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NOTE

Considerations on a Partial Energy Upgrade of the LHC

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ABSTRACT

In the frame of the HL-LHC project, a few accelerator dipole and quadrupole magnets of higher critical field and/or larger aperture are being produced. The new inner triplet quadrupoles and dispersion-suppressor dipoles are made from Nb3Sn superconductor, which supports a higher field than the classical Nb-Ti magnets used for the LHC. For the longer term future, it has been proposed to replace a fraction of the Nb-Ti arc magnets in the LHC arcs with Nb_3Sn magnets of higher field (e.g. 11 T), in order to boost the beam energy. Here we examine several options: the replacement of every third dipole by a stronger one, the substitution of the present Nb-Ti quadrupole by Nb_3Sn combined-function magnets, the excitation of the horizontal orbit correctors, and pushing all the dipole magnets to their ultimate field. We discuss challenges and constraints, including issues related to mechanical aperture, powering, or other hardware limitations, and we estimate the potential energy reach for each of the options.

ARIES Consortium, 2017

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1. Motivation

Increasing the LHC energy by 10-20% could considerably expand its discovery potential, especially if there is a sign of New Physics at the very limit of the energy reach of the present LHC, as is illustrated in **Figure 1**. The parton luminosities and associated energy reach were computed using the tool of Ref. [1].

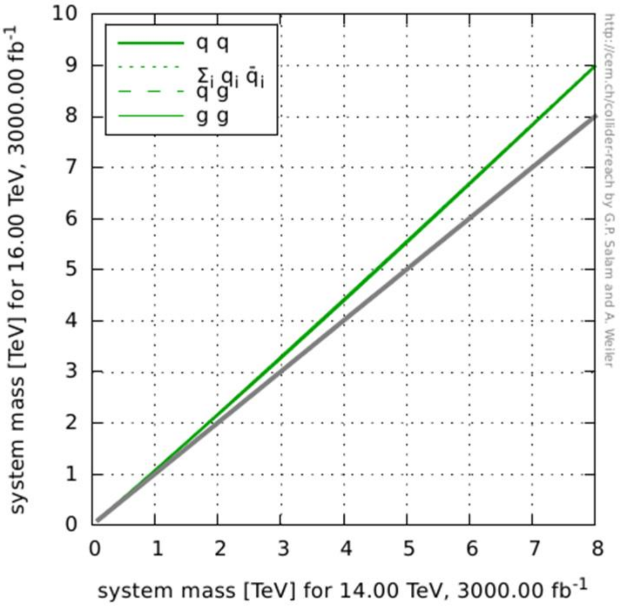

Figure 1: Relative energy reach of an enhanced HL-LHC at 16 TeV c.m. energy compared with that of the 14-TeV HL-LHC, both with a total integrated luminosity of 3 ab^{-1}. The green curves were computed using the tool of Ref. [1] under the assumptions stated in that reference: The estimate is obtained by determining the system mass at 16 TeV for which the number of events is equal to that produced at 14 TeV, assuming that cross sections scale with the inverse squared system mass and with partonic luminosities. The exact results depend on the relevant partonic scattering channel, as represented by different (here overlapping) lines.

One possibility to increase the LHC energy would be replacing every third dipole magnet (about 420 magnets in total) with a stronger dipole based on Nb_3Sn and a maximum field of about 11 T [2] (or possibly 14 T, or perhaps even 16 T as planned for the Future Circular Collider [3], though currently the FCC-hh arc dipoles feature an inter-beam distance of 204 mm, incompatible with the LHC magnets), to be compared with the LHC design dipole field of 8.33 T or ultimate field of 9 T. The unequal field of dipoles inside each arc FODO cell would most probably persist at injection energy, and lead to some problems and issues reminiscent of those encountered for the “missing dipole” schemes historically proposed for phased constructions of the SPS [4] and the LHC [5][6].

