KEK Cryogenics

OKAMURA Takahiro

Cryogenic Section

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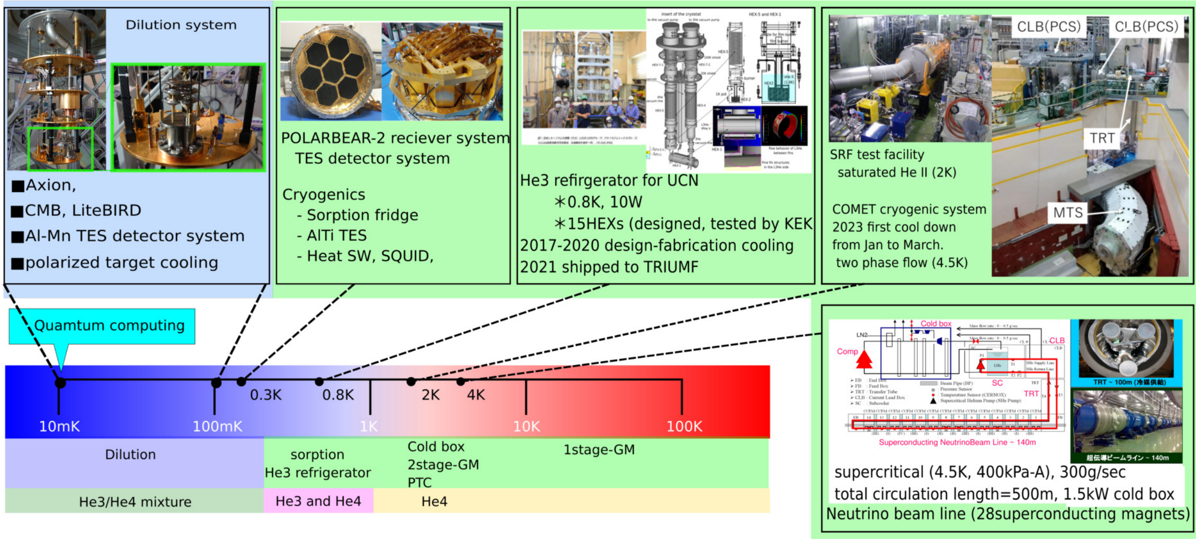
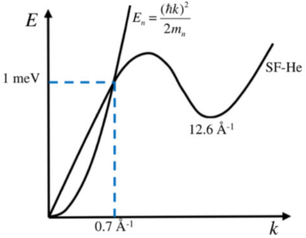
Introduction of KEK Cryogenics

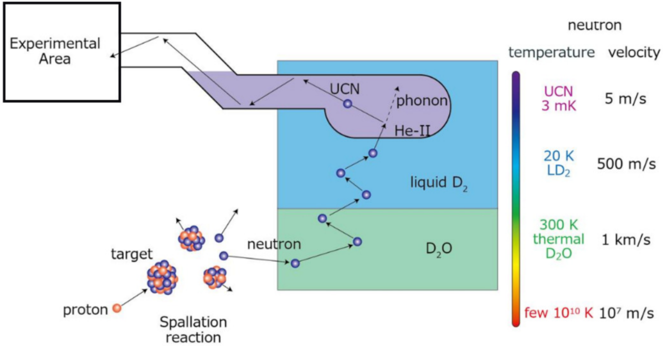


- Sub-Kelvin Refrigerator (UCN cryogenics)
- COMET Cryogenic system

Ultra Cold Neutron Experiment

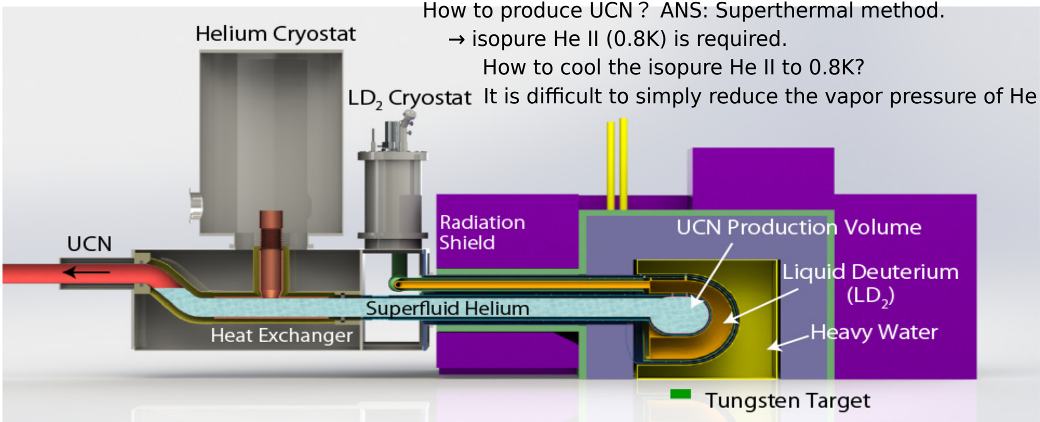
- 480 MeV protons on tungsten target produce spallation neutrons
- Moderators thermalize neutrons
- Down-scatter by interaction phonons / rotons in He-II to ultracold





