Design and Simulation Studies for IR Cryogenics

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Purpose

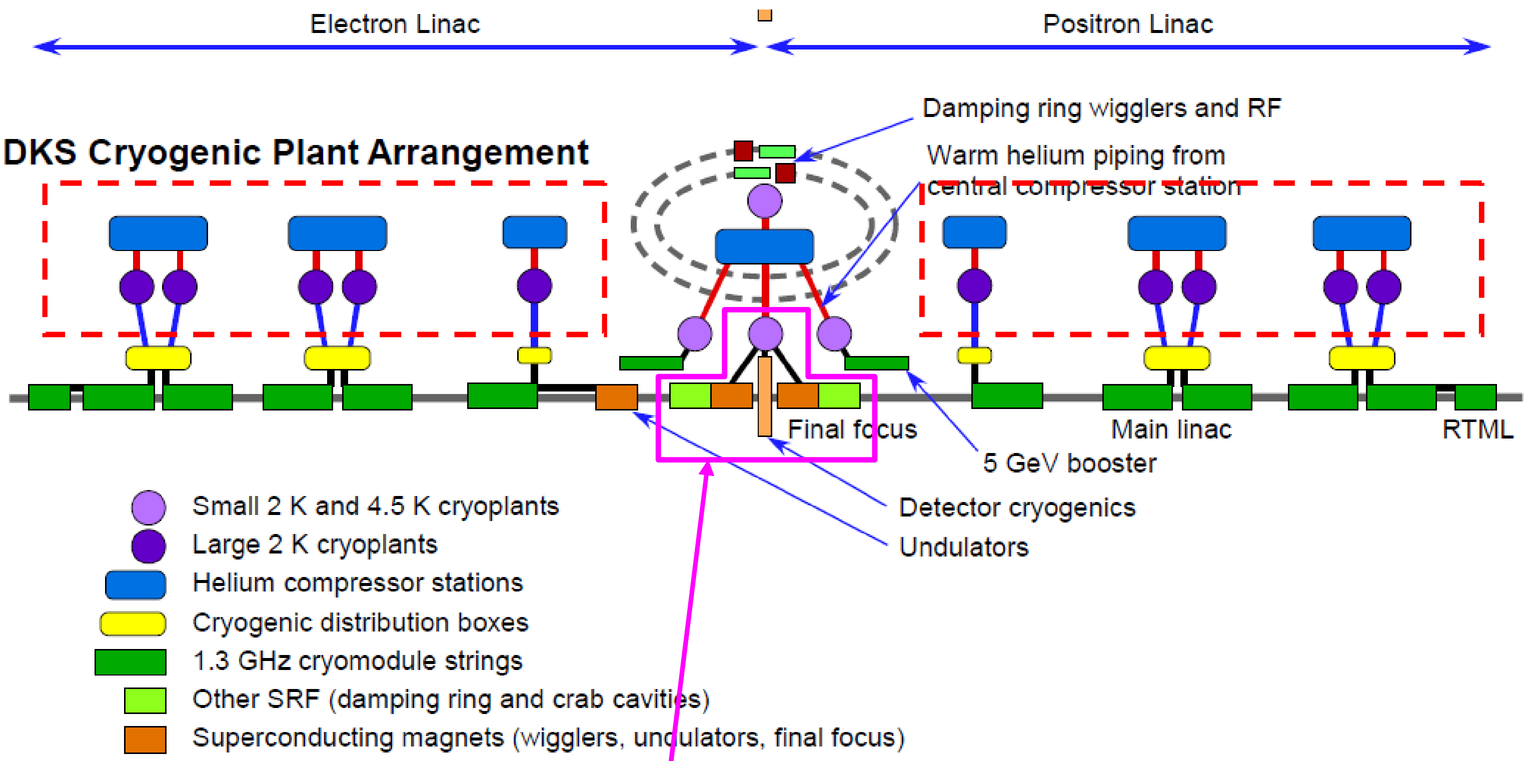
- Design and numerical studies on IR cryogenics
  (detector, final focus, crab cavity)

Following 3 kinds of simulation studies should be performed to establish optimal design of IR cryogenics.

1. Two phase flow simulation for large superconducting solenoid including thermo fluid behavior during solenoid quench.
2. Superfluid simulation for QD0 cooling including magnet quench.
3. Dynamic Simulation on 2K-4K combined cryogenic system.

Configuration of Cryogenic System for ILC

- Four small cryo-plants for detector, final focus, crab cavity, damping ring.
- 10 large cryo-plants for electron positron Linac



- Purpose is to establish optimal configuration for IR cryogenics （Detector,　Final focus, ・・）
- Cooled object is detectors, QD0, QF1 and CC. (cooled with various cooling method)

Cooling method of superconducting equipment

Three kinds of cooling methods

Cooled object	Cooling method	Installation location
ILD (superconducting solenoid)	Two phase flow of 4.5 K He (forced flow or thermo-siphon)	Platform (pushpull)
SiD (superconducting solenoid)	Two phase flow of 4.5 K He (forced flow or thermo-siphon)	Platform (pushpull)
QD0 (final focus)	Pressurized He II (1.8 K)	Inside detector (pushpull)
QF1 (final focus)	Pressurized He II (1.8 K)	Accelerator tunnel
CC (crab cavity)	Saturated He II (1.8 K)	Accelerator tunnel

These superconducting equipment are installed in and near the experimental hall

Strategy: Refrigerators should be installed in the exp hall

Question: Number of cold box, Installation location, configuration of 2K & 4K refrigerator.

Simulation Studies

1. **Superconducting solenoid cooling**

   Flow simulation of two phase flow cooling

   in the case of forced convection cooling
   in the case of thermo siphon cooling
   to find the flow condition such that flow instability doesn't occur.
   → flow instability induce mechanical vibration due to the void fraction fluctuation.
   → flow instability induce inhomogeneous cooling of superconducting magnet.

   Quench simulation

   to find thermo fluid behavior during quench
   → pressure shock
   → safety system estimation
   → quench recovery system

2. **QD0, QF1, CC cooling**

   Flow simulation of superfluid helium

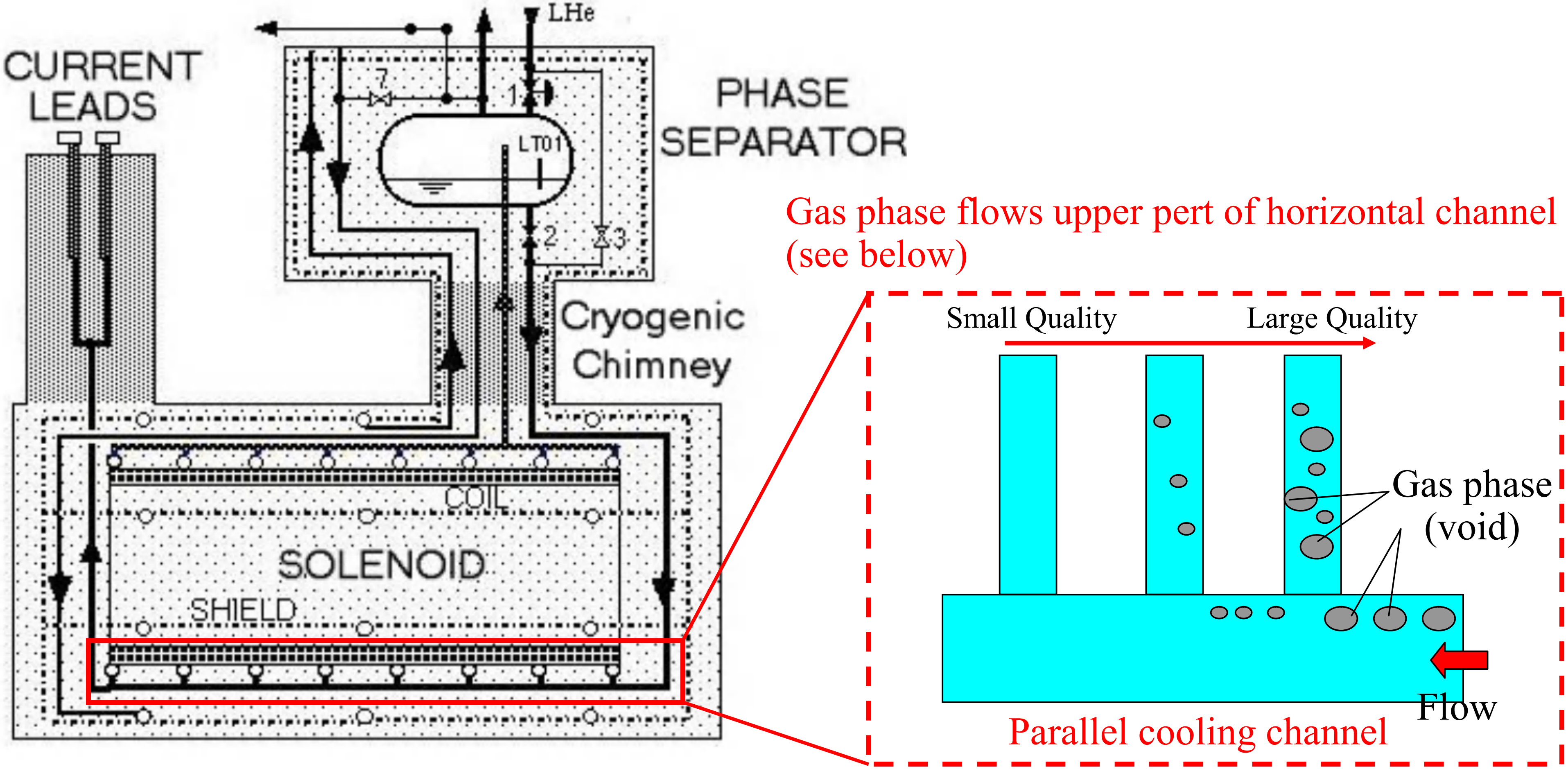
   Superfluid is not perfect fluid,
   Thermo fluid behavior strongly depends on dimension and shape of cooling channel.
   → Optimal shape and dimension of cooling channel.

