EP R&D Day

Work Package 8
Detector Magnets

Benoit CURE, Matthias MENTINK

22.05.2024

Outline

1. Scope of WP8
2. Members of the team
3. Summary of activities 2020-2023 (*)
4. Motivations for WP8 extension beyond 2023
5. Status and plans for 2024-2028

(*) Details and publication references are available in the EP R&D annual reports:
CERN Document Server, EP R&D Programme on Technologies for Future Experiments
https://ep-dep.web.cern.ch/scientific-activities

Scope of Work Package 8

Main objectives:

- Support the CERN's expertise on detector magnets,
- Explore the technologies relevant for future detector magnets (ECFA roadmap),
- Build scalable prototypes.

R&D areas:

1. Advanced magnet powering for high-stored energy detector magnets,
2. Aluminium-stabilized reinforced superconductors,
3. Demonstrator magnets,
4. Magnet controls and instrumentation.

WP8 team

Members of the team over 2020-2024 :

Fellows: Shuvay Singh, Anna Vaskuri, Eino Tiirinen;

Doctoral Student: Weronika Głuchowska;

Technical Students: Filip Malinowski, Michela Neroni, Weronika Głuchowska, Robert Jurco, Michal Sajdak;

Interns: Tonke Boelens, Pieter Kruyt, Dennis Klaassen, Jeop Van Den Eijnden, Gerrit Flier, Veerle Ellenbroek, Jurriaan Bruggeman, Nathan Arpin, Thijs Beene, Thomas Hanhart;

Staff: Philippe Benoit, Benoit Cure, Alexey Dudarev, Matthias Mentink, Nicola Pacifico;

Atlas Magnet Team Fellow: Nikkie Deelen, Jasper Van der Werf.

And the much-appreciated support of: EP-DT, EN-MME and TE-CRG teams, and CERN Service Groups.

Summary of activities 2020-2023

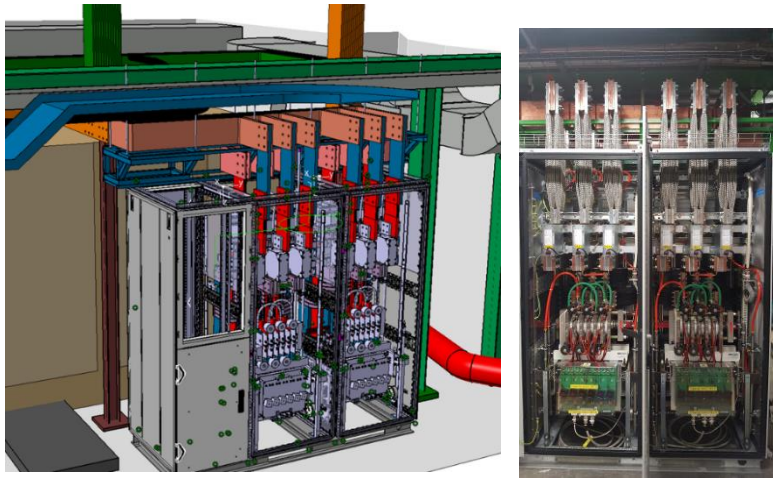
WP8.1 Advanced magnet powering for high-stored energy detector magnets

Completed activities :

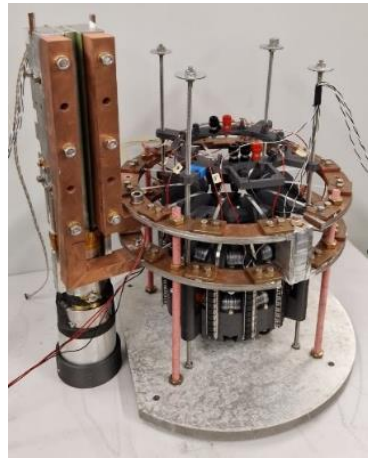
Development of systems for experimental facilities, and demonstrator:

- Implementation of snubber on Atlas Barrel Toroid powering circuit,
- Commissioning of CMS free wheel system,
- Design, assembly & test of flux pump demonstrator: rectified current up to 1kA at 77K.

Atlas-Toroid snubber (2020-2021)



CMS Free Wheel Thyristor (2021)



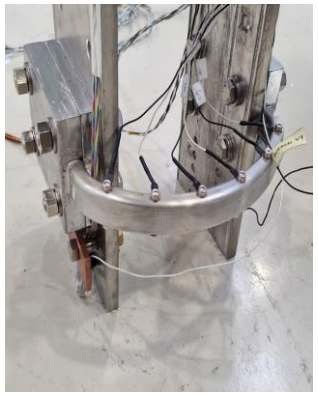
HTS flux pump (2022-2023)

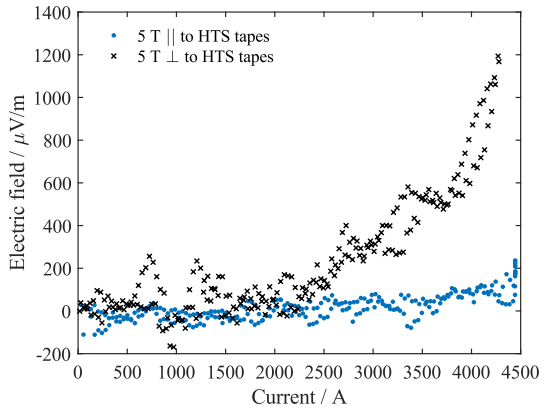
WP8.1 Advanced magnet powering for high-stored energy detector magnets

Completed activities :

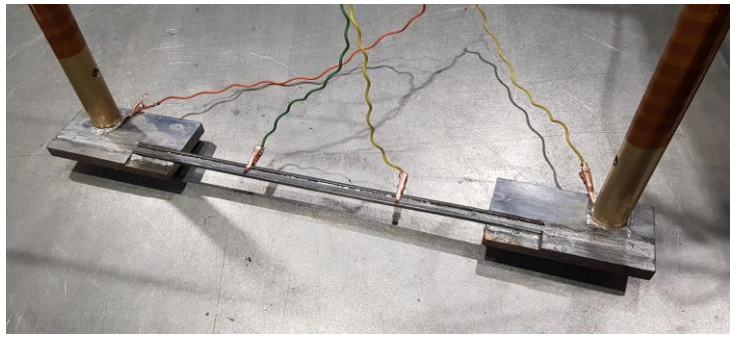
High Temperature Superconductor studies:

