Helium Cryostat and cryogenic tests

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for the TUCAN Collaboration

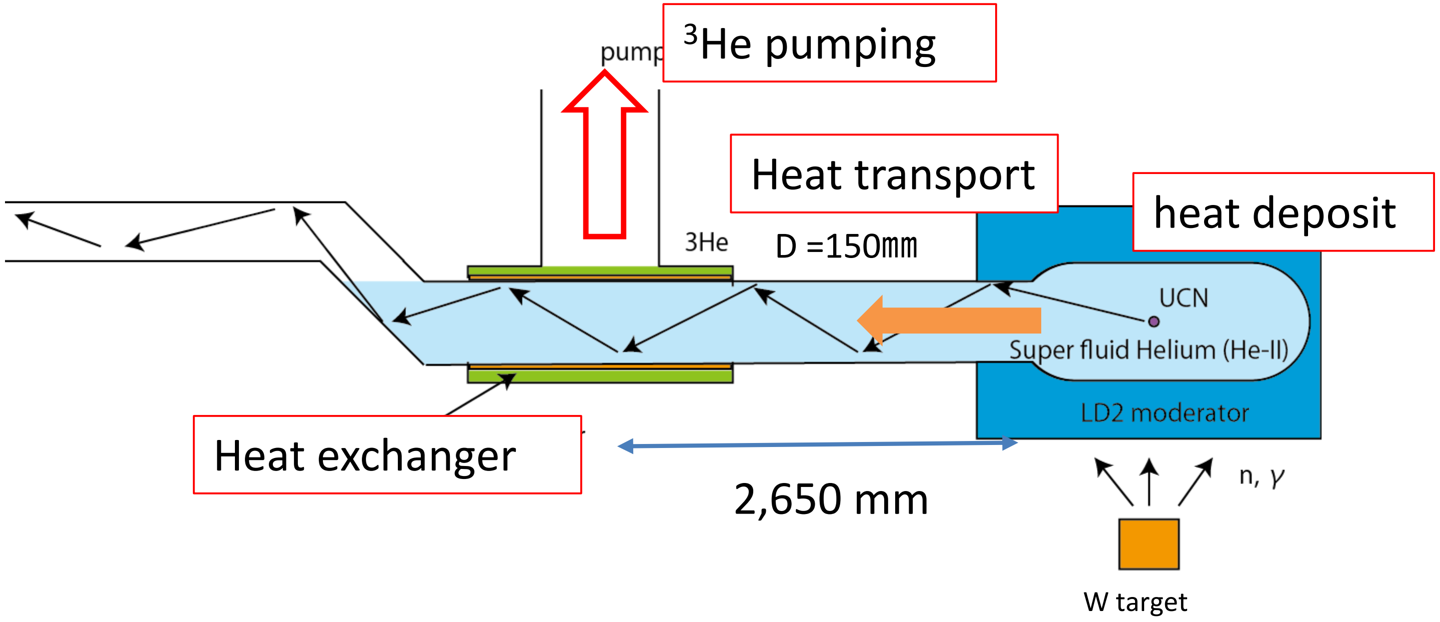
Outline

- Working group
- Overview
- Helium-3 cryostat
  - Heat exchanger
    - Design
    - Test
  - Fabrication status
- ^{3}He – ^{4}He heat exchanger
- Heat Transfer in superfluid helium
- Uncertainty and risks
- Summary and schedule

Working group

• S. Kawasaki (KEK)	Working Group Leader
• T. Okamura (KEK)	Cryogenic calculation, Experimental design, Analysis
• C. Marshall and TRIUMF engineer group (TRIUMF)	Design, Cryogenic calculation, Mechanical calculation
• T. Higuchi (RCNP)	DAQ software, Data taking, Data analysis
• S. Imajo (RCNP)	DAQ hardware, Data taking Data analysis
• R. Matsumiya (TRIUMF)	Cryogenic calculation, Data analysis

Overview of Superfluid helium UCN converter cooling



$$T_{prod} = T_{3He} + \Delta T_{3He\text{-}Ni} + \Delta T_{Cu\text{-}HeII} + \Delta T_{HeII}$$

^{3}He Cryostat

Kapitza cond. (HEX1)

Heat transfer in He-II

Components

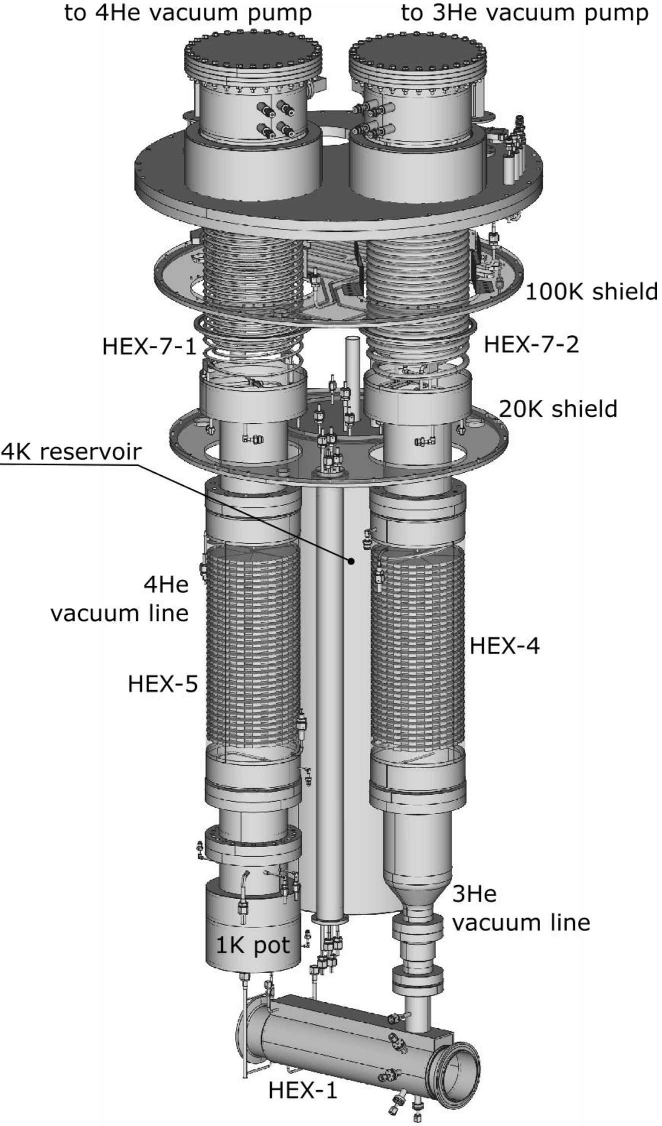
1. Helium-3 cryostat
   - Large cooling power : ~11 W @1.0K,
     - 10 W: beam, 1 W: static
       - Including safety margin
       - Actual heat deposit: 8.1 W by beam
2. ^{3}He -^{4}He Heat Exchanger design
   - Kapitza conductance
3. Heat transport in superfluid helium
   - Flow pattern
     - Superfluid turbulent
     - Gorter-Millink heat transfer

1. Helium-3 cryostat

- We decided to use a helium-3 cryostat as a superfluid helium-4 converter
  - better performance than helium-4 direct puming
    - Discussed in UCN source review in 2017
- Function
  - Condensate isotopically pure helium-4
  - Keep isotopically pure helium-4 temperature below 1.15 K
    - In order to produce UCN effectively
- Requirements
  - Cooling power: 11 W @ 1.0 K
    - Heat load: 10 W from beam, 1 W from static
      - Including safety margin
      - Actual heat deposit: 8.1 W by beam
  - Has to be placed behind radiation shield
    - L = 2.65 m
  - Minimize liquid helium consumption

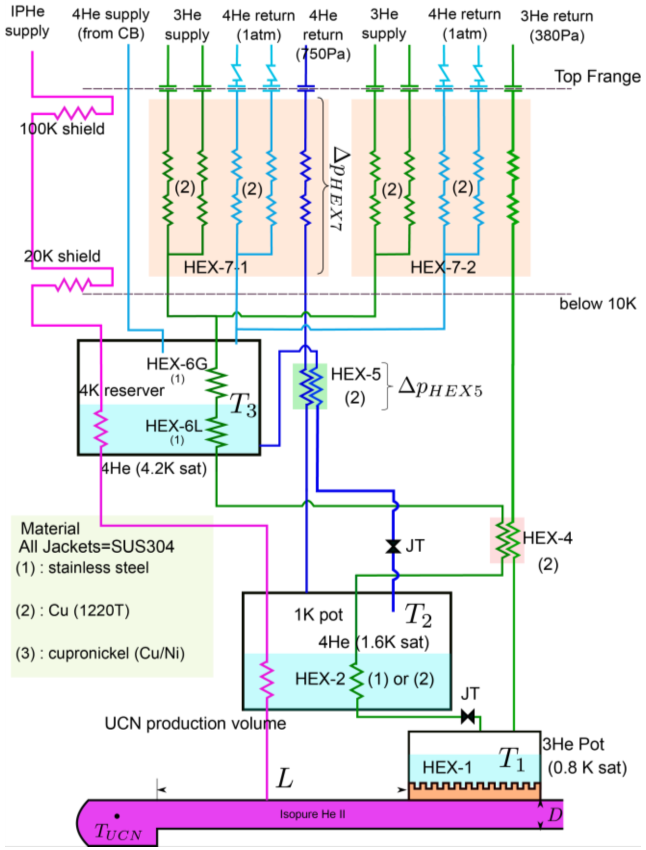
Flow Diagram and Schematic Drawing

insert of the cryostat



Liquid bath condition

	3He pot	1K pot	4K reservoir
Bath temperature	0.8 K	1.6 K	4.2 K
vapor pressure	378 Pa	746 Pa	1 bar
Mass flow	1.14 g/sec	1.20 g/sec	2.28 g/sec
Pumping speed	> 8,800 m^3/hour	> 3,700 m^3/hour	No pumping