3. **Optimization of 2K – 4K combined cryogenic system**

   Dynamic simulation of various operation mode. (steady, quench, precooling mode, etc)

Solenoid Cooling
(Flow simulation of gas-liquid two phase flow)

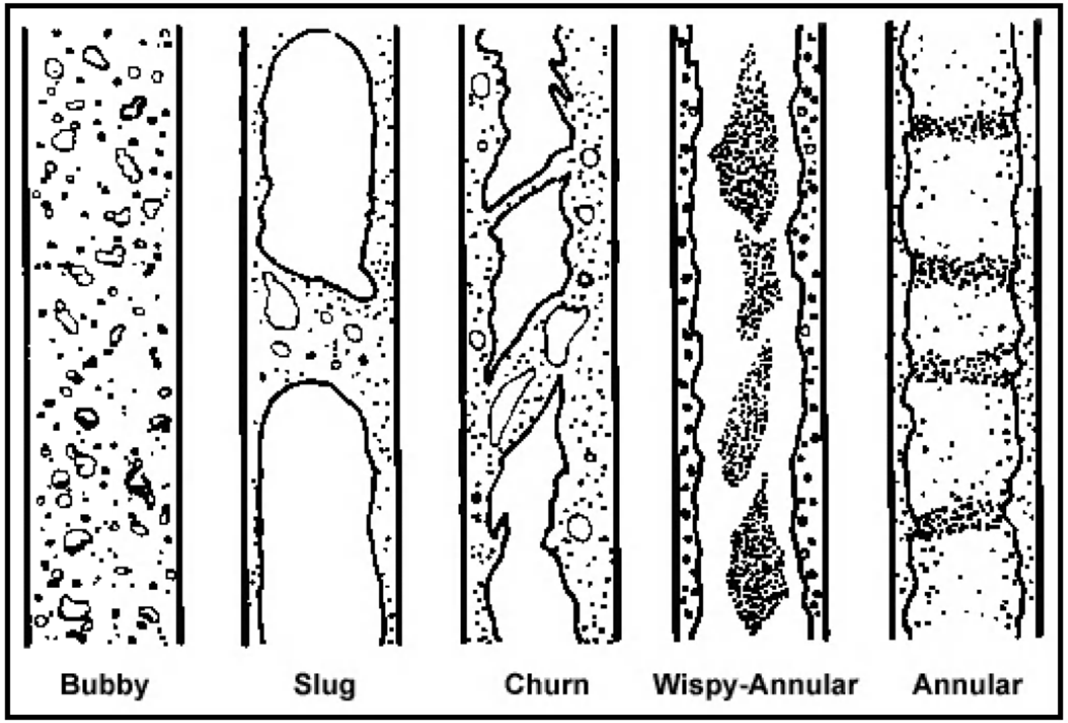
There are parallel cooling channels in the detector cryostat such as CMS cryogenic design.
In this case, flow instability sometimes occurs.
→ flow instability induce mechanical vibration and inhomogeneous cooling
Whether flow instability occurs or not strongly depends on cooling channel shape and flow condition.
Flow instability induce inhomogeneous cooling of superconducting magnet.

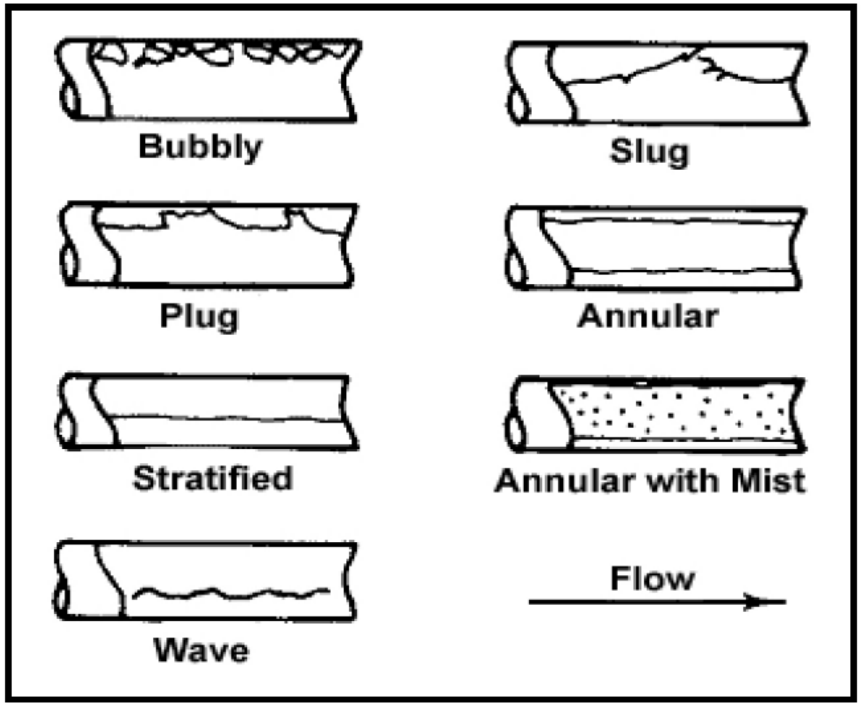


Gas phase flows upper pert of horizontal channel (see below)

Purpose is to clarify cooling channel information and flow condition such that the instability does not occur.

Two Phase Flow Pattern
in horizontal and vertical channel





Flow patterns of Vertical channel

Flow patterns of horizontal channel

We are developing the numerical simulation code by employing gas-liquid two phase model.

Gas-Liquid Two Fluid Model

We are developing the numerical simulation code by employing gas-liquid two fluid model.

- Mass conservation of gas and liquid phase

$$\frac{\partial}{\partial t}(\alpha\rho_g) + \nabla\cdot(\alpha\rho_g\mathbf{u}_g) = \Gamma_{gi}$$

$$\frac{\partial}{\partial t}[(1-\alpha)\rho_l)] + \nabla\cdot[(1-\alpha)\rho_l\mathbf{u}_l] = \Gamma_{li}, \qquad \Gamma_{gi} + \Gamma_{li} = 0$$

- Momentum conservation of gas and liquid phase

$$\frac{\partial}{\partial t}(\alpha\rho_g\mathbf{u}_g) + \nabla\cdot(\alpha\rho_g\mathbf{u}_g\mathbf{u}_g) = -\alpha\nabla p - \mathbf{F}_{wg} + \alpha\rho_g\mathbf{g} - \mathbf{F}_{lg} - \mathbf{F}_{\mathrm{VM}}$$

$$\frac{\partial}{\partial t}[(1-\alpha)\rho_l\mathbf{u}_l] + \nabla\cdot[(1-\alpha)\rho_l\mathbf{u}_l\mathbf{u}_l] = -(1-\alpha)\nabla p - \mathbf{F}_{wl} + (1-\alpha)\rho_l\mathbf{g} + \mathbf{F}_{lg} + \mathbf{F}_{\mathrm{VM}}$$

