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# Cryogenic system for the MYRRHA superconducting linear accelerator

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**Abstract.** SCK•CEN, the Belgian Nuclear Research Centre, is designing MYRRHA, a flexible fast spectrum research reactor (80 $MW_{th}$), conceived as an accelerator driven system (ADS), able to operate in sub-critical and critical modes. It contains a continuous-wave (CW) superconducting (SC) proton accelerator of 600 MeV, a spallation target and a multiplying core with MOX fuel, cooled by liquid lead-bismuth (Pb-Bi). From 17 MeV onward, the SC accelerator will consist of 48 $\beta$=0.36 spoke-loaded cavities (352 MHz), 34 $\beta$=0.47 elliptical cavities (704 MHz) and 60 $\beta$=0.65 elliptical cavities (704 MHz). We present an analysis of the thermal loads and of the optimal operating temperature of the cryogenic system. In particular, the low operating frequency of spoke cavities makes their operation in CW mode possible both at 4.2 K or at 2 K. Our analysis outlines the main factors that determine at what temperature the spoke cavities should be operated. We then present different cryogenic fluid distribution schemes, important characteristics (storage, transfer line, etc.) and the main challenges offered by MYRRHA in terms of cryogenics.

**Keywords:** superconducting linear accelerator, large cryogenic infrastructure, MYRRHA
**PACS:** 07.20.Mc

## MYRRHA

The MYRRHA project being designed by the SCK•CEN at Mol, Belgium, is an Accelerator Driven System (ADS) based on a liquid PbBi (LBE) cooled fast reactor (80MWth). It will show how efficient transmutation of nuclear waste products can be achieved in dedicated industrial facilities, called transmuters. In subcritical operation mode the required spallation neutrons are obtained from collision of a 600MeV and up to 4mA proton beam with the LBE target (and coolant). The beam is provided by a CW superconducting linac. A mean-time between failure exceeding 250 hours is needed for successful operation and optimal integrity of the ADS. This constitutes MYRRHA's main challenge. A combination of parallel redundant and fault tolerant schemes is used to reach this goal. Two parallel identical injectors, made out of warm and SC components (CH cavities) (for redundancy needs) deliver a 17 MeV beam at 176MHz. The SC linac is then split into three sections: Spoke, low $\beta$ elliptical and high $\beta$ elliptical (see Table 2). The two injectors are connected to the SC linac by means of a common switching magnet and a Medium Energy Beam Transport line (MEBT). Once the beam reaches its peak energy, it is transported through a High Energy Beam Transport (HEBT) to the spallation target inside the reactor. The beam is delivered vertically to the reactor. The full power beam dump (2.4MW) will be an essential tool for commissioning and validation of the accelerator before beam delivery to the actual reactor.

The MYRRHA ADS is planned to be operational in 2024 and is presently in its R&D phase, which includes programs around the ambitious accelerator design as well as the liquid PbBi coolant and spallation target of the reactor.

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# OPERATING TEMPERATURE & HEAT LOADS

## Operating Temperature

*Operating Temperature of Spoke Cavities*

We analyze here the important factors that determine the operating temperature of Spoke cavities, and apply them to the specific case of MYRRHA. The quality factor $Q_0$ of a superconducting RF cavity is inversely proportional to the surface resistance $R_S$ [1]:

$$Q_0 = G/R_S \qquad (1)$$

$Q_0$ being the geometrical factor of the cavity (units : Ω). $R_S$ is composed of two terms,

$$R_S = R_{BCS} + R_{res} \qquad (2)$$

The BCS term $R_{BCS}$ due to the inertia of Cooper pairs depends strongly on frequency $f$ and temperature $T$ [2]:

