9 Conclusion

9.1 Findings

This report documents the findings and recommendations of the five expert panels, based on a six-month process of community consultation and input. Each panel has: identified the key R&D objectives for the next five to ten years; prioritised and ordered the objectives; determined a plan of work to achieve concrete results by the time of the next European Strategy for Particle Physics Update (ESPPU); and provided an approximate cost estimate for their plan under a number of different funding scenarios.

- The high-field magnets panel has identified the need for continued and accelerated progress on both Nb_3Sn and HTS technology. This should encompass developments in conductors, cables, and materials, placing strong emphasis on their inclusion into practical accelerator magnet systems, to address the wide range of associated engineering challenges. Considerations of large-scale production and costs, operational challenges, and energy-efficiency must be taken into account in all aspects of the programme, including eventual magnet development. The parameters and design of the final magnets will be balanced between ultimate performance and ease of manufacture, testing and operation.
- The high-gradient RF structures and systems panel finds that work is needed on the basic materials and construction techniques for both superconducting and normal-conducting RF structures. There are significant challenges in improving efficiency beyond the accelerating structures themselves, since couplers, dampers and RF sources may be limiting elements. There is the need for the development of specialised and automated test, tuning and diagnostic techniques, particularly where large-scale series production is needed. The link to the sustainability of future accelerators is clear.
- The high-gradient plasma and laser accelerators panel has focused on the ambitious developments needed specifically for particle physics applications of the rapidly developing plasma-wakefield and dielectric-acceleration technologies. These include the further development of existing techniques for: acceleration of high charge with low emittance and improved efficiency; acceleration of positrons; and combination of accelerating stages in a realistic future collider. The goal here will be to produce by 2026 a concrete and evidenced statement of the basic feasibility of such a machine to inform decisions on future investment into larger-scale R&D.
- The bright muon beams and muon colliders panel has examined the choice of parameters for a future muon collider concept, and suggests to focus in particular on a 10 TeV machine with a 3 TeV intermediate-scale facility. They have considered the challenges to be met in the construction of a 3 TeV machine targeted for the mid-to-late 2040s, and the immediate feasibility studies that must be carried out in the next five years. The goal for 2026 will be to demonstrate that further investment into a well-specified R&D plan is scientifically justified, and to have developed concrete plans for an intermediate-scale technology demonstrator with scientific utility in its own right.
- The energy-recovery linacs panel bases its strategy on several medium-scale projects now under way around the world, with complementary goals in different aspects of the technologies involved. The next practical step, with key roles for the bERLinPRO and PERLE facilities amongst others, is to approach the 10 MW power level based on progress on high current sources, high quality cavity technology, and multi-turn operation. Future sustainability also rests on developing 4.4 K

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superconducting RF technology for advancing the field and as the basis of a sustainable next-generation e^+e^- collider. Progress in ERLs is expected to impact particle physics, industry, and neighbouring sciences, and to open new areas in low-energy physics.

Several common themes emerge from the mostly independent work of the panels.

