Budker Institute of Nuclear Physics

Design and production of the PANDA solenoid magnet

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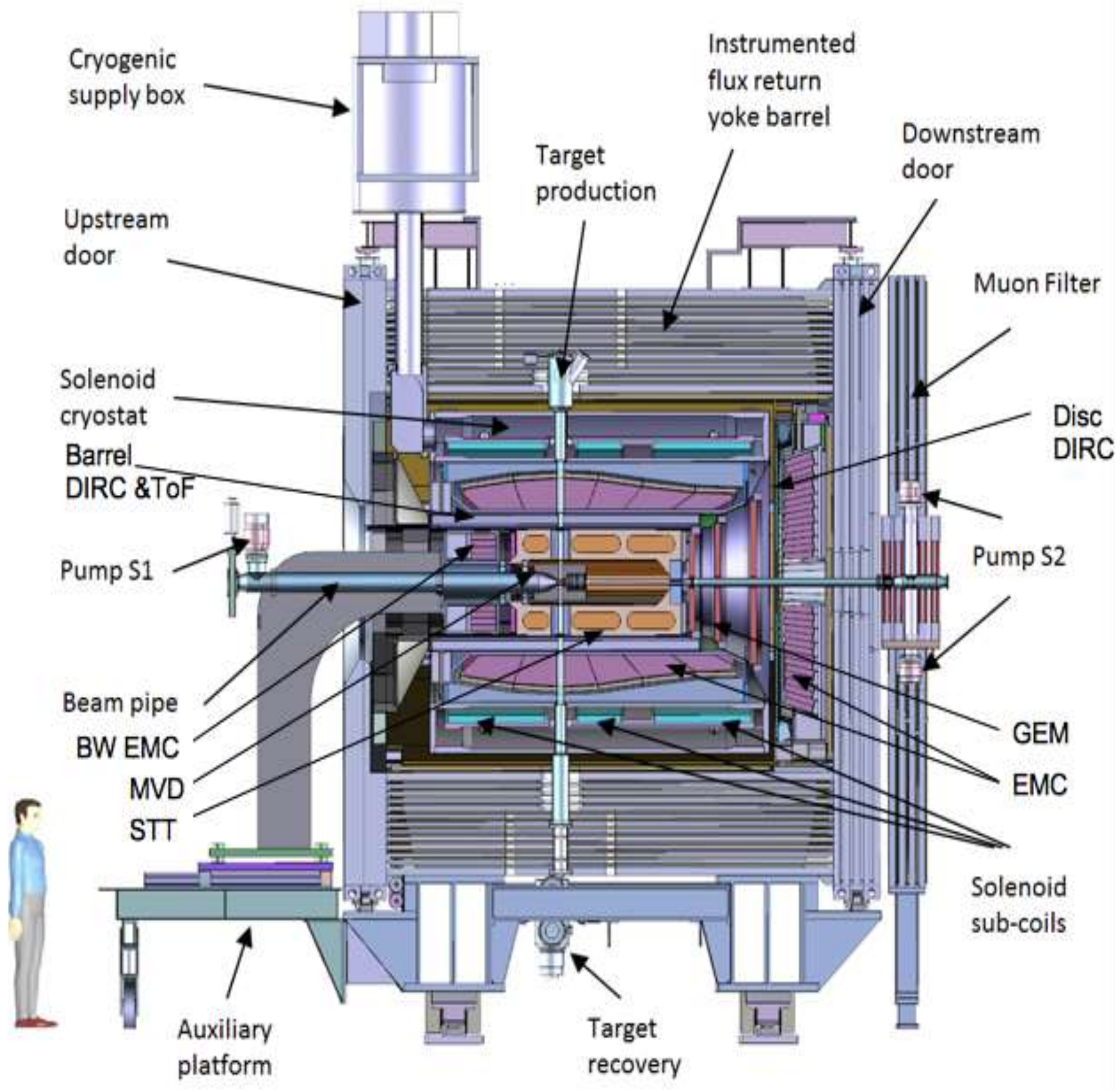
PANDA solenoid magnet

The PANDA solenoid is designed to provide a magnetic field of 2 T with a uniformity of ± 2% and radial magnetic field integral in the range 0 to 2 mm over the central tracking region. The magnet is characterized by a warm bore of 1.9 m diameter, a free length of 4 m and 22.4 MJ of stored energy.

Since PANDA is a fixed target experiment, the main technical challenge is the insertion of a warm target pipe vertically to the solenoid axis in correspondence with the interaction point located at 1/3 of the length of the solenoid. In order to meet the above requirement while satisfying the magnetic field homogeneity constraints, the magnet is split in 3 interconnected coil modules.



Artistic view of the solenoid magnet including detector systems

The main milestones of production of the PANDA solenoid magnet

The scope of delivery includes:

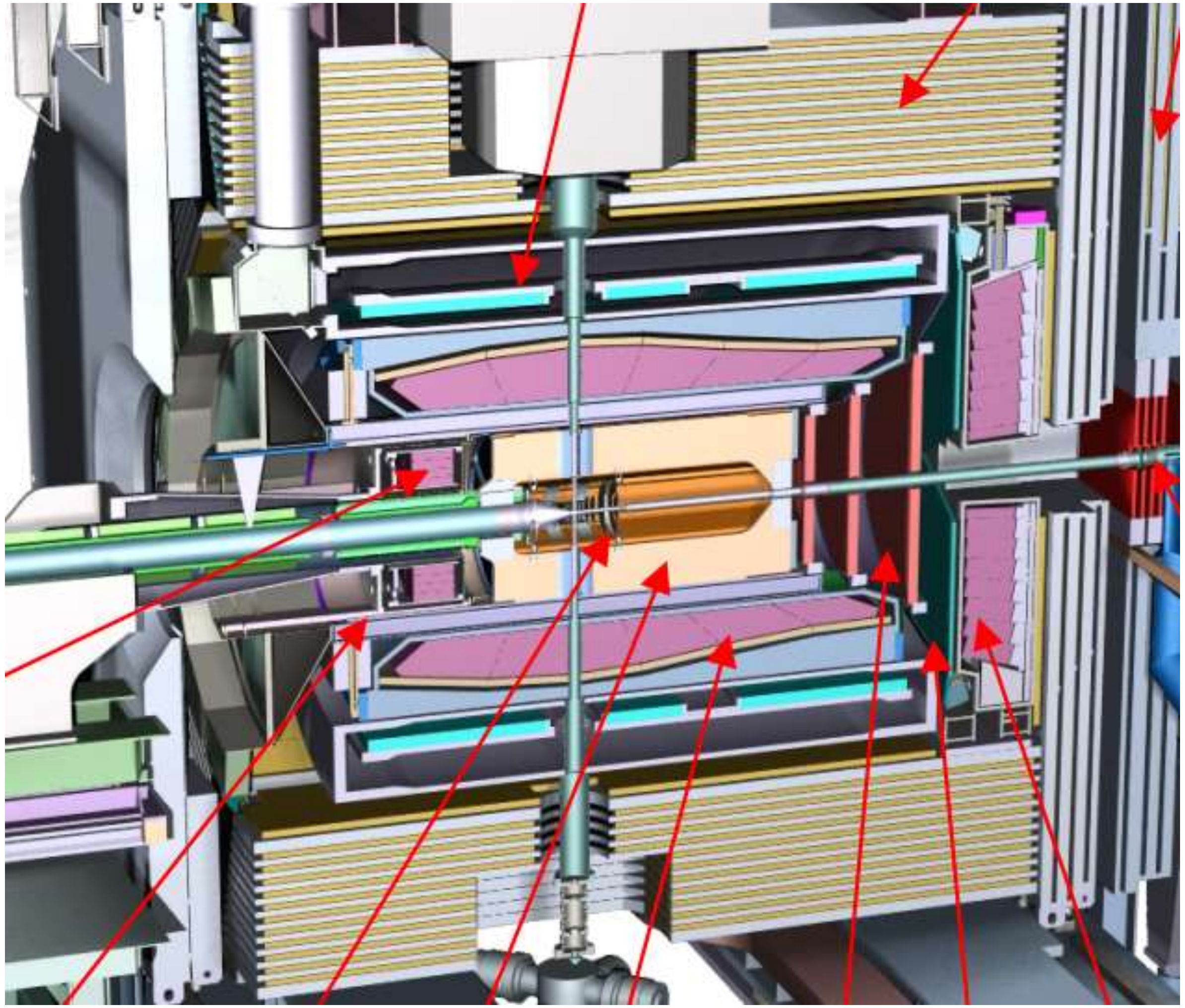
- Magnetic and engineering design of the magnet including tools and support;
- Production and delivery of the magnet (consisting of yoke, cold mass and cryostat, alignment components, proximity cryogenics, support frame and platform beams) and all tools;
- Power converter and quench protection and instrumentation.

Item	Date
Start contract	03/2017
Control assembling of the Yoke of solenoid at the BINP site	09/2020
Magnetic tests of the PANDA solenoid including safety system and electrical components at BINP (additional contract)	07/2021 - 05/2022
Assembling and tests at the FAIR site	
Assembling of the magnet at Darmstadt	06/2022
Acceptant tests at FAIR	08/2022
Installation of the PANDA solenoid magnet at worked position and final acceptance tests	01-05/2023

Magnetic field

A few detectors are located inside the cryostat - the barrel DIRC detector, barrel Time of Flight, Straw Trube Tracker and Micro Vertex Detector.