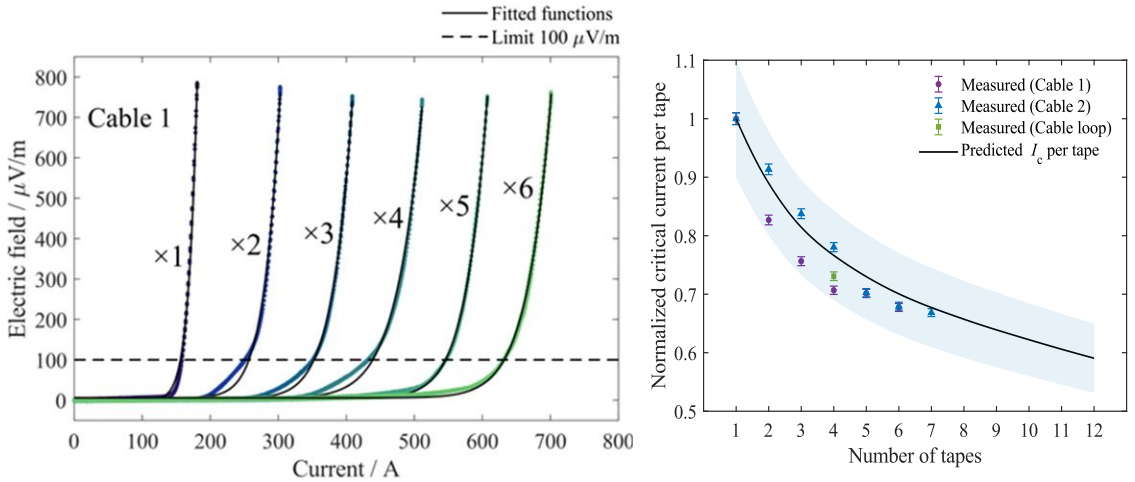
- Modelling and test of stacks of REBCO tapes,
- Test of aluminium stabilized HTS.





R&D on HTS-based aluminium-stabilized conductor with background field up to 5 T at 4.2K (2022-2023)



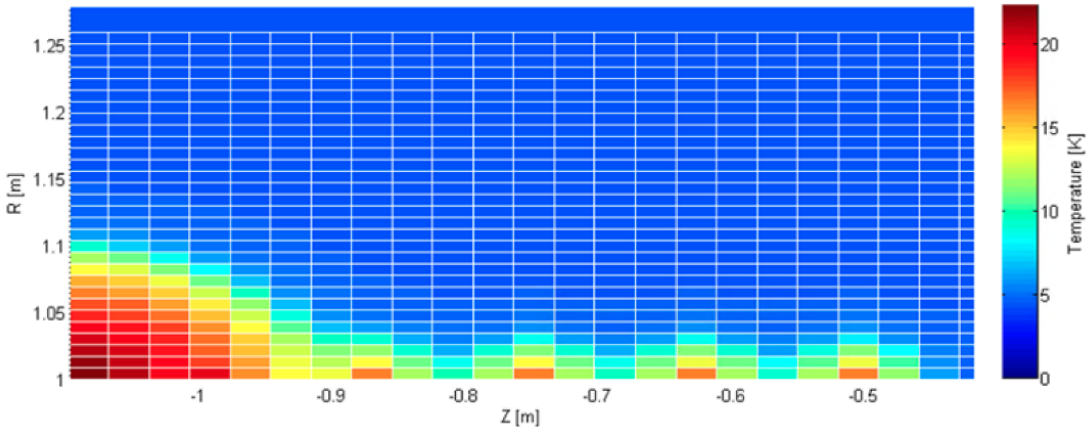


Critical current at 77K of REBCO tape stacks (2022-2023)

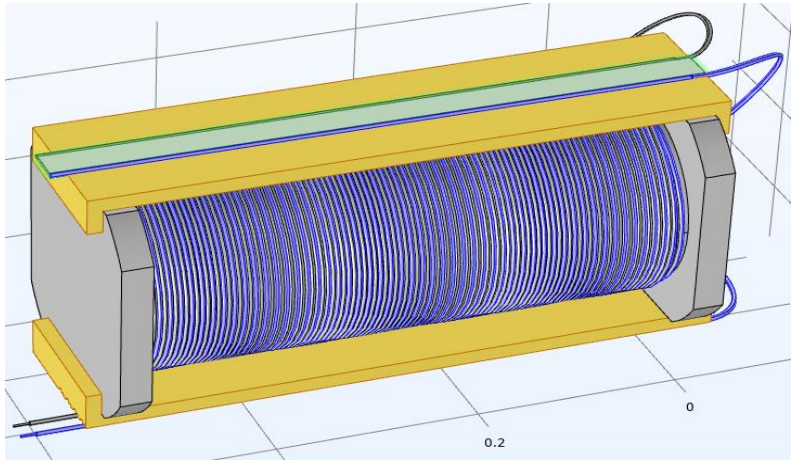
WP8.1 Advanced magnet powering for high-stored energy detector magnets

Other completed studies :

- Quench protection and modelling, applied to the 4-T magnet studies,
- Persistent mode current switch.

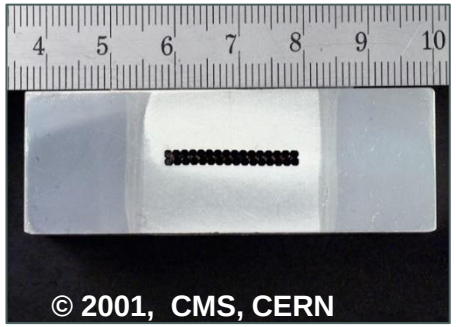


Quench propagation in a coil + quench heaters, in the longitudinal cross section (2020)



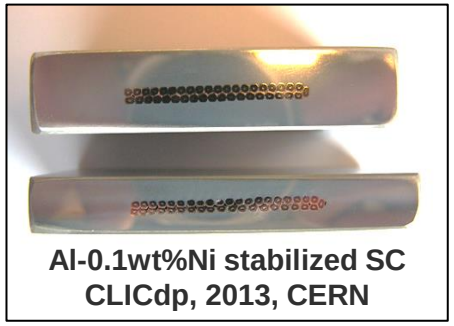
Design of a persistent current mode switch, with Nb-Ti/Cu-Ni (2020)

WP8.2 Aluminium-stabilized reinforced superconductors



- Proposed in 2019 for the onset of the EP R&D program,
- Delayed for budget reasons, due to expected costs of prototyping,
- Re-activated in 2023 (following the Superconducting Detector Magnet Workshop, Sept 2022, CERN):

  Commercial availability of coextrusion for Al-stab SC identified is critical.


Al-0.1wt%Ni stabilized SC
CLICdp, 2013, CERN

In 2023:

- ✓ Re-definition of scope,
- ✓ Identification of industrial partners (CERN ILOs + Request for Interest through IPT).

