

HIGH POWER TARGET R&D FOR THE LBNE BEAMLINER: STATUS AND FUTURE PLANS*

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Abstract

The Long Baseline Neutrino Experiment (LBNE) Neutrino Beam Facility at Fermilab will use a high energy proton beam on a solid target to produce a neutrino beam aimed at underground detectors at the DUSEL site in South Dakota. Initial proton beam power is planned to be 700 kW with upgrade capability to greater than 2 MW. Solid target survivability at such incident beam power is of great interest, and an R&D program has been started to study the relevant issues. Areas of study include irradiation testing of candidate target materials at the BLIP facility at BNL, multi-physics simulations of solid target/beam interactions at RAL, autopsies of used NuMI targets, and high strain rate effects in beryllium. Status and results of these studies are presented as well as a summary of planned future high power target R&D efforts.

INTRODUCTION

The LBNE Neutrino Beam Facility conceptual design for a future 2+ MW upgrade includes targeting 60-120 GeV pulsed proton beam (1.6e14 protons per pulse, 1.5-3.5 mm sigma radius, 9.8 micro-sec pulse length) on a 0.9 m long graphite target rod. Although analysis has shown the graphite can withstand the thermal shock and resulting stresses of the beam interaction, concerns over long-term survivability of the graphite in the high radiation environment have motivated research into the radiation damage limits of graphite as well as research into beryllium as an alternate candidate target material for LBNE.

To gain an understanding of the material property changes of various graphite materials under high energy proton beam irradiation, two efforts have been started. One is to autopsy failed graphite targets from the NuMI Target Hall which have shown decreased neutrino yield during operation with 120 GeV proton beam. The second is to measure key material properties of various graphite samples after exposure to 118 MeV proton beam at the BLIP facility at BNL.

To better understand the viability of using beryllium as a high power target material, the LBNE project has entered into an accord with STFC-RAL's High Power Targets Group to perform design studies and multi-physics simulations of beryllium targets under LBNE-like beam parameters. In addition, work has begun at FNAL to understand the correlation of simulation results with real-world experience of beryllium exposed to high intensity proton beam.

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GRAPHITE R&D

Graphite has been chosen as a target material for many neutrino beam facilities (NuMI, T2K, CNGS) because of its excellent resistance to thermal shock and other advantages for neutrino production. However, graphite degrades rapidly by oxidation when heated in air environments to temperatures above 400° C [1]. This adds complexity to the target design in the form of an inerted or evacuated chamber and properly designed and cooled beam windows. In addition, and perhaps more importantly, graphite exhibits radiation damage that changes its material properties significantly at relatively low dose or Displacements Per Atom (DPA).

Figure 1 shows the significant decrease in thermal conductivity of three different graphite grades exposed to neutron irradiation. Moreover, with increased gas production associated with high energy proton irradiation (relative to neutron irradiation), the effects on graphite structure may be more severe as demonstrated by irradiation tests of graphite at BLIP (BNL) in 2006 [2]. Figure 2 shows a set of graphite samples from the 2006 BLIP test completely destroyed in the central beam spot area after irradiation to an integrated flux level of ~0.5-1e21 protons/cm². This level of structural damage at relatively low dose is obviously of great concern when considering graphite as a candidate target material.

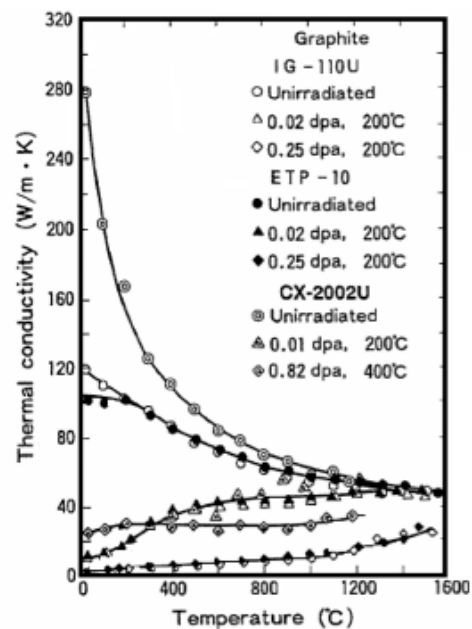


Figure 1: Effect of neutron irradiation on thermal conductivity of 3 grades of graphite [2].

