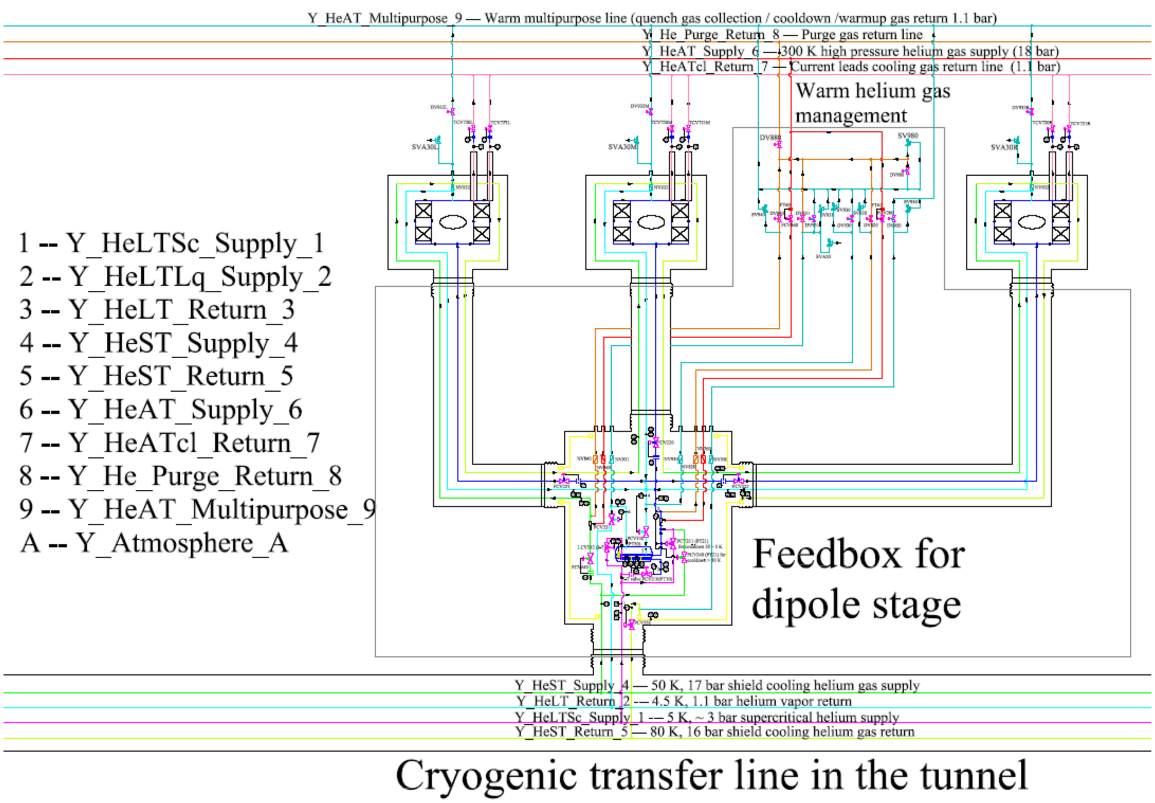
1 Local Cryogenics for Super-FRS SC magnets

1.1 Cryogenics for dipole stages

There are 28 superconducting dipoles units in the Pre- and Main-Separator including the three branches (High-Energy-Branch, Low-Energy-Branch, and Ring-Branch) and in the experimental area of the Super-FRS (Magnetic Spectrometer and Energy-Buncher) as well. Being coincident with the lattice design, all three dipole units of each dipole stage are grouped together and supplied by one feedbox with liquid helium in parallel. The flow scheme for such a dipole stage including one feedbox is shown in *Figure 1*. It shows that the cryogenic fluids is transferred via the cryogenic transfer lines to the feedbox through which the cooling power is distributed to three dipole magnets under control. The four-header piping system in the cryogenic transfer line brings cold helium at 4.5 K and 50 K throughout the Super-FRS tunnel. The warm helium gas management setup and the piping for safety protection help to realize the variant procedures of operation like purge, warm gas supply and return for cooldown and warmup of the magnets, current leads cooling gas return, safety release of cold helium to prevent the dipole cryostats and feedbox from over pressure during the quench or under some other unusual situations, i.e., power failure, malfunction of control valves and instrumentations, and even in the worst cases like insulation vacuum breakdown, helium piping break-up, fire, etc.



For more clear and detailed view, please click the icon of the PDF file: Flow scheme for Feedboxes for Dipole Groups.pdf

***Figure 1**: Flow scheme of three Super-FRS dipole units and one feedbox unit.*

Figure 2 shows a zoomed view of the flow scheme for the feedbox. Together the T-s diagram in *Figure 3* for the 4.5 K helium flow in the feedbox, the following cooling principles are presented.

Normal operation

Supercritical helium (5 ~ 5.5 K, 3.0 ~ 4.0 bar at point 1 --- PT10 on the T-s diagram of *Figure 3*, the inlet point of the feedbox on the pink line in *Figure 2*) is expanded with mass flow rate about 4 g/s through one flow control valve FCV210 which works as a J-T valve. The discharging pressure at the outlet of the valve (PT20) varies between 1.2 bar and 1.5 bar (or even higher) as requested by the magnets. On the T-s diagram, the point 2 (PT20) represents the states of cold helium after J-T expansion which is already in the two-phase region at 4.7 K and 1.5 bars with about 30% flash gas. To re-condensate the flash gas the J-T flow (blue) will be re-cooled (sub-cooled) through a heat exchanger in the so-called subcooler. The heat exchanger is immersed in a liquid helium bath whose temperature could be maintained at 4.4 K as indicated as the horizontal yellow line on the T-s diagram. With the assumption of 0.1 K temperature difference as the minimal requirement for the heat transfer between J-T flow and the liquid helium bath, the two-phase J-T flow is expected to be subcooled into the single-phase region as the point 3 (PT21) at 4.5 K and 1.45 bars. It is also assumed here that the J-T flow has maximum 50 mbar pressure drop when it gets through the heat exchanger of the subcooler. Therefore the sub-cooling process of the J-T flow follows nearly the isobar shown as the cyan lines connecting the points 2 and 3 on the T-s diagram.

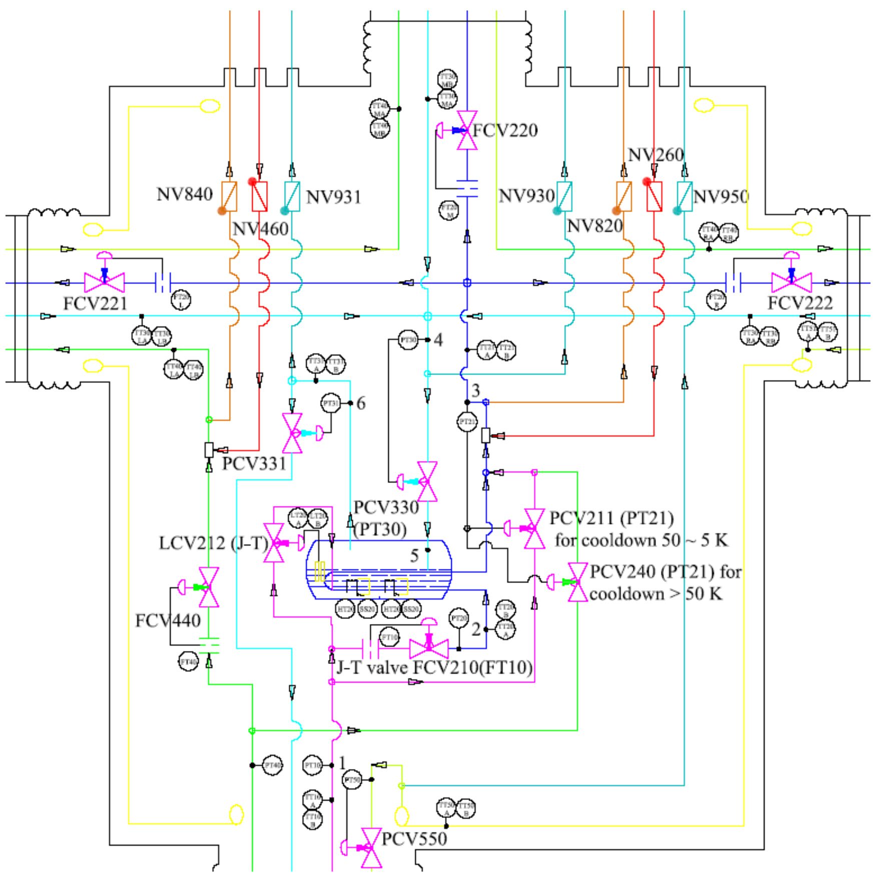


Figure 2: Zoomed view of the flow scheme for the feedbox.