Support for WP8.2 from :

- ➢ **New AT-RC Sectors joint Committee for Experiment Magnets** set up at CERN in 2023,
- ➢ **Dedicated Working Group :** CERN (EP, EN, TE) and KEK experts.

WP8.2 Aluminium-stabilized reinforced superconductors

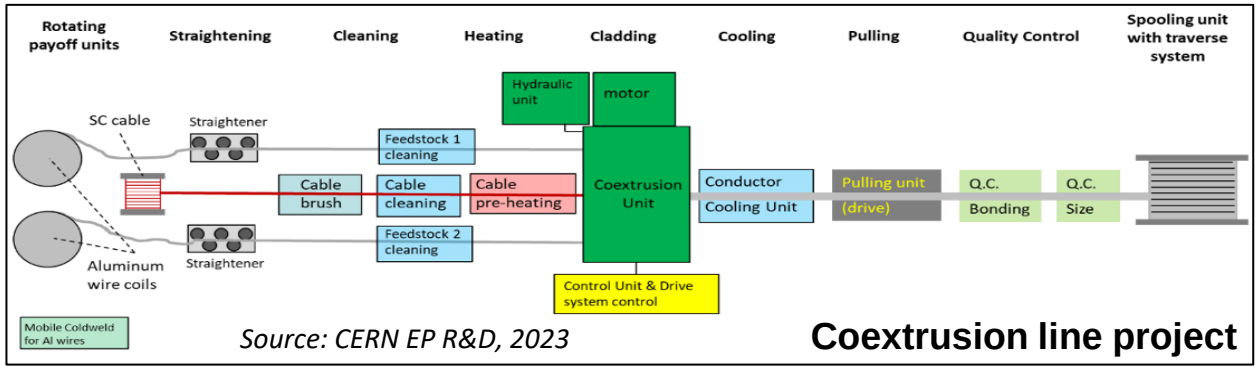
Objective:

Restoring industrial availability of Aluminium-stabilized coextruded superconductors:

- to maintain R&D and production capacity widely available in the future,
- not only relying on one supplier for coextrusion for future R&D and production.

Scope:

Produce demonstrator lengths in view of scaling up to production for future detector magnet conductors.



Source: CERN EP R&D, 2023

Coextrusion line project

Set up a coextrusion + coldwork line to perform

1. R&D with LTS (and HTS),
2. Production of demonstrator lengths,
3. Future production of superconductors.

Establish a sustainable solution

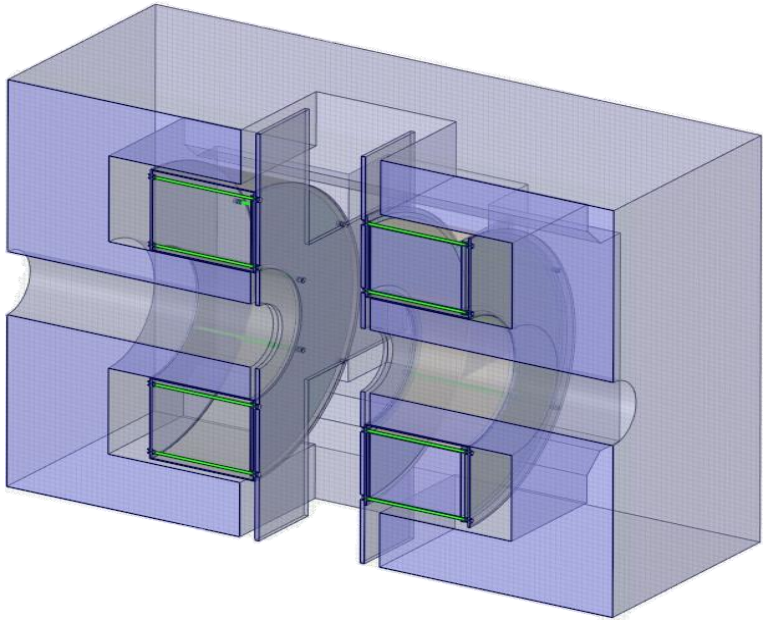
1. For future needs,
2. With industrial partner,
3. Internalization in a lab. as an option.

WP8.3 Demonstrator magnets

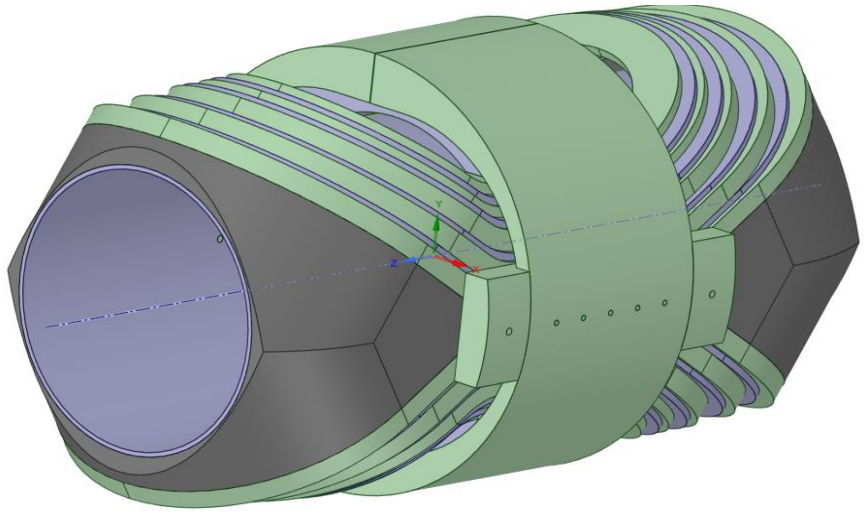
Completed activity:

Conceptual design of a large bore (1m) 4-T magnet for a test beam facility.

