Current status and challenges of cryogenic systems for RAON accelerator

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- Requirements and challenges
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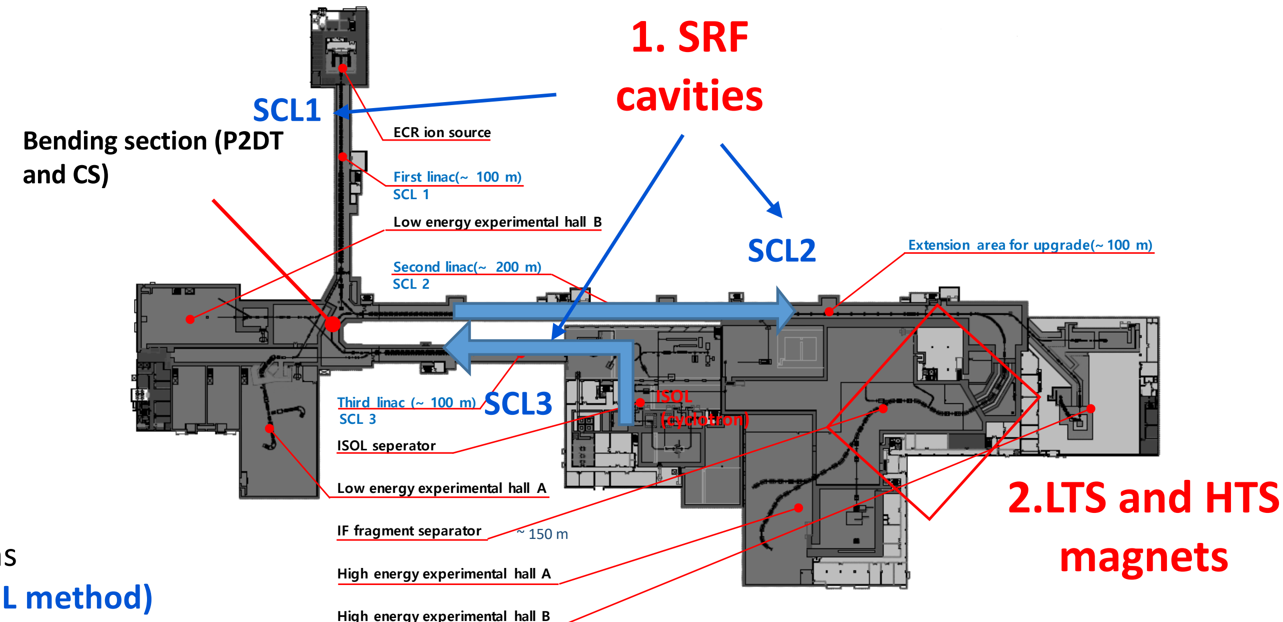
- Summary

RAON accelerator (ISOL + IF)

- Heavy ion linear accelerator

(Isotope Separation On-Line + In-flight Fragment separator <u>for Rare Isotope beams</u>)

- Three SuperConducting LINACs (SCL)
- Third Linac (SCL3) : accelerate unstable beams ($^{132}Sn^{47+}$) made by ISOL and stable beams made by ECR (~2020)
- Second Linac (SCL2) : reaccelerate stable or rare isotope beams from SCL1 and SCL3 (~2021)
- First Linac (SCL1) : accelerate stable beams ($^{1}H^{+}$, $^{16}O^{8+}$, $^{238}U^{79+}$) made by ECR and charge stripper (in the future)



Our options

Cyclotron -> ISOL -> SCL3 (ISOL method)

<u>Cyclotron -> ISOL -> SCL3 -> SCL2 -> IF (ISOL + IF)</u>

ECR -> SCL1

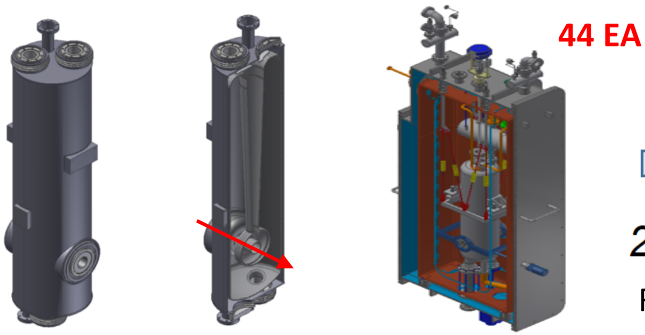
ECR -> SCL1 -> SCL2 -> IF (IF method)

More rare isotopes !

RAON accelerator

- SRF cavities in cryomodules (SCL 1, 2, and 3 LINACs)

Quarter Wave Resonator (4.5 K) and cryomodule **for SCL 1 & 3**

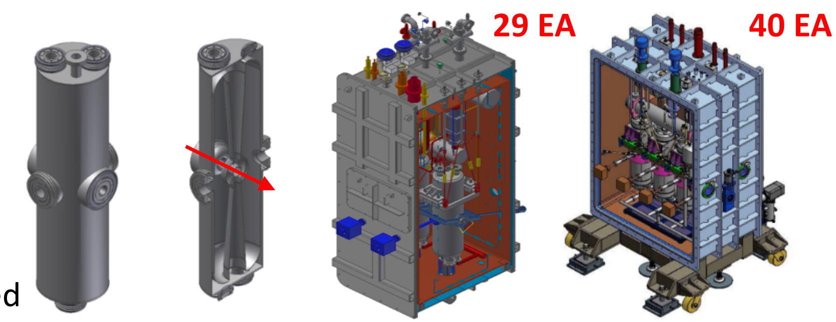


Resonance frequency : 81.25 MHz

$2d\nu_0 \le \beta c$

Freq. Speed

Half Wave Resonator (2.05 K) and cryomodules **for SCL 1 & 3**

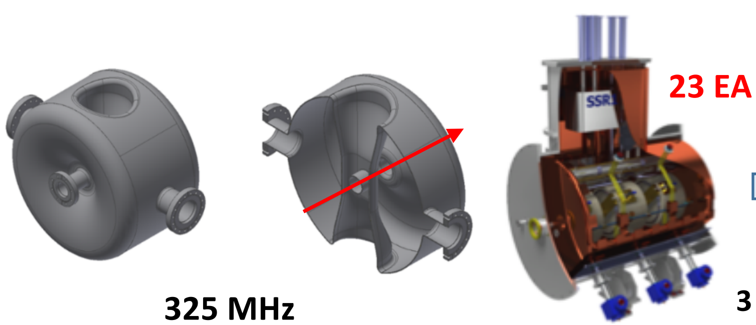


162.5 MHz

HWR A (2 cavities)

HWR B (4 cavities)

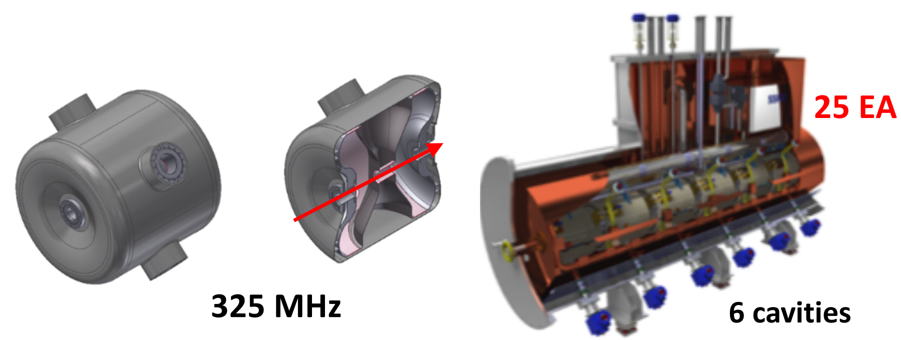
Single Spoke Resonator 1 (2.05 K) and cryomodule **for SCL 2**



