Dipoles for High-Energy LHC

E. Todesco, L. Bottura, G. De Rijk, L. Rossi

Abstract — For the High Energy LHC, a study of a 33 TeV center of mass collider in the LHC tunnel, main dipoles of 20 T operational field are needed. In this paper we first review the conceptual design based on block coil proposed in the Malta workshop, addressing the issues related to coil fabrication and assembly. We then propose successive simplifications of this design, associating a cost estimate of the conductor. We then analyse a block layout for a 15 T magnet. Finally, we consider two layouts based on the D20 and HD2 short models built by LBL. A first analysis of the aspects related to protection of these challenging magnets is given.

Index Terms—superconducting accelerator magnets, dipoles, quadrupoles, low-temperature superconductors

I. INTRODUCTION

THE first proposal of increasing the energy of the LHC by replacing the 8 T dipole with higher field magnets goes back to the end of the 90's [1]. At the Malta workshop [2], a 20 T design based on block coils and 400 A/mm² overall current density (with insulation) has been proposed [3]. The layout aimed at minimizing the superconductor costs, resulting in a pretty complex design, with a pole made of six different coils and three materials, plus a current grading in the Nb₃Sn part. It sets a target of 500 A/mm² overall current density at 25 T for the High Temperature Superconductor (HTS).

The HTS has a large cost and its technology is still to be proven in accelerator magnets. The community is passionately debating about the 20 T target, and about the maturity of HTS. It has been suggested that a lower field dipole with a larger tunnel could be more economic w.r.t. to the 20 T idea. At the same time, a more ambitious target of 100 TeV has also been proposed [4]. So, having an estimate of cost versus field is valuable information for the HE-LHC studies. A second remark was that the protection of a magnet with such a large stored energy could be a showstopper.

In this paper we first review some specific features of the design of this magnet as critical current, field quality, saturation, and the two-in-one features. We then consider two simplifications of the Malta proposal, namely removing the Nb₃Sn grading and the Nb-Ti coil, giving the associated costs. We then make a first proposal for a 15 T magnet based on Nb₃Sn and Nb-Ti. Two 1-m-long magnets D20 [5] and HD2 [6] and have the record of dipole field ~13.5 T: here we consider these layouts in a two-in-one version to see the ultimate limit for these designs. We also present the first analysis of protection aspects related to hotspot temperature, finding a requirement on the stabilizer content for the HTS.

II. CURRENT DENSITY SELECTION AND REQUIREMENTS

We start our analysis by discussing the choice of the current density j . Superconductivity is limited by the critical surface. Giving the fact that the critical current j_c is a decreasing function of the field, to reach high field implies operate the winding at lower current density. Two additional constraints point to the direction of low current density: stress and protection. Forces are proportional to j^2 , plus a factor from [7], so going to high current densities increases stress beyond the 150-200 MPa limit of degradation of conductor and/or insulation. For protection, high current density is also a killer [8,9] as we will show in the last section for the D20 case.

Fig. 1: Critical surface of practical superconductors for magnets [data from P. Lee, NHFML].

On the other hand, large j gives more compact coils. Therefore, the problem is to quantify what high and low mean, and to find a compromise between these conflicting requirements. In the design presented in [3], quoted as the “Malta design”, we made a rather conservative choice based on the history of superconducting dipoles for particle accelerators (see Fig. 2), where one achieves 400-500 A/mm² of overall current density (i.e. over the insulated coil, but excluding the copper wedges).

With a value of 380 A/mm², 10 mm of coil width provides ~2.7 T, so 20 T can be achieved with ~75 mm coil. This was the base of Malta design, radically different w.r.t the work on a 24 T design [1], which was assuming 800 A/mm² current density, betting on a large improvement of the superconductor properties shown in Fig. 1. These large current densities also pose a challenge for the management of large stresses.

Manuscript received July 14, 2013.

E. Todesco, L. Bottura, G. De Rijk, L. Rossi are with the CERN Technology Department, 1211 Geneva 23, Switzerland. (e-mail: Ezio.Todesco@cern.ch)

Fig. 2: Operational field versus coil width for accelerator magnets (black dots), for Nb₃Sn models (80% of design short sample unless specified) and for HE-LHC.

As shown in Fig. 2, a 75 mm coil width goes well beyond what has been done in the past: accelerator magnets range from 10 mm (RHIC) [10] to 30 mm (LHC) [11] coil width; short models of 40-50 mm coil width are the present world record field of 13.8 T [6]. Indeed, there is a dipole under construction for a test station with 80 mm coil width [12]: this will be the first magnet addressing issues stemming from the use of very large coils. The fusion community has built a 12 T magnet with 200 mm width coil [13], but with another cable layout (cable-in-conduit).

