Mechanical Design of the Iseult 11.7 T Whole Body MRI Magnet

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***Abstract*—The Iseult system is a highly homogeneous 11.7 T superconducting magnet. This high field 900 mm warm bore coil will provide the main field of the Iseult/Inumac MRI system, dedicated to the Neurospin center of the CEA life science division.**

The cold mass structure of the magnet is designed to support and accurately locate the central and shielding coils. The main winding is made of a 3.8 m length stacking of 2 m outer diameter double-pancakes. Under self load, the axial compression of the main coil reaches 8100 t. The two shielding coils are 4 m outer diameter short length solenoids.

The cold mass assembly consists of the main coil suspension and preload system, surrounded by the shielding coils casing. It weighs 105 t with envelop dimensions of 4 m diameter × 4 m length. The engineering design of the cryostat has been carried out. This paper gives a description of the system, and an overview of the mechanical behavior of the cold mass assembly.

***Index Terms*—Mechanical engineering, MRI magnets.**

I. INTRODUCTION

THE Neurospin research center (CEA) aims to go further in the understanding of the operation of the human brain. By 2012, an 11.7 T magnetic resonance imaging (MRI) system (see Fig. 1) will come to supplement the existing facilities. This imaging system will require a very high magnetic field, and a warm bore of 900 mm. The technology of this magnet is based on a NbTi superconducting coil. The main coil (2 m outer diameter, 4 m length) will be carried out starting from a stack of double-pancakes (DP). The magnet will be actively shielded by two solenoids of 4 m of external diameter. It will operate at 1.8 K under a pressurized HeII bath in order to ensure the cryostability of the conductor.

The most challenging feature is to achieve a spatial field homogeneity of 0.5 ppm in a 22 cm diameter spherical volume. This specificity has a significant impact on the mechanical tolerancing of the coils, as well as that of the components of the cold mass. In addition, as the DP winding is rather unusual for MRI magnet, the development of a specific technology is required. Moreover, the cryostability requirements induce the need of clearance around the conductor in order to ensure the wetting of the coil, which forbids classical suspension techniques.

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The design of the cold mass of the cryostat has been apprehended in the light of these different requirements, in order to ensure the mechanical strength of the structure, as well in nominal operating mode as in the event of malfunction.

This paper describes the principal design choices. After having established a description of the architecture of the cryostat, we will present the principal results of the analyses of dimensioning of the cold mass.

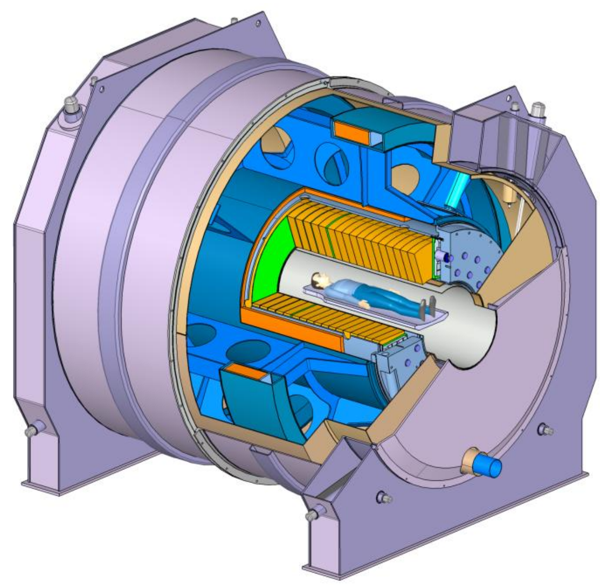

Fig. 1. Cut-away view of the Iseult 11,7T MRI magnet cryostat

II. MECHANICAL DESIGN REQUIREMENTS

Following the field strength and homogeneity requirements of the Iseult magnet [1], a specific technology is demanded for the suspension of the main coil (MC) of the magnetic circuit.

