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# Design of a Horizontal Test Cryostat for Superconducting RF Cavities for the FREIA Facility at Uppsala University

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**Abstract.** Uppsala University is constructing a large scale facility, called FREIA (Facility for Research Instrumentation and Accelerator Development). FREIA includes a helium liquefier and an accelerator test facility and has the capacity to test superconducting radio-frequency (RF) cavities with the same RF system and RF power level as in an accelerator. A central element of FREIA is a horizontal test cryostat connected in closed loop to a helium liquefier. This cryostat can house two fully equipped (tuners, piezo, power coupler, helium tank) superconducting cavities to perform full RF high power tests and operate at temperatures between 1.8 K and 4.2 K. The cryostat is designed to accommodate a large array of superconducting cavities and magnets, among which the European Spallation Source (ESS) type spoke and high-β elliptical cavities as well as TESLA/ILC type elliptical cavities. The present status of the project and the design of the cryostat are reported.

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Keywords: superconducting RF cavity, test facility, ESS, TESLA, cryostat
PACS: 07.20.Mc

## THE FREIA FACILITY

The new FREIA laboratory at Uppsala University is constructed for research and development of new accelerators and instrumentation for accelerator based research. The FREIA laboratory is situated in a $1000m^2$ hall as a stand-alone facility: all equipment required for high power testing of superconducting accelerator cavities is within the laboratory, see Figure 1. It includes two radio-frequency (RF) power stations delivering up to 400 kW peak power at 352 MHz, 3.5 ms pulses at 14 Hz repetition rate. A horizontal test cryostat, installed inside a concrete bunker for radiation protection purposes, is the central part to cool down and test the accelerating cavities at temperatures down to 1.8 K. A helium liquefier with a capacity of 140 l/h liquid helium production, 2000 l liquid helium storage and 20 $m^3$ liquid nitrogen storage will provide the required cooling power. To recycle the helium gas, a gas recovery system is part of the complex and consists of a 100 $m^3$ gas balloon and 3 high pressure recovery compressors. For testing at temperatures below 4.5 K, sub-atmospheric pumps and a gas heater will be installed.

The present main project for the FREIA laboratory is the high power testing of the prototype RF power station, double spoke cavity and spoke cryomodule for the European Spallation Source (ESS) linear proton accelerator. Horizontal test cryostat, liquefier and RF power stations are to be commissioned by June 2014 to immediately perform tests of the first prototype spoke cavity; testing of the first prototype spoke cryo-module, with two spoke cavities, is scheduled for July 2015. FREIA will be built-up in stages starting with an RF development facility for accelerator research and a helium cryogenic system. The latter will be used to supply liquid Helium to experiments at FREIA as well as other experiments at Uppsala University. The experiments at FREIA will include one station with a horizontal test cryostat and at a later stage, a cryomodule; both will be connected in closed loop to the helium liquefier. A second station with a vertical test cryostat connected in closed loop to the helium liquefier is planned. An overview of the layout is given in Figure 1.

