Mechanical Design and Analysis of Capture Superconducting Magnet for EMuS

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An Experimental Muon Sourse (EMuS) is proposed to construct at the facility of China Spallation Neutron Source (CSNS) by IHEP (Beijing, China), for the R&D of key technologies of the next-generation neutrino beam facility. The capture superconducting solenoid magnet is one of the key components of the EMuS. It consists of 4 coils which are an axially graded solenoids with a peak central field of 5-T at 3944 A of nominal current. The capture magnet has an iron yoke for flux return and field shield. This paper presents the mechanical design and analysis of the capture magnet.

I. Introduction

- The Experimental Muon Source (EMuS) is proposed at China Spallation Neutron Source (CSNS) in order to explore mainly muon science and especially µSR experiments for material science. The EMuS will be built in the so-called high-energy proton experimental area(HEPEA).
- The EMuS adopts a complicated design by combining a long internal carbon target and high-field capture superconducting solenoid that can provide high-intensity muon and pion beams. Using 1.6 GeV/5 kW proton beam from the CSNS, the EMuS extracts the proton pulses to hit the target to produce muon beam .
- The capture superconducting magnet is one of the important components of the EMuS. The muons and pions are produced inside the capture solenoid and then are transported to the muon experimental area through the decay channels.
- The capture superconducting magnet located in a serious radiation environment. the aluminum stabilized NbTi Rutherford cable is adopted to wind the coils. Conduction cooling method with a small quantity of helium will be applied for the capture solenoid to avoid activation of tritium.
- The capture solenoid magnet is designed in order to allow a maximum tilting angle of the proton beam of 15°. It is enclosed by an iron yoke. The iron yoke, consisting of a barrel yoke and two end-cap yokes, serves as a magnetic field flux returning and magnetic field shielding.
- In this paper, the coils configuration of the capture solenoid and the mechanical design and analysis are presented.

II. Capture Solenoid Winding design and analysis

- Capture Solenoid winding structure

The capture solenoid is adopted a 4-coils/3-steps structure, and has wedge shaped shielding for the coils in order to accommodate the radiation.

Aluminum stabilized NbTi Rutherford cable is adopted to wind the coils for less nuclear heating.

- Electromagnetic Analysis of the Capture Solenoid

The magnetic field along the axis of the magnet is gradually changed.

The magnet has a maximum of 5 T at the center of CS1 that is degraded to 2.2 T at the entrance of the matching solenoid at 3944 A of nominal current.

