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# Calculation of Helium Inventory in LHC Arcs from Geometry and Comparison with Observations

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## Summary

This report estimates the helium inventory inside the 1.9K cryogenic circuit of the LHC arcs. The assessment is based on geometrical considerations obtained from the construction files of the cold masses and its result is compared with test results and the specified design value.

## 1. INTRODUCTION

This work presents the assessment of the geometrical void space available for superfluid $^4$He filling, and compares it with design requirements [1][1]. Making use of both experimental and geometrical results, a confident value for real helium content can be derived.

## 2. PROCEDURE

In the following approach the helium content is evaluated by calculating the geometrical void space available to superfluid helium, which is contained inside an envelope defined by the magnet cold mass, diode box, line N and cold mass interconnection. The available void space is then simply calculated by subtracting from the volume of the envelope, the volume occupied by each component or body which is internal to it.

### 2.1 *Cold Mass*

This procedure is based on geometrical estimations from hardware drawings and material databases. It requires an accurate knowledge of the cryomagnets design and of their interconnections, and it is different depending on the cold mass type.
To minimize errors, the volume of the bodies which are internal to the cold mass is derived from their well known masses and densities:

$$V_{\mathrm{ibs}} = \sum_j \frac{m_j}{\rho_j} \qquad (1)$$

where $j$ stands for the material type (steel, copper, aluminum, etc... see Table 2 in the Appendix), $m_j$ is the $j$-material overall mass (kg) within the cold mass and $\rho_j$ is the $j$-material density (kg/m$^3$).
The masses considered in the formula above include only parts and components which are internal to the cold mass helium vessel: every component constituting the cold mass assembly (different insert types, laminations, end plates, collared coils and superconductor distribution), corrector magnets, helium heat exchanger tube and cold bore tube assembly.
Hence the volume effectively available for helium filling, within the magnet cold mass, is obtained considering also the volumes of hollow parts, filler pieces and bus bars:

$$V_{\mathrm{sc}}^{\mathrm{eff}} = V_{\mathrm{sc}}^{\mathrm{int}} - V_{\mathrm{ibs}} - V_{\mathrm{cb}}^{\mathrm{int}} - V_{\mathrm{het}}^{\mathrm{int}} - V_{\mathrm{fp}} - V_{\mathrm{bb}} \qquad (2)$$

where $V_{\mathrm{ibs}}$ has been defined in (1) and:

$V_{\mathrm{sc}}^{\mathrm{int}}$ is the internal volume of the He vessel (shrinking cylinder for the dipole, inertia tube for the quadrupole)

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[1] For reasons of enthalpy buffering and to guarantee the storage of gaseous helium, the superfluid helium quantity inside the cryomagnet cold masse was established to be between 15 l/m and 20l/m.

$V_{\mathrm{cb}}^{\mathrm{int}}$ is the internal volume of the cold bores
$V_{\mathrm{het}}^{\mathrm{int}}$ is the internal volume of the heat exchanger tube
$V_{\mathrm{fp}}$ is the overall volume of the filler pieces
$V_{\mathrm{bb}}$ is the overall volume occupied by the bus bars

## 2.2 *Other Parts*

To this value $V_{\mathrm{sc}}^{\mathrm{eff}}$, the volume of all the other parts filled with superfluid $^4$He and in communication with the cold mass at ~1.8K has to be added. These volumes, although external to the helium vessel in a proper sense, affect the thermal performance of the cryomagnet. These parts are line N, cryomagnet interconnections and diode boxes, so that the overall volume available for helium filling inside the mentioned envelope is

$$V_{\mathrm{He}} = V_{\mathrm{sc}}^{\mathrm{eff}} + V_{\mathrm{N}}^{\mathrm{eff}} + V_{\mathrm{conn}}^{\mathrm{eff}} + V_{\mathrm{diode}}^{\mathrm{eff}} \tag{3}$$

where

$V_{\mathrm{N}}^{\mathrm{eff}}$ is the line N internal volume effectively available for helium filling
$V_{\mathrm{conn}}^{\mathrm{eff}}$ is the interconnections internal volume effectively available for helium filling
$V_{\mathrm{diode}}^{\mathrm{eff}}$ is the diode internal volume effectively available for helium filling

In (3) the quantity $V_{\mathrm{N}}^{\mathrm{eff}}$ was calculated considering the presence inside line N of cables and of its own filling pieces, as well as for $V_{\mathrm{conn}}^{\mathrm{eff}}$ where the presence of bus bars and insulating pieces has been taken into account. Finally, the volume $V_{\mathrm{diode}}^{\mathrm{eff}}$ was calculated in the same way as for the cold mass helium vessel, subtracting from the internal volume of the diode box the volume occupied by each of its various components.

