SPY@DND and MgB_2 cables for detector magnets

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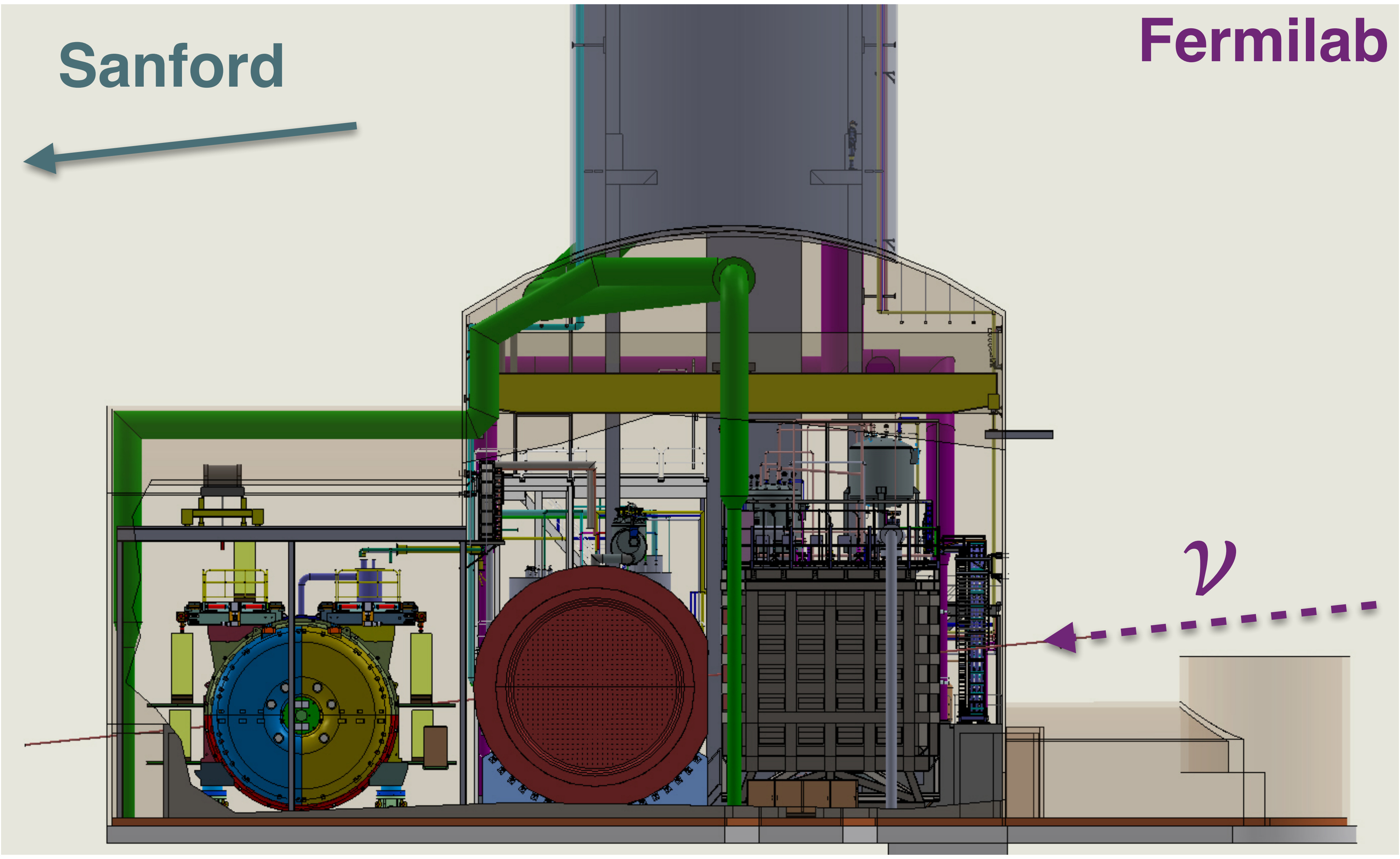
on behalf of **SPY group:**
Albany, Fermilab, Indiana, INFN and University of Genova

DUNE Near Detector

- DUNE features a Near Detector, which, asymptotically, should be made of three elements
  - **ND-LAr:** liquid argon tracker, movable, no magnetic field — Approved for Phase 1
  - **ND-GAr:** high pressure argon gas tracker, movable, with magnetic field — Phase 2 upgrade
  - **SAND:** multipurpose detector, non movable, with magnetic field — Approved for Phase 1

- For ND-GAr a **S**olenoid in a **P**artial return **Y**oke (SPY@DND) has been designed by INFN Genova in collaboration with Fermilab, Albany, and Indiana Univ.



SAND ND-GAr ND-LAr

ND-GAr magnet requirements

- The SPY group was focussed on the design of an **innovative magnet** for ND-GAr
  - The following **requirements** were identified
    - **< 50 g/cm^2** material budget on the side facing ND-LAr
    - **0.5 T ± 1%** magnetic field in the TPC region
      - **5 m** diameter, **5 m** length
      - operated perpendicular to the neutrino beam
    - Warm bore sufficiently large to host the TPC and a 4π electromagnetic calorimeter
    - Limited **stray field** on ND-LAr and SAND
    - **Movable** along the magnetic field direction

Paper in preparation

SPY: A Magnet System for a High-pressure Gaseous TPC Neutrino Detector

Magnet concept

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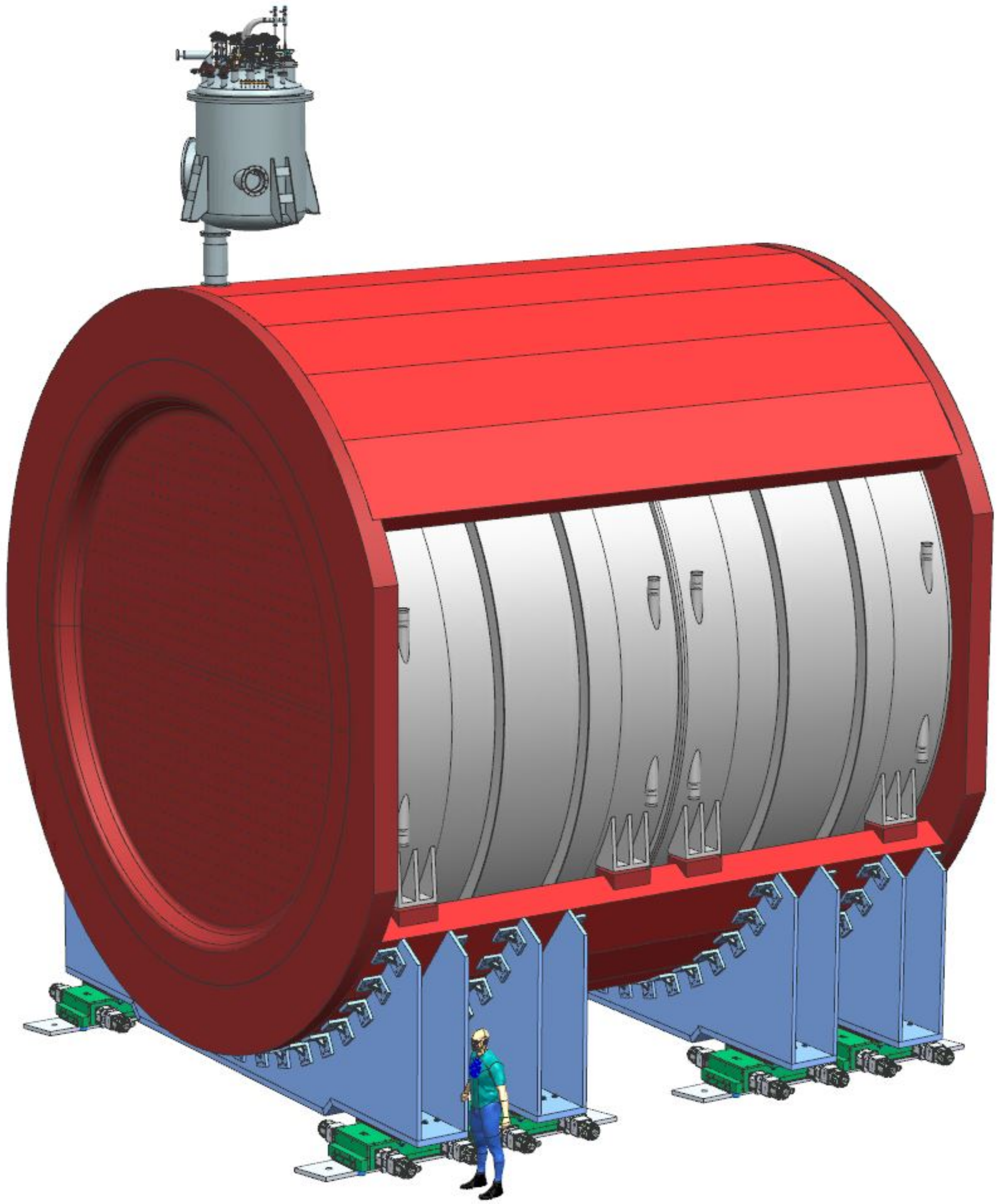
- Quasi-continuous **solenoid**
  - optimises field quality and simplifies construction
- **Partial** return yoke
  - to keep material budget low facing ND-LAr
- **Solenoid** cryostat and **TPC** vessel **integration**
  - the inner shell of the coil cryostat is the container of argon gas
  - TPC vessel inner pressure transferred to yoke end-caps
    - via an array of screws adjustable *in situ*

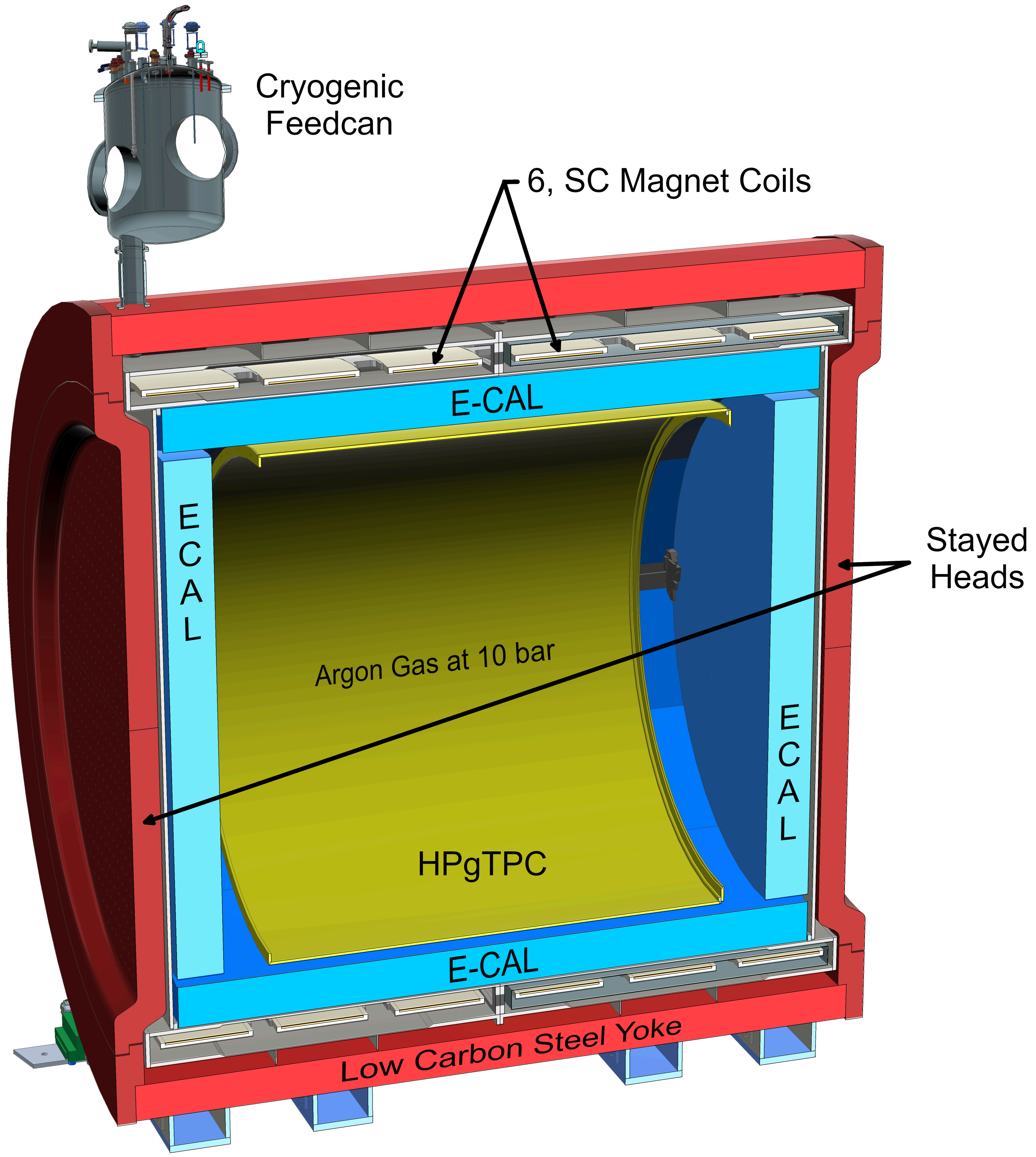


ND-GAr integration

- Stayed heads allow for a compact design
  - to contain 10 bar gas, hemispherical end-caps for the pressure vessel would have been needed
  - The heads are flat but leaned to return yoke

