CERN-2021-XXX

European Strategy for Particle Physics
Accelerator R&D Roadmap

Interim Report – Draft 0.3 – 3-Sept-2021

Editors: TBC

Published by CERN, CH-1211 Geneva 23, Switzerland

ISBN 978-92-9083-XXX-X (paperback)
ISBN 978-92-9083-XXX-X (PDF)

This volume should be cited as:
European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report),
D. Newbold (ed.)
A contribution in this report should be cited as:
[Chapter editor name(s)], in European Strategy for Particle Physics - Accelerator R&D Roadmap
(Interim Report), D. Newbold (ed.)
CERN-2021-xxx (CERN, Geneva, 2021), pp. [first page]–[last page],
http://doi.org/10.23731/CYRM-2021-XXX.[first page]

Corresponding editor: Y.XXXX@cern.ch.

European Strategy for Particle Physics - Accelerator R&D Roadmap
Interim Report

Editor: D. Newbold

Section editors: R. Assmann, S. Bousson, E. Gschwendtner, M. Klein, D. Schulte, P. Vedrine

Abstract

This report ....

Keywords

Particle Physics; European Strategy; Accelerator; R&D; Roadmap.

Contents

1 Introduction

Proposed content of Interim Report introduction section:

- Executive summary: *One-page summary of progress and findings to date*
- Summary of the relevant recommendations of the ESPPU
- Scope and role of the roadmap. *Including timeline chart of future facilities, identical to that included in the ECFA roadmap*
- Goals and remit of the roadmap process
- Topics, panel structure, and organisation of the process

2 High-field Magnets

B. Auchmann[a], *A. Ballarino*[b], *B. Baudouy*[c], *L. Bottura*[b], *Ph. Fazilleau*[c], *M. Noe*[d], *S. Prestemon*[e], *E. Rochepault*[c], *L. Rossi*[f], *C. Senatore*[g], *B. Shepherd*[h], *L.-G. Tabares*[i], *P. Vedrine*[c]

[a]PSI, Villigen, Switzerland
[b]CERN, Geneva, Switzerland
[c]CEA, Saclay, France
[d]KIT, Karlsruhe, Germany
[e]LBNL, Berkeley, California, USA
[f]INFN-LASA, Milano, Italy
[g]University of Geneva, Switzerland
[h]ASTEC, Daresbury, UK
[i]CIEMAT, Madrid, Spain

2.1 Historical perspective

High Field Magnets (HFM) are among the key technologies that will enable the search for new physics at the energy frontier. Starting from the Tevatron in 1983, through HERA in 1991, RHIC in 2000 and finally the LHC in 2008, all frontier hadron colliders were built using superconducting (SC) magnets. All colliders listed above made use of the highly optimized superconducting alloy of Nb and Ti, and it is a well-accepted fact that the LHC dipoles, with a nominal operating field of 8.33 T when cooled by superfluid helium at 1.9 K, represent the end-of-the-line in terms of performance of accelerator magnets based on this material.

A strong focus was given at the end of the 1990's by the US-DOE programs devoted to Nb_3Sn conductor and magnet development. These programs unfolded as a collaboration among the US-DOE accelerator Laboratories and associated Institutions, and are now continuing in consolidated form under the US Magnet Development Program, with the added goal of developing HTS materials and magnets. On the EU side the first targeted EU-wide activities were initiated under the EU-FP6 CARE (Coordinated Accelerator Research in Europe) initiative and in particular the Next European Dipole Joint Research Activity (NED-JRA). NED-JRA ran from 2004 to 2009, and was followed by the EU-FP7 EuCARD. The main fruit of these collaborations is FRESCA2, the magnet that still detains with 14.6 T the highest dipole field ever produced in a clear bore of significant aperture.

The fruit of the technology development sketched above is the High-Luminosity LHC upgrade (HL-LHC), presently at the forefront of technology and construction, with the highest field ever attained by accelerator magnets. The results achieved with the 11T dipoles and QXF quadrupoles demonstrate that Nb_3Sn has the ability to surpass the Nb-Ti state-of-the-art mentioned earlier.

The result of the efforts briefly outlined above can be appreciated graphically in Fig. 2.1, reporting the steady increase of field produced by dipole magnets built with Nb_3Sn over the past forty years. The data is a loose collection of results obtained with short demonstrator magnets (simple configurations that lack an aperture for the beam and are not built with other constraints such as field quality), short model magnets (short versions of magnets that are representative of the full-size accelerator magnets), and full-size accelerator magnets. Still, it gives a good impression of the timeline and state-of-the-art.

This contribution should be cited as: High-field Magnets, DOI: 10.23731/CYRM-2021-XXX.3, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold,
CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 3.

While Nb_3Sn is the baseline for the high field magnets beyond HL-LHC, the next step in SC accelerator magnet technology, great interest, and significant progress was achieved recently in HTS accelerator magnet technology, reported graphically in Fig. 2.1. To date, the results of these activities are small demonstrator magnets that have reached bore field in the range of 3 to 5 T in stand-alone mode.

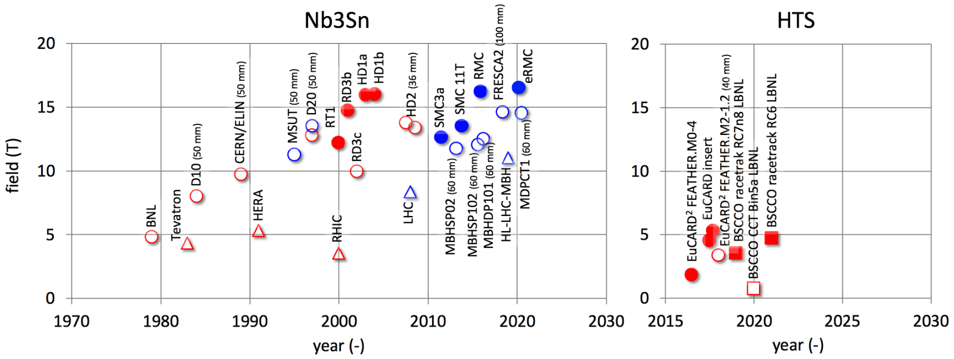


Fig. 2.1: Record fields attained with Nb_3Sn and HTS dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short demonstrator, i.e. "racetracks" with no bore, while open symbols are short models and long magnets with bore. For HTS, round symbols are magnets built with REBCO, square symbols with BSCCO-2212. For comparison, superconducting collider dipole magnets past and present are shown as triangles.

To complement this simplified but interesting perspective, we observe that:

- Lead times for the development of high-field magnets are long, the cycle to master new technology and bring novel ideas into application has a typical duration in excess of a decade. It is hence important to pursue R&D in parallel with scoping studies of new accelerators, to anticipate demands and guarantee that specific technology is available for a new HEP realization at the moment when the decision of construction is taken;
- The development of novel SC magnet technology at the high field frontier requires specific infrastructure, often of large size. The necessary investment is considerable. Continuity is hence important in a program that requires such infrastructure and the associated investment;
- The development of high field magnets naturally spans over many fields of science and requires a broad mix of competencies, implying a research team assembled as a collaboration ranging from academia to industry. As for the infrastructure, any such research team needs considerable investment for its constitution and operates most effectively with continuity.

These considerations support the need for a sustained and inclusive R&D program for high-field superconducting accelerator magnets as a crucial element for the future of HEP, as underlined by the strong recommendation emitted by the European Strategy.