The second critical point of the conceptual design is the margin on the loadline: in the Malta design, we assume a challenging value of 20%, in line with the experience of many accelerator magnets. This means that to operate at 20 T and 380 A/mm², the magnet should be able to reach 25 T and 470 A/mm² (what is usually called short sample). We are aware that 20% margin on 20 T means a 5 T margin (larger than the Tevatron field !), but we consider not credible the choice of a lower margin, given also the LHC results, and the experience with the most recent Nb₃Sn models, both exhibiting considerable training in the 70%-90% region.

The third choice is material grading. Given the large difference in cost between superconductors, and the large amount of coil needed, a 20 T magnet must rely on material grading to reduce the cost. This means to use Nb-Ti in low field regions, Nb₃Sn in intermediate field regions, and HTS only where it is strictly needed.

Finally, we assume a dilution factor 0.3. This means that the volume of superconductor in the insulated coil is 30%. We chose not to go to larger values 0.35-0.40, as done in many Nb₃Sn short models [5,6,14,15], to keep in our pockets some margin for protection.

Having taken these values as starting point, we find that 380 A/mm² operational current density can be used (see Fig. 3):

- for Nb-Ti in regions up to 8 T, corresponding to a short sample of 1600 A/mm² in the superconductor at 10 T, as in the LHC main magnets;
- in Nb₃Sn in regions up to 13 T, corresponding to a short sample of 1600 A/mm² in the superconductor at 16.3 T. This is what is currently achieved in Nb₃Sn conductors, with 10% cable degradation.

The Malta design, aiming at a cost optimization, introduces a further complexity, i.e. covering the 13 T to 15 T range with

Nb₃Sn operating at lower current density. This allows some cost saving, since the HTS has to provide only the last five tesla, and not the last seven. The price to pay is to have a part of coil in Nb₃Sn operating at ~200 A/mm², i.e. larger coil dimension, and more complex manufacturing. In this case Nb₃Sn can be used in regions up to 15 T, corresponding to a short sample of 900 A/mm² in the superconductor at 18.75 T. Loadlines, critical surfaces and operational points are shown in Fig. 3.

We finally assumed to have an HTS able to operate at 380 A/mm² at 20 T. This means to have an overall current density at short sample of 470 A/mm² at 25 T. Whereas at the time of the Malta workshop (2011) we were short of the target by a factor two, nowadays Bi-2212 is close to the target (see Fig. 1).

Fig. 3: Sketch of critical surface assumed for Nb-Ti and Nb₃Sn (thick and thin curves), loadlines (lines) and operational conditions (triangles)

III. ISSUES AND FEATURES IN THE MAGNETIC DESIGN

The design of a magnet with such a large coil width has some specific features. We have good news for field quality: the large ratio of between the coil width and the aperture radius (of the order of 4) makes field errors naturally small. This can be shown by using the standard multipolar expansion

$$B_y + iB_x = B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1} \quad (1)$$

and computing the multipoles in a sector coil of width w , aperture r , and angular width α , for a reference radius of $2/3$ of the aperture

$$B_n = -\frac{j\mu_0}{\pi} \frac{2\sin(\alpha n)}{n(2-n)} r \left(\frac{2}{3} \right)^{n-1} \left[\left(1 + \frac{w}{r} \right)^{2-n} - 1 \right] \quad (2)$$

The above factor is limited for $n > 2$ (sextupole or higher order) and for $w \rightarrow \infty$. Moreover, the normalizing factor B_1 is proportional to w . So, for very large coil width b_n vanish with $1/w$ (see Fig. 4). Therefore, the multipoles of the HE-LHC dipole are “naturally” a factor 3-4 lower than the multipoles of the LHC dipoles. Therefore, the field quality optimization will concern only b_3 , b_5 , b_7 , and not up b_{11} , as in the LHC.

The second aspect concerns the iron. A rough estimate of the field increase due to iron is $(r+w)r/R_I^2$. Having $r=20$ mm of aperture, $w=80$ mm of coil, 20 mm of spacer, the iron radius is at $R_I=120$ mm, and one gets a main field increase of 14%, not far from the LHC dipole value (18%). Therefore, notwithstanding the very large coil, the iron can still play some role in reducing the current density. This brings

additional advantage for protection. Iron will be highly saturated, so a finite element code is necessary to simulate the case properly; we used ROXIE [16].