- Compact iron yoke allows for a **better field quality** in a large volume

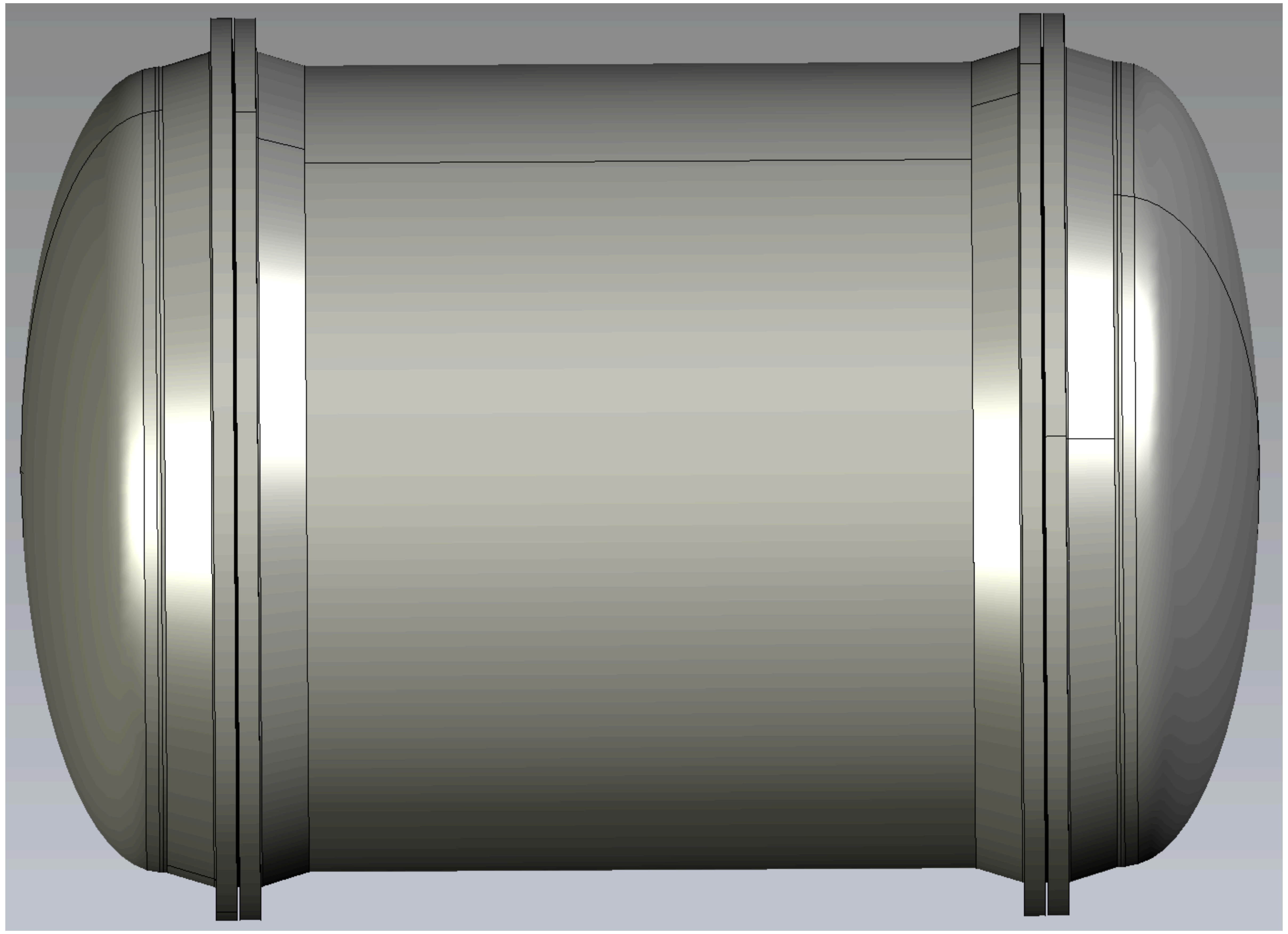
  - overall, **coils diameter** exceeds **7 m**
  - **yoke length** exceeds **8 m**



- Electromagnetic calorimeter (ECAL) is foreseen to be operated inside the pressure vessel

A few notes on pressure vessel

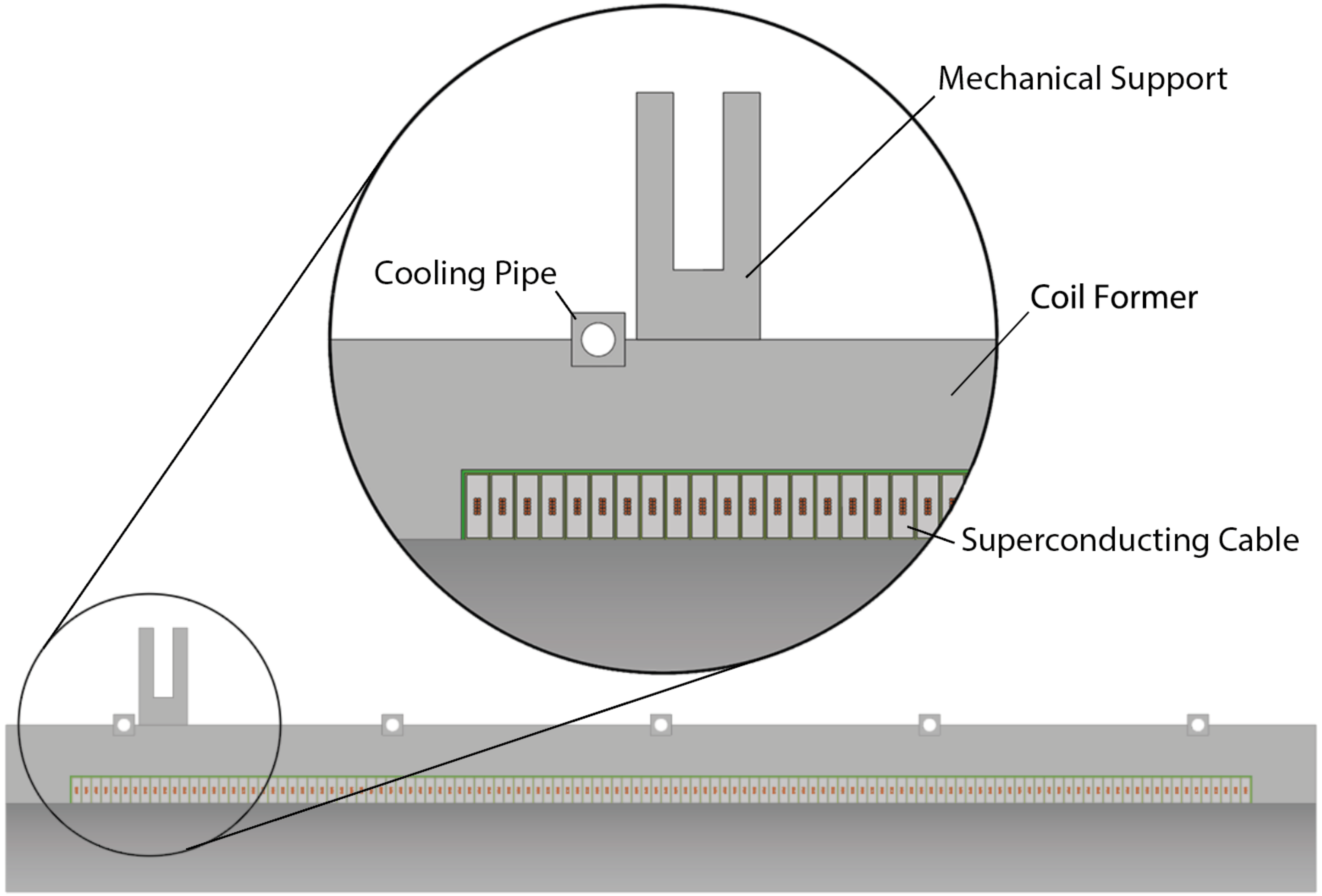
- Adds **dead material**
  - Degrades ECAL performance
  - Increase backgrounds
- Adds **length**
  - ~ 50% of cylinder diameter (3-4 m)
- For a given magnet bore reduces
  - Target mass
  - Tracking volume
- Cost - $\mathcal{O}$ \$10M (US quote 2018)



Coil design: NbTi option

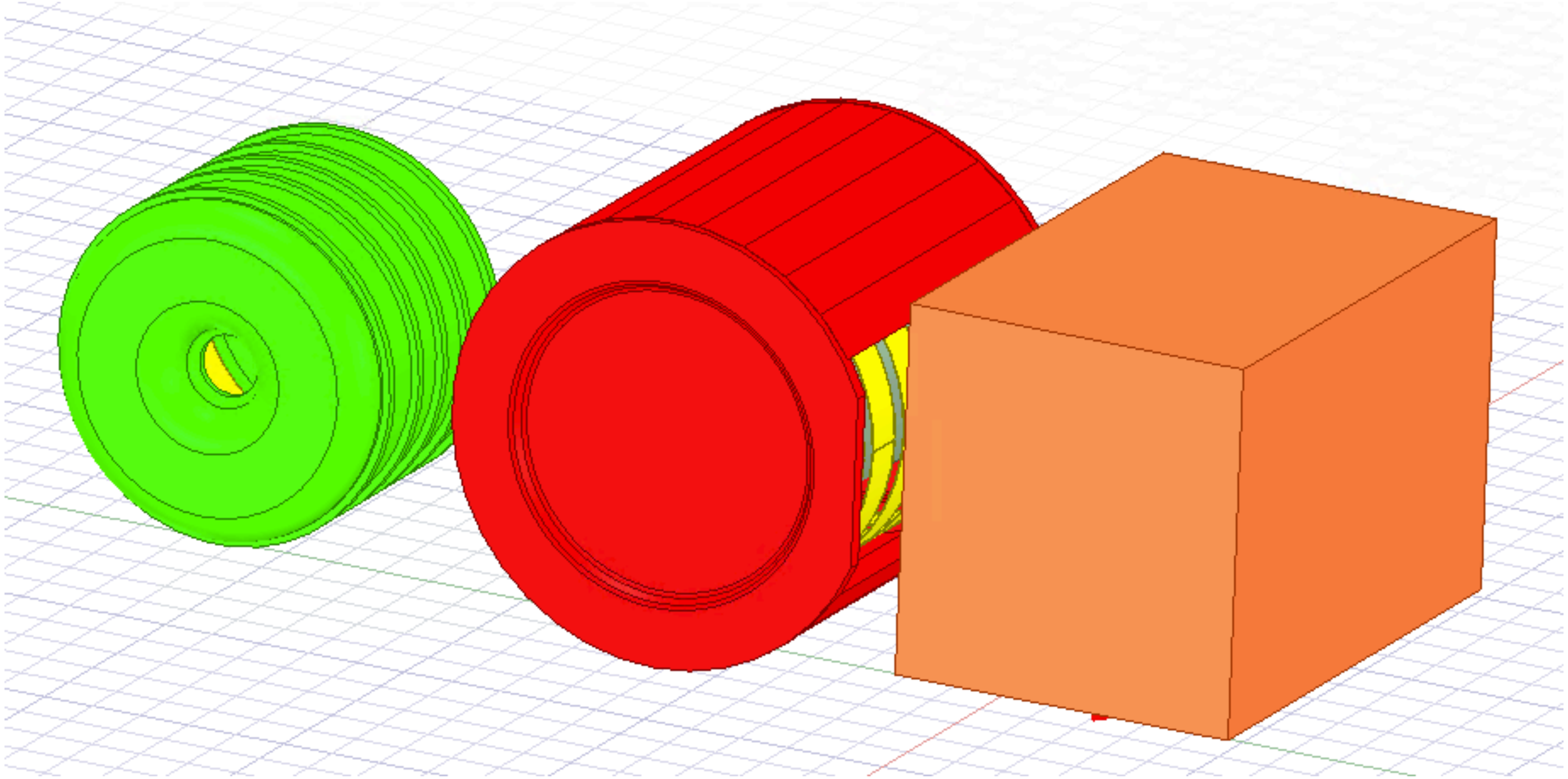
- **NbTi** superconducting Rutherford cable stabilised in pure aluminium is the **baseline option**
  - insulated: **~ 20 x 7.5 mm²**
  - total cable length: **16.5 km**

