutralization in collisions with hydrogen molecules⁹. This is due to the rather low ionization degree of the plasma (1-3 %). Distance of 12 cm corresponds to the value used in the measurements. In the calculation it was assumed that the energy of the H^- ions emitted from the converter is 275 eV and neutral gas is molecular hydrogen (H_2). The corresponding cross-section for the neutralization was taken from Ref. 10. The losses due to other collision mechanisms (H^- with electrons, positive ions, neutral cesium etc.) can be estimated to be independent of the neutral hydrogen pressure and less important at pressure range of > 1 mTorr.

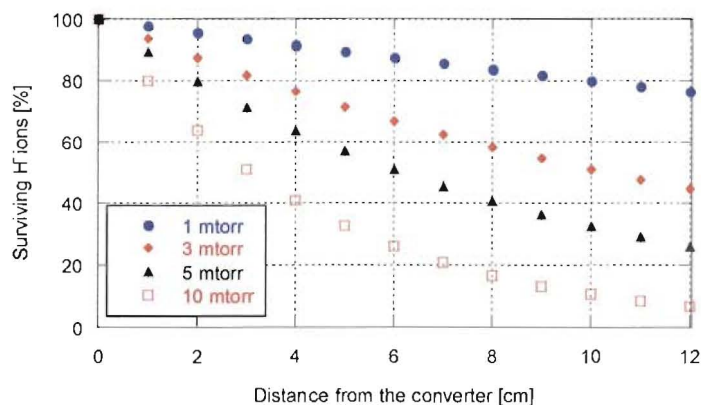


FIGURE 5. Calculated fraction of surviving H^- ions as a function of distance at different neutral gas pressures. The dominating loss mechanism is collisions with neutrals (H_2)⁹. H^- energy of 275 eV was assumed.

The calculation presented in Figure 5 suggests that the extracted beam current could be increased by a factor of 2-3 if the neutral pressure was reduced from 4-6 mTorr to 1-2 mTorr (and other loss processes would remain unchanged). Therefore the focus of our efforts has recently been in developing techniques to assure source operation at very low neutral gas pressures (on the order of 1 mTorr). We have identified three possible methods to accomplish this:

1. *Increasing the volume of the plasma chamber:* Our preliminary studies with different sizes of plasma chambers have indicated that increasing the neutral gas volume helps to ignite the plasma at lower pressures. However, increasing the diameter of the plasma chamber reduces the power density and subsequently the plasma density, which is not desirable.

2. *Pulsed gas feed:* The purpose of the pulsed gas feed is to provide higher neutral gas pressure at the beginning of the rf-pulse. The neutral gas pressure is then allowed to decay towards the end of the rf-pulse. This method would require longer rf-pulses (on the order of 2-3 ms) due to the fact that stripping losses would still reduce the beam current during the 1-2 ms measured from the leading edge of the rf-pulse. A gas feed system capable of providing 150 μ s gas pulses at 60 -120 Hz has been developed for the purpose. The system is similar to the one reported in Ref. 11. Initial tests of the gas pulsing system were conducted at an ion source processing stand normally used for filament pre-processing. The neutral gas pressure variation within 3 ms intervals corresponding to the rf-pulse was observed to be several mTorr. The variation of the neutral gas pressure can be changed by adjusting the time separation of gas pulses and rf-pulses as the neutral gas pressure decays exponentially. This method will be tested at ISTS at later time. The effect of the varying gas pressure on the H⁻ production is unknown.

3. *Ignition of discharge in gas feed line with Tesla coil transformer:* The most promising option to facilitate plasma ignition at low neutral gas pressures and consequently increase the extracted beam current is to utilize a Tesla coil transformer. The purpose of the Tesla coil is to ignite the discharge in the gas feed line where the neutral gas pressure is significantly higher. The low-density plasma diffuses from the gas feed line into the main discharge chamber and makes it possible run the discharge at lower pressures. This method has enabled us to shift the threshold pressure for plasma ignition from 8 mTorr to 4 mTorr in pure hydrogen discharges. Experiments with cesiated source have not yet been conducted. Ignition systems for inductively coupled rf ion sources have been used before by Peters¹² and Welton¹³.

Reliable plasma ignition will most probably enable us to reduce the amount of cesium in the plasma chamber. This is desirable to obtain stable conditions for rf-matching.