2. Options

Several options have been proposed for increasing the effective dipole field strength and thereby the energy of the proton beams circulating in the LHC:

1) Pushing all the existing dipoles to their “ultimate field” of 9 Tesla, resulting in an energy of ~7.56 TeV per beam [7][9][12].
2) Replacing every 3rd LHC dipole magnet with higher field dipoles based on Nb_3Sn superconductor. For example, adding 11 T dipoles (while the others remain at 7.74 or 8.33 T) would increase the beam energy by slightly more than 10%; adding 14 T dipoles would provide a gain >20%, 16 T dipole a gain >30%. See Table 1.
3) Replacing all quadrupole magnets in the arcs and dispersion suppressors with combined-function magnets based on Nb_3Sn superconductor [S. Fartoukh]. Adding an 8.33-T dipole field together with 240 T/m would increase the beam energy by $3.2/(3\times14.3)$~7.5% [S. Fartoukh]. Such scenarios are also included in Table 1. This option avoids the so-called “busbar problem” of the dipole scheme “2)” (see later).
4) Exciting all horizontal orbit correctors. The orbit correctors can provide a bending kick of 88 μrad at 7 TeV compared to an angle of $6\times2\pi/1232=30$ mrad for 6 MB dipoles (1 FODO cell). Therefore, the orbit correctors could raise the beam energy by no more than 0.3% [estimate by S. Fartoukh].

Options 1) – 3) are sketched in **Figure 2**. Also combinations of options 1) to 4) could be considered if there were no other obstacles to raising the beam energy by more than ~10%.

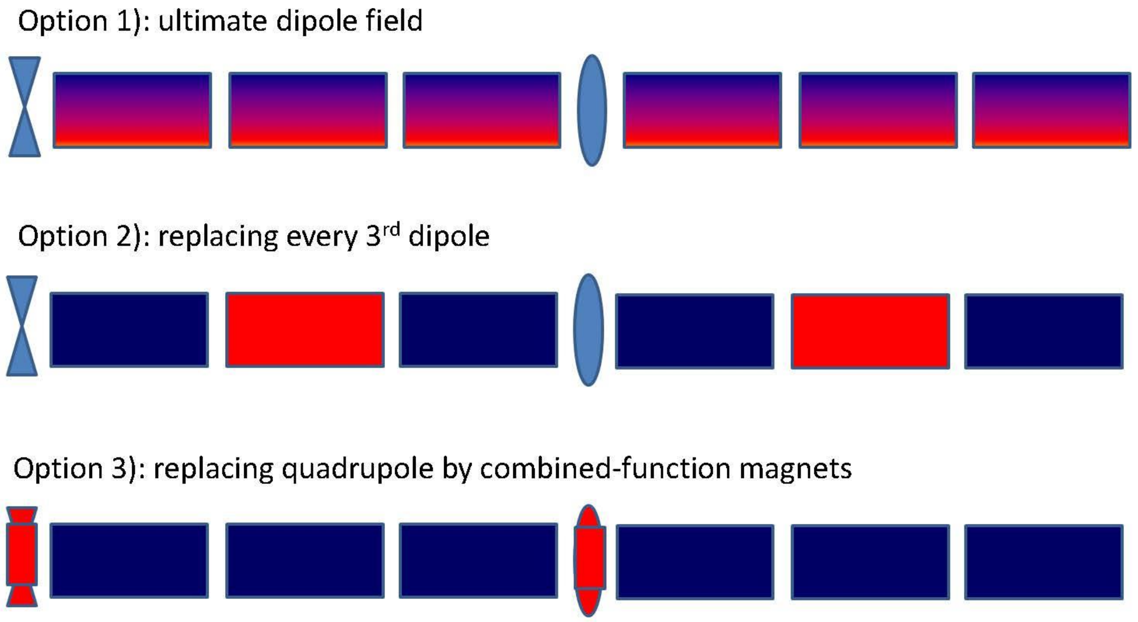

Figure 2: Three options for raising the LHC beam energy – 1) powering the dipole magnets up to their ultimate field [top], 2) replacing every 3rd dipole magnet with a Nb_3Sn magnet of 11 or 14 T field [centre], 3) replacing the arc quadrupoles by Nb_3Sn combined function quadrupoles [bottom].

