SPD solenoid

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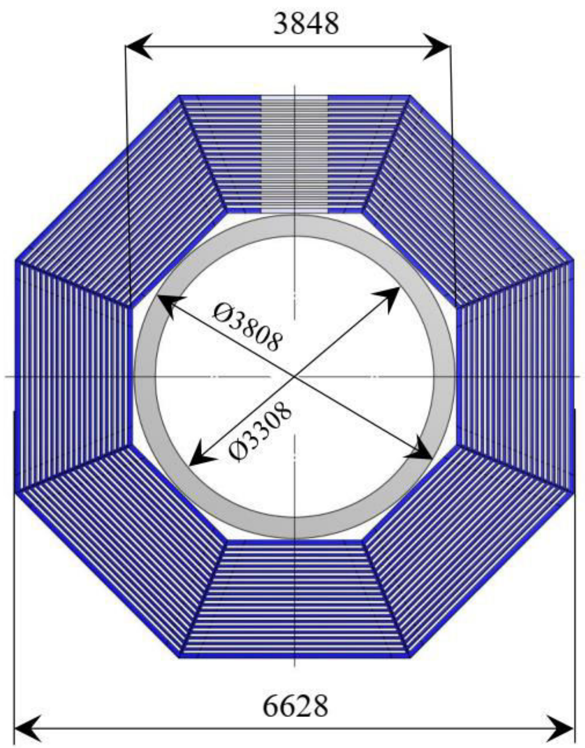
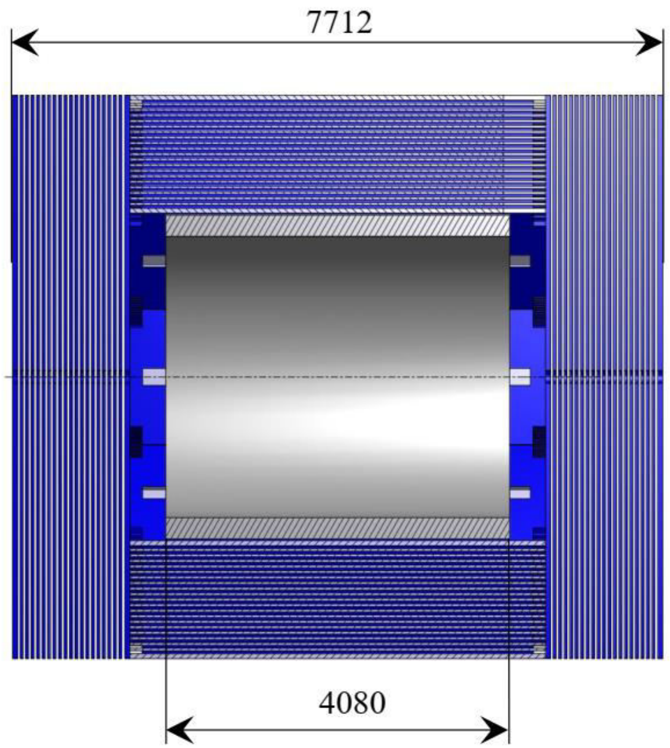
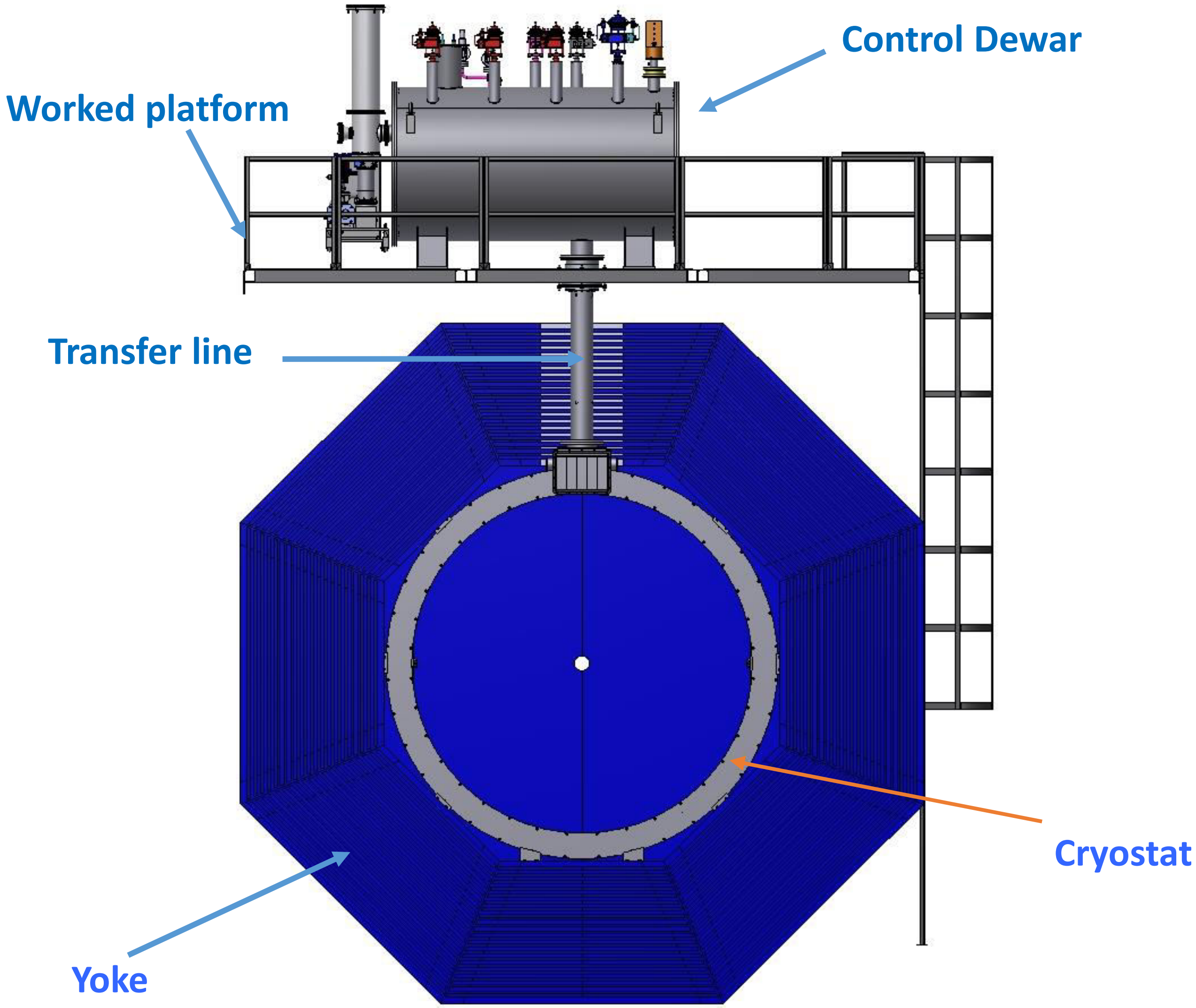
SPD solenoid

The magnetic field along the solenoid axis should be from 1.0 T.
The cryostat of the magnet with the coils, cold mass and thermal shields is located inside of the yoke.
The main dimensions of the cryostat of SPD are defined. Outside diameter of the cryostat is 3808 mm and a gap between the yoke and the cryostat about 20 mm. Radially a free diameter is 3308 mm. The length of the magnet is 3800mm and the magnet should be installed symmetrically inside the yoke.
The total weight of the cryostat, transfer line and Control Dewar is ~17 t.





SPD solenoid

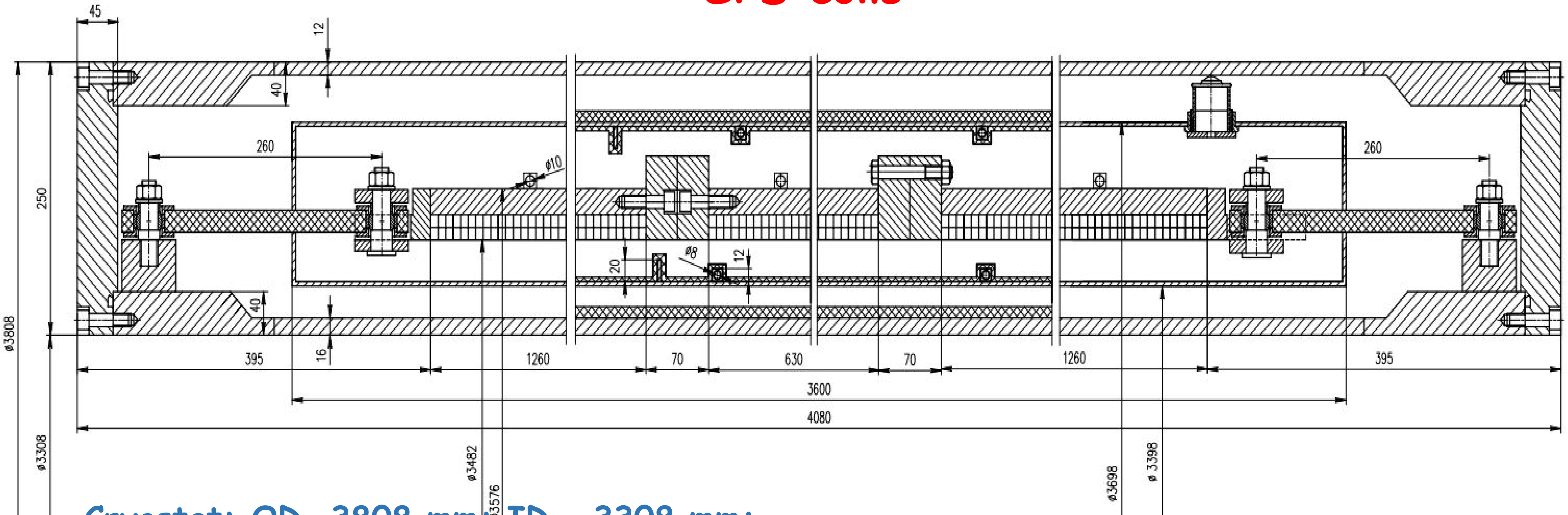


The magnetic field along the solenoid axis should be from 1.0 T.

BINP presents our participation in SPD project with the following items:

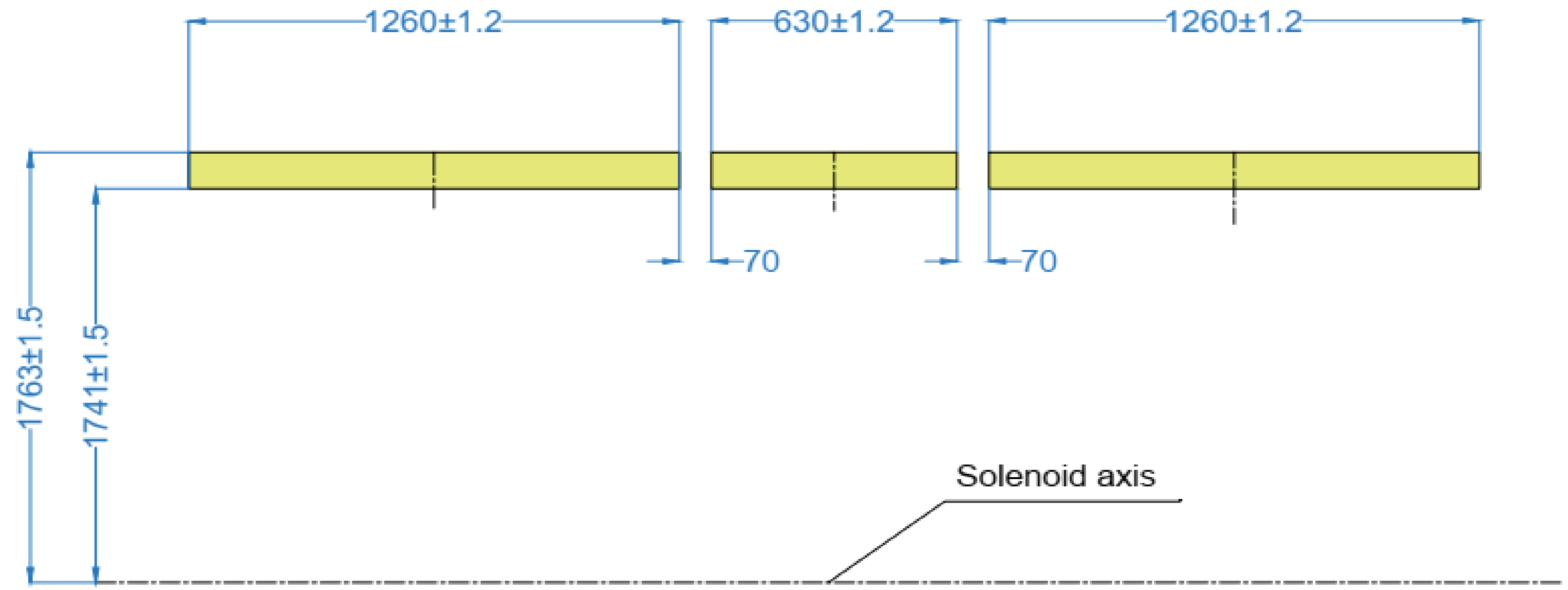
- Magnetic and engineering design of the magnet including tools and support;
- Production and delivery of the magnet (consisting of the cryostat with cold mass, alignment components, proximity cryogenics, supports);
- Power converter and quench protection and instrumentation.