- Energy conservation of gas and liquid phase

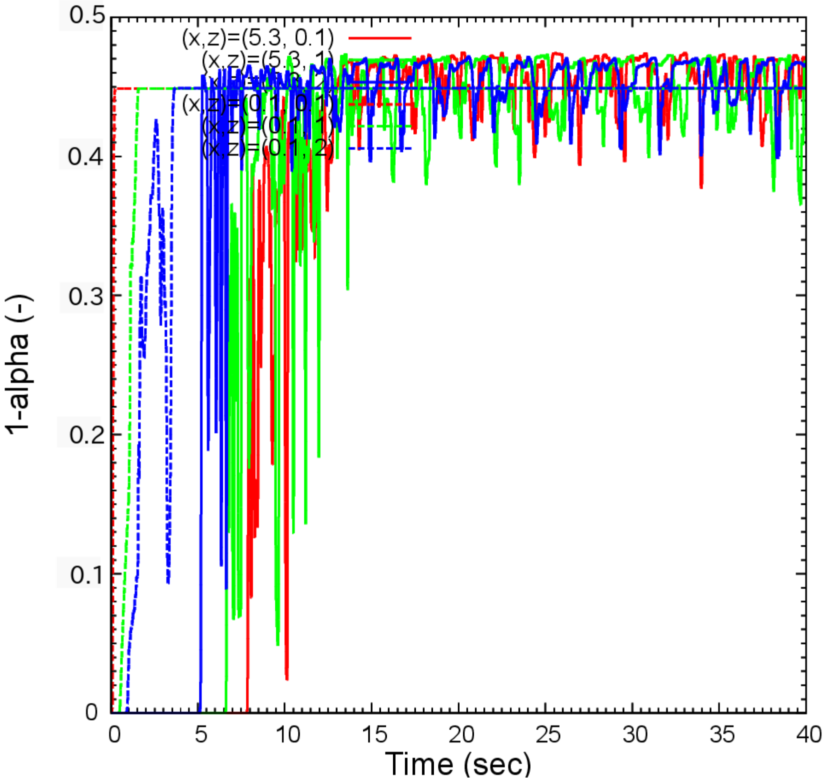
$$\frac{\partial}{\partial t}(\alpha\rho_g e_g) + \nabla\cdot(\alpha\rho_g e_g\mathbf{u}_g) = -p\nabla\cdot(\alpha\mathbf{u}_g) - p\frac{\partial\alpha}{\partial t} + Q_{wg} + Q_i - Q_{tg}$$

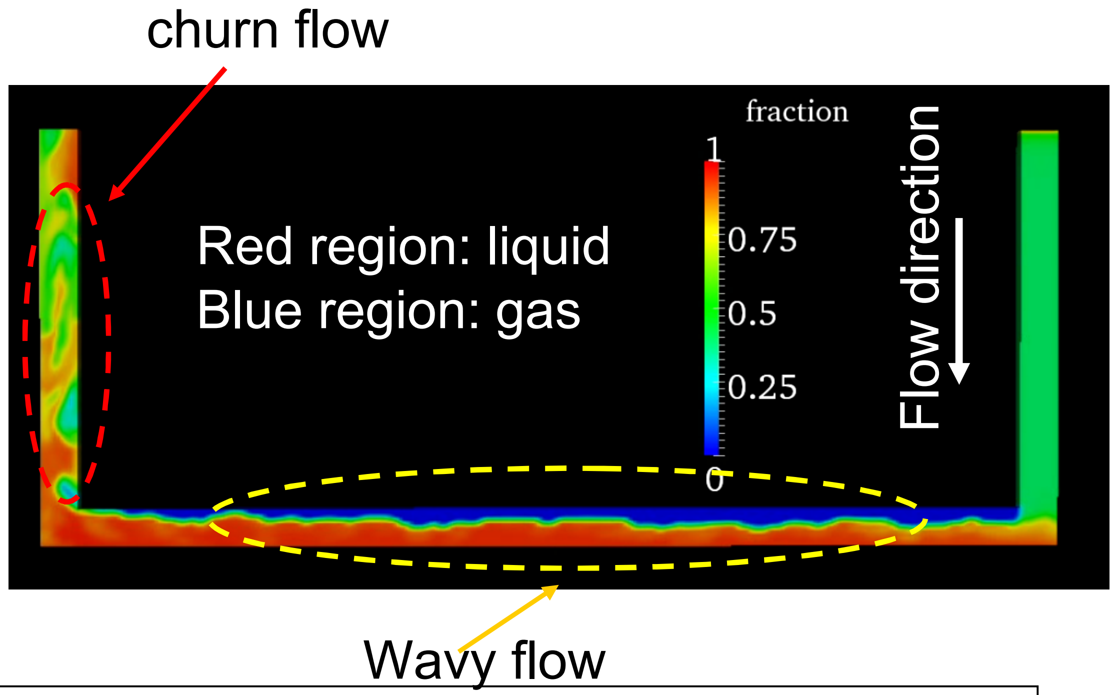
$$\frac{\partial}{\partial t}[(1-\alpha)\rho_l e_l] + \nabla\cdot[(1-\alpha)\rho_l e_l\mathbf{u}_l] = -p\nabla\cdot[(1-\alpha)\mathbf{u}_l] + p\frac{\partial\alpha}{\partial t} + Q_{wl} - Q_i - Q_{tl}$$

In this presentation, we focus on two phase forced convection cooling .

Test RUN 1
(simple case with vertical & horizontal cannel @ forced flow)

Test code to analyze two phase forced flow of helium is now developed in the simple system with horizontal and vertical cooling channel.





Red region: liquid
Blue region: gas

Flow Pattern in the two phase forced flow helium

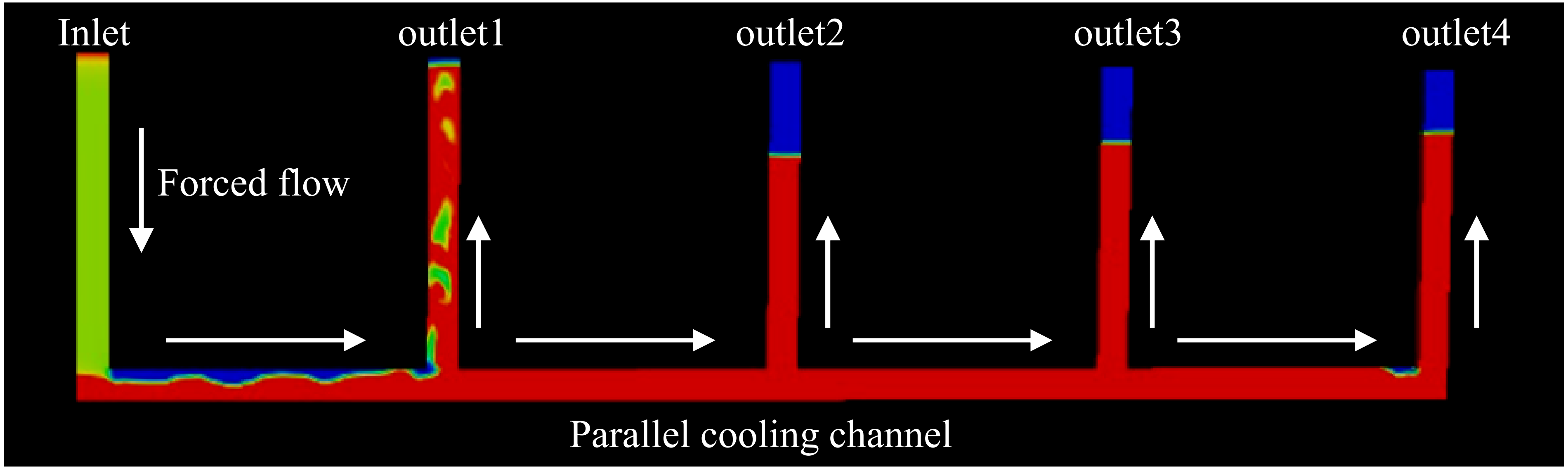
Wavy flow occurs in the **horizontal channel.**
Churn flow occurs in the **vertical channel.**

Void fraction fluctuation exists in the cooling channel.
We will investigate the relation between vibration and void fraction fluctuation.

Test RUN 2
(Parallel cooling channel system @ forced flow)

Mass flow heterogeneity in vertical parallel cooling channels (outlet1,2,3,4) has the possibility to occurs because buoyancy is acted on gas phase which exists in the horizontal channel.

