Table 3.1b: Work package description

For each work package:

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<th>Work package number</th>
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<th>Lead beneficiary</th>
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Objectives

The objective of this work package is to respond to crucial questions on the feasibility and technology challenges associated with the magnet and powering systems for a muon collider, and provide critical input to assess technology readiness and timeline of a muon collider. The leading questions that we plan to answer are: (i) the value of the maximum field and free aperture that can be realistically achieved in the solenoids for the target, capture and cooling complex, aiming at steady state fields well in excess of 40 T, (ii) the feasibility and performance reach of the fast accelerator chain, with field swing in the range of 4 T or higher and shortest ramp time of a fraction of ms, and (iii) finding suitable design options for the dipole and quadrupole magnets of the collider complex, which require very high field, up to 20 T peak, and large aperture, up to 150 mm, being subjected to large heat deposition and radiation from particle decays and interactions. We plan to address the above questions through a combination of conceptual design work, targeted tests and specific characterization measurements. It is important to remark that while we do not plan hardware demonstration, we still believe that some well-planned experimental activities in support of the feasibility study are unavoidable to yield the desired answers to the above challenges. A critical result of the study will finally be the identification of the research and development work required to achieve the desired performance reach. The planned activities in the three domains of ultra-high-field solenoids, fast ramped accelerator systems, and high-field and large aperture collider magnets have very strong synergy and relevance to other fields of applications of magnet technology for science and society. We plan to exploit such synergies, sharing results, and profiting from the on-going developments in other fields, thus optimizing the return on investment of our work.

Description of work

Task 1. Coordination, Integration and Communication (Leader Institution: CERN)

The aim of this task is twofold. On the management side it provides coordination and documentary support for magnet design studies and R&D, organizing regular communication and topical meetings among the partners within the magnet activities, as well as with the actors in other activities of the study. CERN (Task Leader) will provide the administrative and documentary support, and organization of regular WP7 meetings co-chaired by CEA. It is planned to hold three magnet workshops, regularly spaced through the execution of the program. The workshops will cover advances in the WP7 activities, with significant involvement and participation from other projects and institutions whose activities are synergistic to the scope of WP7.
On the technical side, activities within this task are devoted to the establishment and maintenance of a magnet catalogue, including a set of target specifications, baseline concepts and technology options, and estimates of power consumption and system cost. The catalogue will include the results from the three tasks in this work package, focussed on specific magnets, and will complete it for the whole collider complex. This task also provides the interface for magnet energy deposition and radiation studies, magnet cooling studies, as well as safety and environmental aspects of the magnet system. CERN will provide the resources and technical support for the construction of the magnet catalogue, polling actively the demands from accelerator physics (WP2, WP3, WP4, WP5), and interfacing to the other aspects of the study, including the compilation of a power and cost model in collaboration with CEA.

Task 2. Target, Capture and Cooling Magnets (Leader Institution: INFN)

This task covers the conceptual design work required to establish performance limits, assess feasibility, and identify outstanding R&D for the target, capture and final cooling solenoids, in close collaboration with the activities on beam capture and cooling, target and absorber design (WP4), and RF (WP6). Specific focus will be put on the two magnets that represent the spectrum of magnet challenges, namely (i) the target solenoid, which requires high field (20 T) in a large bore (150 mm), subjected to substantial energy deposition (100 kW) and radiation, and (ii) the final cooling solenoid, where the required field (40 T minimum to 60 T target) in a small bore (50 mm) is well beyond the present state of the art. The task will maintain a close interface with the engineering design of the solenoid for the test module (WP8), an in particular for what regards the integration aspects. The task provides coordination for a limited experimental activity devoted to establishing material and technology limits, towards the identification of priority R&D.

The work will be performed by INFN (Task Leader), CEA, CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE, in collaboration with KEK, KIT and US-MDP. INFN will coordinate the conceptual design and experimental activities.

