Cryogenic characteristics of the R3B-GLAD magnet

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The R3B-GLAD magnet is a large acceptance superconducting dipole that will allow experiments with radioactive beams on FAIR facility at GSI Darmstadt, Germany. The cold mass of 25 tons is made from a set of 2 main coils and 2 lateral pairs of coils in their aluminum casings and covers, fixed on three cryogenic supports. The indirect cooling of the coils with copper braids attached on the aluminum casings has been chosen to cope with the differential thermal expansion. The thermosiphon circuit with a two-phase helium flow, which maintains the cold mass at 4.4 K with a small temperature margin can operate with a variable heat load exceeding 15 W. Its originality is the gentle slope of the heat exchanger tubes glued on the cold mass and its compact geometry, where the phase separator is placed above the tubes in the main vacuum chamber, while the current leads connections and the valves for fluid distribution are in the lateral satellite. This paper presents the cryogenic design of the magnet in the cryostat, and gives its thermal characteristics.

1 . GENERAL CHARACTERISTICS

The R3B-Glad dipole has an original butterfly shape design [1] made of 6 coils, 2 for the main magnetic field and four lateral for the active shielding (see figure 4). The superconducting coils are in the 47.5 tons main cryostat (see figure 1) with the LHe phase separator for the thermosiphon and inside a 80 m^2 stainless steel thermal shield. A 8.5 tons side satellite holds the eight cold valves and a pair of current leads with their LHe pot.

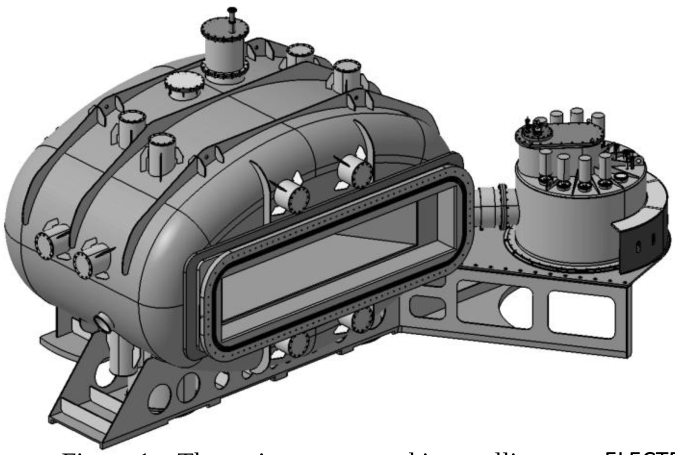


Figure 1 . The main cryostat and its satellite

The 27 electrical connections between pancakes and between coils are made outside the casings onto the entry arch The busbar joins the coils to the current leads in the satellite, it is cooled by LHe flowing from the phase separator to the C.L. pot.

