Nb_3Sn RRP® Strand and Rutherford Cable Development for a 15 T Dipole Demonstrator

E. Barzi[1], N. Andreev, P. Li, V. Lombardo, D. Turrioni, and A.V. Zlobin

***Abstract*—Keystoned Rutherford cables made of 28 strands and with a stainless steel core were developed and manufactured using 1 mm Nb_3Sn composite wires produced by Oxford Superconducting Technology with 127 and 169 restacks using the Restacked-Rod-Process®. The performance and properties of these cables were studied to evaluate possible candidates for 15 T accelerator magnets.**

***Index Terms*— Accelerator magnet, critical current density, Nb_3Sn strand, Residual Resistivity Ratio, Rutherford cable.**

I. Introduction

INTEREST in a Hadron Collider (HC) with energy above the LHC reach for High Energy Physics research has gained momentum in the U.S., Europe and China [1]-[3]. A 100 TeV center of mass energy machine in a 100 km tunnel requires dipoles with a nominal operation field of 15 T and appropriate operation margins, which can presently be obtained only with the Nb_3Sn technology. A practical demonstration of this field in accelerator-quality magnets and reduction of magnet costs are key conditions for the realization of such a machine. A decade-long investment in the Nb_3Sn technology produced at FNAL the first series of 10 to 12 T accelerator-quality dipoles and quadrupoles, as well as their scale-up [4]-[7]. Such advanced technology can now be pushed up to its limits of ~15-16 T by improving Nb_3Sn strands and cables, and developing innovative design approaches. For cost-effective 15 T accelerator magnets, the critical current density $J_c(16T,4.2K)$ of commercial Nb_3Sn composite wires has to be pushed to >1500 A/mm^2 [8]. In addition, wider cables are required to reduce the number of coil layers and decrease the number of turns, thereby the inductance which, in turn, simplifies magnet quench protection and allows increasing the magnet length.

FNAL has started the development of a 15 T Nb_3Sn dipole demonstrator for a 100 TeV scale HC based on the optimized "cos-theta" coil [9], [10]. A 4-layer coil design is needed to achieve the coil width necessary for a design field of 15 T [9]. To increase coil efficiency the 4-layer coil was graded by using two cables with the same 15 mm width and different thicknesses. The cable in the two innermost layers has 28 strands 1.0 mm in diameter and the cable in the two outermost layers has 40 strands 0.7 mm in diameter. Similar Nb_3Sn cables have already been developed and produced at FNAL and used in earlier dipole models [11], [12]. The two outermost layers of the 15 T dipole demonstrator use the same 40-strand cable [12] as the 11 T dipole [6] developed for the LHC upgrades [13]. Three unit lengths of this cable are available already. Instead, for the two innermost layers of the magnet, a new Rutherford cable with 28 strands of 1 mm diameter, and same nominal width of 14.7 mm and keystone angle of 0.79 degree, was optimized using state-of-the-art RRP® wires. Critical current and residual resistivity ratio were measured for strands extracted from cables and compared with the values obtained for the virgin wires and for wires flat-rolled to various sizes. Flat-rolling round wires is a method to evaluate the response of a strand to deformation during cabling, and to perform systematic studies of the resulting effects on the conductor. This paper summarizes the results obtained in these studies.

II. Strand and Cable Sample Parameters

A. Strand Description

Table I shows parameters of the Restacked Rod Process (RRP®) wires of 1 mm size produced by Oxford Instruments - Superconducting Technology (OST) and used in these studies. The wires denoted as RRP1, RRP2 have a 108/127 stack design, and RRP3 has a 150/169 design. This notation represents the number of superconducting (SC) bundles within the billet layout over the total number of SC and Cu restacks. D_S is the equivalent subelement diameter calculated in the approximation of round instead of hexagonal geometry. The final heat treatment steps shown in Table I are those used by OST to obtain the data shown. All the wires also have extra Cu between the subelements. Pictures of the RRP® wire cross sections are shown in Fig. 1.