2.2 Panel Activities

The HFM Expert Panel held eleven meetings to date. All meetings are collected under an *indico* category containing the material presented and minutes (https://indico.cern.ch/category/13420/). Two open international workshops were organized 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. Open consultation process is now completed. 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 final report containing the proposed HFM roadmap for November 2021.

2.3 State of the Art and Challenges of High Field Magnets

2.3.1 Superconductor

The prime challenge to achieve high magnetic fields of interest to HEP is to have a conductor with sufficiently high engineering current density, J_E, with good mechanical properties. Based on experience from superconducting accelerator magnets built to-date, a target of $J_E \approx 600$ A/mm^2 is appropriate to yield a compact and efficient coil design. The J_E target should be reached with no degradation and limited training, and making use of the highest possible fraction of the current carrying capacity of the specific superconductor. All known high field superconductors (Nb_3Sn and HTS) are brittle, and it is of paramount importance that the state of stress and strain be mastered and controlled throughout all magnet fabrication and operation conditions.

In the case of Nb_3Sn the target of J_E, which enables the construction of compact and affordable magnets, requires a minimum critical current density in the superconductor, J_C, of the order of 1500 A/mm^2 at the reference design conditions (i.e. at 16 T and 4.2 K). This target exceeds the performance of the HL-LHC Nb_3Sn wire state-of-the-art. As a result of the R&D initiated with the FCC CERN Conductor Development Program, Nb_3Sn 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).

For HTS, the target J_E is actually common practice for the present production industrial standards of REBCO and BSCCO materials, so we do not envision focused effort in the direction of increasing J_E. We witness the spectacular electrical performance of HTS tapes, and 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 (potential for improved 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 the cost of HTS may decrease because of substantial investment and demand from fusion and power applications.

2.3.2 Forces and Stresses

Forces increase with the square of the bore field, making mechanics one of the main challenges of high field magnets. Length effects and electro-thermo-mechanics of Nb_3Sn magnets are also a crucial issue (11T magnet 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.

Filament breakage caused by excessive transverse pressure or axial tension during assembly, cool-down, powering, quench, or WU-CD-powering cycle and irreversible change of pre-load or de-bonding, leading to excessive conductor motion could induce degradation of the critical current. Performance issues have been also identified like strain-dependent J_C-curve with a lack of knowledge of the actual strain status, instabilities at low field (in particular for the conductors in the low field area), training, coupling between longitudinal and transverse forces/strain, memory with thermal cycles.

An initial tentative to identify suitable design options for the various field levels targeted has yielded the following result:

- 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.

The 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 a direct spin-off to other fields.

2.3.3 Stored Energy and Protection

Aiming at the range of 16 to 20 T, the stored energy increases proportionally to the square of the field. This yields a factor 4 to 10 with respect to the LHC, ranging from 1 to 3 MJ/m per aperture. This in itself may result in severe limitations on the powering of strings, both from the point of view of their inductance (voltage required to ramp the string of dipoles), as well as magnet protection (energy density and dump time).

In addition, the energy per unit volume, that drives the maximal temperature (hot-spot) during a quench, also increases, proportionally to the field. The LHC magnets have a stored energy density of 50 MJ/m^3. This will increase up to 80 to 100 MJ/m^3 for the HL-LHC Nb_3Sn magnets, with a design hot-spot limited to 350 K. Moreover, this value reaches 200 MJ/m^3 for the most compact 16 T FCC designs, increasing with a factor 4 with the LHC magnets as reference.

Considerations of magnet ramping would favor large voltage or current, or a combination of both, to power magnets of large stored energy. Increasing either terminal voltage or cable current is not a trivial matter. Furthermore, conventional wisdom states that in order to keep the hot-spot temperature in the coil after a quench below reasonable values (around 300 K to 400 K, but actual damage limits are not well assessed), the quench detection and active dump need to act at least three to five times faster than in the LHC. This is already challenging for Nb_3Sn, but may be perceived as a tantalizing task for HTS, whose quench propagation speed is an order of magnitude slower than in LTS, and quench detection based on established instrumentation would take an order of magnitude longer. In reality, quench initiation and evolution in the case of HTS is a much different process than the well-characterized behavior of LTS. Though relatively unexplored, the large difference in quench initiation and propagation in HTS vs. LTS may actually be an opportunity to develop alternative schemes, e.g. profiting from the early low voltage quench precursors arising during the current sharing process to anticipate the evolution, or the relatively long time scales of voltage development to improve measurement sensitivity.

2.3.4 Cost

Cost is the last main challenge faced by high-field magnets for a next step collider. We have identified 3 main cost drivers.

The first is the conductor, among which the superconductor strand (round wire, or tape for REBCO) is the primary cost driver of HFM. In LHC, the Nb-Ti cost was about 25% of the total cost of the magnet (excluding the external services like power supply and other ancillaries). The Nb_3Sn cost for FCC-hh is projected to be half of the cost of the magnet system. Therefore, developing conductor architectures that include features such as tolerance to raw material properties and scalability to reduce SC cost is a good return of investment. Not only unit cost must be reduced but also use of superconductor in the magnet. Designs must be assessed also based on the use of superconductors and we need to encourage solutions that go in that sense.

The second largest driver is coil construction, in which winding remains the most expensive part. Today winding is basically a manually driven operation, with the help of some automation in the winding operation. Given the experience of recent projects, such as ITER and JT60-SA, and given the number of coils (an FCC-hh would require 20,000 identical coils for the main dipoles) an investment in advanced robotics seems a crucial point to reduce winding cost.

The third cost driver is the mechanical structure. Here the community must make the choice among alternatives such as collars, bladder&key, yoke-as-restrain, or other options. Performance consideration put aside, they are not all equal in terms of cost: some operation seems more suitable to automation. Besides the performance evaluation, injecting also this type of study may be a good investment to make the right decision when the time will come. Automation is not only beneficial for reducing construction cost, but also for increasing construction quality and enhancing the uniformity of the production.

The main challenge remains to find the optimum between performance and cost, including operational cost. High temperatures (4.2 K for Nb_3Sn and 20 K for HTS) should be seriously considered, as it could result in a significant reduction of operation costs. We need to favor simpler designs with repeated operations that might be more suitable to automation, even if field performance may be slightly reduced.

Industrial partners should be involved as soon as possible. However, industry will consider this involvement seriously only if there is continuity of budget and work. Industry needs to make plans with an horizon of at least 5 years to be effective. The issue of IP needs clarifying. It is unlikely that industry disclose their methods, or commit high-level engineering, if the IP is not suitably protected. In case of uncertainty on IP matters it may be better to involve industry at a later stage.

An important matter underlying the above considerations is that of the cost of the R&D itself, which may limit the scope and stretch the timeline, against the wish for a fast turnaround. This is especially true for HTS materials, which explains why the scale of the demonstrators described earlier, as well as the future ones, shall be kept intentionally small (i.e. inserts in background field). An effective R&D program will hence include practical consideration of cost and will need to rely on a high degree of synergy.

2.3.5 Objectives of a High Field Magnets R&D Program

Based on the state-of-the-art and challenges described above, and the strong and precise statements encouraging a high-profile R&D activities on high field accelerator magnets contained in the 2020 upgrade of the European Strategy for Particle Physics, we can formulate the following provisional long-term technical goals of the HFM R&D:

1. Demonstrate Nb_3Sn magnet technology for large-scale deployment, pushing it to its practical limits, both in terms of maximum field as well as production scale. The drivers of this first objective are to exploit Nb_3Sn to its full potential, which we think is not yet unfolded, developing design, material and industrial process solutions that are required for the construction of a new accelerator. We separate the search for maximum field from the development of accelerator technology by defining the following two dependent and linked sub-goals:
   (a) Quantify and demonstrate Nb_3Sn ultimate field. This effort consists in the development of conductor and magnet technology towards the ultimate Nb_3Sn performance. The projected upper limit is presently 16 T dipole field (the reference for FCC-hh). This field should be

intended as a target, to be quantified and measured against the performance of a series of short demonstration and model magnets.

