A magnet for a muon collider detector

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MuCol

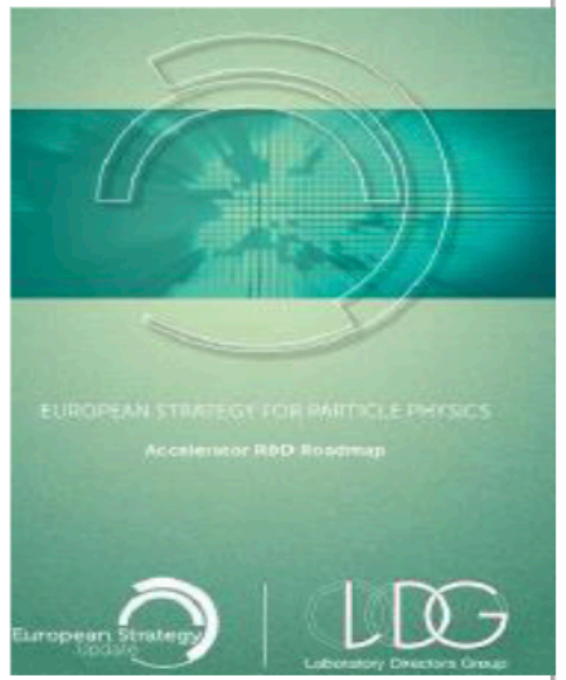
Workshop in October 2023

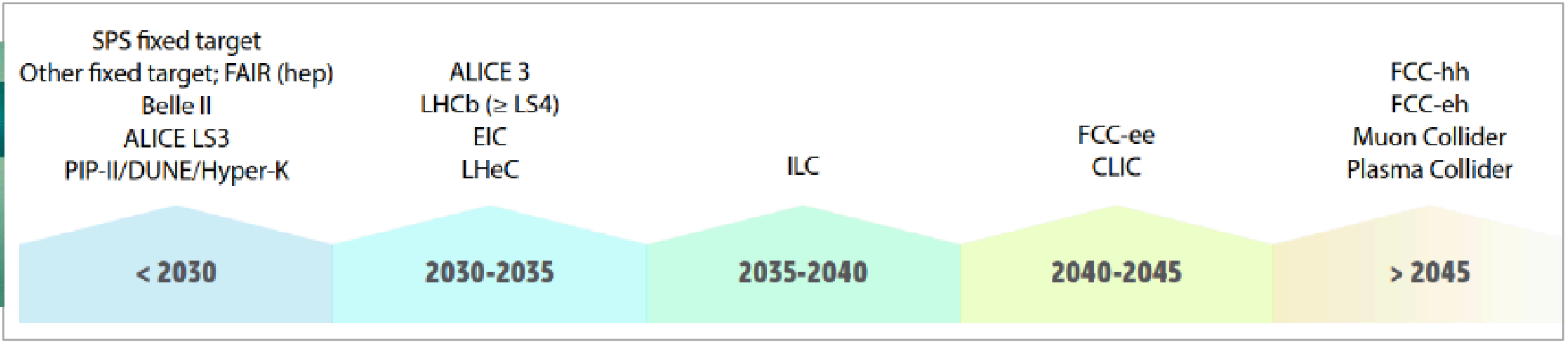
- Dedicated meeting has been held:
  - Detector requirements (M. Casarsa)
  - MDI requirements (D. Calzolari)
  - SC tech. for future colliders and detectors (A. Yamamoto)
  - Alu. stabilised SC cables R&D at CERN (B. Cure)
  - 3.6 T CLIC like detector (M. Mentink)
  - Detector magnet survey (AB)

- CLIC detector is considered a good starting point for the Muon Collider detector
- "Traditional" aluminium stabilised NbTi based Rutherford cable is the baseline
- Other possibilities should be taken into account
  - different SC materials
  - different cable protection
  - different geometries

Aluminium stabilised cables (B. Cure slides)

- All major detector magnets are based on this technology
- Presently this is disappearing from industry
- CERN has a R&D program to resume production and disseminate in industry
- Wuxy Toly Electric Works demonstrated some capability (Chinese company)
- Collaboration has been initiated among CERN and KEK
- This is considered crucial for the future detectors generations
- Both pure aluminium and NiAl co-extrusion are of interest
- Both NbTi and other SC materials are of interest





Future proposed particle physics experiments being studied: from LDG Accelerator R&D Report, CERN 2022-001

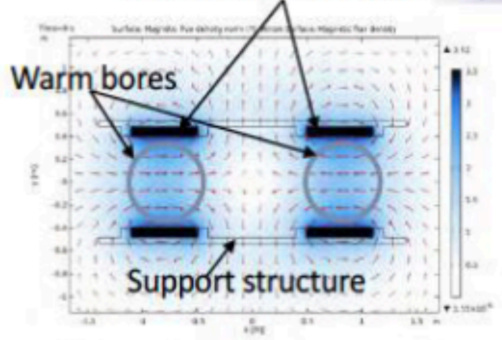
Near future programs (A. Yamamoto slides)

BabyIAXO

	Detector dipole
Warm bore diameter [m]	2x 0.7
Cold mass length [m]	11
Magnetic field in the centre [T]	2.0
Stored magnetic energy [MJ]	40