Fig. 4: Multipole of a sector coil at 60 degrees for a 20 mm aperture radius, versus ratio between coil width and aperture radius.

In the Malta design, see Fig. 5, the large saturation reduces the field of 25% w.r.t. a linear extrapolation of the low current values. It is a very large value, even compared to the 5-10% in RHIC magnets, but should not pose particular problems for operation. The saturation effect produces a strongly nonlinear inductance visible already at low currents. Nonlinearity is so strong that using the differential inductance at nominal is a pretty good approximation for a large range of current.

Fig. 5: Revision of Malta lay-out: 20 T with three materials and grading in Nb₃Sn: field in the iron (left) and in the coil (right) are given in T.

The third aspect concerns the two-in-one structure. This dipole will be a twin coil, with full mechanical and magnetic coupling. The cross-talk between the apertures induces larger field in the inner part of the coil (i.e. the side of the coil towards the magnet centre). This is limiting the short sample, and some optimization must be done involving the iron. In the Malta design we proposed to increase the beam separation from 192 to 300 mm and to shape the iron to correct for this effect (this is the origin of the iron step visible in the cross-section, see Fig. 5). So, a magnetic simulation must also take into account the two-in-one structure.

IV. COIL LAY-OUTS

A. 20 Tesla

The first case we consider is a revision of the Malta design (Malta rev.), based on Nb-Ti, Nb₃Sn with two current densities, and HTS. To optimize the sextupolar component, the height of the block must be of the order of 70 mm. A two layer layout would considerably reduce the complexity of the manufacturing and assembling, but it would require a 35-mm-width cable, which appears too daring to us. Therefore, we

used the largest manufactured cable (HD2, 22 mm, 51 strand of 0.8 mm diameter [6]), arranged in three layers. One can also use 15-mm-width cable arranged on four layers. We end up with a pretty complex coil made of 11 blocks, which can be made of a double pancake of HTS, a double plus a single pancake of Nb₃Sn operating at 190 A/mm², a double plus a single pancake of Nb₃Sn operating at 380 A/mm², and a double pancake of Nb-Ti (see Fig. 5). A pole is made by six coils which have to be independently cured and then spliced together. This is the most complex layout, optimized for minimizing the cost (see Table I, where cable quantity is given for one quarter of aperture). W.r.t. to the Malta layout we slightly modified the block position to have a match in the vertical position of blocks to ease assembly and mechanics.

TABLE I

COMPARISON OF DIFFERENT OPTIONS – CABLE SURFACE GIVEN FOR ONE POLE

Layout	Field (T)	HTS (mm ²)	Nb ₃ Sn (mm ²)	Nb-Ti (mm ²)	Total (mm ²)	N. coils (adim)	Cost (a. u.)	Cost/T (a. u.)
20 T Malta Rev.	20.0	1726	6689	2589	11005	6	1.00	1.00
No Nb-Ti	20.0	1726	9279		11005	5	1.14	1.14
No Nb ₃ Sn grading	20.0	2733	3668	2589	8991	4	1.07	1.07
No grad, no Nb-Ti	20.0	2733	6258		8991	3	1.21	1.21
15 T Snowmass	15.0		5961	1799	7760	3	0.45	0.60
No Nb-Ti	15.0		7873		7873	2	0.55	0.74
D20	13.8		4499		4499	2	0.32	0.46
HD2	12.6		3884		3884	1	0.27	0.43

We now analyze successive simplifications of this layout, estimating the increase in cost. The hypothesis is that Nb₃Sn costs four times Nb-Ti, and HTS four times Nb₃Sn. The first option is to simply remove the Nb-Ti, using Nb₃Sn also in the areas with field lower than 8 T. One has 9 blocks, and the magnet can be assembled in five coils. The foreseen cost increase w.r.t. previous option is 14% (see Table I).

The second option is to remove the Nb₃Sn grading, having only Nb₃Sn at 380 A/mm². This leads to a considerable simplification, with only three coils to form a pole, one of HTS and two in Nb₃Sn (as shown in Fig. 6). The cost penalty is 21% more than the Malta rev., which becomes 7% if Nb-Ti grading is used.

Fig. 6: Revision of Malta lay-out: 20 T with three materials and without grading in Nb₃Sn: field in the iron (left) and in the coil (right) are given in T.