Following an initial review of candidate concepts, preliminary designs will be developed for the target and final cooling solenoids by CEA, CERN, LNCMI, SOTON and PSI. The study will focus on identifying and quantifying key requirements and performance indicators, and associated performance limits (e.g. margin, mechanics or protection). We plan to consider various alternatives in this initial scoping study, such as (initial list): (i) superconducting material (e.g. LTS+HTS, all-HTS, and type of HTS); (ii) dry vs. impregnated, insulated vs. non-insulated or controlled insulation windings, (iii) conductor configurations (e.g. single tape, stacks, internally cooled). Key performance indicators to be quantified could be based on (initial list): (i) field, bore, and length; (ii) operating current, current density and voltage; (iii) stress and strain; (iv) magnetic energy density; (v) footprint, mass and cost.

The experimental activity will be focussed on missing information and properties specific to the planned use of HTS to generate the high- and ultra-high-fields targeted, probing and quantifying Technology and Performance Limits (TPL). We expect that stress and strain, either driven by electro-magnetic forces, or induced by the interaction of screening current and background field, will put an upper limit to the ultimate field. Similarly, quench management (detection and protection) will result in an upper bound for the stored magnetic energy and hence the field. Aware of these challenges, we will use the results of the conceptual study to guide the definition of TPL experiments that will provide hard evidence for the projected and yet unknown limits, including consideration of magnet construction (winding impregnation or soldering) and operation (thermal cycles and fatigue). A crucial milestone will be the definition of bespoke TPL experiments. The intention of TPL is to reproduce as closely as practical the conditions identified by the study, largely profiting from existing configurations and installations. Experimental work on TPL samples will be conducted at CERN, LNCMI, PSI, SOTON, UNIGE and TWENTE.

We finally propose to use the combination of the analytical study, substantiated by the collected TPL experimental data, to define the expected performance of the solenoids for the target, capture and cooling complex, establishing their technical readiness, and as a guide the definition of the necessary R&D. This will include considerations on available and required test infrastructure, where on the medium term we expect a
clear need for upgrades in support of high- and ultra-high-field testing.

Task 3. Fast Ramped Accelerator (Leader Institution: CERN)

The aim of this task is to develop realistic targets and propose concepts for the fast-ramping accelerator complex, in close collaboration with beam physics (WP5) and RF (WP6). The challenges addressed are centred around the management of the large energy stored in the magnet system (of the order of 100 MJ), the power flow required for ramping (in excess of 50 GW reactive power), and the quality of the fast field ramp (0.5 ms for the shortest cycle time). The specific focus of this task is on the integrated development and optimization of concepts for the power storage, conversion and distribution in normal-conducting fast ramping magnets. The focus will be on the present baseline scheme, i.e. a Hybrid Cycled Synchrotron (HCS) consisting of a combination of DC dipoles (superconducting, up to 16 T) and AC dipoles (resistive, bipolar, ± 2 T). Alternative schemes will be considered at the level of conceptual study, and in particular HTS fast ramped magnets to see whether performance can be improved and consumption reduced.

The work will be performed as a collaboration among CERN (Task Leader), KYOTO, LNCMI, TUD, UNIBO and TWENTE. CERN will provide the design and optimization framework for the accelerator magnet and powering system, and will cover all aspects related to the energy storage and power conversion, with participation of LNCMI in matters of power converter topology, technology limits, dimensions and cost. UNIBO and TUD will provide magnet concepts and design (2D and 3D) aiming at the lowest stored energy and AC loss, as well as the model reduction necessary to include the magnet characteristics in the optimization framework. Given the high level of integration of the system, we anticipate that the design and optimization studies will require a continuous and intense level of exchange among the specialties, which is an innovative approach. An HTS magnet option, targeting a wider field swing than the resistive AC dipole (e.g. up to a range of ±3 T) will be studied in collaboration among CERN, defining the magnet requirements and possible magnetic configurations, TWENTE, proposing conductor concepts suitable for fast pulsed magnets, KYOTO and UNIBO supporting the study with calculation and analysis. If promising, the HTS magnet characteristics will be added to the design and optimization framework, and included in the direct comparison of performance of the various options considered.

