1 Introduction

1.1 Motivation

The 2020 update of the European Strategy for Particle Physics Update (ESPPU) [1] outlined the current status and prospects in the field, and identified priorities for future particle physics accelerator facilities. In time order, these are: completion and commissioning of the CERN High Luminosity LHC (HL-LHC); a future electron-positron Higgs factory; and a future hadron collider at the highest achievable energy and luminosity.

It is recognised in the community, and was acknowledged in the ESPPU, that construction of the next generations of colliders will be extremely challenging. In most cases, there are major technical obstacles to meeting the exceptional performance requirements. As documented throughout this report, achieving our long-term scientific goals will require the exploration and maturation of new technologies, materials and techniques to well beyond the current state of the art. Since many of these technologies are unique to particle physics in their immediate application, then this can only result from a new and extended phase of R&D organised within our own institutes and in conjunction with industry and related scientific fields. This is similar to the precursor R&D that led to the successful delivery of previous generations of machines, but is likely to be longer in duration and wider in scope.

In addition to the technical challenges, it is clear that there are practical issues in delivering the future machines. There are limits to the level of investment available to support both the construction and operation of new facilities, and energy consumption, efficiency, and environmental impact are key considerations. Optimal scientific progress depends on the timely availability of new data from previously unexplored physical regimes, as well as on new opportunities to attract and train future generations of scientists, engineers and technicians. Therefore, the accelerator R&D programme must focus not only on enabling new levels of machine performance, but also on making the new machines available at affordable cost, on useful timescales, and with appropriate consideration for sustainability. These requirements may motivate changes in the way we approach both R&D and the design of new facilities, and in the way we organise cooperative developments.

The ESPPU commented that

> *The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies.*

and that

> *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

The European Laboratory Directors Group (LDG) was mandated by CERN Council in 2021 to oversee the development of an Accelerator R&D Roadmap, complementary to the Detector R&D Roadmap being developed in parallel under the guidance of the European Committee for Future Accelerators (ECFA). Whilst LDG members represent the large laboratories and national infrastructures

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through which the majority of accelerator R&D investment is made, it is clear that the first step in any such process should be the gathering of inputs and evidence from the widest possible set of stakeholders in the European and international fields. To this end, a set of expert panels was convened, covering the five broad areas of accelerator R&D highlighted in the ESPPU, drawing upon the international accelerator physics community for their membership, and tasked to consult widely and deeply. The roadmap is the result of their efforts, and builds upon many hundreds of contributions by experts in the community.

1.2 Goals of the roadmap

The European Strategy for Particle Physics (ESPP) represents the collective view of the European community on the priorities for current and future work. Although it is not prescriptive on actions or investments to be undertaken by countries, laboratories, or institutes, it forms a structure around which decisions and plans can be made with confidence. In a field where practically every new development requires extended cooperation between many partners, and investment over an extended period, this is an essential element in ensuring coherence. As an extension and specialisation of the Strategy, the Roadmap should play a similar role in its own domain. It should express the views of stakeholders on the pathway to delivering the necessary future facilities for particle physics, and likewise form an established basis for European, national and local planning.

The Roadmap is therefore required to:

- provide an agreed structure for a coordinated and intensified programme of accelerator R&D across national institutes and CERN;
- complement corresponding roadmaps in detectors, computing and other technologies, with a compatible timeline and deliverables;
- seek to further the scientific goals expressed in the European Strategy for Particle Physics;
- be defined in consultation with the community and, where appropriate, through the work of expert panels;
- take into account, and coordinate with, international activities and work being carried out in other related scientific fields, including the development of new large-scale facilities;
- specify a series of concrete deliverables, including demonstrators, over the next decade;
- inform through its outcomes future updates of the European Strategy for Particle Physics.

