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The 6 layer Cu-stabilized solenoid magnet with the reduced barrel yoke for the FCC

CERN

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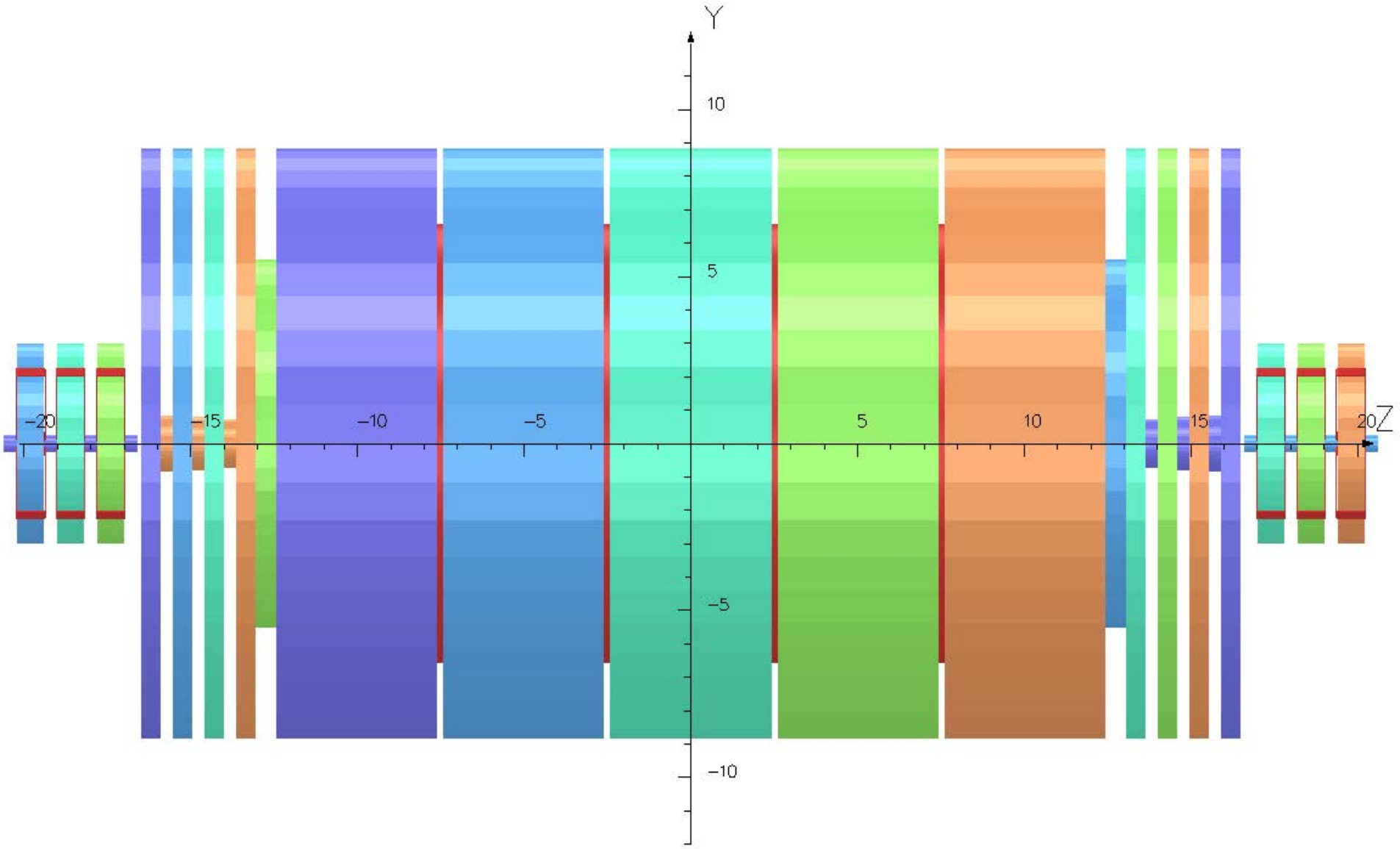
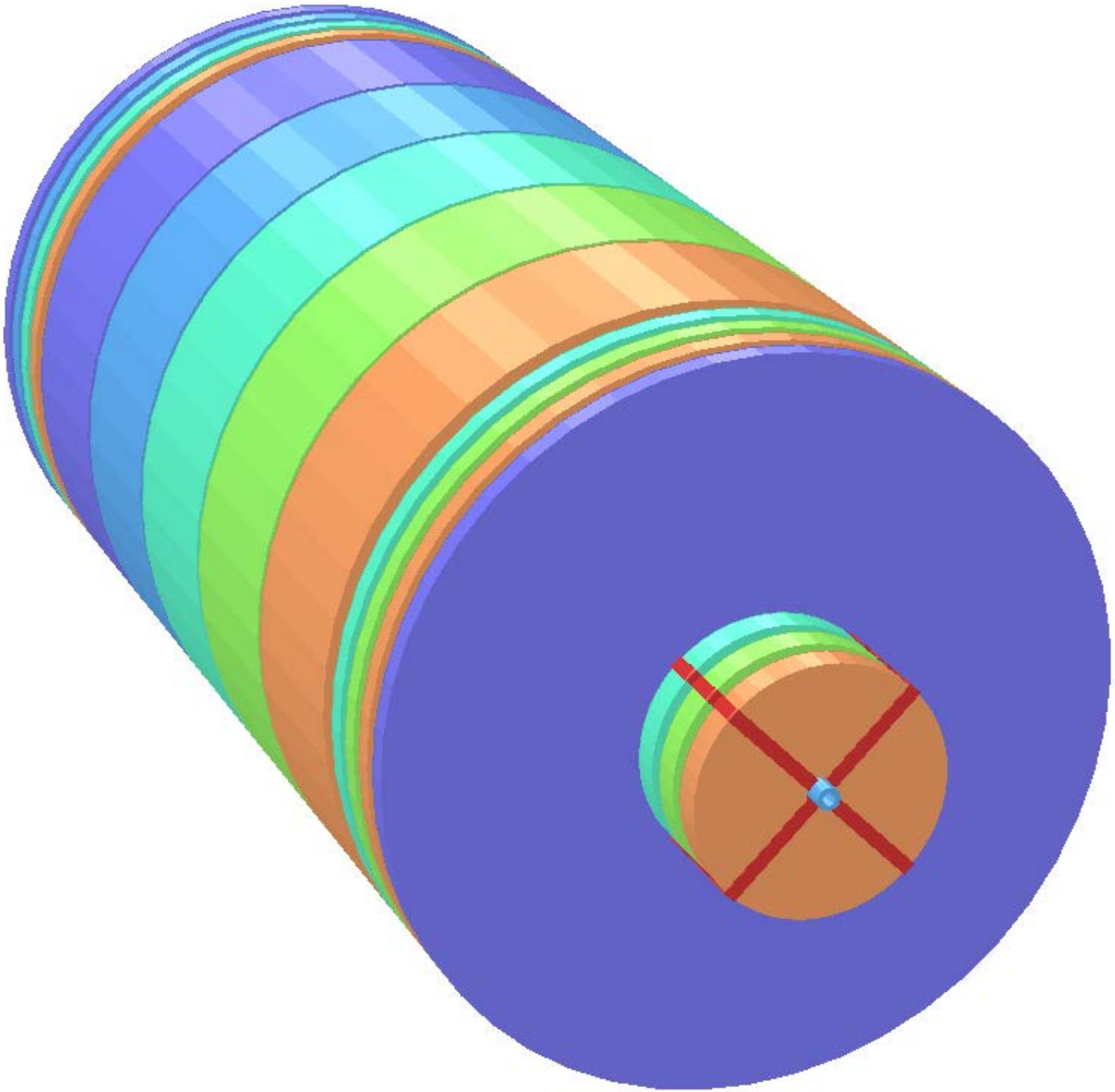


The coil in red, the five barrel wheels of 4.84 m width each, the two nose disks of 11 m diameter each, the eight end-cap disks of 17.7 m diameter each, the end-cap rings between the disks, and the six muon toroids of 6 (7) m diameter with the conventional coils in red and the protection tubes inside.