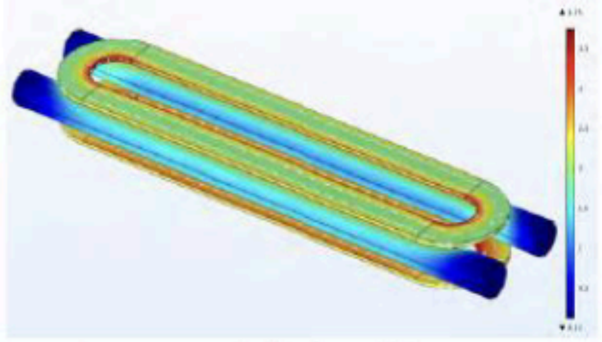
Magnet parameters

BabyIAXO detector

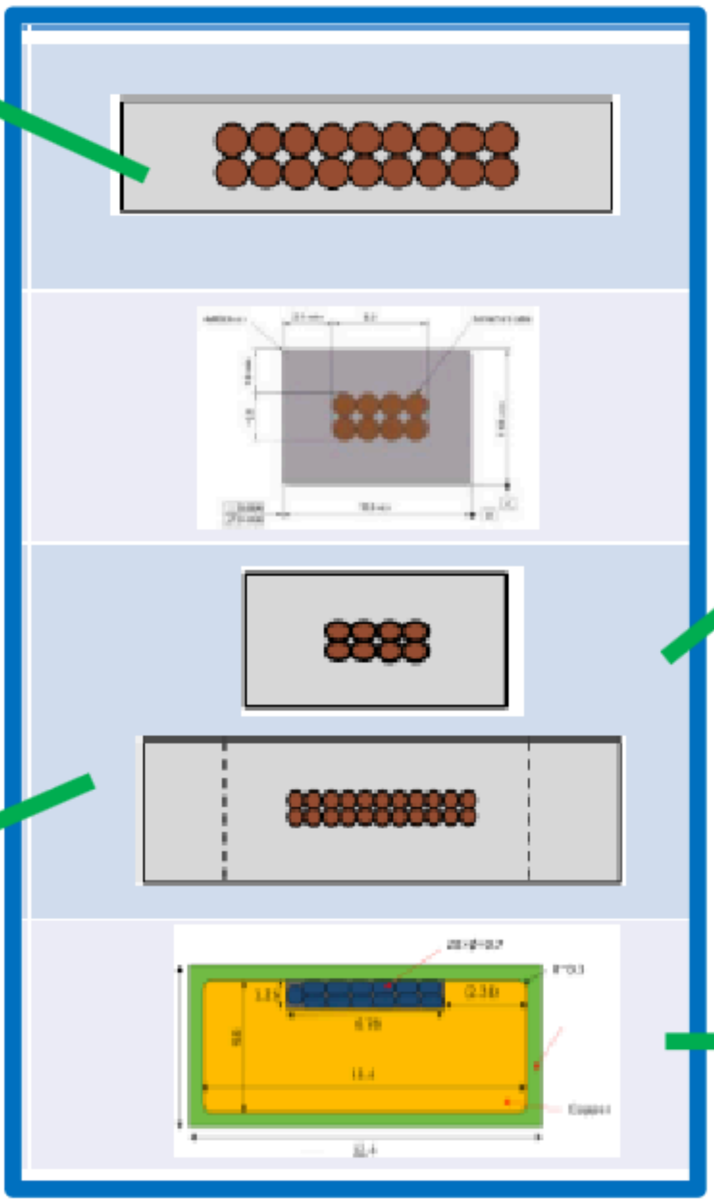


Magnetic field in cross-section

- Presentation by U. Schneekloth (DESY)
- BabyIAXO detector, for studying axions emanating from the sun
- Featuring a superconducting common-coil dipole with a 2 T transverse magnetic field in two 0.7 meter warm bores of 11 meters length
- Conductor: Featuring an aluminum-stabilized Nb-Ti/Cu conductor



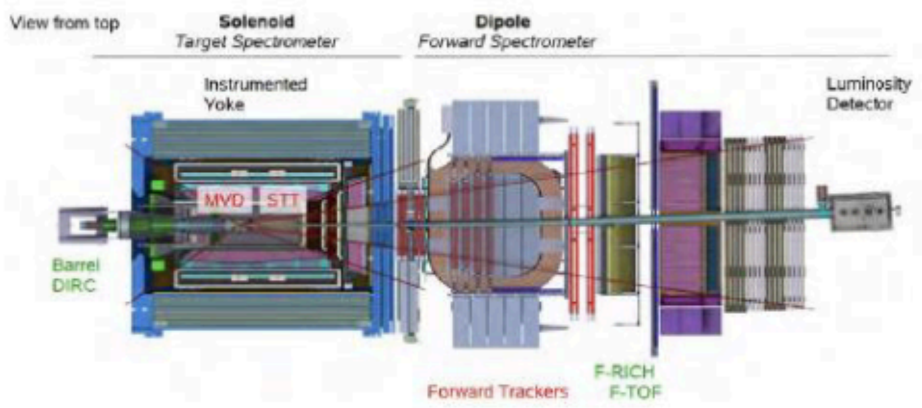
Common-coil dipole, with counter-flowing current in two superconducting race-track coils



The PANDA detector

	Target spectrometer solenoid
Warm bore diameter [m]	1.8
Cold mass length [m]	~3.1
Magnetic field in the centre [T]	2
Stored magnetic energy [MJ]	22

Magnet parameters



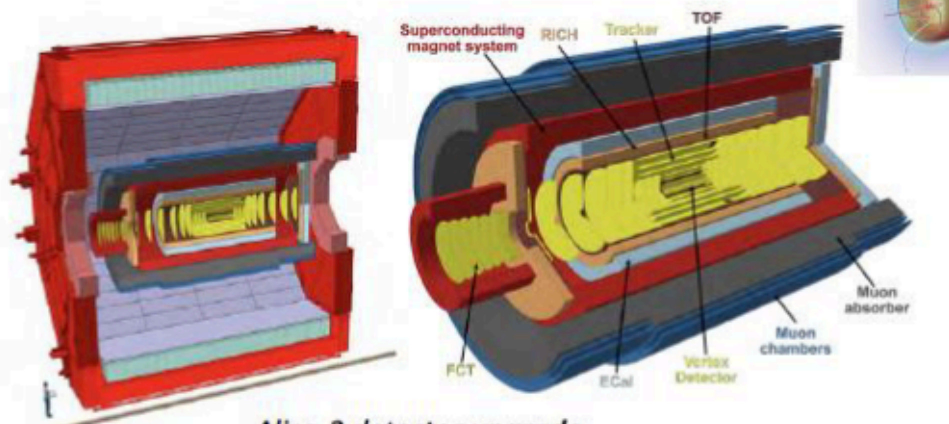
The PANDA detector layout

- Presentation by L. Schmitt (GSI)
- For fixed-target anti-matter physics at FAIR, foreseen to start operation by 2029
- With strong involvement of various Russian institutes, including the Budker Institute of Nuclear Physics
- Featuring a 2 T superconducting solenoid, with a stored magnetic energy of 22 MJ
- Conductor: Aluminum-stabilized Nb-Ti/Cu conductor technology, under development through a R&D effort by Russian institutes and industry (BINP, VNIINM Bochvar, VNIIKP, SARKO)

Alice-3

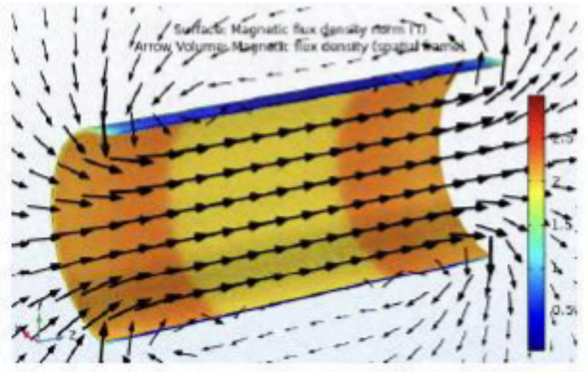
	Detector solenoid
Warm bore diameter [m]	3
Cold mass length [m]	7.5
Magnetic field in the centre [T]	2
Stored magnetic energy [MJ]	130

Magnet parameters



Alice-3 detector upgrade

- Presentation by W. Riegler (CERN)
- Planned to be installed by LS4 (which is currently foreseen to start in 2033)
- Featuring a superconducting solenoid, with 2 T in the center and additional windings at the end to augment bending power for high-pseudo-rapidity particles
- Also featuring a forward (superconducting) dipole
- Conductor: Proposal to use a reinforced aluminum-stabilized conductor



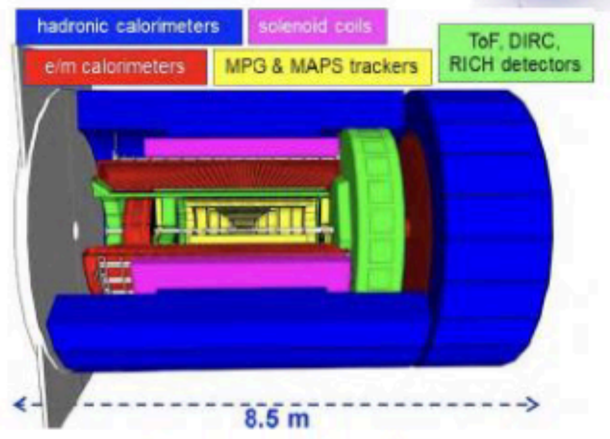
Magnetic field configuration

The Electron-Ion Collider

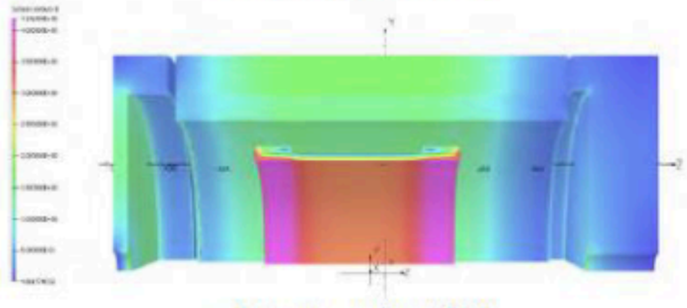
	Detector solenoid #1	Detector solenoid #2
Warm bore diameter [m]	2.8	3.2
Cold mass length [m]	3.5	3.6
Magnetic field in the centre [T]	2.0	3.0
Stored magnetic energy [MJ]	46	~150

