**Template JRA**

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| **Work package number** | WP28 | **Start date** | 01/06/2019 |
| **Activity Type** | Joint Research Activity | | |
| **Work package acronym** | JRA10 - CryPTA | | |
| **Work package title** | Cryogenic Polarized Target Applications | | |

1. Work carried out and overview of progress
   1. **Project objectives**

*[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]*

An ambitious spin program is underway at the infrastructures ELSA (Bonn) and MAMI (Mainz), with double polarization experiments with polarized beams on polarized targets.

Technically, the polarized nucleons for double polarization experiments are provided by polarized solid state targets, using the method of Dynamic Nuclear Polarization (DNP).

To improve this class of experiments and to overcome the drawbacks of the frozen-spin polarized targets: intensity, time loss for re-polarization, external DNP magnet, objective of this WP is to optimize the small low mass internal LTS (low temperature superconducting) coils to strengthen the magnetic field for permanent DNP (“4-DNP continuous mode” target). Since the PANDA detector will operate with a strong longitudinal magnetic field to provide the measurement of charged particle trajectories with high resolution, it is necessary to shield the polarized gas target from the magnetic field of the spectrometer coil.

The development of a low mass HTS (high temperature superconducting) active or passive shielding is the first step towards a transverse polarized gas target in PANDA.

The third task of the JRA is the development of active polarized targets at cryogenic temperatures and the further implementation of this technology with new, improved prototypes. The overall objective of the JRA is hence to develop future key technologies for new and innovative polarization experiments using polarized targets in Europe.

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]*

***Table 1.2 Progress made during the reporting period for each task***

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| ***Task 1: Development of low mass superconducting high field magnets*** |
| In the last two years of the funding period (2022-24), we further deepened and concretized the development of the combined coil concept according to the work plan with the support of an experienced postdoc (Victoria Lagerquist) funded by the project. As mentioned in the last report, in Subtask 3 we developed a concept for a holding coil in which a solenoid is coupled to a dipole coil. We call this magnet a "combined longitudinal and transverse holding coil", it is designed for the frozen spin mode of the polarized target and allows variable adjustment of the polarization direction in the plane spanned by the superposition of the two magnetic fields. Both magnets, the solenoid and the "racetrack" dipole, generate a maximum field of 0.5 Tesla.  This idea could be ideally combined with the intention to measure double polarization observables with elliptically polarized photons in the future. Since an elliptically polarized photon beam results from photons with linear rather than circular components, it is possible to simultaneously measure polarization observables associated with these polarization states. Since these polarization observables require different field orientations, it would be useful to change the field/polarization direction of the target nucleons during the scattering experiment.  To that end, a combined holding coil is being developed which pairs longitudinal and transverse coil functionalities within a single configuration. The most straightforward arrangement for such a pairing is to simply concentrically nest the solenoid and racetrack geometries. The primary concern for this configuration is maintaining sufficient field strength without excessively increasing the radiation length material budget. The current single-purpose coils available for use at ELSA (which serve as an initial basis for this design) each have four layers of windings. An ideal combined coil would achieve the dual-purpose without greatly exceeding that number across both coils.  The initial step in attaining that is generating an optimizable model. The basis coils were originally developed using finite element analysis which models blocks of current densities. For the purpose of fine optimization, though, we elected to model our coils computationally using MatLab. Using the Biot-Savart law  we calculate each individual winding. The element of interest in this equation is the current path *l*. The *x* and *y* components of *l* are trivially selected by their theta dependence () and ). The *z* component, however, defines the coil shape.  For a solenoid, the *z* component can either be modeled as a series of discrete circular loops () or as a continuous spiral  .  Checking the result between the two techniques found them to be negligibly different within the target region. With this, we found we can reduce the solenoid by 2 layers while still (barely) meeting the minimum field requirement.  The racetrack coil, however, presents a more interesting geometry. Ideally, it would be composed of straight lines (down the length of the mandrel) connected by semicircular connections (around the mandrel perimeter). However, the superconducting magnet wire has physical limitations in its bending radius which necessitates a gentler transition between straight sections and connecting arcs. The original transverse coil layers were wound flat then bent over the mandrel generating a smooth curve. We chose to emulate this by modeling the connecting arcs as ellipses wrapped around the polar axis  (with appropriate handling of the various quadrants). The result of this parameterization was checked against a standard 3d modeler (Opera3D) and found commensurate. Additionally, like the solenoid, we also tested its sensitivity to single loops and continuous winding calculations.  Optimizing the racetrack geometry presents several options. Analyzing the central field contribution of each winding based on its angular position and layer number allows us to clearly understand the relationship between coil geometry and field strength. From there, decisions can be made regarding the relative importance of material budget, material uniformity, field uniformity, and absolute field strength. The current transverse coil traded maximum field strength and material uniformity for field uniformity and material budget. Choosing differently, we can reduce the layer number to 3 by extending the upper layers to match the angular coverage of the lowest one (increasing the material uniformity) and still reach the required field strength - albeit less uniformly.  Altogether, we anticipate being able to produce a combined holding coil with only 1 additional layer compared to current coils. The next steps are to manufacture and test a prototype coil using the impressive winding facilities at the University of Bonn. Additionally, we can consider the opportunity of arbitrary angle polarization using this configuration. For this, however, the question of relative component uniformities becomes more relevant. Efforts are currently underway to generate a coil configuration which meets those requirements. |
| ***Task 2: Development of low mass HTS active or passive shielding*** |
| As already reported in RP2, the periodic report of 30.04.2022, the consortium member "HIM JGU Mainz" has left the joint research activity CryPTA. As a consequence, task 2 "Development of low mass HTS active or passive shielding" could not be continued. |
| ***Task 3: Detection of recoil particles in active polarized targets at cryogenic temperatures*** |
| In the reporting period (06/2022 – 07/2024) the Mainz group has continued to work on the realization of new prototypes for an active polarized target. Originally it was planned to test new versions of the active target for the Mainz/Dubna dilution refrigerator in cooperation with the colleagues from the Joint Institute for Nuclear Research in Dubna, Russia. Since this was not possible due to the actual political situation, the necessary steps were realized in Mainz by strengthening the local group. Two student assistants were hired in Mainz and worked with the supervision of the Mainz staff (A.Thomas, M.Biroth, P.Drexler). They have setup a test box to test the new scintillators with fiber readout and SiPM electronic readout, first in lab with a radioactive probe and finally in the MAMI photon beam. The corresponding parts (specifically shaped scintillators, electronic boards, optical fiber connectors) were produced within the local workshops in Mainz.  Finally, a light tight cryogenic test box has been constructed, which was used in 07/2024 in beam. The materials could be tested successfully with liquid nitrogen cooling at 77K and the result were reported (see attached deliverable report). |