- Six 120-turn coils in series to generate solenoidal field
  - current **< 5000 A**
  - current density (average): **< 35 A/mm²**
  - stored energy: **< 40 MJ**
  - inductance: **< 3.2 H**



Magnetic model of the complete ND hall

- All DND detectors simulated **together** to assess the **cross-talk** between magnets and the stray fields both in **active volumes** and where **electronics** will be installed

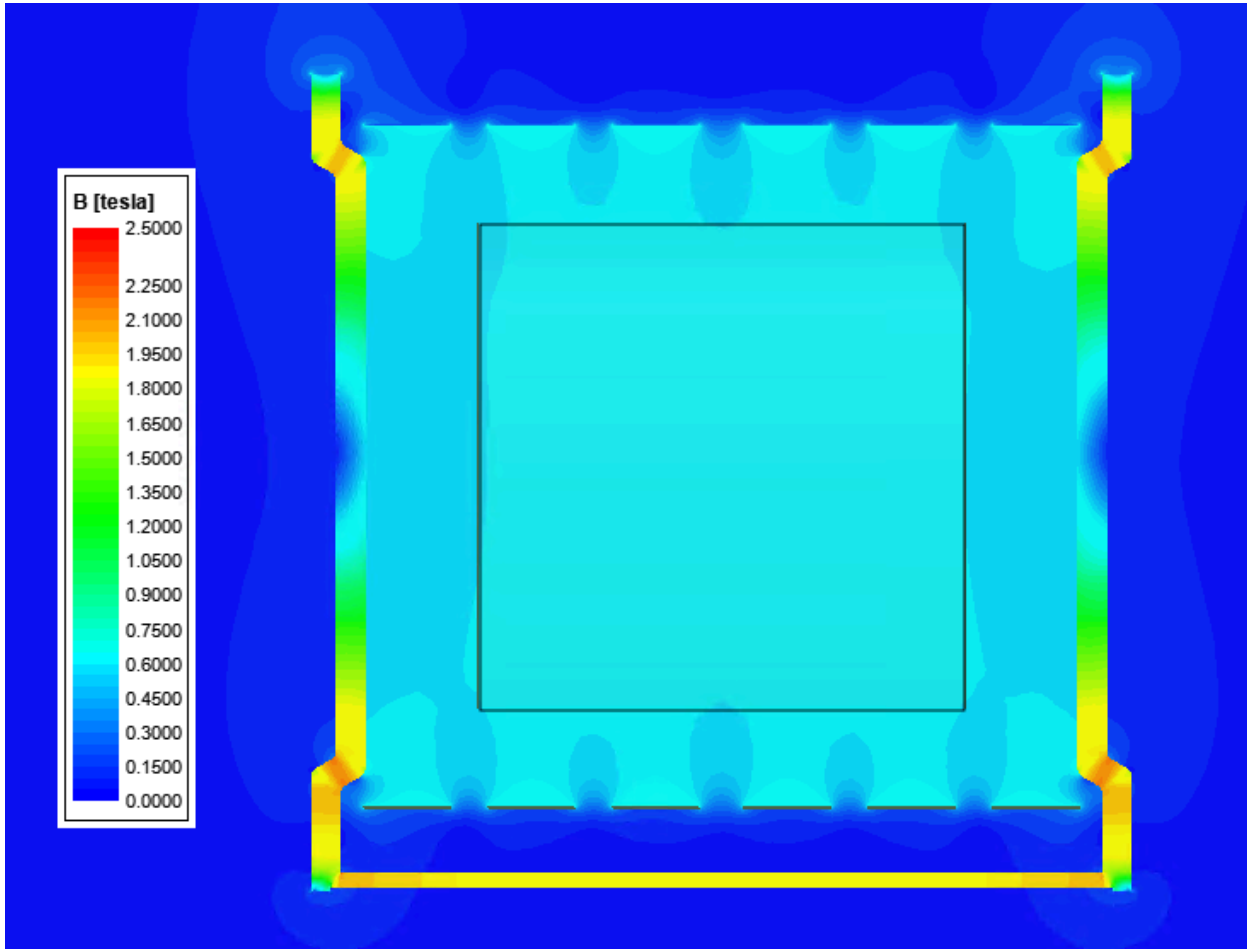


Magnet performance (v 22.1)

- Horizontal cross section
- Rectangle: TPC active volume
- Operating current: 4585 A
- Minimum **field on TPC: 0.5034 T**
- Maximum **field on TPC: 0.5161 T**

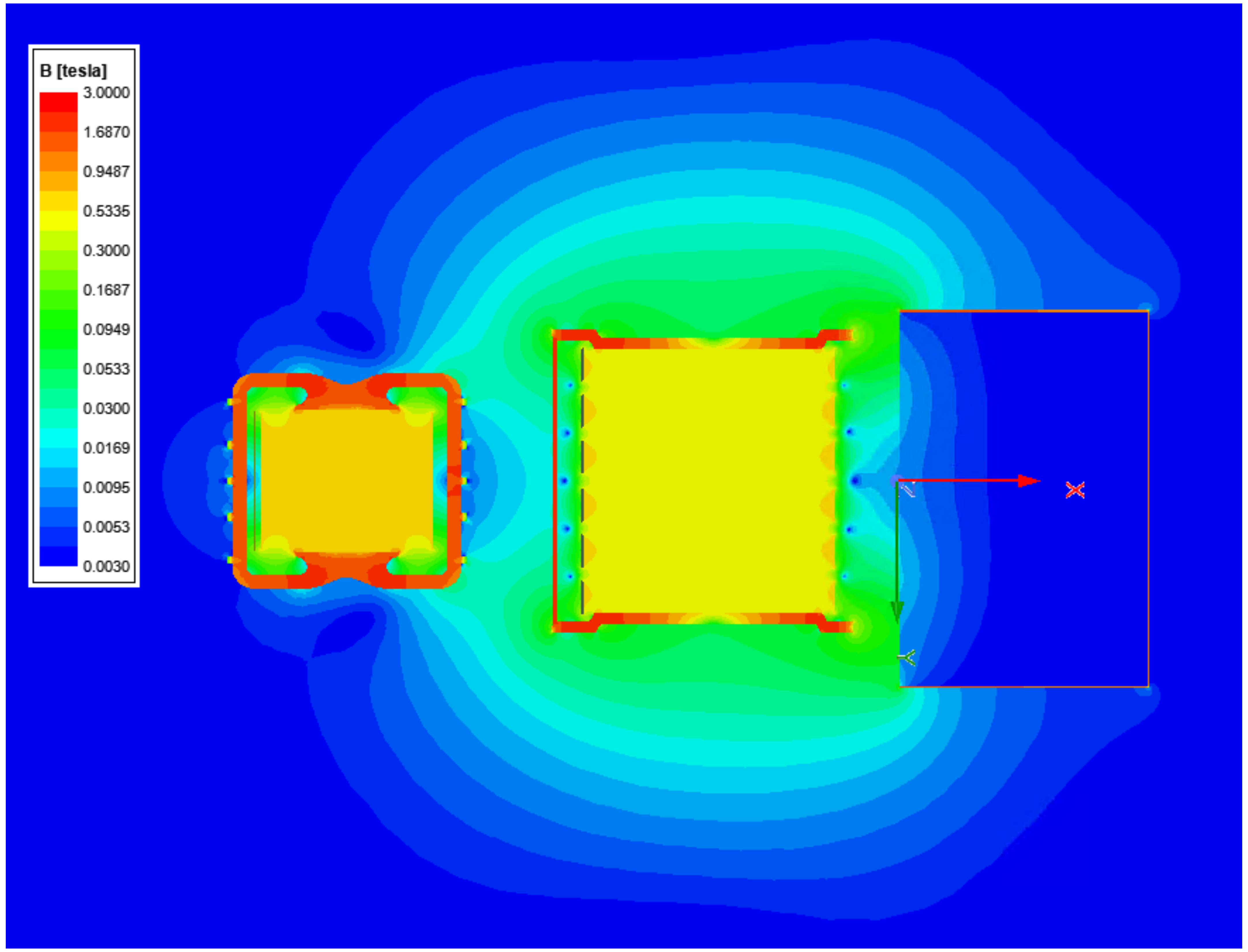
± 1.1 % max

- Stored energy: 32.5 MJ
- Inductance: 3.1 H
- Force on SAND yoke: 6 kN
- Force on coils: 150 kN (to SAND)
- Force on ND-LAr structure: 60 kN
- Residual field in SAND: < 0.0005 T



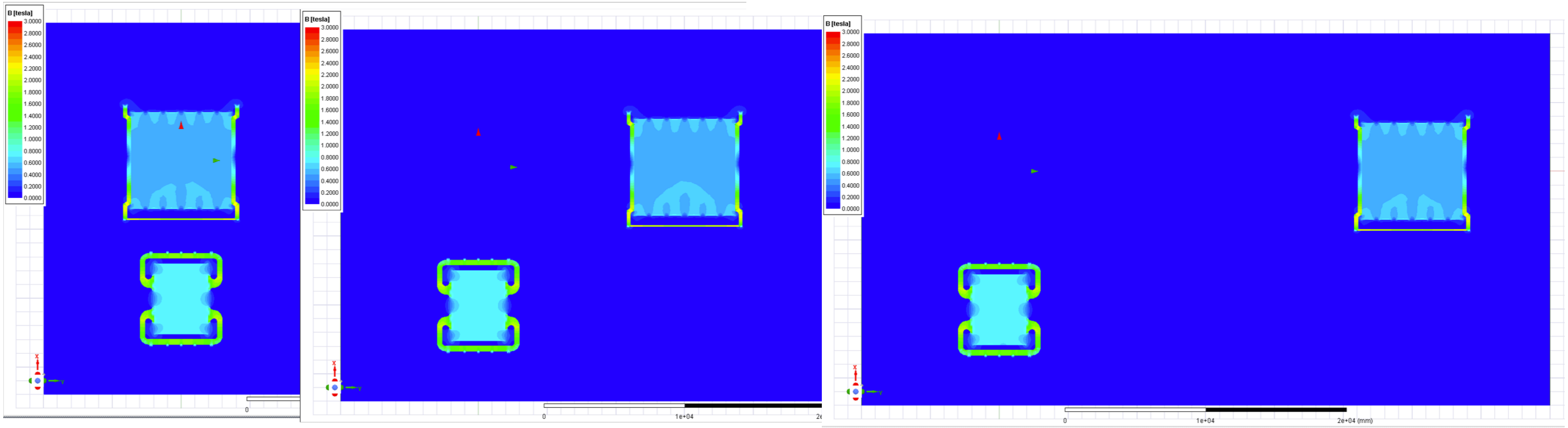
Field on the whole Near Detector volume

- Full simulation is needed to evaluate cross-talk and interactions between magnets
- Size and weight constraints limit the amount of iron in SPY@DND yoke
- Stray field up to 0.1 T is foreseen
- Note that the scale is logarithmic



