ML Cryogenics

T.Okamura, H.Nakai, A.Yamamoto

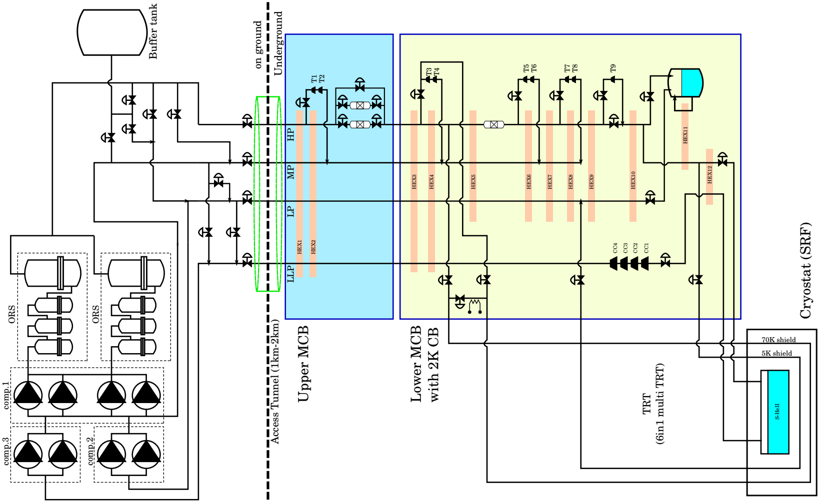
KEK

2017/3/13

Contents

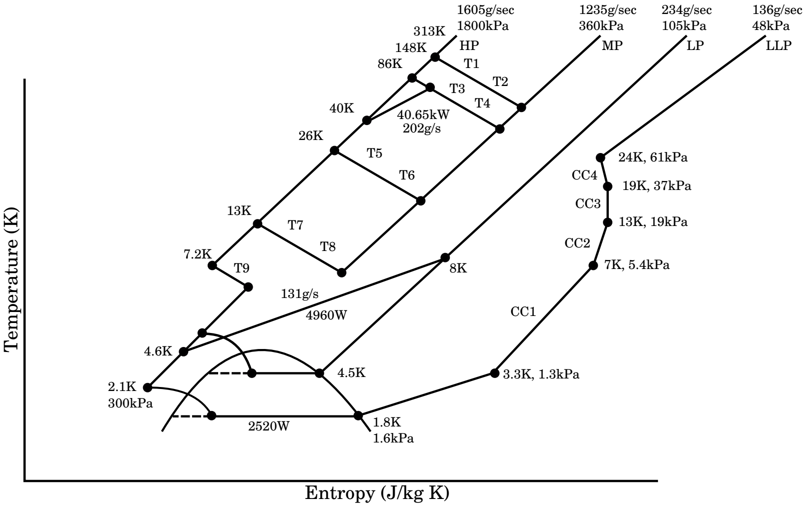
1. Flow and TS diagram
2. Inventory
3. Diagram for power failure etc..
   - Necessity equipment for power failure and other operation modes
4. Mass flow requirement during power failure
5. Buffer tank and small liquifier system
6. Discussion about inventory storage scheme
   - Cost evaluation
   - Required exclusive area
7. Summary

Main Flow Diagram



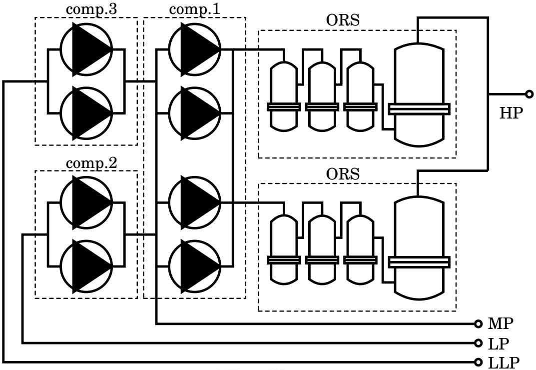
Not including cryo system for power failure.

T-S Diagram



based on the Main Flow Diagram

MCS Configuration and Input Power



comp.1: MP to HP
comp.2: LP to MP
comp.3: LLP to MP (subatmospheric comp.)

- 8 compressors (3 kinds of compressor)
  - 2 sub-atmospheric comp, 2 low stage comp, 4 high-stage comp
- Total input power $5 \sim 5.5$ MW / plant
  - too large input power to run **during power failure**

He inventory per 1-cryo plant

He inventory

- 63000 liquid L/plant = about 8.2 metric tons/plant
  - Fig. 3.26 (ILC Technical Design Report: Volume 3, Part II) , most of the helium inventory consists of the liquid helium which bathes the RF cavities in the helium vessels. (TDR)

Equivalent buffer tank volume of 63000L of LHe

- 12 buffer tanks with 250m^3, 2 MPa-A (including 10% contingency)
- If 6 buffer tanks with 250m^3 are prepared, half of all can be stored in the buffer tanks.