Conceptual Flow diagram

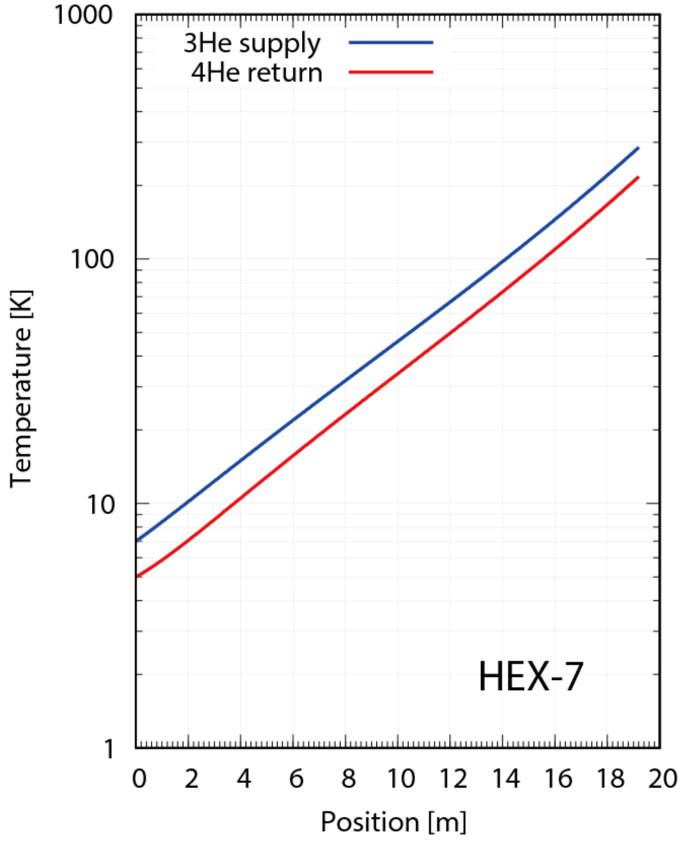
Heat Exchangers

Name	Type	Coolant	Cooling Target
HEX-1	Pool cooling	Liquid 3He (0.8 K, 380 Pa)	Isopure helium-4
HEX-2	Pool cooling	Liquid 4He (1.6 K, 740 Pa)	Supplied 3He (G/L, 2.6 K -> 1.6 K)
HEX-4	Counter flow	Return gas from 3He pot	Supplied 3He (G, 4.2 K -> 2.6 K)
HEX-5	Counter flow	Return gas from 1K pot	Supplied 4He (L, 4.2 K -> 2.8 K)
HEX-6	Pool cooling	Liquid 4He (4.2 K, 1 bar)	Supplied 3He (G, 10 K -> 4.2 K)
HEX-7	Counter flow	Return gas from 4K res.	Supplied 3He (G, 300 K -> 10 K)

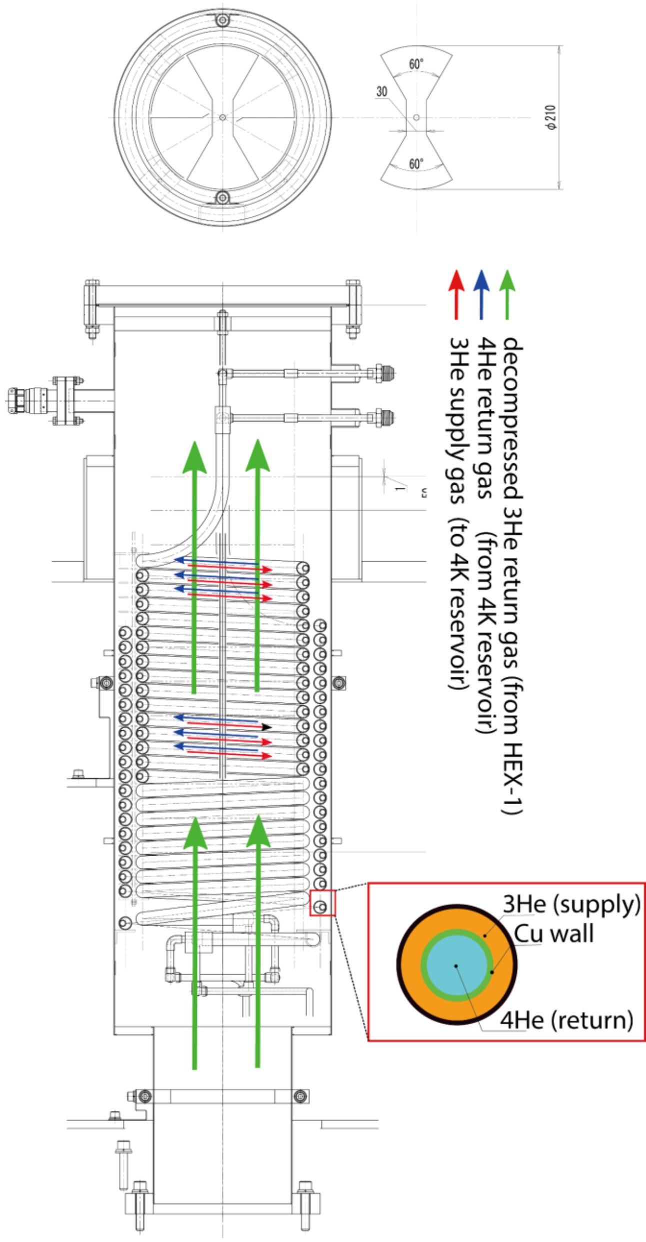
HEX-7

- Counter flow type heat exchanger
  - Cooling target: supply ^{3}He
    - 300K -> 10K
  - Coolant: return evaporating ^{4}He from 4K reservoir
- 4 parallel tube in tube
  - In order to reduce pressure drop inside tube
    - Outer tube: supply ^{3}He
    - Inner tube: return ^{4}He
- Total mass flow
  - Supply ^{3}He: 1.14 g/sec
  - Return ^{4}He: 1.91 g/sec
- Locate ^{3}He and ^{4}He pumping duct
  - To get additional cooling by pumping gas
- Simulation
  - To decide necessary length of each coil, numerical simulation was conducted
  - Only cooling by evaporated 4He is take into account
    - Conservative assumption
  - Assumption
    - Exit ^{3}He temperature: 7 K
    - Inlet 4He temperature: 5 K
  - Result: necessary length of each coil

    18 m



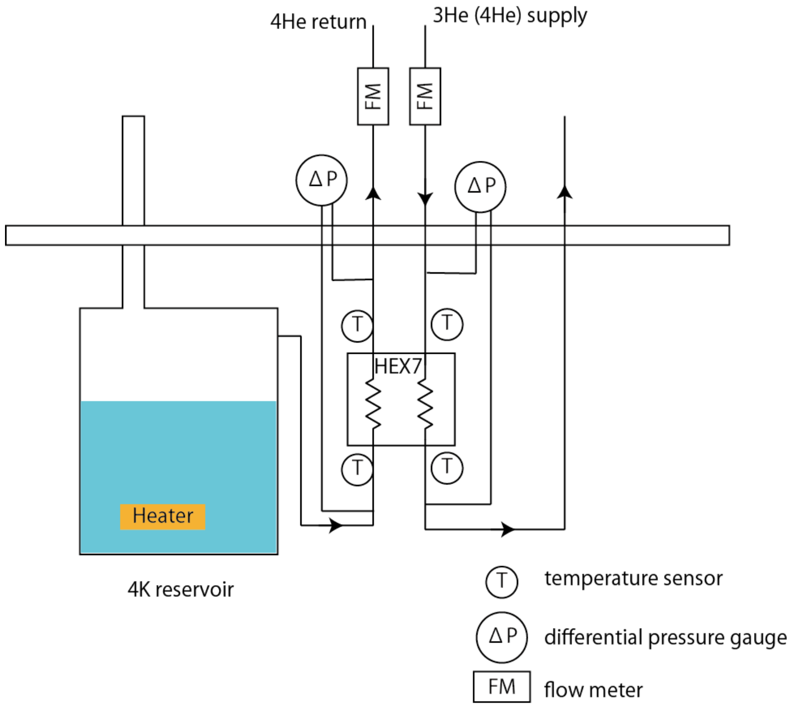
Simulation result



Design of HEX-7

- Cryogenic test of the HEX-7
  - Conducted at KEK
  - One tube in tube coil
  - Use ^{4}He instead of ^{3}He
    - Main purpose of the test is to check validity of numerical simulation
  - Test in different mass flow condition

	^{3}He	^{4}He	(g/sec)
RUN-1	0.28	0.47	
	Designed value		
RUN-2	0.28	0.36	
RUN-3	0.14	0.36	
RUN-4	0.14	0.28	
RUN-5	0.14	0.20	



Test set up

One of the HEX-7 coil

Test result

Run-No	$\dot{m}_{3He}$ (g/sec)	$\dot{m}_{4He}$ (g/sec)	T_{in_3} (K) (exp/num)	T_{out_3} (K) (exp/num)	T_{in_4} (K) (exp/num)	T_{out_4} (K) (exp/num)
RUN-1	0.28	0.47	296/291	6.4/7.6	6.1/6.1	181/176
RUN-2	0.28	0.36	295/293	6.7/11.4	5.9/6.1	225/223
RUN-3	0.14	0.36	294/289	6.2/6.2	6.0/6.1	123/115
RUN-4	0.14	0.28	294/292	6.4/6.4	6.0/6.1	150/148
RUN-5	0.14	0.20	294/292	7.4/8.4	6.2/6.1	206/204

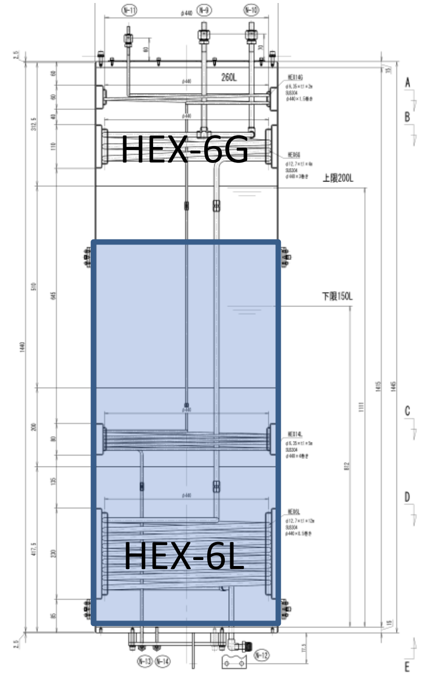
Actually ^{4}He

  - Test result is consistent with the simulation
    - Except Run-2
      - Not to reach stable condition?