The lattermost point is crucial. The next updates to the Strategy are likely to involve significant decisions on the future direction of particle physics. These decisions can only be made if full and robust information on the feasibility of possible future options is available. The Roadmap must set down the steps to be taken over the next decade so that a full picture on the benefits, challenges, feasibility, risk and costs of each new development is in place. In essence, it should seek to answer the fundamental questions raised when considering long-term strategy, both in the present, and then in greater detail at subsequent updates.

- What R&D remains to be done towards future facilities, and what are the priorities?
- How long might it take, and what investments and resources are required?
- What are the dependencies and relationships between activities?
- Which scientific outputs could be obtained from demonstrators or the intermediate outputs of R&D?

1.3 Scope of the roadmap

The ESPPU identified five key areas where an intensification of R&D is required to meet scientific goals:

1. Further development of high-field superconducting magnet technology.
2. Advanced technologies for superconducting and normal-conducting radio frequency (RF) accelerating structures.
3. Development and exploitation of laser/plasma acceleration techniques.
4. Studies and development towards future bright muon beams and muon colliders.
5. Advancement and exploitation of energy-recovery linear accelerator technology.

Expert panels were convened to examine each of these areas, with membership drawn primarily from European accelerator institutes, but with international representation. The overall structure set up to deliver the Roadmap is shown in Fig. 1.1. An important additional issue in accelerator physics is the attraction, training and career management of researchers. The issues in this area are very similar to those for detector-focussed particle physicists; both have been considered in common by Task Force Nine of the ECFA Detector R&D Roadmap, and the findings are documented there.

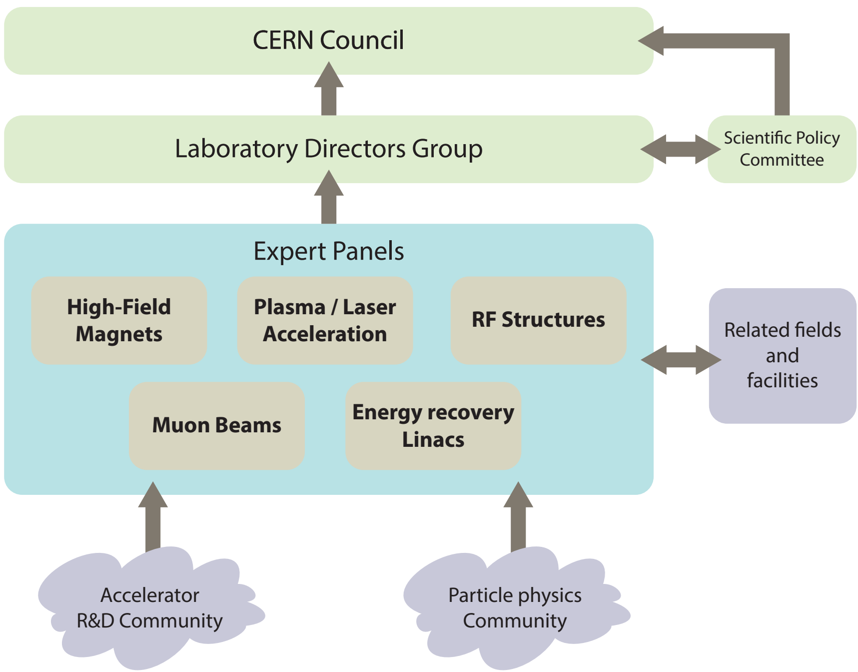

Fig. 1.1: Roadmap panel structure.

The five study areas are of course not fully independent, with technological cross-links between the 'fundamental' areas of acceleration and magnets, and the more 'applied' areas of muon beams and energy-recovery linacs (ERLs). Neither are all the areas at equal stages of maturity. In the magnets and RF areas, the Roadmap constitutes the next phase of planning in an ongoing and mature R&D programme. For laser / plasma and ERLs, it attempts to capture specific particle physics requirements and plans within ongoing R&D programmes of wider applicability. For muons, it documents the first phase of a new European study. It is clearly understood that these five topics are only a subset of the necessary R&D to deliver all the required new technologies for future facilities. Moreover, investment into long-term R&D must sit alongside the need to complete existing projects and to conduct studies and detailed planning for nearer-term new machines. The balance must be carefully struck, taking into account both the short- and long-term requirements of the field.