Basic Design Guideline during Power Failure

1. **No loss of Helium resource** even during a total power or cryogenics system failure
   - Unfortunately, this guideline was missing in the TDR.
   - Annual loss of helium may not be zero because of regular maintenance work, but it may be assumed to be smaller than 10 %.
   - Sudden large amount of helium resource would not be available especially in Japan.
2. **SRF should be protected from a damage due to pressure increment** which is induced by static heat load and loss of cooling capacity. Boil off gas should be discharged from SRF-CM so as not to be beyond allowable pressure of SRF.
   - Allowable pressure of SRF cavity is 2 bar-abs.
   - Significantly different from superconducting magnet system allowing 20 bar (as same as the cryogenics design pressure).

- **Recovery system** meeting the above requirements is needed!

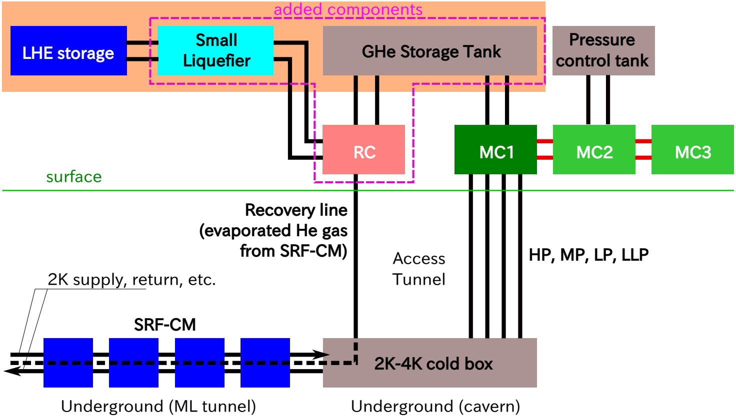
Technical Design Guideline during Power Failure

1. **A QUICK ACTION is essential against the MCS stop.**
   - A simple and robust GHe recovery action made by using a dedicated GHe compressor system, immediately after the Main Compressor stop.
   - Recovery system can be operated by using natural-gas/oil generators with a capacity of 1 MW $\times(1 \sim 3)$ days per cryo-system: meaning 2 MW $\times(1 \sim 3)$ days per access tunnel portal point.
2. **MCS and MCB with 5-5.5 MW may not be restarted even though main electrical power is quickly recovered after the failure.**
   - because of unexpected problem which are generated by sudden inadequate stop due to the failure.

- Liquefaction of recovery gas should not be done.
  - it is not easy to ensure a high response and stability of liquefaction system.
- **Recovery helium gas should be stored in buffer tank by means of Recovery Compressor (RC) system.**

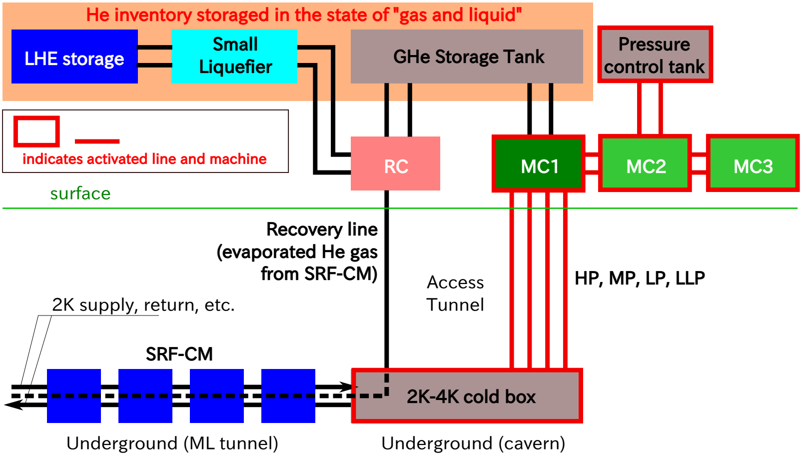
Basic Diagram including various kinds of modes

steady-state, power-failure, warm up, maintenance



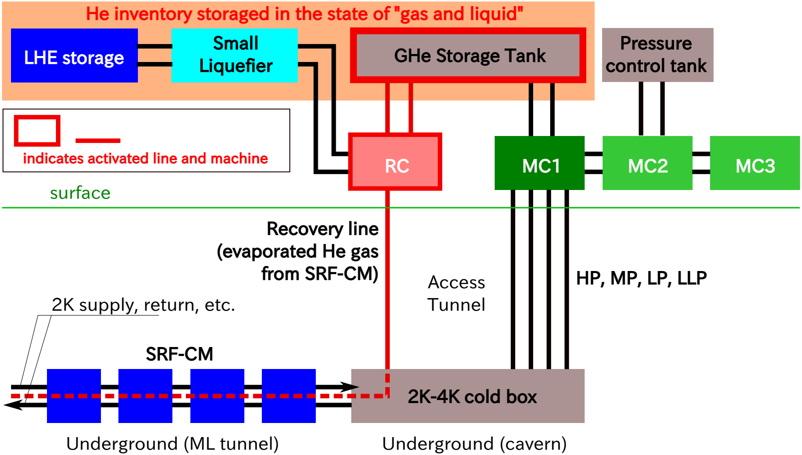
- Following three cryo-components are revised and added to the block diagram
  (1) GHe buffer tank, (2) Recovery Compressor (RC), (3) Small Liquefier
- **The LHe and GHe fraction balance should be optimized, depending on the site environmental condition.**

