First-cut design of an all-superconducting 100-T direct current magnet

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A 100-T magnetic field has heretofore been available only in pulse mode. This first-cut design demonstrates that a 100-T DC magnet (100 T) is possible. We base our design on: Gadolinium-based coated superconductor; a nested-coil formation, each a stack of double-pancake coils with the no-insulation technique; a band of high-strength steel over each coil; and a 12-T radial-field limit. The 100 T, a 20 mm cold bore, 6-m diameter, 17-m height, with a total of 12 500-km long superconductor, stores an energy of 122 GJ at its 4.2-K operating current of 2400 A. It requires a 4.2-K cooling power of 300 W. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4852596>]

A 100-T DC field, one million times the earth field, is more than double 45 T,¹ the highest DC field created to date. Upon completion, a 32-T magnet at the National High Magnetic Field Laboratory (NHMFL) will achieve the highest DC field by an all-superconducting magnet.^{2,3} Fields greater than 45 T have been beyond DC magnet technology. Simply stated, this is because no electrical conductor meets two requirements for generation of a >45-T *continuous* field: high mechanical strength and good electrical conductivity. Copper is unable to withstand the high magnetic stresses. Steel can cope with the large stresses, as has been demonstrated by pulse magnets,^{4,5} but its large electrical resistivity leads to huge Joule heating that rapidly overheats the steel, reducing its strength and thereby forcing >45-T steel magnets to operate only in pulse mode.^{6,7} Although the range of experiments that can be done with pulsed fields continues to expand,⁷ the words of Francis Bitter remain valid, “there are many experiments that are extremely difficult or impossible to perform in a hundredth of a second”⁸ as a reason to drive the maximum DC field limit much higher. Our 100-T DC magnet (100 T) uses a superconductor of sufficient strength, with the winding reinforced by overbands of high-strength stainless steel. With electrical resistivity anchored to zero, one inherent weakness of the pulse magnet is eliminated.

The two crucial design issues in high-field superconducting magnets are: (1) mechanical integrity; and (2) protection. In this first-cut design, based on the no-insulation (NI) technique,^{9–18} we assumed 100 T self-protecting; thus, we focused chiefly on mechanical stress. Our key design approach is fourfold.

1. The 100 T is wound with GdBCO tape manufactured by SuperPower, specifically 12-mm wide and 95- μ m thick, comprising 50- μ m thick Hastelloy substrate (room-temperature yield stress and strain, respectively, of 970 MPa and 0.95%¹⁹), two 20- μ m thick electroplated copper layers, and 5- μ m thick remainder (1- μ m thick GdBCO layer and other materials).
2. The 100 T consists of 39 nested coils, each a stack of double-pancake coils (DPs) wound with the NI technique.

3. To keep the peak tensile stress on GdBCO tape to ≤ 700 MPa at 4.2 K, each DP is reinforced over its outer diameter with a high-strength stainless steel band (overband) of 300-K ultimate strength of 1400 MPa and Young’s modulus of 200 GPa.
4. To limit the maximum radial field, $B_{r_{max}}$, to < 12 T within the 100 T (here, $B_{r_{max}} = 11.1$ T), the ratio of winding height ($2b$) to winding i.d. ($2a_1$), $\beta = b/a_1$, is chosen > 3 . As β increases, $B_{r_{max}}$ approaches zero, though the greater the β , the taller the coil, hence the more expensive the coil.

It is worth clarifying the technical uncertainties regarding the four design principles. First, all the NI GdBCO *test* magnets to date have proven self-protecting^{11–18} at 4.2 K and 77 K; the largest has a center field of 4 T with a 140-mm winding diameter.¹¹ Nevertheless, the self-protecting feature of a “large” NI magnet, such as our 100 T, needs further verification. Second, although > 800 MPa of 95%- I_c -retention tensile stress was reported for selected GdBCO conductors after $\sim 10\,000$ load cycles at 77 K,^{19,20} our 700-MPa stress limit at 4.2 K: this assumption too requires further verification. Finally, in this first-cut design, no optimization was performed. Our target here is to demonstrate, through application of the state-of-the-art HTS (High Temperature Superconductor) magnet technology, that an all-superconducting 100-T DC magnet is a technical possibility. Note that, though as yet unproven experimentally, a 12-T limit for $B_{r_{max}}$ is a result of this first-cut design.