Table 1: Theoretical energy increase for partial dipole exchange according to option 2) and for additional combined function magnets according to option 3), or a combination thereof, considering three different field levels for the existing dipole magnets (present [as of 2016], nominal and ultimate). A few plausible scenarios are highlighted in blue.

base field (2/3 of dipoles) [T]	base energy [TeV]	stronger field (1/3 of dipoles) [T]	dipole field in quad. [T]	total beam energy [TeV]	relative energy increase above 7 TeV [%]
7.74	*6.5*	*11*	*0*	*7.41*	*6*
7.74	*6.5*	*14*	*0*	*8.25*	*18*
7.74	*6.5*	*16*	*0*	*8.82*	*26*
8.33	**7**	**8.33**	**8.33**	**7.52**	**7.5**
8.33	**7**	**11**	**0**	**7.75**	**11**
8.33	7	14	0	8.59	23
8.33	7	16	0	9.15	31
9.00	**7.56**	**9**	**0**	**7.56**	**8**
9.00	**7.56**	**9**	**9.0**	**8.13**	**16**
9.00	7.56	11	0	8.12	16
9.00	7.56	14	0	8.96	28
9.00	7.56	16	0	9.52	36
9.00	7.56	16	9.0	10.09	44

3. Limitations and Constraints

1.1 ORBIT CHANGES IN THE ARCS

For the primary option 2) (see Table 1, sixth row, with 8.33 T and 11 T magnets), the beam energy will be $\delta \approx 10\%$ too high in two thirds of dipoles and $\delta \sim -20\%$ too low in the other third.

With a dipole magnet length of $l_{\mathrm{bend}} \sim 14.3$ m, and a dipole bending radius of $\rho \approx 2800$ m, the resulting maximal orbit deviation is of order $\approx 1/2\ l_{\mathrm{bend}}^2\ \delta/\rho \approx 4$ mm, or equal to one fifth of the total radial aperture of ~2 cm. At first order in the field difference, or the equivalent momentum offset δ, the orbit remains centered in the arc quadrupoles, since the orbit displacements due to two weaker and one central stronger dipole exactly cancel over one half cell. In a higher-order calculation the systematic horizontal orbit shift between two consecutive quadrupoles is about 13 μm, which appears negligible compared with the natural closed-orbit error of the order of 1 mm.

If all the dipoles, those reaching a high field and those staying at lower field, are powered (only) through the same common busbar, the orbit offsets and potential aperture reduction would be encountered already at injection energy, where the aperture is most precious. However, the design of the 11 T dipoles could be made so that they provide the nominal field of the main dipoles for the nominal current. Then, a strong "trim" circuit, acting only on the 11 T dipoles, could bring up their field to 11 T. In this way, the issue of aperture at injection would be avoided. In the tunnel there would need to be a second powering circuit, for each sector, carrying (at least) up to 4 kA of current, as required for bringing the field up from 8.33 to 11 T, connected to every third dipole magnet.

The general closed orbit control in one or the other configuration may need to be re-examined [S. Fartoukh].

If there are systematic offsets of several mm (with alternating sign) in all the dipole magnets the resulting multipole feeddown effects are likely to decrease the dynamic aperture. As a mitigation one could displace the existing magnets in the appropriate direction and the new higher-field magnets may be built with a larger aperture[1], in addition to being curved (the HL-LHC 11 T dipole magnets are straight) From the survey point of view, the nominal range of jack movement in radial and longitudinal direction for the arc magnets is ±10 mm from a neutral position of the jack. However, the heads of the jacks were aligned initially within 2-3 mm. Taking into account this initial misalignment of the head of the jacks and a possible misalignment of the interface between the jack and the cryostat, the range of the available displacements may be ±5 mm or less. In any case, a full realignment of all dipoles will be needed [placed inwards and outwards from the straight line defined by the quadrupoles], including an opening of the interconnections, etc.