Block Diagram (during Steady State Operation)



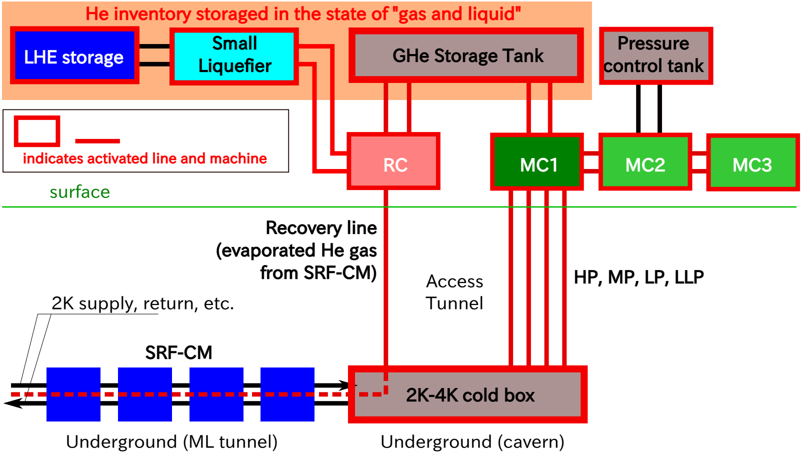
- LHE storage is almost empty during steady-state mode.
- During steady state operation, maintenance of small liquefier should be done.

Block Diagram (during Power Failure Operation)



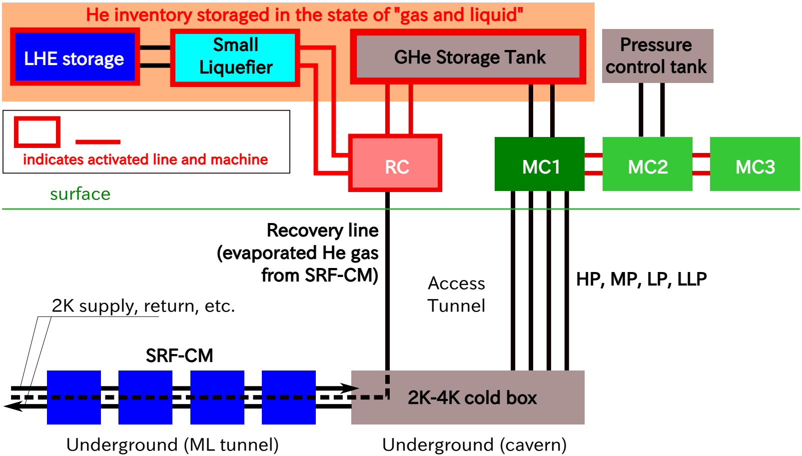
- RC is operated by using Natural gas/oil generator.
- Other equipment keeps halting condition

Block Diagram (during Warm Up Operation)



- All he inventory should be recovered on surface (recovery time ~ 1 week.)
- Small liquefaction system (Small liquefier and RC) should be operated.
- In addition, MCS and MCB have to be running state to control boil off He mass flow rate within 290 L/h which is the capacity of small liquefier system.

Block Diagram (during maintenance season)



- **Not necessity for continuous operation of small liquefier.**
- **1 week resting state of small liquefaction system induce pressure increment only 0.5 bar if LHe dewar with 0.2 %/day is employed.**

How to operate during power failure

- MCB (Main Cold Box) ⇒ NOT Restarted!
- MCS (Main Compressor System) ⇒ NOT Restarted!
- **Small Liquefier and LHe Storage dewar ⇒ NOT Started!**

- **RC (Recovery Compressor) ⇒ Started !**
  - Not necessity for large input power
  - input power ~ 400 kW ($=$ 71.5 g/sec).
- **POSSIBLE to operate by using natural oil/gas generators**

Requirement for recovery mass flow rate

- **Mass flow rate control within ~ 30 g/sec is essential.**
  - **According to our estimation, evaporated mass flow becomes much larger than 30 g/sec due to heat load increment unless some ingenuity is made.**

⇒ **How to reduce the mass flow rate ?**

Evaporated mass flow control during Power Failure

How to reduce evaporated mass flow rate

- Due to the loss of cooling capacity, increment of static heat load into SRC induce evaporated mass flow increment.
- Cold boil off gas should go through radiation shield to cool down the shield temperature and to reduce heat load.
  = Enthalpy recovery of boil off gas with cryogenic temp.

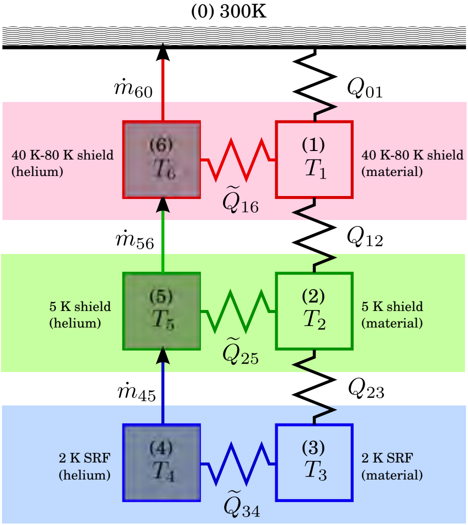
If the evaporated mass flow rate during the failure can be reduced, redundancy of recovery system during the failure can be obtained.

