High Energy LHC
Document prepared for the European HEP strategy update

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Foreground
The LHC will run to produce physics at the energy frontier of 13-14 TeV c.o.m. for protons for the next 20-25 years. The possibility of increasing the proton beam energy well beyond its nominal value of 7 TeV has been addressed in a study group in 2010 and then discussed in a workshop in October 2010.

The reuse of the CERN infrastructure, the “ease” in producing luminosity with proton circular collider and the practical and technical experience gained with LHC, all are concurring reasons to explore this route. The High Energy LHC relies on the “natural” evolution of the LHC technologies. The High Luminosity LHC (HL-LHC) demands going 50% beyond the limit of magnetic field of LHC: therefore HL-LHC can be considered as the first milestone in the path toward the highest energy. The beam energy is set by the strength of superconducting magnets: assuming a dipole field in the range 16 - 20 T, the maximum attainable collision energy falls in the range of 26 to 33 TeV in the centre of mass.

The driving technology is the superconductivity, and final performance and cost of HE-LHC are directly related to the progress of this technology. However, this machine will requires substantial advance in many other domains: from accelerator physics to collimation (with increased beam energy and energy density), from beam injection and beam dumping with a double rigidity to handling a synchrotron radiation level almost 20 times the LHC one, a real challenge for vacuum and cryogenics. However, the synchrotron radiation will also constitute a real advantage for HE-LHC design: for the first time a hadron collider will benefit of a short dumping time 1-2 hours instead of 13-25 h (longitudinal and transverse respectively) of the present LHC.

The physics landscape of the HE-LHC
The recent LHC discovery of a new particle, consistent with the Higgs boson that has been searched for decades in other accelerators, says a lot about the power of energy in the exploration of the frontier of particle physics. At the same, nevertheless, none of the particles that most theories beyond the Standard Model (BSM) predict to exist at the TeV scale has yet been found, pushing even higher the limits on their masses. These BSM theories emerge from the need to provide a more convincing theoretical setting for the Higgs mechanism of the Standard Model (SM), as well as to
address plain shortcomings of the SM, such as its lack of an explanation for dark matter or for the matter-antimatter asymmetry in the universe. The further clarification of the true nature of the possible Higgs boson found at the LHC, its relation to electroweak symmetry breaking (EWSB), and the continued search for those new BSM particles, are intimately tied aspects of the same challenge, which the future LHC programme should be prepared to undertake.

Many properties of the Higgs boson will be precisely measured during the runs at 14 TeV, and improved during the HL-LHC phase, as documented in the papers submitted by ATLAS and CMS. But a key element in the study of EWSB, namely the scattering of pairs of W gauge bosons, will need, for compelling quantitative studies, higher energies. The theoretical description of WW scattering requires the exchange of the Higgs boson, or of some other new particle, in order to tame an otherwise unphysical rate growth at energies around the TeV and above. Verifying the details of this process is essential to confirm whether the Higgs boson is a fundamental particle or, as postulated in some BSM theories, a composite object, something that could also manifest itself with the appearance of new resonances in the TeV range. As has been known and documented for many years, these studies require the highest possible energies, and the design energy of the SSC, 40 TeV, was chosen precisely to optimize the reach and precision of these measurements. The need to complete this part of the EWSB studies remains today as strong as it was in the days of the SSC planning, and the interest in this issue, if anything, has only increased in the recent few years, and with the exciting recent LHC discovery. This physics goal provides the single strongest and best justified reason to invoke, already today, a substantial LHC energy upgrade.

