DESIGN OF CRYOMOUDLES FOR RAON *

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Abstract

RAON, the name of the heavy ion linear accelerator, utilizes four types of superconducting cavities such as QWR (β=0.047), HWR(β=0.21), SSR1(β=0.3), and SSR2(β=0.51) which are operating at 2 K in order to accelerate the various ion beams. The main role of the cryomodules is to maintain the cryogenic temperature for the superconducting cavity operation. Five types of cryomodules will be necessary since one QWR cavity, three and six HWR cavities, four SSR1 cavities, and eight SSR2 cavities will be installed in the dedicated cryomdoules. Total number of the cryomodule is 147, 48 for QWR, 60 for HWR, 22 for SSR1, 17 for SSR2. The cryomodules of RAON does not include focusing magnets in them. This paper describes the current status of the RAON cryomodule design. The issues included in the paper are the thermal load estimation, design of the components such as thermal shield and intercept of the cryomodules, and cryogenic flow circulation system according to the cryomodule operation.

INTRODUCTION

The layout of the RISP accelerator is shown in Fig. 1. The Uranium ions produced in an electron cyclotron resonance ion source are pre-accelerated to an energy of 300 keV/u by a radio frequency quadrupole and transported to the superconducting cavities by a medium energy beam transport. The driver linac is divided into three different sections: low energy superconducting linac (SCL1), charge stripper section and high energy superconducting linac (SCL2). Fig. 1 shows a conceptual structure of SCL1 and SCL2. The SCL1 uses the two different families of superconducting resonators, i.e., quarter wave resonator (QWR) and half wave resonator (HWR). The SCL11 consists of 24 QWR's whose geometrical beta is 0.047 and 24 doublets. The resonance frequency of QWR is 81.25 MHz. The cryomodule of the SCL11 hosts one superconducting cavity. The SCL12 consists of 138 HWR's whose geometrical beta is 0.12 and 36 doublets. The resonance frequency of HWR is 162.5 MHz. This segment has the two families of cryomodules: one type of cryomodule hosts three superconducting cavities and the other hosts six superconducting cavities [1].

The Linac has five types of cryomodules for four different kinds of cavities as shown in Table 1. The main roles of the cryomodule are maintaining operating condition of superconducting cavities and alignment of the cavities along the beam line. High level of vacuum and thermal insulation is required for the cryomodule to maintain the operating temperature of superconducting cavities.

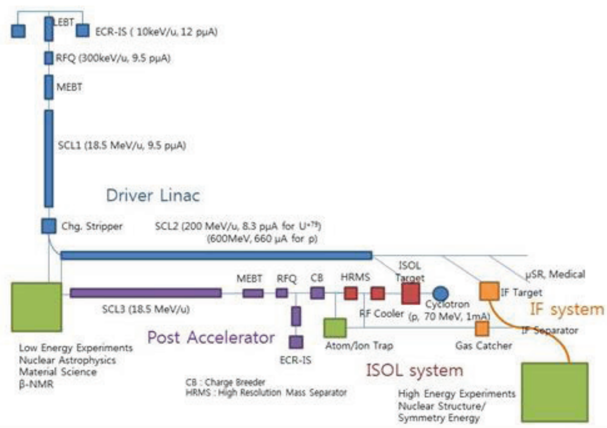

Figure 1: Layout of the SCL

Table 1: Summary of Cryomodules for RAON

SCL	Cavity	No. of cavity in CM	No. of CM	CM length (mm)	Segment length (m)
SCL11/ SCL31	QWR	1	22	450	26.6
SCL12/ SCL32	HWR	3	13	1400	55.7
		6	14	2720	
SCL21	SSR1	4	21	2216	105.6
SCL22	SSR2	8	18	5600	200.8

The QWR is vertically installed while the HWRs are horizontally installed in the cryomodule. The main components of the cryomodule are dressed cavities and two phase pipe, power couplers to supply RF power to the cavities, tuners to control the operation of the cavities, support systems to fix the cavities along the beam line, and so on. Since the operating temperature of the superconducting cavities are 2 K, the 70 K thermal shield which is cooled by cold helium gas and 70 K and 4.5 K thermal intercepts are installed to minimize the thermal load. The cold mass including cavity string, coupler and tuner is installed on the strong-back and then inserted into the vacuum vessel with thermal shield and MLI.

