Superconducting magnets developed in BINP: status of works

Alexey Bragin

on behalf of BINP team

Budker Institute of Nuclear Physics (BINP),

Novosibirsk, Russia

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Outline

- **Superconducting wigglers and undulators for SKYF project – the scope of work and status**
- **Superconducting dipole magnet for CBM detector, FAIR project**
- **Superconducting solenoid for PANDA detector, FAIR project**

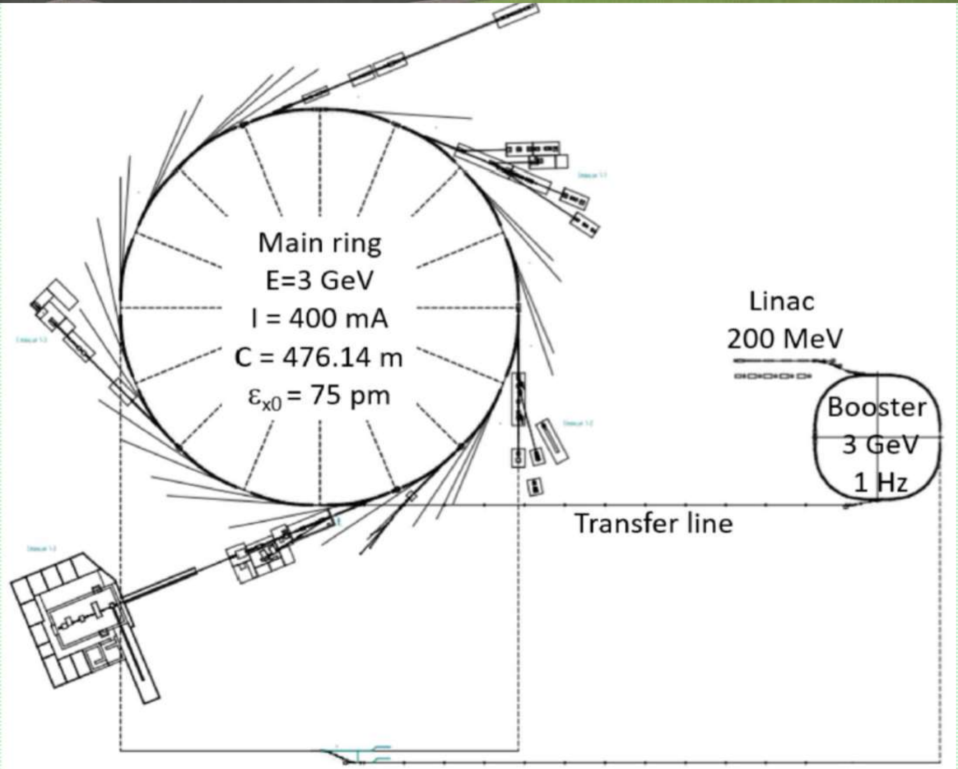
SKIF project

Synchrotron radiation accelerator is being built in Novosibirsk region
Generation type 4+
Energy 3 GeV
Accelerator length 476 m
Emittance 75 pm•rad
The operation should start in December 2024

The list of first set of the insertion devises

The type of insertion device and the station number	Magnetic field, T	Period, mm	Number of poles	Vertical gap, mm	Vertical beam aperture, mm	Radiation power, kW
SKIF wiggler, 1-5 station	4.5	48	18	7	5	39
SKIF wiggler, 1-3 station	2.7	27	74	7	5	33

The type of insertion device and the station number	Magnetic field, T	Period, mm	Number of poles	Radiation horizontal angle, mrad	Radiation power, kW
Undulator, 1-1 station	1.25	15.6	128	± 0.32	7.66
Undulator, 1-2 station	1.25	15.6	128	± 0.32	7.66
Undulator, 1-4 station	1.6	18	111	± 0.46	11.75

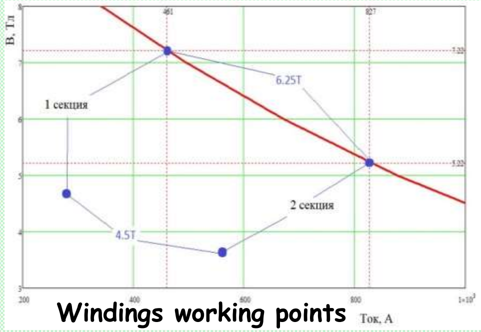


SKIF superconducting wiggler

Superconducting wiggler for the 1-5 station with period of 48 mm and 4.5 T magnetic field *«Diagnostics in high x-ray range»*

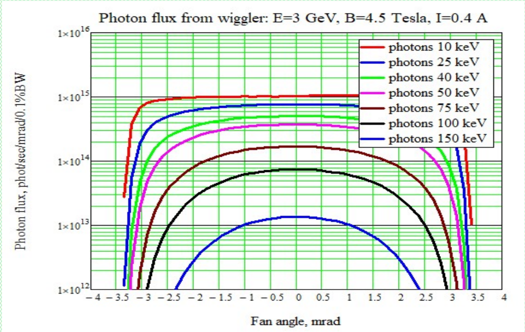
- ❑ Demands and conditions. Radiation energy ($\varepsilon_c \propto B$) + wide angle (>>1/γ). Wide angle and high radiation energy (up to ~150 keV). To be used in research in materials, geology, medicine;
- ❑ The wiggler design was optimized at high magnetic field 4.5 Тл;
- ❑ The wiggler was manufactured and tested in the test cryostat at 4.2 K temperature. There was achieved ~4.6 T of magnetic field (February 2023).
- ❑ Now the wiggler cryostat is being assembled.

Parameters	Value
Nominal magnetic field, T	4.5 (4.6)
Period, mm	48
Pole gap, mm	7
Beam vertical aperture, mm	5
Beam horizontal aperture, mm	40
Number of periods	18
Number of main poles	36
Number of ¾ poles	2
Number of ¼ poles	2
Magnet length, mm	~950
Flange distance, mm	~2700
Current, A	350
Radiation power (B=4.5 T, I=0.4 A, E=3 Gev), kW	39
Angle of horizontal radiation, mrad	± 3.5

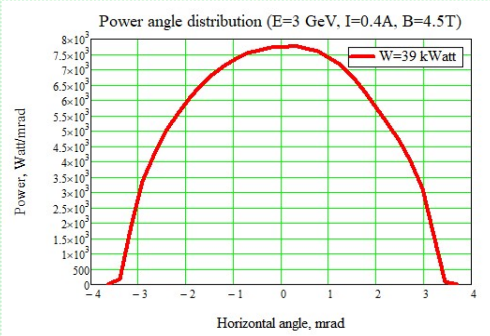


Windings working points


Assembling of the wiggler

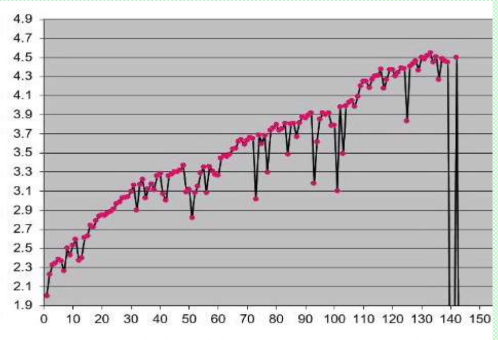


Angle-spectrum distribution of photons flow



Angle distributions of radiation power


The wiggler before tests


Training history

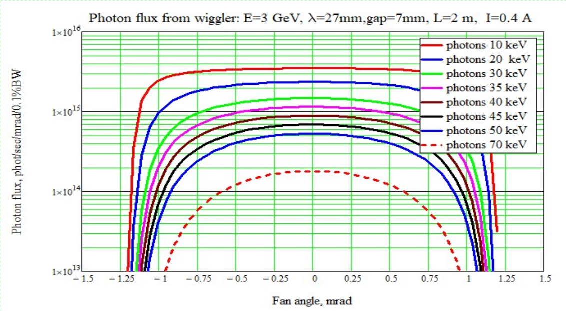
SKIF superconducting wiggler

Superconducting wiggler for the 1-3 station with period of 27 mm and 2.7 T magnetic field
«Fast processes»

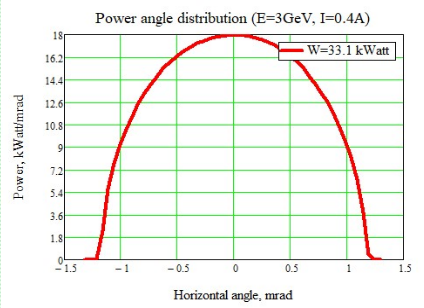
- The wiggler will be used in research of very fast processes having duration period in the range from ps to ms (1 bunch – 1 «picture»). The maximal ration of photons/bunch is required in the range of 20 - 70 keV;
- Power limit is ~30 kW;
- Wiggler parameters are high (magnetic field of 2.7 T at 27 mm of period). The wiggler with close parameters was installed in ALBA (Spain) having 119 of poles and magnetic field of 2.1 T and period of 30 mm;
- The short prototypes of this wiggler was tested in LHe bath in 2 of March, 2023. There was achieved the field of 3.06 T.