Magnet parameters

- Presentation by R. Rajput-Ghoshal (Jefferson Lab)
- For the Electron-Ion Collider project to be hosted at BNL, with full project finalization foreseen by 2034
- Two superconducting detector solenoids, for two interaction points:
  - #1: 2 T in solenoid with a 2.8 meter warm bore diameter and a 3.5 meter cold mass length
  - #2: 3 T in solenoid with a 3.2 meter warm bore and a 3.6 meter cold mass length
- Conductor:
  - Solenoid #1, initial preference for reinforced aluminum-stabilized Nb-Ti/Cu, but copper-stabilized conductor can work as well
  - Solenoid #2, a reinforced aluminum-stabilized Nb-Ti/Cu conductor is foreseen



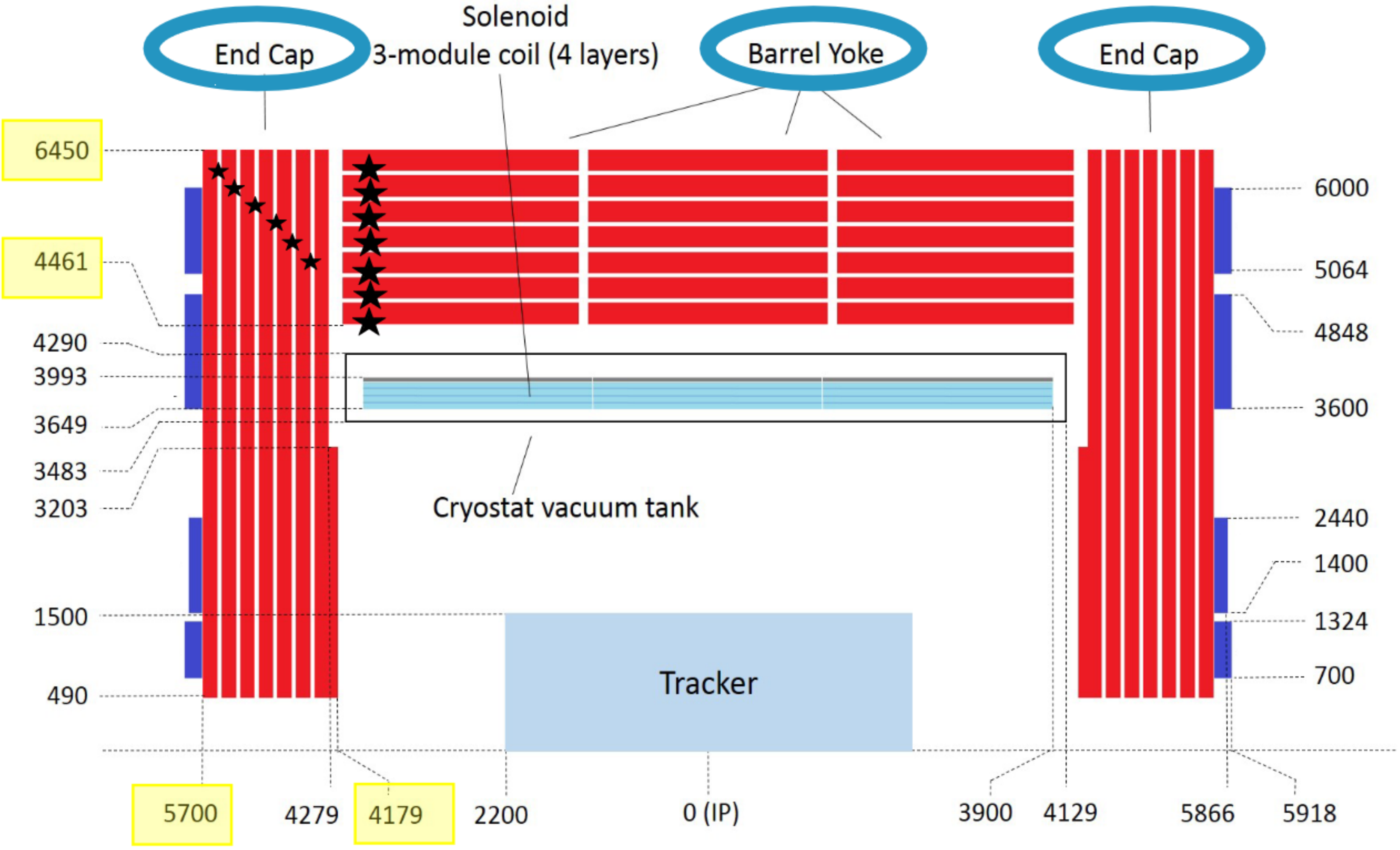
Detector solenoid #1



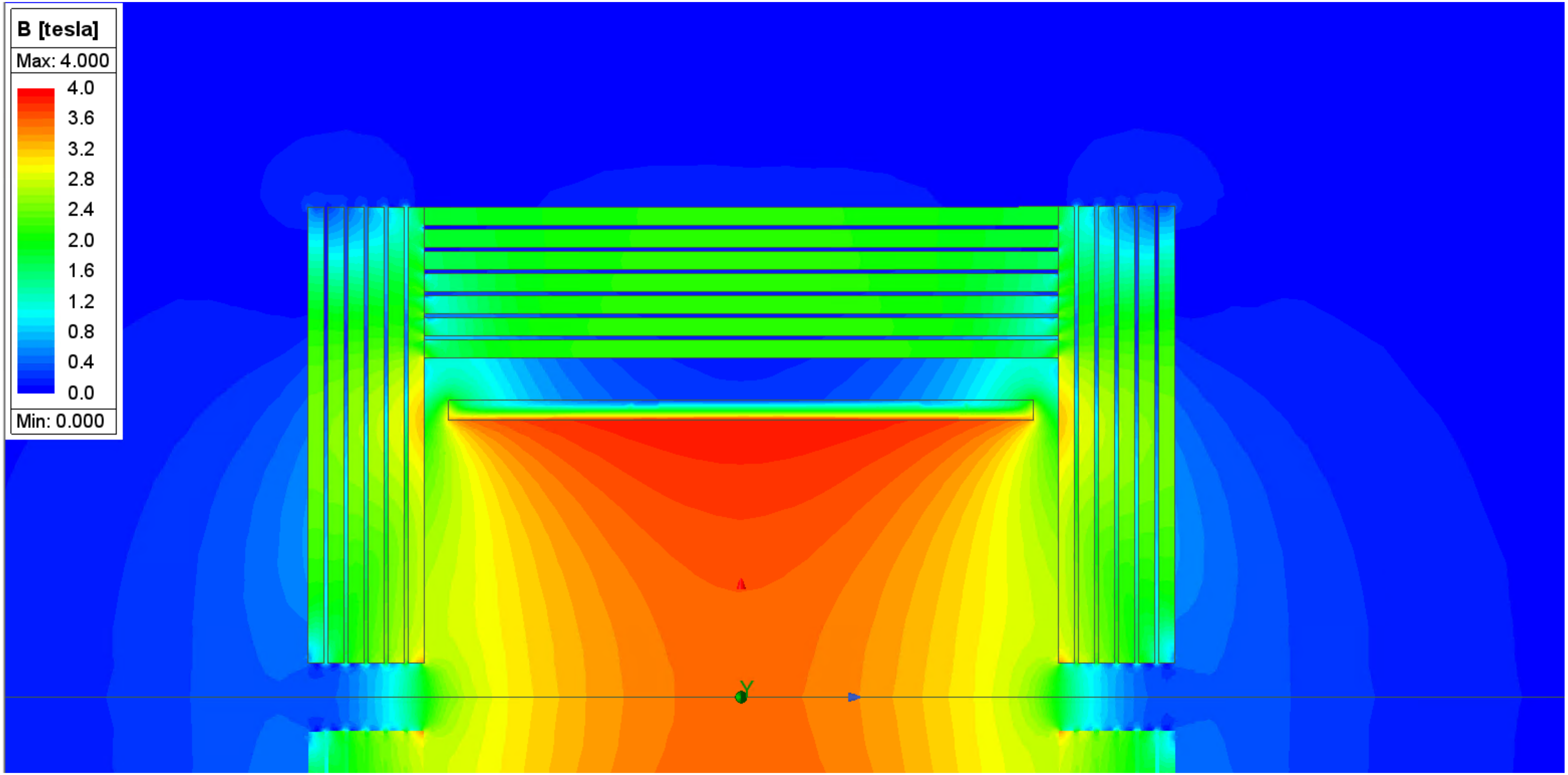
Detector solenoid #2

Tentative Design