The Coil

- The coil is assumed to be made of the Cu-stabilized conductor of 68·22 mm^2 cross-section with the CMS-like NbTi insert of 20.63·2.34 mm^2.
- The insulation thickness around the conductor is 0.5 mm, the additional insulation between the layers is 0.4 mm, the additional insulation at the inner and outer radii is 1 mm, the insulation between the coil modules is 3 mm.
- Only the superconducting insert is included in the model in 6 layers.
- The radial thickness of the coil with insulation is 0.418 m.
- The thickness of the copper quench back cylinder could be 0.1 m.
- At room temperature the coil consists of 7 sections of 6.19 m inner radius and 3.5 m long: from Z=-12.259 to 12.259 m.
- The total Ampere-turns for the 6 T central field are 127254686.28 A-turns.
- The number of turns in one layer of one coil section could be 151. That means the total number of turns is equal to 151·6·7=6342, and the current is 127254686.28 A-turns/6342 turns = 20065.39 A that is reasonable.
- The mass of the coil is not less than 3418 t.
- The magnetic flux density in the coil center is 5.9930 T.
- The maximum magnetic flux density inside the coil is 6.1589 T.
- The stored energy is 43.14 GJ.
- The E/M ratio is less than 12.62 kJ/kg that is about the CMS value.
- The axial pressure in the coil middle plane is 68.47 MPa.
- The averaged radial pressure is 14.35±0.79 MPa.
- The hoop strain is 0.00153 that gives tangential stress of 178.65 MPa.



Model

- The yoke comprises:
  - Two nose disks of 0.7 m thick with the inner radius of 0.303 m and the outer radius of 5.5 m; the disks start at Z=±12.35 m;
  - Two end-cap disks of 0.6 m thick with the inner radius of 0.303 m and the outer radius of 8.85 m; the disks start at Z=±13.05 m;
  - Two rings of 0.35 m thick with the inner radius of 0.324 m and the outer radius of 0.746 m; the rings start at Z=±13.65 m;
  - Two end-cap disks of 0.6 m thick with the inner radius of 0.324 m and the outer radius of 8.85 m; the disks start at Z=±14 m;
  - Two rings of 0.35 m thick with the inner radius of 0.345 m and the outer diameter of 0.798 m; the rings start at Z=±14.6 m;
  - Two end-cap disks of 0.6 m thick with the inner diameter of 0.345 m and the outer radius of 8.85 m; the disks start at Z=±14.95 m;
  - Two rings of 0.35 m thick with the inner radius of 0.366 m and the outer radius of 0.85 m; the rings start at Z=±15.55 m;
  - Two end-cap disks of 0.6 m thick with the inner radius of 0.366 m and the outer radius of 8.85 m; the disks start at Z=±15.9 m;
- The inner bores of the end-caps follow the angle of 1.273° w.r.t. the coil axis that corresponds to $|\eta|=4.5$.
- The outer radii of the rings between disks follow the angle of 3.130° w.r.t. the coil axis that corresponds to $|\eta|=3.6$.

Model

- The first layer of the barrel wheel has the inner radius of 7.5 m, the outer radius of 8 m. The second layer of the barrel wheel has the inner radius of 8.35 m, and the outer radius of 8.85 m. The wheel width is 4.84 m, the gaps between the wheels are 0.175 m.
- The gaps between the barrel and end-caps are 0.6 m.
- The total mass of the yoke is 21208.19 (21594.08) t.
- The parts masses are as follows:

