Architecture on ML Cryogenics

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Abstract

Cryogenic configuration for ML have been reconsidered by assuming that WCS and LSD are located on surface from the view point of vibration and safety such as deficiency of oxygen because cryogenic configuration proposed in TDR has problems about these two points.

In this presentation, two cryogenic configurations so called " Case-A " and " Case-B " are proposed instead of TDR scheme.

- **"Case-A"**
  - 4K cold box (MCB) is located on surface and 2K system is located in cavern.
- **"Case-B"**
  - 2K system and 4K cold box are combined each other and it is installed in cavern.

Optimal flow diagram for both options are established {P24,25} after several case studies about cryogenic efficiency and cost.
In this presentation, I did not determine which is better scenario. But not only cryogenics but also other items such as cost, reliability, maintenance,safety are considered and compared for two options.

Contents

Nomenclature

- MCB: Main 19kW Cold Box (=UCB or =UCB+LCB)[1]
- WCS: Warm Compressor System (Helium Screw Compressor)
- LSD: Liquid Helium Storage Dewar (LHESD)
- BSS: Baby-Sitter Liquefier System (BSLS)
- CDB: Cryogenic Distribution Box
- TRT: TRansfer Tube (multi-structure Liquid Helium Transfer Tube)
- ML: Main Linac
- MS: Molecular Sieves

- $\rho_p = \rho(p)$: Helium density which is a function of pressure, p.
- $\rho_{pt} = \rho(p, T)$: Helium density which is functions of pressure and temperature, T.
- λ: Wall Friction Coefficient [-]
- $Re = uD/\nu$: Reynolds number [-], u, D, ν are velocity, diameter of pipe and kinematic viscosity coefficient [m^2/sec].
- $\dot{m} = \rho u A$: Mass flow rate [kg/sec]. $A = \pi D^2/4$ is cross section of pipe.

[1] UCB: Upper Cold Box, LCB: Lower Cold Box. They were described in Tom Peterson's scheme. (see next page.)

Mountain Site Constraint

Moutain Site Constraint

1. **Access tunnel length = $1 \sim 2$ km** [a]
2. **Access tunnel depth = 180m (maximum)**
   - Pressure drop and head through access tunnel can not be negligible.
3. **During maintenance, Most of helium inventory is stored in the state of liquid in LHe Storage Dewar (LSD) to reduce storage tank yard.**
   - **Baby-Sitter Liquefier System (BSS) has to be employed for LSD** in case of an emergency (eg. loss of power.) [b]
   - **LSD should be located on surface** to guarantee underground safety to a deficiency of oxygen.

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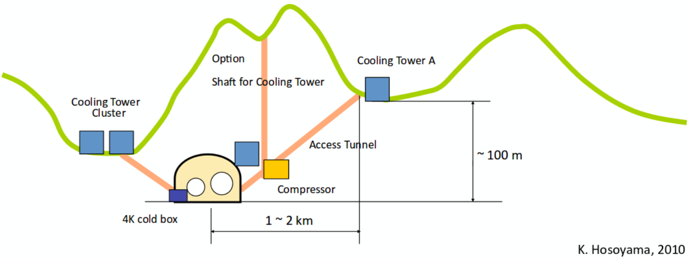
[a] Access tunnel is not vertical but horizontal with around 9% gradient.

[b] BSS is composed of small CB and small compressor (Kaeser comp). BSS had better be installed adjacent to the LSD.

TDR scheme



- Only cooling towers on surface for effective heat removal, and others underground

Change Scheme Motivation

1. Safety Issue: All Helium inventory stored in the cavern.
   ⇒ Dedicated Safety counter-plan (eg. ventilation system)
   ⇒ Unexpected event consideration.
2. Vibration Issue: from WCS

Major Premise

Major Premise:

- **WCS[a] should be located on surface.**
- **LSD should be located on surface.**
- **2K system except 2K warm compressor system is installed in cavern.**
  $\Rightarrow$ 2K WCS location is not determined so far.
- Some kinds of redundancy function should be employed.
- Architecture should have fully safety system during operation and maintenance.
- Cryo scheme is fully logical.
- Cost is fully reasonable.

[a] WCS means Warm compressor system for MCB.

