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Cooling Design for the Magnetic Structure of SHINE Superconducting Undulator

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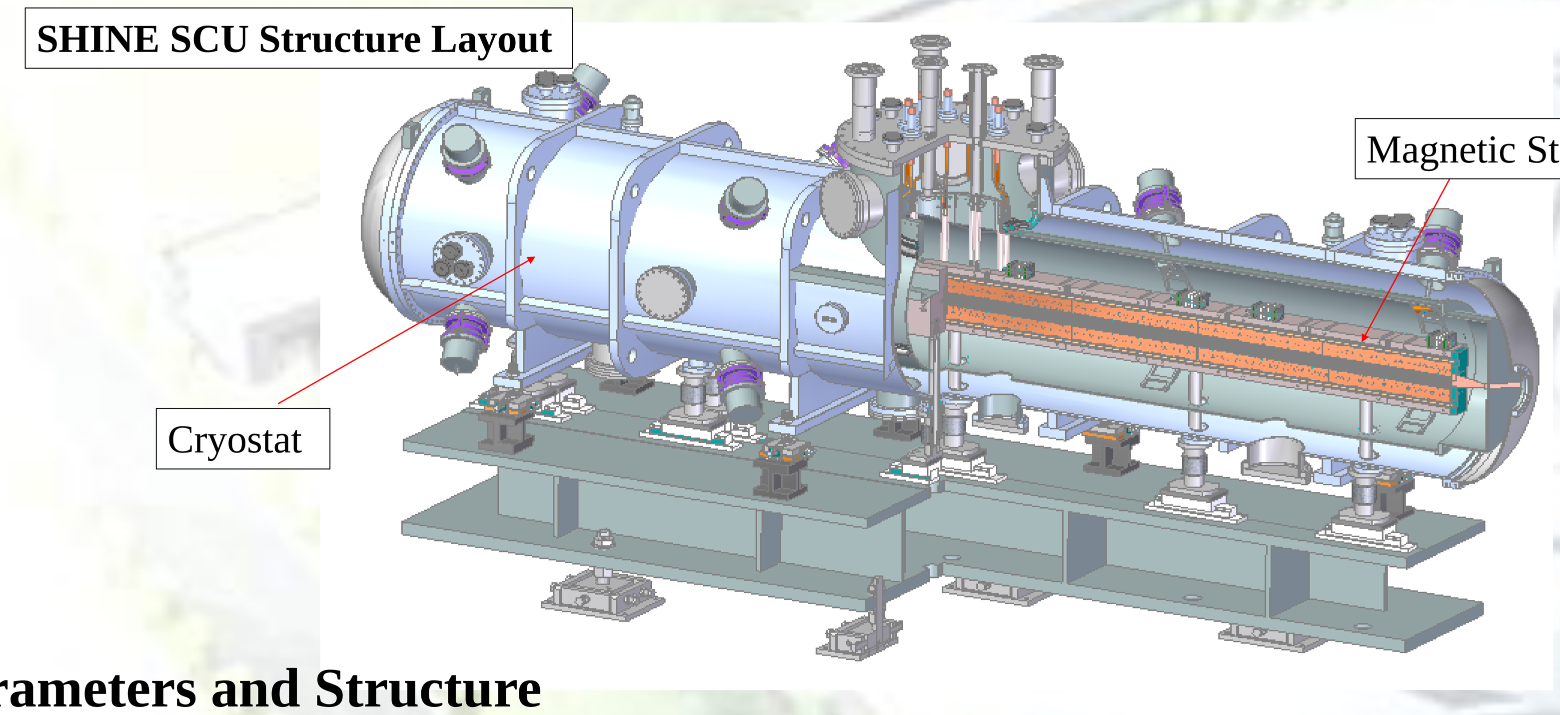
Abstract:

