PLASMA OPENING SWITCH EXPERIMENTS ON HAWK WITH AN E-BEAM DIODE LOAD

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Abstract

Successful application of inductive energy storage depends critically on the performance of the opening switch. The new Hawk generator at NRL[1] is used in plasma opening switch (POS) experiments in the 1-μs conduction time regime to study long conduction time POS physics. In this experiment, different POS configurations were used, including various switch to load distances and different cathode center conductor radii. The load was an e-beam diode. Peak load powers of 0.5 TW, with load current risetimes of 20 ns and current transfer efficiencies of 80%, were achieved with a POS conduction time of 0.75 μs using a 5 cm diam cathode. Typically, 40 kJ were coupled into the diode, which is 20% of the energy stored in the Hawk capacitance. The data indicate that above a critical load impedance the final switch gap, as determined from magnetic insulation arguments, is fixed to 2.5-3 mm, independent of conduction current and center conductor radius. Above this critical load impedance, current is shunted into the transition section between the switch and the load such that the voltage remains constant. At lower impedance values, the load voltage decreases in proportion to the load impedance. This critical load impedance is then the optimum impedance for maximum load power. Increasing the cathode magnetic field by conducting more current (up to a limit) or by decreasing the cathode center conductor radius at a given current level allows the switch to remain insulated at a higher voltage. Peak load voltages up to 1.7 MV were achieved using a 5 cm diam center conductor, a factor of 2 higher than that obtained with a 10 cm diam center conductor and 2.7 times higher than the erected Marx voltage (640 kV).

Introduction

Pulsed power generators traditionally use water line and vacuum transmission line technology for power conditioning--power gain and pulse compression--of the microsecond output pulses from Marx banks. The emergence of inductive store technology[2] allows the development of more compact pulsed power generators. An opening switch such as a POS is used for power conditioning of the output pulse from the Marx. Hawk uses a 607 nH Marx, designed by Physics International Co.,[3] with 225 kJ stored at 80-kV charge to deliver up to 700 kA in 1.2 μs to a POS. By varying the switch plasma density, the switch can be made to conduct from 0 to 1.2 μs. The goals of these experiments were to study the physics of the switch for these long conduction times and optimize the switch/e-beam diode performance to generate high power short duration (<100 ns FWHM) power pulses.

Hawk Experimental Configuration

The switch/load vacuum section of one experimental configuration is shown in Fig. 1. Different center conductor (cathode) diameters were used, notably a 10 cm diam cathode (pictured here) and a 5 cm diam cathode. The current monitors shown here consist of a Rogowski loop, ISU, on the generator side of the POS (upstream) and two B-dot monitors, ILU and ILL, on the load side of the POS (downstream) at the e-beam diode. The plasma was produced by 18 carbon-coated flashboards in the POS region. The banks driving the flashboards were typically fired 1-2 μs before current was conducted in the switch.

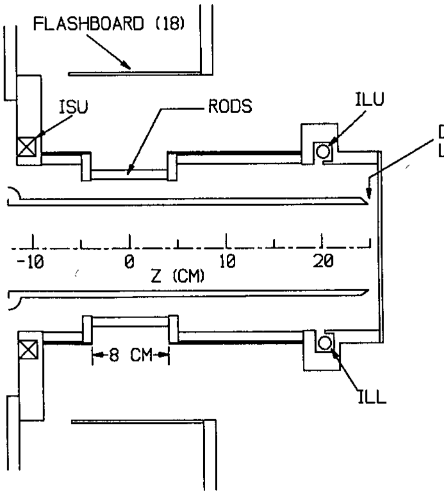

Fig. 1. Hawk switch/load vacuum section in the standard configuration.

The set-up in Fig. 1 with a switch to load length of 26 cm is called the standard configuration. In this configuration, for conduction times greater than 0.6 μs, plasma reaches the diode before switch opening. This is plasma directly from the flashboards and plasma accelerated to the load by JxB forces during conduction (confirmed by Faraday cups in the load). The bulk of the plasma does not reach the load--independent magnetic probe measurements indicate the center of mass motion of the plasma is only about 4 cm downstream--but enough plasma reaches the load for it to act like a plasma-filled diode with a rising load impedance. This uncontrolled load plasma ultimately limits the impedance to a relatively low value, independent of the actual diode gap spacing and well below the vacuum value (for large enough gaps).