  - Nose disk of 11 m outer diameter: 522.21 t;
  - First end-cap disk of 17.7 m outer diameter: 1161.11 t;
  - First ring of 1.492 m outer diameter: 3.91 t;
  - Second end-cap disk of 17.7 m outer diameter: 1160.92 t;
  - Second ring of 1.596 m outer diameter: 4.48 t;
  - Third end-cap disk of 17.7 m outer diameter: 1160.71 t;
  - Third ring of 1.7 m outer diameter: 5.10 t;
  - Forth end-cap disk of 17.7 m outer diameter: 1160.49 t;
  - One end-cap: 5178.92 t;

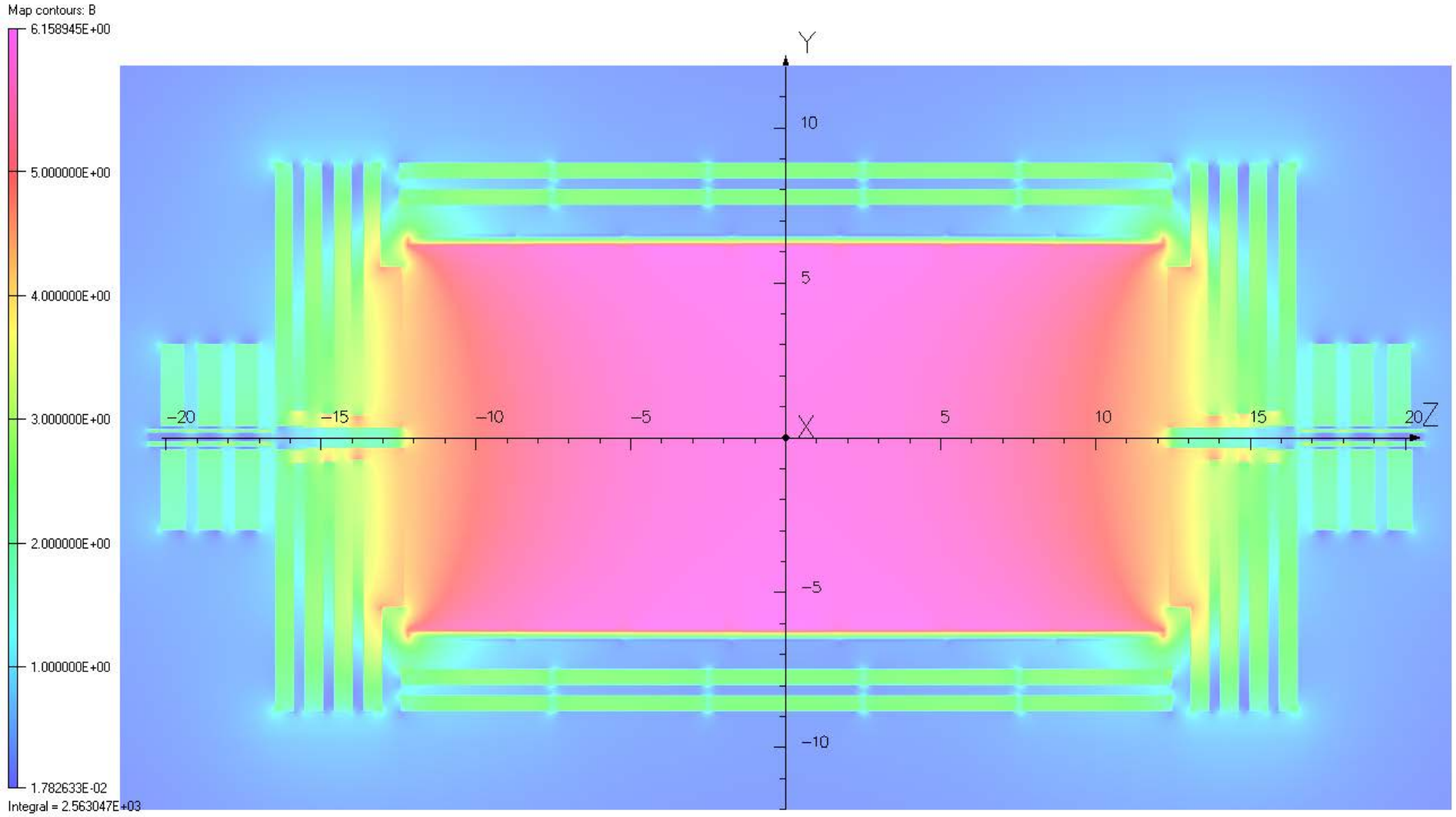
  - One barrel wheel of 17.7 m outer diameter: 1957.53 t;
  - All barrel wheels: 9787.65 t;

  - One toroid disk of 6 (7) m outer diameter: 175.45 (239.77) t;
  - Three toroid disks with the tube of 4 m length: 531.35 (724.30) t.