(b) Develop Nb_3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing processes, and cost reduction. The present benchmark for Nb_3Sn accelerator magnets is HL-LHC, with an ultimate field in the range of 12 T, and a production of the order of a few tens of magnets. Nb_3Sn magnets of this class should be made more robust, considering the full spectrum of electro-thermo-mechanical efforts, and the processes adapted to an industrial production on the scale of thousand magnets. The success of this development should be measured against the construction and performance of long demonstrator and prototype magnets, initially targeting the 12 T range.

2. Demonstrate suitability of HTS for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the reach of Nb_3Sn. The leitmotif of this program is to break the evolutionary changes of LTS magnet technology, from Nb-Ti to Nb_3Sn, by initiating a revolution that will require a number of significant innovations in material science and engineering. A suitable target dipole field for this development is set for 20 T, significantly above the projected reach of Nb_3Sn (see above). Besides answering the basic question on field reach and suitability for accelerator applications, HTS should be considered for specific applications where not only high field and field gradient are sought, but also higher operating temperature, large operating margin and radiation tolerance.

In addition, it is also important to underline that the HFM R&D program is intended as a focused, innovative, mission-style R&D in a collaborative and global effort.

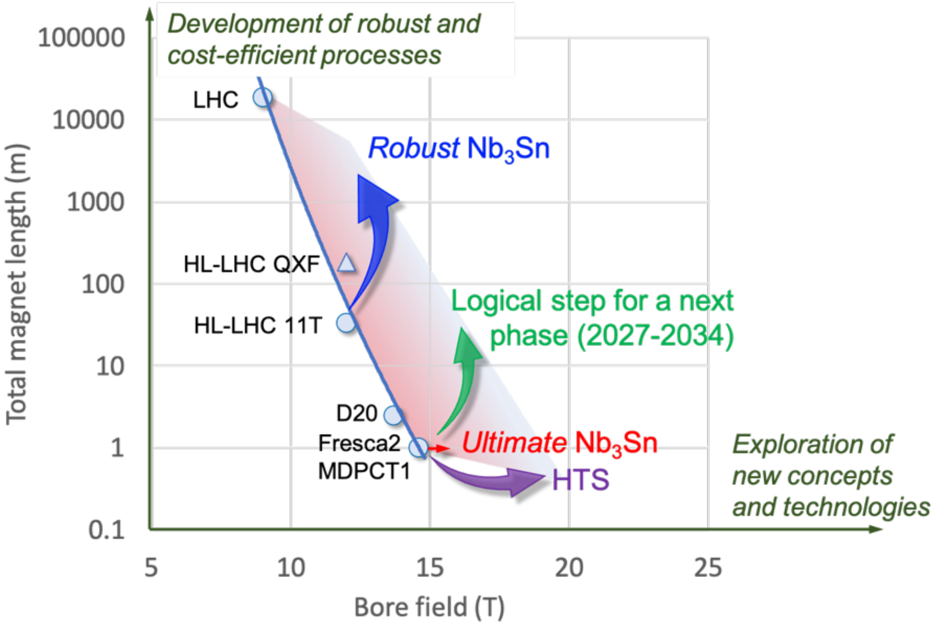


Fig. 2.2: Graphical representation of the objective of the HFM R&D program in this phase, 2021-2027. Both fronts of maximum field (red for Nb_3Sn, purple for HTS) and large-scale production (blue) are intended to be advanced at the same time. Also represented, in green, a possible evolution for the longer term, 2027-2034.

It is possible to represent graphically these main objectives in the form reported in Fig. 2.2, where we plot a length of dipole magnets produced (i.e. magnet length times the number of magnets) vs. the bore field. The directions of developments are represented by arrows. The parallelism in the development is an important element of the program. We believe this is necessary to provide the requested significant advances within a five to seven years' time frame, i.e. responding to the notion of a mission-style R&D that needs to feed the discussion for the next upgrade of the European Strategy for Particle Physics with crucial deliverables.

The graphical representation of Fig. 2.2 only defines the first step in the R&D, which should enfold in the 2021-2027 period. Naturally, once it is proven that the field reach can be extended, and the actual level is demonstrated, we can foresee the need for a follow-up phase. This should enfold in the period 2027-2034, being dedicated to proving the new generation of high field magnets on a scale of magnet prototype, i.e. several meters of cumulative magnet length. This is represented by the green arrow in Fig. 2.2, whereby the choice of the field level, and the actual magnet length to be realized are again only indicative, and will depend on the results of the next years of R&D.

A further element in support of the R&D targets formulated above is that they respond directly to the demands coming from principal stakeholders. As evident from the quotations of the reference ESPP documents, the HFM R&D targets formulated for Nb_3Sn magnets are stemming directly from the demands of an FCC-hh. In the staged approach described here, they are also compatible with the allotted development time of the integrated FCC program. Indeed, the parallelism proposed has the advantage that it will provide options for an earlier decision on magnet technology towards the construction of the next hadron collider.

Given the ambitious scope, the long-term engagement, and the cost, one such program will have to be of collaborative nature, with strong partnership among national laboratories, universities and industry. Last but not least, it will be important to measure the impact of the R&D program against its relevance and impact on other applications in science and society.

2.4 Key points of Roadmap

2.4.1 High Field Magnets R&D Program Drivers

Driven by the challenges outlined above, and in line with the main objectives set for the HFM R&D, we can formulate practical questions that should be addressed in priority by a High Field Magnet R&D Program. These questions are the R&D program drivers, and they can be broadly divided into questions of relevance for Nb_3Sn, HTS, and common to both lines of development.

For Nb_3Sn high-field accelerator magnets the following leading questions can be drawn from the earlier discussion, and will need to be addressed largely looking at the pioneering Nb_3Sn development that has led to the milestone HL-LHC magnets, the present reference technology:

- Q1: What is the practical magnetic field reach of Nb_3Sn 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 Nb_3Sn accelerator magnets realistic?
- Q2: Can we improve the robustness of Nb_3Sn 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 Nb_3Sn accelerator magnet?
- Q4: What are the design and material limits of a quenching high-field Nb_3Sn magnet, and which detection and protection methods need to be put in place to remain within these limits?
- Q5: How can we improve the design and manufacturing processes of a high-field Nb_3Sn accelerator magnet to reduce risk, increase efficiency and decrease cost as required by an industrial production on large scale?

For HTS high-field accelerator magnets, the leading questions are more essential to the potential and suitability for accelerators, with the awareness that the body of work in progress is not yet at the point where a reference technology can be defined:

- 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 Nb_3Sn, 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?

Finally, common to Nb_3Sn and HTS:

- Q9: What is the specific diagnostics, instrumentation, and infrastructure required for a successful HFM R&D, taking into account the 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?

2.5 Proposed Program Structure and Deliverables

2.5.1 Conductor development

Nb_3Sn

The main focus of this R&D line is threefold: (i) to advance the performance of Nb_3Sn wires beyond present state-of-the-art, (ii) to make the performance of present and future Nb_3Sn conductors more robust, (iii) to increase the number of qualified manufacturers of HEP-class Nb_3Sn conductors and make the material less expensive in view of a demonstration of production scale-up. Here we intend with performance the full set of requirements, including manufacturing, mechanical and magnetic properties as specified for the FCC Conductor Development Program. Development is still needed to achieve those targets.