To obtain higher load impedances and control the impedance with the gap spacing, plasma must be kept out of the load. This was accomplished by extending the conductors downstream of the switch so that the switch to load length is 40 cm or more. The two (originally load) B-dot current monitors were left in place to measure current in the transition section, about halfway between the switch and the load, and two B-dot monitors were added at the load. In this configuration, called the extended

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14. ABSTRACT

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configuration, the load looks like a vacuum diode with a falling load impedance and the impedance can be controlled by changing the gap spacing.

Results with a 10 cm Diam Cathode

Fig. 2 shows representative data from a Hawk shot with a 10 cm diam cathode in the standard configuration. The plasma delay is 1.5 μs and the switch conducts for 0.9 μs before opening. The 10-90% load current risetime is 40 ns with an 80% current transfer efficiency and 500 kA delivered to the load. There is about 100 kA of residual current in the switch. Peak load voltage is 770 kV, peak load power is 0.4 TW, and almost 40 kJ is delivered to the load. Best opening (highest voltage and power and fastest risetimes) on shots with a 10 cm diam cathode occurs for conduction times of ~1 μs, near peak current.

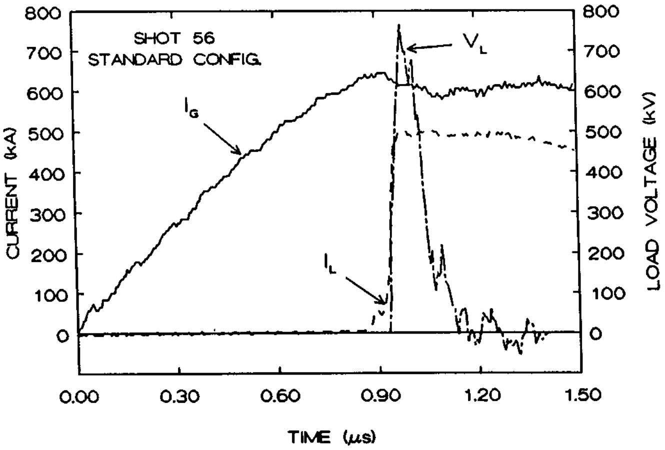

Fig. 2. Current and voltage data for a 0.9 μs conduction time POS shot with a 10 cm diam cathode in the standard configuration.

Load data for this shot are shown in Fig. 3. The load acts like a plasma-filled diode with an impedance rising from 0 Ω to 1.5 Ω at peak load power. The diode gap spacing is 1 cm which represents a vacuum impedance, assuming critical current, of 8 Ω. An impedance of 1.5-2 Ω was the highest that could be obtained in this configuration, regardless of the gap spacing (including removal of the anode plate) for conduction times over 0.6 μs.

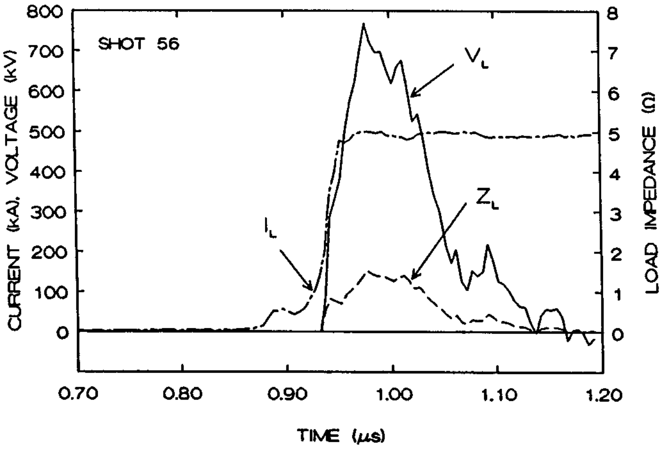

Fig. 3. Load data for the shot in Fig. 2.

Fig. 4 shows data from two shots in the extended configuration. Here the load looks like a vacuum diode with a falling load impedance. By increasing the diode gap spacing from 0.5 cm to 1.0 cm the load impedance at peak power increases from 2 Ω to about 4 Ω. However, the voltage generated on these shots is the same, ~800 kV, so the impedance "mismatch" with the larger gap spacing resulted in greater current loss.

