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, which may be 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/mm^2, as typical for SC#1 (~60% steel);
2) Current density in solenoids #2 to #7 = 45 A/mm^2 (~10% steel); I.R. = 60 cm for coils #5-#7;
2) 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;
3) Field derivative B' ≡ dB/dz = 0 at z = −0.5 m & z = 5 m; B' < 0 from z = −0.5 m to 5 m;
4) Goal function strongly penalizes ampere-meters of conductor usage, to reduce magnet cost;
5) Penalized gently is I.R. < 120 cm for solenoid #2 and O.R. > 100 cm for solenoids #3 & #4;
6) Penalized for z > 5 m is a weighted sum of the squares of $\Delta B \equiv B - B_{min}$, B', & B'' ≡ d^{2}B/dz^2;
7) Figs. 4 & 5 prolong the taper by constraining B' < 0.5 (5 − z/100) from z = −0.5 m to 5 m;
8) Fig. 5 achieves a full-length taper by moving Coil #2 from Cryostat # 2 into Cryostat #1.

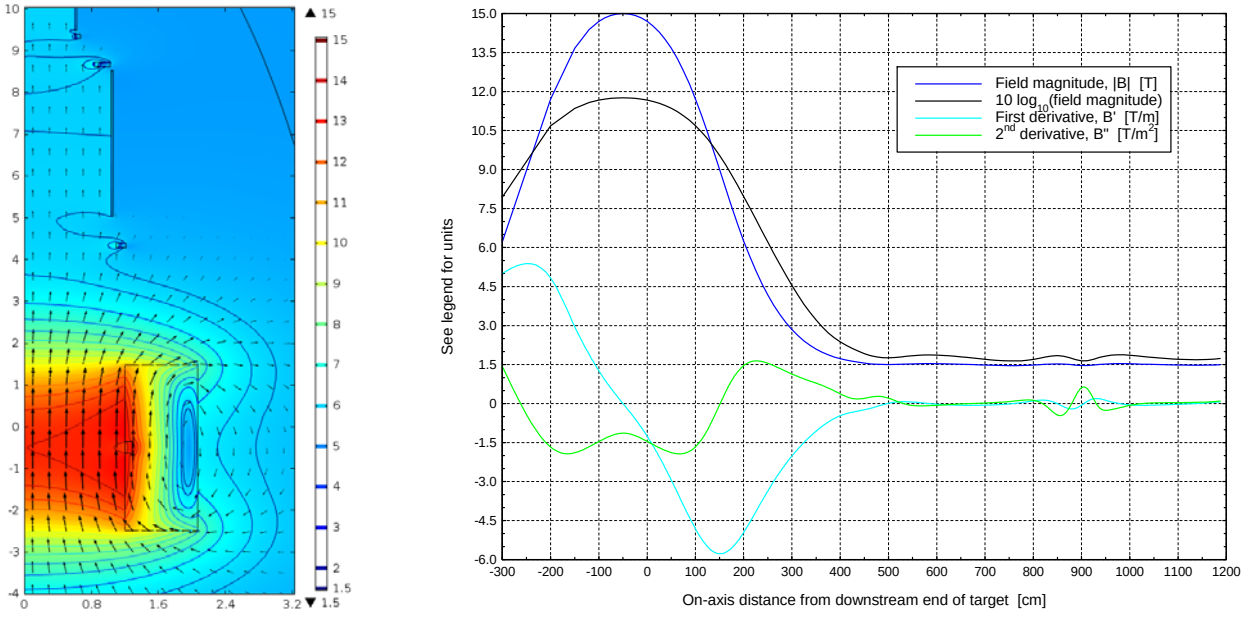

Fig. 1a&b. Target Magnet 15to1.5T5m1+3+3. Left: Conductor cross sections and field direction (arrows) & magnitude (color & contours). Inner radius of successive coils is [1.20, 1.10, 1.03, 0.83, 0.60] m. Gap between coils #1 & #2 is 2.8 m; between triplets #1 & #2 is 0.56 m = 1/3 of sum of outer radii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