SPD coils



Cryostat: OD –3808 mm; ID – 3308 mm;
Length - 3800 mm; Thickness – 250 mm;
Coils (3 pc.): Vertical winding PANDA conductor – 2 layers; Turns = 750.
Weight: - cryostat about 9500 kg
- thermos shields – 850 kg
- coils about 4200 kg
Total: ~15 ton

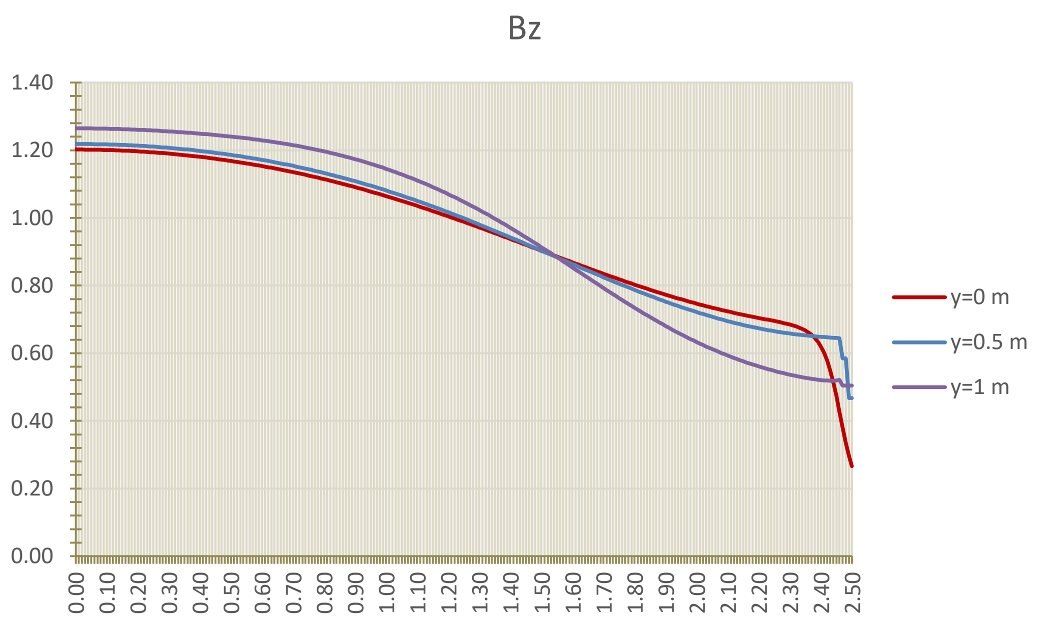
SPD coils



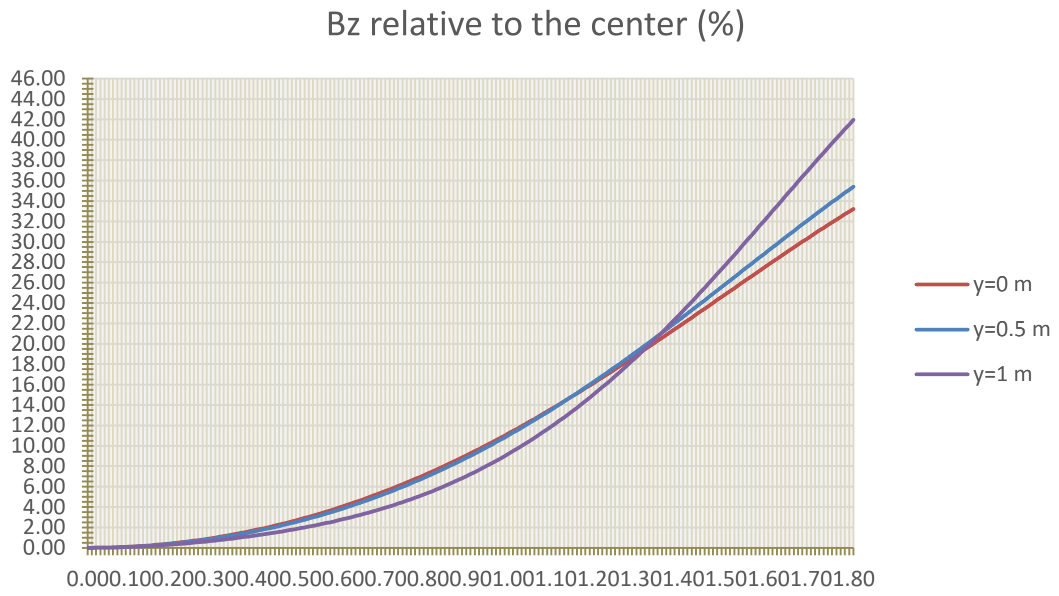
The cold mass of the SPD solenoid consists of three epoxy resin impregnated coils reinforced by shells made of structural aluminum.
The Upstream and Downstream winding packs are identical and feature 2 layers of 150 turns. The Center coil instead is smaller featuring 2 layers of 75 turns. The conductor is wound around the aperture with a tension. The tension of the conductor is set with tensioning rollers with value about 50 kg. The coils should be prepared and impregnated in vacuum according to the standard BINP technological scheme TTS4 STO 103-2011.

SPD magnet analysis

Input conditions for 3D simulations had been taken as:
The configuration of the superconducting coil and magnetic design according to the latest STEP model with three coils. The current of the coil is 5200 A.
The calculations were carried out on the 3D software package MASTAC of Evgeniy Antokhin team.



Distribution of Bz in the section YZ at x = 0 for basic version of three coils and current 5200 A.



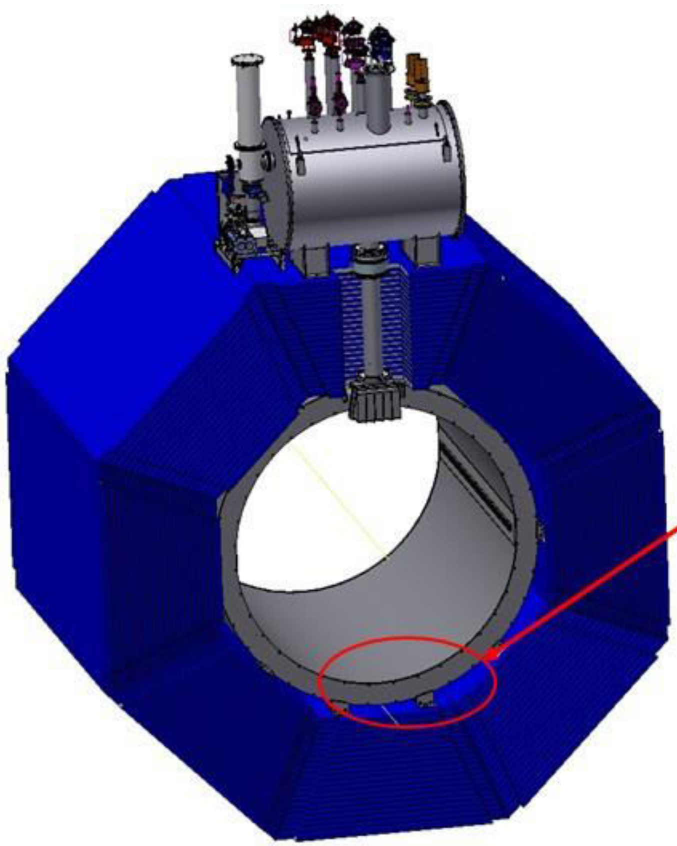
Uniformity of Bz in the section YZ at x = 0 for basic version of three coils and current 5200 A.

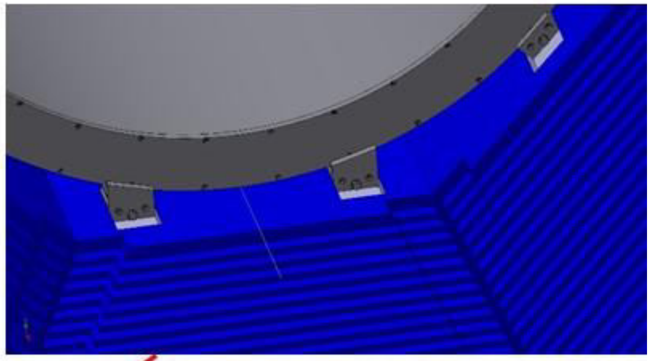
SPD magnet analysis

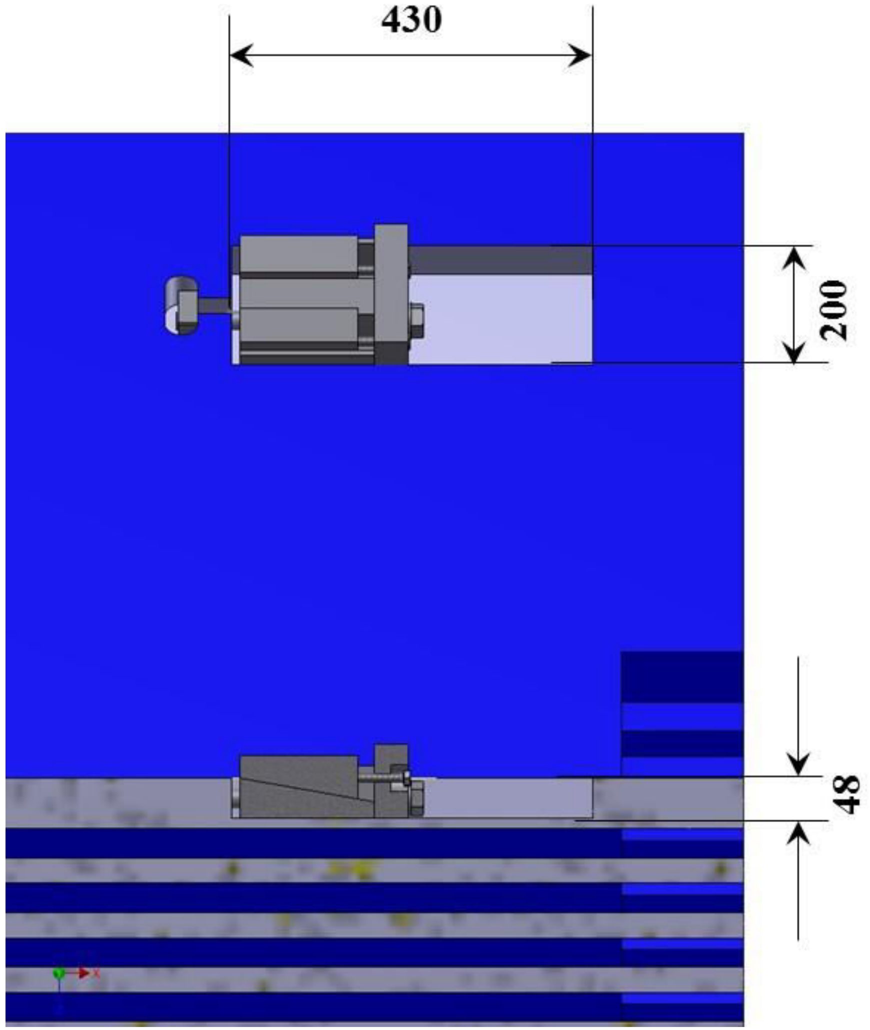
The results of calculation for the magnetic forces acting on the coils during their displacement had shown in Table. These forces used for calculation mechanical loads on the supports system of the cryostat – yoke connections.