♠ Information on Mass Flow Rate

- Required (Desired) ~ 30 g/sec.
- RC Capacity ~ 71.5 g/sec
  - During steady state cooling $= 18$ g/sec (w/o Dynamic Loss)

TOY Model for Evaporeted Mass Flow Estimation

Following balance equations with TOY model are solved numerically.



Heat transfer Correlation

$$\widetilde{Q}_{ij} = h_{ij}(T_i - T_j)A_{ij}$$

$$Nu_{ij} = \frac{h_{ij}D_j}{\nu_j} \quad Re_j = \frac{u_j D_j}{\nu_j}$$

Dittus-Boelter Correlation

$$Nu_{ij} = 0.023 Re_j^{4/5} Pr_j^{0.4}$$

Don't apply summation convention

Energy Balance Equation for material

$$C_i M_i \frac{\partial T_i}{\partial t} = Q_{i-1\,i} - Q_{i\,i+1} - \widetilde{Q}_{i\,j}$$

Energy Balance Equation for helium

$$\left[\frac{\partial}{\partial t}(\rho_j h_j) + \frac{\partial}{\partial x}(\rho_j u_j h_j)\right] V_j \simeq -V_j \frac{\partial q_j}{\partial x} + Q_{ij}$$

Convection term are including to estimate enthalpy recovery effect.

Full form of energy conservation is described as follows.
In this model, some effect (term) are neglected.

$$\rho\left[\frac{\partial h}{\partial t} + (\mathbf{u}\cdot\nabla)h\right] = \frac{\partial p}{\partial t} + \mathbf{u}\cdot\nabla p - \boldsymbol{\tau} : \nabla\mathbf{u} - \nabla\cdot\mathbf{q} + Q_{in}$$

$i \in \{1,2,3\}$, indicate material of each stage; $j \in \{4,5,6\}$ indicate Helium of each stage

Calculation and Control Scheme

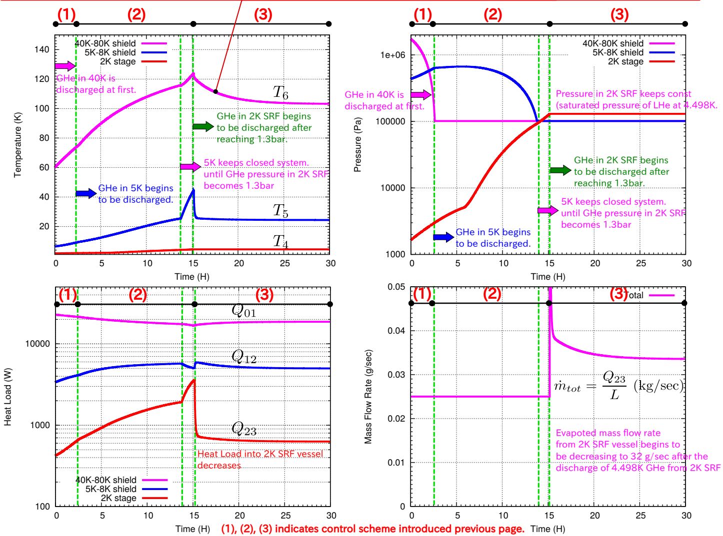
Initial Pressure of each stage

- 40K shield = 18 bar (inlet pressure of T3)
- 5K shield = 3.6 bar (outlet pressure at HEX in the 4K subcooler)
- 2K SRF = 1.6 kPa (satureted pressure of He II)

1. **Helium gas in 40 K shield is discharged from 18 bar to 1 bar.**
   - During this operation, 5K shield and 2K SRF keep closed system.
   - Pressure in 5K shield and 2K SRF gradually increase due to static load.
2. **After 40 K shield becomes 1 bar, He gas in 5K shield is discharged to 1 bar**
   - Discharged He gas go through 70K shield to recover enthalpy.
   - 2K SRF keeps closed system and pressure gradually increases.
3. **After 5K shield becomes 1 bar *and* 2K SRF pressure becomes 1.3 bar from 2K, 1.5 kPa, He gas in 2K SRF begins to be recovered.**
   - Discharged He gas go through 5K shield and 70 K shield.
4. **If residual mass in 2 K SRF becomes almost zero, calculation is finished.**

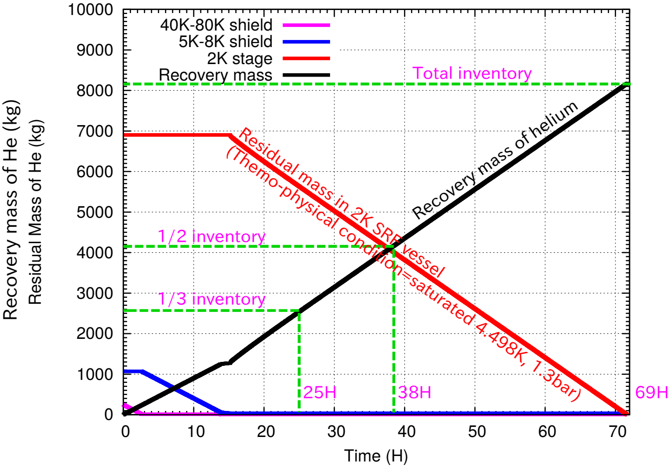
Results (1): Time Evolution of T, p, Q and $\dot{m}$

Temperature in 70K shield begins to decrease due to enthalpy recovery of 4K GHe.
Temperature increment of each stage stops and keeps constant.