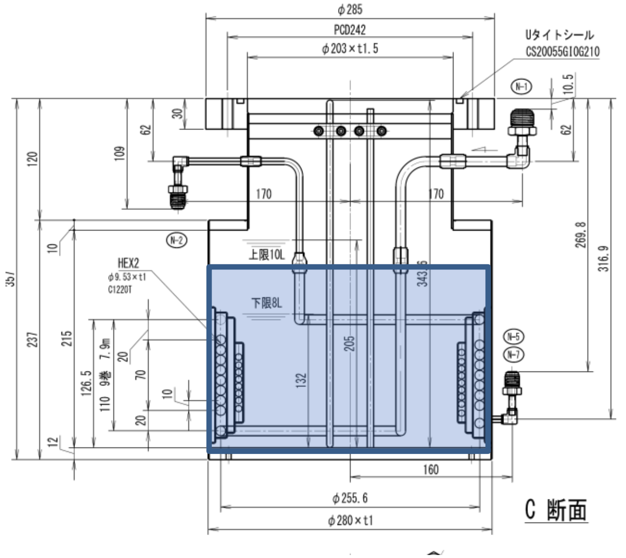
HEX-2 & HEX-6

- Pool cooling heat exchanger for ^{3}He cooling
  - HEX-6: 10 K -> 4.2 K
    - HEX-6G in gas phase of 4K reservoir is used for a contingency when the HEX-7 doesn't work as expected
  - HEX-2: 2.8 K -> 1.6 K
    - ^{3}He is condensed inside the HEX-2
- Numerical simulation conducted to decide necessary length of coils
  - In order to have safety margin, HEX-2 was designed to cool down from 4.2 K

	HEX-6G	HEX-6L	HEX-2
	4K reservoir		1K Pot
Coolant	1.6K Gas ^{4}He	4.2 K liquid ^{4}He	1.6 K liquid ^{4}He
Cooling target	^{3}He Contingency of HEX-7	^{3}He 10 K -> 4.2 K gas/liquid	^{3}He 2.8 K -> 1.6 K gas
Coil material	Stainless Steel (SS304)		Copper (c1220)
Coil length	4m	12 m	8 m

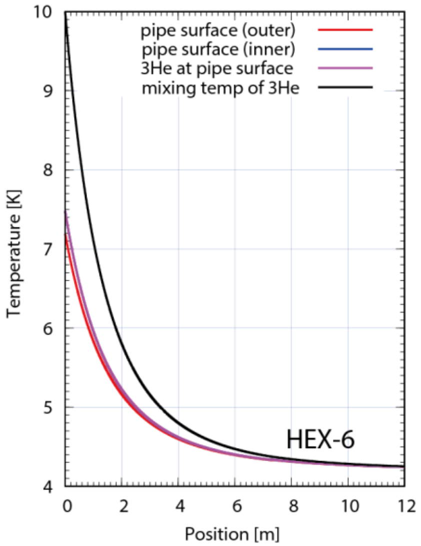


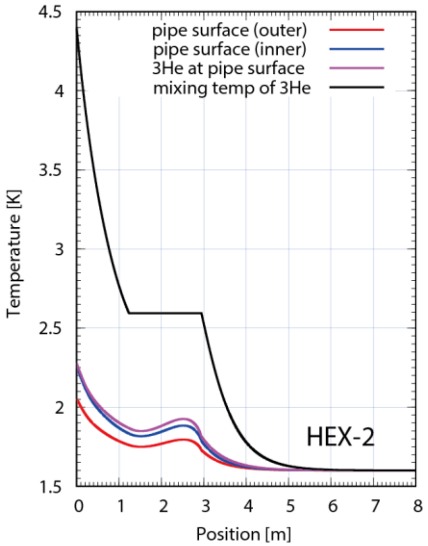
HEX-6 in 4K reservoir



HEX-2 in 1K pot

simulation

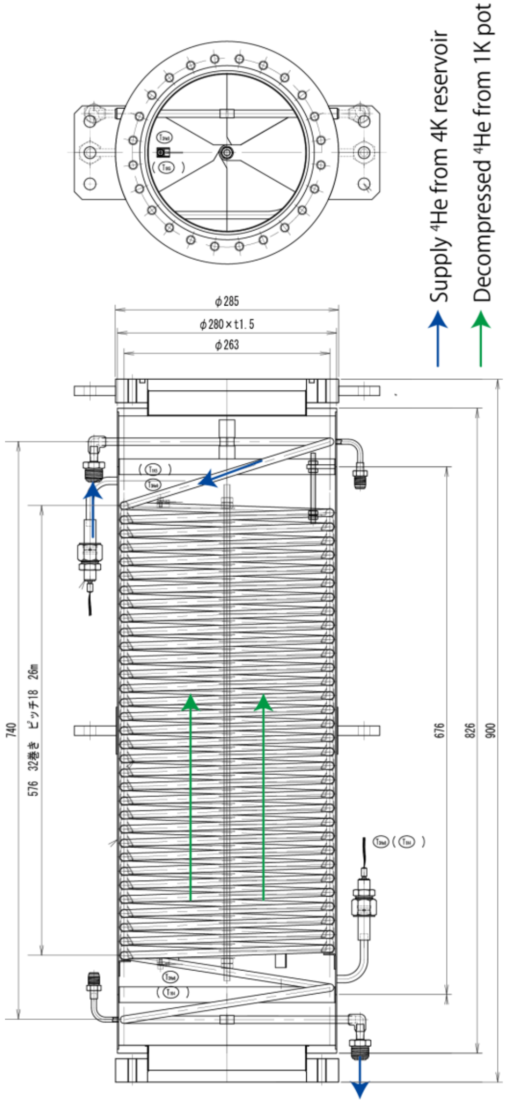




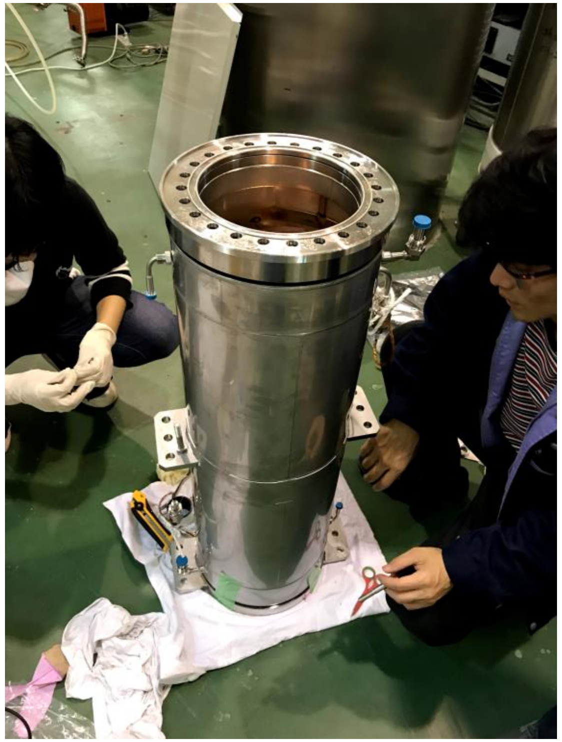
HEX-4 & HEX-5 design

- HEX-4 and HEX-5 have same structure
  - HEX-4: precooling of ^{3}He before the 1K Pot
  - HEX-5: precooling of ^{4}He before JT expansion
- Counter flow type heat exchanger
  - Originally designed Prof. Hosoyama (KEK)
  - Coil inside ^{3}He/^{4}He pumping duct
  - Use a number of fins to make the heat transport efficiency high

	HEX-4	HEX-5
Location	Above 1K pot	Above ^{3}He pot
Cooling target	^{4}He liquid	^{3}He gas
Coolant	Return ^{4}He gas from 1K pot	Return ^{3}He gas from ^{3}He pot
Coil tube	Material: Copper (C1220T) Length: 26 m Diameter: 9.53 mm (O.D.) Thickness: 1 mm	
Pumping duct diameter	Diameter: 280 mm (O.D.) Thickness : 1.5 mm	

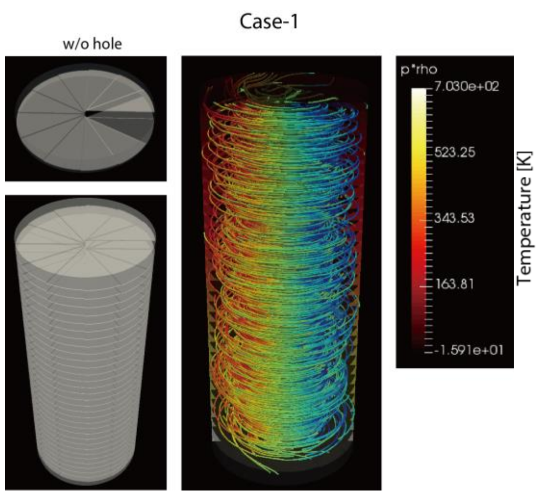


HEX-4 and HEX-5 design

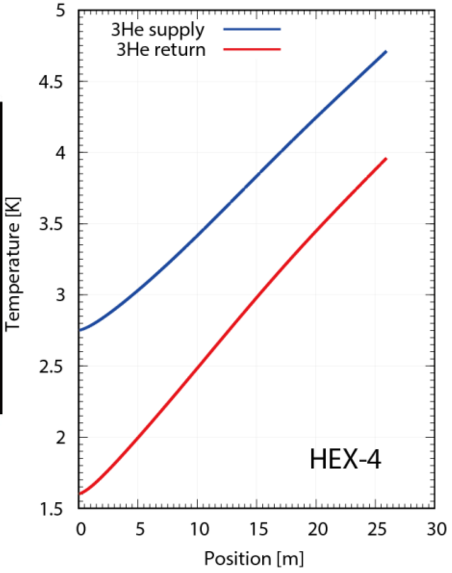


- Numerical simulation was conducted to decide dimension of HEX-4 and HEX5
- Cryogenic test of HEX-5was performed
    - Bench mark test of the simulation
    - Smaller mass flow
        - Design value : 1.3 g/sec
        - Experiment: 0.58 g/sec
            - Pumping power restriction
        - Control by heater power
- Results show HEX-5 works well
    - Outlet temperature is lower than simulation
    - Pressure drop is smaller than simulation