- ✓ Two concepts developed: a Spit Coil Solenoid and a Dipole



4 T superconducting split-coil solenoid conceptual design



“Magnadon” preliminary conceptual design of a 4 T superconducting dipole

WP8.3 Demonstrator magnets

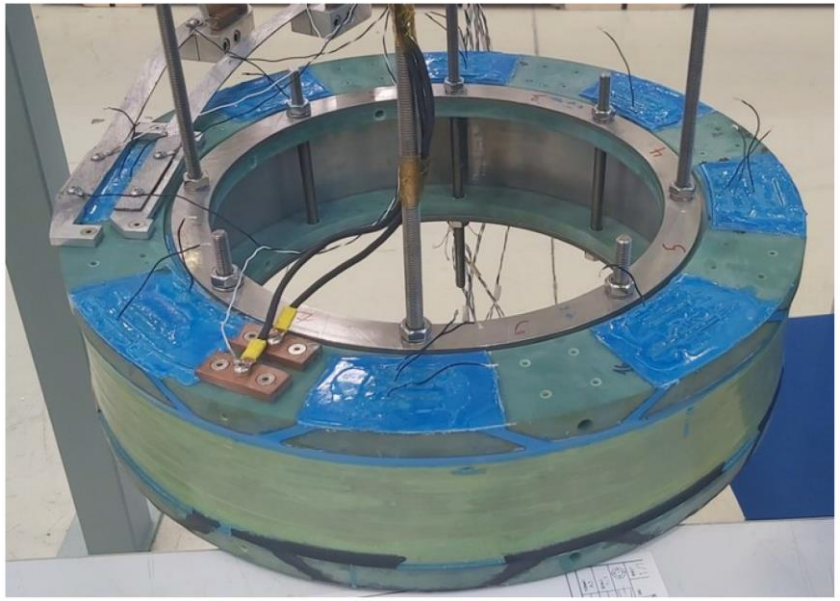
Completed activities:

Design and construction of a prototype to validate a novel co-wound coil concept :

- Featuring interleaved layers of insulated superconducting (Nb-Ti/Cu) and insulated normal-conducting copper strands,
- Demonstrator coil design and winding completed in 2023 (special thanks to Francois Garnier and EP-DT colleagues).

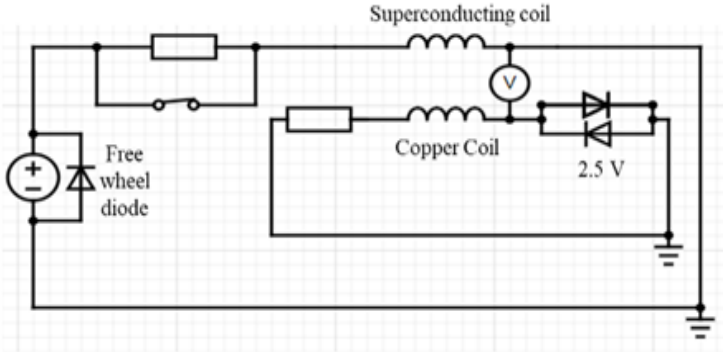
First demonstration test expected in the coming months:

- Intrinsic suppression of inductive noise, high-sensitivity and low-complexity quench detection,
- Lowering voltage and hot spot temperature during quench.



Co-wound Cu-stab LTS Demo coils (2023)

Winding done at CERN by EP-DT team



Co-winding concept (2023)

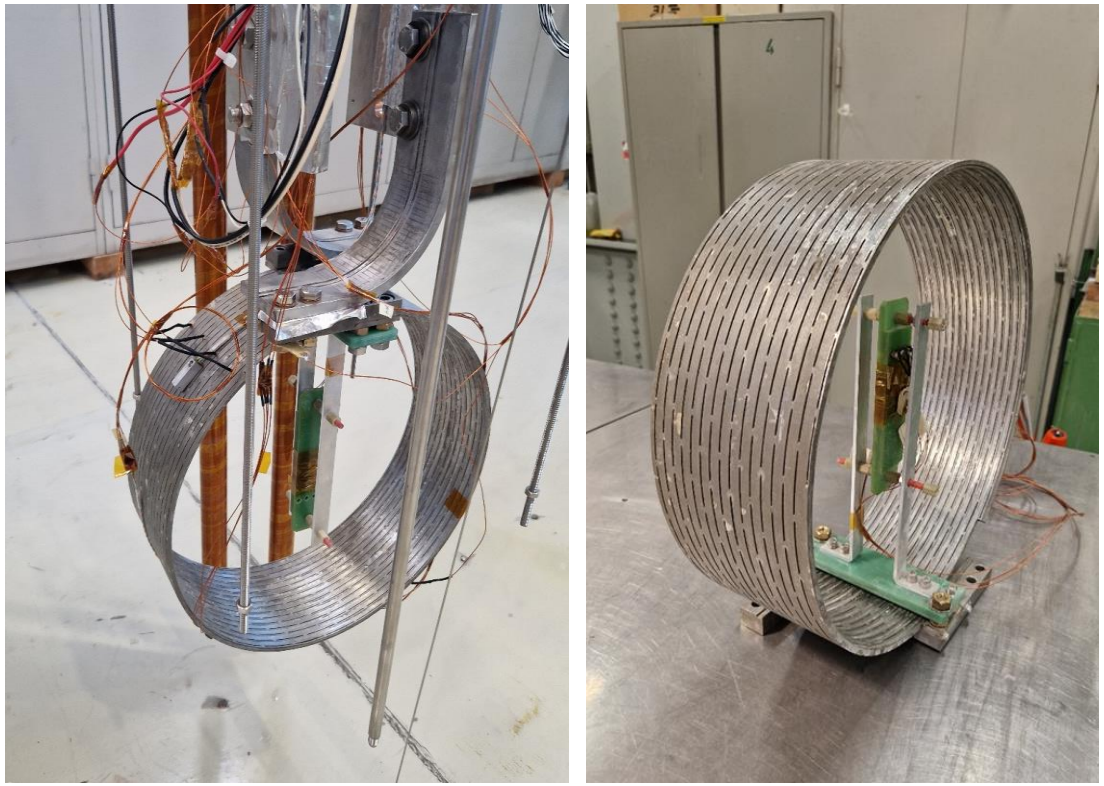
WP8.3 Demonstrator magnets

Completed activities:

Design, construction and test of aluminium stabilized self-protected HTS coils:

- 3D-printed aluminium alloy and Cu&Sn-electroplated cylindrical support,
- stack of 4 REBCO tapes,
- Successfully tested up to 4.4kA at 30K (1.2kA at 77K),
- Stability validated against local quench.

Poster session



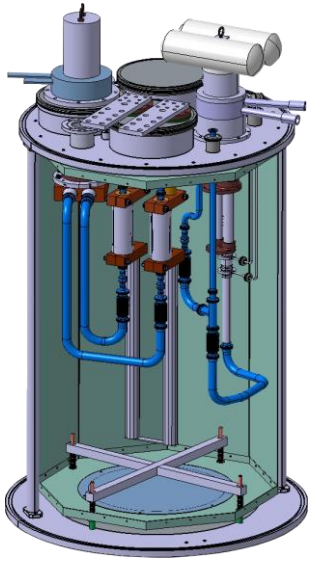
Al-stab. HTS Demo coils (2023)

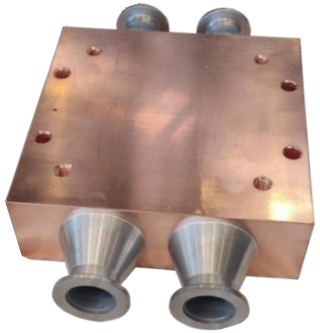
WP8.4 Magnet controls and instrumentation

Completed activities:

- New test facility designed & assembled (4.4K, up to 4.5kA, 5T, Ø200mm bore),
- Design & tests of N_2 boiling thermosiphons for hybrid current lead cooling,
- Design of cryocooler-based remote cooling for HTS hybrid current leads.