Requirement on the Cryogenic Scheme

- **Cryogenics, Safety system, Civil, Operation, Maintenance, Cost**

Alternative Architectures

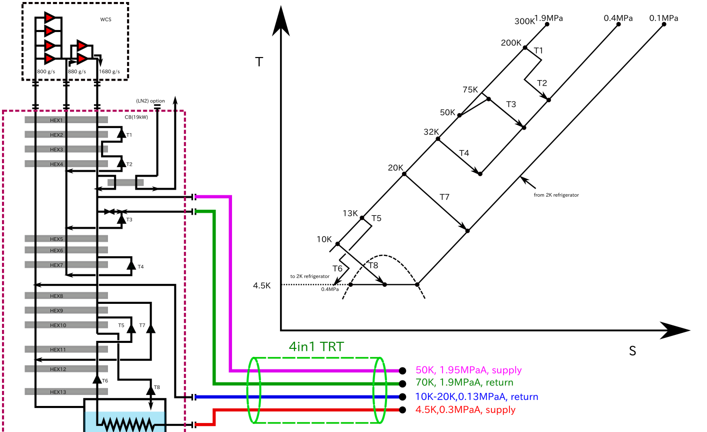
Alternative configs.

- **Case-A**
  - MCB with 19kW is located on surface. MCB is located near the LSD and linked each other.
- **Case-B**
  - MCB with 19kW is located in cavern. MCB and 2K system is combined each other.

There are three different structures between case-A and case-B.

Cryogenic Architectures	Helium pipes through access tunnel	2K system	LSD (Liquid He Storage Dewar)
Case A MCB is located on surface	•4in1 Multi TRT •Additional 1 or 2 Warm Pipes it depends on 2K-WCS location.	•2K-WCS had better be employed. to reduce enthalpy loss of CC return line	•It can keep cryo-temp during operation automatically.
Case B MCB is located in underground	•3 warm pipes •2in1 simple TRT	•w/o 2K-WCS •2K system and 4K CB are combined each other.	•To keep cryo-temp, additional CB (baby sitter system) has to be intentionally operated during operation. •4K System (MCB) may have a LHE dewar.

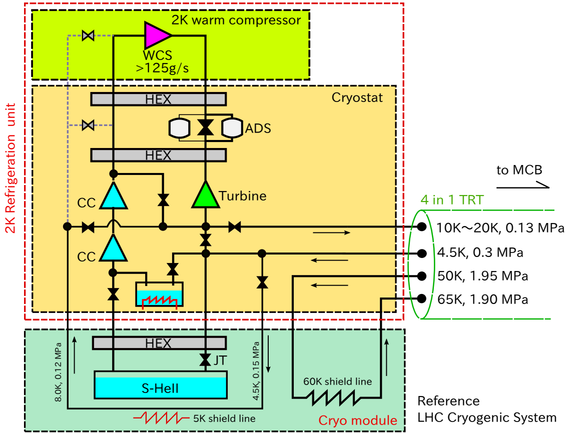
4K MCB Example



Connection destination of 4.5K 0.3 MPa supply line is different between Case-A and Case-B.
In the case of "Case-A", 4.5K supply is connected to JT valve which is installed in LHESD.
In the case of "Case-B", 4.5K supply is connected to 2K refrigeration system.

- **In the case of "A", total shield length is very long (8km).**
  $\Rightarrow \Delta p$ in shield line should be less than 1bar to obtain correct inlet pressure of T3.
- **In the case of "B", total shield length is $\sim$ 4.5km whose length is equivalent to summation of supply and return line length of one Cryo-Unit.**

2K System Example



Reference
LHC Cryogenic System

- 2K WCS and turbine plays an rule in enthalpy recovery of 2K Gas helium return.
  ⇒ **This system is effective in case of "A".**
- In case of "B", Similar scheme that does not have 2K-WCS and turbine can be considered.
  ⇒ **CC return line is returned to LP line in MCB with corresponding temperature level.**

Structure of 2K system strongly depends on location of 4K MCB.

Optimal mass flow control for 2K system

- **Dynamic heat load is beyond 2 times larger than static load.**
  - **Static Heat Load** $\sim$ 526 W (one cryo unit)
  - **Dynamic Heat Load** $\sim$ 1855 W (one cryo unit)
    - Static + Dynamic = 2381 W
- **Mass flow rate of 2K return line due to heat load is completely different.**
  - **Static Heat Load** $\dot{m} = 22$ g/sec
  - **Total Heat Load** $\dot{m} = 101$ g/sec