The following constraints have been considered as a basis for the design of the MC cold mass:

- the superconductor volume needs to be optimized, so the distance between warm bore and coil inner diameter requires to be minimized. Any contact between the helium vessel inner cylinder and the winding is to be avoided, in order to avoid friction during the cool-down of the magnet.
- in addition, mechanical interaction between the helium vessel inner cylinder and coil should be minimized, in order to allow helium circulation at the coil inner radius
- differential shrinkage between MC winding and cold mass structure is to be avoided
- electrical connections between pancakes proscribes a continuous structure around the external diameter of the coil

- the external diameter of the pancake is not strictly circular, so the accurate positioning of the winding is difficult
- tensile axial stress is to be avoided in the MC winding.
- strong Lorentz forces are to be managed
- 5.7 kV ground insulation requires a 10 cm gap between DP and frame non isolated components.

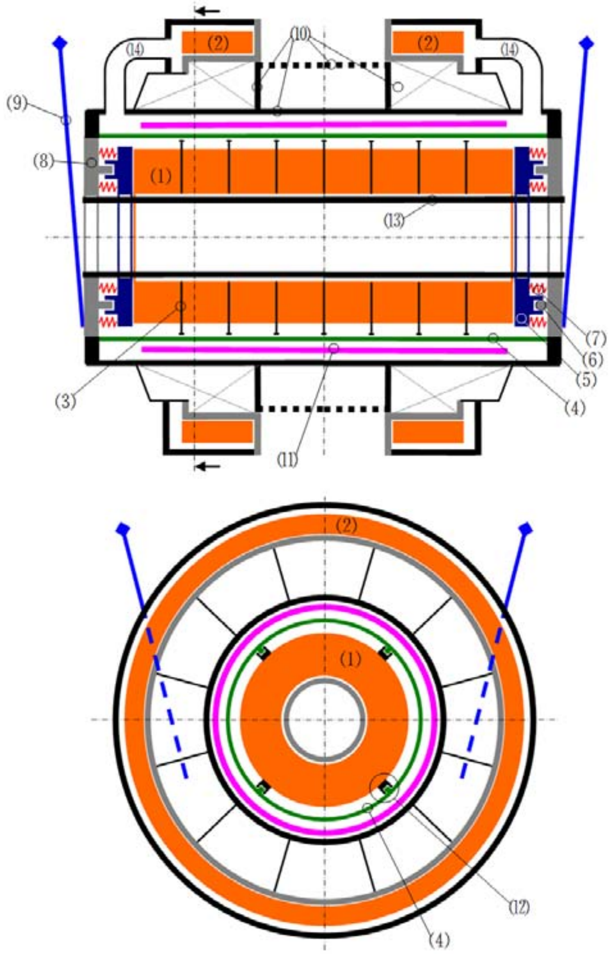

Fig. 2. Schematic drawing of the cold-mass - (1):Main Coil (2):Shielding Coil (3):Inter-pancake insulation shim (4):MC outer cylinder (5):MC base plate (6):Lateral guidance dowels & adjustable axial stops (7):Belleville washer stacks (Pre-load system) (8):Cold mass end-plate (9):Supporting rod (10):Cold mass structure (11):Cryoshim (12):Keys & Key-slots (MC radial locking) (13):Helium vessel inner cylinder (14):Coils connection pipe)

III. Design concept

A. Main coil

The architecture is based on the concept of holding the main coil by its lateral sides, compressing the winding with Belleville washers stacks. The weight of the coil is thus equilibrated with the counteracting friction force developed by this axial preload. A schematic drawing of the cold mass is presented in Fig. 2.

The main coil (1) is fitted between two base plates (5), on which the preload (7) is applied by counter action on the cold mass end plates (8). The preload is applied by the way of Belleville washer stacks (7). The MC base plates (5) are supported into the end plates (8) by the way of lateral guidance dowels (6) in order to hold the weight of the coil.

Four adjustable axial stops (6) restrain the axial translation of the coil, and serves to lock the displacement of the coil at room temperature. This axial locking of the coil will self release at operating temperature, since the thermal shrinkage of the coil is greater than the one of the cold mass structure.

Both outer (4) and inner (13) cylinders play the role of tie-rods. The MC outer cylinder (4) allows to limit the vertical movement of pancakes by the way of keys and key slots (12) practiced in the insulation plates (3), which are impregnated with the winding. This locking system allow the latching of the coil in order to avoid any slipping due to the unbalance of axial stresses between the winding and base plate (see Fig. 2). The cold mass is suspended into the cryostat by the way of low conduction rods (9). These rods are fitted to the cold mass end plates (8).