$$R_{BCS} = 1.3 * 10^{-13} \frac{f^2 \exp(-17.67T)}{T} \qquad (3)$$

While the residual resistance term $R_{res}$ includes all other contributions to the resistance, caused by impurities in the Niobium or trapped magnetic field. $R_{res}$ is weakly temperature dependent [3, 4]. Other important factors such as electron emission are responsible for significant deviations of $Q_0$ from (1-3) as the field within the cavity increases. For 700 MHz cavities, continuous wave (CW) operation in 4.5 K normal He is avoided due to prohibitively high BCS losses. For 350 MHz Spoke cavities however, the BCS term is of the same order as the residual resistance. From the point of view of total electric power consumption of the cryoplant, operation in superfluid helium (around 2K) becomes relevant only if the gain in $Q_0$ is higher than the concomitant increase in COP of the cryoplant at 2K:

$$\frac{Q_0(2K)}{Q_0(4.5K)} > \frac{COP(2K)}{COP(4.5K)} \qquad (4)$$

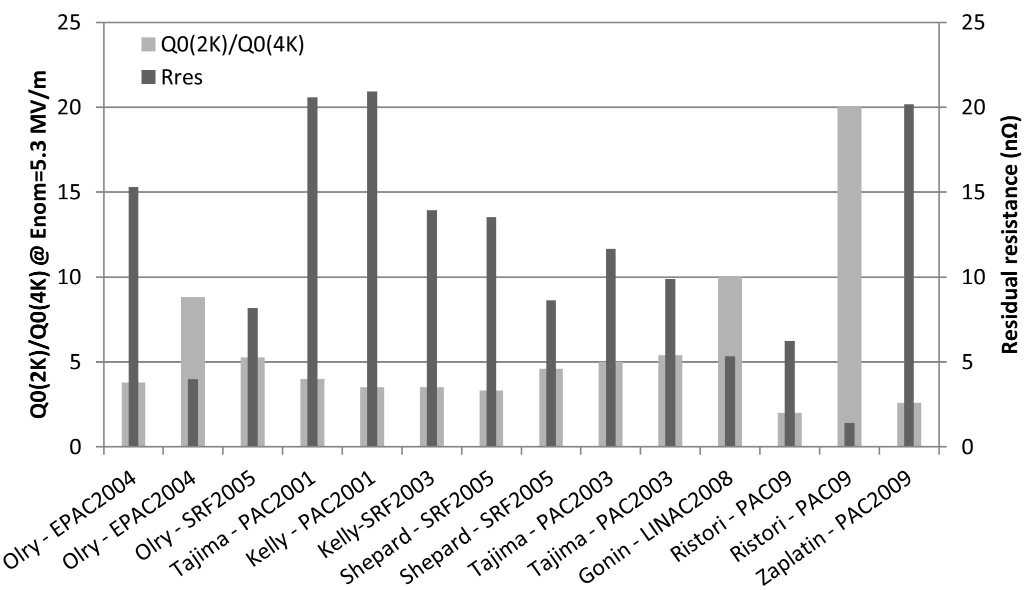


**FIGURE 1.** $Q_0(2K)/Q_0(4.5K)$ values for simple, double and triple Spoke cavities tested worldwide, at the nominal operating field of the MYRRHA linac, 5.3 MV/m. Residual resistance data is evaluated from measured $Q_0$ values at two temperatures and at the lowest electric field at which experimental data was taken (E~0).



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We have compiled in Figure 1 quality factor experimental data from the literature on Spoke cavities; averaging over all these measurements we find the average $< Q_0(2K)/Q_0(4.5K) >= 5.6$ ; we can further deduce using (1-3) an experimental average residual resistance $< R_{res} >= 10.8$ nΩ. Typical $COP(2K)/COP(4.5K)$ values (see Table 1) are in the range 3-5, meaning that, considering only dynamic losses, it would be energetically favorable to run the Spoke cavities at 2K. Static losses mitigate this conclusion however; in the case of MYRRHA, where static losses are relatively high (see next section), the total power consumption of the cryoplant with Spoke cavities at 2K or 4.5K ends up being the same (2.3 MW).