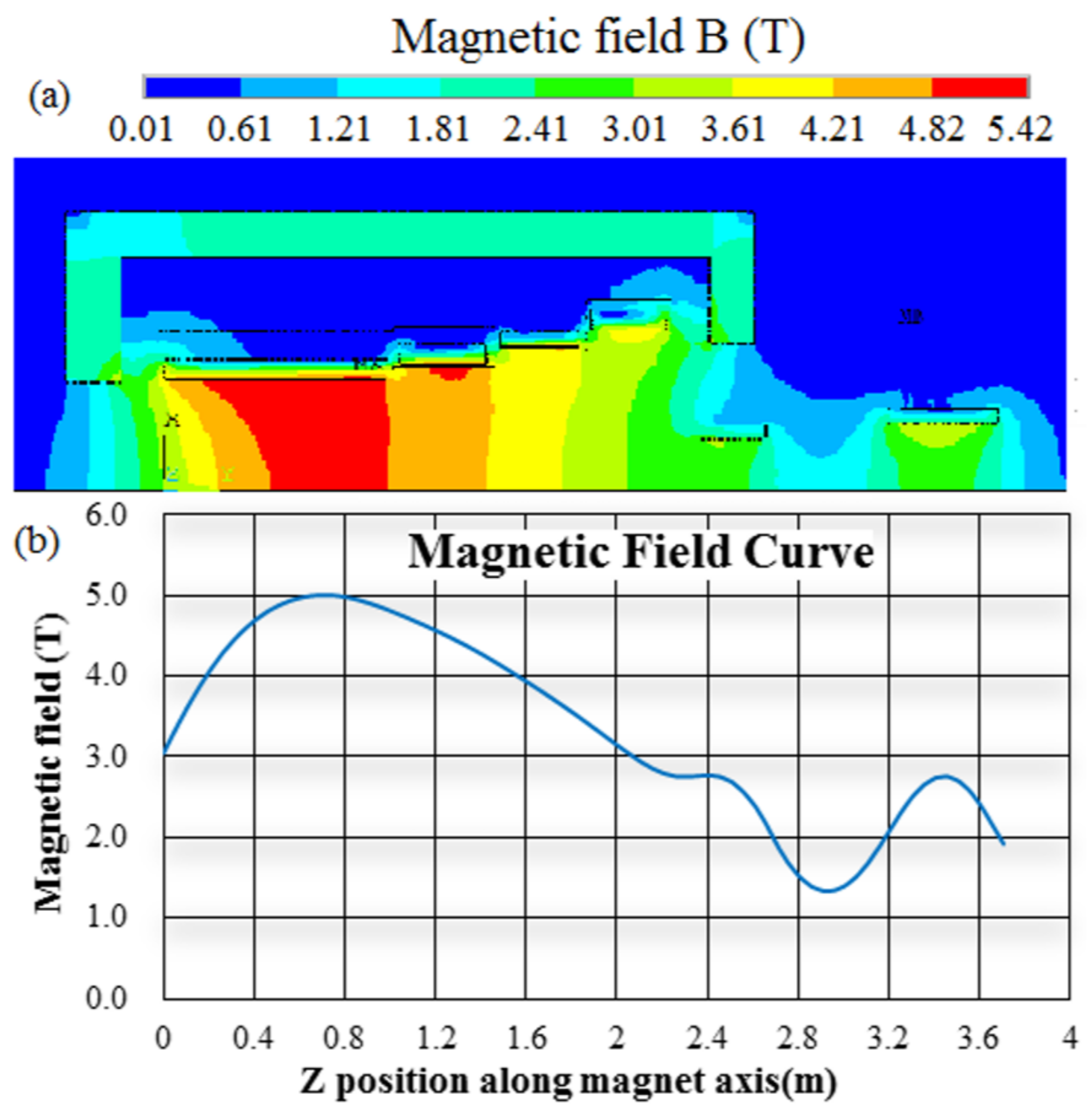

Fig. 3. (a) Magnetic field distribution in 2D axisymmetric model. (b) Magnetic field curve along the axial of the capture magnet. The peak magnetic field is 5.42 T. The pion target is located at z = 0.5.

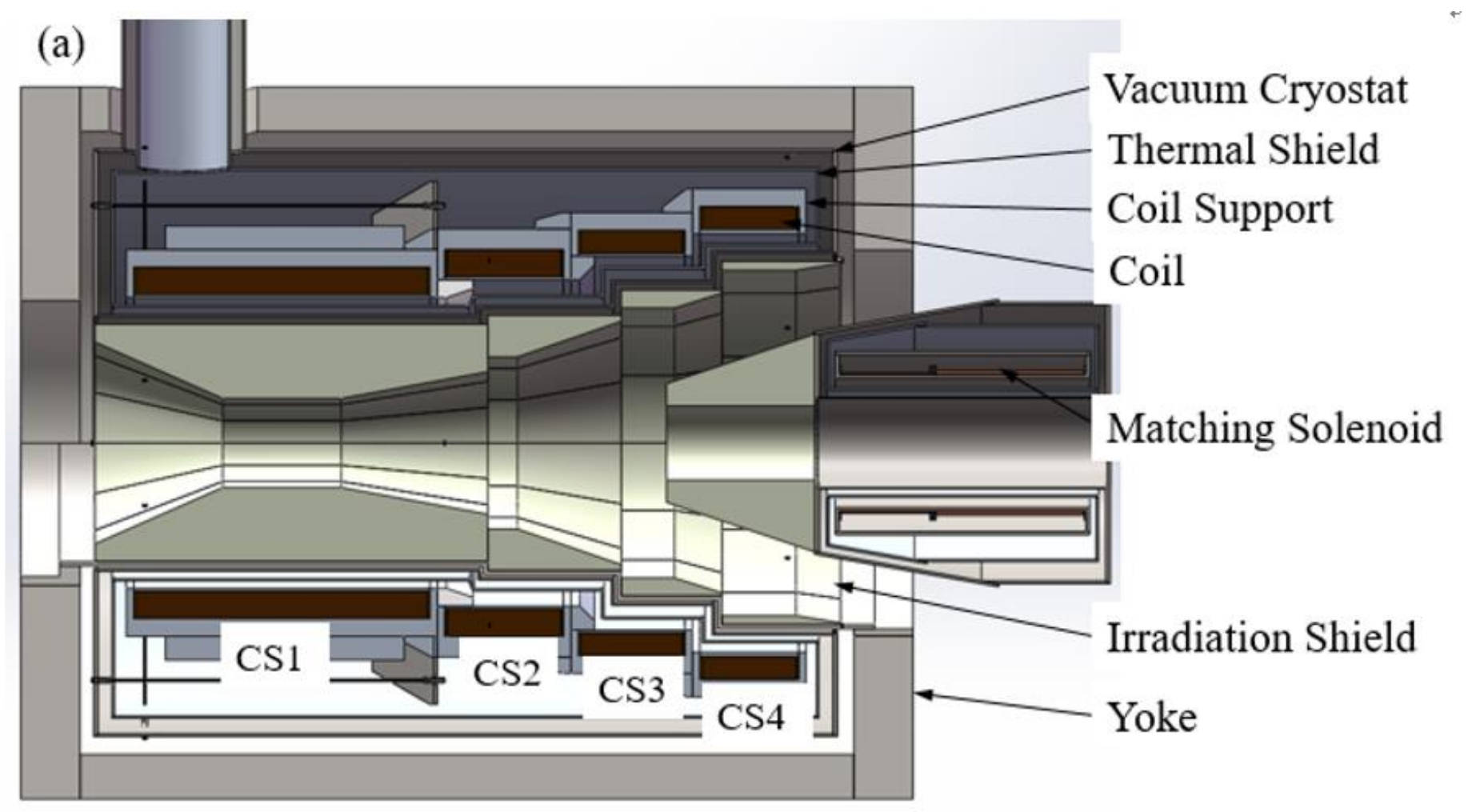

Fig. 2. The schematics of the 4-coils/3-steps capture solenoid, the coils are called CS1, CS2, CS3 and CS4. The coils are winded by the aluminum stabilized NbTi Rutherford cable.