HTS

Activities in Europe are focusing on REBCO tapes. The focus will be on achieving controlled, homogeneous and reproducible geometrical and electro-mechanical properties along the full length, e.g. internal resistance in between layers, copper stabilizer electrical resistivity, effect dog-bone shape of copper stabilizer. Feedback shall be given by the community to tape manufacturers to make them aware of the needs and identified problems. Some innovative and more fundamental rethinking will be required, that may bring advantages in magnet design, e.g. material engineering to mitigate the anisotropy of REBCO. Industrialization should be addressed to assure the feasibility of long - 1 km target – unit lengths as required for magnet manufacturing. It is important to resolve the question of cables, through development, qualification, and identification of cable configurations suitable for accelerator quality magnets (stack, CORC, Roebel, novel concepts), addressing (among others) the need for transposition.

A decision on practical conductor specifications (Nb_3Sn and HTS), with a cost-effective production perspective, will be one of the main outcomes of the development work planned in the coming years.

2.5.2 Nb_3Sn magnet development

There is intimate synergy between the development of ultimate-field and robust magnets. The development at this stage intends to master building blocks that may or may not be relevant for the eventual ultimate-field design (e.g. compare different needs for high/low pre-stress compact coils, SM coils). Timing of technology R&D vs. demonstrators is challenging. The need for technology R&D and innovation must be balanced with the need for demonstrator magnets tested by the next ESPP update. And in the end, all developments must constitute steppingstones towards robust ultimate-field magnets. Specifically, developments that are applicable only in the 12 T (present HL-LHC) range shall not be in the scope of this roadmap. The R&D shall strive for fast-turnaround step-by-step validation, using agile design that incorporates insights from previous steps: from material samples to coil-composite samples and powered-cable samples, to subscale coils (e.g. SMC) or directly to 12 T range mirrors and magnets, and on to 14, 15, or 16 T magnets (depending on available conductor, robustness and maturity of technology). It is important to plan length scale-up from earliest design stages, promote automation and innovations leading to simplified processes, even if these do not yet get implemented in the first coils.

A decision on a feasible, cost-effective, and practical operating field for Nb_3Sn magnets will be one of the main outcomes of the development work planned in the coming years.

2.5.3 HTS magnet development

Given the cost of HTS the natural solution is a hybrid solution where LTS are used in the lower magnetic field area (below say 15 T), and HTS are used above. Such a configuration requires the use of liquid helium as coolant (there are some concerns about using he-II with HTS, this has to be checked). However, there is a great opportunity to work at 20 K with J_E well in excess of the 500-800 A/mm² that is usually required. We hence need to explore the possibility of intermediate temperature range (10-20 K) and dry magnet (conduction cooled). This may have deep implications on the overall thermal, mechanical and magnetic design.

The R&D on HTS magnets will likely focus on manufacturing and testing sub-scale and insert coils as a “R&D vehicle” and demonstration of operation beyond the reach of Nb_3Sn. The ‘controlled-insulation’ scheme for HTS coil will be explored by testing coils with reasonable current and with requirements for accelerators (e.g. ramp rate of 20 T in 1000 s in LHC, 20 mT/s). This question is very important since it can change dramatically the design principle not only of the magnet but also of the conductor. The coil shape design will be optimized to reduce wrong field components (//c). The end design options (cloverleaf, CCT,. . .) is a crucial issue that needs to be addressed to mitigate the complexity of tape ratio aspect and hard way bending. Finally, screening currents effects (magnetization and time stability) need to be understood in detail, with ways to decrease/remove these effects (overshoot/vortex shaking/temperature increase)

2.5.4 Cross cutting technologies

Advances will be required in these fields that are common to both Nb_3Sn and HTS magnets (i.e. cross-cutting):

Materials, Cryogenic and Modeling

R&D programs on material development and characterization are already in place in the EU and the USA and must be reinforced. The global strategy to follow is to

- Develop and characterize materials and composites relevant to HFM applications (including detailed material studies, advanced imaging and analytical techniques, material measurements and descriptions);
- Develop new engineering solutions for thermal management of high field magnets (both internal, heat transfer to coolant, and external, heat transfer to cryoplant) to be integrated from the start;

- Consolidate the modelling tools to complement short model magnets (constitutive equations and models adapted to the whole spectrum of electro-thermo-mechanical, cryogenics and thermo-physical properties relevant to HFM R&D).

Magnet Protection and Powering

The challenges posed by magnet powering and protection have multiple facets, and they will need to be addressed in an integrated manner.There is a remarkable parallel between the magnet protection and magnet mechanics challenges. Firstly, detection and protection in the regime of stored energy and energy density described above will require new concepts, especially for HTS (e.g. non-insulated or 'controlled-insulation' windings). Secondly, measurement and characterization of the thermo-mechanical and dielectric properties and limits of coils and structures will be a mandatory step to ensure that the design is safely within allowables. Finally, comprehensive multi-physics models with augmented accuracy will be the main tool guiding design and analysis in the extended regime of field, stored energy, temperature and voltages. Also of high importance, and related to materials characterization, is the determination of degradation limits of Nb_3Sn and HTS magnets.

2.6 Facilities and Infrastructure

The development of high field magnets requires, at the partners' laboratories, dedicated infrastructure suitable for R&D, at the start. Construction of full-scale prototypes, also engaging industry, is needed in a more advanced phase of the activity.

Among the dedicated infrastructure required for manufacturing both superconductors and magnets activities, we see a critical need of: Rutherford cabling machines for producing Nb_3Sn cables with large in-field current capability and a large number of strands (40 to 60); cabling machines for HTS cables; automated winding machines for the production of LTS and HTS coils.

The goal is to acquire such infrastructure by the end of this phase of the R&D, to be shared among all collaborators.

For test and measurement of magnets, we need test stations for the electro-mechanical qualification of conductors, at 1.9 K and 4.5 K, in external magnetic fields of up to 20 T and possibly beyond; test stations with high-field magnets having large bore aperture and enabling the measurement of HTS coils in a background magnetic field—this is a specific requirement for the qualification of HTS coils; multi-purpose vertical or horizontal test stations for long coils and magnets.

A basic step at the beginning of this R&D is to review existing diagnostic, instrumentation and test infrastructure as required by HFM R&D, and establish future needs. We will then need to coordinate instrumentation and test infrastructure development and upgrades and facilitate sharing of test resources within the scope of HFM R&D.