White arrows indicate flow direction



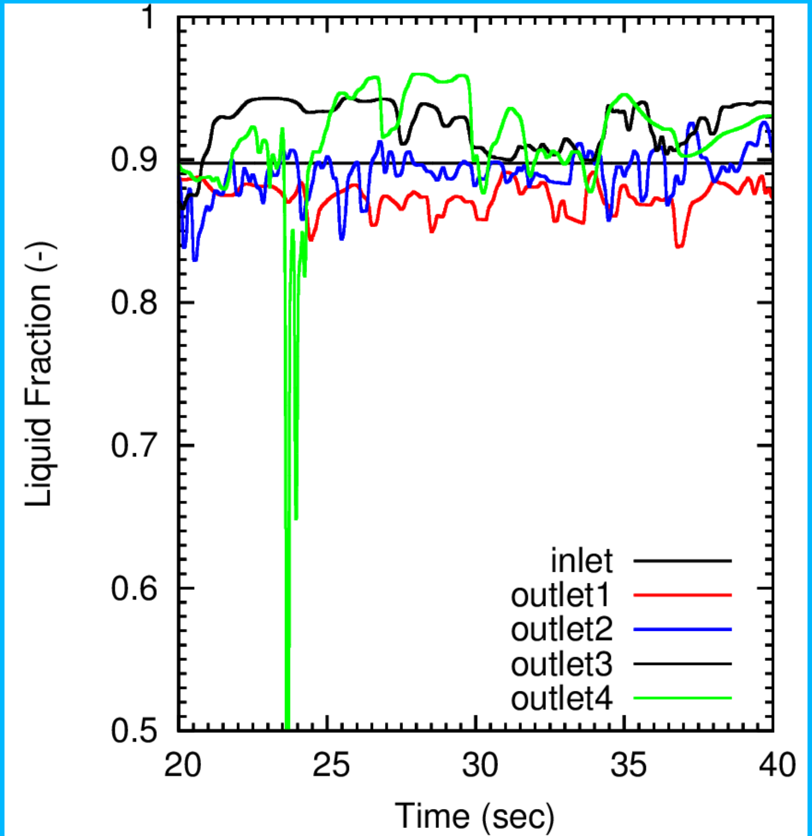
In this studies, we investigate the relation between void fraction and mass flow heterogeneity.

Case1) void fraction = 0 ~ 0.1
Case2) void fraction = 0.3 ~ 0.5
* Other flow conditions such as mass flow rate are completely same between two cases.

Void fraction means the fraction of the channel cross-sectional area that is occupied by the gas phase.

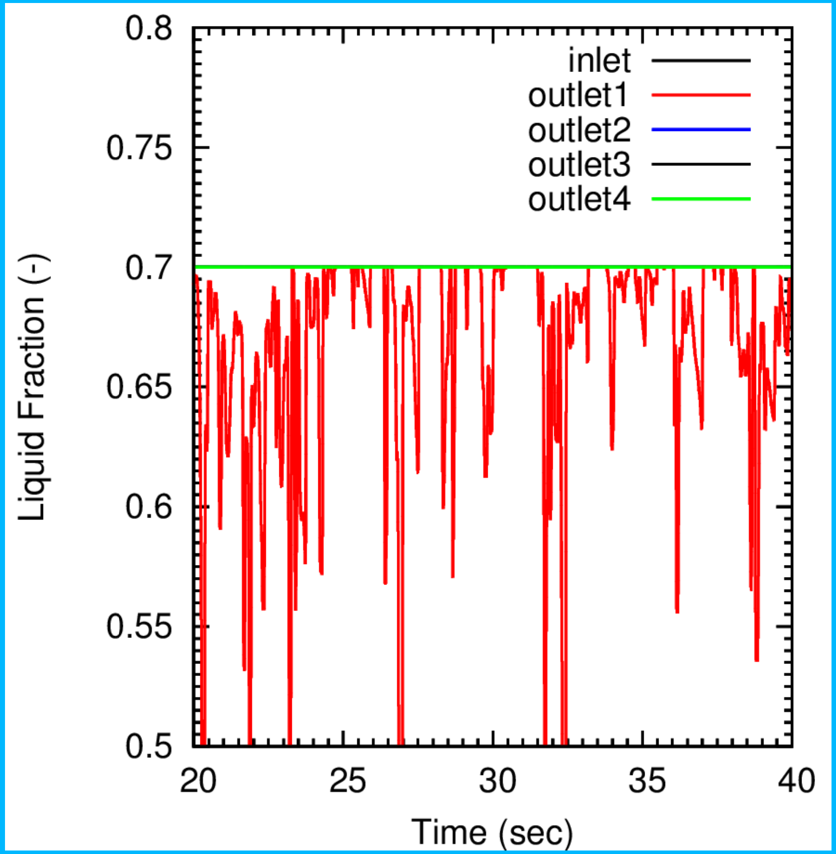
Test RUN 2
(Parallel cooling channel system @ forced flow)

In case of **void fraction=0~0.1**
(liquid fraction=1~0.9)



Mass flow heterogeneity does not occur.

In case of **void fraction=0.3~0.5**
(liquid fraction=0.7 ~ 0.5)