TABLE I
PARAMETERS OF ALUMINUM STABILIZED NBTI RUTHERFORD CABLE

Item	Value
Cable dimension (without insulation)	15 mm×4.7 mm
Cable dimension (with insulation)	15.3 mm×5.0 mm
Strand diameter	1.2 mm
Strand number	16
Al/Cu/NbTi	5.9/1.0/1.0
Aluminum RRR	500
Copper RRR	70
NbTi Jc @ 4.2 K, 5 T	2600 A/mm^2
Al yield strength@4.5K	95 Mpa
Overall yield strength	150 MPa
Cable Ic @4.2 K, 5 T	> 17280 A
Nominal current	3944 A

TABLE II
PARAMETERS OF THE CAPTURE COILS

	R_{in} (m)	R_{out} (m)	Z_{min} (m)	Z_{max} (m)	J_e (A/mm^2)	Layer
CS1	0.50	0.592	0.986	0	50.35	6
CS2	0.56	0.652	1.05	1.436	50.35	6
CS3	0.64	0.717	1.5	1.846	50.35	5
CS4	0.72	0.812	1.91	2.23	50.35	5

- Mechanical Design and Analysis of Coils

The allowable tensile stress of the stabilizer is less than 65 MPa. The huge hoop stress in the winding will be more than 130 MPa when the magnet is excited at nominal current.

An outer support cylinder with high strength and high thermal conductivity material is needed for each coil.

Estimated based on previous experience, the peak electromagnetic stress in the winding is nearly 65 MPa with a thickness 140 mm outer support cylinder.

To reduce the cold mass, the thickness of the outer support cylinder need to be optimized.

The first method is by dividing the support cylinder into two layers of cylinders which should be interference assembled.

The second method is by binding the coil with high strength and high thermal conductivity aluminum alloy wire, then an outer support cylinder is assembled with the coil by transition fits.

It is necessary to cure the coil by vacuum pressure impregnation (VPI) with a bismaleimide-triazine (BT) resin to fill the space between turns and layers.

(1) Two layers of support cylinder.

Interference fit can be used to reduce the peak stress on the coil.

Pressure stress will be produced when the outer layer of support cylinder is interference assembled. It will counteract on the electromagnetic stress produced by excitation of the magnet.

To minimize the cold mass the thickness of the two layers of outer support cylinders and the interference fit between them need to be optimized.

In current design, the thickness of the cylinders is respectively 40 mm and 80 mm, the interference fit is 0.5 mm.

(2) Binding the winding with Al alloy wire

6063-T6 Al alloy wire can be used to binding the winding to decrease the peak electromagnetic stress for its high strength and high thermal conductivity.

To minimize the cold mass the tensile stress of the binding wire, the thickness of the binding wire and the outer support cylinder need to be optimized.

In current design, the tensile stress of the binding wire is 50 MPa, the thickness of the binding wire and the outer support cylinder is 40mm and 80 mm, respectively.

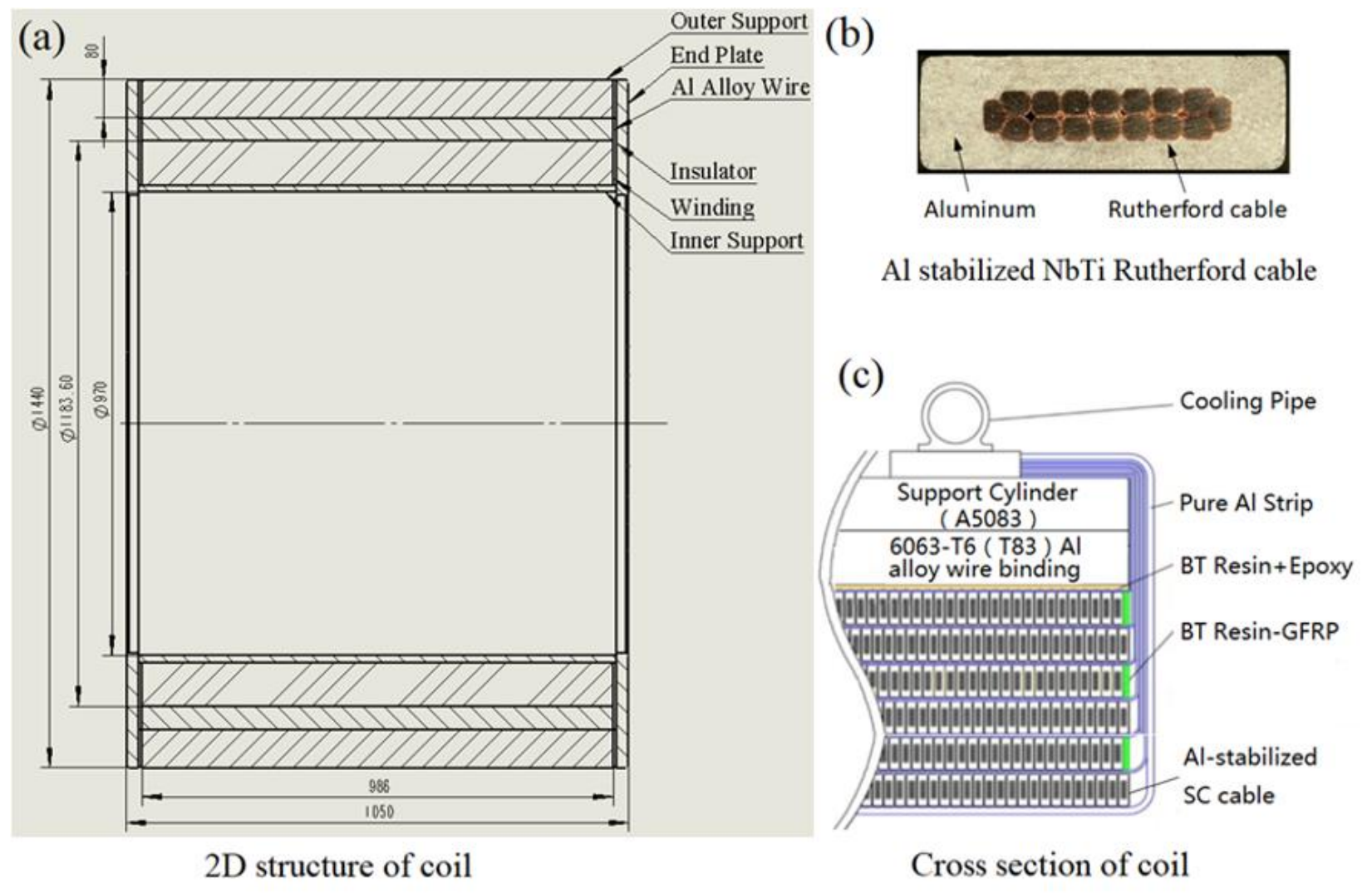

Fig. 4. (a) Dimensions of CS1. (b) Cross section of the Al stabilized NbTi Rutherford cable. (c) Cross section of the coil.