The cryoshim (11) is directly fixed on the MC outer cylinder (4). Several ports exist in MC outer cylinder in order to allow helium circulation.

The end plate (8) is welded to the cold-mass structure (10) and to the inner cylinder (13), in order to constitute the helium vessel closure.

A cross section of the cold-mass is presented in Fig. 3. Detailed sections of the preload/support system are presented in Fig. 4. The stiffness of the Belleville washer stacks will be fixed in order to provide a sufficient preload, even under unbalanced forces due to mechanical misalignment of the structure.

This architecture allows free contraction of the coil due to thermal and self load.

B. Shielding coil

The shielding coil (SC) is wounded on an aluminium coil former. After impregnation, the coil and its former remain assembled. These SC assemblies (2) will be inserted directly on the helium vessel frame (10). A preload system will ensure that the coil remains in abutment on the cold mass frame, in order to avoid any slipping during the energization phase. A radial clearance of 0,5 mm between the frame bearing surface and the coil former will ensure that no hooping occur at cool-down.

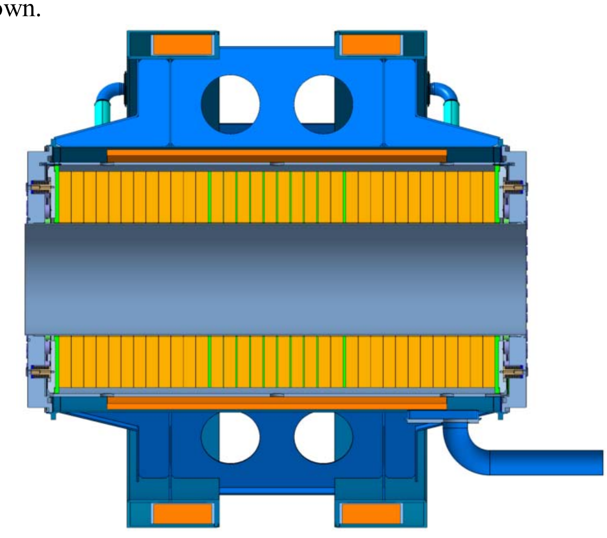

Fig. 3. Cut-away view of the cold-mass

The helium volumes surrounding the SC are separated from the MC helium volume. Coils connection pipe (14) will allow the coils electrical and cryogenic coupling.

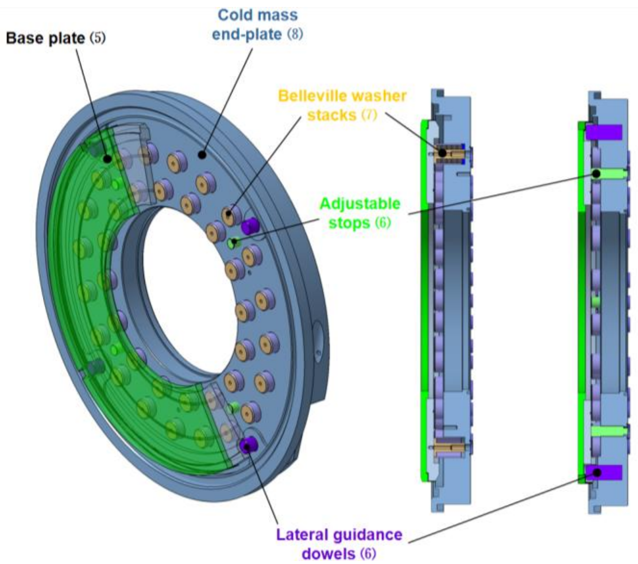

Fig. 4. MC suspension system cut-away views

IV. Design evaluation

A. Load acting

This section describes the loads that shall be taken into consideration in pre-designing the cold mass of the magnet. The cold mass design loads are given in Table 1.

1) Preload requirement

The main coil suspension requires an axial preload in order to suspend the coil by its end through the way of friction. If we consider the total weight of the main coil (MCW=50 t), the load induced by the coil misalignment (EML=10 t), and the coefficient of friction between two epoxy-glass plates (CEFP>0.125), the corresponding axial preload is given by

$$PL = \frac{\frac{MCW}{2} + EML}{CEFP} = 280t. \quad (1)$$

The preload will be applied between then endplate and the lateral plate by the way of 36 elastic spring stacks. Each stack is composed of 20 Belleville washers arranged in opposition two by two.