- To start, I took parameters from CLIC-based design
- I assumed a ~ 50 mm gap for muon chambers between iron layers (magnet design not so sensitive to this, at this level)
- 6 layers in the end-caps, 7 layers in the barrel
- Total coil length 7.8 meters, diameter 7.3 meters
- Field at centre 3.75 T
- Very similar calculations in M. Mentink slides

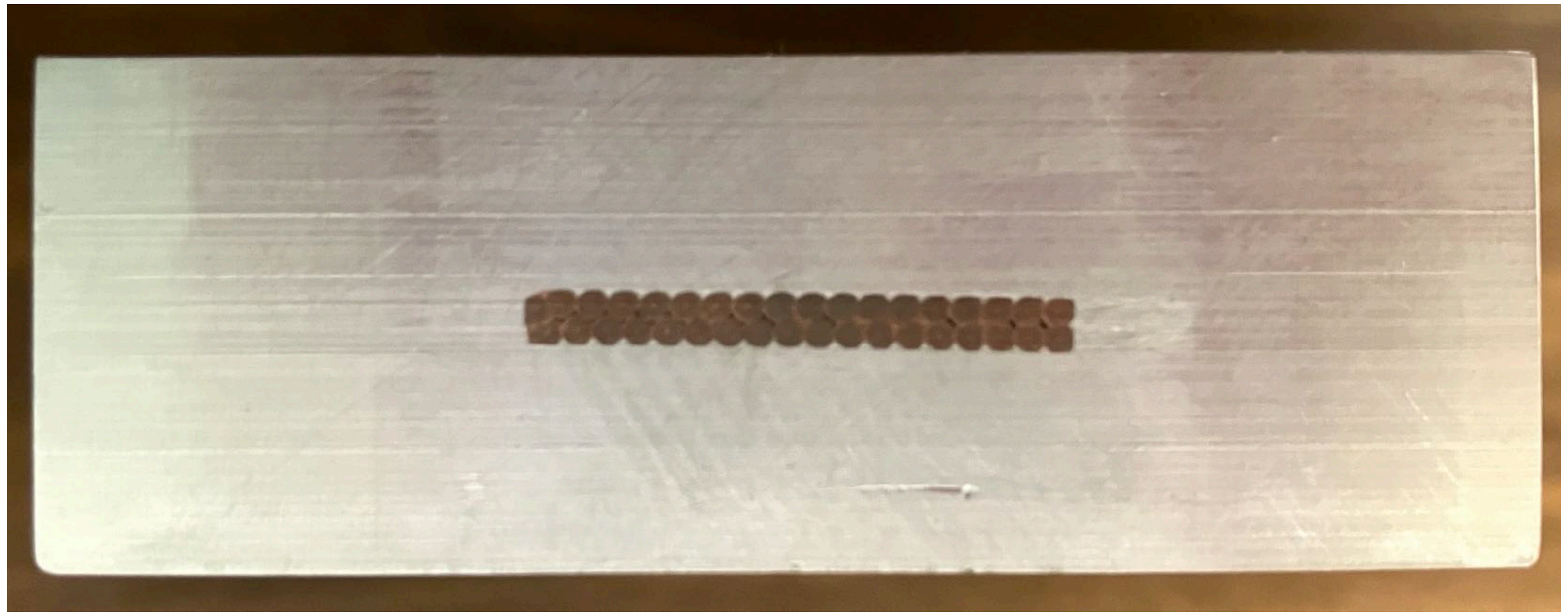


Picking inspiration from CMS



CMS-like

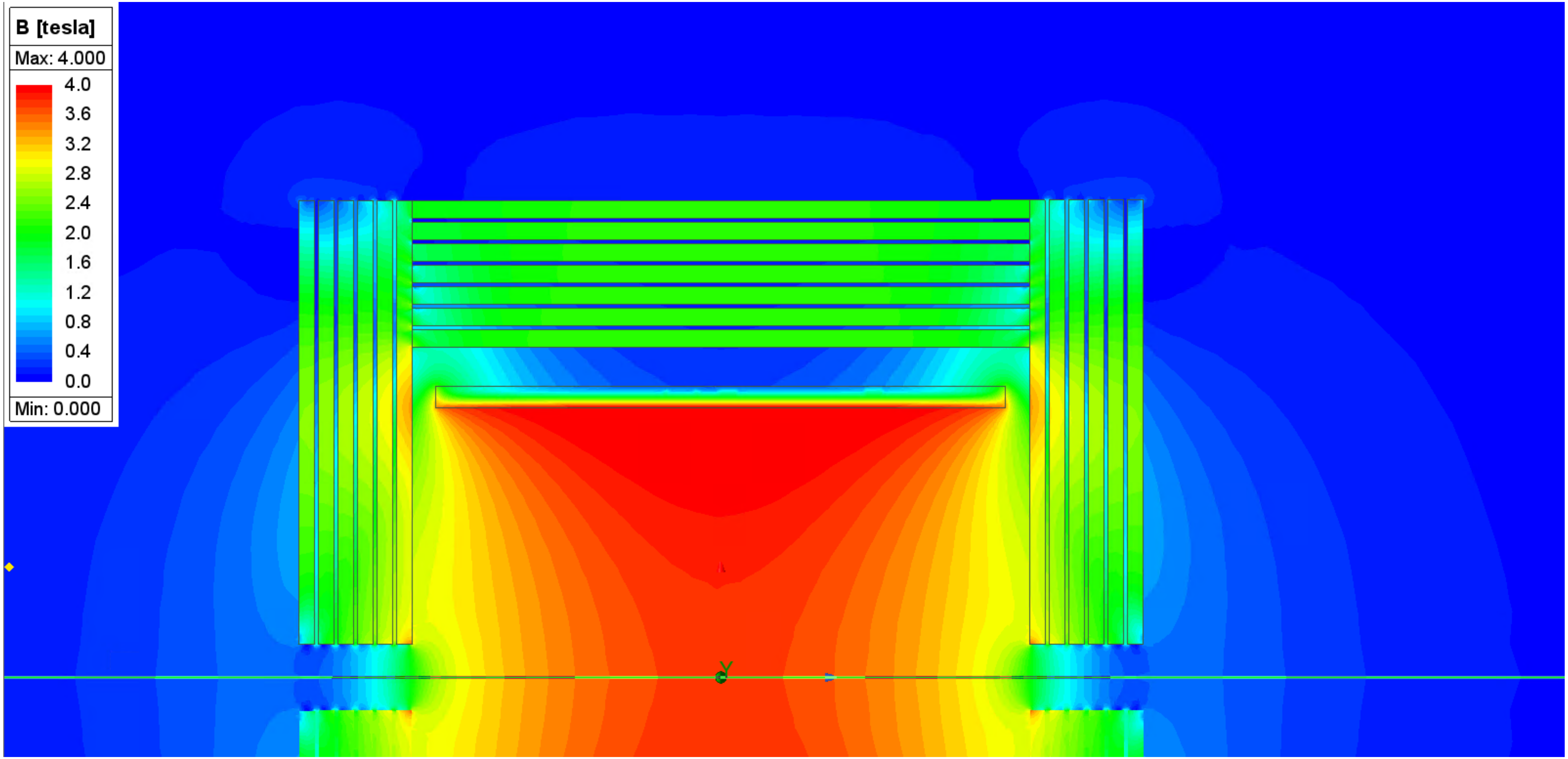
- Current: 20 kA - equal to CMS
- No. of layers: 4 - equal to CMS
- Total winding thickness: 252 mm - equal to CMS
- Cable bare section: ~ 63 x 21 mm^2 - equal to CMS
- Current density: ~ 13 MA/m^2 - equal to CMS
- Stored energy: 1.93 GJ - 75% of CMS one
- Inductance: ~ 10 H - 70% of CMS one
- Field at centre: 3.5 T - CMS is 4 T
- No. of turns: ~ 1500 - CMS is > 2000