Simulation

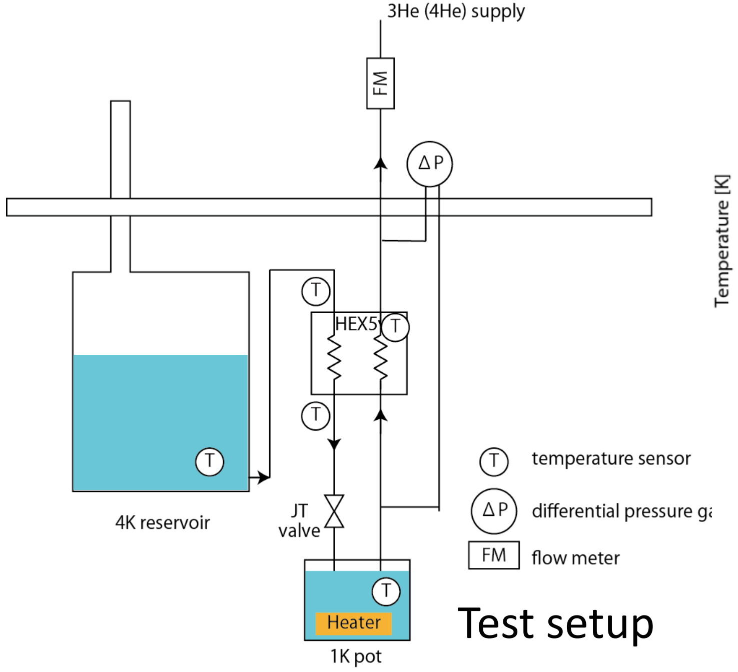


Gas flow

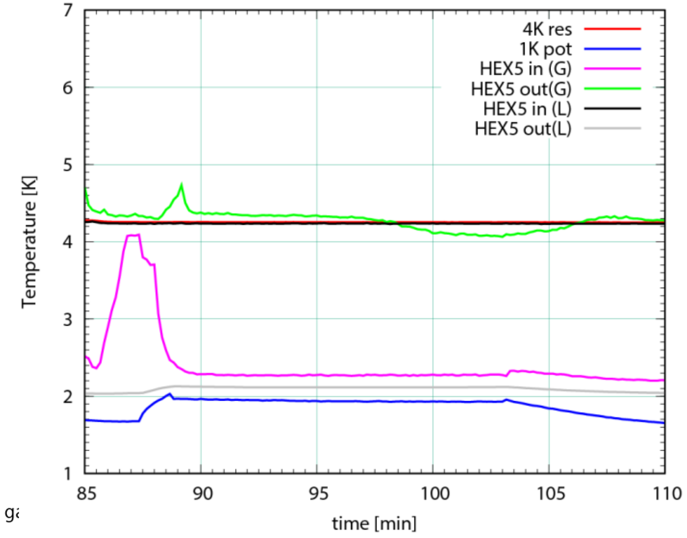


temperature

Cryogenic test at KEK



Test setup



Temperature log

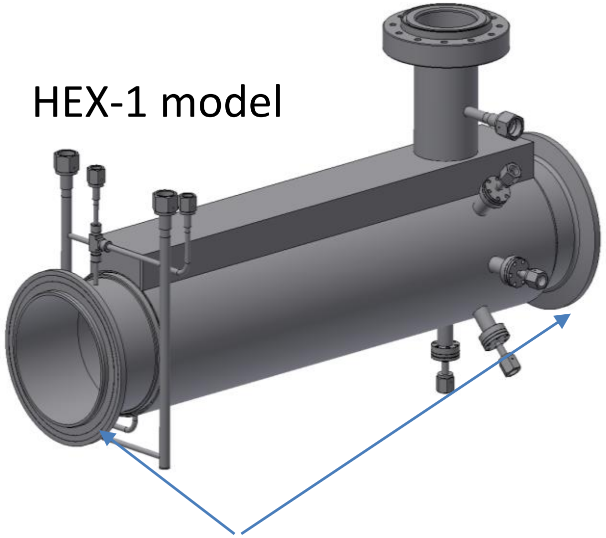
Results		Simulation	Experiment
mass flow rate	g/sec	0.58 (input)	0.58
temperature: 4He (L) inlet	K	4.5 (input)	4.23
temperature: 4He (L) outlet	K	2.45	2.11
temperature: inlet FIN	K	2.27 (input)	2.27
temperature: outlet FIN	K	4.27 (input)	4.27
temperature: 4K reservoir	K	4.25 (input)	4.25
temperature: 1 K pot	K	1.93 (input)	1.93
pressure drop (Gas)	Pa	12	6.62

Other Cryogenic test

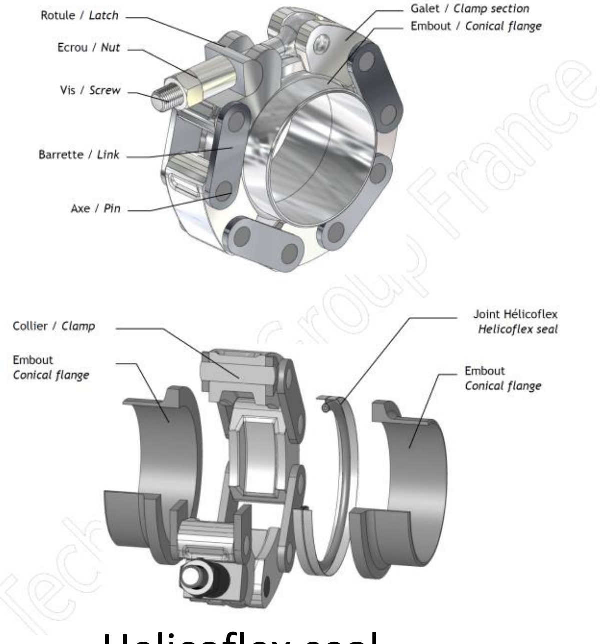
- Superleak tightness
  - New design Helicoflex flange for the HEX-1
  - Al – SS junction using the UCN guide
    - UCN production volume: Al
    - UCN guide base material: SS

We found no superleak

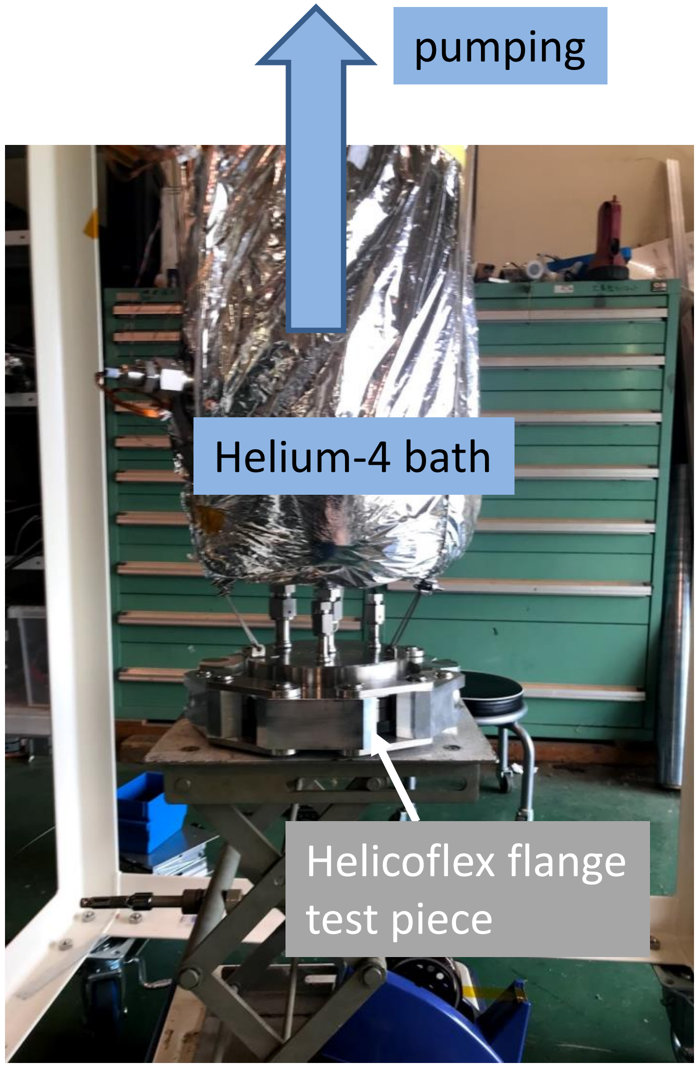
HEX-1 model



Helicoflex flange



Helicoflex seal



Test setup of superleak of the Helicoflex flange

Current status of the Cryostat construction

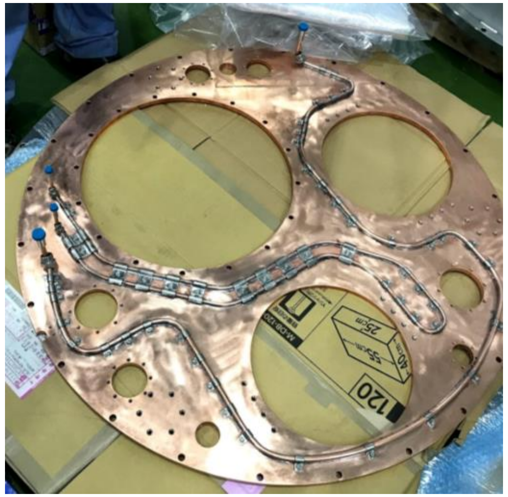
The Helium-3 Cryostat is constructed by JECC Torisha

- ✓ All heat exchangers were fabricated
- ✓ Leak check of fabricated components have done
- ✓ Almost all parts procurement was done

- Assembling has started
- Final acceptance/inspection will be done March 15th, 2020
- Assemble test of all the parts except the HEX-1 will be done at the company
- The cryostat will be delivered to KEK at the end of March, 2020

Top Flange (Upside –down)

Thermal shield top plate (100K)