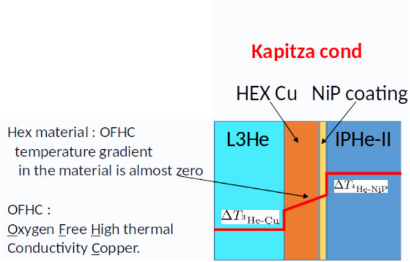
System Overview

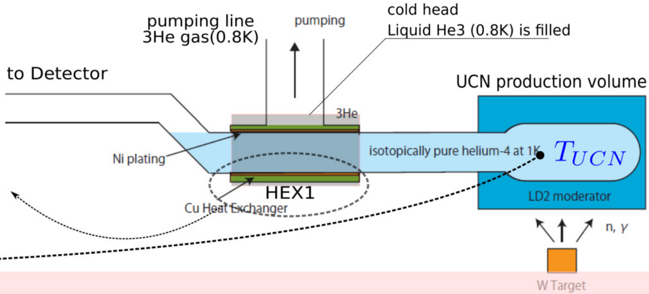
How to produce UCN ? ANS: Superthermal method.
→ isopure He II (0.8K) is required.
How to cool the isopure He II to 0.8K?
It is difficult to simply reduce the vapor pressure of He II.



- Helim3 refrigerator 0.8K@10W
- Proton beam power 20 kW at TRIUMF
- Important cryogenic technology
  1. to design the Helium3 refrigerator with the cooling capacity of 10W, 0.8K
  2. to evaluate temperature increase of isopure He II during ucn production.

UCN Production Volume Temperature



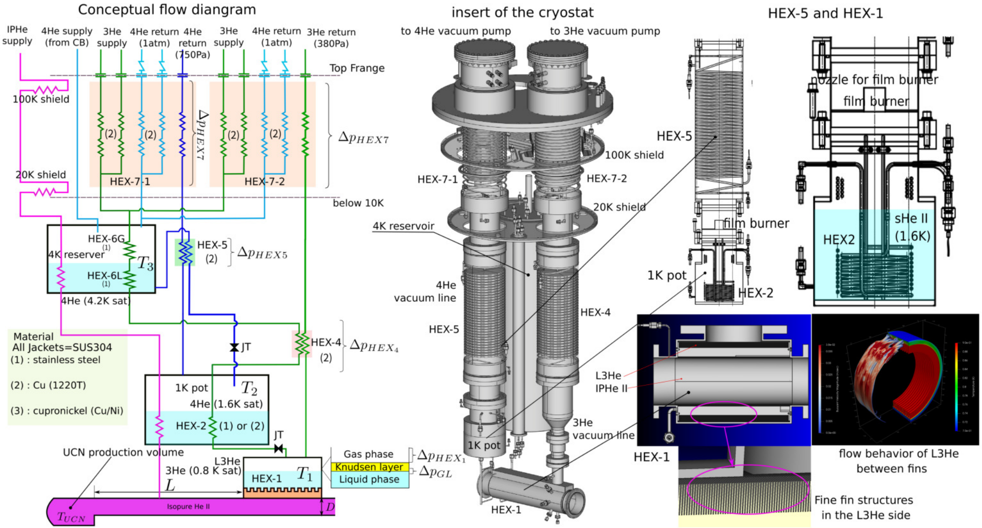


$$T_{UCN} \simeq T_g + \Delta T_{GL} + \Delta T_{sat} + \Delta T_{K1} + \Delta T_{cond} + \Delta T_{K2} + \Delta T_{GM}$$

- ΔT_{GM}: He II heat transfer
- ΔT_{K2}: Kapitza bet. He II and Cu (NiP coating)
- ΔT_{cond}: Thermal conductivity
- ΔT_{K1}: Kapitza bet. LHe3 and Cu
- ΔT_{sat}: Superheat in the L3He
- ΔT_{GL}: Gas liquid interface in the Knudsen layer (usually be ignored)
- T_g: L3He temp = 0.8 K