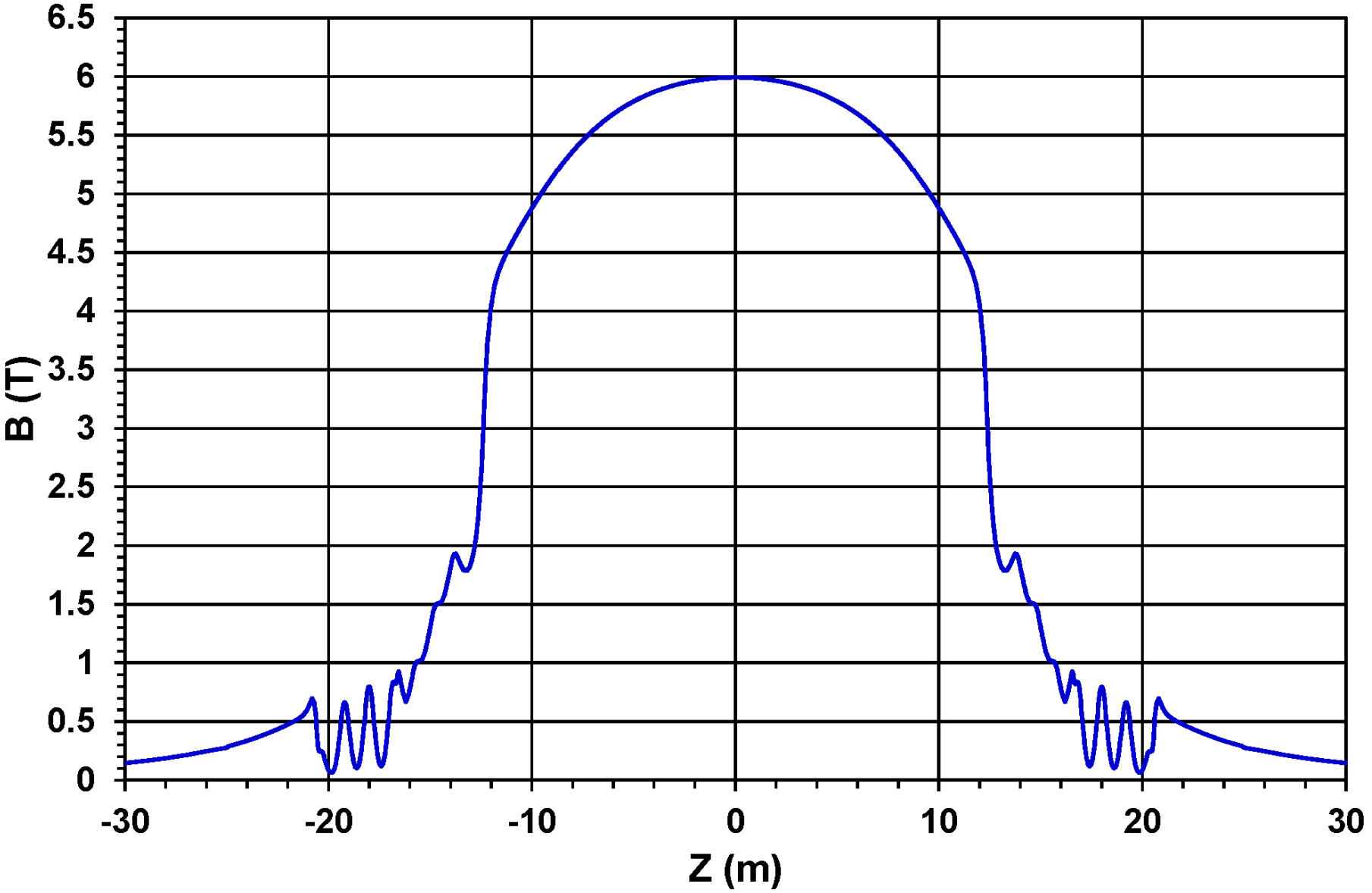
The forward muon spectrometer

At each yoke size it consists of 3 steel toroid disks of 0.8 m thick with the inner diameter of 0.732 m and the outer diameter of 6 (7) m.

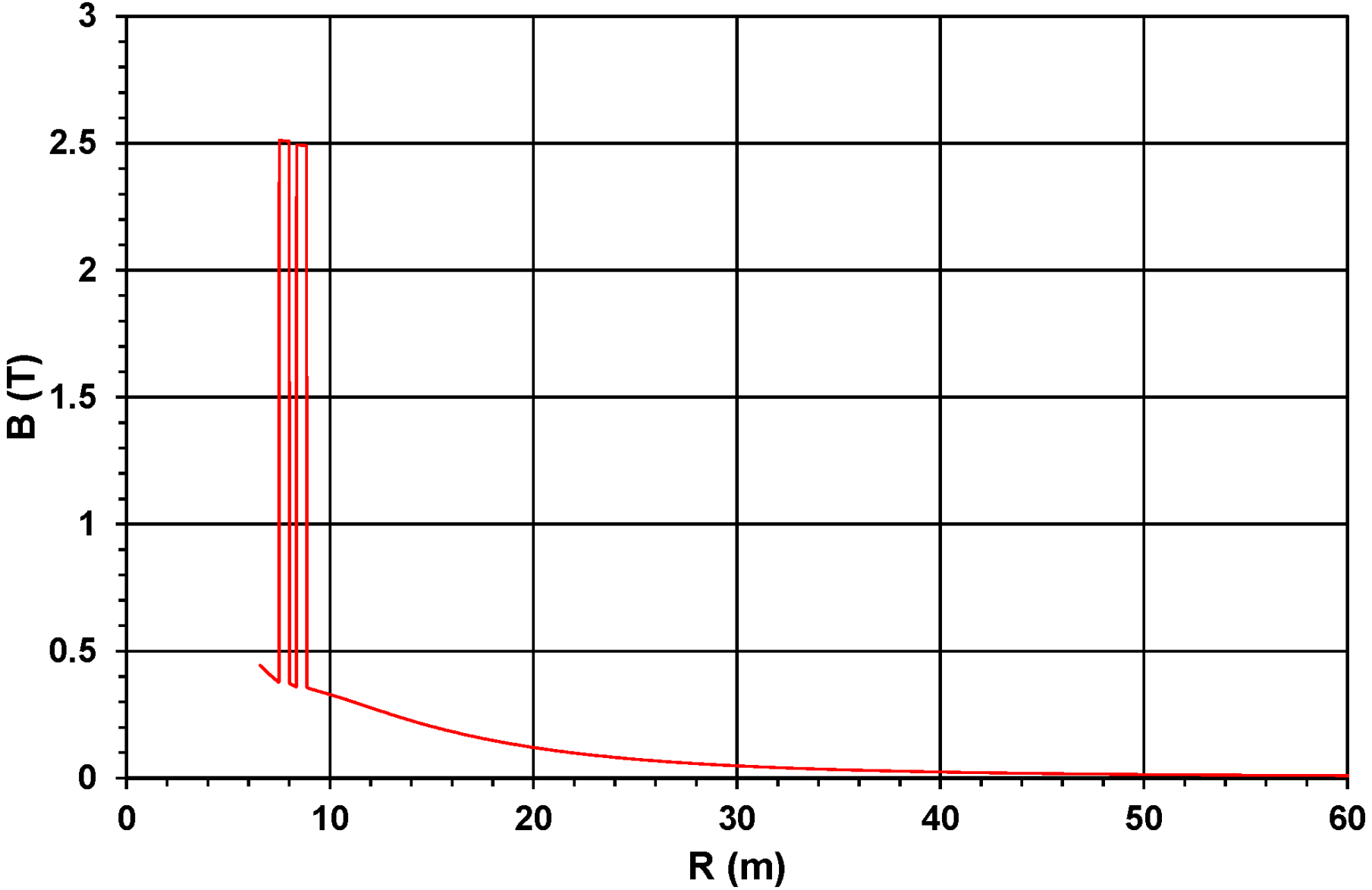
- **Each disk is magnetized by 4 conventional copper coils with the current of 907.6 A.**
- **Each coil consists of 34 turns of 17.5×17.5 mm² copper conductor wound in two layers.**
- **The hole of 10 mm diameter in the conductor cross-section serves for water-cooling of the coils.**
- **The tubes of steel with the inner diameter of 0.3 m and the outer diameter of 0.54 m keeps the toroids in the positions providing the gaps of 0.4 m between the disks.**
- **The total mass of the steel yoke is 21.21 (21.59) kt, the outer diameter is 17.7 m, and the length included both forward muon spectrometers is 41.2 m.**