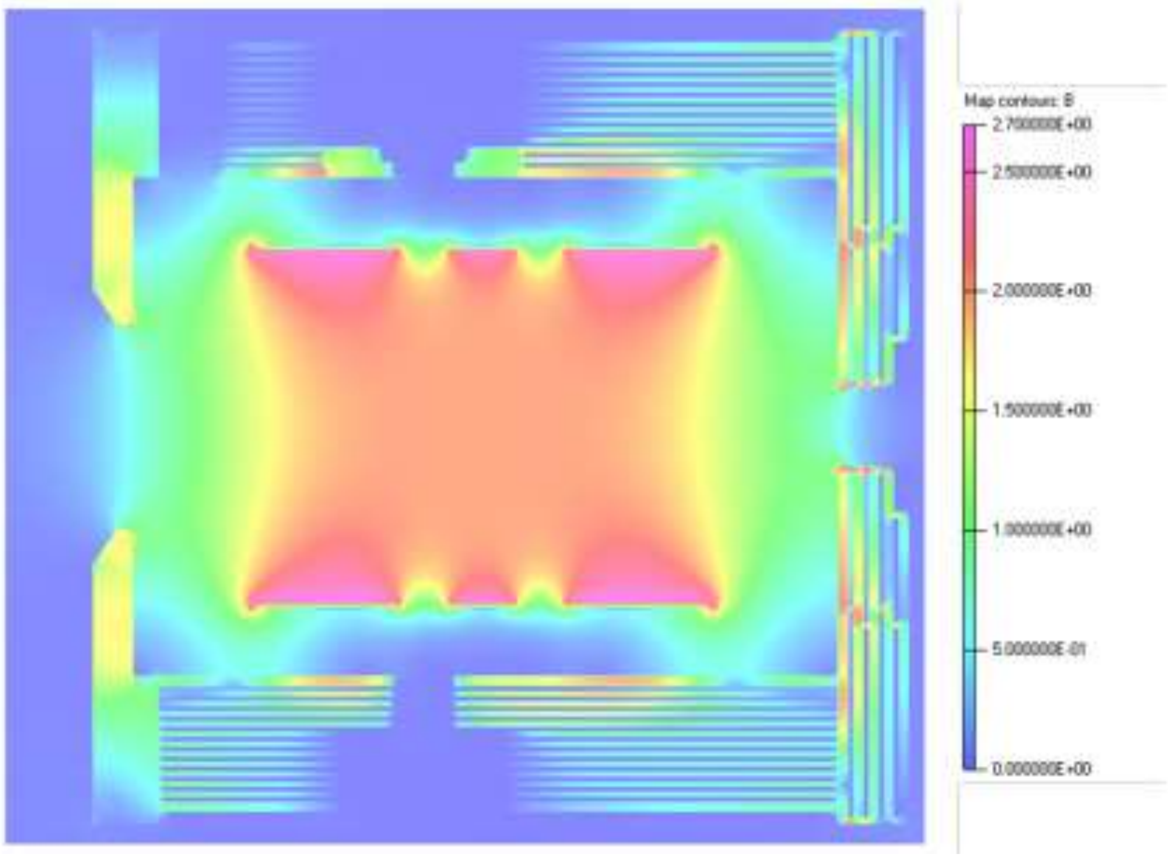
In the region occupied by the MVD and the central tracker there are very stringent requirements for the magnetic field homogeneity. According to these, the absolute magnitude of the field shall not vary by more than 2% from the nominal field of 2 T over the whole tracker region, which is the main aim of the magnet design.



Barrel DIRC and ToF

MVD STT EMC

Magnetic field



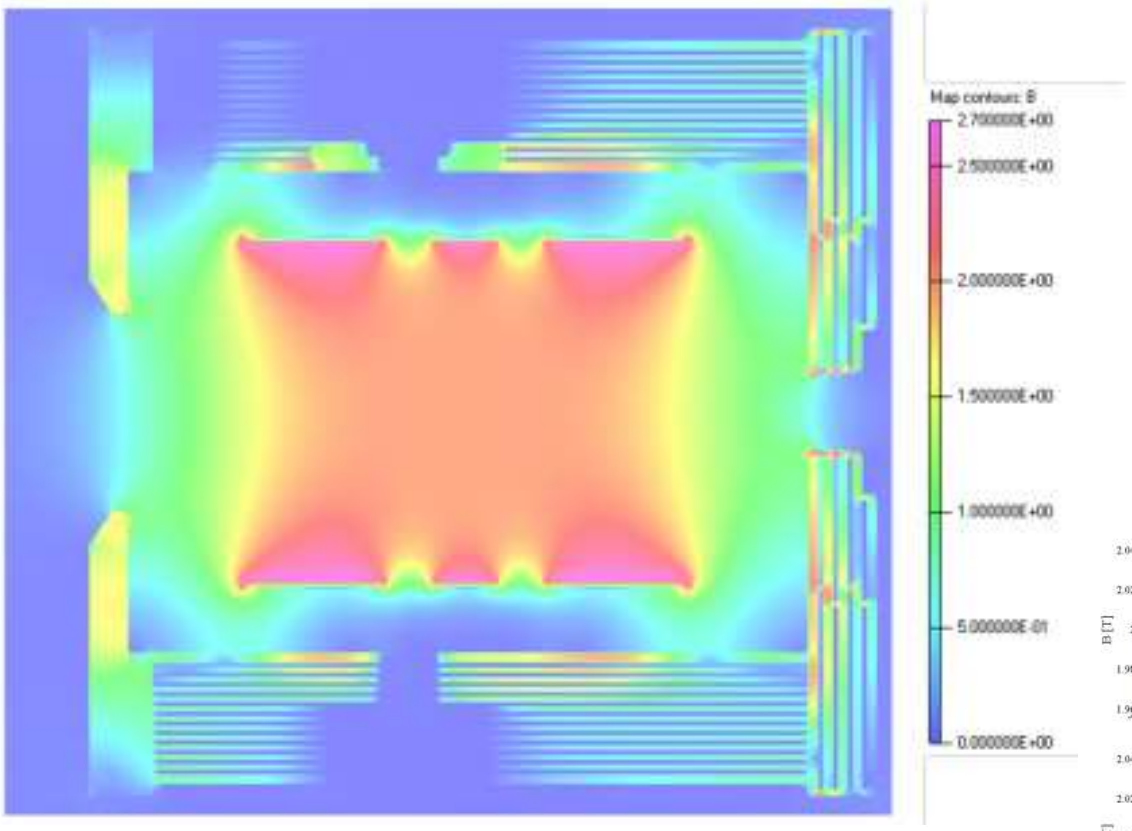
Magnetic flux density distribution in the YZ-plane of the PANDA detector.

The design has been revised by CERN for improved stability as well as simpler and cost optimized winding and assembly procedures. The optimization has been carried out considering the additional constraint that, due to the advanced design state of the other detector components, the solenoid layout could not be heavily modified. In particular, the changes applied to the size of the coil envelop and operating current had to be minimized.

As result the conductor and coil designs were developed and used for production of the magnet.

Magnetic measurements were made by our colleagues from JINR and presented in the TDR. The evaluation measurements made at BINP show good agreement with these results.

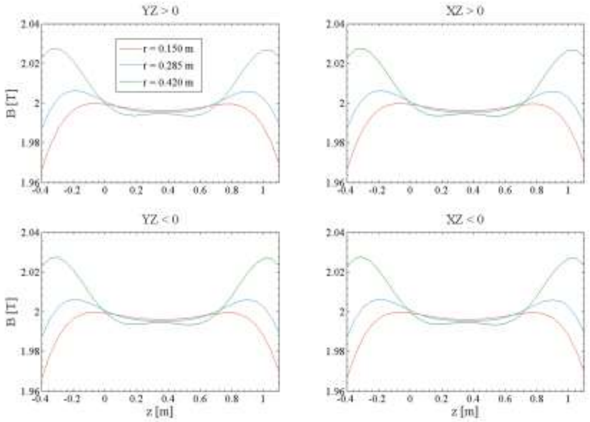
Magnetic field



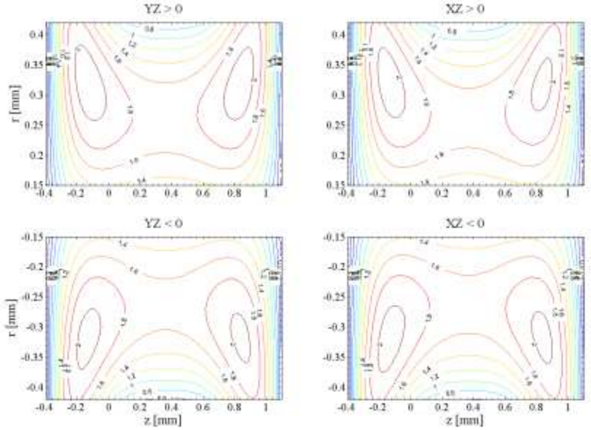
Magnetic flux density distribution in the YZ-plane of the PANDA detector.

Criteria	Absolute Value	Definition
Micro Vertex Detector		
Dimensions, longitudinal: $-0.25\text{m} < z < 0.2\text{m}$, radial: $0.0\text{m} < r < 0.12$ m		
$\frac{\Delta B}{B_0} < 2\%$	$\Delta B := \lvert B(r,z) - B_0 \rvert$	B_0 := nominal field, *i.e.* 2 T $B(r,z)$:= field at any point in given region
Central Tracker		
Dimensions, longitudinal: $-0.4\text{m} < z < 1.1\text{m}$, radial: $0.15\text{m} < r < 0.42$ m		
$\frac{\Delta B}{B_0} < 2\%$	$\Delta B := \lvert B(r,z) - B_0 \rvert$	B_0 := nominal field, *i.e.* 2 T $B(r,z)$:= field at any point in given region
$I_B(r,z_0) < 2\text{mm}$	$I_B(r,z_0) := \int_{z_0}^{-400} \frac{B_r(r,z)}{B_z(r,z)}\, dz$	$z_0 :=_{any}$ z value in region B_r, B_z := radial, long. field components, resp.