If the evaporation velocity approaches sound velocity, it cannot be ignored. (sonic velocity of He3 is small)

Helium-3 Refrigerator developed by KEK



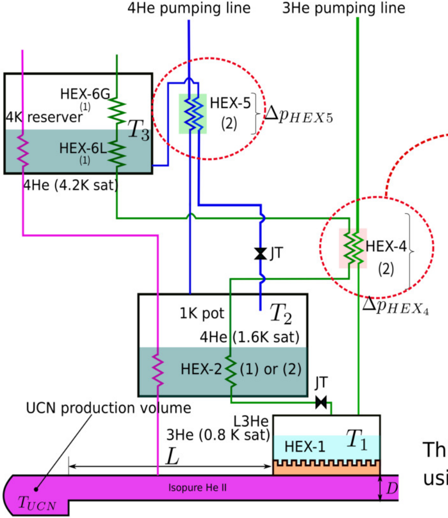
Cold head : HEX-1 (saturated 3He with 0.8 K)

circulated 3He mass flow ~ 1.1 g/sec at 10 W heatload.

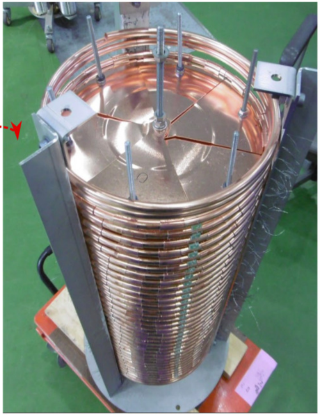
To keep such conditions during ucn production, 16 HEXs are installed in the system.

HEX-7, 6, 5,4,2,1 plays quite important role in keeping the HEX-1 and isopure He II at 0.8 K

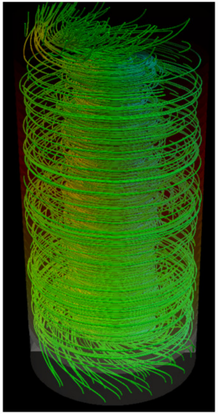
Structure of Heat exchanger, HEX-4



HEX4



gas flow pattern



This heat exchanger has the role of cooling the supplied He3 using the evaporative gas from the cold head.

Spiral flow is induced due to a lot of fins arranged in a helical shape.
This flow pattern induces the large pressure drop. but heat transfer efficiency enhances.

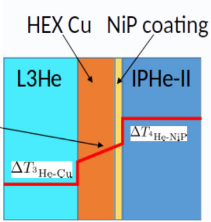
$\Delta T_{K1}, \Delta T_{K2}$, Kapitza Conductance

$$T_{UCN} \simeq T_g + \Delta T_{GL} + \Delta T_{sat} + \Delta T_{K1} + \Delta T_{cond} + \Delta T_{K2} + \Delta T_{GM}$$

3He - Cu   4He - Cu w/ NiP

Hex material : OFHC
temperature gradient
in the material is almost zero

OFHC :
Oxygen Free High thermal
Conductivity Copper.



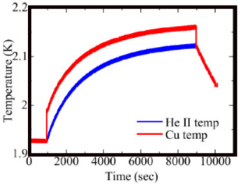
Kharatnikov theory

$$h_K = \frac{2\pi^2 \rho_L c_L k_B^4}{15\hbar^3 \rho_s v_t^3} F T^3,$$

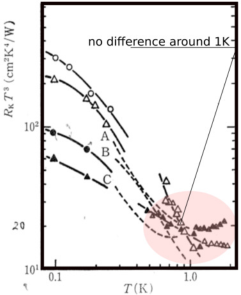
Phonon Radiation Limit theory

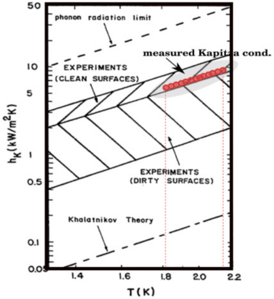
$$h_K = \frac{4\pi^5 k_B^2}{5\Theta_D^2 h} \left(\frac{3n}{4\pi}\right)^{2/3} T^3,$$

Experimental results



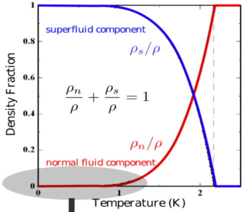
3He and 4He difference



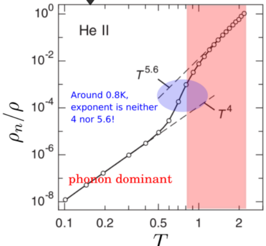


ΔT_{GM}, temperature gradient in the isopure He II

- In sub-K region, normal component (excitation component) ρ_n becomes dilute.
- In such a case, we have to check violation of continuum assumption.



