MAGNETS FOR FUTURE HIGH ENERGY AND HIGH INTENSITY HADRON BEAMS

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Abstract

This paper gives a summary of the general needs and trends in superconducting magnet development for future high energy, high intensity hadron beam accelerators. Although a large part of the discussion is based on LHC upgrades, and the associated need for large aperture and increased peak field in the coils, some space is also given to the development of different technologies such as those required for pulsed magnets in the low to medium field range, superconducting undulators, or combined function magnets. I finally review the motivation for the development and sketch a plan for medium term R&D.

1. INTRODUCTION

The technology of superconducting bending (dipoles) and focussing (quadrupoles) magnets has gone since the beginning hand-in-hand with the developments in accelerator technology, so much that the two are considered since a quarter of a century good companions [1]. This is particularly true for circular colliders, the technology of choice today for high energy and high intensity hadron beams, where the field strength in the bending dipoles is proportional to the energy of the beam E, and the strength and aperture of the final focussing quadrupoles are a major driver for the luminosity L at the interaction points.

As the quest for new discoveries and for more measurements of basic particle properties at increased precision continues, there is a steady push to increase the energy and the luminosity in existing and future accelerators. This qualitative statement is best quantified by the *physics discovery potential* (PDP), which is a relative measure of the probability of a new discovery, observing in particular its dependence on energy and luminosity. Taking as an example the case of the LHC, the estimated scaling of the PDP for the discovery of a Higgs boson at an energy of 120 GeV scales as follows [2]:

$$PDP = (E-1)\sqrt{L} \tag{1}$$

in the range 4 TeV to 7 TeV. The physics reach of a given machine can hence be extended by increasing energy, luminosity or both. Magnet technology will have to follow accordingly, producing magnets with yet higher field and wider bore.

The aim of this paper is to give a view of the magnet developments that will be demanded in the medium term to follow the evolution of large scale accelerator programs. The requirements on magnets will be discussed in terms of peak field B, aperture D, specific geometry and configuration, as useful to identify key technologies that need R&D to achieve the objectives set by accelerator physics.

2. MAGNET SCALING LAWS

To be more specific on the requirements, we recall below the simple analytical dependencies of the main parameters for accelerator magnet design, peak field B and bore aperture D, on energy and luminosity. In the following discussion we neglect the peaking factor on the field, so that in a dipole the peak field can be taken as equal to the bore field and in a quadrupole we have that the peak field is proportional to the product of field gradient G and bore radius D/2:

$$B = G\frac{D}{2} \tag{2}$$

Once the collider geometry is fixed, and in particular if the curvature radius of the central beam trajectory ρ is given, the scaling between the bending field B and the particle momentum p is the simple proportionality [3]:

$$B[\mathrm{T}] = \frac{1}{0.2998}\frac{p[\mathrm{GeV/c}]}{\rho[\mathrm{m}]} \tag{3}$$

which implies that an increase of the beam momentum (and associated energy) can only be achieved increasing proportionally the dipole field in the bending magnets.

The relation between luminosity L and the characteristics of the magnets in the Interaction Region (IR), i.e. located in front of the Interaction Point (IP), is more involved. The definition of the luminosity L is the following:

$$L = \frac{N_b^2 f_{rep}}{4\pi\sigma^{*2}} F\left(\theta_c\right) \tag{4}$$

where N_b is the number of particles per bunch, σ^* is the transverse beam size, $F(\theta_c)$ is a geometric factor that depends on the crossing angle θ , and f_{rep} is the average bunch repetition frequency given by the product of the number of bunches n_b and of the bunch revolution frequency f_0:

$$f_{rep} = n_b f_0 \tag*{(5).}$$

Once the machine and its injector chain are optimised for maximum beam intensity, the most effective way to increase the luminosity at the interaction points is by reducing the transverse beam size σ^*. The value of σ^* depends on the beam emittance ε and on the value of the betatron function at the IP:

$$\sigma^* = \sqrt{\varepsilon\beta^*} \tag{6}$$

The beam emittance, in turn, is broadly conserved from injection through acceleration to collision, but the value of the betatron function can be changed by modifying the characteristics of the final focussing quadrupoles, in front of the IP. In the drift space bewteen the IP and the final focussing quadrupole, separated by a distance L^*, the betatron function grows parabolically from the value at the interaction point, β^*, to the maximum value β^{max}:

$$\beta^{\max} = \beta^* + \frac{L^{*2}}{\beta^*} \approx \frac{L^{*2}}{\beta^*} \tag*{(7).}$$

The corresponding beam size in the quadrupole σ^{max}, using Eq. (6) at the quadrupole location and substituting (7), is given by:

$$\sigma^{\max} = \sqrt{\varepsilon\beta^{\max}} \approx \sqrt{\frac{\varepsilon}{\beta^*}}L^* \tag{8}$$

that shows that the beam diverges from the IP towards the IR magnets. The magnet aperture D required to clear enough space for the beam passage can be expressed in terms of the beam size as follows:

$$D \approx K_\beta N\sigma^{\max} + \delta_x + \delta_{al} \tag{9}$$

where N is a multiplying constant, K_β is a factor that accounts for β-beating, δ_x is the maximum orbit error and δ_{al} is the maximum of the sum of the geometric tolerances on the bore position and alignment errors. We see from Eq. (9) that, as expected, the magnet aperture must scale as the maximum beam size. Using Eqs. (8) and (9), and neglecting for this discussion the geometric quantities δ_x and δ_{al}, we have hence that:

$$D \propto \sqrt{\frac{\varepsilon}{\beta^*}}L^* \tag{10}$$

from which we observe that if the layout of the interaction region is left unchanged (i.e. at constant L^*) a decrease of the beta function at the IP implies an increase of the bore diameter of the final focussing quadrupole. An alternative to limit the magnet bore diameter, and still achieve a decrease of the beta function, is to put the final focussing quadrupole closer to the IP. This option is limited by the space requirements from the detectors that enclose the IP and by the need of heavy shielding, especially when considering luminosity in the range of 10^{34} to 10^{35} cm^{-2} s^{-1} as we do here.