Requirements to magnetic field for MVD and Central Tracker

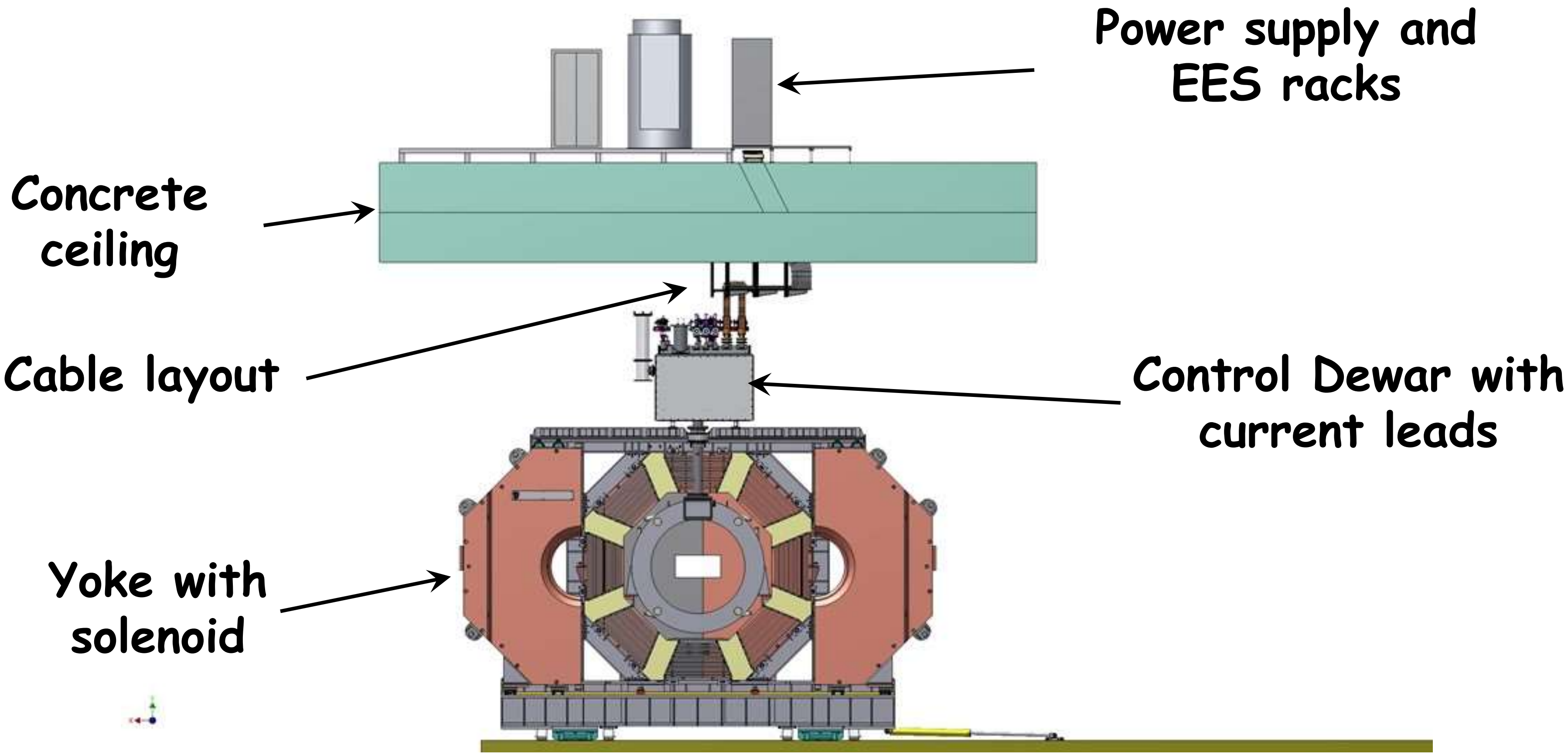


Magnetic flux density distribution in the Central Tracker volume in the XZ and YZ planes.



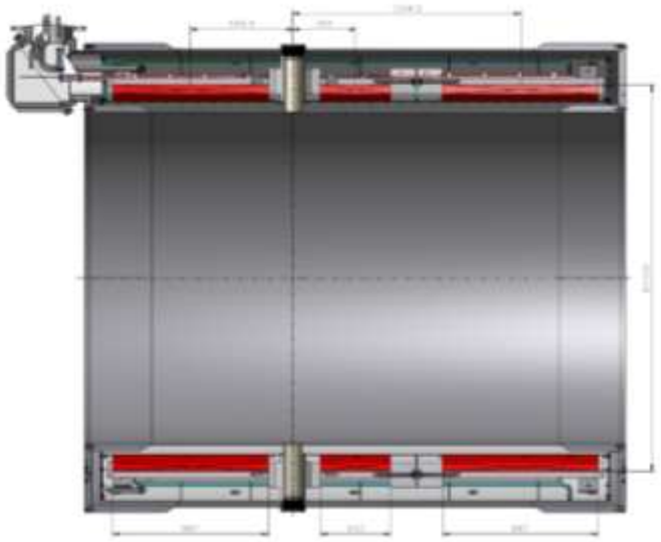
Radial field integral in the Central Tracker volume in the XZ and YZ planes.

The views of the PANDA Solenoid



The PANDA Solenoid parts.

Cryostat and cold mass of the PANDA solenoid magnet



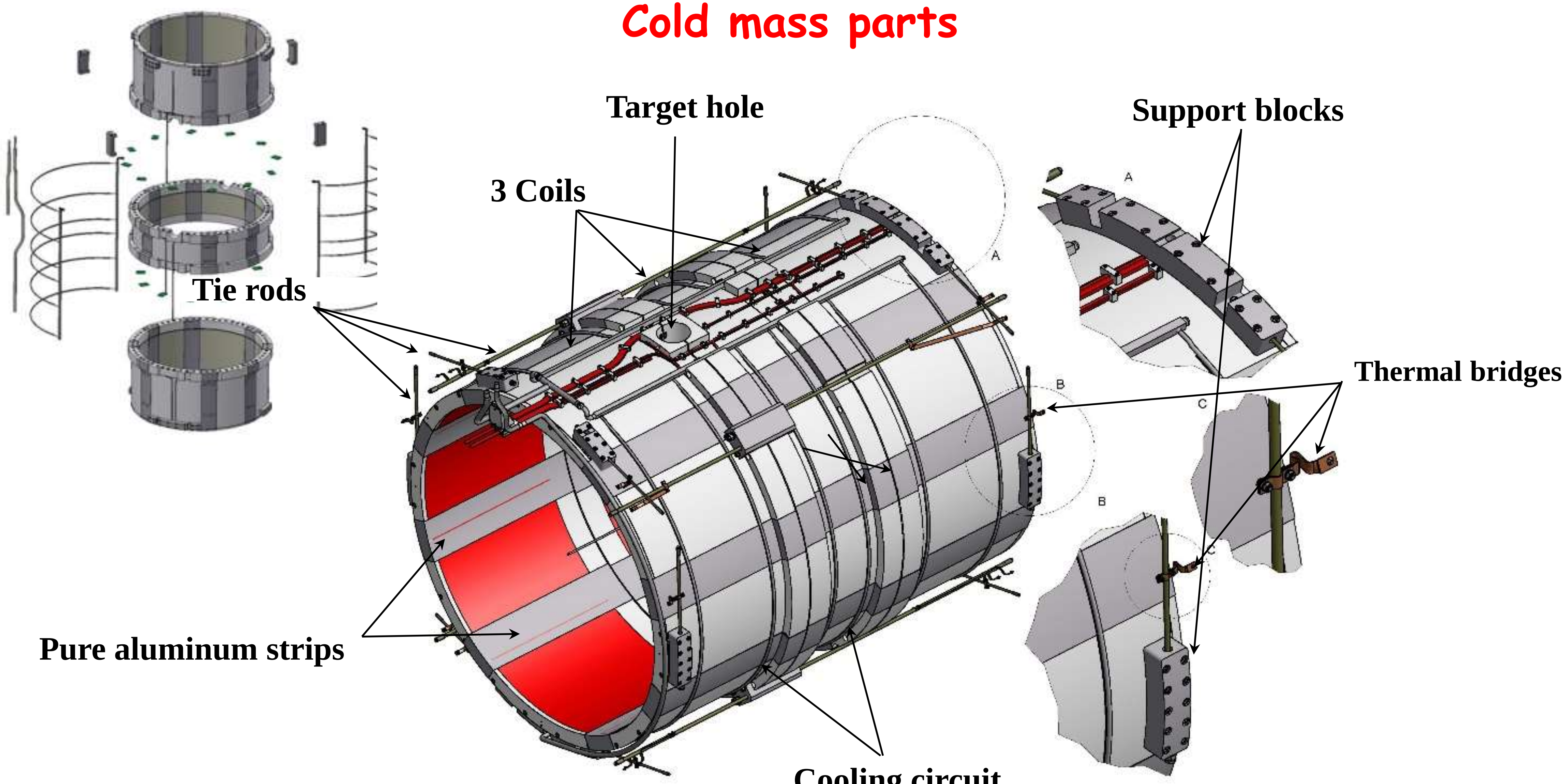
3D model PANDA solenoid.

Parameter	Unit	Value
Outside diameter	мм	2680
Inner diameter	мм	1900
Length	мм	3090
Magnetic field in coil	T	3
Current	kA	5
Stored Energy	MJ	22,4
Weight	t	14.5

Axial length variation [mm]	B_{peak} [T]	δ_{max} [%]	Int_{max} [mm]	F_{axial} [kN]
- 6	2.67	1.63	2.03	-36.9
- 3	2.67	1.65	2.07	-37.0
0 (nominal)	2.66	1.67	2.10	-37.1
+ 3	2.65	1.70	2.13	-37.2
+ 6	2.65	1.72	2.17	-37.2

Outer diameter of coils is 2200 mm,
length: two coils - 887 mm, one – 400 mm.

Cold mass parts

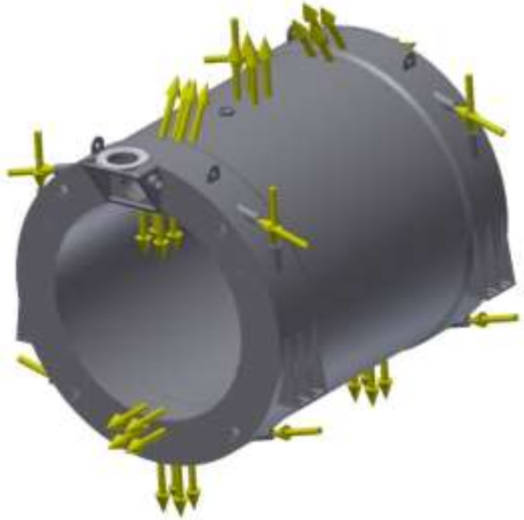


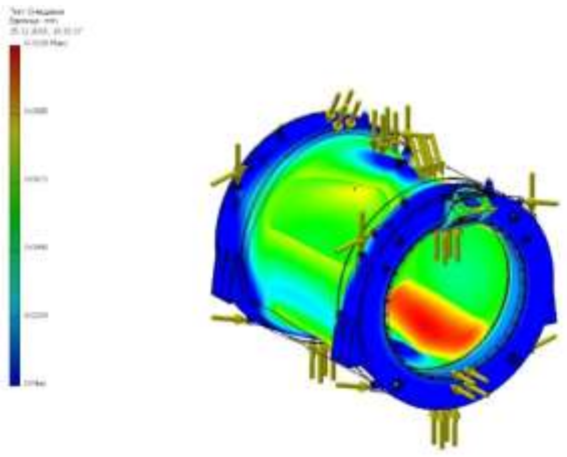
3D model of the PANDA cold mass.