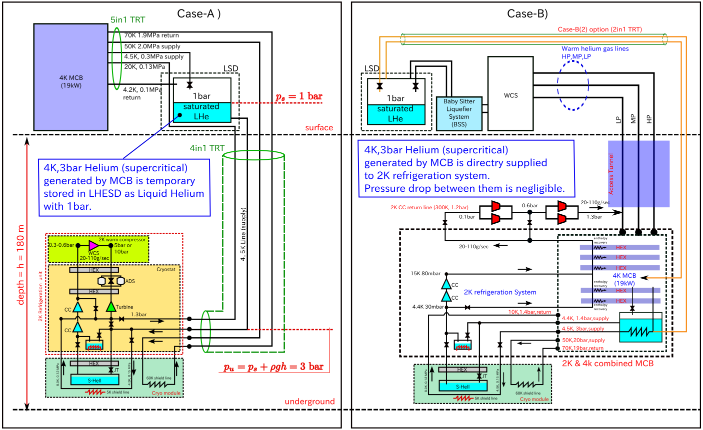
Optimal mass flow control systems should be designed in hardware.

Heat Load Estimation

		40K-80K	5K-8K	2K
predicted module static heat load	W/module	59.19	10.56	1.7
predicted module dynamic heat load		94.3	4.37	9.66
Number of modules per cryo unit		192	192	192
Non-module heat load per cryo unit	W	1000	200	200
Total Predicted Heat Load per cryo unit	W	30470.08	3066.56	2381.12
Total Predicted Static Heat load per cryo unit	W	12364.48	2227.52	526.4
Total Predicted Dynamic Heat Load per cryo unit	W	18105.6	839.04	1854.72
Static / Total	-	0.4057908611	0.7263904831	0.2210724365
Total Predicted Heat Load including Contingency	W	46920	4720	3670
Total Predicted Static Heat Load including Contingency	W	19040	3429	811

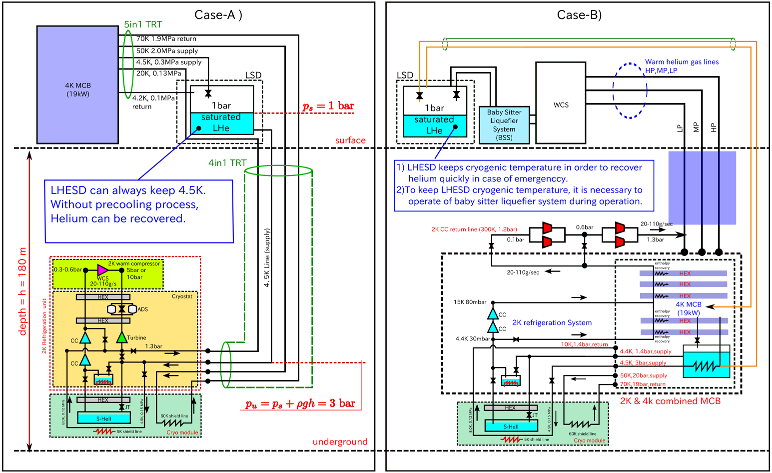
(reference : ILC CRYOGENIC SYSTEMS REFERENCE DESIGN by Tom Peterson)

Schematic Configuration of A & B



- **CASE-A:** 4K supply line is once connected to LSD. Due to the hydrostatic pressure and pressure drop between long and deep access tunnel, LHe at 1bar on surface becomes supercritical with 3bar in underground. 2K-WCS and dedicated turbine for 2K refrigeration unit should be employed to recover enthalpy of 2K return line effectively.
- **CASE-B:** In the case of "B", 2K and 4K MCS can be combined each other. In addition, 2K-WCS and dedicated turbine need not to be installed. To control mass flow rate of 2K return line, warm ring compressor unit should be employed.

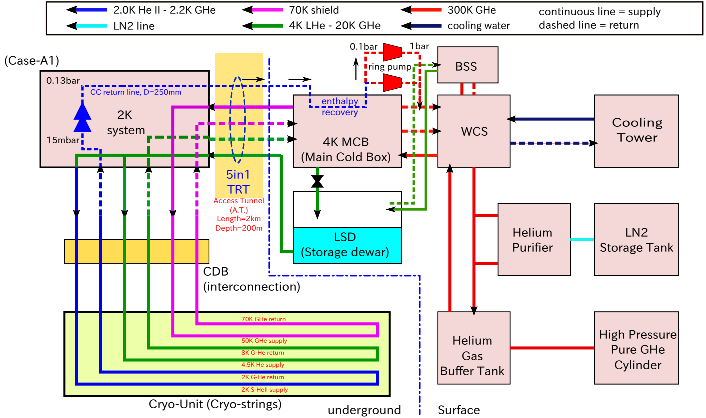
How to operate LSD



to perform quich response against emergency.