Poster session





HTS current lead cooling test setup and heat exchangers(2023)

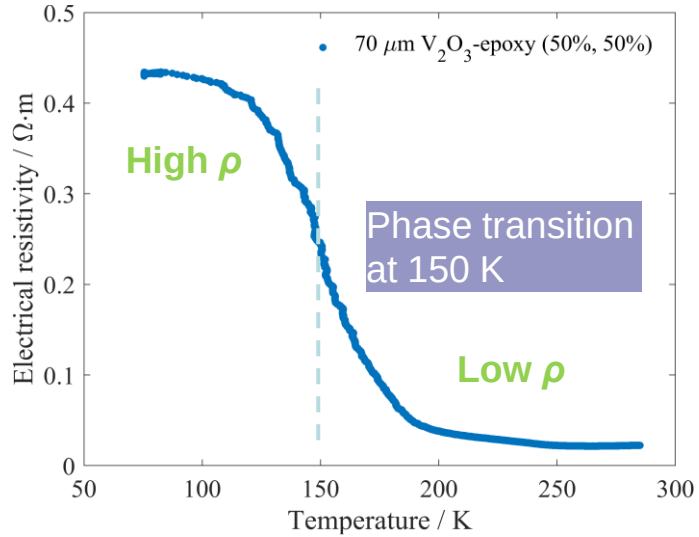
Test facility (2022) with Control System provided by EP-DT

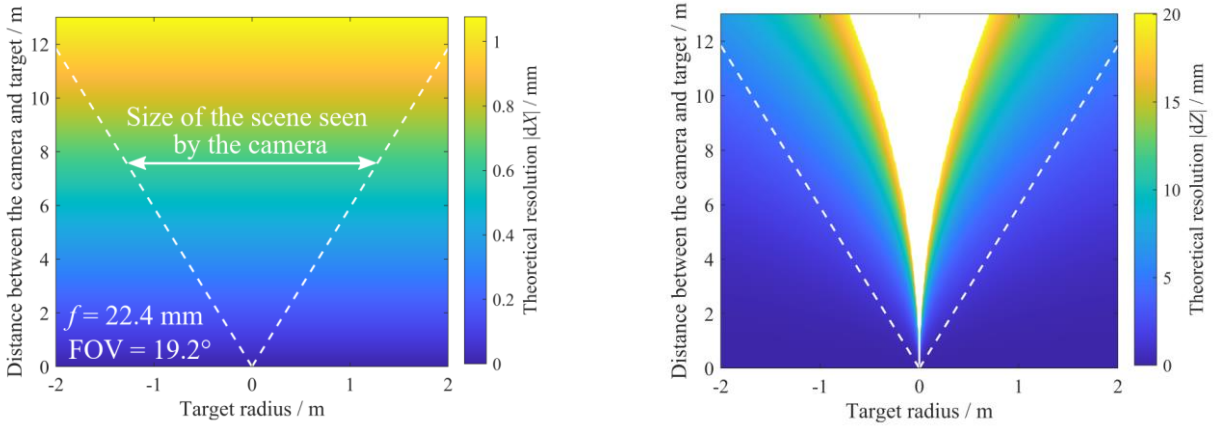
Insert with a 5T magnet for the new test facility (2022)

WP8.4 Magnet controls and instrumentation

Other completed activities:

- Study of an innovative insulation system for HTS coils using V_2O_3 epoxy composite (insulator to metal phase transition at ~150K),
- Study of stability at 77K of 3-D printed plastics materials,
- Study of applicability of optical positioning systems for field mapping versus encoder-based systems.





Optical position mapping: photogrammetry with one camera and time-of-flight laser distance meter in Z

3D-printed part using carbon-fiber reinforced PET-G (PolyEthylene Terephthalate Glycol)

Motivations for WP8 extension beyond 2023

The 2021 ECFA Detector Research and Development Roadmap

DRDT 8.1: ***Develop Novel Magnet Systems –***

Summary of the key technologies needed, as listed in the ECFA report :

Magnets for collider experiments:

- Development of next generation of **Al-stabilized high-yield strength Rutherford cable superconductors** and prototyping for 30-40 kA large coils placed behind calorimeters.
- **R&D on conductors and prototyping for thin conductors Al/Cu/NbTi** for small coils placed in front of the calorimeters.
- Long term: development **of high temperature superconductors for coils and current leads**.
- **R&D for assemblies** with dual solenoids for magnetic shielding.

Magnet for non-collider experiments:

- large volume magnets for axion searches […], *and high field*

Development of quench protection, energy extraction and high voltage designs for coils with high energy/mass ratios is also needed.

Integration (Task Force 8)
Magnet requirements are very specific to the design of the detector. Considering the very long lead time, generic R&D programmes must be established and maintained on dedicated conductors and prototyping to achieve the variety of magnet specifications.

Conclusions of the Superconducting Detector Magnet Workshop-2022

What we need to resume / do next ?

Investigate multiple approaches for Al-stabilized SC

- Cooperation with industry
  - NbTi/Cu cable, Al-co-extrusion, Assembly with Al-reinforcement
  - Cost-effective approach need to be seriously investigated
- **Laboratory own effort**, in particular on
  - **Al-coextrusion facility and own R&D for leading technology advances**

Seek for common SC and magnet design concept, even part, for cost-effective development,

Seek for worldwide cooperation among laboratories and industry

Context

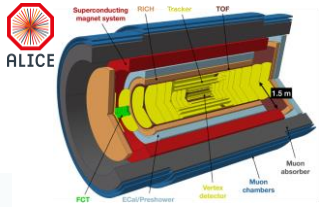
Future Physics Experiments anticipated :

- **Colliders:**

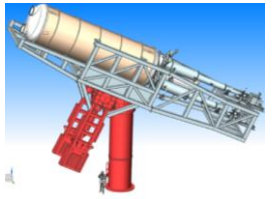
  Alice3 (CERN), FCC-ee -hh –he (CERN), CLIC(CERN), Muon Collider (CERN), ILC (IDR,SLAC), CEPC (IHEP), Panda (GSI/Fair), EIC(BNL, J-Lab).