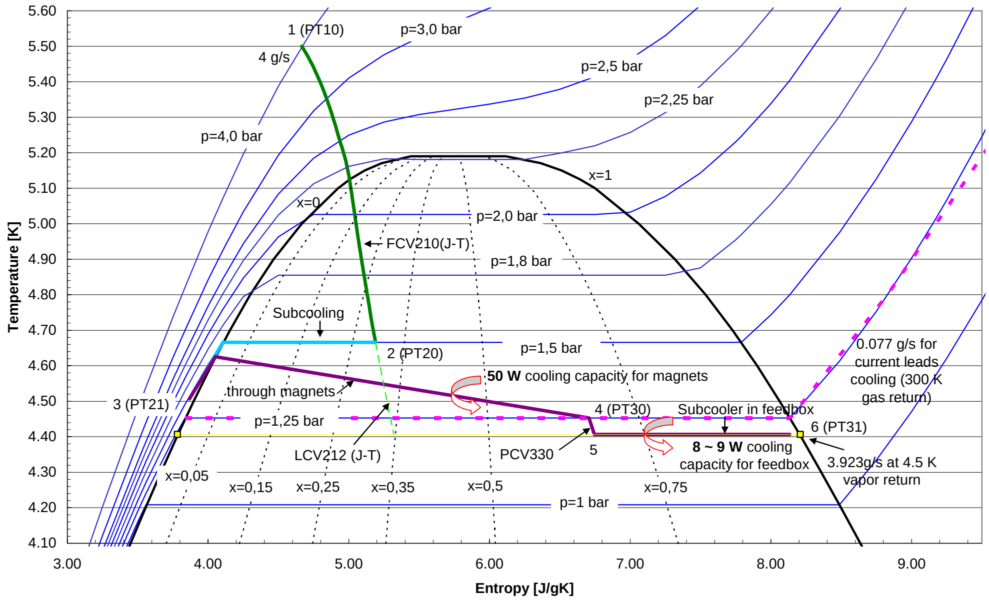


Figure 3: T-s diagram of 4.5 K helium flow in feedbox and in dipoles

After being subcooled the single-phase helium (4.5 K at 1.45 bars) flows into three streams in parallel with the flow rates controlled by three flow-control valves (FCV220, FCV221 and FCV222) in the circuits for the dipoles individually. The heat losses of the connection lines between the feedbox and the dipole cryostats may eliminate the subcooling of the three flow streams. Liquid helium is fed from the bottom of the coil container in the magnet cryostat and circulated through the flow channels around the coils. The heat load (steady state heat in-leaks, Joule heating of the instrumentation cables, SC wire junctions and AC loss during ramping, etc.) in the magnet cryostat may cause the evaporation of liquid helium. Therefore two-phase helium may be present in the return flow which comes out from the top of the coil container. A small fraction of such flow (nominal value, 0.077 g/s for three pairs of current leads with 232 A current) is used for cooling the resistive current leads. The rest of the return flow (possibly two-phase helium) from the individual magnet cryostats merges with the others before it enters into the subcooler. On the T-s diagram it is indicated that return flow (3.923 g/s) from the dipole cryostats contains two-phase helium with up to 66% vapour quality (point 4 --- PT30: 4.45 K at 1.25 bars) if 50 W of cooling capacity is required by the three dipole magnets. It is assumed here that pressure drop of 0.2 bars is allowed when the 4.5 K helium flows through the coil case inside the dipole cryostats.

The return flow from the dipoles flows through one pressure control valve PCV330 into the helium bath of the subcooler. The flow control valve, FCV210 and the pressure control PCV330 work together to keep the setting range of the supply pressure at point 2 (PT20) as large as possible, e.g. 1.2 bars ~ 1.5 bars or higher, for better subcooling of the J-T flow. The valve PCV330 may have additional J-T cooling effects by making use of the pressure drop from Point 4 to Point 5 (4.4 K and 1.2 bar, helium bath) on the T-s diagram. The 30 % remaining liquid helium into the subcooler can provide up to 8 to 9 Watts of cooling power to compensate the heat loss of the feedbox itself. If the liquid helium level in the helium bath can not be sustained by insufficient liquid fraction in the return flow, the helium level control valve LCV212 fills the helium bath as auxiliary which is shown as the dashed line between the Point 1 (5.5 K, 4.0 bars) and the helium bath (4.4 K, 1.2 bars) on T-s diagram. In case of complete dry-out filling, i.e., only vapour left in the return flow, the subcooling operation of the helium bath has to rely on the filling with the LCV212 alone. After the phase separation in the helium bath, only the vapour flows back into the cryogenic transfer line through the pressure control valve PCV331. The PCV331 controls the vapor pressure in the helium bath shown as the Point 6 (PT31) on T-s diagram and thus the temperature (4.4 K) of subcooler.

The 50 K to 80 K shield flow is connected in series for three dipoles in one group but in parallel with the other magnet groups. It is tuned in its flow rates by the flow control valve (FCV440) at the inlet and the pressure control valve (PCV550) at the outlet. Therefore the independent purge, cooldown, warmup, normal operation and commissioning, maintenance, service and even repairing of each magnet group are possible. Non-return check valves (NV) are used to reduce the potential risk of the thermoacoustic oscillations and the induced large heat in-leaks.

Purge operation for the circuits of 4.5 K and 50 K

Before cooldown starts, the system should be purged with high purity of gas helium at room temperature. During the purge process, the valves FCV210 (J-T), LCV212 (J-T), PCV211, PCV240, and PCV331 in the 4.5 K circuit and the valves FCV440, PCV550 in the 50 K circuit of the feedbox (*Figure 2*) are kept to be completely closed, and the valves PCV330, FCV220, FCV221, and FCV222 fully opened. The operation of purge starts with the valves DV880, DV820, DV831, and DV840 opened to the purge line but the rest valves in the warm helium management system (*Figure 4*) being closed. The helium volume inside the magnets and the piping including subcooler in the feedbox are to be evacuated down to the pressure of 10E-3 mbar level and flushed with warm helium gas by switching the FCV260, FCV460 with those DV valves for several times. After the purge is finished, the helium volume in the magnets and feedbox is maintained with over-atmospheric pressure. The evacuated helium volume in the warm gas management system is also flushed with warm helium by the DV980 from the quench/cooldown/warmup line and protected from over-pressure during any operation conditions by the SV980. If all the processes are finished, the magnet and feedbox system are ready for cooldown. Some of the warm valves like FCV260, FCV460, DV880, DV820, DV831, DV840 and DV 980 should be closed and blocked to be open by accident.

Cooldown operation for the circuits of 4.5 K and 50 K

The cooldown of the dipole magnets can be carried out in groups. The flow control valves FCV220, FCV221 and FCV222 in the feedbox allow tuning of the cooldown flow through the individual cryostats. Therefore the cooldown speed and the temperature gradient over the individual cold mass structures are controllable with respect to the specification.

It is assumed that the cryogenic transfer line in the tunnel is already in its normal operation conditions, i.e., 4.5 K and 50 K at corresponding pressures before the cooldown of the dipoles and feedbox starts. Therefore the piping in the connection line between the feedbox and the cryogenic transfer line is ready to accept the cold helium for cooldown.