- Good: with a "known" cable, design etc. you get something very close to what you need
- Coil is larger in diameter and shorter than CMS, total cable length is similar

- Not so good: no one produces CMS cable anymore

Slightly more optimised design



4 or 6 layers

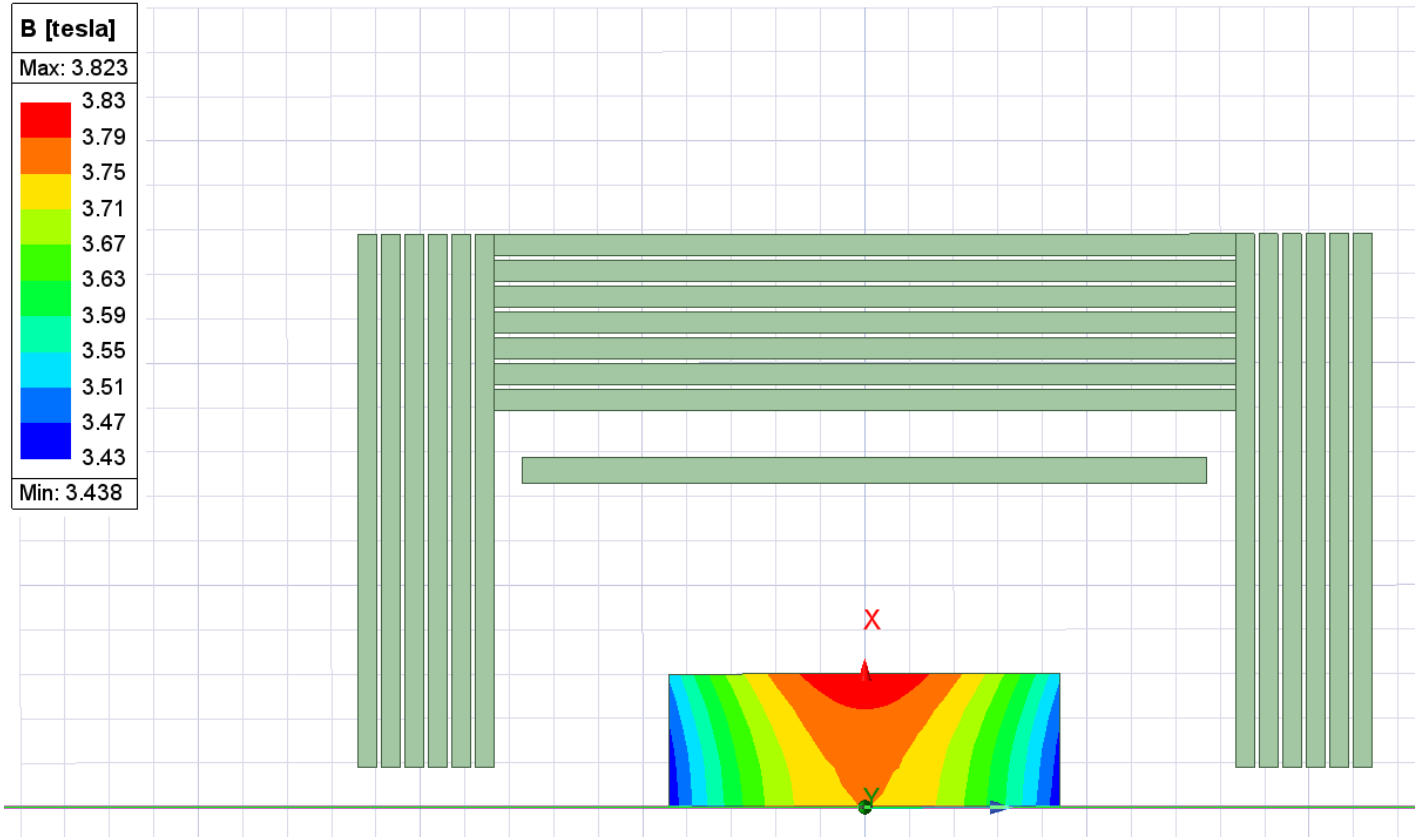
- Central field: 3.75 T
- Stored energy: 2.19 MJ
- Current density: 12.3 MA/m^2
- Total coil thickness: 288 mm
- 6 layers:
  - Current: 17.7 kA
  - Cable size: 48 x 30 mm^2
  - Inductance: 14 H
- 4 layers:
  - Current: 19.5 kA
  - Cable size: 72 x 22 mm^2
  - Inductance: 11.5 H

- No significant difference
- A cable to be completely designed for both options (and a supplier must be found)

To be noticed:
Forces are non trivially contained
No optimisation on longitudinal stress at today
Some splitting in sub-coils will be needed
This is a challenging design, overall

Some remarks on field quality

- Tracker region: -2200 < z < 2200, 0 < r < 1500
- B at IP: 3.75 T
- B = 3.63 ± 0.2 T
- Field uniformity: ±5.5%
- (No optimisation)
- Max Br = 0.2 T

