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Design and calculation of the 4π-Continuous-Mode-Target current leads

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The new concept of the "4π-Continuous-Mode-Target" will allow the simultaneous usage of a large angular acceptance detector with a continuously polarised target. For polarising a target the process of Dynamic Nuclear Polarisation (DNP) is used which requires low temperatures and a high homogeneous magnetic field within the target volume. A thin, superconducting magnet as a part of the new horizontal cryostat creates a longitudinal magnetic field of 2.5 T with a field homogeneity of 10^{-4}. Since the internal superconducting magnet is operated with a high direct current there has to be two current leads for connecting the magnet terminals found in the low temperature region to the power supply located at room temperature. Due to *Fourier's Law* and joule heating a current lead may imply a large heat load on the magnet and the cryostat. As the magnet is operated near its critical parameters, it is important to reduce the heat flux to the superconducting wire to an absolute minimum. The geometry of the normal conducting part of these current leads has been adapted to the cryostat requirements and has been optimised to minimize the heat load. A calculation using the *Finite Volume Method* (FVM) has been additionally used to check the fulfilment of the requirements.

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1. Introduction

For improving the figure of merit of double-polarization experiments at the *Crystal Barrel* (CB) experiment at the *Electron Stretcher Accelerator* ELSA in Bonn the development of the '*4π-Continuous Mode-Target*' has been introduced in 2001 [1]. One key element for this concept is a thin, high field polarisation magnet, which is placed within the refrigerater.

With such a magnet the *Dynamic Nucleon Polarization* (DNP) can be used during the measurement of the experiment. Hence, the target polarisation can be increased above the mean polarisation of the *Frozen-Spin-Mode* [2]. The complex handling of the huge detector components and external magnet is no longer required. There is no interruption of the experiment for re-polarising the target. The target temperature is about 300 mK, which is the same temperature during the Continuous-Mode. At this temperature more cooling power of the refrigerator is available than in the 'Frozen-Spin-Mode' at which typically about 30 mK are necessary. Therefore, a higher beam intensity could be accepted for the target.

A first promising prototype of an internal magnet has presented in 2015 [3]. Its dimensions are about 155 mm in length and about 45 mm for the inner bore diameter. It is designed for producing a magnetic field of 2.5 T at a temperature of 1 K with a current of 90 A. For meeting experimental requirements, the magnet's overall wall-thickness is ≤ 2 mm. To achieve the required technical current density > 1000 A mm^{-2} a multi-filament *Low Temperature Superconductor*[1] (LTS) is used. As a consequence, the magnet may only be passively cooled and is operated within the insulation vacuum. For polarising deuteron materials with DNP, the field must have homogeneity $\Delta B/B_0 \ll 10^{-4}$ within the target volume. In this case, this is achieved by a field correction concept called *Inverse Notched Coil*, at which two shim coils are very precisely placed within the inner bore diameter as an integrated part of the main coil [4, 5].

First tests with the material ^{6}LiD at 1 K could confirm the feasibility of dynamically polarising deuterons with this prototype [6]. Nevertheless, the field could not kept stable in long time scales since the magnet's current leads produced to much heat within the test-cryostat. As a result the temperatures were rising near the superconducting parts of the current leads which lead inevitably to a quench. This fact demonstrates that the design of the current leads is an important part when using a high current magnet within a cryostat. Under the aspect of a long term stable operation the current lead design of the new 4π-Continuous-Mode-Target dilution refrigerator [7] shall be presented in the following.

2. Design of Current Leads

Due to *Fourier's Law* a current lead can act as a large heat load on the magnet and the refrigerator, especially, when using high conductive materials like copper with high cross-sectional area which is typically used for the reduction of joule heating. As the magnet is operated near its critical parameters [4], it is important to reduce the heat flux to its superconducting wire to an absolute minimum for establishing a stable operation without any quench. For conduction cooled current leads this can be achieved by using a *High Temperature Superconductor* (HTS) extension in the

[1] Supercon Inc NbTi 54S43, ∅0.254 mm, insulated

medium range temperature region $< 77\,\mathrm{K}$ and optimizing the geometry of the *Normal Conducting* (NC) leads.