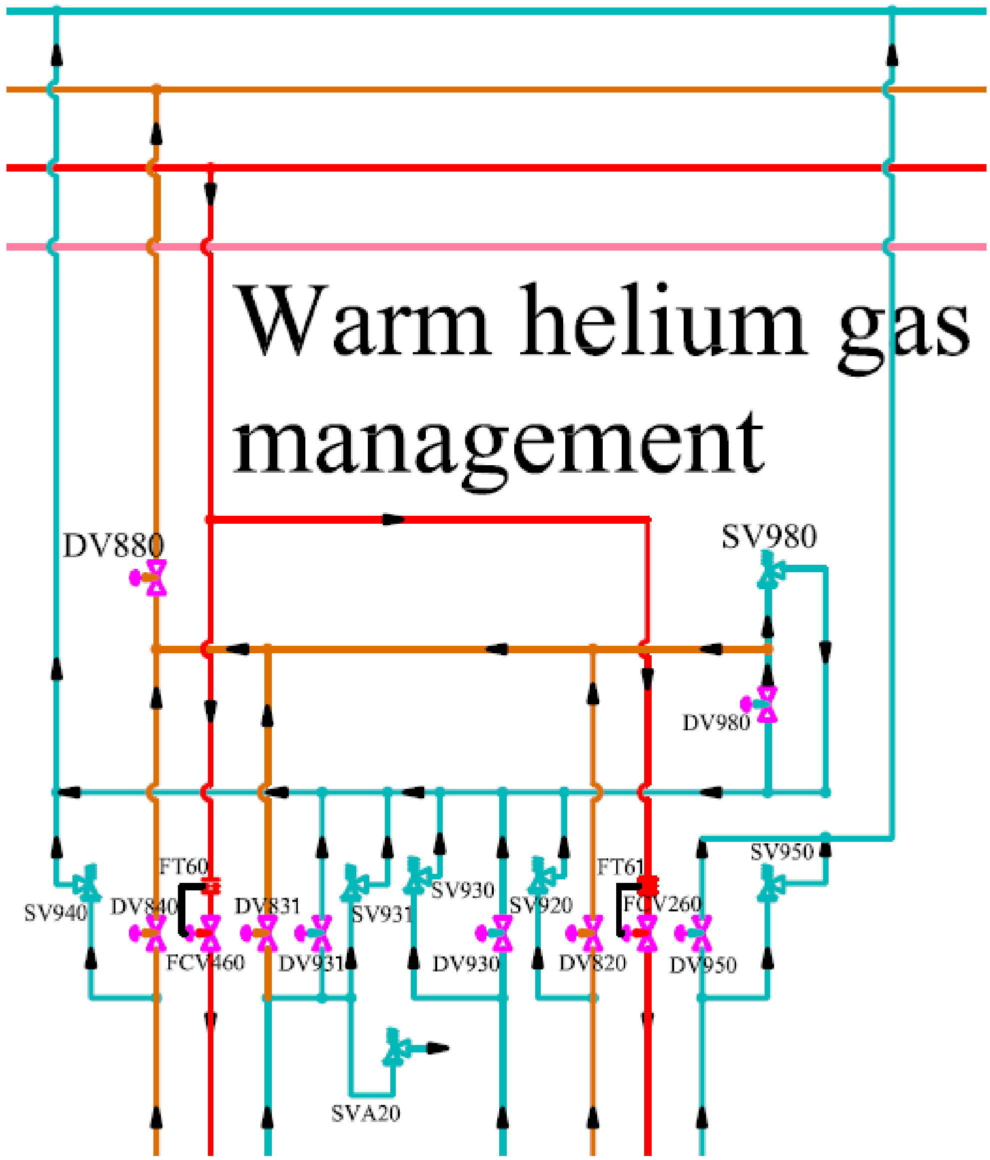


Figure 4: Warm helium management for cryogenic feedbox and the magnets

For the circuit of 4.5 K, the cooldown process consists of two phases. The first phase presents if the temperature of the magnet cold mass is above 70 K. During this phase cooldown flow mainly comes from the 50 K shield flow through the pressure control valve PCV240 (PT21) in *Figure 2*. The pressure (PT21) of the cooldown flow should be always maintained below the Maximum Allowed Working Pressure of the helium vessel of magnets. The cooldown speed of the magnets could be controlled by mixing the 50 K cooldown flow with the 300 K warm helium in the FCV260 circuit. Depending upon its temperature level, the cooldown flow returns to the warm multipurpose line either by the three warm valves/circuits DV932 (*Figure 1*) which connect the helium vessel inside the individual magnet cryostats to the multipurpose gas return line, or back to the feedbox but through the DV930 in the warm gas management system (*Figure 4*), or further cooldown the subcooler and back through the DV931 to the multipurpose gas return line.

The cooldown of the 50 K shield circuit for magnets and the feedbox could be done simultaneously with the first phase of 4.5 K circuit cooldown. The cooldown flow for 50 K shield is controlled by the valve FCV440 (*Figure 2*) with the possibility of mixing 300 K warm helium through FCV460 in the warm gas management system (*Figure 4*). Contrast to the cooldown of 4.5 K circuits in dipole magnets in parallel, the 50 K shield circuits are cooled down from one magnet to another in series. The shield of the feedbox is cooled down by the return flow at last. Again depending upon its temperature level, the cooldown flow returns either by through DV950 to the warm multipurpose line (*Figure 4*), or back to the normal 80 K return loop in the cryogenic transfer line through PCV550 (*Figure 2*).

If the temperature of dipole cold mass approaches 80 K, the cooldown flow through valve PCV240 from 50 K shield circuit could be stopped. The cooldown of 4.5 K circuits go to the second phase. The cooldown flow is resumed through the valve PCV211 (PT21) for the further cooldown from 50 K to 4.5 K level. Again depending upon its temperature level, the cooldown flow returns either by through DV931 to the warm multipurpose line (*Figure 4*), or back to the normal 4.5 K return loop in the cryogenic transfer line through PCV331 (*Figure 2*). If the cooldown flow is cold enough (< 10 K) to be returned through the transfer line, the filling of the helium vessel in the subcooler could be started with the valve LCV212 (J-T). Meanwhile the cooldown flow through the PCV211 (PT21) could be stopped but resumed again through the FCV210 (J-T) circuit which is the process flow for normal operation. Then the cooldown processes are close to the end. To avoid the influence of any malfunction of control valves for cooldown, the interlock is necessary for the PCV240, FCV210, and PCV211 which means only one of them is allowed to be operationable at any time during the any operations.

Warm-up operation for the circuits of 4.5 K and 50 K

The warm-up of the magnets can be done on the base of a group by circulating the 300 K helium gas through both the 4 K and 50 K circuits of the magnet cryostat and feedbox. For warm-up the dipoles, the two valves FCV260 and FCV460 in the warm gas management system control the 300 K warm helium gas to flush the cold mass at required flow rates in the 4.5 K and 50 K circuits. During the warm-up operation, the feedbox is completely isolated from the cryogenic transfer line by shutting off the FCV210, PCV211, LCV212, PCV331 in the 4.5 K circuit and the FCV440, PCV240, PCV550 in the 50 K circuit. The return of helium gas for warm-up makes the way to the warm multipurpose line through the valves DV931 and DV950 if the dipoles and feedbox are necessary to be warmed-up simultaneously. One of the most important scenarios for warm-up operation is that only individual dipole in one dipole group needs to be warmed-up but with the rest two dipoles and the feedbox being at cold (floating) conditions. Then the return of helium gas for warm-up may bypass the feedbox by making the way to the warm multipurpose line through the valve DV930. However the 50 K circuits for three dipoles have to warm-up simultaneously because they are in series connected.