In many BSM scenarios for EWSB, the Higgs boson is accompanied by several new particles, with masses in the range of hundred(s) GeV to possibly several TeV. These could be other Higgs-like scalar states, or heavier partners of the W and Z gauge bosons and of the top and bottom quarks, or, as in the case of Supersymmetry (SUSY), a complete doubling of the spectrum, where each known particle has a partner, with a different spin. Any deviation of the measured Higgs properties from the SM expectation would require the existence of some of these particles, and viceversa. The strong limits on such new particles derived so far from the LHC leave ample room for their discovery after the upgrade to full nominal energy, 14 TeV. It is therefore premature to argue about the need for a further energy step on the sole basis of the discovery reach. However, any discovery at 14 TeV will require a follow-up phase of precision measurements, to understand the origin of the newly observed phenomena. Depending on the mass and couplings of these new particles, the most effective way to increase their statistics could either be higher luminosity, or higher energy. This is illustrated in a simple concrete case in the following Fig. 1, which represents the LHC discovery potential for Z' gauge bosons decaying to lepton pairs, in different energy and integrated luminosity conditions. The reach is expressed by the product of their coupling strength, g', and the square root of the leptonic decay branching ratio. The red dashed line corresponds to the results after 3000 fb^{-1} at 14 TeV, the solid blue line to 300 fb^{-1} at 33 TeV. We notice that for masses below ~2.5 TeV the factor of 10 higher luminosity at 14 TeV leads to a better discovery reach (or, in the case of a previous discovery, leads to higher statistics and better precision in the measurement of the Z' properties). On the contrary, if the Z' is heavier than ~2.5 TeV, the increase is energy is more powerful. The figure also shows that the run at 7 TeV has already excluded the existence of Z' bosons up to 2.5 TeV, at least for some range of their couplings. This means that, at least for some models, Z' that were discovered at 14 TeV would be sufficiently heavy that their precision studies would greatly benefit from the energy upgrade, even after the completion of an extensive HL-LHC
phase. Similar reasoning applies to other BSM new particles. The HE-LHC is therefore a powerful tool to extend and improve the precision studies of the Higgs boson and of other phenomena to be uncovered during the nominal and HL-LHC runs at 14 TeV, as well as to open the way for the exploration of a new energy range, unattainable by any of the other current proposals for new high-energy facilities.

Figure 1. Discovery potential for new $Z'$ gauge bosons decaying to lepton pairs, as a function of their mass. The reach is expressed in terms of their coupling strength times the leptonic branching ratio.

**Main accelerator parameter**

The target is attaining 16.5 TeV/beam, based on the assumption of reaching a dipole field of 20 tesla in operative conditions: since we assume a conservative 5 tesla margin with respect to the critical surface, the nominal quench design value is 25 T! In the present paper we assume the same dipole fill factor of 2/3 as in the present LHC ring. Rather than discussing a single target value, it is actually more appropriate to talk about a target range: 16 to 20 T dipole field. The reason for 16 T is that it is the field limit that can be approached, with use of classical low $T_c$ superconductors, Nb$_3$Sn. As discussed later, above 16 tesla the use of HTS (High Temperature Superconductors, like YBCO-123 or BSCCO-2212), which are much less developed and not yet suitable for accelerator quality magnets, is necessary.