325 MHz

3 cavities

Single Spoke Resonator 2 (2.05 K) and cryomodule **for SCL 2**

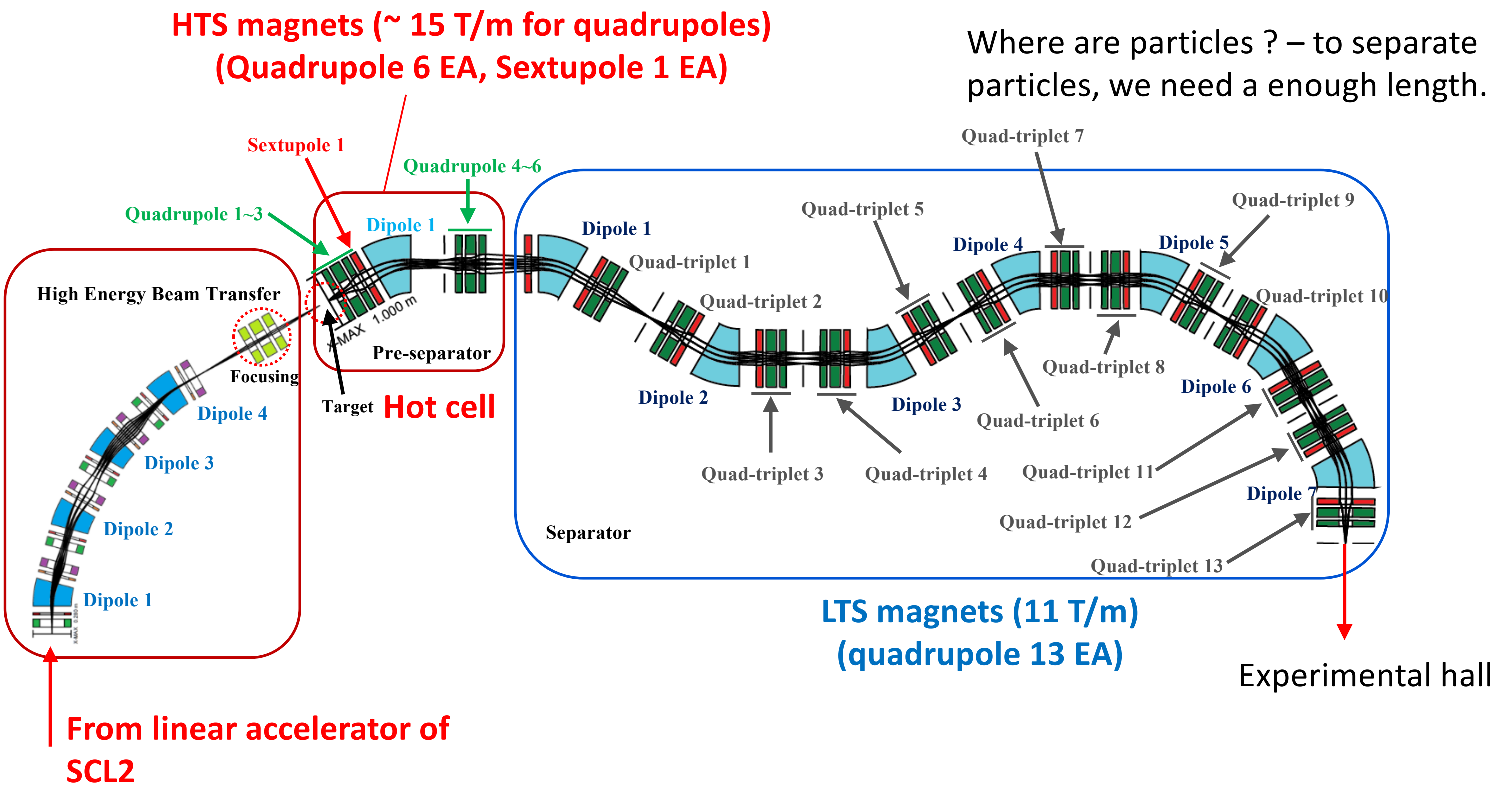


325 MHz

6 cavities

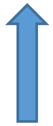
RAON accelerator

- LTS and HTS magnets (IF)



Requirements for cryogenic systems

- **Superconducting systems <u>(ISOL+IF)</u> in stable conditions (T, P)**
  - Cryomodules with superconducting cavities (bath cooling) @ LINACs **(SCL1, 2 and 3)**
    - ✓ QWR @ 4.5 K (44 EA), HWR (29 EA, 40 EA), SSR 1 (23 EA), and SSR 2 (25 EA) @ 2.05 K
    - ✓ Fast cool-down required fro QWR
    - ✓ Microphonics : Especially, helium pressure fluctuations
  - Superconducting magnets (LTS and HTS) @ IF separator
    - ✓ LTS magnets @ 4.5 K (13 EA, bath cooling)
    - ✓ HTS magnets (7 EA, heat transfer with gas helium in pipe) @ 35 K ~ 40 K
- Heat loads and operation modes
  - **21.4 kW ; equivalent heat load @ 4.5 K (dynamic + static heat loads)**
  - 2 K (cavities), 4.5 K (cavities, thermal intercepts, and LTS) and 35 K (HTS, thermal shields) circuits: **3 helium flows needed**
  - **5 operation modes**
    - ✓ Nominal mode : 100 % beam power
    - ✓ Beam commissioning mode : 25 % beam power
    - ✓ 2 K turndown mode : 0 % beam power, only static heat loads
    - ✓ 4.5 K standby mode + liquefaction : only static heat loads @ 4.5 K and no operation of cold compressors
    - ✓ TS mode : emergence mode (any failures of turbines and short maintenance), effective below 19 K of cavities' T



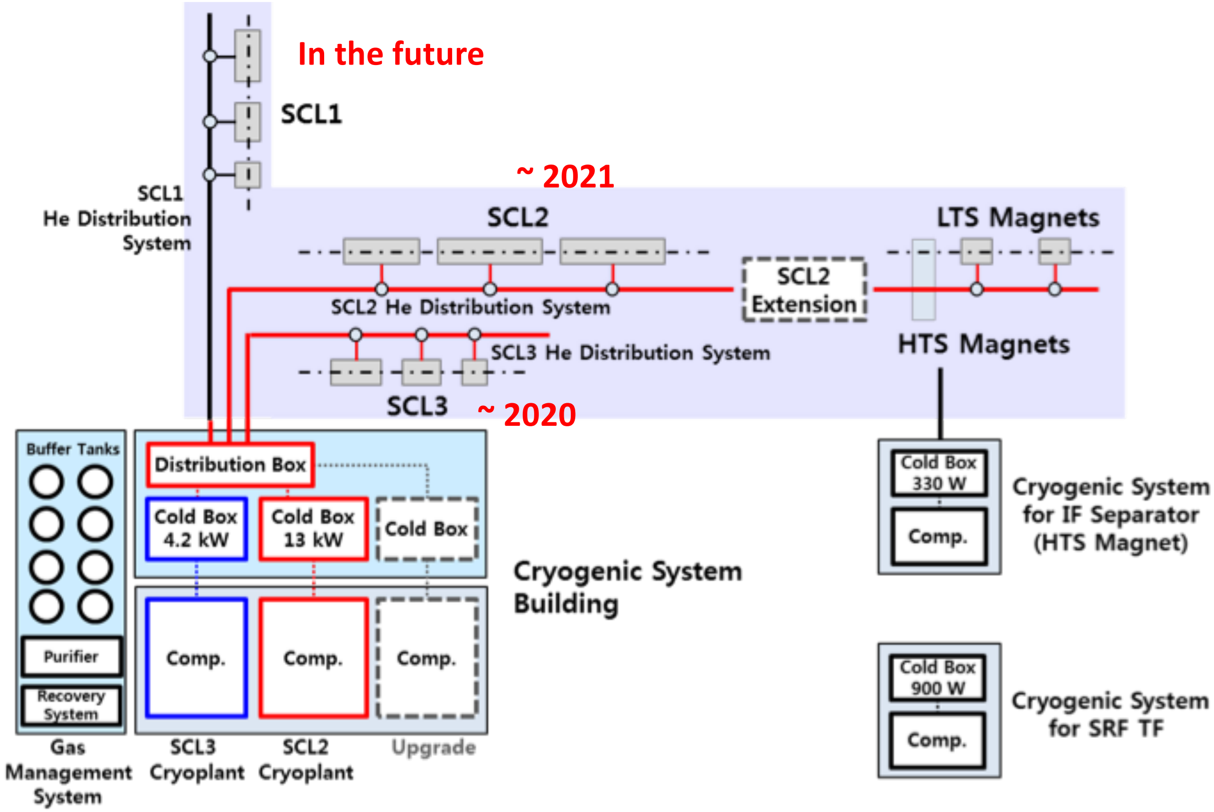
<u>+ Transient modes! (cool-down, warm-up…), interlocks</u>