Safety Release for helium vessel in the subcooler and the circuits of 4.5 K and 50 K

Liquid helium produces large volumes of gas by a factor of 800 when it vaporizes. Therefore the pressurized cryogenic containers are normally protected with multiple safety devices for over-pressure prevention as one of the most important design rules. In general the common pressure-relief devices are a pressure-relief valve for primary protection and a rupture disc for secondary protection[1]. For the Super-FRS magnets, the coil containers in the individual dipole cryostats are protected from the overpressure in case of possible quenches and any emergency situations by their own safety devices SVA30 in *Figure 1*. Those safety devices are expected to be in operation when all the other safety measures are not sufficient to restrain the pressure rising in the 4.5 K circuit. As the worst case scenario, they will release the gas helium into the atmosphere inside the accelerator tunnel. As the primary protection, the safety relief valves shown in the *Figure 4* protect the 4.5 K and 50 K circuits in the feedbox and the magnet cryostats. For 4.5 K circuit protection those are the SV920, SV930 and SV931. In addition the SVA20 works as secondary protection together with SV931 for the liquid helium vessel in the feedbox. For the 50 K circuit protection those are SV940 and SV950. As mentioned above, the protection of the warm gas management system from over-pressure is carried out by SV980. Except the SVA20 and the SVA30 safety devices, all the safety relief valves release gas helium into the warm multipurpose line which is connected with the warm helium buffers outside the accelerator tunnels.

All the safety devices discussed above are the passive protection measures. When any abnormal pressure rise occurs in any individual magnets within one group, the control valves (FCV and PCV) located at the upstream of the 4.5 K flow process will be shut off and the control valves (PCV) at the downstream will be completely open as the active action of the protection logic control. The active protection measure is expected to ease the pressure build-up in the liquid helium vessels. Nevertheless, as a passive action the safety relief valves will be opened once their set pressures are exceeded.

[1] Safe Handling of cryogens, Air Products, http://www.airproducts.com/

1.2 Cryogenics for multiplets/quadrupole stages

In the Super-FRS there are 118 superconducting quadrupoles and hexapoles located in between every two groups of dipoles and in front of the Super-FRS target region. In the Main-Separator, usually five neighboring quadrupoles and hexapoles form a multiplet. This is installed in one single cryostat with a length up to 7 m and cooled in a common liquid helium bath. The multiplet has cold iron mass up to 37 tons. Therefore high cooling capacity is required to cool down such magnets. It is foreseen that one feedbox unit controls the liquid helium distribution for two multiplet cryostats. Figure 5 shows the flow scheme of two neighboring multiplets and the corresponding cryogenic feedbox. The feedbox unit is identical to the one for the dipole units except that only two connection lines are necessary. Almost all the technical descriptions for the local cryogenics of dipole stages are suitable to the local cryogenics of multiplet stages.

Since the weight of the cold mass in one multiplet is larger than that in one dipole by a factor of 10, the cooldown time of the Super-FRS superconducting magnets is mainly dominated by the time which is required to cooldown 23 multiplets and some 10 individually located quadrupoles and hexapoles, i.e., totally about 1100 tons cold mass.

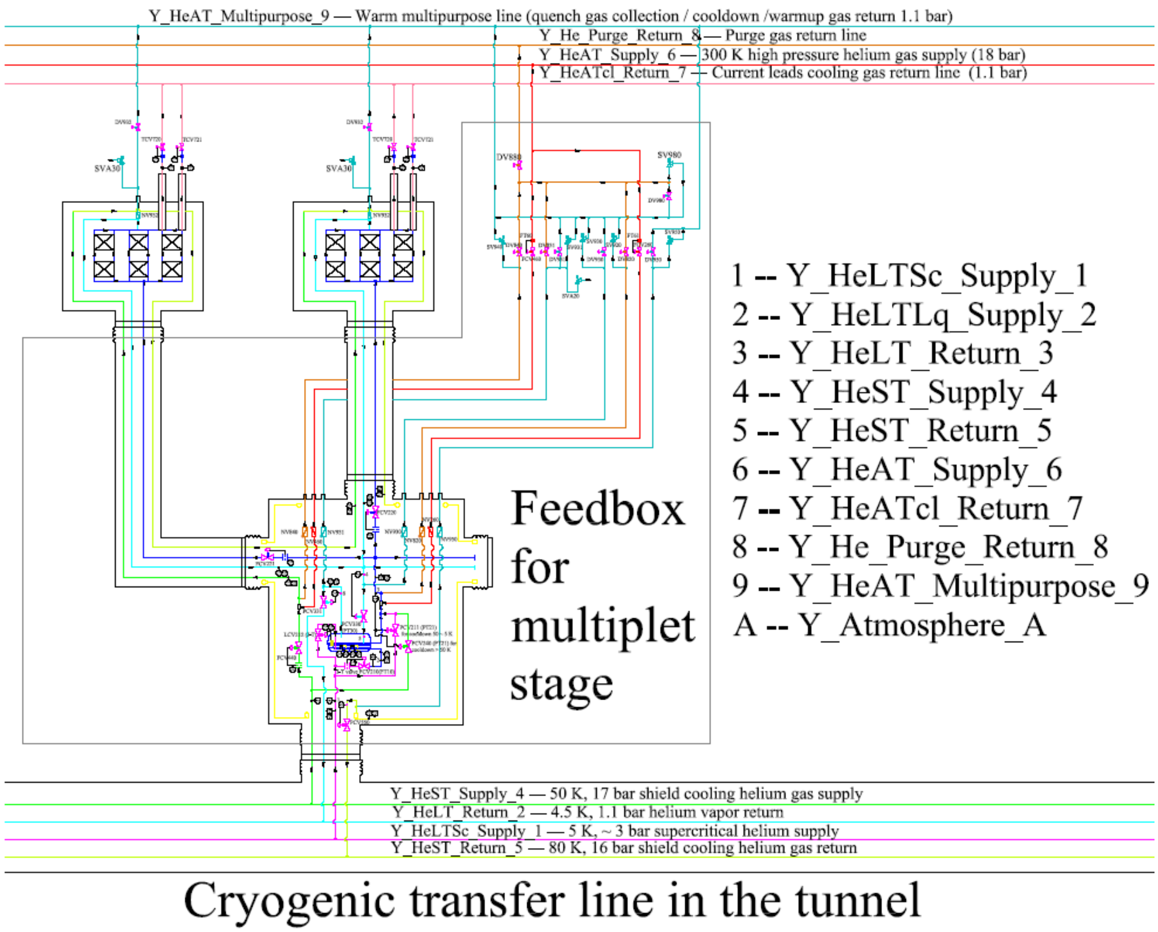


Figure 5. ***Flow scheme of two Super-FRS multiplets and one feedbox unit (Flow scheme for Feedboxes for multiplet Groups.pdf)***

1.3 Module Design for Local Cryogenic facilities of Super-FRS

The schematic layout of the cryogenic distribution for all the superconducting dipoles, quadrupoles and multiplets in the Super-FRS and in front of the target region is shown in Figure 6. The cryogenic cooling power for the main part of the Super-FRS is supplied by the FAIR refrigerator CRYO1 over the cryogenic transfer lines inside and outside the accelerator tunnel.