Two assumptions on GdBCO, also as yet unproven experimentally, are: (1) its irreversible field is above 100 T;²¹ and (2) its critical current density, J_c , at 4.2 K remains above 10^{10} A/m² at 100 T. Based on J_c data up to 30 T at 4.2 K, J_c for field parallel to the a - b plane appears nearly field-independent at $> 10^{11}$ A/m² and that for field parallel to the c axis $> 10^{10}$ A/m².^{22–25}

Fields, axial and radial, within the winding and over the winding exterior were calculated.²⁶ A force balance equation,²⁷ Eq. (1), is applied to stress analysis, where σ_r and σ_θ are radial and hoop stresses, while λJ and $B_z(r)$ are overall current density and field distributions within the winding, respectively. Equations (2a) and (2b) are constitutive. The GdBCO tape is assumed mechanically isotropic, with a

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FIG. 1. Sketch of the 1st-cut design 100-T superconducting DC magnet (100 T). Inset: in-scale winding details of Coil20 and its overband.

Young's modulus, E , of 120 GPa and Poisson ratio, ν , of 0.3.¹⁹ The conductors $300\text{ K} \rightarrow 4.2\text{ K}$ thermal contraction, ϵ_T , was measured to be 0.29%.²⁸

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} + \lambda B_z(r) = 0, \quad (1)$$

$$\epsilon_r = \left(\frac{1 - \nu^2}{E_r} \right) \sigma_r - \left(\frac{\nu + \nu^2}{E_\theta} \right) \sigma_\theta + (1 + \nu) \epsilon_T, \quad (2a)$$

$$\epsilon_\theta = - \left(\frac{\nu + \nu^2}{E_r} \right) \sigma_r + \left(\frac{1 - \nu^2}{E_\theta} \right) \sigma_\theta + (1 + \nu) \epsilon_T. \quad (2b)$$

We designed 100 T one coil at a time, from Coil1 (innermost) to Coil39 (outermost). A primary target is to maintain the total conductor strain to $\leq 0.6\%$, by limiting the peak magnetic hoop stress, which in each coil occurs at its innermost turn ($r = a_1$) in the range 400 (Coil1)–700 (Coil38) MPa. The peak bending strain on the conductor at $r = a_1$ decreases from 0.27% (Coil1) to 0.001% (Coil39). A stainless steel overband of a thickness sufficient to limit the total conductor strain to 0.6% is placed at each coils o.d. To keep the maximum radial magnetic field, $B_{r_{\max}}$, to 12 T and keep the conductor requirement in check, the β s of Coils1839 were set to 3. Once the j th coil is designed, the next $(j+1)$ th coil inner radius is

TABLE I. Key Parameters of 100 T.

Parameters	Values
Total nested coils	39
Winding i.d. (mm)	20.0
Winding o.d. (m)	5.564
Winding height (m)	16.663
Total DP coils	14 589
Total GdBCO tape length (km)	12 367
Maximum tape length per DP (m)	2973
Total Joints (DP-to-DP & Coil-to-Coil)	14 588
Operating temperature (K)	4.2
Operating current, I_{op} (A)	2400
Number of parallel tapes, each I_{op}	4
$[\lambda J]_{Magnet}$ (A/mm ²)	30.9
$B_{r_{\max}}$; B_z at $B_{r_{\max}}$ (T)	11.1; 9.8
Self inductance (kH)	42.4
Stored energy at I_{op} (GJ)	122

TABLE II. 39-Coil 100T winding dimensions. 4.2-K cold bore:20 mm; o.d.: 5.6 m; height: 16.7 m.

Coil	a_1 (mm)	a_2 (mm)	$2b$ (mm)	Coil	a_1 (mm)	a_2 (mm)	$2b$ (mm)
1	10.0	15.3	6015.0	21	1295.0	1297.7	7785.6
2	30.3	35.6	6015.0	22	1374.9	1377.5	8270.6
3	50.6	57.0	6015.0	23	1455.0	1457.7	8731.4
4	82.0	86.9	6015.0	24	1535.4	1538.1	9216.6
5	112.0	119.9	6015.0	25	1616.1	1618.7	9701.6
6	174.9	181.4	6015.0	26	1696.9	1699.5	10186.6
7	236.5	241.8	6015.0	27	1777.9	1780.5	10671.8
8	297.0	301.6	6015.0	28	1859.0	1861.6	11156.8
9	356.9	361.1	6015.0	29	1940.1	1942.8	11642.0
10	416.7	421.6	6015.0	30	2021.3	2024.0	12151.2
11	497.1	501.7	6015.0	31	2102.5	2105.1	12636.4
12	577.5	581.6	6015.0	32	2183.5	2186.5	13121.4
13	657.6	661.4	6015.0	33	2266.0	2269.1	13606.4
14	735.5	740.9	6015.0	34	2348.2	2351.6	14091.6
15	817.0	820.4	6015.0	35	2431.5	2435.3	14601.0
16	896.9	899.9	6015.0	36	2515.4	2519.6	15110.2
17	976.3	979.3	6015.0	37	2599.6	2604.9	15619.6
18	1056.0	1059.0	6354.6	38	2685.5	2693.8	16129.0
19	1136.1	1138.7	6839.6	39	2774.5	2782.1	16662.4
20	1215.4	1218.0	7300.4				

determined by addition to the j th coil outer radius: (1) the overband thickness of the j th coil; (2) 5.0-mm radial gap; and (3) the j th coil radial displacement due to thermal contraction and magnetic expansion.