Magnetic force on coils				
	comp.	Left coil	Central coil	Right coil
F, kN	X (horiz.)	0	0	0
	Y (vert.)	0	0	0
	Z (long.)	4748.0	0	-4748.0
F, kN z +5 mm	X (horiz.)	0	0	0
	Y (vert.)	0	0	0
	Z (long.)	4521.4	-69.6	-4743.4
F, kN y +5 mm	X (horiz.)	0	0	0
	Y (vert.)	-2152.8	-1065.1	-2152.8
	Z (long.)	4752.8	-0.3	-4753.3

SPD magnet mechanical loads

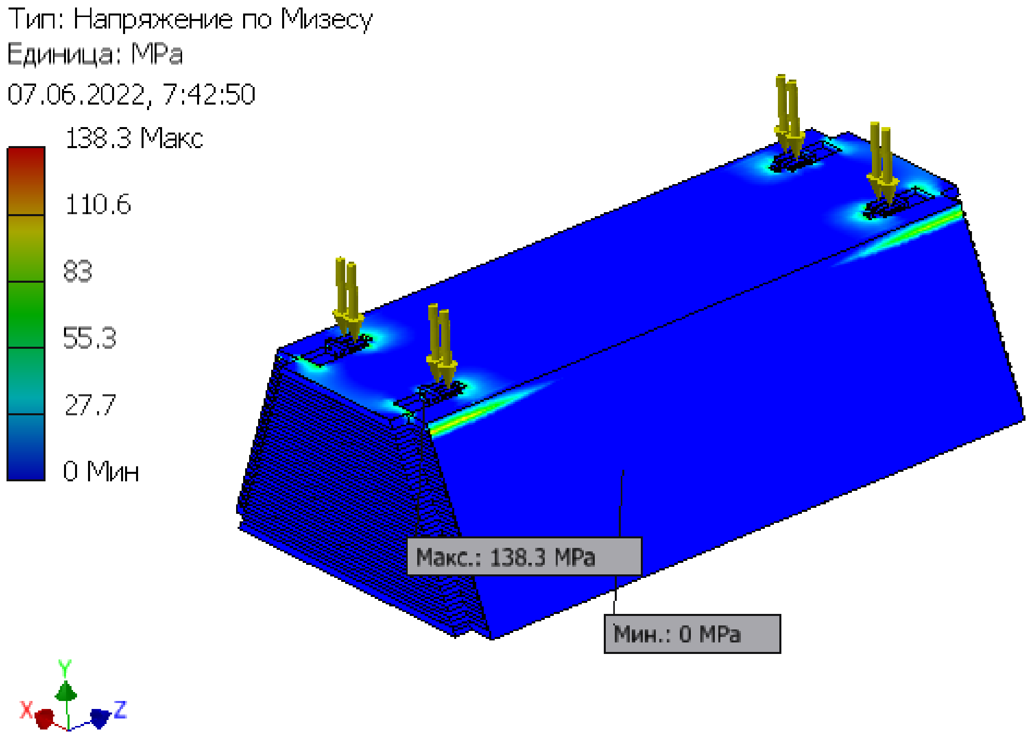


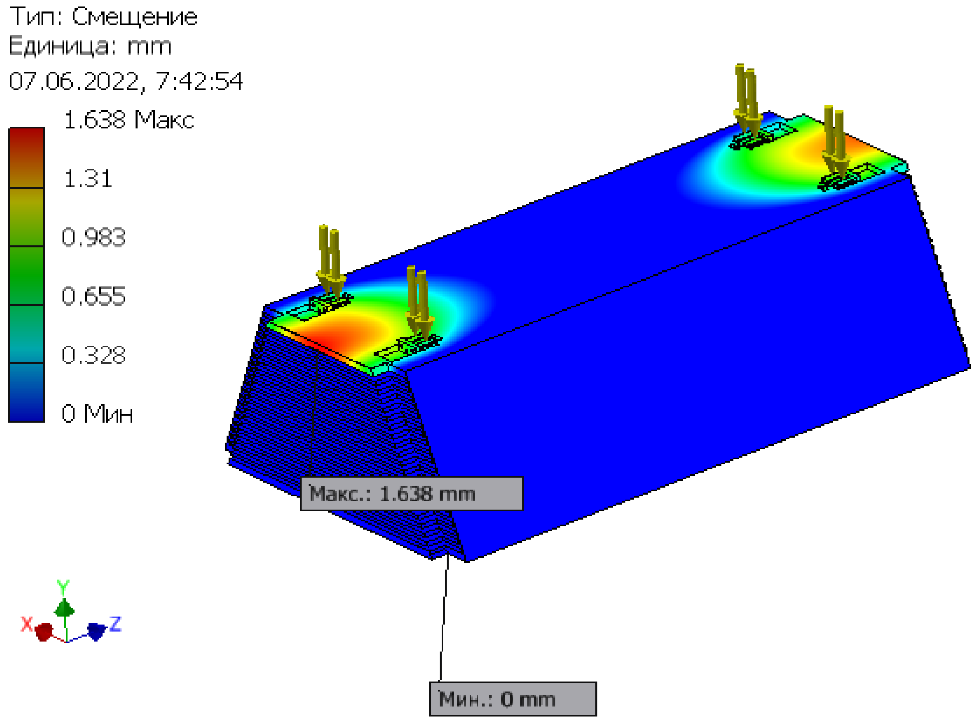




Supports system of the cryostat – yoke connections and main dimensions of the supports.

SPD magnet mechanical loads





Maximal stress - 138.3 MPa. Maximal deformation - 1,6 mm.

SPD solenoid. Cold mass support

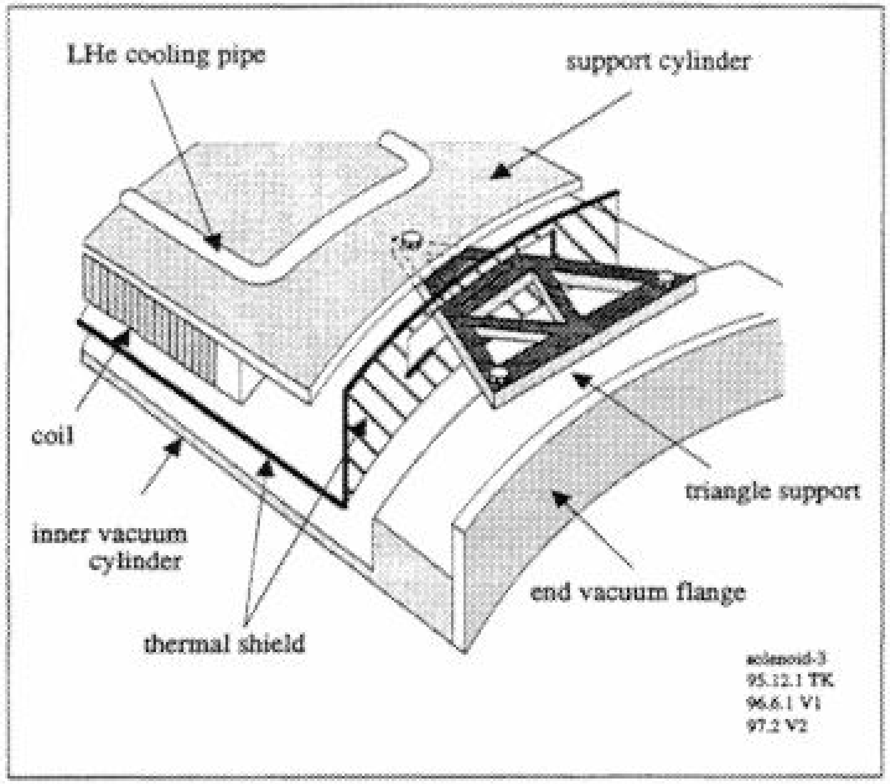


Figure 3-19 A schematic view of the triangle coil support.

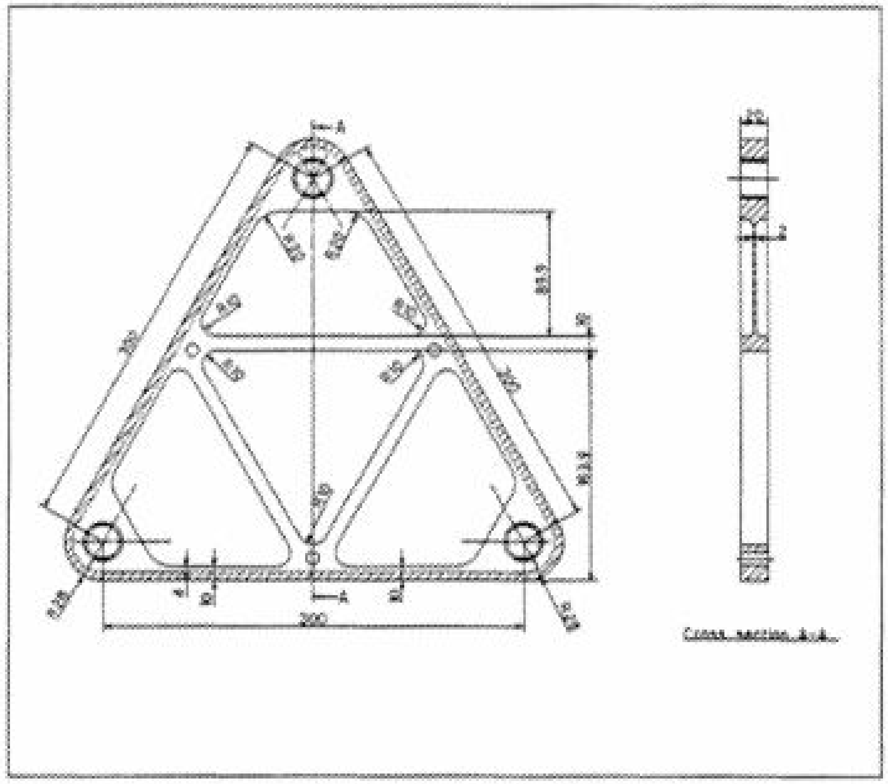
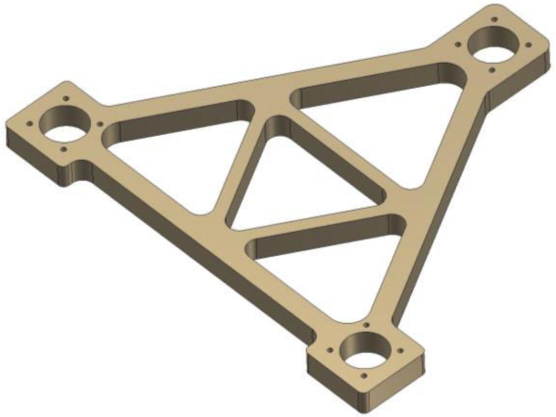
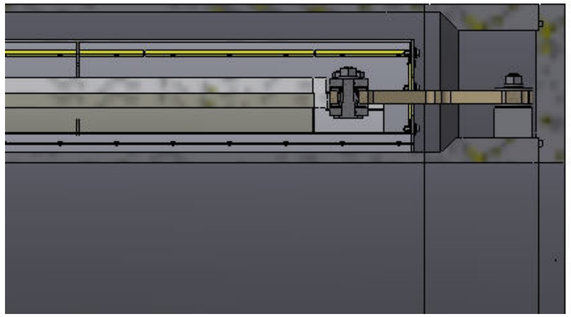


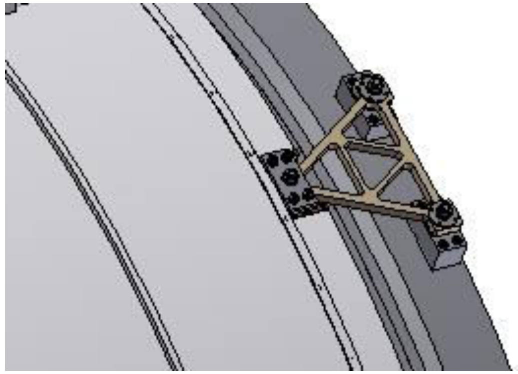
Figure 3-20 Design of the triangle support.

Choice of a support system's type for SPD cold mass.

SPD solenoid. Cold mass support



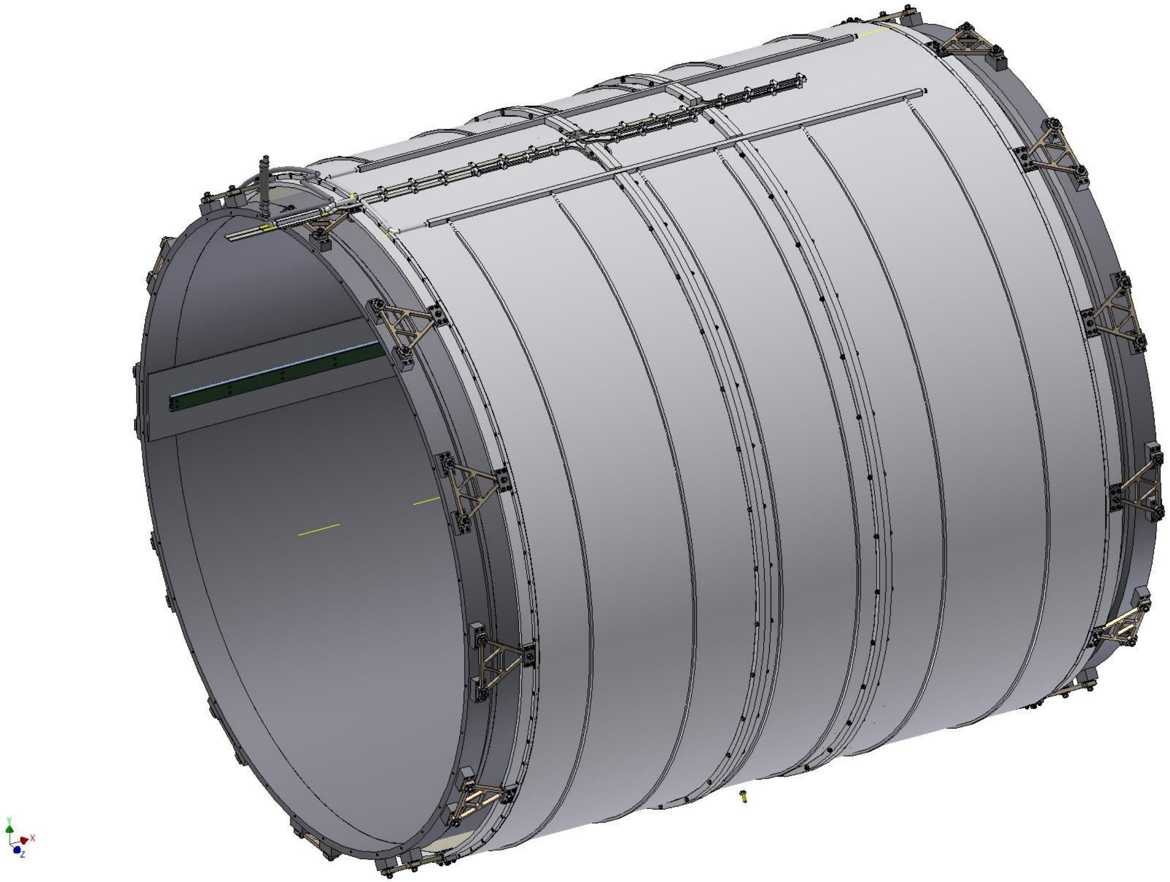




The wide side of a triangle support is attached to a part of the vacuum shell to a special flange with two M16 bolts.
The apex of the triangle is attached to the cold mass. The shape of the support is made taking into account mechanical and thermal loads, as a compromise.