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[1] Though the trend for FCC-hh high-field Nb_3Sn magnets is in the opposite direction, namely towards smaller cold bore and even smaller beam-screen aperture.

1.2 DISPERSION SUPPRESSORS AND INSERTION REGIONS

The dispersion suppressors and straight sections pose some additional challenges for beam energies above ultimate:

- The present separation dipoles prevent energies beyond the ultimate (or even lower energies already, as e.g. D4 in IR4), and would need to be replaced should a larger energy increase be targeted.
- Also the inner-triplet quadrupoles will be limited to ultimate energy. Going beyond the ultimate energy will have a significant impact on the β^* reach.
- Changes in the crossing schemes maybe required. The MCBX is also limited to ultimate energy (or lower, as is presently the case with the current limited to 400 A instead of 550 A).
- The performance of the orbit correctors above 7 TeV energy should be examined, given typical excitation levels and overall strength limits.
- A strategy needs to be worked out for the dispersion suppressors, where only 2 MB dipoles are installed per cell, which certainly is the most difficult conceptual problem to be solved in this scenario.
- Many of the matching quadrupoles (MQM and MQY) are near maximum/nominal field (200 T/m) at the end of the squeeze [S. Fartoukh]; also the trim quadrupoles (in particular MQTL) will limit the insertion optics “matchability” at energies higher than nominal.

Some possible solutions or concepts, e.g. for the dispersion suppressor, may be found in the historical studies on “missing dipole schemes” for the original LHC [5][6].

1.3 HARDWARE LIMITS

All LHC magnets, power converters, protection system, mechanical structures, etc. were meant to be designed for “ultimate” performance, i.e. with an 8% energy margin above nominal [7][8], but not more (which means that a beam energy of 8 TeV is out of reach).

The HL-LHC design and HL-LHC magnets are consistent with the ultimate principle [9], which allows for a maximum energy of 7.56 TeV, corresponding to an arc dipole magnet current of 13 kA with the present magnets.

A few weak magnets, limited earlier, below ultimate, would need to be replaced, e.g. some quadrupoles in the matching sections, and one separation dipole.

The main power converters are limited at a maximum current of 13 kA (8% above nominal); they would need to be exchanged or upgraded for operating at 8 TeV with existing magnet configuration.

Above 7.56 TeV, the main quadrupoles may be limited and the phase advance per cell would need to be dropped, e.g. to 80 or 60 degree per cell.

In addition there are limitations in the corrector magnets, e.g., spool pieces, Landau octupoles etc. Indeed the Landau octupoles may already be limited at 6.5 TeV. One solution is the ATS optics [10], whose increased beta functions in the arcs are rendering the octupoles (and chromaticity sextupoles) much more efficient at constant octupole (sextupole) strength. A possible additional mitigation would be the novel use of electron lenses for beam stabilization [11].

Even the 8% margin in beam energy may not be available for some of the key systems used in present LHC operation [12][13]. Limitations are expected, for example, from the kickers and diluters of the beam dump system, and possibly from the dump itself. Also the collimation system might have to be reviewed for the most optimistic scenarios shown in Table 1. For any “visible” rise in beam energy the synchrotron-radiation power will increase significantly, which will either require a reduction in total beam intensity or an upgrade of the cryogenics system and possibly even of the beam screen, if the hydraulic limits on the helium flow in the beam-screen capillaries is exceeded.

1.4 MAIN DIPOLES

For reaching a beam energy of 7.56 TeV, i.e. the ultimate energy of the blue book [8], one of the primary bottlenecks are the present main dipoles. Most of them have reached a field strength of 9 T equivalent to 7.56 TeV in the test station [14]; see also [15]. The test-station field distribution [16] is illustrated in Figure 3. About 92% of the magnets reached a field of 8.7 T of above, corresponding to an energy of (or above) 7.3 TeV.