TABLE I
STRAND PARAMETERS – OST DATA

Strand ID	RRP1	RRP2	RRP3
Stack design	108/127	108/127	150/169
Ternary element	Ti	Ta	Ti
Production year	2006	2006	2014
Diameter d, mm	1.0	1.0	1.0
I_c (4.2K, 12 T), A	854	1103	1077
J_c (4.2K, 12 T), A/mm^2	2,323	3,066	2,650
I_c (4.2K, 15 T), A	437	570	578
J_c (4.2K, 15 T), A/mm^2	1,188	1,582	1,424
D_S, μm	65	65	58
Twist pitch, mm	43	26	23
Cu fraction λ, %	53	54.0-54.3	48.1-48.4
RRR	153	264	369
Final HT step	650ºC/40h	665ºC/50h	665ºC/50h

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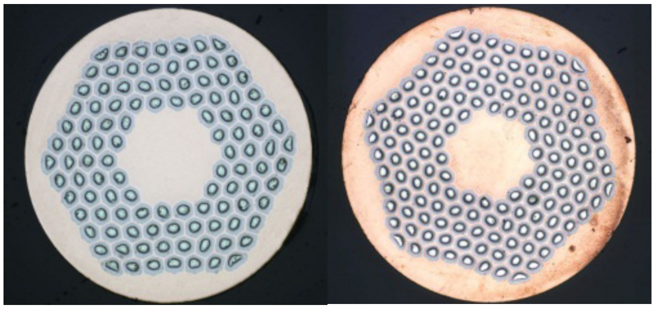

Fig. 1. Cross sections of 1 mm 108/127 (left) and 150/169 (right) RRP® wires.

B. Cable Development and Fabrication

Rutherford cables with 28 strands of 1 mm diameter and 14.7 mm unreacted nominal width were produced using first older RRP® wires, denoted as RRP1 and RRP2. The cables, as described in Table II, were fabricated in one pass using a turk-head designed for one-pass cable fabrication [12]. They all included an 11 mm wide stainless steel core to suppress eddy currents and obtain better field quality and ramp rate dependence in magnets.

TABLE II
CABLES FOR DEVELOPMENT OF 15 T DIPOLE

Cable ID	RRP® wire design	Width (mm)	Mid-thickness (mm)	Lay angle, (deg)	*PF* (%)
1	RRP1, RRP2	14.84	1.804	16	86.7
2	"	14.87	1.759	16	88.7
3	"	14.82	1.737	16	90.2
4	"	14.85	1.707	16	91.6
5	"	14.89	1.689	16	92.3
6	RRP3	14.89	1.835	17.5	85.4
7	"	14.89	1.812	17.5	86.5
8	"	14.93	1.786	17.5	87.6
9	"	14.94	1.762	17.5	88.7
10	"	14.94	1.736	17.2	89.9
11	"	14.94	1.710	17.4	91.4
12	"	14.94	1.685	17.6	92.8
13	RRP3, pre-treated	14.90	1.836	16.9	85.0
14	"	14.89	1.813	17.0	86.2
15	"	14.92	1.787	17.0	87.3
16	"	14.91	1.766	17.0	88.4
17	"	14.91	1.734	17.3	90.2
18	"	14.94	1.710	17.3	91.3
19	"	14.90	1.684	17.0	92.8

This first series of cable samples made of RRP-108/127 strands was pushed to the highest compaction levels of ~92% allowed by the FNAL cabling machine. Based on the negligible critical current degradation (i.e. 3 to 4 %) that was found in this first study over the entire packing factor range, the RRP3 wire most recently procured for the 15 T Dipole models was then used to reproduce cable geometries in a range of packing factor (*PF*) between ~85% and ~93%.

An experiment was also conducted in pre-heat treating the RRP3 wire at ~210°C for 3 days before using it in cables with IDs from 13 to 19 in Table II, which summarizes the parameters of all these keystoned cables. The cross section of one of these cables is shown in Fig. 2 (bottom), together with the existing cable (top) to be used for the 15 T dipole innermost layers.

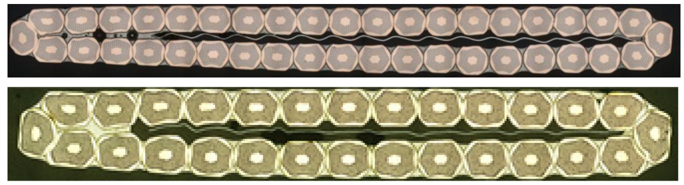

Fig. 2. Cross section of keystoned cable ID 7 (bottom), and of 11 T Dipole cable (top). Both cables in Figure are ~15 mm wide.