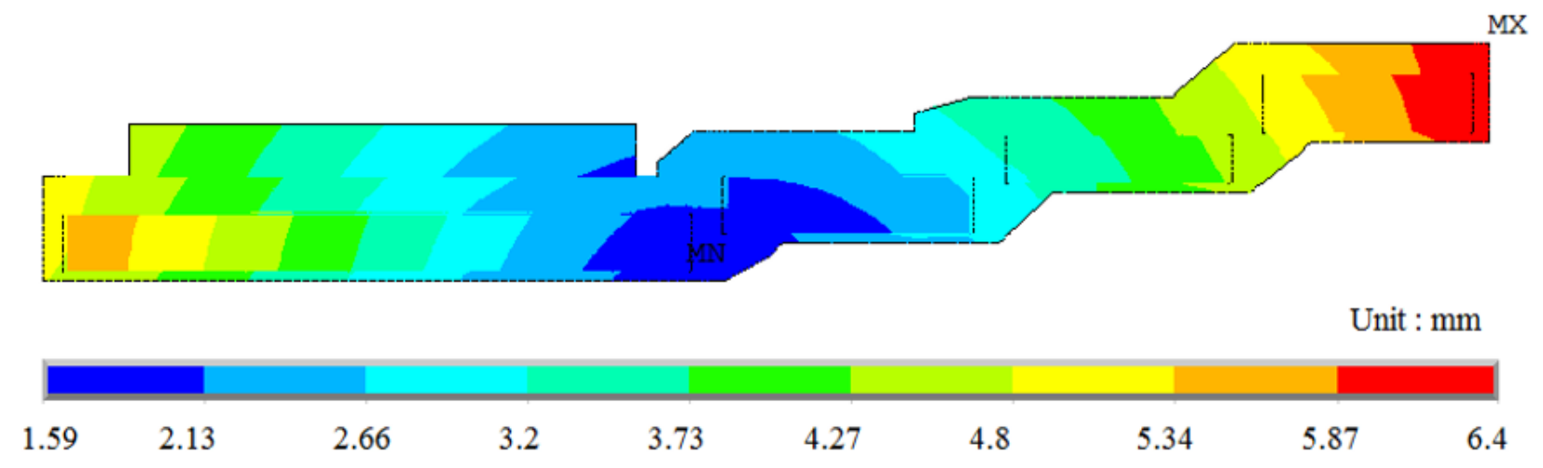

Fig. 5. Deformation distribution of the coils.

