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Conceptual Design of Pion-Capture Magnets of up to 15 cm Bore and 20 T Peak Field

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Conceptual Design of Pion-Capture Magnets of up to 15 cm Bore and 20 T Peak Field

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***Abstract*—For the Neutrino Factory and Muon Collider Collaboration, BNL has considered solenoidal magnet systems of several types to capture pions generated by bombarding a mercury jet with multi-GeV protons. The magnet systems generate up to 20 T, uniform to 5% throughout a cylindrical volume 0.15 m in diameter and 0.6 m long. Axially downstream the field ramps gradually downward by a factor of sixteen, while the bore increases fourfold. The steady-state system needed for an accelerator has many superconducting coils and a radiation-resistant insert of mineral-insulated hollow conductor. Less costly, pulsed systems suffice to study pion capture and the effect of a magnetic field on a jet hit by a proton beam. BNL has explored three types of magnets, each with its principal coils precooled by liquid nitrogen. One type employs two sets of coils energized sequentially. Charged in 23 s by a power supply of 5 MVA, the 14-ton outer set generates 10 T and stores 28 MJ, from which, in 1/3 s, to charge a half-ton inner coil that adds 12½ T to the 7½ T remaining from the outer set. An alternative design uses 25 MVA to energize, in 1.4 s, a single 3-ton set of coils. The third type bows to budgetary constraints and is more modest in size and performance. A magnet of 2-3 tons generates 10-11 T with only 2 MVA, in a bore big enough (11 cm) to accommodate the jet. It forgoes the field ramp that improves pion retention.**

***Index terms*—cryogenic pulse magnet; hybrid magnet; radiation-resistant magnet**

I. Performance Parameters of Pion-Capture Magnets

One component of a neutrino factory or muon collider is the magnet system to capture pions that emanate when multi-GeV protons in a beam of 1 MW or more bombard a target, such as a mercury jet 0.6 m long tilted 100 mr with respect to the magnet axis. To capture most of the pions, by bending their trajectories into helices, requires a field of about 20 T in a bore of 0.15 m. To retain the pions, and the muons into which they decay, the on-axis field profile a distance z downstream from the target should approximate $B(0)/(1+kz)$, with k small, so that particles experience little change in field in any Larmor orbit. The bore should increase inversely with the square root of the field, enclosing constant flux. The field should fall by an order of magnitude or so, to convert transverse momentum into longitudinal momentum; then the field can level out.

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II. Hybrid Magnet System for Accelerator

The steady-state magnet system required by a neutrino factory or muon collider must be a hybrid system, with many superconducting coils surrounding a resistive insert, as in Fig. 1 [1]. The field is 20 T over the target, ramping downward to 1.25 T, a factor of 16, over the next 18 m, the bore growing fourfold to 0.6 m. Its main coil generates a peak field of 14 T on the axis of a bore of 1.3 m. A precedent for the coil is the International Thermonuclear Experimental Reactor's 140-ton Central Solenoid Model Coil [2]. In a larger bore, 1.6 m, it has generated almost as much field, 13 T, storing 600 MJ, the same as the entire pion-capture magnet. The upstream five superconducting coils employ cable-in-conduit conductor, the conductor of choice for large magnets operating at many kA; smaller, lower-field coils use Rutherford cable.

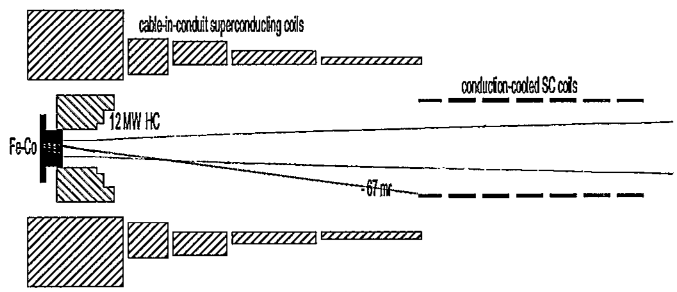

Fig. 1. Cross section (foreshortened axially by factor of two) of upstream 11 m of windings of steady-state pion-capture magnet. The system stores 600 MJ; its main coil generates 14 T in a 1.3 m bore. Inside are a ferromagnetic plug (black T) and mercury target (tilted black rod) and three nested coils of mineral-insulated hollow conductor. The proton beam is tilted −67 mr. The long flared tube shows the radial limit of pion retention.