Quench data for the main dipole magnets installed in the tunnel are available from commissioning campaigns in 2008, 2010, and 2015 [17]. Between 500 and 600 first quenches are expected to be necessary to reach 8.33 T (7 TeV), of which 161 quenches have already been accomplished [17]. Pushing one sector towards 7 TeV and beyond would give additional information. It is expected that more than thousand quenches will be needed to reach the ultimate energy [17].

The field quality of the MBs at ultimate field strength may need to be determined if not yet known.

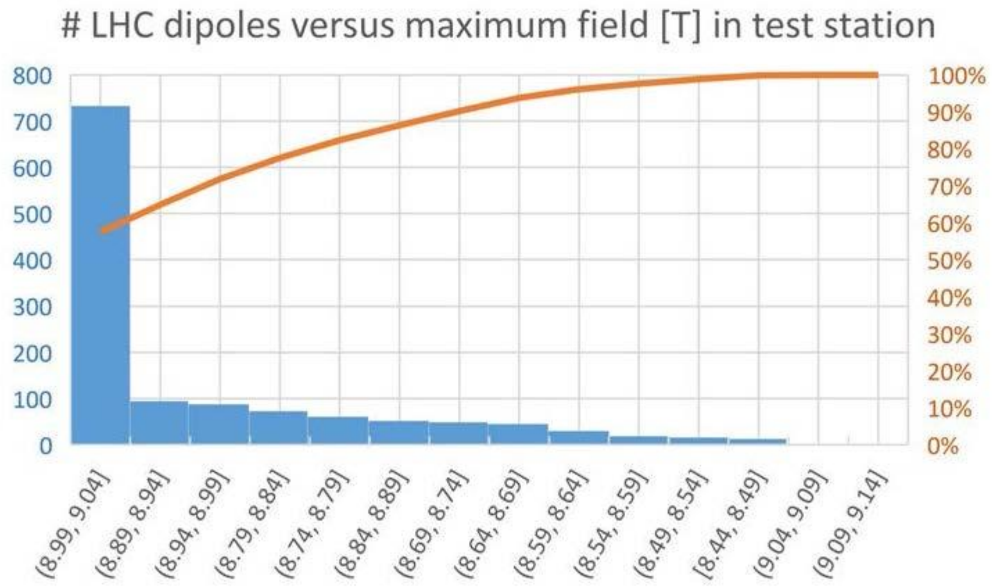

Figure 3: The number of LHC dipoles as a function of the maximum field reached in the test station (blue histogram, left axis) and the percentage of LHC dipoles with a maximum test-station field above a certain value (orange curve, right axis) [Data courtesy of Sonia Mallon Amerigo, David Widegren, and Davide Tommasini].

1.5 COST AND R&D ISSUES

Replacing every third dipole in the LHC will not be a “cheap” upgrade [18]. It might be more cost-effective to replace the entire machine as is being proposed with the HE-LHC design.

4. Conclusions

Among all the scenarios considered, pushing the LHC performance towards the ultimate beam energy of 7.56 TeV appears to be the most promising and most cost-effective strategy. Reaching this ultimate energy requires changes to a number of magnets in the dispersion suppressors and straight sections, plus possibly other modifications [12].

The least expensive and most straightforward approach to achieve the ultimate energy would be to train the existing dipole magnets towards the ultimate field level, while exchanging a couple of weak magnets around the machine.

Another approach to achieve the ultimate energy without increasing the strength of the main dipoles beyond 8.33 T, or, alternatively, an option to go beyond ultimate energy, would be to replace the arc and dispersion-matching quadrupoles by Nb_3Sn combined-function magnets so as to increase the effective bending field. This possibility could be further explored, and could possibly be combined with the previous one.