Task 4. Collider Ring Magnets (Leader Institution: INFN)

This task aims at assessing realistic performance targets for the large bore (range of 150 mm) collider magnets, in close collaboration with beam optics (WP5), machine-detector interface, and energy deposition studies (WP2). Both a 3 TeV and a 10 TeV center-of-mass collider will be considered in sequence, focussing on the design of the combined functions dipoles in the arc, which are a good sample of the magnet challenges. The study for the 3 TeV center-of-mass collider will consider a LTS magnet, with field up to 10 T (NbTi or Nb3Sn), covering both magnetic and mechanical design aspects. A 10 TeV center-of-mass collider will require magnetic fields up to 16 T. Estimates based on first principles show that the electromagnetic force in a dipole midplane is a severe limitation for the use of known coil technology, and especially for Nb3Sn. The study will hence consider adopting a stress management mechanical system, which is an innovative approach for accelerator magnets, especially as it will have to be adapted to a combined functions magnet. As an alternative we will consider using HTS materials, whose state of the art is less mature, but are known to have superior tolerance to stress and strain and are expected to unfold their potential for magnet technology in the next future. The task will cover quench management, with the selection of a suitable protection strategy, e.g. comparing the effectiveness of using quench heaters, CLIQ, or other innovative methods (e.g. for HTS). Finally, the study will address the effects of the expected heat and radiation load, up to 0.5 kW/m linear power density in the coils, considering aspects such as thermal stability, heat removal and radiation-induced damage.

The work will be performed by INFN (Task Leader) and UNIMI in collaboration with KEK, PSI and US-MDP. INFN has relevant and direct experience, having produced the reference design of the 16 T Nb3Sn dipole for FCC, and being presently in the process of building a single aperture short Nb3Sn dipole model. INFN and UNIMI will contribute the mechanical and magnetic design and analyses, while KEK, thanks to
the experience gained on combined function magnets at J-PARC, high field accelerator magnets R&D, and conductor R&D, can provide valuable support in the development of the magnet concepts. PSI and US-MDP have on-going activities in the design of stress-managed Nb₃Sn 16 T dipoles and will contribute sharing design solutions and results of analysis.

**Milestones**

M-7.3.1. Design and optimization tool for integrated analysis available (M12)
M-7.2.1. Survey of solenoid technologies and requirements on TPL experiments (M12)
M-7.4.1. Review of magnet design options for the arc of the collider with a specific focus on “stress managed” Nb₃Sn and HTS dipoles Conceptual design of combined function arc magnets. Preliminary cost estimate (M12)
M-7.1.1. Workshop on Pulsed Magnets (in collaboration with WP5) (M12)
M-7.2.2. Commissioning of TPL experimental configurations for ultra-high-field solenoids (M24)
M-7.1.2. Workshop on Ultra-High-Field Solenoids (M24)
M-7.3.2. First summary results of accelerator configuration options (M24)
M-7.4.2. Selection of concept baseline and parameters for 3TeV center-of-mass collider magnets. Magnetic and mechanical calculations of arc magnets, design of protection system. Cost estimate (M24)
M-7.3.3. Complete the scoping study of HTS fast pulsed magnets (M30)
M-7.2.3. Intermediate report on target and final cooling solenoid conceptual design (M30)
M-7.2.4. Report on TPL experiments for ultra-high-field solenoids (M36)
M-7.1.3. Workshop on Collider Dipoles (M36)
M-7.4.3. Selection of concept baseline and parameters for 10TeV center-of-mass collider magnets. Magnetic and mechanical calculations of arc magnets, design of protection system. Cost estimate (M38)
M-7.3.4. Estimate of cost, power and footprint (powering system) (M40)
M-7.3.5. Report on impact of R&D on energy storage, powering and magnet technology to other fields of science and society (M40)

**Deliverables** (brief description and month of delivery)

D-7.3.1. First conceptual baseline for magnets and powering system (M36)
D-7.2.1. Final report on target and cooling solenoids: conceptual design options, result of supporting tests and measurements, technology selection (M42)
D-7.3.2. Final report on magnet and power system for the muon collider (M42)
D-7.4.1. Final report on collider magnets: conceptual designs of arc dipoles for 3 TeV and 10 TeV (M42)
D-7.1.1. Final report on muon collider complex magnets: magnet catalogue, baseline technology selection, consolidated power and cost estimates, R&D plan (M44)