# HIGH FIELD MAGNETS*

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*Abstract*

In this paper we review the progress on the High Field Magnets program (HFM) in Europe aimed to the LHC upgrade. We first revisit the reasons for the program and then we make a concise, however important, discussion on the available materials. After an overview of the main progress in the US where the HFM program is by far the most advanced, we finally describe the more recent advances in HFM in Europe obtained for superconductors, giving the perspective for the next years.

## MOTIVATIONS FOR THE HIGH FIELD PROGRAM FOR THE LHC

### *Inner triplet for the LHC luminosity upgrade*

In the accelerator physics community, there is a general consensus on the fact that after a few years of operation, the LHC luminosity will saturate. Whether this will happen at nominal luminosity, or at a lower level, this is an open issue that goes beyond the aims of the present paper. The early studies about the LHC luminosity upgrade [1,2] proposed an improvement of the triplet regions to allow an increase in the interaction regions focusing for the years 2014-2015. After several years of studies, including the activities carried out in the CARE-HHH network, a staged approach has been proposed. The idea, first proposed in [3], has been to split the luminosity upgrade into two phases. For phase I, Nb-Ti technology can be sufficient to reach the goal of 2-2.5×$10^{34}$ $cm^{-2}s^{-1}$ of peak luminosity, i.e., the so-called ultimate luminosity for what the present machine was designed [1]. However, a few years after phase II implementation, a new leap forward in luminosity will be possibly necessary, i.e. reaching 10×$10^{34}$ $cm^{-2}s^{-1}$. A possible scenario is reported in Fig. 1, where the consequences of 19th September 2008 incident in LHC have not been taken into account, since a new schedule has not been yet worked out. For the further gain of a factor 4-5 in luminosity foreseen for phase-2 substantial improvements are needed, namely a much higher beam intensity and very large aperture quadrupoles to allow stronger focusing for the inner triplets. We need not only to improve the optical performance of the triplets, but also to improve the shielding of the superconducting coils from the radiation debris. The larger aperture coils should have better heat transfer characteristics, indeed: dealing with the heat deposition coming from collision debris will be a real challenge, when working at 10×$10^{34}$ $cm^{-2}s^{-1}$, both for the coils and for the cryogenic system.

The Nb-Ti new inner triplet foreseen for the phase I can reach a $\beta^*$ of 25 to 30 cm. The ultimate limit to focusing is set by the correction of aberrations, and is related to the triplet aperture and compactness. A $Nb_3Sn$ triplet of about 150 mm aperture can reach a $\beta^*$ of 15 cm. Of course in order to convert the decrease in $\beta^*$ into an increase in peak luminosity one has to counter the adverse effects of the geometrical loss factor through an early separation scheme [4] and/or crab cavities.

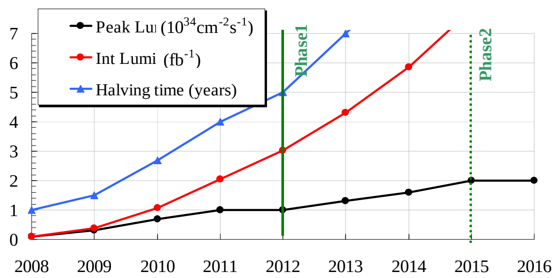


Figure 1: Possible scenario for luminosity and time to half the experimental error in detectors. Consequences of incident of 19th September 2008 are not accounted (courtesy of E. Todesco, CERN).

The focusing is not the only parameter determining the luminosity increase, but it is certainly one of the most relevant. One of the big advantages of the improvement of the triplet is that it involves, at first order, a limited region of the machine and the impact on peak luminosity is straightforward and fast. On the contrary, an increase of beam intensity and/or other parameters linked to luminosity involves reaching new regimes in the beam physics, and the gains are longer to be obtained. The graph of Fig. 2, based on the experience of existing colliders, and certain hypothesis on degree of complexity of LHC operations, illustrates the different effect of an increase in luminosity by beam intensity only (to a level that has still to be demonstrated) without change of inner triplet and the increase of luminosity by a change of triplet coupled to a moderate increase of beam intensity. The effectiveness of the second scenario on integrated luminosity looks not negligible.