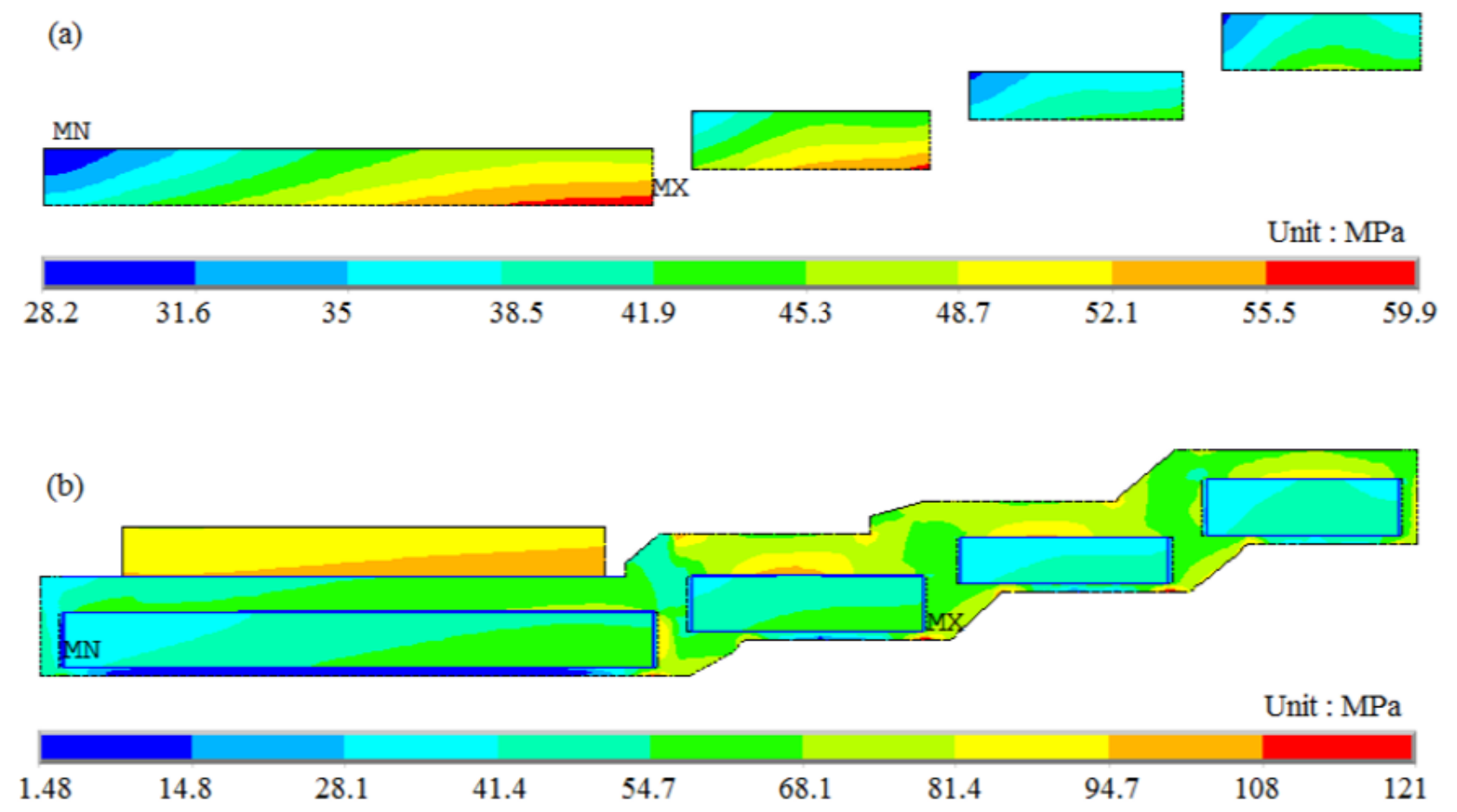

Fig. 6. Von Mises stress distribution in (a) the coils and (b) the cold mass.

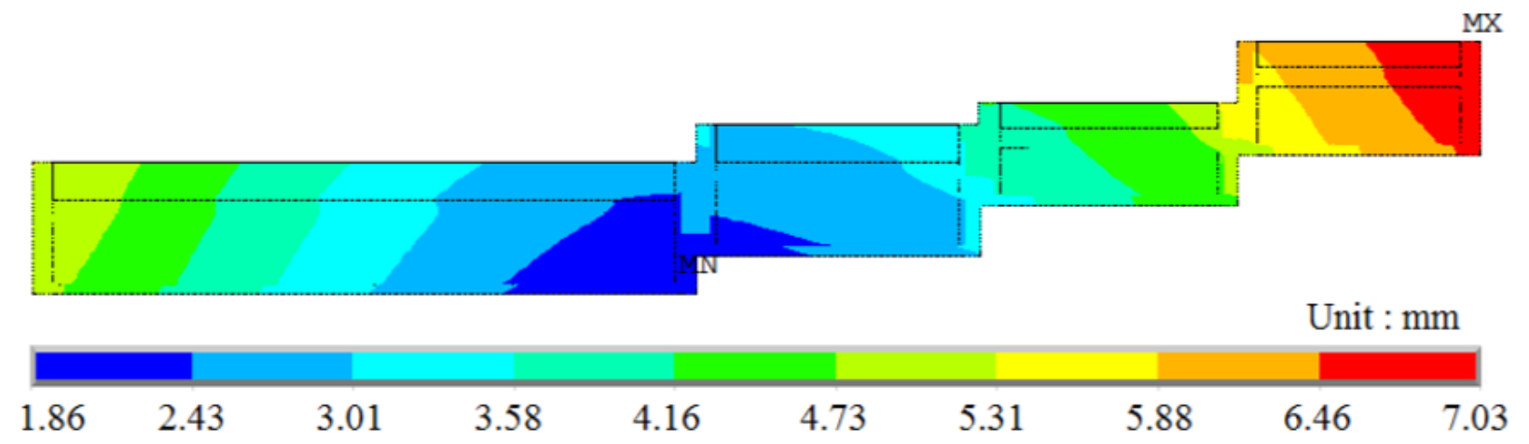

Fig. 7. Deformation distribution of the coils.