The parameter list for HE-LHC is reported in the following table: the space of parameters has not been fully investigated, yet. In many case we stick to the LHC value or a value not too far. For example, the bunch spacing choicer of 25 ns, the nominal LHC value, can (and will) be challenged, once we will gather evidence that we can deal with the e-cloud instability, maybe with better cooling of the beam screen. In such a case 10 or 15 ns bunch spacing can be considered, with a considerable reduction of pile-up.
Table 1: LHC main parameters compared with the HE-LHC with round beams (right column) and flat beam (middle column)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal LHC</th>
<th>HE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [TeV]</td>
<td>7</td>
<td>16.5</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>8.33</td>
<td>20</td>
</tr>
<tr>
<td>dipole coil aperture [mm]</td>
<td>56</td>
<td>40</td>
</tr>
<tr>
<td>beam half aperture [cm]</td>
<td>2.2 (x), 1.8 (y)</td>
<td>1.3</td>
</tr>
<tr>
<td>injection energy [TeV]</td>
<td>0.45</td>
<td>&gt;1.0</td>
</tr>
<tr>
<td>#bunches</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>bunch population [$10^{11}$]</td>
<td>1.15</td>
<td>1.29</td>
</tr>
<tr>
<td>initial transverse normalized emittance [µm]</td>
<td>3.75</td>
<td>3.75 (x), 1.84 (y)</td>
</tr>
<tr>
<td>initial longitudinal emittance [eVs]</td>
<td>2.5</td>
<td>4.0</td>
</tr>
<tr>
<td>number of IPs contributing to tune shift</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>initial total beam-beam tune shift</td>
<td>0.01</td>
<td>0.01 (x &amp; y)</td>
</tr>
<tr>
<td>maximum total beam-beam tune shift</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>beam circulating current [A]</td>
<td>0.584</td>
<td>0.328</td>
</tr>
<tr>
<td>RF voltage [MV]</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>rms bunch length [cm]</td>
<td>7.55</td>
<td>6.5</td>
</tr>
<tr>
<td>rms momentum spread [$10^{-4}$]</td>
<td>1.13</td>
<td>0.9</td>
</tr>
<tr>
<td>IP beta function [m]</td>
<td>0.55</td>
<td>1 (x), 0.43 (y)</td>
</tr>
<tr>
<td>initial rms IP spot size [µm]</td>
<td>16.7</td>
<td>14.6 (x), 6.3 (y)</td>
</tr>
<tr>
<td>full crossing angle [µrad]</td>
<td>285 (9.5 $\sigma_{x,y}$)</td>
<td>175 (12 $\sigma_{x,y}$)</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>0.65</td>
<td>0.39</td>
</tr>
<tr>
<td>geometric luminosity loss from crossing</td>
<td>0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>stored beam energy [MJ]</td>
<td>362</td>
<td>478.5</td>
</tr>
<tr>
<td>SR power per ring [kW]</td>
<td>3.6</td>
<td>65.7</td>
</tr>
<tr>
<td>arc SR heat load dW/ds [W/m/aperture]</td>
<td>0.17</td>
<td>2.8</td>
</tr>
<tr>
<td>energy loss per turn [keV]</td>
<td>6.7</td>
<td>201.3</td>
</tr>
<tr>
<td>critical photon energy [eV]</td>
<td>44</td>
<td>575</td>
</tr>
<tr>
<td>photon flux [$10^{17}$/m/s]</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>longitudinal SR emittance damping time [h]</td>
<td>12.9</td>
<td>0.98</td>
</tr>
<tr>
<td>horizontal SR emittance damping time [h]</td>
<td>25.8</td>
<td>1.97</td>
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<tr>
<td>initial longitudinal IBS emittance rise time [h]</td>
<td>61</td>
<td>64</td>
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<tr>
<td>initial horizontal IBS emittance rise time [h]</td>
<td>80</td>
<td>~80</td>
</tr>
<tr>
<td>initial vertical IBS emittance rise time [h]</td>
<td>~400</td>
<td>~400</td>
</tr>
<tr>
<td>events per crossing</td>
<td>19</td>
<td>76</td>
</tr>
<tr>
<td>initial luminosity [$10^{34}$ cm$^2$·s$^{-1}$]</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>peak luminosity [$10^{34}$ cm$^2$·s$^{-1}$]</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>beam lifetime due to $p$ consumption [h]</td>
<td>46</td>
<td>12.6</td>
</tr>
<tr>
<td>optimum run time $t_r$ [h]</td>
<td>15.2</td>
<td>10.4</td>
</tr>
<tr>
<td>integrated luminosity after $t_r$ [fb$^{-1}$]</td>
<td>0.41</td>
<td>0.50</td>
</tr>
<tr>
<td>opt. av. int. luminosity per day [fb$^{-1}$]</td>
<td>0.47</td>
<td>0.78</td>
</tr>
</tbody>
</table>
The dipole magnet field and the synchrotron radiation will be discussed later; here it is worthwhile to underline a few points:

1. The aperture of the magnets is fixed at 40 mm. This is required by the need to keep magnet size and cost in an acceptable range. Decreasing the aperture from 56 mm to 40 means halving the useful aperture for the beam, which implies an injection energy of at least 1 TeV, which in turn requires a new injection chain. Given the implication of the aperture on the injectors, a detailed study of the impact of the aperture will be carried out.

2. The luminosity has been fixed to a “modest” $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, a value not far from the present LHC. However we will apply all technology and means that we will learn during LHC and HL-LHC (High Luminosity LHC). The factor two over the nominal LHC is just a guideline, an effect of just doubling the energy, which reduce the beam emittance. In principle, HE-LHC should be able to deliver a luminosity which is double than the one eventually reached in HL-LHC, provided that the beam energy be properly handled.

3. Collimation and machine protection issues don’t look dramatically different from the lay-out we have in LHC with the improvement foreseen for HL-LHC.