Parameters	Value
Nominal magnetic field, T	2.7
Period, mm	27
Pole gap, mm	7
Beam vertical aperture, mm	5
Beam horizontal aperture, mm	40
Number of periods	74
Number of main poles	148
Number of $\frac{3}{4}$ poles	2
Number of $\frac{1}{4}$ poles	2
Magnet length, mm	~200
Flange distance, mm	~2700
Current, A	820
Radiation power (B=2.7 T, I=0.4 A, E=3 Gev), kW	33.1
Angle of horizontal radiation, mrad	± 1.2

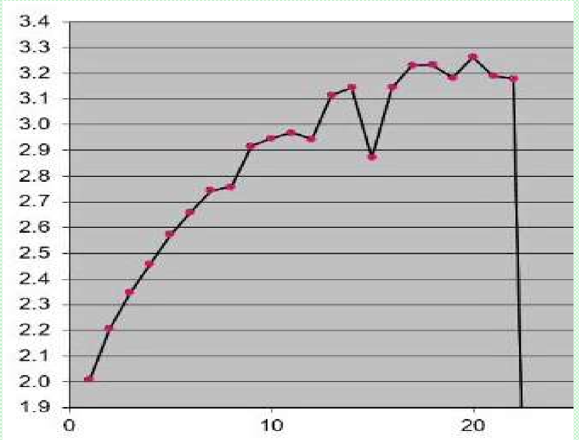
Assembling of the short prototype



Angle-spectrum distribution of photons flow



Angle distributions of radiation power



Training history of the short prototype

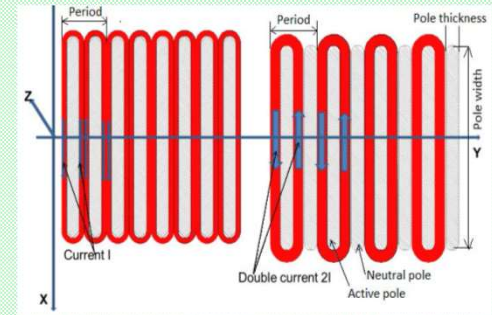
SKIF superconducting undulator

The superconducting undulators having 15.6 mm of period and 1.25 T of magnetic field will be used for the 1-1 «Microfocus» station and 1-2 «Structure diagnostics» station

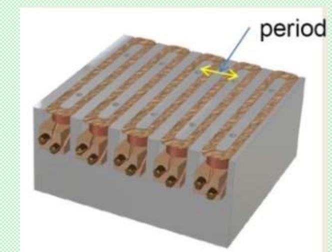
- ❑ Full size prototype was manufactured having 1.2 T of magnetic field and 8 mm of pole gap. All tests and magnetic field measurements were performed;
- ❑ The undulator design includes the sequence of active and neutral poles

Parameters	Value
Nominal magnetic field, T	1.25
Period, mm	15.6
Pole gap, mm	7
Beam vertical aperture, mm	5
Beam horizontal aperture, mm	40
Number of periods	128
Magnet length, mm	~2000
Flange distance, mm	~2700
Current, A	~440
Radiation power (B=1.25 T, I=0.4 A, E=3 Gev), kW	7.66
Angle of horizontal radiation, mrad	± 0.32
Average phase error, deg	<3
Maximal value of deviation parameter	K ~1.89

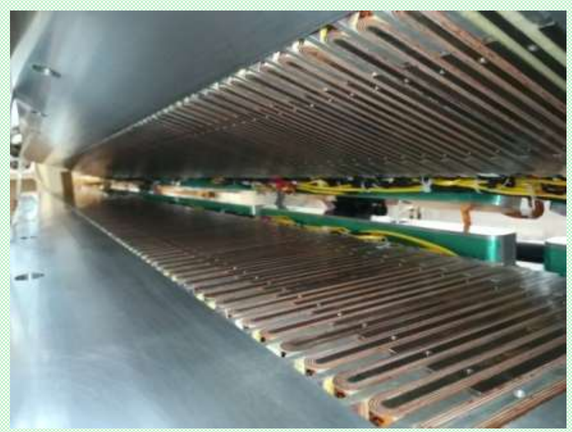
SC undulator installed in its own cryostat



The undulator design with active and neutral poles



The view of the undulator cryostat during the tests

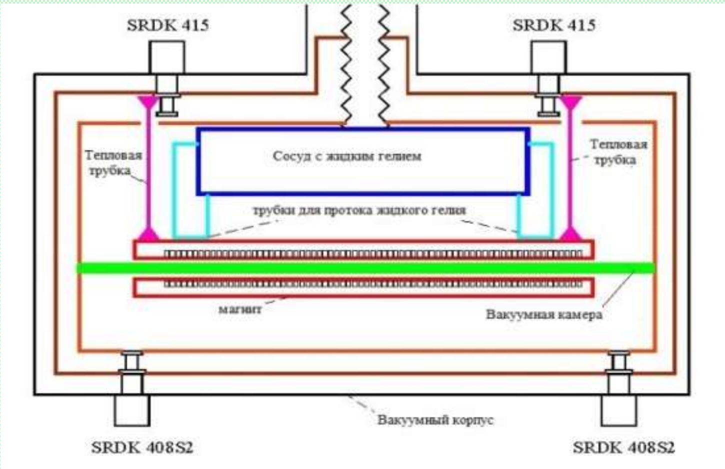


The view of the superconducting coils inserted into the magnet structure

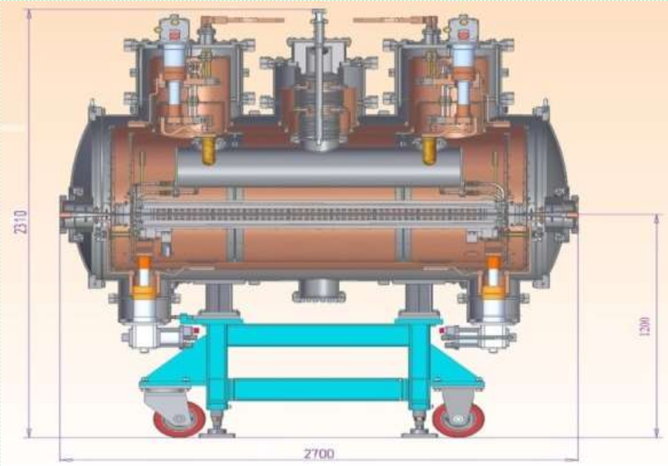
The undulator is assembled with LHe volume

Cryogenics of the SKIF insertion devices

- The magnets are indirectly cooled be liquid helium. The cryocoolers are used to give zero helium boil off. Liquid helium is kept in small volume. The cooling channels are installed in the magnets structure.
- The premature cooling can be performed by use nitrogen heat pipes. It is working down to 64 K temperature (nitrogen freezing).
- The residual pressure in the helium volume is about 0.5 bar, magnet temperature is ~ 3.5 K.
- The magnets can work several years without helium refill.