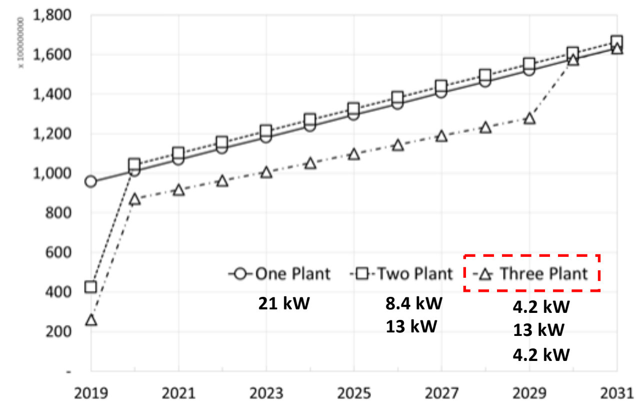
Challenges

- Various operations of beam lines (combination of SCL lines)
  - Operation strategy for SCLs : **how many cryoplants we need ?**
    - ✓ Installation and operation : first -SCL3, second -SCL2, third - SCL1;
      Long operation (goal : over 30 years)
    - ✓ Beam acceleration : SCL3-SCL2, SCL1-SCL2, SCL3, SCL1;
      A distribution box is necessary (flexibility with multi-cryoplants).
  - **Cool-down** and warm-up : how ?, How long time ?
    - ✓ **Fast cool-down** required (especially QWR : 150 K – 50 K within 2 hours; Q disease) and **slow cool-down** required (LTS magnets, 3 K/hr)
    - ✓ **Individual** cool-down and warm-up for cavities and magnets (replacements)
    - ✓ Strategies are necessary for cool-down and warm-up; + control logic
      (thermal stress VS requirement)
- Stability
  - **Pressure stability**
    - ✓ **±1 mbar @ 4.5 K, ± 0.3 mbar @ 2 K due to performances of cavities**
  - Safety @ various conditions : need dynamic simulation.
    - ✓ Quenches (LTS magnets) and leaks of insulation vacuum and LHe

Cryogenic systems – Three cryoplants

- Three cryoplants with Helium Distribution System





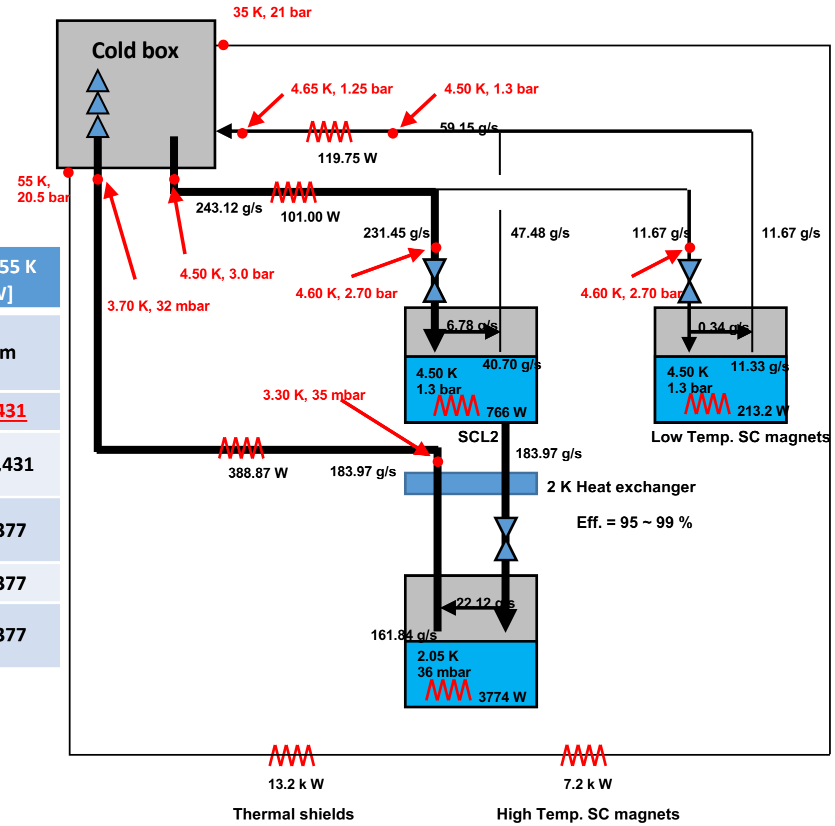
Each linac has each cryoplant.

Cryogenic systems – Three cryoplants

- Heat loads of SCL 2 cryoplant
  - Pre-study with ALAT and Linde
  - With 1.5 margin

SCL2 Cryo. Modes	2.05 K [W]				4.5 K [W]				35 – 55 K [W]
	Isothermal		Non-isothermal	Sum	Iso-thermal	Non-isothermal		Sum	Sum
	Static	Dynamic				Supply	Return		
Nominal	524	3,250	389	4163	980	101	120	1201	20,431
Beam commissioning	524	831	389	1744	980	101	120	1201	~ 20,431
2.05 K Turndown	524	-	389	913	980	101	120	1201	14,377
4.5 K standby	-	-	-		1504	101	509	2114	14,377
TS standby	-	-	-		-	-	-		14,377

Boundary conditions of SCL2 cold-box



Nominal mode

4.2 kW @ 2.05 K circuits, 1.2 kW @ 4.5 K circuits, 20.5 kW @ 35 K circuits

Cryogenic systems – Three cryoplants

- Heat loads of SCL 3 or 1 cryoplant
  - With 1.5 margin

SCL3 Cryo. Modes	2.05 K [W]				4.5 K [W]					35 – 55 K [W]
	Isothermal		Non-isothermal	Sum	Isothermal		Non-isothermal		Sum	Sum
	Static	Dynamic			Static	Dynamic	Supply	Return		
Nominal	199	519	263	981	378	401	70	77	926	11,757
Beam commissioning	199	191	263	653	378	113	70	77	638	11,757
2.05 K Turndown	199	-	263	462	378	-	70	77	525	11,757
4.5 K standby	-	-	-		577	-	70	340	987	11,757
TS standby	-	-	-			-	-	-		11,757

Nominal mode

980 W @ 2.05 K circuits, 930 W @ 4.5 K circuits, 11.8 kW @ 35 K circuits

Cryogenic systems – Design of cryoplants

- PFDs of SCL3 cryoplant (ALaT)
  - HP : 15 bar (LP -> HP : 4 compressors, 1 back-up with VFD, Kaeser compressors)
  - 3 turbines (Isentropic eff. ~ 78 %)
  - 3 cold compressors with VFD + VLP pumps for 32 mbar (eff. ~ 70 %)
  - 4.2 kW @ 4.5 K equivalent, ~ 25 % Carnot efficiency
  - Recovery and external purifier (25 bara, 30 g/s)

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  - P stability : ±1 mbar @ 4.5 K and 35 K,
    ± 0.1 mbar @ 2 K

It will be commissioned in Q2 of 2020.

Cryogenic systems – Design of cryoplants

- PFDs (Pre-study) of SCL2 cryoplant : 13 kW @ 4.5 K equivalent
  - Now, bidding and contract phase

~ 27 % Carnot efficiency

No-LN2 precooling

HTS magnets and thermal shields

Customized compressors (4 or 5 EA and 1 back-up)

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SRF cavities and LTS magnets

VLP

3 cold compressors and 1 VLP compressor : for wide ranges of cooling capacity and cost efficiency

It will be commissioned in the end of 2020.