- The R&D is mission-oriented, aimed squarely at achieving the scientific goals expressed in the ESPPU by addressing the fundamental challenges associated with future generations of particle accelerators.
- Each panel has identified a staged approach to R&D, whereby the basic plausibility of a given technology or approach is first investigated, and then increased investment made only as the confidence level increases and the key challenges become understood. In the case of the 'mature' R&D areas in magnets and RF, this implies the modelling and small-scale test of new materials and structures before committing to large purchases of materials for significant-scale tests. In the case of ERLs, experience gained at existing facilities can motivate and inform investments in high-performance elements of future ERL test-beds. For laser / plasma and muon developments, a significant level of 'paper studies' or simulations is needed to justify and motivate possible large future investments to bring the technology to bear on particle physics goals.
- The need for rapid turn-around on R&D, providing continuous feedback on progress and likely outcomes, is recognised by all panels. In several cases, there is an emphasis on 'vertically integrated' tests and systems-level developments, whereby a range of new technologies with different readiness levels can be accommodated by a single test vehicle or facility. This not only promotes rapid take-up of new developments in future iterations, but also maximises efficient use of facilities.
- Most of the topics considered in the Roadmap have sustainability and power-efficiency as a prime motivation. Where the R&D is aimed at improving the basic performance of accelerators, the plan also takes into account the need to achieve this under reasonable conditions of cost, environmental impact and power consumption.
- Although none of the R&D plans calls for major capital investment in new facilities in the immediate future, it is clear that the direction of travel will require this around the time of the next ESPPU. It is the goal in each case to identify and justify the needed investment, which must be based on strong collaboration between laboratories and a commitment to common efficient use of Europe's distributed research infrastructure.
- The involvement of industrial partners in the R&D from the earliest possible stage is a major consideration. A clear commitment to R&D in the medium term, with a documented plan for investments and developments, will motivate industry to commit its own time and resources towards the goals of particle physics. This engagement over the long term is in many cases the only way to reduce the cost of basic materials and components to an affordable level.
- The 'external applications' of the technology, both for industry and other research fields, have been highlighted. Both the immediate outputs of the R&D programme and the longer-term machines they can make possible are relevant here. It is essential to interact closely with other fields with relevant needs and large-scale research infrastructures to find further benefits from the R&D investment.

9.2 Resources

The indicative costs of the first five years of the R&D programme are shown in Fig. 9.1, for the range of scenarios considered by each panel. Counted within 'project staff' and 'project resources' are the direct costs of the described R&D to the particle physics field, i.e. expenditure from the budgets of particle

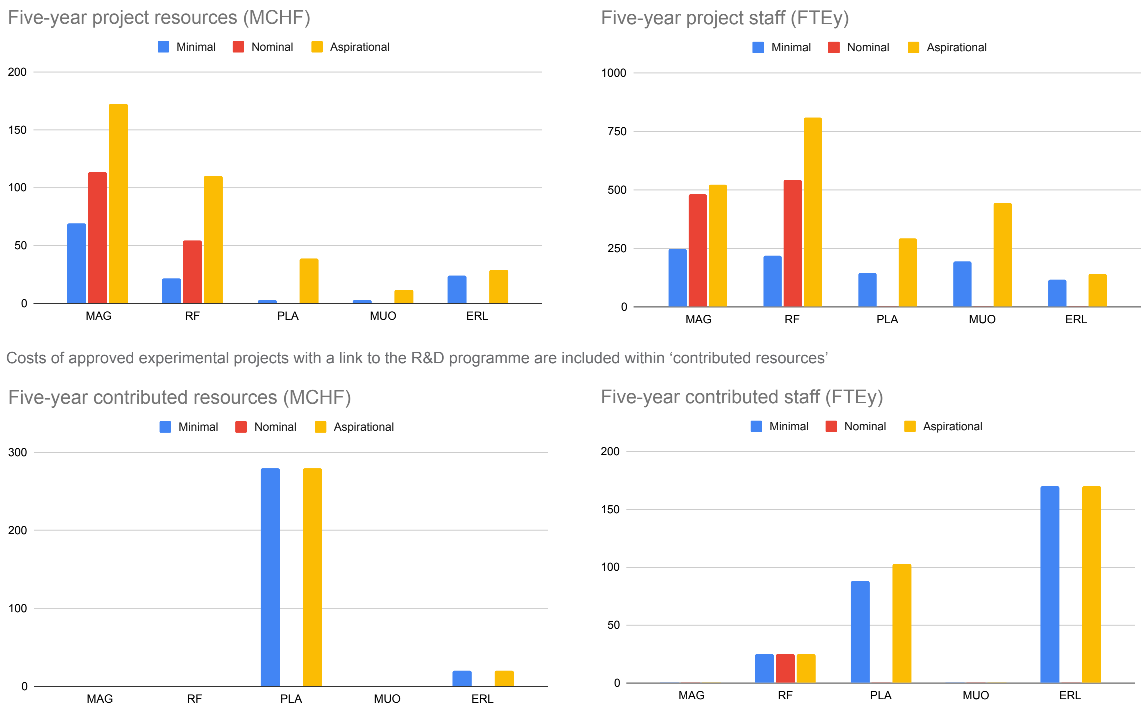

Fig. 9.1: Indicative cost of the R&D programme.

physics laboratories or from the related national budgets of funding agencies. 'Resources' here include capital investment, operational costs, and general staff support costs. Some components of the R&D programme are already approved.