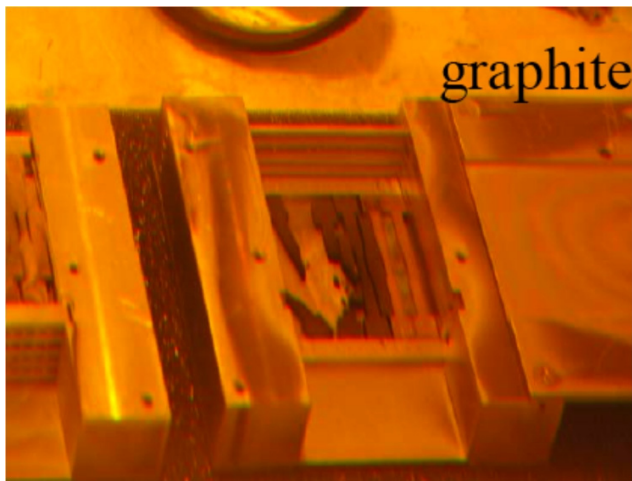


Figure 2: Graphite samples after irradiation at BLIP facility in 2006 (photo courtesy of N. Simos).

Autopsy of NuMI Target NT-02

The structural degradation indicated in the 2006 BLIP irradiation test is one possible explanation for the decrease of neutrino yield seen during the operation of the NuMI graphite target NT-02. Figure 3 shows a plot of the neutrino event yield as a function of energy bin over a time period equivalent to about 4.5×10^{20} protons on target. The decrease in yield in the 2-4 GeV bins is obvious. When the NT-02 target was replaced with the NT-03 target (identical design to NT-02) the yield was restored to expected values.

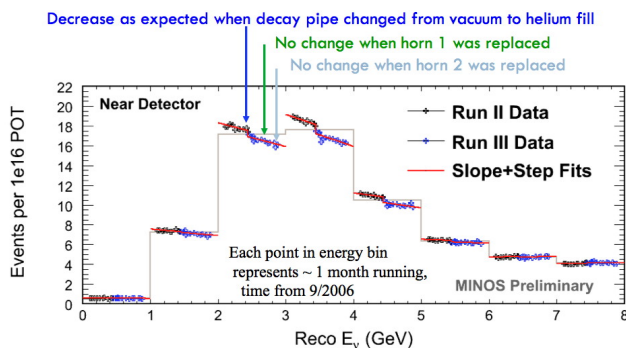


Figure 3: Normalized neutrino yield versus energy bin for NuMI target NT-02 operations.

Figure 4 shows a picture of a typical NuMI target with and without the aluminum sheath that contains the graphite fins. The fins are constructed of POCO ZXF-5Q amorphous graphite and brazed at their ends to a thin walled stainless steel water cooling tube. This tube also provides the structural mounting for the fins. Maximum energy deposition in the graphite (referred to as “shower-max”) occurs several fins in from the upstream end and thus any structural degradation would first occur in those few fins at shower-max. Since downstream fins remain intact, the shower-max location would shift downstream as fins were degraded resulting in a gradual reduction in yield as was observed.

Plans to autopsy NT-02 include using radiographic techniques to view the state of the fins through the sheath, using a bore-scope to view the fins under the sheath, and cutting and removing the sheath to view the fins unobstructed. It is possible that fins may be recovered for further testing

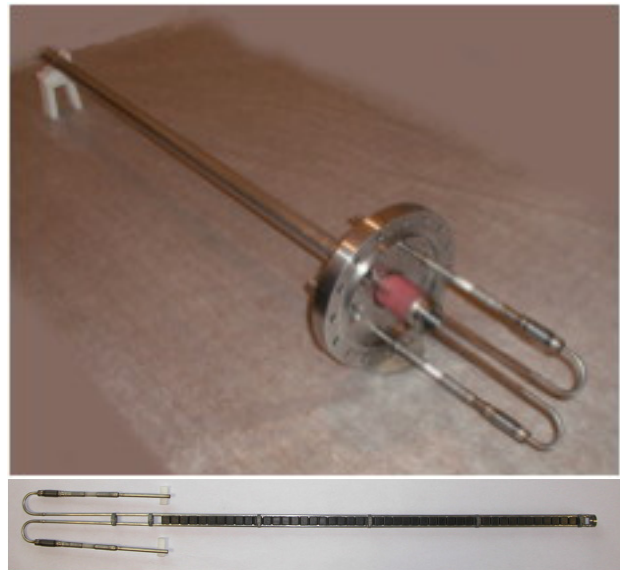


Figure 4: NuMI Target fin assembly with aluminum tube sheath (top) and without (bottom).