2.1 Design concept

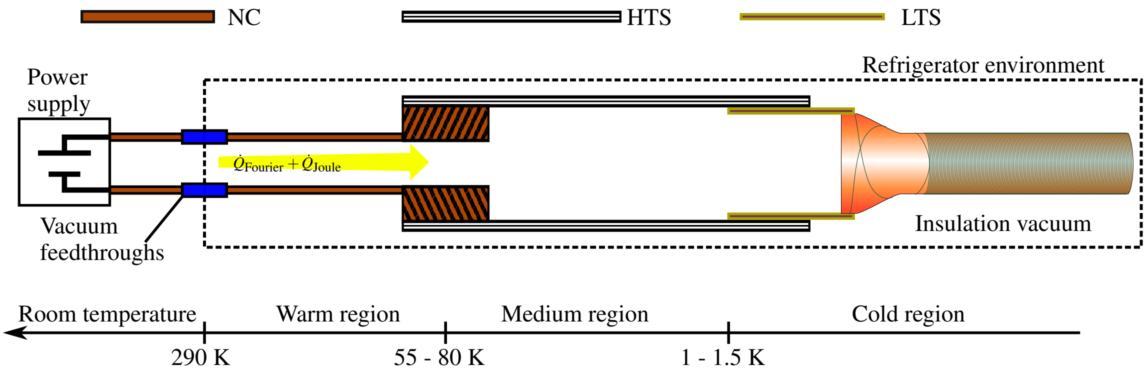

Figure 1: Concept of the current leads including Normal Conducting (NC), High Temperature Superconducting (HTS) and Low Temperature Superconducting (LTS) parts

The concept of the current leads for the 4π-Continuous-Mode-Dilution cryostat is shown in Fig. 1. The magnet's power supply is connected to a pair of vacuum feedthrough by conventional current leads which are at room temperature. Each feedthrough is attached to a BSCOO-HTS-tape[2] by a normal conducting lead. From the thermal point of view, this normal conducting part of the current leads represent the warm temperature region at which a superconductor is practically unusable. The NC-HTS junction should be typically adjustable to a temperature of 55 K to 80 K. From there, the HTS transfers the current to the magnet's terminals located at the cold temperature region (1 K to 1.5 K). The magnet's LTS-wire and the HTS are soldered over a minimum length of 10 cm.

Finally, the HTS-extension as described above thermally decouples the magnet from the warm region due to the favourable characteristics of the HTS-tapes (very low heat conduction, no joule heating). Any remaining heat input on the LTS (radiation, heat conduction from the tapes, joule heating by soldering contact resistance) can removed by the cooling stages of the refrigerator.

Nevertheless, the problem of degrading the performance of a superconductor by a heat leak is only transferred from the LTS to the HTS. With an optimized geometry according to McFee [8], a direct connection from room temperature to 77 K at the NC-HTS-junction can be minimized to a heat load of approx. $2 \times 4\,\mathrm{W}$ for both leads at 90 A. It could be seen at first tests, that this additional heat can not be dissipated by the heat sink at the NC-HTS junction. The reason can be found at the limited cooling transfer surface. Thus, the heat input must be minimized at that point to achieve a stable operation of the HTS.

2.2 Optimization of the normal conducting leads

Fig. 2 shows a block scheme of the refrigerator's inner structure within the warm region including the normal conducting leads and their cooling parts. Beginning at the vaccuum feedthrough,

[2]Sumitomo BSCCO Wire (DI-BSCCO) Type G, 200 A @ 77 K

the current is guided to the inner cryostat parts by flexible, braided copper straps (cross-sectional area of conducting material: 25 mm^2). Theses straps are connected to a pair of half-ring shaped conductors made of OFHC copper. On the one hand, this geometry provides a high reduction of joule heating due to the high cross-sectional area (260 mm^2). On the other hand, the half-rings can pressed on the underlying vacuum casing (stainless steel tube with electrical insulation material, not indicated in Fig. 2) to optimize the thermal contact. A heat sink is are also mounted with high contact pressure against the inside of the tube. The heat sink is a turbine shaped and is actively cooled by a ^{4}He-gas-stream which is fed by the cryostat's preecooling units. Overall, there exist three pairs of half-rings which are connected in series by small, optimised bridges. According to McFee [8], if the geometry of these bridges is well chosen, the rings can be thermally decoupled at full current. Here, the cross-sectional area of these bridges has been chosen to 1.5 mm^2 at a length of 40 mm. In the ideal case, the first pair of ring conductors absorbs the full heat load which comes from the copper straps. The next two rings only have to dissipate joule heating produced by the energised bridges. The forth (screwshaped) heat sink refrigerates the NC-HTS junction and the outer heat shields. Since this heat-exchanger is also connected to the last ring pair by optimised bridges it is only additionally loaded with the joule heat produced by the last bridge pair. Finally, there exist a well defined (stepwise) temperature gradient over the three rings which is depended from the adjusted ^{4}He-flowrate. The important fact is that the last heat exchanger is thermally decoupled from the warm region.