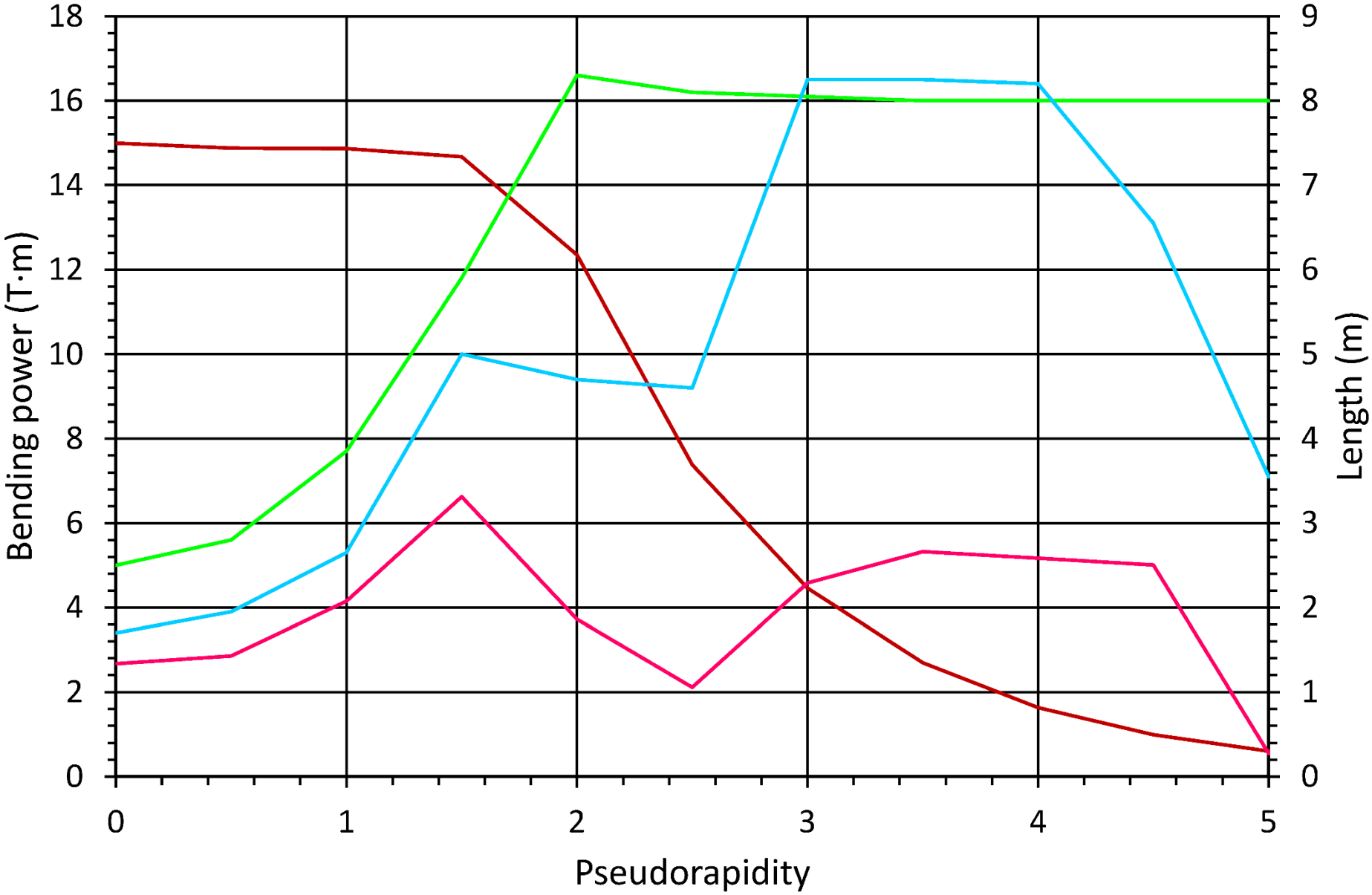
Magnetic flux density distribution in the vertical plane. The color magnetic field map plotted with the cell size of 0.05 m has the width of 43 m and the height of 24 m. The color scale unit is 1 T. The minimum and maximum magnetic flux density values are 0.0178 and 6.1589 T.