All of these investigations are complicated by the residual radiation dose of the target and surrounding structure (several R/hr at 1 ft). Unfortunately a work cell that would facilitate these investigations is not currently available at FNAL. Construction of such a work cell is underway (C-0 Remote Handling Facility) and should be ready for operations in late 2010 or early 2011. Meanwhile efforts continue to plan and practice the autopsy procedures.

Irradiation Tests at BLIP

In order to further explore the structural degradation of graphite under high energy proton beam, a new test program was undertaken at the BLIP facility at BNL under the guidance of N. Simos. In this test, several grades of graphite and one grade of hexagonal-Boron Nitride were exposed to 181 MeV proton beam at BLIP. However, unlike the earlier BLIP tests where cooling water was in direct contact with the samples, most of the new samples were encapsulated in stainless steel containers purged with argon gas. This was done to separate any effect of the beam interaction with water from the beam interaction with the samples. One set of samples in this new test was installed in the water without a capsule so a direct comparison could be made between samples in a water environment and samples in an argon environment.

Figure 5 shows a typical set of graphite tensile and CTE specimen loaded into an open capsule before welding the capsule covers on. Tensile specimen have small gauge

cross-section dimensions of 1mm x 2mm. Planned tests include tensile tests (yield/ultimate strengths, elastic modulus) and thermal tests (expansion coefficient, conductivity).

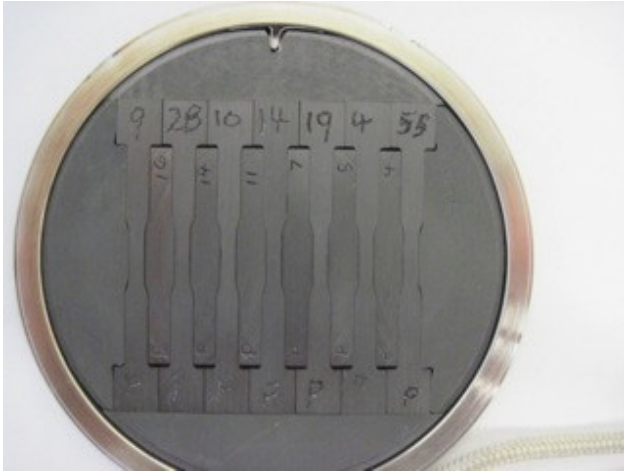


Figure 5: Graphite BLIP samples in capsule prior to irradiation.

Table 1: BLIP Test Materials

Material	Motivation
C-C Composite (3D)	2006 BLIP failure
POCO ZXF-5Q	NuMI/NOvA target material
Toyo-Tanso IG-430	Nuclear grade for T2K v2
Carbone-Lorraine 2020	CNGS target material
SGL R7650	NuMI/NOvA baffle material
St.-Gobain AX05 h-BN	Hexagonal Boron Nitride

Table 2 shows the materials included in the irradiation test along with brief descriptions of the motivation for including the material in the test.

The samples received a peak integrated flux of about 5.9×10^{20} protons/cm² from the BLIP beam. This is about half of the integrated flux in earlier BLIP tests. Visual inspection revealed no evidence of structural degradation of any graphite samples within the argon filled capsules.



Figure 6: Water immersed C-C composite samples after irradiation at BLIP showing damage.

Figure 6 shows a post-irradiation picture of the carbon-carbon composite samples that were immersed in the water cooling medium while being irradiated. The central beam spot area was damaged with broken fibers exposed and carbon powder granules flaking off the surface. This damage on the directly water cooled samples while none was observed on the argon encapsulated samples indicates that the damage shown in the earlier BLIP tests was due, at least partially, to the water environment.

Testing of the irradiated samples is currently beginning. Preliminary results should be available by the end of 2010.