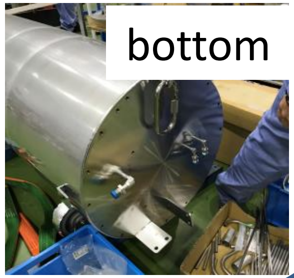
Vacuum chamber

Thermal Shield

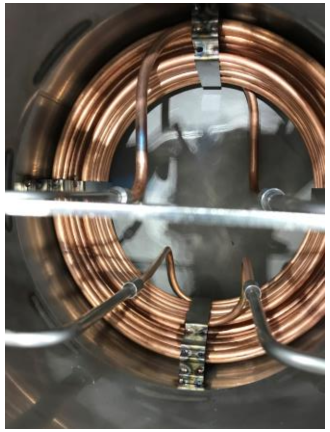
4K reservoir

top

bottom



1K pot

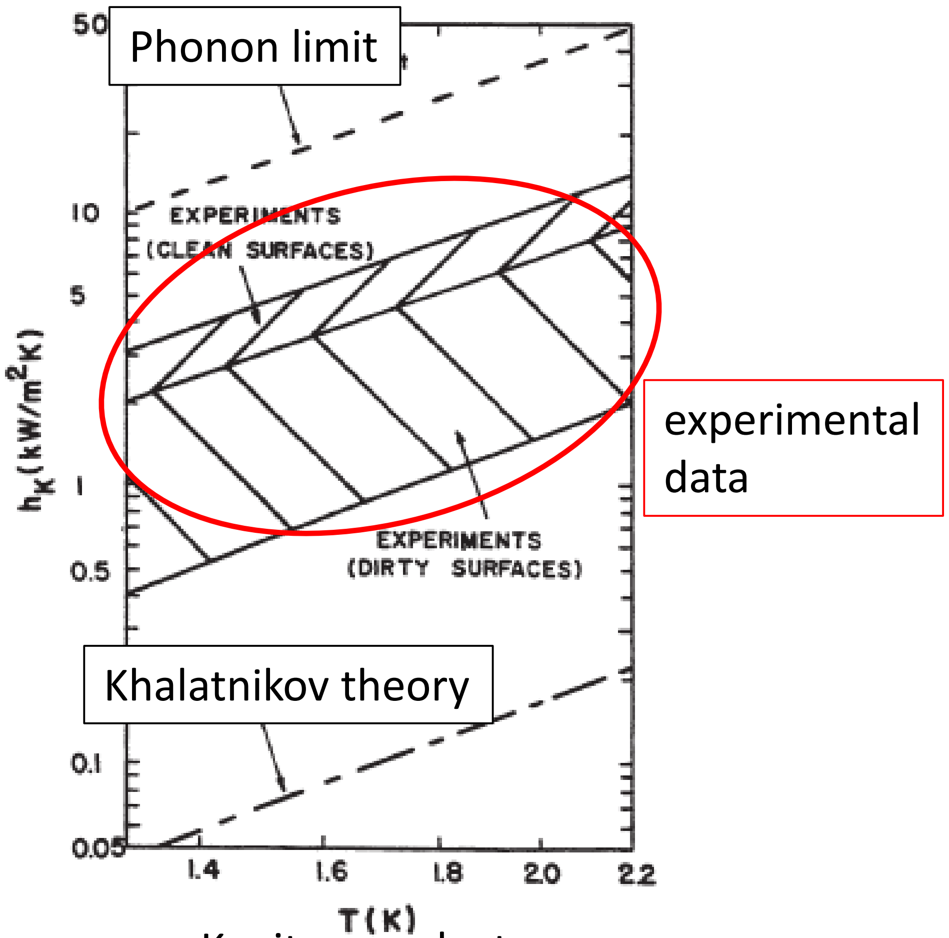


2. ^{3}He-^{4}He heat exchanger (HEX-1) design

- In order to convey the heat of isotopically pure ^{4}He UCN converter to ^{3}He, a heat exchanger is necessary
  - ^{3}He must be away from UCN
    - ^{3}He has large absorb crosssection to neutron
- Cylindrical shape is adopted for the ^{3}He - ^{4}He heat exchanger
  - Inside : isotopically 4He
    - Serve as a part of UCN guide
      - Should be UCN friendly
      - Cannot have a fin structure
- At low temperature around 1.0 K, Kapitza conductance dominates heat transport at thermal boundary

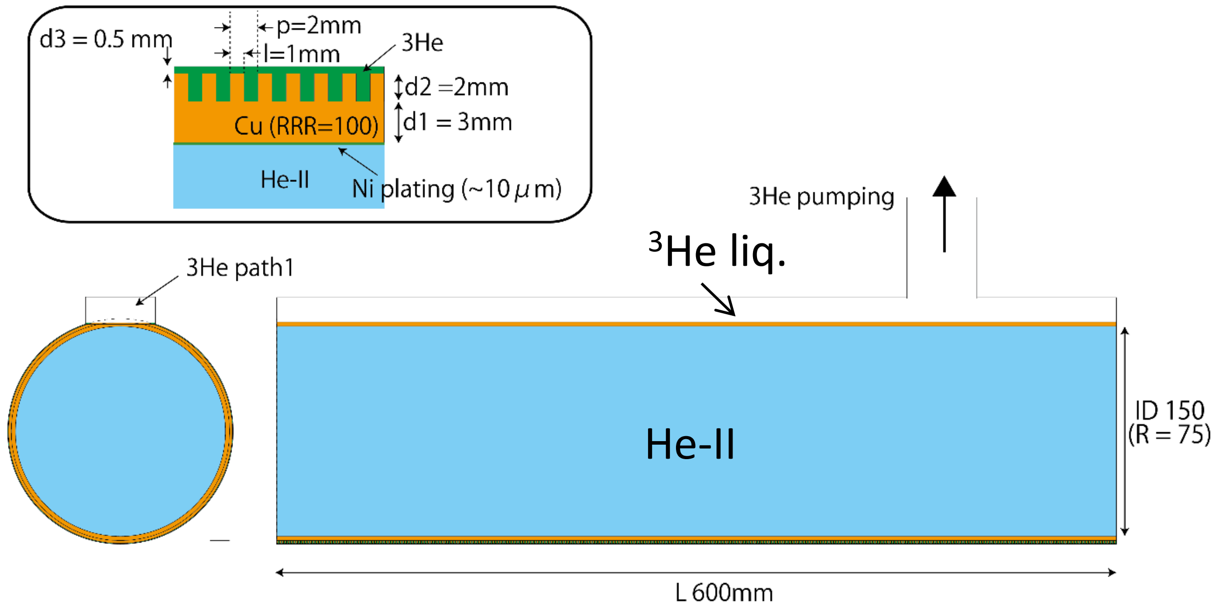
Kapitza Conductance

- Kapitza conductance is Conductance at the surface between liquid and solid is small at low temperature
- Kapitza conductance, $h_K(T)$ is a function of temperature.
- There are several theory on Kapitza conductance.
  - Phonon limit
    - $h_K(T)$ ~ 4500 T^3 [W/m^{2}K]
      - 2 - 10 times larger than measured
  - Khalatnikov theory
    - $h_K(T)$ ~ 20 T^3 [W/m^{2}K]
      - 10 - 100 times smaller than measured
  - K_G is commonly used for parametarization
    - $h_K(T)$ ~ 20 K_G T^3 [W/m^{2}K]
- Experimental data strongly depends on surface quality



Kapitza conductance between Copper and He-II
Helium cryogenics, Steven W. Van Sciver

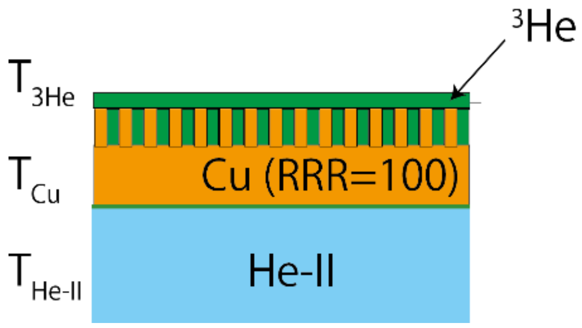
HEX-1 (Main Heat Exchanger) design



- Cylindrical shape
- Material : OFHC (RRR = 100)
- Inside : He-II
  - No fin
  - Surface area :Si = 0.28 m^2
  - Ni plating
    - UCN friendly
- Outside : ^{3}He
  - Fin structure
    - Fin gap = 1 mm
    - Fin length = 2 mm
  - Surface area : So = 0.89 m_2

Kapitza conductance

- Kapitza conductance between Cu and He-II
  $h_K(T) \sim 20*K_G* T^3$ [W/m²K]
  K_G = 20 - 60
- Kapitza conductance between Ni and He-II
  $h_{K\,Ni}$ (T) = f*h_K(T) f = 0.61
- Kapitza conductance between Cu and ^{3}He
  h_{K_3He}(T) = a*h_K(T) a = 1.2 – 2.6



ex) K_G = 40 , T_{3He} = 0.8 K, Q = 11 W

- junction between 3He and Cu
  - $\Delta T_{Cu\text{-}3He}$ = 0.078 K
  - T_{Cu} = 0.878 K
- junction between Cu and He-II
  - $\Delta T_{Ni\text{-}HeII}$ = 0.118
  - $T_{He\text{-}II}$ = 0.996 K

Temperature difference in the heat exchanger can be neglected

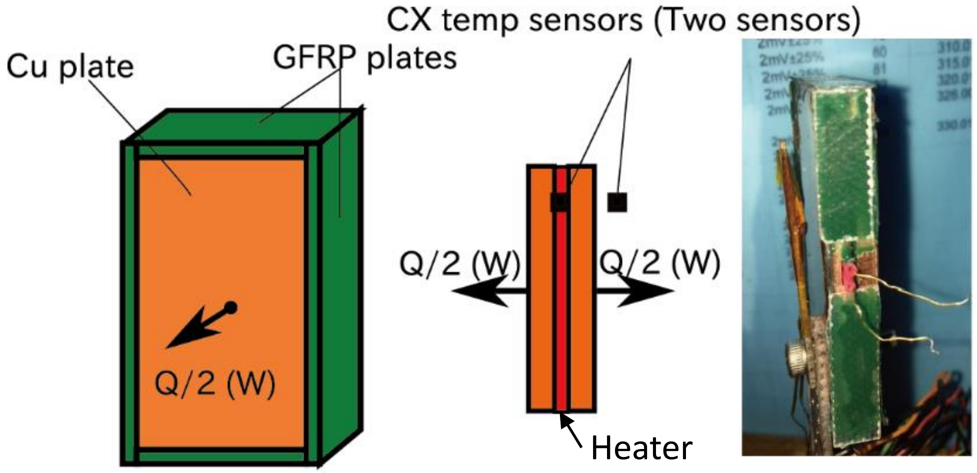
Kapitza conductance Measurement

- first Kapitza conductance test at KEK
- Sample
  - Material : Copper (OFHC)
  - A heater is inserted between two copper
- The temperature difference was measured as a junction of bath temperature