Other important factors should be considered:

- Boiling 4.5K He has higher pressure fluctuations than superfluid baths. These pressure fluctuations cause cavity detuning [5]; to maintain cavity performance, more RF power has to be injected through the coupler. This effect can be limited by minimizing the pressure sensitivity of the cavity $\Delta f / \Delta p$ by mechanical design (see for example [6]), or by installing fast compensating piezo-tuners [7, 5].
- 2K operation is more difficult to implement, requiring subcooling heat exchangers, JT valves, low-pressure pumps and return lines. It is consequently also less reliable than 4.5 K operation. In the case of MYRRHA, return lines and pumps will in any case be installed for the elliptical section.

All in all, these factors have led us to choose 2K operation of Spoke cavities for the reference design of MYRRHA. 4.5K operation might be reconsidered after more experience is gathered from prototype Spoke cryomodules.

In general, determining the operation temperature of Spoke cavities should be done on a case-by-case basis. From an energetic point of view, 2K operation becomes more favorable as static losses and residual resistance decrease. Other factors such as electron loading (experimental $Q_0$), cavity detuning due to pressure fluctuations, 2K implementation constraints, cost and consequences on reliability play an equally important role.

*Optimal Operating Temperature of the Linac*

The optimal temperature of the linac at close to 2K can be determined by finding the right compromise between a low BCS resistance (3) and a low COP to minimize overall electrical consumption of the cryoplant [8]. COP as a function of temperature was taken as:

$$COP = \alpha \frac{T_r - T}{T} \tag{5}$$

With $T_r = 300$ K, a factor $\alpha = 0.2$ yields a COP of 720 W/W at 2K as will be discussed in the next section. Figure 2 shows that the optimal temperature is located around 1.9-2K.

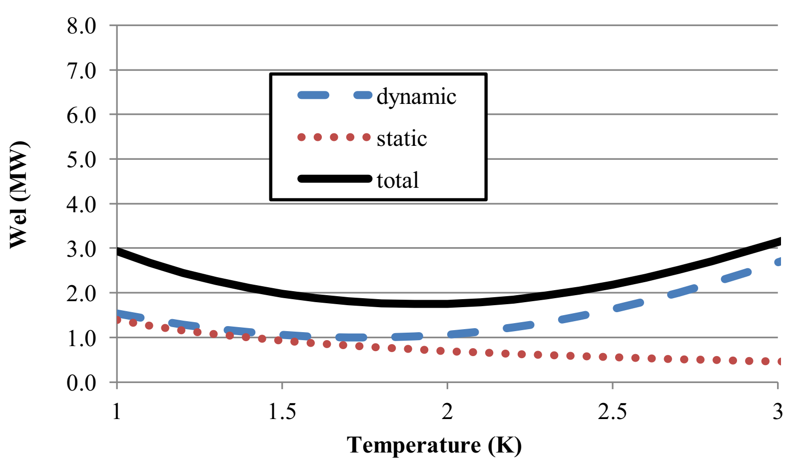


**FIGURE 2.** Optimal operating temperature of the MYRRHA linac to minimize total electric power consumption of the cryogenic plant. The optimum temperature has a broad minimum around 1.9-2 K. Note that we did not include in this optimization the electron loading effects at non-zero electric field.



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## Heat Loads

The MYYRHA linac will present three distinct temperature levels: cavity cooling in superfluid (2K), coupler cooling with supercritical helium at 5-210K, and cryomodule thermal shield cooling with gaseous helium at 40-80K. To accurately size the required power of the cryogenic plant at these different temperature levels, we need to estimate static and dynamic heat losses on a realistic basis. Static loss is related to the non-ideal insulation of the cold parts of the linac from their environment: radiation fluxes, conduction through supports, pipes, etc. They are present even when the beam is shut off. We list in Table 1 static losses reported for other important accelerator projects. The computed value is based on the total length of cold components (cryomodules) and does not include warm sections. It generally lies in the range 1-5 W/m and decreases with an increase of the number of cavities per cryomodule (i.e, when the number of room temperature – low temperature transitions of the linac is reduced). For the MYRRHA project, the number of cavities per cryomodule (between 2 and 4, see Table 2) was deliberately restricted in order to facilitate defective cryomodule localization, diagnostic and maintenance, to provide near perfect optical lattice regularity and to install room temperature focusing magnets between cryomodules [9]; the average CM length of MYRRHA is 3.38 m, slightly shorter than the SNS medium β CM [10]. We therefore consider as a preliminary estimate of static losses 5W/m on the 2K level and 40 W/m on the 40K level.