1.4 Assumptions concerning future facilities

Although the ESPPU highlighted a number of potential long-term future facilities, it did not provide an explicit timeline for their delivery. Indeed, the information required to make such a plan is dependent upon the results of early R&D and feasibility studies. On the other hand, without some common initial assumptions on the target dates and parameters of future machines, it is not possible to motivate and construct an R&D strategy for accelerators or detectors.

To this end, Fig. 1.2 illustrates an indicative timeline for future collider and larger accelerator facilities. The projects shown in the diagrams are at differing stages of definition, approval and technical maturity. Each is described in detail in the ESPPU supporting documents [1]. The dates shown in the diagram have low precision, and are intended to approximately represent the 'feasible start date' (where a schedule is not already defined), taking into account the necessary steps of approval, development and construction for machine and civil engineering. They do not constitute any form of plan or recommendation, and indeed several of the options presented are mutually exclusive. The projects mentioned here are limited to those mentioned in the ESPPU. For some other proposed projects (e.g. CEPC in China) there are substantial overlaps and synergies, and the specific needs of these projects have been considered by the expert panels where relevant to the R&D programme.

The timelines—and potentially the scope—of the projects will naturally change depending on both future strategic decisions and the outcomes of the R&D programme. The key objective of both the Accelerator and Detector Roadmaps is to ensure that: (a) the basic R&D phase is not the limiting step, i.e. that R&D is started sufficiently early and prioritised correctly to meet the needs of the long-term European particle physics programme in its global context; and (b) that the outcomes of the R&D programme are able to provide the necessary information on the feasibility and cost of future deliverables to allow strategic decisions to be made.

Fig. 1.2: Future accelerator facilities timeline.

1.5 Status and organisation of the field

Accelerator physics is a large, complex, multi-disciplinary field that is of relevance beyond the needs of particle physics. The field is fully international, and to some extent a 'European Roadmap' can only represent a portion of what must remain a fully-integrated worldwide programme. To the extent that the field necessarily centres around large infrastructures, much of the work is focussed on facilities at national or regional laboratories. However, it is also clear that key developments (including those with the potential to radically affect our assumptions and future plans) are taking place at institutes and universities. The majority of accelerators built are for industrial, medical or other scientific purposes. Some of these applications will also benefit directly from parts of the proposed new R&D. To that extent, accelerator physics is therefore not just a key element in enabling new scientific discoveries, but also a primary route for economic and societal impact from particle physics.

The field is well-organised, with a plurality of existing structures, steering bodies, cooperative programmes and communication channels. The field has benefited in the past from investment by supra-national agencies (e.g. the European Commission) in recognition of its key supporting role across disciplines and industries. The Roadmap must take into account these pre-existing structures, commitments, and projects, and build upon them. The execution of the Roadmap will require sufficient oversight to make sure the goals are being met, to ensure that the results and conclusions of the overall R&D programme are readily available to stakeholders, and to ensure consistency with corresponding work taking place in detector. It is likely that in some cases there will be a thin layer of formal structure above projects coordinated on a multi-lateral basis by laboratories and institutes. In other cases, for instance where new topics are being given priority, it may be necessary to convene new groupings and formal collaborations within an overall R&D governance structure, or to merge or re-optimise existing programmes for greater efficiency. These aspects have been the topic of consultation with the community and recommendations for future coordination are given later in the report.

As noted above, the vast majority of particle accelerators are not constructed for fundamental research, but for a multitude of other applications in science, medicine and industry. However, these machines exist due to the foundational work driven by particle physics over almost a century. Many of the key topics for the R&D programme—especially in the areas of energy-efficiency and sustainability—are also directly relevant for wider applications, and particle physics is still the crucible in which such developments can be driven forward. In the Roadmap, the applicability of the proposed R&D to external applications has been highlighted, and in many cases forms a strong secondary motivation for the programme.