As the thermal cool-down will produce a differential contraction between the coil casing and the winding, a loss of preload of roughly 1.6 mm will occur. Again, under self-load, a loss of preload of 1.8 mm will overlap the previous one. Finally, as the end-plate expands axially of 0.15 mm under the helium pressure induced by a quench, we must take into account a total deflection loss of about 3.6 mm.

The pre-dimensioning will be based on a preload axial force of 360 t in order to restrain the deflection loss such that the load is maintained at a value greater than 290 t, considering the load-deflection curve of the Belleville stacks. This will give a sufficient margin regarding the 280 t minimum pre-load as defined in (1). It should be pointed out that this calculation considers a supplementary margin of safety on the coefficient of friction, as the computation is based on a coefficient of friction of 0,125 which constitute a lower bound.

TABLE I. Loads Classification

Type	Description
DL	Dead load : Weight of the coils and support structure (***105 t***)
PL	Preload : Axial pre-compression of the main coil
PQ	Pressure load during quench : maximum pressure that can occur during a quench of the magnet (***0.4 MPa***)
TL	Thermal loads : Loads induced by difference in the thermal contraction of materials
EL-I	Electromagnetic interaction loads : Loads imposed on the coil due to their mutual interaction
EL-F	Electromagnetic loads during fault : Loads imposed on the coil during abnormal operating events, such as a shorted coil
SL	Seismic loads : Loads induced by transportation or earthquake

2) Electromagnetic interaction loads (EL-I)

We shall here consider both the ideal configuration and the flawed configuration.

In the nominal configuration, the attraction force between the shielding coils is 91 t. The self load of the main coil (8000 t axial compression and strong radial expansion) will have no effect on the cold-mass structure, since the coil is free to contract axially and expand radially, following the suspension system.

In the flawed configuration, if we consider displacements of 5 mm and tilts of 0.25 °, unbalance forces will appear. In the worst case, additional loads will superimpose with the main coil dead load as following:

- an additional radial components of 10 t
- an additional axial component of 5 t
- a 20 ton.meter torque acting between MC and both SC.

3) Electromagnetic loads during fault (EL-F)

Strong electromagnetic forces can occur in case of a short in the magnet. Several fault scenarios have been studied. The maximum potential axial unbalance force has been estimated to 334 t.

B. Design criteria

In the focus of a preliminary design evaluation, the criteria applied are based on the ASME BPVC [2]. The materials allowable are based on the design Tresca stress intensity S_m, which is established as a function of the yield or ultimate strength. We have here considered that the cold mass structure is made of 304L stainless steel ; the corresponding design stress S_m is 160 MPa at room temperature (RT), and 300 MPa at operating temperature (4 K). The limits for each stress category which are commonly considered in the superconducting magnet community are given in Table 2.

TABLE II. STRESS LIMITS (MPa)

Operating conditions	Stress category Membrane (general)	Membrane (local)	Membrane + bending
Limits	k x S_m	1.5 k x S_m	1.5 k x S_m
Normal operation @RT (k=1)	160	240	240
Normal operation @4 K (k=1)	300	450	450
Fault condition @4 K (k=1.2)	360	540	540

TABLE III. STRESS RESULTS (MPa)

Load case (operating cond.)	Stress category Membrane (general)	Membrane (local)	Membrane + bending
DL+PL @RT (normal)	42	113	116
DL+PL+EM-I @4 K (normal)	42	113	116
DL+PL+EM-I+PQ @4 K (normal)	73	144	146
DL+PL+EL-F+PQ @4 K (fault)	180	405	412

C. Cold mass Finite Elements Analysis (FEA)

The cold mass structure was modeled in the ANSYS Finite Elements Analysis code. As the coil suspension decouples the mechanical behavior of the coils and the cold mass frame, the coil windings meshes are not accurately detailed, and are only considered for their mass and axial rigidity. The magnetic internal Lorentz forces are not considered, but the magnetic interaction load and the preload loss are taken into account. The contact behavior between the main coil and the base-plate, and between the dowels and end-plates is modelized. A quarter symmetry model is studied for normal operating conditions (Fig 5). Full geometry is analyzed for fault conditions, as these loads are not symmetric.