Cryogenic systems – DB of HDS system

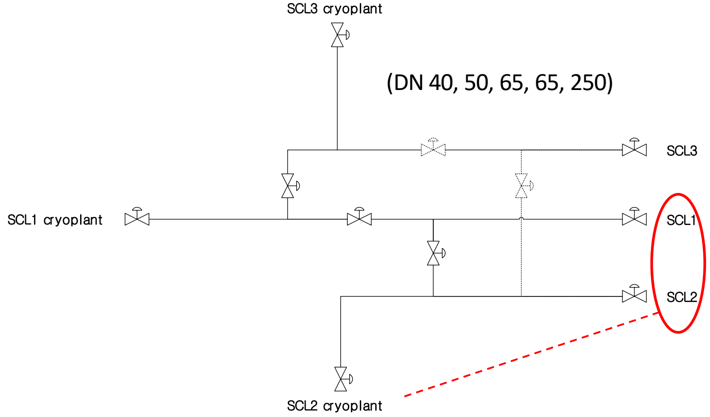
- Operation concept of Distribution Box (DB) (why we need it ?)

1. SCL3 line (2020~) with SCL3 cryoplant
   - ✓ SCL3 (partial loads) with SCL3 cryoplant – Settlement and test

2. SCL3 and SCL2 lines (2021~2024) with SCL3 and SCL2 cryoplants
   - ✓ SCL3 and SCL2 (partial loads) : SCL3 cryoplant (SCL3) and SCL2 cryoplant (SCL2) - Settlement
   - ✓ SCL3 and SCL2 (partial loads) : only SCL2 cryoplant
   - ✓ SCL3 and SCL2 (increased partial loads) : SCL3 cryoplant (SCL3) and SCL2 cryoplant (SCL2)

3. SCL3, SCL2, and SCL1 lines (in the future) with SCL3 and SCL2 cryoplants
   - ✓ SCL1 (partial loads) with SCL3 cryoplant – Settlement and test
   - ✓ SCL2 and SCL1 (partial loads) : only SCL2 cryoplant (similar with SCL3 and SCL2 case)
   - ✓ SCL3 and SCL2 (full loads) : SCL3 cryoplant (SCL3) and SCL2 cyroplant (SCL2)
   - ✓ SCL3 (full loads) with SCL3 cryoplant

4. SCL3, SCL2, and SCL1 lines (in the future) with SCL3, SCL2, and SCL1 cryoplants
   - ✓ SCL2 (full load), SCL3 (full load), SCL1 (full load) : three cryoplants



'9 sections (valves) required to satisfy beam-operation strategies'

Cryogenic systems – DB of HDS system

- Current status of DB

<u>**54 cryogenic valves**</u>

Estimated heat loads in DB
~ 865 W @ Thermal shield's circuit
~ 34 W @ 4.5 K circuit
~ 90 W @ VLP flow

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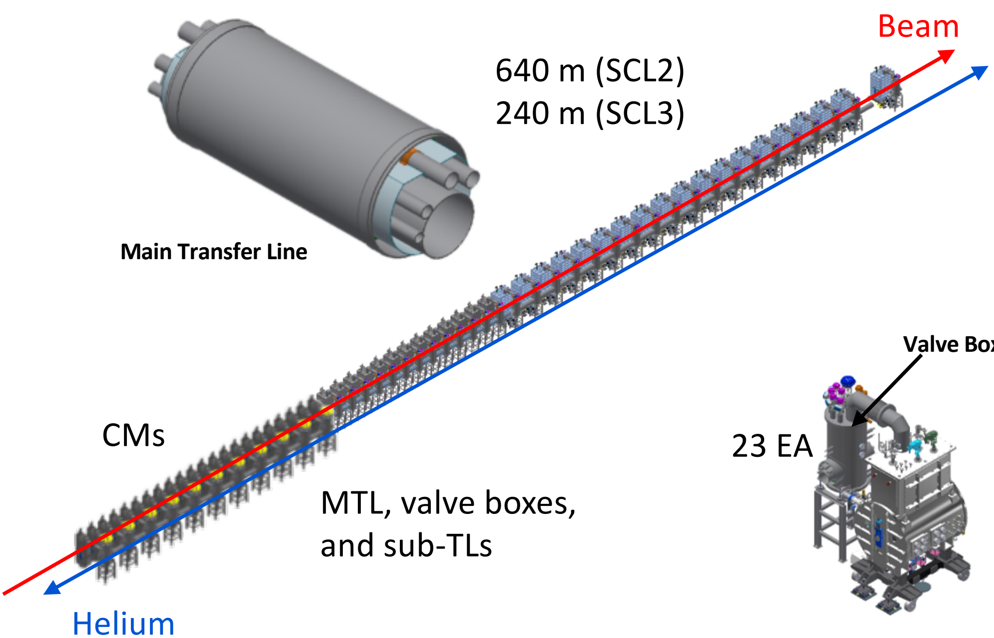
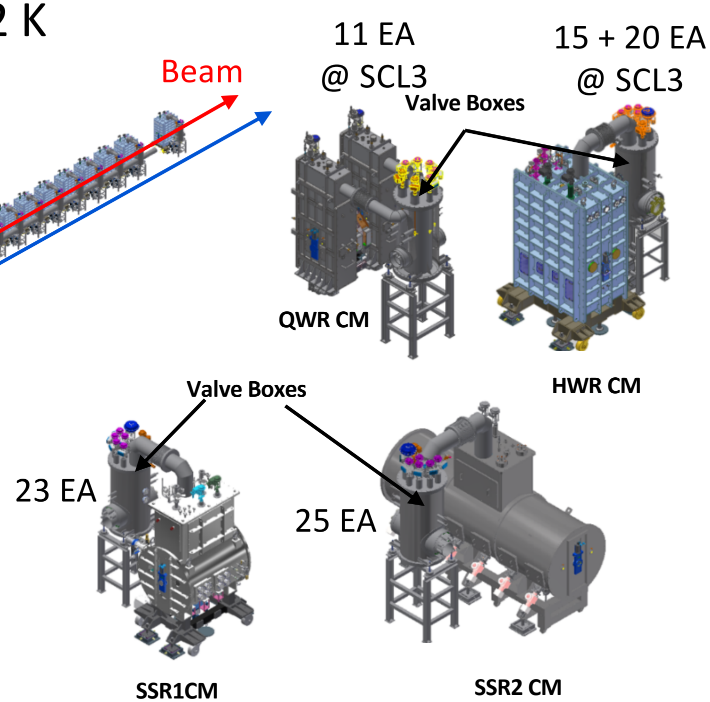
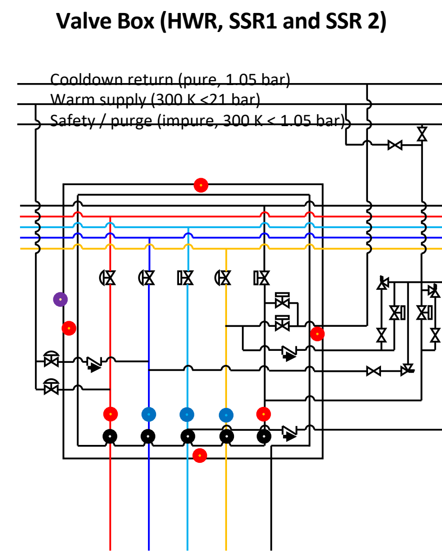
<u>**It will be fabricated in the end of 2019.**</u>

Cryogenic systems – HDS system for SC systems

- Transfer lines and valve boxes (to supply and return helium flows)
  - MTLs : TS supply and return, SHe supply and GHe return, VLP return (HWR, SSR 1 and 2: 5 pipes, QWR : 4 pipes) + Sub-TLs
  - Valve boxes : To supply and return required helium flows to/from CMs and MGs,
    To cool down and warm up SC systems with mixed helium flows
  - P stability : ±1 mbar @ 4.5 K and 35 K,
    ± 0.3 mbar @ 2 K





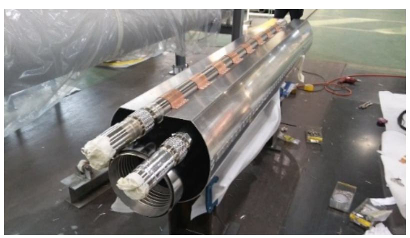


780 EA cryogenic valves for SCL2 and 3 valve boxes

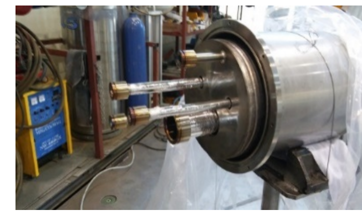
It will be fabricated in 2019 (SCL3) and 2020 (SCL2).