**TABLE 1.** Static heat loads, COP of cryoplant and overcapacity factors of some reference projects for MYRRHA. COP data for SNS, JLAB and LHC is measured; they are specifications for XFEL. Note that XFEL has a second thermal shield at 5-8K not indicated in this table, which explains the very low static losses at 2K. LHC static losses data are not given since they are not representative of heat losses in a linac cryomodule. JLAB static losses are taken from the upgrade cryomodule; COP data is from the first CEBAF cryogenic plant.

| **Characteristic** | **SNS [10]** | | **XFEL [11]** | **JLAB [12], [13]** | **LHC (one sector) [14]** |
|---|---|---|---|---|---|
| Cryomodule content | 3 med-β elliptical | 4 high-β elliptical | 8 β=1 elliptical | 8 β=1 elliptical | - |
| Focusing magnets localization | outside cryomod | outside cryomod | 1 inside | outside cryomod | - |
| Cryomodule Length (m) | 4.24 | 6.29 | 12.2 | 8.25 | - |
| Static Loss into 2 K (W/m) | 4.64 | 3.55 | 0.11 | 1.8 | - |
| Static Loss into 40-K (W/m) | 36.55 | 30.36 | 5.82 | 17 | - |
| Operating Temperature (K) | 2 | | 2 | 2 | 1.8 |
| Equivalent 4.5 K Power (kW) | 10 | | 12 | 10.8 | 18 |
| Power at op. temp. (kW) | 2.4 | | 2.8 | 4.8 | 2.4 |
| COP at op. temp. (W/W) | 1150 | | 870 | 950 [15] | 950 |
| COP at 4.5K (W/W) | 386 | | 220 | | 240 |
| Overcapacity factor | 2 at 2K and 5K<br>1.5 at 35K | | 1.5 | 1.45 [16] | ~1.65 [17] |

Dynamic losses of the cavities and their couplers are listed in Table 2 for the MYRRHA linac reference design [18]. Each cavity type has already been prototyped and the $Q_0$ values at the nominal electric fields foreseen for MYRRHA measured. The high β elliptical section is responsible for 46% of the cryogenic losses (dynamic + static); the Spoke and low β elliptical section represent 22% and 27% respectively while the injector CH cavities account for only 5%. Total static losses amount to 1015 W; dynamic losses to 1860W. The dynamic range, defined as the ratio of total losses over static losses of the MYRRHA linac is therefore 2.8.

Safety margin on the overall heat load of the cryogenic system is inspired by the experience of the LHC [17]: the uncertainty factor $F_{un}$ = 1.25 takes into account lack of reproducibility in construction (e.g. MLI wraps); variance of thermal processes at work (e.g. insulation vacuum); evolution in time (ageing, contamination of reflective surfaces; imperfect niobium, electron loading. The overcapacity factor $F_{oc}$ = 1.5 takes into account the fact that linac cool down should be completed in a reasonable amount of time (<week), that refrigerator loading should be less than 100 % and the variability of machine performance. Overall, we multiply each of the cryogenic load obtained (on 2K, 5K and 40-80K) by a factor 1.5x1.25 = 1.875; this resulting overall safety margin is higher than that taken at the LHC after 15 years of component testing [17].