*Forty planar superconducting undulators (SCUs) with 4 m long magnetic structure will be used on Shanghai High Repetition rate XFEL and Extreme Light (**SHINE**) facility. As the longest SCU being developed in the world, they can produce the photons with energy of 10 keV – 25 keV. NbTi/Cu wire with the diameter of 0.6 mm and the ratio of Cu to NbTi 0.9 is adopted to fabricate the superconducting coils and the temperature of the coils must be below 5 K when the operating current is up to 400 A. The magnetic gap is no more than 5 mm in order to obtain the peak field of 1.58 T and it is impossible to design a beam vacuum chamber inside the gap. Instead, two copper foils parallel to each other are installed near the pole surfaces in the gap to shield the beam heat load. The special copper spacers are designed to cool the copper foils while four liquid Helium tubes are located symmetrically around the beam channel which is comprised of copper foils and spacers. The liquid Helium is provided by the cryogenic plant of SHINE.*

Introduction

Radiated photon with high flux can be generated by superconducting undulator with short period. There will be 3 lines of undulators developed in SHINE facility. One of the lines consisted of 40 superconducting undulators can generated vertical polarization photon with energy 10 - 25keV.

SHINE SCU Structure Layout



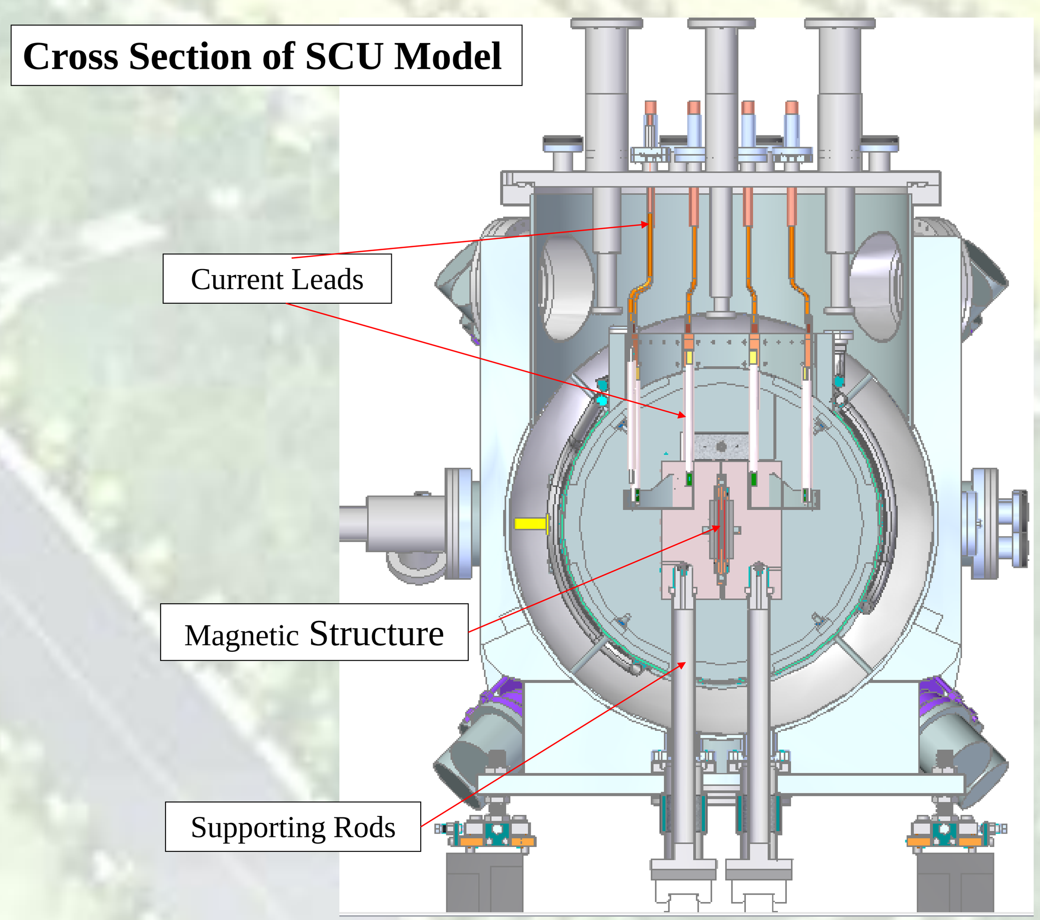
Parameters and Structure

The Superconducting undulator is consisted of main vacuum chamber, thermal shield cooled by 60K Helium gas, magnetic structure cooled by 4.5K liquid Helium, cooling tubes and supports. There is no independent cooler installed on the SCU because both Helium gas and liquid Helium are all supported by SHINE cryoplant. Cooling tubes and binary current leads are all passed through middle holes of the vacuum chamber and shield.

Design Specification for SHINE SCU

Parameter	Value	Unit
Quantity	40	
Period Length	16	mm
Magnet Length	4	m
Beam Energy	8	GeV
Beam Space	> 4	mm
Peak Field	1.583	T
K	1.019-2.366	
Roll-off@Field Region（H）	$< 2\times10^{-4}$ @ ±0.5mm	
RMS Phase Error	< 5°	
RMS Track Linearity	< 1.0 @ 8.0GeV	μm
Primary Integral Field Error	< 30	Gs×cm

Cross Section of SCU Model



Thermal Load

Thermal load on 4.5K Helium used to cool magnetic structure is transmitted from thermal shield, current leads, magnetic measurement device, support rods, electron beam and so on.

Materials and Working Temperature

Item	Material	Temperature
Vacuum Chamber	SS 304	Room Temp.
Thermal Shield	Al 1060	60 -75 K
Poles	Fe	4.5 - 5 K
Coils	NbTi/Cu	4.5 - 4.8 K
Current Leads	(Superconducting)	4.5 - 78 K
Support Rods	SS 304	5 K - Room Temp.
Framework	Al 7075	4.5 -5 K