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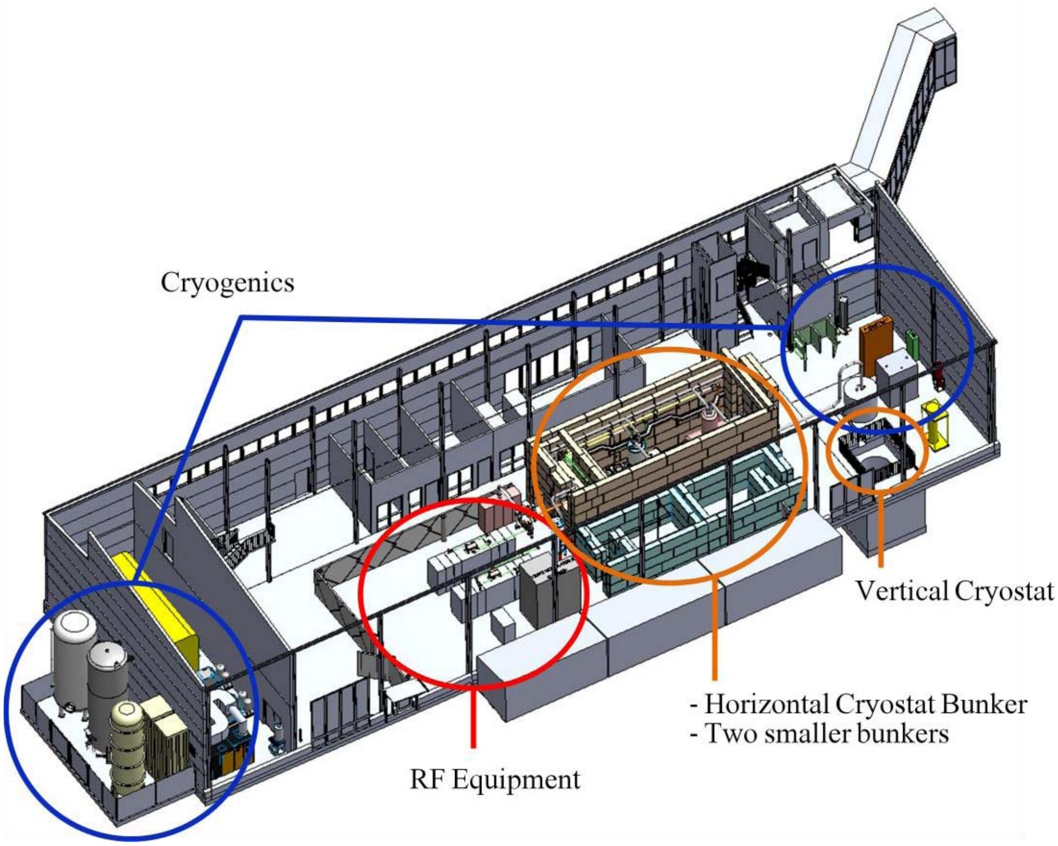



**FIGURE 1.** Layout of the FREIA facility.

## SPECIFICATIONS OF THE CRYOSTAT

The horizontal cryostat's primary aim is the testing of superconducting RF cavities equipped with their helium tank, cold tuning system, piezo tuners and power couplers. The layout of the horizontal test cryostat is based on previously built cryostats for superconducting cavity testing like HoBiCat [1], CryHoLab [2], or CHECHIA [3].

The electric fields in the cavities will be generated either by antennas (low power) or by connection of the fundamental power couplers. Different tests can be performed: coupler initial conditioning with detuned cavity; quality factor $Q_0$ as a function of the electric field in CW or pulsed mode; cavity frequency sensitivity to microphonics and He bath pressure fluctuations; Lorentz force detuning coefficient (CW or pulsed) measurement with antenna or coupler; slow and fast tuner tests including microphonics compensation; $Q_0$ sensitivity to residual magnetic field; quench localization and study.

The versatile cryostat design enables accommodation of a whole range of different superconducting devices: ESS double spoke β=0.50 352 MHz, ESS 5 cell elliptical β=0.89 704 MHz cavity [4] TESLA 9 cell 1.3 GHz elliptical cavities [5], superconducting solenoids or dipole magnets. Characteristics of some of these devices are listed in Table 1. The cavities will either rest on a helium-cooled table or be attached by tie beams.

**TABLE 1.** Estimated heat loads of the devices [4, 6] that will be tested in the FREIA cryostat. ESS coupler heat loads have been scaled from SNS: 40 W at 5-210 K for an average 50 kW per coupler taking into account the $f^{2/3}$ dependence of this heat load on frequency [7]. "Therm." means thermalization.