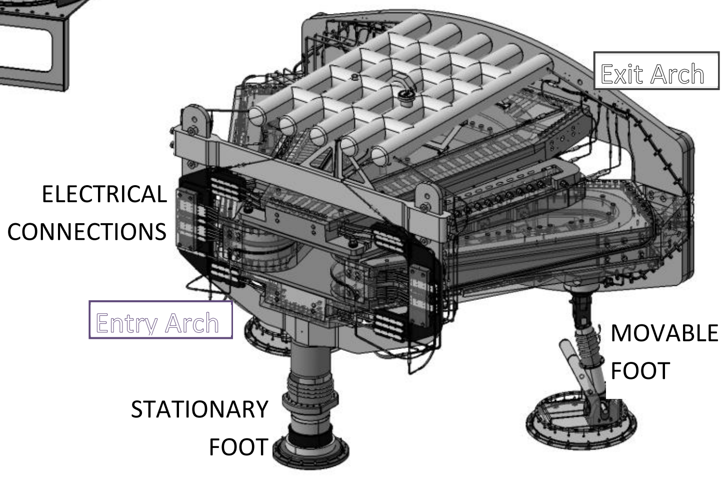
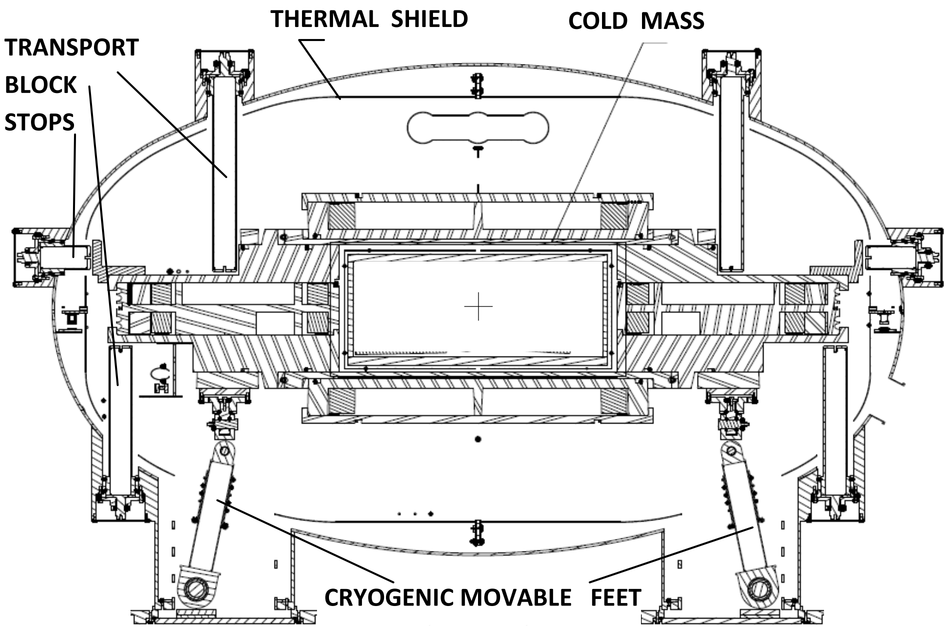


Figure 2 . View of the cold mass

The coils are imbedded in the coil-casings and covers which are made of aluminum alloy 5083 [2]. There are four coil-casings - two main coil-casings and two lateral coil-casings - together with the linking components between the coil casings they are fastened in a single (25 t – 60 m2) cold mass (see figure 2), which is supported by three cryogenic feet with thermal intercepts: one is stationary and two are movable. A set of 18 adjustable and dismountable transport block stops tighten the cold mass in the vacuum vessel (see figure 3) :



4 upper vertical,
4 lower vertical,
4 on exit cover,
2 on entry cover,
2 on left side and
2 on right
cope with accelerations during transport on roads but also, if needed,at GSI for moving the magnet in its final cavern.

Main cryostat	L =4.1 m
Dimensions	l =7.6 m
	H =4.5 m

Figure 3 . Section of the cold mass in its vacuum vessel

Table 1 . Heat load allocation

	Shield TEMP 50-80 K at 22 - 23 bar	**LHe TEMP** 4.42 K at P=1.2 bar
Current leads 4 kA	-	0.55 g/s
Thermal radiation	240 W	12 W
Feet conduction	85 W	3.5 W
Valves, pipes, shield supports	50 W	5 W
Electrical connections	-	2.9 W
Eddy currents at dB/dt ≠ 0	-	*up to 60 W*
Standing alone consumption at $\mathbf{I}_{\text{nominal}}$ = **3600 A**	**375 W**	**23.4 W** **0.55 g/s**

The cryostat will be connected at GSI to a dedicated cryogenic distribution system, the foreseen cryogenic budget including consumptions in the transfer lines, in the connection box and Eddy current losses in the cold mass is:

Table 2 . R3B-Glad cryogenic budget

CRYOGENIC BUDGET	Required helium @ 3 bar, 4.5 K	4	g/s	Supercritical helium
	Return @ 1.2 bar, 4.4 K	3,45	g/s	Helium vapour
Return @ 1.1 bar, 300K		0,55	g/s	e.g. current leads 4 kA
Shield cooling refrigeration power 50-80 K		450	W	3g/s GHe @ 22/23 bar abs
Cooling down mass flow 300 K -> 4,5 K		10	g/s	20 days with GHe and $\Delta T_{io} \leq 50$ K

2 . THERMAL BEHAVIOUR of the COLD MASS

The differential expansion between coils and casings (2 mm maximum displacement), as well as the mechanical behavior of the structure [3] prohibited us from gluing the coils in the aluminum casings as it has been done for previous superconducting magnets with indirect cooling like CMS solenoid, in its cylinder, or the race tracks of the Atlas barrel toroid etc… already under operation at LHC, CERN Geneva. Thus the thermal links between the coils and the casings are copper braids. There are 60 braids for one main coil and 55 braids for one lateral coil. They are glued on the upper side of the coils for one end and for the other end on the upper side of the casing wall, the braids are thus embedded in between the casing and the cover. The thermal contact between the braids and the cover is achieved with glue and grease. In fact for these ends of the braids, as they are actually braided tubes that have been flattened and appear to have two layers, the lower layer is glued on the upper wall side whereas the upper layer is kept free of glue to be able to be coated with grease.