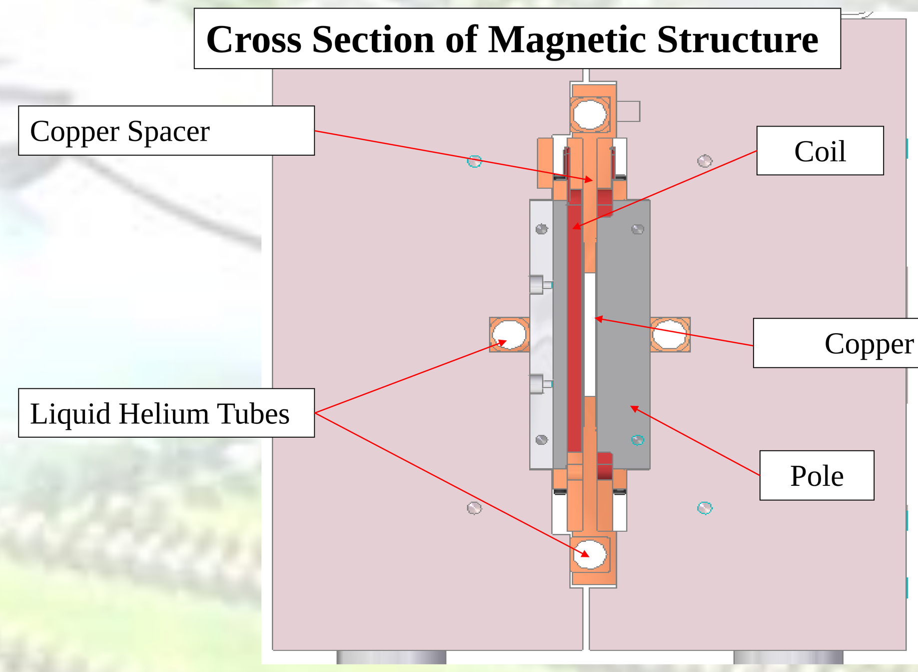
Thermal Load @4.5 K

Transfer Model	Transfer between Components	Power (W)
Thermal Radiation	Thermal Shield→Al Framework	0.02
	Support Plate of Magnet Measurement → Channel	0.29
	Lead Rail of Magnet Measurement → Channel	2.07
	Dragging Wires of Magnet Measurement → Channel	0.65
Thermal Conduction	PCB of Magnet Measurement→ Magnets	0.54
	Signal Wires→ Magnets	1.03
	Current Leads→ Magnets	0.45
	End Tapers→ Magnets	0.29
Resistance	Current Leads (Superconducting)	NA
	Signal Wires	1.2×10^{-6}
	RTDs	4.3×10^{-4}
	Superconducting Connector	8.1×10^{-4}
Beam Load	Beam → Channel	10