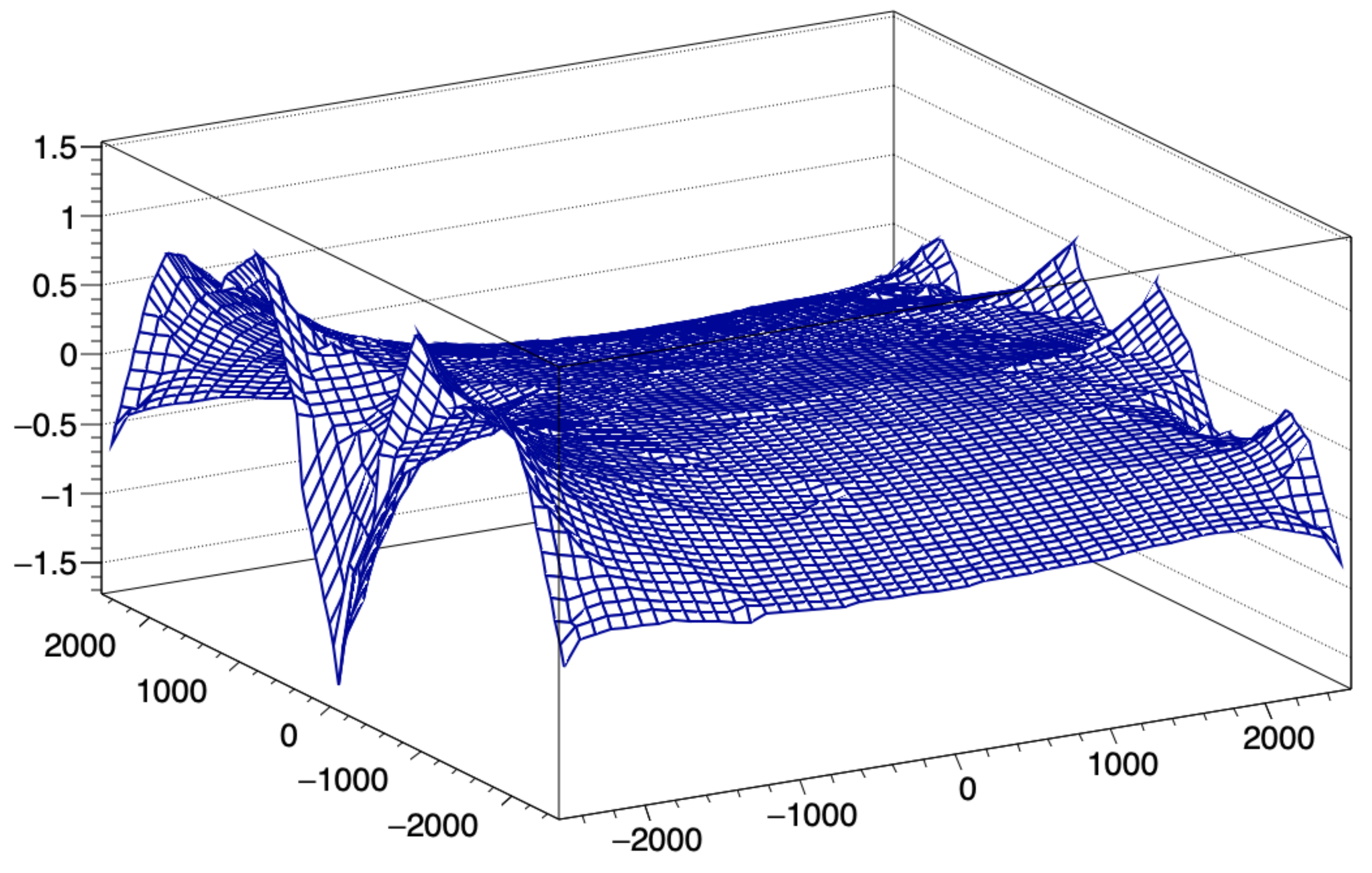
Interaction with SAND

- SPY@DND behaviour has been simulated in different positions w.r.t. SAND
- Cross-talk between SAND and SPY@DND has been calculated with each magnet off and both on, either with the same or opposite polarities

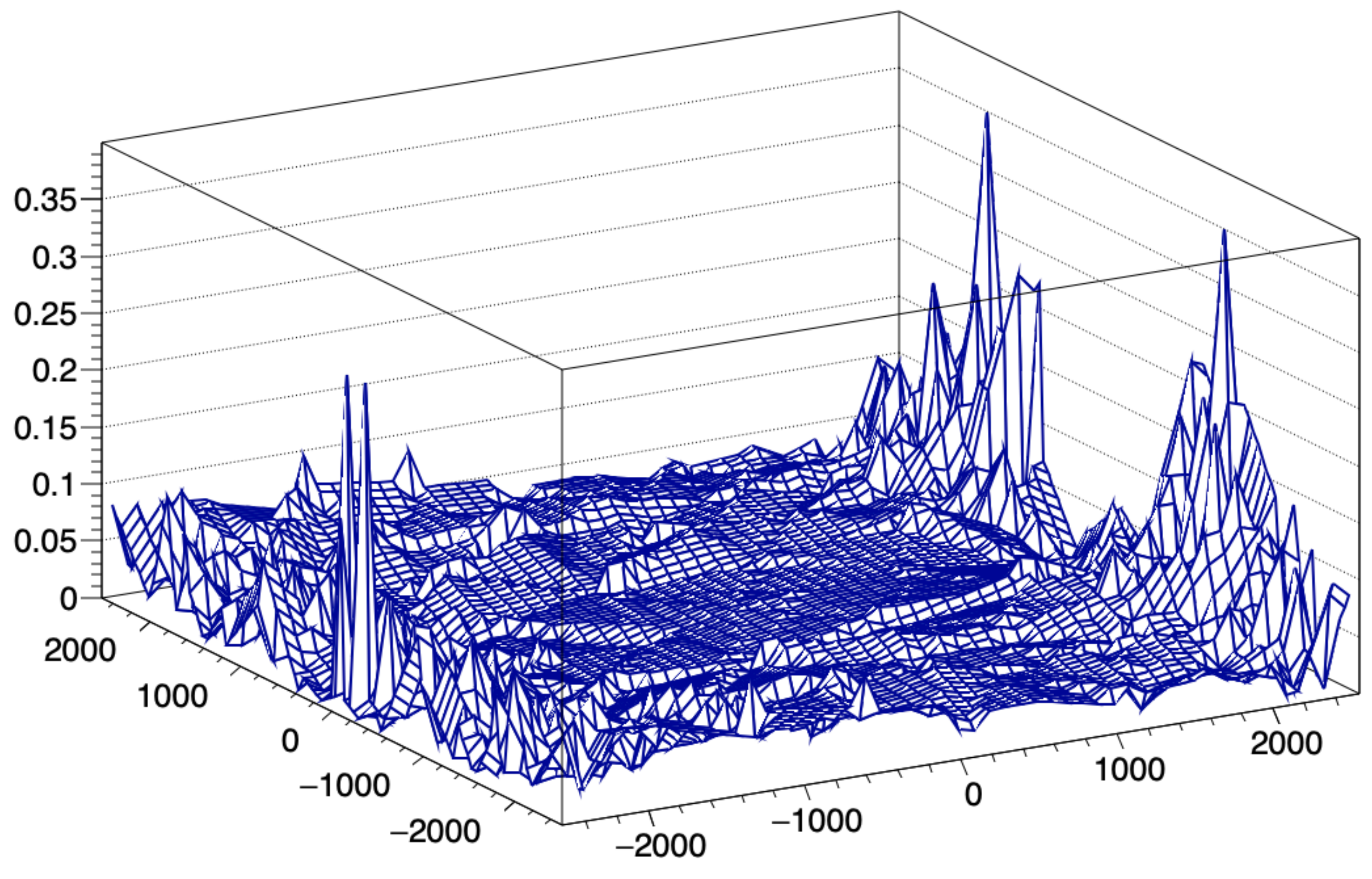


How SAND affects SPY@DND field

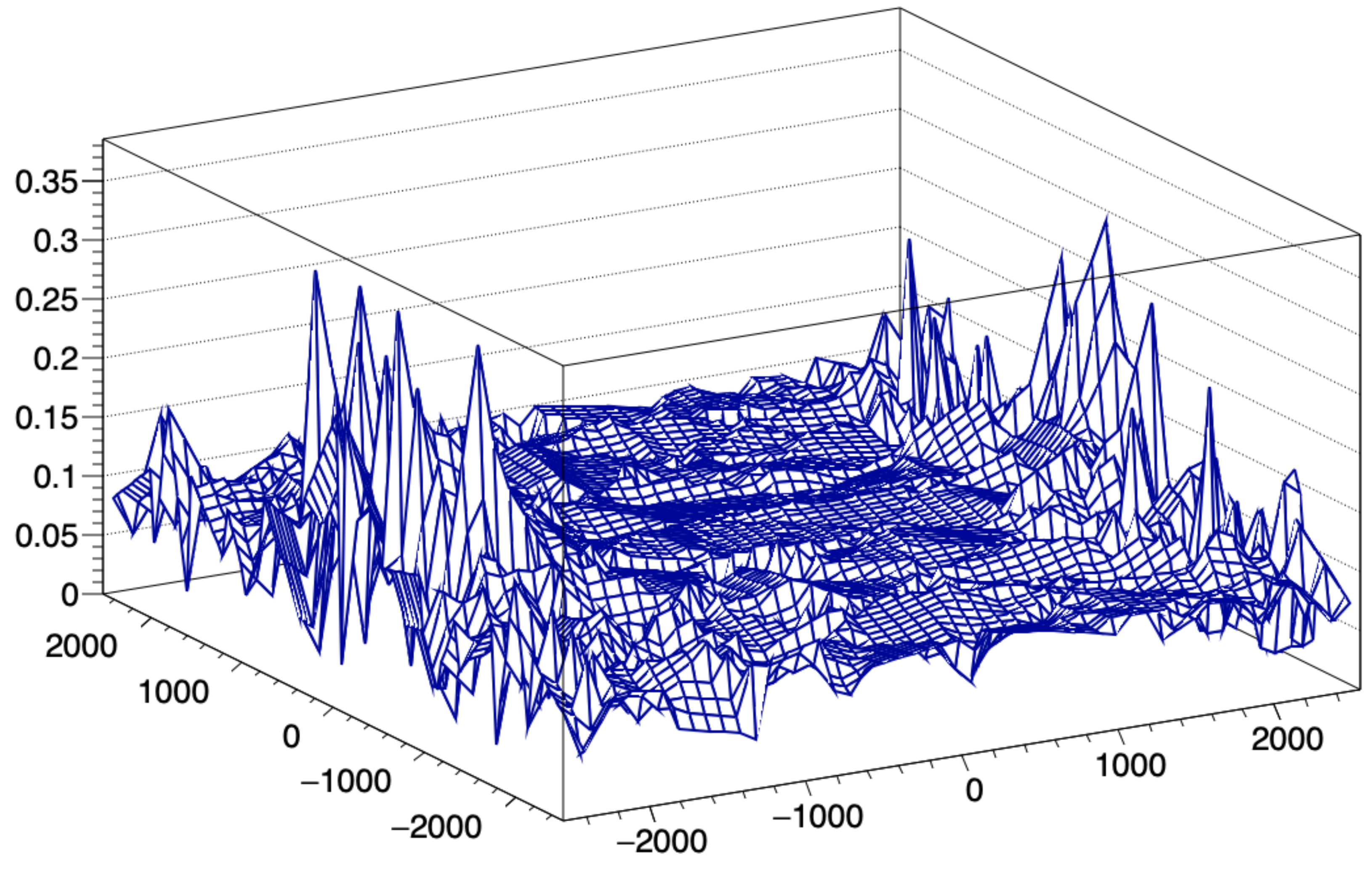
B deviation in the TPC w.r.t. 0.51 T (%)