To survive the intense radiation from the target, the insert employs mineral-insulated hollow conductor, as developed by Tanaka [3] for the Japan Hadron Facility. Stainless steel reinforces the weak conductor, whose copper is soft for fabricability. Because only about one third of the winding cross section carries current, the coil requires 12 MW to generate only 6 T. Radiation-resistant hollow conductor with much less space devoted to insulation and sheathing might generate the field with half the power. Better yet might be a Bitter coil that at 6 MW might generate 7½ T. An R&D program to perfect an insulator (presumably ceramic) to withstand high levels of radiation and the hostile environment of the Bitter magnet could save millions of dollars in power supplies and superconducting magnets.

III. Magnet System with Inductive Energy Storage

Part of any R&D program leading to a neutrino factory or muon collider should be the design and fabrication of a magnet system to study the behavior of a mercury jet traversing a magnetic field and hit with a high-energy proton beam. Pion capture and retention also are of interest. To this end BNL has studied three types of magnet systems. For economic reasons none is steady state; all use copper precooled by liquid nitrogen. The first enlists inductive energy storage and a power supply of 5 MVA that BNL might purchase. The second draws 18 MJ from the kinetic energy of the rotor of the 25-MVA Westinghouse generator that is the backup power source for BNL's Alternating Gradient Synchrotron. The third, dictated by budget considerations, employs four standard BNL power supplies in series/parallel (~2 MVA), to generate only 10-11 T, and in a smaller bore (11 cm), and without the field tail that improves pion retention.

The first type of system includes two sets of cryogenic pulse coils [4]. Fig. 2 sketches the cross section of the coils; Fig. 3 plots the time dependence of its current, field, cumulative heating and temperature rise. A 5 MVA power supply charges the outer set of coils to 16 kA, 10 T in 23 s. Disconnection of the power supply, followed by insertion of a ¼ Ω resistor across the terminals of the set, then creates a voltage—initially 4 kV—with which to charge the inner set of coils. In about 1/3 s it reaches 10.4 kA, 12.6 T. Meanwhile, inductive coupling and resistive losses discharge the outer set to 12 kA, 7.5 T. A resistor introduced across the terminals of the inner set discharges it quickly, to limit its temperature rise. With a resistor of 385 mΩ (for an initial discharge voltage of 4 KV, as with the outer set) the inner coil decays to 4 kA in 0.8 s; the outer set reaches 4 kA at 2 s.

A ferromagnetic plug immediately upstream of the nozzle for the mercury jet improves its entry into the field by halving the field gradient. Centered 3 m from the end of the jet may be a radio frequency cavity, to test its performance in a high radiation environment. If so, water-cooled coils generate the 1¼-T dc field in which to condition and run the cavity.

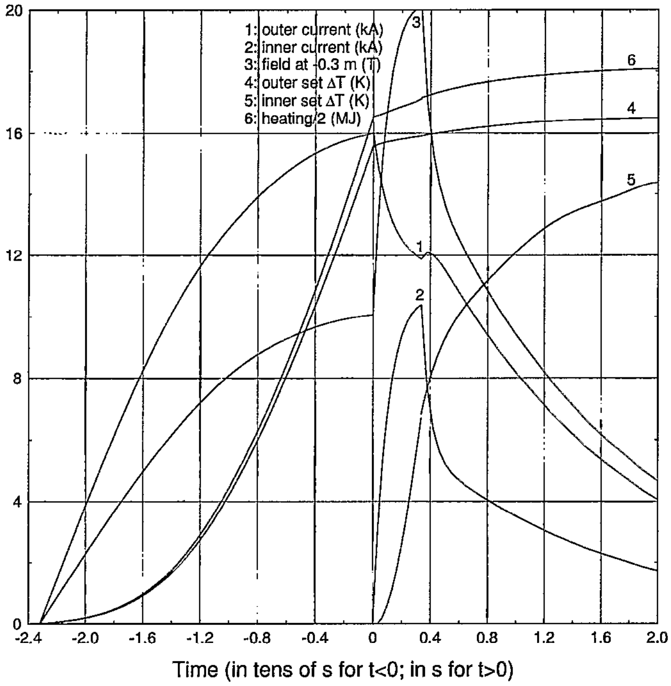

Fig. 3. Time dependence of current and temperature rise in inner and outer sets of coils of magnet of Fig. 2. Also, combined field and cumulative heating. Charging the outer set takes 23 s; the inner set, only 1/3 s.

