DRAFT - mmWG and EU MuCol WP7 - DRAFT
Work Plan 20/6/2023

Deliverables

D7.1 – January 2026: Preliminary report on muon collider magnets, containing a first conceptual baseline and technology selection for magnets and powering system, preliminary power and cost estimates
D7.2 – January 2027: Consolidated report on muon collider complex magnets: magnet catalogue, technology selection for baseline and alternatives, consolidated footprint, power and cost estimates, R&D plan

Milestones

M7.1 – March 2024: Report on solenoids and TPL experiments
M7.2 – March 2025: Report on RCS and HCS configurations
M7.3 – October 2025: Workshop on ultra-high-field solenoids
M7.4 – December 2025: Report on HTS fast-cycled magnets
M7.5 – January 2026: Report on high-field collider magnet design
M7.6 – February 2026: Report on solenoid conceptual design
M7.7 – September 2026: Workshop on high-field collider magnets
M7.8 – November 2026: Report on footprint, power and cost model
M7.9– November 2026: Report on R&D and impact

Task 1 – Technical coordination and integration (CERN, CEA)

Scope of work: Overall coordination and communication task. Act as interface to other WP's. Organization of transverse activities such as radiation studies and cryogenic design. Documentary support.

- Create and maintain the magnetic configuration (magnet catalog)

Who: S. Fabbri (CERN), L. Bottura (CERN), L. Quettier (CEA), M. Statera (INFN), F. Boattini (CERN), S. Mariotto (INFN), B. Caiffi (INFN)
When: first version end 2023; draft final version end 2025; final version end 2026

- Interface to physics for magnet specifications and feedback on performance

Who: S. Fabbri, L. Bottura (CERN), L. Quettier (CEA)
When: continuous activity

- Cryogenic and cooling studies, transverse activity

Who: P. Borges De Sousa (CERN), R. Van Weelderen (CERN), M. Randi (CERN), L. Bottura (CERN)
When: TBD

- Radiation studies, transverse activity in collaboration with BMI and RP – Collect input as to dose, energy deposition and residual dose (RP) in the various parts of the complex. Define required R&D and limits

Who: L. Bottura (CERN), L. Quettier (CEA), A. Lechner (CERN)
When: mini-workshop on radiation hardness of HTS magnets beginning 2024

- Run periodic meetings of the Muon Magnets Working Group, as well as other WP and project meetings and reports

Who: L. Bottura (CERN), S. Fabbri (CERN)
When: continuous activity, regular frequency

Task 2 – Target, capture and cooling complex (INFN, CERN, CEA, LNCMI, TWENTE, UNIGE, PSI, SO'TON)

Scope of work: Magnet concept selection and design for the muon beam production part of the complex, from the target to the final cooling. All magnets are solenoids, with the exception of tunable dipole correctors as necessary to steer and introduce dispersion in the beam. NOTE: use results from HFM HTS developments for technology selection and design assumptions.

- Review and define broad conductor requirements (operating temperature, materials, electrical, mechanical,…) for the various types of solenoids (target, 6D cooling, final cooling): tapes and wires, cables

Who: M. Statera (INFN), L. Bottura (CERN), H. Ten Kate (TWENTE), A. Kario (TWENTE), C. Senatore (UNIGE), Y. Yang (SO'TON)
When: by mid May 2023 (mmWG meeting)

- Review material options for HF and UHF HTS solenoids (REBCO, Bi-2212, Bi-2223, IBS), providing broad evaluation of potential of each material for high field and temperature higher than liquid He, with Pro's and Con's

Who: Y. Yang (SO'TON)
When: early 2024

- Cost and power estimate

Who: M. Statera (INFN), L. Bottura (CERN), S. Fabbri (CERN), L. Quettier (CEA)
When: draft version June 2025; final version June 2027

Task 2.1 – HTS Conductors for solenoids (INFN, CERN, TWENTE, UNIGE, SO'TON)

- Conductor specification (performance and quantity) and procurement of relevant materials for tests and small-scale demonstration experiments

Who: L. Bottura (CERN, procurement), C. Senatore (UNIGE, material storage)
When: short samples from leading manufacturers by April 2023; 6-8 km procurement launched end of June 2023; additional 10 km procurement launched mid 2024

- Standard characterization measurements, review and establish present Ic(B,T,angle) database, perform minimal characterization (e.g. Ic at reference points for procured material), critical surface mapping (additional angles) and UHF data

Who: C. Senatore (UNIGE), Y. Yang (SO'TON)
When: first update to database and scaling by end 2023; final results by end 2026
Material: tape samples and short witness lengths from procurement

- PROPOSAL - Mechanical and electro-mechanical properties, measure Ic degradation and limits under stress and strain in tapes, stacks and conductors (bending, twisting, pressure) TBD

Who: A. Kario (TWENTE), Y. Yang (SO'TON)
When: TBD
Material: tape samples, stack samples and short conductor lengths

- Novel experiment #1: delamination under I x B force

Who: C. Senatore (UNIGE)
When: experiment definition and first tests autumn 2023; test of tape samples end 2024
Material: tape samples

- PROPOSAL - Novel experiment #2: internal joint technology TBD

Who: A. Kario (TWENTE)
When: TBD
Material: tape samples, coil samples ?