$Nb_3Sn$ has much higher field limit and critical temperature than Nb-Ti: this is a plus for the luminosity upgrade that can be translated either into larger aperture, or higher gradient, or greater margin, or in a mix of all of this. The diagram of Fig. 3 illustrates the different paths to take advantage of the $Nb_3Sn$ properties for the luminosity upgrade of LHC.

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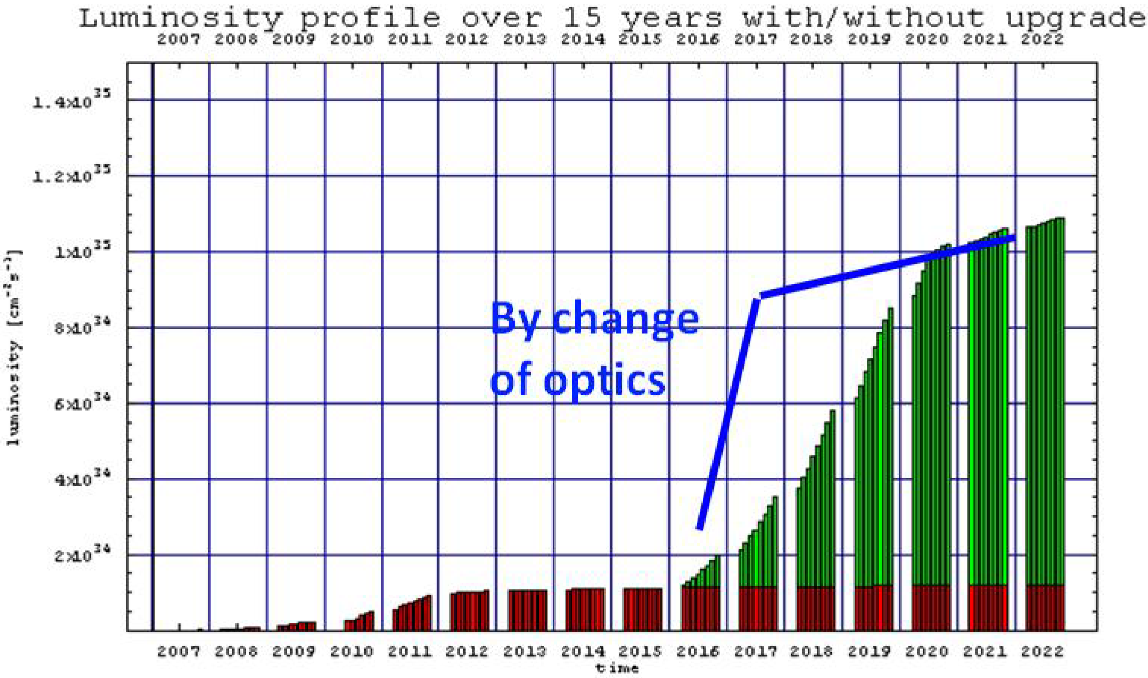


Figure 2: This graph, courtesy of J. P. Koutchouk (CERN) and based on an original study of V. Shiltsev (Fermilab), illustrates the expected increase in luminosity according to reference scenario [1] driven by beam intensity at constant optics (histograms) and increase due to upgrade of focusing through a $Nb_3Sn$ triplet, coupled with a moderate beam intensity increase (thick solid line).

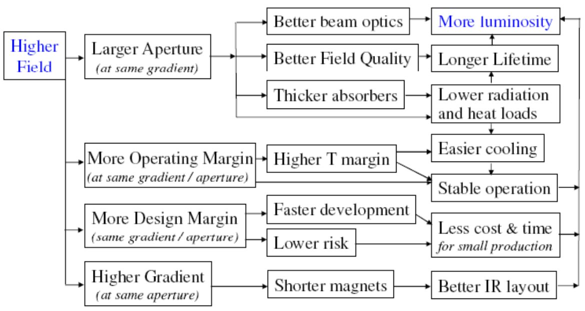


Figure 3: Different paths from the higher critical field of $Nb_3Sn$ to higher peak luminosity for LHC via an upgrade of the inner triplets (courtesy of G. Sabbi, LBNL).