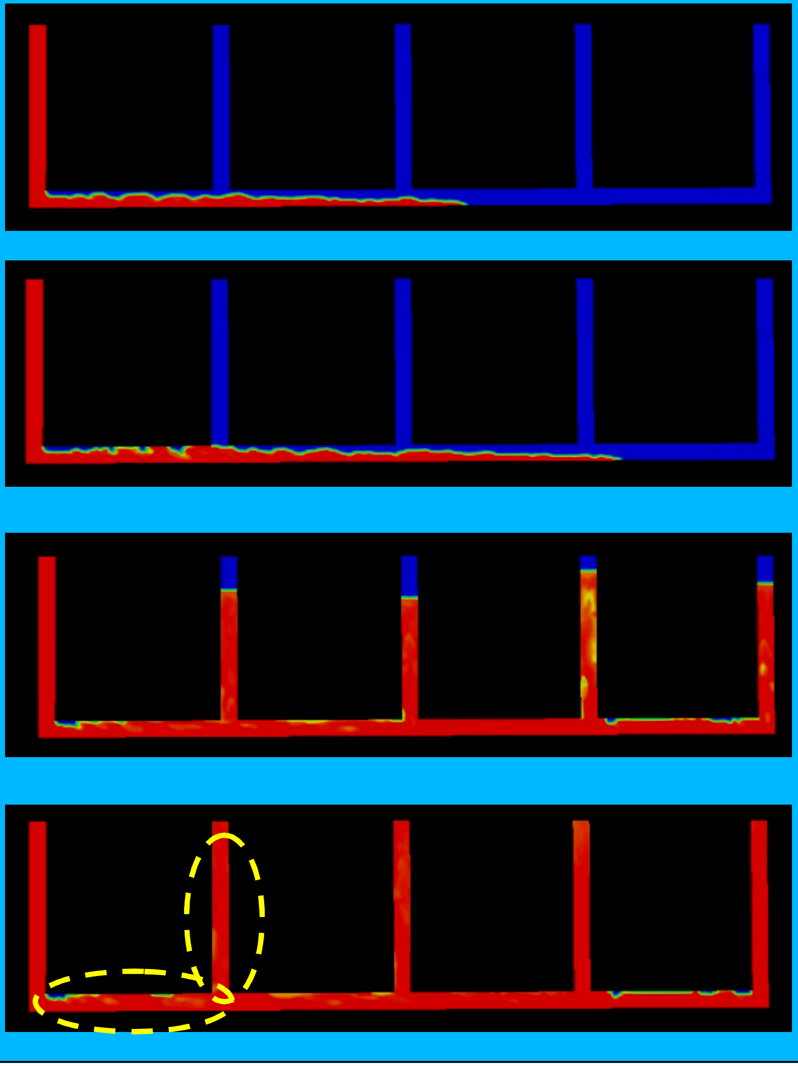


Mass flow heterogeneity occurs in the outlet1

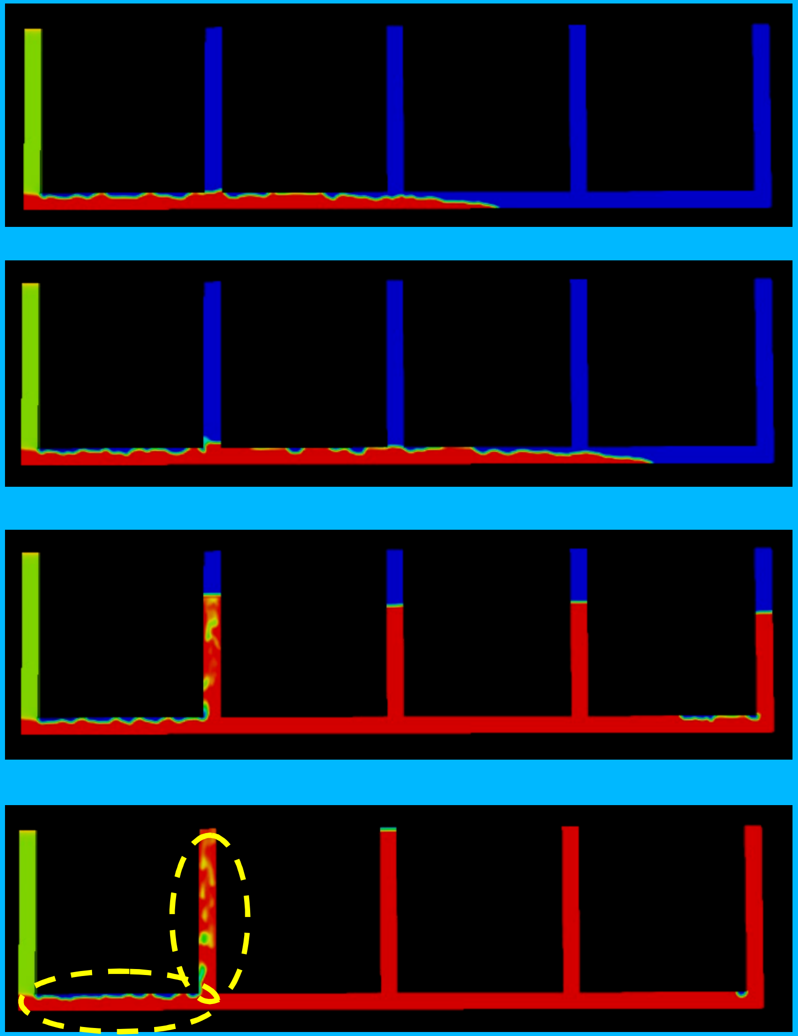
Cooling efficiency in the outlet1 channel decreases in comparison with other cooling channels due to the existence of mass flow homogeneity in the cooling channel (outlet1).

Test RUN 2
(Parallel cooling channel system @ forced flow)

In case of **void fraction=0~0.1**
(liquid fraction=1~0.9)



In case of **void fraction=0.3~0.5**
(liquid fraction=0.7 ~ 0.5)



Red region : liquid phase (same as void fraction = 0) , blue region : gas phase (same as void fraction=1)

Summary on stability conditions of two phase flow cooling (incompletion)

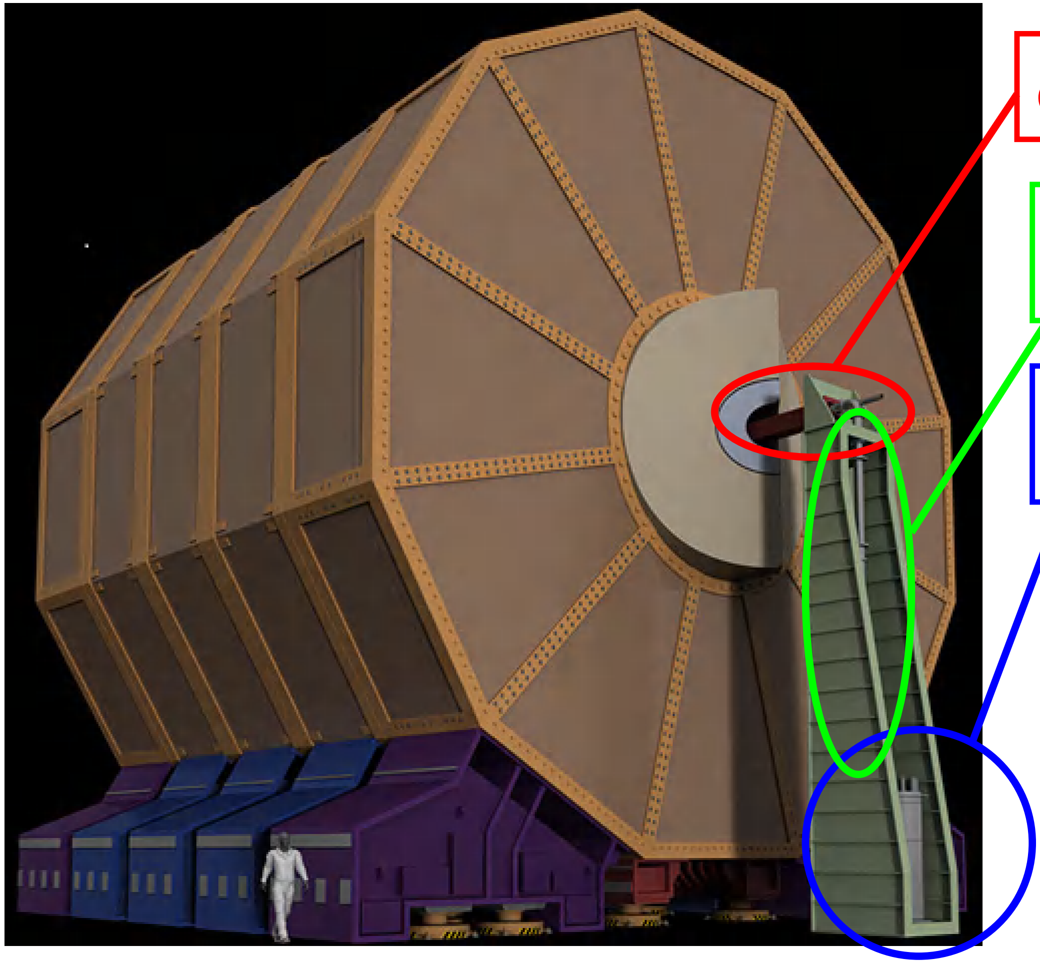
- In the case of forced convection and parallel channel system

Parameter	flow instability	condition
large void fraction	mass flow homogeneity	void fraction > 0.3
large mass flow rate (large flow velocity)	****	****
*****	****	****

- In the case of forced convection and **
- In the case of thermo-siphon and **
- In the case of thermo-siphon and **

We will clarify stability conditions of two phase flow cooling in various kinds of situation in the case of both forced convection and thermo-siphon cooling.

Investigation on fluid behavior of QD0, QF1
(Flow simulation on superfluid helium)



QD0

TRT for superfluid helium
Between QD0 and 2K refrigerator

2K refrigerator for QD0
Heat exchanger to obtain He II is installed

The distance between 2K and QD0 (TRT length) is about 4m

Due to the dissipation process in the superfluid turbulence

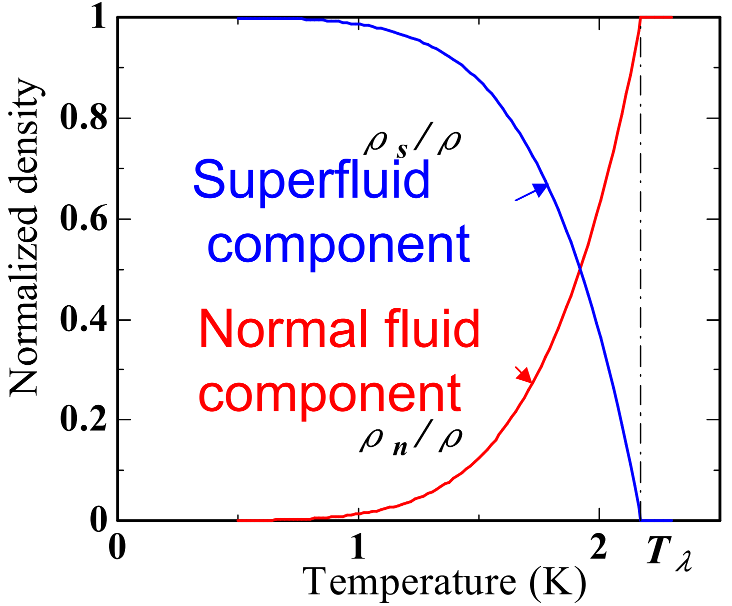
Temperature gradient is generated because of the existence of the heat load from TRT etc..
The norm of temperature gradient strongly depends on the size and shape of cooling channel.

Therefore we have to investigate and confirm the design validity of final focus cryogenic system.

Practical Superfluid Two fluid Model

Behavior of superfluid helium can be described by Landau two fluid model with Gorter-Mellink superfluid turbulent model.