IV. Magnet System Powered by 25 MVA Generator

A two-stage system can multiply the effective size of its power supply, but requires many tons of conductor and expensive switchgear. Thus, it was tantalizing to learn that one might consider a magnet matched to the 25 MVA Westinghouse generator that once powered the Alternating Gradient Synchrotron, but now is only a backup. Fig. 4 sketches the system. The pulse coils use only 3.2 tons of copper, only 22% as much as in the two-stage system. The system is compact, so as not to overtax the ~20 MJ energy rating of the Westinghouse generator. Fig. 5 plots the time dependence of the magnet's current, field, resistance, cumulative heating and maximum temperature rise. Fig. 6 plots its on-axis field profile.

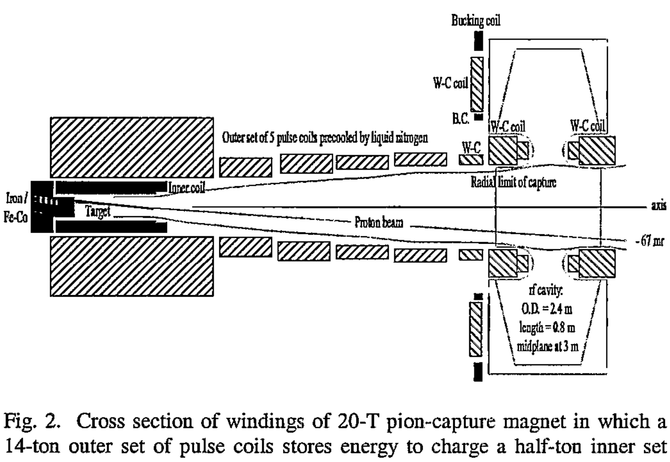

Fig. 2. Cross section of windings of 20-T pion-capture magnet in which a 14-ton outer set of pulse coils stores energy to charge a half-ton inner set (black). The ferromagnetic plug (black T) at left halves the magnetic shear on the mercury jet (tilted black rod). Water-cooled coils at right generate 1¼ T in the bore of the rf cavity centered 3 m downstream from the jet.

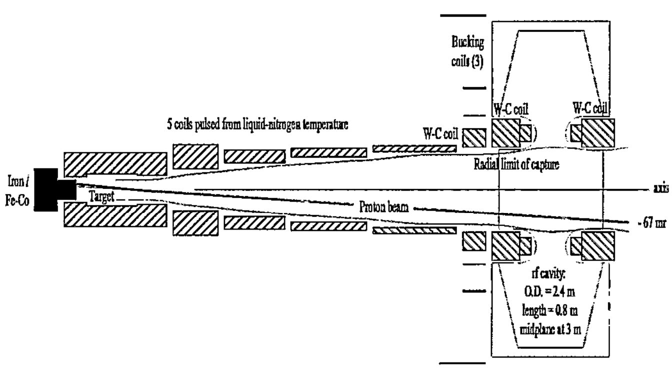

Fig. 4. Cross section of windings of 20-T pion-capture magnet energized by 25 MVA Westinghouse generator. The pulse coils weigh 3.2 tons. The ferromagnetic plug (black T) and contouring of the bore of the main coil achieve a field homogeneity of 5% over the length of the mercury jet (tilted black rod). Water-cooled coils at right generate 1¼ T in the bore of the radio frequency cavity centered 3 m downstream from the jet.