Results of the calculations of the Cryostat.

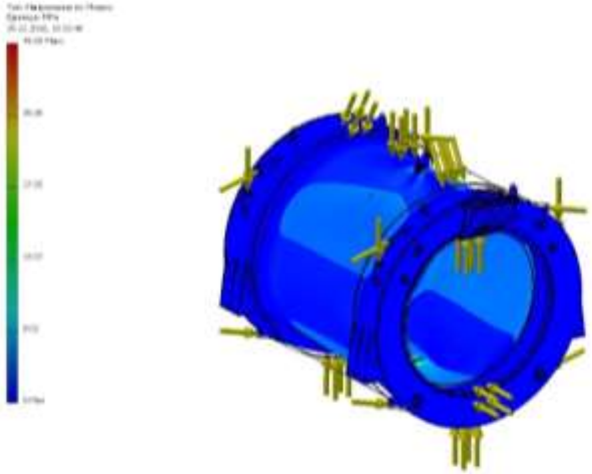
Results of calculation of the Cryostat.
Operation condition (p=0.1 Mpa, the weight of Cold mass is 57 kN, the initial tightening force is 3.7 kN)

Results of calculation of the Cryostat.
Operation condition (p=0.05 Mpa, the weight of Cold mass is 57 kN, the initial tightening force is 3.7 kN)

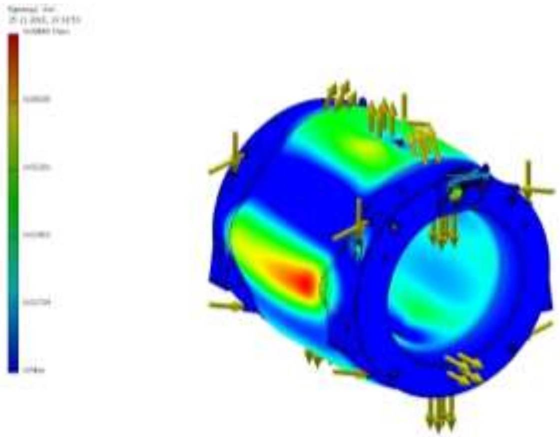




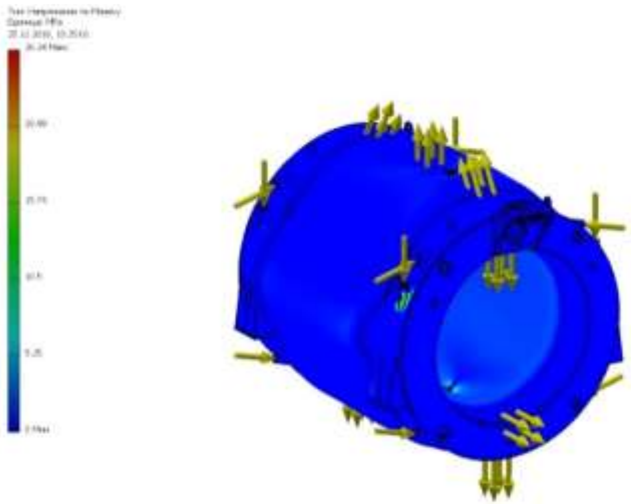
The maximum deformation is 0,1 mm.



The maximum equivalent stress is 45 MPa.

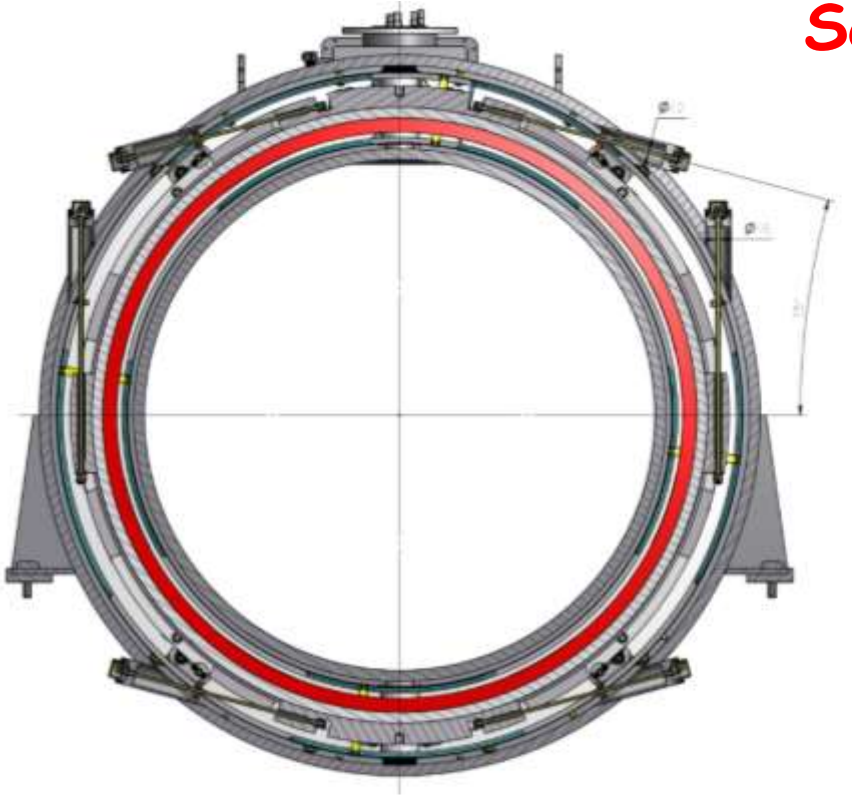


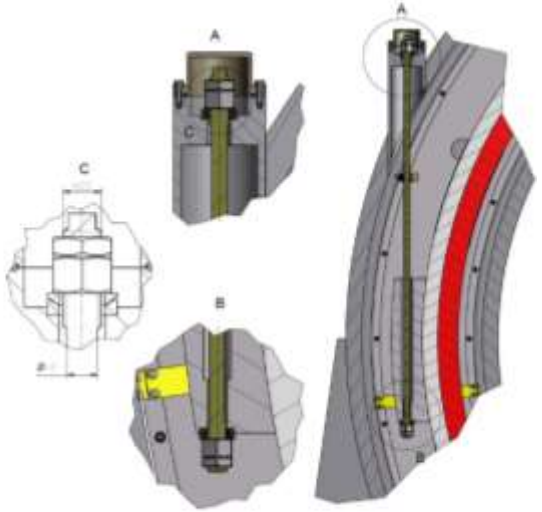
The maximum deformation is 0,08 mm.



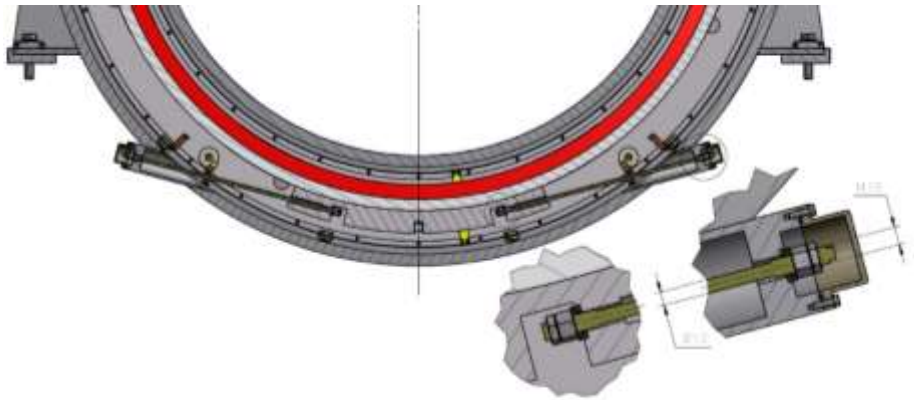
The maximum equivalent stress is 26 MPa.

Scheme of fixation of the cold mass.



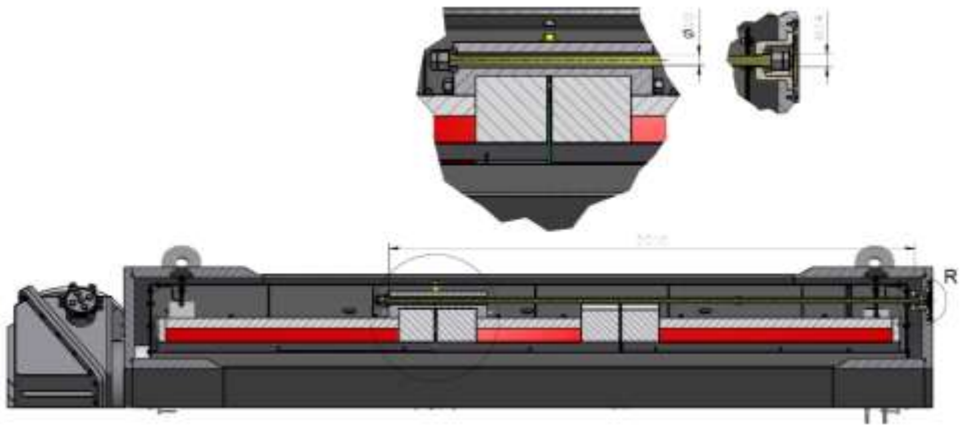


The diameter of suspension is 16 mm, the length is 840 mm.