(1), (2), (3) indicates control scheme introduced previous page.

Results (2): Recovery Mass



- Mass flow rate of boil off gas can be reduced to around 30 g/sec.
- 1.5 days to recover half inventory into the 6 buffer tanks/plant.
- 3.0 days to recover all inventory into 12 buffer tanks/plant.

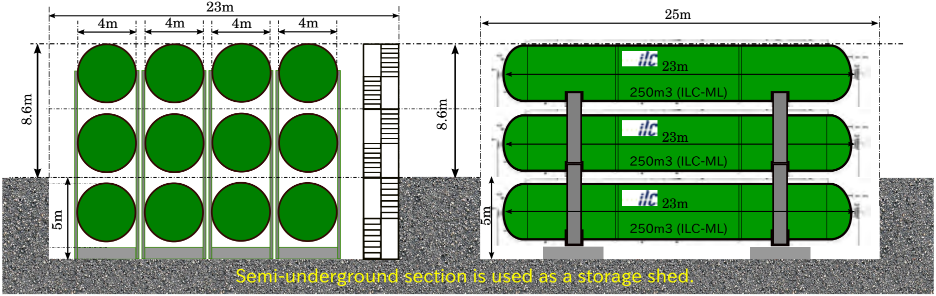
How to set up buffer tanks

- 6 buffer tanks / plant. ⇒ 12 tanks / location.
- Transportation and unloading scheme should be considered carefully.

6 buffer tanks (each for 250m3)
example of JT60SA (NAKA / Japan)

Unloading of 250m3 tank
at NAKA port

250m3 buffer tank
Weight = 70t
H=4.3m (including base)
W=4m, **L=23m**



BOG behaviour during planned outage

Dewar Specification

- Volume : 43000 L (at 6 buffer tank (250×6 m^3)
- Size : $\sim$ L=12m, W=2.5m, H=2.6m
- Spec : $0.2 \sim 0.5$ %/day

During planned outage (3days continuously shutdown)

- (1 bar, 4.2 K) $\Rightarrow$ (1.60 bar, 4.70 K) (@ 0.5%/day)
- (1 bar, 4.2 K) $\Rightarrow$ (1.24 bar, 4.44 K) (@ 0.2%/day)

No problem during 3 days outage

Small Liquefaction System (Small Liquefier)

Definition

Small Liquefaction System can be defined as follows.

- Compressor : (Recovery Compressor is used.)
- Small Liquefier : (Cooling capacity can be determined automatically from input power of RC.)

Assumption

- If 6 buffer tanks are employed, half inventory should be stored in LHE dewar.

Specification

- Liquefier : maximum liquefaction capacity=290 L/h
  $\Rightarrow$ MCB has to be continuously operated to keep this condition.
- Required mass flow : 80 g/sec (410 kW = RC power)
- Half inventory can be liquefied for 4.5 days (within 1 week).

Discussion on Storage Scheme

- GHe and LHE mixing storage scheme has a source of unrest shown below from the view point of inventory loss.
  - In the case of severe damage of MCB such that MCB can not be operated within 1.5 days
  - In the case of severe damage of small liquefaction system such as liquefier and LHE dewar.
- Recovery time can be reduced from 1 week to 3 days in the case of GHe storage scheme.
- Manufacturing cost without small liquefaction system is a little bit cheaper than half and half mixing storage scheme.
- Required surface area is almost same each other. (if config. shown P19 is applied)

Storage Scheme unit : (**)		buffer tank	Small liquefaction system	Other, Transport etc.	Total Cost
12 buffer tanks	w/o small liquefier	6.72	0	4.1	10.82
6 buffer tanks	w/ small liquefier	3.36	5.4	2.6	11.36

Storage Scheme unit : (m2)		buffer tank	Small liquefaction system	Other, Transport etc.	Total Area
12 buffer tanks	w/o small liquefier	46m x 25m	8m x 14m (RC)		1263
6 buffer tanks	w/ small liquefier	23m x 25m	30m x 23m (RC, Liquefier, LHe dewar)		1265

Detailed comparison

Comparison Item		12 buffer tanks scheme	6 buffer tanks and LHE Dewar scheme
Cryo components for recovery system	buffer tanks	12	6
	recovery compressor	400kW	400kW
	small liquefier	-	280L/h
	LHE dewar	-	42000L
	cryogenic pipe	-	4 cryo pipes (3-5m)
	cryo control system	-	necessary
Piping through access tunnel	HP	318.5mm	318.5mm
	MP	508mm	508mm
	LP	406mm	406mm
	LLP	406mm	406mm
	Recovery line	165.2mm	165.2mm
exclusive area on surface(m2)		1265	1265
necessity for building		-	necessary
Cost	buffer tanks	6.72	3.36
	recovery compressor	0.7	0.7
	Cold box	-	4.4
	LHE dewar	-	1
	Transportation	1.8	0.9
	unloading crane	0.4	0.4
	Site construction	1.2	0.6
	SUM	10.82	11.36