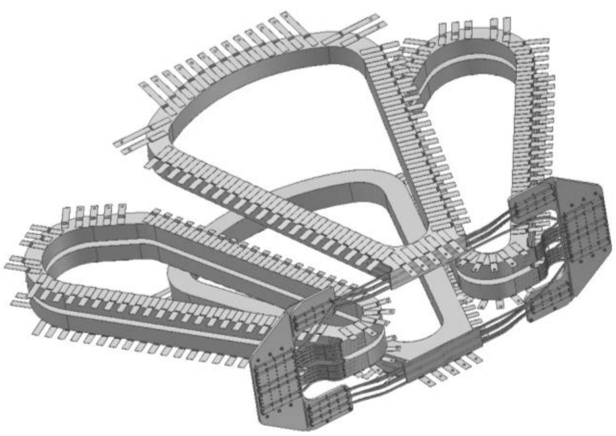


Figure 4 . Coils, braids and electrical connections

This position of the copper braids (high purity RRR=80) allows to have them connected to the coolest areas of the casings and covers.

As it can be seen on the half section of the cold mass figure 5 , the coils are isolated from thermal radiation and conduction by the casings, covers and linking plates. Casings and covers are cooled by 20 heat exchangers which are glued in rectangular grooves. The arches have both 2 HX tubes.

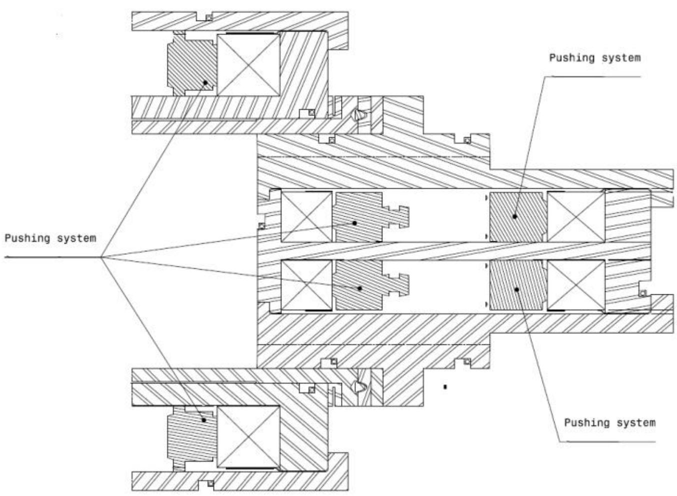


Figure 5 . Half section of the cold mass

The temperatures of the coils are then determined by the temperatures of the casings where the braids are glued and also by the internal heat loads and the conductivity in the coils [4]. In variable magnetic field conditions heat loads appear in the cable itself [5] and in the casings and the covers [6] due to Eddy currents (see table 3), whereas in steady state field conditions the only heat loads are thermal radiation (0.2 W/m2 – 12 W) on outer surfaces of the cold mass and the conduction through the three feet (1–1.5 W / foot – 3.5 W).

Ramping time	(mn)	30	60	150	300	450
dI/dt	(A/s)	2	1	0,4	0,2	0,133
Ptotal conductor	***(W)***	***50***	***25***	***10***	***5***	***3.3***
Ptotal Alu 5083 structure	***(W)***	***11***	***2,8***	***0,45***	***0,11***	***0,05***

Table 3 . Dynamic heat loads

The thermal loads of the feet have no influence on the coils because they are intercepted in the structure by the heat exchanger in areas not connected to the braids. Then the conductor temperature, with respect to material conductivities and geometry and the hypothesis of no thermal contact between coils and casings except copper braids, depends only on:

- the thermal radiation which a steady heat load
- the Eddy currents in 5083 structure, which is a heat load proprotionnal to $(dI/dt)^2$
- the hysteresis currents in the cable, which is a heat load proprotionnal to dI/dt

The temperature calculation show that the coldest point and the warmest point in the coils exhibit an almost linear dependence on dI/dt due to the fact that with thermal radiation the hysteresis in the cable give the main heat load.