## 2.3 *Average Helium Quantity in the Arc*

Each component considered in the procedure will be at about 2K in nominal operating conditions. Hence each volume, as calculated from the design specifications, has been properly corrected considering its thermal contraction[2].
The values obtained with this procedure for the main dipole $V_{\mathrm{He}}^{\mathrm{D}}$ and main quadrupole $V_{\mathrm{He}}^{\mathrm{Q}}$ were then multiplied respectively by the number of dipoles $n_{\mathrm{D}}^{\mathrm{arc}}$ and quadrupoles $n_{\mathrm{Q}}^{\mathrm{arc}}$ in the arc. The average helium quantity per unit length in the arc $\overline{V}_{\mathrm{design}}^{\mathrm{arc}}$ is then given by the sum of these two quantities divided by the overall arc length $L_{\mathrm{arc}}$ :

$$\overline{V}_{\mathrm{design}}^{\mathrm{arc}} = \frac{\left(n_{\mathrm{D}}^{\mathrm{arc}} \cdot V_{\mathrm{He}}^{\mathrm{D}} + n_{\mathrm{Q}}^{\mathrm{arc}} \cdot V_{\mathrm{He}}^{\mathrm{Q}}\right)}{L_{\mathrm{arc}}} \tag{4}$$

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[2] For a list of material properties see Table 3 in Annex.

where the subscript *design* emphasizes that the result is based on construction files and material databases. One may now question that the validity of this result in representing the *real* quantity $\overline{V}_{\text{real}}^{\text{arc}}$ would be affected by any difference between the design geometry, as used in (1) to (4), and the "as installed" geometry. If some elements were omitted in equations (1) or (2) in respect of what have been installed, $\overline{V}_{\text{design}}^{\text{arc}}$ would overestimate $\overline{V}_{\text{real}}^{\text{arc}}$ and then constitutes an upper limit on the real helium quantity:

$$\overline{V}_{\text{real}}^{\text{arc}} \leq \overline{V}_{\text{design}}^{\text{arc}} \qquad (5)$$

On the other hand, the intrinsic limitation of the approach is that parts which have been omitted or removed during the assembly (i.e. filling pieces) cannot be taken into account in the evaluation of $\overline{V}_{\text{design}}^{\text{arc}}$.

To confirm the result of the applied procedure, at this stage, an experimental measure on some random cryostat specimen becomes anyhow important, even if carried over a little sample: the closer is the agreement between the experimental average value $\overline{V}_{\text{exp}}^{\text{arc}}$ and $\overline{V}_{\text{design}}^{\text{arc}}$, the stronger becomes the equal sign in equation (5).

## 3. RESULTS

### 3.1 *Calculations*

Results from the application of the procedure are summarized in Table 1 for the arc dipole, the arc quadrupole and for the average value in the arc.

**Table 1 – Helium quantity per unit length for the main dipole and main quadrupole, together with the average linear quantity in the arc. Error bars have to be considered as an estimation of standard deviation.**

| | **Total Quantity [l]** | **Quantity per Unit Length [l/m]** |
|---|---|---|
| Main dipole [a] | 371.5 ± 8.4 | 24.50 ± 0.55 |
| Main quadrupole [b] | 162.0 ± 1.8 | 30.30 ± 0.33 |
| Arc [c] | 61590 ± 1162 | 25.12 ± 0.47 |

[a] Dipole cold mass length is 15.160, from LHC General Layout v6.5 (https://edms.cern.ch).

[b] Quadrupole cold mass length is considered here, which is 5.345m.

[c] Arc length is 2452m and contains 138 dipoles and 45 quadrupoles. Interconnections length obtained from LHC General Layout v6.5 (https://edms.cern.ch). Line N data from Ref (3)

So, the real arc helium quantity per unit length should be lower than the average value estimated according to the procedure above:

$$\overline{V}_{\text{real}}^{\text{arc}} \leq 25.1\left(\pm 0.47\right)\text{l/m}$$

### 3.2 *SM18 and Sector Tests* [2]

An experimental estimate of the helium quantity per unit length was made on 8 cryomagnets, on the testing station in SM18, leading to an average value[3] of 25.7 ± 1.3 l/m. Another estimate, implemented using the pressure expansion method and considering the compressibility factor, resulted in 25.8 l/m, while a direct measure of helium filling during the first commissioning of sector 7-8 gave an estimate of 30 l/m.

## 4. CONCLUSIONS

The procedure adopted for the assessment of linear helium filling inside the arc cryostats led to a value of 25.12 ± 0.47 l/m, which is in perfect agreement with the experimental result of 25.7 ± 1.3 l/m provided by SM18 tests and the value of 25.8 l/m resulting from the pressure expansion test, while the value of 30 l/m, estimated from sector filling, is probably too imprecise.
The estimated linear helium filling is therefore about 25% greater than the 20 l/m upper limit specified.

