DESIGN OF A SUPERCONDUCTING GANTRY CRYOSTAT

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Abstract

The University of Huelva in collaboration with the Andalusian Foundation for Health Research (FABIS) [1] and the TTI Company [2] is currently involved in developing and assembling a prototype for a compact superconducting proton gantry with the goal to generate a business case within the narrow niche of hadron therapy. While main beam characteristics are reported in [3], this article presents the current status of the engineering design for the cryostat and beam steering system. An account for the mechanical deformations due to magnetic forces and weight is also presented.

INTRODUCTION

Beam dynamics studies have shown that protons of 175 MeV±20% kinetic energy can be handled and delivered at the target using a simple gantry made of two arcs of radius 2.5 m with 90° and 180° respectively, as shown in Fig. 1.

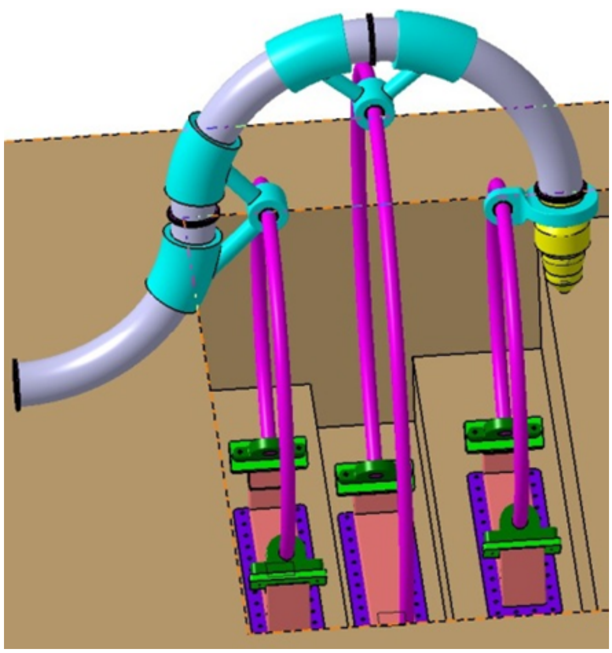

Figure 1: Overview of the gantry and its beam steering system installed on three support rings.

Within a preliminary design carried out in Catia [4] the gantry is installed on three rings which both take the load and constrain its motion within the plane defined by the isocentre. The main problems to be addressed for the cryostat are:

- mechanical support which cam minimize the deformations and stress due to the mass of the cryostat, coolant and magnets;
- rotation mechanism to enable a 270° excursion around the isocentre;
- technical solution for the junction between the rotating gantry arm and the fixed accelerator line to enable transfer of coolant and vacuum pumping;
- design of the support collars for the SC coils;

ASSEMBLY

The SC cryostat accommodates 36 combined-function magnets made of one one-layer quadrupole coils assembled on the top of one-layer dipole coils, their collars (clamps) and special channels for the coolant and vacuum insulation. In a simplified view as shown by Fig. 2 the cold liquid helium enters at 4 K through a coaxial pipe and fills the channel near the collars at hydrostatic pressure.

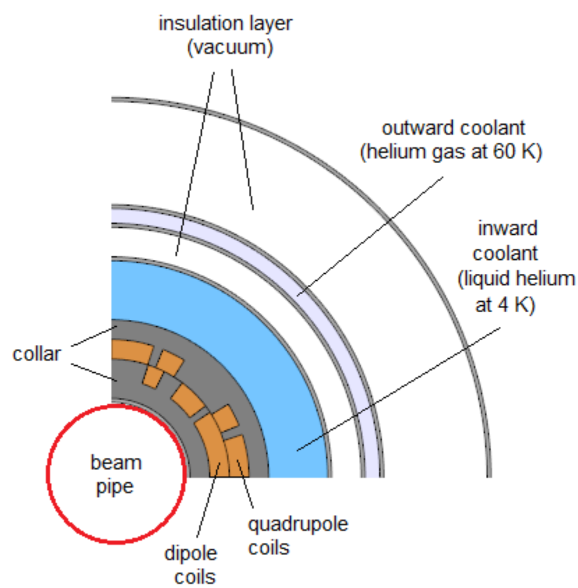

Figure 2: Sketch of the transverse layers to be considered for cryogenic cooling of the gantry.