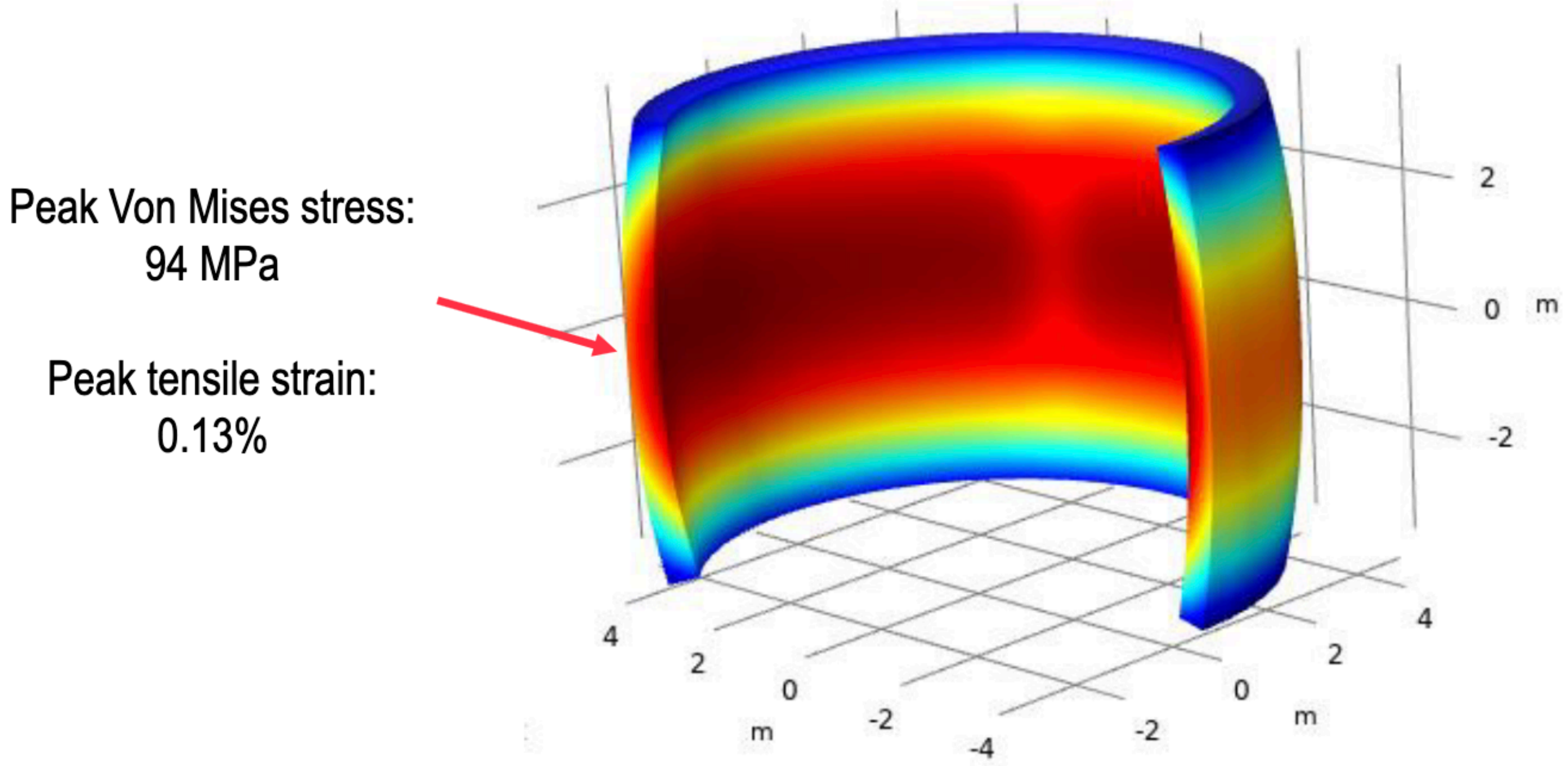


Some technicalities

- Maximum field on conductor: 4.125 T
  - NbTi stabilised in aluminium can work properly
  - CMS cable seems very promising as a starting point for the development
  - No company is producing this cable
  - No trivial alternative is available IMHO
- Forces on the coil are HUGE (super preliminary results - no sense to give numbers at this stage)
  - Hoop stress is possibly not terrible
  - Compressive forces are really large
  - Stress management via sub-coils with mechanical supports, reduction of Br and other tricks can be attempted
- No optimisation at all has been performed
  - Some interface with the detectors can possibly be defined

Mechanics (M. Mentink slides)

- The energy density (= Stored magnet energy / cold mass) = 11.6 kJ/kg (same as CMS)
- At nominal current: 94 MPa maximum von Mises stress, and 0.13% tensile strain applied to conductor due to powering of the coil

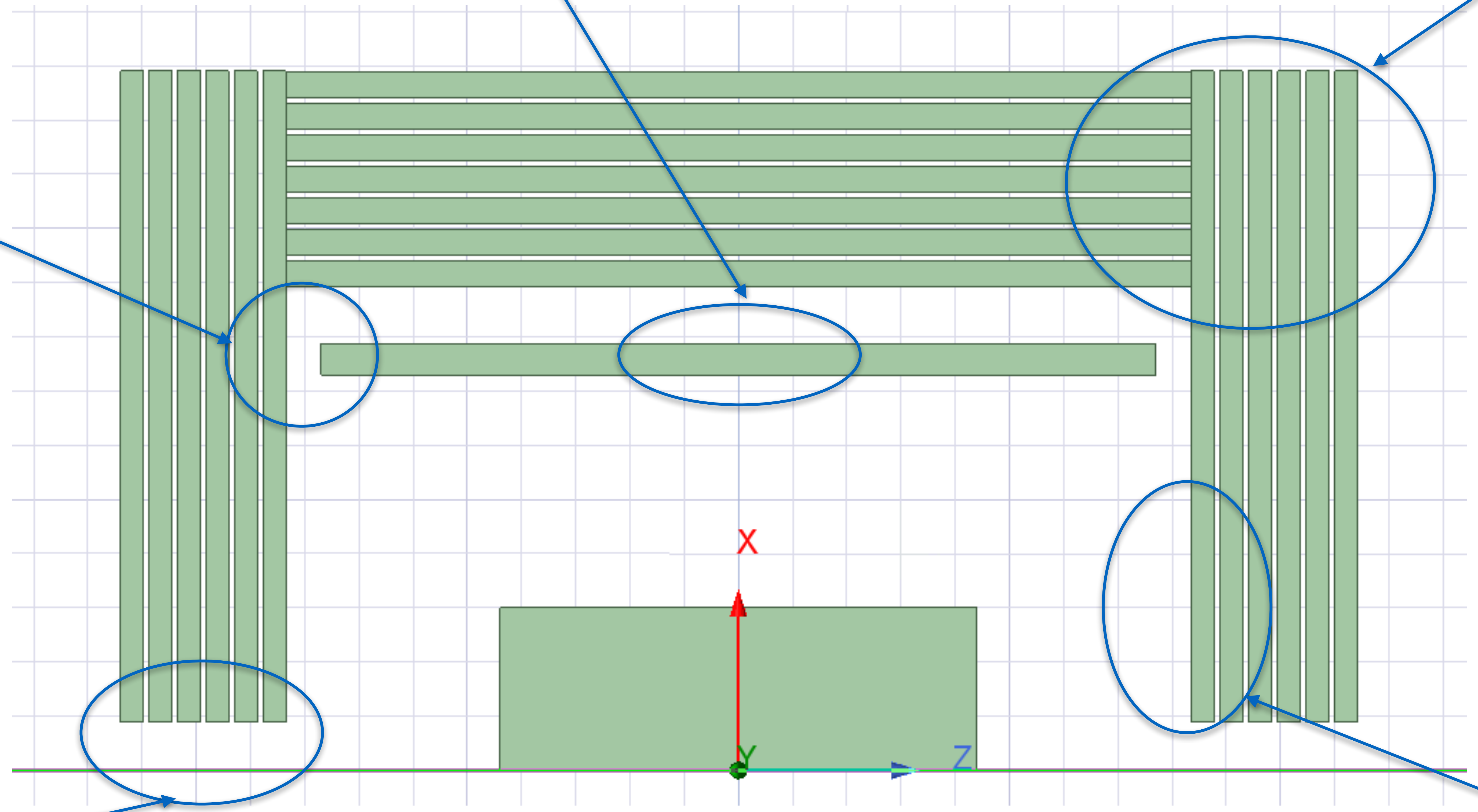


Conductor alternatives (M. Mentink slides)