## 5. REFERENCES

[1] EDMS Document n. 90032, LHC_Q_ES_0001: *Dimensions, pressures, temperatures, and sizing of valves and piping in the LHC machine cryostat and cryogenic distribution line*.
[2] MARIC Document 155-2007, http://lhc.web.cern.ch/lhc/maric/maric.htm: *Minutes*, from the LHC Main Ring Committee of April 25, 2007.
[3] J-P. Tock private communication.

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[3] Line N is included in this estimate.

## 6. ANNEX

**Table 2 – Materials found to be part of the cryomagnet assemblies, for the case of the main dipole and quadrupole. All the values are in kg. The table is built thanks to data from [a]M. Modena, [b]K. Shirm and [c]T. Tortschanoff, in conjunction with design specifications and drawings.**

| | **Main Dipole**[a b] | | **Main Quadrupole**[c] | | **MO, MQT or MQS** (tuning) | | **MSCB** (sextupole) | |
|---|---|---|---|---|---|---|---|---|
| **Low carbon steel** | | | | | | | | |
| laminations, inserts & other | 16549.0 | ± 41.4 | 2455.6 | ± 6.1 | 225.9 | ± 0.6 | 963.1 | ± 2.4 |
| **Polymers, epoxies & other** | | | | | | | | |
| without filler pieces | 172.2 | ± 2.0 | 46.2 | ± 0.5 | 1.2 | ± 0.0 | 4.8 | ± 0.0 |
| filler pieces | 33.0 | ± 0.7 | 55 | ± 1.1 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| **Austenitic steel** | | | | | | | | |
| feet | 1104.0 | ± 11.0 | 1291.0 | ± 21.8 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| helium vessel | 2181.0 | ± 21.8 | | | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| inserts | 291.0 | ± 0.7 | 0.0 | ± 0.0 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| end plates, cold bore & other.. | 109.0 | ± 1.1 | 81.0 | ± 0.8 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| collars | 5269.8 | ± 13.2 | 620.6 | ± 1.6 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| **Copper** | | | | | | | | |
| coils | 605.5 | ± 16.7 | 144.0 | ± 3.7 | 5.6[d] | ± 0.2 | 22.5[d] | ± 2.6 |
| bus bars | 158.8 | ± 4.4 | 82.6 | ± 2.3 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| heat exchanger tube, OF copper & other.. | 178.0 | ± 1.8 | 83.8 | ± 0.8 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| **NbTi superconductors** | | | | | | | | |
| coils | 244.5 | ± 6.8 | 54.0 | ± 1.4 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| bus bars | 64.2 | ± 1.8 | 33.4 | ± 0.9 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| **Aluminum** | | | | | | | | |
| shrinking cylinder | 0.0 | ± 0.0 | 0.0 | ± 0.0 | 11.1 | ± 0.1 | 44.4 | ± 0.4 |
| **Other components** | | | | | | | | |
| diode | 68.9 | ± 0.7 | 85.2 | ± 4.3 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| dipole correctors | 36.2 | ± 0.7 | 0.0 | ± 0.0 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| BPM | 0.0 | ± 0.0 | 7.0 | ± 0.1 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| MO, MQT or MQS | 0.0 | ± 0.0 | 243.8 | ± 0.6 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| MSCB | 0.0 | ± 0.0 | 1020.3 | ± 3.5 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |
| **Total Mass** | 27061.7 | ± 55.5 | 6303.4 | ± 24.2 | 243.8 | ± 0.6 | 1020.3 | ± 3.5 |
| **Cold Mass** | 23448.6 | ± 49.5 | 3540.1 | ± 8.3 | 0.0 | ± 0.0 | 0.0 | ± 0.0 |

[d] Copper and superconductor strands considered together.

**Table 3 – Material properties.**

| | Theoretical linear thermal contraction $\alpha(T)/10^{-3}$ at $T$ = 0K, relatively to 293K [d] | Density (at 293K) [kg/m$^3$] |
|---|---|---|
| Low carbon stainless steel | 2.94 [b] | 7851[a] |
| Aromatic Polymide | - | 1480 [a] |
| EP-GC-22 epoxy | - | 1800 [a] |
| ULTEM 2100 | - | 1340 [a] |
| ULTEM 2300 | - | 1510 [a] |
| Stycast 2850FT | - | 2290 [a] |
| Austenitic steel | 2.94 [b] | 7950 [a] |
| Copper | 3.26 [c] | 8960 [a] |
| Nb-Ti superconductor | 1.43 ÷ 1.49 [b] | 6550 [e] |
| Aluminum | 4.15 [b] | 2660 [a] |

[a] http://www.matweb.com

[b] Cryogenic Data, D.H.J. Goodall A.P.T. division, CULHAM Laboratory 1970

[c] Helium cryogenics, S.W. Van Sciver, Plenum Press 1986

[d] $\alpha(0) = ( L_{293} - L_0 ) / L_{293}$. For isotropic and homogeneous material the volume expansivity is $3\alpha$.

[e] B. Bordini private communication