- **CASE-A:** LSD is always cooled by MCB.
- **CASE-B:** LSD is always cooled by BSS.
  $\Rightarrow$ To improve responsiveness, 2in1 TRT had better be used between MCB and LSD.

5in1 TRT with 2K return gas line with large diameter instead of 2K-WCS

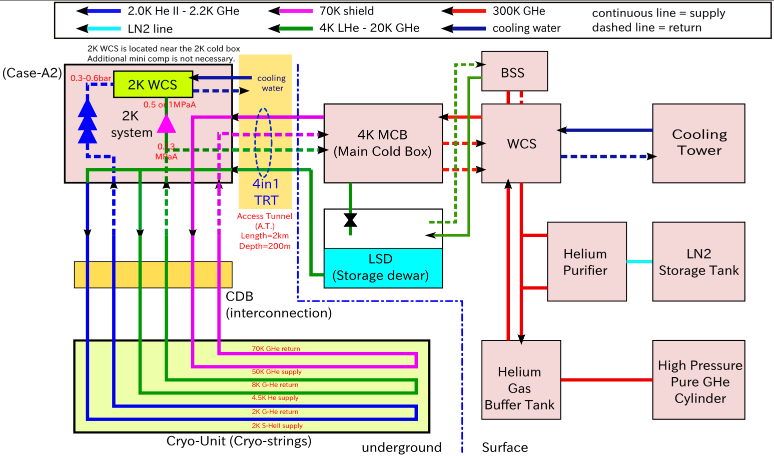


- **Large size of ring pump (0.1bar to 1bar) should be necessary instead of 2K-WCS.**
- **Return pipe through access tunnel is 250mm in inner diameter to reduce pressure drop. So diameter of 5in1 TRT is very large. (not sophisticated scheme!)**

Unrealistic scheme!!

Case-A (2)

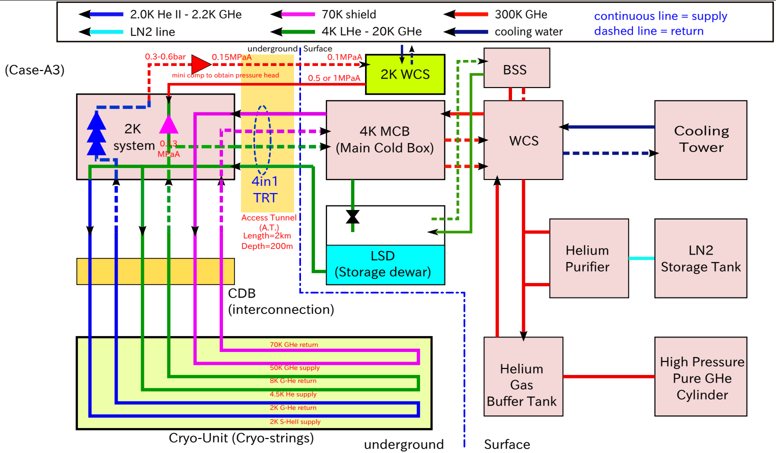
2K-WCS is installed in cavern.



- Most of enthalpy with 125g/sec of GHe is recovered to 4K MCB.
- Cooling water for 2K-WCS should be prepared with the 1500L/min.
- We have to do research on how vibration from 2K-WCS affects ML.

Case-A (3)

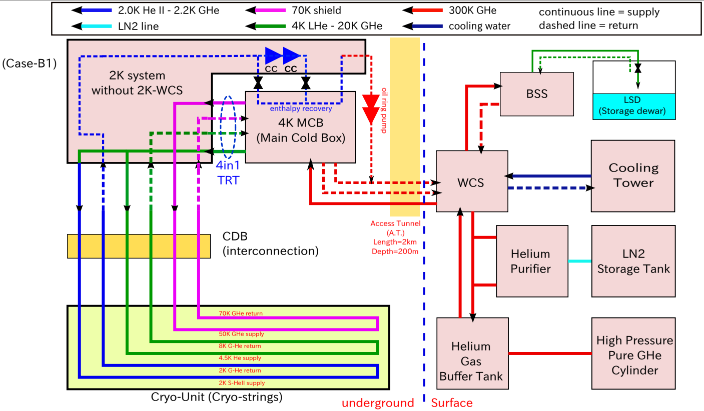
2K-WCS is installed on surface.



