Field Profiles of Target Magnets with B(z>5m) = 1.5 T, 2 T, 2.5 T & 3 T

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Each of the magnets described below consists of a main coil, notched on its inner surface to improve field homogeneity, plus downstream coils that achieve a field profile that ramps downward to 1.5, 2.0, 2.5 or 3.0 T at z = 5 m. The Excel spreadsheet used to design the system embodies the following goals and constraints:

1) Main-solenoid I.R. = 120 cm; current density = 18 A/mm², as typical for SC#1 (~60% steel);
2) Current density in solenoids #2 to #7 = 45 A/mm² (~10% steel); I.R. = 60 cm for coils #5-#7;
3) B(z), is 15 T at z = -0.5 m, B_min at 5 m, and 14.7 T (ΔB = 0.3 T = 2% of 15 T) at 0 & -1 m;
4) Field derivative B' ≡ dB/dz = 0 at z = -0.5 m & z = 5 m; B' < 0 from z = -0.5 m to 5 m;
5) Goal function strongly penalizes ampere-meters of conductor usage, to reduce magnet cost;
6) Penalized gently is I.R. < 120 cm for solenoid #2 and O.R. > 100 cm for solenoids #3 & #4;
7) Penalized for z > 5 m is a weighted sum of the squares of ΔB ≡ B - B_min, B', & B'' = d²B/dz²;
8) Figs. 4 & 5 prolong the taper by constraining B' < 0.5 (5 - z/100) from z = -0.5 m to 5 m;
9) Fig. 8 achieves a full-length taper by moving Coil #2 from Cryostat #2 into Cryostat #1.

Fig. 1a&b. Target Magnet 15to1.5T5m1+3+3. Left: Conductor cross sections and field direction (arrows) & magnitude (color & contours). Inner radius of successive coils is [1.20, 1.10, 1.03, 0.83, 0.60] m. Gap between coils #1 & #2 is 2.8 m; between triplets #1 & #2 is 0.56 m = 1/3 of sum of outer radii of flanking coils. Peak ambient field is 16.0 T. Right: Field profile, |B(z)| (blue); 10 log₁₀(|B|) (black); 1st derivative, dB/dz (turquoise); and 2nd derivative d²B/dz² (green). B(−50 cm) = 15 T; B(500 cm) = 1.5 T. B(−100 cm) = B(0) = 14.7 T.
Fig. 2a & b. On-axis field profile, $|B(z)|$ (blue); $\log_{10}(B)$ (black); $dB/dz$ (turquoise); & $d^2B/dz^2$ (green) of target magnets with $B(\pm 100 \text{ cm}) = B(0) = 14.7 \text{ T}$ and $B = B_{\text{min}}$ at $z = 500 \text{ cm}$. Left: $B_{\text{min}} = 1.5 \text{ T}$. Right: $B_{\text{min}} = 2.5 \text{ T}$.

Fig. 3 compares the field profiles of the target magnets in Figs. 1 & 2 and also one with $B_{\text{min}} = 3.0 \text{ T}$. Only for $B_{\text{min}} = 1.5 \text{ T}$ does the field profile extend nearly to $z = 5 \text{ m}$; the other field profiles reach their asymptotic values prematurely, at $\sim 4.2 \text{ m}$, $\sim 3.8 \text{ m}$ and $3.5 \text{ m}$, respectively.

Fig. 3: On-axis field profiles of target magnets as in Figs. 1 & 2, with $B_{\text{min}} = 1.5$ to $3 \text{ T}$. Upper set of curves is $B(z)$; lower set is $\Delta B/B_{\text{min}}$.

One can prolong the taper by requiring that each field profile rapidly acquire a significant downward slope upstream of $5 \text{ m}$. Figure 4 introduces the constraint $-dB/dz \geq \frac{1}{2}(5-z) \text{ T/m}$ throughout the range $2.5 < z < 5 \text{ m}$.

To achieve a full-length taper requires transforming the upstream coil of Cryostat # 2 into the downstream coil of Cryostat #1. The gap between cryostats shrinks from $\sim 2.8 \text{ m}$ to 1.04-1.10 m, which is one-third the sum of the maximum coil outer radius in each cryostat.
Fig. 4: On-axis field profiles that prolong the taper by requiring \(-\frac{dB}{dz} \geq \frac{1}{2}(5-z)\) T/m for \(2.5 < z < 5\) m. Upper set of curves is \(B(z)\); lower set is \(\Delta B/B_{\text{min}}\).

Fig. 5: On-axis field profiles of full-taper Target Magnets with \(-\frac{dB}{dz} \geq \frac{1}{2}(5-z)\) T/m and \(\frac{d^2B}{dz^2} \geq 0\) for \(2 < z < 5\) m, and two coils in each of Cryostats #1 and #2. Upper set of curves is \(B(z)\); lower set is \(\Delta B/B_{\text{min}}\).
Fig. 6a&b. Conductor cross sections and field direction (arrows) & magnitude (color & contours). Left: Target Magnet 15to2T5m1+3+3 (Fig. 4, blue curve); I.R. of successive coils is [1.20, 1.02, 1.14, 0.84, 0.60] m; gap between coils #1 & #2 is 2.25 m. Right: Target Magnet 15to2T5m2+2+3 (Fig. 5, blue); I.R. of coils is [1.20, 1.10, 1.02, 0.81, 0.60] m; gap between coils #2 & #3 is 1.04 m = 1/3 of sum of max. coil outer radii in flanking cryostats.
Fig. 7. Field profile of Target Magnet 15to2T5m1+3+3 and curve-fit, over length $-100 \text{ cm} < z < 500 \text{ cm}$, by two current-sheet solenoids. Upstream current sheet: [multiplicative factor = 9.105; radius = 149.8 cm; upstream end = $-265.1 \text{ cm}$; downstream end = 158.2 cm]; downstream current sheet: [$I = 1.112; 255.8 \text{ cm}; 355.9 \text{ cm}; 800.6 \text{ cm}$].