A common feature of the configuration of the IR magnets of modern colliders is that the IP is close to the focal point of the final focussing quadrupole. This relation is only approximate, as in reality the value of the betatron function depends on the whole optics in the matching section as well as the final focus. Nonetheless we make use of it to gain further insight in the scaling. Using the normalised quadrupole gradient, defined by:

$$k\left[\frac{1}{\mathrm{m}^2}\right] = 0.2998\frac{G[\mathrm{T/m}]}{p[\mathrm{GeV/c}]} \tag{11}$$

we can express the relation between the distance L^* and focal point location as follows:

$$kL^{quad}L^* \approx 1 \tag{12}$$

where we have introduced the magnetic length of the quadrupole L^{quad}. From Eq. (12) we observe that a change in the distance between the final focussing quadrupole and the interaction point implies an increase of the integrated gradient of the quadrupole. Combining Eqs. (12) and (10), we finally obtain the following scaling for the product of the quadrupole gradient and bore diameter, which is proportional to the peak field in the coil:

$$B \approx GD \propto \sqrt{\frac{\varepsilon}{\beta^*}} \tag{13}$$

which shows in summary that to decrease the betatron function at the interaction point we would need a final focussing quadrupole with larger aperture, or larger gradient, and in any case higher peak field on the coil.

Many additional factors have an influence on the required magnet aperture. One of the main unknowns for high luminosity colliders is the effect of parasitic interactions that take place among the particle bunches as they approach the IP [4]. This effect may eventually limit the luminosity. This *beam-beam* interaction can be reduced increasing the crossing angle of the two colliding beams, separating them faster as the beam bunches fly out of the IP. A larger crossing angle, however, also requires more space, i.e. a larger free bore, for the separated beams in the magnet facing the IP.

A second factor that is of large importance for the IR magnets is the radiation dose and heat loads from the collisions at the IP [5]. Radiation and collision debris are intercepted by the magnets and cause material damage, limiting the lifetime of the magnet, as well as nuclear heating that must be removed at cryogenic temperatures. In order to limit both effects, heavy shielding is required in front of the IR magnets, thus setting a lower limit to the minimum distance L^* of the magnet to the IP, and hence on the magnet aperture (see Eq. (10)). In addition it is generally beneficial to leave a wide aperture to let radiation and collision debris traverse the magnet, and intercept them at the downstream side.

3. MAGNET REQUIREMENTS FOR AN LHC UPGRADE

As discussed by Brüning [5] and Ruggiero [4] there is a good case for increasing the luminosity and the energy of the LHC above its nominal and, eventually, ultimate performance, aiming naturally at extending the physics reach of such an exceedingly large and complex instrument. The present commissioning and running-in plan [6] foresees an initial year of operation in the 6 TeV range (corresponding to a dipole field of approximately 7 T) and a luminosity of 10^{33} cm^{-2} s^{-1}.

The energy and luminosity will then be increased over the first 3 years of operation to their nominal values of 7 TeV (corresponding to a dipole field of 8.33 T) and 10^{34} cm^{-2} s^{-1} respectively. It is conceivable that using the engineering margin built in the accelerator design, the performance could be increased above the nominal values. Ultimate energy is expected to be in the 7.5 TeV range (corresponding to a dipole field of 9 T), while ultimate luminosity is estimated at 2.3×10^{34} cm^{-2} s^{-1}. The actual values that will be achieved depend, nonetheless, on many beam and operation parameters, discussed in [5] and [4], that go beyond the scope of magnet technology.

The lifetime of the magnets facing the experiments in the radiation environment is estimated at 6 years at nominal conditions, and 2 years at ultimate conditions [5]. By then the number of events accumulated for a particular channel of interest will be such that further operation at the same level of luminosity is not expected to significantly improve the statistics. Provided that the accelerator performance evolves as sketched above, a replacement of the magnets in the interaction region should hence be planned for the years 2013 to 2017.

An LHC upgrade scenario has been elaborated on this basis, and is presented in the various references cited in the bibliography. The backbone of the scenario is to stage the upgrade in two phases after reaching ultimate luminosity, by which we intend the maximum luminosity that will be possible in the LHC configuration as achieved around 2010. The two phases are the following:

- Phase 1 – luminosity increase to 10^{35} cm^{-2} s^{-1} with modest hardware changes, and in particular leaving the LHC arcs unchanged. This phase concentrates on improving the layout of the interaction region, including mainly the final focussing quadrupoles and the separation/recombination dipoles;

- Phase 2 – energy increase to 14 TeV, achieved by a major hardware change in the LHC arc as well as the injector chain.

3.1 Phase 1

Various alternatives have been considered in Phase 1, going from a straightforward update of the magnet performance to a major change in the magnet layout and optics. A summary of the various options considered in these studies, from [7] and [8], is reported in Fig. 1. The corresponding magnet parameters for the quadrupoles and dipoles are given in Tab. 1.

As discussed in the previous section an increase in luminosity requires an increase in the aperture of the final focus quadrupole, as well as an increase of the peak field in the coil (see Eq. (13)). The quadrupole gradient in these studies is kept at values close to the present level, pending a verification of the limits of the present technology. Indeed, as discussed in [5], to profit from high-Jc superconducting strands it may be better to design large aperture quadrupoles with moderate gradient than quadrupoles with smaller aperture but higher gradient.

Among the options considered in Fig. 1, some of the variants include a change of the topology of the magnets in front of the interation region. The variant with a separation doublet in front of the IP reduce the length where parasitic beam-beam interactions take place, but increase the distance between the IP and the focussing quadrupoles. Hybrid solutions, with interleaved dipoles and quadrupoles, or large crosing angles, have been considered to reduce the distance between the final focus quadrupoles and the interaction point, hence reducing the aperture requirements in accordance with Eq. (10).

		baseline	quadrupole first	dipole first	duadrupole beteen dipoles	dipole first large crossing angle	quadrupole first large crossing angle
L^*	(m)	23	23	52.8	42.5	34	23
β^*	(m)	0.5	0.16	0.26	0.19	0.15	0.10
$D^{\text{quadrupole}}$	(mm)	70	110	100	100	100	100
G	(T/m)	200	200	200	200	200	200
D^{dipole}	(mm)	80	110	135	165	75	105
B^{dipole}	(T)	2.75	15.3	15	14.6	14.5	14.3

Table 1. Summary of main magnet parameters (aperture, gradient, peak field) for the configurations considered for an upgrade of the LHC interaction region as reported in Fig. 1.