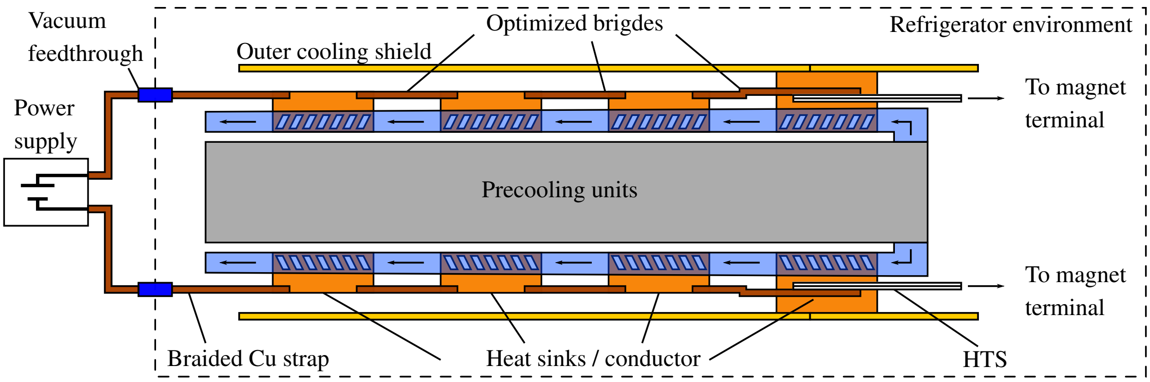

Figure 2: Block scheme of the cooling concept of the normal conducting part in the warm region.

3. FVM-simulation

McFee's analytical model for finding the optimal geometry needs the knowledge of the temperatures at the hot and the cold end of a current lead. Heat sources or sinks or more complex geometries are not taken into account. In this case, the temperatures on the rings could only be estimated by experimental data with unloaded heat sinks. Hence, the ideal cross-sectional area of the optimized bridges can be calculated only in a certain range and, finally, must be chosen by experiment. Another approach to pre-check the quality of this solution is the FVM which has been successfully used by Runkel [7] for calculating the refrigerator's preecooling stages. As Runkel, OpenFOAM

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has also been used for the simulating the normal conducting leads. A brief introduction to OpenFOAM and its usage for the He-gas/fluid regions can be found in [9] or [7]. In the following, only important changes should be mentioned for adapting the joule heating to the solid regions.

3.1 Joule heating

The steady-state solver chosen for this case is the *chtMultiRegionSimpleFoam* which models the conjugate heat transfer between solid and fluid regions. In this case the solid parts are represented by the copper current leads which are thermally coupled to the copper heat sinks by conduction. The ^{4}He-gas-stream can be modelled as a compressible fluid. The OpenFoam version 2.4.0 used here lacks of the functionality of calculating an electric potential and, consequently, the joule heating contribution. Therefore, a new solver has to be added which solves the electric potential equation (3.1):

$$\nabla(\sigma\nabla\Phi) = 0 \tag{3.1}$$

here, Φ corresponds to the electric potential and σ to electrical conductivity, which is in this case temperature depended. The current density $\mathbf{J}$ can be obtained from (3.1) by *Ohm's law*:

$$\mathbf{J} = -\sigma\nabla\Phi\,. \tag{3.2}$$

From that, the joule heating power per unit volume of the form

$$\dot{q} = \frac{1}{\sigma}\mathbf{J}^2 \tag{3.3}$$

could be implemented into the following energy equation

$$\nabla(\alpha\nabla h) + \dot{q} = 0\,, \tag{3.4}$$

with $\alpha = kc_\mathrm{p}^{-1}$ as the thermal diffusivity (temperature depended) and h as the specific enthalpy. The temperature-dependent thermal properties has been defined by polynomial functions which is sufficient for the expected temperature range from 40 K to 300 K.