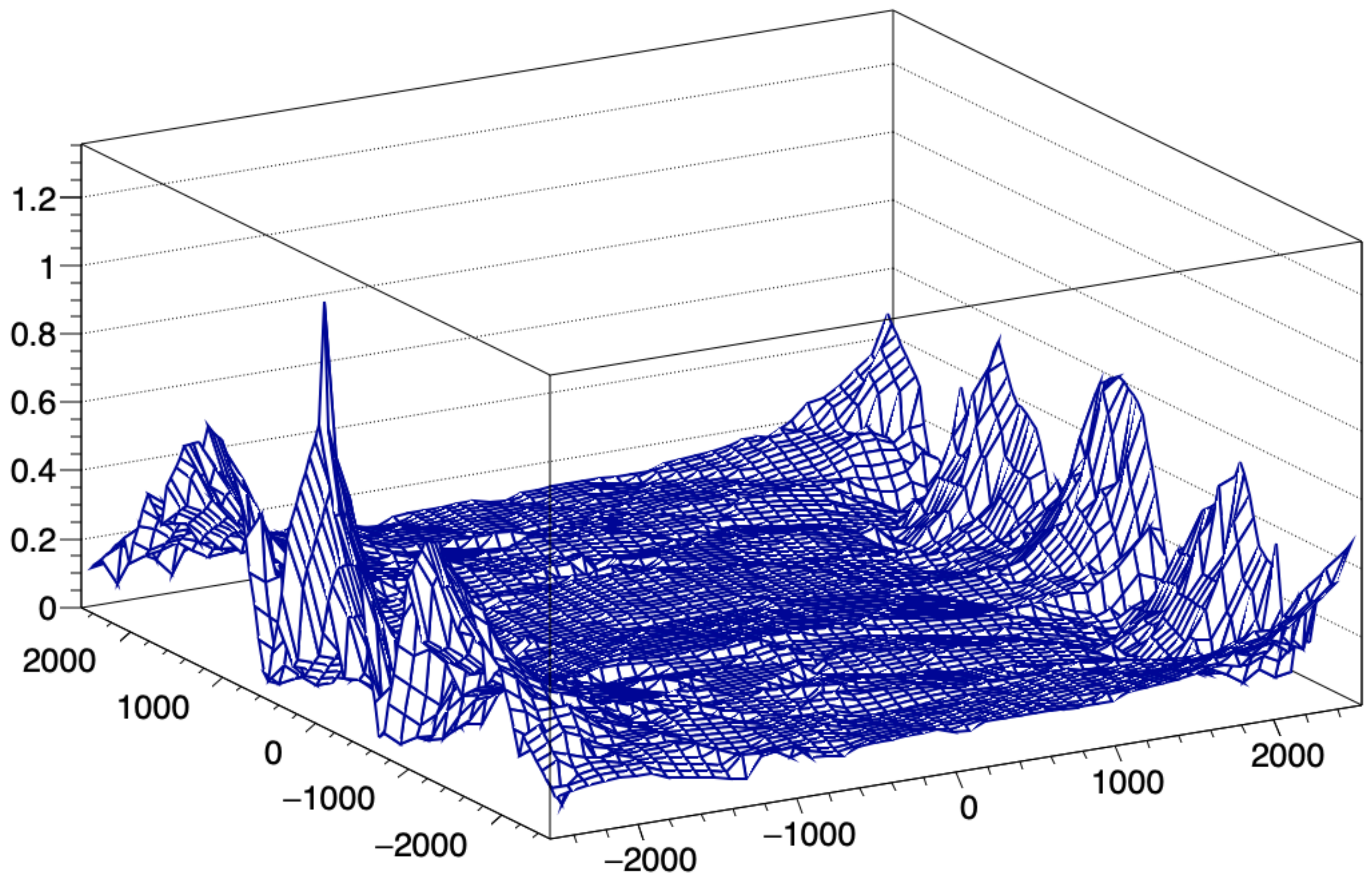
B deviation in the TPC with SAND on and antiparallel (%)



B deviation in the TPC with SAND on and parallel (%)

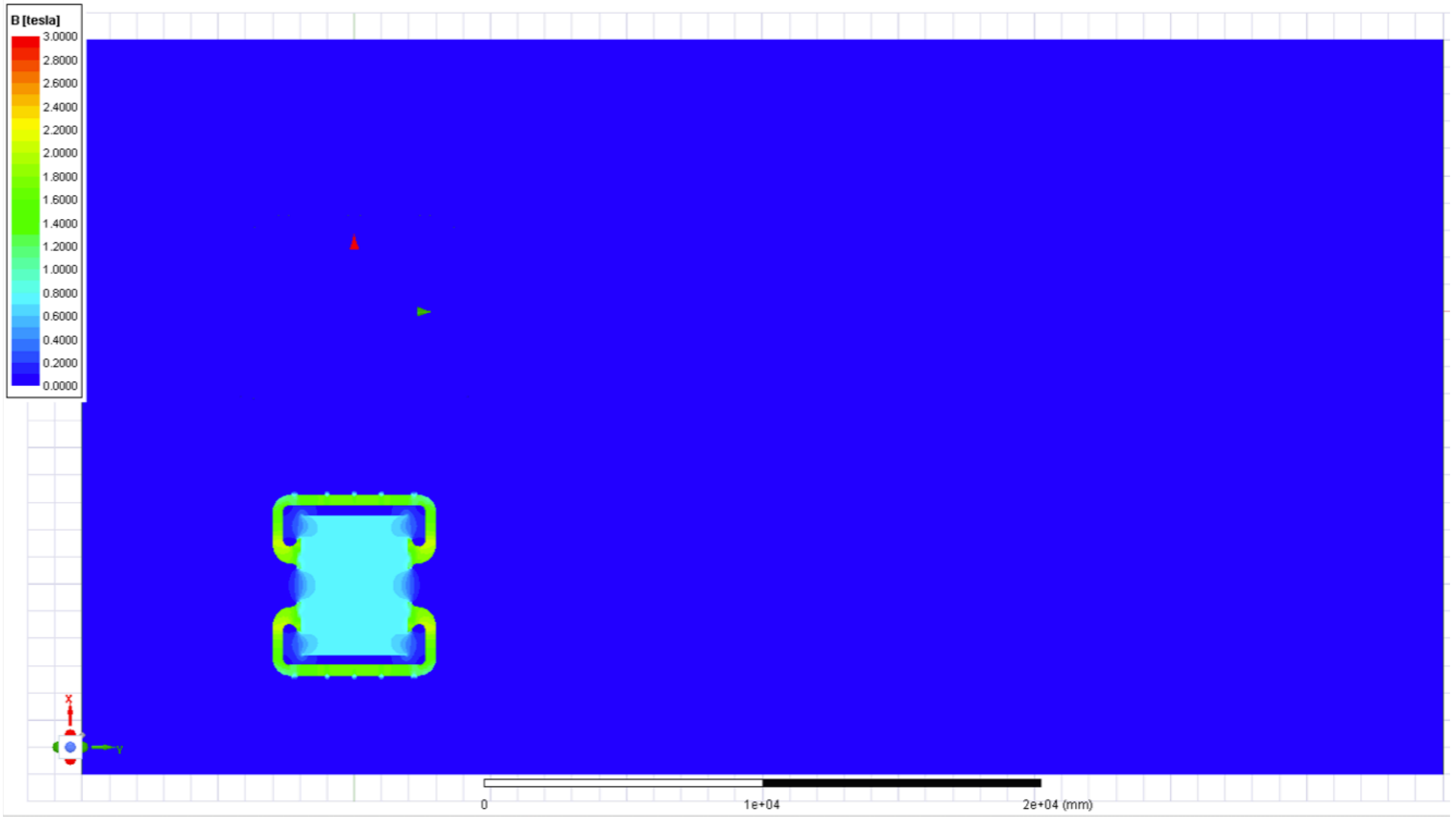


B deviation in the TPC without SAND (%)



Interaction with SAND

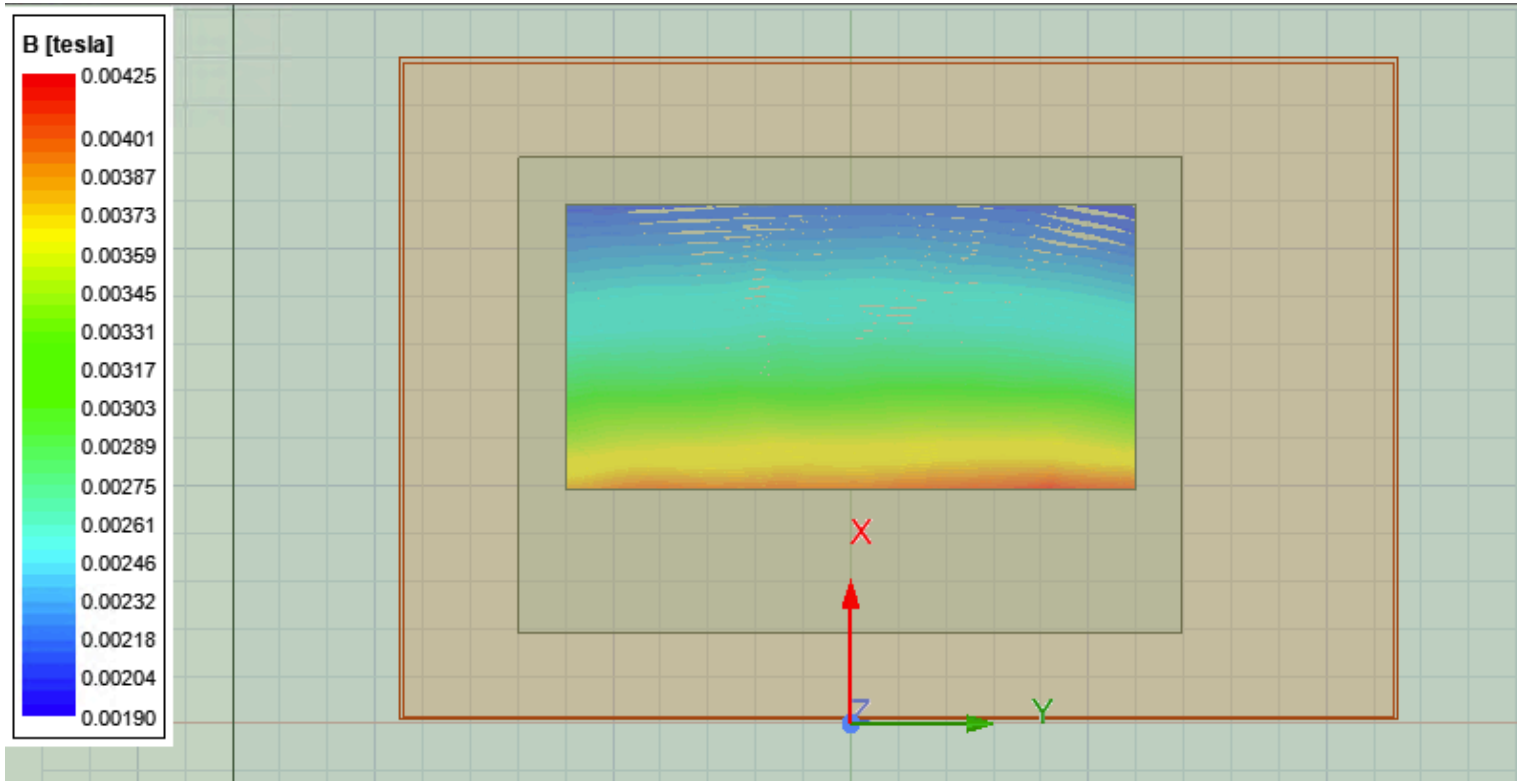
- Amount of iron and distance between the magnets keep the cross-talk effects well below 1%
- The stray field of ND-GAr on SAND detectors is less than 5 Gauss
- The behaviour of field and forces suggests to have SAND and ND-GAr fields parallel
- The parameters look very similar to the ones without SAND
  - this situation mimics the off-axis configuration for ND-GAr
- Field generated by SAND on ND-GAr TPC is below 1 Gauss



Stray field on ND-LAr

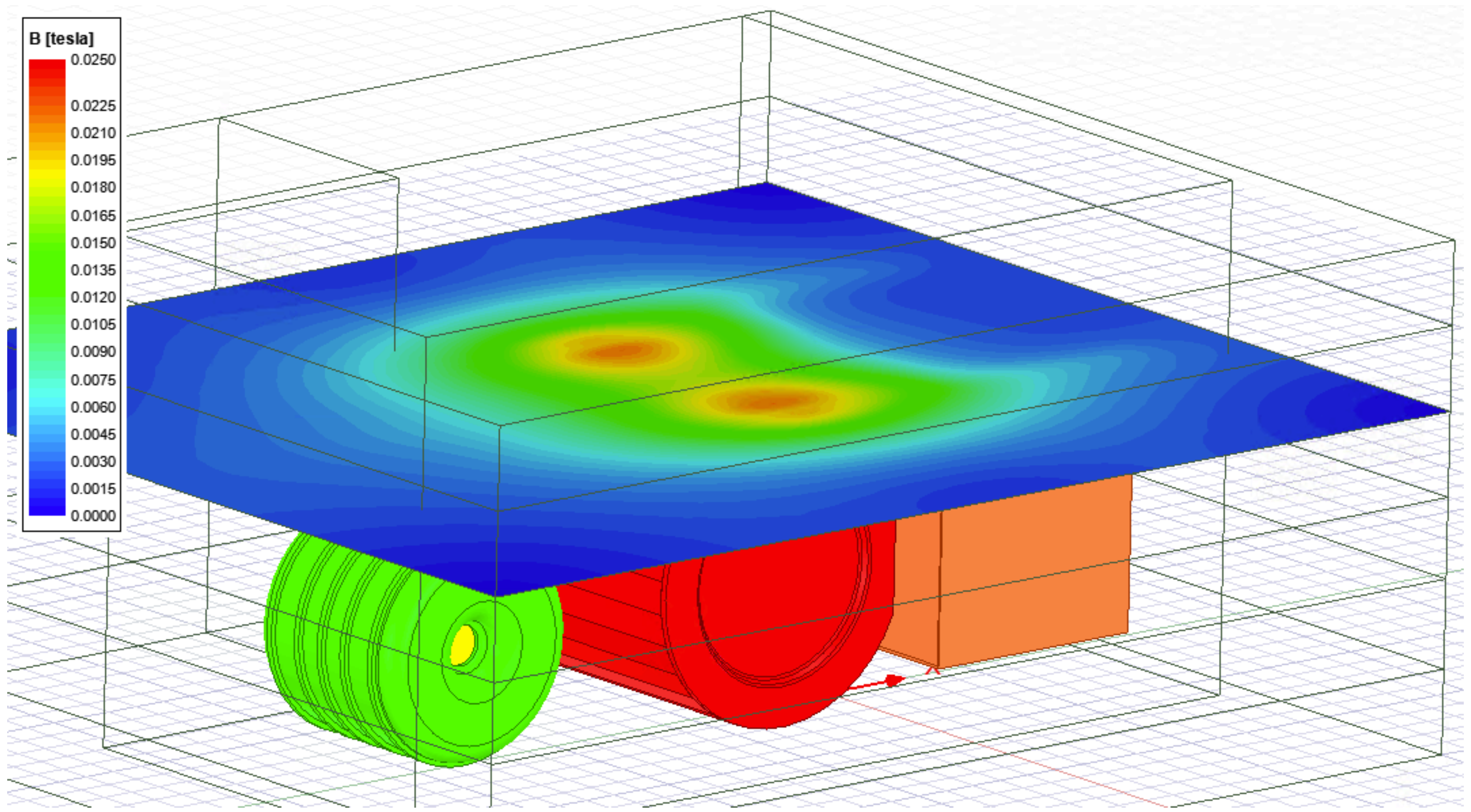
- Field in the active volume is expected in the range 10 - 200 G
  - less than 5% of the volume will see more than 100 G