- **ILC site-specific utility designs are same for each storage scheme.**

Summary (1)

Power Failure

- Instead of Storage Scheme introduced in TDR, not only LHE dewar but also GHE buffer tanks are employed for preventing loss of He inventory during power failure.
- Recovery compressor (RC) should be located on surface but its capacity should be enough small to be operated using LNG generator during the failure. Several hundreds kW can be acceptable. (MW order can not be acceptable.)
- To perform this, recovery mass flow rate during the failure should be reduced. Enthalpy recovery operation seems effective way to reduce the mass flow rate.
- According to the simulation based on toy model, mass flow rate can be reduced to around 30 g/sec. In this case, if 6 tanks with 250 m3 are located on surface, resting state of MCS and MCB for 1.5 days can be acceptable.

Summary (2)

Maintenance and other operation

- When all inventory is recovered for maintenance season, small liquefier is needed. RC can also be applied to small liquefaction system.
- Fraction between Liquid and Gas can be optimized by considering site environmental condition.
  - Recently, we considered 1/2 in Gas and 1/2 in LHE.
  - to be discussed further with Tohoku group.
- Recovery time for the total inventory is within 1 week by using small liquefaction system. To perform this, MCS and MCB have to be operated continuously during recovery mode.
- Tentative stop of the Small liquefaction system such as planned outage can be acceptable. To ensure it, allowable pressure should be 10 bar or so and less heat load into the dewar such as 0.2-0.5 %/day should be used.

Summary (3)

- Brief cryogenic equipment is summarized in following table

			Input Power		Specification			Size	Weight
Surface	MCS	Main Compressor System	5-5.5 MW	6.6kV	Pout=2MPa	8 comps	1614 g/sec	(L5.7m x W2.8m x H3.3) x 8 sets	13t x 8sets
	RC	Recovery Compressor	370-410 kW	6.6kV	Pout=2MPa	1 comp	71.5-85.5 g/sec	(L5.5m x W3m x H2.9m) x 1 set	18.5 t
	BT	Buffer Tank			250m3 x (4+2)	22000 L @LHE		(L23m x W4m x H4.3m) x 6 sets	70 t x 6 sets
	SD	Storage Dewar				44000 L @ LHE		OD3.5m x L13m	under investigation
	SL	Small Liquefier with Turbines		3P200V	290 L/h				
	CE	Cold Evaporator		3P200V	10000 L				
Access Tunnel	HP	High Pressure Pipe			Single , SUS304TP-A	not insulated	1606 g/sec, 300K	OD=318.5mm	
	MP	Middle Pressure Pipe			Single , SUS304TP-A	not insulated	1235 g/sec, 300K	OD=508mm	
	LP	Low Pressure Pipe			Single , SUS304TP-A	not insulated	234 g/sec, 300K	OD=406mm	
	LLP	Negative Pressure Pipe			Single , SUS304TP-A	not insulated	136 g/sec, 300K	OD=406mm	
	RP	Recovery Pipe			Single , SUS304TP-A	with drain	30g/sec, 80K-300K	OD=165.2mm	
	CR	Cable Rack			W600mm x 2 stages		LAN Cable, Signal Cable	W600mm x 2 stage	
Cryo Cavern	Upper MCB	300K to 70K Main Cold Box		3P200V	see Flow diagram and TS diagram			L9.1m x W3.7m x H4.35m	34 t
	Lower MCB	70K to 1.8K Main Cold Box		3P200V	see Flow diagram and TS diagram			L14m x W3.5m x H4m	50 t
	SCB	Sub Control Box for MCB	3P200V, 2P200V, 2P100V		under investigation			L5m x W600m x H2.1m	
	TCR	Tentative Control Room		2P100V				L4m x W2.5m x H2.5m	
Access Tunnel to ML	TRT	Transfer Tube			6 pipes in one Jacket /			Jacket OD=650A-750A	
					2 for 70K shield / 2 for 5K shield / 2 for 2K shield			70K shield (sup/ret) OD=72mm/80mm	
					under investigation			5K shield (sup/ret) OD=56mm/70mm	
								2K (sup/ret) OD=70mm/300mm	

- small equipment described as follows are not listed in the table.
  - air compressor for control valves
  - cryo purification system
  - Gas analyzer
  - dryer
  - vacuum pump
  - 6.6 kV High voltage control unit for MCS
  - cooling water system for MCS and turbines installed in MCB
  - etc...

Back Data

Recovery Pipe Specification

Assumption

- Cryomodule pressure (inlet pressure) : 130 kPa-A
- mass flow rate : 30 g/sec
- Total pipe length : 2000 m
- Required pressure drop in the pipe : < 30 kPa.