C. Heat Treatment

A three step reaction cycle, which is typical for Internal Tin Nb_3Sn composite wires, was used. The heat treatment cycles for this study are described in detail in Tables III and IV. Samples were heat treated in a 3-zone controlled tube furnace in argon atmosphere. Two calibrated, sheathed and ungrounded, type-K thermocouples, TC1 and TC2, were mounted in the vicinity of the samples for temperature monitoring. TC1 and TC2 were placed 6 inches apart, and TC2 was the closest to the end of the retort. The wire used to fabricate cable samples with IDs from 13 to 19 was pre-heat treated first as shown in Table IV. Round wire and extracted strand samples from cable IDs 13 to 19 were then heat treated (Table IV) to complete the same cycle followed for the untreated RRP3 wire at 400°C and 665°C. The rolled wires were heat treated separately using the same nominal size. The average final temperature for the latter was 664.8°C, i.e. very close to the average temperature of 665.1°C obtained for the extracted strands.

TABLE III
HEAT TREATMENT PARAMETERS

RRP1, RRP2			RRP3		
TC1, °C	TC2, °C	t, h	TC1, °C	TC2, °C	t, h
209.5	214.0	72	204.8	209.9	48
397.7	403.2	48	396.9	400.9	48
649.9	651.8	50	663.7	665.9	50

TABLE IV
HEAT TREATMENT PARAMETERS FOR RRP3 PRE-PROCESSED WIRE

RRP3 - Pre treated			RRP3 - Post treated		
TC1, °C	TC2, °C	t, h	TC1, °C	TC2, °C	t, h
209.5	211.5	72	205.6	208.7	12
-	-	-	397.8	400.9	48
-	-	-	663.9	666.3	50

III. RESULTS

A. Critical Current and Magnetization

Sample preparation and testing techniques used at FNAL for Nb_3Sn wires are detailed in [11], [12]. The closed markers in Fig. 3 show the $I_c(4.2K)$ as function of magnetic field for a number of round, extracted and flat-rolled RRP3 wires. Open markers indicate early quenches without any *V-I* transition. It can be seen that for a *PF* below 88%, unstable transport behavior for the RRP3 wire starts at or below 11 T, which provides ample margin for a 15-16 T dipole load line. The magnetization *M* of the RRP3 round wire, as measured with a balanced coil magnetometer per total strand volume, is shown in Fig. 4. Flux jumps can be seen only below 0.5 T. From the available I_c and *M* data, the effective subelement size or d_{eff} was calculated to be 60±3 μm.

The results of I_c measurements made on the RRP® extracted strands were compared with those made on the round strands. The critical current I_c at 4.2 K normalized to the average I_c of the virgin wires (*PF*=78.5%) is plotted in Fig. 5 at 15 T as a function of cable packing factor. At least two round samples were tested for an accurate normalization. At least one extracted sample was measured per packing factor. The first series of cable samples made of the RRP-108/127 RRP1 and RRP2 strands demonstrated critical current degradation smaller than 4% over the whole packing factor range (up to ~92%) encompassed by the cables. For the RRP3 strand the I_c degradation was less than 3% for cables up to ~90% cable compaction. The superconducting performance in the RRP3 wires started decreasing for compactions above 90%. The $I_c(4.2K)$ of the virgin RRP3 wire was 543 A at 15 T (J_c = 1335 A/mm^2) and 1021 A at 12 T (J_c = 2510 A/mm^2), with an overall variation over the number of sample tested of about 3%. The B_{c20} obtained through parameterization of the transport data and of the magnetization data ranged from 27 T to 28.4 T.