Concept of Landau two fluid model



Mass conservation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho_{(s)}u_{(s)j} + \rho_{(n)}u_{(n)j}\right) = 0$$

Total fluid momentum equation

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial x_j}\left(\rho_{(s)}u_{(s)i}u_{(s)j} + \rho_{(n)}u_{(n)i}u_{(n)j} - T_{ij}\right) = \rho f_i$$

Superfluid momentum equation

$$\frac{\partial u_{(s)i}}{\partial t} + u_{(s)j}\frac{\partial u_{(s)i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + s\frac{\partial T}{\partial x_i} + \frac{\rho_n}{2\rho}\frac{\partial}{\partial x_i}\left|u_{(n)j} - u_{(s)j}\right|^2 - A\rho_{(n)}\left|u_{(n)j} - u_{(s)j}\right|^2\left(u_{(n)i} - u_{(s)i}\right)$$

Energy conservation

$$\frac{\partial}{\partial t}\left(\rho s\right) + \frac{\partial}{\partial x_j}\left(\rho_{(n)} s u_{(n)j}\right) = \frac{A\rho_{(n)}\rho_{(s)}\left|u_{(n)j} - u_{(s)j}\right|^4}{T}$$

Constitutive equation

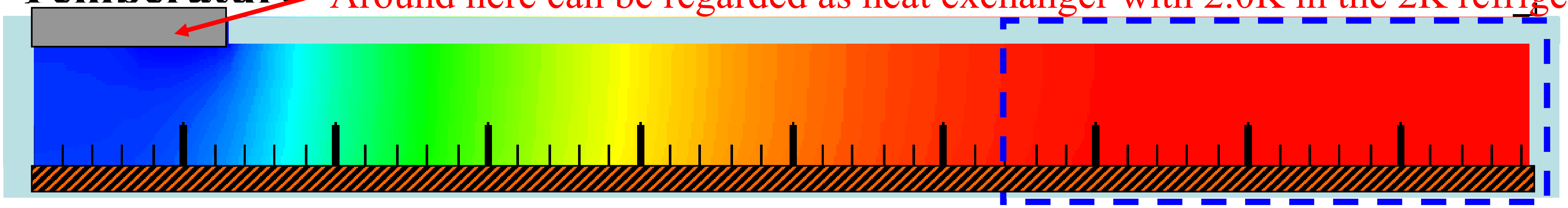
$$T_{ij} = -p\delta_{ij} + 2\mu\left(D_{ij} - \frac{1}{3}\delta_{ij}\frac{\partial u_{(n)k}}{\partial x_k}\right), \qquad D_{ij} = \frac{1}{2}\left(\frac{\partial u_{(n)i}}{\partial x_j} + \frac{\partial u_{(n)j}}{\partial x_i}\right)$$

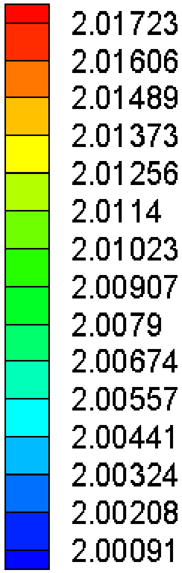
Numerical Results example

▨ means heat load from TRT

Temperature

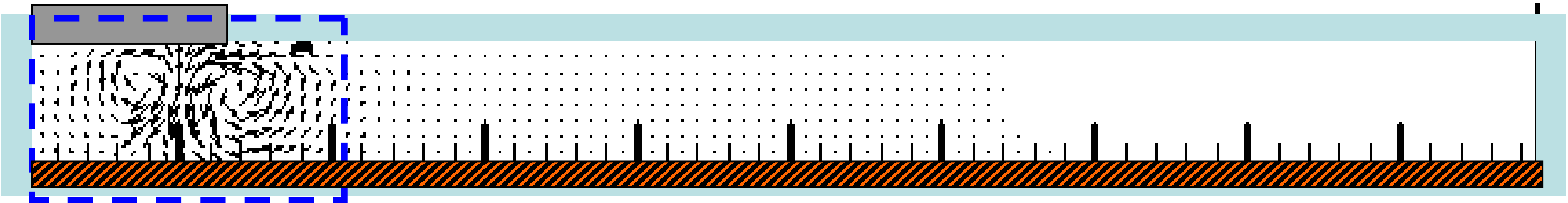
Around here can be regarded as heat exchanger with 2.0K in the 2K refrigerator.





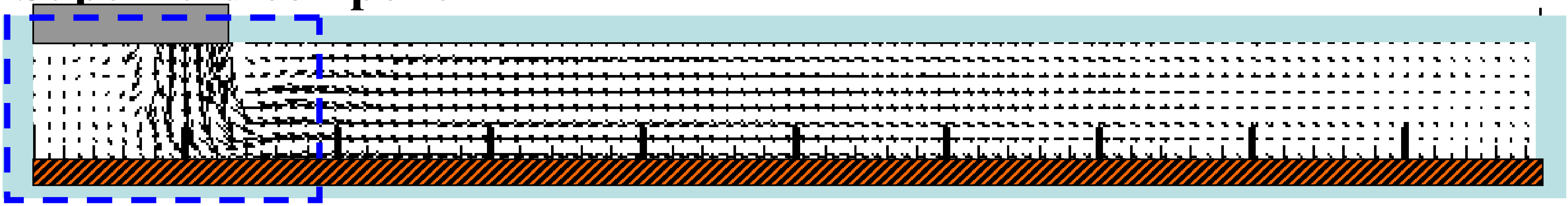
Far from the heat exchanger, superfluid temperature becomes large due to heat load of TRT

Total fluid

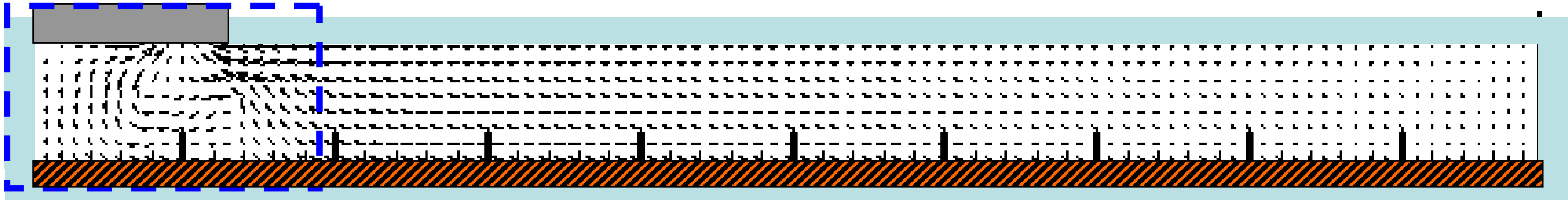


Total fluid is almost static except near the heat exchanger.

Superfluid component



Normal fluid component

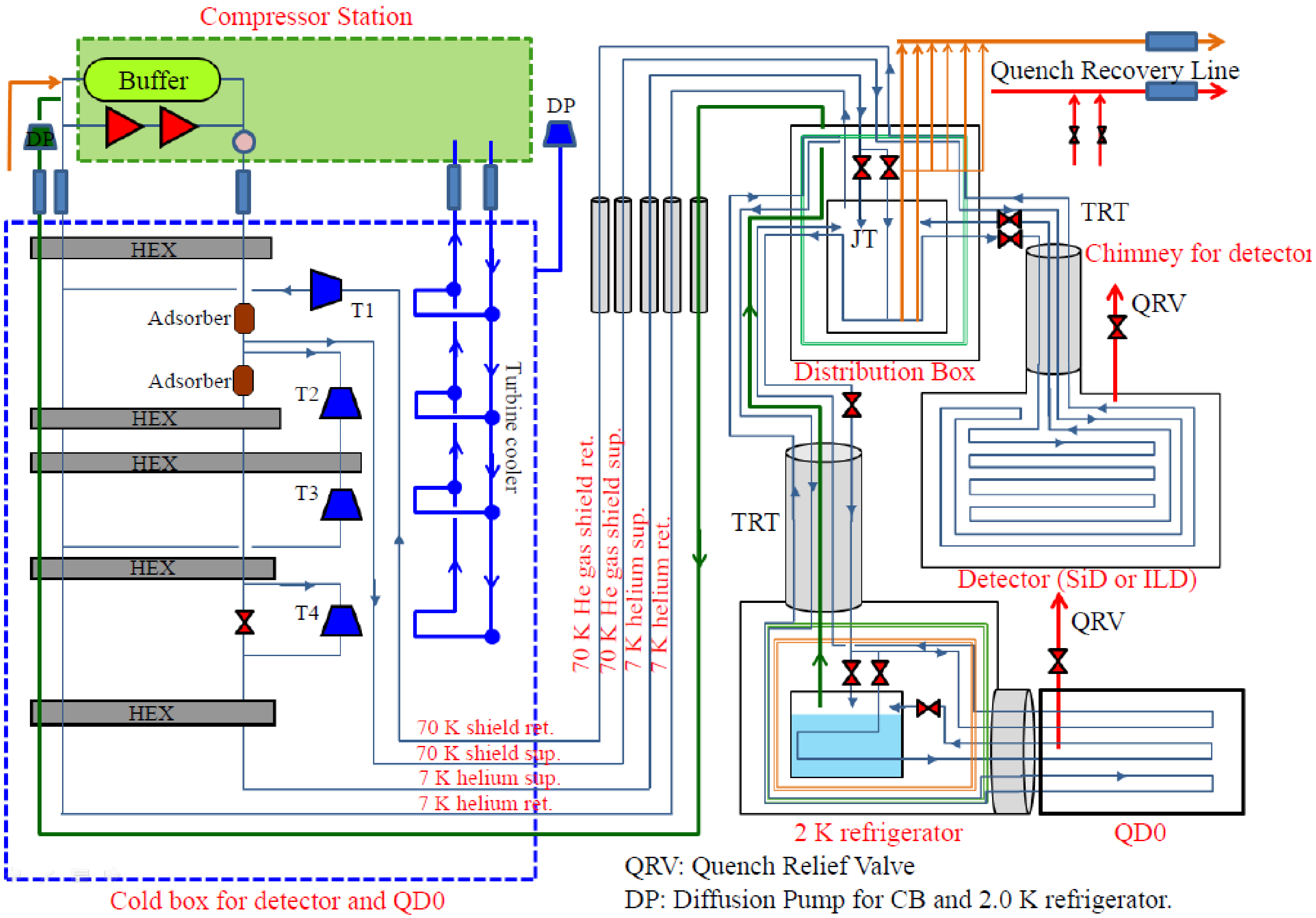


The macroscopic flow as to super and normal fluid component exist near the heat exchanger.