**Magnet technology and R&D**

The possibility to reach such an ambitious goal is based on the studies carried out in previous programs: in Europe FP6 CARE –NED/HHH and FP7-EuCARD-Fresca2; in the US the DOE-Nb$_3$Sn program, the Laboratory basic programs and – above all – the DOE-LARP. All programs, and especially the US ones, have paved the way for making the jump from 8 T accelerator magnets (LHC) to 12-13 T accelerator magnets, enabling two applications for the High Luminosity LHC (HL-LHC) program:

- The development of an **11 T twin dipole**, for special application (collimation) in LHC by 2018.
- The development of a **12-13 T peak field large aperture quadrupole for the low-beta** insertion, on the horizon 2020.

It is worth mentioning the very high performance of the Nb$_3$Sn developed for the 11 T and the IR low-$\beta$ quads, a jump of 2.5-3 times above of the ITER specifications for $J_c$. Furthermore the quantity of Nb$_3$Sn conductor needed for HL-LHC is respectable for a pre-series industrial production.

In order to enable the goal of 33 TeV collision energy, **20 T operating field** dipole magnets are needed. Twenty tesla dipole field requires a magnet size near the maximum we can hope to place in the present LHC tunnel. To give an idea of the challenge posed by the LHC upgrades, in luminosity and energy, the past and future evolution of dipole magnets for hadron colliders is depicted in the Fig. 2.
Figure 2: Historical development and projection of high field magnets for hadron colliders. Red lines indicate the approximate limit of each material.

**Superconductors**

In Fig. 3 the current density of practical superconductors is reported as a function of the field. It shows that Nb$_3$Sn is limited at 15 T at 4.2 K (curves are at 4.2 K, except for LHC Nb-Ti). By use of superfluid helium its field domain may be extended to $\sim$16 T.

**Nb-Ti**

Nb-Ti is a superb and mature superconductor. Therefore, it is important for reasons of cost to design the magnet in a way to use Nb-Ti for the low field coils.
**Nb$_3$Sn**

ITER is finally making this superconductor an industrial material. However, as previously mentioned, we need a critical current density $J_c$ at least 2.5 times higher than ITER $J_c$, with filaments as fine as 30 µm. In Fig. 4 the cross sections of two Nb$_3$Sn wires, under development in the US and EU industry for high field accelerator magnets, are reported: in the same Fig. 4 our final HE-LHC targets and the present performance are sketched in the proper parameter space. The situation is very positive and we estimate that a moderate effort on the top of the R&D for HL-LHC will buy us the needed performance. However a common Laboratory-Industry program is need to find the technical solutions capable to drive down the cost of Nb$_3$Sn, today a factor 5 above the one of LHC Nb-Ti. This is not a big problem for HL-LHC, requiring 20 tonnes of superconductors, however it is major problem for HE-LHC, requiring in total 3000 tonnes of superconductor, most than half in Nb$_3$Sn. To gauge these figures in the context, LHC has used 1200 tonnes of Nb-Ti, while ITER requires about 500 tonnes of Nb$_3$Sn.
Figure 4. Two advanced Nb₃Sn wires (cross section) under development by OST in USA and Bruker in Germany. In the figure at right, their performance is compared to the target (inner triangle in light blue), courtesy of L. Bottura (CERN).

**HTS (High Temperature Superconductors)**

Developments in HTS for high energy colliders are progressing through “regional” programs. FP7 EuCARD, which includes the design, construction and test of a race-track HTS (specifically YBCO, also called 2G-second generation) insert, capable of producing 5-6 T on the top of the 13 T design field of FRESCA2 Nb₃Sn dipole. However, the magnet will not be designed with accelerator characteristics. The program is to be finished in 2013 and will continue as EuCARD2 (see later).

The DOE ARRA program (4 M$, in 2010-2011) has focused on the development of Bi-2212, and has shown the route to increase the critical current density beyond 400 A/mm² at 20 T with uniform properties. ARRA is now continuing as a collaboration of the USA laboratory basic programs.

In Japan a collaboration between University of Kyoto and KEK is aiming at developing high performance YBCO suitable for accelerators (FFAG) for medical application and in perspective for high intensity proton accelerators.

The two HTS materials have very different issues which can be summarized as following.

**Bi-2212**

Based on Bi-Sr-Ca-Cu-O powder, in Ag or Ag-alloy tubes, it has the shape of round wire, see Fig. 5, it has isotropous properties and therefore is well suitable for classical Rutherford cabling, which opens the way of using existing technology for high compact, high amperage cable. However it needs a thermal treatment in controlled atmosphere after winding, at 900 °C, much more severe than the one needed for Nb₃Sn. Furthermore it is very much strain sensitive. Technical problems linked to porosity and powder leakage could be solved or mitigated (as shown by ARRA).