Specificaltion

- Diameter : 150 A, thickness=3mm,
- Single tube (with drain)
- Passive heat exchanger : located on surface.
- total pressure drop : 3 kPa (recovery pipe) $+$ 11 kPa (heat exchanger)

Small Liquefaction System (Small Liquefier)

Definition

Small Liquefaction System can be defined as follows.

- Compressor : (identical to Recovery Compressor)
- Small Liquefier

Assumption

- LHe of 43000L is liquefied for around 7 days.
- 43000L is 2/3 amount of total helium inventory (65000L).
  - Assumption of 4+2 buffer tanks located on surface.

Specification

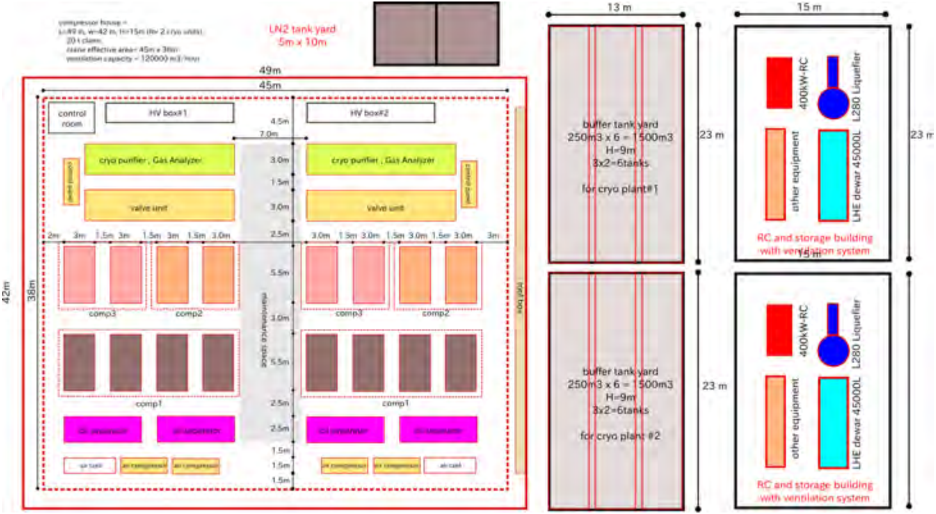
- Liquefier (L280) : maximum liquefaction capacity=290 L/h
- Required mass flow for L280 : 80 g/sec.
- Cost : 2.2 億円

Small Liquefaction System (Compressor=RC)

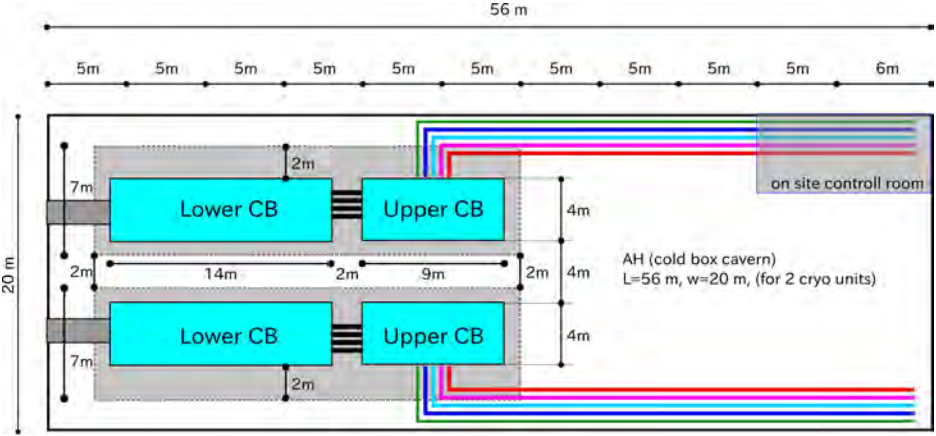
Specification

- Two candidate are considered.
  - MYCOM 2520MSC (Medium Length Screw):
    - Mass flow rate : 71.5 g/sec
    - Shaft Power : 370 kW
    - Cooling water : 63.5 ton/h ($\Delta T = 5$ K)
    - Size : L5500mm x W3000mm x H2900mm
    - Weight : 18.5 ton
    - Cost : 109 百万円
  - MYCOM 2520LSC (Long Length Screw):
    - Mass flow rate : 85.5 g/sec
    - Shaft Power : 410 kW
    - Cooling water : 70.5 ton/h ($\Delta T = 5$ K)
    - Size : L5700mm x W3000mm x H2900mm
    - Weight : 19 ton
    - Cost : 119 百万円