To compensate for radial changes in the lengths of the cold mass and the vacuum shell, more than 12 mm, spherical washers are installed in all attachment points. So that the change in the position of the cold mass is not significant, we assume the pre-setting of the cold mass at + 5 ÷ 6 mm from the plane of the support flange and after cooling down to 4.5 K, at -5 ÷ 6 mm from the plane of the support flange. To compensate for longitudinal changes in length, more than 12 mm, a slot is proposed in the cold mass, at the point of attachment of the triangle apex.

SPD solenoid. Cold mass support



Arrangement of triangle supports on the SPD cold mass.

SPD solenoid. Cold mass support loads

Load conditions	load	F (max. load) to support
Cold mass weight	42 kN	40 kN
Decentering force (5mm)	47,5 kN	44,7 kN
Total loads	89,5 kN	84,7 kN

Quantity of supports – 12 pieces for each side. Material – GFRP (glass fiber reinforced plastic).

Maximal stress – 96 000 kPa, deviation of the cold mass – 0,9 mm.

Prototypes of the supports are in production. We are planning to have breaking tests this year.

Стеклотекстолит СТЭФ ГОСТ 12652-74

Атрибут	Значение
Плотность	1800.000 кг/м^3
Коэффициент теплового расширения	0.0000080 /C
Теплопроводность	1.900 Вт/м-C
Удельная теплоемкость	840.000 Дж/кг-C
Модуль упругости	21000000 кПа
Коэффициент Пуассона	0.400
Предел текучести	0.000 кПа
Предельные напряжения	132 000 кПа
Удлинение %	0.000

Имя загрузки	Тип нагрузки	Значение нагрузки	Распределение нагрузки	Направление нагрузки	Параметр направления нагрузки
Сила 1	Сила	1e+07 мН	На элемент	(1.00, 0.00, 0.00)	Вдоль вектора

SPD solenoid. Cold mass support loads

Maximal stress – 96 000 kPa, deviation of the cold mass – 0,9 mm.

Имя загрузки	Тип нагрузки	Значение нагрузки	Распределение нагрузки	Направление нагрузки	Параметр направления нагрузки
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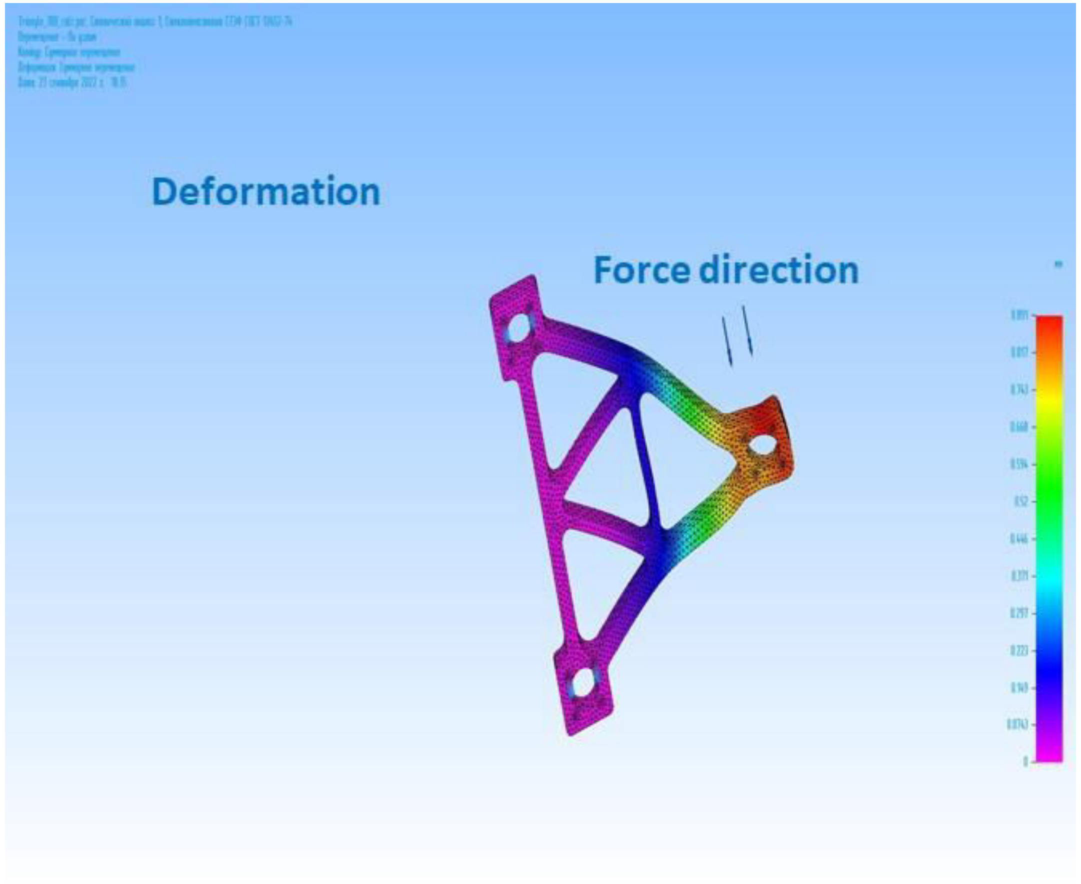
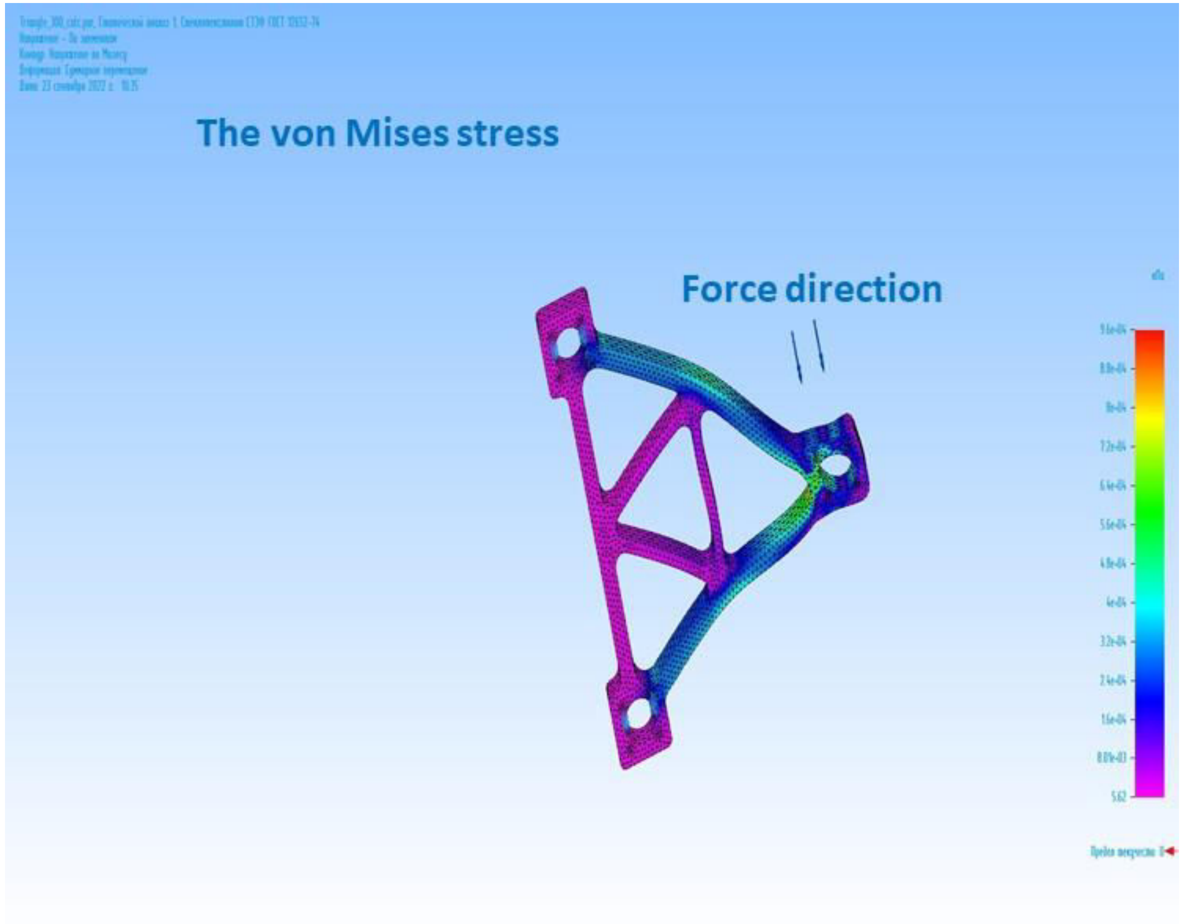
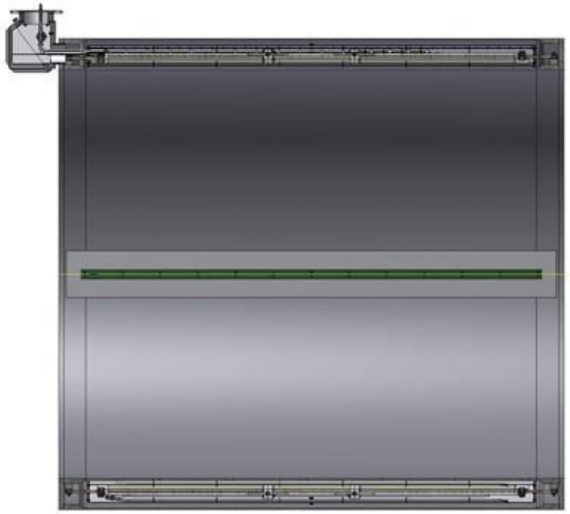
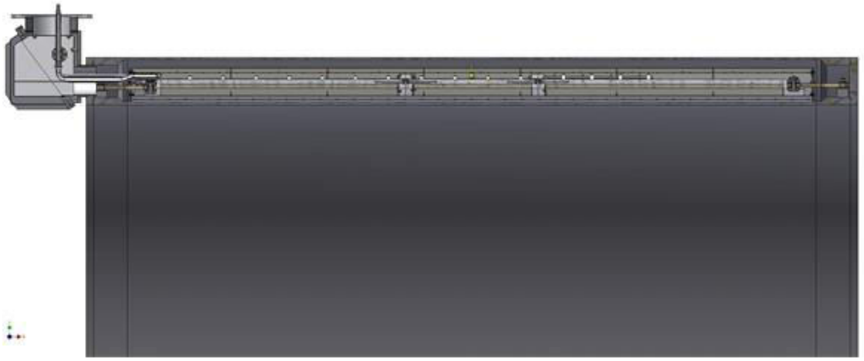
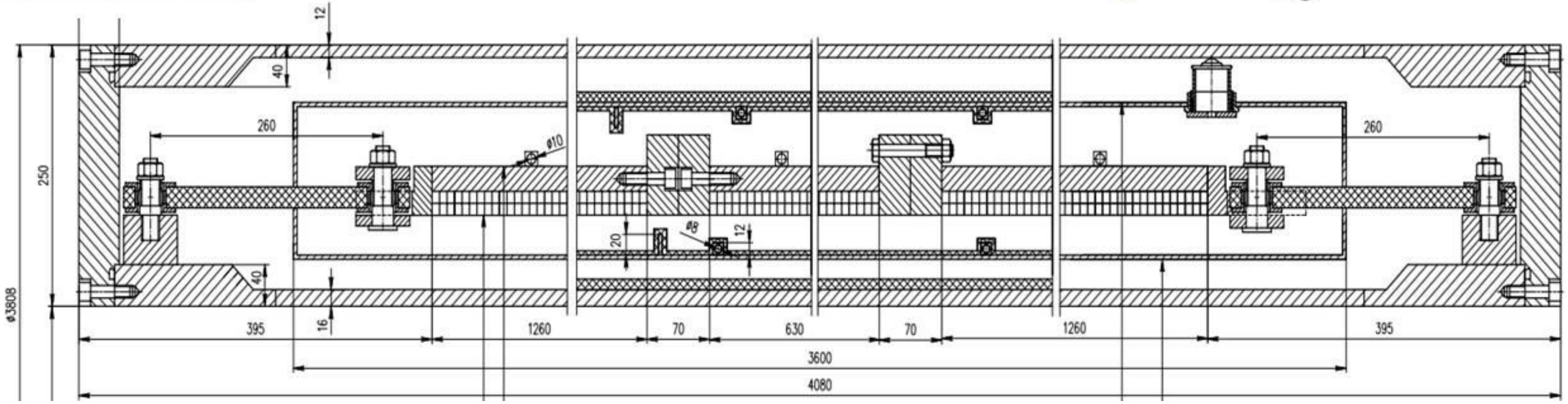