THERMAL LOAD ESTIMATION

The operating temperature of the superconducting cavities is 2 K and the cavities are cooled in the saturated bath of superfluid helium under subatmospheric pressure

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3.1 kPa. Three levels of cryogenic flow are necessary such as 2 K, 4.5 K and 70K for the cryomodules. A single 70 K thermal shield is used and the two sections of MLI (Multi-Layer Insulation) are also installed for minimizing the radiation heat load. The radiation thermal load value are generally known as 1~1.5 W/m^2 from 300 K to 80 K surface through 30~40 layers of MLI and 0.05 W/m^2 from 80 K to 5 K surface through 20 layers of MLI [2]. The thermal conduction through the solid components such as coupler, support post, and so on is minimized by the thermal intercepts cooled to 70 K and 4.5 K. Thermal intercept and cryogenic flow pipes are thermally connected with the copper braid-wires. The location of the thermal intercepts are decide to minimize the 4.5 K equivalent load which can be estimated by equation [3] as bellow:

$$q_{4.5Keq} = 3q_{2K} + q_{4.5K} + 0.07q_{70K} \qquad (1)$$

The results of the thermal load estimation are listed in Table 2. The static load includes the thermal radiation through the 2 sections of MLIs and 70 K thermal shield, conduction through the couplers, pick-up, tuners, beam pipes and supports while the dynamic load includes heat dissipation of the cavities by the RF excitation and couplers. Since most of components are under design, the configurations of the coupler and supports are referenced from other facilities [4, 5].

Table 2: Thermal Load Estimation for each Cryomodule

		Static (W)			Dynamic (W)	Sum (W)
		2 K	4.5 K	70 K	2 K	4.5 K
SCL11		7.4	15.9	58.9	1.0	45.2
SCL12	3cav.	8.8	24.5	91.5	3.6	68.2
	6cav.	10.8	37.0	139.7	7.3	101.2
SCL21		9.9	30.6	113.3	6.8	88.6
SCL22		12.9	46.6	182.7	29.0	184.7

COMPONENT DESIGN

The design of the cryomodule components has been conducted based on the thermal and structural concerns. The thermal design starts from the estimation of the thermal loads that determines the required size of the components such as two phase pipes and other cryogenic pipes and so on. The uncertainty factor 1.5 is multiplied on the estimated thermal load value to design conservatively. The structural design is conducted based on the KS codes [6] on the pressure vessel design. The MAWP (Maximum Allowable Working temperature) is 4 bar at cryogenic temperature and 2 bar at room temperature for the sub-atmospheric components while 20 bar for the general cryogenic pipes.

Helium Jacket and Vertical Pipe

Helium jacket and the vertical pipe that connects the helium jacket and the two phase pipe are designed with the consideration on the heat transport through the superfluid helium [7]. The criterion generally utilized is 1 W/cm^2 heat flux through the HeII liquid cross-section. The minimum gap between the helium jacket and the cavity, and the diameter of the vertical pipe can be calculated according to the criterion. The calculated gap between the helium jacket and the cavity is smaller than 10 mm due to the superior heat transfer characteristic of superfluid helium. Therefore, the consideration on the RF characteristics and the structural strength is necessary to complete the helium jacket design. The commercial stainless steel pipes will be utilized for the vertical pipe and the other cryogenic pipes in the cryomodule. Fig. 2 shows the 3 dimensional drawing of the cavity string and two phase flow pipe of SSR1 cryomodule.

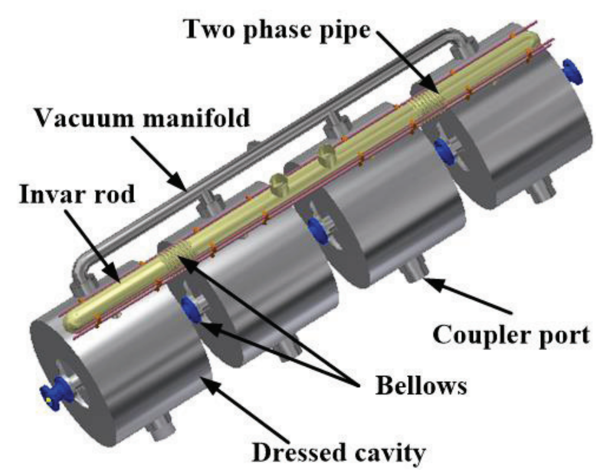

Figure 2: 3D drawing of cold mass assembly of SSR1 cryomodule.