The scheme of the wiggler/undulator cryogenics



Cryostat design

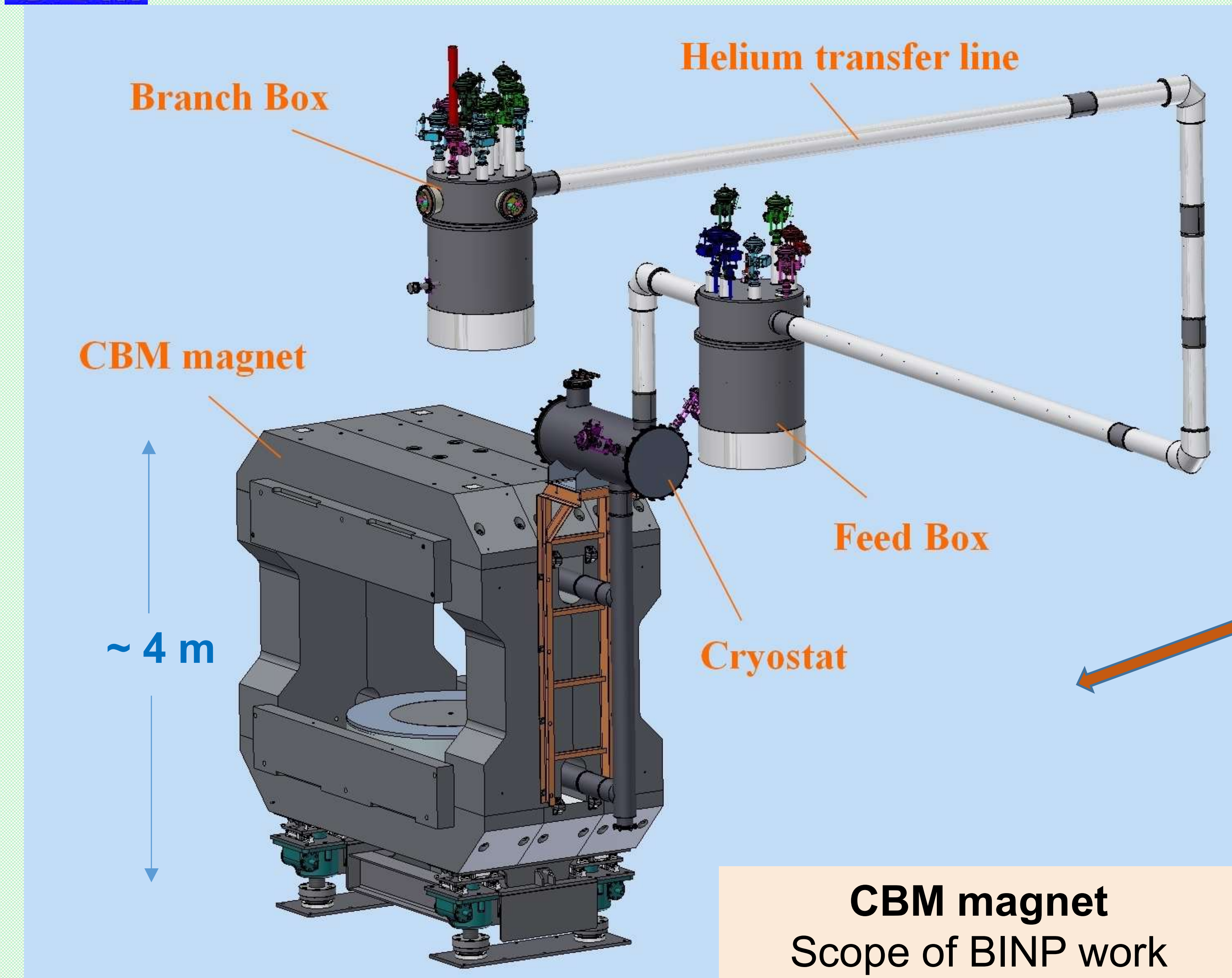
Assembling of the cryostat

Typical parameters

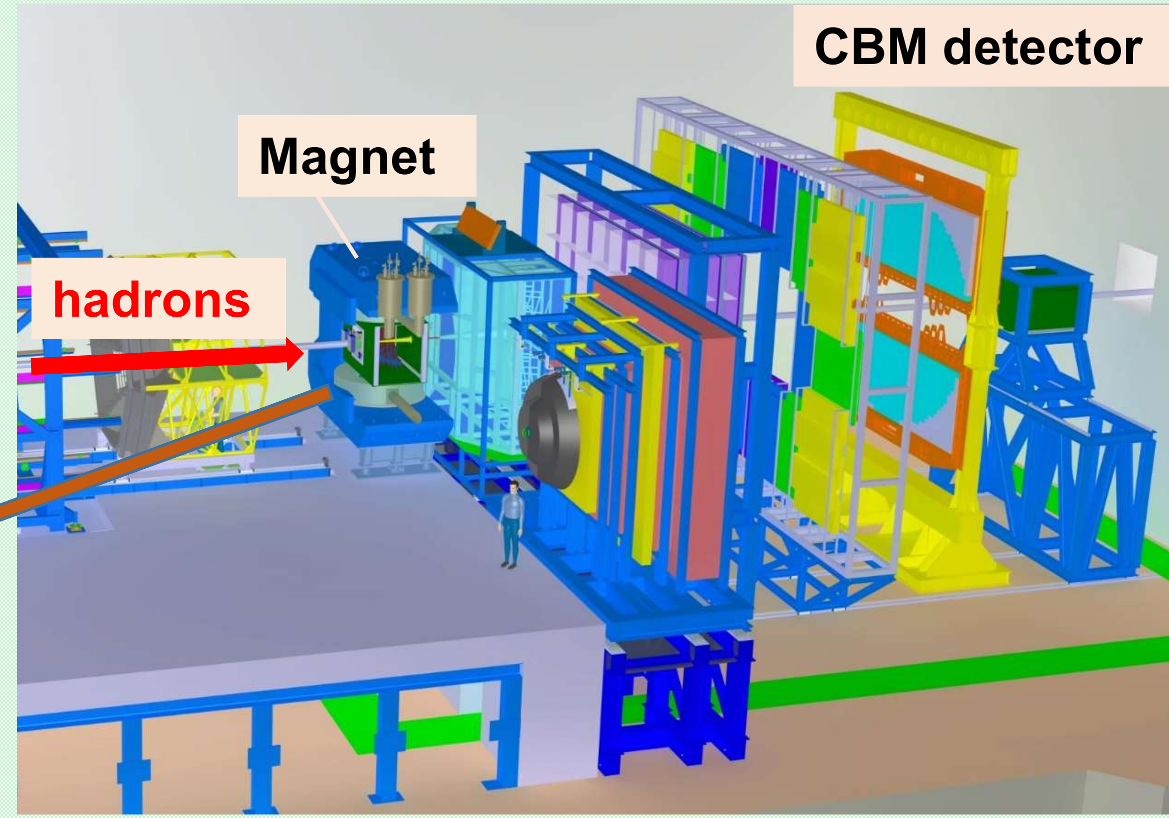
	Outer shield (60 K), W	Inner shield (20 K), W	Surfaces at 4 K, W
Thermal radiation	8	0.05	0.0002
Central neck	2.5	0.3	0.06
Vacuum chamber bellows	5.3	0.25	0.04
Suspension strings	0.5	0.1	0.01
Current leads (thermal conductivity)	50	0	0.3
Current leads (Joule heating)	50	0	0.3
Measurement wires	5	0.1	0.01
Liner	10	10	0.2
Total in leak	131.3	10.8	0.92
Cryocoolers cooling capacity	180 (at 50 K)	15 (at 20 K)	3 (at 4.2 K)

The CBM detector view

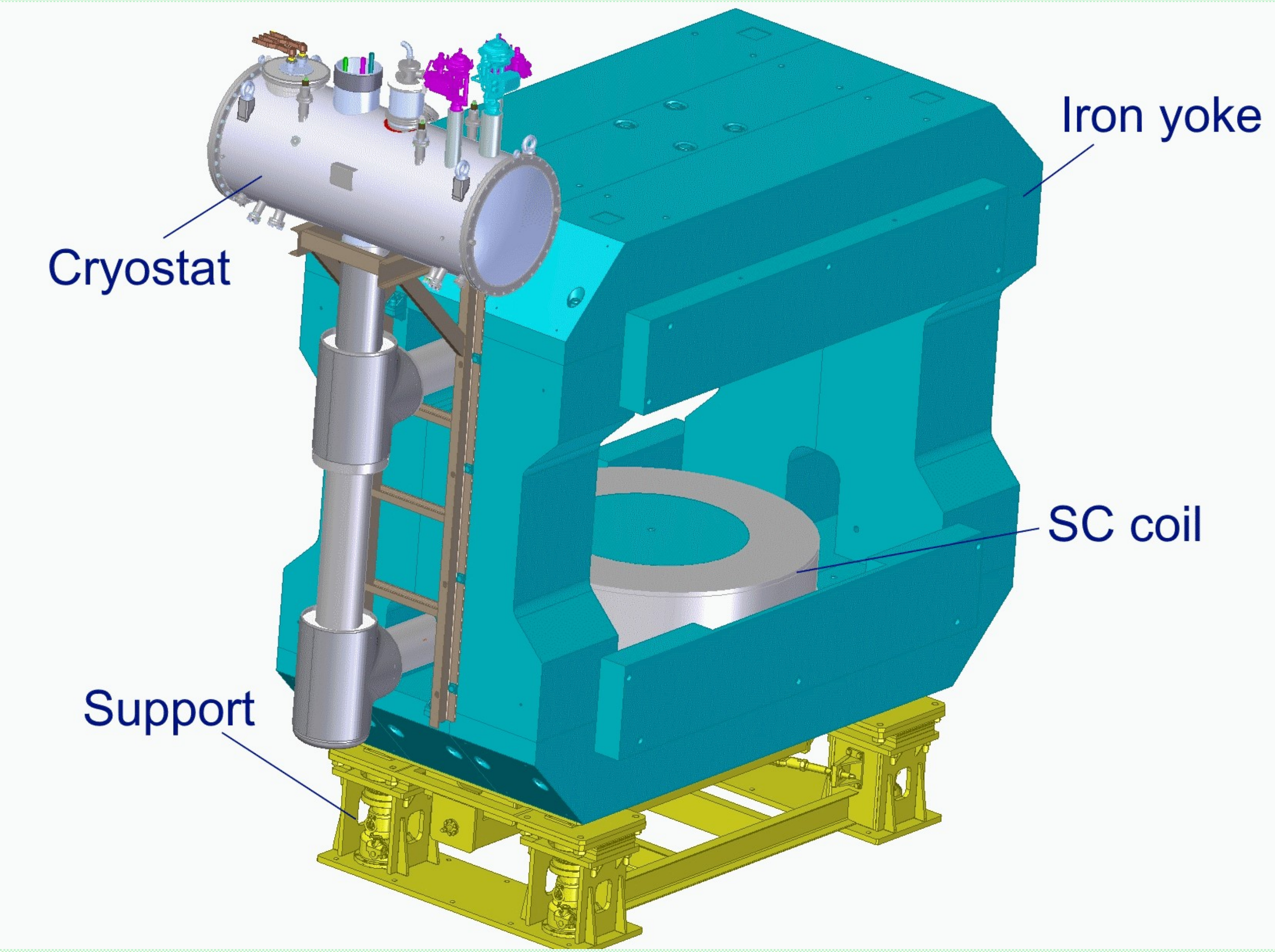
Compressed **B**aryon **M**atter **(CBM)** will be researched with the CBM detector, FAIR facility, GSI, Germany. The CBM detector is designed to measure the collective behavior of hadrons, together with rare diagnostic probes such as multi-strange hyperons, charmed particles and vector mesons decaying into lepton pairs with unprecedented precision and statistics. The hadrons will be collided on the target inside the center of the dipole magnet.



CBM magnet
Scope of BINP work



The CBM magnet total view



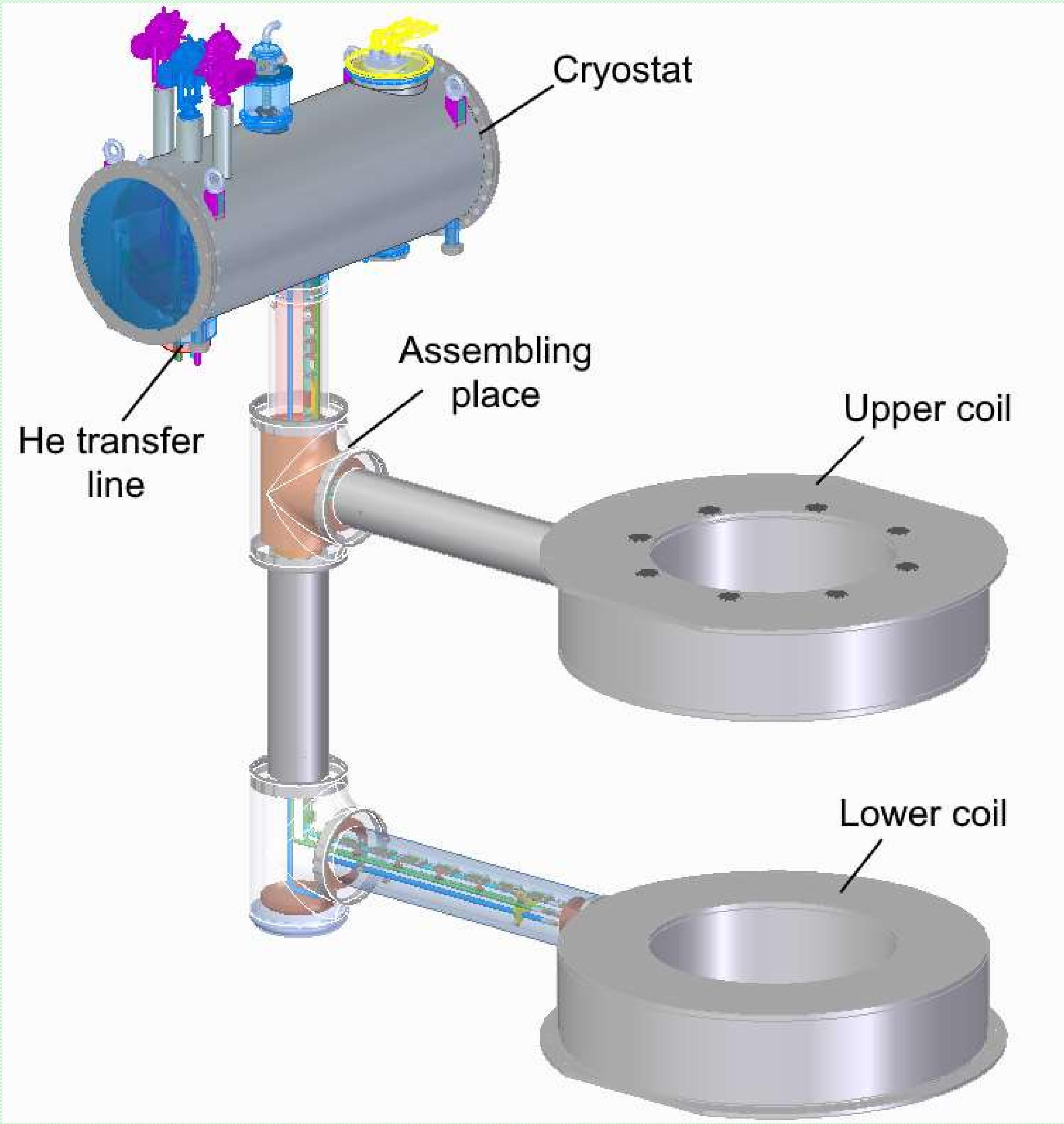
The CBM magnet is superconducting dipole magnet having the 150 t iron yoke.
The superconducting coils are indirectly cooled by liquid helium at 4.5 K by natural conditions.