- Most of enthalpy with 125g/sec of GHe is recovered to 4K MCB.
- Very long warm He gas lines (supply and return) should be laid through the access tunnel.
- Effect of vibration from WCS may be reduced.

Case-B1

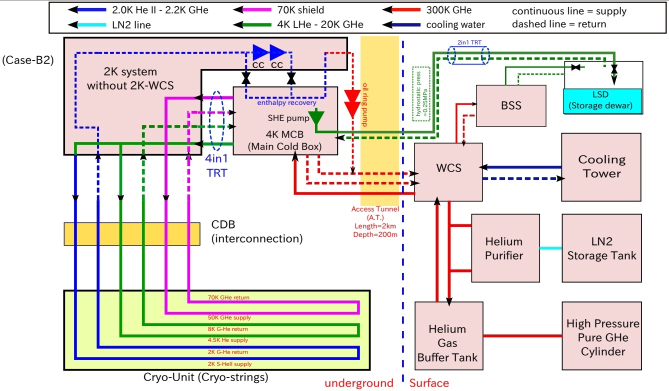
- 4K-MCB and 2K system are comvined and installed in cavern.
- No cryogenic pipe through access tunnel.



- Enthalpy of 2K return gas is recovered in MCB.
- In order to storage LHe in LSD, BSS with middle size had better be employed because He pipes between surface and underground are just warm pipes.

Case-B2

- **4K-MCB and 2K system are comvined and installed in cavern.**
- **2in1 TRT through access tunnel between 4K-MCB and LSD. .**



- In order to overcome the pressure drop and hydrostatic pressure in 2in1 TRT through access tunnel, **SHE pump** (3bar to 5bar) has to be installed in 4K-MCB.
- In order to improve recovery response, cold helium gas should be supplied to the 2in1 TRT continuously during operation (precooling operation).

Evaluation of Baby Sitter System (BSS)

Helium inventory
(total = 10 cryo-unit)

Pipes	Inventory %	Inventory per cryo unit (L)	Inventory per cryo unit (L)
2K supply	12.3	79967	544879
2K return	1.71	11117	
2 phase pipe	0.09	585	
2K He vessel in RF cavity	69.71	453210	
5K supply	9.32	60593	83022
8K return	3.45	22430	
40K supply	2.2	14303	22098
80K return	1.199	7795	
Total Helium inventory	99.979	650000	650000

The total helium inventory in ILC will be roughly equal to that of the LHC at CERN, about 650,000 liquid liters, or about 100 metric tons

Heat Load Estimation

		40K-80K	5K-8K	2K
predicted module static heat load	W/module	59.19	10.56	1.7
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- In case of an emergency (WCS is stopped), total mass flow rate of helium return gas due to "static" heat load is 130 ∼ 200 g/sec.[2] Corresponding BSS (middle class) is as follows.
    - **Compressor for BSS: 700kW axial power**
    - **Cold Box for BSS: 2.0kW (COP_{irr}∼ 330 W/W)**
- In the case that small BSS (like TCF50) is employed,
    - Case-B(2) is better than Case-B(1) because LHE can be recovered by 4K-MCB in addition to BSS.
    - If 1000 m^3 buffer tank with allowable pressure of 2 MPa can be prepared on surface, emergency shutdown time of WCS for 4 hours can be acceptable. In this case, 36 % of He inventory can be recovered in the buffer tank.

[2] 200 g/sec includes contingency which is around 1.5 times larger than estimated value. And thermo physical state of 5K shield is regarded as LHE with 4.5 K.

Summary on Helium pipes through access tunnel

- Basic equation [a]

$$\Delta p = \lambda \frac{L}{D}\frac{1}{2}\rho_{pt}u^2, \qquad \lambda = \max[0.02,\ 0.3164/Re^{0.25}], \qquad Re = \frac{uD}{\nu_{pt}}$$

[a] $\rho_{pt} \stackrel{\text{def}}{=} \rho(p,T)$ and $\nu_{pt} \stackrel{\text{def}}{=} \nu(p,T)$ indicate He density and kinematic viscosity which are functions of p and T. 0.02 means a kind of safety factor to do practical pipe design.