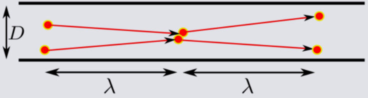
phonon & other excitation



power of 4 : phonon dominant
power of 5.6 : phonon + other excitation (roton, QV)

$$T_{UCN} \simeq T_g + \Delta T_{GL} + \Delta T_{sat} + \Delta T_{K1} + \Delta T_{cond} + \Delta T_{K2} + \Delta T_{GM}$$

Ballistic Heat Transfer (Molecular model)
(Phonon Dominant region)



Mean free path is larger than reference length, D.

$$Kn = \frac{\lambda}{D} > 1$$

Boltzmann equation

Continuum assumption (Continuum model

Mean free path is much smaller than referece length, D

$$Kn = \frac{\lambda}{D} < 1$$

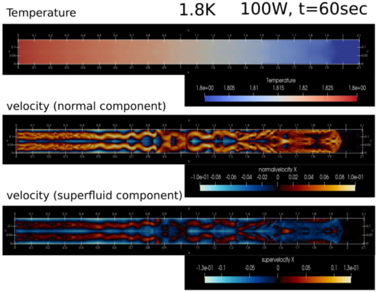
Landau Two fluid equation

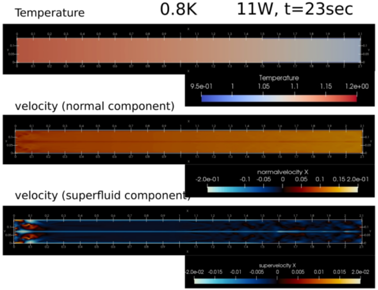
In most cases, He II in the sub-K region are filled in capillary tubes or pipes with small aparture.
In such cases, normal component tends to be treated molecularly because λ and D are of the same order.

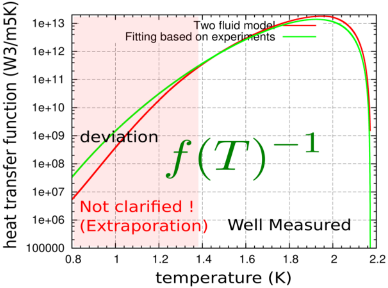
In the UCN case, UCN guide pipe diameter is large (165mm) to increase the transport conductance.
In such a case, λ is much smaller than D, then normal component is treated as a continuum.

UCN case, ΔT_{GM} is evaluated from superfluid turbulent model + Landau two fluid model.

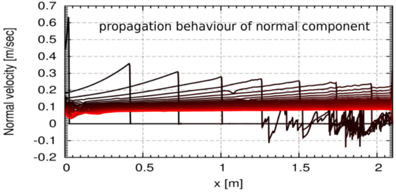
Flow behaviour of ispure He II in the UCN guide temperature increament uncertainty

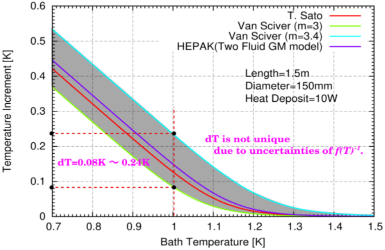






According to simulation,
Behaviour of normal fluid component
under sub-K (shock wave like)
at beginning.