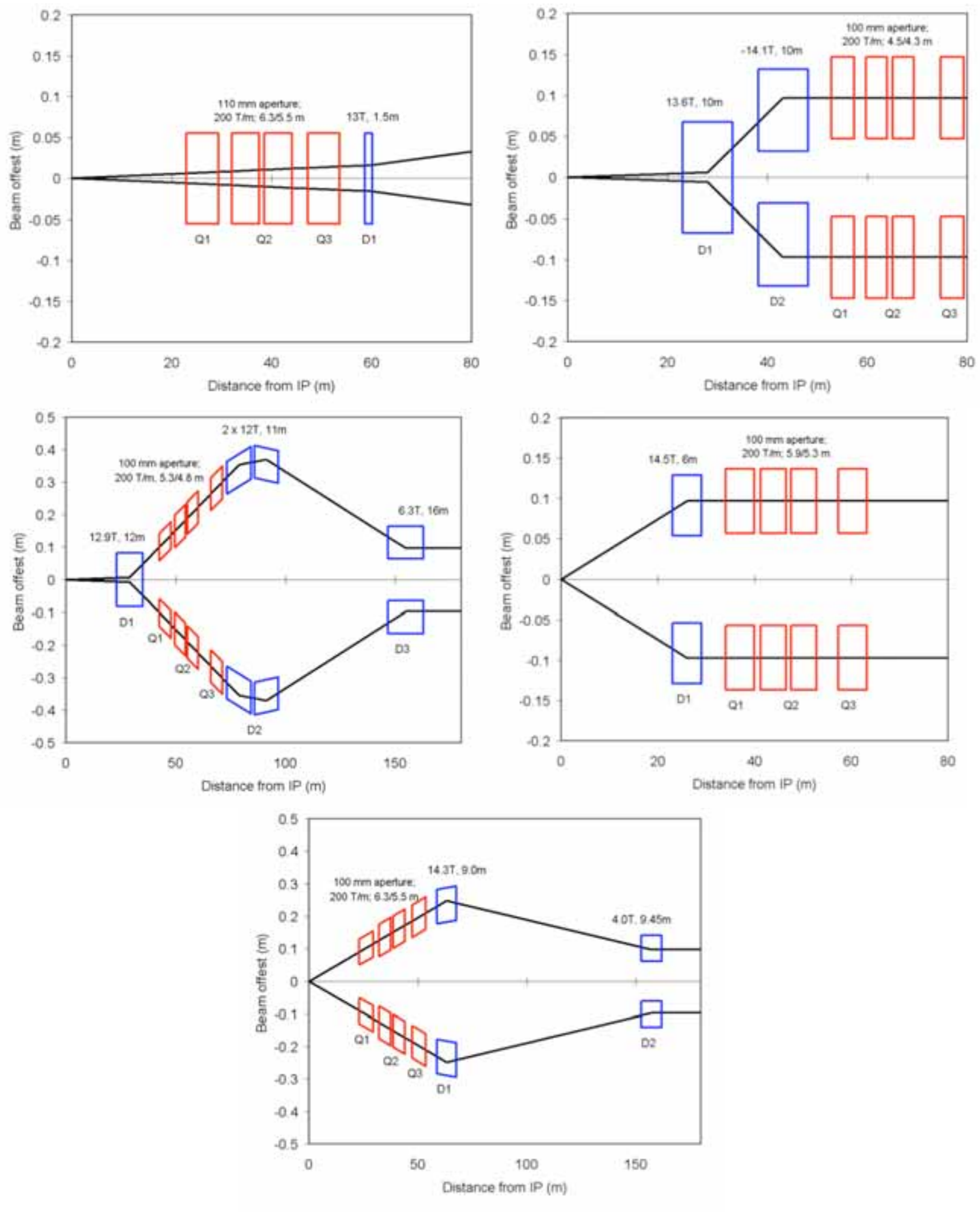

Figure 1. Various alternatives for a Phase 1 upgrade of the LHC interaction region. The present scheme has the focussing quadrupoles first (top-left). Alternatives considered have separation dipoles first (top-right), interleaved separation dipoles and focussing quadrupoles (middle-left), dipoles first with large crossing angle (middle-right) or quadrupoles first with large crossing angle (bottom).

Scanning the envelope of the set of parameters found in this study we see that Phase 1 of the LHC upgrade will require the development of dipoles and quadrupoles with aperture of the order of 100 mm, peak field in the dipoles of 15 T and field gradient in the quadrupole of 200 T/m. Taking appropriate enginnering margins this implies magnets design with peak field in the range of 16 to 17 T for dipoles and 12 to 13 T for quadrupoles.

Finally, the IR magnets for the Phase 1 of the LHC upgrade will have to sustain exceptional radiation dose and heat loads. The radiation dose and the power from the IP scales linearly with the luninosity. at the target luminosity of 10^{35} cm^{-2} s^{-1} the power from the IP amounts to 9 kW per beam. Innovative heat removal solutions shall be found to avoid large cryogenic overheads. As far as the radiation dose is concerned, at the target luminosity, magnets with the same insulation technology as used presently would have a lifetime of 6 months, which is clearly not acceptable. Again, innovative materials and shielding shall be prepared for the Phase 1 upgrade.

3.2 Phase 2

An energy increase in the existing tunnel, as planned for the Phase 2 of the LHC upgrade, will need an increase of the dipole field, as results from Eq. (3). Energy doubling from 7 TeV per proton to 14 TeV per proton will mean an increase of the dipole field from 8.33 T to above 16 T. This can be conceived maintaining the magnet aperture constant, around 50 mm.