Option	4in1 TRT or 5in1 TRT						2in1 TRT			warm helium pipes for WCS			warm pipe for 2K WCS	
	shield sup	shield ret	4K sup	20K ret	2K ret	vacuum jacket	4K sup	4K ret	vacuum jacket	HP	MP	LP	HP	LP
Case-A(1) 5in1 TRT	100	100	65	100	220	600								
Case-A(2) 4in1 TRT	100	100	65	120	-	500								
Case-A(3) 4in1 TRT	100	100	65	120	-	500							100	150
Case-B(1) warm										225	250	360		
Case-B(2) 2in1 TRT							50	80	190	225	250	360		

unit : [mm]

Cryogenic Efficiency Comparison

- Input power to obtain 4.5K equivalent cooling capacity for one cryo-unit are roughly re-estimated.
- Reference equivalent cooling capacity is 19.57 kW.
- Additional heat load are added to the reference value.
- Input powers are roughly obtained by considering COP.

Option	4K-MCB			WCS	2K-WCS	BSS		WCS for BSS	Total input Power for one Cryo-Unit	Appendix
	4.5K equivalent power for one cryo-unit (TDR)	Additional heat load from TRT	COP	Calculated power input of WCS	estimated power input of 2K-WCS (125g/sec)	cooling capacity	COP	Calculated power input of WCS		
	(kW)	(kW)	(W/W)	(kW)	(kW)	(kW)	(W/W)	(kW)	(kW)	
Case-A(1)	19.57	0.4	218.7	4367	0	0.28	330	92.4	**4460**	unrealistic
Case-A(2)	19.57	0.4	218.7	4367	440	0.28	330	92.4	**4900**	vibration
Case-A(3)	19.57	0.4	218.7	4367	440	0.28	330	92.4	**4900**	-
Case-B(1)	19.57	0	218.7	4280	0	2	330	660	**4940**	large BSS
Case-B(2)	19.57	1.2	218.7	4542	0	0.28	330	92.4	**4635**	SHE pump
reference	A	B	C	D=C*(A+B)	E	F	G	H=G*F	**I=D+E+H**	

High Efficiency Claude Cycle

Case-B(2) > Case-A(2) = Case-A(3) > Case-B(1)

"High Efficiency" ∩ "low vibration"

Case-B(2) > Case-A(3) > Case-B(1)

Cost Evaluation

	Access Tunnel				4K system	2K system			Baby Sitter CB	Total Cost
	cold pipe	warm pipes (Diameter)				2K-WCS	cryogenic view point	Cooling water in cavern		
Case-A1	5in1 TRT (OD=550mm)	-	-	-	19kW w/o LSD	-	enthalpy loss	-	small class @ 280W	10.5 GJPY
Case-A2	4in1 TRT (OD=450mm)	-	-	-	19kW w/o LSD	o	-	o	small class @ 280W	8.3 GJPY
Case-A3	4in1 TRT (OD=450mm)	150mm from 2K system	100mm to 2K system	- -	19kW w/o LSD	o	-	-	small class @ 280W	10.3 GJPY
Case-B1	-	HP=225mm	MP=250mm	LP=360mm	19kW w/ LSD	-	-	-	middle class @2kW	7 GJPY
Case-B2	2in1 TRT (OD=200mm)	HP=225mm	MP=250mm	LP=360mm	19kW w/ LSD + SHE pump	-	-	-	small class @280W	6.5 GJPY

SHE pump :: 4.5K 3bar -> 4.5 K 5bar

Specification of 2K-WCS : mass flow rate = 125 g/sec
1bar →5bar at CC@AL, 1bar →10bar at CC@IHI

How to evaluate?

- **Cost**
  - **TRT :** 30E4 JPY/m@4in1 TRT, 10E4 JPY/m@2in1 TRT, 40E4 JPY/m@5in1 TRT
  - **Warm Pipes:** 5E4 JPY/m
  - **WCS,BSS :** 8E7 JPY/WCS, 280W-CB:1.5E8 JPY/CB, 2kW-CB:4.0E8 JPY/CB
- **Access Tunnel**
  - Length / Depth = 2000m / 200m
  - Number of Cryo-Facility = 10

Operation cost difference between A(3) and B(2) per year is 21 million JPY which is estimated from input power of WCS by assuming 7 month operation and 12JPY/kWh.

Scheme Evaluation

Candidate scheme

Candidate scheme is "**Case-A(3)** [a] and **Case-B(2).**

[a] If 2K-WCS can be located in cavern from the view point of vibration and cooling water with 1400L/min, Case-A(2) is more sophisticated scheme than Case-A(3).