3 High-gradient Plasma and Laser Accelerators

R. Assmann[a,b], K. Cassou[c], S. Corde[d], L. Corner[e], B. Cros[f], M. Ferrario[b], E. Gschwendtner[g], S. Hooker[h], R. Ischebeck[i], A. Latina[g], O. Lundh[j], P. Muggli[k], P. Nghiem[l], J. Osterhoff[a], T. Raubenheimer[m], A. Specka[n], J. Vieira[o], M. Wing[p]
Associated members: C. Geddes[q], M. Hogan[m], W. Lu[r], P. Musumeci[s]

[a]DESY, Hamburg, Germany
[b]LNF/INFN, Frascati, Italy
[c]IN2P3/IJCLab, France
[d]IP Paris, France
[e]Liverpool University, United Kingdom
[f]LPGP-CNRS-U Paris Saclay, France
[g]CERN, Geneva, Switzerland
[h]Oxford University, United Kingdom
[i]PSI, Villigen, Switzerland
[j]Lund University, Sweden
[k]MPI Physics, Munich, Germany
[l]CEA/IRFU, France
[m]SLAC, Stanford, United States
[n]IN2P3/LLR, France
[o]IST, Lisbon, Portugal
[p]UCL, London, United Kingdom
[q]LBNL, Berkeley, United States
[r]Tsinghua University, Beijing, China
[s]UCLA, Los Angeles, United States

3.1 Executive Summary of Findings to Date

The field of plasma and laser accelerators has reached the stage of setting up first user facilities in the European research landscape. The many national and regional activities will continue until the end of the 2020's with a strong R&D and construction program, aiming at lower energy research infrastructures (for example, a GeV-scale free-electron laser facility, high-resolution medical imaging). Various important milestones have been achieved or will be achieved over the next years at those ongoing programs, including strong programs at CERN, INFN, DESY, RAL, Helmholtz, CNRS, STFC, ELI, EuPRAXIA, SLAC, LBNL, Tsinghua University, Shanghai XFEL and others. This should be complemented by early HEP targeted tests and R&D activities. Given that funding for ongoing activities is mostly from non-HEP sources, several HEP aspects are neglected, for example staging to high energy, efficiency, positrons and polarization. The panel proposes an R&D roadmap for particle physics that is based on three pillars (see section 3.7.1). The concept includes the first international feasibility and pre-CDR study for high gradient plasma and laser accelerators and their particle physics reach. This paper study will lead to a comparative report on various options, a feasibility assessment, performance estimates, physics cases and a cost-size-benefit analysis for high energy (see section 3.7.2). A second pillar will demonstrate a number of technical feasibility issues of importance for particle physics experiments through a prioritised

---

This contribution should be cited as: High-gradient Plasma and Laser Accelerators, DOI: 10.23731/CYRM-2021-XXX.13, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 13.

list of technical R&D topics. A full list of three technical R&D areas and 16 topics has been established and analyzed for State-of-the-Art and R&D objectives (see sections 3.4, 3.5 and 3.7.3). A third pillar on integration and outreach in our proposed roadmap aims at capitalizing on the high synergistic potential with other fields and large projects like EuPRAXIA. This pillar also discusses access to distributed R&D facilities under clear rules and supports innovation with closely connected industry. After successful demonstration of various milestones and successful completion of ongoing major programs (AWAKE, EuPRAXIA, national programs), a dedicated HEP test facility will likely become necessary and should be operational in the mid 2030's. At this time the effort could evolve to develop a plasma and laser accelerator test facility at CERN or another suitable location.

3.2 Motivation

The progress in accelerator-based high energy physics is affected by practical limitations in size and cost with the RF accelerator technology used so far. Novel accelerator technologies overcome limitations in accelerating gradients by relying on plasma or dielectric structures, driven by modern high-power lasers or particle beams. Accelerating fields can be increased from today's values (below 0.1 GV/m) to values above 1 GV/m, typically even to the 10-100 GV/m regime. A new generation of highly compact and more cost-effective accelerators can be envisaged, promising new scientific reach with particle accelerators, also for High Energy Physics (HEP).

The potential of high gradient plasma and laser accelerators is illustrated by recent advances, including up to 42 GeV energy gain in electron-driven, 8 GeV in laser-driven and 2 GeV in proton-driven plasmas. This is complemented by progress in beam quality (low energy spread, small emittance, ...) and stability in different facilities or experiments and by the demonstrations of first lasing with a beam from a laser-driven plasma accelerator at SIOM and from a beam-driven plasma accelerator at LNF/INFN. The community has grown together in the EU-funded EuroNNAc network, in the ALEGRO activity, the AWAKE collaboration and the EuPRAXIA conceptual design study. Parallel progress has been achieved for dielectric accelerators (ACHIP, as well as individual efforts on dielectric laser and terahertz acceleration) with the potential of very high repetition rate (MHz) and mass production (accelerator on a chip).

The field is driven by a rapidly growing, successful, diverse and young community with strong links to universities, research centers and industry. There are growing links to users in the fields of Free Electron Lasers (FEL) and health. It is important to grow links to the users in High Energy Physics (HEP) in parallel. Only with support from HEP can the promise of a highly compact and more cost-effective collider be realized on the 30-year horizon, opening new discovery reach for particle physics. We note that the plasma and laser accelerator technologies can support intermediate steps at lower energy, enabling HEP experiments in dark matter search and highly non-linear QED. It can also be used to boost energy in adequately designed RF collider designs or to replace large-scale beam injectors.

3.3 Panel Activities

3.3.1 Mandate and scope

The expert panel "High Gradient Acceleration – Plasma, Laser" is charged with defining the roadmap in the area of plasma wakefield and dielectric structures acceleration. This includes as particular tasks: (1) Develop a long-term roadmap for the next 30 years towards a HEP collider or other HEP applications. (2) Develop milestones for the next 10 years taking explicitly into account the plans and needs in related scientific fields, as well as the capabilities and interests of the stakeholders. (3) Establish key R&D needs matched to the existing and planned R&D facilities. (4) Give options and scenarios for European activity level and investment. (5) Define deliverables and required resources for achieving these goals until the next European strategy process in 2026, in order to enable as best as possible critical decisions for R&D lines for HEP.

3.3.2 Activity

The expert panel was formed during February 2021 and had its kick-off meeting on March 2, 2021. Since then, an elaborate process of consultation with the advanced accelerator community has been put in place. The process has been steered through 16 meetings of the expert panel. The activity was announced world-wide, and experts were invited to subscribe to an email list. At the end of May, 231 experts in total have registered to this list and are participating in the roadmap process. A first town hall meeting was held on March 30 and set the scene for advanced accelerators for HEP. The meeting included talks on high-energy physics facilities or experiments at the energy frontier (linear collider) and at lower energies (dark matter search, highly non-linear QED, low energy gamma-gamma). HEP relevant parameter examples and two possible case studies were assembled and distributed. Also, a number of questions were formulated by the panel and sent to the community, asking for input. A second and a third town hall meeting were held on May 21 and 31, where in total 48 speakers presented their input to the roadmap process. The meetings were attended by up to 135 participants at a given time. A fourth town hall meeting will take place later, where the roadmap will be reviewed.

3.3.3 International Activities and Integration

Particle physics is an international endeavor, and we recognize that a coordinated strategy will be the most successful. In parallel to the activities of this expert panel, there are ongoing international activities in the United States and Asia. These international processes will define the most important questions for the field of particle physics and identify promising opportunities to address them. In the U.S., the Particle Physics Community Planning Exercise (a.k.a. "Snowmass") is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners.

Input to Snowmass is organized through ten different frontiers including the Accelerator Frontier. The Accelerator Frontier has several topical groups including AF-6 'Advanced Accelerator Concepts'. Advanced Accelerator programs are developing new concepts for particle accelerators, generation, and focusing that could revolutionize the cost paradigm for future accelerators. To ensure the required international coordination and to arrive at a globally coherent roadmap for novel accelerators, the AF-6 convenors include membership from the Expert Panel and vice versa.

3.4 State of the Art

The state of the art and specific challenges are shortly reviewed and described in this section.