Main parameters of the CBM magnet	
Magnetic field integral along 1 m about the center, T*m	1.02
Maximal magnetic field on the coils, T	3.6
Inner diameter of the SC winding, m	1.4
Vertical distance between the poles, m	1.44
Operating current, A	666
Number of turns per coil	1716
Stored energy, MJ	5.0
Coils cold mass, kg	3600
Operating temperature, K	4.5
Inductance at operating current, H	21
Vertical force acting on the coils toward the iron yoke, MN	3.0

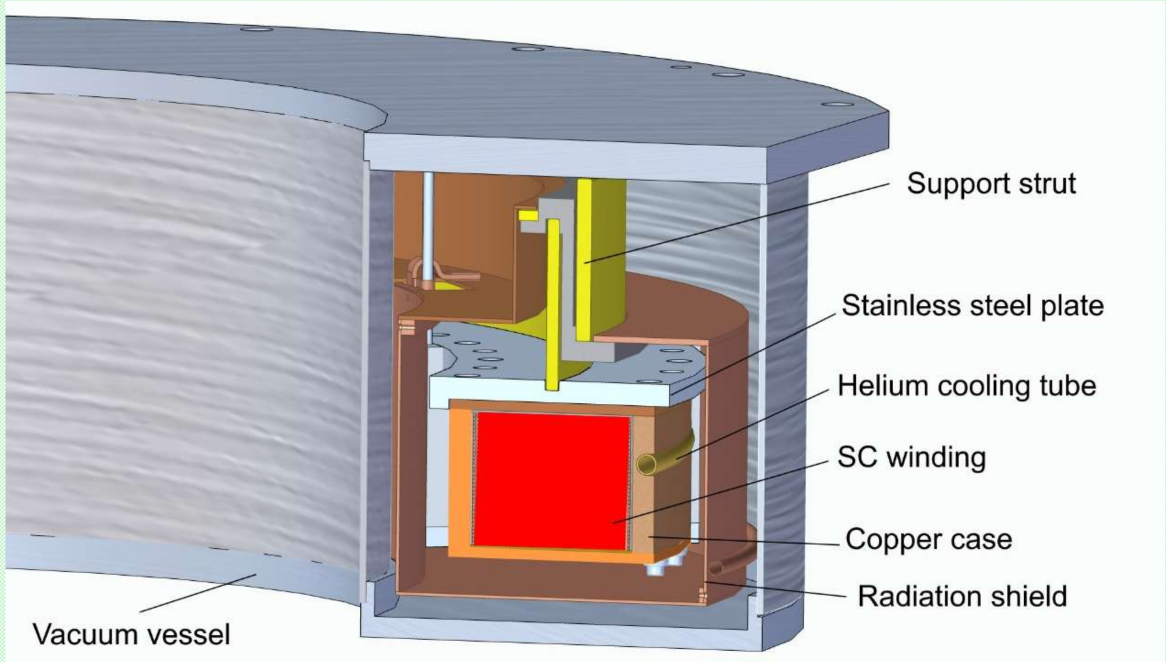
The support can move the magnet in three directions and can slightly rotate it around vertical axis.

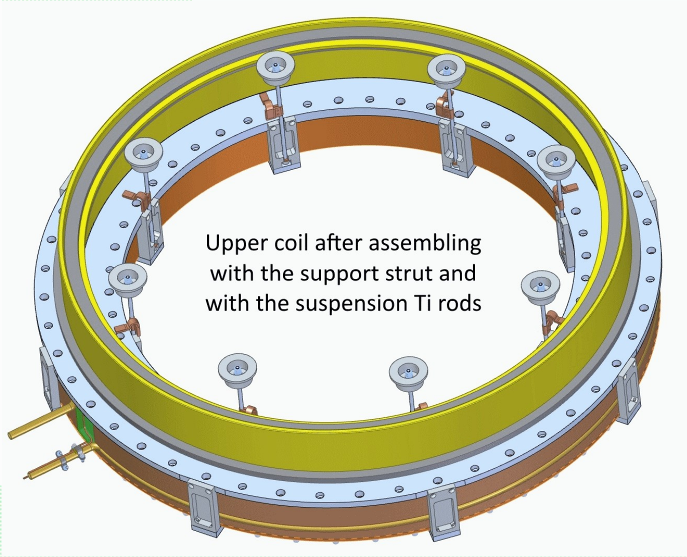
The magnet will be cooled by two helium flows from the GSI cryoplant at 4.6K@ 3 bar and 50K@ 18 bar. That is mostly determines the design of the coils.

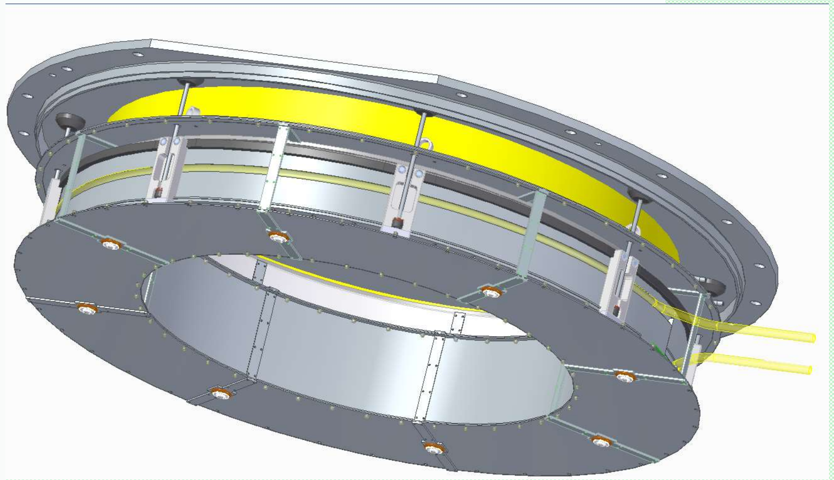
The coils and the cryostat – main part of the magnet