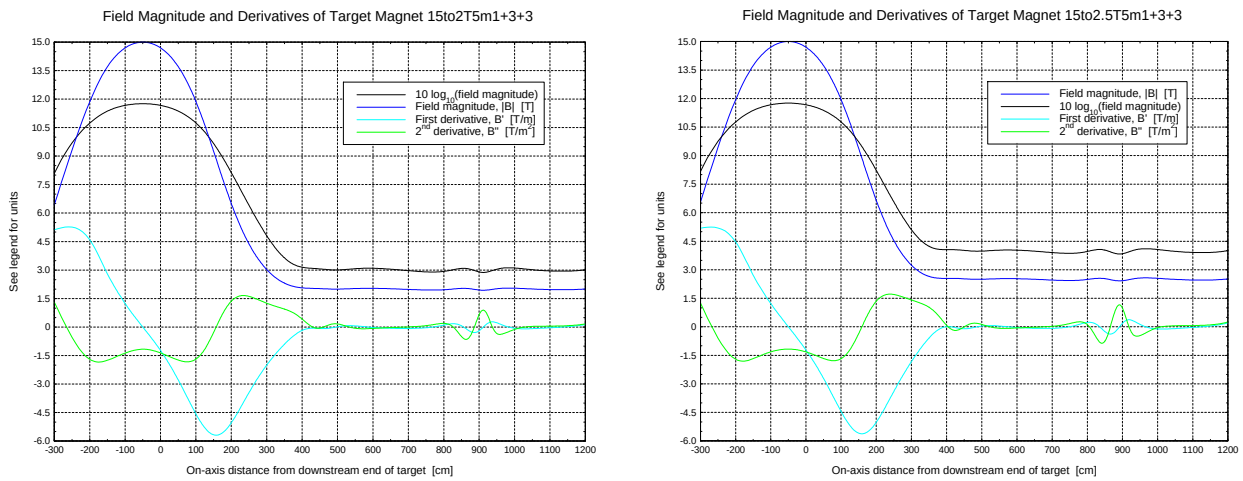

Fig. 2a&b. On-axis field profile, $|B(z)|$ (blue);$10\ \log_{10}(|B|)$ (black); dB/dz (turquoise); & d^2B/dz^2 (green) of target magnets with $B(-100\text{ cm}) = B(0) = 14.7$ T and $B = B_{min}$ at $z = 500$ cm. Left: $B_{min} = 2$ T. Right: $B_{min} = 2.5$ T.

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

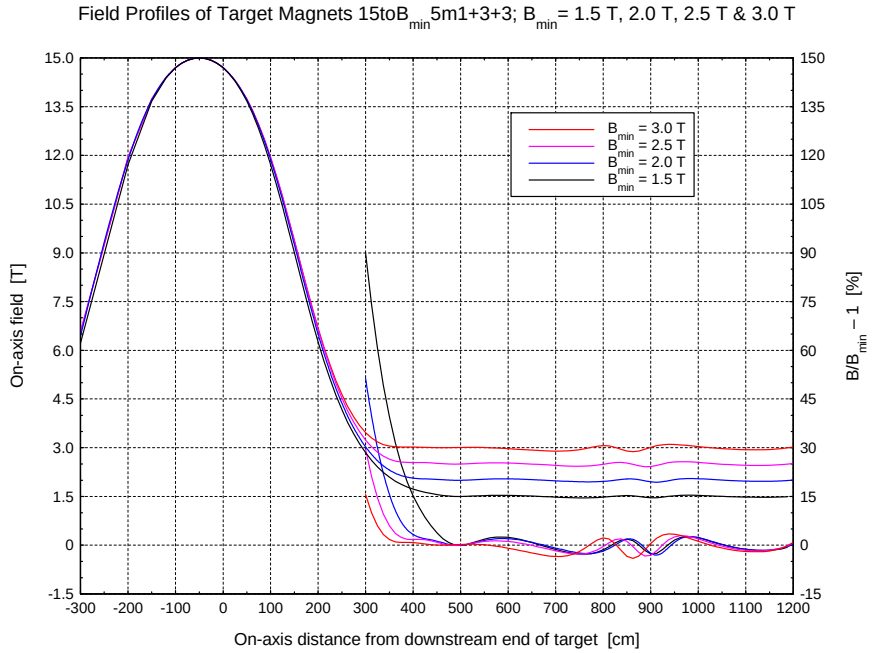

Fig. 3: On-axis field profiles of target magnets as in Figs. 1 & 2, with B_{min} = 1.5 to 3 T. Upper set of curves is B(z); lower set is $\Delta B/B_{min}$.