**1.3 Highlights of significant results**

*[Include an overview of the project results towards the objectives in line with the structure of the Annex 1 to the Grant Agreement*.*]*

**CryPTA 2022, annual meeting**

One of the highlights of the reporting period was the annual meeting (CryPTA2022) of the CryPTA consortium in September 2022. It was the first annual meeting where the participants were able to meet again in person for scientific exchange. The meeting took place from 20.09. to 22.09.2022 in Boppard am Rhein. 20 participants from 10 institutions in the USA, Japan and Europe took the opportunity to present the latest developments in polarized targets and to enjoy the direct scientific exchange after the corona crisis.

The meeting was thematically oriented towards the three tasks of the CryPTA project: CryPTA:ScM, CryPTA:ScS and CryPTA:APT. The invited presentations were all related to these subprojects.

Detailed information about the program and all presentations of the annual meeting can be found on the workshop web page [1] and in the proceedings of the PSTP2022 workshop [2]. In the following, the most important results and ideas of the CryPTA annual meeting are briefly summarized and reviewed.

1. Superconducting magnet systems using LTSC materials: CryPTA:ScM

1.1 Thin superconducting magnets for DNP

In the double polarization experiments at the large acceptance detector systems Crystal Barrel at ELSA and Crystal Ball at Mami, the target technology of the horizontal frozen spin target with an internal holding coil developed in Bonn [3] has been used very successfully for many years. To improve the figure of merit for future polarization experiments, the thin internal holding coil of the frozen spin target should be replaced by a coil of the same geometry but with a stronger magnetic field. Ideally, the magnet should provide the field of the external polarization magnet, typically 2.5 Tesla. The advantages of this scheme of an internal polarization magnet are obvious: the target polarization can be kept at a high level even during data acquisition by DNP, there is no more loss of time due to the otherwise usual post-polarization phases. We call this scheme ‘4-continuous polarized target’ [4].

However, the DNP process requires a high field homogeneity over the target volume and since the magnetic field volume of the planned internal polarization magnet is of the same order of magnitude, appropriate correction windings have to be placed on the solenoid. All this requires precise winding of thin superconducting wires on a thin-walled copper substrate using wet winding techniques [5].