Magnetic flux density variation along the coil axis.



Magnetic flux density out of the coil in the coil middle plane vs. radius.



Magnetic flux density bending component integrals and the length of the charged particle trajectory in the inner tracker (dark red and green curves), and in the muon system (pink and the light blue curves, started from R=7.15 m or Z=12 m) vs. the pseudorapidity.

- **The axial forces onto the coil sections are as follows:**
  - **CB-3: +1023 475 490.2 N (toward center);**
  - **CB-2: +281 128 147.24 N (toward center);**
  - **CB-1: +95 661 782.81 N (toward center);**
  - **CB0neg: +36 864 471.077 N (toward center);**
  - **CB0pos: -36 863 858.78 N (toward center);**
  - **CB1: -95 659 793.6 N (toward center);**
  - **CB2: -281 116 932.9 N (toward center);**
  - **CB3: -1023 488 680 N (toward center).**
- **Thus the axial force onto the half of the coil is ±1437.13 MN (toward center).**
- **Assuming the thickness of the quench back cylinder to be 0.1 m, the area of the coil cross-section is equal to 20.99 m^2 and the pressure in the middle plane is equal to 68.47 Mpa (22.5 MPa in CMS).**
- **The axial force onto each end-cap is ±480.3 MN (toward center).**

- The integral B·dl from 7.15 to 8.85 m is 2.758 T·m that is, in principle, enough to measure the momentum of muons from 5 to 20 GeV to reduce the hadronic punch-through and the muons from decays in flight background in the muon identification and finding track in the tracker.

- The maximum magnetic flux density is 2.5119 T at R=7.51 m.
  The minimum magnetic flux density is 0.2773 T at R=12 m.

- The stray field in the middle plane at 50 m radius is 0.0141 T and 0.0054 T at 100 m radius.

Conclusions

- **The parameters of the solenoid coil and the steel yoke seem to be reasonable.**
- **The magnet provides the required free bore of 12 m diameter and the central magnetic flux density of 6 T.**
- **The magnetic flux density distribution allows measuring the charged particle momenta in the pseudorapidity interval of ±3.5, and the conventional forward toroids increase the region for the muon identification up to the pseudorapidity of ±4.6.**
- **To increase the region of the charged particle measurements to the large pseudorapidity values, the dipole magnet with the bending power of at least 5 T·m should be considered between the end-cap disks and the forward muon toroids, and opening the end-cap inner cone should be decreased at the least to the pseudorapidity value of ±3.**