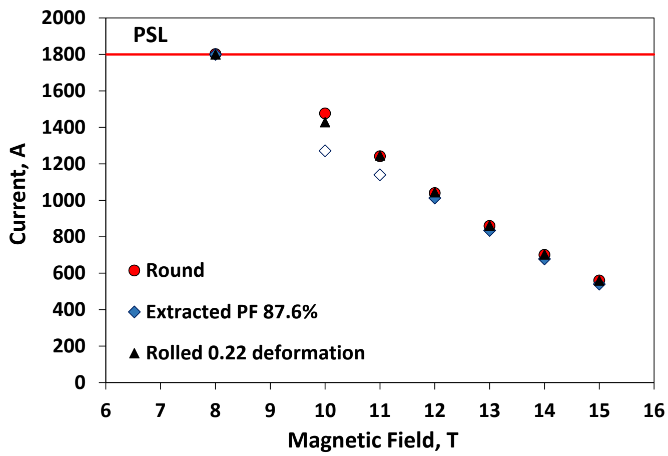

Fig. 3. Critical current at 4.2 K as function of magnetic field for a number of round, extracted and flat-rolled RRP3 wires (closed markers). Open markers indicate early quenches without any *V-I* transition. The horizontal line represents the 1800 A power supply limit.

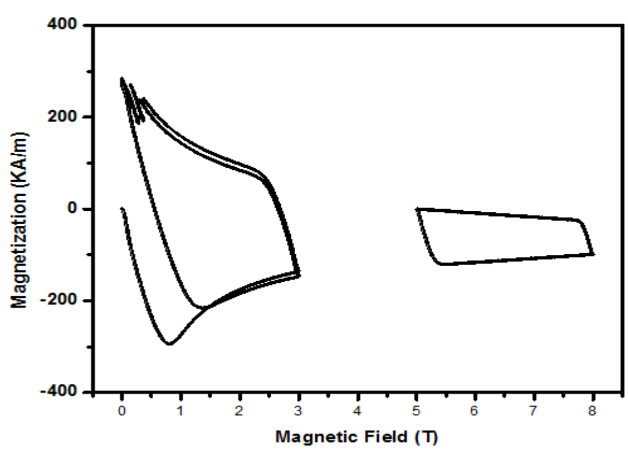

Fig. 4. Magnetization measurement at 4.2 K of round RRP3 wire per total strand volume.

On the other hand, cables made with RRP3 wire that had been pre-heat treated at 210°C before cabling show less critical current degradation at cable packing factors above 90% than in the RRP3 wire used as-is in the cables (Fig. 6). In preparation of further heat treatment studies, the RRP3 round wire was flat-rolled to a number of size values to compare its behavior to the extracted strands. Fig. 7 shows such comparison for the $I_c(15T,4.2K)$. For RRP3 cables between 86% and 88% compaction, a good match is obtained at deformations between 0.18 and 0.22.

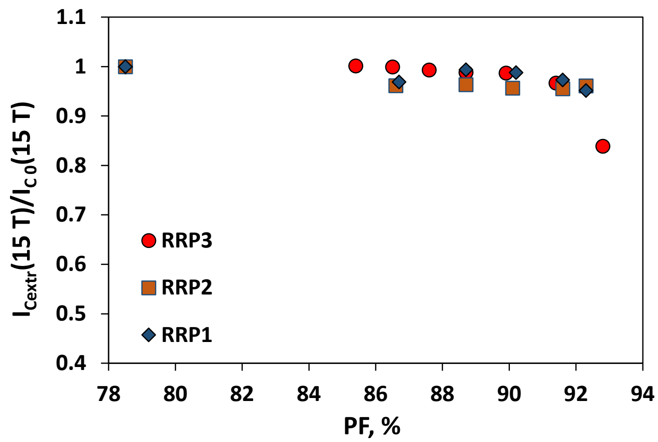

Fig. 5. Normalized I_c *(4.2 K,15T)* of extracted strand vs. cable *PF*.

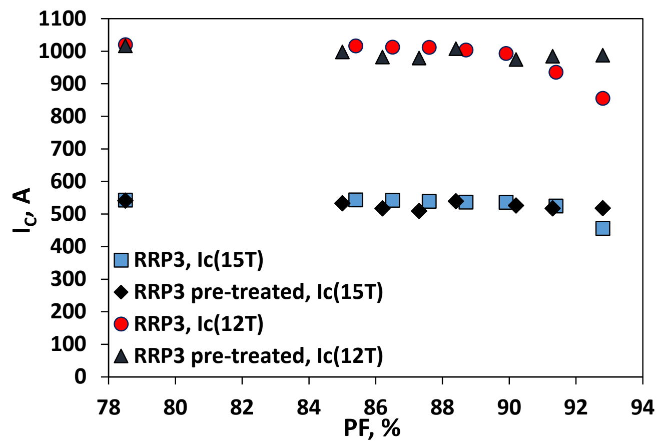

Fig. 6. Comparison of extracted strand I_c*(4.2K)* vs. cable *PF* for as-is and pre-treated RRP3 strands at 12 T and 15 T.