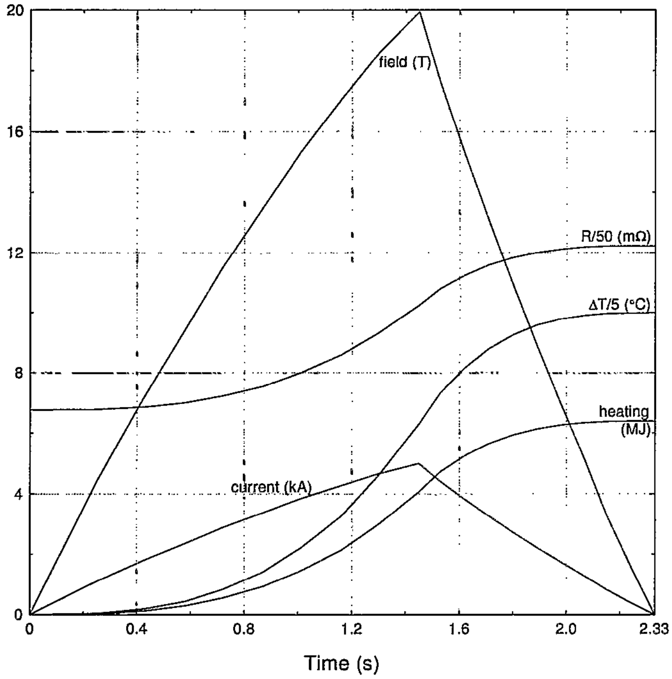

Fig. 5. Time dependence of current, field, resistance, cumulative heating and temperature rise of magnet of Fig. 4. Charging takes 1.4 s; the total pulse length is 2.3 s.

The field is within a few percent of its peak intensity for several times as long as with the two-stage system, because the peak current density not as high. Recool should take much less liquid nitrogen, because the cumulative dissipation is only 6.4 MJ instead of 36 MJ. However, recooling may take longer, because the peak temperature rise is 50 K, instead of 14 K (for the inner set) to 17 K (for the outer set).

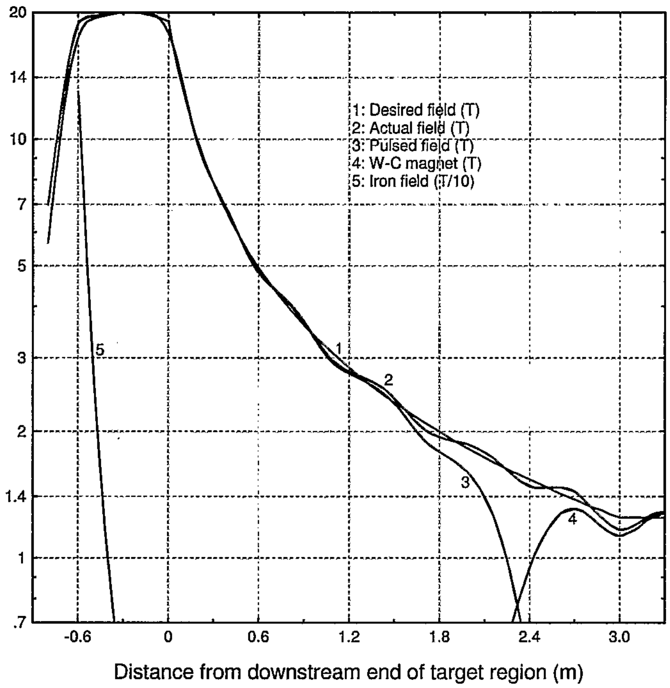

Fig.6. On-axis field of pion-capture magnet of Fig. 4. The pulse magnet generates most of the field everywhere except at the very upstream end, where a ferromagnetic plug contributes 1.2 T and cancels up to half of the field gradient. Water-cooled coils generate most of the field beyond 2.3 m.

V. 10 T, 2 MVA Pulse Magnet without Field Tail

Unfortunately, as our exploration of alternative magnet systems progressed, it became more and more clear that all were beyond our budget. The two-stage system might cost well over a million dollars for the magnet and cryostat, and at least another million for the new power supply and switchgear. The Westinghouse system, despite availing itself of rotating machinery that is free, calls for transformers, rectifiers and bus work to the tune of a least a couple million dollars. Our budget compels us to settle for less ambitious performance, and to employ existing, rather antiquated, BNL power supplies. The most numerous of these deliver 3.6 kA at either 125 V or 150 V. BNL electrical engineers consider it feasible to gang four of these in series/parallel, to give 1.8 MW or 2.16 MW, respectively.