Cross-section of the coil





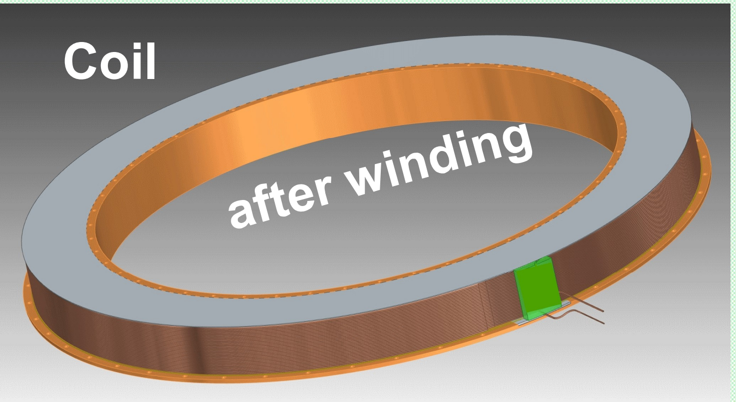


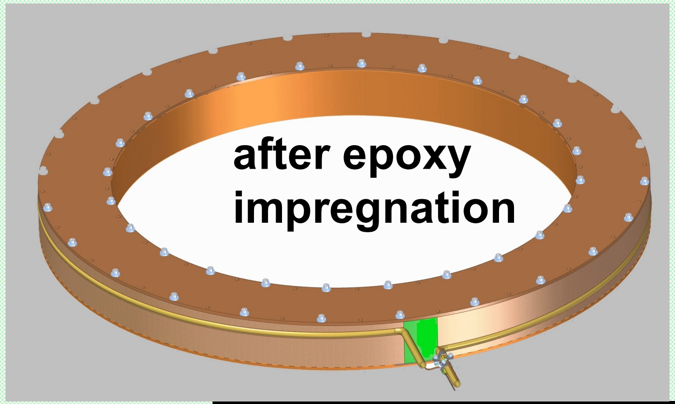
The coil during assembling

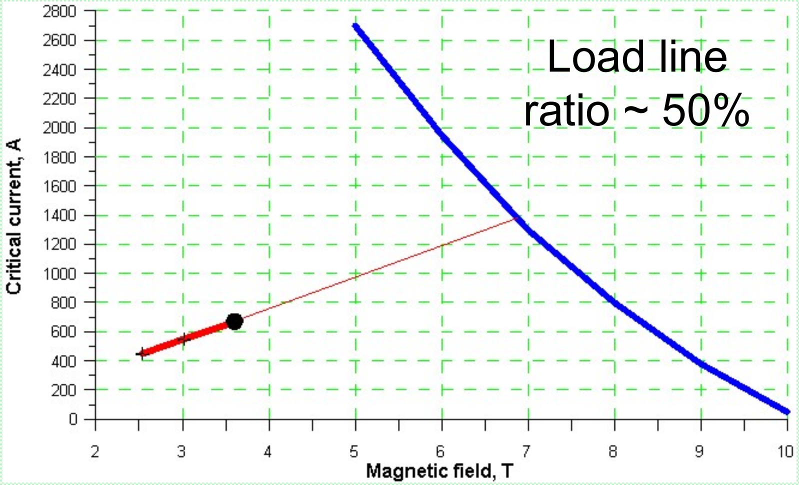
SC winding and the cable

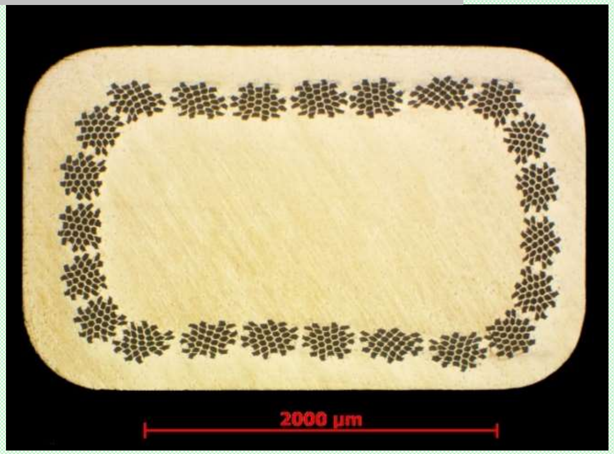
The SC cable will be dry wound on the copper bobbin.
One winding will use two pieces of the cable, so one splicing will be needed.
The winding will be impregnated with epoxy+ fine powder compound.
A mock up coil will be tested with boron nitride powder as a filler in close months.

SC cable parameters (monolith technology)	
Rectangular bare sizes: h × w, mm	2.02×3.2 5
Insulated sizes: h × w, mm	2.62×3.8 5
Cu/NbTi ratio	7/1
Critical current 8T@ 4.2K, A	>780
RRR measured on bare wire	>200
Number of filaments	713
Diameter of the filament, um	38
Twist pitch, mm	39
Length of one piece, km	5.2







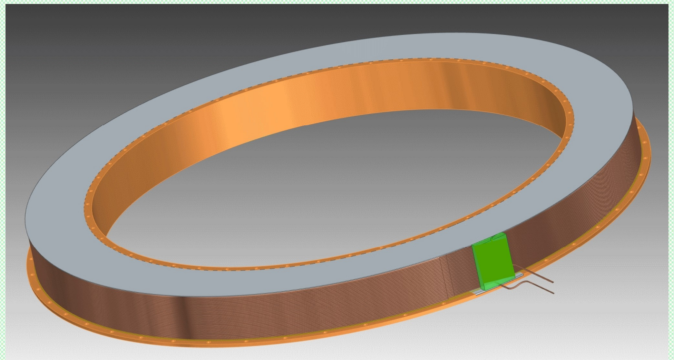


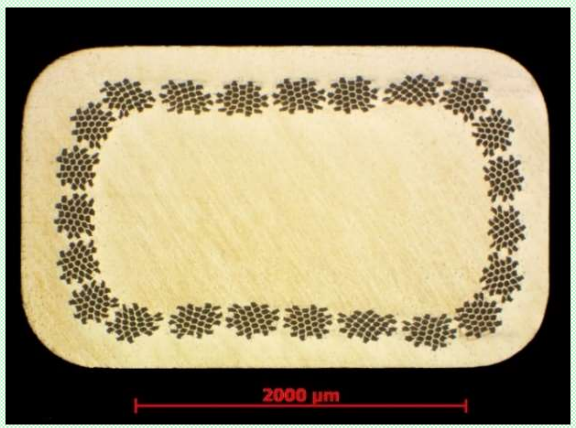
Cross-section photo of the wire

Six pieces of the wire were manufactured in December 2018

Design peculiarities of the CBM dipole magnet, before the conclusions

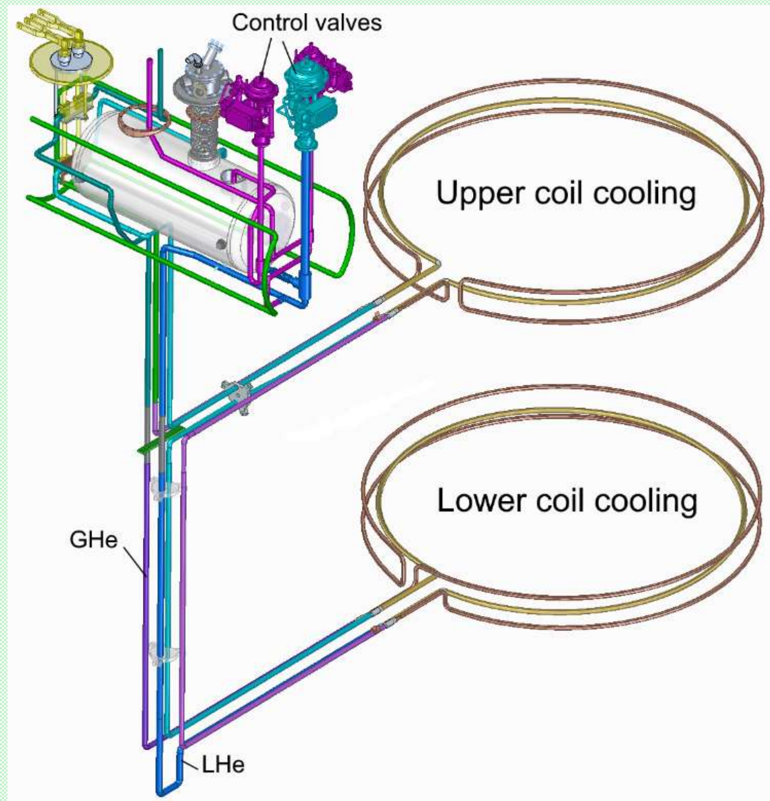
Indirectly cooled design of the coil.
The SC cable has large cross-section/length sizes, more than in MRI SC wires



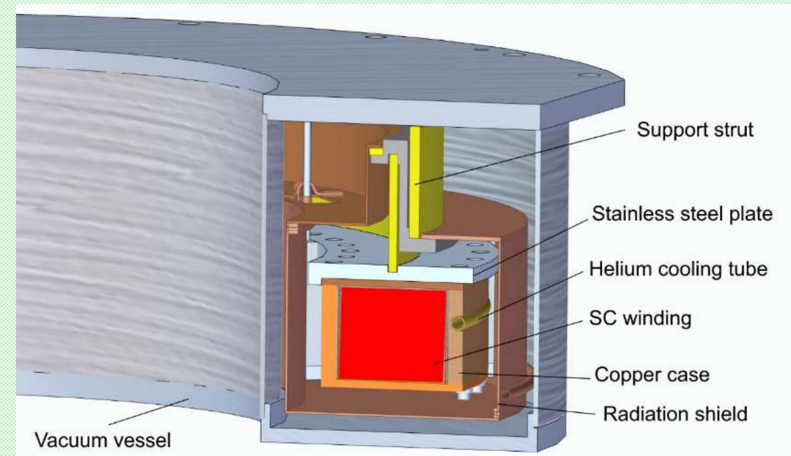


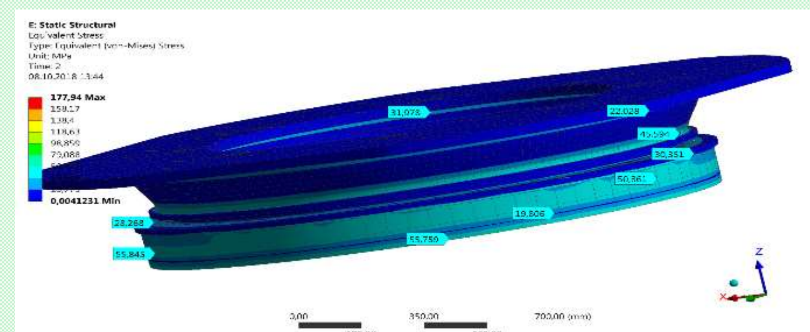
SC wire production was presented in MT-26, September 2019

The coils are serially connected with helium cooling tubes in thermosyphon cooling regime. The vapor quality value is below 10% in the outlet of loop.