  $Q/2 = h_K * A * \Delta T$

  h_K: Kapitza conductance

  A : surface area
- Temperature range : 1.82 - 2.15 K

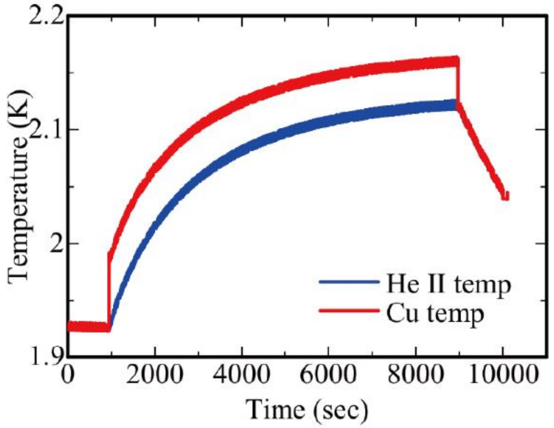


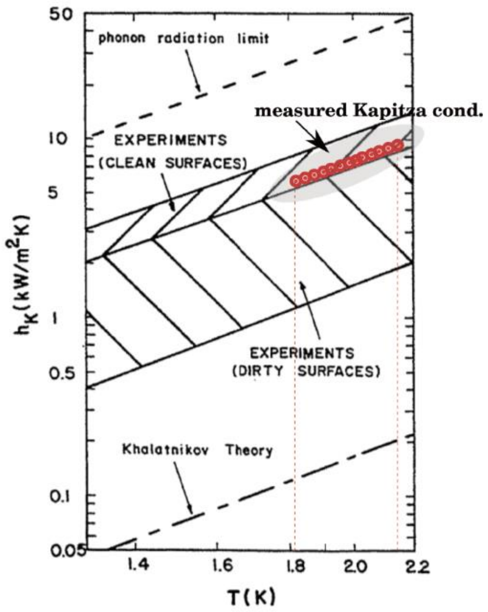
Test sample

Result

- Confirm dependence of T^3
- Enough Kapitza conductance
  - K_G = 45 – 48

- Lower temperature measurement is plan to be performed

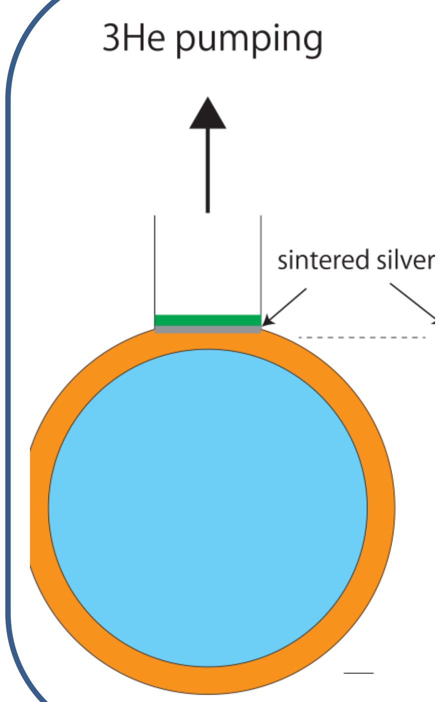




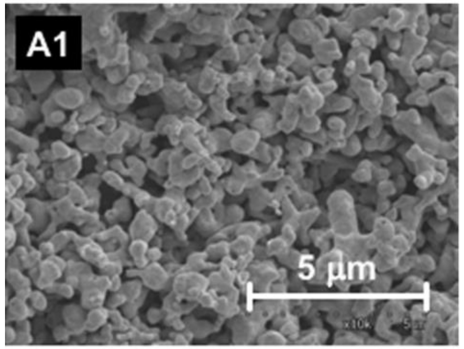
Van Sciver, Helium cryogenics

R&D for the HEX-1

- HEX-1 prototype was fabricated at the KEK machine shop
  - ✓Machining test
  - ✓Superleak tightness
    - Performed superleak check -> found no leak
  - Cooling test
    - Will be done in Feb. – Mar. 2020
    - Critical heat flux measurement
      - Not to occur film boiling
      - Critical heat of ^{3}He at 0.8 K: $\sim 10^{-2}$ W/cm^2
      - Safety factor 10 for the 2.0 m fins
      - Critical heat in case of narrow channel might be different
- New design to reduce necessary amount of ^{3}He
  - 2mm fin design needs 61.6 g of ^{3}He
    - Include piping
  - Shorter fins
    - Impact to the temperature at production volume is not so large
    - Depends on the result of critical heat flux
  - Sintered Ag
    - reduce necessary amount of helium



Sintered Ag
- Surface area gain
  > 100
- Necessary amount of 3He
  39.0 g

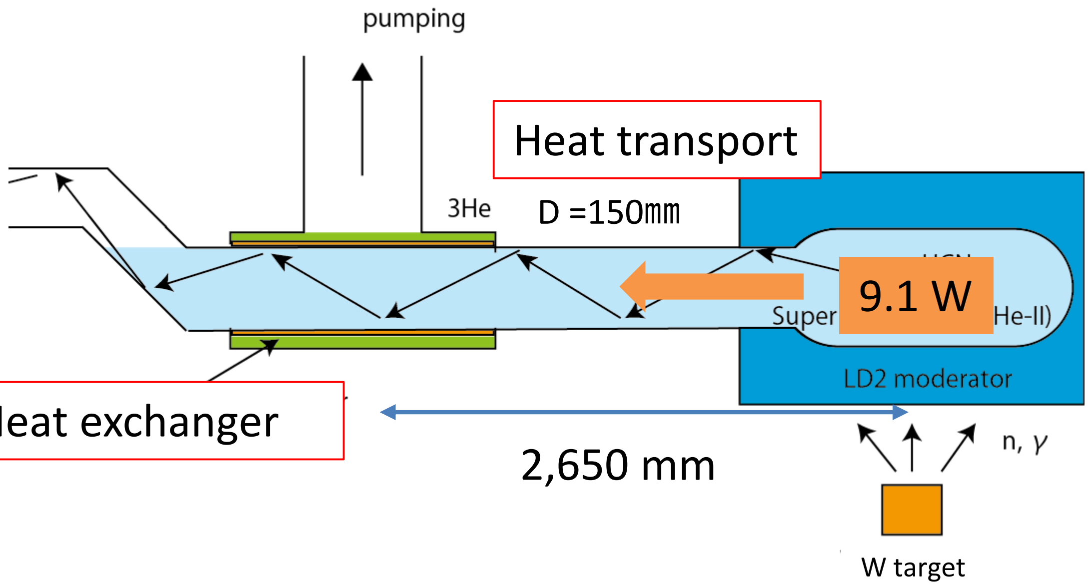


Fin length	Heat Flux [W/cm²]	Temperature (Q=9.1 W, T_{3He} = 0.8 K, KG=40, a = 2.6, f = 0.61, HEPAK)			3He amount
		T_{HEX} [K]	T_{HeIIL} [K]	T_{HeIIH} [K]	g
2.0 mm	1.0×10^{-3}	0.865	0.967	1.148	61.6
1.5 mm	1.2×10^{-3}	0.878	0.975	1.149	57.0
1.0 mm	1.5×10^{-3}	0.898	0.989	1.149	52.3
0.5 mm	2.1×10^{-3}	0.931	1.012	1.150	43.8
No fin	3.1×10^{-3}	0.996	1.063	1.156	35.3

Production volume

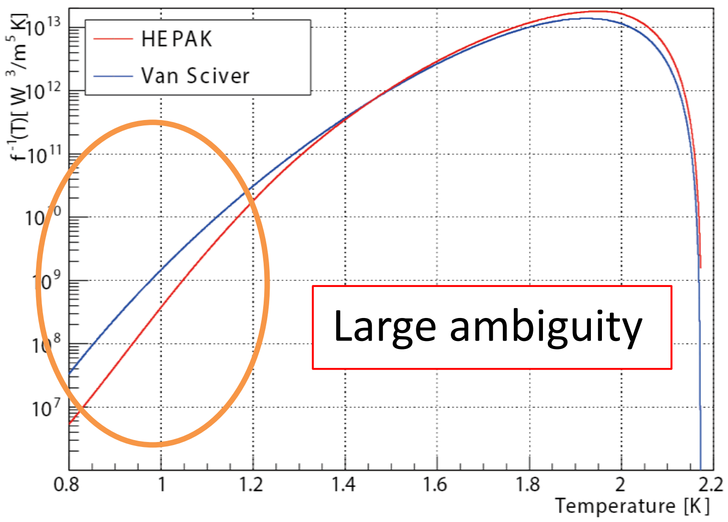
Temperature transfer in He-II

- below 1 K, heat transfer is not good because of low fraction of normal fluid which convey heat (two fluid model)
- Temperature difference in superfluid helium can be calculated numerically using following Gorter-Mellink equation

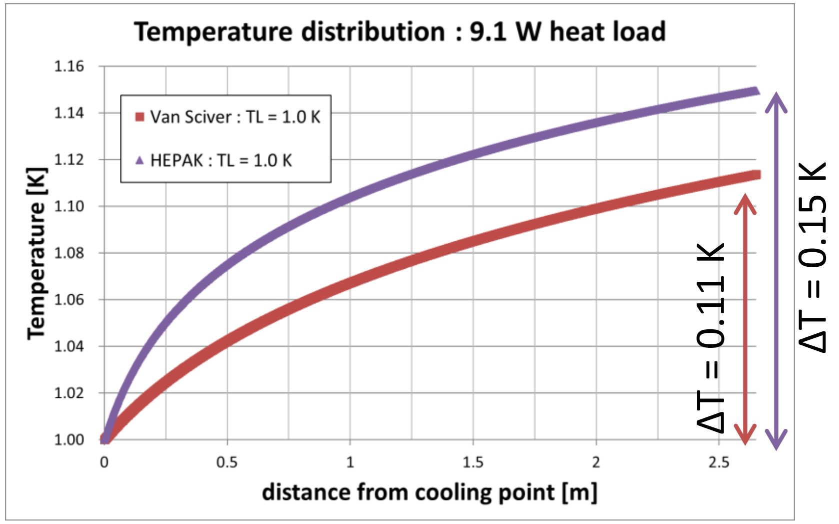


$$Q_{in} = \left(\frac{A^3}{L} \int_{T_L}^{T_H} f(T)^{-1} dT \right)^{1/3}$$

T_L : He-II temperature at the heat exchanger
T_H : He-II temperature at the UCN production volume
A : cross section of He-II diameter = 150 mm
L : distance of heat transfer L = 2.65 m