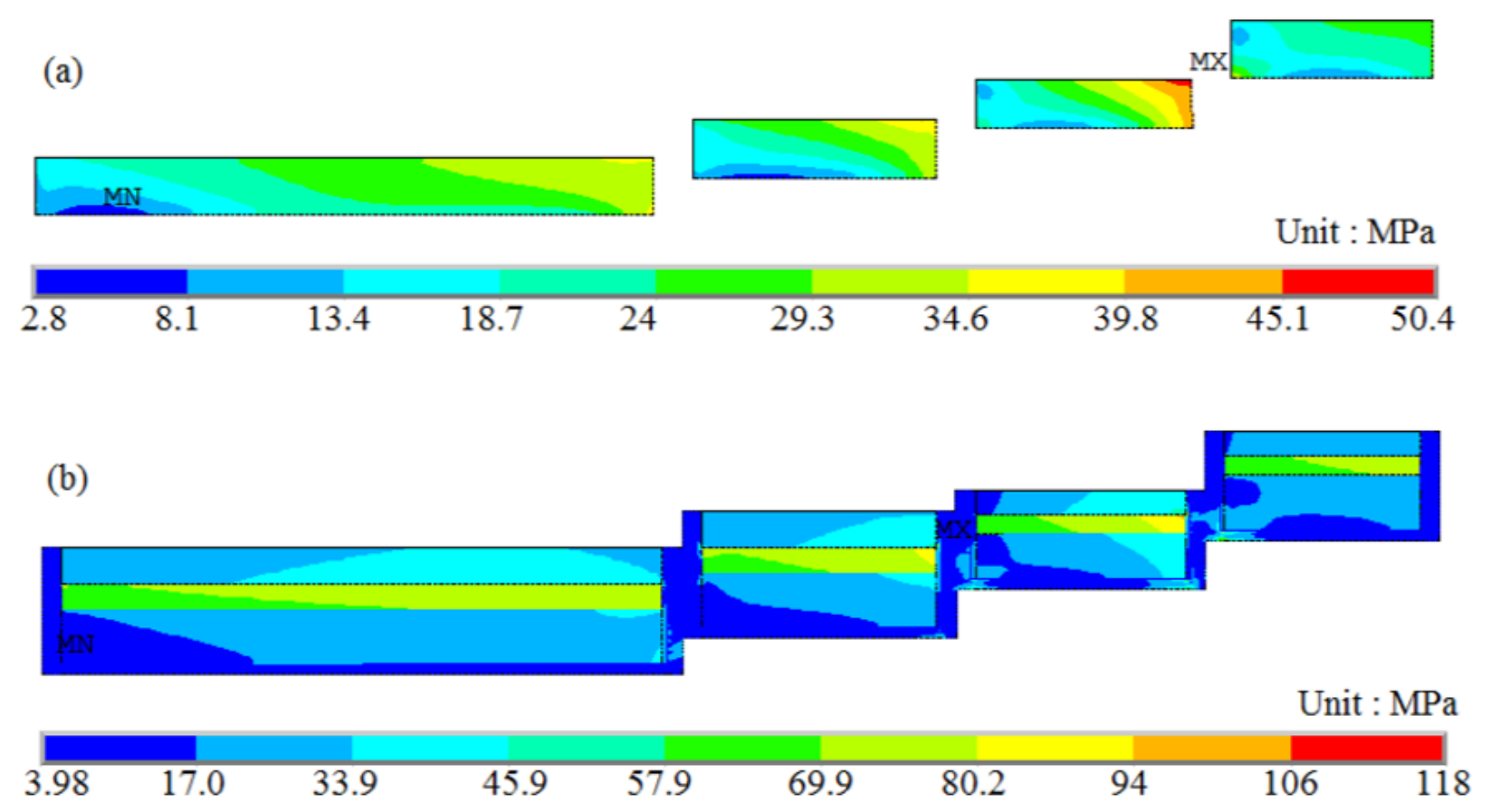

Fig. 8. Von Mises stress distribution in (a) the coils and (b) the cold mass

VI. Conclusion

The mechanical design of the EMuS capture superconducting solenoid has been finished. The stress distribution in the coil is acceptable. At the same time, the support of the cold mass is feasible, the stress of the vacuum vessel is reasonable. Because of less BT-resin used, in the case of binding the winding with aluminum alloy wire, the temperature difference of the coil will be smaller when the cold mass is cooling down. It's good for the stability of the magnet. Therefore, this method will be used to manufacture the coil in the next step.

III. Cold Mass Support

The four coils will be manufactured separately, then are connected to each other to form a single cold mass.

The cold mass is encased in the cryostat which provides vacuum isolation and thermal insulation after packed with multilayer insulated material.

The cryostat is then enclosed by an iron yoke.

The electromagnetic force between the iron yokes and the coils is larger than 470 kN, when the magnet is excited at 3944 A.

At the same time the cold mass of the magnet is subject to the force of gravity which will be about 36 kN.

The support structure will be designed such that the cold mass does not move with respect to the iron yoke.

Ti alloy Ti-6Al-4V rods are adopted to support the cold mass.

Four axial pull rods are designed with a diameter of 16 mm at each end of the magnet. Four radial pull rods with a diameter of 10 mm are adopted at each end of the magnet too.

VI. Vacuum Vessel

The vacuum vessel consists of an outer cylinder, a stepped inner cylinder and two end-plates.

304 stainless steel will be used to manufacture the vacuum vessel.

The loads of the vacuum vessel include the atmospheric pressure, the longitudinal electromagnetic force and the gravity of the cold mass.

The longitudinal electromagnetic force and the gravity of the cold mass act on the vacuum vessel via the four axial rods and four radial rods.

The FEA soft was used to analyze the stress and deformation distribution considering the electromagnetic force, the gravity of the cold mass and the atmospheric pressure.