SPD solenoid cryostat

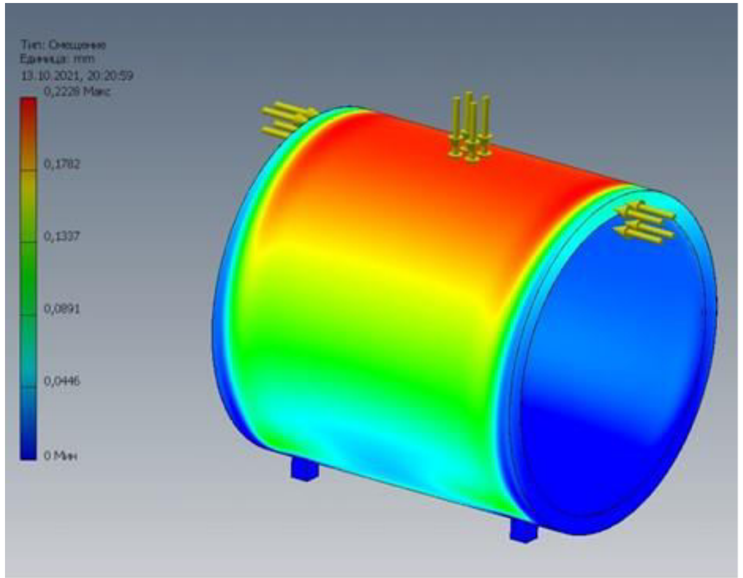




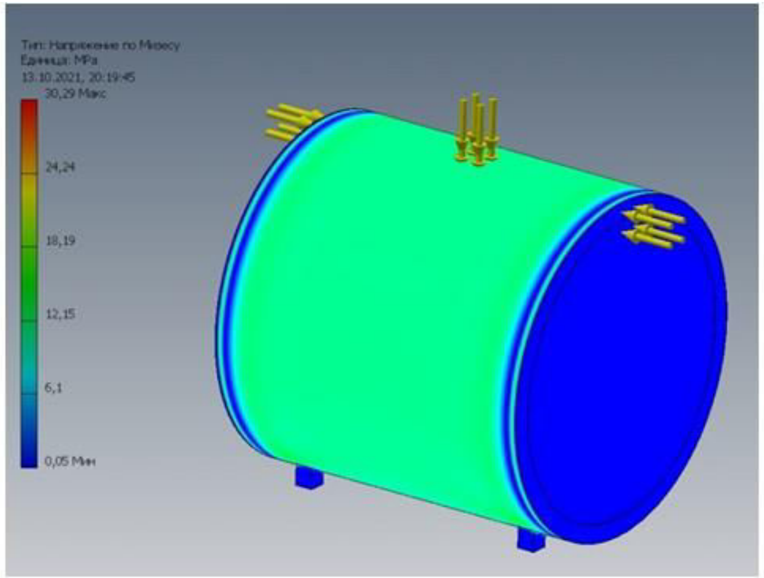


The nominal wall thickness is 12 mm for the outer cryostat shell and 8 mm for the inner shell. The thickness of the flanges is 40 mm. The thickness of the shells allows to minimize the displacement of the cold mass under the action of magnetic forces relative to its nominal position and the Calorimeter with total mass 40 ton into the cryostat.

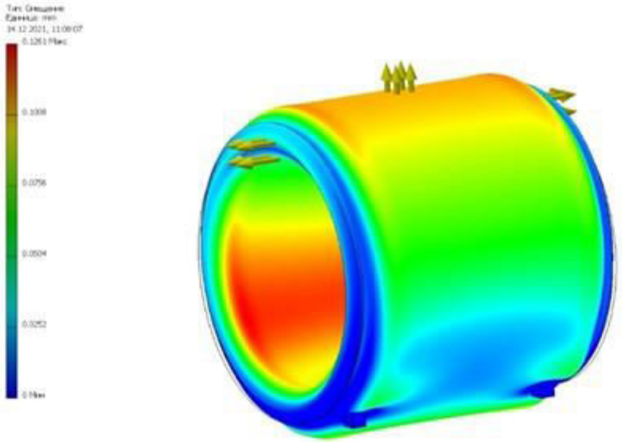
SPD solenoid cryostat



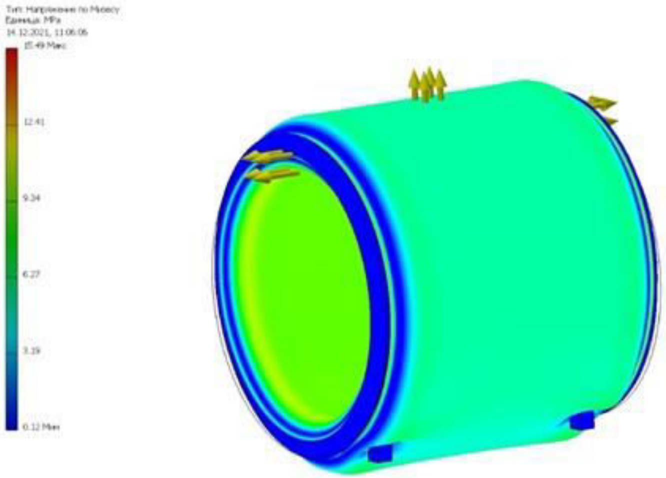
SPD Magnet (Deformation, p=0,1MPa)



SPD Magnet (Stress, p=0,1MPa)



SPD Magnet (Deformation, p=0,05 MPa)



SPD Magnet (Stress, p=0,05 MPa)

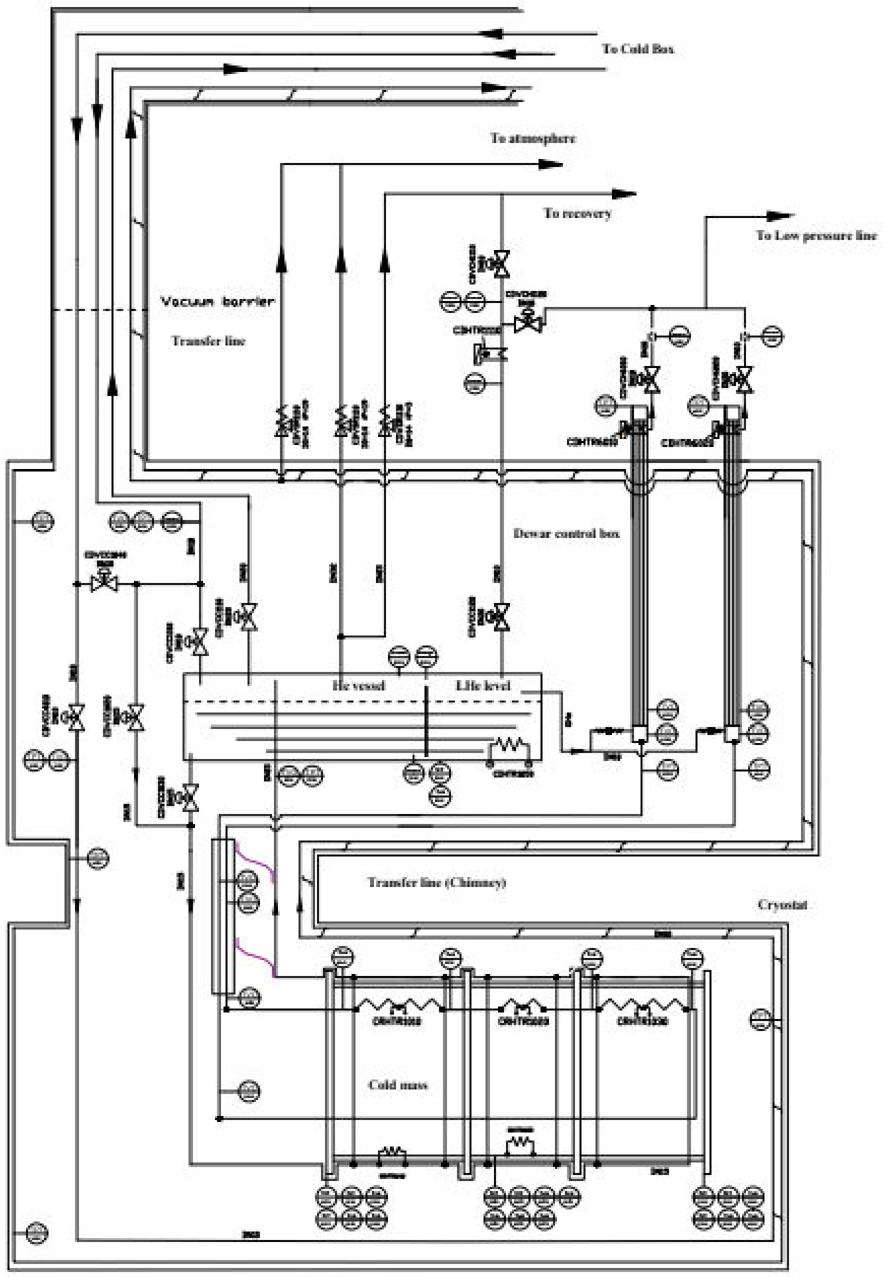
Calculation loads of the cryostat vacuum shell.

SPD solenoid. Flow scheme

The cryogenic system of the cryostat and the control Dewar shall be designed in order to take the loads resulting from all operation scenarios. Design pressure for all pipelines and helium vessel is 19 bar absolute (bar-a).

Liquid helium that is used for cooling the cold mass is fed from the liquefier at 4.5 K. Thermal shields of the solenoid surround the cold internal parts and are cooled by gaseous helium, which passes through a pipes of the heat exchanger of serpentine type.

The helium flow leaves the liquefier at a temperature level of 40 or 50 K and returns to the liquefier after passing the thermal shields at a temperature level about 80 K.
The Process Flow Diagram (PFD) of the SPD cryogenic system has the same principle as for CMS solenoid (CERN) and PANDA (FAIR).