- Aluminium-stabilised Nb-Ti conductor advantages/disadvantages:
  - Nb-Ti strands are cost-effective, mechanically extremely resilient, and widely available.
  - Nb-Ti gives sufficient magnetic field range for typical superconducting detector magnet applications: Comfortably up to 4 T in aluminium-stabilised conduction-cooled superconducting detector magnets
  - Aluminum is lightweight, transparent, good for quench protection, stability, and mechanics
  - Well-understood and extensively proven technology, has been in use for 50 years
  - It requires low operating temperature (4.5 K) and commercial availability is presently unclear
- (Aluminium-stabilised) MgB2 conductor technology advantages/disadvantages:
  - More expensive than aluminium-stabilised Nb-Ti, requires development for use in superconducting detector magnets, less mechanically robust than
  - Nb-Ti, currently only allows a limited magnetic field range (probably not suited for 4 T)
  - Useful for superconducting busbars
  - Allows operation at higher temperatures, and benefits from technology developments through the HL-LHC Superconducting Link project
- Aluminium-stabilised High Temperature Superconducting (ReBCO / Bi-22223) conductor advantages/disadvantages:
  - More expensive than aluminium-stabilised Nb-Ti, not yet available in long lengths, not yet fully understood, less mechanically robust than Nb-Ti
  - High-purity aluminium-stabilisation is not needed, although aluminum is still required to carry the current during a quench
  - Useful for superconducting busbars
  - Enables operation at much higher temperatures and magnetic fields