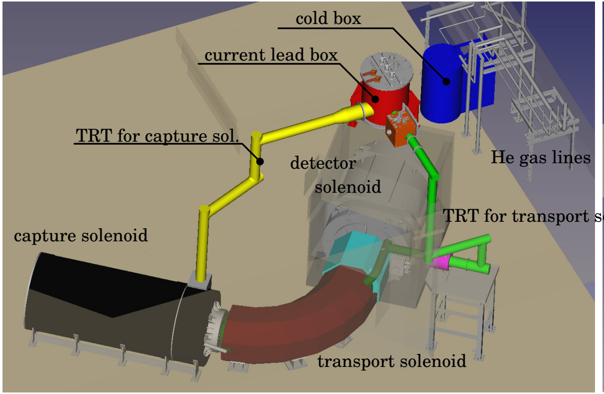




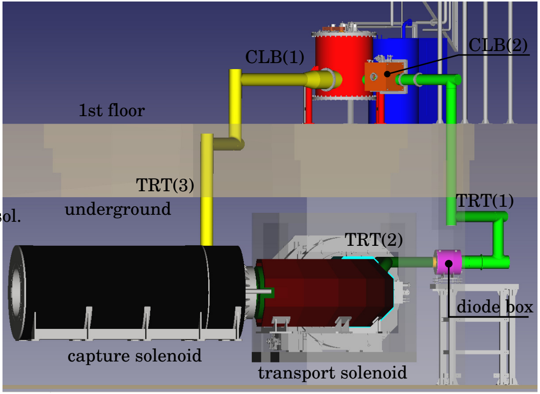
- $||\mathbf{u}_n|| \gg ||\mathbf{u}_s||$
- Normal component (excitation component propagates like shock wave.
- Counterflow does not work properly. It induces small $f(T)^{-1}$.

COMET Cryo Overview (except compressors)

overhead view



side view



- Cryogenic system is almost conventional. Highlight points are as follows.
- Abandoned cold box and control system was restored mainly by KEK cryo staff to reduce construction cost.
- Cooling capacity of the cold box is 100 W which is almost equal to estimated load. So, all the 9 current leads such as 3kA are HTS leads instead of the usual gas cooling.
- The transfer line has a function in which superconducting wires and busbars are conductively cooled from a two-phase flow line.

cooling scheme for capture sol.

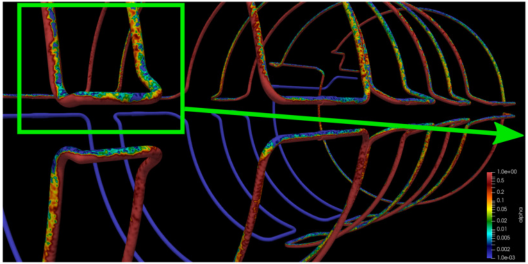
- cooling pipe structures: up-down, bending and curved piping (no branch)

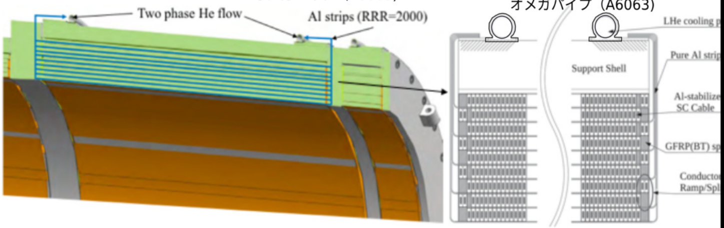
LES-VOF simulation using gas-liquid interface tracking algorithm in the turbulent flow

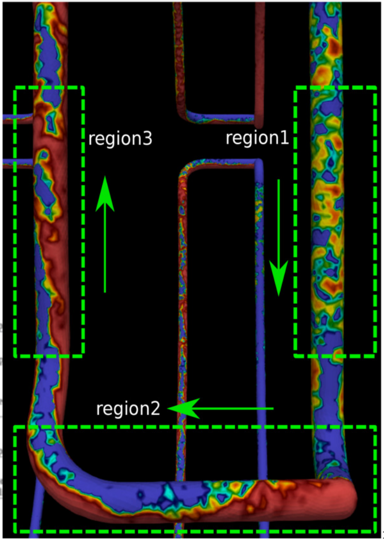
shield: 40K@0.8MPa
magnet: two phase of 4.5K

blue domain:gas
red domain: liquid

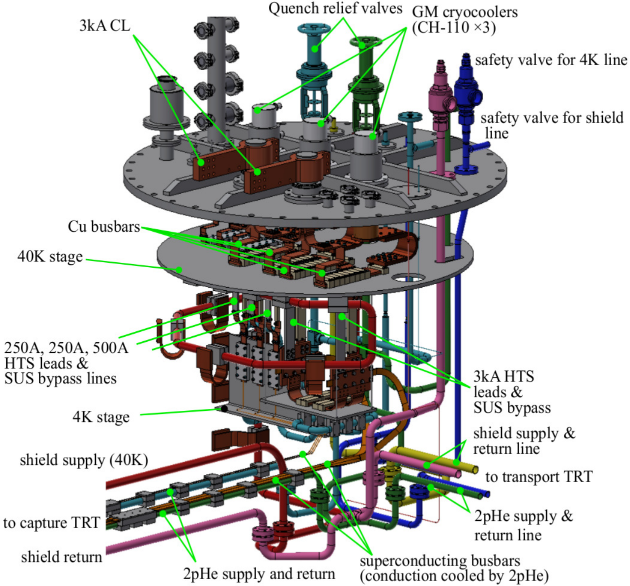
cooling pipe for capture solenoid (void fraction of LHe at 175.6 sec)