- Evaluate current distribution and time dependencies in multi-tape and NI windings, integrate results in magnet design (field ramping and field persistence), benchmark against small scale experiments

Who: Y. Yang (SO'TON)
When: intermediate report spring 2024; final report end 2025
Material: tape and stack samples

- Missing: characterization of resistive properties (internal resistance) of tapes

Task 2.2 – Design and demonstrate UHF HTS solenoids using NI/PI technique for final cooling (INFN, CERN, PSI, CEA, LNCMI, TWENTE, SO'TON)

- Define performance specifications (beam physics). Initiate meetings with beam/shield/absorber/cryo/vacuum on magnet specifications and accelerator configuration

Who: S. Fabbri (CERN), L. Bottura (CERN), M. Statera (INFN)
When: first version September 2023; draft final version September 2025; final version September 2026

- Define reference geometries and estimate material needs for technology R&D

Who: M. Statera (INFN), L. Bottura (CERN)

When: April 2023

- CERN - Engineering design of final cooling solenoid, 40 T (or higher), 50 mm bore, 500 mm length, stand-alone

Who: A. Dudarev (CERN), B. Bordini (CERN), T. Mulder (CERN), A. Bertarelli (CERN), C. Accettura (CERN)
When: first concept consolidated September 2023; final concept September 2025

- CERN - R&D pancakes manufacturing and test at CERN, geometry and loading alternatives, resistance control, mechanical testing, powering test

Who: A. Dudarev (CERN), B. Bordini (CERN), T. Mulder (CERN), A. Bertarelli (CERN), C. Accettura (CERN)
When: design and tooling by end 2023; mechanical tests 2023 and 2024; manufacturing start 2024; testing 2025 and 2026

- INFN - R&D pancakes manufacturing and test at INFN, small coils having different configurations and characteristics (insulated, non-insulated, dimensions,…). Provide test windings for characterization and test at collaborators

Who: M. Statera (INFN), S. Sorti (INFN)
When: start construction mid 2023, starting test beginning 2024

- PSI - R&D pancakes manufacturing and test at PSI. Share advances and make available small windings for characterization and test at collaborators

Who: J. Kosse (PSI), B. Auchmann (PSI)
When: start 2023

- PSI- Enabling technologies for the stable operation and protection of final cooling solenoids. Investigation of combining fast-ramping and stability, for example by using materials that switch between resistive and conductive behavior as a function of temperature or of electric field. Develop diagnostics to detect and localize electro-thermal instabilities.

Who: J. Kosse (PSI), B. Auchmann (PSI), PhD student
When: end 2023 - end 2026

- SO'TON – R&D pancakes manufacturing with insulation/potting technology as tested in EuCARD2

Who: Y. Tang (SO'TON)
When: TBD

- CEA/LNCMI – Testing of small R&D pancakes in background field (20 T, 120 mm maximum)

Who: X. Chaud (LNCMI), L. Quettier (CEA)
When: TBD

- Testing of small R&D pancakes in background field (10 T, 100 mm maximum) at variable temperature in gaseous helium, for currents up to 1500 A

Who: Y. Tang (SO'TON)

When: first tests mid 2024

Task 2.3 – Design of 6D cooling solenoids (INFN, CERN)

- Define performance specifications (beam physics). Initiate meetings with beam/shield/absorber/cryo/vacuum on magnet specifications and accelerator configuration

Who: S. Fabbri (CERN), L. Bottura (CERN), M. Statera (INFN)
When: first version September 2023; draft final version September 2025; final version September 2026

- Conceptual design of 6D cooling solenoids

Who: S. Fabbri (CERN), J. Pavan (INFN)
When: first concept consolidated September 2023; final concept September 2025

- Participation in the engineering design of the solenoids for the demonstrator.

Who: TBD
When: TBD

- Engineering design of the most challenging cooling solenoid system. Design the electromagnetics, mechanics, protection and cooling of the solenoid magnets of the cell B8 of the present baseline. This work is a magnet benchmark study, and does not contain the integration in a cooling cell, as done for the demonstrator. Results and specific solutions are however shared with the integration and demonstrator work

Who: J.P. Rigla Perez (UPV), J. Benlloch Baviera (UPV)
When: TBD

Task 2.4 – Design of HTS options for target solenoid (all-SC or SC/NC) (CERN, F4E)

- Magnetic design of solenoid channel alternatives (field profile, aperture, integration of target and shield) in meetings with beam/shield/target/cryo/vacuum on magnet specifications and accelerator configuration. Electromagnetics, mechanics, margin and protection, cooling and cryogenic calculations. Integration

Who: L. Bottura(CERN), C. Accettura(CERN), A. Kolehmainen(CERN), A. Portone (F4E), J. Lorenzo Gomez (F4E), P. Testoni (F4E)
When: first version June 2023; draft final version September 2025; final version September 2026

Task 3 – Accelerator complex (CERN, UNIBO, TUDa, TWENTE, LNCMI)

Scope of work: integrated magnet and powering study for the Rapid Cycling Synchrotrons. Focus is on the resistive dipole magnets and their power converters, including efficient energy storage and management of large power. Basic concept considerations and study of options for the superconducting steady dipoles (no complete design).