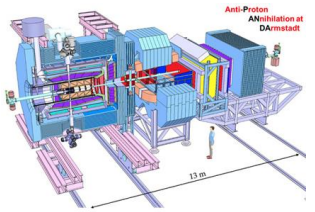
- **Non-Colliders:**

  BabyIaxo (Desy), SHiP (CERN), Muon Beam Experiments (Comet-KEK, Mu2e-Fermilab), MadMax (Desy), AMS100 (RWTHAAchen)



Alice-3


BabyIAXO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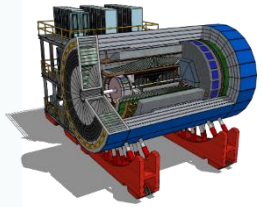
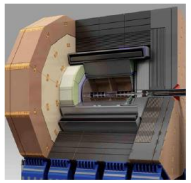
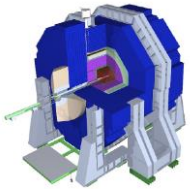
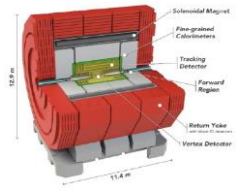

EIC


ILC-ILD


ILC-SiD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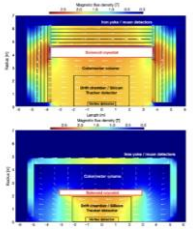
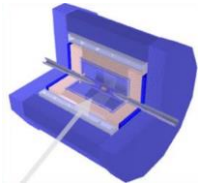
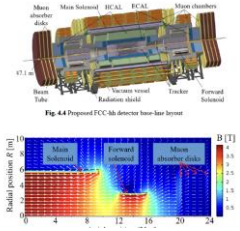
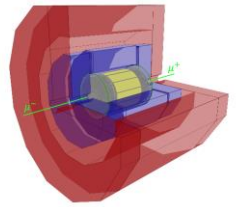
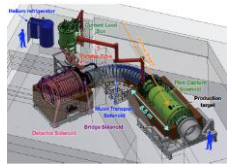

FCC-ee

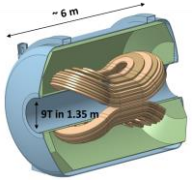

CPEC


FCC-hh

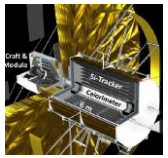

iMuC


Comet


Mu2e



MadMax

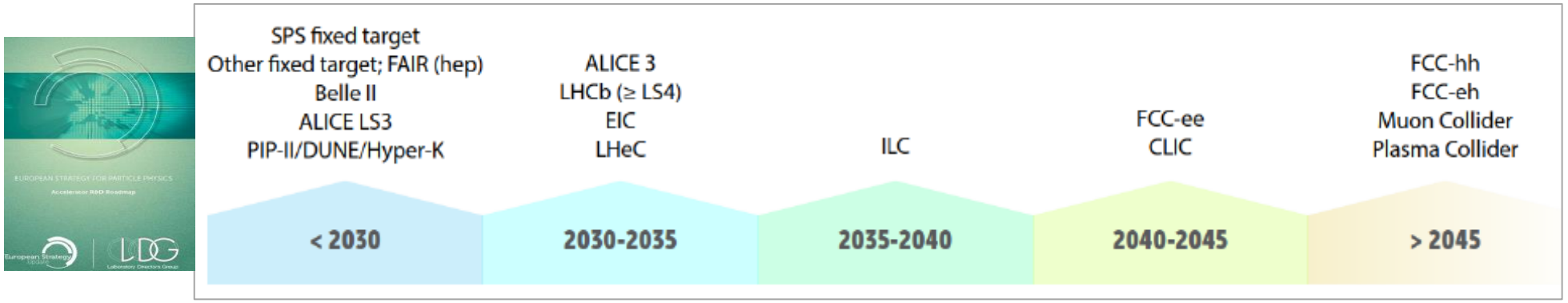

AMS100

More than 15 projects with SC magnets

either:
- Under construction,
- Design phase,
- Conceptual phase.

Mainly Alu-stabilized superconductors.

Timeline of High Energy Physics projects



Future proposed particle physics experiments being studied: from LDG Accelerator R&D Report, CERN 2022-001

DRDT 8.1: *Develop Novel Magnet Systems*

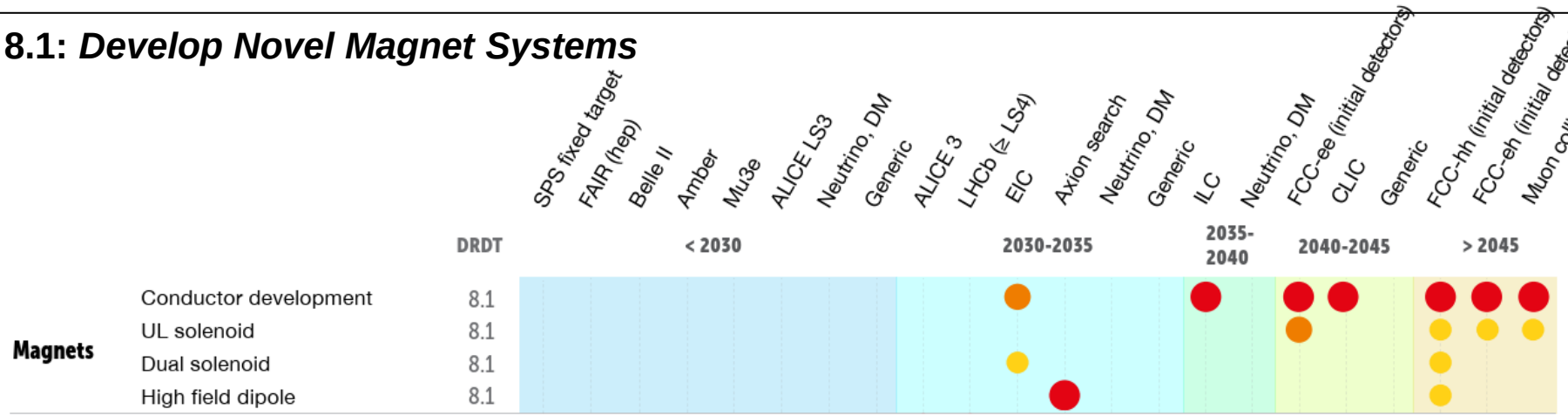


Figure 8.1: Schematic timeline of categories of diverse R&D topics [...]