One additional difficulty relative to the development of this bismuth based SC is the fact HEP is almost the only application of such material with little synergy with the rest of magnet community. Its cost ~ 2-5 times than the Nb₃Sn and this factor, that is driven by the Ag stabilization, will be hard to lower down.
Figure 5. Left: cross section of Bi-2212 wire (powder in a silver matrix). Right: expansion showing the presence of porosity, which is detrimental for performance.

**YBCO**

Given the potential lower cost than the one of Bi-based HTS, and the great potential in terms of $J_c$ (see Fig.2, curve YBCO B II Tape plane) about 90% of the SC community is focusing on this material. YBCO comes in form of tape, and has a very complicated architecture, see Fig. 6. It is manufactured by vacuum coating, with either laser or ion beam assistance. Many different layers needed to be superimposed and the final tape, typically 4-10 mm wide and 0.1-0.2 mm thick, is quite robust. The layer of superconductor is very thin, a few $\mu$m, like the thickness of the protective silver layer. Intrinsically the cost of this Yttrium based superconductor is much lower than the Bi-2212, and its performance potentially superior, making it a very attractive solution. However in HEP accelerator magnets we need big amperage (10 kA or more) compact conductor with only 10-15% void fraction and in form of flat cable, like a Rutherford cable. Unfortunately is difficult to get this if the basic element is a tape. A possible solution, not yet developed, is the use of Roebel cabling, see Fig. 6.

The cabling issue and the intrinsic anisotropy of the transport properties are the major technical problems of YBCO. The cost is today by far too high (ten times the one of Nb$_3$Sn) since the process is based on very expensive equipment and is not yet fast enough. However the assessment of the SC community is that its final cost for mass production should not be higher than the one of Nb$_3$Sn.

Figure 6. Left: sketch of the various layer of an YBCO tape, with indication of the thickness of the various components. Centre: an YBCO tape, 40 mm wide, 0.2 mm thick, being cut into ten, 4 mm wide, tapes ready for winding. Right: a test Roebel cable composed by a few YBCO tapes.
**Magnet design**

LHC magnets are designed to operate nominally at 8.33 T which is 86% of the critical value, calculated along the load line. Despite the fact that each single magnets went well beyond the nominal design, the LHC is scheduled to restart after the 2013-14 shutdown for consolidation of the interconnections, at 7.8 T, i.e. just 80% of the critical value, to provide $E_{beam}$ of 6.5 TeV. Therefore for the time being, we integrate such 20% margin in the design of HE-LHC dipoles, to be on the safe side.

Various results collected in these years on different magnets in Nb-Ti and Nb$_3$Sn are shown in Fig. 7, in terms of peak field performance vs. coil thickness. The plot shows that for Nb-Ti the theoretical limit of 10 T has been attained, while Nb$_3$Sn superconductors still some 10-15% below its limits, so some R&D is still needed to push it to its maximum.

To go beyond 15 T of operational field means to design the dipole for 18 T: at this value the plot of critical current indicates that HTS is better than Nb$_3$Sn, whose performance falls down quickly with increasing fields. Therefore, to go beyond 16 T of central field the use of HTS is mandatory, as suggested by the trend of Fig. 7.

![Figure 7. Nb-Ti magnets (black) and Nb3Sn ones (red). The field is quoted at the maximum theoretical value (not operating field) to allow comparison between test magnets and operational ones; Fresca (test station) and the Nb3Sn magnets are single prototypes.](image)

A possible design of a 20 T HE-LHC dipole, first sketched for the CERN HE-LHC Working Group and then refined for the first HE-LHC Workshop in Malta is shown in Fig. 8. Although no attempt has been done to investigate the magnet extremity (or 3D part), the cross section has been checked for consistency and has the following characteristics:

1) It is based on coil block lay-out, rather than classical $\cos\theta$ coil layout-out. This solution seems the most promising for field above 15-16 T, although not without problems.