3.4.1 Sources of Electrons, Positrons, Plasmas and High Power Laser Pulses

High-quality LWFA injector: Many laser wakefield acceleration (LWFA) experiments employing low repetition rate lasers (typically $f_{\mathrm{rep}} = 1\,\mathrm{Hz}$) have demonstrated the generation of electron bunches with energies of order 1 GeV , a bunch charge of tens of pC , a divergence of 0.1 - 1 mrad . We observed in the last years a transition from demonstration and physics studies experiments to accelerator research and development; Maier et al. have reported continuous operation for 24 hours of a LWFA at a pulse repetition rate of 1 Hz.[1] This experimental arrangement designed as an accelerator allows the first advanced studies leading to strong improvement of the beam quality . We note that kHz laser driver have been used to demonstrate LWFA with beam energy up to $15\,\mathrm{MeV}$.[2]

High average power, high efficiency laser drivers and schemes: Currently Ti:sapphire lasers, pumped with frequency doubled diode lasers or flash lamp pumped Nd:YAG, are the drivers of choice for LWFA.

---

[1] as example: Maier et al. have reported $E = 368\,\mathrm{MeV} \pm 2.5\%$; $Q = 25\,\mathrm{pC} \pm 11\%$; $\Delta E/E = 15\%$; $\Delta\theta = 1.8\,\mathrm{mrad}$

[2] as example: Salehi et al. have generated $E = 15\,\mathrm{MeV}$, $Q = 2.5\,\mathrm{pC}$, $\Delta\theta = 7\,\mathrm{mrad}$ bunches at $f_{\mathrm{rep}} = 1\,\mathrm{kHz}$

Commercial systems operate at high peak power (10 PW at ELI-NP) and useful repetition rates (1 PW @ 1 Hz, BELLA). However, laser drivers for LWFA-based colliders require much higher average power. Options for achieving this performance come under two main headings: improving Ti:sapphire lasers includes more efficient cooling of the laser for higher repetition rate and better pump lasers (higher energy, repetition rate and efficiency) i.e. frequency doubled diodes or Yb-doped fibre lasers. The EuPRAXIA project, together with European laser industry, Amplitude and Thales, is aiming at the 20-100 Hz regime and there are concepts for up to kHz rates. Beyond this, new lasers and technologies are needed to overcome the intrinsic limitations of Ti:sapphire lasers and to reach the tens of kHz required for an HEP relevant collider. Options under development include the combination of multiple low energy, high repetition rate Yb-doped fibre lasers, recently demonstrating pulses of 10s mJ, 100 fs, 10s kHz , thin disk Yb-doped lasers generating joule-level pulses at kHz repetition rates so far at longer durations , Thulium doped lasers operating at 2 μm having produced GW, < 50 fs pulses , the Big Aperture Thulium (BAT) developing Th:YLF lasers. Each of these technologies is being developed towards the capability to produce 30 J-class pulses at 10's of kHz and at pulse durations at or below the 100 fs level, providing multiple options to enable efficient plasma accelerators.

Positron technical demonstrations: Results on the acceleration of injected positrons in a beam-driven plasma accelerator have been achieved at FACET. An overview and outlook for efficiency and beam quality has been reported . Concepts for positron generation at the GeV level have been developed at the Queens University Belfast and others. Publications include the conceptual design of a positron source and line for the EuPRAXIA facility.

Advanced plasma photoguns with ultra-low emittance: Plasma photocathodes promise production of electron beams with ultra-low normalized emittance in both planes. Such beams may obviate the need for damping rings for potential future HEP injectors and would be compatible with plasma-based collider schemes, and could on short term be used as test beams. The first plasma photogun was realized in proof-of-concept experiments at SLAC FACET , and next experiments, e.g., at SLAC FACET-II aim to demonstrate the potential of the scheme towards normalized emittances of the order of 10 nmrad.

Hybrid laser-beam driver schemes: demonstration, stability, efficiency: LWFA-driven PWFAs utilise high peak-current > 6 kA electron beams from compact laser-driven wakefield accelerators to subsequently drive a phase-constant PWFA stage. A European 'Hybrid' collaboration has been formed and has achieved major conceptual and experimental milestones in quick succession . The hybrid concept aims at demonstrating an overall highly compact platform that combines the LWFA and PWFA schemes and delivers at the same time high quality electron beams.

Development of plasma sources for high-repetition rate, multi-GeV stages: Operation of plasma accelerators at high repetition rates of O(10 kHz) and high average powers of O (100 kW) driver per stage will be crucial to realize high-energy-physics experiments. Modern plasma sources are based on various technologies, e.g. capillary discharges, gas jets, plasma cells, and laser-shaped channels. These sources have been robustly characterised and used in low-repetition-rate (Hz to kHz-level) plasma-wakefield experimentation . Different source concepts are needed for laser or beam drivers and electron or positron acceleration to fulfil the specific requirements for high-quality and efficient plasma accelerator modules, all of which must become compatible with the required high rates and powers.

3.4.2 System Tests: High Quality Electrons

Dielectric accelerator module with high quality beam for first applications: Significant progress has been made on dielectric laser accelerators (DLA) in recent years . The stated goal of the Accelerator-on-a-Chip International Program (ACHIP) is to demonstrate an energy gain of 1 MeV in a dielectric laser accelerator. The collaboration is confident to be able to reach this by the year 2022. Simulations of the focusing effects of suitably designed structures have been verified by experiments.

High quality beams: electron-driven plasma accelerator-based FEL in saturation: Two test-facilities in Europe, FLASHForward at DESY and SPARC_LAB at INFN-LNF, and a group at the Strathclyde University (in collaboration with ASTeC, UCLA and SLAC), are currently conducting experiments with beam driven plasma accelerators in order to produce high quality beam parameters and the possibility to observe FEL gain. Great progress has been made in recent years in demonstrator experiments for the preservation of beam quality in terms of energy spread and emittance and the first experimental evidence of the feasibility of a plasma photocathode has been shown. Very recently the first demonstration of exponential gain in a SASE FEL at 830 nm driven by a plasma accelerated beam has been also reported .

High quality beams: laser-driven plasma accelerator-based soft-Xray FEL in saturation: Several proof-of-principle experiments for a laser-driven free-electron laser are being pursued in Europe, for example COXINEL at LOA/Soleil and LUX at DESY. In addition experiments in Shanghai, China, and LBNL, United States, are making important progress. Beam quality is advanced, first lasing of a laser-plasma based free-electron laser has been reported and a new high quality plasma acceleration scheme has been proposed within the EuPRAXIA project .

Proton-driven plasma wakefield acceleration: Proton drivers available today carry a large amount of energy of typically 10s to 100s of kJ (less than 100 J with laser and electron drivers) and can therefore, in principle, accelerate electrons to TeV energies in a single plasma. The Advanced WAKEfield Experiment (AWAKE) at CERN, led by a world-wide Collaboration of 23 institutes, is a proof-of-concept experiment active at CERN, where suitable proton bunches and infrastructure are available . The AWAKE Collaboration has demonstrated for the first time that a long proton bunch, too long to drive large amplitude wakefields, self-modulates in a high-density plasma in a phase controlled way due to seeding, and then drives large amplitude fields . In addition the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields was demonstrated .

3.4.3 Collider Components

Staging of electron plasma accelerators including in- and out-coupling: Staging of plasma accelerators is essential to reach high energies together with high efficiency and high repetition rate. Major challenges arise from strong focusing in plasma and therefore highly diverging beams outside the plasma, as well as the need to in- and out-couple the driver without disrupting the accelerating beam. Advanced beam optics including plasma lenses and plasma ramps will therefore be key to staging, as well as managing sub-fs synchronization and sub-µm misalignment tolerances , for example by deploying novel self-stabilization concepts . Experiments at LBNL demonstrated first acceleration in two independent laser-driven stages.