| Device type | Cavity | | | | | Coupler | | |
|---|---|---|---|---|---|---|---|---|
| | Nominal gradient (MV/m) | $Q_0$ @ $E_{nom}$ | Duty factor | Heat load @ 2 K Pulsed (W) | Heat load @ 2 K CW (W) | Average RF power (kW) | Cooling method | Dynamic Heat Load Pulsed |
| ESS Spoke β=0.50 352MHz | 8.0 | 1.2E+09 | 0.047 | 2.4 | 50.9 | 10 | SHe 5-210 K | 4.6 W@ 5-210 K |
| ESS elliptical β=0.89 704MHz | 18 | 6.0E+09 | 0.047 | 4.5 | 94.8 | 36 | SHe 5-210 K | 26 W@ 5-210 K |
| XFEL TESLA elliptical β=1 9 cell 1.3GHz | 23.6 | 1.0E+10 | 0.014 | 0.8 | 57.9 | 1.6 | Therm.@ 80 K Therm.@ 4.5 K | 6 W @ 80 K 0.5 W @ 4.5 K 0.06 W @ 2 K |

The cryostat can contain two different SC cavities simultaneously, which makes it possible to test either a 352 MHz or a 704 MHz power amplifier chain in combination with a superconducting cavity without the need to open the cryostat and replace the cavity. The cavities are contained in the same insulation vacuum and share a common helium bath; cavity cool-down and coupler cooling loops have been doubled to provide independent control of each of the cavity's /coupler's temperature during cooldown/coupler operation.