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

To achieve the full-length taper of Fig. 5 requires transforming the upstream coil of Cryostat # 2 into the downstream coil of Cryostat #1. The gap between cryostats shrinks from ~2.8 m to 1.04-1.10 m, which is one-third the sum of the maximum coil outer radius in each cryostat.

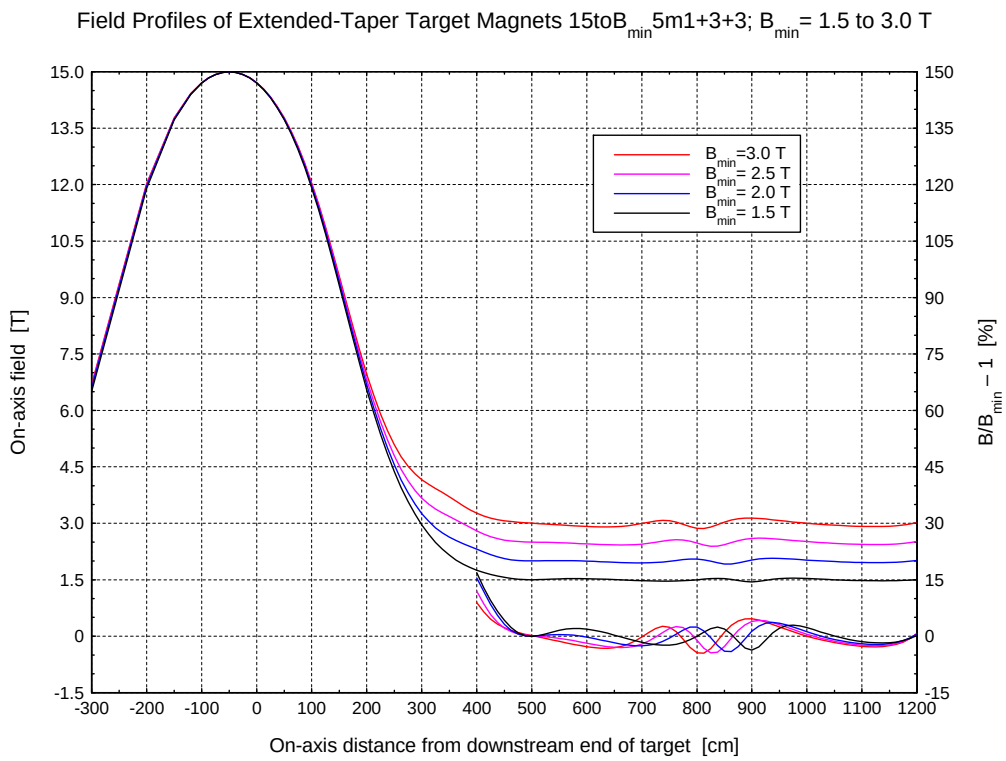

Fig. 4: On-axis field profiles that prolong the taper by requiring $-dB/dz \geq \frac{1}{2}(5-z)$ T/m for $2.5 < z < 5$ m. Upper set of curves is B(z); lower set is $\Delta B/B_{min}$.