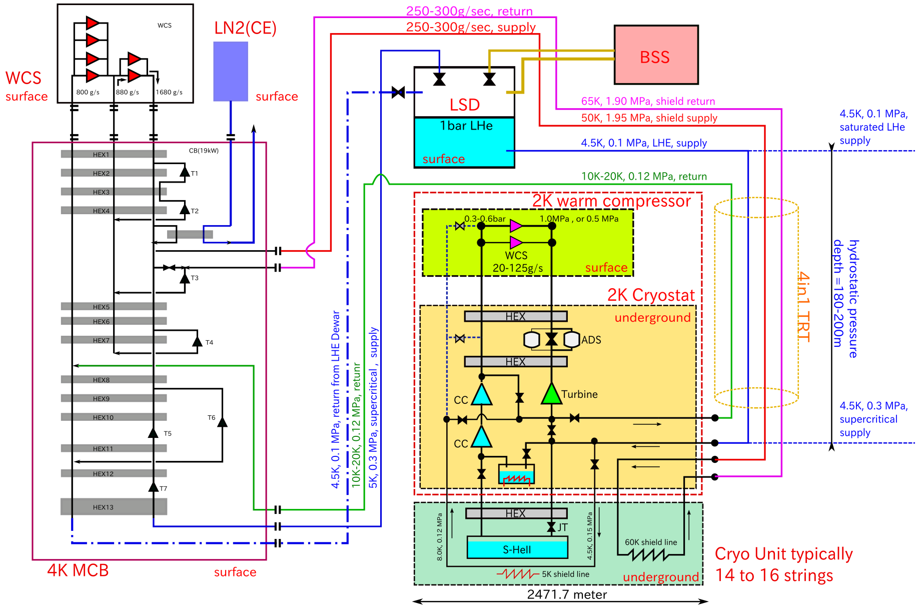
Cryogenics

- **Efficiency**
  ⇒ Case-B (1.1 times higher)
- **Reliability for breakdown**
  ⇒ Case-B
  - small number of cryogenic components
  - no 2K-WCS, expansion turbine for 2K system
  - 4in1 Multi-TRT with short length

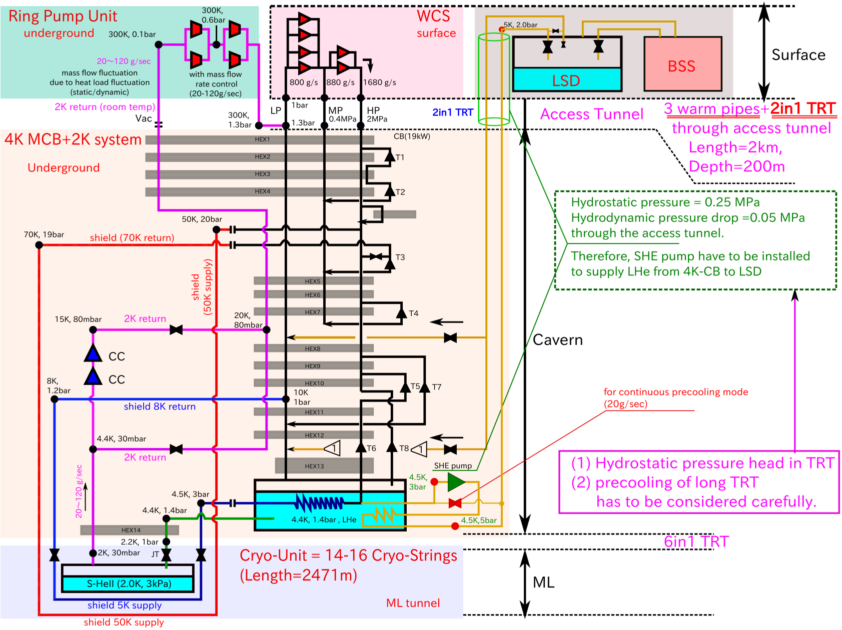
Other Items

- **Cost**
  ⇒ Case-B
- **Safety**
  ⇒ Same
- **Daily Check**
  ⇒ **4K-System**: Case-A(3)
  ⇒ **2K-System**: Same
- **Redundancy** :
  ⇒ Same
- **LN2 applicable for 4K-MCB**
  ⇒ Case-A(3)