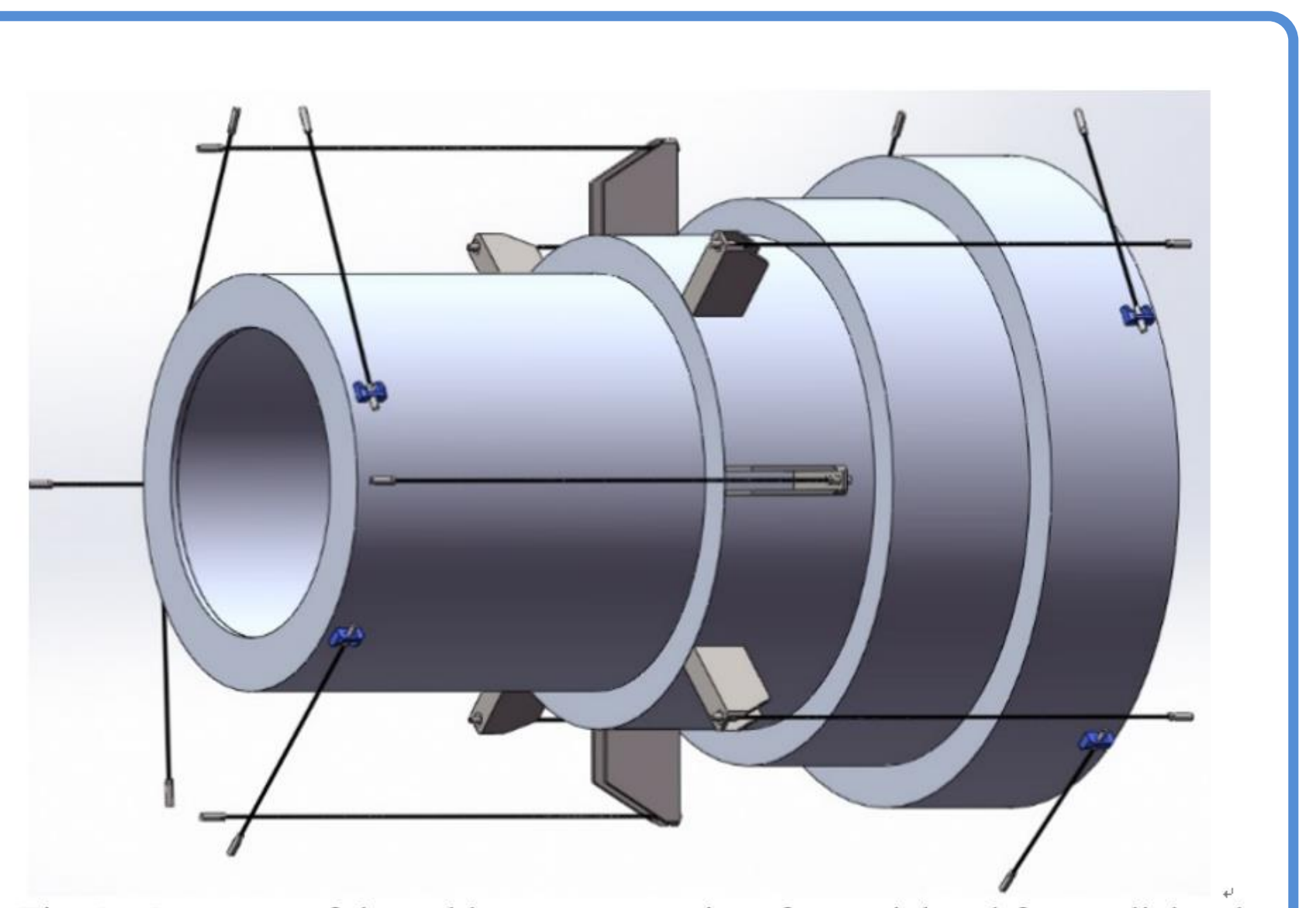

Fig. 8. Structure of the cold mass suspension, four axial and four radial rods are adopted at each end of the coils.

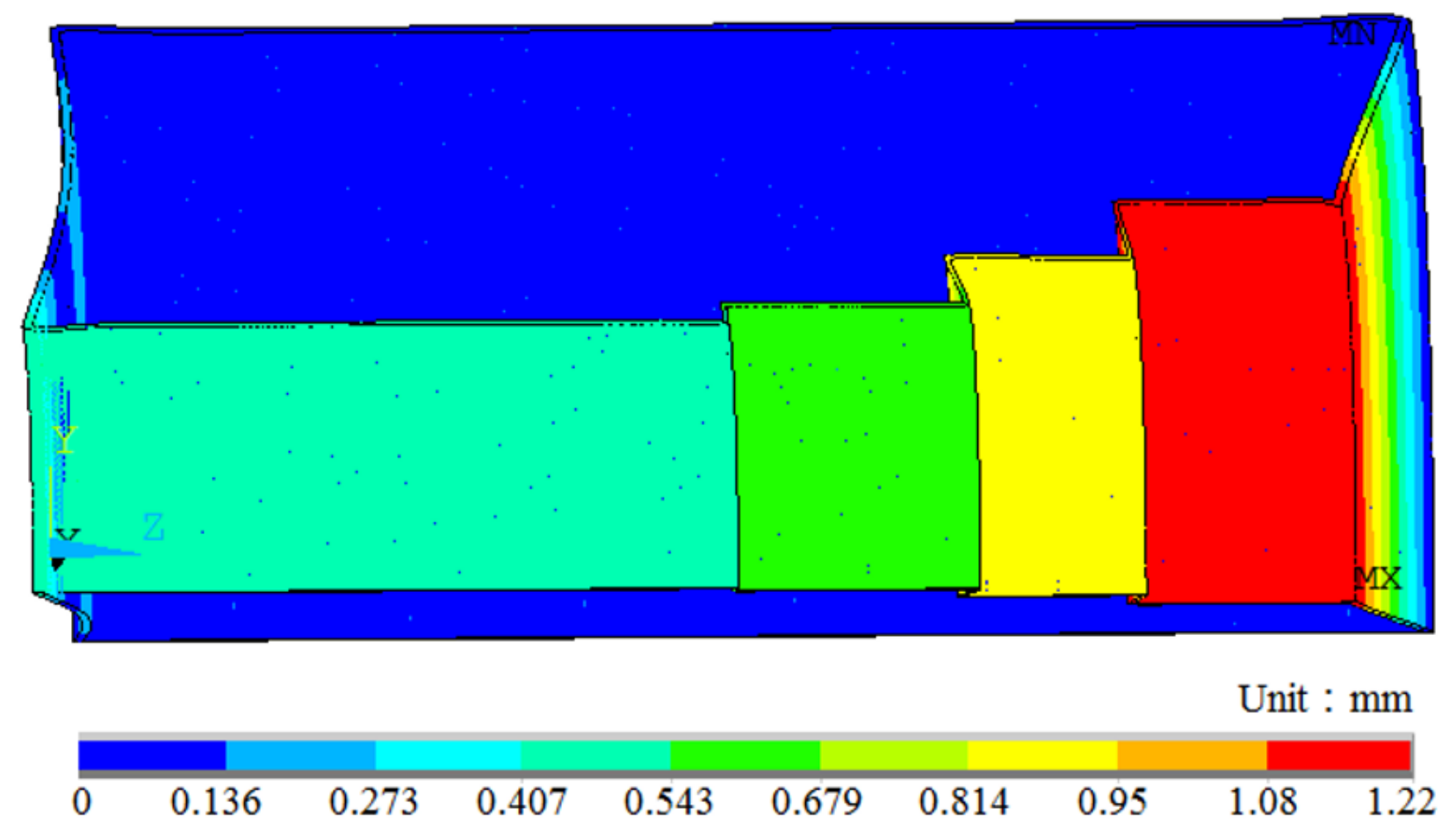

Fig. 9. The deformation of the vacuum vessel.