B. 15 Tesla

A 15 T layout based on the Nb₃Sn technology has been proposed in [17]. The coil width is reduced by approximately by 25%, since we keep the same current density. The needed height of the coil is reduced to 50 mm, and we opted for a pretty daring rescaled HD2 cable with 1 mm strand to have a two-layer coil (see Fig. 7), with one pole made of three coils.

The cost is 45% of Malta lay-out, and 55% if Nb-Ti is not used (see Table I).

Fig. 7: 15 T layout: field in the iron (left) and in the coil (right) [17], in T.

C. HD2 and D20 layout

We finally conclude this analysis by considering a lay-out with the HD2 coil [6], in the two-in-one configuration (see Fig. 8). With a copper to superconductor fraction of 1.4, the magnet can provide 12.6 T with 20% margin on the loadline. The layout is very simple, with one pole made of a two-layers coil, and no grading, with a cost of 27% of Malta lay-out (see Table I).

The HD2 model was built with a much lower stabilizer content, i.e. a copper to superconductor ratio of 0.8. With these properties, the magnet gains about one tesla, reaching 13.5 T with 20% margin. The issues related to the protection are discussed in the next paragraph.

Fig. 8: HD2 dressed as a 12.6 T HE-LHC dipole: field in the iron (left) and in the coil (right) are given in T.

We also analysed the case of D20 [5]. This is a highly optimized cos-theta layout, with four layers and strong current grading. Each pole is made of two coils with different cable (see Fig. 9), the outer cable having a current density 80% larger than the inner cable. With the hypothesis of the Malta design on the j_c and Cu/noCu ratio, the magnet reaches 13.8 T with 20% margin. The original design was relying on a much lower copper content, 0.45 in the inner layer and 1.0 on in outer. With these challenging values, the magnet would reach the amazing value of 15 T with 20% margin. This layout may look very appealing but we will show that protection constraints are not satisfied, not even to reach 12 T.

D. Fringe field

An estimate of the fringe field at 1 m from the centre of the magnet is given in Table II. The 20 T design has 50 mT, which is a large value but tolerable in the tunnel provided that no instrumentation is on the magnet cross-section.

Fig. 9: D20 dressed as a 13.5 T HE-LHC dipole: field in the iron (left) and in the coil (right) are given in T.

TABLE II
MAIN PARAMETERS FOR THE FOUR LAYOUTS

		Malta	Snow	D20	HD2
Bore field	(T)	20.00	15.00	13.80	12.60
Peak field	(T)	20.45	15.12	13.96	13.01
Current	(kA)	13.95	20.80	7.27	13.45
Fringe field	(mT)	53	18	15	0.05
Cu/NoCu	(adim)	1.40	1.40	1.40	1.40
Strand diameter	(mm)	0.800	1.000	0.75	0.800
Curr. Dens. H	(A/mm ²)	388	370	555	374
Curr. Dens. L	(A/mm ²)	194	185	308	
L_d	(mH/m)	63	13	70	11
Energy	(MJ/m)	6.40	2.95	2.43	1.06

V. PROTECTION: HOTSPOT TEMPERATURE

The energy extraction on a dump resistor for the long version of this magnet is negligible, already for a single 14-m-long magnet. Therefore, the dipole has to rely on quench heaters to ensure that enough resistivity is developed to rapidly dump the current, i.e., the magnet energy must be absorbed by the magnet itself.

We first estimate the energy density over the insulated cable, which sets the scene. This is a crucial parameter with an ultimate limit of the order of 0.5-0.7 J/mm³, given by the enthalpy of the cable at room temperature (with some mild dependence on the cable type [9]), and a lower limit at 0.3 J/mm³ given by an analytical approach [8]. Nb-Ti magnets usually operate with energy densities of the order of 0.05 J/mm³. The Nb₃Sn magnets developed in the past 20 years have at 50%-100% larger energy density, i.e. in the range 0.07-0.10 J/mm³ (see Fig. 10).

Fig. 10: Energy density versus current density for Nb-Ti (black dots), Nb₃Sn (blue triangles) and the lay outs presented in this paper (red triangles).

The 20 T layout has an additional 50%, being in the range of 0.15 J/mm³. So in terms of energy density we are still

below the ultimate limits, but protection is getting more challenging. The main advantage of the proposed layouts is that we chose a very prudent value of the current density, which is the other relevant parameter, together with the stabilizer fraction.

The 15 T layout falls within the Nb₃Sn range of energy density, and together with the low current density it looks very reassuring in the plot of Fig. 11, whereas a shadow of doubt is cast for the outer layer of D20, featuring large energy density and a very large current density in the outer layer.