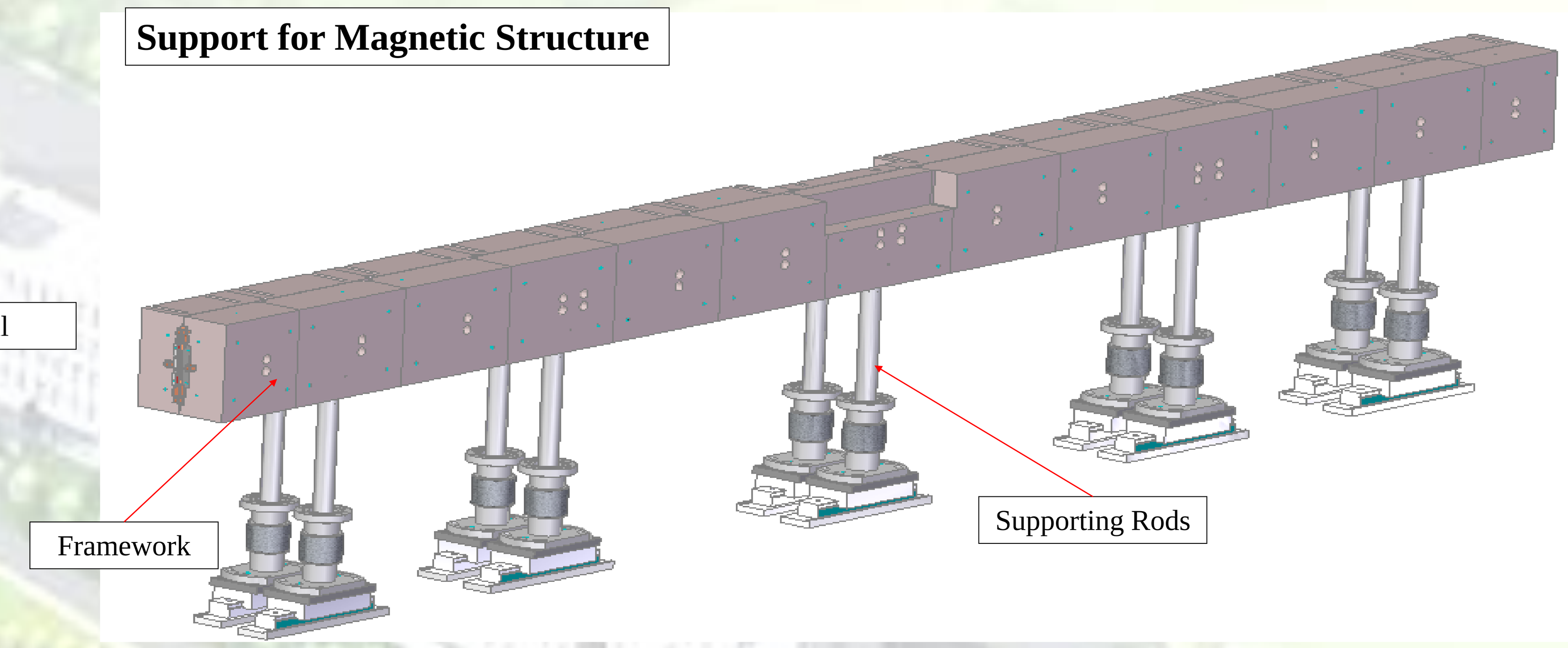
Cooling for Magnetic Structure

The working temperature of superconducting coils must be below 5K to avoiding quench when current get 400A. Magnetic gap is no more than 5mm in order to obtain the peak field of 1.58T. Therefore, it is impossible to install a vacuum chamber with 4m long in the gap. Two copper foils parallel to each other installed in the gap are used to shield the superconducting coils from the heat generated by beam effect. The gap between foil and pole is 0.4mm so that most of heat of beam effect is transmitted to two sides of foil while minimum transmitted to coils by radiation. Special copper spacers are employed to fasten the copper foils and cooling tubes and to provide 5mm fixed gap. Beam chamber with low impedance of the SCU is formed by the Copper spacers and foils. Four