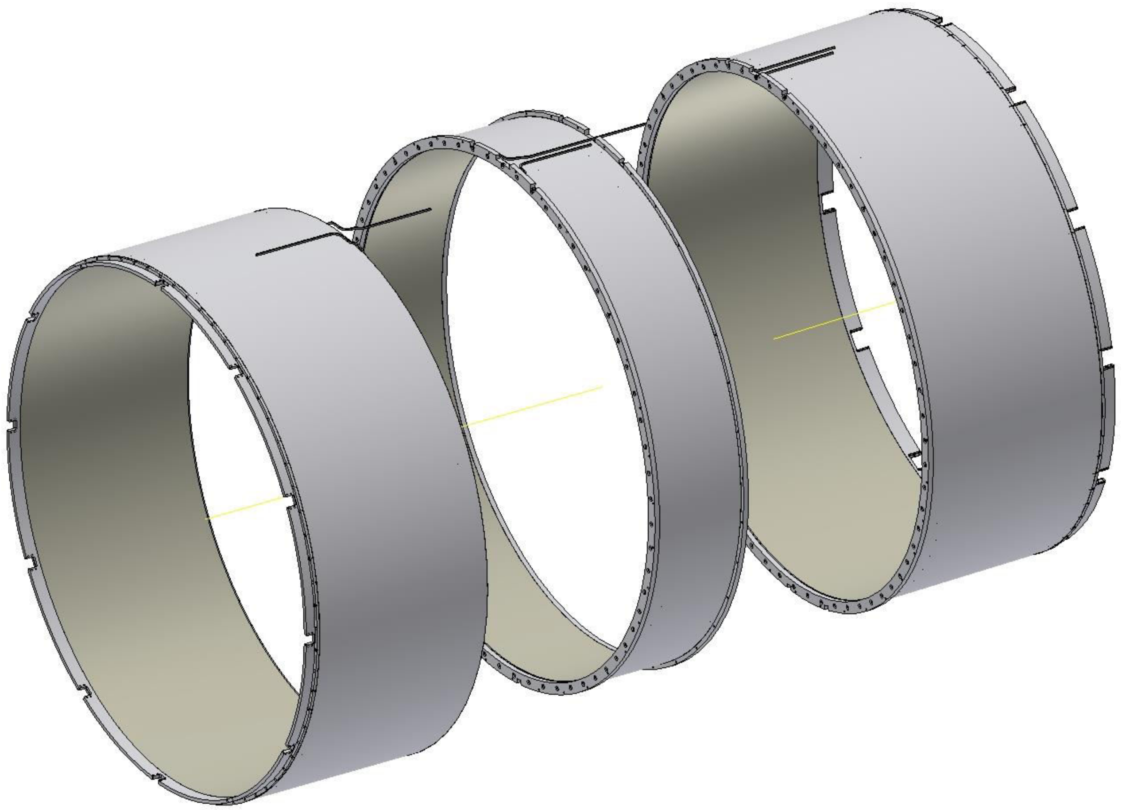
SPD heat loads

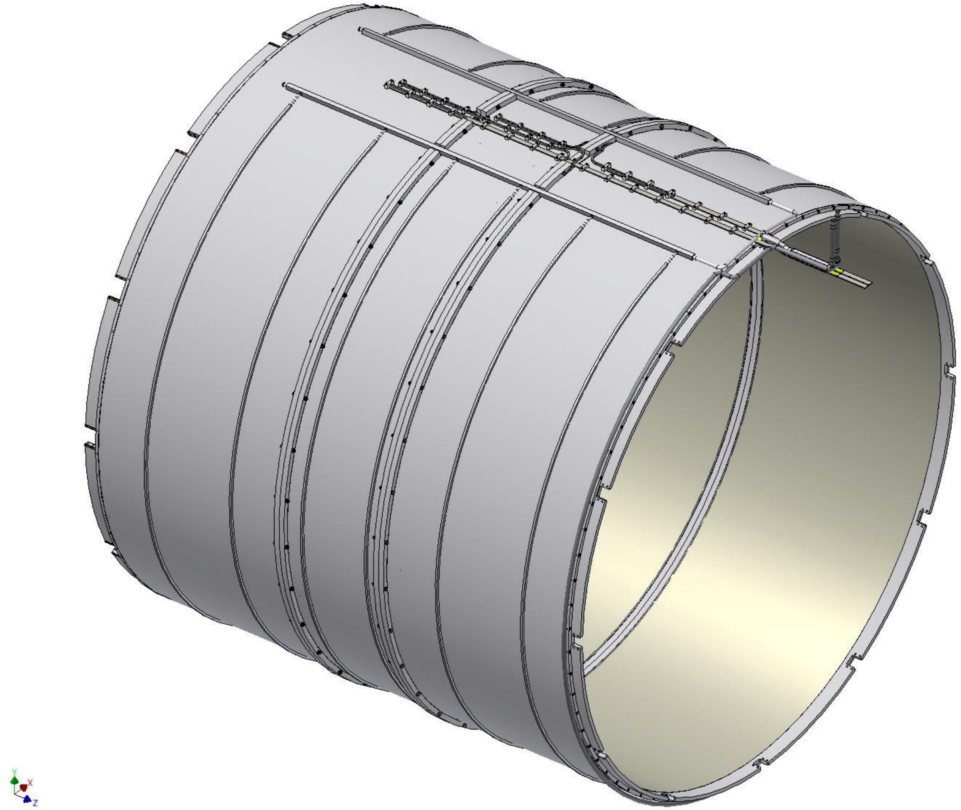
Table 1. Estimated heat loads of the SPD solenoid			
T = 4,5 K	Heat loads		
	Worked condition	Without m.f.	With m.f.
Cryostat			
Radiation	7.8	7.8	7.8
Supports	5*	5*	5*
Eddy current loss in casing	-	-	11.50**
Eddy current loss in conductor	-	-	0.09**
Current leads, 4,5 kA B=1.0 T	10	8	8
Distribution box**			
Radiation	0.55	0.55	0.55
Supports of the LHe vessel	0.26	0.26	0.26
Cold control valves	1.05	1.05	1.05
Safety relief valves	3,22	3,22	3,22
Vacuum barrier	0.35	0.35	0.35
Transfer line**			
Radiation	0.06	0.06	0.06
Supports	0.20	0.20	0.20
Total	28,49	26,349	38,08

* Data of ATLAS central solenoid

** Data of PANDA solenoid

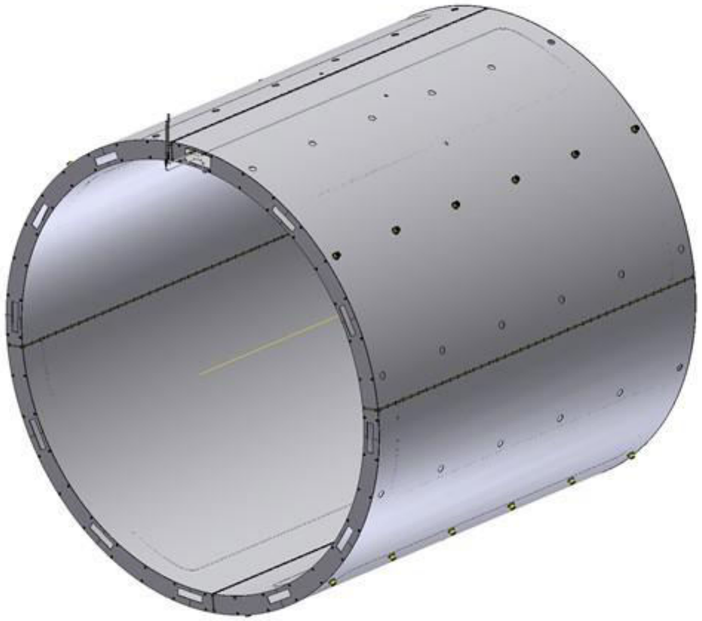
SPD solenoid.

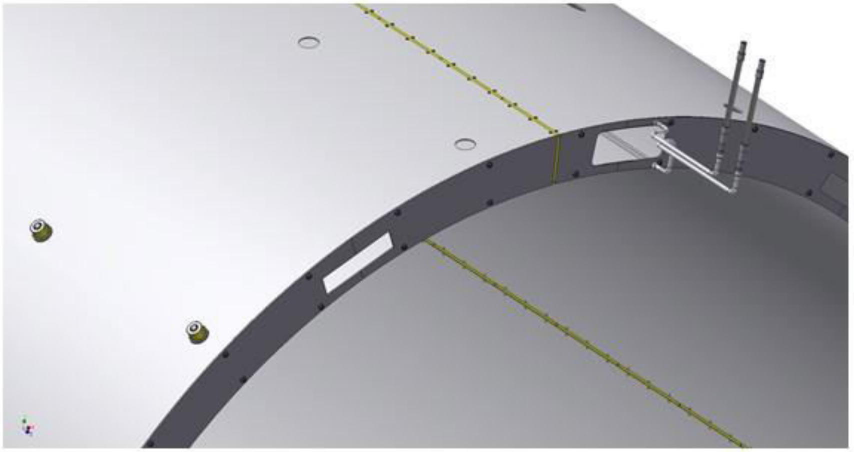


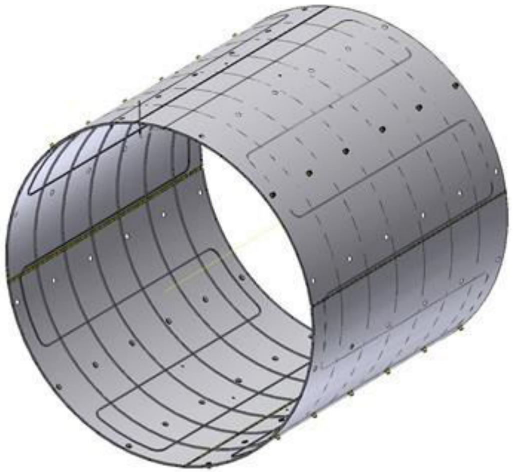


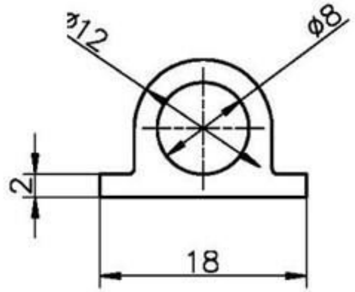
Cold mass design.

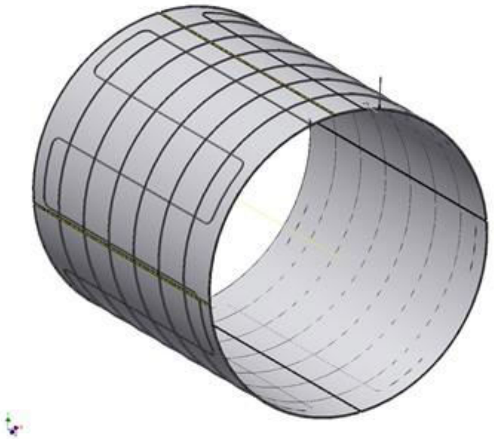
SPD solenoid. Thermal screen.





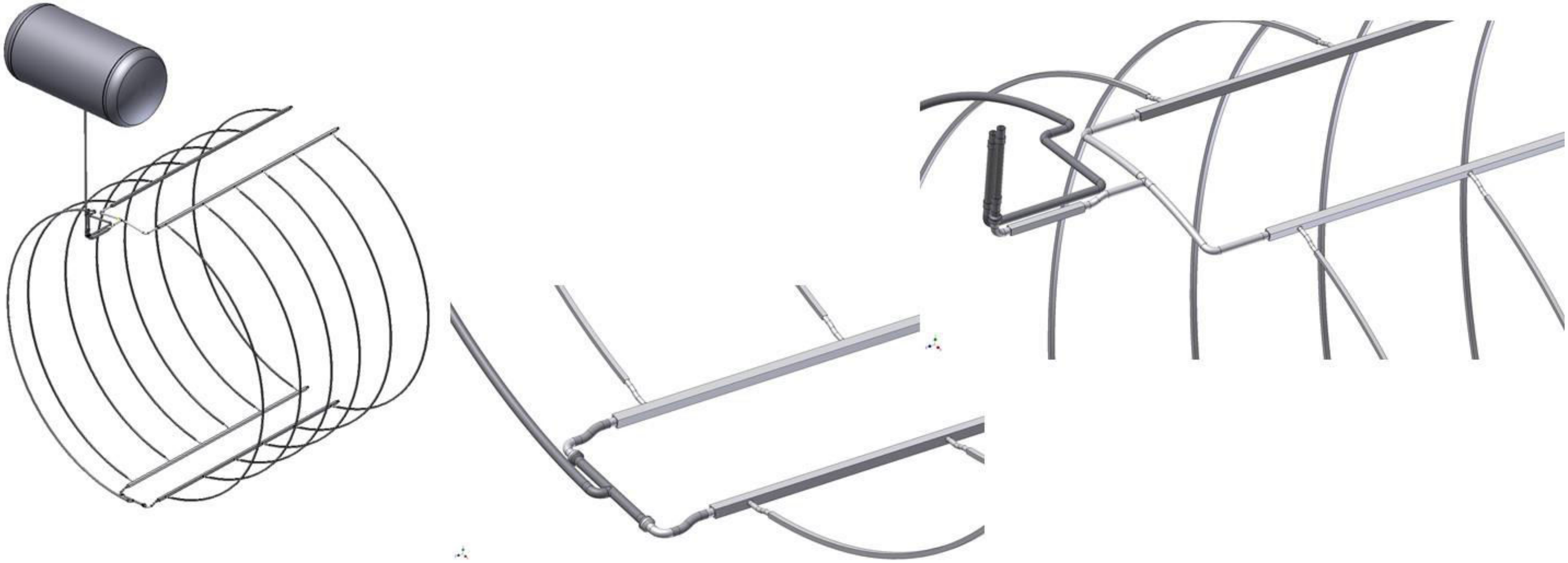






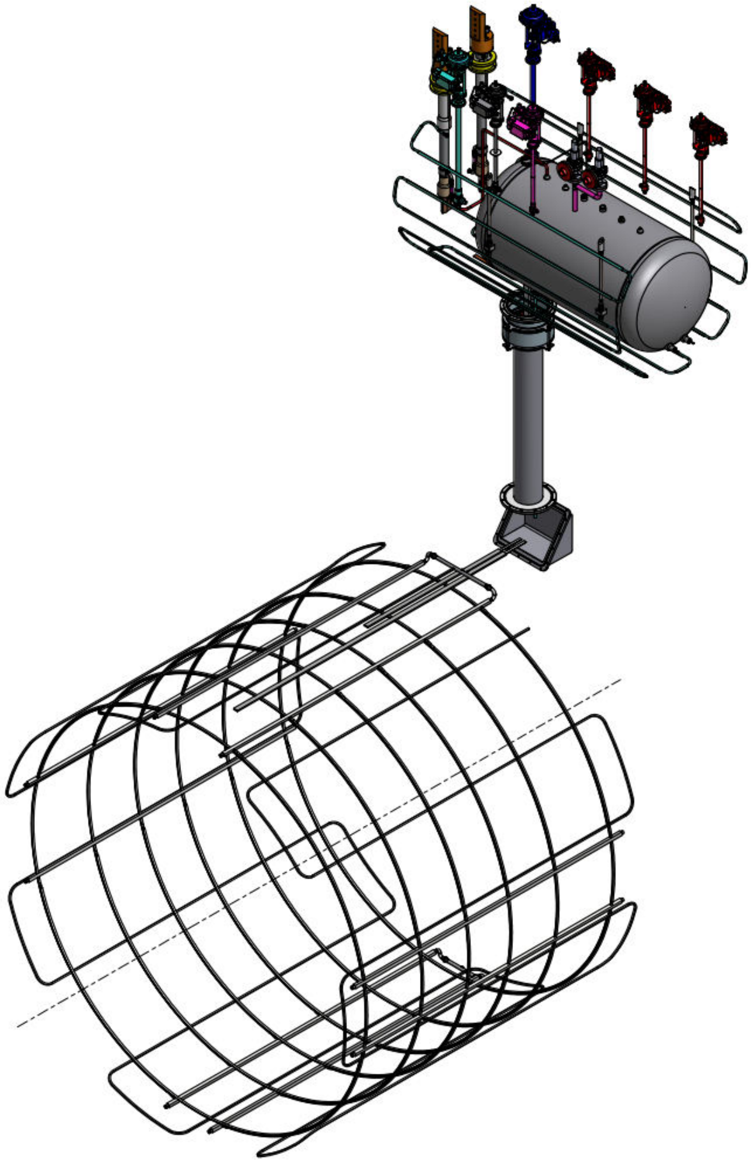
The cryostat thermal shield surrounds the cold mass with the coil. It consists of two cylindrical sectors and two flanges. The shield envelope is split up into electrically separated parts (quadrants) to avoid damage and deformations of the screen when the coil undergoes an emergency discharge. The quadrant shells are separated by gaps of about 14 mm covered by sheets of insulating material G10.