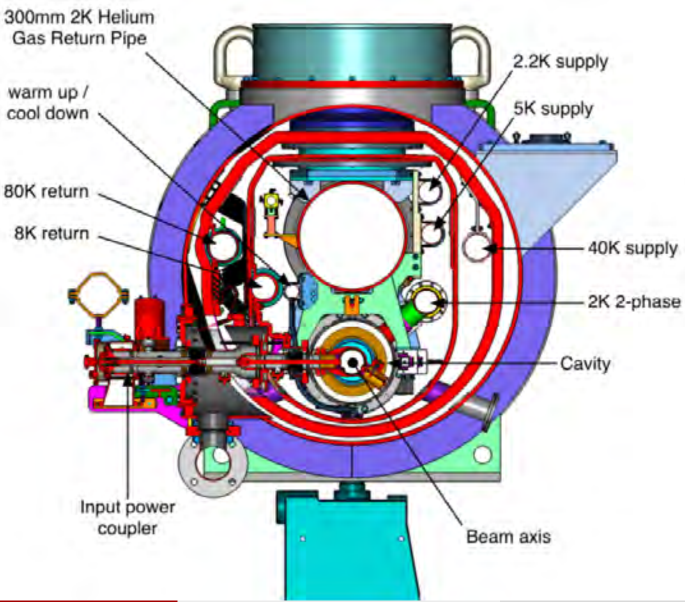
Surface Layout for 2 plants



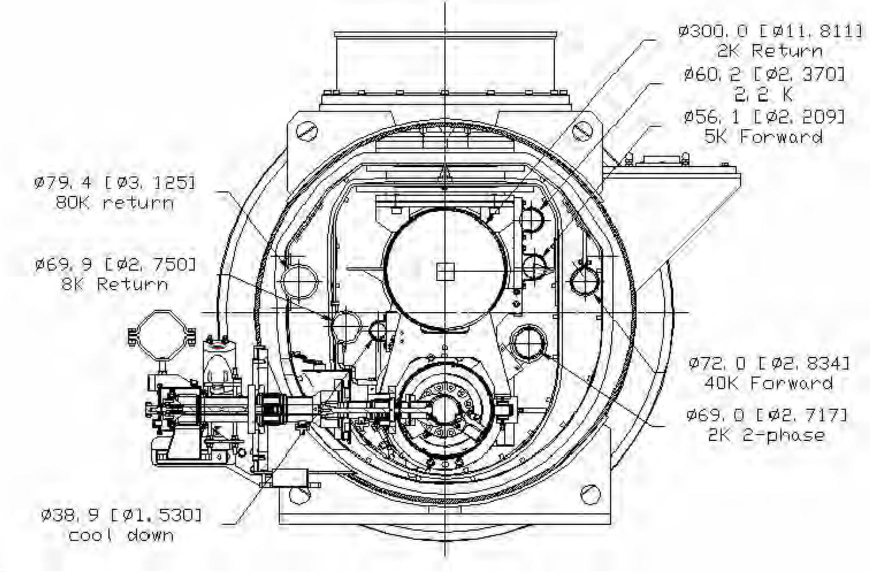
Underground Layout for 2 plants



Cross Section of SRF-CM



Cross Section of SRF-CM



Pipe Specification (MCB in Underground)

- 4 Warm pipes
  $\Rightarrow$ 318.5mm ,508mm, 406mm, 406mm
- Recovery Pipe
  $\Rightarrow$ 165.2mm (150A)

	2.0K (MCB underground)				1.8K (MCB underground)			
	HP	MP	LP	LLP	HP	MP	LP	LLP
mass flow rate (g/sec)	1842	1405	252	185	1605	1235	234	136
Pressure (kPa) *1	1800	360	105	105	1800	360	105	48
Pipe diameter (mm)	318.5	508	406.4	406.4	318.5	508	406.4	406.4
Pressure drop (kPa)	15	5.1	2.5	1.5	11.3	4.1	2.1	1.7

- Mass flow at 1.8K cooling is 13 % less than at 2.0 K.

Evaporated mass vs Buffer tank volume

Recovery Time and Buffer tank volume are shown at around 30 g/sec.

HE Inventory (kg / plant)		evaporated mass flow (kg/sec)	recovery time (H)	recovery time (Days)	Number of 250m3 Buffer tank required	Number of 250m3 Buffer tank contingency
40K shield	246	0.03	2	0.1		
5K shield	1068	0.03	10	0.4		
2K SRF	6901	0.03353	57	2.4		
1/3 inventory	2738	0.03	25	1.1	4	2
1/2 inventory	4108	0.03	38	1.6	6	2
Total inventory	8215	0.03291	69	2.9	11	-

Time to fill up at 30 g/sec.

- 4+2=6 tanks (1/3 inventory) ⇒ 25H
- 6+2=8 tanks (1/2 inventory) ⇒ 38H
- 11 tanks (total inventory)⇒ 69H

Further detailed dynamic simulation will be performed continuously instead of using TOY model.

Modeling and Scheme

- Case-1

1. Energy balance equation for the material is solved explicitly.

Basic Configuration during power failure

- MCB (Main Cold Box) ⇒ NOT Restarted!
- MCS (Main Compressor System) ⇒ NOT Restarted!
- **Small Liquefier and LHe Storage dewar ⇒ NOT Started!**

- **RC (Recovery Compressor) ⇒ Started !**
  - input power : 370 kW (410 kW)
  - mass flow rate: 71.5 g/sec (85.5 g/sec)
  - output pressure 2.1 MPa
  - compressed recovery He gas is stored in buffer tank.

- **POSSIBLE to operate by using natural oil/gas generators**
- **Mass flow rate control within ~ 30 g/sec is essential.**
  - **Without control, evaporated mass flow exceeds 71.5 g/sec.**
    ⇒ How to control (reduce) it ?