Purpose is to clarify the system condition such that lambda transition does not occur.

Dynamic Simulation for IR cryogenics

- Dynamic simulation will be done to find optimal flow diagram of 2K-4K combined system.



QRV: Quench Relief Valve
DP: Diffusion Pump for CB and 2.0 K refrigerator.
T1 - T4: Expansion Turbine (T4 :Supercritical Turbine)

SUMMARY

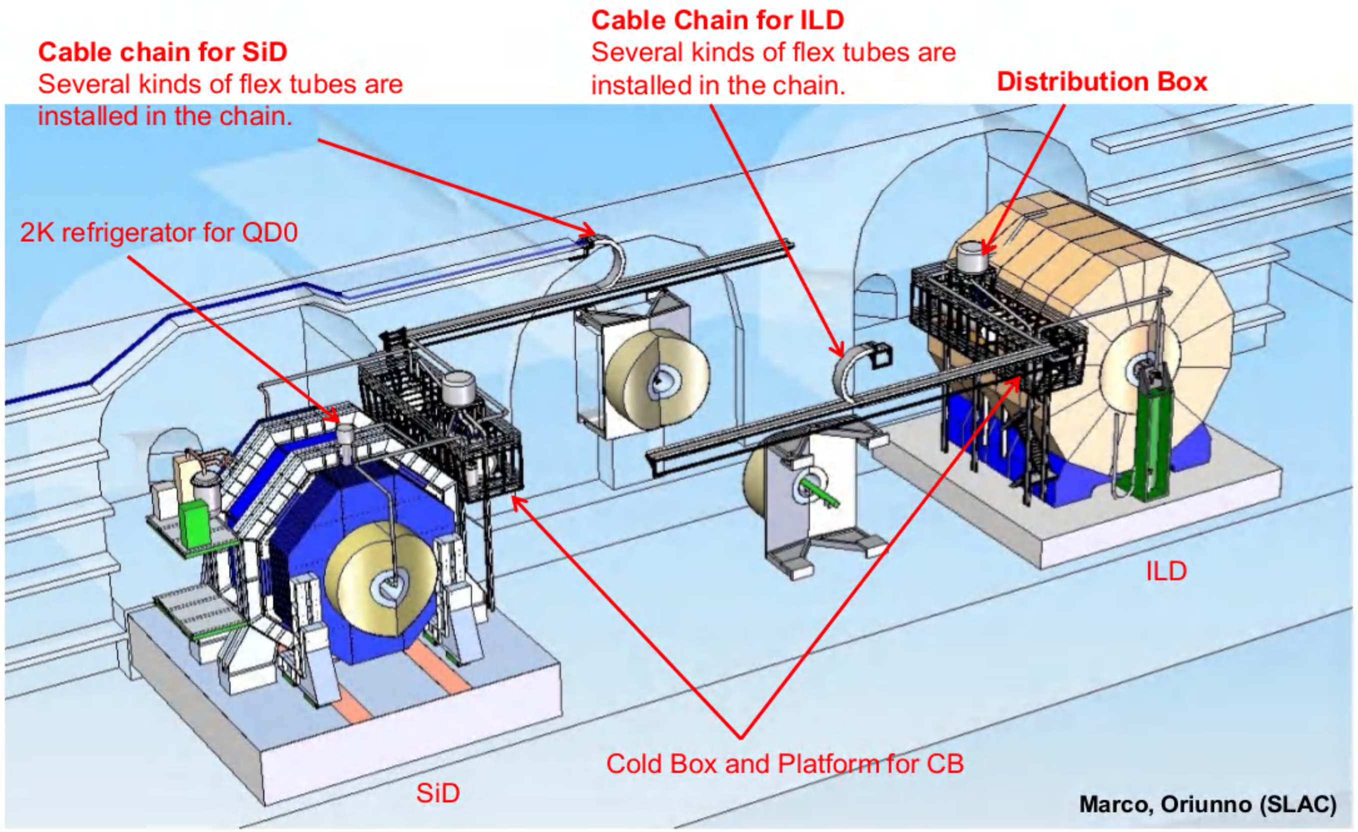
Now we are performing 3 kinds of simulation studies to establish optimal design of IR cryogenics.

1. To establish the detector cooling design, various conditions (mass flow, void fraction, geometry of channel, etc.) such that flow instability does not occur in the cooling channels are partially clarified in case of two phase forced convection cooling. We will also investigate in case of thermo-siphon cooling.
2. Allowable TRT length and other geometrical restriction of cooling channel for QD0 and QF1 cooling will be clarified by the superfluid simulation based on Landau two fluid model including G-M superfluid turbulent model.
3. From these simulation studies, finally we will perform dynamic simulation of 2K – 4K combined cryogenic system including not only detectors but also final focusing magnets.
4. The validity of the condition obtained from simulations described above will be (should be) confirmed by referring various experimental data and actual cryogenic system.

APPENDIX

Pushpull

- ILD and SiD are installed on the platform(20m x 20m), independently.
- QD0s are also installed in each detector. 2K refrigerator for QD0s should be installed on the platform.



Marco, Oriunno (SLAC)

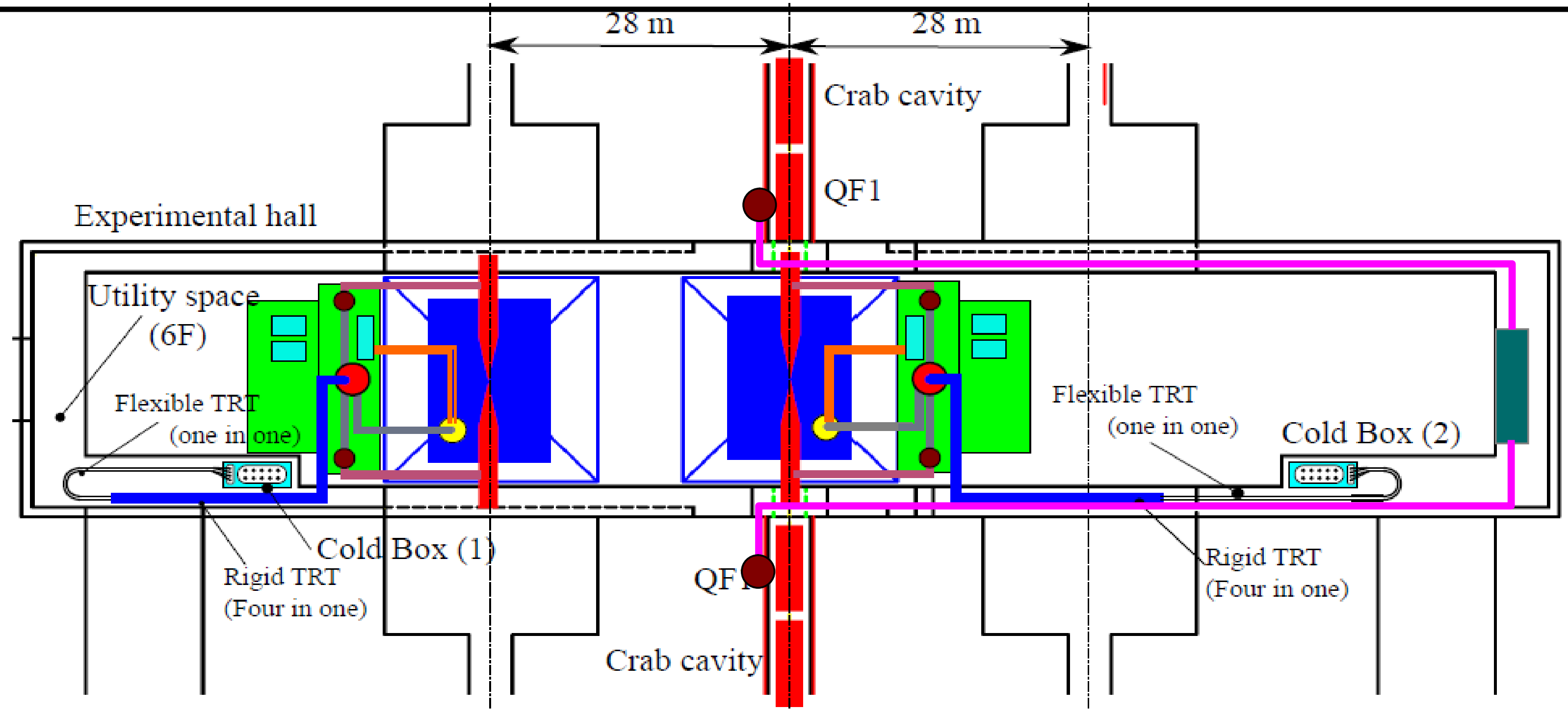
１） **Location of Cold Box (on platform or utility space of EX. hall ?)**
Vibration problem of QD0
Flexible TRT technical problem.
Malfunction of cold box.