A third option for either reaching or exceeding the ultimate energy consists in replacing a third of the dipole magnets by Nb_3Sn dipole magnets with a higher field. This option may face some additional challenges, both conceptual ones (cells in the dispersion suppressor) and technical ones as the new and old magnets should preferably not be powered in series in this scenario, or be powered through additional nested circuits with additional busbars and additional connections in the tunnel. Though this dipole replacement scheme could, in principle, lead to a potentially much higher energy gain, most LHC systems are limited at (or even below) the ultimate energy. Therefore, for going beyond the ultimate energy, an entirely new machine, like the HE-LHC, might be a more attractive, alternative recipe.

The studies reported in this note were initially triggered by the 9th meeting of the CERN CMAC in 2014 [20].

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References

[1] G. Salam and A. Weiler, Collider Reach Tool, http://collider-reach.web.cern.ch .

[2] S. Bertolucci, private communication, around 2012.

[3] M. Benedikt, F. Zimmermann, “Towards Future Circular Colliders,” J. Korean Phys. Soc. 69 (2016) 893-902

[4] J.B. Adams and E.J.N. Wilson (eds.), "Design Studies for a Large Proton Synchrotron and its Laboratory," CERN-1970-006 (CERN, Geneva, 1970) http://dx.doi.org/10.5170/CERN-1970-006 .

[5] F. Galluccio, W. Scandale, "Missing-magnet cells for the LHC," SPS/AMS/note/89-7 (1989)

[6] X. Luo and W. Scandale, "Missing Magnet Scenarios for the LHC Lattice," CERN SL/Note 95-63 (AP) (1995).

[7] O.S. Brüning et al., "LHC Luminosity and Energy Upgrade: A Feasibility Study," LHC-Project-Report-626 (2002).

[8] O.S. Brüning et al. (eds.), "LHC Design Report, v.1: the LHC Main Ring," CERN-2004-003-V-1 (2004).

[9] F. Bordry, "Ultimate Energy Exploitation of the LHC," CERN Memorandum 22 September 2017

[10] S. Fartoukh, "Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade," Phys. Rev. ST Accel. Beams 16, 111002 (2013).

[11] V. Shiltsev, Y. Alexahin, A. Burov, and A. Valishev, "Landau Damping of Beam Instabilities by Electron Lenses," Phys. Rev. Lett. 119, 134802 (2017).

[12] O.S. Brüning et al., Report in preparation (private communication).

[13] G. Arduini, private communication (2017)

[14] A. Siemko, private communication (2017)

[15] P. Pugnat and A. Siemko, "Review of Quench Performance of LHC Main Superconducting Magnets," IEEE Transactions on Applied Superconductivity, Vol. 17, no. 2, June 2007, 1091

[16] S. Mallon Amerigo, D. Widegren, D. Tommasini, private communication (2017).

[17] E. Todesco, et al., "Training Behavior of the Main Dipoles in the Large Hadron Collider," IEEE Trans. Appl. Supercond. 27 (2017) 4702807

[18] L. Rossi, "Possibility for LHC Upgrade by New Magnet Technology," CMAC#9, informal meeting at Chamonix, September 2014.

[19] F. Zimmermann, "HE-LHC & FCC-eh Conceptual Machine Design – CDR Plan and Status" FCC Week 2017 Berlin, https://indico.cern.ch/event/556692/contributions/2483407/

[20] S. Fartoukh, M. Giovannozzi, D. Missiaen, E. Todesco, F. Zimmermann, "LHC Incremental Energy Upgrade," CMAC#9, informal meeting at Chamonix, September 2014.

Annex: Glossary

Acronym	**Definition**
FCC	Future Circular Collider, a 100-km collider in the Lake Geneva basin, under design by an international collaboration, with focus on 100-TeV hadron collisions (FCC-hh), and including a possible intermediate e+e- factory (FCC-ee), a lepton-hadron option (FCC-he), and a High-Energy LHC (HE-LHC)
FCC-hh	Future Circular Collider (hadron-hadron version), proposed in the Geneva region
HE-LHC	A 27-TeV collider in the LHC tunnel based on FCC-hh magnet technology
MB	LHC Main Dipole
MCBX	Inner Triplet nested Horizontal & Vertical Dipole Orbit corrector