Contributed costs include in-kind materials, facilities, and support from laboratories primarily funded from outside the field (e.g. laser laboratories or ERL demonstrators) that are essential to the R&D. This category also includes costs associated with already-approved programmes at particle physics laboratories which interlink strongly with the R&D programme (e.g. work already in progress at CERN in the context of the HL-LHC project, and in the AWAKE experiment).

The costs are dominated by the magnets and RF areas. The total costs of the programme per annum in each scenario range from 24 MCHF plus 184 FTE for the minimal scenario to 72.3 MCHF plus 440 FTE for the aspirational scenario. These scenarios are intended to be illustrative, and self-consistent R&D programmes can be constructed at a range of costs between the extremes, resulting in a correspondingly varying breadth, depth and rate of R&D outcomes. Taking into account the typical annual cost of scientific / technical posts in Europe, the expenditure in each scenario is approximately balanced between staff and other costs, as is typical for projects of this type.

9.3 Recommendations

The Laboratory Directors Group makes the following recommendations concerning the adoption, future governance, and implementation of the Roadmap.

1. The findings and priorities expressed in the Roadmap should be accepted as the collective view of the European accelerator physics and particle physics communities. Further discussion, organisation, and prioritisation will be needed to finalise the R&D programme and determine the available resources.

2. Appropriate governance structures should be put in place to oversee the ongoing R&D programmes, to ensure that: they are properly coordinated and balanced in their goals and execution; their focus remains on implementation of the scientific goals of the European Strategy; and regular updates on progress are available to the community and to CERN Council.
3. In light of the findings of the panels that a mixture of medium-term and long-term R&D is needed to fulfil the future needs of the field, and in light of the multiple future possibilities for new facilities, a broad front of R&D should be maintained, corresponding to at least the minimal scenario identified in each of the five areas.
4. Within the structured framework of R&D outlined in the Roadmap, provision must be left for the generation and pursuit of novel developments and 'blue skies' research; revolutionary ideas have arisen via such routes in the past.
5. Once decisions on the R&D programme are made, priority should be given to continuity of funding over the medium term, allowing the necessary investments in infrastructures and facilities to be made with confidence, to ensure practical support for the resulting capabilities. This is as important as the actual funding level.
6. Environmental sustainability should be treated as a primary consideration for future facilities, including those in the near-to-medium future, and the R&D programme should be prioritised accordingly. Objective metrics should be set down to allow appraisal of the impact of future facilities over their entire life cycle, including civil-engineering aspects, and of the resources needed to ensure sustainability.
7. Emphasis should be placed on prompt scientific exploitation of R&D outputs to achieve near- and medium-term results, in addition to the delivery of longer-term facilities. This should include direct use of new technologies and systems for experiments, and also careful appraisal of the potential of novel R&D to impact nearer-term major facilities such as Higgs factories. The direct and close engagement of the particle physics community is necessary in achieving this.
8. Practical considerations of the cost and speed of manufacturing, assembly, testing, and commissioning of accelerator components should factor into the design and parameters of future machines, with the close engagement of industry from the earliest possible stage. Industrial norms in materials, processes, and operating parameters should be adopted, widening the applicability of new developments, and increasing the potential return on investment for industry.
9. Close cooperation between European and international laboratories is required to deliver the desired outcomes of the R&D programme, and this should be facilitated through focused discussions during the ramp-up phase, taking into account the planning and funding cycles of different countries. This is important to ensure that major infrastructural investments at laboratories around the world are of wide applicability and used efficiently over the long term.
10. The training and professional development of accelerator physicists is a key factor in sustaining a vibrant and productive field, capable of meeting the significant challenges of both R&D and delivery of new facilities over the long term. Building on existing efforts within the community and the internal capabilities of institutes, increased emphasis must be placed on skills training, preferably in concert with corresponding initiatives for detector physicists, engineers and computing specialists.