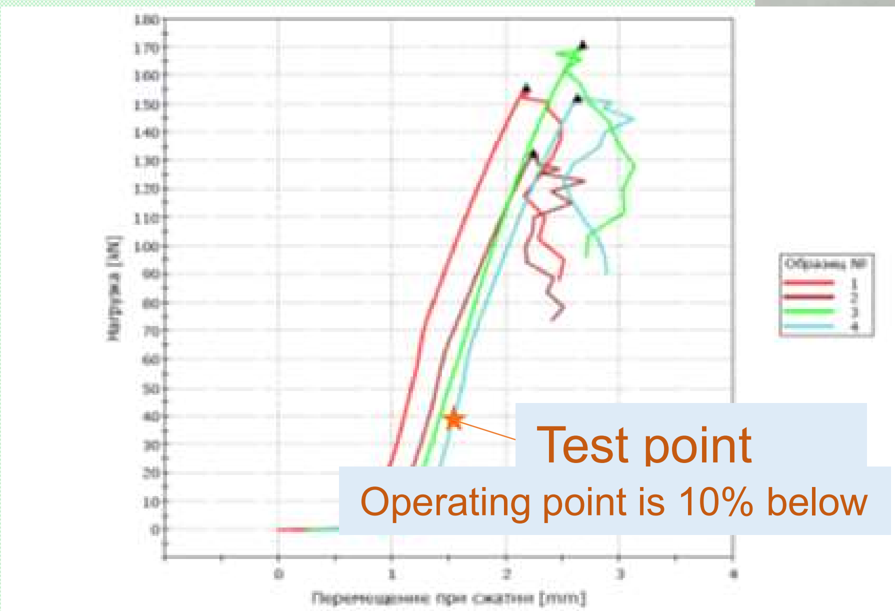


The single strut design has the following advantages:
- reduces the stresses in the coils
- reduces shear stress in the struts
- increases radial rigidity





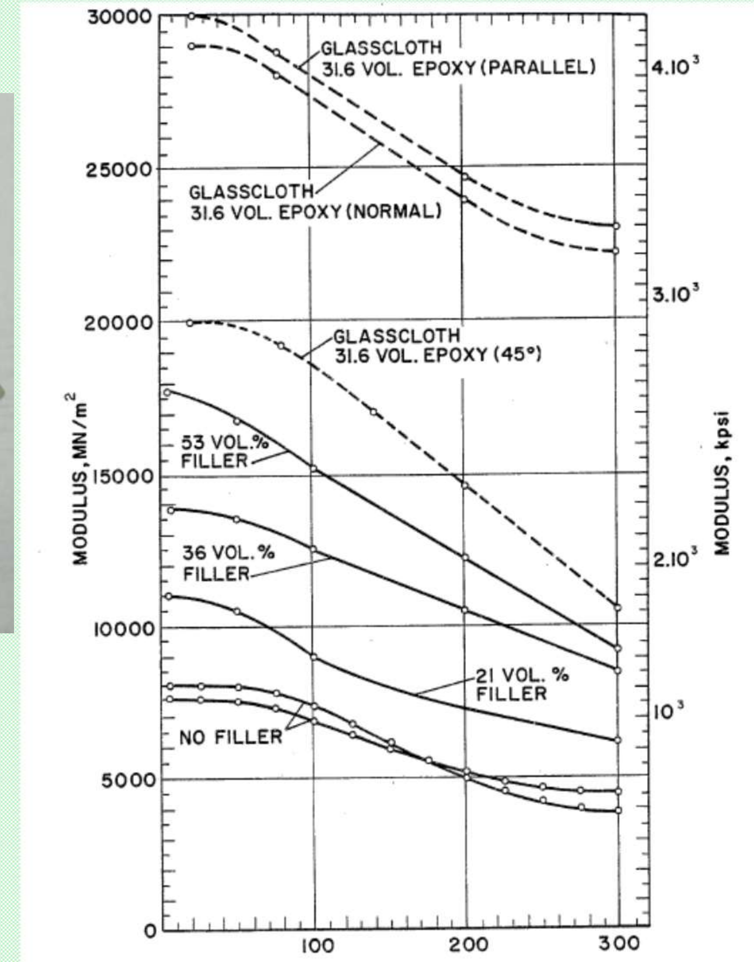
Измерения образцов из стеклопластика



	Максимум Нагрузка при сжатии [kN]	Напряжение при сжатии [MPa]	Площадь [mm^2]
1	155,69008	204,96324	759,59998
2	132,79662	173,84032	763,80002
3	171,83122	225,48611	758,50000
4	152,10041	198,25392	767,20001
Среднее	152,90458	200,63590	762,30000
Стандартное отклонение	15,71953	21,29113	4,01249

Labara cylinder consists of:
- epoxy, ether compound
- glass roving (threads)
- glass cloth

The thermal parameters were also measured:
Thermal conductivity
Thermal contraction – immersing in LN2.



TENSILE MODULUS OF ELASTICITY OF UNFILLED, GLASSFIBER-REINFORCED AND FILLED EPOXIES

The Young's modulus of GFRP – low temperatures dependence.

Cylinder by	Ult. Stren, MPa	Young mod., GPa	Density, g/cm³	Coef. ther., W/(m*K)
JY machinery	153,8	~ 7	2,04-2,05	0,075 (5K); 0,34 (80K)
SIZ	121,7	5,3	2,00	
Labara	200,6	5,8	2,04	0,070 (6.8K); 0,311 (81K)

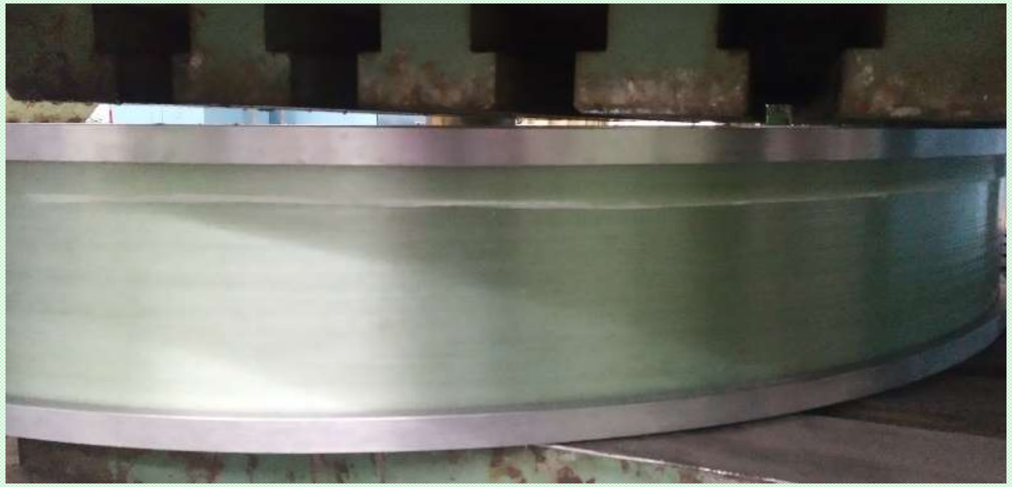
The safety factor of 4 should be designed.

Large press tests – consistency and buckling problem

The view of 1000 t press

The sample was broken at 740 t force value. The compression was not uniform.

The results were satisfying.



The view of the broken sample

The prototype coil was manufactured

The winding process, March 2022

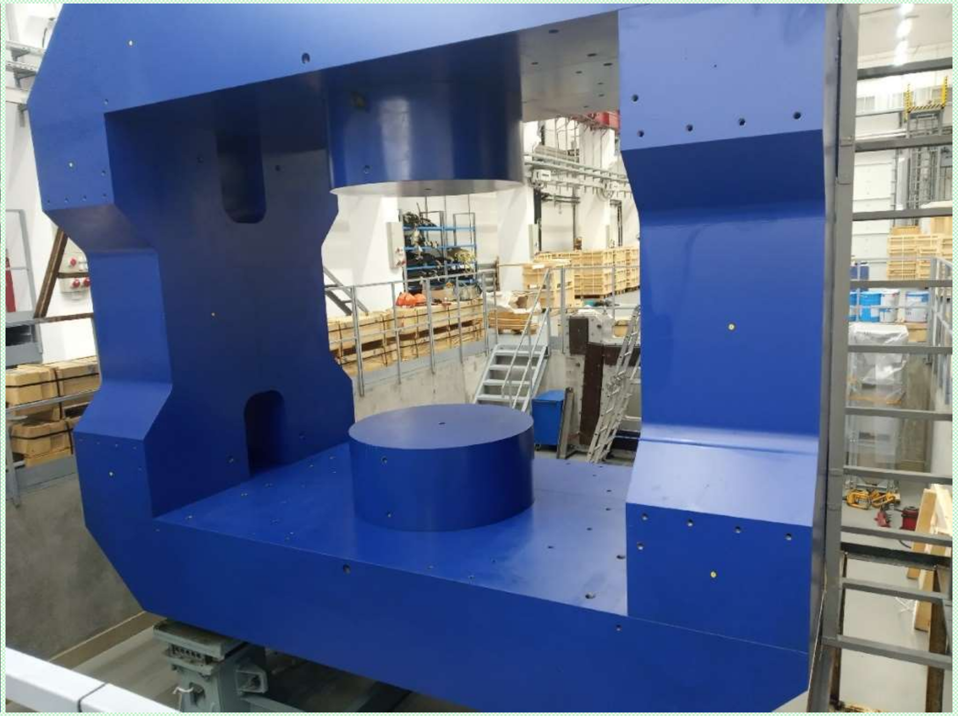
Close view

The prototype is ready for impregnation

The iron yoke is manufactured

Iron yoke was manufactured in December 2021.
The geometry measurement procedure is shown here.

The assembling process in BINP
April 2022



The view of the assembled iron yoke.
April 2022

PROGRESS in DEVELOPMENT of the PANDA SOLENOID, FAIR

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 21 MJ of stored energy.