An implication of an energy increase that is not directly spelled out in [5] and [4] is that also the lattice quadrupoles will have to feature doubled integrated strength, as results from Eq. (11). For a constant lattice geometry, i.e. keeping the magnetic lengths of the FODO lattice cell, this implies doubling the field gradient in the focussing and defocussing quadrupoles, aiming at $G \approx 450$ T/m and peak field in the quadrupole coils in the 14 T range. Although it is clear that a complete optimization of the cell layout is needed to set precisely the requirements for the lattice magnets, we see already that doubling the LHC energy will be possible only when the technology for 15 T dipoles and quadrupoles will be at hand and sufficiently established to allow large scale manufacturing at acceptable cost. For this reason it is important that during Phase 1 the R&D program on magnet technology addresses the design and fabrication of both high field quadrupoles as well as dipoles, whose results will give key input for the energy upgrade.

As for the IR magnets in Phase 1 of the upgrade, heat loads will be one of the problems that will require innovative solutions. Taking as a reference the cooling scheme of the LHC, the heat loads at superfluid helium temperature (1.9 K) are expected to scale up by a factor of 2, from the present 0.4 W/m to 0.8 W/m. At the intermediate temperature level of the LHC beam screen, 4.6 K to 20 K, the increase of the heat load can be as much as one order of magnitude, from the present value of 1.7 W/m to 17 W/m at doubled energy and ten-fold luminosity. This large rise results mainly from the increased synchrotron radiation that scales with the fourth power of the beam energy.

A second important consideration when planning for an energy upgrade is on the injector chain. The present dynamic range of acceleration in the LHC, around 15, is already very large, and cannot be expanded easily to cover the desired energy span. A much better situation would be obtained injecting in the last ring at 1 TeV, i.e. at twice the present value (450 GeV), or higher. To achieve this increase there are two possible alternatives:

- Upgrade the injector chain, and in particular the SPS, adding an additional, superconducting booster ring (a Super-SPS) that would accelerate and eject beam at 1 TeV or higher. The dipole magnets for this ring would require a bore field in the range of 2 to 4 T, aperture in the range of 80 to 100 mm, and high field ramp-rate in the range of 1 to 5 T/s. A superconducting option for the SPS was already considered more than 30 years ago, at the time of its conceptual design [9], and discarded because the technology was not judged available for construction. Note that an upgrade of the injector chain also requires novel, superconducting transfer lines for the increased energy. These represent several km of magnets with complex powering schemes, for which a cost optimization is surely worthwhile;

- Add a booster ring in the LHC tunnel that would receive beam from the existing SPS (at 450 GeV), accelerate over a limited dynamic range, up to 1 TeV or higher, and eject into the upgraded LHC. This booster would require dipoles with bore field in the range of 2 T at most, 50 mm aperture and moderate field ramp-rate, typically 0.1 T/s or smaller depending on the operating constraints.

As discussed in [5] and [4] an increase of the injection energy is expected to produce an increase in the beam performance, and less difficulties in the acceleration, even in the present LHC configuration. It is hence logic to plan for an upgrade of the LHC injectors sufficiently in advance before an energy upgrade.

In summary, based on the considerations above, a feasible plan for the LHC upgrade would be the following

- develop and install large aperture, high field dipoles and quadrupoles for an upgrade of the LHC interaction region aiming at a ten-fold increase in luminosity. The dipoles have a bore field of $B \approx 15$ T, and aperture $D \approx 100$ mm, the quadrupoles have a field gradient of $G \approx 200$ T/m, and aperture $D \approx 100$ mm. These magnets need to be compliant with the large radiation and heat load coming from the interactions at the IP. Technology development, rather than unit cost, is a major driver for the R&D, and these magnets can be regarded as prototypes for the large scale production that would be needed for an energy upgrade. Magnets for the upgrade would be needed by 2014, and the cost estimate for this program is 300 MEUR (≈ 450 MCHF).
- develop and install magnets for an increase of the injection energy into the LHC. Pursue initially both alternatives, i.e. $B \approx 2$ to 4 T, $D \approx 100$ mm, $dB/dt \approx 1$ to 5 T/s pulsed dipoles (and quadrupoles) for a Super-SPS, and low field $B \approx 2$ T, $D \approx 50$ mm DC dipoles (and quadrupoles) for an LHC booster ring. This activities could profit largely from parallel and independently driven R&D on compact, high intensity hadron collider such as the GSI-IAF, discussed later on. Cost reduction is a major driver in this R&D. The acceptable cost range for these magnets (per unit bending power produced) is 20 to 25 kEUR/Tm, which is comparable to the present LHC magnets. An upgrade of the injector chain can be planned at the earliest by 2015, once the LHC will have produced sufficient results in the present configuration. The associated cost is estimated at 250 MEUR (≈ 375 MCHF)
- finally, develop and install dipoles and quadrupoles for an energy upgrade to reach 14 TeV per proton in the existing tunnel. The dipoles have a bore field of $B \approx 16$ T, and aperture $D \approx 50$ mm, the quadrupoles have a field gradient of $G \approx 450$ T/m, and aperture $D \approx 50$ mm. As is the case for the upgrade of the injection chain, the cost of these magnets will be a major driver in the R&D and industrialization of the production. An acceptable magnet cost (per unit bending power produced) would be at a level of 10 to 15 kEUR/Tm, i.e. below the cost of the present LHC magnets. Given the R&D required, and the operation constraints, an LHC energy upgrade is credible only by year 2020, and the total cost associated is estimated at 3000 MEUR (≈ 4500 MCHF).