9.4 Implementation of the roadmap

In order to achieve timely results from the R&D programmes, the momentum gained during the Roadmap definition process should be preserved, and the implementation phase should begin as soon as possible in 2022. On the other hand, it is clear that an initiative of this scale requires careful coordination, oversight, and support both at national and European level. There will of course be a ramp-up period following delivery of the Roadmap, during which the necessary structures and collaborations are set up, the level of available resources determined, and commitments negotiated.

The Roadmap necessarily presents a top-down view of the R&D programmes. In practice, the actual work and prioritisation will to a large extent be steered by (a) the interests, motivation and existing commitments of the accelerator physics community, and (b) the large-scale investments made or planned by the major laboratories. These two views must be reconciled during the ramp-up phase, leading to a revised set of delivery plans for the next five years, and this process must be overseen by a competent body responsible for maintaining the overall strategic direction of the Roadmap.

The interplay of European Strategy and national approval processes for specific projects will inevitably be complex. It is essential to put in place appropriate governance arrangements at European level, such that the programme is demonstrably well-coordinated and monitored, and to provide a sound overarching structure providing a framework for national commitments. The independent peer-review and 'blessing' of individual R&D proposals within the context of an overall programme is often a helpful or necessary step in achieving funding from either national or supra-national funding agencies.

One successful model of how such an R&D programme can be structured is the 'CERN RD collaboration' system set up for detector technology R&D as a precursor to the LHC. This has a number of advantages.

- It provides a structured approach to the division of tasks, with each RD collaboration having a well-defined scope of work, leadership and organisation, and routes for resourcing.
- It allows for oversight and visibility of R&D work, both through an initial gateway step via which the proposed R&D is approved, and through ongoing reporting against well-defined objectives.
- The semi-formal structure of an RD collaboration provides an ongoing route into R&D activities for new participants, as well as a useful basis for restricted sharing of research outputs and their subsequent open publication.
- The long-lived nature of RD collaborations can allow expertise, resources and knowledge in specific R&D areas to be accumulated and sustained, improving efficiency and cooperation, and providing opportunities for training.

The benefits of this or similar models should be considered at the start of the ramp-up period, in order to define an appropriate long-term structure for the organisation of R&D. The relationship with other areas such as detector technology and computing should also be considered, noting both the common need for strong strategic oversight, but also the fundamental differences in the nature of these programmes. For instance, CERN must clearly take a central role in the accelerator R&D programme, but the diversity of topics and the need for significant regional or national investments indicates that other host laboratories should also take responsibility. Any new arrangements should recognise the strong past record of the accelerator community in self-organising to deliver major R&D and construction projects, and respect and build on the established role of other coordinating bodies in the field.

9.5 Summary

In accordance with the recommendations of the 2020 update of the European Strategy for Particle Physics, the European Laboratory Directors Group has completed a year-long process to determine the status and prospects of particle accelerator R&D in five key areas, and has proposed R&D objectives for the next five-to-ten years with an outline delivery plan to achieve them. The analysis and planning have been conducted by five expert panels, with membership from the European and international field. The panels have in turn consulted with a wide cross-section of the accelerator physics and particle physics communities, and relied upon their input and views for the identification, prioritisation and organisation of the future work plan.

This report therefore represents the view of the community within the five areas considered, whilst acknowledging that the future R&D programme will exist in the context of many other activities and demands on the resources of the field. The LDG has made ten recommendations concerning the future adoption and prioritisation of the roadmap, along with observations on the implementation and governance of the programme. It is our hope that the European accelerator physics community, in concert with the international partners, will use the Roadmap as a platform to move swiftly forwards into a new era of ambitious, cooperative, fundamental and applied R&D, and follow current projects such as Hl-LHC with increasingly rapid progress towards future generations of sustainable particle accelerators. The delivery of the facilities foreseen in the European Strategy, and the potential for future scientific discoveries in the long term, depends on it.