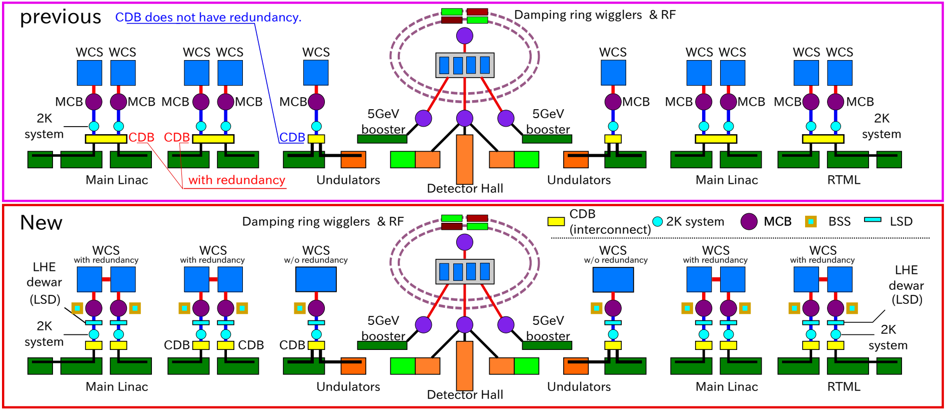
Summary: Flow Diagram of Case-A



Summary: Flow Diagram of Case-B

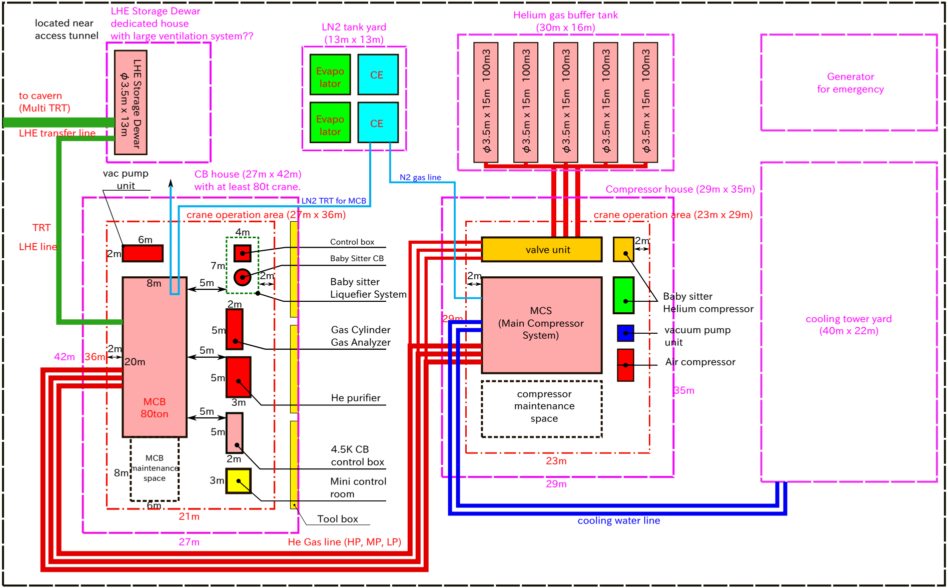


Redundancy–System Overview



- **Compressor:**
  - Two WCSs are linked each other for redundancy except both side of IR.
- **CDB does not have a function of redundancy but a interconnect between 2K-system and Cryo-Unit.**
- BSS has a function of redundancy in case of an emergency.

Surface Configuration (Case-A)



Summary

1. **Main WCS and LSD are located on surface. (change scheme)**
2. **BSS have to be employed for LSB and is located on surface. BSS has CB and WCS with small or middle class.**
3. **Location of 4K-MCB is not determined so far. But two schemes so called Case-A and Case-B are proposed.**
   - **Case-A: $\Rightarrow$ 4K-MCB is on surface.**
     - 2K-WCS has to be prepared to recover enthalpy effectively.
     - 4K-MCB and LSD are linked each other.
   - **Case-B: $\Rightarrow$ 4K-MCB is in cavern.**
     - 2K-WCS does not have to be employed.
     - 2K-system and 4K-MCB are combined each other
     - Simple TRT had better be employed between 4K-MCB and LSD.
   - **Cryogenic schemes on Case-A and Case B are proposed in this presentation.** $\Rightarrow$ (see pp-24, pp-25).
   - From the view point of cost, Case-B is relatively reasonable scheme.
   - From the cryogenic view point, Case-B seems relatively reasonable scheme.
   - From the maintenance view point, Case-A seems better than Case-B.
   - From the view point of breakdown reliability, Case-B seems better than Case-A.
4. **Redundancy:** Two main-WCSs are linked each other.
5. **Emergency:** BSS is prepared near the LSD.