In the target laboratory of the Physics Institute of the University of Bonn, a small superconducting solenoid with a nominal field of BP = 2.5 T was successfully wound on the specially developed winding machine. The coil can be installed in the existing or in the future horizontal dilution cryostat. The coil was tested in a 1K 4He evaporation refrigerator. We demonstrated that both PE and 6LiD can be dynamically polarized [6]. The next step is to install the coil in the new dilution refrigerator and use it in the Crystal Barrel experiment at ELSA.

In order to measure as many polarization observables as possible with one setting of detector system and polarized target, we are currently developing a coil system in which a solenoid is combined with a race-track coil pair in a cylinder carrier [6].

1.2 Superconducting correction coils for DNP in a spectrometer magnet

At JLab, the technique of internal superconducting coils is used at the CLAS12 experiment to correct for an external strong magnetic field. There, the 5 Tesla magnetic field of the large acceptance detector system is used to dynamically polarize the target material in a continuously operated horizontal 1 K evaporation refrigerator. In contrast to the frozen spin operation, the target material is also permanently dynamically polarized during data taking. In this sense, this is also a '4 continuous polarized target' [7]. However, since the homogeneity requirements for the DNP process must also be met here, superconducting correction coils were installed in the cryostat in the target area after prior precise measurement of the spectrometer magnetic field. The coil system was designed to not only correct the external field, but also to provide a significant field shift to reverse the polarization direction in the individual target cells and measurements for NMR calibration. Overall, then, a very elegant solution and use of internal coil technology [8].

2. Superconducting magnet systems using HTSC materials: CryPTA:ScS

In recent years, the development of high-temperature superconductors has progressed to such an extent that these materials are also suitable for special magnet applications. The special geometrical requirements of the thin magnet systems used in the polarized target suggest the use of tubes made of solid high-temperature superconductor material. In addition, tubes made of high-temperature superconductor open the possibility to induce and practically store or completely shield the magnetic field of an external magnet when passing through the critical parameters of the material.

2.1 Bi-2212 shielding tube

Within the framework of CryPTA:ScS, the working group from HIM (UMainz) has investigated the shielding properties of HTSC tubes consisting of bulk Bi-2212 (Bi2Sr2CaCu2O8). Background of this measurement is the planned use of this shielding in the Panda magnetic field to create a field-free space for a polarized target at the interaction point. The measurements on the shielding behavior of the Bi-2212 tube have shown that at a temperature of TBi-2212 = 4.2 K a longitudinal external magnetic field of Bext = 1.4 T can be almost completely shielded with a shielding factor of SF = Bext/Bres = 3\*105 (Bres: field inside the cylinder) [9]. Further measurements on shielding behavior at higher temperatures and magnetic fields are planned for the future. It is also planned to systematically investigate the high-temperature superconductor YBCO under the same conditions and to test its suitability as a shielding material [9].

2.2 Bulk MgB2 holding magnet

A really promising concept for field generation or field storage using a high-temperature superconductor as a holding coil for a polarized target was presented by G. Ciullo from INFN Ferrara [10]. There, one uses a tube of magnesium diboride (MgB2) sintered in one's own laboratory. The tube is produced by the so-called magnesium 'reactive liquid infiltration' process. MgB2 is an intermetallic compound that currently has the highest transition temperature (39.5 K) among metallic superconductors and is characterized by a high critical current density. To measure the properties of the MgB2 tubes, the cylinder was cooled to TMgB2 = 13 K via a cold head and subjected to an external axial and longitudinal magnetic field of Bext = 980 mT. Depending on the condition under which the temperature fell below the critical temperature, the external magnetic field could be trapped or shielded. This showed that the external magnetic field was almost completely trapped (Bres = 943 mT). The shielding behavior of MgB2 is less pronounced than Bi-2212 at TMgB2 = 13 K, but a clear temperature dependence is evident. Thereafter, a much higher shielding factor can be expected at 4.2 K for MgB2. The long-term stability measurements show a stable shielding behavior and a high stability of the trapped field. In further measurements in the near future, the temperature of the cylinder will be lowered further and exposed to higher external magnetic fields, thus testing its suitability for use in the polarized target. But already now it can be said that the concept of cylindrical high-temperature superconductors is a good alternative to the classical superconducting coils based on low-temperature superconductors. Thus, the high-temperature superconductors significantly expand the application and experimental range of the polarized solid-state targets in polarization experiments. Thus, the use of the concept is envisaged in the future at the CLAS12 experiment.