Status and plans for 2024-2028

Status and plans for 2024-2028

Keep same WP8 sub-work packages,

Building on the 1st phase of the program 2020-2023.

WP8.1 - Advanced magnet powering for high-stored energy detector magnets

WP8.2 - Aluminum-stabilized reinforced superconductors

WP8.3 - Demonstrator magnets

WP8.4 - Magnet controls and instrumentation

WP8.1 Advanced magnet powering for high-stored energy detector magnets

Objectives:

Study and develop powering systems based on HTS for detector magnets, to improve cost-efficiency and sustainability with reduced energy consumption.

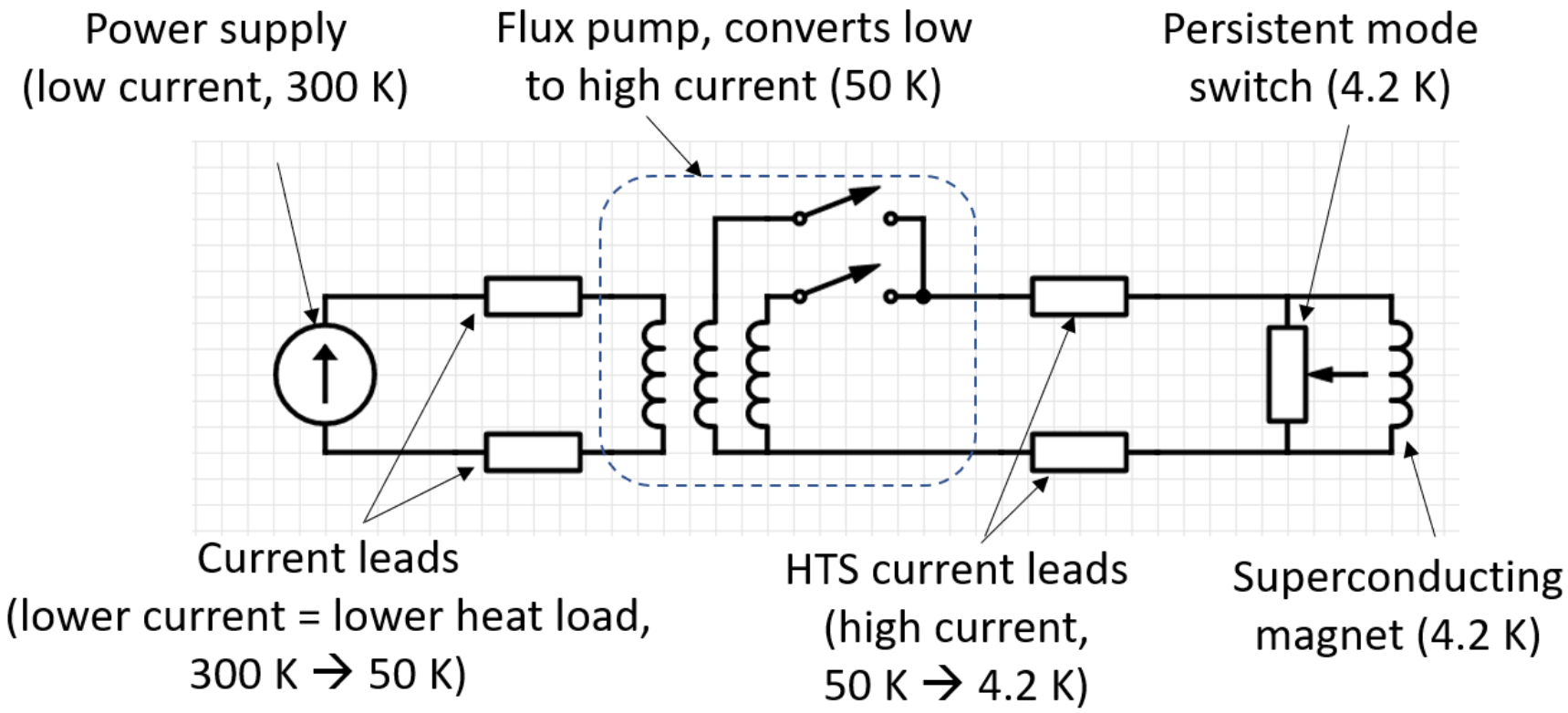
- Study power distribution and converter technologies giving minimal cryogenic heat load,

  moving beyond the present state-of-the-art for superconducting detector magnets,

- Develop HTS-based aluminium-stabilized conductors for busbars connecting coils, but also for the coils themselves.

  Advantage: HTS allows for much higher operating temperature (= lower cryogenic cost) and higher magnetic fields in the bore, albeit presently at higher capital cost for the conductor itself.

WP8.1 Advanced magnet powering for high-stored energy detector magnets



Powering Circuit optimum configuration

WP8.1 Advanced magnet powering for high-stored energy detector magnets

Work plan 2024-2028

Year	Deliverable
1	HTS conductor and current lead demonstrators
2	Powering systems for a test facility (5kA): HTS flux Pump and HTS switch prototypes design and test.
3	HTS powering system demonstrator: prototype design.
4	HTS powering system demonstrator test.
5	Study for a large-scale magnet application.

WP8.2 Aluminium-stabilized reinforced superconductors

Objectives:

- Re-establishing manufacturing of aluminium stabilized LTS (Nb-Ti) superconductors,
  - by setting up a **co-extrusion and coldwork** facility,
  - to perform **prototyping with demo conductor** lengths, and R&D for on-going projects.
- Perform further developments of this technology with HTS conductors.

First part of the work plan:

- Place a contract to industry to produce demonstrator lengths.
  - Using a **facility available now in industry,**
  - Qualification done with sample testing at CERN with **EN & TE Dpts expertise and support**,
  - Benefit from available **expertise within the WG.**
  - **Gain knowledge** through this exercise.
- **On-going,** aiming at placing a contract second half 2024.

WP8.2 Aluminium-stabilized reinforced superconductors

Second part of the work plan (launched in parallel to the 1st one):

- Build a new facility with an industrial partner aiming at a sustainable solution
  - **Business case** to be validated first by industry (production volume low if only detector magnets; cable market is highly competitive); **study on-going.**
  - **Either in industry** with support from institute(s), **or in an institute** with industrial support (retaining the possibility of internalization if the industrial partner decides to withdraw).
- Large budget required, including availability of a manufacturing hall, investment in equipment and associated infrastructure, trained staff, etc.

  Requires funds external to the EP R&D WP8 budget.
- Such a facility will offer as well the possibility to :
  1. Extend the R&D to **coextruded Al-stabilized HTS**: BSCCO, MgB2, (etc.) in various configurations,
  2. Develop, and potentially produce, with **dedicated funds**, final conductors for projects.