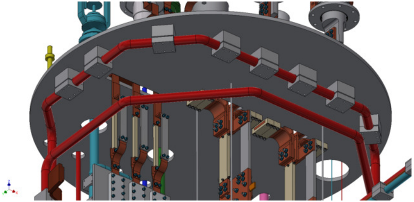


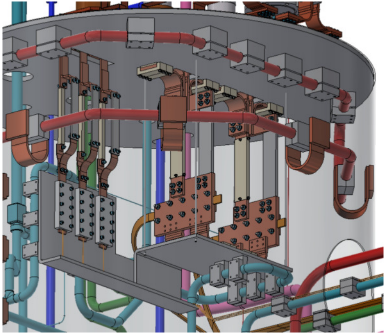




Structure on PCS-CLB



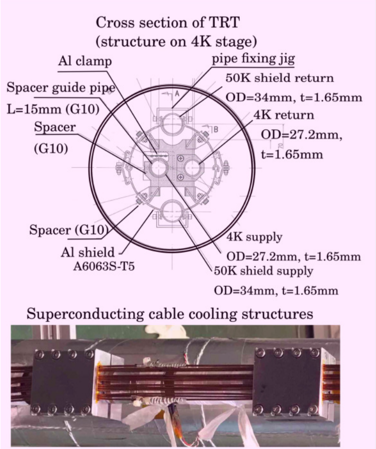




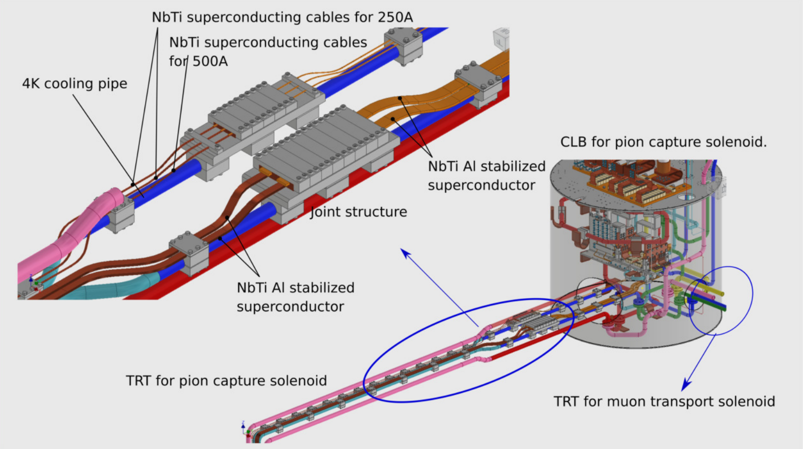
- HTS current leas for 3kA etc are installed to reduce static heat load.

structure of cryogenic transfer line (TRT)

Transport TRT



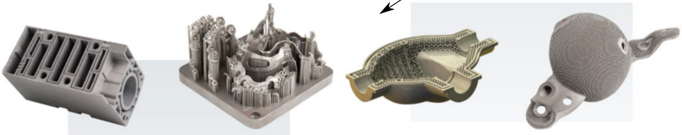
Capture TRT



- Al stabilized NbTi superconducting busbar and cables are installed in parallel with the cooling pipes and cooled by heat conduction via a lot of Al clamps.

Summary and Future plan

- cryo systems recently developed by KEK were designed by using not only experiments but also numerical simulation with high accuracy such as LES techniques.
- We think that low temperature technology is generally classical, but advances in computational science and verification through experiments will make it possible to build highly efficient cryogenic systems and reduce the inventory of expensive helium.
- As a further application of these attempts, we aim to reconstruct ultra-low temperature technology using dilution で.
  In particular, we would like to start the following development items.
  - Hydrodynamic problems associated with large capacity
    (transition, micro fluid dynamics, superfluid, Fermi liquid, inventory reduction)
  - Kapitza resistance reduction
  - New production technology with leak free of He3 using Selective Laser Melting : SLM method
  - Heat load reduction induced by vibrations.
  - precooling time reduction.



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