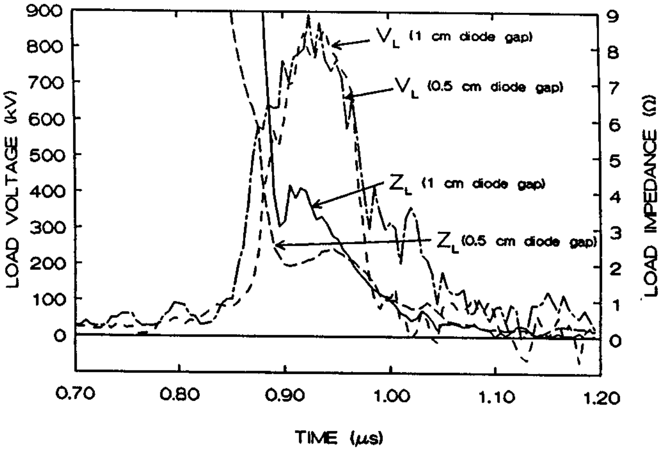

Fig. 4. Load data for two shots in the extended configuration.

The dependence of voltage on load impedance is shown in Fig. 5 for numerous shots with a 10 cm diam cathode. Below a critical load impedance, ~1.7 Ω, the voltage decreases in proportion to the load impedance. This is termed the load limited regime. Above the critical impedance, the voltage is constant for a given conducted current. This is called the switch limited regime. As the load impedance is increased above 1.7 Ω, current is lost between the switch and the load, although well downstream of the switch, where the plasma density is zero. Also, the maximum voltage increases with conducted current. For example, with conducted currents of 500 kA the maximum voltage is ~500 kV, for 650 kA it is ~900 kV.

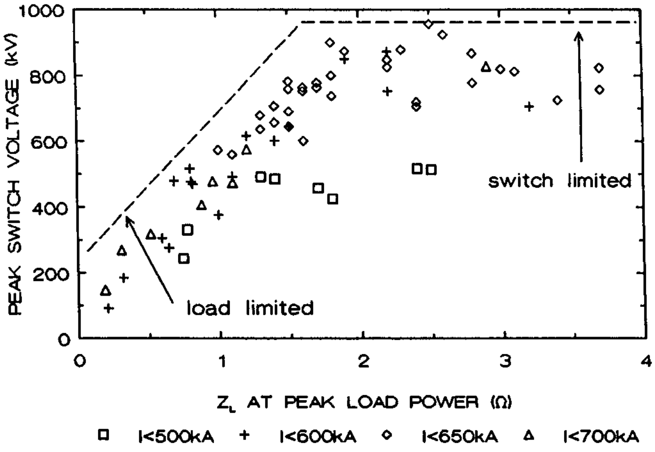

Fig. 5. Peak voltage as a function of load impedance with the 10 cm diam cathode. Above a critical impedance, ~1.7 Ω, the voltage is constant for a given conduction current.

Maximum power is delivered to a load operating at the critical impedance, as shown in Fig. 6. Furthermore, the peak load power increases with conduction time up to 1 μs. Thus, the highest power generated, 0.4 TW, occurs for 1 μs conduction at a load impedance of 1.7 Ω.

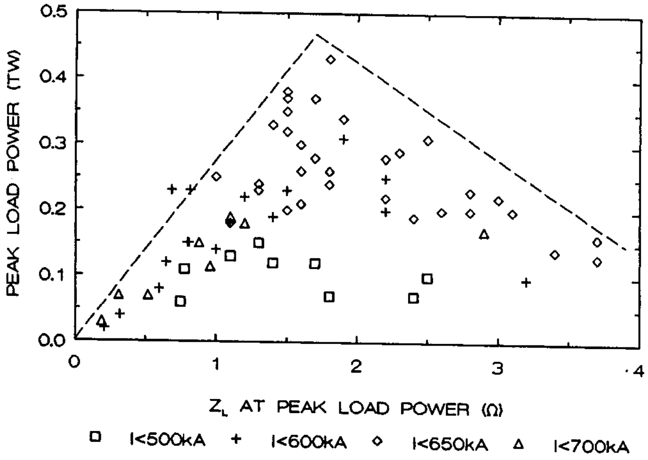

Fig. 6. Peak load power versus load impedance with the 10 cm diam cathode. Maximum power is delivered to a load operating at the critical impedance with ~1 μs conduction times.