3.2 Case setup

The CAD-model of the normal conducting leads can be seen in Fig. 3, including the copper straps, the half-rings connected by the optimsed brigdes and the turbine heat sinks which lay within the flowbox. The corresponding mesh was created by the OpenFOAM tool *snappyhexMesh* and consist of about $16 \cdot 10^6$ cells with a smallest possible cell edge length of 0.125 mm for the turbine blades. The flexible, braided structure of the straps is not modelled due to its complexity. Instead a straight reactangle conductor with equal cross-sectional area is assumed. The straps including half-rings and bridges represent the conducting parts and are consequently defined as a solid region. Each turbine has to be defined as a separate solid region. The chosen boundary condition *externalWallHeatFluxTemperature* for the interfaces between the conductors and the heat sinks provides the definition of thin baffles. This is necessary to simulate the additional thermal layers like the vacuum casing or the electrical insulation since their direct meshing is not practicable. The flowbox represents the fluid region, where the ^{4}He-gas-flow and the resulting heat transfer to the turbines is calculated. The boundary conditions for the important faces are set as Tab. 1 shows. These conditions correspond to experimentally determined data.

Table 1: Boundary Conditions for the shown case setup.

Region	**Face**	T	Φ	U	P
Conductor 1/2	inlet	290 K	$\nabla\Phi = I(\sigma A)^{-1}$	-	-
	outlet	zerogradient	0 V	-	-
Flowbox	inlet	40 K	-	13.3 mmol s^{-1}	zerogradient
	outlet	zerogradient	-	-13.3 mmol s^{-1}	50 mbar

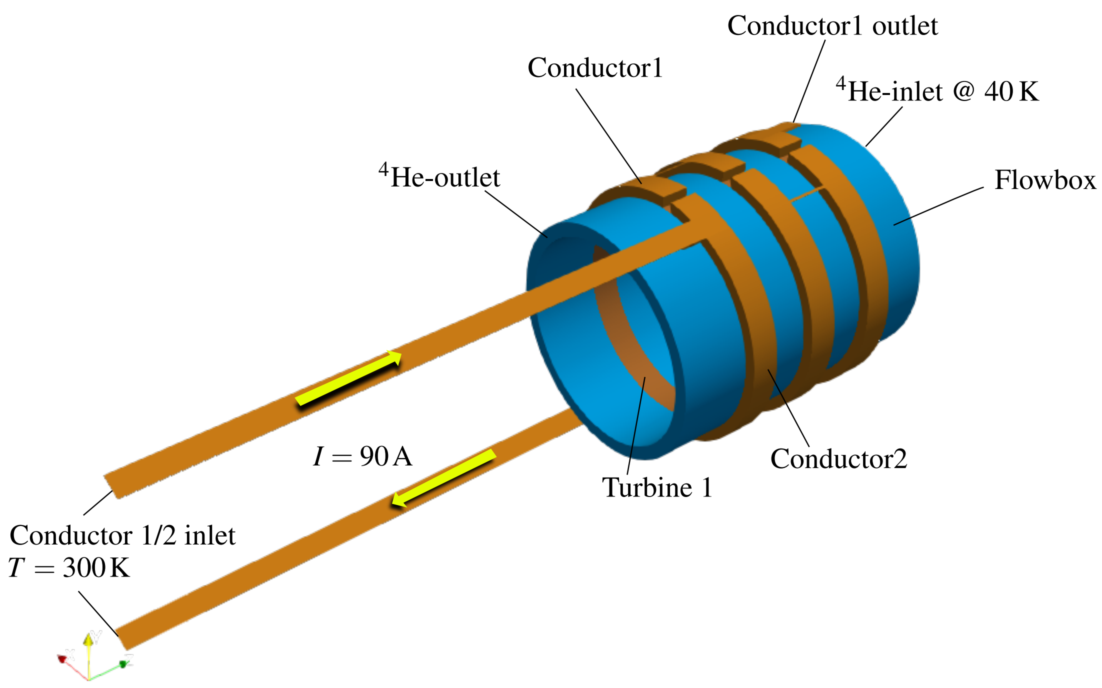
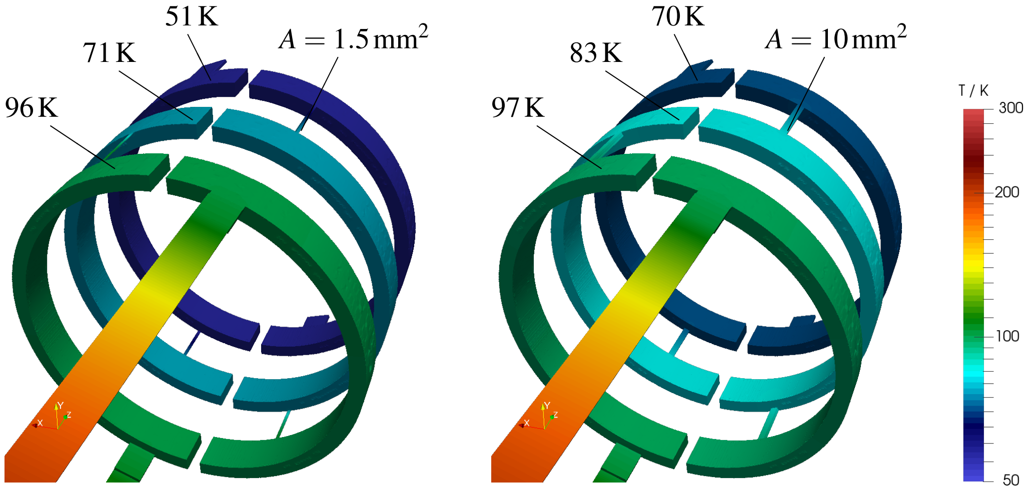