２） **Location of 2K refrigerator for QD0 (on the platform or other location ?)**

Cryogenic Layout Example

Realistic number of cold box is three.

1. ILD＋4 QD0s
2. SiD＋2 QD0s
3. CC+QF1



🟩 Platform for cryogenic equipment

▭ Cold box (2 kW)

🔴 4K distribution box

● 2K refrigerator for QD0

🟡 Chimney and current lead box for detector

🟦 Power supply for detector and QD0

━ Rigid TRT for 7 K and shield gas (Four in one)

━ Rigid TRT for 4.2 K liquid helium (Four in one)

━ Rigid TRT for superfluid helium (2K, 4K 70K shield).

⊃ Flexible TRT for 7 K and shield helium gas with One in One or Two in One or Four in One ?

━ Bus bar for detector between PS and chimney.

Cooling Strategy of IP cryo system

Definition : IP cryo system → cryo system for “Detector”, “QD0”, “QF1”, “CC”

- Three cold boxes are installed in the experimental hall (Utility Space).
- Two kinds of 2K refrigerator should be prepared.
  - One for QD0, the other for QF1 and CC

Table1 : Summary of cryogenic system for each superconducting equipment of IR

	Total num	ILD + QD0 (pushpull)	SiD + QD0 (pushpull)	CCs + QF1s (fix)
4K Cold BOX (W, location)	3	2.0 kW platform or hall space	2.0 kW platform or hall space	~1.0 kW hall space
2 K refrigerator (location)	6	P-He II Platform	P-He II Platform	S-He II & P-He II Accelerator tunnel
TRT from CB (length)		rigid or flexible (5m or 30m)	rigid or flexible (5m or 30m)	Rigid (40m)
Compressor	3	700 kW	700 kW	350 kW

* 1.8 K refrigerator : 850 W / W, 4.5 K refrigerator : 350 W / W

Flexible TRT

In case that cold boxes aren't installed on the platform

Multilayer flex tubes have to be employed.

- bending frequency : twice a month
- bending diameter : 2-3m
- reliability ?
- bending occurs

It have never been developed until now.

Flex TRT with multi structure for insulation

It has large degree of freedom to reduce vibration of QD0 due to the cold box oscillation.

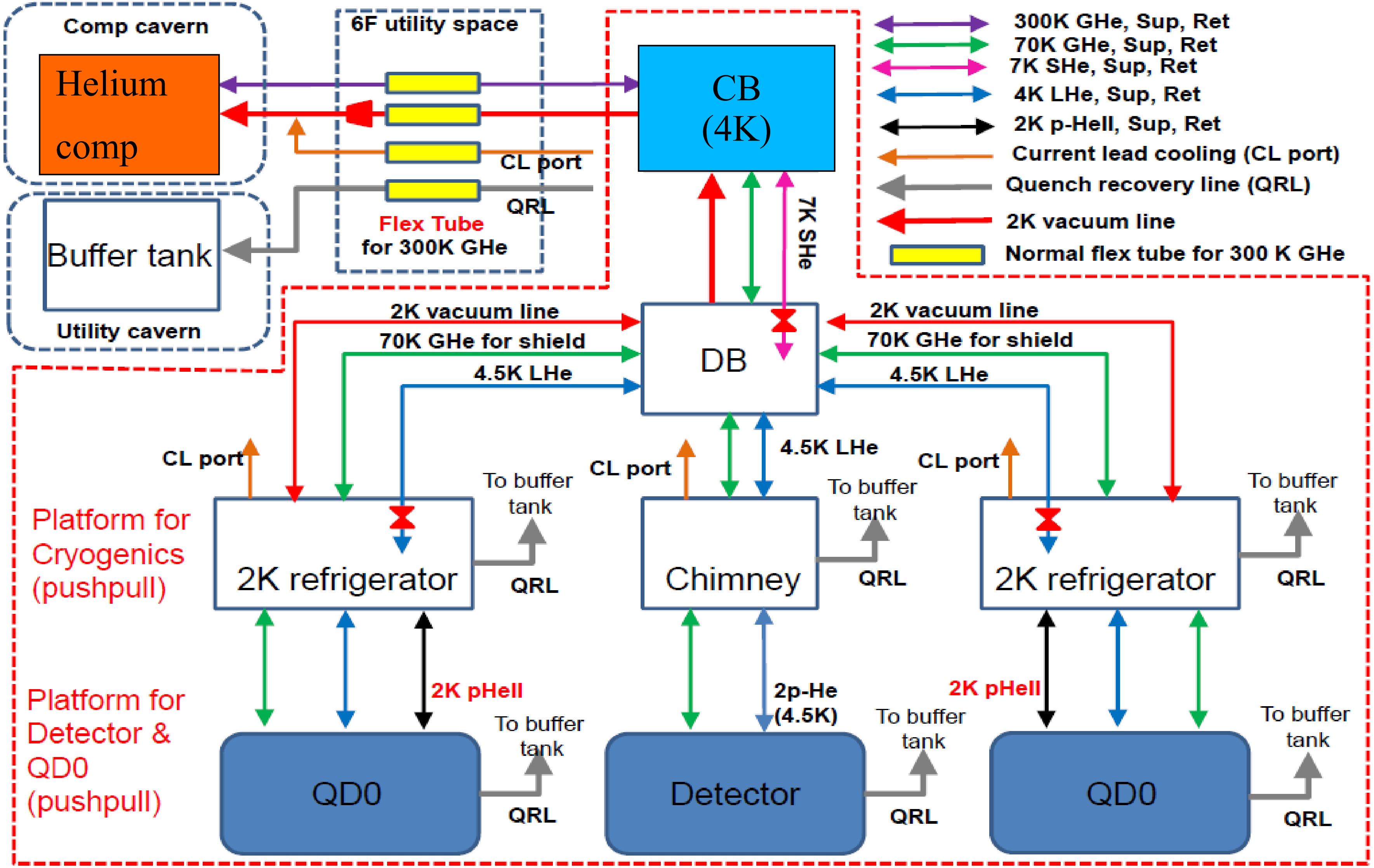
In case that cold boxes are installed on the platform.

Single layer flex tubes can be employed.

In this case, influence of vibration of QD0 induced by cold box should be considered.

Cryogenic block diagram example

It it necessary to use 4K refrigerator to obtain pressurized and saturated superfluid helium .
So, cold box which have cooling capacity with the heat load of detector and QD0



Comp cavern

Helium comp

Buffer tank

Utility cavern

6F utility space

Flex Tube for 300K GHe

CL port

QRL

CB (4K)

7K SHe

300K GHe, Sup, Ret

70K GHe, Sup, Ret

7K SHe, Sup, Ret

4K LHe, Sup, Ret

2K p-HeII, Sup, Ret

Current lead cooling (CL port)

Quench recovery line (QRL)

2K vacuum line

Normal flex tube for 300 K GHe

2K vacuum line

70K GHe for shield

4.5K LHe

DB

2K vacuum line

70K GHe for shield

4.5K LHe

4.5K LHe

CL port

CL port

CL port

To buffer tank

To buffer tank

To buffer tank

Platform for Cryogenics (pushpull)

2K refrigerator

QRL

Chimney

QRL

2K refrigerator

QRL

2K pHeII

2p-He (4.5K)

2K pHeII

To buffer tank

To buffer tank

To buffer tank

Platform for Detector & QD0 (pushpull)

QD0

QRL

Detector

QRL

QD0

QRL