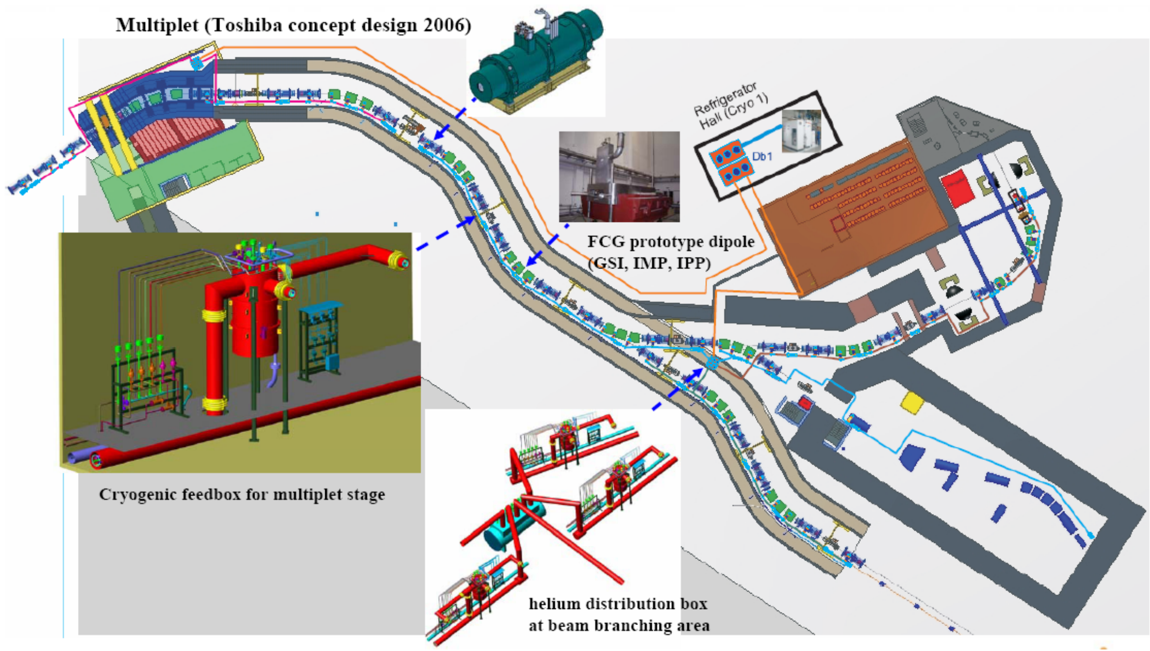


Figure 6 . ***Schematic layout of Cryogenic Distribution for SC Magnets in the Super-FRS***

The grouping of the dipoles and multiplets benefits the module design not only for the feedbox but also the other cryogenic infrastructures. **Table 1** contains almost all the local cryogenic infrastructures for Super-FRS in terms of module design. The module naming in the **Table 1** is corresponding to the schematics in the **Figure 7** and **Figure 8**. The typical configuration of local cryogenic facilities for SC magnets is shown in Figure 9.

Table 1. Module List for Local Cryogenics of Super-FRS (02-2011)

No.	Module name	Description	Quantity
1	Feedbox D module	cryogenic Feedbox for Dipoles	9 (= 8+1 for 3 quadrupoles in front of target)
2	Horizontal - Left Bend Connection Line D module	Horizontal Connection Line with Bend between feedbox and the dipole at the Left with respect to the feedbox for Dipoles	same number as Feedbox D module
3	Horizontal – Middle Straight Connection Line D module	Horizontal Connection Line between feedbox and the dipole at the Middle with respect to the feedbox for dipoles	same number as Feedbox D module
4	Horizontal - Right Bend Connection Line D module	Horizontal connection line with Bend between feedbox and the dipole at the Right with respect to the feedbox for dipoles	same number as Feedbox D module

5	Feedbox M module	cryogenic Feedbox for Multiplets	13 (=11+2 for 2 multiplets in high energy branch)
6	Horizontal - Left Bend Connection Line M module	Horizontal Connection Line with Bend between feedbox and the Multiplet at the Left with respect to the feedbox for Multiplets	same number as Feedbox M module
7	Horizontal - Right Bend Connection Line M module	Horizontal Connection Line with Bend between feedbox and the Multiplet at the Right with respect to the feedbox for Multiplets	same number as Feedbox M module
8	Vertical Connection Line D/M module	Vertical Connection Line between feedbox and Cryogenic Transfer Line Joint D/M modules	22 (= 13 + 9 total number of feedbox D/M modules)
9	Cryogenic transfer line D/M module	straight section (~10 m or ~ 12 m) of cryogenic transfer line	~ 20
10	Cryogenic Transfer Line Joint M module	Joint Box with two connections to Cryogenic transfer line D/M modules and one connection to Vertical Connection Line D/M module for feedbox M module	same number as Feedbox M module
11	Cryogenic Transfer Line Joint D-1 module	Joint Box for connections between Cryogenic transfer line D/M modules (acute angle) and Vertical Connection Line D/M module for feedbox D module	4
12	Cryogenic Transfer Line Joint D-2 module	Joint Box for connections between Cryogenic transfer line D/M modules (obtuse angle) and Vertical Connection Line D/M module for feedbox D module	4
13	Transfer Line Joint - End module	Joint Box ends the Cryogenic transfer line and connects Cryogenic transfer line D/M modules with Vertical Connection Line D/M module	5
14	Branch Box module	helium distribution box in the beam branching area	1
15	Cryogenic transfer line B module	Cryogenic transfer line between Branch box and Transfer Line Joint Modules (D-1, D-2, etc.)	to be specified later
16	Warm helium management and safety relief module	warm piping, instrumentations and valves for purge, cool-down, warm-up and safety relief	22 for feedboxes + 1 for Branch box