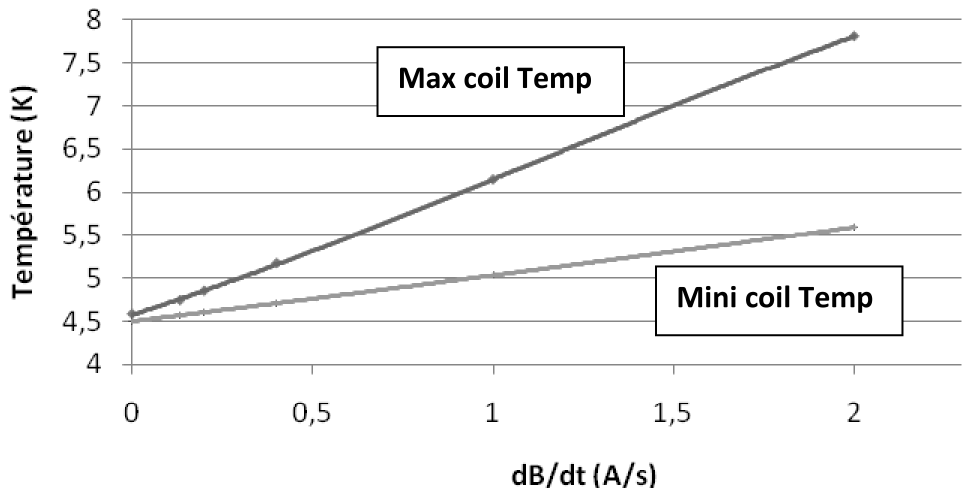


Figure 6 . Mini and maxi temperature of upper main coil

It appears that the temperature margins are the smallest at the maximum magnetic field points in entry and exit of the different coils. The critical point is the point of maximum magnetic field on the entry of the upper main coil. Anyway a nominal working point is possible with a ramping time Td = 300 mn (= 5h, else dI/dt= 0.2 A/s) and a temperature margin Marj**T** = 1.5 K, which is the difference between the sharing temperature and the actual temperature at the chosen point of the conductor.

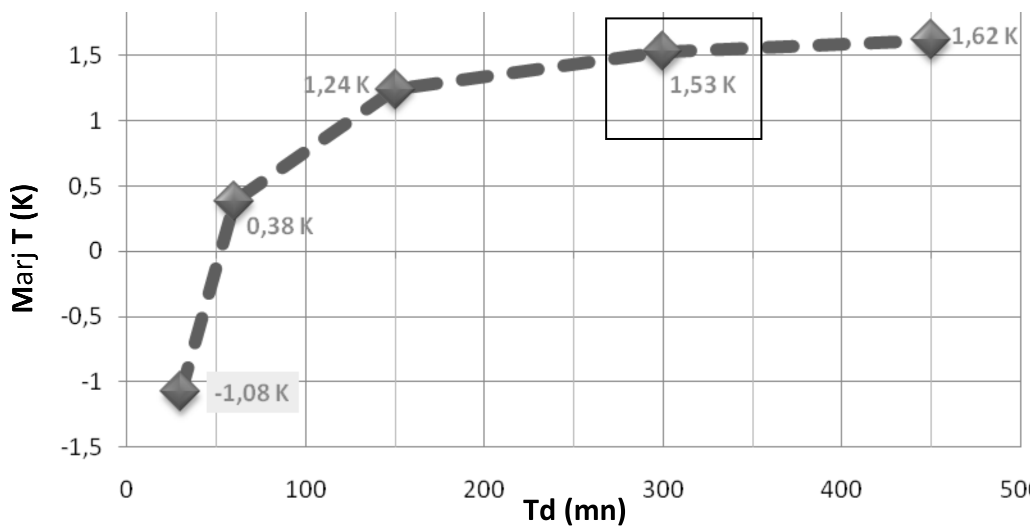


Figure 7 . Temperature margin for the critical point of the cold mass

3 . THERMOSIPHON

There are 24 heat exchangers tubes on the cold mass:

- 20 on the casings and covers : 12 go up from entry to exit, 8 go up from exit to entry
- 2 for the two special plates on which the electrical connections are fastened and glued . These plates are also tightened onto the entry arch which is thus indirectly cooled.
- 2 directly glued on the exit arch