Fig. 7 sketches the winding cross section of a magnet optimized for 1.8 MW. For efficiency the magnet has two grades of conductor, the outer layers with about half the current density of the inner ones. Not shown are the internal cooling passages required for rapid recooling. One generates these passages by spacer strips, either axial (if the magnet is layer wound) or radial, like wheel spokes (if the magnet is of double pancakes).

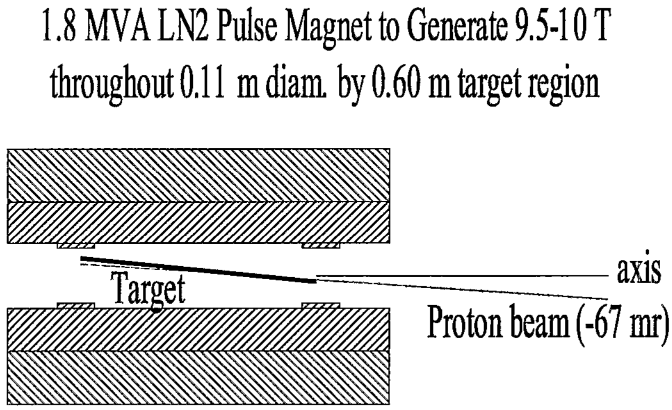

Fig. 7. Cross-section of windings of magnet with which to study the behavior of a mercury jet traversing a magnetic field and hit by a high-energy proton beam. The coil weighs 2 tons. The outer winding have half the current density of the inner ones. Contouring the inner radius keeps the field constant to 5% throughout the target (tilted black rod).

At 2.16 MVA, a magnet of this type can generate 11 T with 2.4 tons of copper. A magnet without the conductor grading requires about 1/6 more power to generate a given field. Of course, fabrication is simpler. Current density that is invariant with radius also allows one to consider double-pancake construction, with its virtue of modularity. Pancakes of larger bore near the ends of the magnet can improve experimental access and allow more room for the mercury jet to enter and exit. Alternatively or additionally, pancakes permit grading the conductor axially for exquisite field homogeneity, without the complexity of a non-constant bore diameter.

Fig. 8 plots the time history of the current, field, resistance, cumulative heating and peak temperature rise. Fig. 9 plots the on-axis field profile.

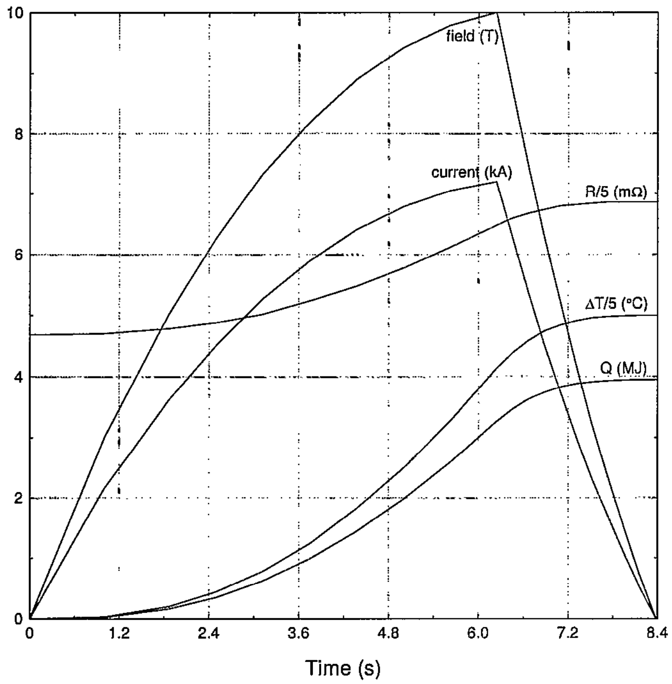

Fig. 8. Time dependence of current, field, resistance, cumulative heating [Q] and temperature rise (of the inner windings) of the magnet system of Fig. 7. Charging takes 6.2 s; the total pulse length is 8.4 s. The temperature rises 25 K by the end of the pulse.