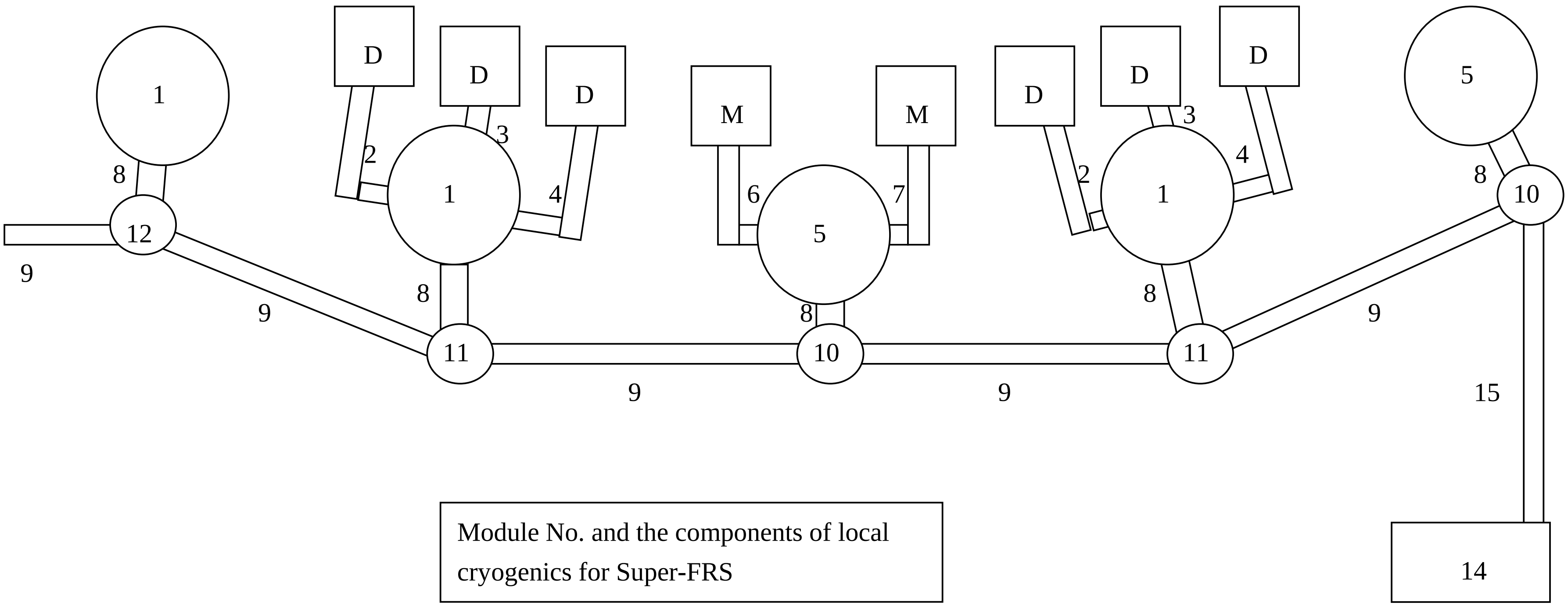


Figure 7. *schematic for module list in Table 1.*

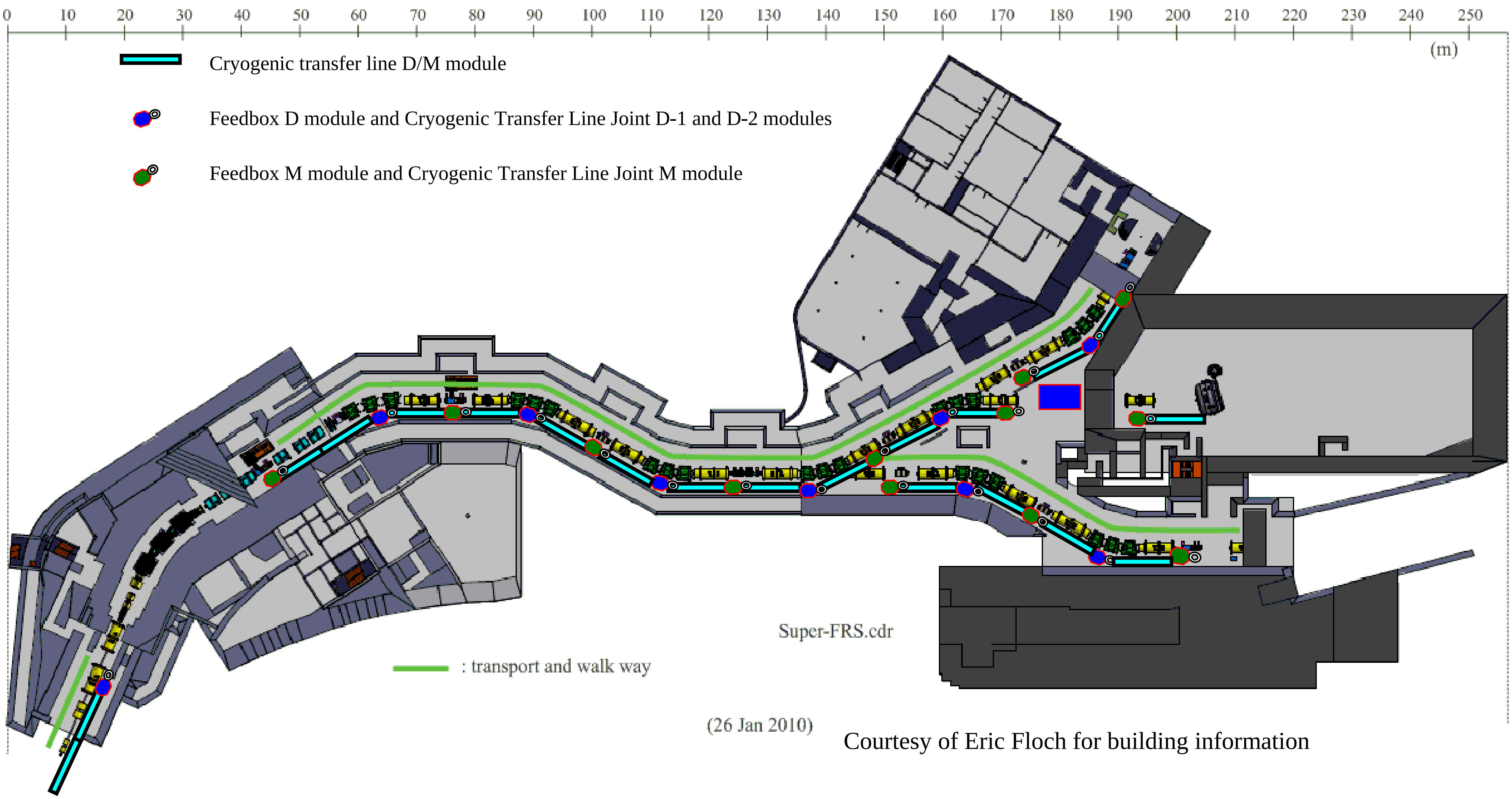


Figure 8. *Modulization for feedboxes and cryogenic transfer lines*

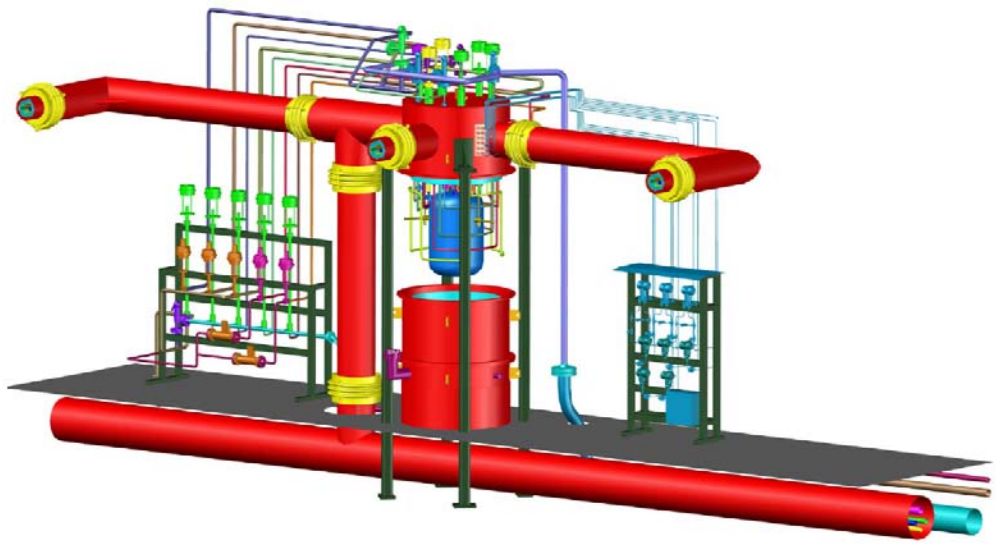


Figure 9. One typical configuration of the feedbox for three dipoles in one dipole stage

The module conceptual design is still under development. The following sections present the some of the design modules in the Table 1 which is available for engineering study.

Module list No. 1 and 5 --- Feedbox D and M modules

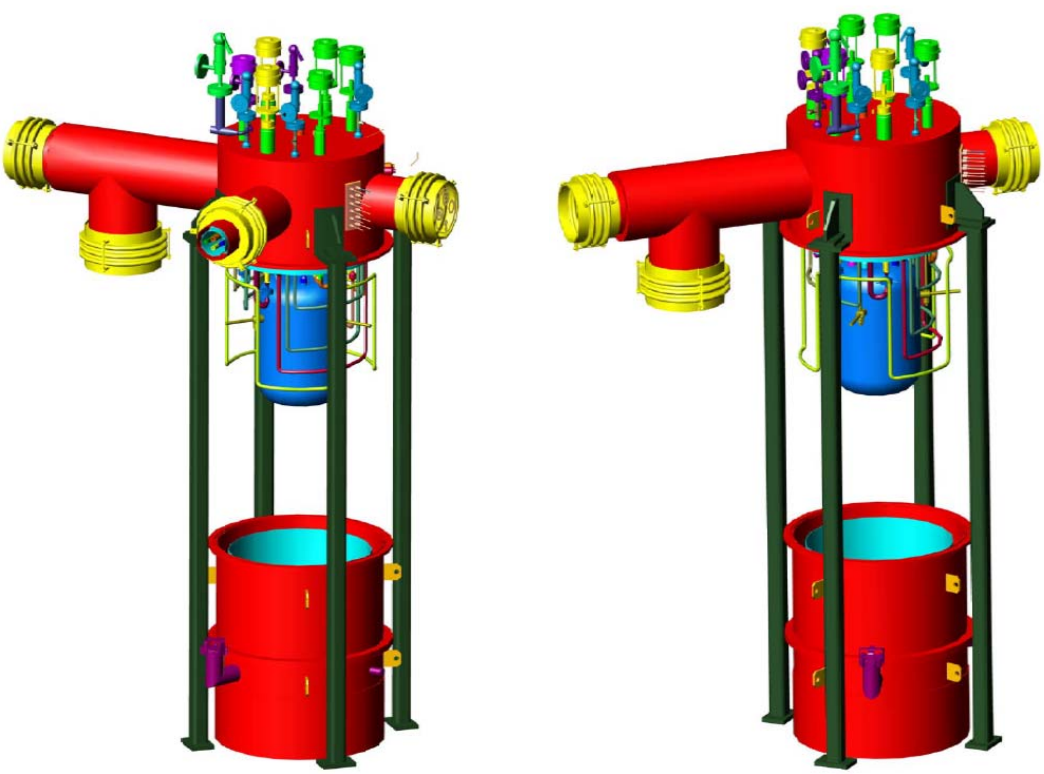


Figure 10. Conceptual Design of the Feedboxes for Super-FRS SC magnets in dipole stage and in multiplet stage (Feedbox D module on the left hand side; Feedbox M module on the right hand side)