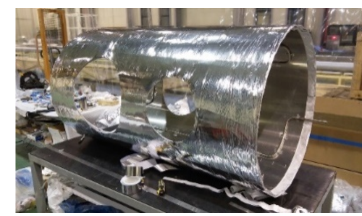
Cryogenic systems – HDS system for SC systems

- HDS prototype test (finished)



Main transfer line



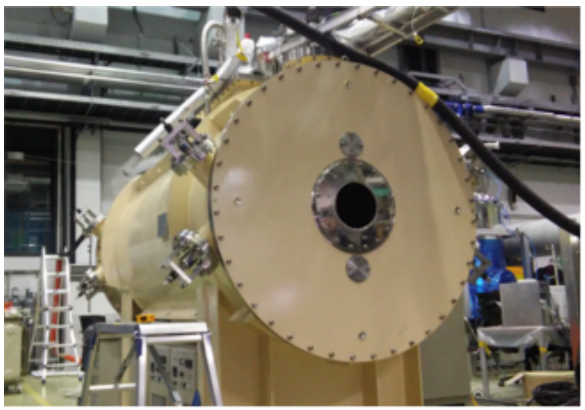


Valve box

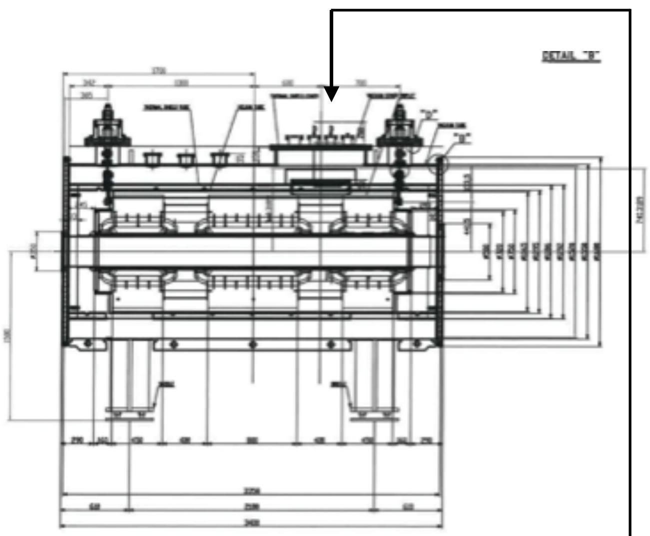
	MTL	VB (thermal shield)	Sub-TL with vacuum barrier
Required heat leaks	≤ 0.5 W/m (equiv. @ 4.5 K)	≤ 2.0 W/m² @Thermal shield	≤ 2.5 W/ea (equiv. @ 4.5 K)

Cryogenic systems – LTS magnets (13 EA)

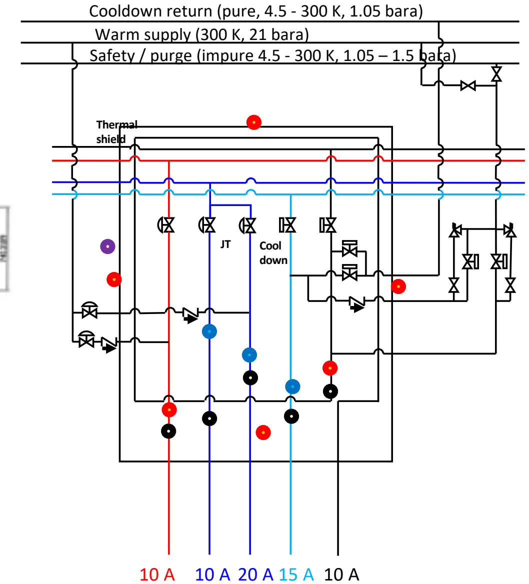
- Cooldown method (slow cool-down)
  - Basically, with cold-box of SCL2 cryoplant and HDS, simultaneously
  - Helium flows controlled by valve boxes (JT, cool-down valves included)
- Estimated heat load (bath cooling)



Quadrupole magnet triplet Tested in this Oct.



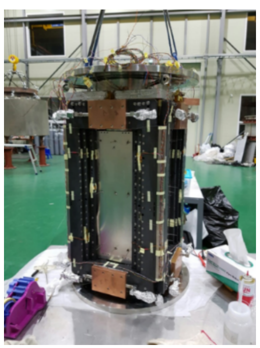
11 T/m

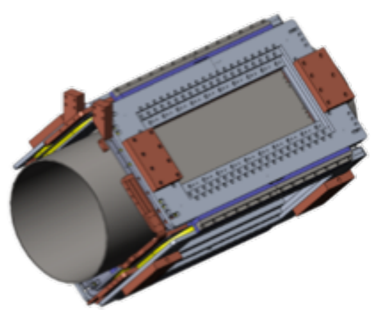


# of magnet	Heat load [W] @ Quadrupole magnet triplet	
	4.5 K	35 – 55 K
LTS #1	10.92	159.84
LTS #2~#13	8.52	145.76

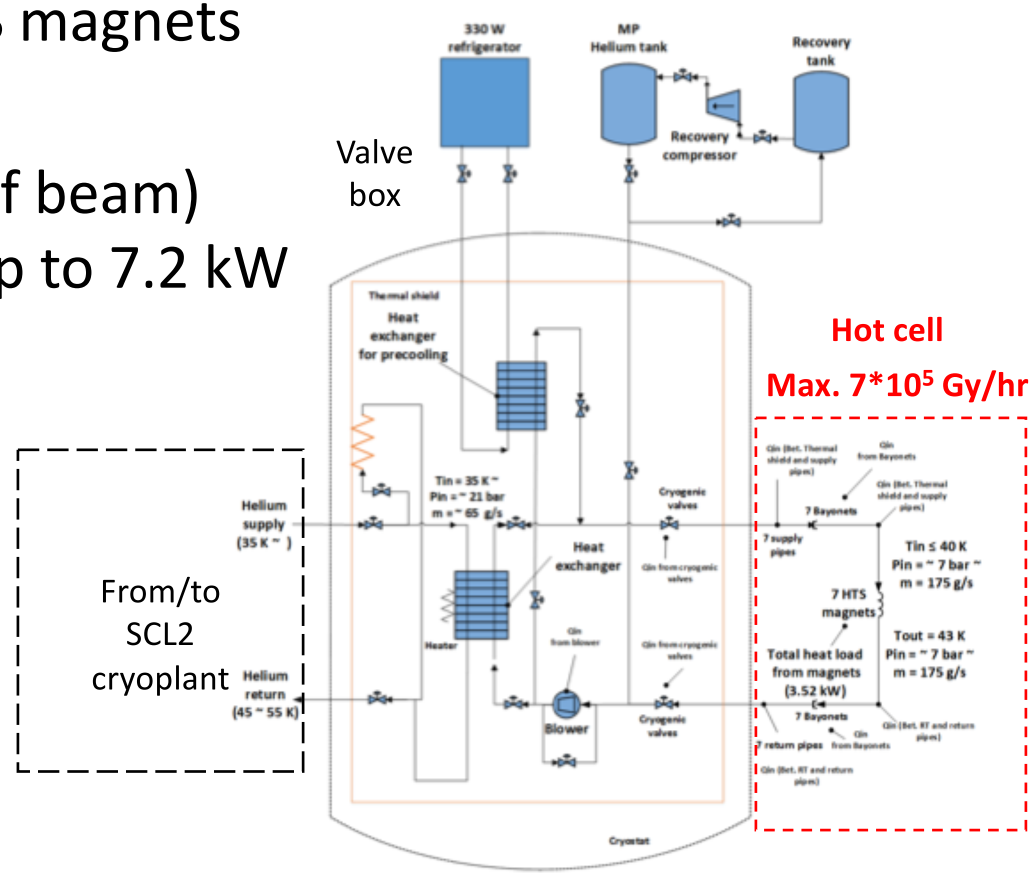
Cryogenic systems – HTS magnets (7 EA)