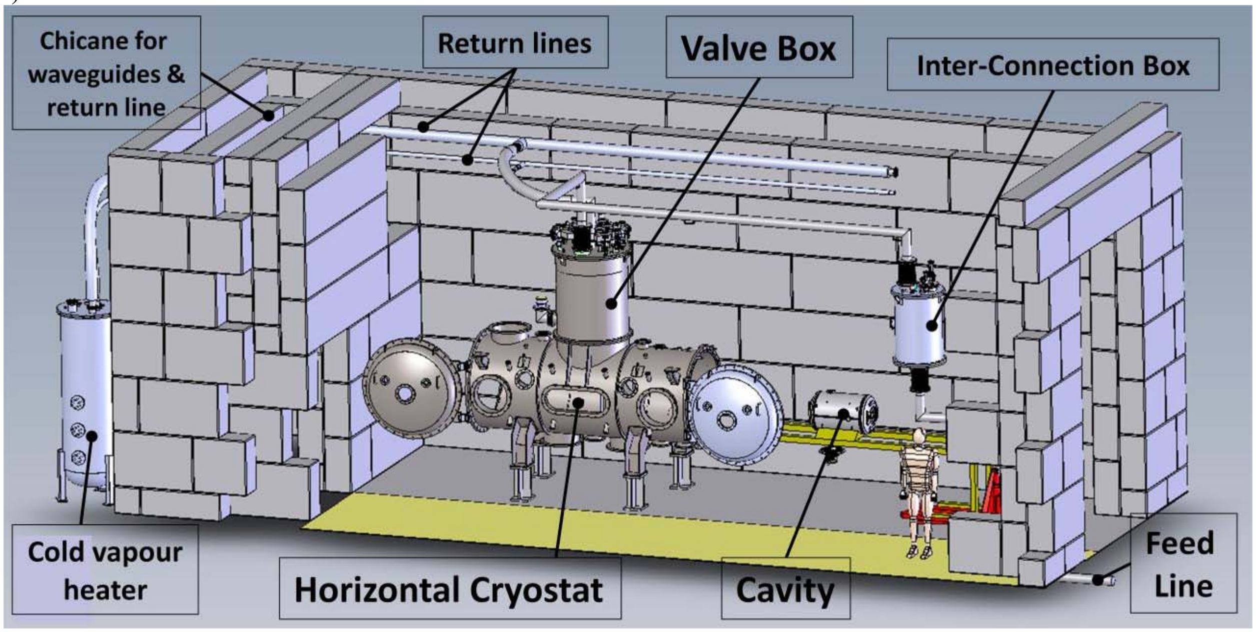
## CHARACTERISTICS OF THE CRYOSTAT

### FREIA Bunker

86 K@2.5 bar LN2 and 4.5 K@1.25 bar LHe are transferred via a transfer line (TL) from the dewars to the inter-connexion box (ICB). The TL is composed of Ø=20 mm LHe and LN2 pipes, a flexible nitrogen-cooled 80 K aluminium shield and insulating spacers. The ICB is composed of four stop valves (two for each circuit in the transfer line) that direct the flow of the cryogens either to the valve box of the horizontal cryostat or to the valve box of the future ESS Spoke cryomodule. A view of the cryostat and associated equipment is shown in Figure 2. Its main parameters are listed in Table 2. The valve box (VB) contains the necessary set of tanks, valves, and heat-exchangers (HX) to provide LN2 @ 80 K, LHe @ 2 K, LHe @ 4.5 K and He supercritical 5 K to the cryostat. He bath temperature in the cryostat is adjustable between 1.8 K and 4.2 K to enable measurement of BCS and residual resistance of cavities. This is achieved by pumping on the bath with a warm 75W@1.8K pump with 10 mbar inlet suction pressure. The load loss at the pump inlet is regulated between 1-1000 mbar by a warm butterfly-type valve situated after the cold vapour heater (Figure 2) with a pressure stability at 2 K of +/- 0.1 mbar to limit cavity detuning due to pressure fluctuations [8]. Supercritical helium at room temperature is provided by a separate circuit that must be filled from a pressurized helium bottle or from storage. The gas circulates in the circuit via an oil-free diaphragm pump.

The return LN2 cold vapors will be heated to room temperature in a heater cartridge in the valve box. They are then routed via a warm pipe to the atmosphere. The atmospheric pressure GHe is directed towards the cold vapour heater and sent back to a gasbag or to the coldbox. The subatmospheric pressure He return vapors are also heated then compressed back to near atmospheric pressure and routed back to the gasbag.

a)




b)

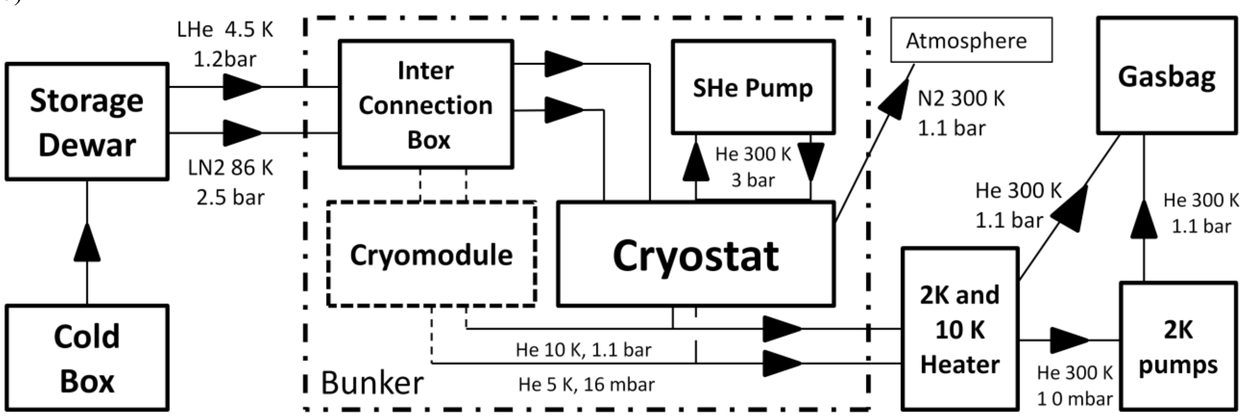



Figure 2. a) 3D view of the FREIA bunker, horizontal cryostat and associated components. The ICB and the transfer line are fastened to the wall (not shown here) b) Cryogenic distribution diagram of the FREIA bunker and its connections to the cold box and gasbag. Bunker limits are represented by dot-dash lines. The future ESS Spoke cryomodule is indicated in dashed lines; the interconnection box makes it possible to feed either the cryostat or the cryomodule. Return lines are shared by the cryomodule and the cryostat.