The feedbox D module and the feedbox M module will share the same design as possible as they can. The major difference is that the feedbox D module has three connection ports as interfaces to three dipole cryostats but the feedbox M module has only two to two multiplets.

Module list No. 2 and 6 --- Horizontal-Left Bend Connection Line D and M modules

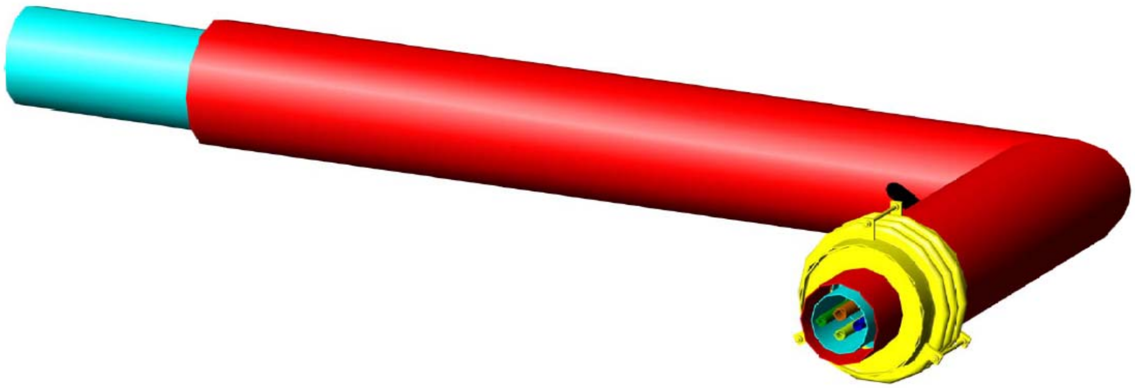


Figure 11. Vacuum jacketed connection line with left bend between the connection ports of the feedbox and of the dipole cryostat. Its bend facilitates the connection to the cryostat located at left hand side of the feedbox D and M Modules.

Module list No. 4 and 7 --- Horizontal - Right Bend Connection Line D and M modules

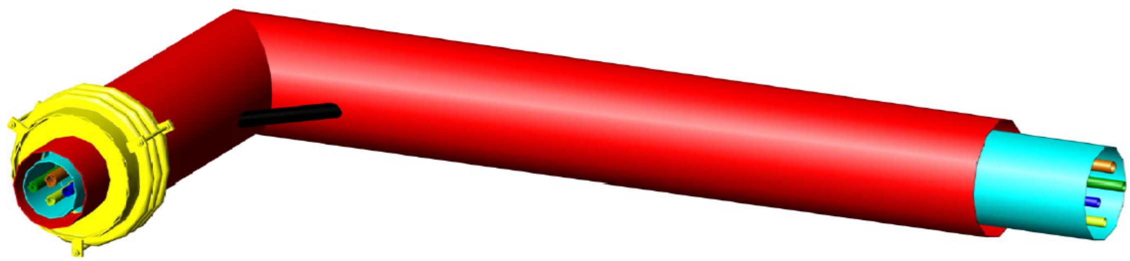


Figure 12. Vacuum jacketed connection line with right bend between the connection ports of the feedbox and of the dipole cryostat. Its bend facilitates the connection to the cryostat located at right hand side of the feedbox D and M Modules.

Figure 13. conceptual design of vacuum barrier to separate insulation vacuum among dipole cryostats and feedbox (left: front side; right: rear side)

In order to limit the mutual influence between dipole cryostats and feedbox in case of insulation vacuum breakdown, vacuum barriers are necessary to be installed inside the connection line D and M modules at the ends close to the feedbox.

Module list No. 11 --- Cryogenic Transfer Line Joint D-1 module

The super-FRS tunnel has several bends (about 30 degrees) at the locations of dipole stages. Therefore the cryogenic transfer line has also same number of bends at the corresponding positions. For the feedbox of each dipole stage, there should be also one vertical connection line (**module list No. 8 -- Vertical Connection Line D/M module**) which connects the feedbox with the main transfer line.

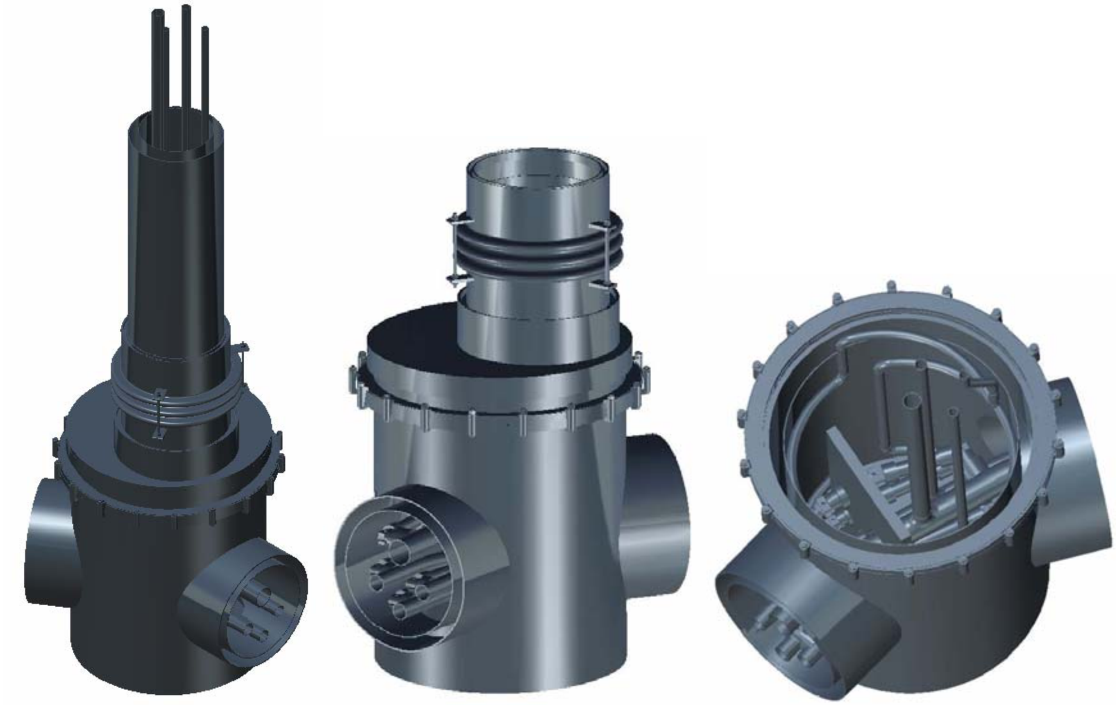


Figure 14. Bend structure for the cryogenic transfer line including the vertical connection line for the feedbox of dipole stage (left: cryogenic transfer line Joint D-1 module and Vertical Connection Line D/M module; middle: cryogenic transfer line Joint D-1 module; right: inner structure of the cryogenic transfer line Joint D-1 module)