1.6 Process

The overall timeline for the Roadmap process is shown in Fig. 1.3. As with the ESPPU process, it consists of two phases: a public consultation and documentation of the R&D priorities; and the definition of the Roadmap which must deliver them.

The charge to each of the expert panels was to:

- establish the key R&D needs in each area, as dictated by scientific priorities;
- consult widely with the European and international communities, taking into account the capabilities and interests of stakeholders;
- take explicitly into account the plans and needs in related scientific fields;
- propose ambitious but realistic objectives, work plans, and deliverables;
- give options and scenarios for European investment and activity level.

In order to avoid confusion between the definition of the Roadmap and the subsequent implementation phase, and to avoid overlap with other R&D activities happening in parallel within laboratories, the following topics were deemed explicitly 'not in scope':

- detailed planning for specific future facilities;
- planning of funding routes, beyond documenting an indicative cost of the proposed R&D programme;
- statements of institutional or national commitment.

From January to July 2021, each of the expert panels held regular working meetings to define the scope and boundaries of their area, and to carry out a process of community consultation. This typically took the form of a number of workshops combining invited talks with an open call for contributions. In other cases, the panels were able to draw upon the documented work of pre-existing consortia or collaborations. Some panels launched a formal written consultation within their community. These initiatives attracted the participation of a wide and representative subset of the international accelerator physics community, along with many stakeholders from particle physics. Overall, several hundred researchers

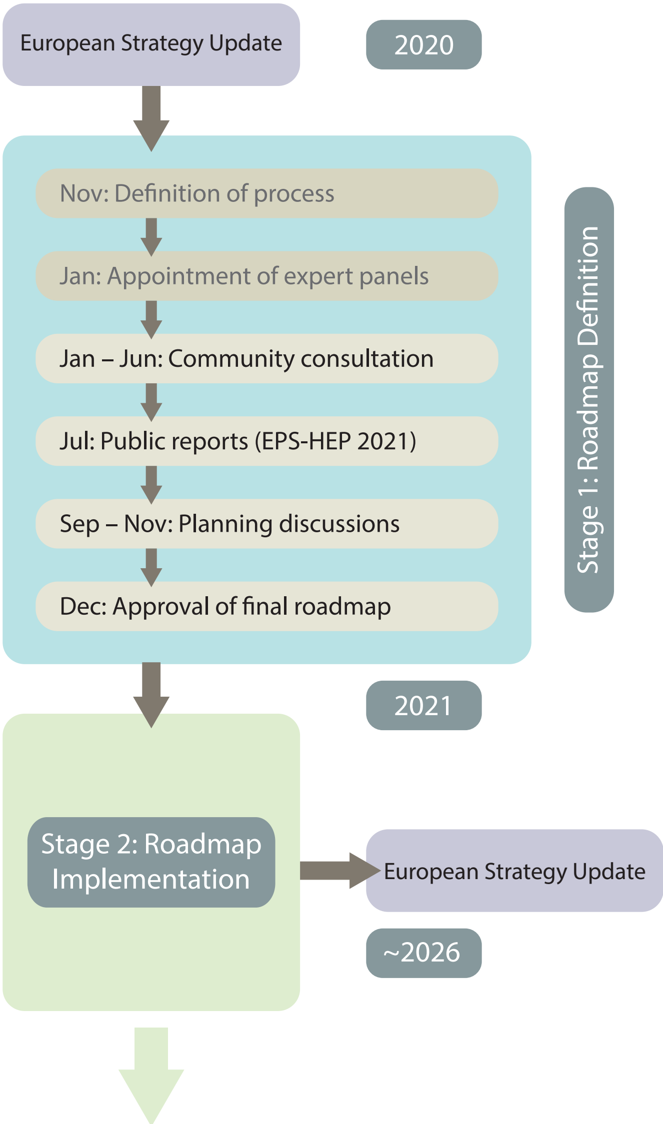

Fig. 1.3: Accelerator R&D Roadmap timeline.

have been actively involved in the process, with concrete contributions to this report from a large subset of them. In some cases, it has been necessary to set up sub-panels with co-opted membership from the particle physics community, to consider specific aspects or applications of future technologies.