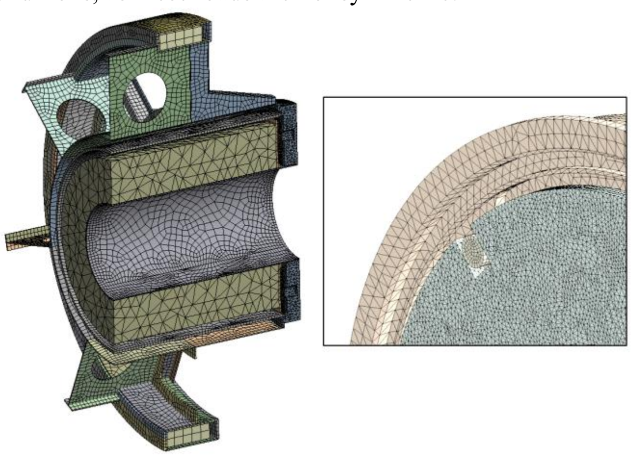

Fig. 5. Mesh of the cold-mass FEA model (quarter symmetry) and detail of contact area between dowel and end-plate.

D. Cold mass FEA results

Membrane, bending and Tresca stresses are post-processed in order to check that the stress levels satisfy the limits as specified by the criteria. Only primary load is considered, since secondary loads are not relevant in the cold-mass frame. Table 3 summarizes the results.

Under pre-load and self load, at room temperature, the stress levels are much lower than the allowable (about 50 % ratio). Under operating conditions, at 4 K and considering the electromagnetic interaction load, the stress levels are even much lower than allowable (about 25 %).

In case of quench, the pressure rise increases the stress level such that we reach 33 % of the allowable. In addition, a buckling analysis shows that the first buckling factor is 5.

In case of a short in the magnet, strong unbalance forces increase the stress levels up to 400 MPa (see Fig. 6). The ratio of local primary membrane stress vs allowable is about 80 %.

In addition, the displacements of the cold mass frame are computed under the flawed configuration electromagnetic interaction load. The axial deflection of the shielding coils is 0.22 mm, the relative displacement between MC and SC is lower than 0.33 mm, and the tilt of the MC and the SC structure is limited to 3 arcmin. These values remain much lower than those considered to assess the Lorentz forces unbalances due to geometric imperfections.

The contact status between the main coil and the base plate remains closed. No loss of contact is observed in case of normal operating mode or in the event of a quench, as well as in the case of flawed configuration.

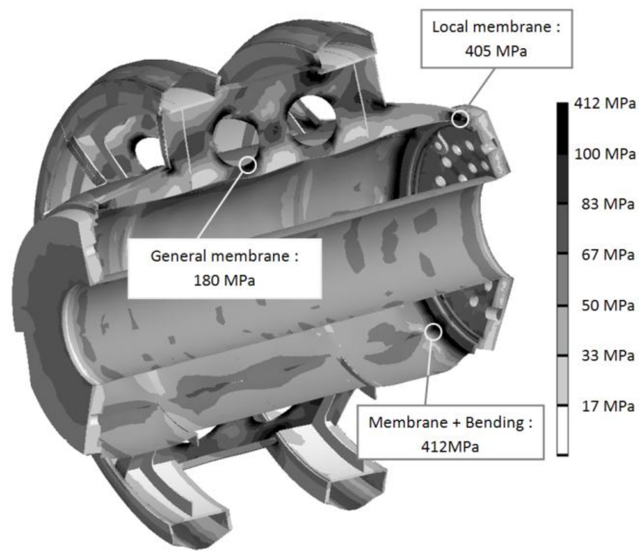

Fig. 6. Tresca Sress and displacements (x200) in the cold-mass frame, under fault conditions and quench pressure (DL+PL+EL-F+PQ).

CONCLUSION

The preliminary mechanical design of the Iseult 11.7 T cold mass has been evaluated. The levels of solicitation satisfy the stress levels as specified in the criteria. Further studies will be conducted in order to begin the detailed design of the cryostat.

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