Figure 1 shows an in-scale sketch of 100 T, based on its parameters in Table I. The inset shows winding details with Coil20 and its overband identified. This 39-coil 100 T has a 20-mm cold bore, a nearly 5.6-m outermost winding o.d., and a 16.7-m maximum winding height. It contains 14 589 DPs and requires a total 12 mm $\times$ 0.095 mm GdBCO tape over 12 500 km. Its self inductance is 42.4 kH and its magnetic energy is 122 GJ at 2400 A. Table II lists dimensions (a_1 ; a_2 ; $2b$, respectively, winding inner and outer radii and height) of all 39 coils.

Figure 2 shows plots of superconductor material requirements vs. Coil number: (red strips) total number of DPs per coil; (blue squares) GdBCO tape length required per coil; and (green circles) tape length required per DP. The

FIG. 2. Plots of superconductor material requirements vs. Coil number: (red strips) total number of DPs per coil; (blue squares) GdBCO tape length per coil; (green circles) tape length per DP.

FIG. 3. Plots of field and current parameters vs. Coil number: (red strips) B_z at $r = a_1$, $z = 0$; (blue strips) $B_{r_{max}}$; (green circles) $[\lambda J]_{Coil}$.

maximum tape length per single DP is 2974 m, for each of the 685 DPs of Coil 38.

Although the 100 T, in a bath of 4.2-K liquid helium, will be operated at 2400 A, shared among four parallel tapes, the winding itself is *adiabatic*, i.e., no liquid helium and thus no its vapor bubbles within the winding.²⁷ Due to the domineering overbands, the 100 T has an overall current density, $[\lambda J]_{Magnet}$, of 30.9 A/mm². Figure 3 shows plots of field and current parameters vs. Coil number: (red strips) B_z at $r = a_1$, $z = 0$; (blue strips) $B_{r_{max}}$; and (green circles) $[\lambda J]_{Coil}$. Note that the maximum $B_{r_{max}}$ is 11.1 T in Coil 38, where $B_z(a_1, 0)$ is 9.8 T.

To keep the hoop stresses ≤ 700 MPa and the radial (normal) field < 12 T on GdBCO tape, the coils are “thin” and “tall.” Figure 4 shows plots of structural parameters vs. Coil number: (red circles) overband hoop stress; (blue squares) GdBCO tape hoop stress; and (green strips) overband radial thickness. Note that σ_θ on overbands are kept below 1200 MPa and on GdBCO tape below 700 MPa.

Figure 5 shows in-scale drawings of (a) the 100 T and, for comparison, two recent superconducting magnets of similar sizes: (b) the 18-coil TF magnet of ITER,²⁹ and (c) ATLAS magnet of LHC.³⁰ Table III presents selected

FIG. 4. Plots of structural parameters vs. Coil number: (red circles) overband hoop stress; (blue squares) GdBCO tape hoop stress; (green strips) overband radial thickness.

FIG. 5. In-scale drawings: (a) 100 T (GdBCO); (b) 18-coil (Nb₃Sn) TF magnet, ITER; (c) ATLAS magnet (NbTi), LHC.

parameters of the three magnets. In terms of conductor tonnage (superconductor and nonsuperconducting materials that together constitute the conductor), 100 T (wound of GdBCO) is close to ATLAS (NbTi) and roughly 1/3 of 18 TF Coils (Nb₃Sn). On magnetic energy storage, the 100 T dwarfs the other two.

The four remaining key issues for superconducting magnets—stability, protection, superconductor, and cryogenics—are briefly discussed. (1) At 4.2 K, HTS has a stability margin > 100 times greater than that of LTS: HTS magnets are not susceptible to quench caused by disturbances that affect LTS magnets.²⁷ Measurements with NI coils have demonstrated their high stability.^{9–13} (2) NI DP coils have proven self-protecting.^{9–13} Currently, more NI coils are being tested to further assess their self-protecting feature. (3) For this 100 T, the GdBCO tape is assumed to remain superconducting and capable of carrying an operating current of 600 A at 4.2 K, which must be verified. Quality control and testing will be essential to eliminate conductor defects. Note that in all HTS magnets operated to date in our laboratory, a quench, though rarely, originated at a defective (or damaged) spot. (4) The 100 T cryogenics has two major sources of

TABLE III. 100 T; ITER 18 TF Coils;²⁹ LHC ATLAS.³⁰

System	Conductor		Magnetic
	Superconductor	Weight (ton)	Energy (GJ)
100 T	GdBCO	125	122
18 TF coils	Nb ₃ Sn	410	41
ATLAS	NbTi	163	1.6

dissipation: Joule heating of the DP-DP and coil-coil joints; and structural, which is estimated at ~ 300 W.