Task 3.1 - Resistive fast pulsed magnets (CERN, UNIBO, TUDa, LNCMI)

- Optimal design of resistive dipoles and quadrupole with emphasis on minimization of energy content (UNIBO). Simplified analytical magnet models including nonlinear magnetic effects, losses, energy and thermal computation, to be used for global powering-magnet optimized design

Who: P.L. Ribani (UNIBO), M. Breschi (UNIBO), R. Micelli (UNIBO)
When: first version June 2023; draft final version September 2025; final study results September 2026

- Analysis of magnet optimized designs with 2D and 3D time dependent FEM simulations. These models will focus on most promising design options and address important calculations as losses, field quality, electrodynamic effects, saturation effects etc…

Who: H. De Gersem (TUDa)
When: first version end 2023; updated version end 2024; final study results September 2026

- Integrated power system / magnets optimization to minimize the total power requirements / cost and land occupation (CERN, LNCMI). Evaluation of different powering concepts based on full wave and/or switched resonance.

Who: F. Boattini (CERN), J. Beard (LNCMI)
When: first version mid 2024; updated version mid 2025; final study results September 2026

- Cost and power estimate

Who: F. Boattini (CERN), M. Breschi (UNIBO), H. De Gersem (TUDa), L. Bottura (CERN), S. Fabbri (CERN), L. Quettier (CEA)
When: draft version June 2025; final version June 2027

Task 3.2 - Superconducting magnets (CERN, UNIBO, TWENTE)

- Study suitable geometries and materials for fields in the hypothesis of magnetic fields in the range of 8…10T. Look at impact on accelerator layout (e.g. limiting maximum to 8 T), aperture and winding options (e.g. rectangular vs. round aperture). Basic 2D electromagnetic design

Who: L. Bottura (CERN), S. Fabbri, M. Breschi (UNIBO)
When: first version end 2023; updated version end 2024; final study results September 2026

- Study HTS option for fast pulsed dipoles, scoping studies for dB/dt in the range of 300T/s and Bgap > 2T (U-TWENTE, FNAL potential cooperation)

Who: A. Kario (TWENTE), H. Piekarz (FNAL)
When: study completed by mid 2024

Task 4 – Collider complex (INFN, CERN, TUT)

Scope of work: Design of LTS/HTS option for collider magnets for the 3 TeV and 10 TeV configurations. The two studies are considered independent as e expect to find different magnet solutions for the two energies. NOTE: use results from HFM dipole design for technology selection and design assumptions.

- Set performance specifications (Physical Aperture, Dipole Field, Quadrupole Field, Tunability of Quadrupole Component, Field quality) in meetings with beam/shield/cryo/vacuum on radial build, magnet specifications and accelerator configuration

Who: S. Mariotto (INFN), B. Caiffi (INFN), L. Bottura (CERN), S. Fabbri (CERN)
When: first version June 2023; draft final version September 2023; final version December 2023

- Setup analytic expressions for fast evaluation of magnet parameters (main field component, peak field, field errors, forces, stresses, protection). Analytic study of field vs. aperture, and relative weight of a combined function magnet

Who: D. Novelli (INFN), S. Mariotto (INFN), B. Caiffi (INFN), S. Farinon (INFN), T. Salmi (TUT)
When: first version June 2023; draft final version December 2023; final version June 2024

- Basic decisions and technology selection
    - Select the material of the conductor (Nb3Sn, HTS, Hybrid) for the ARC and IR magnets
    - Conductor configuration, margin and protection
    - Open midplane
    - Operating temperature
    - LTS/HTS

Who: S. Mariotto (INFN), D. Novelli (INFN), B. Caiffi (INFN), S. Farinon (INFN), T. Salmi (TUT), L. Bottura (CERN), S. Fabbri (CERN)
When: tentative version June 2024; final version and concept selection review December 2024

- Dipole magnet design
    - Select layout of the coil (Block, CosTheta) for the ARC (and IR magnets)
    - Select Nested/Asymmetric Coil for the ARC Magnets
    - Create a 2D optimized magnet cross-section (Roxie, Ansys)
    - Mechanical calculations
    - Margin and protection calculations
    - Cooling and cryogenics concept

Who: S. Mariotto (INFN), D. Novelli (INFN), B. Caiffi (INFN), S. Farinon (INFN), T. Salmi (TUT)
When: starting January 2025; final version June 2027

- Cost and power estimate

Who: S. Mariotto (INFN), D. Novelli (INFN), B. Caiffi (INFN), S. Farinon (INFN), T. Salmi (TUT), L. Bottura (CERN), S. Fabbri (CERN), L. Quettier (CEA)
When: draft version June 2025; final version June 2027