This scenario, and in particular the first item, is consistent with the present, worldwide R&D programs on high field superconducting accelerator magnets. Work on the upgrade of the LHC high-luminosity interaction regions is taking place under the auspices of the US-LHC Accelerator Research Program (US-LARP) [10] as well as with the Nb3Sn cable development that forms the core of the recently launched Next European Dipole (NED) Joint Research Activity (JRA) within the Coordinated Accelerator Research in Europe program (CARE) of the European Steering Group for Accelerator R&D (ESGARD) [11], [12]. Indeed, the targets outlined above appear to be possible today mostly thanks to the work performed within the US National Program for the development of high-performance Nb3Sn wires, which has led to a spectacular increase in J_c in the past 4 years, and a series of record-breaking dipole magnet models opening the 15 T range. This series started with the 50 mm bore, cos θ, MSUT model, built at Twente University and cold tested at CERN in 1995, which reached 11 T on its first quench at 4.4 K [13], and continued with the 50-mm-aperture, cos θ, D20 model, built and cold tested at LBNL, which, after some training, reached 13.5 T at 1.8 K in 1997 [14]. Lately, the 25-mm-gap, racetrack dipole, RD-3 model, also built and cold tested at LBNL, reached after some training 14.7 T at 4.2 K in 2001 [15]. Finally, the HD1 racetrack dipole, an evolution of the RD-3, has reached in 2003 the record field of 16 T after just more than ten training quenches [16].

4. PULSED MAGNETS FOR THE GSI-IAF

The Gesellschaft fuer Schwerionenfosrschung (GSI) in Darmstadt has proposed to build a new, International Accelerator Facility (IAF) for radioactive ions and antiprotons [17]. The central part of this complex are the two rings SIS100 and SIS300 that will be built in the same tunnel and will have magnetic rigidity $B\rho$ = 100 Tm and $B\rho$ = 300 Tm respectively. To achieve this magnetic rigidity the dipoles of SIS100 will have a bore field of 2 T in a rectangular bore of 130 mm x 65 mm. The dipoles of SIS300 will require a peak field of 6 T in a round bore with a diameter of 100 mm. The magnets for these two rings are especially challenging because the operation mode of the complex foresees fast ramping of the energy. SIS100 should undergo a full cycle in 1 s, corresponding to a ramp-rate of 4 T/s. The ramp-rate requirements for SIS300, which will operate as a storage ring, are more soft, but still the aim is to ramp the ring at 0.5 to 1 T/s.

The main challenge for the magnets of SIS-100 and SIS-300 is to achieve the field and ramp-rate specified without showing ramp-rate limitated behaviour as observed in superconducting magnets for accelerators [18] and thermonuclear fusion [19]. An additional requirement, and especially for SIS100 which will be the work-horse of the complex, is that the magnets will have to withstand long-term operation that will cumulate to several hundreds of millions of cycles.

An artist view of the dipole designs being considered for The SIS100 ring is reported in Fig. 2. The SIS100 dipole is based on a superferric design, derived from the Nuclotron dipole magnets and optimised for low stored energy as well as low AC loss in pulsed operation. With the present configuration a 2.6 m long dipole magnet stores 45 kJ, i.e. nearly 3 times less energy than a conventional design as presently used in the SPS or at the existing SIS18 ring at GSI. The reduction of the stored energy is clearly a must to limit pulsed electric power requirements at the high ramp-rates demanded. The AC loss achieved at liquid helium temperature is around 20 W/m, and there is a potential for further reduction by a factor 2 by adopting a taylored magnet design with the iron at an intermediate temperature (80 K). The R&D program on the SIS100 magnets is actively pursued and is planned to produce prototypes for the final design by end 2004.

The SIS300 dipole, whose schematic cross section is reported in Fig. 3, will be a conductor dominated design, where the Rutherford cables in the cos(θ) coils with 100 mm aperture are either coated or have a central core to reduce AC loss. This cable design is the result of a demonstration program that has been pursued jointly at GSI and BNL, aiming at testing a dipole for a ring option with 200 T m rigidity (rather as 300 T m as in the present baseline). A prototype magnet, GSI001 with a single layer coil and similar in construction to the RHIC dipole, was built and tested successfully at BNL, demonstrating operation up to 4 T bore field in pulsed conditions up to 4 T/s. The magnet sustained short pulse sequences between 2 T/s (500 repeated cycles) and 4 T/s (3 repeated cycle) without quenching [20], [21]. Most probably a two-layer coil design will be necessary to achieve the 6 T peak field requested for the 300 T m rigidity, as shown in Fig. 3. The R&D program for SIS300 is presently addressing issues of temperature margin and should produce a model magnet to verify quench performances and heat loads, both in steady state and pulsed operating conditions.

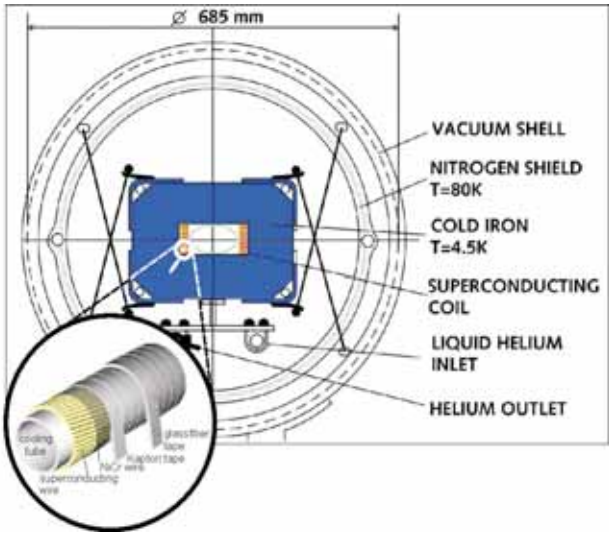

Figure 2. Cross section of the dipole design that is presently considered for the SIS100 ring at the GSI-IAF. The inset shows an exploded view of the NbTi superconductor. This design has been obtained taking as a reference the superferric Nuclotron dipole.