3. Low temperature detection techniques: CryPTA:APT

Naturally, the polarized solid-state target reaches its limits with respect to the detection probability of the reaction products when measuring threshold reactions or at generally low beam energies. The density of the target material and the large radiation length of the structural materials surrounding the target, and here in particular the internal holding coil, shadow the target material and shift the detection threshold for particle detection by about 100 MeV. Thus, among other things, the measurement of the 'Proton Spin Polarizabilities with Double-Polarized Compton Scattering' is planned at MAMI. Due to the reaction kinematics and the competing processes, the detection of the recoil proton is essential for the process. From this constraint for the experiment, the idea of the active polarized target has been developed in the working group at MAMI [11].

Typically, doped alcohols are used in polarization experiments with real photons because of their high content of polarizable nucleons. Since polystyrene also has this property and at the same time functions as a classical scintillation material, the obvious conclusion is to dope polystyrene, polarize it dynamically and read out the light from the recoil protons. However, all components, scintillator, light guide and first readout electronics are located in the dilution cryostat and are thus partially exposed to temperatures in the millikelvin range. This places high demands on the coupling of the light guide to the scintillator and the quality of the light guide itself. In the meantime, the concept has been used in a first scattering experiment and first data have been taken. The polystyrene used could be polarized to just under Pp ~ 50%. The relaxation times reached  ~ 80h in the frozen spin mode of the target. The low relaxation times were due to the high thermal conductivity of the optical fiber and are not unusual for now. What was important was the successful detection of recoil protons, which were detected in the analysis process. The tests confirmed the concept, but a modified version of the active target will be used in the future. The idea of a semi-active target is being discussed. It is planned to embed a small classical alcohol target material (high polarization, significantly improved relaxation times) a cage of strongly segmented scintillators and to guide the light via thin fiber elements from the low temperature range to the medium temperature range of the cryostat. This significantly reduces the thermal load on the mixing chamber and improves the performance of the refrigerator [12].

Regardless of the difficulties, the concept has proven that the active target opens a new class of polarization experiments with the polarized solid-state target, offering a significant expansion of experimental possibilities in hadron physics.

In summary, the meeting once again brought together all those involved in the development and operation of solid-state polarized targets worldwide. The polarized target is a well established and reliable experimental device in scattering experiments. For almost 60 years it has been the instrument of choice for studying spin-dependent quantities in hadron and particle physics. But the meeting also showed that in the future only a few laboratories will be able or willing to afford this complicated infrastructure and that further development will shift to the USA (Jlab) due to a lack of young talent here in Europe. In this respect, it was probably the last meeting of its kind in Europe dealing with the topic of polarized targets.

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| [1] | H. Dutz and A. Thomas, *CryPTA2022, Annual meeting of the STRONG2020 Joint Research Activity ‘Cryogenic Polarized Target Applications’* (WP28), [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/>. |
| [2] | H. Dutz, *CryPTA2022, Status Report from this year's annual Meeting*, [PoS(PSTP2022)021](https://pos.sissa.it/433/021/pdf), p. 21, 2022. |
| [3] | Ch. Bradtke et al, *A new frozen-spin target for 4pi particle detection*, Nucl.Instr. and Meth.A 436 (1999) 430-442, p. 13. |
| [4] | H. Dutz, *Summary of the 9th International Workshop on polarized solid-state targets and techniques*, Proceedings of the 16th International Spin Physics Symposium, pp. 221–225, WORLD SCIENTIFIC, 2005. |
| [5] | M. Bornstein, *Development of a thin, internal superconducting polarisation magnet for the Polarised Target*, [PoS(PSTP2015)006](https://pos.sissa.it/243/006/pdf), p. 6, 2015. |
| [6] | H. Dutz, *Status of CryPTA:ScM*, CryPTA2022, 2022. [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/contributions/896/>. |
| [7] | C. Keith, *Activities of the Jefferson Lab Target Group*, CryPTA2022, 2022. [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/contributions/887/>. |
| [8] | V. Lagerquist, *Optimization and Implementation of Magnet Correction Coils for the Jefferson Lab Polarized Target*, CryPTA2022, 2022. [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/contributions/892/>. |
| [9] | F. Maas, *Experimental tests of the shielding tube BSCCO-2212*, CryPTA2022, 2022. [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/contributions/899/>. |
| [10] | G. Ciullo, *A versatile bulk superconducting MgB2 cylinder for the production of holding magnetic field for polarized targets and nuclear fusion fuels*, CryPTA2022, 2022. [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/contributions/893/>. |
| [11] | A. Thomas, *Status of the polarized target at MAMI*, CryPTA2022, 2022. [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/contributions/883/>. |
| [12] | M. Biroth, *The Mainz Active Polarized Proton Target - Review and Perspectives*, CryPTA2022, 2022. [Online]. Available: <https://indico.hiskp.uni-bonn.de/event/84/contributions/895/>. |