WP8.2 Aluminium-stabilized reinforced superconductors

Work plan 2024-2028

Year	Deliverable
1	First coextrusion tests with dummy conductor. Sample testing at CERN. Study on installing a dedicated line (external funds).
2	Second coextrusion test series with dummy and/or real Rutherford cable, and cold work tests using short lengths. Sample testing at CERN.
3	Manufacturing of trial lengths with coextrusion and coldwork lines. Quality control testing on samples at CERN.
4	Coextrusion and coldwork of conductor demonstrator. Quality control testing on samples at CERN.
5	Long length prototype manufacturing and reporting. Sample testing at CERN.

WP8.3 Demonstrator magnets

Objectives:

Develop and keep expertise in-house on LTS and HTS magnet design and assembly, covering various fields such as mechanics, integration, winding, splices, protection, powering, cryogenics, vacuum vessel, quench detection and protection.

Demonstrate new technologies through:

- Study and construction of demonstrator magnets,
- Comprehensive effort, from conductor to vacuum vessel,
- Small and cost-effective coils, allowing step-by-step design and trials,
- Novel method for simplified quench detection and significantly reducing voltage during a quench, applicable for both LTS and HTS.

WP8.3 Demonstrator magnets

Work plan 2024-2028

- Test the co-wound demonstrator coil,
- Extend the concept(s) to novel HTS demo coils.

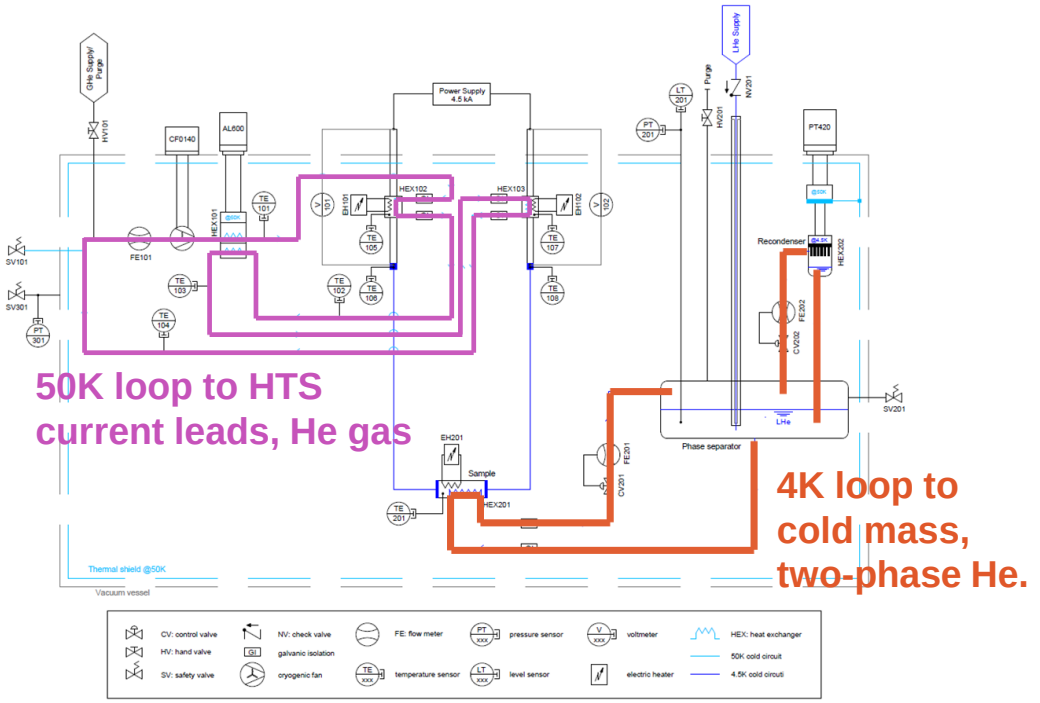
Year	Deliverable
1	Modelling of demonstrator coils, technical report. Coil winding (NbTi and HTS).
2	Preliminary test report and final specifications.
3	Demonstrators testing and reporting.
4	Study for large scale magnet application and report.

WP8.4 Magnet controls and instrumentation

Objectives:

Design and assembly of specific instrumentation and test setups for the studies on HTS superconducting Al-stabilized cables and coils performed in the other WP8 sub-workpackages.

- **A cryocooler facility** to test hybrid current leads cooling and thermosiphon cooling.
- **An HTS test setup** will be developed with anti-Dewar to test up to 70K with background magnetic field up to 5 T.
- **Specific PID control** will be developed and installed with the support of the EP-DT-DI team.



Remote and thermosiphon cooling with cryocoolers
Courtesy W. Gluchowska et al. (2024)

WP8.4 Magnet controls and instrumentation

Work plan 2024-2028

Year	Deliverable
1	HTS test setup development. Technical specification and report.
2	Cryocooler installation with instrumentation.
3	Simulation and validation tests, report.
4	Final report.

Summary

EP R&D WP8 Program Proposal 2024-2028

- WP8.1: Advanced Magnet Powering for high-stored energy detector magnets

  → For reduced power consumption and sustainable science

- WP8.2: Aluminum-stabilized (reinforced) conductor technology

  → Enables SC technology for future superconducting detector magnet projects

- WP8.4: Demonstrator magnets, to demonstrate technology for future superconducting detector magnets

  → Allows to demonstrate new technologies developed in the context of EP R&D

- WP8.5: Magnet controls and instrumentation

  → Expand the use of cryocooler with novel approaches, and support activities of sub-WPs 8.1, 8.2, and 8.3.

Thank you for your attention ☺

Backup Slides

Conclusions of the Superconducting Detector Magnet Workshop-2022

Outlook:

- Al-stabilized superconductor/magnet technology needs to be resumed,
- Industrial cooperation to be anticipated and strongly encouraged, in particular,
  - "Co-extrusion technology" of Al-stabilizer and NbTi/Cu-conductor to be resumed and widely available, and
  - "Hybrid-structure technology" by using electron beam welding (EBW) or by other approaches, to maximize the performance of Al-stabilized SC (Ni or Cu/Mg doped) combined with ultimately high-strength Al-alloy structure.
- **Laboratory's leading effort will be very important to advance the technology to be openly transferred to the industry.**

Remarks:

- It will be **also important** to investigate/seek for backup solutions such as soldering technology of NbTi/Cu conductor with Cu stabilizer, Cu-coated Al-stabilizer, and/or CICC.
- In long-term future, Al-stabilized HTS will provide important potential in specific detector magnet applications.

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