### Heat Loads

Estimated static heat losses of the cryogenic components in the bunker are shown in Table 3. Radiation static heat losses are minimized by isolating the 4 K components with a 2.5 bar 86 K LN2 cooled radiation shield. Insulation is ensured by 30 layers of single-aluminized mylar sheets between 300 K and 80 K and 10 layers between 80 K and 4 K; corresponding radiation flux values are 2 W/m² to 80 K and 0.05 W/m² to 4 K.

Conduction losses are minimized by using low conductivity material for all supports and thermalizing to the 80 K shield where possible. The cryostat shield is separated from the main vessel by 16 cylindrical teflon spacers. The LHe 4 K tank is held in place by three 80 K-thermalized epoxy glass tie-beams hanging from the valve box top. The 2 K tank is supported by the 4 K tank. All cryogenic valves which are in permanent contact with liquid helium (e.g., the 4 K cavity feed valve but not the cooldown valve) are thermalized to the 80 K shield. The cryostat main return lines are provided with gas counters so the static losses of the cryostat can be measured.

**TABLE 2.** Main parameters of the FREIA horizontal cryostat.

| Characteristic | Value |
|---|---|
| Interior length | 3.2 m |
| Interior diameter | 1.2 m |
| Number of cavities | 2 cavities |
| Helium bath temperature & pressure | 1.8 K-4.5 K<br>16 mbar-1.25 bar |
| Design capacity | 120 W @ 4.5 K (limited by liquefier)<br>90 W @ 1.8 K<br>400 W @ 86 K |
| Pressure stability | ±0.1 mbar @ 16 mbar |
| Static losses | 9 W @ 4.5 K<br>90 W@ 86 K |
| Table cooling | 4.5 K loop |
| Coupler cooling | Supercritical He 5 K-200 K<br>LN2 86 K |
| Radiation shield | LN2 86 K |
| 4 K cold mass | 600 kg (stainless steel, niobium) |
| 300K-4 K cool-down time | 9.6 h @ 2g/sec |
| 80 K cold mass | 200 kg (aluminium alloy) |
| 300-80 K cool-down time | 12.4 h @ 2g/sec |
| He bath pump suction pressure | 10 mbar |
| He bath pump power | 75 W @ 1.8 K |
| RF frequency | 352 MHz / 704 MHz / 1.3 GHz |
| RF power | 350 kW / 900 kW / 250 kW |

**TABLE 3.** Main static heat loads calculated for the FREIA cryostat.

| Heat load source | Conduction | Radiation | Total |
|---|---|---|---|
| **80 K** | | | |
| Horizontal cryostat shield | 10,0 | 29 | 39,0 |
| Transfer line (with vacuum barriers) | | | 28,0 |
| Valve box shield | 0,3 | 8 | 8,2 |
| Couplers | 6,0 | | 6,0 |
| Table | 1,2 | 3 | 4,3 |
| Interconnexion box shield | 0,4 | 4 | 4,1 |
| Total @ 80 K | | | **90** |
| **4.5 K** | | | |
| Cryogenic valves | 3,6 | 0 | 3,6 |
| Transfer line + vacuum barriers | | | 3,5 |
| Table | 0,1 | 0,21 | 0,3 |
| Cavities (includes couplers) | 1,19 | 0,10 | 1,3 |
| 4 K tank + 2 K tank | 0,06 | 0,22 | 0,3 |
| Other (piping, safety valve, etc.) | | | 1,0 |
| Total @ 4.5 K | | | **10** |

## Cool-down and warm-up

Cool-down of each cavity is ensured by a separate loop for each cavity. This loop reaches the cavity tank from below so that the cavity is cooled down by the cold vapors. Cool down times are dominated by the contribution of the 80 K shield cold mass (Table 2). During cooldown, if the cavity hasn't been heat-treated, the transition from 150 K to 70 K can be made in <1 hour to minimize the effects of Q-disease [9]. Thirty-five 100 W thin film kapton insulated heaters are uniformly distributed on the cold mass to ensure warm-up of the installation within 8 h.