In July 2021, an open symposium was held specifically for the particle physics community, in order to ensure that the field was kept well informed of progress. This was attended by around 150 people, and resulted in valuable feedback on priorities and traversal aspects of the R&D programme (for instance, the highlighting of sustainability as a primary consideration). In addition, the particle physics community was challenged to provide input on potential direct scientific uses of intermediate-scale demonstrators and facilities. At the EPS-HEP conference in late July, both ECFA and LDG reported on the progress towards the Roadmaps, and the panels presented their initial findings.

1.7 Delivery plans

The final stage of the process has been to outline delivery plans. In each of the five areas, R&D themes have been established, related to the key R&D objectives. These have been broken down further into R&D tasks of limited duration and scope and an indicative resource envelope has been established. The delivery plans explicitly do not constitute a ready-for-execution resource-loaded plan. Rather, they are intended to illustrate the potential scope and pace of the R&D programme for particular resourcing scenarios, allowing informed decisions to be made on the shape, balance and scale of the overall R&D effort.

Each panel has constructed alternative delivery plans corresponding to a number of resource scenarios. For the 'mature' areas already in receipt of substantial investment, these comprise:

- a 'nominal' scenario, illustrating the direction and pace of future development if current funding conditions continue;
- an 'aspirational' scenario, indicating the progress possible with additional resources;
- a 'minimal' scenario, documenting what could be achieved with restricted resources.

For other areas, only the aspirational and minimal scenarios are documented. In each case, consideration has been given to the structure and organisation of the R&D programme, and the interdependencies within and across areas.

The resource estimates associated with each scenario are indicative, and in some cases approximate. The necessary resources include human effort (stated in FTEy for full-time equivalent-years), direct capital investment into R&D, and in some cases in-kind contributions from established programmes or facilities. Where the delivery plan builds upon pre-existing commitments or investments, the rough level of associated resource is indicated for information; in some cases, the exact level of commitment is still under discussion, and so these numbers are typically an under-estimate. The overall intention is to document the 'incremental cost to the field' of undertaking each aspect of R&D, and to separate this cost from that of externally funded infrastructure, even where the same funding agencies are involved. Only costs for the next five years are tabulated, since investment after this point depends on decisions and prioritisation following the next ESPPU; however, the longer-term resource implications in each area have been documented by the panels.

The delivery plans reflect the prioritisation of tasks within each area, and in most cases already represent a focus on only the key topics. Conversely, the Roadmap does not make recommendations on the relative prioritisation of the five R&D areas, though it does in some cases highlight their interdependence. Decisions on resource levels and priorities can only be made in light of the many other ongoing activities in the field, and after balancing short- and long-term scientific goals. The intention of the Roadmap is to document the collective view of the field on the priorities within each area, and to provide sufficient information to allow strategic decisions to be made.

The Roadmap mainly concerns long-term R&D towards facilities to be constructed in the 2040s or beyond, though where there is relevance to nearer-term accelerators or to other scientific projects this is indicated. In order to provide the necessary context and counterbalance, the report also contains a summary of the ongoing R&D and planning towards future electron-positron colliders. These machines and the related programmes are documented in depth in the references in these sections. Finally, a separate section summarises the sustainability issues associated with future facilities, and highlights the potential of the R&D programme to address these.

References

[1] 2020 update of the European Strategy for Particle Physics, Technical Report CERN-ESU-015, (Brochure), Geneva, 2020, https://doi.org/10.17181/CERN.JSC6.W89E.