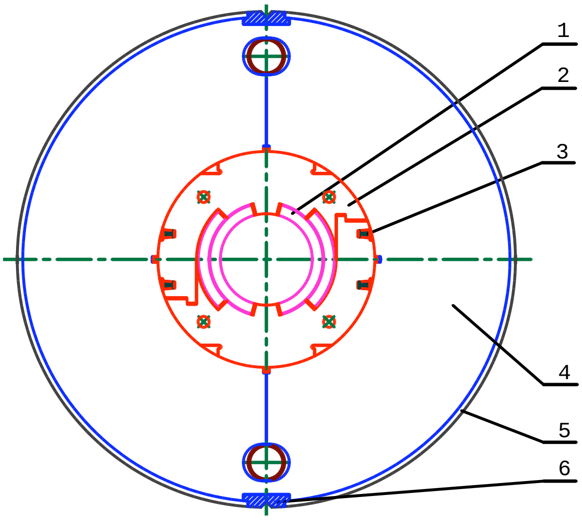

Figure 3. Schematic cross section of the one of the options presently considered for the dipoles of the SIS300 ring at the GSI-IAF, from [22]. This design has been obtained as an evolution of the UNK dipole prototype magnets. The numbering refers to (1) coil, (2) collars, (3) keys, (4) iron yoke, (5) outer skin, (6) staples.

Further important matters to be adressed for both SIS100 and SIS300 are the dynamic field quality at the large ramp-rate specified, as well as the ability to withstand the exceptional number of cycles planned for the accelerator complex without failure, nor decrease in performance. Specifically to this last point a joint INTAS activity between GSI, VNIIKP, SINTEZ and CERN has been launched to investigate the possibility to use alternative cable designs, sketched in Fig. 4, that have better cooling and could provide additional engineering margin for long term operation.

The set of parameters that are presently considered for the GSI-IAF main ring magnets are very close to those that would be needed for an upgrade of the LHC injector chain, i.e. the Super-SPS variant described earlier. This folds in nicely with the planning for an LHC upgrade, both in terms of objectives and timing. Therefore, we can expect that the upgrade of the LHC injector chain can take direct advantage of the on-going R&D at the GSI, and possibly use manufacturing and testing facilities that would be put in place for the procurement of the SIS100 and SIS300 cables and magnets.

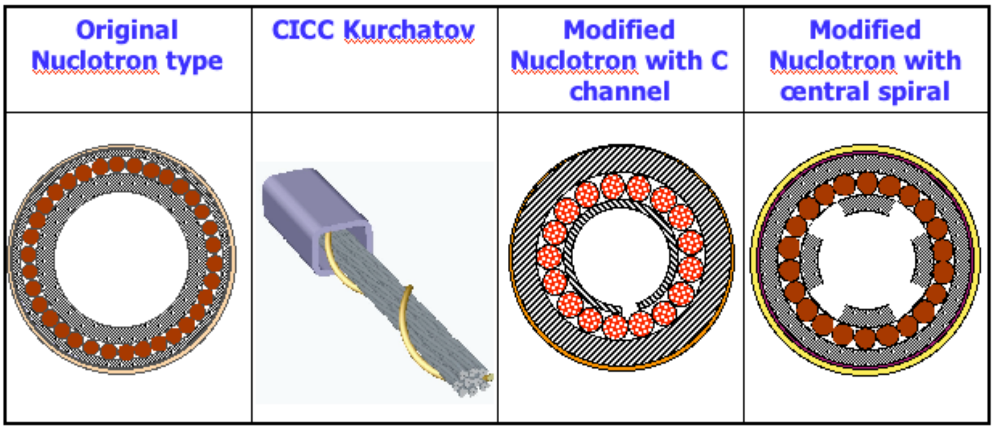

Figure 4. Cable design options for increased cooling and energy margin that are being considered for the SIS100 dipole magnet. A short cable test is planned to compare the performances of selected designs

5. SPECIAL DEVELOPMENTS

The developments detailed in the two preceding sections represent at the date of writing what we expect to be the mainstream of the R&D on accelerator magnets for the coming next year. Nonetheless, they do not represent the full picture, which needs to be completed with on-going activities and plans for magnets with special features, or for special applications. Below are few specific examples that are either in the conception, design or demonstration phase.

5.1 Quadrupoles for Compact Interaction Region Designs

We have been considering so far the magnet technology requirements stemming from the development of circular colliders. In linear colliders magnet technology is nonetheless important in the high gradient and compact final focussing quadrupoles.

One such example is the Tera Electron volts Superconducting Linear Accelerator (TESLA). The layout proposed in the Technical Design Report (TDR) has a final focussing quadrupole with a 250 T/m and a 56 mm aperture, i.e. close to the parameters as presently produced for the LHC [23]. The special feature of this magnet is the fact that it operates in the 4 T background field produced by the detector solenoid, as shown in Fig. 5.

A specific development has been launched for this demanding operating condition. To achieve the field gradient specified, the quadrupole design described in [24] has a peak field on the coil of 8.6 T at an operating current of 14 kA, with the design point at 80 % of the quench current along the magnet loadline (at 10.4 T). Nb3Sn has been selected as the superconductor to have sufficient operating margin. The second issue is the large and complex force distribution due to the presence of a background field. The force generated by the field of the detector adds up to 120 tonnes/m on a coil octant. The IR magnets are expected to be available by the mid 2010’s for the first IP of TESLA.

BNL is pursuing a development of comparable scope [25] aiming at the design of a 20 mm bore, 144 T/m quadrupole with a nested 1300 T/m^2 sextupole magnet for the final focus (QD0) of the NLC detector. This magnet is located in the background field of the detector solenoid and must be extremely compact. The outer magnet diameter in the design produced, including the cryostat, is as small as 114 mm.