## *Other magnets for improving the LHC performances*

Besides the inner triplet quadrupoles, other magnets of the IR will require $Nb_3Sn$ technology to reach a peak luminosity of $10\times10^{34}$ cm$^{-2}$s$^{-1}$, either for the required field or for the better resistance to heat deposited by radiation:

- Corrector magnets; since these magnets are impregnated, the larger temperature margin of $Nb_3Sn$ is a necessary quality.
- Separation dipoles: although here a study is required, $Nb_3Sn$ can provide more compact separation, freeing space for shielding or offering more flexibility in the optics.

Other types of magnets, not directly related to the IR, may need to be replaced and substituted with better performing magnets in the LHC when luminosity will go beyond the present nominal value. The slots for these upgraded magnets are:

- Dogleg dipoles for cleaning insertions;
- Q6 for cleaning insertions;
- 10 m dipoles for the dispersion suppression region: a normal 8.3 T dipoles of 15 m could be substituted by a 13 T magnet about 10 m long. This will make room enough to install additional collimators in a very sensible zone.

Of course all cases must be studied and evaluated more in detail; however it is clear that the availability of magnet technology increasing by 50% the magnetic field of Nb-Ti could be a great asset for the LHC project, which has always had to fight against strong space constraints due to the existing infrastructures.

## *Energy upgrade of LHC*

An energy doubler as final upgrade of the LHC machine has been already envisaged in [1]. Such a study has not been developed, due to the lack of resources and the low priority in the CERN program. Only the first years of the LHC physics will provide the information necessary to assess the interest of a doubler of the LHC energy as a real competitor/complement of future lepton colliders. In our opinion, it is a must for CERN to have a conceptual design of such a project because it can be very attractive if lepton collider should appear too expensive or impractical. It will build on a solid existing base and infrastructure. A first broad evaluation of the cost was done in [5] and a cross section of a 20 T operational field dipole has been sketched, based on existing superconductor. In Figure 4 the cross section of the dipole, using $Nb_3Sn$ for the outer coils and Bi-2212 for the inner ones shows that the corresponding center of mass energy of 33 TeV is not out of reach. This would be the LHC-FEF (Farthest Energy Frontier). Of course this hypothesis stays on the –far– background since to arrive to the 20 T for the LHC energy upgrade in the middle of the 2020's we need to pass throughout the 15 T magnet technologies, necessary for $10\times10^{34}$ $cm^{-2}s^{-1}$ luminosity goal, expected for around 2018.

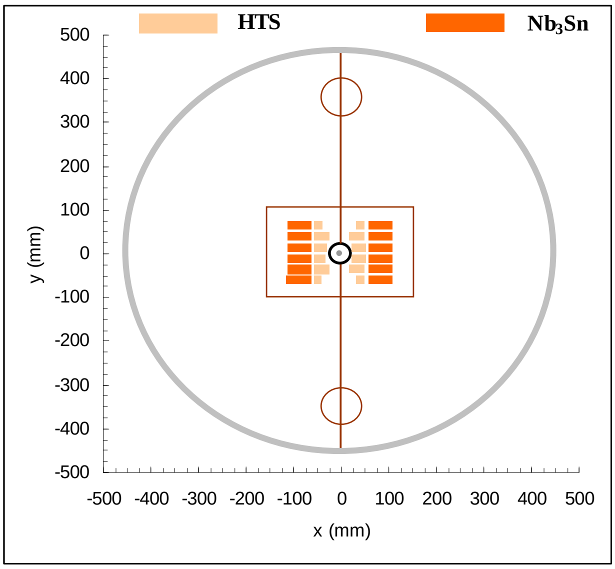


Figure 4: Sketch showing the coil package of a dipole capable of 20 T central field ($B_{max}$=24 T). HTS is Bi-2212 and $J_{cr}$ used according to best present value (see section on superconductors and Fig.7). Courtesy of E. Todesco, CERN.

## SUPERCONDUCTORS

### *Critical temperature*

To choose the superconductors, the first important parameter is the critical temperature $T_c$. In Fig. 5 the historical plot of $T_c$ is reported. One can see that $Nb_3Sn$ is actually one of the first practical materials which have been discovered; the large temperature leap given by HTS is clearly visible. Finally, one can observe how $MgB_2$ is well in line with the progress of the classical material, or LTS (Low Temperature Superconductors). In the same plot the recently discovered class of the oxy-ferropnictides is reported.