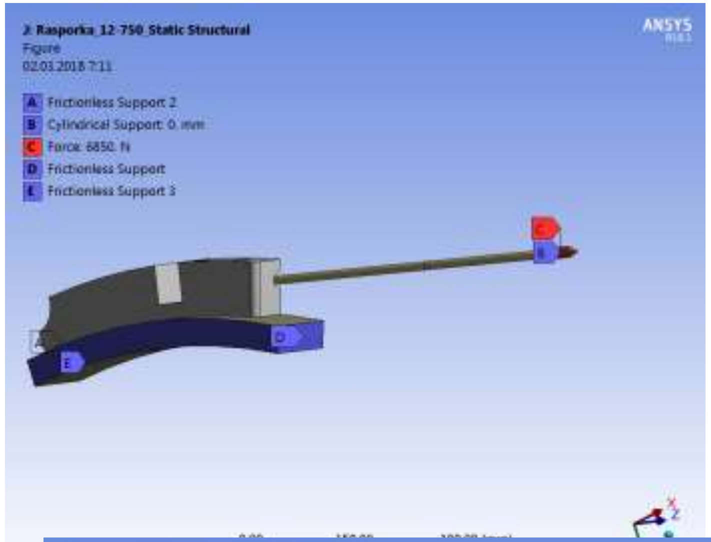
In the radial direction the Cold mass fixed with help radial rods. The diameter of radial rods is 12 mm, the length is 720 mm.

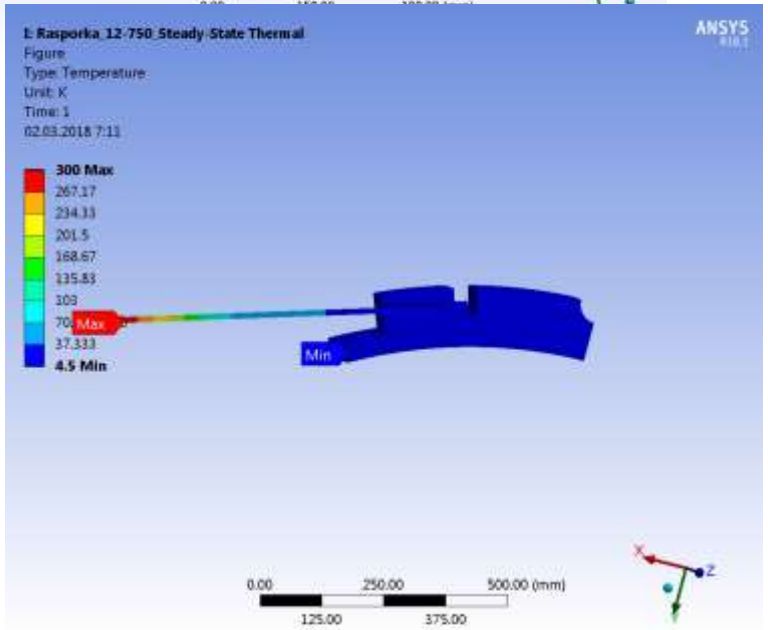
Cold mass is based into Cryostat with help suspensions and axis rods. Material of rods is Ti-5Al-2.5Sn

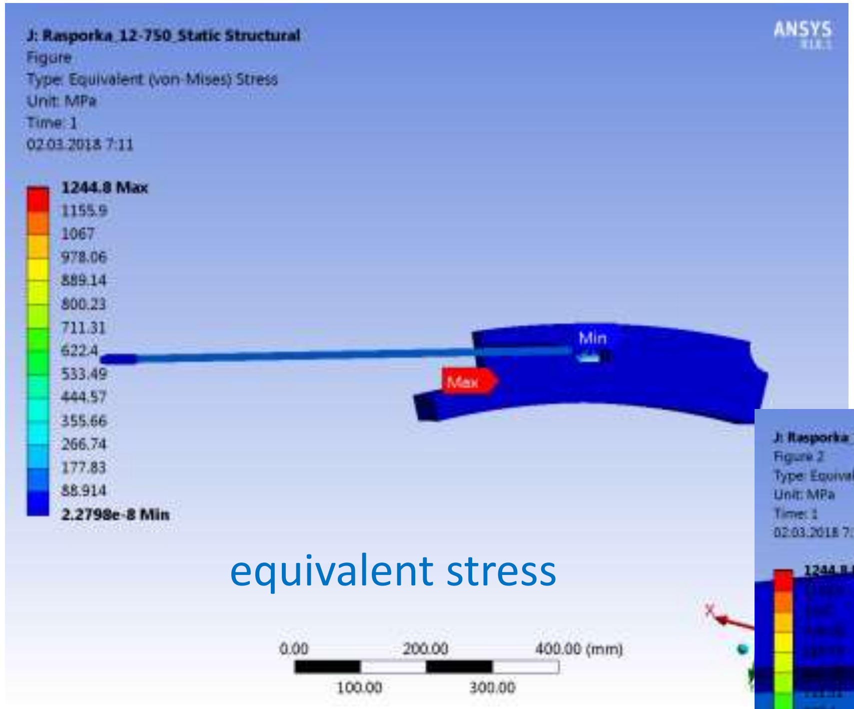


In the axial direction the Cold mass is fixed with help longitudinal rods. The diameter of longitudinal rods is 20 mm, the length is 2010 mm downstream side and 1120mm upstream side.

Results of calculation of the radial rods.





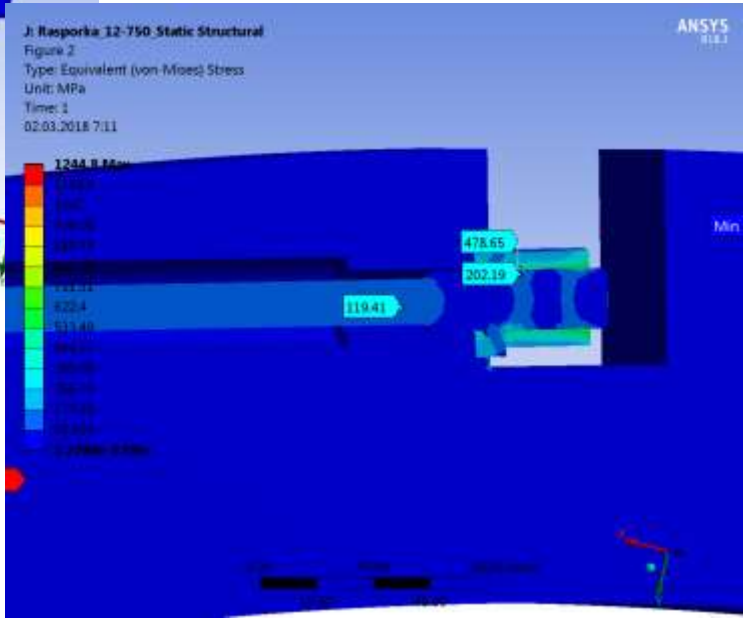


The equivalent stress of radial rods is ~120 MPa.

Maximum radial decentering magnetic force of 51 kN.

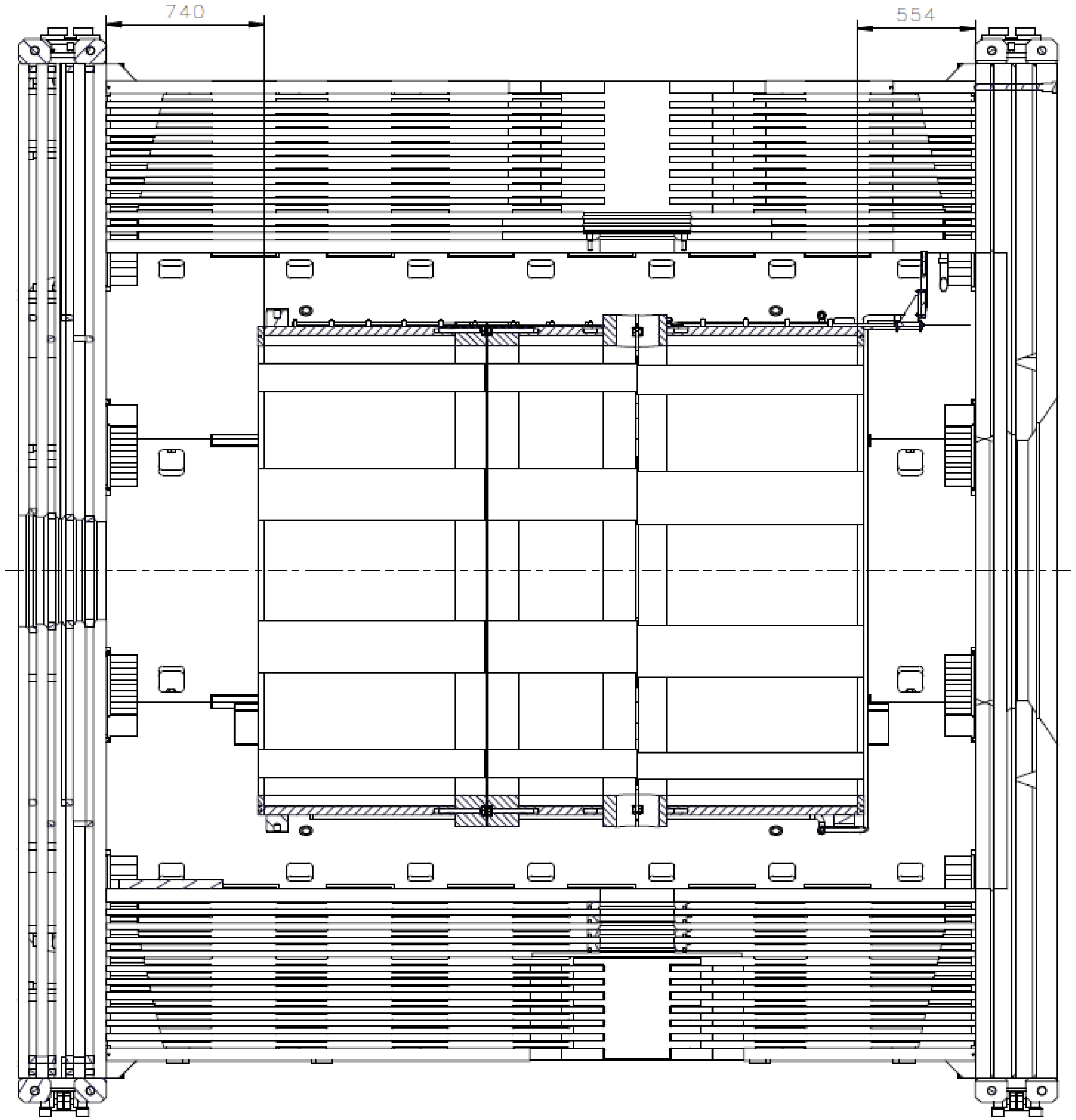
The initial tightening force is 3.7 kN.

