

# Development of Recondensing Cryostat for PAMELA

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## ABSTRACT

PAMELA (Particle Accelerator for MEDical Applications) is a design study of a novel accelerator for cancer therapy using protons and carbon ions. The accelerator utilizes the non-scaling Fixed Field Alternating Gradient (FFAG) principle and features superconducting combined-function magnets with dipole, quadrupole, sextupole and octupole field components for steering the ion beam. The proton ring for PAMELA will consist of 12 cryostats, each with three sets of the superconducting magnets having a large bore of about 250 mm. We propose to develop these cryostats using the re-condensing technology with the help of closed-cycle cryocoolers. Several issues arise, mainly due to the complex combination of superconducting magnet components and associated current leads. In this paper we address some of the key cryogenic issues and our approach in designing a cryostat suitable for PAMELA.

## INTRODUCTION

Charged Particle Therapy (CPT) [1] uses protons and light ions (for example, carbon) to treat some cancers. Existing facilities use cyclotrons or synchrotrons to accelerate charged particles. In principle FFAGs can accelerate very quickly (repetition rate about 1 kHz), which can lead to shorter treatment times and hence lower treatment cost and better patient experience. PAMELA (Particle Accelerator for MEDical Applications) is a project [2] to design a compact accelerator for proton and light ion therapy using ns-FFAG technique as part of the CONFORM [3] project in the UK. The design assumes that PAMELA will consist of two accelerator rings (see Fig. 1); the first will accelerate protons from 30 MeV to 250 MeV and carbon ions from 8 to 68 MeV; the second ring accelerates carbon ions from 68 to 400 MeV/c per nucleon. The lattice consists of 12 identical triplets. Each triplet consists of three superconducting combined function magnets with components from dipole to octupole nested in a helical coil with trim coils. With one cryostat for each triplet operating at 4.2 K, PAMELA will consist of 12 identical liquid helium cryostats. We propose to develop these cryostats employing the recondensing technology using closed cycle cryocoolers. Several issues arise, mainly the high heat load due to a complex combination of superconducting magnets with large bore of diameter 246 mm and associated high current flowing through the magnet leads. In this paper we address some of the key cryogenic issues and our approach in designing a cryostat suitable for PAMELA.

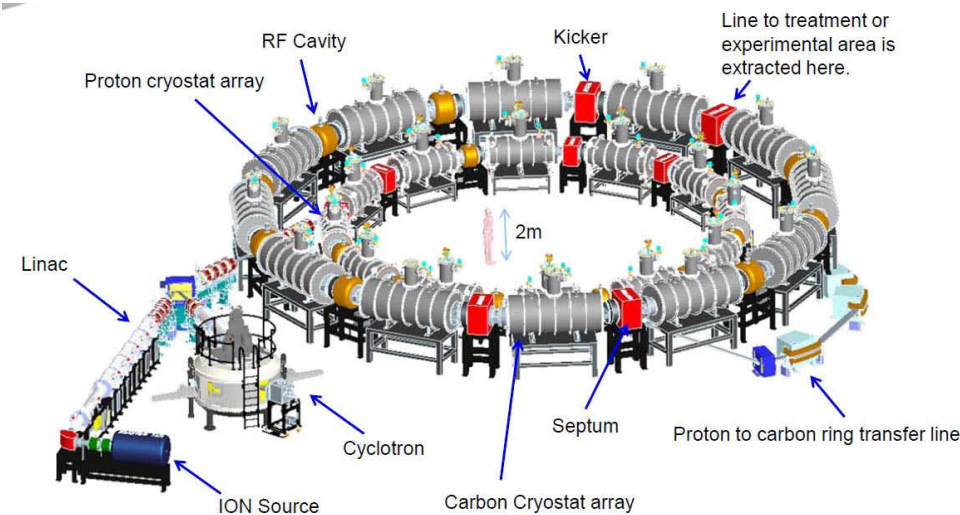


Figure 1. Layout of PAMELA

MAGNET-TRIPLETS AND CRYOGENIC REQUIREMENTS

The magnet coil designs for proton beam were optimized through several iterations using Opera 3D from VectorFields [4]. The current design with a combined function magnet requires a peak field of 4.5 T at a current density of 403 A/mm<sup>2</sup>. The triplets are immersed in a liquid helium cryostat with an offset in the axis as shown in figure 2. Overall bore size is 246 mm and its temperature will be maintained below 80 K. The primary goal of the cryogenic design process is to minimize the consumption of liquid helium (and hence the heat load). It is therefore intended that in the final configuration all the three combined function magnets will be connected in series and only one pair of current lead will supply the energizing current. Trim coils will be used for fine tuning the field profile. However, in the development phase it is necessary to have some flexibility in controlling the field profile of individual magnets and a combination of several high and low current leads will be used with increased heat load.