As the SC coils trigger phase transition of helium from liquid to gas, bubbles accumulate at the highest point of the cryostat from where they can pass into a return coaxial channel through valves. These valves are distributed around the cryostat circumference and open synchronized with its motion only if they are at the highest altitude within some error margin. With rising vapour pressure the gas is pushed towards a larger coaxial port installed at the junction between the beam line and the gantry. There is a layer of vacuum between the liquid and gas helium layers and another one surrounding them in order to reduce heat transfer. Technical implementation of these ideas can be seen in Fig. 3 with the main components:

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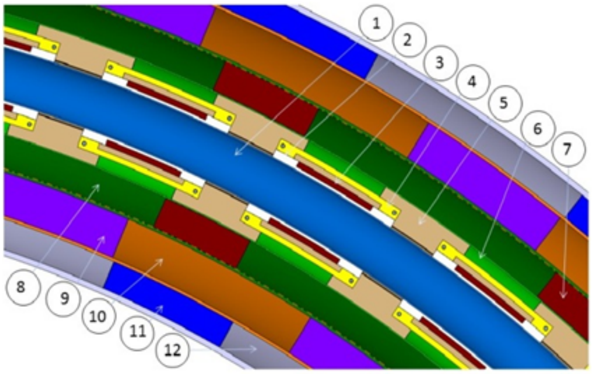

Figure 3: View of the cryostat assembly featuring combined function magnets and cooling channels.

- Beam pipe (1).
- Inner magnet support (2).
- Superconducting dipole and quadrupole coils (3).
- Outer magnet clamp (4).
- Spacers (5, 7, 9, 11).
- Liquid helium cryostat (6).
- Intermediate vacuum pipe (8).
- Gas helium cryostat (10).
- Outer vacuum pipe (12).

The coils and their clamps are chained along the gantry using spacers made of steel. These clog the cooling and return channels to some extent but should enable the flow through ports cut along.

MAGNET PROTOTYPING

A combined-function magnet can be designed with high purity of dipole and quadrupole magnetic field using one layer of superconductor distributed in a few coil blocks around the magnet bore [5, 6]. SC dipole and quadrupole coils have been modelled using three and respectively two conductor blocks as shown in Fig. 4.

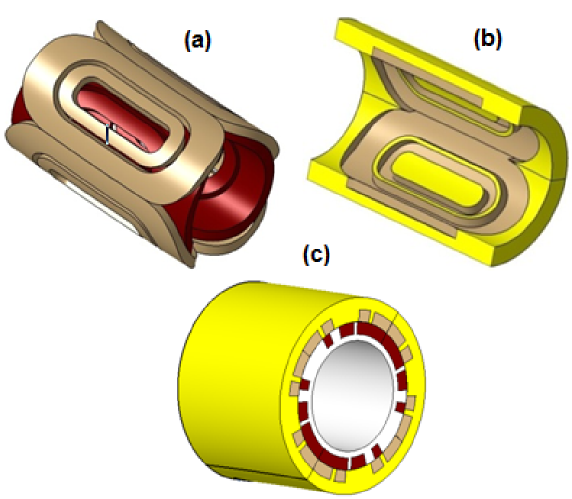

Figure 4: Layout of the SC coils (a), their clamps (b) and the complete assembly (c).

They are bent along the gantry arcs, spanning 15 cm or about 3.5° with respect to the curvature radius of 2.5 m. Current density limits listed in Table 1, were tested in particle tracking studies using the proton beams of 250 MeV kinetic energy, which is the highest level desired.

Table 1: SC Dipole Current Density Calculated for a 250 MeV Proton Beam

Coil block	**Transverse Surface** [mm^2]	**Current Density** [A/mm^2]	**Magnetic Field**
	Dipole		
outer	319.2		
middle	153.4	349.12	$B_y = 2.19\,T$
inner	80.6		
	Quadrupole		
outer	203.8	975.90	$\partial B_y/\partial x \simeq 90\frac{T}{m}$
inner	113.3		

A prototype for demonstrative purposes is currently being assembled with copper conductors on polycarbonate support as Fig. 5 shows. The goal is to install the combined-function magnet on a test bench where real magnetic field maps can be measured and checked with simulation results.

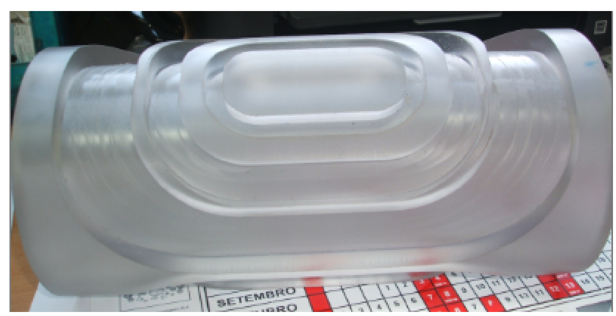

Figure 5: Prototype of a magnet support on which copper-made coil blocks will be winded.