Temperature distribution 4,5-300K.



The maximum equivalent stress is 178 Mpa of the support blocks.

Diagram of position of the target`s axis after cool down and max magnetic forces.



The maximal displacement of the Cold mass is 0,95 mm to upstream direction

Upstream side

Magnet position into the yoke.

Misplaced, cm	Lorentz force, t	Sesmic, t
+- 0	4	+- 1
+- 2	14	+- 1

Thermal loads of the cold mass

T=4.5 K	Thermal load, W
Radiation	2.2
Heat inflow to the cold mass supports	2.52
Conductor joints	<0.5
Gas load	0.5
Eddy current losses in the Al cylinder	11.5
Eddy current losses in the conductor	0.09
LHe vessel, tubing, valves, supports, wiring	3.3
Transfer line	9.7
Total (worked condition/extraction energy regime):	20.1/31.7

Thermal loads of the cold mass and thermal shields of the PANDA solenoid are summarized in Tables for operation conditions and in case of energy extraction during 2000 seconds.

Heat loads of 4.5K surfaces.

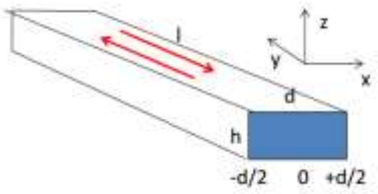
T= 60 K	Thermal load, W
Radiation	62.4
Heat intercepts of the coil supports	33.4
Shield supports	91.2
Gas load	2
Wires	1
Thermal screen, valves, supports	36.5
Transfer line	14.1
Total:	240.6

Heat loads of 60K surfaces

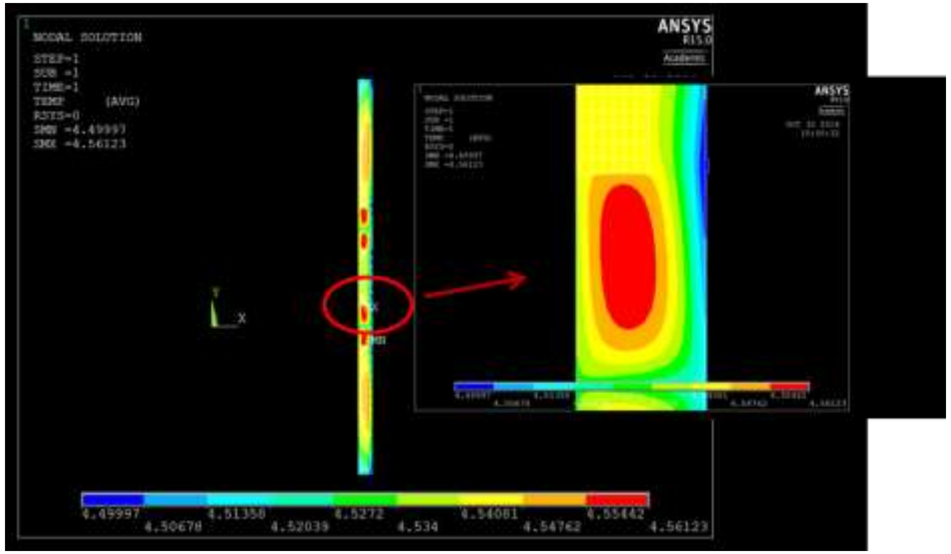
Thermal loads of the cold mass

Eddy current loss in the coil windings.

$$P = 2\int_0^{d/2} dP = \frac{lh}{12}\frac{d^3}{\rho}\dot{B}_z^{\,2}$$



- Eddy currents in a rectangular thin plate



Temperature distribution in the cold mass.

Eddy current loss in the casing.

$$P = \frac{V^2}{R_{casing}}$$

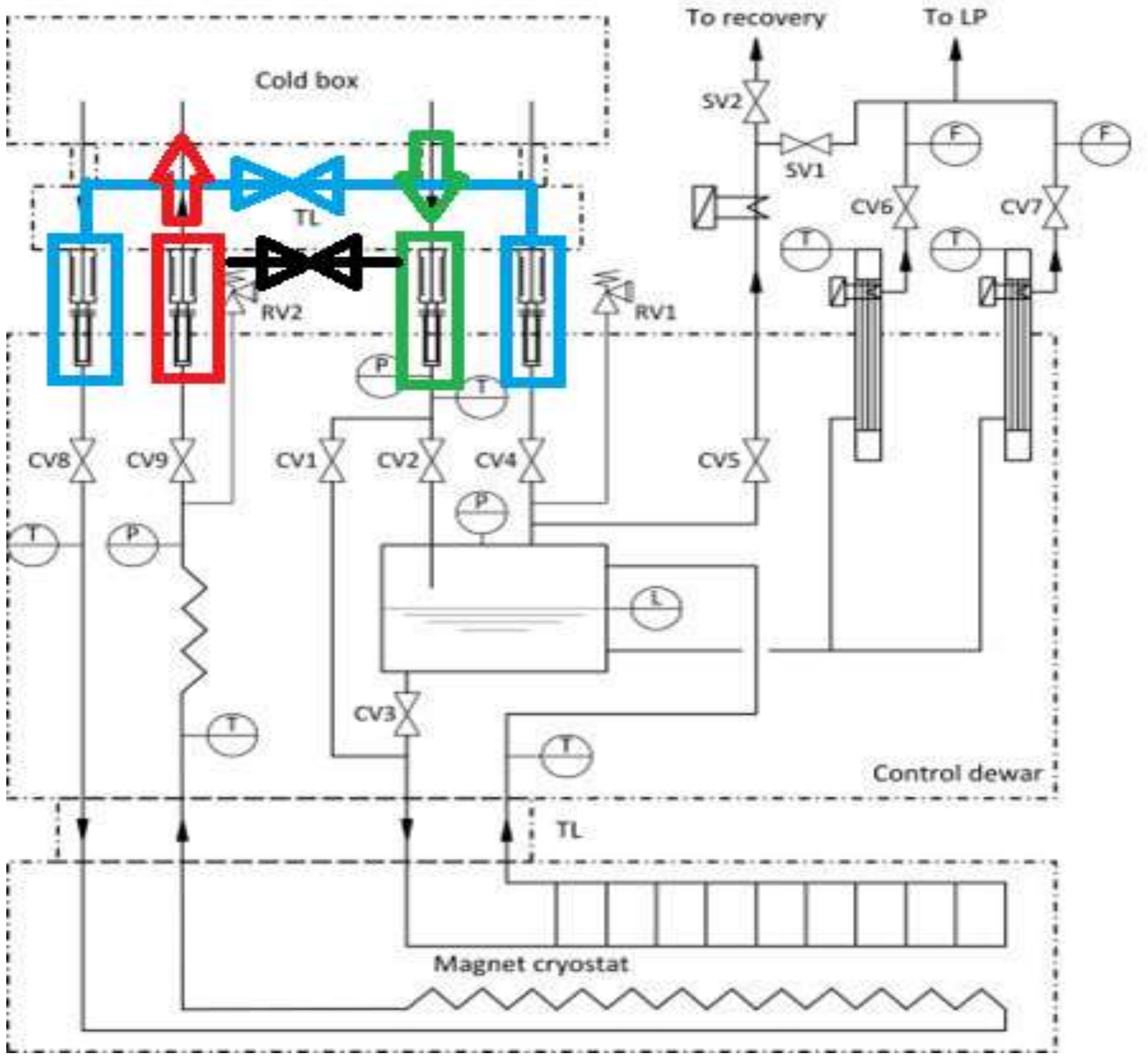
$$V = M \cdot \frac{dI}{dt}$$

- **Eddy currents in the casing produce the main loss contribution during ramp and slow dump.**
- **The thin high purity Al strip in thermal contact with the cooling ribs ensures minimal increase of the cold mass temperature during current ramp up and slow dump of the magnet 2000 seconds.**

Cryogenic system

The cryogenic system of the PANDA magnet consists of a Control Dewar with helium vessel, transfer line and thermosyphon circulation loop. It is a self-regulating thermosyphon circulation flow system. A natural circulation loop is operated on the principle that a heat load on the channels of the heat exchanger produces a two-phase flow that is on average of lower density than the liquid phase. Homogenous model is used for the preliminary study for CMS detector solenoid, CERN.

