Accelerator R&D Roadmap

High Field Magnet
R&D Roadmap
Status

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on behalf of HFM Expert Panel

Accelerator R&D Roadmap Planning: Process and Remit

As an outcome of the European Strategy for Particle Physics 2020, CERN Council has mandated the Laboratory Directors Group (LDG) to define and maintain a prioritized accelerator R&D roadmap towards future large-scale facilities for particle physics.

The roadmap should define a route towards implementation of the scientific goals of the European Strategy, bringing together the capabilities of CERN, large particle physics laboratories, and other institutes, to carry out R&D and the construction and operation of demonstrators.

The European Strategy highlights five key areas where progress in R&D is needed:

- High-field magnets, including use of high-temperature superconductors
- High-gradient acceleration (plasma / laser)
- High-gradient RF structures and systems
- Bright muon beams and muon colliders
- Energy-recovery linacs

The initial phase of this process is to define the R&D roadmap through the work of expert panels (EP) drawn from the European and international community.

HFM Expert Panel (13 experts)

- Pierre Vedrine, IRFU, chair
- Luis Garcia-Tabares Rodriguez, CIEMAT, co-chair

- Bernhard Auchmann, PSI
- Amalia Ballarino, CERN
- Bertrand Baudouy, CEA
- Luca Bottura, CERN
- Philippe Fazilleau, CEA
- Matthias Noe, KIT
- Soren Prestemon, LBNL, US MDP program
- Etienne Rochepault, CEA
- Lucio Rossi, INFN
- Carmine Senatore, Uni Genève
- Ben Shepherd, STFC Daresbury

Development of High Field Magnets : scope and challenges

SCOPE

- Establish the R&D needs to demonstrate Nb3Sn magnet technology for large sacle deployment, pushing it to its practical limits both in terms of maximum performance as well as production scale
    - Demonstrate Nb3Sn full potential in terms of ultimate performance (target 16 T)
    - Develop Nb3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing processes and cost reduction (benchmark 12 T)
- Demonstrate suitability of HTS for accelerator magnet applications providing a proof of principle of HTS magnet technology beyond the reach of Nb3Sn (target around 20 T)
- In addition, propose collaboration schemes and options for EU investment.

GRAND CHALLENGES AND KEY ISSUES

- Need for superconductors with high engineering current density, $J_E \approx 600$ A/mm^2, appropriate to yield a compact and efficient coil design, with requirements for high mechanical strength and good tolerance to stress and strain, associated magnetization, and internal resistance, including production quality, etc..
- Need for new mechanical solutions and stress management concepts to withstand large electromagnetic forces larger by a factor 4 to 6 with respect to the one experienced by the LHC dipoles and mechanical stresses in the range of 150 to 200 MPa.
- Need for new powering systems, detection and protection methods, to handle the increase of stored energy per unit length higher than the LHC by a factor of 4 to 6, including the difference of behavior between LTS and HTS coils.
- Need to set realistic cost targets to be able to move from R&D to industrial-scale production, in order to build a future collider

Status of roadmap process

At the time of writing, we have held nine meetings of the Expert Panel. All meetings are collected under an indico category (material presented and minutes): https://indico.cern.ch/category/13420/.

The main outcome of the meetings is the definition of structure and content of the roadmap report, and initial structure of the report which is in the drafting phase.

Two open international workshops were organized by the Expert Panel and held virtually. Details on the workshops can be found at:

- "HFM State-of-the-Art" (SoftA workshop) took place April 14-16, 2021: https://indico.cern.ch/event/1012691/
- "HFM Roadmap Preparation" (RoaP workshop) took place June 1&3, 2021: https://indico.cern.ch/event/1032199/

The workshops included :

- an expert evaluation of the state of the art in HFM for accelerators,
- topical reviews and technical roadmaps, and
- an overview of the strategic positioning of the main EU actors, including laboratories, universities and industry.

The proceedings of the workshops constitute the main body of the wide and open consultation of the community demanded by the LDG. A report is in preparation, based on the executive summaries provided by all contributors.

INITIAL FINDINGS - 1

- **Conductors – Nb3Sn**

Nb3Sn is reaching the upper limit of performance.

Advances in composition and architecture need to be consolidated (laboratory), and made practical for large-scale production (industry), including considerations on all performance parameters (mechanics, magnetization – laboratory; homogeneity, unit length, cost – industry).

- **Conductors – HTS**

Spectacular electrical performance, the challenge is now to combine critical current with mechanical and protection properties. This may need some innovative thinking about tapes and cables (tape structuring, no transposition, no insulation), which may bring a revolution in magnet engineering

High temperature operation (20 to 65 K) is an interesting option (cryogenic efficiency, high radiation and thermal loads for muon collider), also driven for other fields (fusion and power machinery).

Industry drive for high-field performance is independent of HEP (fusion and NMR, power applications for motors and generators at 50…65 K) and cost of HTS will decrease because of substantial investment from fusion and power applications.

INITIAL FINDINGS - 2

- **Magnets Nb3Sn**

Length effects and electro-thermo-mechanics of Nb3Sn magnets are a crucial issue (11T experience), we need to find a way to address them. Model and prototypes developments need to be better integrated and supported by basic R&D. However, length effects can only be investigated with long coils.