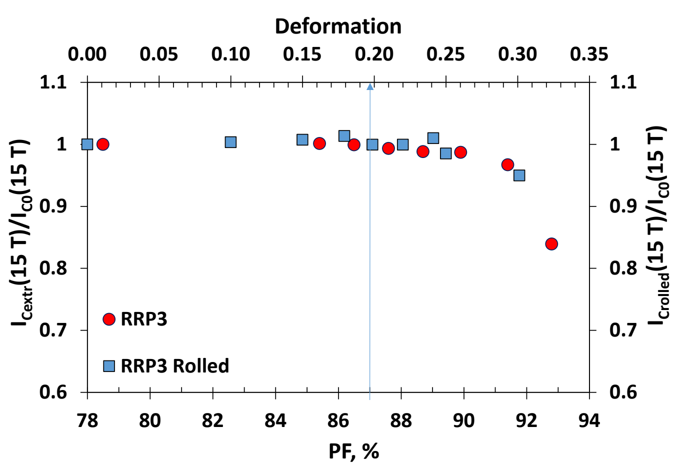

Fig. 7. Comparison of extracted strand I_c *(4.2K,15T)* behavior with rolled wire I_c *(4.2K,15T)* behavior.

B. Residual Resistivity Ratio (RRR)

The Residual Resistivity Ratio (*RRR*) was measured as the ratio of the wire resistivity at room temperature over its residual resistivity at 19 K. Fig. 8 shows the *RRR* as a function of *PF* for the RRP® extracted strands. The overall *RRR* of the wires decreased more or less linearly with compaction and similarly among the various types of wires. For RRP3, the *RRR* was above 250 up to ~90% cable compaction.

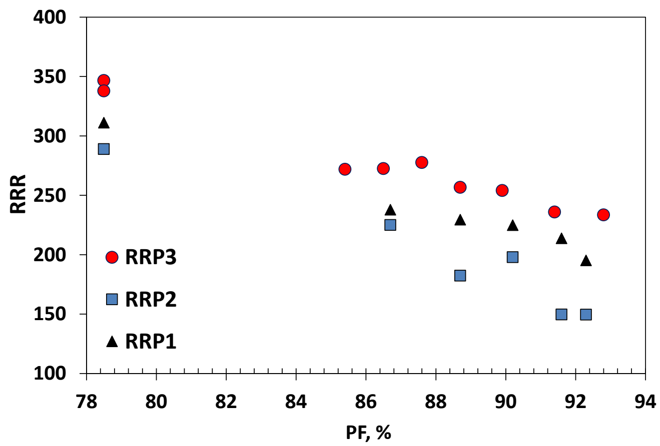

Fig. 8. *RRR* as function of cable packing factor.

Whereas cables made with RRP3 wire that had been pre-heat treated at 210°C before cabling have better critical current in the highest compaction range, their *RRR* is somewhat reduced, as shown in Fig. 9. However, at the nominal *PF* of 87% the *RRR* is still ~200. More studies on heat treatment procedures will follow.

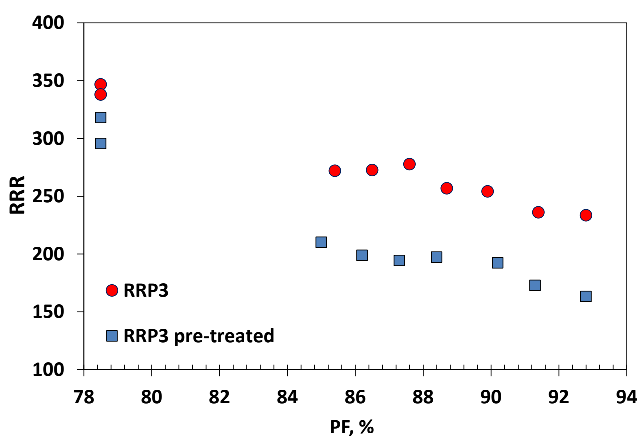

Fig. 9. Comparison of *RRR* vs. cable *PF* for as-is and pre-treated RRP3 strands.