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**TABLE 2.** Cavity and coupler characteristics and dynamic heat loads. Coupler heat loads have been scaled from SNS (0.038g/sec heated from 5 to 210 K for an average 50kW per coupler, taking into account the $f^{2/3}$ dependence of this heat load on frequency).

| Characteristic | CH β=0.1 352 MHz | Spoke β=0.36 352 MHz | Elliptic β=0.47 704 MHz | Elliptic β=0.65 704 MHz |
|---|---|---|---|---|
| Length of section with warm spaces (m) | 2x5 | 69 | 64 | 101 |
| Number of cavities | 8 | 48 | 34 | 60 |
| Number of cavities per cryomodule | 4 | 3 | 2 | 4 |
| Residual resistance (nΩ) | 43 | 10 | 10 | 10 |
| $Q_0$ theoretical | 1.3E+09 | 9.4E+09 | 1.0E+10 | 1.3E+10 |
| $E_{acc}$ (MV/m) | 4 | 6.2 | 8.2 | 11 |
| $Q_0$ experimental @ $E_{acc}$ | >2.0E+08 [19] | 2.0E+09 [20] | 1.0E+10 [21] | 3E+10 [22] |
| Heat per cavity, based on lowest exp. or theor. $Q_0$ (W) | **11.2** | **8.9** | **11.3** | **15.5** |
| Average RF power per cavity (kW) | 25 | 15 | 30 | 55 |
| Coupler Cooling method | Cooling loop SHe 5 -210 K | Cooling loop SHe 5 -210 K | Cooling loop SHe 5-210 K | Cooling loop SHe 5-210 K |
| Static & dynamic coupler load for section (g/sec @5-210K) | 0.07 | 0.24 | 0.53 | 1.71 |

For MYRRHA, we thus obtain a total equivalent power at 4.5K of 14.3 kW (including safety margin), i.e. between that of the XFEL cryoplant (12 kW) and of one LHC unit (18 kW).
Realistic COP values for the MYRRHA project were estimated from discussions with S. Claudet at CERN [23]. In LHC, the 2K cold box is physically separated from the 4.5K part, to limit the hydrostatic heads on the low-pressure return [24]. Given that the 2K and 4K cold boxes will be integrated in a single component in MYRRHA, COPs of 720W/W at 2K and 220W/W at 4.5K are realistic goals. The liquefaction COP value for coupler cooling was obtained by applying the ratio of real-to-Carnot COP of a refrigerator (220/70 ~ 3.1) to the Carnot COP of a liquefier. With these COP values, the total electrical power will reach up to 4.3MW (including safety factor). The main characteristics of the MYRRHA plant are summarized in Table 3.

**TABLE 3.** Required power of the MYRRHA cryogenic plant

| Temperature level | Heat load | COP | Function | Equivalent 4.5K power |
|---|---|---|---|---|
| 2 K | 5.4 kW | 720 W/W | Cavities | |
| 40 K | 15.2 kW | 20 W/W | Shield | 14.3 kW |
| 5-210 K (liquefaction) | 4.8g/sec | 21.4 kW/(g/sec) | Coupler cooling | |

## CRYOGEN DISTRIBUTION

For 2K refrigeration, it is necessary to subcool the helium stream in a heat exchanger before JT expansion to increase the liquid yield [25]. In the centralized subcooling heat exchanger scheme [26] subcooling to 2K (3 bar) is done in the cold box, and the subcooled gas is then distributed in a dedicated transfer line; JT expansion is realized in the valve box of each cryomodule. In the distributed scheme [27], only one supply line is necessary for cool-down, coupler cooling and cavity 2K refrigeration: subcooling and JT expansion is achieved in the valve box of each cryomodule. We list in Table 4 pros and cons of each scheme (see [28] for a similar discussion). In view of those, we have opted for a distributed scheme for MYRRHA.