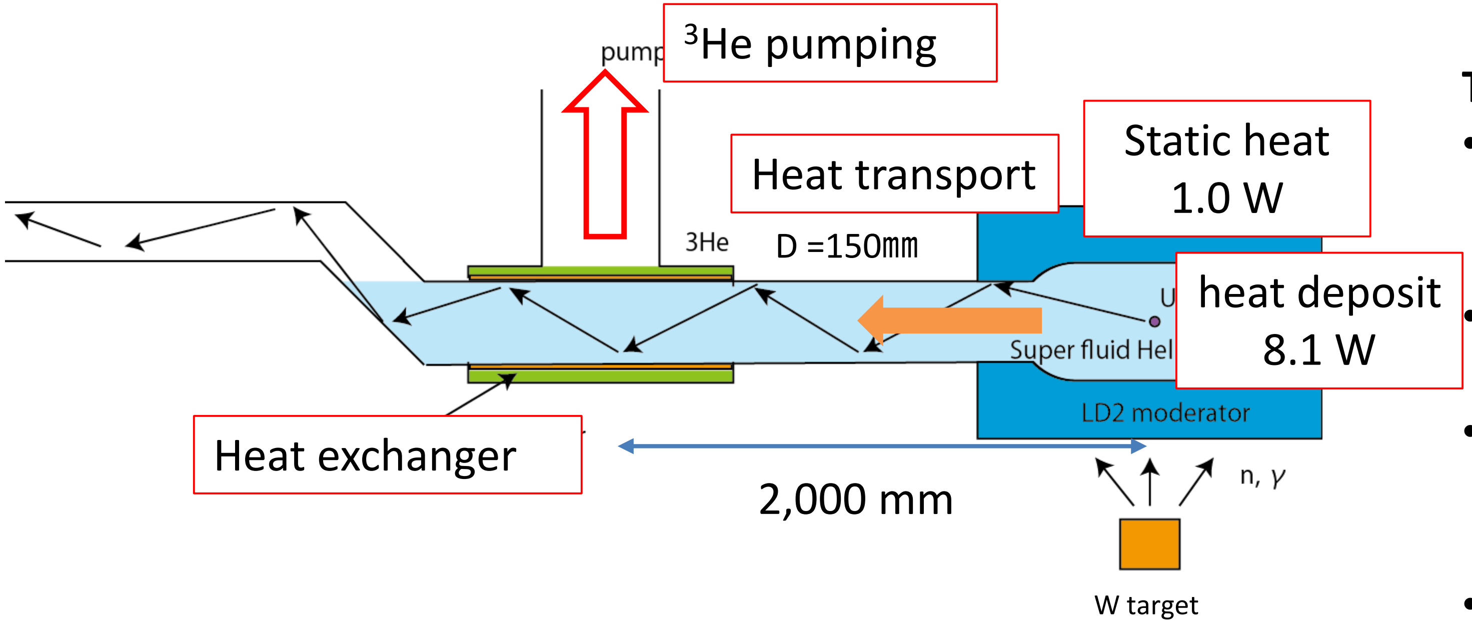


f(T) : Heat transfer function



Temperature distribution in UCN guide

Temperature distribution in our system



$$T_{prod} = T_{3He} + \Delta T_{3He\text{-}Ni} + \Delta T_{Cu\text{-}HeII} + \Delta T_{HeII}$$

Temperature distribution

- ^{3}He pot
  T_{3He} = 0.800 K
- Heat exchanger
  T_{HEX} = 0.878 K
- He-II at HEX
  $T_{He\text{-}II1}$ = 0.996 K
- He-II at UCN prod.
  $T_{He\text{-}II}$ = 1.15 K (HEPAK)
  = 1.11 K (Van Sciver)

Kapitza conductance
(KG = 40)

GM heat transfer

Current design meets our requirement
Temperature at the production volume < 1.15 K

Uncertainty and Risk

- Helium-3 cryostat
  - Liquid helium shortage

  Mitigation
    - Reduce beam current or duty cycle
    - Liquefier upgrade
      - Will discuss by C. Gibson

- HEX1
  - Kapitza conductance at low temperature is smaller than expected
  - Critical heat in narrow channel is smaller than our expectation
  - Helium-3 procurement

  Mitigation
    - Alternative HEX-1 design
    - HEX-1 can be replaceable

- GM heat transfer
  - GM heat transfer function is lower than expected

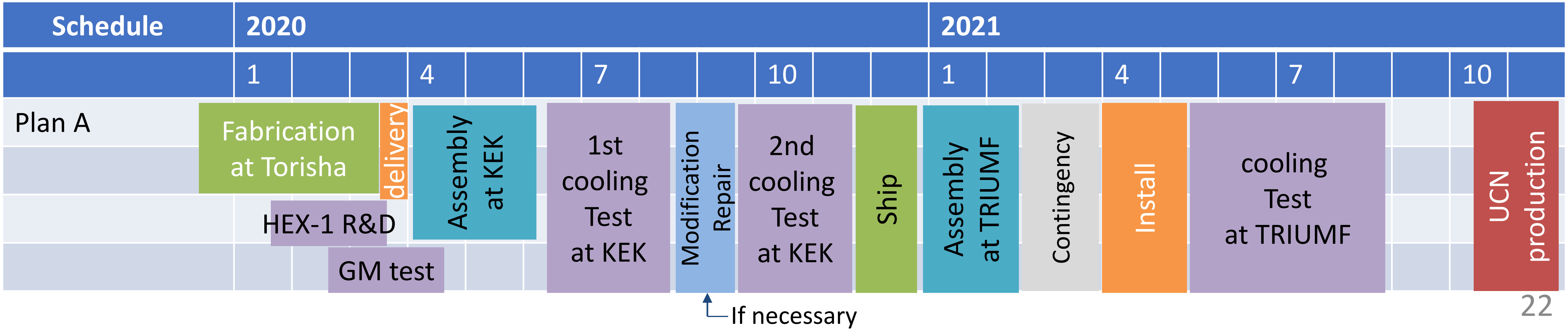
  Mitigation
    - Reduce beam current or duty cycle

Summary and Schedule

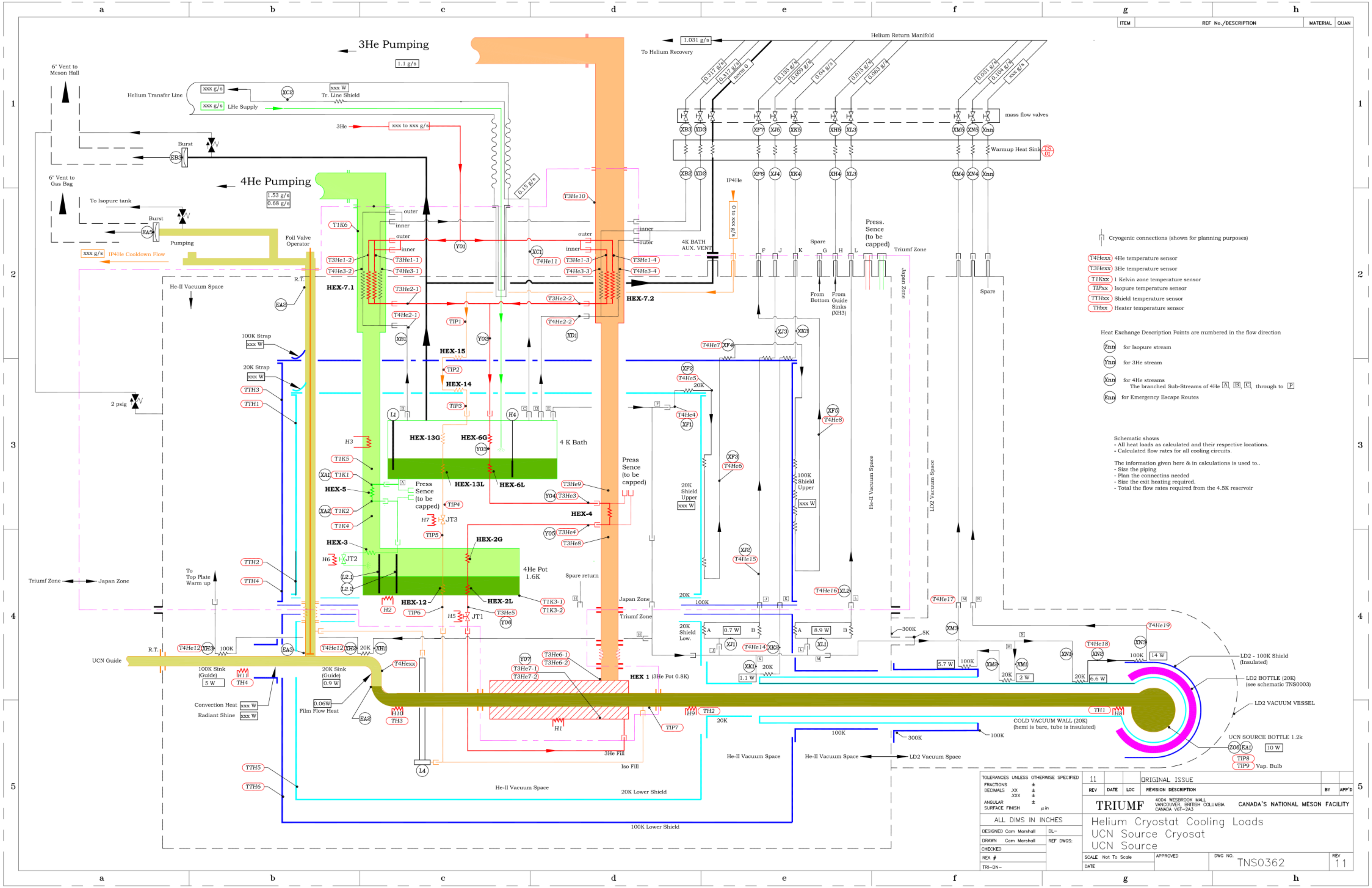
- Achieved Milestone
  - CDR in 2017
  - Cryogenic test
    - HEX-5, HEX-7
    - Kapitza conductance test
    - Superleak tightness check
- Current status
  - Constructing helium cryostat
  - HEX-1 R&D

Cooling test

- At KEK
  - Use ^{4}He instead of ^{3}He since there is no ^{3}He available
  - Performance check,
    - Cold & Superleak, static, heat load, mass flow and pressure drop, cooling power, etc.
- At TRIUMF
  - Cooling test with ^{3}He
  - Ultimate cooling power will be tested