- Cooldown method (to be determined)
  - Mainly, from SCL2 cryoplant
  - Back-up : 330W refrigerator just for cooldown (while the SCL2 cryoplant already is cooled down)
  - Closed loop for cooling HTS magnets
- Estimated heat load
  - 3.52 kW @ 40 K (full load of beam)
  - Cooling system : possible up to 7.2 kW





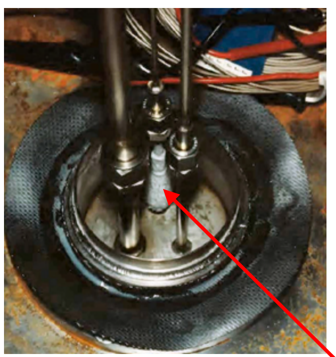
Prototype of HTS quadrupole magnet



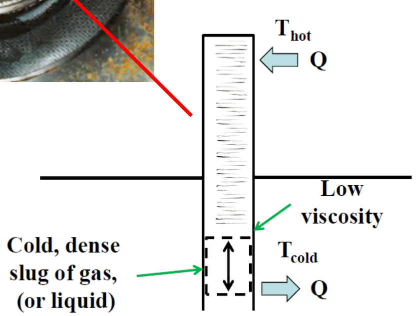
Cryogenic systems – TAO

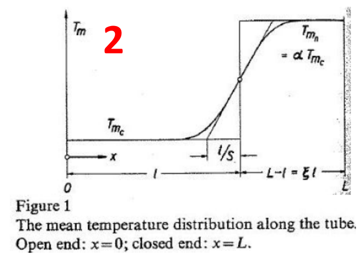
- TAO (Thermo Acoustic Oscillation) is very important !
  - Cold gas enters the warm end and rapidly expands and makes TAO.
  - The pressure oscillation can shift the resonance frequencies of SRF cavities and the shifted ranges should be in possible tuning range (tuners).

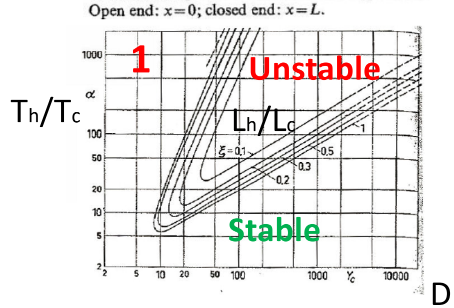
Remember : our need
±1 mbar @ 4.5 K, ± 0.3 mbar @ 2 K



Where ?
Safety lines in 2 K and 4.5 K regions

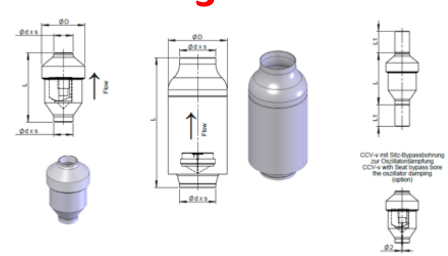






Small seat bore :
to dampen oscillation
and to avoid chattering

3



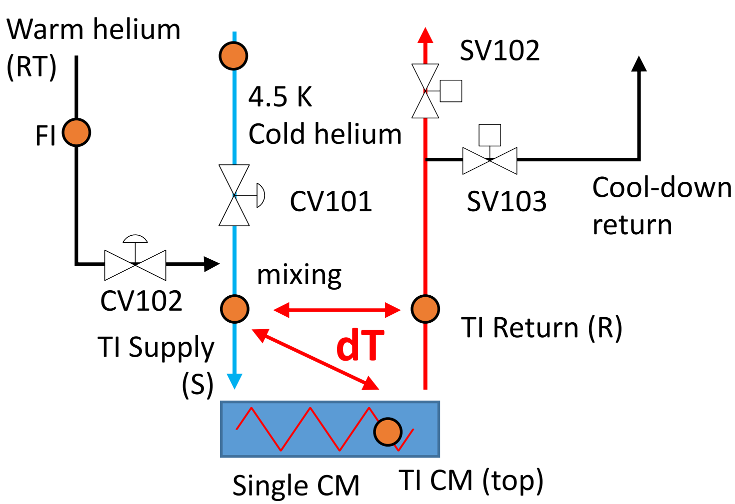
Solutions
1. **Tube dimensions (by using map)**
2. **Thermal anchoring (smooth dT)**

3. Block (cryo-checkvalve)

Cryogenic systems – Cool-down method

- Cool-down (updating)
  - Step by step
    - ✓ Basically, cryoplants with HDS system and thermal shields of SC systems (simultaneously)
    - ✓ In the case of SCL2 cryoplant, LTS magnets (3 K/ hour) will be cooled down with the SCL2 cryoplant.
    - ✓ SC cavities (150 K – 50 K within 2 hours for QWR; Q disease, others; fundamentally no requirement for fast cool- down, but if possible fast cool-down is preferred)
    - ✓ Mixing method, we need to think about total cool-down time. ~ 1 month ?

Mixing method



Fast cool-down VS thermal stress

1. TI R. - TI S. < 20 K
TI R. – TI S. > = 50 K : close supply valves to protect CMs
There are steps (300 – 280 K, 280 – 260 K, 260 – 240 K, ….100 – 90 K,…, 20 -10 K), first TI supply = 280 K, next step become to 260 K.

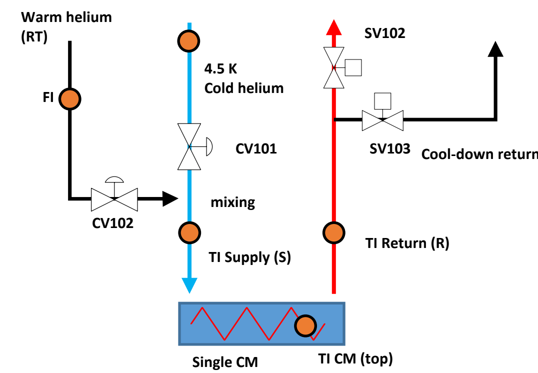
Cryogenic systems – Cooldown method

- Rule of Thumb

For checking the possibility of cool-down with the method and cool-down time,

1. Development of excel sheet to calculate required mass flow rates of mixed cold and warm helium (**it uses enthalpy balance and perfect heat transfer.**)
2. To get some margins, complete the fast cool-down from 300 K to 50 K within 2 hours

Example for QWR's CM

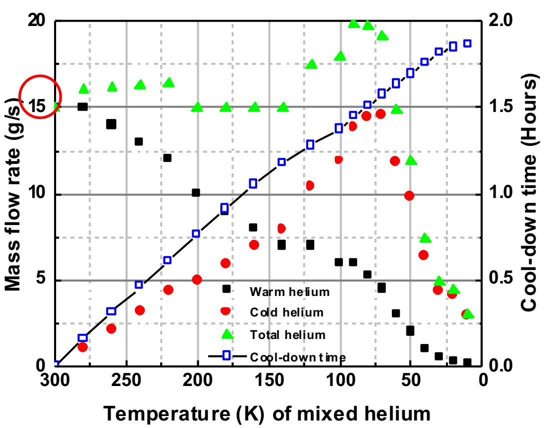


Cold mass @ 4.5 K

CM's thermal shield region	[g]
Al	110000
SUS	
Total	

CM's 4.5 K region	[g]
Al	
Ti	22000
Nb	24000
SUS	65000
Total mass for 4 K cooldown	111000