2) By using the engineering current density (i.e. average also on the total cross section of the wire) shown in Fig.3, which is currently available in Industry for Nb-Ti and Nb$_3$Sn and that has been reached on a pilot production for Bi-2212, the design reaches a theoretical maximum (critical surface) of 25 T. So 20 T of operational field is a reasonable assumption.
3) The field quality at high field is already in the acceptable range. At low and intermediate field a careful study is needed to understand magnetization and coupling effect, but we have ideas how to control it.

4) Given the present current density and the increase of coil thickness, the beam inter-distance is increased from the 194 mm of LHC to 300 mm in this design. The outer diameter of the magnet iron yoke has been controlled by means of anti-coil to reduce stray field: in this way it does not exceed 800 mm, deemed to be about the maximum compatible with the tunnel size.

5) The mechanical structure, based on the innovative bladder structure devised in LBNL and used in LARP quadrupole for HL-LHC, should keep peak stresses at about 150 MPa, a value very high but still in the manageable range as demonstrated recently in a LARP quadrupole magnet for HL-LHC.

6) Magnet protection looks within acceptable limits. Behaviour of the magnet circuit has not yet been investigated. However at least two solutions are envisaged: either multiple fractioning of the magnet circuits to keep energy of each circuit at the level of the LHC ones, or separate powering of each coil section (Nb-Ti, Nb₃Sn and HTS sections) inside every individual magnet, an innovative solution that might be used also to improve the field quality.

Other designs have been put proposed, with coil block or in cosθ or with so called canted-solenoid winding. While interesting, none of them have been checked in details.

<table>
<thead>
<tr>
<th>Material</th>
<th>N. turns</th>
<th>Coil fraction</th>
<th>Peak field</th>
<th>J_{overall} (A/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-Ti</td>
<td>41</td>
<td>27%</td>
<td>8</td>
<td>380</td>
</tr>
<tr>
<td>Nb₃Sn (high Jc)</td>
<td>55</td>
<td>37%</td>
<td>13</td>
<td>380</td>
</tr>
<tr>
<td>Nb₃Sn (Low Jc)</td>
<td>30</td>
<td>20%</td>
<td>15</td>
<td>190</td>
</tr>
<tr>
<td>HTS</td>
<td>24</td>
<td>16%</td>
<td>20.5</td>
<td>380</td>
</tr>
</tbody>
</table>

Figure 8: Cross section of 20 T dipole - 25 T at critical surface - based on three types of superconductors. J_{overall} is the J_{engineering} of Fig.3, further diluted by voids and insulation.

**Magnet R&D**

All together the Superconducting Magnets for HE-LHC are extremely challenging but do not appear at all out of range, provided that a vigorous R&D is initiated, to tackle the most urgent points which are:

1) Development the HTS, both in form of Bi-2212 and YBCO and making, out of these excellent materials, a real technical conductor capable of 10 kA in 20 T in compact cables and of
accelerator quality, industrially feasible in large quantity and affordable in price. This is the most urgent R&D to establish if the 20 T level with HTS is attainable or not. To this scope a care program has been launched and approved in the FP7-EuCARD2 (WP10- Future Magnets)

2) Explore in detail a baseline magnet design, with possibly at least one alternative, to be sure that all issues can be faced and no show-stopper appears: quench limit under very high mechanical forces (6 times the LHC), field quality, alignment as cold mass and inside cryostat, stability and protection, coil connections (internal) and magnet interconnections, integration in the LHC.

3) Built at least two prototypes to validate the solution and test the superconductor and coils.

Would the most risky part, HTS cable development fail, the way-out is to “limit” the magnet operation to 16 T, a field level that will allow attaining about 13 TeV/beam. The Nb$_3$Sn technology should be fully developed for the HiLumi upgrade 12 tesla magnets while ITER is demonstrating production of Nb$_3$Sn in large quantity (500 tonnes, about 1/3 of the HE-LHC needs, although of lower performance).

Other critical points

Injector and Transfer Lines

The most straightforward solution is to increase the beam injection energy at 1-1.2 TeV by replacing the resistive magnets of SPS with SC ones rated for 4-6 tesla and able to sweep the field at 1-2 T/s. The collaboration program between GSI-INFN is developing such type of magnet for the ring SIS300, the final stage of the FAIR project. Indeed the first magnet prototype (called INFN-Discorap) which is a 4.5 T, 4 m-long curved dipole, rated for a field ramp rate of at least 1T/s, has been completed and is just ready for testing. The characteristics of this magnet match at 80% the needs for the SPS at 1TeV (called also SPS+).