**Task 3:**

The results of the first active polarized runs with MAMI beam have been reported in the framework of a PhD thesis. New ideas and concepts for an improved version of the polarized active target insert have been developed and reported. The light transport system of the next generation active target insert was replaced by optical fibers with a SiPM readout electronics. Tests with scintillators operating at cryogenic temperatures have been performed in a real photon beam.

1. Critical Implementation risks and mitigation actions

**2.1 Risk materialization**

*[Provide the information on the project risks described in Annex 1 to the Grant Agreement*.*]*

1. Development of low mass superconducting high field magnets: The main risk is to overestimate the thermal properties of the carrier of the coil and the resin of the windings. (low)

Whether the risk has materialized? (No)

1. Development of low mass HTS active or passive shielding: Up to now it is an open question as to how thin a HTSC-material can be sintered into a cylindrical shape to fulfill our requirements. (low)

Whether the risk has materialized? (No)

1. Detection of recoil particles in active polarized targets at cryogenic temperatures: Since high variety of exiting target material preparation techniques offer broad development potentialities, the most critical aspect is the time consuming material preparation. (low). The second enterprise is the development of an optical and electronic readout chain capable of operation at cryogenic temperatures (low)

Whether the risk has materialized? (No)

**2.2 Risk-mitigation measures applied**

*[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period*.*]*

1. In case of a failure we will take a step back to proven parameters (well-established materials and resins). A cooperation with the manufacturer of low temperature glue is envisage to find out the best solutions.

Whether the risk-mitigation plan was applied? (No)

1. To minimize the risk a close cooperation with a HTSC manufacturer is already stipulated to achieve state-of-the art parameters.

Whether the risk-mitigation plan was applied? (Yes/No)

1. The intention of the sub-project is to maximize the actual achievable target polarization in plastic scintillators. This will substantially improve the quality of planned scattering experiments. Slightly lower values will not call them into question. In the meanwhile, preliminary test in our existing apparatus have shown the principal feasibility of running read out electronics components at temperatures below 4.2 K.

Whether the risk-mitigation plan was applied? (No)

**2.3 Comments/new risk-mitigation measures proposed**

*[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above*.*]*

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

**3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package**

*[Explain the reasons for deviations, the consequences and the proposed corrective actions.]*

No deviations

**3.2 Deviations between actual and planned person months**

*[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]*

No deviations

1. Deliverables and milestones tables

**4.1 Deliverables**

*[Please list all the deliverables due in this reporting period, as indicated in Annex I.*

*Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]*

***Table 4.1 List of deliverables***

| **Deliverable No.** | **Deliverable name** | **Lead Beneficiary** | **Nature** | **Dissemination level[[1]](#footnote-1)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D28.1 | Prototype of a low  mass, internal horizontal  polarizing solenoid | 10 - UBO | Demonstrator | PU | 62 | yes | 05/24 |  |
| D28.2 | Prototype of a HTSC  shield for a large  acceptance magnetic  detector | 9 - JGU MAINZ | Demonstrator | PU | 54 |  |  |  |
| D28.3 | Prototype of a cryogenic  insert with active target  material | 9 - JGU MAINZ | Demonstrator | PU | 62 | Yes | 07/24 |  |

*In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate “uploaded report” in correspondence of a deliverable*

**4.2 Milestones**

*[Please complete the table if milestones are specified in Annex I.*

*Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]*

***Table 4.2 List of milestones***

| **Milestone number** | **Milestone name** | **Lead beneficiary** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |

**No Milestones in the RP3 (months 37-62)**

**4.3 Deliverable Reports**

*[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]*

Deliverable D28.1: Prototype of a low mass, internal horizontal polarizing solenoid, 29 pages, Bonn (2024)

Deliverable D28.3: Detection of recoil particles in active polarized targets at cryogenic temperatures, 5 pages, Mainz (2024)

1. PU = Public

   PP = Restricted to other programme participants (including the Commission Services).

   RE = Restricted to a group specified by the consortium (including the Commission Services).

   CO = Confidential, only for members of the consortium (including the Commission Services). [↑](#footnote-ref-1)