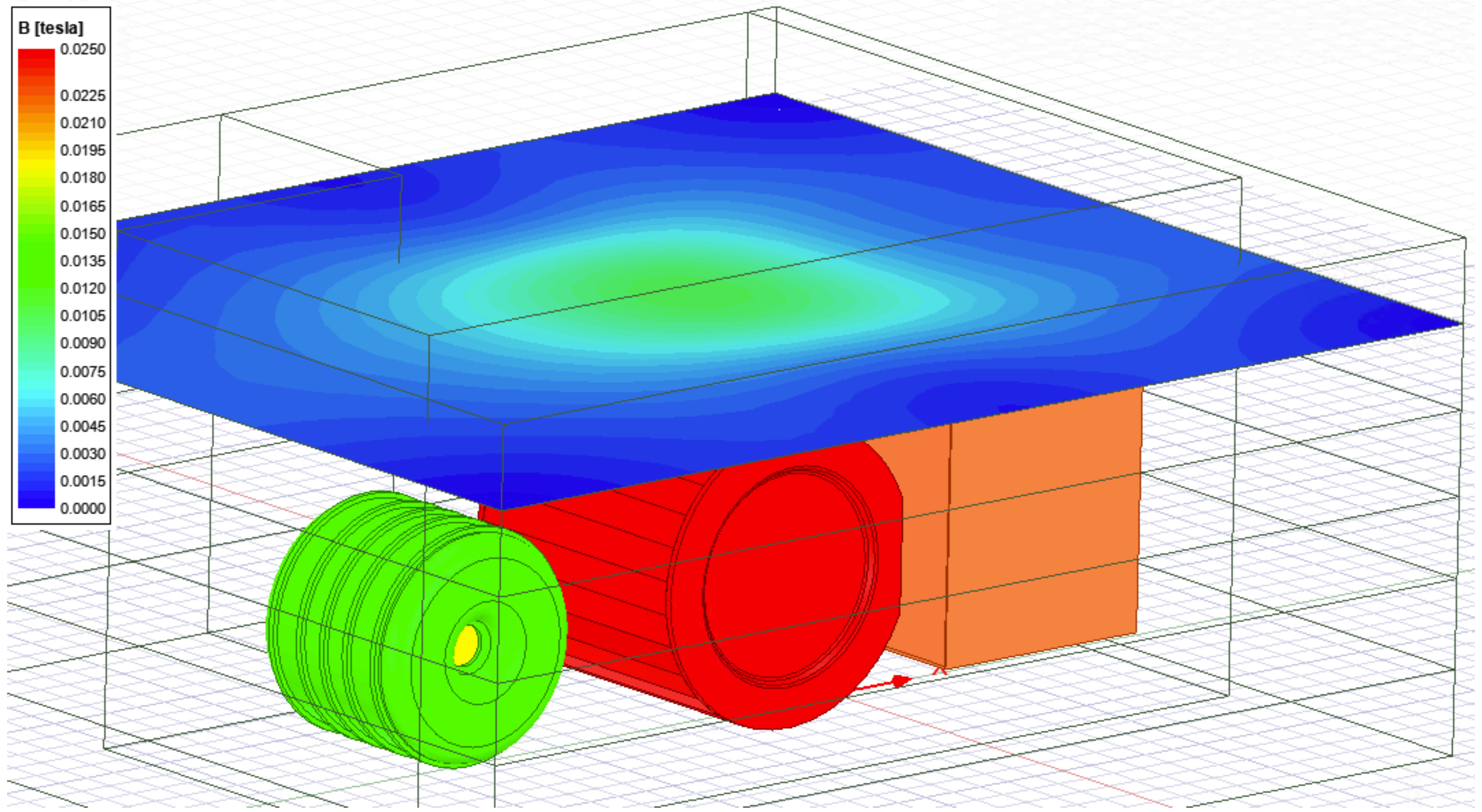
- In the fiducial volume (shown in figure) 20 to 45 G are foreseen



Stray field on front-end electronics

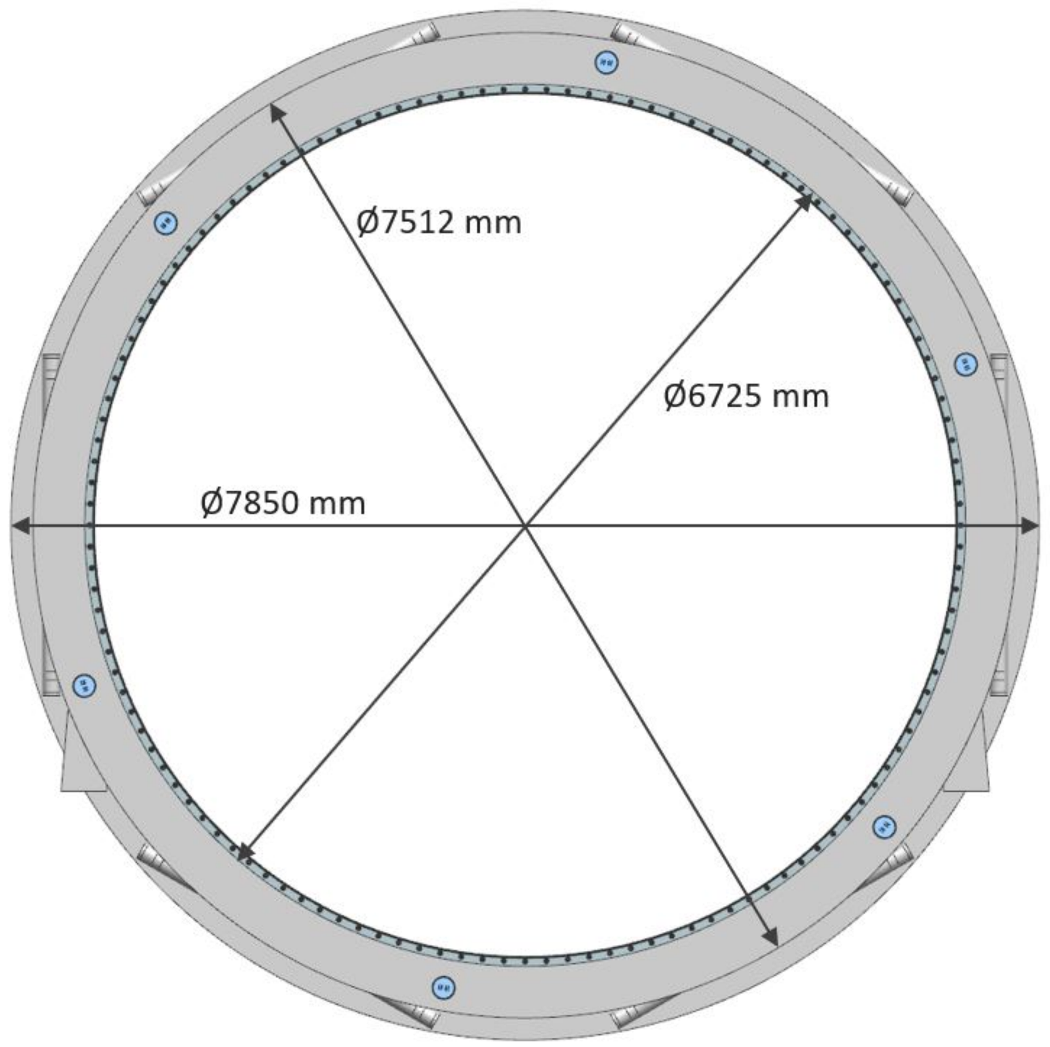
- Immediately above ND-GAr and ND-LAr up to 250 G are expected (left)
- 2 metres above ND-GAr (where front-end electronics will be hosted) less than 100 G are expected (right)