## HORIZONTAL CRYOSTAT

### Main vessel

The cryostat main vessel (Figure 3) is 4 m long and 1.3m in diameter and made out of 8mm thick 304L stainless steel, closed at either end by convex doors on hinges. The vessel with its flanges and doors weights about 2 tons. Fully equipped with SC cavities and together with the valve box, up to 4 tons rest on the four feet of the cryostat. The feet will rest on a steel frame so that the cryostat axis will be at 1.5m from the floor, as in ESS. The cryostat presents numerous flanges to make it as versatile as possible. A table made out of cast aluminium profile, cooled by a 4 K helium loop can be mounted at the bottom of the cryostat. It is supported by 3 epoxy fiberglass Ø=150mm posts thermalized on the 80 K shield that rest on 3 distinct flanges (Figure 3). Alternatively, support of the cavities can be ensured by tie-beams (16 x 40 mm flanges). Power couplers can be connected to either side (4x500 mm, e.g. for TESLA couplers) or to the bottom (ESS couplers). The bottom flanges have deliberately been positioned close to the center of the cryostat so the user can have better access to the cold tuner (situated on the other side of the cavity) once the cavity with its coupler is installed. A 500 mm flange on the top of the cryostat will provide connections for of current leads for SC magnet tests. Access to the center of the cryostat is eased by a 800 mm long oval flange in the center of the cryostat. Spectrometers can be connected to measure photon/electron emission along the cavity axis via 2x200 mm flanges on the doors. Various other smaller flanges are included for insulation & cavity vacuum, instrumentation, safety valves etc. As the center of the cryostat is subject to an important bending stress (valve box weight and atmospheric pressure) the cryostat has been reinforced at this location by 4 ribs and two stiffening rings. A room-temperature magnetic shield is fixed to the inner cryostat wall, doors, and valve box sides to prevent penetration of the vertical (50 µT) Earth magnetic field component. Considering a 1 mm thickness and a relative permeability of $\mu_r$ = 15000 (this value can be guaranteed by the manufacturer), we expect an average shielding factor (outer to inner magnetic field ratio) of ~5 for ESS cavities in the case where the table feet flanges are capped but not the bottom couplers. To take some safety margin, we have chosen a magnetic shield design a thickness of 2 mm. The magnetic field can further be lowered to ~1 µT by installing a cavity-specific magnetic shield [10] as envisioned for ESS.