Figure 3: Model of the normal conducting leads including ^{4}He-flowbox and heat sinks. Turbine 2 and turbine 3 are covered by the flowbox and the conducting rings.

3.3 Results

There has been set up a few similar cases. The differences can be found in varying the cross-sectional area of the bridges: In the following, the results of only two cases are presented: In Fig. 4(a) the cross-sectional area of all bridges is chosen to 1.5 mm^2 - the 'thin bridge case'- which gave the best results. For comparison the bridges in the second 'thick bridge case' (Fig. 4(b)) have a cross-sectional area of 10 mm^2. As it can be seen, the first ring pair is at a similar temperature (∼100 K) in both cases. The temperature of the next ring pair in Fig. 4(a) is about 70 K. This is the lowest temperature which can only archived at the third ring pair in the second case (4(b)). The lowest temperature in the thin-bridge case is about 50 K near the conductor outlet faces. The joule heating power has been calculated to 4.15 W (thin bridge case) respectively 3 W for the thick bridge



(a) Case 1, thin bridges: A=1.5 mm^2 (b) Case 2, thicker bridges : A=10 mm^2

Figure 4: Temperature distribution of the copper current leads with different bridge geometries. The colour legend for both figures can be found on the right. The best results is the geometry with thin bridges.

case. In spite of higher joule heating contribution, the bridge geometry of the 'thin bridge case' is preferred due to the much lower temperature at the cold end. This result is certainly compatible to the introductory idea of thermal decoupling the serially connected rings, but has to be verified by the experiment.

4. Conclusion

A key element for the 4π-Continuous-Mode-Target is a thin, internal polarisation magnet with sufficient field homogeneity within the target volume. Such a magnet needs a high current (90 A) compared to the current of typical holding coils ($\sim$25 A) used in the Frozen-Spin-Mode. For operating this magnet, the refrigerator's internal current leads has to be designed to a minimum heat input on all used superconductors. For the normal conducting part of the current leads, this results in three copper rings which are indirectly cooled by a ^{4}He-gas-flow. The geometry of the ring connecting bridges plays a key role for thermally decoupling the heat leak from the medium temperature region. An analysis with a Finite-Volume-Method has been made to see the influence of the different cross-sectional areas of these bridge. Therefore, a customised solver has been implemented to OpenFOAM for considering Joule heating. A temperature of about 50 K is archived on the cold end of the NC-leads when using bridges with a cross-sectional area of 1.5 mm^2. This is sufficient to guarantee a stable operation of the following superconducting stage. This result still needs to be verified with experimental data. If a validation will be successful a new tool is available for calculating ^{4}He-gas-cooled current leads with high details.

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