Fig. 10 shows the comparison of the *RRR* of the flat-rolled wires with that of the extracted strands for RRP3. Contrary to I_c, in the case of *RRR* a good match cannot be obtained because above some minimal deformation, the *RRR* in the rolled strand is systematically smaller than in an extracted strand. This is due to the fact that in a rolled wire the deformation, which is typically associated only to the edges in a cable, is instead imparted homogeneously along the whole wire.

The magneto-resistivity effect is also known to strongly reduce copper *RRR*. This effect was measured on a round, extracted and rolled RRP3 wire in a perpendicular magnetic field, and the results are shown in Fig. 11. The *RRR* at 15 T is ~20 independently of the *RRR* values.

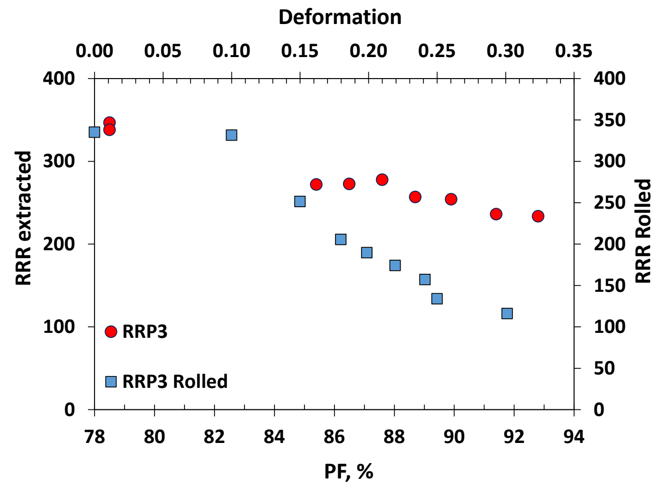

Fig. 10. Comparison of extracted strand *RRR* behavior with rolled wire *RRR*.

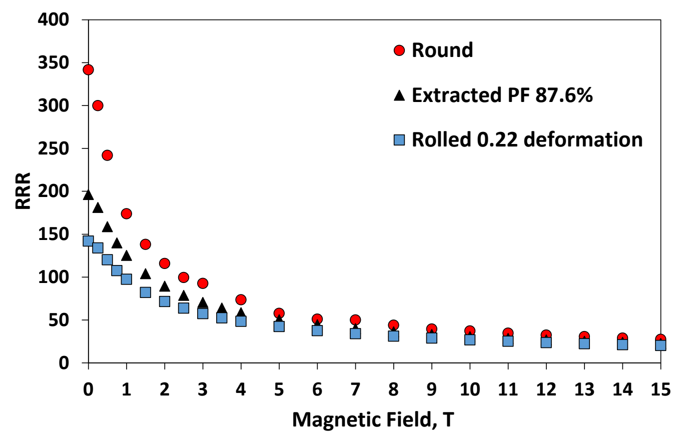

Fig. 11. Magneto-resistivity effect for a round, extracted and rolled RRP3 strand in perpendicular magnetic field.

Based on the above results, the nominal cable mid-thickness that was chosen for the 15 T dipole demonstrator is 1.8 mm, i.e. *PF*~87%. The $I_c(B)$ dependence, measured using extracted strands at 4.2 K, and parameterized [14] at 4.5 K and 1.9 K for the 28-strand cable, provided the following short sample limit (SSL) data for the 15 T dipole demonstrator: 11.05 kA (B_{ap}=15.25 T) at 4.5 K and 12.2 kA (B_{ap}=16.65 T) at 1.9 K [10]. When using other parameterizations [15], [16] the SSL limits changed by 0.2% at the most both at 4.5 K and at 1.9 K.

IV. Conclusions

A 15 T Nb_3Sn dipole demonstrator for a future HC is being developed at FNAL. The Rutherford cable used in the two innermost layers has 28 strands of 1.0 mm diameter and the cable used in the two outermost layers has 40 strands of 0.7 mm diameter. Cable samples for the inner coils with various packing factor using Nb_3Sn RRP® wires of different architecture were fabricated and tested. The cable packing factor was optimized to achieve a low degradation of critical current and copper matrix *RRR*. The magnet maximum field estimated based on the cable data is 15.25 T at 4.5 K and 16.65 T at 1.9 K.

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