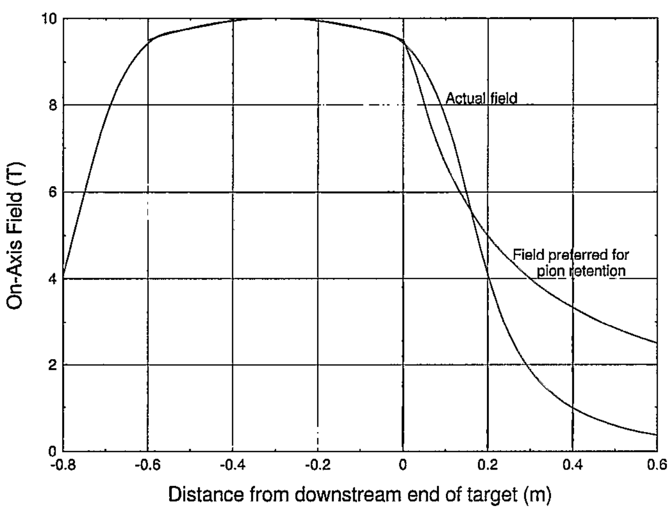

Fig. 9. On-axis field profile of magnet of Fig. 7. The field profile matches the desired one very well within the target, but declines much too quickly for good pion retention beyond ~0.2 m.

Fig. 10 explores the relationship between peak field and power-supply size for pulse magnets of two bore diameters and field profiles. The smaller bore is the minimum that can accommodate the tilted target. The larger bore provides superior experimental access and captures more pions. The field profiles labeled "with tail" include a 3 m ramp, as defined in Part I and plotted in Fig. 9, to improve pion retention. All four lines show that field at first (<10 T) increases almost as the square root of power, and later (~20 T) more like the cube root. The larger bore costs ~13% in field; the pion-retention ramp, ~18%.

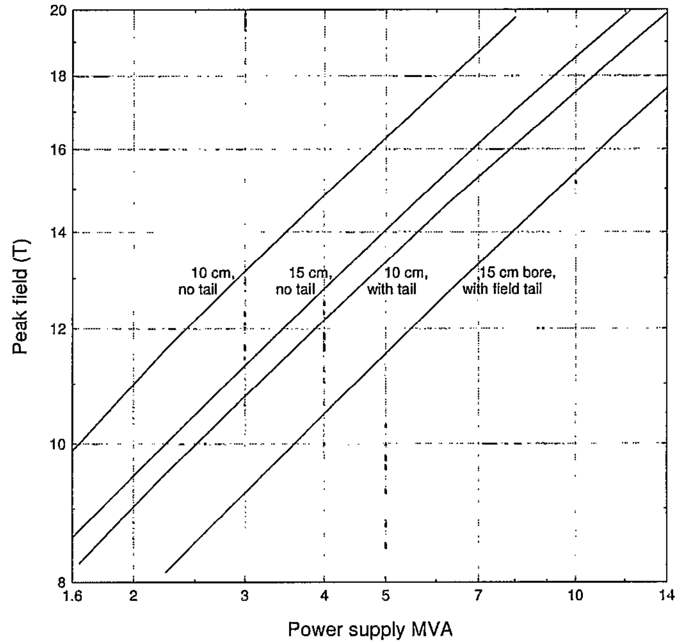

Fig. 10. Field vs. power for magnets similar to Fig. 7 (if no field tail) or the pulse coil of Fig. 4 (if with field tail). At any given power, decreasing the bore from 15 cm to 10 cm improves the field by ~15%. Abandoning the field tail that improves pion retention increases the field by ~22%.

VI. Conclusions and Plans for Future Work

As one can gather from the frequent references to budget constraints, only the final option, based on existing power supplies, is viable now. The hybrid magnet system must await approval for the design and construction of a Neutrino Factory or Muon Collider. The two-stage system makes clever and effective use of inductive energy storage, but is too ambitious and costly, probably even if some other department at BNL would consent to share the cost of the power supply that they then would inherit. The design that uses the Westinghouse power supply could be attractive, but only if the AGS is willing to share much of the cost of the new transformers and other components that they would inherit from the upgrading of this power supply.

The system based on existing BNL power supplies is most appealing. If cooled to ~30 K, it might generate as much as 15 T. We have prepared budgetary cost estimates for the magnet and cryostat and are examining magnet stresses, cool-down considerations, and the cost of ganging power supplies. We hope to prepare a detailed design during 2002. If so, fabrication may begin in 2003.

VII. References

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