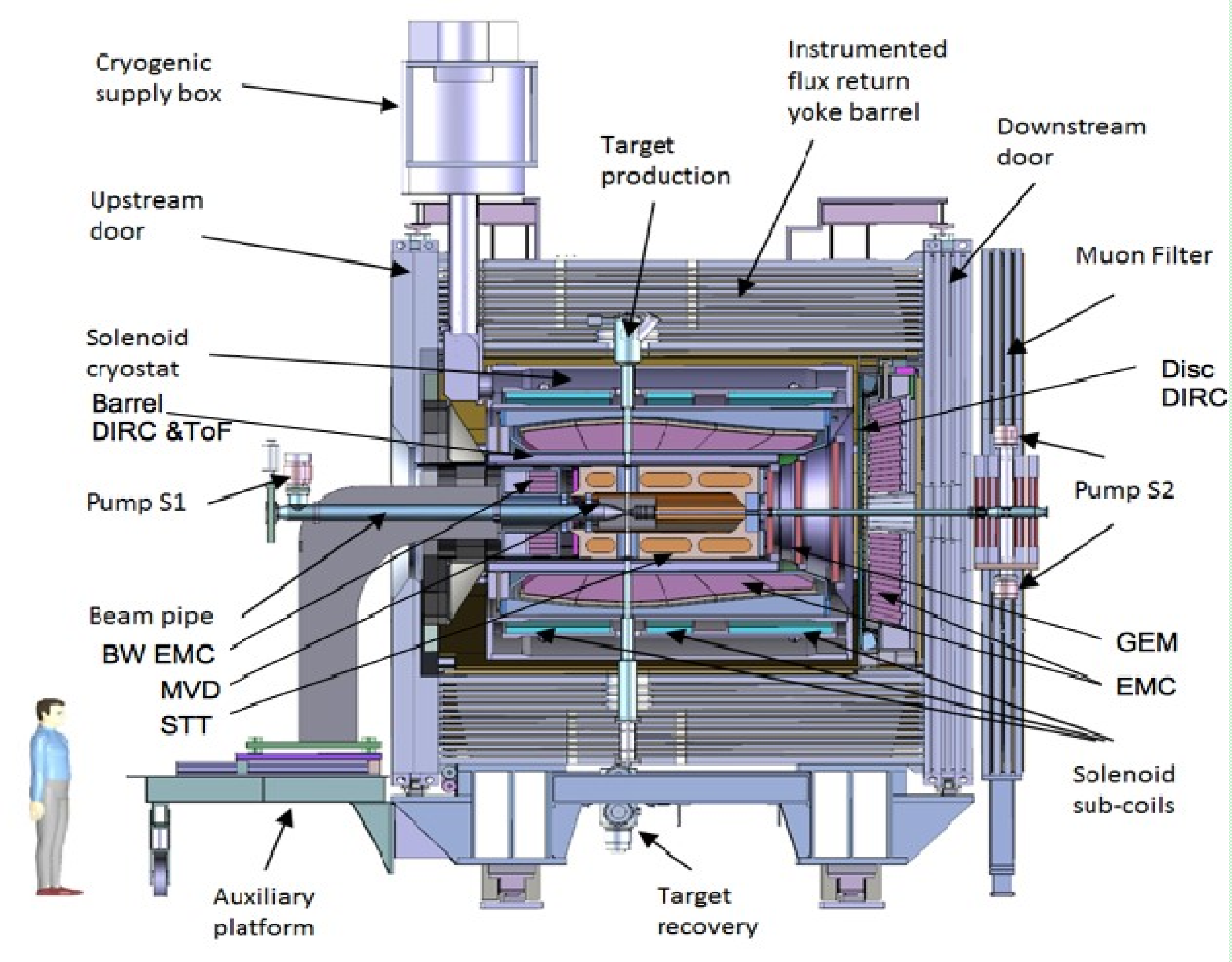
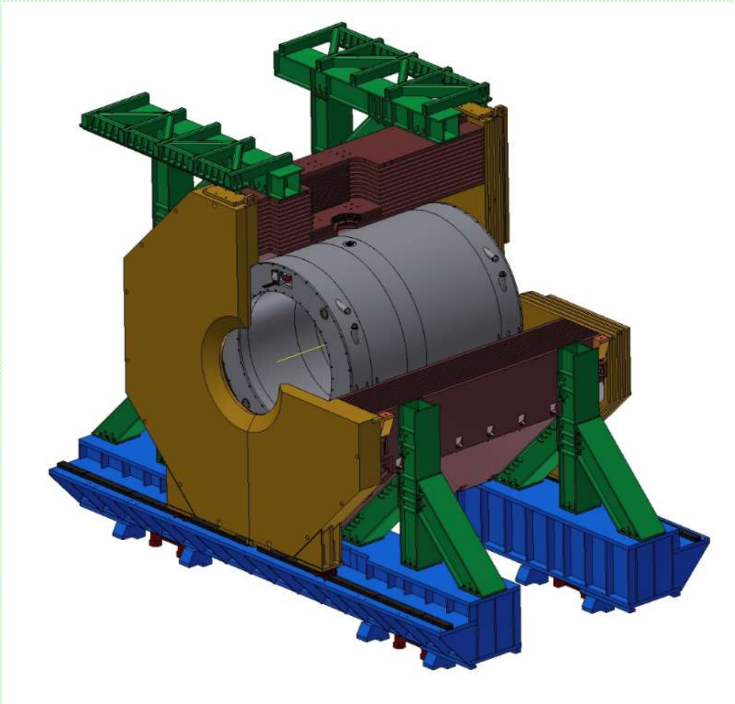
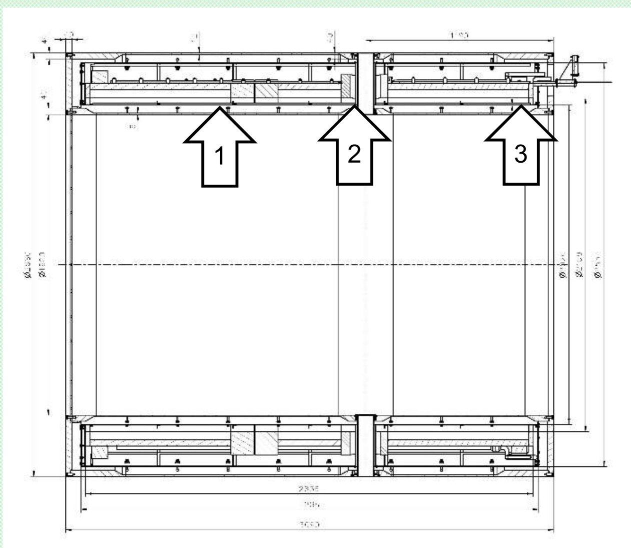


Figure 1. Artistic cut side view of the solenoid magnet including contained detector systems.

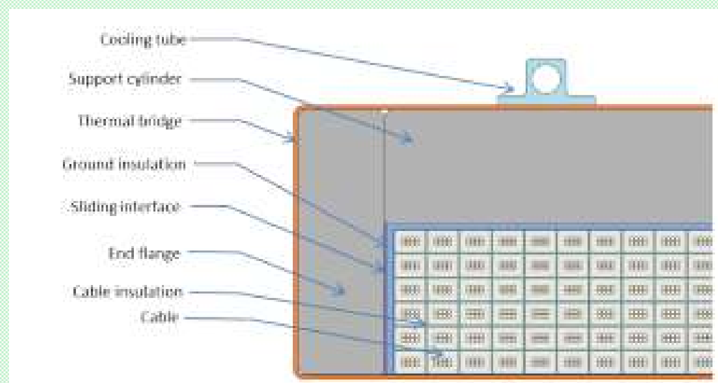


3D view of the PANDA solenoid

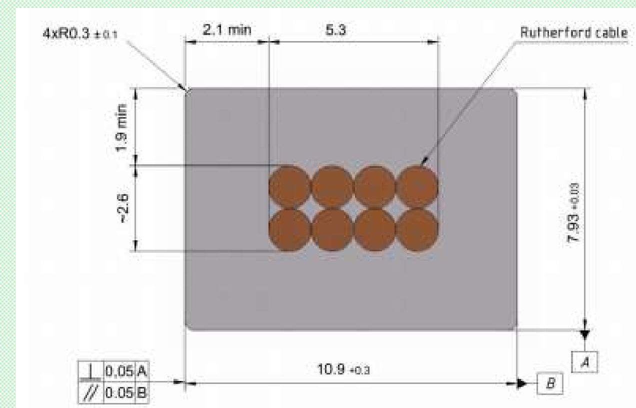
Solenoid parameters	Values
Inner radius of the winding, mm	1048
Outer radius of the winding, mm:	1140
Total length of the solenoid, mm	2828
Number of turns in the solenoid (12*78 + 6*35)	1146
Number of layers	6
Length of one turn, m	6.75
Operating current Io, A	4960
Test current, Io*1.05, A	5208
Magnetic field on the coil Bmax, T	2.95
Io/Ic ratio along the load line, %	30
Operating temperature, K	4.5
Temperature of current sharing, K	6.7
Stored energy of the magnet, MJ	21
Cold mass, kg	5283
Cold mass of the SC cable without insulation, kg	2251
Inductance of the magnet at full current, H	1.68
E/M ratio for cold mass, kJ/kg	4.0
E/M ratio for SC cable mass, kJ/kg	9.3



Longitudinal section of the cryostat with cold mass.