Polarized electrons: Laser-driven generation of polarized electron beams in combination with the development of advanced target technologies is being pursued in the framework of the ATHENA consortium and EuPRAXIA . Novel target technologies will be tested at different laser facilities, e.g. at DESY in the near future. The goal is to demonstrate the capability of plasma wakefields to preserve beam polarization during the acceleration process.

Plasma lens R&D: Radially symmetric focusing with a magnetic gradient of the order of kT/m has been demonstrated for electron beams by means of plasma-based lenses. Several results have been also obtained with active plasma lenses (APLs), showing the focusing of relativistic electron beams both from laser-plasma and RF accelerators . Experimental measurements demonstrating that the beam emittance can be preserved (and lensing effect improved) by enhancing the linearity of the focusing field have been also reported .

High transformer ratio in PWFA for high efficiency and low energy spread: Shaping the current profile of the drive bunch (DB) and witness bunch (WB) can control the excitation of wakefields and maximize the energy transfer efficiency from the DB to the WB . A DB longer than the plasma period and with a triangular current profile, or a train of bunches with increasing charge can drive wakefields with accelerating fields much larger than decelerating fields. The ratio of these fields, the transformer ratio, as high as ∼8 has been demonstrated experimentally . Shaping of the WB further allows for minimization of the final energy spread through precise flattening of the wakefields, i.e. beam loading. This field flattening has been controlled to the %-level in experiment . Conservation of the transverse normalized emittance requires precise matching of the WB to the focusing force of the plasma column.

3.4.4 Conceptual Pre-Design Advanced Linear Collider at Energy Frontier

There exists a number of very rough parameter sketches and ideas for an e^+e^- or $\gamma\gamma$ collider based on plasma or dielectric technology. In strong contrast to other novel concepts (for example the muon collider) there has never been a coordinated, pre-conceptual design study for such a collider world-wide. Such a coordinated study is missing to address feasibility, perform supporting simulations and to estimate rough size and costs.

3.4.5 Numerical and Theoretical Tools

Computer simulations and theory have been providing critical support to the development of plasma-based accelerators for decades. In order to enable successful endeavours towards HEP, it is now of the highest importance to address previously unexplored scientific questions and to prepare an open-science model capable of taking full advantage of pre-exascale and exascale systems . Global and time-enduring efforts over the next decades targeting theory/numerical R&D activities, code maintenance and development will be pivotal to perform accurate collider-relevant predictions.

3.5 R&D Objectives

The R&D Objectives that the panel has identified are shortly reviewed and described in this section.

3.5.1 Sources of Electrons, Positrons, Plasmas and High Power Laser Pulses

High-quality LWFA injector : Reaching injector charge and emittance, at the level or above the ones expected for a collider requires an increase in the mean current of four orders of magnitude, and a decrease in the normalized emittance by about one order of magnitude compared to present values. We therefore identify three priorities: 1) Increasing the bunch charge of high-repetition-rate LWFAs by one or two orders of magnitude to the 0.1 - 1 nC range; 2) Developing laser drivers capable of $f_{\mathrm{rep}} > 10\,\mathrm{kHz}$; 3) Decreasing the bunch emittance for high-repetition-rate LWFAs by one or two orders of magnitude.
Dedicated accelerator test beamlines for all aspects of laser-driven accelerators are urgently required. These could be hosted in existing facilities, or one or more new facilities could be considered. Proposed milestones are:

2024: Models for nC-level, low emittance LWFA injector proposed and validated by simulations.
2025: Experiments, optimization studies, possibly at lower charge and repetition rate at existing facilities.
2027: Experimental demonstration of $Q > 100$ pC, $\epsilon_n < 1$ μm, $10 \leq f_{rep} \leq 100\,\mathrm{Hz}$.
2032: Experimental demonstration of $Q > 500\,\mathrm{pC}$, $\epsilon_n < 100\,\mathrm{nm}$, $f_{rep} > 1$ kHz.
2037: Experimental demonstration of $Q > 500\,\mathrm{pC}$, $\epsilon_n < 10\,\mathrm{nm}$, $f_{rep} > 10$ kHz.

High average power, high efficiency laser drivers and schemes: For HEP applications, the goal is to produce a laser with an average power output of $> 300\,\mathrm{kW}$, a wall plug efficiency $> 15\%$, and $< 100\,\mathrm{fs}$ pulse duration. For the power consumption to drive a 1 TeV beam at 15 μC/s (1 5 MW beam power) to be less than 200 MW, the wall plug to beam efficiency needs to be $> 7.5\%$. In addition, such a TeV accelerator with 100 stages requires the beam to gain 150 kW per stage; for a laser-to-beam efficiency of less than 50% this requires the average output power of the drive laser for each stage to exceed 300 kW and have an efficiency $> 15\%$. In order to eventually deliver 1, 10 and 300 kW lasers we identify three milestones:

2026: 1 kW: 10 J, 100 Hz, $<$ 100 fs laser for driving a high repetition rate test beamline facility.

2030: EuPRAXIA laser at 800 nm wavelength (few kW): pulse energy 50-100 J, repetition rate 20-100 Hz, pulse duration 50-60 fs, energy stability (RMS) 0.6–1%, pointing stability (RMS) 0.1 μrad.

2032: 10 kW: 10 J, 1 kHz laser producing multi-GeV beam energies at kHz rates.

2035: 300 kW: 30 J, 10 kHz $>$ 15% efficient laser for HEP collider stages.

Positron technical demonstrations: R&D on generation and handling of high energy positrons is emerging with limited but rapidly evolving efforts. The key R&D objectives for positrons include:

2023: Demonstration of high-quality (pC, μm normalized emittance, 2% energy spread) positron beam from a plasma wake-field accelerator at the few hundred MeV level.

2026: Demonstration of high-quality positron beam from a plasma wake-field at the 1 GeV level.

Advanced plasma photoguns with ultra-low emittance: The key R&D objectives of advanced plasma photoguns concerning HEP activities for the next years include:

2024: Demonstration of few 10's nm rad normalized emittance.

2026: Demonstration of ultra-low normalized emittance beams with collider-level energy spread and energy stability.

2027: Development and demonstration of high-charge (100's of pC to nC, moderate to extreme currents), plasma photoguns with ultra-low normalized emittance.

2028: Demonstration of spin-polarized ultra-low emittance electron beams from plasma photocathodes.

Hybrid laser-beam driver schemes: demonstration, stability, efficiency: The compact LWFA→PWFA platform can be implemented at numerous LWFA facilities worldwide for rapid development and testing of HEP-relevant building blocks, such as plasma energy boosters, components for inter-stage beam transport and beam extraction, and ultra-high brightness injectors based on selective ionisation injection in the PWFA stage . Hybrid plasma wakefield accelerators can thus address a wide range of HEP-relevant R&D objectives, e.g.:

- Fundamental PWFA research, including energy transfer efficiency, driver depletion and emittance preservation (ongoing).
- Demonstration of physics concept-based stability enhancement from hybrid plasma wakefield accelerators (ongoing).

2023: Realization of tuneable PWFA internal injection schemes, including miniaturized plasma photoguns.

2024: Demonstration of emittance and brightness enhancement by a factor of 10 to 10000 compared to the initial LWFA output.

2027: Demonstration of advanced sources such as X-FEL.

Development of plasma sources for high-repetition rate, multi-GeV stages: A number of objectives will need to be reached in order to meet the R&D goal of plasma sources for collider relevant repetition rates and average powers. This includes plasma containment and generation to maintain beam quality and high-rate operation, durability, energy transfer during plasma acceleration, plasma vessel cooling, and more. The route towards a demonstrator high-repetition-rate and high-average-power plasma accelerator may be broken down into three key parts:

2026: Demonstrate essential physics questions, e.g. wakefield process efficiency and repeatability.