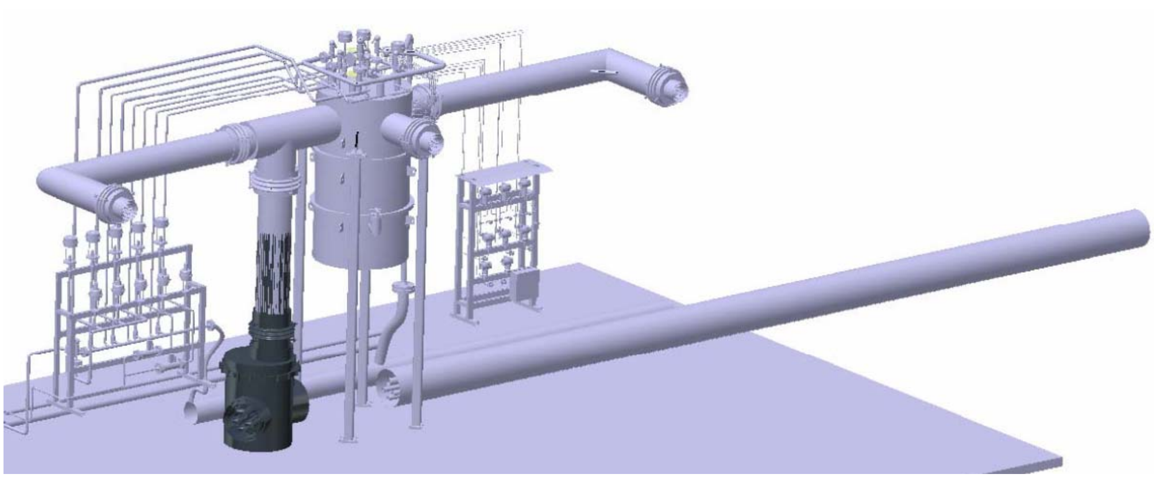
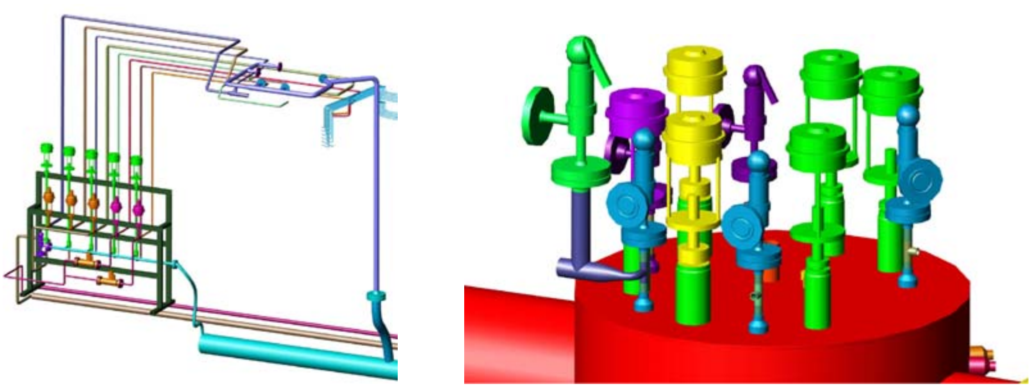


Figure 15. The cryogenic transfer line Joint D-1 module and the cryogenic feedbox facilities

Module list No. 16 --- Warm helium management and safety relief module



1.4 Instrumentation list

Instrumentation lists for one Feedbox of dipole stages in Super-FRS (03-2011)												
Point No. in flow scheme	Valve positioners	Valve positioners	Pressure Sensor	T-sensor (4.5 K circuits)		T-sensor (50 K circuits)		Flow Meter	Level Meter		Heater	Safety Switch for Heater
	Cold valves	Warm valves	(locations: in niches)		(Redundancy)		(Redundancy)	(locations: in niches)		(Redundancy)		
1	FCV210(J-T)		PT10	TT10A	TT10B			FT10				
2	PCV211		PT20	TT20A	TT20B			FT20R	LT20A	LT20B	HT20A	SS20A
	LCV213(J-T)		PT21	TT21A	TT21B			FT20M			HT20B	SS20B
3	FCV220							FT20L				
	FCV221	DV920		TT30RA	TT30RB							
	FCV222	FCV260	PT30	TT30MA	TT30MB							
4	PCV330	DV930		TT30LA	TT30LB							
5	PCV331	DV931	PT31	TT31A	TT31B							
	PCV240	DV931	PT40			TT40LA	TT40LB	FT40				
	FCV440	DV940				TT40MA	TT40MB					
	PCV550	DV950	PT50			TT40RA	TT40RB					
		FCV460				TT50A	TT50B					
		DV960				TT51A	TT51B					
		DV980										
sub total	11	10	7	7	7	5	5	5	1	1	2	2
total no.	11	10	7	14		10		5	2		2	2
Instrumentation lists for all Current leads of three dipoles in one dipole stages of Super-FRS (03-2011)												
3 pairs of current leads						T-sensor (300 K)		Flow Meter+Regulator				
						TT70L		FT70L				
						TT71L		FT71L				
						TT70M		FT70M				
						TT71M		FT71M				
						TT70R		FT70R				
						TT71R		FT71R				
total no.						6		6				
Total Instrumentation No. for one dipole Stage												
		Valve positioners	Pressure Sensor	T-sensor (4.5 K circuits)		T-sensor (50 K circuits)	Flow Meter	Flow Meter + regulator	Level Meter		Heater	Safety Switch for Heater
		Cold valves + warm valves	(locations: in niches)				(locations: in niches)	(locations: in niches)				
		21	7	14		16	5	6	2		2	2

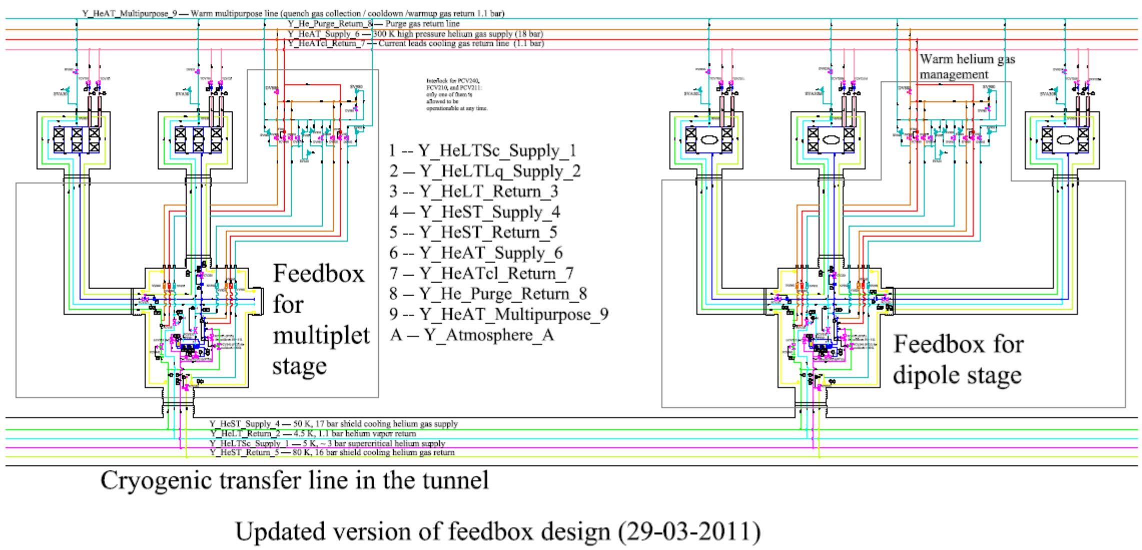


Figure 16. ***Flow scheme of cryogenic feedboxes for multiplets and dipole stages (Flow scheme of cryogenic feedboxes for multiplets and dipole stages)***