The switch gap at peak power is calculated assuming the switch operates at the critical current for magnetic insulation, $I_C = 1.6 \times 8500 \beta\gamma r/D$, where I_C is the generator current, r is the cathode radius, D is the gap between the plasma and the cathode (or cathode plasma), and 1.6 is an empirical factor. The switch gap at peak power is plotted versus load impedance, Z_L, at peak power in Fig. 7. At a given load impedance, the gap is independent of conduction current. The voltage increases with conduction current such that the gap size, at a given load impedance, is the same for different conduction currents. The gap is 2.5-3 mm, independent of Z_L, for $Z_L > 1.7$ Ω. For $Z_L < 1.7$ Ω, the calculated gap decreases as Z_L decreases to zero. The calculation may be misleading in this case, because the switch voltage is limited by the load; the switch gap could still be 2.5-3 mm. This data analysis gives a physical picture of the Hawk POS: at peak power the switch acts like a magnetically insulated transmission line (MITL) operating at critical current with an effective electrode gap of 2.5-3 mm. Important implications of this fixed gap size model include a voltage limit as the load impedance is increased and a load impedance for maximum load power (data shown above). The current that is lost operating above the 1.7 Ω critical impedance appears to be mainly electron loss. It occurs in regions where the plasma density is zero and from x-ray pinhole pictures as well as observation of physical damage the loss is at the outer conductor (anode). Higher power would be possible if the gap size could be increased (the electrode gap in the POS is 2 cm), or if the magnetic field could be increased at the same gap size. The latter approach was investigated by decreasing the center conductor radius.

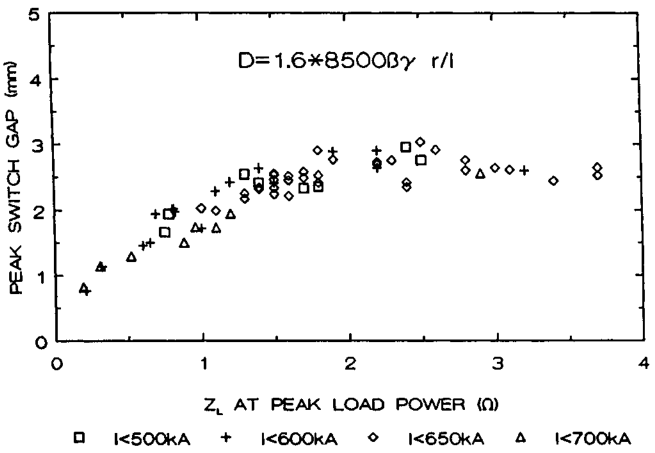

Fig. 7. Switch gap calculated at peak power, assuming the switch is at critical current, as a function of load impedance with the 10 cm diam cathode. The gap is independent of conduction current and, above the critical impedance, is fixed to 2.5-3 mm.

Results with a 5 cm Diam Cathode

Data from a Hawk shot with the 5 cm cathode in the standard configuration are shown in Fig. 8. The switch conducts for 0.7 μs and opens in 20 ns, delivering 80% of the current, 400 kA, to the load. There is about 100 kA of residual switch current. The voltage generated on this shot is 1.2 MV, well above the ~900 kV voltage limit of the 10 cm cathode. The peak load power is 0.5 TW and 40 kJ is coupled into the load. Optimum switch opening with a 5 cm cathode occurs for ~0.75 μs conduction with a ~1.6 μs plasma delay, also the delay for best opening with the 10 cm cathode. To conduct longer than this requires a large increase in plasma delay. (A similarly large increase is necessary to conduct beyond 1 μs with the 10 cm cathode.) The poorer switch opening observed with these much longer plasma delays could be due to a small gap in the higher density switch and not a consequence of load-limited operation.