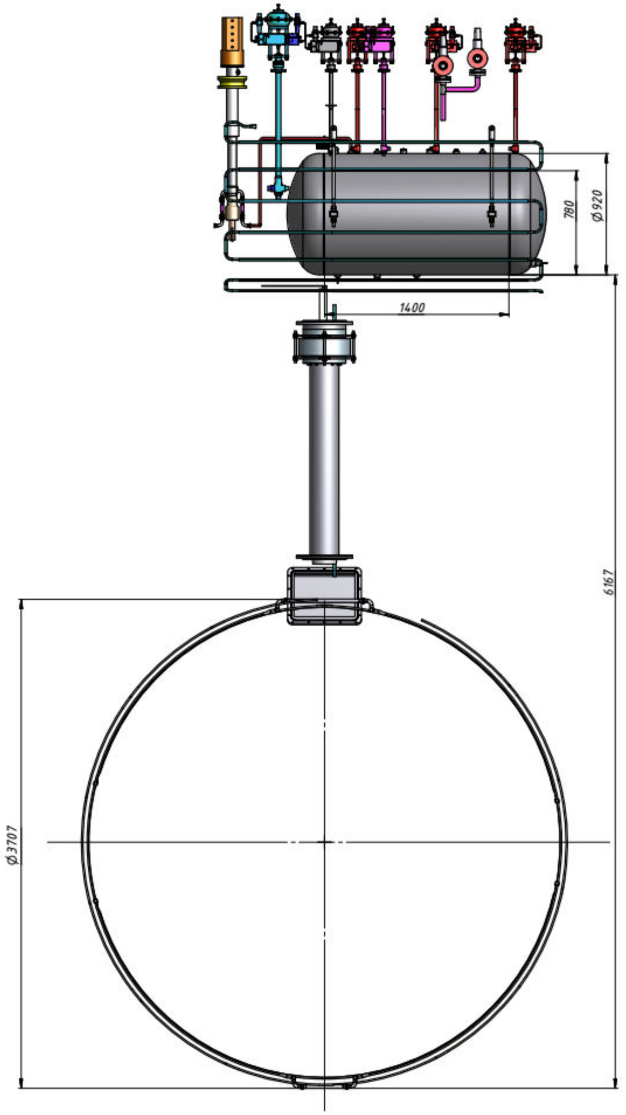
SPD solenoid. Cold mass cooling design.



The cryogenic scheme of the SPD solenoid relies on indirect cooling of the cold mass by circulating saturated helium at 4.5 K by natural convection.

SPD solenoid. Cold mass cooling design.



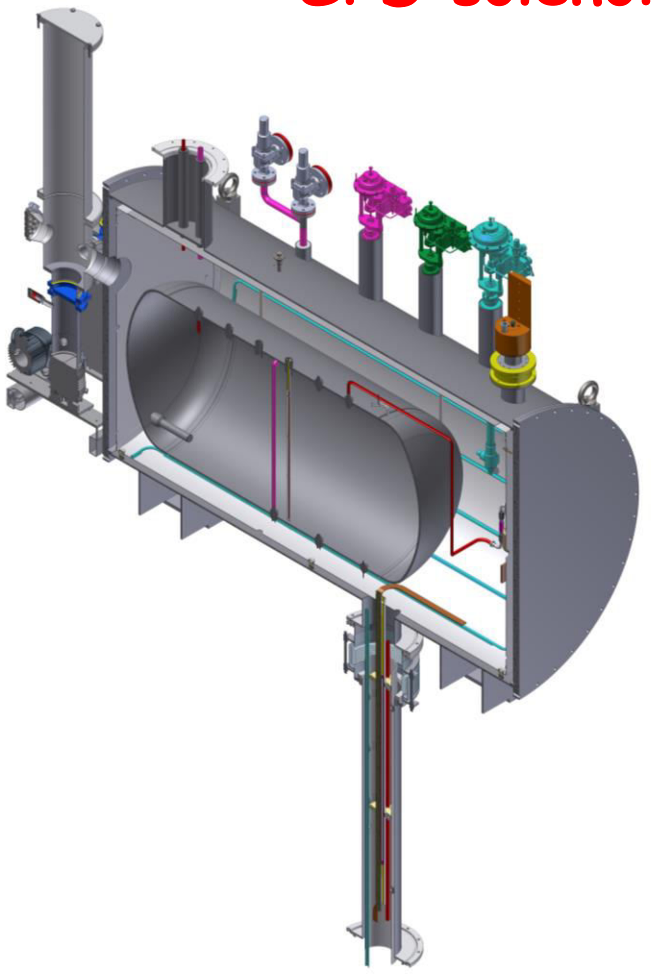


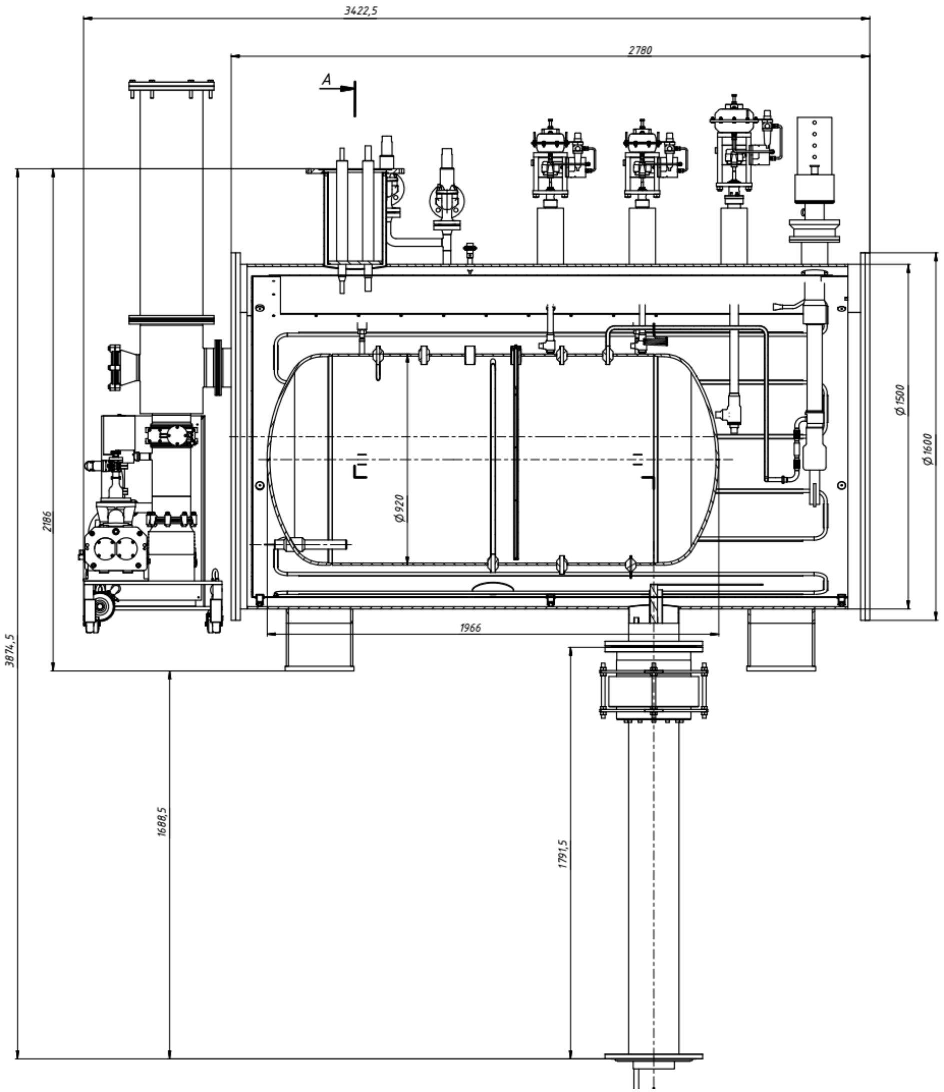
The thermo-syphon circuit consists of a bottom and top manifolds connected by 12 parallel syphon tubes attached to the outer surface of the support cylinder of cold mass.

The cooling method chosen for the SPD magnet's superconducting coil is based on the natural convection of liquid helium flow. It is a self-regulating thermosyphon circulation flow system. Natural circulation loop works on the principle that a heat load on the channels of the heat exchanger produces a two-phase flow that is on average less dense than the liquid phase.

Mass Helium flow SPD - 9-10 g/sec

SPD solenoid. Distribution box





The distribution box includes cryogenic valves, safety relief valves, vessel with liquid helium 600l volume, instrumentation and current leads to ensure the operation of the solenoid.

SPD solenoid. Superconductor.

BINP suggest to use a superconducting NbTi/Cu wire based Rutherford cable co-extruded with a high purity aluminum-stabilizing matrix. This type of conductor was used for production larger detectors such as CELLO, CDF, TOPAZ, VENUS, ALEPH, DELPHI, CLEO, SDC, BELLE, ATLAS CS, ATLAS ECTs, ATLAS BT, CMS, Mu2e solenoids and PANDA.

The SPD solenoid is designed to operate at a current of 4,5 – 5,2 kA for vertical position of the conductor, i.e. about 24 – 28 % of its critical current at 4.5 K and 2,0 T peak magnetic field.

The insulated conductor dimensions at 4.5 K are 10.90 mm in width and 7.90 mm in height. The Rutherford cable is composed of 8 strands with a diameter of 1.40 mm and a Cu/SC ratio of 1.0. The critical current density of the superconductor at 4.2 K and 5 T shall be larger than 2800 A/mm2 to ensure a temperature margin for quench well above 2.0 K. The same type of the conductor is produced in Russia and used for the PANDA solenoid, FAIR, Darmstadt.

Conductor.

Production strands

Producer: "A.A. Bochvar High-technology Research Institute of Inorganic Materials" (JSC "VNIINM").

Protocol measurements 01-400/423 from 29.09.2021/18.10.2021

Superconductive NbTi strand PANDA solenoid

Strand cross section

Parameter	Unit	Certified		1-C2-1P-1-21/1 > 1400 m	1-C2-1P-1-21/2-1-1-2 > 200 m
		Value	Tolerance		
Diameter filament	μm	< 20	-		
Diameter strand	mm	1.400	± 0.005		
Cu/SC ratio	-	.50/.50	± 0.05	/0.5187	/0.5132
Surface coating	-	none	-	none	none
NbTi J_c (at 4.2 K, 5 T)	A/mm^2	> 2800	-		
Critical current (at 4.2 K, 5 T)	A	> 2160	-	2220	2175
n-value (at 4.2 K, 5 T)	-	> 30	-	71*	70*
Conductor RRR	-	> 100	-	196	191
Twist direction	-	left	-	left	left
Twist pitch	mm	25	± 5	22	21

*Magnetic field value is 6 T

Table 1 NbTi/Cu strand mechanical and electrical specifications.

Conductor.