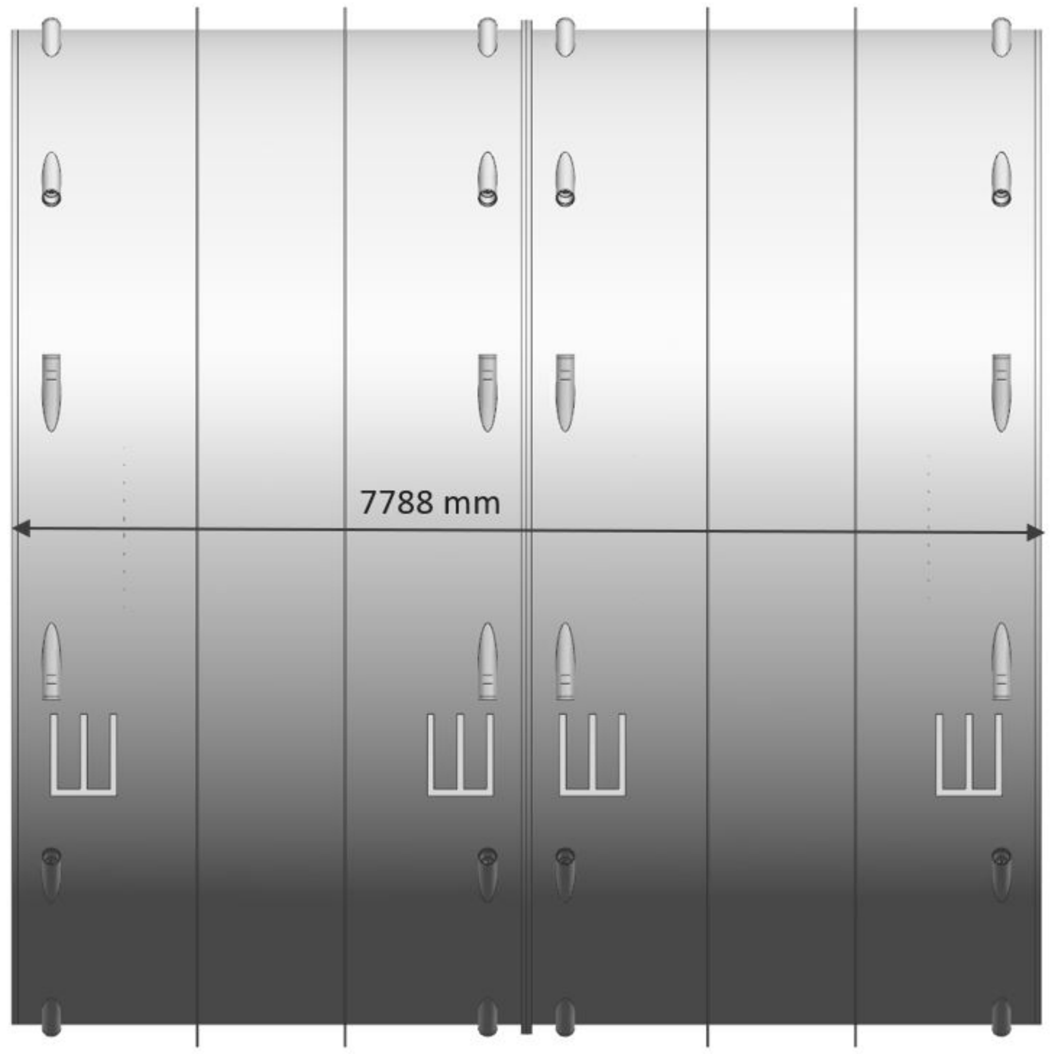


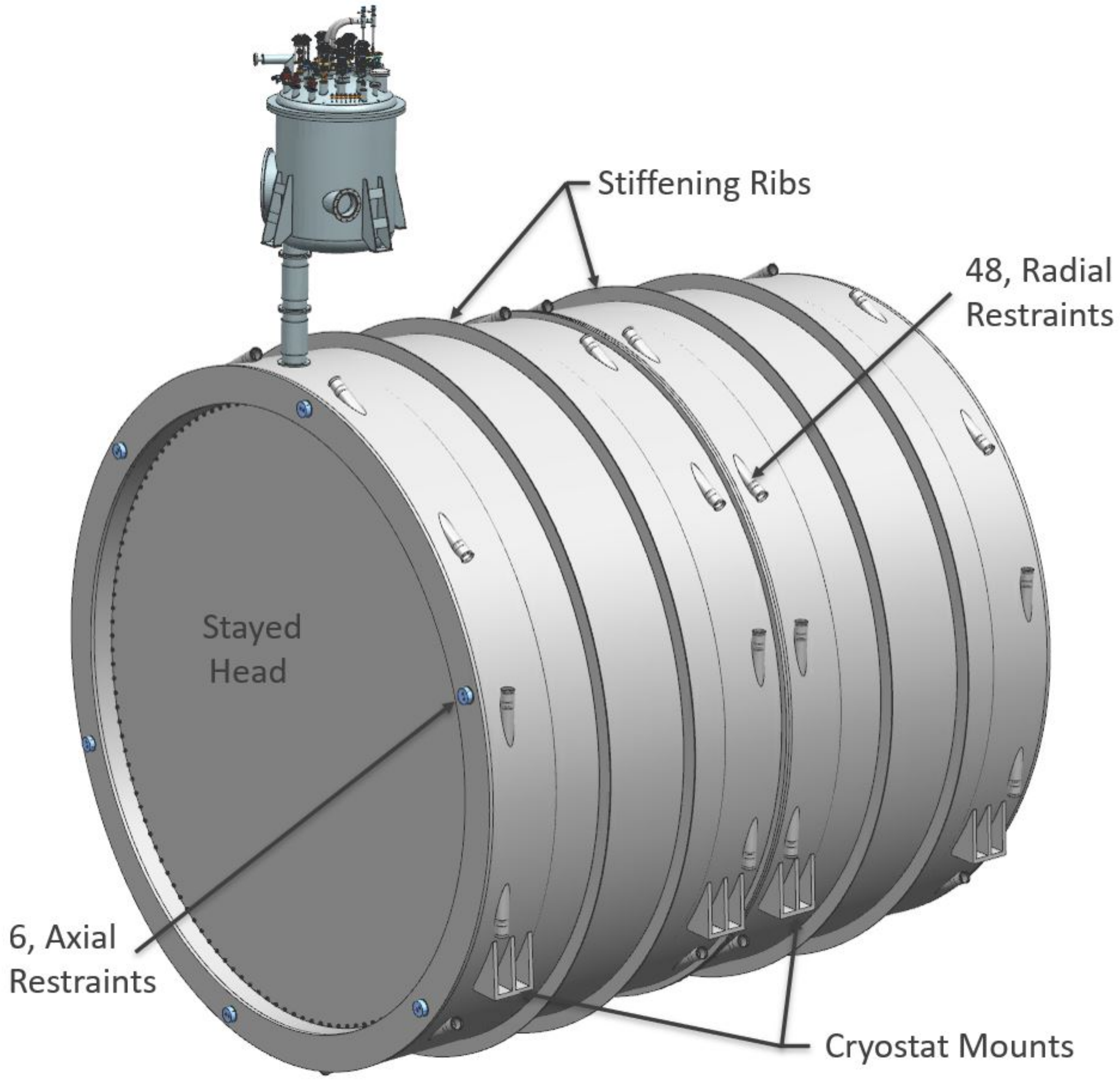


Coil and cryostat mechanics

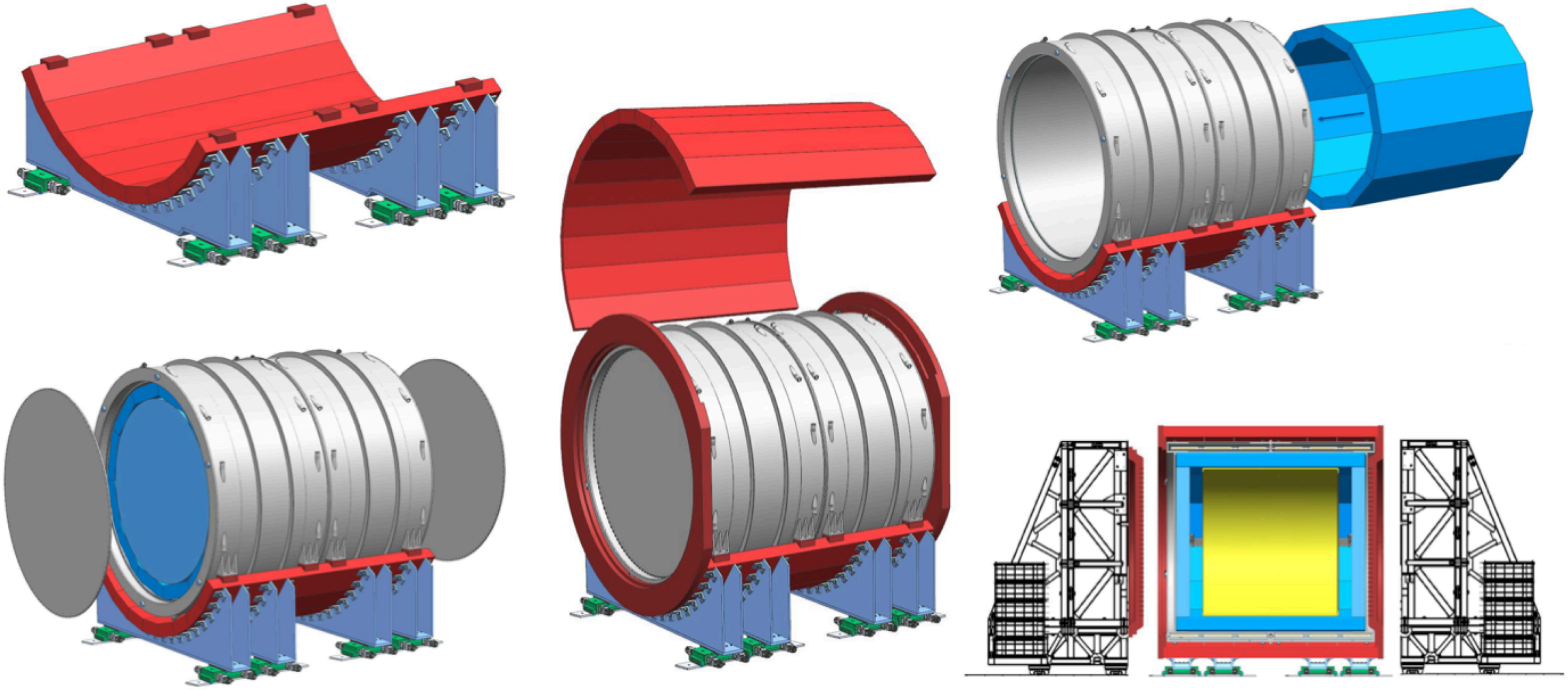
- **The coil is among the largest ever proposed for particle physics**
  - Possibly it will be delivered in two halves and assembled *in loco*
  - End plates will be welded to allow for the containment of high pressure argon gas
  - Proper feed-throughs for cabling are foreseen