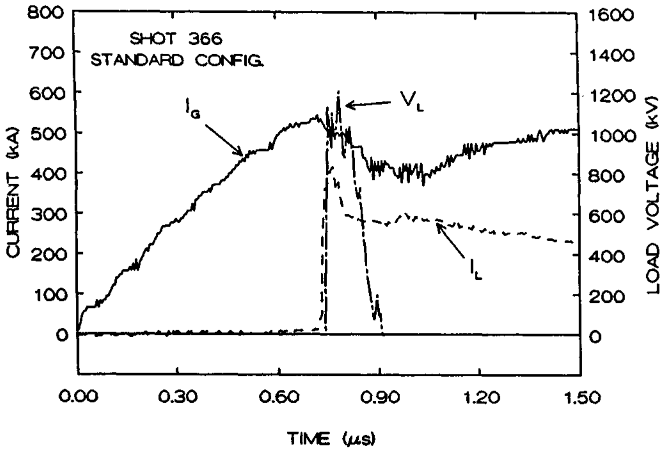

Fig. 8. Current and voltage data for a 0.7 μs conduction time POS shot with a 5 cm diam cathode in the standard configuration.

Load voltages as high as 1.7 MV have been generated with the 5 cm cathode, a factor of 2 higher than the best 10 cm cathode shots and 2.7 times higher than the erected Marx voltage. The data indicate gap opening rates up to dD/dt = 10^7 cm/sec.

The relationship between voltage and load impedance for numerous shots with the 5 cm cathode is shown in Fig. 9. Similar to the results using the 10 cm cathode, there is a critical or optimum impedance, here 3.5 Ω. Below this value the voltage depends on impedance; above it the voltage is limited for a given conducted current. For ~0.75 μs conduction, this limit is 1.5-1.7 MV.

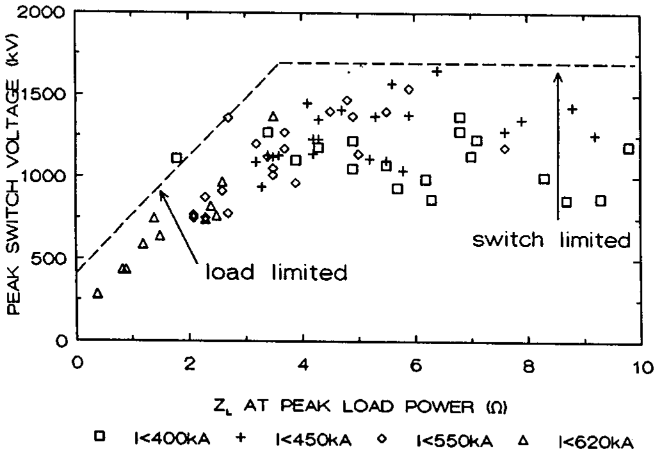

Fig. 9. Peak voltage as a function of load impedance with the 5 cm diam cathode. Above a critical impedance, ~3.5 Ω, the voltage is constant for a given conduction current.

In Fig. 10 the calculated switch gap is shown as a function of load impedance for the 5 cm cathode shots. The switch gap is 2.5-3 mm, for Z_L > 3.5 Ω, the same gap size as the 10 cm cathode shots. The larger magnetic field associated with the smaller radius cathode allows a larger voltage to exist across the gap at peak power (critical current). Above the 3.5 Ω critical impedance, current is shunted into the transition section, the losses occurring well downstream of the switch, where the plasma density is zero.

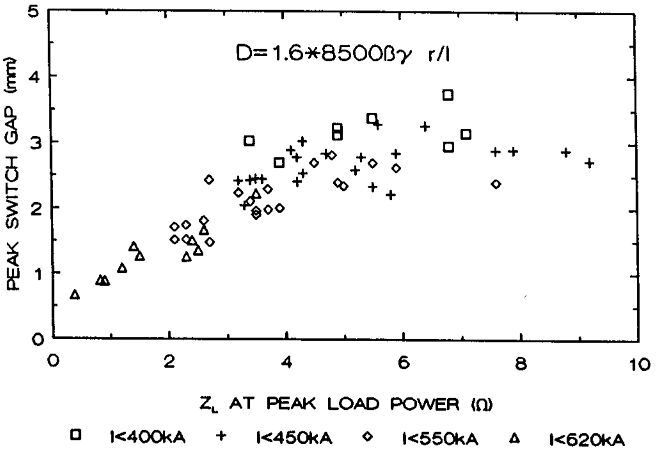

Fig. 10. Calculated switch gap at peak power versus load impedance with the 5 cm diam cathode. The gap is fixed to 2.5-3 mm above the critical impedance.