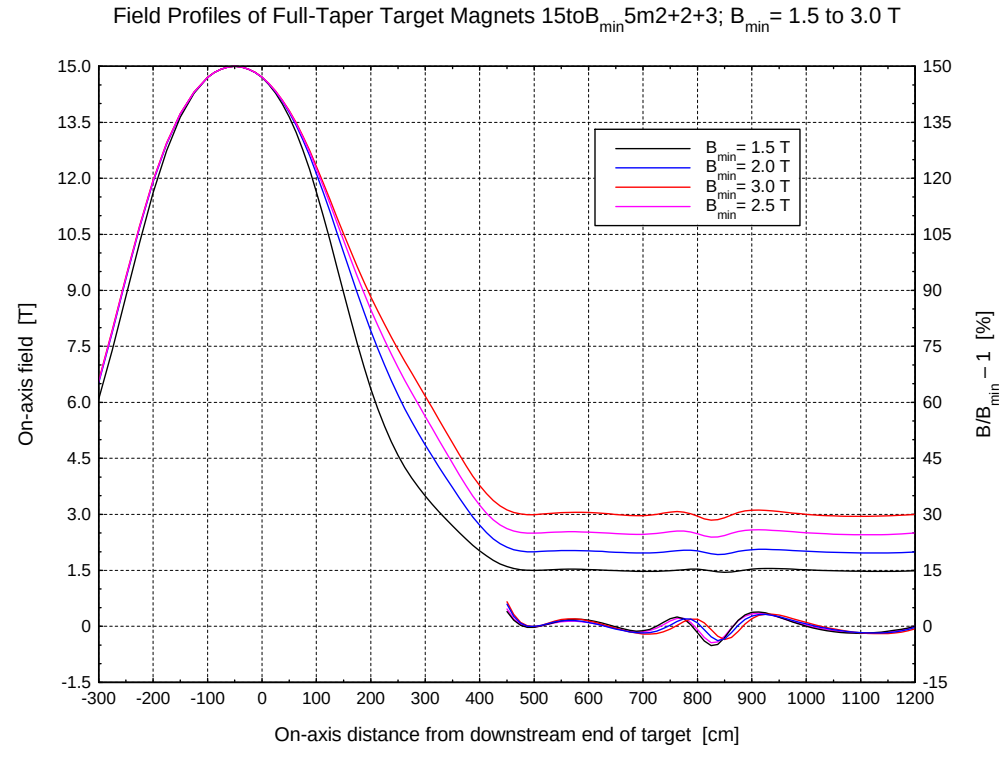

Fig. 5: On-axis field profiles of full-taper Target Magnets with $-dB/dz \geq \frac{1}{2}(5-z)$ T/m and $d^2B/dz^2 \geq 0$ for $2 < z < 5$ m, and two coils in each of Cryostats #1 and #2. Upper set of curves is B(z); lower set is $\Delta B/B_{min}$.