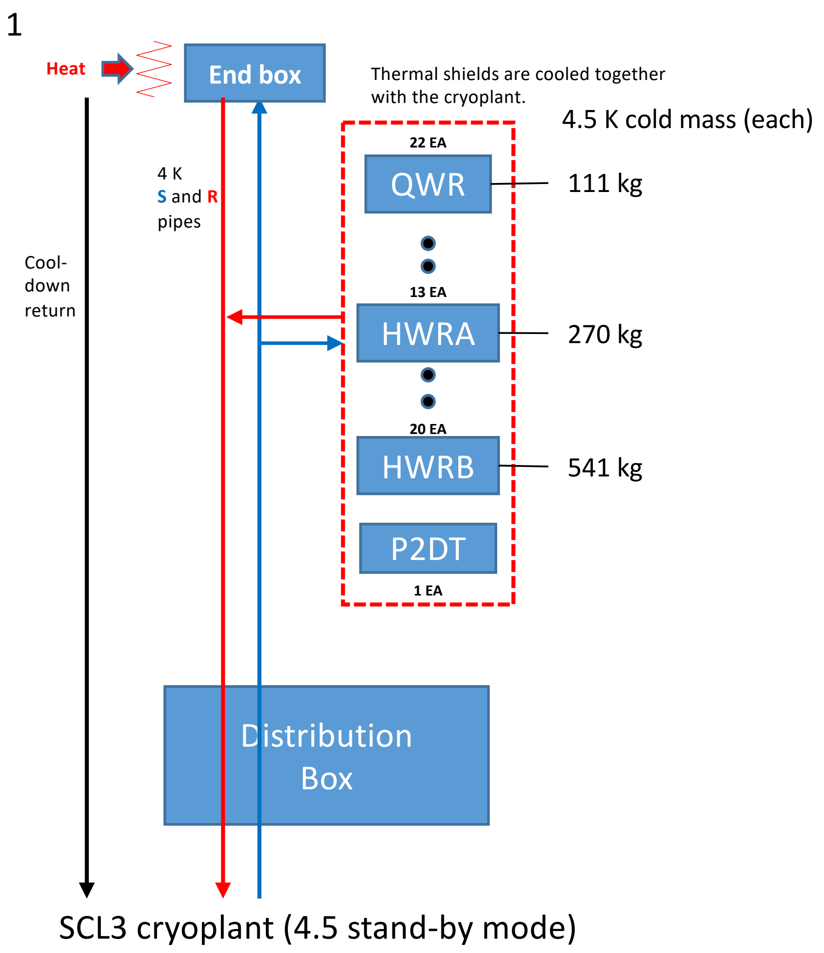
Temperature (K)	Ti enthalpy (J/g)	Nb enthalpy (J/g)	SUS304 enthalpy (J/g)	Aluminum enthalpy (J/g)	Helium enthalpy [J/g]	Temperature change	Average Enthalpy [J/g]	Enthalpy change [J/g]
300	99.8	56.6	89.2	170.4	1573.999084	300	84.25225225	
280	89.5	51.4	79.8	152.5	1470.141423	300 to 280	75.58198198	8.67027027
260	79.4	46.2	70.7	135	1366.283175	280 to 260	67.12702703	8.454954955
240	69.5	41	61.9	117.8	1262.42405	260 to 240	58.88738739	8.23963964
220	59.8	35.9	53.4	101	1158.563625	240 to 220	50.88468468	8.002702703
200	50.4	30.9	45.2	84.8	1054.701261	220 to 200	43.13873874	7.745945946
180	41.4	26.1	37.4	69.2	950.8359698	200 to 180	35.74954955	7.389189189
160	33.1	21.4	30.1	54.5	846.9661635	180 to 160	28.81351351	6.936036036
140	25.4	17.1	23.3	40.7	743.0891832	160 to 140	22.37567568	6.437837838
120	18.4	12.9	17.1	28.4	639.200315	140 to 120	16.44954955	5.926126126
100	12	9	11.3	17.76	535.2905615	120 to 100	10.94144144	5.508108108
90	9.1	7.2	8.7	13.25	483.3226212	100 to 90	8.454954955	2.486486486
80	6.7	5.6	6.4	9.37	431.3409133	90 to 80	6.286486486	2.168468468
70	4.5	4.1	4.4	6.15	379.3387563	80 to 70	4.354954955	1.931531532
60	2.8	2.8	2.8	3.64	327.3047897	70 to 60	2.8	1.554954955
50	1.6	1.8	1.6	1.85	275.2182331	60 to 50	1.643243243	1.156756757
40	0.74	1.1	0.831	0.755	223.037087	50 to 40	0.871126126	0.772117117
35				0.436	196.8847162			
30	0.23	0.607	0.357	0.232	170.6631406	40 to 30	0.385882883	0.485243243
25				0.112	144.330598			
20	0.048	0.36	0.127	0.048	117.8039301	30 to 20	0.161720721	0.224162162
15				0.018	90.88693349			0
10	0.006	0.16	0.029	0.0049	62.92694984	20 to 10	0.052765766	0.108954955
8				0.0026	50.83397144			
6				0.00121	36.12141543			
4.5	0.0007	0.001	0.0045		11.66466601			