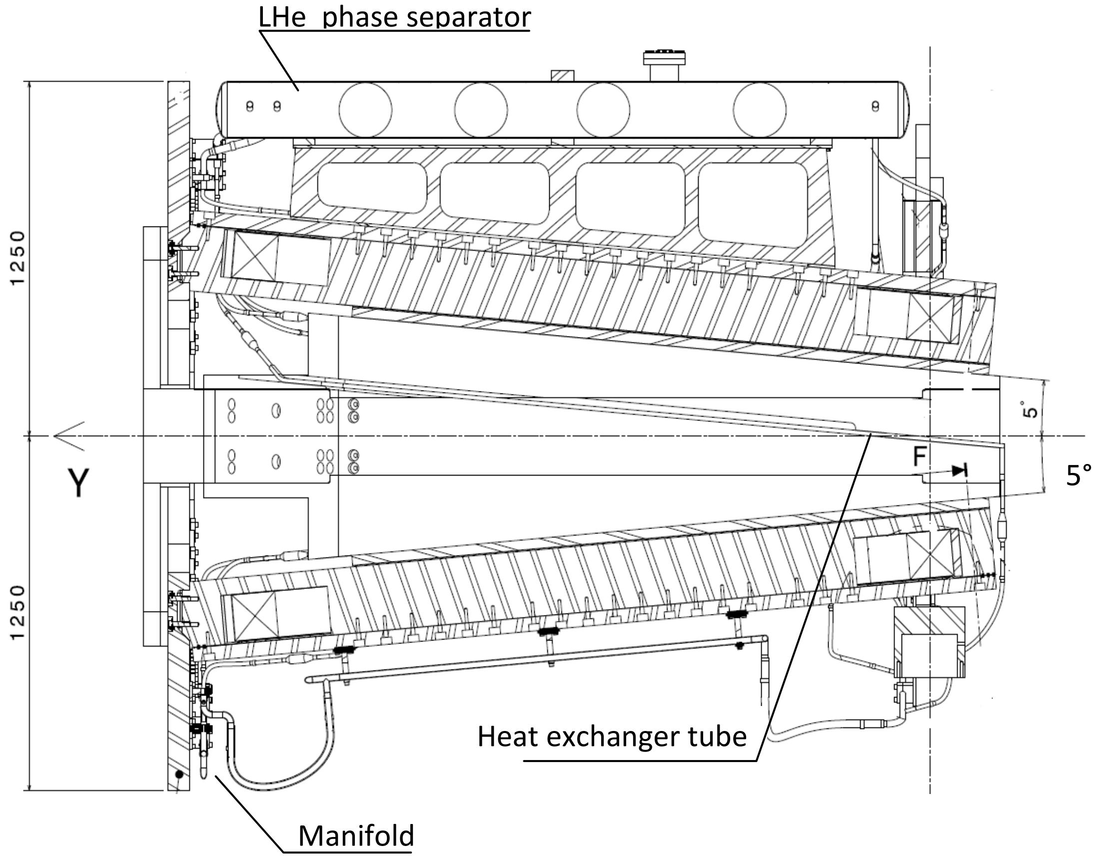


Figure 8 . Cold mass cross section with LHe phase separator tank

A thermosiphon provides the helium two phase flow cooling, as the slopes are gentle (# 5°) and the overall height of the circuit is small,l they are connected to a phase separator tank (see table 4) that is very flat and made of 5 interconnected pipes of 200 mm diameter. This compact geometry allows to have the tank in the same vacuum vessel than the cold mass, whereas the valves and the current leads are in a side satellite, more convenient for maintenance operations. One valve (FV23) bypass the thermosiphon during cooling down process, the two valves (FV28, FV29) are also used to disconnect the cold mass from the tank in case of a quench [7], to restrict the heat transfer to liquid helium when the coils warm up.