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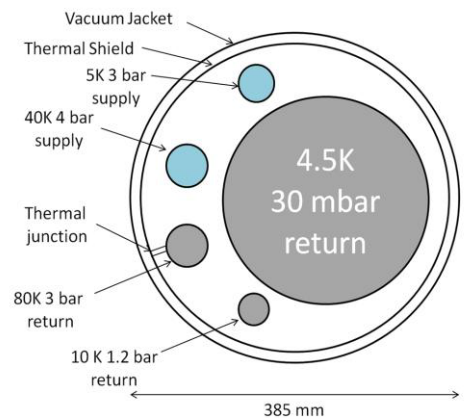
**TABLE 4**. Advantages of each distribution scheme. Advantages of one scheme are also drawbacks of the other.

| **Distributed scheme** (SNS, LHC, XFEL) | **Centralized scheme** JLAB (CEBAF) |
|---|---|
| Better control of individual cryomodules (necessary for commissioning, cooldown) | Only one HX: more economical, compact, and reliable HX |
| No additional supply line necessary : more economical and reliable TL | Return line load losses are reduced at 2K, smaller LP pipe diameter (190 mm rather than 236 mm) |
| Less heat flux on the 2K level | Simplified VB design |

The helium feed-in and return lines will be installed in a thermally shielded, vacuum insulated vessel, running parallel to the linac, as in SNS [29]; the XFEL design, that uses a common vacuum for both cavities and transfer lines [11], is poorly compatible with the design of MYRRHA, based on warm focusing solenoids between each cryomodule. Main cryogenic transfer lines (TL) are presented in Table 5; they are similar to those of SNS. Helium for cavity and coupler cooling is supplied in supercritical form; it is used as such for coupler cooling, and is first expanded through a JT valve for superfluid cavity cooling. Return vapors are pumped through a low-pressure return line. During cooldown, when the low-pressure pumps are not active, the close-to-atmospheric pressure vapors are returned through a separate line; this line could possibly also be used to return warm coupler vapors during operation. Finally, two lines provide for thermal shield cooling at 40K, 3bar and return at 80K. The 80 K return will be used to shield the TL, as in the LHC design [30].

**TABLE 5.** Transfer line characteristics and scheme. Line diameters are computed from max pressure drops and mass flow [25].

| **Line** | **Function** | **Max mass flow (g/sec)** | **Max pressure drop (kPa)** | **Ø (mm)** |
|---|---|---|---|---|
| Supply Supercritical 4.5 K, 3 Bar | Supply for coupler cooling and cavities (after JT expansion) | 158.2 | 10 | **40** |
| Supply and Return 40-80 K, 4-3 bar | Thermal shield of cryomodules and transfer line | 37.9 | 100 | **2 x 45** |
| Low Pressure Return 4.5K, 30 mbar | Cavity return in operational mode | 153 | 0.1 | **238** |
| Gas return 10 K, 1.2 Bar | Cooldown return & coupler return | 67.5 | 10 | **29** |




In the current design, each cryomodule will be associated to one valve box (1VB-1CM). It would be possible to use one valve box to feed several cryomodules (e.g. 1VB-2CM) to save space in the linac tunnel, and reduce the number of components such as heat-exchangers, tanks and vacuum vessels without compromising control over the cryogenic process of each cryomodule (the total number of valves would be identical to the 1VB-1CM scheme). One valve box could be placed between two cryomodules for example and feed both of them by means of short connecting arms. Maximum mass flows through the subcooling heat exchangers are 5.3 g/sec for elliptical $\beta$=0.65 cryomodules. Heat exchangers designed for the LHC [31], which have a similar nominal mass flow (4.5 g/sec), could therefore be used. We estimated the cold mass of the MYRRHA linac to be 34 tons at 2K and 36 tons at 40K. Cool-down time of one cryomodule at a mass flow of 2 g/sec is determined by cool-down time of the thermal shield; it would take ~8h.



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## CRYOGENIC PLANT MAIN COMPONENTS & IMPLEMENTATION

Main cryogenic plant components are outlined in Figure 3.