Another issue that needs to be addressed in order to improve the production of H⁻ with the helicon ion source is the optimization of the magnetic field for beam extraction. So far our experiments have concentrated on maximizing the beam production through optimized plasma density. The effect of the magnetic field on the beam extraction was studied with ion tracking simulations after it was observed that the surface of the repeller electrode had no signs of cesium accumulation near the extraction aperture while other parts of the source facing the plasma chamber were

covered with a visible layer of cesium. This observation indicates that the ion beam intersects with the repeller electrode. Figure 6 shows the calculated beam envelope in the plasma chamber for three different permanent magnet strengths (0.1 – 0.35 T i.e. 1 – 3.5 kG). The given strengths of the magnets are measured on the surface of the each PM block. For the ion tracking calculations it was assumed that the ions are sputtered perpendicularly from the converter electrode (concave surface with 127 mm radius of curvature) and reach the energy corresponding to the converter voltage within a thin plasma sheath adjacent to the surface. In the example presented in the Figure the converter voltage was set to -300 V. The magnetic field was calculated with Radia3D¹⁴ and the magnetic field components at each point along the ion trajectories were imported to an ion tracking code written with Mathematica® (Wolfram Research). Possible electric fields on the beam trajectory were not taken into account.

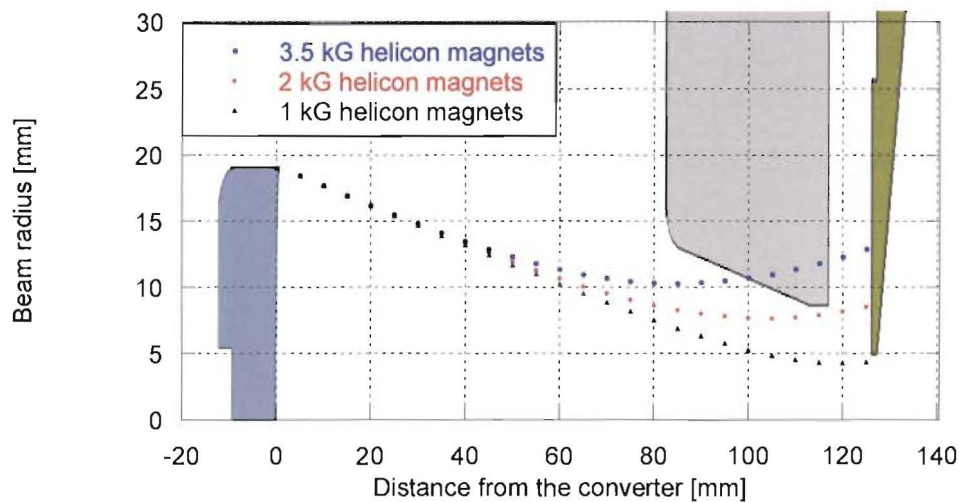


FIGURE 6. Calculated beam radius as a function of distance from the converter with different permanent magnet strengths. The solid surfaces are from left to right: converter electrode, repeller electrode and outlet aperture.

In the case of 3.5 kG magnets, which are currently used, the H^- beam envelope on the outlet plane is much larger than the extraction aperture. The deviation between the simulation result (point where the beam intercepts the repeller) and the observed cesium tracks on the repeller surface is less than 2 mm. The simulation result suggests that using weaker magnets would be beneficial to the beam extraction. Changing the converter curvature and/or voltage seems not to be as effective as reducing the magnetic field. However, weaker magnetic field yields lower plasma density (at given rf-power) and requires higher neutral gas pressure for plasma ignition. This was confirmed in an experiment without beam extraction. Therefore, reducing the neutral gas pressure remains the most important item of future developments.

Our near term future plans include emittance measurements. The source reliability has to be improved prior to this. Due to similar source geometry, it can be expected that the emittance of the H^- ion beams extracted from the helicon source does not differ significantly from the emittance of the filament source (typically 0.15-0.2 π mm mrad, 95 % norm.-rms).

As a summary of the status of the helicon ion source development at LANSCE we present a Table comparing the filament source to the helicon source (results up-to-date, August 2008).

TABLE I. Comparison of the LANSCE filament ion source to LANSCE helicon ion source.

| | Filament Source | Helicon source |
|-------------------------------|--|--|
| Neutral gas pressure | 1-3 mTorr | 4-7 mTorr (with Cs, without "ignition system") |
| Input power | 4-11 kW discharge + 2-2.5 filament heating | 1-5 (rf) |
| Plasma density | $5 \times 10^{11} - 1.2 \times 10^{12} \text{ cm}^{-3}$ (probe measurement) | $5 \times 10^{11} - 3.5 \times 10^{12} \text{ cm}^{-3}$ (calculated from converter current) |
| Beam current, 9.8 mm aperture | 14-24 mA (15-18 mA is typical) | 7-12.5 mA |
| Emittance | $< 0.2 \pi \text{ mm mrad}$ | ? |
| e/H ⁺ ratio | 3-5 | 5-8 |
| Duty factor | 6-12 % | 1-3.7 % demonstrated |

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