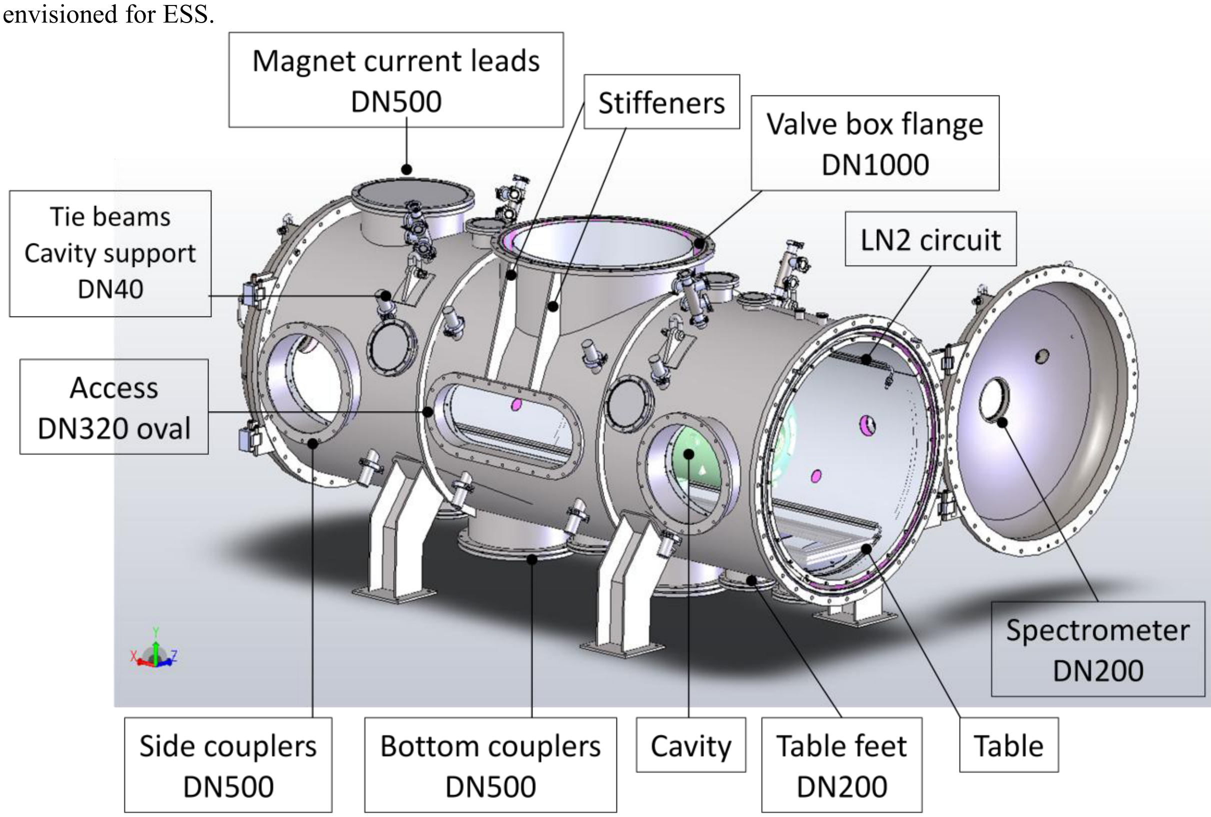



**FIGURE 3.** 3D view of the cryostat with descriptions of some important flange.

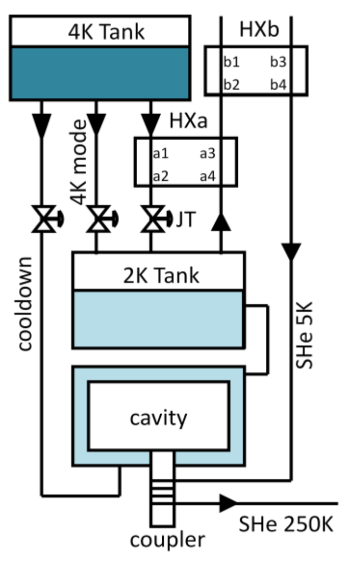
**Thermal shield**

The cryostat thermal shield consists of a 3 mm thick 5454-T6 aluminium alloy sheet cylinder with a mass of 130 kg. It is cooled by four 3.3m longitudinal strips of Ø=10 mm LN2 pipes soldered to the shield. The doors is bolted to the main cylinder after installation of the cavities and are cooled by thermal contact. The cryostat shield is separated from the room-temperature vessel by 16 cylindrical PTFE spacers lying on their side (on one edge). The surface area of contact of the spacers has been computed using the Hertz theory. With a maximum force per support of 170 N, the maximum surface area of contact is 40 mm², leading to a total conduction heat influx for 16 spacers from 300 K to 80 K of 10 W. Including radiation (2 W/m²), we have found that the hottest point on the cryostat shield is at 86.4 K, i.e. 2.4 K more than the LN2 loop. Finally, for SC magnet tests, the thermal shield is cut along its length to prohibit the flow of Eddy currents in the shield around the cryostat axis in case of a magnet quench. Mechanical integrity of the shield is preserved by four electrically insulating EpoxyGlass straps.