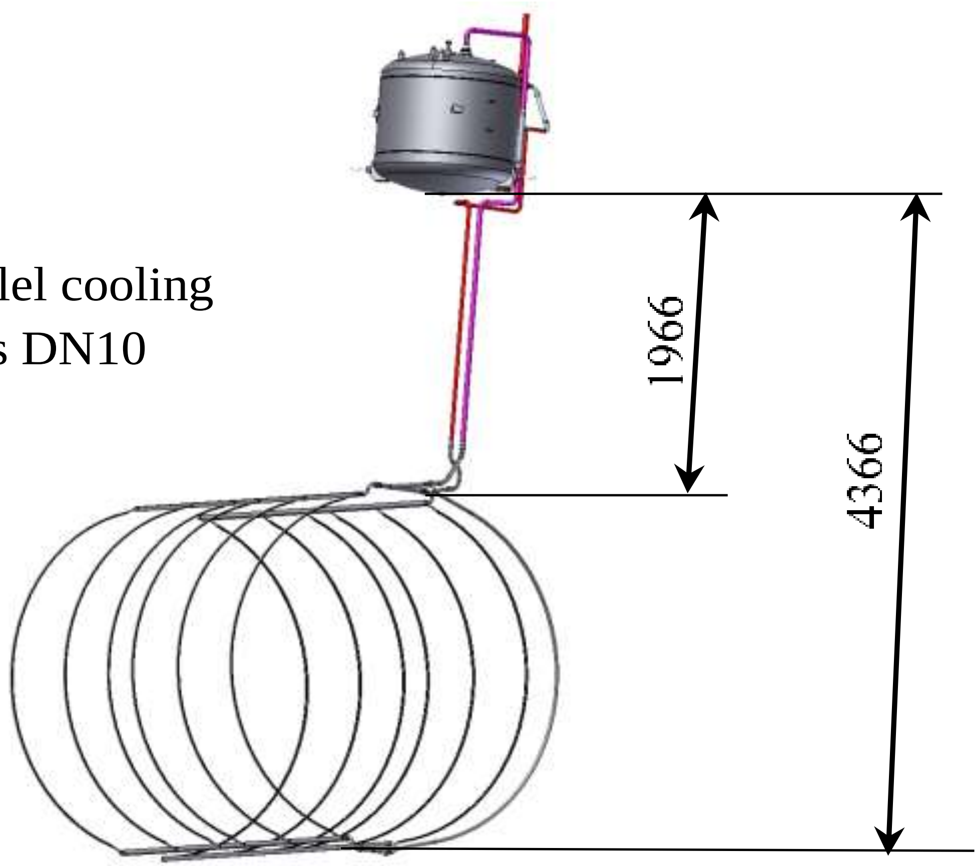
The scheme has a cooling circuit that will work with liquid nitrogen when the solenoid magnet is moved to the assembly area.



PANDA solenoid cryogenic Process Flow Diagram.

Cryogenic system

12 parallel cooling channels DN10

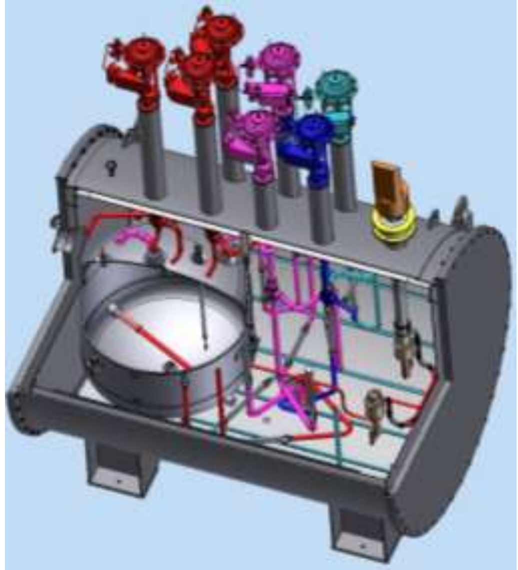


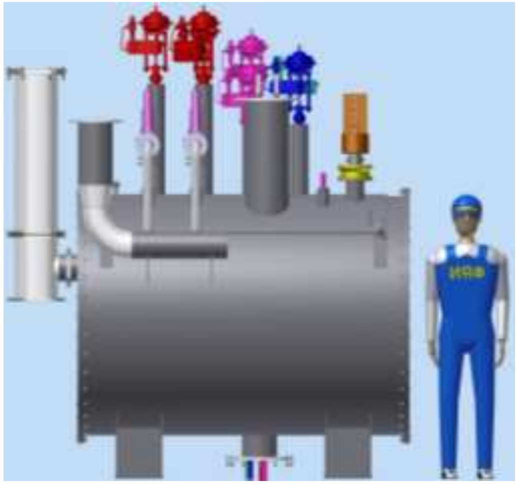
Thermosyphon circuit.

Liquid from the helium vessel of the Control Dewar will be fed through the forward pipeline and manifolds at the bottom of the support cylinder. From there, the liquid will be heated up in the tubes of the heat exchanger (a rib cage configuration) on the surface of the support cylinder.

The two–phase helium from the top manifolds returns back through the reverse pipeline to the upper part of the helium vessel.

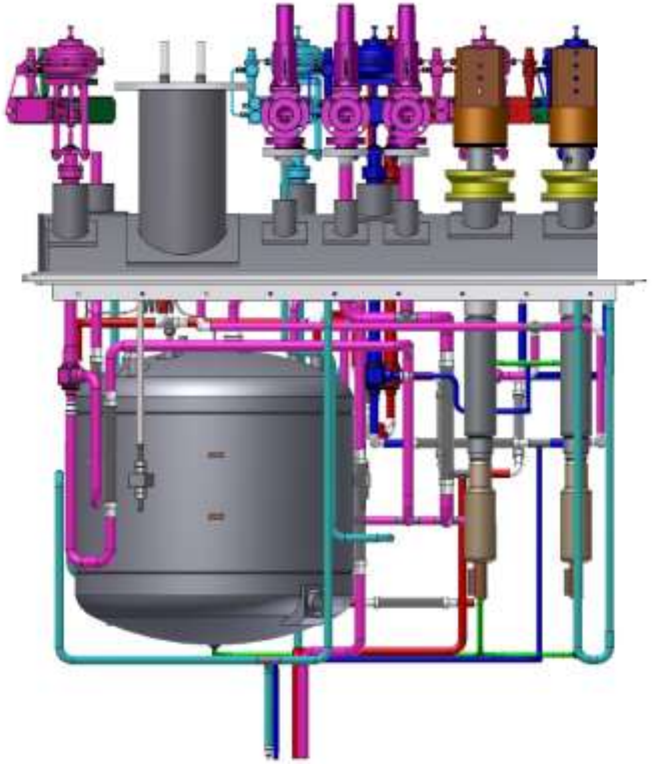
Distribution box – Control Dewar.



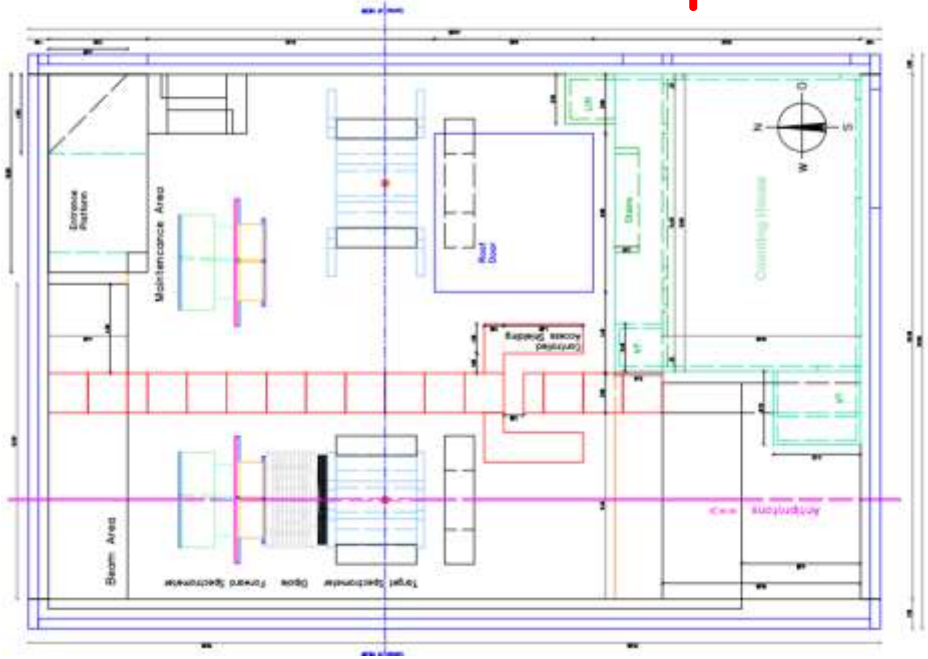


Control Dewar includes:

1. Vessel for liquid helium (~480L);
2. Current leads;
3. Thermal shields;
4. Valves, instrumentation;
5. Vacuum shell;
6. Transfer line (Chimney) connecting the vacuum vessels of cryostat and control Dewar.



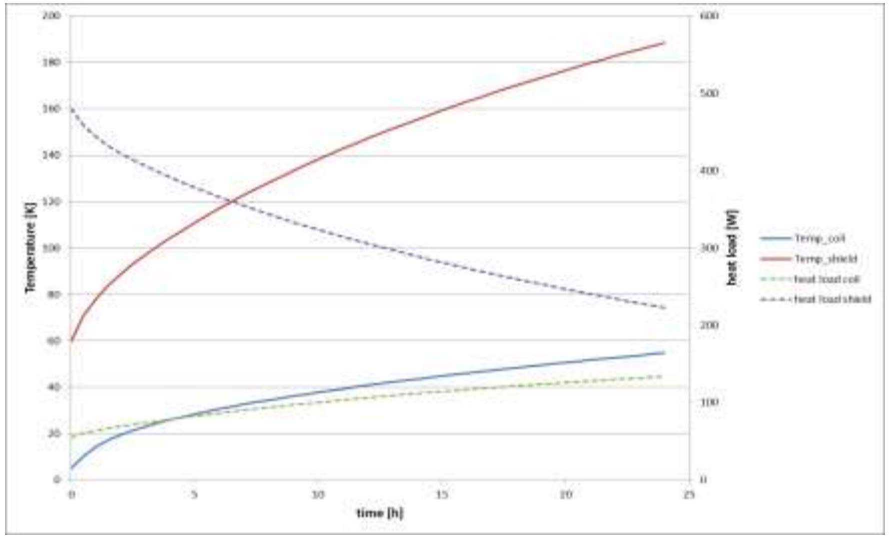
Scheme of location of the PANDA magnet in beam position and in assembling area



The magnet will be approximately 6 month in parking position of the assembling area for maintenance. In this position a forced helium circuit (83-100K) cooled by liquid nitrogen is foreseen.

The travel between the parking and the beam position will take less than a day, and the expected temperature should stay in an acceptable range for the cold mass.

PANDA magnet areas.