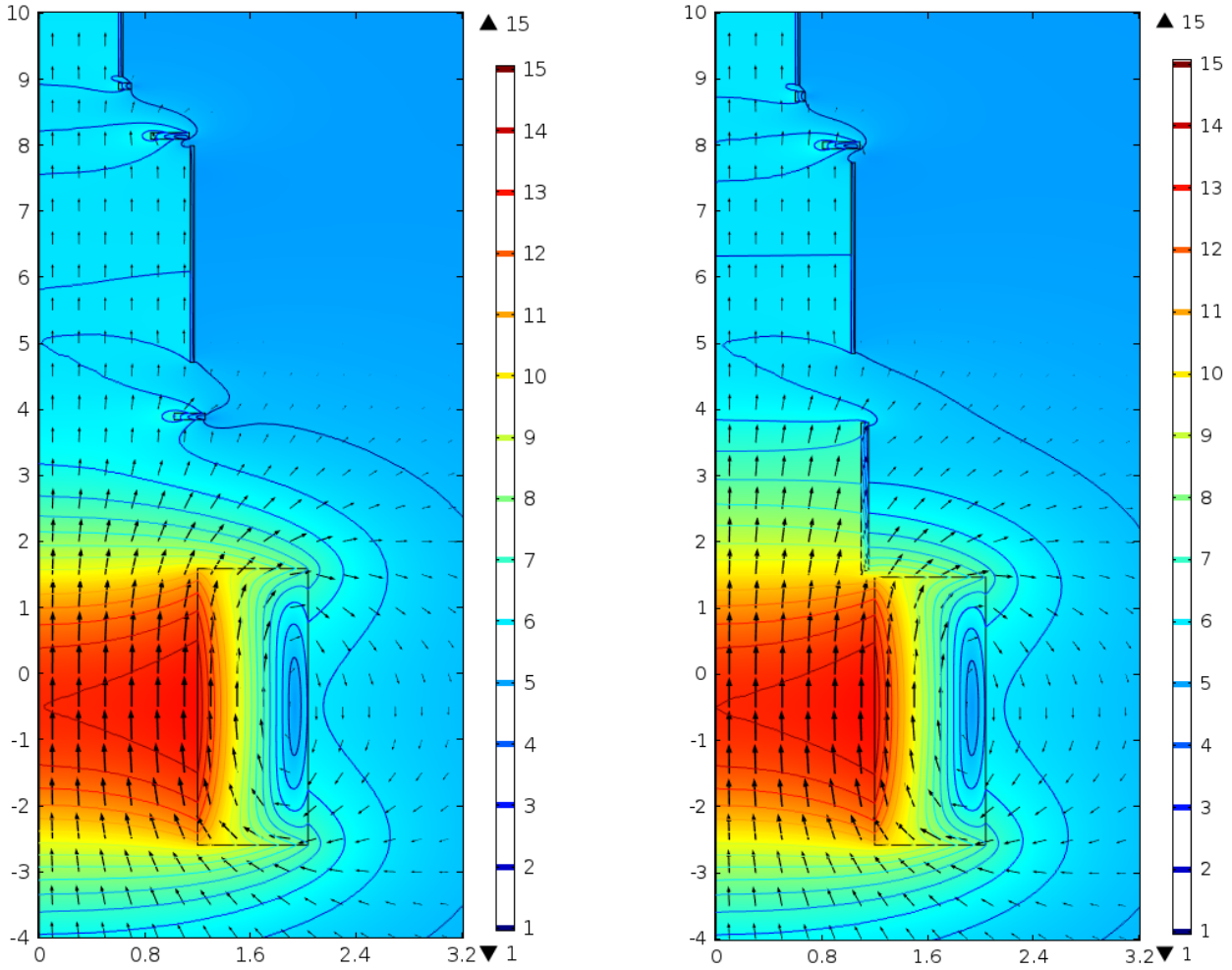

Fig. 6a&b. Conductor cross sections and field direction (arrows) & magnitude (color & contours). Left: Target Magnet 15to2T5m1+3+3 (Fig. 4, blue curve); I.R. of successive coils is [1.20, 1.02, 1.14, 0.84, 0.60] m; gap between coils #1 & #2 is 2.25 m. Right: Target Magnet 15to2T5m2+2+3 (Fig. 5, blue); 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.

Figure 7 plots the on-axis field profile of a magnet similar to that in Fig. 6a but with just a single coil from z = 5.23 m to 20 m. Also plotted are three curve fits of progressively greater simplicity. The blue-curve magnet employs twelve fitting parameters: the radius, upstream end, downstream end, and current-per-unit-length of each of three current-sheet solenoids. Its field profile duplicates that of the fitted curve so accurately as to mask it.

The magenta-curve magnet employs only three parameters: the level of energization of a thick-walled solenoid flanking the target region, plus two current sheets downstream. The parameters of the thick-walled solenoid are: current density = 18.086 A/mm^2, I.R. = 120 cm; O.R. = 208 cm; upstream end = −235 cm; and downstream end = 134 cm. The current sheets each have a radius of 1 m; the upstream one carries 9,957 A/mm and extends from 3 m to 5 m; the downstream one carries 15,616 A/mm and extends from 5.2 m to 20 m. With only three parameters, B(z=−50cm) is not exactly zero.

The red-curve magnet consolidates its current sheets. Its solenoid carries 18.077 A/mm^2; its current sheet, 12,220 A/mm. With only two parameters, B'(5m) differs somewhat from zero. Also, B(5m) is slightly greater than 2 T, so that B(z) does not fall too far below 2 T for z > 5 m.