### *Critical field*

The second most important parameter is the (upper) critical field $B_{c2}$. In practice, a superconductor can be pushed up to 2/3 of its critical field. May be it can go only to a much smaller fraction, but 70% of $B_{c2}$ is certainly a good guess as upper limit for its use. In Fig. 6, the critical field for the best candidate material is reported as a function of temperature. Nb-Ti and even $Nb_3Sn$ are confined in a tiny corner of the graph. However, the reason for their wide use becomes clear in the next graph.

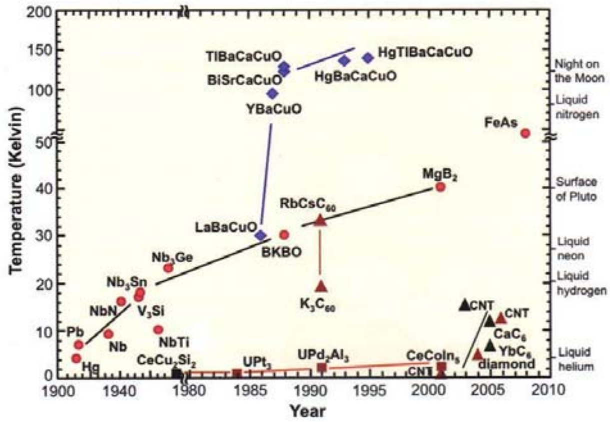


Figure 5: Critical temperature vs. year of discovery for most practical superconductors. Courtesy of C. Senatore, University of Geneva.

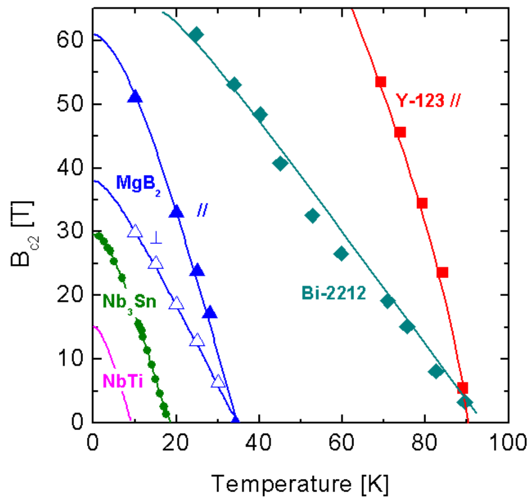


Figure 6: Critical field of most important superconductors vs. temperature (courtesy of C. Senatore, University of Geneva, Switzerland).

### *Critical current*

After temperature and field, the third relevant parameter is the current. For magnets in general, and especially for accelerator magnets that need a high current density in the coil, the most relevant quantity is the critical current averaged over the whole cross section of the wire, called engineering current density $J_e$. In Fig. 7, $J_e$ vs. magnetic field is given for the most important superconductors.