BERYLLIUM R&D

Due to concerns over radiation damage and resulting target lifetimes, efforts to qualify beryllium as a target material were undertaken. A design study was commissioned with STFC-RAL's High Power Targets Group to explore the use of beryllium as an LBNE target for both the 700 kW and 2.3 MW primary beam powers within the parameter space listed in Table 2.

Table 2: Beam parameters for Be design study.

Energy (GeV)	Protons per Pulse	Rep. Period (sec)	Beam Power (MW)	Beam sigma (mm)
120	4.9e13	1.33	0.7	1.5-3.5
60	5.6e13	0.76	0.7	1.5-3.5
120	1.6e14	1.33	2.3	1.5-3.5
60	1.6e14	0.76	2	1.5-3.5

Analysis included modeling the physics in FLUKA to calculate energy deposition and simulating the thermal and structural (static and dynamic) effects in ANSYS and AUTODYN. In addition, FLUKA was used to gauge the effect of target/beam geometry variations on particle production.

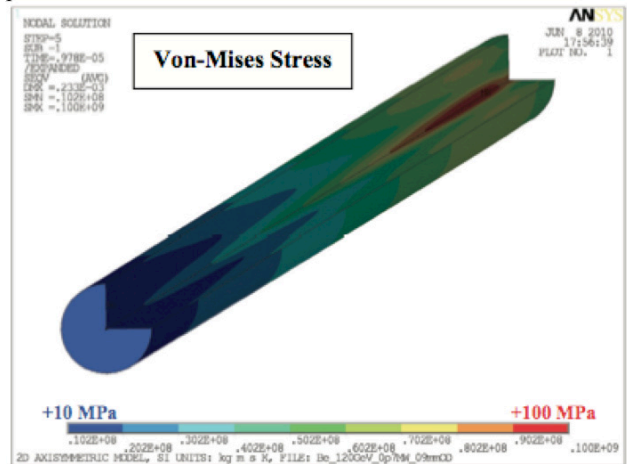


Figure 7: Equivalent stress in Be target rod from 1 pulse of 700 kW beam (static only).

Beryllium Target Analysis

Figure 7 shows a representative contour plot of equivalent stress resulting from a single pulse of 700 kW primary beam. The stress is caused by the rapid expansion of the beam heated central region that is constrained by the surrounding cooler material. Table 3 shows the static analysis results for various cases of beam power and target geometry. With the yield strength of Be about 270 MPa (150°C), the smaller beam spot cases (1.5 mm radius sigma) are not viable at the higher beam powers (2 and 2.3 MW). Whereas, the larger beam spot cases (3.5 mm radius sigma) are viable even at the higher beam powers.

Table 3: Beryllium Target Rod Static Analysis Results.

Beam Energy & Power (GeV, MW)	Beam Sigma (mm)	Peak Energy Density (J/cc/pulse)	Max ΔT per pulse (K)	Max VM Stress (MPa)
120, 0.7	1.5	254	76	100
120, 0.7	3.5	74	22	27
60, 0.7	1.5	243	73	99
60, 0.7	3.5	61	18	23
120, 2.3	1.5	846	254	334
120, 2.3	3.5	245	74	88
60, 2	1.5	707	212	288
60, 2	3.5	176	53	68

When dynamic effects are included however, the peak stresses in the target almost double due to longitudinal stress-wave propagation. For instance, for the 2.3 MW, 120 GeV, 3.5 mm sigma case, the peak stress is 173 MPa compared to 88 MPa for static analysis alone. Since the dynamic stresses are due to longitudinal stress-waves, segmenting the target into shorter segments can reduce the resulting stresses. Figure 8 shows equivalent stress in a 50 mm long segment under the same beam conditions. It can be seen that stresses have been reduced to 109 MPa.

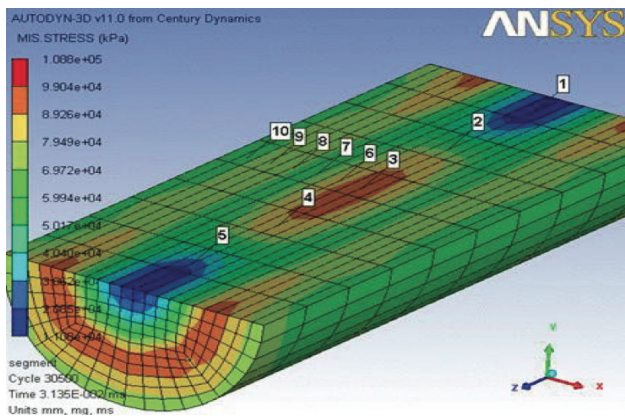


Figure 8: Equiv. stress in Be target segment from 1 pulse of 2.3 MW beam (static and dynamic).