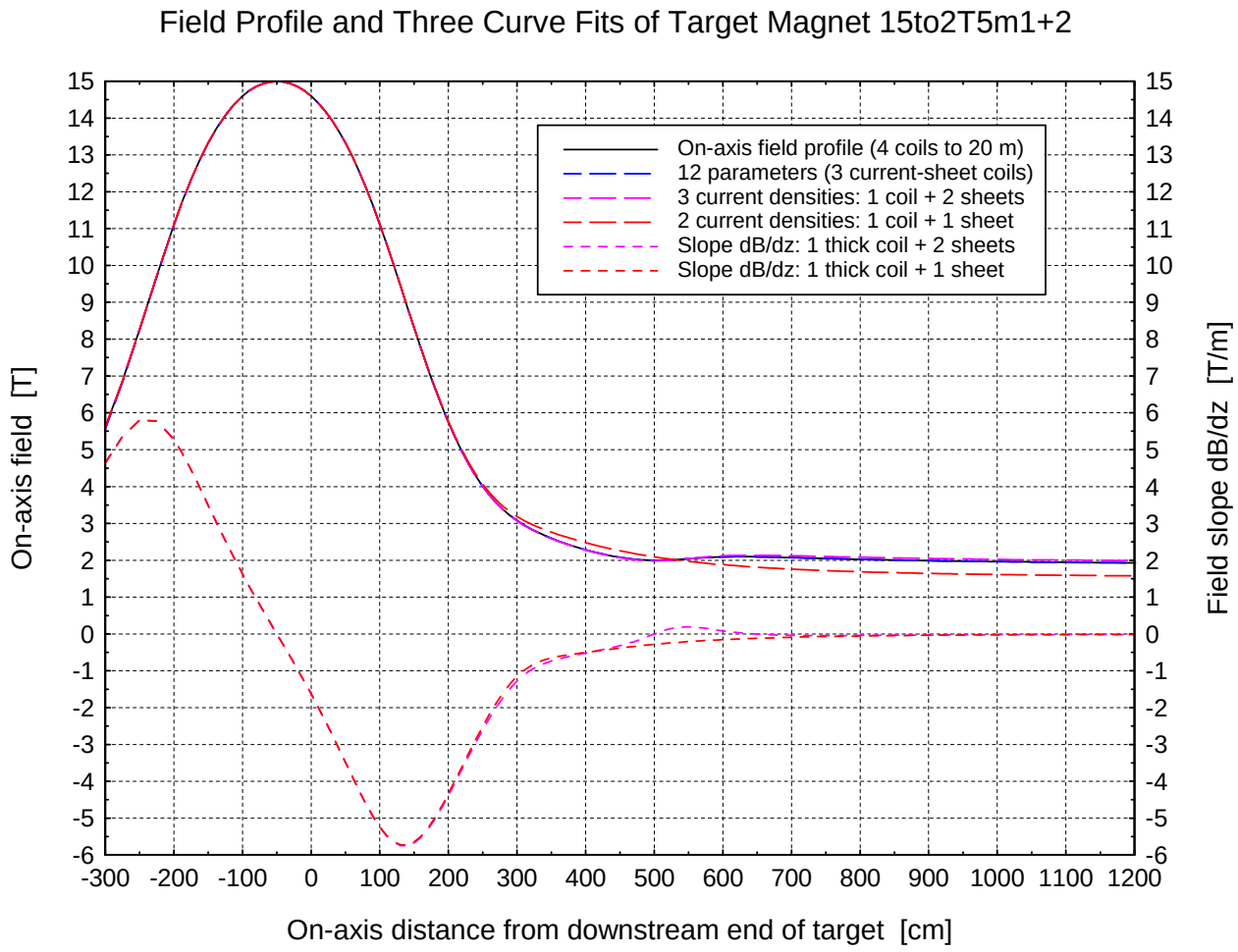

Fig. 7. On-axis field profile of Fig 6 Magnet and three curve-fits over length −3 m < z < 12 m. Blue: 12 parameters; magneta: 3 parameters; red: 2 parameters.