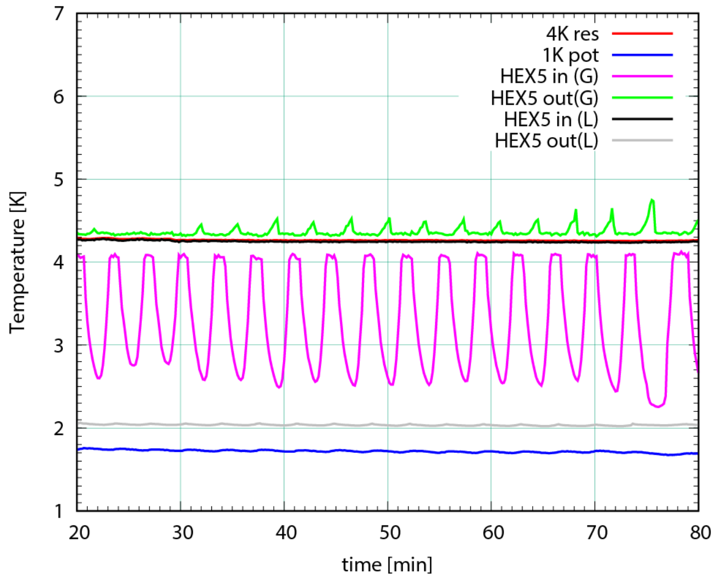


backup

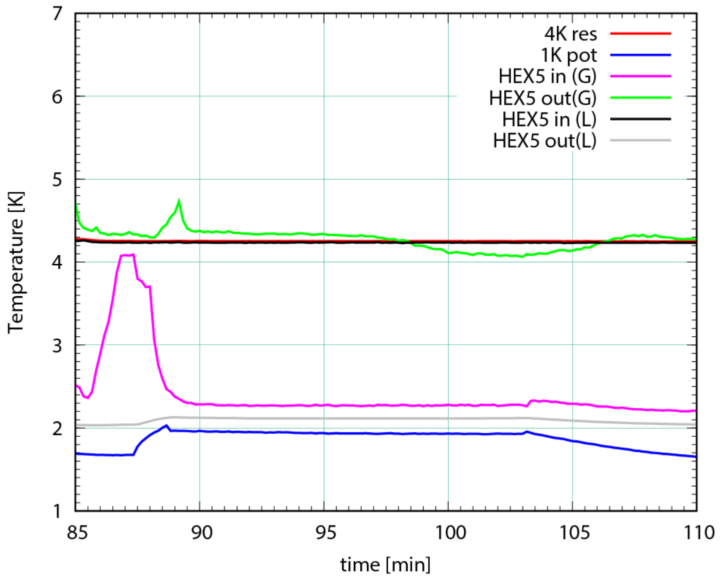

3He Pumping
1.1 g/s
4He Pumping
1.53 g/s
0.68 g/s
Helium Return Manifold
1.031 g/s
To Helium Recovery
mass flow valves
Warmup Heat Sink
6" Vent to Meson Hall
6" Vent to Gas Bag
To Isopure tank
Helium Transfer Line
LHe Supply
Tr. Line Shield
Burst
Pumping
Foil Valve Operator
IP4He Cooldown Flow
He-II Vacuum Space
100K Strap
20K Strap
2 psig
Triumf Zone
Japan Zone
HEX-7.1
HEX-7.2
HEX-15
HEX-14
HEX-13G
HEX-6G
HEX-13L
HEX-6L
HEX-5
HEX-4
HEX-3
HEX-2G
HEX-2L
HEX-12
HEX 1 (3He Pot 0.8K)
4 K Bath
4He Pot 1.6K
Press Sence (to be capped)
4K BATH AUX. VENT
Spare return
UCN Guide
100K Sink (Guide)
20K Sink (Guide)
Convection Heat
Radiant Shine
Film Flow Heat
3He Fill
Iso Fill
He-II Vacuum Space
20K Lower Shield
100K Lower Shield
LD2 Vacuum Space
LD2 - 100K Shield (Insulated)
LD2 BOTTLE (20K) (see schematic TNS0003)
LD2 VACUUM VESSEL
COLD VACUUM WALL (20K) (hemi is bare, tube is insulated)
UCN SOURCE BOTTLE 1.2k
Vap. Bulb
Cryogenic connections (shown for planning purposes)
T4Hexx 4He temperature sensor
T3Hexx 3He temperature sensor
T1Kxx 1 Kelvin zone temperature sensor
TIPxx Isopure temperature sensor
TTHxx Shield temperature sensor
THxx Heater temperature sensor
Heat Exchange Description Points are numbered in the flow direction
Znn for Isopure stream
Ynn for 3He stream
Xnn for 4He streams
The branched Sub-Streams of 4He A, B, C, through to P
Enn for Emergency Escape Routes
Schematic shows
- All heat loads as calculated and their respective locations.
- Calculated flow rates for all cooling circuits.
The information given here & in calculations is used to..
- Size the piping
- Plan the connetins needed
- Size the exit heating required.
- Total the flow rates required from the 4.5K reservoir
ITEM
REF No./DESCRIPTION
MATERIAL
QUAN
ORIGINAL ISSUE
TRIUMF
4004 WESBROOK MALL VANCOUVER, BRITISH COLUMBIA CANADA V6T-2A3
CANADA'S NATIONAL MESON FACILITY
ALL DIMS IN INCHES
Helium Cryostat Cooling Loads
UCN Source Cryosat
UCN Source
DESIGNED Cam Marshall
DRAWN Cam Marshall
SCALE Not To Scale
DWG NO. TNS0362
REV 11

H

- The thermal oscillation was occurred when the mass flow is 0.35 g/sec
  - It was not stable



Mass flow of 0.35 g/sec

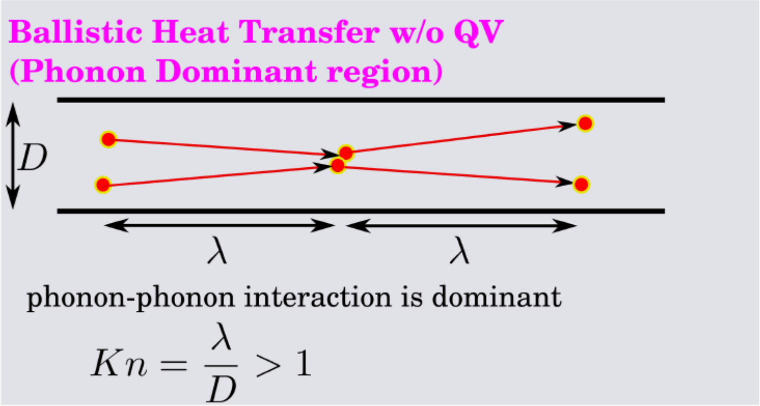


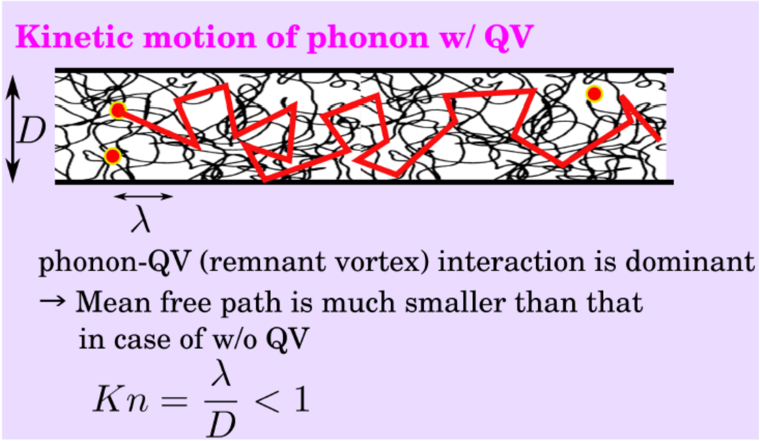
Mass flow of 0.58 g/sec

		Design value	Experiment	
mass flow rate	g/sec	1.3	0.35	0.58
4He (L) inlet	K	4.3	4.25 / 4.66	4.23 / 4.5
4He (L) outlet	K	2.5	2.03 / 2.45	2.11 / 2.45
inlet FIN	K	2.5	2.213-4.12	2.27
outlet FIN	K	3.4	4.36	4.27
pressure drop (Gas)	Pa	< 100	7.78 * / 5	6.62 / 12
4K res	K	4.2	4.26	4.25
1 Kpot	K	1.6	1.72	1.93
			oscillation	no oscillation

Data / Simulation

3. Heat transport in superfluid helium
10 W @ ∼ 1.0 K





- Flow pattern
  - Normal fluid component is dilute around 1.0 K region
    - Knudsen number $K_n = \frac{\lambda}{D_{UCN}} < 1$,

      $\lambda \sim 0.5\ mm,\ D_{UCN} = 150\ mm$

      continuum flow
  - Superfluid laminar or turbulent ?
    - Reynolds number of normal fluid component

      $$R_{e_n} = \frac{|v_n - v_s| D_{UCN}}{v_n} \sim 10^6 \gg 1200 \sim 2600$$

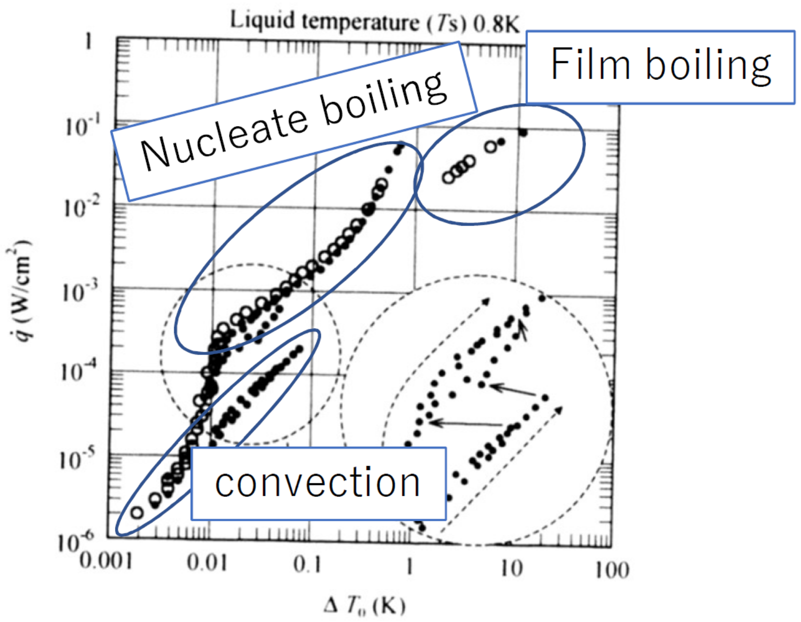
      superfluid turbulent

Gorter-Mellink turbulent model used to evaluate heat transport

Possible problem about short (no) fin HEX1

- Boiling curve
  - Free convection (no boiling)
  - Nucleate boiling
    - Maximum heat transfer
  - Film boiling
- Heat flux

fin length	Heat flux [W/cm^2]
2mm	1.2 x 10^{-3}
1mm	1.8 x 10^{-3}
No fin	3.7 x 10^{-3}



Boing curve of helium-3 at 0.8 K

  - Heat flux of no fin design is still lower than the critical heat flux of 2 x 10^{-2} W/cm^2 for the transition from nucleate boiling to film boiling
  - However, critical heat in narrow channel might be different
    - Will be measured by the HEX1 test piece using helium-4