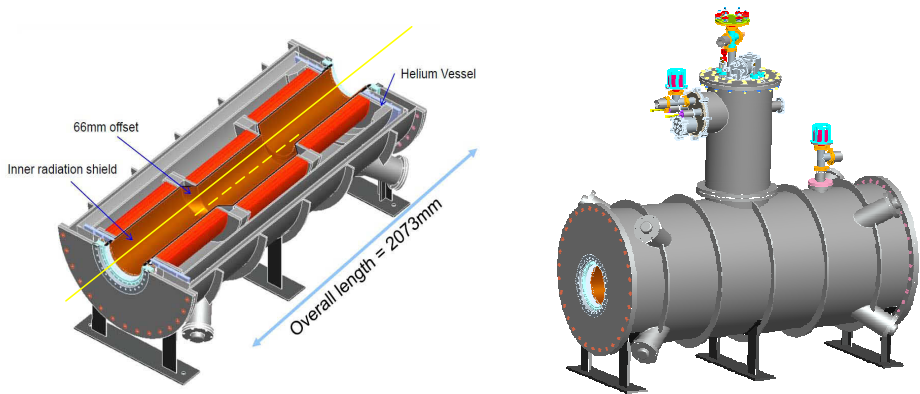


Figure 2. Concept design of the cryostat for PAMELA; the figure on the left shows the offset in the axis of the magnet bore.

**Table 1.** Heat load distribution (in watts) in a single PAMELA cryostat.

Source	4 K	80 K
Supports	0.47	11.52
Radiation bore	0.04	9.46
Radiation other	0.13	5.59
Magnet leads static load(pair)	0.10	5.00
Magnet leads dynamic load( per pair)	0.80	40.00
Instrumentation wires	0.02	1.00
<b>Total budget ( a )</b>	<b>1.56</b>	<b>72.57</b>
<b>Total design ( a x 1.5)</b>	<b>2.34</b>	<b>108.86</b>

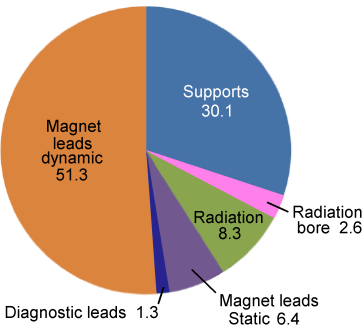


Table 1 shows the estimated heat load distribution in a single PAMELA cryostat. Note that the dynamic heat load from the current leads dominates the overall heat load budget. Two main options were considered for providing the necessary cooling power to PAMELA cryostats. One, to supply cryogenics from a central large refrigerator, and second to use distributed cooling by employing recondensing technology using a closed-cycle cryocooler for each of the twelve cryostats. The first option is more flexible in terms of handling the large variations in the heat load, but the infrastructure required for installation, operation and maintenance is expensive and may not suit a clinical environment. The second option is better suited to the environment, as has already been demonstrated successfully by the number of MRI installations around the world. This option will also keep the system compact, less complex from operational point of view, and costs less.

We therefore intend to use the recondensing technology for PAMELA. The maximum cooling power provided by the commercially available cryocoolers is 1.5 W and 50 W at 4 K and 50 K, respectively. It will be difficult to use this technique with active current leads as the heat load budget will exceed these values. However, in the final design the magnets will be configured to operate in persistent mode and the cooling requirements will fall well within the limits of a cryocooler.

CONCEPT DESIGN OF A CRYOSTAT

We propose to develop the cryostats for PAMELA in two phases. First, a prototype cryostat will be designed to operate the magnet triplet using a conventional liquid helium bath with liquid helium top-up after a week’s operation (see Fig. 3). This design will be capable of handling large variations in the heat load and help us in optimizing the overall cryogenic performance as well as establishing optimal values of the magnet currents. Once the operating parameters are established, the cryostat will be upgraded by redesigning the central service turret to accommodate a cryocooler and the components of a recondenser (see Fig. 4).

The size and performance of the magnet is very sensitive to the size of the bore. The smallest magnet can be designed with the bore at 4 K, but the heat load experienced exceeds the cooling power of the cryocooler by a factor of 10. Through several iterations of magnet and cryostat designs, the bore size has been optimized to 246 mm with its temperature at less than 80 K.