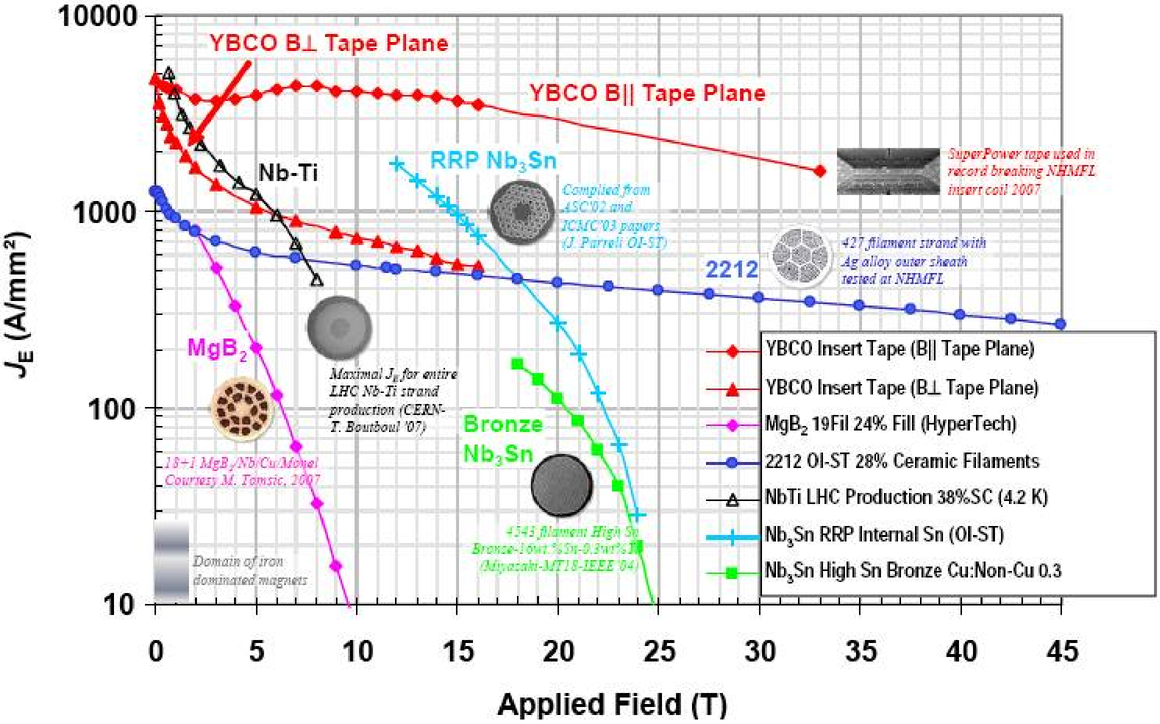


Figure 7: J engineering ($I_{cr}/A_{tot}$) vs field at T=4.2 K (courtesy of P. Lee, Applied Superconductivity Center, Florida State University).

From Fig. 7 it appears clear that $MgB_2$ is still too low in $J_e$, while the high temperature superconductors like Bi-2212 can be used beyond 18-20 T. Ybco is very promising, however its technology is not yet mature for long lengths, and so far it is produced only in thin tapes of relatively low amperage. Magnets require $J_e$ above 500 A/mm$^2$ at the peak field and we can see that in the region of interest, 10-18 T, $Nb_3Sn$ is the best material. Despite the difficulties generated by heat treatment at 700 °C, with induced constraints on insulation, and by the brittleness of the material in the final state, $Nb_3Sn$ is a mature material that is regularly produced and used in tonnes (for ITER some 300 tons of $Nb_3Sn$ will be employed). For these reasons, EU has launched a vigorous program (CARE-NED and CARE-HHH) to develop a $Nb_3Sn$ conductor to reach the performance shown in the Fig. 7, which has been developed in the USA in the frame of an *ad hoc* funded DOE program and in the frame of LARP (Lhc Accelerator R&d Program ).

## LARP PROGRAM

LARP is by far the most advanced program on high field magnets. After a few years of technological development and model magnets, very important also to support cable development, now the accent is on long magnet technology around 11-12 T, and on the development of 14-15 T field quadrupole models [6,7].

### *Long Magnet*

In 2008 a 3.6-m-long race track has proved the soundness of long tooling and of winding technology. A second version with segmented outer shell (to avoid stick and slip behaviour generated by differential thermal contractions) has gone beyond 90% of $I_{max}$ at the first training series, i.e, a very good result.

In 2009 the 3.6-m-long quadrupole with 90 mm aperture and G > 200 T/m at 4.2 K, and with a peak field of about 11 T, will be tested. These will be the first real accelerator magnets featuring field beyond 10 T with a considerable length.

Long coils have been wound and the mechanical structure, based on shell technology with bladders and key, is being prepared. Most probably there will be a second quadrupole assembled with collar technology.

### *Large aperture and high gradient quadrupole*

The next step is the production of a quadrupole model, 1-m-long, with an aperture of 120 mm. If the test is successful, a 4 m long quadrupole of similar cross section will be launched in 2009-2010, and this will constitute a fully qualification of the technology for accelerators based on a magnet that is fully compatible with the Nb-Ti quadrupoles made for LHC-Phase I upgrade. It will be a real leap forward and it will certainly constitute the reference for the Phase II upgrade.