Having set the main scene, we estimate the quench integral

$$\Gamma(T_{\max}) \equiv \nu A^2 \int_{T_0}^{T_{\max}} \frac{c_p^{ave}(T)}{\rho(T)} dT \quad (3)$$

available in the cable choosing a maximum temperature of 300 K. Here A is the cross-sectional cable area, ν the fraction of stabilizer, ρ the stabilizer resistivity and c_p^{ave} the volumetric specific heat. For the HTS part we assume a stabilizer in the same proportion as in the Nb₃Sn cable. Parts of the coil exposed to higher field have lower Γ (see Table III). We then estimate the integral Γ_q during a quench

$$\Gamma_q \equiv \int_0^{\infty} [I_q(t)]^2 dt \quad (4)$$

in the hypothesis that the magnet has no dump resistor and is totally quenched at $t=0$. Subtracting the two terms and dividing by the square of the operational current, we have the time margin for protection [9], i.e. the time available for the protection system to keep the hotspot below room temperature. This time has to include the detection time (a few ms), the validation window (10 ms), and the quench heater delay (10-20 ms), and the propagation time to quench the whole magnet. For the generation of Nb-Ti magnet used in the LHC this time is of the order of 100 ms. For the new generation of Nb₃Sn magnets one has much lower values, of the order of 30-50 ms. Below 40 ms, the protection becomes extremely challenging, and maybe impossible.

The case of the 20 T layout is shown in Table 3: the Nb₃Sn and the Nb-Ti coils have a good time margin, above 50 ms. The HTS part is at ~30 ms, which appears encouraging but not enough, so a larger fraction of copper should be envisaged. Having a stabilizer ratio of 1.7, the time margin reaches 40 ms. So protection in terms of hotspot temperature is critical but not a killer, with the condition of having a larger fraction of stabilizer in the high field zones. The case without grading does not require to increase the copper content in the HTS.

HTS also features a specific challenge due to the fact that the quench velocity is 100 times smaller than in LTS [18], and therefore the time needed to go above threshold is much longer than the 2-5 ms seen in LTS; the other critical point are the inductive voltages, not addressed here. Both aspects could be a showstopper for the magnet.

The cases of 15 T layouts show no issues for the hotspot, with a time margin of 70 ms. The HD2 case has a wide margin (100 ms) and even with a very small fraction of copper and a larger operational current allowing reaching 13.5 T, one is left with a pretty comfortable 50 ms margin. On the other hand, hotspot in D20 is too large, due to a too high current density in the outer layer. With a Cu/NoCu ratio of 1.4 as in the Malta

layout, the outer layer has only 20 ms margin, and to reach 40 ms margin one would need raising the copper ratio to 4. The only way looks to lower the operational current and field. With 6 kA current the time margin is at 40 ms, but the field lowers to 11.5 T. So considering also the protection aspects, a HD2 layout would possibly reach the 13.5 T range, whereas D20 would be blocked at 11.5 T. A final summary of the options taking into account for protection is given in Table IV.

TABLE III
TIME MARGIN AND MIITS FOR PROTECTION (T_{MAX} = 300 K)

Layout	MIITS					Time margin		
	Field (T)	Current (kA)	HTS (MIITS)	Nb ₃ Sn (MIITS)	Nb-Ti (MIITS)	Γ_q (MIITS)	HTS (s)	Nb ₃ Sn (s)
Malta rev.	20.0	13.95	39.0	43.0	52.5	33.5	0.028	0.049
Malta rev. no grad	20.0	13.63	39.0	43.0	52.5	30.0	0.048	0.070
Snowmass	15.0	21.40		105.0	130.0	76.0		0.120
HD2	12.6	13.45		43.0		25.0		0.100
D20	13.8	7.27		4.8		3.8		0.019

TABLE IV
DIFFERENT OPTIONS, INCLUDING PROTECTION CONSTRAINTS

	Field (T)	j_o (A/mm ²)	# coils	Cost (adim)	Material
Malta rev.	20.0	380/190	6	1.00	HTS/Nb ₃ Sn (grad)/Nb-Ti
Malta rev.					
No grad/no Nb-Ti	20.0	380/190	3	1.21	HTS/Nb ₃ Sn
Snow	15.0	380/190	3	0.45	Nb ₃ Sn (grad)/Nb-Ti
HD2	13.5	400	1	0.27	Nb ₃ Sn

VI. CONCLUSION

In this paper we reviewed the concepts developed in the Malta conference [2] for 20 T magnets in the HE-LHC [3]. We discuss some general features of the magnet design with such a large coil, such as field quality, saturation and two-in-one layout. We give a requirement of 400 A/mm² of overall operational current density for the HTS, with 20% margin.