In Fig. 11 voltage generated with four different cathode diameters is plotted vs. cathode magnetic field. Lines of constant switch gap, D, calculated from the critical current formula are also shown. The data show the voltage increase possible as the magnetic field increases, with the switch gap remaining constant at 2.5-3 mm. This happens as the conducted current is increased, up to a 1 μs conduction time with the 10 cm cathode and 0.75 μs conduction time with the 5 cm cathode, or as the cathode radius is decreased. Moving vertically down on this graph is in the direction of decreasing load impedance. Data points below the D=2.5 mm curve are in the load limited regime. The five shots with the 2.5 cm diam cathode were in the standard configuration with enough JxB plasma accelerated to the load to consistently be in the load limited regime.

Higher voltage and power could be achieved if the gap size can be increased, preferably with the 10 cm or larger diam cathode which can readily conduct the full 1-μs current pulse.

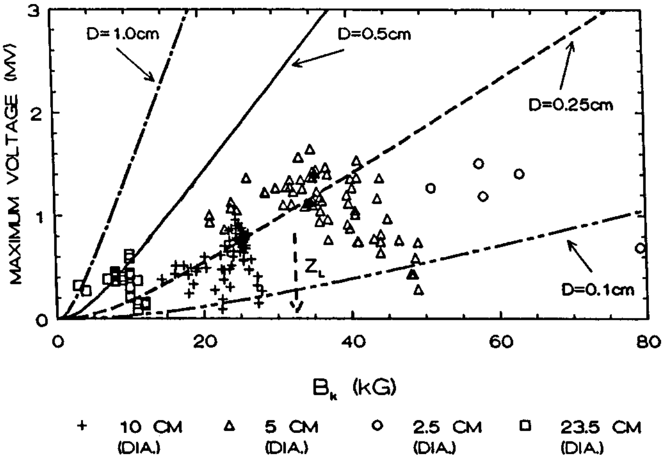

Fig. 11. Maximum voltage generated as a function of cathode magnetic field for different cathode diameters. Here the critical current model indicates ways to increase switch voltage.

Summary and Future Work

High power pulses have been generated on the Hawk generator at NRL using a 0.75-1 μs conduction time POS. Peak load powers of 0.5 TW with 20 ns risetimes were achieved with 0.75 μs conduction times using a 5 cm diam cathode. Typically, 40 kJ was coupled into the e-beam diode, which represents an energy efficiency of 20%.

The data indicate that an effective gap of 2.5-3 mm was produced in the switch. This ultimately limits the voltage and determines an optimum load impedance for maximum load power. The gap is independent of conducted current, center conductor radius, and the load impedance, at least above the critical impedance. Increasing the conducted current (up to a limit) or decreasing the cathode radius increases the voltage consistent with a fixed gap. In particular, the voltage increases from 0.9 MV to 1.7 MV when the cathode diameter was decreased from 10 cm to 5 cm.

Higher power could be achieved if the switch gap size can be increased. One possibility is to use a controlled plasma-filled diode (PFD) decoupled from the switch.[4] Preliminary results on Hawk with the 5 cm diam cathode suggest peak load powers up to 1.7 times higher using such a PFD in conjunction with a POS for short conduction times of 0.4 μs. A second possibility is to use a hydrogen plasma source in place of the carbon flashboard sources for the POS. Experiments[5] have shown higher voltages and powers (presumably larger switch gaps) are generated with a hydrogen POS.

References

[1] J.R. Boller, et. al., NRL Memorandum Report 6748, January 1991.

[2] G. Cooperstein and P.F. Ottinger, Guest Editorial, IEEE Trans. Plasma Science, PS-15, Dec. 1987.

[3] P. Sincerny, et. al., 7th IEEE Pulsed Power Conference, Monterey, CA, 1989, IEEE Cat. No. 89CH2678-2, p. 275.

[4] J.M. Grossmann, et. al., Bull. A.P.S., 34, p. 2076, 1989.

[5] P.S. Ananjin, et. al., 14th Inter. Symposium on Discharges and Electrical Insulation in Vacuum, Santa Fe, NM, Sept. 1990, p. 417.

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