Cryogenic Pipes

The estimated mass flow rate for each temperature level is listed in Table 3. It is assumed that the inlet temperature and the outlet temperature of the 70 K level gas flow are 60 K and 80 K respectively under 15 bar while those of 4.5 K one are 4.5 K and 8 K respectively under 3 bar. For the practical and simple fabrication, commercial pipes will be utilized for the cryogenic pipes and the size of each pipe is same for every cryomodule.

Table 3: Estimated Mass Flow Rate for Each Cryomodule

		2 K evap. (g/s)	2 K return (g/s)	4.5 K (g/s)	70 K (g/s)
SCL11		0.36	0.46	0.47	0.56
SCL12	3cav.	0.54	0.68	0.73	0.88
	6cav.	0.79	0.98	1.11	1.34
SCL21		0.72	0.91	0.92	1.08
SCL22		1.81	2.27	1.40	1.75

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In Table 3, "4.5 K" represents the amount of the mass flow rate required for cooling thermal intercepts only. 4.5 K helium gas flow can also be utilized for producing 2 K liquid by the J-T expansion process. "2 K evap" means the evaporated mass flow rate from the liquid bath due to the 2 K thermal load. "2 K return" means the total gas mass flow rate including "2 K evap" and gas flow rate that does not condensate after the J-T expansion. Therefore, the "2 K return" is same with the required mass flow rate of the 4.5 K helium flow to produce the "2 K evap." mass flow rate. The liquid yield of the J-T heat exchanger is governed by heat exchanger's effectiveness. It is assumed that 80 % of liquid yield can be achieved by the J-T heat exchanger [8].

Two Phase Pipe

The two phase pipe where the liquid and gas phase helium coexist is made of commercial stainless steel pipe. The diameter of the two phase pipe should be large enough that the relative velocity of the gas phase is not faster than 4 m/s [9]. Below the design velocity, the liquid-gas interface remains in stratified, so no pressure fluctuation occurs. The mass flow rate of the gas and liquid phase in the two phase pipe can be found in Table 3. Table 4 shows the minimum diameter and thickness (4 bar MAWP) of the two phase pipe for each cryomodule when the 25 % of the two phase pipe is filled with liquid.

Table 4: Minimum Size of the Two Phase Pipes

		Inner diameter (mm)	Thickness (t)
SCL11		37.2	0.28
SCL12	3cav.	40.2	0.30
	6cav.	43.8	0.32
SCL21		44.0	0.33
SCL22		53.9	0.40

Similar with other cryogenic pipes, the commercial stainless steel pipes are also utilized for the two phase pipe. The bellows are installed to relieve the thermal stress and metal (for example, invar) rods are installed to eliminate the deformation due to the thermal contraction shown in Fig. 2

Pressure Relief System

The pressure relief devices such as rupture disk and re-seat relief valve is necessary. The worst heat ingress situation is caused by the loss of vacuum in the beam pipe and the heat flux at that case can be estimated 4 W/cm^2 [10]. The helium jacket and two phase pipe would be the most dangerous place of increasing pressure since there are large amount of liquid helium during the operation. Therefore, the rupture disk whose diameter is around 300 mm will be installed. Also, the small relief valves and the rupture disks are will be installed other pipe lines such as 70 K and 4.5 K pipes and vacuum vessel.

SUMMARY

Five types of cryomodule for RAON have been designing in RISP and their current status on the thermal design is presented. Since the cryomodule design in RISP is still in very primitive stage for lack of experience, the benchmarking and gathering design criteria have been mainly conducted so far. A first draft of 3 dimensional drawing for the cryomodules is on-going based on the design results presented in this paper. Numerical simulations on the thermal contraction, heat transfer and so on to confirm the design is planned.

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