We then presented a revised version of the cross-section with changes in the block structure to make the assembly and the mechanical aspects easier. The Malta layout is very complex, one pole featuring 6 coils of three different materials (see Table 4). We therefore present successive simplifications, as removing the Nb-Ti grading, removing the Nb₃Sn grading, and aiming at a 15 T magnet without HTS. A 15 T magnet can be priced at ~50% of the 20 T case. We also consider two layouts based on existing models: D20 and HD2.

We then addressed the issue of protection, showing that with mild assumption on the copper content (1.4) the hotspot temperature is below 300 K, with a requirement on the HTS stabilizer ratio of 1.4 to 1.7, depending on the design. Considering protection aspects, HD2 can reach 13.5 T (i.e. 60% of the 20 T Malta design) with a 24% price of the Malta design, and a very simple coil that needs no splices. On the other hand, the D20 design would not be able to go beyond 11.5 T, since the grading of the outer layer is too pushed.

ACKNOWLEDGEMENTS

We wish to acknowledge P. Fessia for useful discussions and comments on the coil fabrication and assembly aspects, and P. Ferracin for reading the manuscript and useful comments.

REFERENCES

- [1] P. McIntyre, A. Sattarov, "On the feasibility of a tripler upgrade for the LHC", PAC (2005) 634.
- [2] E. Todesco, F. Zimmermann, eds., "The High Energy LHC" CERN Yellow Report 2011-3 (2011).
- [3] L. Rossi, E. Todesco, "Conceptual design of 20 T dipoles for High-Energy LHC", CERN Yellow Report 2011-3 (2011) 13-19.
- [4] O. Dominguez, and F. Zimmermann, "Beam parameters and luminosity time evolution for a 80-km VHE-LHC", International Particle Accelerator Conference (2013) 1442-4.
- [5] A. McInturf, et al., "Test results for a high field (13 T) Nb₃Sn dipole", Particle Accelerator Conference (1997) 3212.
- [6] P. Ferracin, et al., "Recent test results of the high field Nb₃Sn dipoles magnet HD2", *IEEE Trans. Appl. Supercond.*, Vol. 20, pp. 292-5, (2010).
- [7] P. Fessia, et al., "Parametric analysis of forces and stresses in superconducting dipoles", *IEEE Trans. Appl. Supercond.*, Vol. 19, pp. 1203-7, (2009).
- [8] L. Bottura, "Magnet quench 101", proceedings of WAMSDO workshop, CERN Yellow Report in press.
- [9] E. Todesco, "Quench limits in the next generation of magnets", proceedings of WAMSDO workshop, CERN Yellow Report in press.
- [10] M. Anarella, et al, "The RHIC magnet system", *Nucl. Instrum. Meth. A* 499 (2003) 280-315.
- [11] L. Rossi, "Superconducting magnet for the LHC main lattice", *IEEE Trans. Appl. Supercond.* **14** (2004) 153-8.
- [12] A. Milanese, "Design of the EUCARD high field dipole magnet FRESA2", *IEEE Trans. Appl. Supercond.* **22** (2012) 4002604.
- [13] A. Portone, et al, "Status report of EDIPO project", *IEEE Trans. Appl. Supercond.* **21** (2011) 1953-9.
- [14] S. Caspi, et al., "Test results of 15 T Nb₃Sn quadrupole magnet HQ01 with a 120 mm bore for the LHC luminosity upgrade", *IEEE Trans. Appl. Supercond.* **21** (2011) 1854-7.
- [15] S. Zlobin, "Status of a single aperture 11 T Nb₃Sn demonstrator dipole for LHC upgrade", International Particle Accelerator Conference (2012) 1098-110 and M. Karppinen, "Design of 11 T twin aperture Nb₃Sn dipole demonstrator magnet for LHC upgrades", *IEEE Trans. Appl. Supercond.* **22** (2012) 4901504.
- [16] S. Russenschuck, "Field computation for accelerator magnets" Wiley VCH, 2011.
- [17] E. Todesco talk given at the workshop "Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting: frontier capabilities for hadron colliders", <https://indico.cern.ch/conferenceDisplay.py?confId=223094>
- [18] J. Schwartz, "Quench in high temperature superconducting magnets", proceedings of WAMSDO workshop, CERN Yellow Report in press.