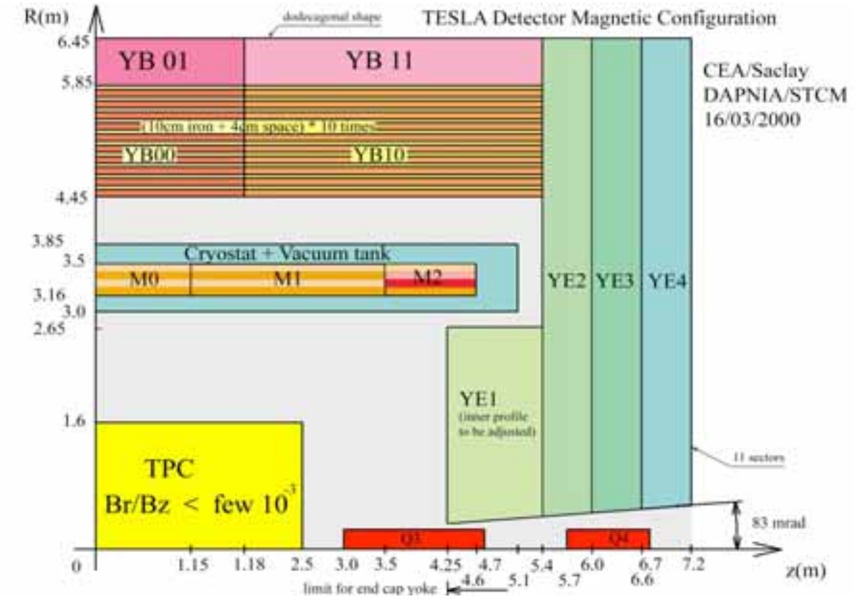

Figure 5. Layout of the first TESLA IR, with the final focussing quadrupole Q1 inside the detector, from [24].

5.2 Undulators and Wigglers

Superconducting undulators and wigglers are of interest because of the large bending power that can be achieved on the pole tips of a superconducting winding. For a given bending ratio the magnet is hence more compact, if compared to a classical electromagnet or to a permanent magnet design, and can fit in tightly constrained space. Alternatively, the high field feature can be used to increase the bending strength and induce larger synchrotron light emission to extract beam energy over a predefined spectrum, monitor the beam or damp transverse particle motion.

Machine	Manufacturer	Coil gap (mm)	Number of poles	Period length (mm)	Peak field on axis (T)	Peak field on coil (T)	Year	Ref.
Daresbury	RAL	62	3	500	5		1981	[26]
LURE	CEA/Saclay	67	5	260	5	7	1988	[27]
Daresbury	Oxford Instruments		3		6		1991	[28]
TERAS	ETL/Sumitomo	48	3		10		1995	[29]
MAX II	Tampere Univ.	36	3	244	6	6.4	1996	[30]
AURORA-2D	Sumitomo	40	3	342	7		1999	[31]
MAX II	MAX-Lab	12	47	61	3.5	4.1		[32]
BESSY II	BINP	19	17	148	7	8.1		[33]
CESR	LNS	76.2	7	400	2.1	4.1		[34]

Table 2. Main features of selected superconducting undulators and wigglers as produced around the world.

Among the many superconducting wigglers and undulators existing in the world, see Tab. 2 that has been extracted from [34], one such application is being pursued at LHC in the synchrotron light monitor that shall be used for the measurement of the beam profile at the Interaction Point 4 [35]. The magnet design, shown schematically in Fig. 6, is based on a NbTi strand and reaches a peak field of 5 T [36]. A prototype of a half period of the undulator has reached a bore field of 4 T without quench and a maximum field of 5.25 T after training.

Extrapolation to the operating conditions of a Super-LHC with doubled energy would require a field in the gap of at least 7 T, or larger, for the synchrotron light monitor to produce useful diagnostics [5]. Although a magnet design has not been produced, we can expect that higher Jc material (e.g. Nb3Sn) would be needed.

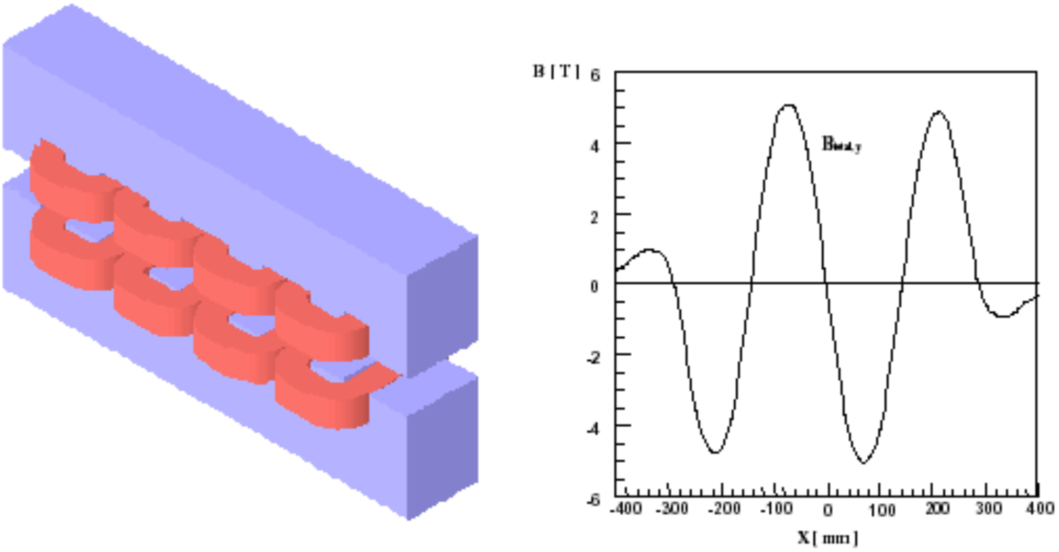

Figure 6. Undulator for the LHC Synchrotron Radiation monitor for the measurement of the beam profile, from [36].

5.3 Combined Functions Magnets

Combined function magnets have been commonly used in accelerators since the first realisation of the weak-focussing principle. The desired field profile is realised in classical magnets by shaping appropriately the iron poles. In case of superconducting combined function magnets the contribution of the iron to the field is small, and to obtain the field profile the coil geometry has a non-conventional shape.

One such example is the combined function dipole and quadrupole magnets that are being built at KEK for the arc section of the 50 GeV proton beam line of the J-PARC neutrino oscillation experiment between Tokai-mura and Kamioka [37], [38], [39]. At the nominal operating point the magnet has a 2.8 T dipole field component superposed to a 18.7 T/m field gradient. The beam line is expected to come in operation in 2006. The combined function magnet has the advantage of a very efficient use of the beam line length, with no unused space between magnetic elements. The KEK design, shown in Fig. 7, has a single layer of conductors which are located in the cross section so as to generate the required field profile to within few units. Special techniques such as the use of low-cost plastic spacers and high precision winding on a computer-assisted machine have been used to reduce the cost of the magnets.