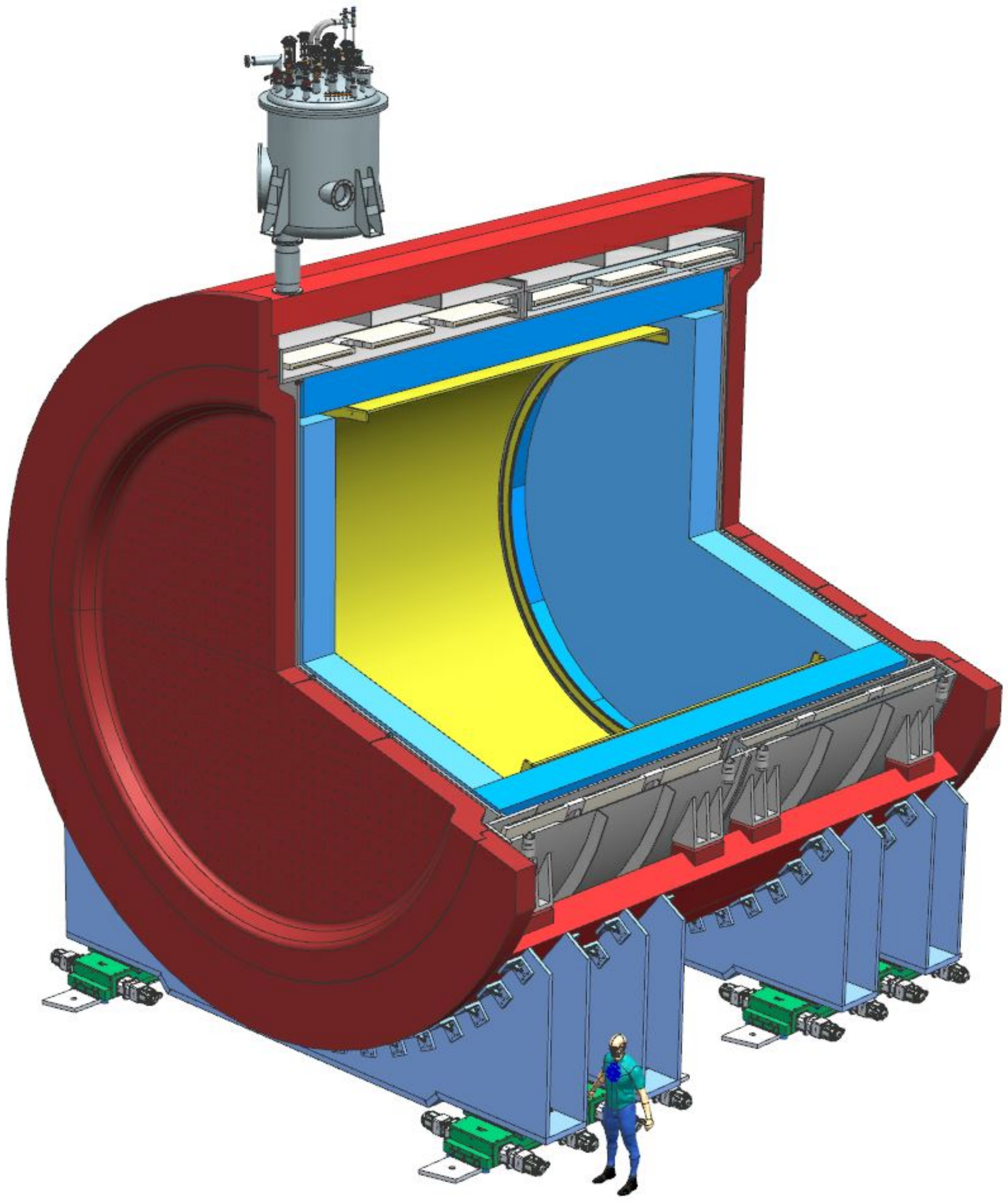


Magnet assembly



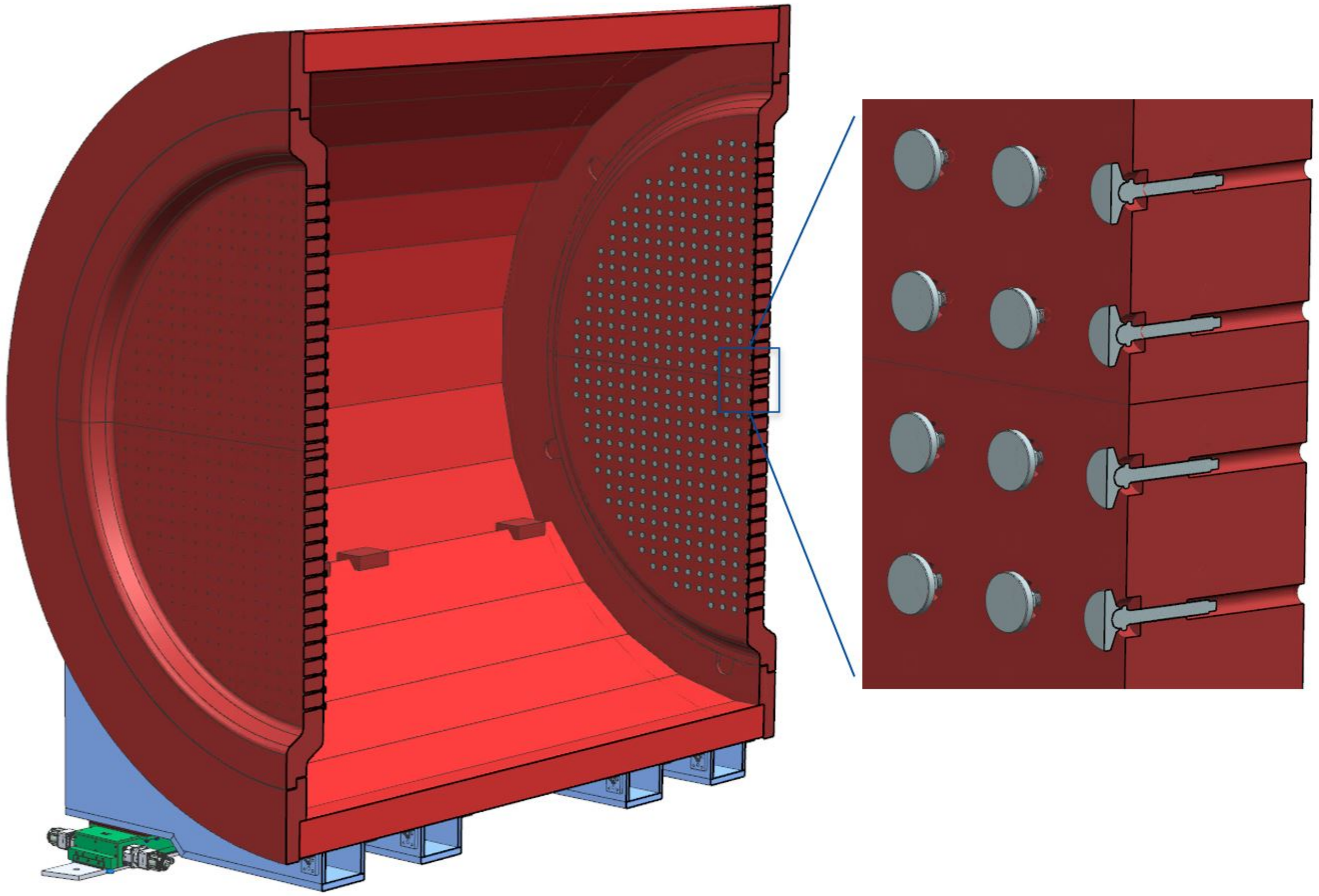
Complete setup

- Movable on 8 Hilman Rollers
- Total mass exceeds **900 tonnes**
- Less than 50 cm on the sides are left
  - big integration effort
  - high pressure vessel integrated with cryostat
  - no domes on the pressure vessel to reduce length
- **Overall size**
  - ~ **7.8 m** wide, ~ **8.6 m** long, ~**11 m** high
- Movable on a 30 metres long path



Stayed heads

- 1596 threaded rod levelling pads are needed to transfer force from pressure vessel end plates to the yoke end-caps
- Detailed FEA studies have been performed to ensure the mechanical reliability of the assembly
- Analyses on vacuum disruption, gas leakages and loads during assembly and movement have been performed

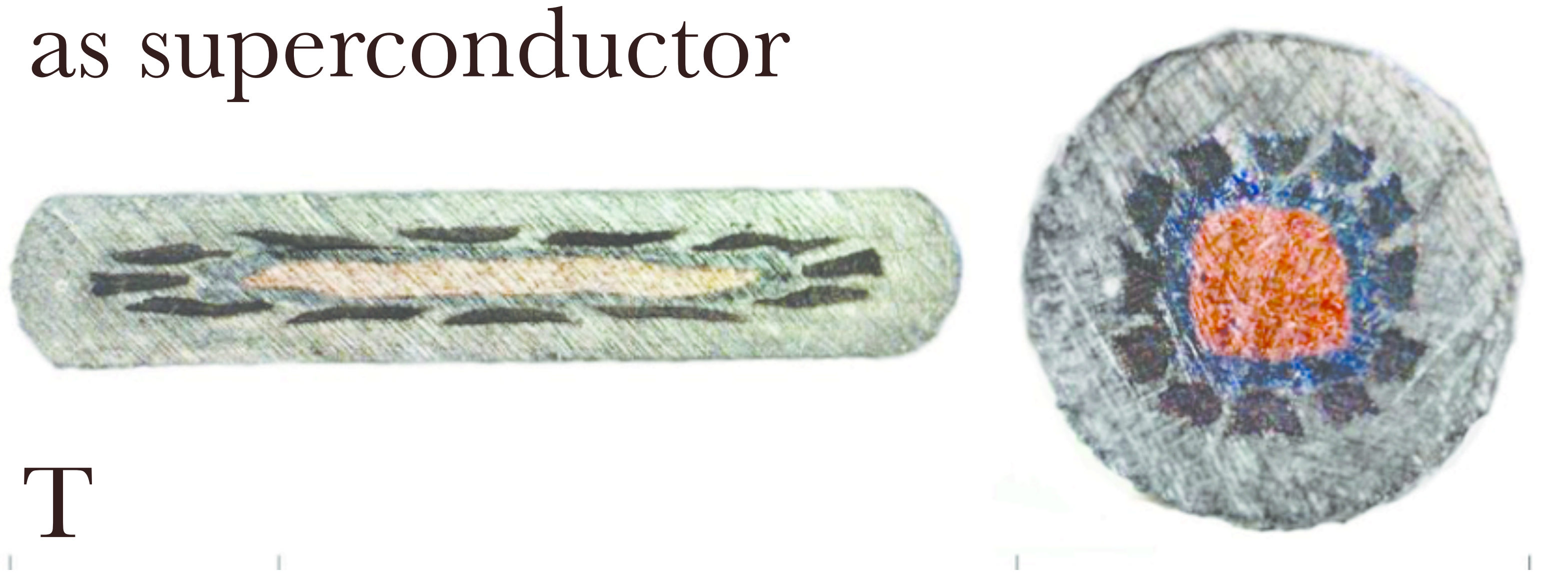


Overall, SPY@DND is an innovative, demanding and state-if the-art magnet for high energy physics experiment

MgB_2 role

- Today, procurement of co-extruded superconducting cable in high purity aluminium is hard

- An alternative could be **magnesium diboride** (MgB_2) as superconductor
  - **higher critical temperature**
  - relatively **low critical field**
    - no issue for SPY@DND, max field on coil below 1 T



- INFN Genova is pursuing a R&D activity to make these cables available

- MgB_2 based cable, if operated at higher temperature, as an example **10 K instead of 4.2,** has a **significantly higher thermal capacity**
  - less needs for stabilisation in pure aluminium → **no co-extrusion needed**
  - cable-in-conduit technique useful to have the proper shape for winding

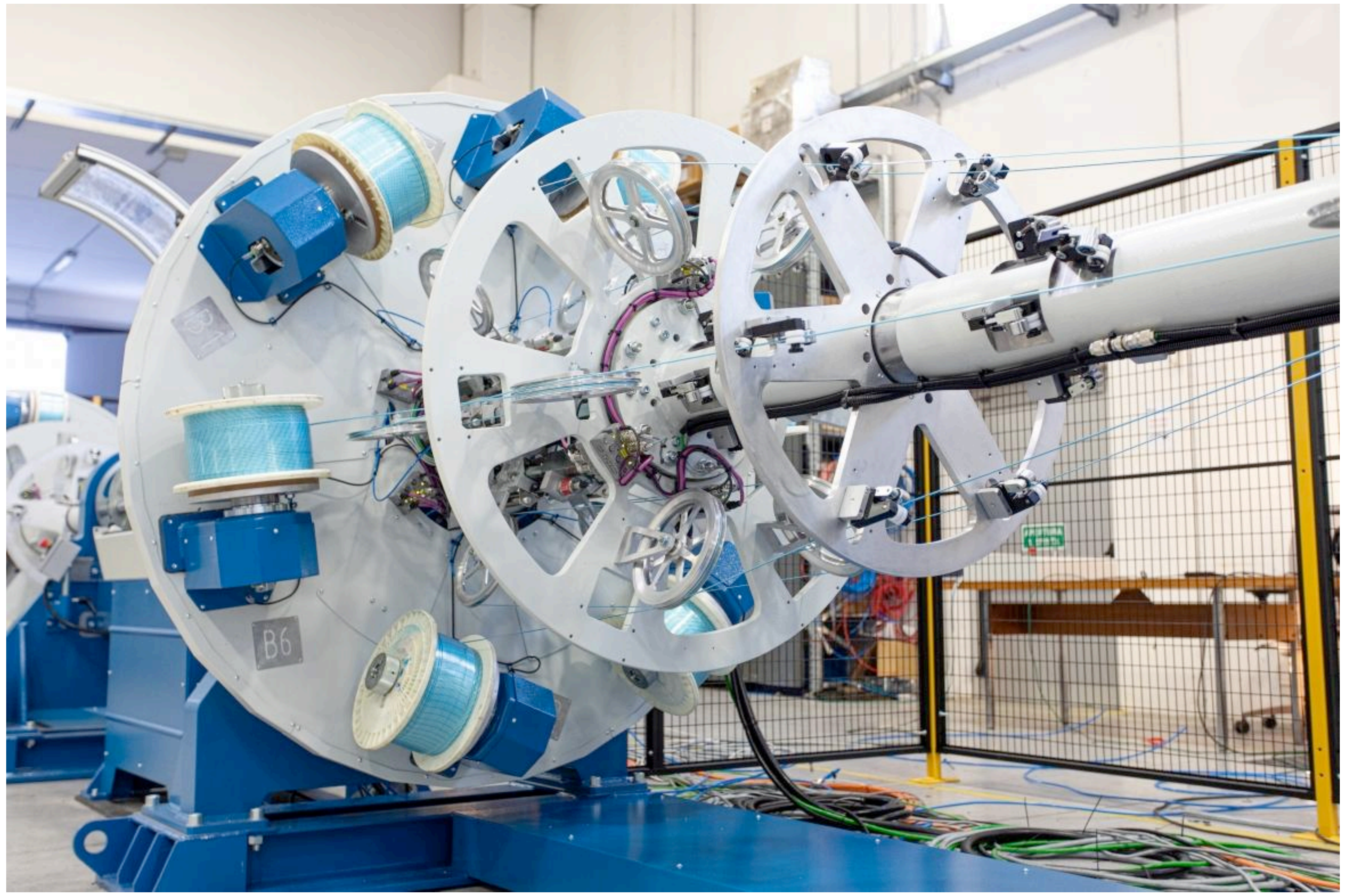
- Depending on the outcome of R&D, a "different" SPY@DND could be envisaged

A MgB_2 based SPY@DND

- No difference in the yoke
- Same technique for winding (internal winding in coil formers)
- Higher operating temperature (no need for liquid helium? simplified proximity cryogenics?)
- Thinner coils (less need of stabiliser)
- Two layers instead of one ("square" cable could be easier to be built), no effect on field
- Cost is an unknown: presently MgB_2 wires are more expensive than NbTi strands (for the same current), but for a sufficiently large batch we expect to have a very similar price figure
- SPY@DND estimated cost was 15 - 20 M$ before Russia-Ukraine war

MgB_2 cable R&D

- The R&D activity is starting
- Several stages foreseen:
  - cable **geometries** simulations for 2 to 5 kA at 2 T and 10 K
  - production of short **samples** with several geometries
  - evaluation of current transport capability after cabling and bending
  - identification of best **geometries** and longer samples production
  - evaluation of **wind-ability and soldering**
  - tests on **joints**
  - production of **long samples** of a selected cable geometry, sampling to evaluate process reliability and production of a small coil, possibly to be used in some real experiment



- The complete R&D activity is expected to be at least last **3 years long**
- The **expected outcome is a cable that can replace NbTi** co-extruded in particle detectors magnets
- The expected **cost** of this R&D is evaluated to be **~ 1.5 M$**

Some remarks on time scales

- Construction of SPY@DND is expected to last 3 years from the signature of the contract to the delivery at Fermilab
- R&D on MgB_2 cables is expected to last not less than 3 years from the purchase of the cabling machine (presently we are performing a market survey)
- Other experiments have shown interest in MgB_2 based magnets for high energy physics, mainly to replace resistive magnets
- SPY@DND might not be the first magnet built with MgB_2 based cable
- If R&D is successful and main project funded, **well on time to deliver such it for Phase 2**

Thank you