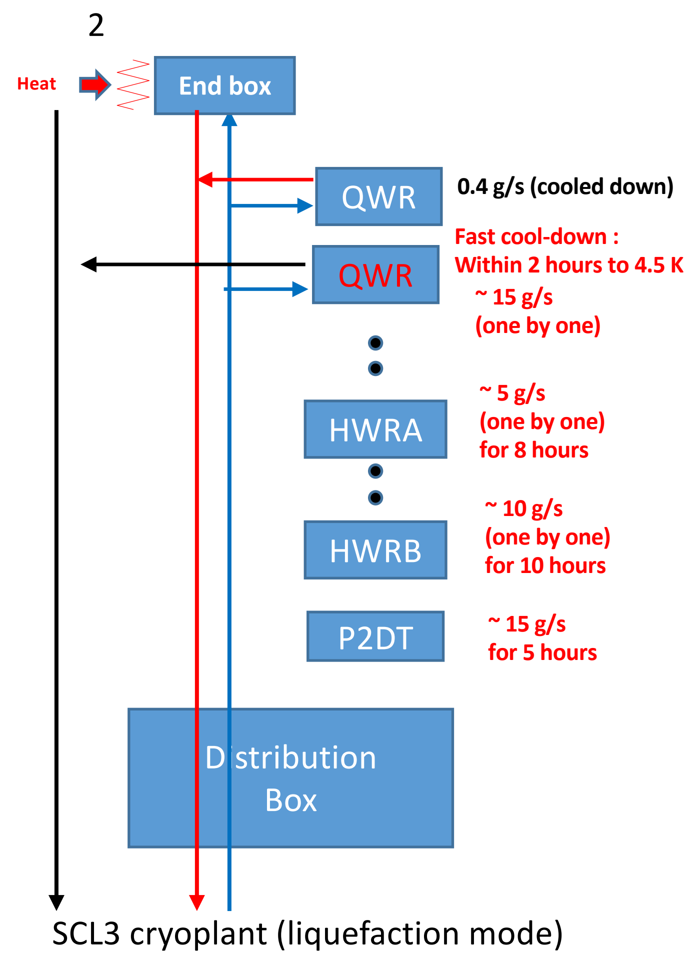


Maximum flow of cold helium : ~ 15 g/s
Maximum flow of mixed helium : ~ 20 g/s

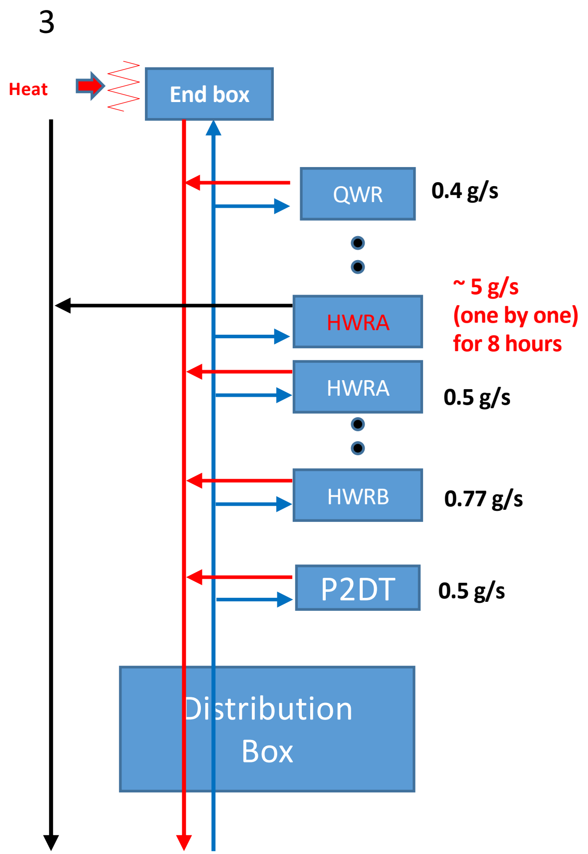
Cryogenic systems – Cooldown method (in the study)

- Cool-down of SCL3 line with SCL3 cryoplant

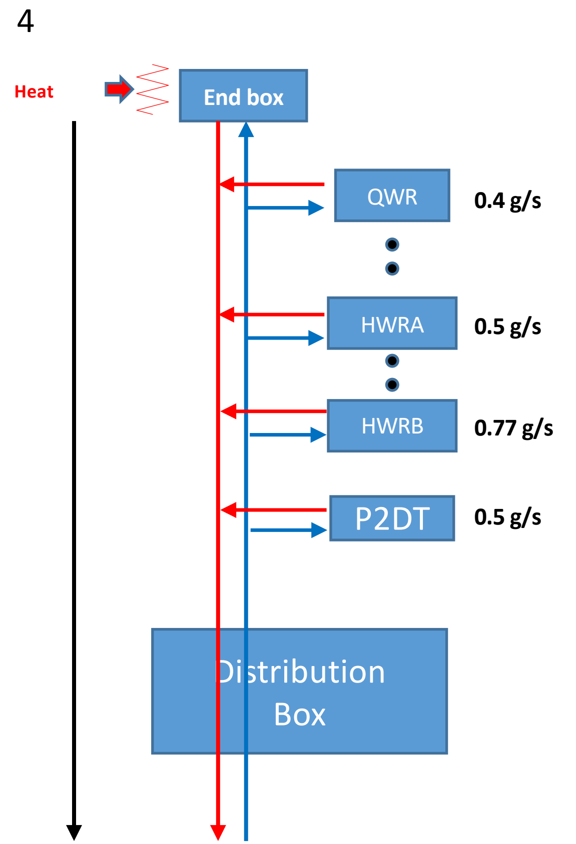




Cryogenic systems – Cooldown method



SCL3 cryoplant (liquefaction mode)



SCL3 cryoplant (4.5 K stand-by mode)

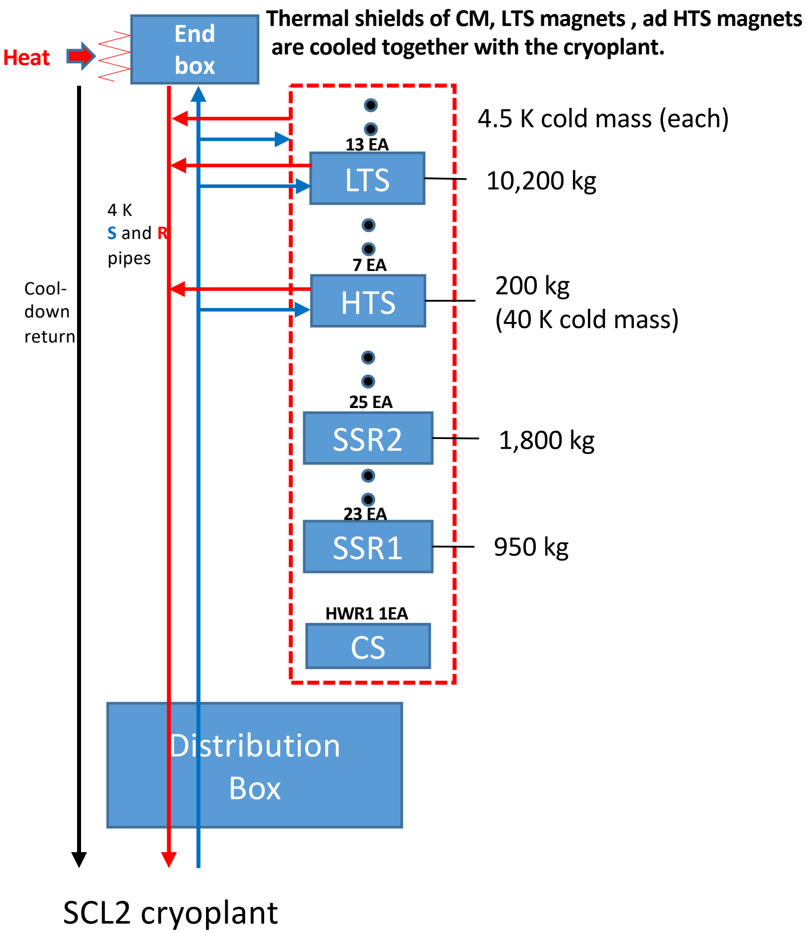
Total cool-down time for cavities :
~ 355 hours (15 days)

+

Stabilization
(~ 5 days)

Cryogenic systems – Cooldown method

- Cool-down of SCL2 line (updating)
  - Cold box, HDS, magnets, all thermal shields are cooled down simultaneously with ~ 9 turbines (additional turbines support the cooldown operation) and no LN2 precooling.
  - An estimated time (with 250 tons) is about ~ 12 days.
  - After cooling them, SSR cavities will be cooled down one by one.



Future works

- SCL3 cryoplant
  - Design (2018) – fabrication and installation (Q1 of 2020) – commissioning (Q2 of 2020)
- SCL2 cryoplant
  - Design (Q2 of 2019) – Fabrication and installation (Q2 of 2020) – commissioning (Q3 and Q4 of 2020)
- HDS
  - Design of HDS system (Q2 of 2018) - mass-production and installation (DB: 2019, SCL3: 2018~2019, SCL2: 2019~2020) – commissioning (SCL3 : ~ 2020, SCL2 : ~ 2021)
- Development of control logic (2018)

Summary

- IBS has a plan to make a heavy ion linear accelerator
  - SCL1, SCL2, and SCL3 lines (for RI beams, SCL3 – SCL2, SCL1-SCL2 ; high energy, SCL3, SCL1 ; low energy)
  - SRF cavities (481 cavities)
  - LTS magnets (13 EA) and HTS magnets (7 EA)

- Requirements and challenges
  - 21.4 kW @ 4.5 K equivalent (2.05 K, 4.5 K, 35 K He supply and return for all SC system.
  - Various operation strategies (combinations, construction, long operation, etc.)
  - Cool-down and warm-up : fast, slow, and individual
  - Stability (especially, pressure)

- Cryogenic systems for cooling cavities, LTS and HTS magnets
  - Three cryoplants
    (SCL3; 4.2 kW - 2020, SCL2; 13 kW - 2020, SCL1; 4.2 kW – in the future)
  - Helium distribution system : A distribution box, transfer lines (240 m SCL3, 640 m SCL2), and valve boxes (139 EA) - commissioned with SCL2 and SCL3: ~2021
  - Development of cool-down method : fast cool-down/slow cool-down
  - Prevention of TAO

Thank you