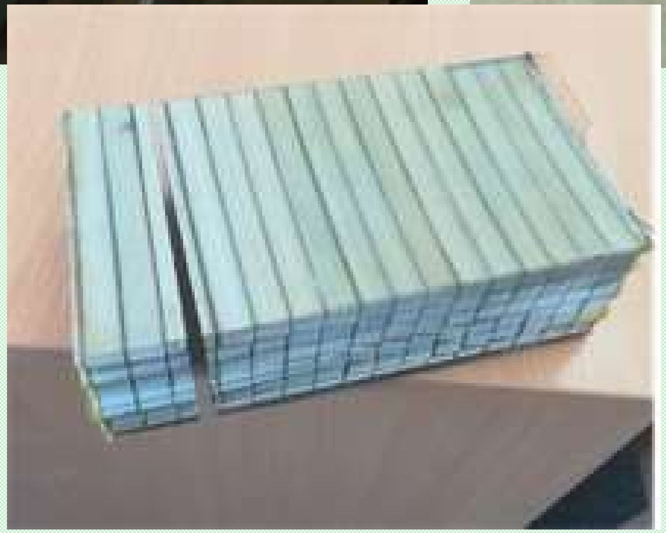


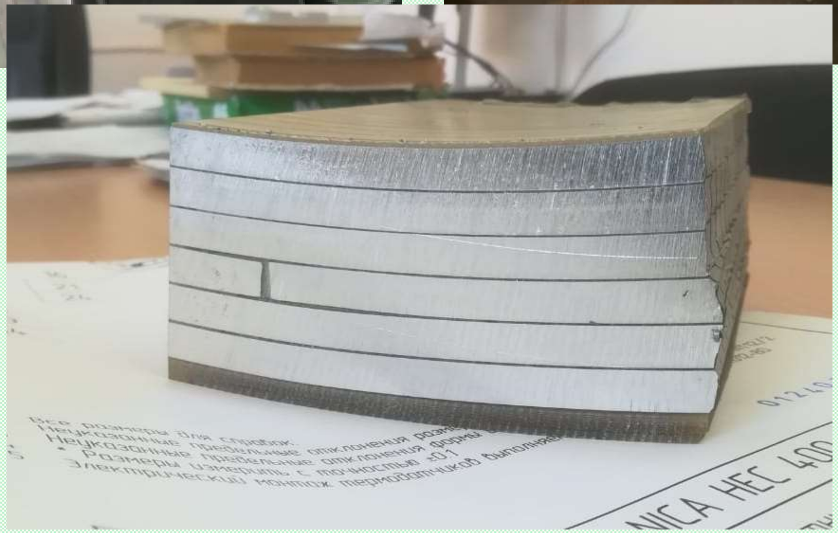
Cold mass cross-section



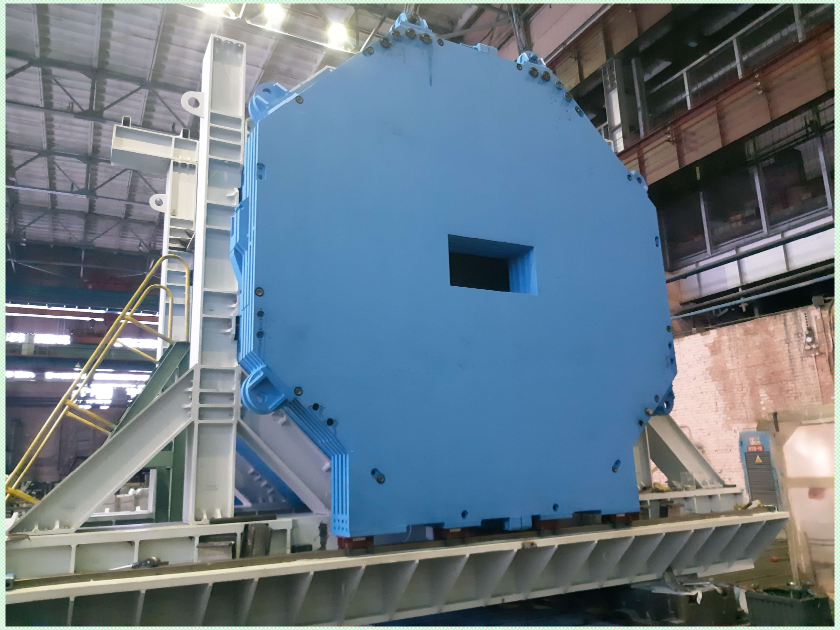
Drawing of the conductor

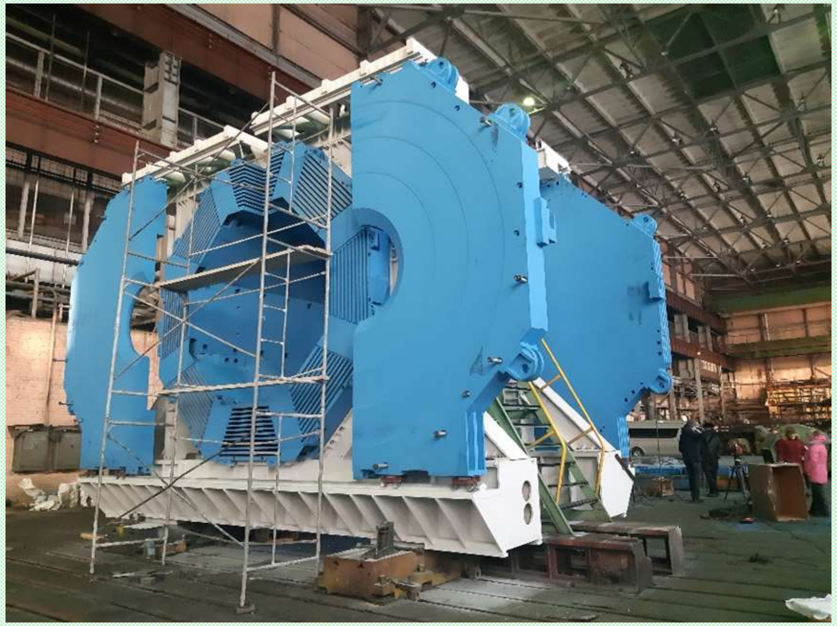
Production of the coil prototype





Assembling of the Yoke 11-12/2020



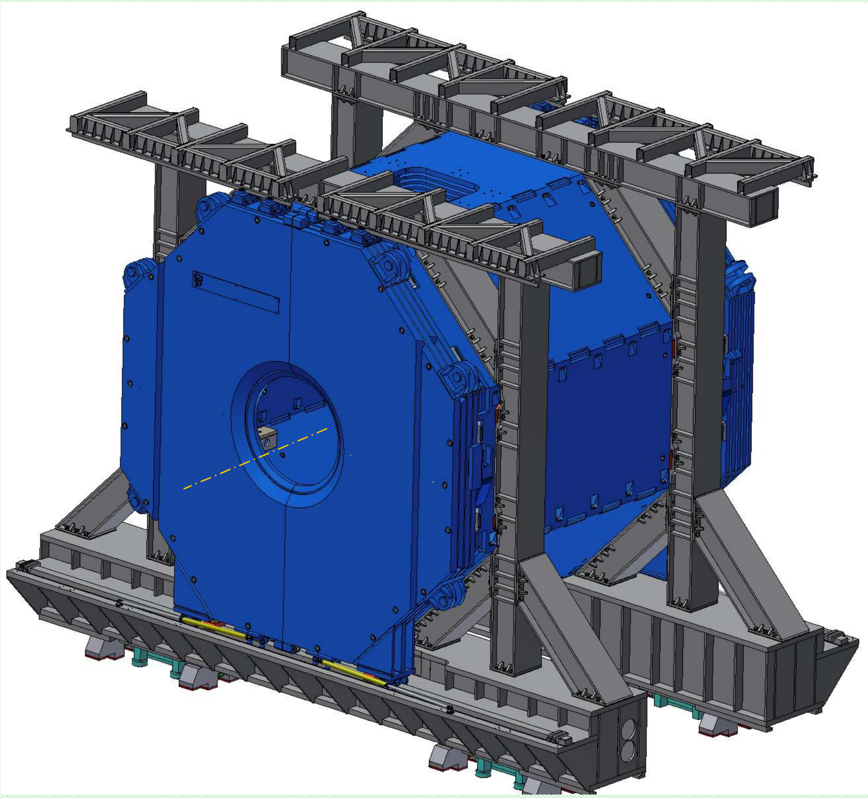
Assembling of the Yoke

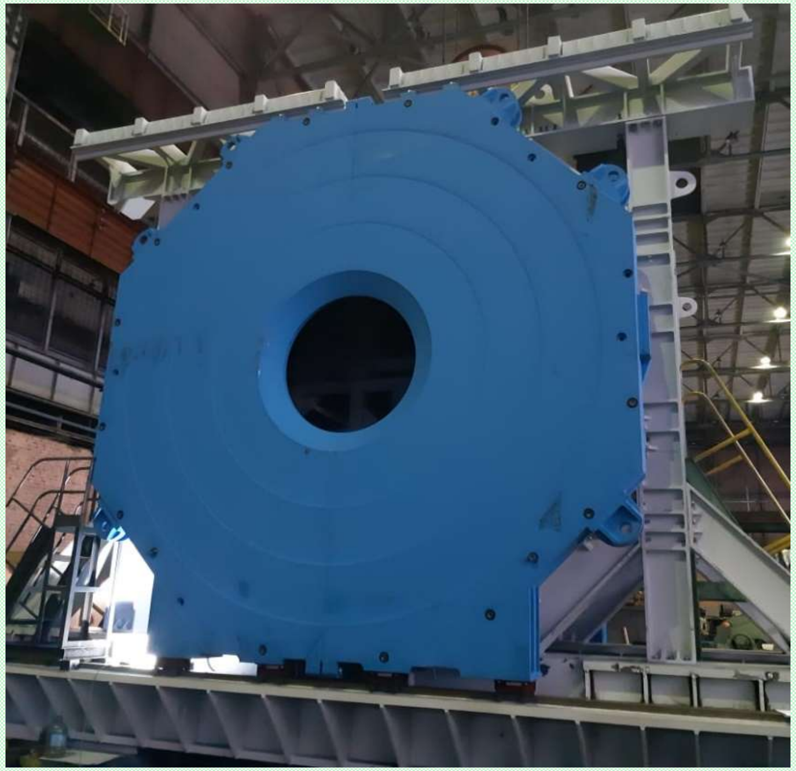
Installed 10 support for detectors of a laser tracker.

Built an axis of the yoke and 3D map of elements by a laser tracker.

Measuring surfaces of the octants and wings we can do correction each part of the frames and barrel part of the yoke.

We plan to install about 30 the same support to do assembly of the yoke more quickly and suitable/

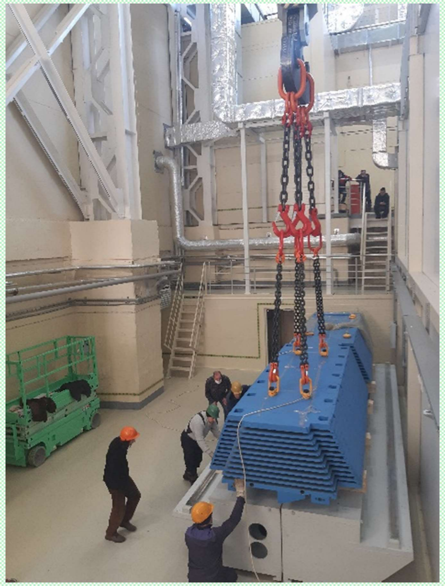




Disassembling of the Yoke and delivery to BINP







Conclusions

- **The insertion devices for the SKIF project are being manufactured and tested. During 2023 year four wigglers and undulators will be finished. In the next three years eight wigglers and undulators will be manufactured and installed on the SKIF ring.**
- **The superconducting dipole magnet for the CBM detector is finished at the design stage. Only iron yoke of 140 t mass was manufactured and assembled. The future of this project is unclear due to position of Germany side. Officially, the contract is not broken.**
- **The same situation with the Panda superconducting solenoid. The iron yoke of 240 t mass was manufactured and stored.**
- **New projects of superconducting magnet system start to appear in Russia.**

Thank you for your attention!