The existing TI2 and TI8 will be used for transfers from the SPS tunnel to the LHC tunnel. If the beam is coming from an SPS+, then the transfer line magnets would have to be replaced. Options for reusing magnets from dismissed accelerators (Tevatron and HERA proton ring) have been considered. The minimum curvature radius of these transfer lines is the same as the SPS, so the same field would be required as the SPS+. Tevatron magnets might be sufficient for a 1 TeV injection energy, but not if the energy is higher. HERA magnets have the required field, but would need significant retrofitting to fit in the tunnel and to handle the fact that the polarity is reversed relative to HERA. Also, TI2 has a large vertical slope, which would present problems for any superconducting magnets not specifically designed for it.

Would for any reason the SPS-1TeV be discarded, another solution is at hand: to place in the LHC tunnel a LER (Low Energy Ring). Based on cheap “Pipetron” magnets, this ring have been examined in various workshops and found quite feasible, except that one need to circumvent the experimental detectors. This would be a real difficulty which also affect the project LHeC in the ring-ring version. However with a new lay-out of the accelerator and new detectors, as required for the HE-LHC, such an obstacle would be fully removed, making this solution feasible and relatively easy.
Whatever the solution, HE-LHC will give the opportunity to redesign the CERN low and medium energy chain, see Fig. 9, possibly in synergy with the other physics program (low-energy physics, neutrinos,...) and to make it more suitable to modern RF gymnastic techniques for beam formation. A final comment on this subject is for underlying that, once LHC Injector Upgrade implemented by 2018 made, a new SPS at 1.2 TeV, with the proper RF power to guarantee the repetition rate, would deliver the 2 MW power on target required by the final stage of the LAGUNA program.

Figure 9. The CERN accelerator chain for HE-LHC with a 1 TeV SPS and the area for the new optimization, between Linca4 and SPS.

Beam in and out
The injection, extraction and dump systems present significant challenges at increased energy; however, they do not appear to be a priori insurmountable. The dump system consists of extraction kickers, septum, dilution sweep magnets, and the physical dump itself, none of which are adequate at 16.5 TeV. In addition, there are passive elements which protect the accelerator in the event of kicker misfires or beam in the abort gap, and these would also be destroyed at the increased energy. Increasing either the length or the field of the existing extraction kickers does not appear feasible. However, one can design new kickers with smaller apertures thanks to the smaller maximum beam size that comes with the increased injection energy. These appear to present a reasonable option.

The extraction appears just feasible by using an increased number of existing B and C type septa, running at the maximum field. The total required length would increase from 73 to 136 m, and the resulting integration issues would have to be carefully studied.

Even in the scenario where the total stored energy of the beam does not increase, the energy density does, requiring an increased amplitude and/or frequency of the dilution kickers. These appear to be feasible, although more study is needed. It might be possible to amplify the effect of these kickers with quadrupoles in the dump line, but integration might be an issue.
The dump itself would have to be redesigned, likely made longer with a lower density material. However, there is room to accommodate this. The passive protection devices in the extraction area are inadequate for the increased energy and energy density, and it’s not clear that a robust solution exists to replace them. In a worst case scenario, “sacrificial” absorbers could be implemented, which would be replaced after (hopefully rare) exposure to high intensity beams.

The injection system is somewhat more challenging. This is because the existing injection kickers use all the available space, assuming that the HE-LHC magnet layout is similar to the current layout. Again, taking advantage of the fact that a smaller aperture can be used with the higher energy beams, new, higher field kickers should be feasible: here is an area where R&D and study should be pursued.

**Handling synchrotron radiation and beam impedance**

A solution LHC-like with a beam screen at 10 K (actually from 4.6 K inlet and 20 K outlet temperature) will be heavy for the cryogenics: the additional 12 KW power needed for each one of the 8 sectors would require to almost double the present 8x18 kW plants (power is always given at reference temperature of 4.2K). In addition the beam screen refrigeration will be complicated by necessity of increasing the local heat removal by a factor 20, by means of higher pressure drop and increased cooling pipe conductance. This solution is certainly not impossible but better options seem viable. One is removal of the synchrotron heat at higher temperature. Vacuum stability indicates two possible windows for beam screen operation: 40-60 K (inlet-outlet temperature) and 85-100 K. The first option maintains the cryogenic power at 4.2 K equal to the LHC one, in principle no additional refrigeration is needed; the second one will make a gain in refrigeration. However, two important considerations favours the first option: a) the heat leakage from a higher temperature beam screen and the 1.8 K cold mass will be more than double in the second option; b) the electrical resistivity, assuming it is copper dominated like in the LHC, increases by a factor 5 above the LHC value for the first option and a factor 22 for the second, higher temperature, option.