liquid Helium tubes located symmetrically around magnets are used to cool both magnets and beam chamber of the SCU, which is different from SCUs developed in any other institute. There are 13 couples of Al framework used to fix magnets and 5 couples of rods used to support magnets.

Cross Section of Magnetic Structure



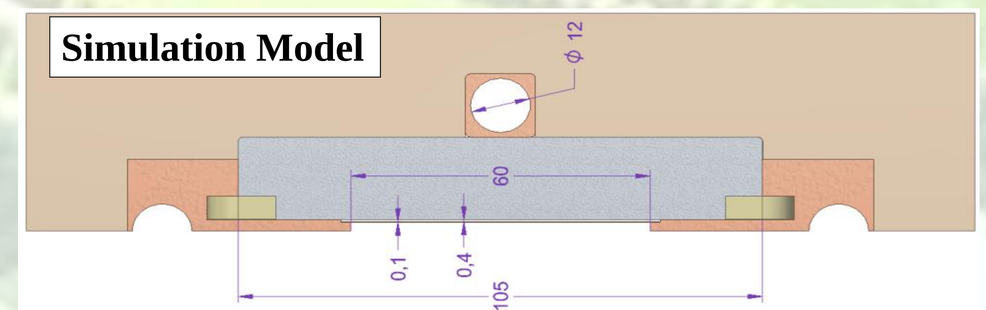
Support for Magnetic Structure



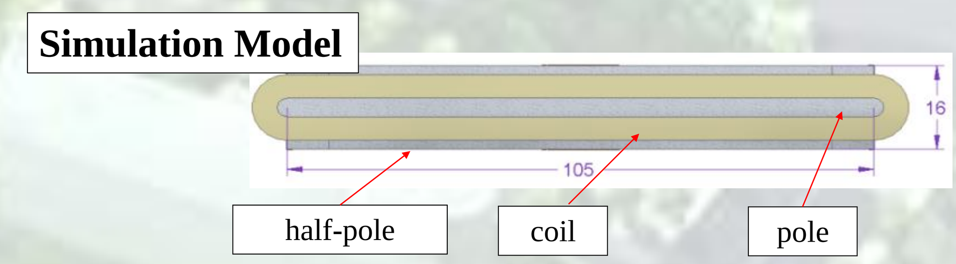
Thermal Simulation

A model of magnetic structure of a period length was set up to make temperature calculation because heat distribution is nearly uniform along the direction of beam path. The model was consisted of a magnetic pole, two half-poles, a whole coil, copper foil and Al framework of 16mm width. Two half-poles' cross section along beam direction can be considered as thermal insulation in the model.