The interesting feature of this magnet is the fact that it has no conductors over a large portion of one side, where the fied is lower, and can hence provide a natural opening for access to the bore. This feature could be used, for instance, to evacuate synchrotron radiation in high field bending and focussing magnets. End design is however not trivial, as well as mechanical support in case of extrapolation to higher fields.

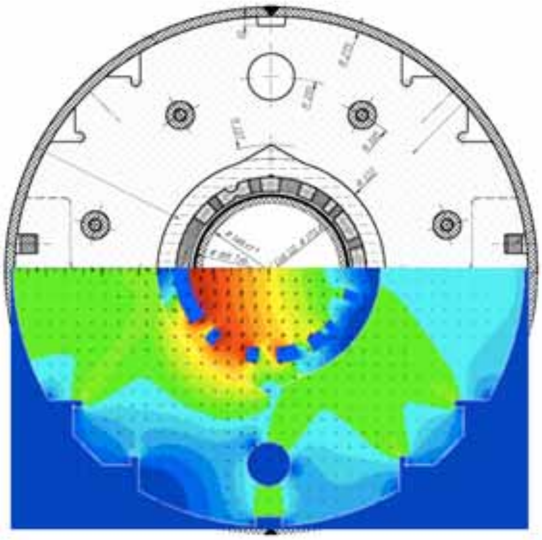

Figure 7. Combined function magnet (dipole and quadrupole) as presently developed for the J-PARC neutrino oscillation experiment [39]

5.4 Magnets for High Radiation Loads

The magnet design can be made tolerant to radiation loads, as generated by particle showers or synchrotron radiation, by changing the design of the cross section. One possibility, as described by Mokhov [40] is to remove cold material from the midplane, where particle showers and synchrotron radiation are mostly concentrated, and intercept the particles and heat loads at higher temperature. A dipole design that goes in this direction is shown schematically in Fig. 8.

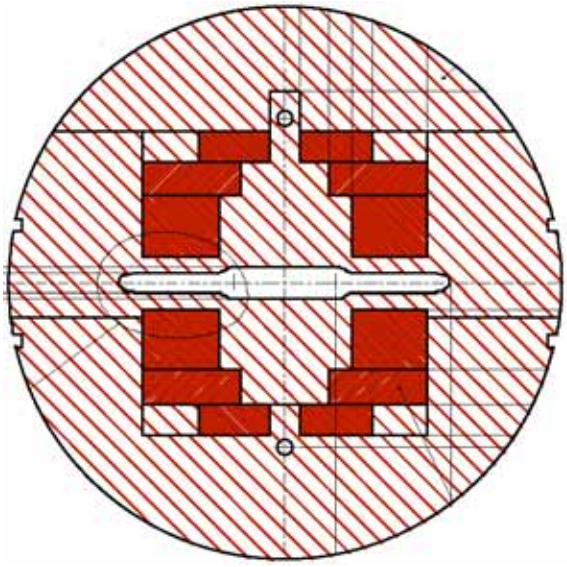

Figure 8. Dipole magnet design with central slit to decrease radiation heat load and dose in the superconducting coil, as described in [40]

The coil is open on the midplane, and the iron is shaped so that the first solid material, where heat load is deposited, is outside the coil perimeter. The midplane slit can be equipped with a dedicated cooling circuit that intercepts heat loads before they diffuse to the superconducting cable. A design of this type is not as efficient as a cos(θ) cable arrangement in terms of A turns required to generate a given bore field. Nonetheless, given the lower cryogenic power to be removed from the coil and the improved life time, it may still prove optimal for the few magnets needed in a high luminosity IR. Indeed, this could be the separation dipole in front of the IP in one of the variants with the dipole first for the LHC IR upgrade sketched in Fig. 1.

6. SUMMARY

In summary, we can expect the accelerator magnet R&D of the coming 10 years to concentrate on:

- high field, large aperture, radiation resistant dipoles and quadrupoles. Peak field in the dipole is in the range of 16 to 17 T, coil diameter of 100 mm. For the quadrupoles the peak field is in the range of 12 to 13 T and coil diameter of 100 mm. Main challenges are mostly related to the high field, and specifically the development of a suitable high-Jc superconductor in the relevant range of operating field and temperature. the mechanical design, quench protection, heat removal and radiation hardness of the coil insulation;
- pulsed dipoles and quadrupoles in the low to intermediate field range, 2 to 6 T, with coil diameter in the range of 50 to 100 mm, and ramp-rate of few (up to 4) T/s. In this case the main challenges are to achieve the specified ramp-rate with no ramp-rate limitation (premature quenches), low AC loss and low stored energy, as well as field quality suitable for accelerator operation (typical field homogeneity over the good field region within few 10^{-4}). Because these magnets will be used in moderate size series, cost reduction is a major issue in this development
- magnets for specific applications that require either complex magnetic configurations (e.g. wigglers), or combined functions (e.g. dipole + gradient) or additional constraints on the operating conditions (e.g. focussing magnets in background field or magnets for extreme heat load conditions). These special developments will provide verification of alternative design concepts and will likely be test-beds for new techniques.

The spectrum of R&D outlined above is vast, and the challenges will require innovation in materials science (superconducting strands, structures, insulation techniques) as well as new design principles. Most of the work along the lines above has started, either at the stage of conceptual design or with specific R&D and prototyping. Indeed, it is the main aim of these proceedings to describe the material aspects that are most relevant to the development of magnets of future high energy and high intensity hadron colliders.

7. ACKNOWLEDGEMENTS

I am indebted to F. Ruggiero and O. Brüning for the documentation and clarifications on the LHC upgrade scenario. The brief but illuminating discussions with T. Taylor have dissipated uncertainties and doubts. Similarly, I owe to S. Fartoukh some insight in the complicacies of beam physics close to the IP. Finally, I wish to thank A. Devred, D. Tommasini, P. Schnizer, P. Wanderer and A. Yamamoto for the material provided and reported in this note.

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