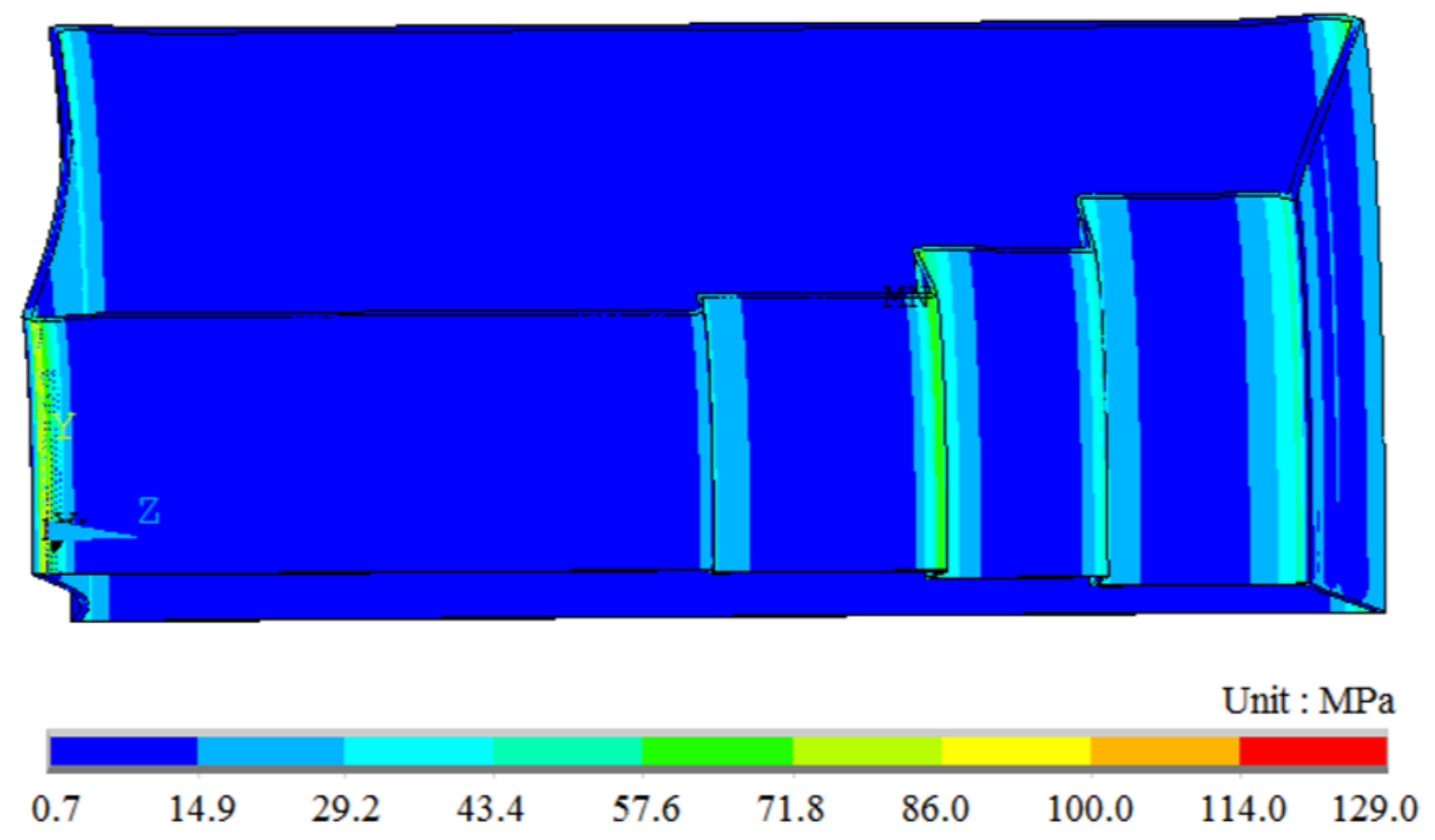

Fig. 10. The Von Mises stress distribution in the vacuum vessel.

V. Discussion

- Two layers of cylinders are used to support the coil, the interference fit between them should be controlled at 0.5 mm to 0.8 mm.

First, the inner layer of cylinder can be assembled with the winding via clearance fits.

Pure aluminum strip will be used to fill the space between the winding and the inner cylinder.

Then the outer cylinder can be assembled via temperature difference method by cooling the winding and the inner layer.

Finally, the space between the winding, the inner cylinder and the outer cylinder will be filled with BT resin blended with epoxy by VPI.

- In the case of binding the winding with Al alloy wire, there will be only once assembly.

After finishing the insulation treatment, the aluminum alloy wire will be winded on the coil with 50 MPa tensile stress.

Then the outer support cylinder will be assembled via temperature difference method by cooling the coil or heating itself.

Finally, the space in the coil and the binding, between the binding and the outer cylinder will be filled with BT resin blended with epoxy by VPI.

In this case, less BT-resin will be used, and the assembly will be more convenient.