Simulation Model

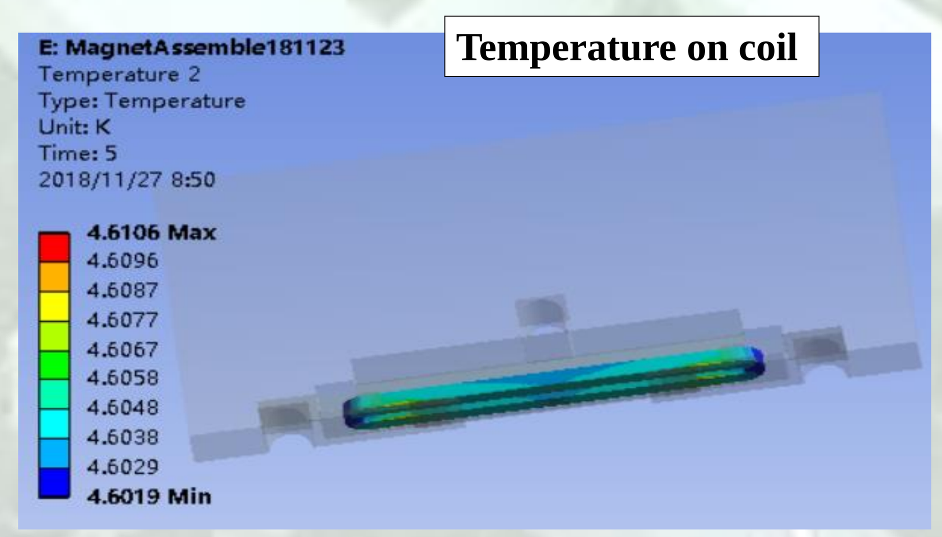


Simulation Model

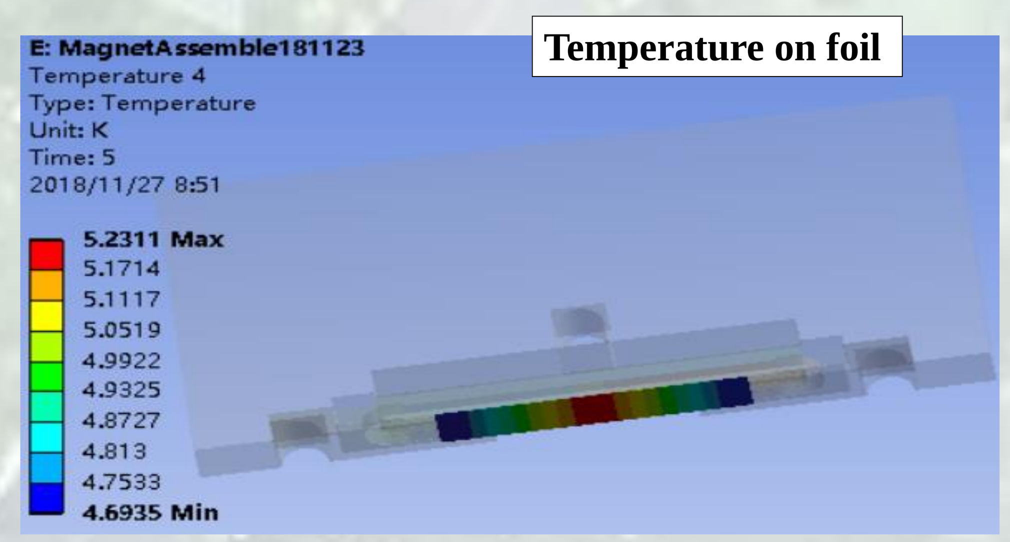


The contour of temperature distribution of the model was got by simulating. The temperature peak of 5.23K is at the center of copper foil because most of beam heat was concentrated on the region. Meanwhile, there are two temperature peaks of 4.61K on the coil. The peaks were located at the regions where the magnetic pole and the copper spacer contact with each other. Temperature peak on the coil will keep constant in the case of invariable total beam heat no matter how it be distributed.

Temperature on coil



Temperature on foil



Summary

There were no separated vacuum chamber in the 4m SCU because of small magnetic gap. Instead, copper foils and spacers were used as beam channel and cooled by liquid Helium tubes. The simulating result showed that the temperature of coils was below critical value of normal operation. Cooling design for the magnetic structure was accomplished. Production for components was being in process and the assembly for SCU was expected to take place in May, 2020.

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