An initial tentative to identify suitable design options for the various field levels targeted:

- 2-layer cos-theta suitable up to 12 T
- 4-layers cos-theta or blocks for the 14-16 T range
- Common coils to resolve the issue of the end (to be demonstrated)
- CCT or other stress managed concept beyond 15-16 T

A decision on a feasible, cost-effective and practical operating field will be one of the main outcomes of the development work planned in the coming years.

Industry would welcome early involvement in the R&D phase, participating in the whole process to gain early experience on a potential manufacturing phase and decrease risk. However, as for SC industry, it is unlikely that a large-scale manufacturing of HEP magnets would have direct spin-off to other fields.

INITIAL FINDINGS - 3

- **Magnets HTS**

Non Insulated/Partial Insulated conductors may be a tool to explore the technology on small scale, avoiding the burden of full magnet engineering. Besides the obvious challenges (long time constants, mechanics with current flow not well defined), the predictability of the transverse resistance is an issue

We need a focused study on what is the best HTS cable configuration for magnet applications , targeted at magnet construction (winding of the ends) and operation (transposition)

Field quality is a declared issue, but this should be revisited, possibly transferring a part of the challenges to beam dynamics, diagnostics and controls.

- **Technologies**

Running programs should be supported in priority. In particular the characterization and development of insulation systems, the development of advanced diagnostics and material analysis and multiscale and multi-physics modelling.

A prioritized program for the upgrade of test infrastructure shall be defined to accompany the needs for high field characterization of conductors and cables, and fast turnaround on magnet sub-scale and full-scale demonstrators and models.

Thermal management of high field magnets (both internal, heat transfer to coolant, and external, heat transfer to cryoplant) will require new engineering solutions that need to be integrated from the start.

Preliminary Key Questions and R&D Topics - 1

For Nb3Sn high-field accelerator magnets,

•Q1: What is the practical magnetic field reach of Nb3Sn accelerator magnets, driven by conductor performance, but bounded by mechanical and protection limits, and in particular is the target of 16 T for the ultimate performance of Nb3Sn accelerator magnets realistic ?

•Q2: Can we improve robustness of Nb3Sn magnets, reduce training, guarantee performance retention, and prevent degradation, considering the complete life cycle of the magnet, from manufacturing to operation ?

•Q3: Which mechanical design and manufacturing solutions, from basic materials, composites, structures and interfaces need to be put in place to manage forces and stresses in a high-field Nb3Sn accelerator magnet ?

•Q4: What are the design and material limits of a quenching high-field Nb3Sn magnet, and which detection and protection methods need to be put in place to remain within these limits ?

•Q5: How can we improve design and manufacturing processes of a high-field Nb3Sn accelerator magnet to reduce risk, increase efficiency and decrease cost as required by an industrial production on large scale ?

PRELIMINARY KEY QUESTIONS AND R&D TOPICS - 2

For HTS high-field accelerator magnets,

•Q6: What is the potential of HTS materials to extend the magnetic field reach of high-field accelerator magnets beyond the present and projected limits of Nb3Sn, and in particular is the target of 20 T for HTS accelerator magnets realistic ?

•Q7: Besides magnetic field reach, is HTS a suitable conductor for accelerator magnets, considering all aspects from conductor to magnet and from design to operation ?

•Q8: What engineering solutions, existing or to be developed and demonstrated, will be required to build and operate such magnets, also taking into account material availability and manufacturing cost ?

Common to Nb3Sn and HTS,

•Q9: What is the specific diagnostics, instrumentation and infrastructure required for a successful HFM R&D, taking into account present and projected needs, and aspects ranging from applied material science to production and test of superconductors, cables, models and prototype magnets ?

•Q10: What is the quantified potential of the materials and technologies that will be developed within the scope of the HFM R&D program towards other applications to science and society (medical, energy, high magnetic field science), and by which means could this potential be exploited at best ?

NEXT STEPS

- Open consultation process is now completed.
- Report writing is initiated, and the tasks are distributed among the Panel Members (see next slide).
- We expect to have 4…6 more meetings of the Expert Panel in the coming 3 months to define the prioritized roadmap.
- A panel-only workshop is planned for Roadmap Implementation (RoaI) on September 15-16, 2021, with the goal of consolidating the 30-page final report and proposed FMH roadmap.

Timeline

- **Timeline**
  - Short (~four pages) written reports from EP sent by 7th June –
    - Structure: remit; key issues; process so far; initial findings; next steps; structure of the final report
  - 14-15 June SPC: preview of final report structure, scope and style
  - June Council: final approval of LDG mandate and roadmap scope
  - 9 July: Open workshop for Particle Physics community to seek input / feedback
  - Interim report by 16th of July (3rd of July first version)
    - A written summary of findings so far and key R&D topics (10 pages per panel)
  - 26-30 July EPS-HEP: presentation in ECFA session of interim findings
    - Note : we will present findings only, not the roadmap planning itself
  - September Council: presentation of interim report (findings, but no planning)
  - September – October: ‘closed’ definition of draft roadmap and scoped plans
    - **15- 16 September : 3rd HFM “Workshop” Roadmap Implementation restricted to the EP**
  - November: Draft final report review and feedback by SPC subcommittee - last chance to change
  - December Council: approval of the final roadmap and report
- **Outcome**
  - Public summary report covering findings plus a scoped roadmap
  - SPC / Council recommendations on priorities and next steps in the process