Table 4 . LHe piping main features

N_{ominal} Pressure = 1.2 bar abs - Max = 5 bar abs	**Surface (m^2)**	**Volume (liters)**
LHe phase separator tank	10	460
Heat exchangers tubes	1.5	3
Current lead pot, in and out piping, manifolds….	6	60.5

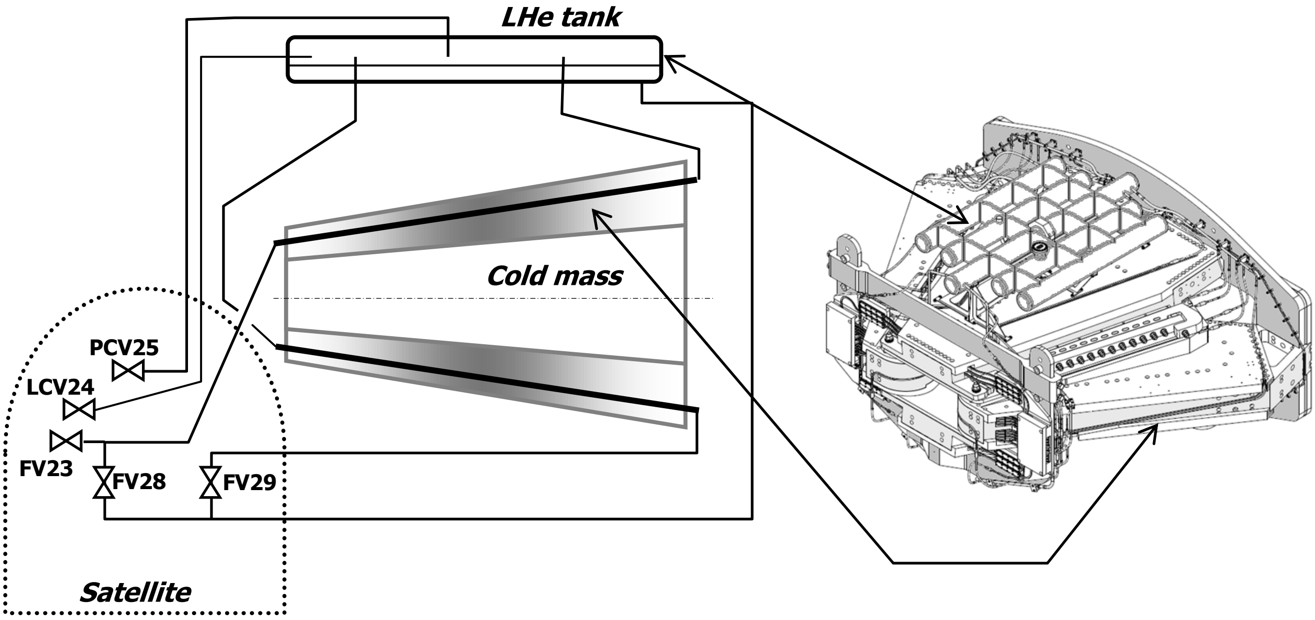


Figure 9 . Internal LHe piping

There are in fact two thermosiphons (see figure 9):

- **Thermosiphon SUP** including the 8 top tubes of the casings and covers and fed by FV28
- **Thermosiphon INF** including the 12 lower tubes + 4 arch tubes and fed by FV29

Calculation with homogenous model give the following vapour qualities X and mass flows $\dot{m}$ (see table 5) for different total heat inputs Q (SUP + INF):

Table 5 . Thermosiphon main features

$\mathbf{Q}_{Sup+Inf}$ (W)	40	**20**	10
$\dot{\mathbf{m}}_{Sup}$ (g/s)	9	**6**	2.8
$\mathbf{X}_{Sup}$ %	9	**7**	5.6
$\dot{\mathbf{m}}_{Inf}$ (g/s)	25	**15**	11
$\mathbf{X}_{Inf}$ %	5.2	**4**	3.2

To prevent high pressure rise in case of a quench the LHe tank will be only half full, thus the available volume of liquid is 230 liters. In case of a refrigerator failure, the autonomy is more than 3.5 hours (consumption= 0.55g/s + 30W) which is sufficient to ramp down the current.

CONCLUSION : The present design of the cold mass of the R3B-Glad magnet gives complete confidence in term of temperature margin, in the pessimistic case where the only thermal link between coils and casings are the copper braids and also in term of vapour quality and autonomy for the two phase flow thermosiphon.

Cryogenic tests that will be undertaken, at Saclay, this year with a thermal mock-up in Schema test facility, and next year with the cold mass itself, in the W7X test facility, will unable to precise the actual margins before the last tests in the final cryostat at Saclay, CEA Irfu Institute.

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