The consequences of the higher resistivity on beam stability are not dramatic, because both transverse and longitudinal beam impedances increase with square root of the wall resistivity. The resistivity of copper at 50 K and 20 T is just a factor 2.5 more than the resistivity at 20 K, 8.3 T, making the impedance increasing of just 60%, a factor that can certainly be managed. A thicker copper coating (in LHC is 75 µm) will partially compensate the increased resistivity, a compensation that is necessary to cut down image currents power losses, too. Despite that copper coating appears to be a viable solution for HE-LHC, use of YBCO coating (Tc = 85 K) on beam screen inner side can virtually null the resistance and solve out the problem: it will make possible even working at 100 K (if the thermal contact to the 1.9 K cold mass can be made very loose). This HTS coating is certainly more expensive and complex that the copper co-lamination of the LHC beam screen, however, given its potential, will be deeply investigated in future.

**The farthest energy frontier**

HE-LHC in the LHC tunnel has many advantages, however inevitably this scheme has two main drawbacks:

1) The use of a narrow tunnel will make integration of larger magnets a difficult exercise.
2) The beam energy reach is necessarily limited, between 13 and 16.4 TeV/beam.

The use of a larger new circular tunnel will remove radically these two limitations. Preliminary studies recently launched at CERN indicate that there are two possible positions for an 80 km circumference tunnel, see Fig. 10, around the CERN site. Such an option is at a very early stage of study, however costing of such a tunnel may be envisaged in the 4 BCHF range.

![Figure 10. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)](image)

In case of the 80 km ring, a new optimization space to explore is open. At this stage we can only envisage the following possibilities of collision energy as a function of the dipole field:

1) 42 TeV c.o.m. with 8.3 T (present LHC dipoles)
2) 80 TeV c.o.m. with 16 T (high field based on Nb3Sn)
3) 100 TeV c.o.m with 20 T (very high field based on HTS)

Actually in a new tunnel, with a cross section larger than the present LEP/LHC tunnel (3.8 m in diameter) a dipole could be larger than the one sketched in Fig.8, therefore in principle 20 T dipole field is not anymore a hard limit. However, considerations about technical complexity and cost indicate that would be extremely difficult, if not unrealistic, substantially increase the field above 20 tesla.

**Time plan**

A realistic time plan can be envisaged relying on the actual LHC time plan. The HE-LHC plan is based on the choice of magnet technology (use of HTS: yes or no), by 2016-17. Afterwards, 3 years are needed for final prototyping and accelerator design. Industrialization could be launched in the beginning of the next decade and, based on the LHC experience, about 7 years would be required for construction and testing of all components and 3 years for installation and commissioning. HE-LHC could produce physics from around 2035, after the conclusion of HL-LHC run, see Fig. 11. The time line could be similar also for the 80 km HE-LHC, assuming that tunnelling is not on the critical path.
Conclusions
Some of the possible options of a High Energy LHC in the LHC tunnel, with a p-p collision energy in the 26-33 TeV range, have been discussed and the most challenging points examined in detail: there are many serious difficulties but no show-stoppers. The machine looks within reach with a moderate effort for a 26 TeV proton-proton collision energy. Reaching 33 TeV is very challenging and considerably more expensive, and in view of this scope a vigorous R&D program on High Temperature Superconductor (YBCO and Bi-2212) has been launched and needs to be restlessly pursued. Use of proton-proton beams so far seems the best choice, however in future use of proton-antiproton (with single bore magnets) will be revisited and evaluated, too. Recently the possibility of a larger tunnel, 80 km in the CERN environment, has been proposed and is being examined, also for its interesting synergy with other projects. The 80 km long machine opens the way to a new optimization; preliminary evaluation indicates that p-p collision energy can be in the range 42-100 TeV, according to the different magnet technology that would be used.

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