## VALVE BOX

The VB main components are two liquid helium tanks, a double heat-exchanger, 8 cryogenic valves (2 stop valves and 6 regulation valves) and an 80 K thermal shield. One of the main innovations of this cryostat is the use of a double heat-exchanger. The first module is used during 2 K operation of the cryostat. The cold vapors (2-3 K) from the cavity bath subcool the incoming LHe from the 4 K tank to enhance Joule-Thomson (JT) liquid yield [11]. The second module uses again the enthalpy of the cold return vapors (~4-5 K) to produce a stream of supercritical helium at 3 bar, 5 K for coupler cooling. The refrigeration capacity of this module naturally increases with coupler power as a greater power in the coupler induces increased cavity dissipation and return cold vapour flow. Since the low-pressure return cold vapour loop is common to both modules, the two modules can be fused in one compact component (Figure 4). We have opted for an annular 4.5 K, LHe tank (capacity 90 L) design to provide room for other components within the VB. A smaller, 35 L 2 K tank is situated below the 4 K tank. The JT valve, which operates between atmospheric and low pressure, is equipped with a helium guard to prevent any leaks. A heat-exchanger bypass is installed to avoid heating of the incoming LHe by return vapors in 4 K mode. The N2 loop outlets are equipped with finned tube and 1kW heaters to warm up to 2 g/sec of GN2 vapors to room temperature just before they exit the valve box. SHe is circulated in closed loop through the cryostat by a diaphragm pump. To prevent any contamination of this loop, we installed an 80 K cooled activated charcoal trap in the valve box. The SHe loop outlet is also equipped with a 1 kW heater for a maximum flow of 1g/sec (for both cavities).

a)




b)

| Heat load source | Low pressure GHe | Atmospheric pressure LHe | Supercritical He |
|---|---|---|---|
| **Module a** | | | |
| Mass flow | 4.5 g/s | 4.5 g/s | |
| Temperature in | 1.8 K (a3) | 4.2 K (a1) | |
| Temperature out | 4.2 K< (a4) | 2.16 K (a2) | |
| Nominal Pressure | 16 mbar | 1.3 bar | |
| Load loss | <50 Pa | <3000 Pa | |
| **Module b** | | | |
| Mass flow | 4.5 g/s | | 1 g/s |
| Temperature in | 4.2 K (b2) | | 300 K (b3) |
| Temperature out | <50 K (b1) | | ~5 K (b4) |
| Nominal Pressure | 15.5 mbar | | 3 bar |
| Load loss | <50 Pa | | <3000 Pa |
| **Module a&b** | | | |
| Total load loss | <100 Pa | <3000 Pa | <3000 Pa |
| Dimensions | 600 x 150 x 150 mm | | |

**FIGURE 4**. a) Functional scheme of the cooldown. 4 K, 2 K (JT) and coupler (SHe 5 K) cooling loops and their connections to the heat exchanger blocks HXa, HXb; b) Main characteristics of the two-module heat exchanger. The letters a1 etc. on the HX refer to positions on the functional scheme.

## OTHER COMPONENTS

Concerning instrumentation, the cryostat and its associated components (VB, ICB, TL) are equipped with about 40 4-wire Cernox thermometers for He temperature monitoring and process and about 50 Pt thermometers for 80 K components. Two pairs of superconducting wire gauges are installed on the 4 K and on the 2 K tanks to monitor liquid helium level. Pressure gauges measure the important pressures within the installation: cavity & insulation vacuum, 4 K and 2 K tanks. Warm flow meters and gas counters monitor the main mass flows to adapt them to the heat load during operation.

Six helium safety valves are installed on the cryostat and its associated equipment with an opening pressure of 1.5 barA. The biggest one, Ø=63 mm, is installed on the 2 K tank (without helium guard). It has been sized to allow exhaust of cold He vapors with little overpressure in case one of the cavity's vacuum ruptures. In this case, air condenses on the inner surface of the cavity, where no MLI is present. The heat flux in this case is 38 kW/m² [12], i.e., 76 kW for a 2 m² inner surface cavity such as the ESS elliptical.

A cold vapor heater, situated outside the bunker, warms the cold helium vapors back to room temperature by heat exchange with a temperature-regulated water bath. Sizing of the pipe for the low-pressure return is particularly critical as the load loss along this pipe should be kept at a minimum (<200 Pa) so that the pressure exerted on the 2 K bath can be as low as possible (16 mbar) given the 10 mbar suction pressure of the pumps. We have computed by considering the temperature and heat-exchange coefficient profile along the pipe that a 4.5 g/sec stream of 5 K helium at 16 mbar can be warmed up to 250 K in a 10 m long Ø=100 mm pipe.

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