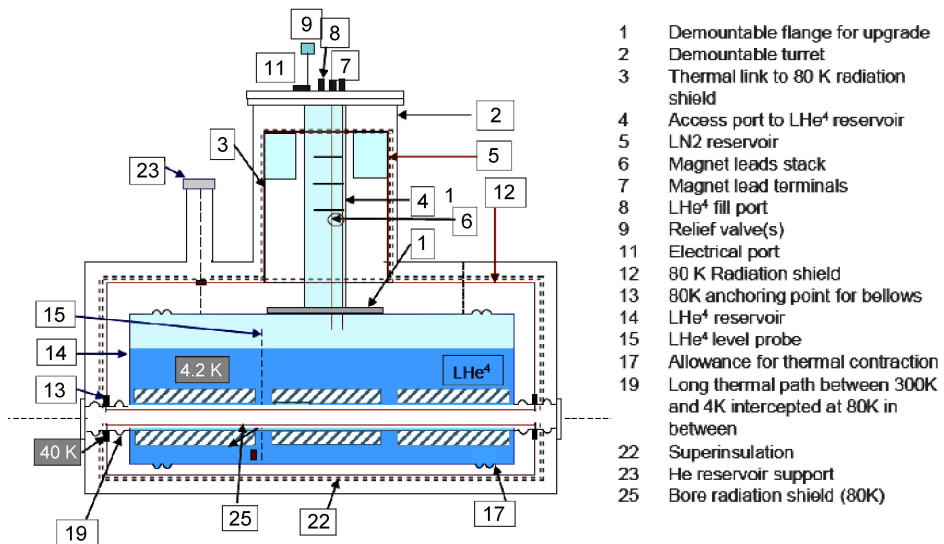


Figure 3. Schematic of a conventional LHe bath cryostat for PAMELA.

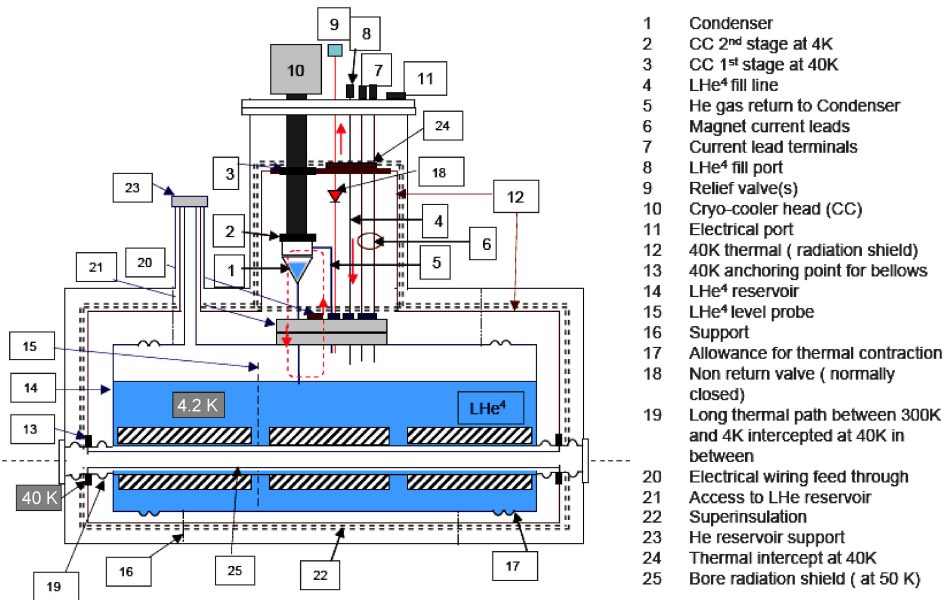


Figure 4. Schematic of a helium bath cryostat for PAMELA with recondenser.

Figure 4 illustrates the PAMELA cryostat with a recondenser. The helium gas boiling off from the bath (14) enters the condenser (1) coupled to the second stage of the cryocooler at 4 K. The re-condensed liquid returns to the helium bath from the bottom (details not shown in the figure) keeping the overall boil-off of the system to zero. The recondenser assembly is attached to the main helium bath at a demountable flange (21). In the first phase of the development this region will have the service ports for liquid helium and nitrogen transfers (as shown in Fig. 3). The recondenser technique developed at STFC has already been applied to several cryostat designs [5, 6].

## SUMMARY

This paper outlines a conceptual design of a cryostat for PAMELA. It consists of twelve magnet triplets, each consisting of three combined function magnets with field components from dipole to octupole. The large bore size and large variation in the magnet current demanded by the complex field profiles make cryogenic operation a very challenging task. Even if the re-condensing technology is well established, achieving stable cryogenic conditions in the presence of the above mentioned constraints will be a complex process. We therefore propose to undertake the development in two phases for PAMELA: first by developing a conventional top-up type bath cryostat to optimize and establish the operating parameters, and then upgrading the design to accommodate the components of a recondenser for the operation in final configuration.

## REFERENCES

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