The effect of mis-steered beam on a beryllium target rod was simulated. Figure 9 shows that, for the 2.3 MW case, the free end of the target deflects more than 12 mm for an offset of 2 sigma. Since the LBNE target is surrounded by the focusing horn inner conductor with a

clearance of 5 mm, this is clearly not acceptable. In addition, bending stresses arising from this off-center beam case exceed comfortable stress limits. Certainly adding transverse support points and segmenting the target should reduce this effect.

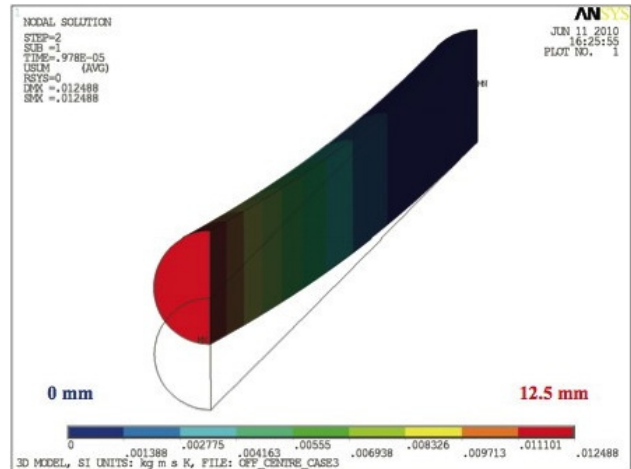


Figure 9: Deflection of Be target rod in response to a 2 sigma offset beam pulse (2.3 MW case).

Integrated Target/Horn Analysis

A simplified target concept is to combine the function of the target and the inner conductor of the surrounding horn as schematically shown in Figure 10. This simplifies the target design by replacing the target cooling circuit with the existing horn spray water cooling. In addition, transverse support of the target for restraint in the case of off center beam can be provided by the inner conductor “spider” radial supports. Analysis results (static) of this configuration, including horn current pulse and beam pulse (but not including end “bell” magnetic forces) are shown in Figure 11. It can be seen that stresses are relatively acceptable, but will likely be higher when dynamic effects are included. Segmenting an integrated target is certainly possible, but would require an exterior containment tube that would also double as the inner conductor.

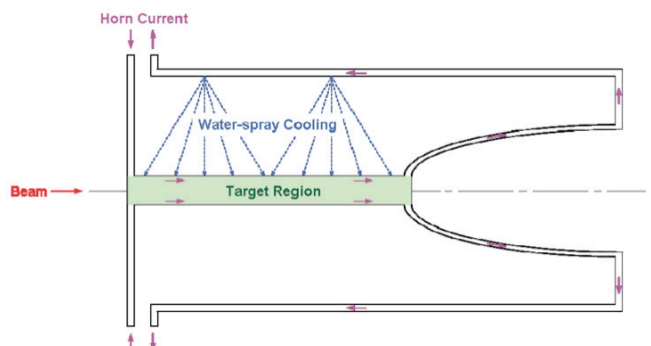


Figure 10: Schematic of integrated target/horn concept.

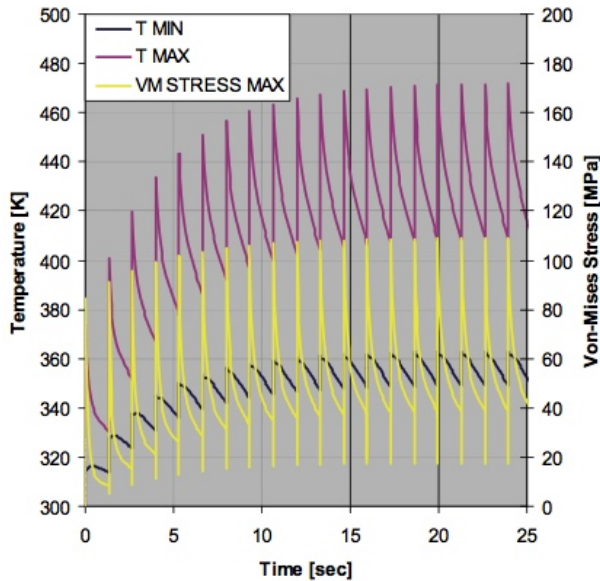


Figure 11: Multi-pulse stress and temp results for integrated target/horn at 2.3 MW beam conditions (static).