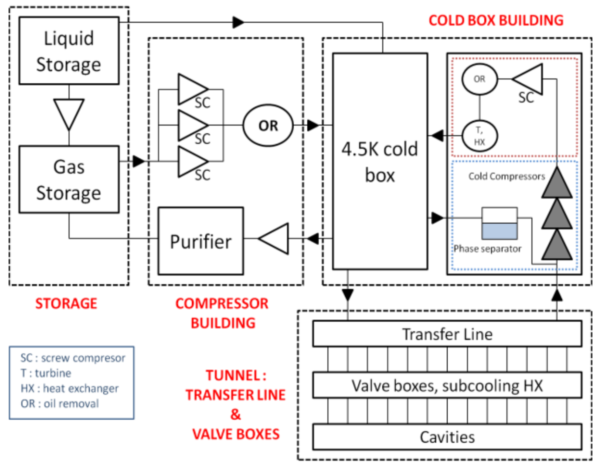


**FIGURE 3.** Cryogenic plant scheme and main components.

The dynamic range (2.8) of the cryoplant indicates over what range of heat loads the cryogenic plant will have to perform, and what range of He vapor mass flows the cold compressors [32] will have to handle. As the latter is limited when several cold compressors are installed in series [33], a mixed compression scheme will have to be considered, where part of the compression of the subatmospheric helium vapours is done after they are warmed up back to room temperature. In MYRRHA, the 2K and 4K cold box can be integrated in one unit: the mixed compression scheme could achieve higher dynamic ranges than at LHC, on the order of ~6 [23].

The heat load center of gravity is located at 140 m from the injector, close to the geometrical center point of the linac (120 m) or the beginning of the high β elliptical section (132 m). The cryogenic plant will be located close to this position; the travel length and the mass flow in each segment is divided by two compared to a scheme where the plant would be placed at one end of the linac (as in XFEL for example). This reduces load losses and pipe diameters.

The liquid helium volume contained in the MYRRHA linac is ~7000 L, assuming a cavity+phase separator volume of 50 L per cavity; 200 L of helium are present in the pipes of the linac; we do not consider the small volumes of liquid in the cold box. Helium storage should be at least 100 % in volume of the total helium comprised in the machine to act as an efficient buffer. This can be achieved by a 250 $m^3$ container of warm He gas at 20 bar. Yearly helium inventory losses at the LHC currently amount to 30 % [34] (see [35] for data on other accelerators). Low pressure elements such as superconducting cavities are however more subject to helium leaks: for MYRRHA, a yearly loss of 50 % of the inventory is a reasonable estimate.

We computed approximate surfaces occupied by each building by scaling the sizes of one LHC unit by the total equivalent refrigeration power at 4K (18 kW for LHC, 14.3 kW for MYRRHA). We find 40 x 24 m² for the compressor, 36 x 24 m² for the cold box. The total length occupied by the cryoplant is about $1/3^{rd}$ of the linac length. These building sizes are comparable to those of XFEL (72 x 32 m² and 14m height for 12 kW@4K [36].

## CONCLUSIONS

We have presented the most salient features of the cryogenic plant preliminary design of the MYRRHA project. LHC and other project [37, 38] have shown that a large scale cryogenic plant can be operated with high reliability (99%) if certain measures are implemented: doubling and allowing easy replacement of all elements containing moving/vibrating parts, strengthening utilities which are a common cause of malfunction, installing dryers, 80K and 20K adsorbers as well as helium guards on low pressure components etc. The cost of the MYRRHA cryogenic plant can be estimated by scaling from other projects [39, 34, 40] or from a cost list of main components [9]: we find it to lie in the range 28-33 M€, including manpower.

The main cryogenic challenge faced by MYRRHA is to handle the large refrigeration power at 2K, 5.4 kW, which comes as a consequence of the CW operation of the linac. This power at 2K is more than twice that of LHC or SNS.



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This might require either upgrading current cold compressor technology (e.g. of the LHC, [32]) so they can handle larger mass flows, or devising parallel cold compression schemes.


## ACKNOWLEDGMENTS

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