MECHANICAL DEFORMATIONS

A high field quality is needed in the gantry magnets if one wants to circulate an intense proton beam at high energies. Mechanical deformations due to weight and magnetic forces are among the most important sources of beam misalignment.

Magnetic Forces

The coils are confined by steel clamps which take up the Lorentz forces and the point here of interest is whether they are thick enough to limit the deformation of the coil blocks such that the real field pattern does not differ much from the ideal one. Mechanical deformation have been evaluated in order to validate the combined-function magnet design using Comsol Multiphysics [7] in which the *Magnetic Fields* and *Solid Mechanics* modules are coupled. For simplicity, only the two-dimensional cross-section of the magnets (coils and collars) have been used, neglecting longitudinal movements which are anyway expected to be smaller than the transverse ones. The highest necessary peak and gradient field values have been used for this purpose. Thus, for a proton beam of 250 MeV kinetic energy the central dipole field must reach 2.195 T while the quadrupole gradient must be around 90 T/m. With both dipole and quadrupole coils in operation magnetic fields are overlapped and thus the deformation forces are added up. However, the effects are not linear due to the non-linear elasticity model used in simulations. As Fig. 6 shows the combined deformation is of horizontally elongated quadrupole pattern with the highest value of ~4.19 µm recorded in the outer quadrupole coils.

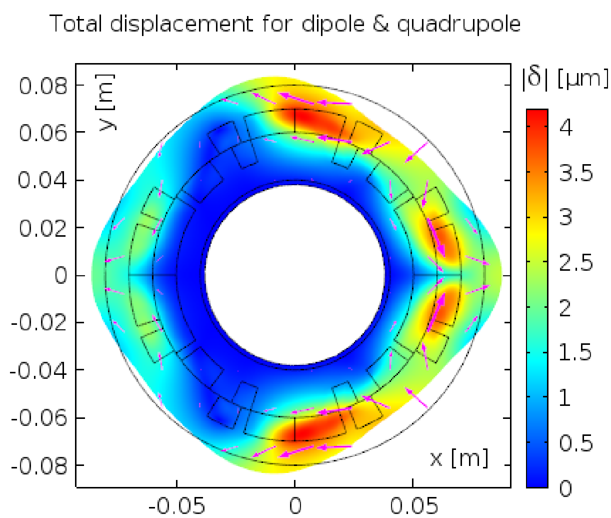

Figure 6: Mechanical deformations due to the combined effects of dipole and quadrupole magnetic fields.

Gravitational Force

With an estimated weight of 5 tons, mechanical deformations and stress have been evaluated applying a fixed constraint condition at the bottom of the three rings and at the contact between the cryostat and the fixed accelerator line. Considering a diameter of 200 mm and 300 mm for the rings and the 1 cm thick cryostat wall, the maximum deformation is about 0.8 mm recorded at the free end of the cryostat vessel. As shown in Fig. 7 the whole assembly has a tendency of moving forward (negative of the x−axis).

CONCLUSIONS

A preliminary design of a compact gantry cryostat has been developed using modelling and engineering software.

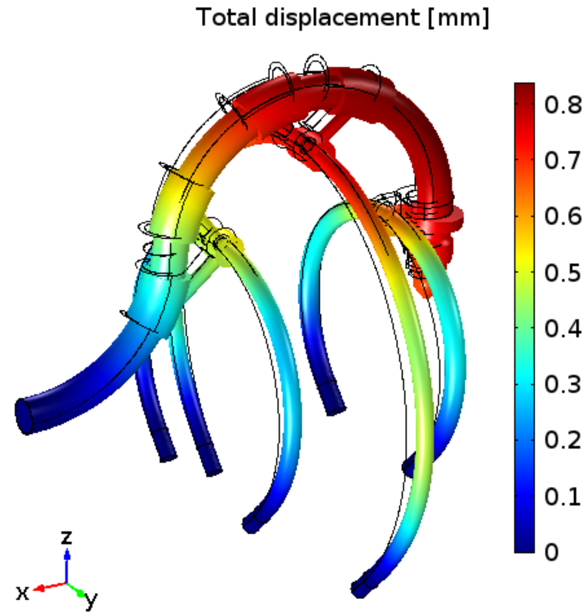

Figure 7: Mechanical deformations due to weight.

It has been shown that the SC coils can be fixed using 1 cm thick clamps made of steel such that the displacement at maximum field does not exceed a few µm. A technical solution for the support and rotation of the gantry has also been implemented to reduce deformations due to weight below 1 mm. Among many other issues to address in the future, the most important are vacuum system design and cryogenic cooling.

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