Simulation Failure Criteria: Correlation with Experience

Peak energy deposition for the 2.3 MW, 1.5 mm beam sigma case was calculated as 846 J/cc which resulted in stresses in the beryllium that exceeded the yield strength. However, the P-bar target at FNAL has a beryllium target which regularly sees about 1000 J/cc with no evidence of damage. An analysis for beryllium under P-bar beam conditions (120 GeV, 8e12 protons/pulse, 0.2 mm beam sigma) indicates predicted peak equivalent stress of over 300 MPa, well beyond yield strength. Figure 12 shows a picture of a p-bar target with beryllium cover that has seen approximately 5e6 pulses without visible signs of damage although analysis indicates it should. The target rotates 17 degrees with each pulse and moved vertically every 2e17 protons. So, the surface of this cover should be “peppered” with damage spots.

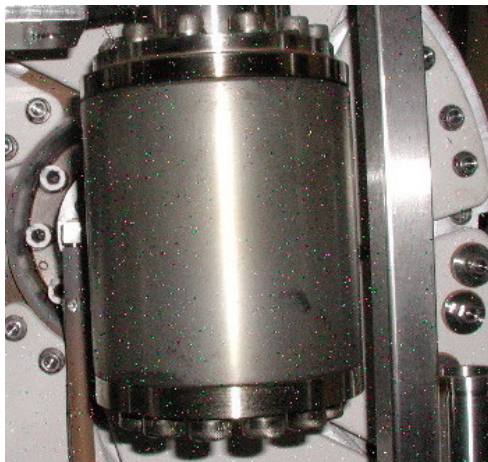


Figure 12: P-bar target with Be cover (photo courtesy of T. Leveling).

Some explanations include non-gaussian beam profile and/or the damage just not being large enough to see optically. Alternatively, the beryllium could be stronger at the high strain rates created by the extremely high beam energy deposition rates. Figure 13 shows how the ultimate tensile strength of beryllium varies with strain rate. It can be seen that at strain rates greater than 100 s⁻¹ the UTS increases by up to 40%. Analysis of the P-bar target conditions predicts strain-rates as high as 6,000 s⁻¹. Analysis of the LBNE 2.3 MW, 1.5 mm sigma conditions predicts strain-rates as high as 340 s⁻¹. Additional analysis of existing beryllium devices in extreme beam conditions as well as possible future in-beam failure tests are in the early stages of development.

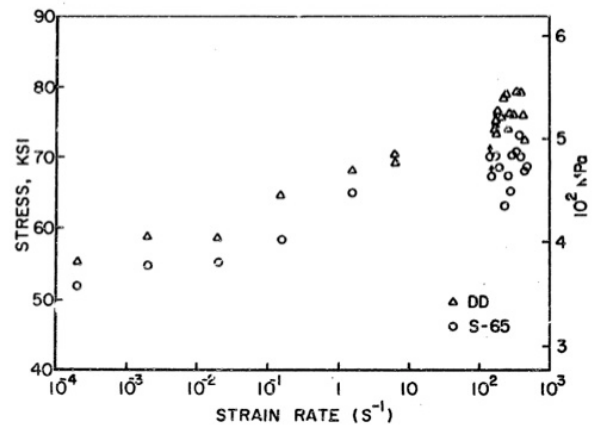


Figure 13: The effect of strain rate on the ultimate tensile strength of structural grade beryllium [4].

FUTURE WORK

Both graphite and beryllium remain viable as candidate high power target materials for LBNE. Near term results from both the autopsy of NT-02 and the BLIP irradiation tests will shed light on the longevity of graphite in high intensity proton beam. Simulation and design work on a segmented beryllium target and cooling system should continue in the near future that includes validation of simulation methods to predict beam induced failure in beryllium

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