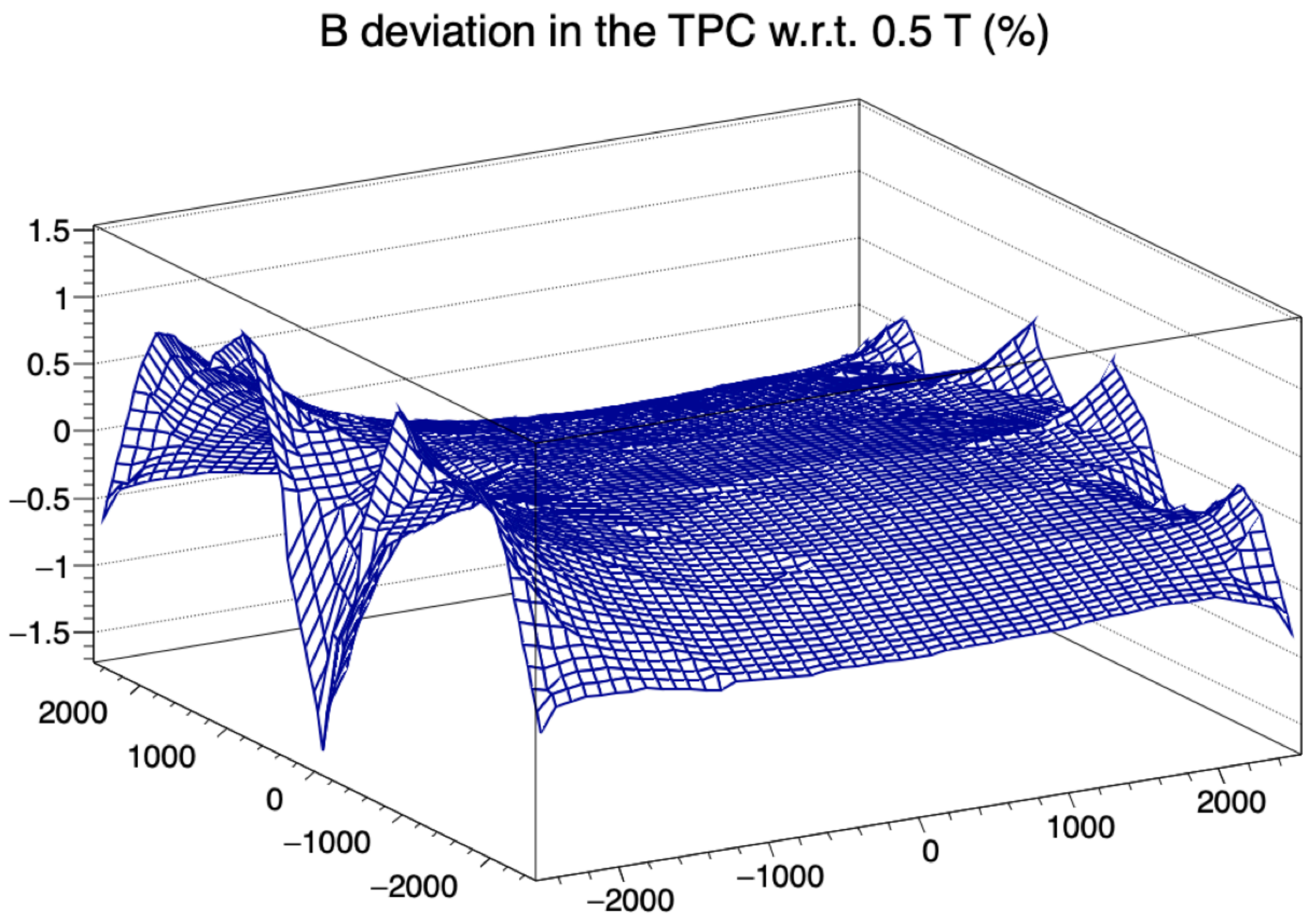
Space for optimisation

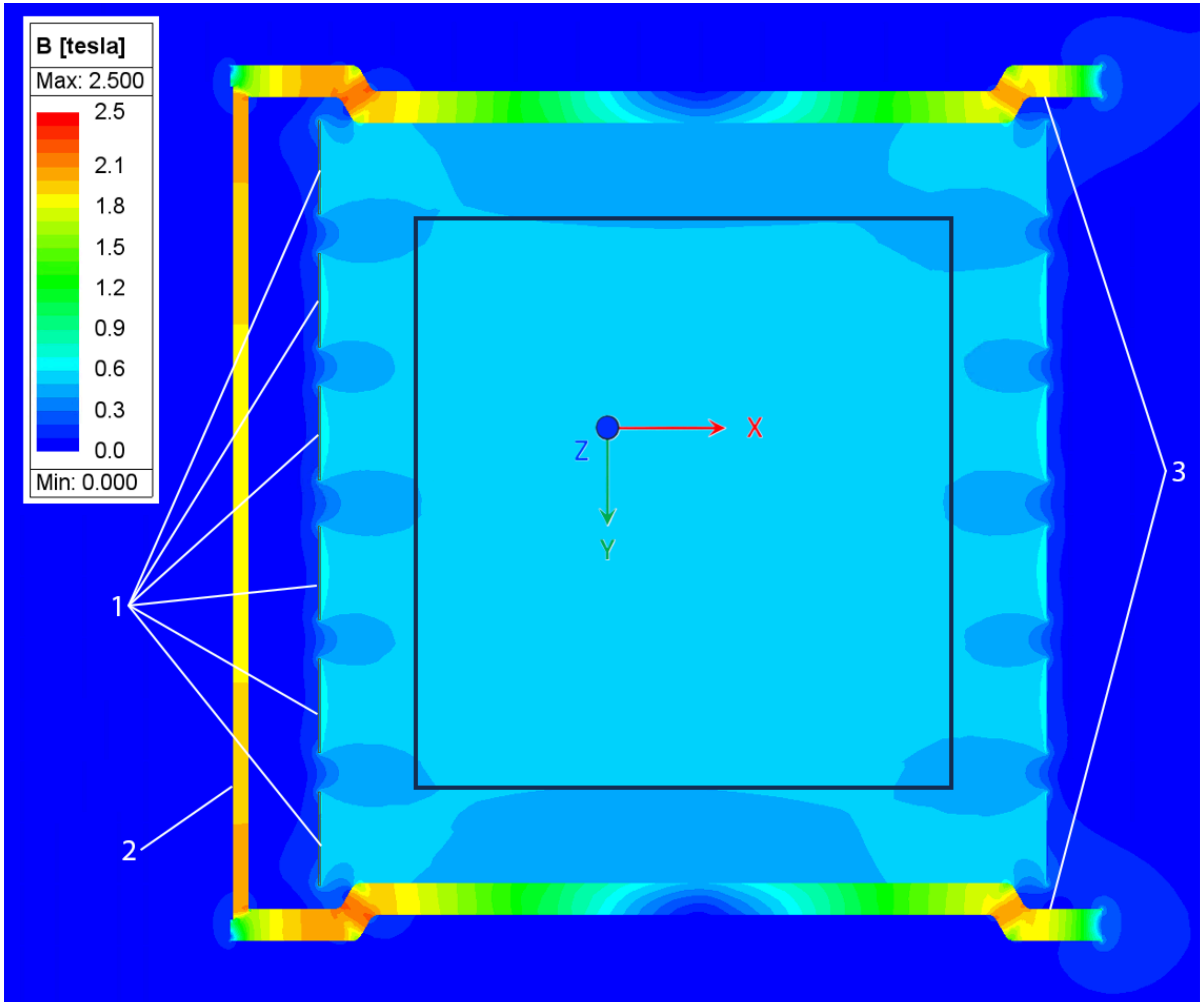
- Sub-coils splitting
- Iron yoke shape
- Coils ends
- End-caps opening
- End-caps shaping



Another magnet (DUNE ND-GAr SPY@DND)

- Way lower field, similar size…
  - Asymmetric iron (2) (axis is vertical)
  - 0.5 T central field
  - 6 sub coils (1)
  - Shaped, closed end caps (3)
- BUT

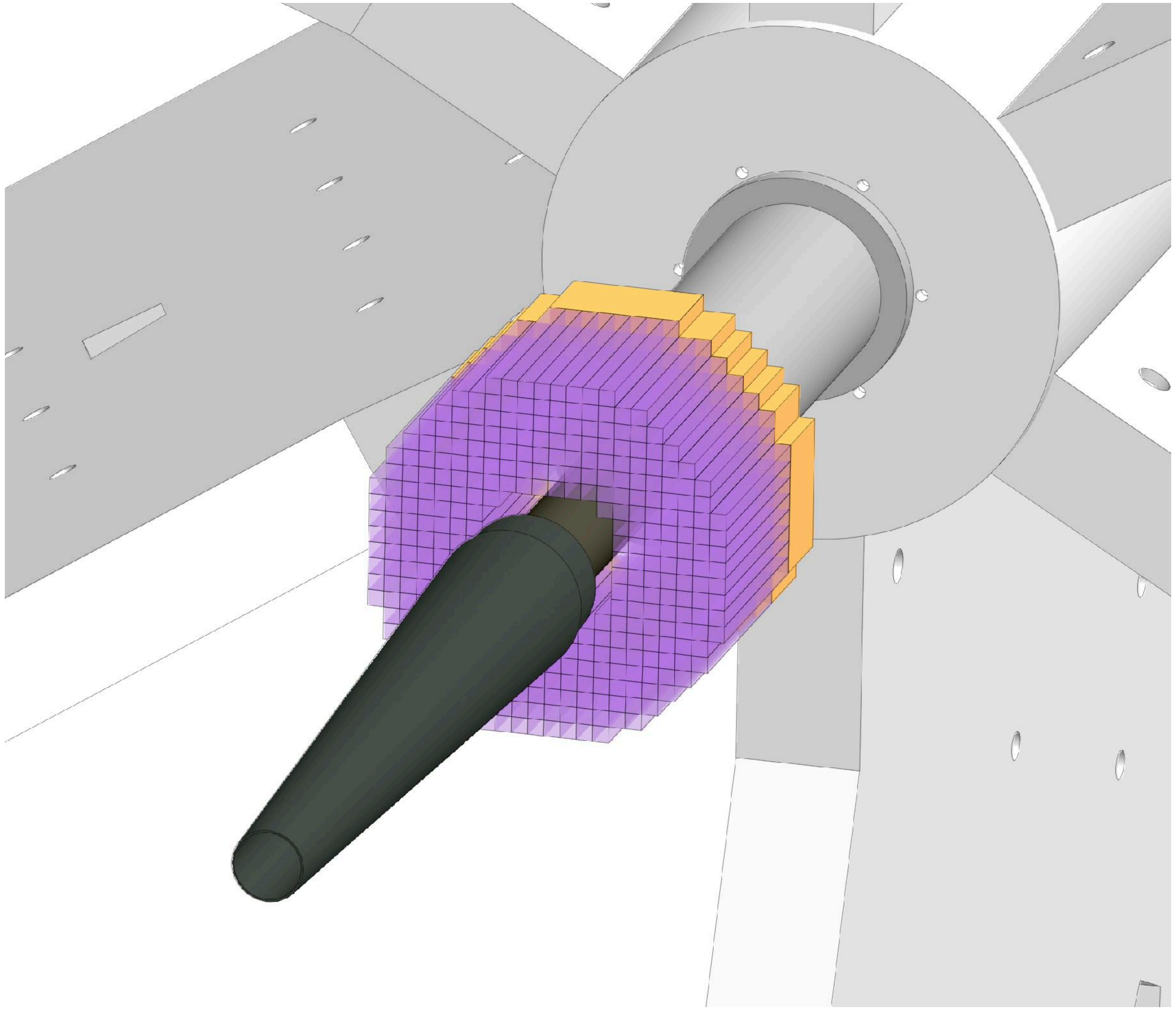




- Indeed, it was easier :-)

Integration with tungsten cones

- Tungsten cones protect the detectors from beams haloes
- These are large and heavy
  - Preliminary chat with JLAB people with experience shows that this could be non trivial
  - Any possible alternative (steel boxes filled with lead, as an example) should be investigated
- Companies work alloys up to 97.5% tungsten
  - different compositions have different mechanical properties and machinability
  - density is always very large
  - it's not fragile
- Picture: JLAB Hall B Forward Tagger, with a tungsten Moeller cone ~ 1 m long



Conclusions and outlook

- A magnet capable of 3.75 T, cold bore dia. ~ 7 m, length ~ 8 m should be technically feasible
- Using the same cable and current as for CMS one gets a field slightly lower than the goal
- Possible small modifications can make the desired field reachable
- Due to the magnet form factor (length is very similar to diameter), the field uniformity is very limited
- Forces on the coil are completely to be studied
- There is plenty of space for optimisation
- According to detectors requirements some further study can be started (manpower?)