### *Collaboration EU-USA and instability*

A new recent development has been fostered in the collaboration among USA and Europe (LBNL and CERN, mainly): a 1-m-long magnet, TQS-02, produced and tested at 4.2 K by LARP, was extensively tested and reassembled at 4.2 and 1.9 K at CERN in 2008. Special tests have proved that in these types of very high current density wires the self-field triggered instability plays an important role [8]. This instability is most probably the cause of a worse performance at 1.9 K than at 4.2 K, despite the better superconducting properties. This might have a repercussion on the future development of the wire size and dimension and on design of $Nb_3Sn$ magnets. Somehow $Nb_3Sn$ is favoured the use for fields ~15 T rather than ~12 T since the critical current $J_c$ at lower fields is too high (the instability depends on $J_c$ and on wire diameter).

## A RESULT OF EUROPEAN CARE EFFORT: CONDUCTOR DEVELOPMENT

Thanks to CARE-NED and to the support of CARE-HHH, the 5 years of development of conductor has produced very positive results. Here the improvements with respect to the situation in Europe in 2004:

- The $J_c$ passed from 1000 to 1500 A/mm$^2$ at 15 T and 4.2 K. This figure is precisely the goal of NED and corresponds to 2800 A/mm$^2$ at 12 T.
- Filament effective diameter decreased from 70 μm down to 50 μm.
- RRR of copper decreased from values with large scatter to a very stable 200 value.
- A factor 10 in billet size and production was taken up by large industry: this is a key point for stability and reliability of production.

One of the most important scientific achievements is reaching the goal of 1500 A/mm$^2$ of $J_c$. A decisive contribution from CERN has been the new heat treatment schedule that, based on detailed studies of tin diffusion in niobium, phase formation and crystal growth, has played a decisive role in the reaching that goal. The cross section of the 1.3 mm diameter wire that has shown the record critical current 820 A at 15 T and at 4.2 K is shown in Fig. 8 [9]. It was obtained with the Powder-in-Tube technology by SMI-EAS joint venture. So far the other route of more classical Internal-Tin-Diffusion process pursued by Alstom and Luvata has not yet reached the goal.

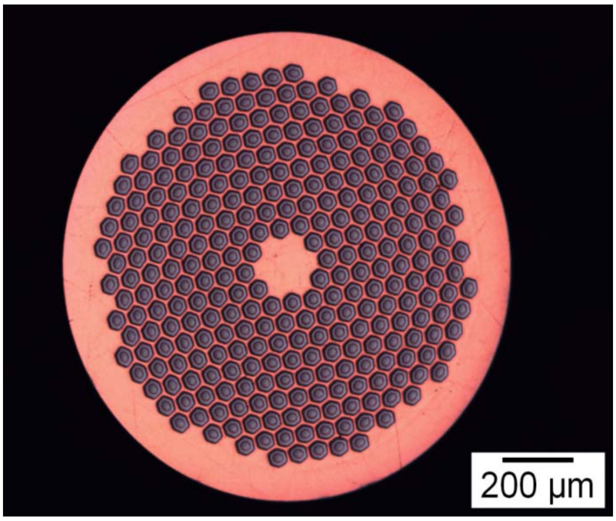


Figure 8: Cross section of the PIT wire that has reached the full goal of CARE-NED specifications.

## CONCLUSIONS

The development of high field magnets is critical for advancing of accelerator technology. Primarily proposed to improve LHC inner triplet, to accompany the rush toward luminosity in the order of $10\times10^{34}$ cm$^{-2}$s$^{-1}$, it may give a serious contribution to improve other regions of the accelerator and to prepare the ground for the big jump in energy.

The success of the NED program and the collaboration fostered by CARE-HHH is the base that has allowed to the high field magnet proposition in the FP7 Eucard [10] to get the best rank in the entire different accelerator R&D. The program consists of using the $Nb_3Sn$ conductor developed to design, manufacture a test l00-mm-aperture dipole for 13 T and beyond. The dipole will constitute the upgrade of CERN cable test facility (FRESCA). This dipoles program is complemented by:

- A vigorous program of small scale magnets to qualify the conductor and all enabling technologies (insulation, heat transfer, radiation resistance, etc.)
- A high temperature superconductor insert to bring the field up to 15-18 T, in a 20-40 mm aperture, to test the suitability of Bi-2212 or Ybco-123 for accelerator magnets.

This program should allow Europe to start a vigorous experimental program in high field magnet, such as to complement the LARP program. Extensive information on the recent development on HFM in Europe and from companion program (LAR, KEK, etc) can be found in proceeding of the last workshop on magnets of HHH [11].

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