The 100 T, comprising 14,589 series-connected DPs, will have 14,550 DP-to-DP and 38 Coil-to-Coil resistive joints. Because each conductor comprises 4 parallel $12\text{ mm} \times 0.095\text{ mm}$ tapes, the 100 T will have 58,352 tape-to-tape joints, each carrying 600 A. Each tape-to-tape joint is bridged by a 12-mm wide, ℓ_j -long GdBCO tape, thus, there are 2 *soldered contacts* in each tape-to-tape joint, resulting in a total of 116,704 *soldered contacts*. An average *soldered contact* resistivity at 4.2 K, including magnetoresistive effects in the field range of 0–100 T, is $150\text{ n}\Omega\text{ cm}^2$, based on measured value of $100\text{ n}\Omega\text{ cm}^2$ at 77 K in zero field³¹ and extrapolated to 100 T, with an assumption that an extrapolation up to 10 T (Ref. 27) is valid to 100 T. A *soldered contact* area is $6\text{ mm} \times \ell_j$, which varies $\sim 3\text{ cm}$ (Coil 1, $\sim 180^\circ$ overlap) to $\sim 300\text{ cm}$ (Coil 39, $\sim 60^\circ$ overlap), or an average *soldered contact* area of $\sim 150\text{ cm}^2$, or an average *soldered contact* resistance of $\sim 2\text{ n}\Omega$. This in turn gives a total joint resistance of $\sim 200\text{ }\mu\Omega$. At 600 A, the 100 T thus dissipates $\sim 10\text{ W}$ within its *adiabatic* winding. A total outer surface of Coil 39 (outermost) overband exposed to *liquid helium* is $\sim 300\text{ m}^2$, $\sim 10\text{ W}$ translates to a heat flux of $\sim 3\text{ }\mu\text{W/cm}^2$, i.e., the joint dissipation will be safely carried away to a liquid helium bath *outside* the winding.

The cryostat heat load is dominated by structural, and its total will be $< 500\text{ W}$. Clearly, the 100 T must have a close-loop helium system. Note that a compressor power requirement of $< 500\text{ kW}$ ($< 500\text{ W@4.2 K}$) is still significantly less than the 40 MW required by the superconducting magnets of LHC or the 30-MW electric power of the 45-T hybrid magnet.

As given in Table III, the GdBCO tape alone will weigh ~ 200 tons. The weight of 39 overbands is ~ 2000 tons, making the cold mass ~ 2000 tons. The magnet support structure adds an estimated ~ 2000 tons to the system. Note that if the 2000-ton cold mass absorbs 122 GJ, it will be heated to $\sim 250\text{ K}$.

To achieve the ultimate goal, a step-by-step forward progression is the absolute must. Starting with a 40-T DC magnet (40 T), of which the field strength is $\sim 20\%$ greater than that of the 32 T at NHMFL,² we must validate, e.g., in a field increment of 10 T, our design approach and assumptions. For each magnet, 40 T–90 T, we propose to: (1) design the nested coils at stress levels close to those in the 100 T, i.e., 700 MPa; (2) test and further develop the overband reinforcement and NI techniques; (3) generate critical current data of GdBCO tape up to the highest field levels.

Our 1st-cut design of the 3-coil 40 T contains a total of 38 DPs, and requires a total GdBCO $12\text{ mm} \times 0.095\text{ mm}$ tape length of 7 km, operating at 600 A. The parameters of the 40 T, 50 T, and even 60 T suggest that these first three all-GdBCO magnets are within realistic budgets; they may be realizable by the end of this decade.

By focusing on mechanical integrity, one of the most challenging design issues in high-field magnets, and incorporating the 2nd generation GdBCO HTS tape, we have demonstrated that a 100-T magnet can withstand mechanical stresses, as has already been demonstrated by steel-based pulse magnets. Here, by having superconductor carry a current and thereby keeping the steel overbands from overheating, we

believe that a continuous (DC) 100-T field is a real possibility. Importantly, the latest advancements in HTS magnet technology, adopted in the 100 T, permit it operate at a current density 10 times greater than those of conventional HTS magnets. Furthermore, a refrigeration power of $< 500\text{ kW}$ to operate the 4.2-K 100 T is minuscule compared with *megawatts* for $< 35\text{-T}$ nonsuperconducting counterparts.

We believe that the 100 T, perhaps the ultimate hallmark of the enabling technology of superconductivity, will certainly spur the researchers' creativity, inspiring them to envision studies that would have remained dreams or been unimaginable, if it were not for this 100 T. Unquestionably, the 100 T will have a sweeping impact on superconductivity and most decisively challenge superconducting magnet technology to its utmost limit.

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