Production strands

Batch number / strand piece number	Diameter, mm (1,400 ± 0,005 mm)	Cu/SC ratio NbTi, %	Twist pitch		RRR
			begin	end	
1-C2-1P-1-21/1	1,4	0,5187	22	22	196
1-C2-1P-1-21/2-1-1-1	1,4	0,5140	21	22	207
1-C2-1P-1-21/2-1-1-2	1,4	0,5132	21	21	191
1-C2-1P-1-21/2-1-2	1,4	0,5126	22	22	205
1-C2-1P-1-21/2-2	1,4	0,5122	22	24	205

Table 2 Technical parameters

Batch number / strand piece number	Sample	Measurement	Mechanical properties	
			Ultimate resistance, MPa	Yield strength, MPa
1-C2-1P-1-21/1	1n	1	903	838
		2	897	836
		3	909	845

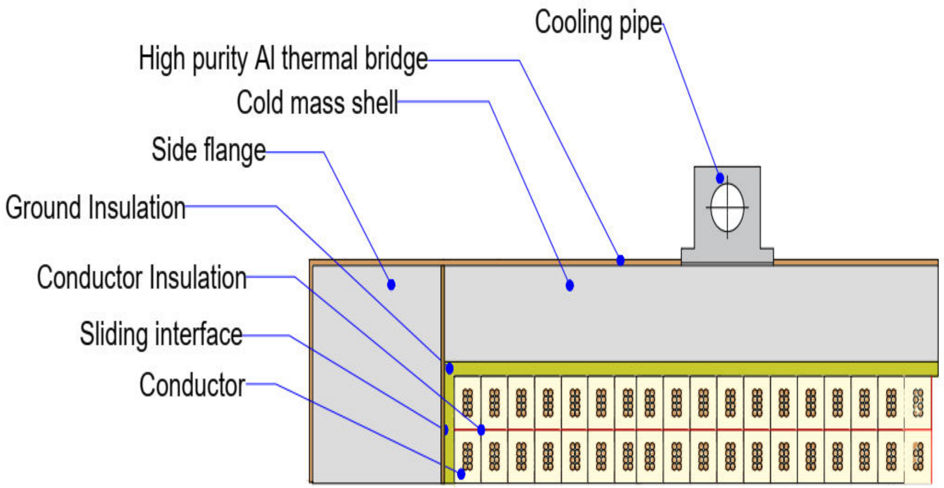
Table 3 Mechanical properties

Batch number / strand piece number	Field, T	I_c, A (4,2 K; 0,1 mkV/sm)	n-value
1-C2-1P-1-21/1	8	789	35
	7	1253	52
	6	1746	71
	5	2220 (calc.)	-
1-C2-1P-1-21/2-1-1-1	8	750	35
	7	1208	53
	6	1694	71
	5	2175 (calc.)	-
1-C2-1P-1-21/2-2	8	750	36
	7	1200	50
	6	-	-
	5	2165 (calc.)	-

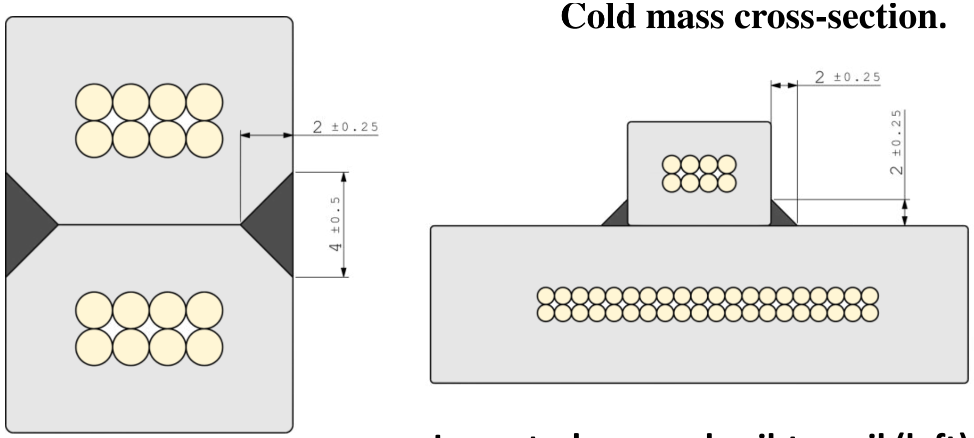
Table 4 Critical current (at 4.2 K) and n-value (at 4.2 K) vs magnetic field.

PANDA conductor

Rutherford cable, 8 strands, extruded in Al matrix



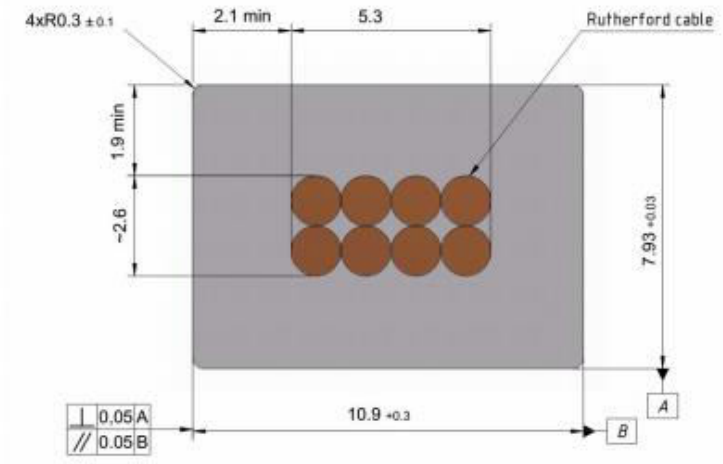
Cold mass cross-section.



Layer-to-layer and coil-to-coil (left) and terminal (right) joint layouts.

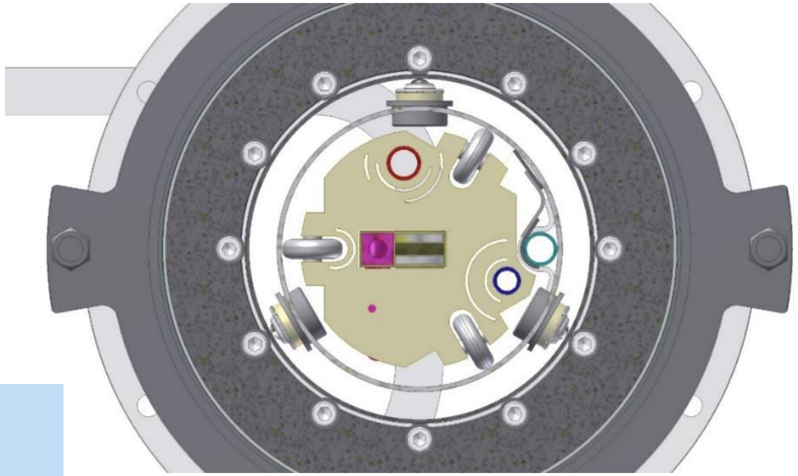
Thickness (after cold work) at 300 K	mm	7.93	± 0.03
Width (after cold work) at 300 K	mm	10.95	± 0.03
Critical current (at 4.2 K, 5 T)	A	> 14690	
Critical current (at 4.5 K, 3 T)	A	> 16750	
Overall Al/Cu/sc ratio		10.5/1.0/1.0	
Aluminum RRR (at 4.2 K, 0 T)		> 1000	
Al 0.2% yield strength at 300 K	MPa	> 30	

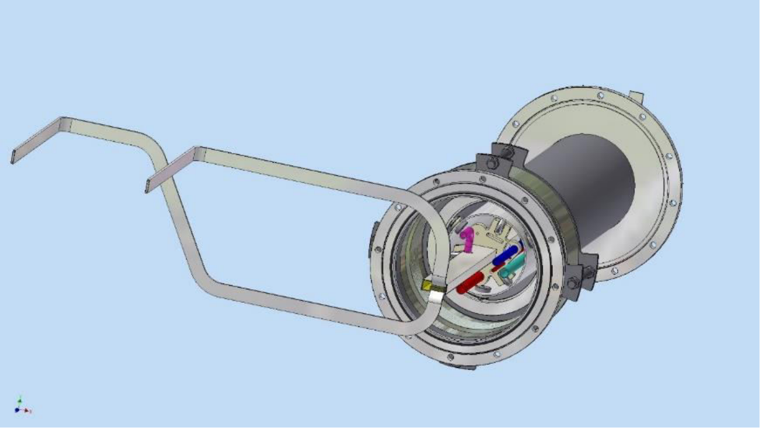
Conductor mechanical and electrical parameters.

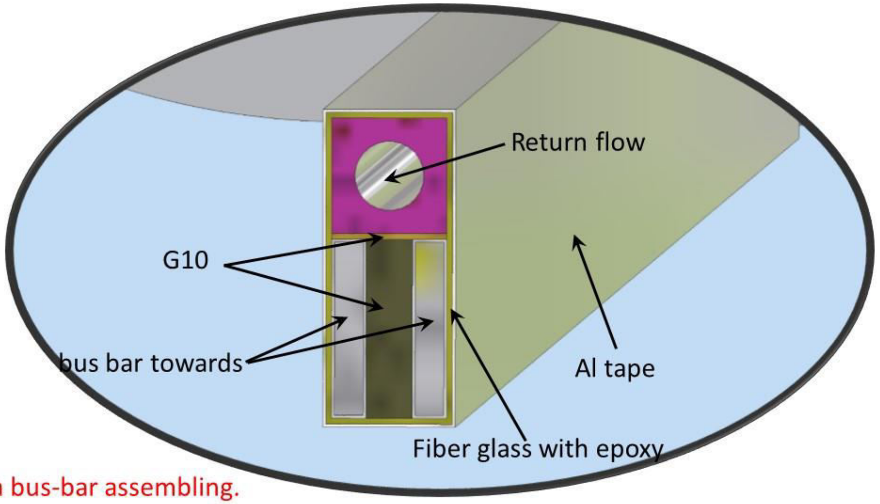


Cross-section of the conductor.

SPD solenoid. Distribution box and transfer line



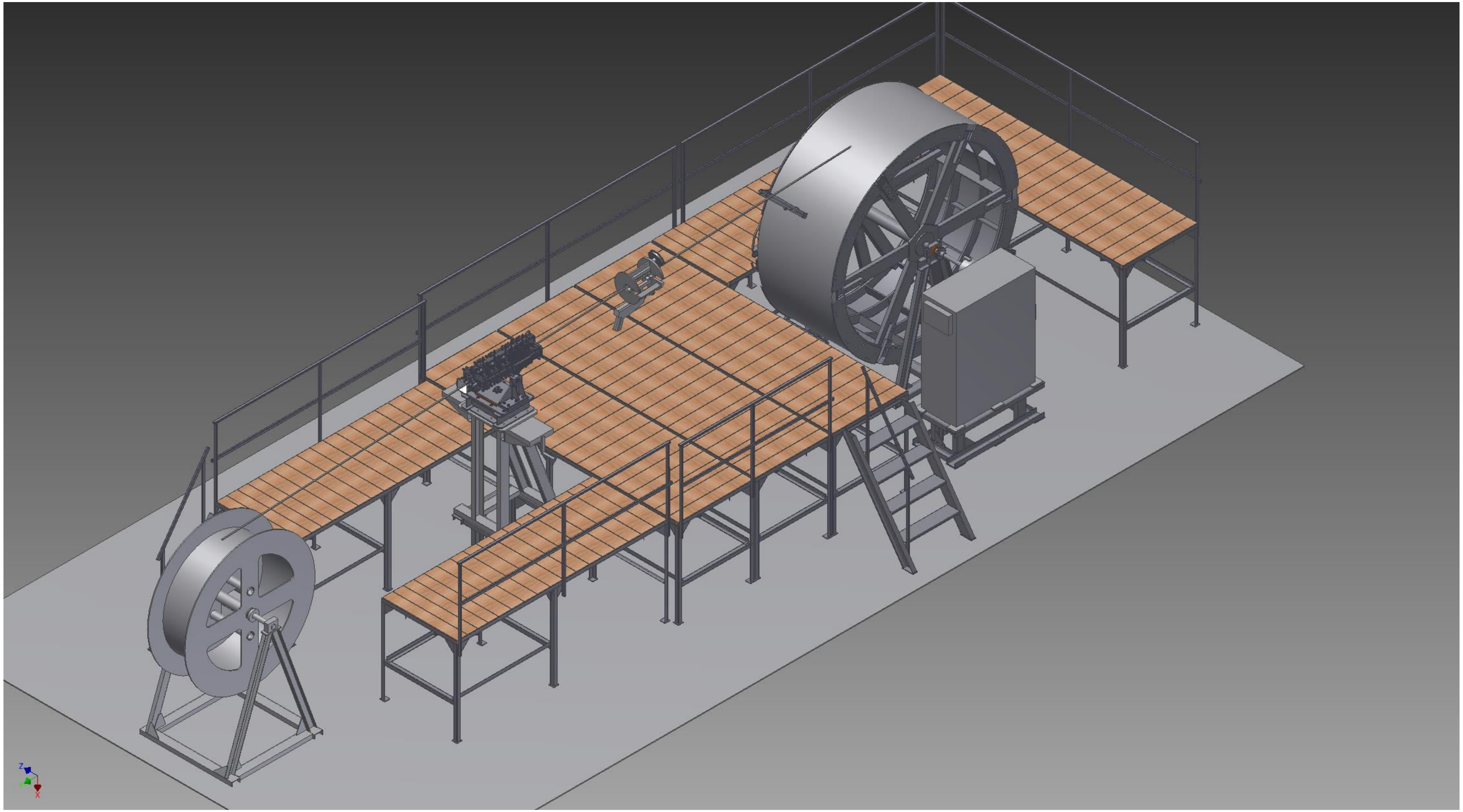




Cross section of a bus-bar assembling.

The transfer line (chimney) connects the vacuum volumes of the cryostat and the control Dewar. The outer diameter of the chimney is 219.1 mm, the wall thickness is 2 mm. It encloses the superconducting bus bars, direct and return pipes for gaseous and liquid helium flows, measurement wiring, all of which are surrounded by a thermal shield

Drawing of the Devices for winding coil (scheme).



Thank you for your attention