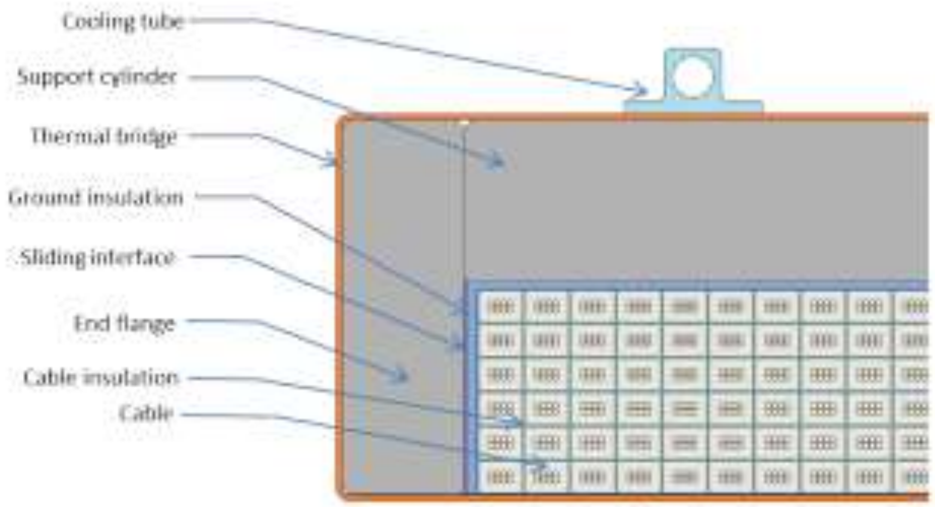
The maximal temperature of the thermal shield is estimated about 130K after 8 hours and the maximal temperature of the cold mass ≈ 35 K.

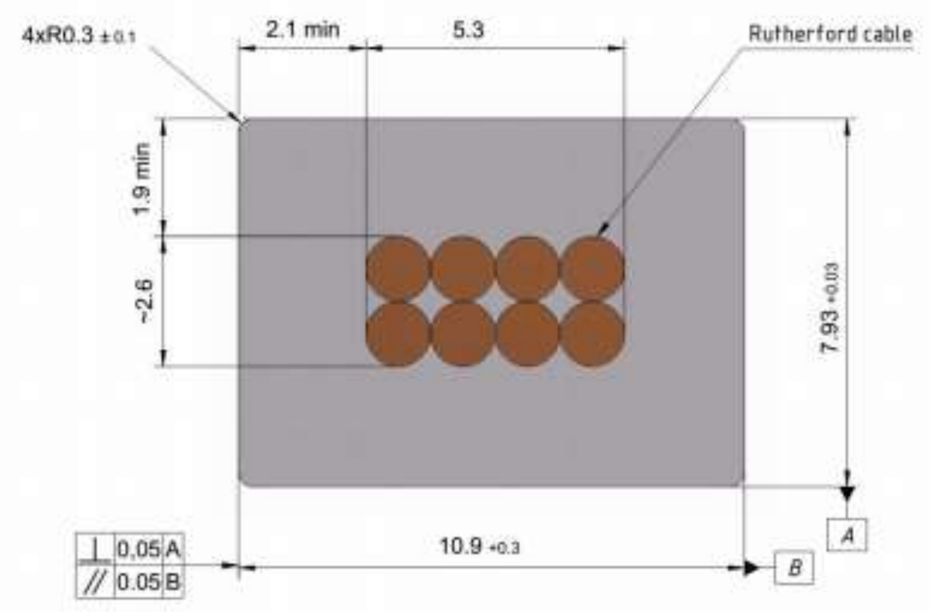
Dependence of temperature and thermal loads of the cold mass and thermal shield.

Main risks. Conductor.

Thickness (after cold work) at 300 K	mm	7.93	± 0.03
Width (after cold work) at 300 K	mm	10.95	± 0.03
Critical current (at 4.2 K, 5 T)	A	> 14690	
Critical current (at 4.5 K, 3 T)	A	> 16750	
Overall Al/Cu/sc ratio		10.5/1.0/1.0	
Aluminum RRR (at 4.2 K, 0 T)		> 600	
Al 0.2% yield strength at 300 K	MPa	> 30	

Conductor mechanical and electrical parameters.





Rutherford cable, 8 strands, extruded in Al matrix

Development of the conductor.

Sarko.

- Produced about 20 meters a conductor from A95 and NbTi cable;
- 4 pieces the conductor 3,5m prepared for following tests;
- Mechanical tests should be in BINP;
- Cryogenic tests for RRR and critical currents should be carried out in Bochvar institute and CERN.

Main risks. Conductor.

- **Purchasing superconductive conductor - lack of a manufacturers**

Status of the PANDA conductor development/ procurement

VNIINM Bochvar
VNIIKP
Saransk cable optic (SarKO)

Rutherford cable co-extrusion/ conklad in a pure Al

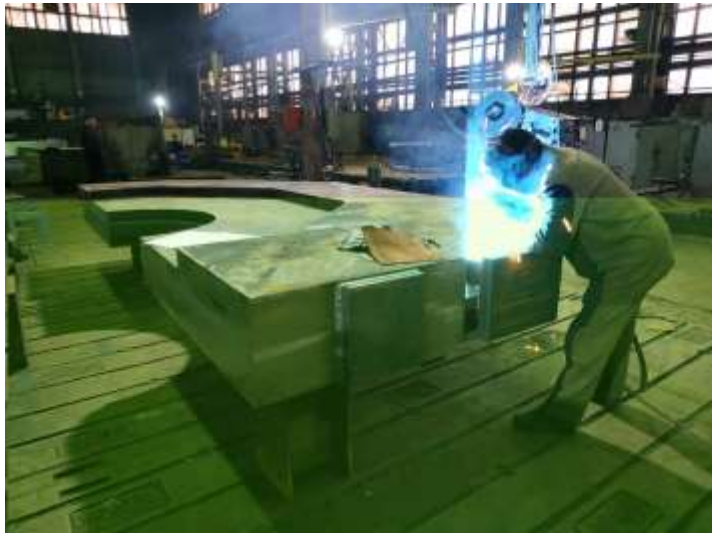
Production1000m Cu Rutherford cable for tests in SARKO - 03-04/ 2020
1000m Cu Rutherford cable for tests in SARKO - 03-04/ 2020

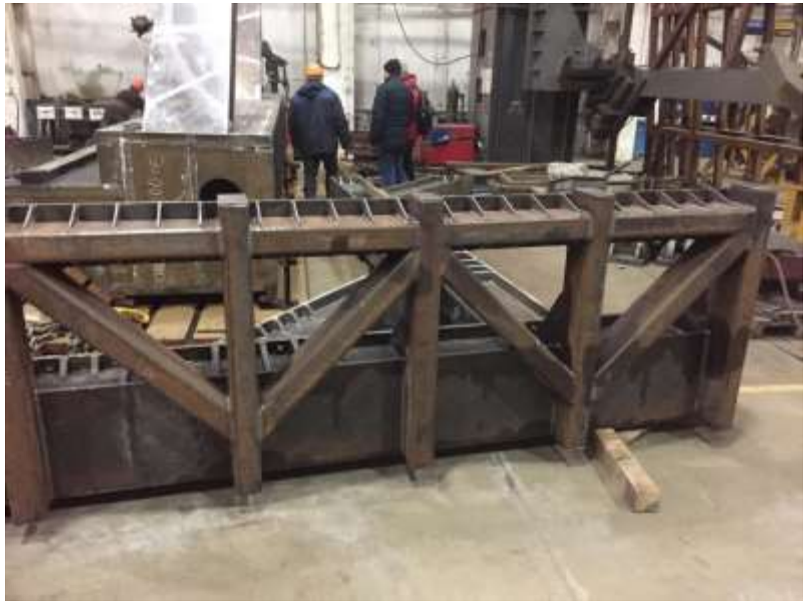
Preparation contracts for PANDA NbTi strands production, VNIINM - 03/ 2020
Production strands VNIINM - 02/2021

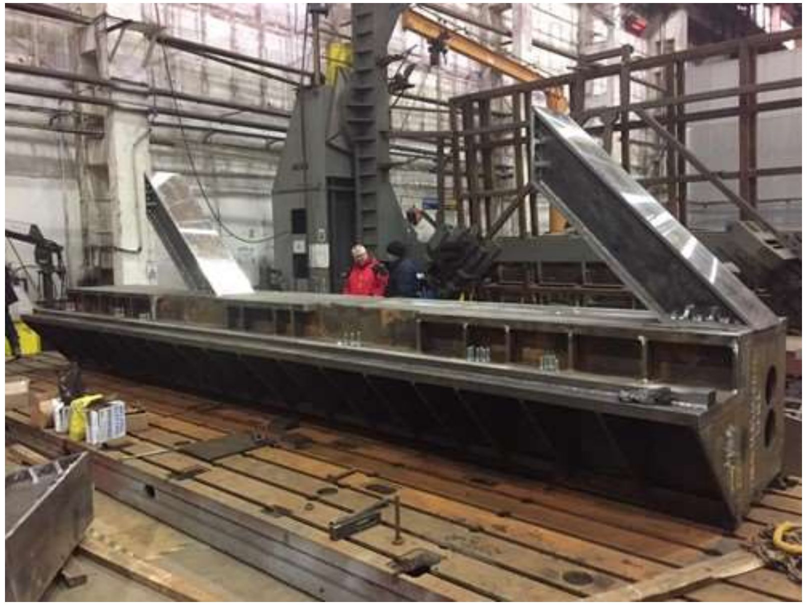
PANDA Rutherford cables production, VNIIKP - 04-05/ 2021

Production PANDA conductor with SARKO - 01 - 06/ 2021

Yoke production and assembling







Conclusion

Name of item	Status of work
Yoke and frame	In production
Cryostat of solenoid	Design is ready, technological development, purchasing raw material, preparation drawings of tooling. Call for tender
Cold mass	Design is ready, technological development, purchasing raw material, preparation drawings of tooling. Call for tender
Conductor purchasing	Development work, Call for tender for production of the Rutherford cable
Control Dewar box	Preliminary design April 2020
PANDA solenoid power cabling	Design is ready, production
Power supply and energy extraction system	Detail design is ready Purchasing power supply and electrical components, production
Magnet safety system	in process
FAT	Preparation place for PANDA solenoid installation, procedures installation, development a flow scheme of connection KEDR-PANDA solenoid cryogenics

Thank you for your attention