2035: Push plasma source technology as close as possible towards that working point. To achieve this, a dedicated testbed for iterative plasma-source development will be required as part of a new test beamline for high-repetition-rate plasma accelerator research. Each iteration of the technology must then be tested with sustained operation at a repetition rate conducive with those of plasma-based-collider designs e.g. 10 kHz.
2035: The average powers per stage are pushed into the relevant multi-10 to 100 kW regime at a dedicated new facility consistent with the outcome of the proposed conceptual design report.

For the case of laser-driven acceleration, this strategy needs to be closely synchronized with the development of high repetition rate, high average power, and efficient drive laser technology.

3.5.2 System Tests: High Quality Electrons

Dielectric accelerator module with high quality beam for first applications: The ongoing and proposed work is demonstrating many of the elementary components of dielectric laser accelerators. At the same time, key aspects of relevance for high energy physics accelerators should be investigated. These include further improvements on beam focusing and containment, energy efficiency, as well as beam control, instrumentation and feedbacks. The proposed milestones are:

2023: Generation of a 5 MeV beam.
2024: Develop a simulation code capable of simulating a billion accelerating cells.
2025: Apply DLA beams for applications outside HEP and design and simulate a source of GeV beams.
2026: Design and simulate a linear collider at the energy frontier.
2028: Instrumentation and feedbacks for DLA: measurement of orbit and profile.
2030: Synchronization of laser sources, alignment of structures and develop a concept for power recirculation.

High quality beams: electron-driven plasma accelerator-based FEL in saturation: The main goal of FLASHForward is to demonstrate high-fidelity acceleration of electron bunches in GV/m-gradient wakes with final beam quality sufficient to produce gain in an FEL. The UK collaboration is aiming to drive an FEL with new beam injection schemes in plasma. On a longer time scale the European project EuPRAXIA aims at the construction of a user facility driven by a plasma wakefield module. Expected to be operational by the end of 2029, EuPRAXIA envisions producing 10^{12} photons/pulse at 4 nm, in the so called "water window" spectral region, by using a 30 pC electron bunch with 3 kA peak current, normalized rms emittance $<1\,\mu$m and rms energy spread of 0.1 %. The proposed milestones and the final deliverable are:

2021: Demonstration of FEL-SASE and seeded exponential growth at 830 nm.
2024: Demonstration of FEL saturation at short wavelength (<830 nm).
2025: EuPRAXIA Technical Design Report ready.
2029: EuPRAXIA facility in operation with users.

High-quality beams: laser-driven plasma accelerator-based soft-xray FEL in saturation: A laser-plasma based FEL in full saturation is expected to be achieved at the DESY LUX experiment by 2030 at latest, proving sub % energy spread, kA peak current, 24/7 operation at low repetition rate (up to 5 Hz). The EuPRAXIA project has produced a conceptual design of a 5 GeV plasma-based FEL facility including all required infrastructure. The proposed milestones and the final deliverable are:

2021: Demonstration of FEL-SASE .
2023: Decision laser-driven plasma FEL site EuPRAXIA.
2026: EuPRAXIA Technical Design Report ready.

2030: Demonstration fully saturated FEL at LUX. EuPRAXIA laser-driven facility operates with users.

Proton-driven plasma wakefield acceleration: demonstration of high energy gain, emittance control, scalability: AWAKE has a clear roadmap towards early application for HEP; AWAKE Run 2 starts in 2021 and aims to bring the technology to a point where particle physics applications based on the AWAKE scheme can be proposed and realized.

2026: Until 2026 AWAKE plans to demonstrate the seeding of the self-modulation process with an electron bunch and optimize the process of generation of wakefields using a plasma density step to accelerate electrons to multi-GeV energies.
2030: In the next 10 years AWAKE aims to demonstrate the acceleration of an electron witness bunch to 10 GeV in 10 m with control of the incoming normalized emittance at the 10 mm-mrad level and percent energy spread, to develop scalable plasma sources 50-100 m long, and to demonstrate acceleration in a scalable plasma source (helicon or discharge) to 50 to 100 GeV energies.
>’30: Starting in 2030, by the successful end of Run 2, the AWAKE scheme will be ready for first high-energy physics applications . Proton-driven plasma wakefield acceleration technology could be used in fixed target experiments for dark photon searches, and also for future electron-proton or electron-ion colliders at very high energies, where lower luminosity is acceptable.

3.5.3 Collider Components

Staging of electron plasma accelerators including in- and out-coupling: The challenges are described in 3.4.3 and include also developing and demonstrating the staging optics in a proof-of-principle experiment, understanding the full 6D dynamics across numerous stages in the presence of such optics and whether any further self-correction mechanisms can be exploited, especially in the transverse phase space (e.g., betatron radiation damping at high energies). The required steps are:

2027: Experimental check of staging at 5 GeV. Extend the design to its use at 50 GeV and 180 GeV, for quadrupoles and for plasma lenses.
2027: Design and build plasma lenses for the high energy beams of 50 GeV and 180 GeV.
2034: Design, implement, and test complete transfer lines at 50 GeV and 180 GeV.

Polarized electrons: The generation of few 100 MeV polarized electron beams from plasma with high polarization fraction for injection into conventional accelerators, and storage rings is an important next step. To reach this goal, hardware development and spin tracking simulations to provide polarized sources and polarization conservation in plasma are carried out. In parallel, R&D work for polarized targets and polarimetry is being conducted. All developments will be supported by proof-of-principle experiments with polarized beams, e.g., at ARCturus and EuPRAXIA. Milestones are:

2024: Demonstration of polarized electron beams from plasma with 20% polarization fraction.
2031: Increase of the polarization fraction to >85%.

Plasma lens R&D: The demonstration of focusing effectiveness at high energy with round and flat beams, while preserving the quality of both electron and positron beams, is a fundamental achievement that could be integrated in a dedicated linear collider plasma module test facility. The proposed milestones are:

2024: Demonstration of focusing effect of high quality electron beams at multi-GeV energy range.
2025: Development and demonstration of collider concept for positron focusing with plasma lenses.
2026: Integration of plasma lenses in the HEP test facility CDR.
2030: Demonstration of a transversely tapered design for local chromaticity correction.

High transformer ratio PWFA for high efficiency and low energy spread: While plasma-based accelerators driven by particle bunches or laser pulses can operate with usual Gaussian-shaped beams or pulses, shaping of the driver and/or of the witness bunch will considerably improve the accelerator parameters in terms of beam quality and energy transfer efficiency. Milestones are:

2026: Emittance preservation over many betatron periods in a plasma module with simultaneous large energy gain (of order drive energy), high total efficiency (30% driver to witness), normalized emittance conservation (at the 1 μm level), and narrow energy spread (0.1%).

2030: Optimization of the transformer ratio while mitigating beam-plasma instabilities, such as beam hosing .

3.5.4 Numerical and Theoretical Tools

The priorities identified for the numerical and theoretical tools are (i) include missing physics (quantum-mechanics and hydrodynamics), (ii) account for relevant radiation emission processes , (iii) develop user-friendly, numerically stable and accurate full and reduced computational models , combined with AI/ML (iv) model driver/witness beams with arbitrary space-time and phase-space structures , (v) ensure stable acceleration and mitigate unwanted instabilities , (vi) increase efficiency and quality of positron acceleration in plasma towards collider and HEP applications, (vii) determine repetition rate limits based on the long-term plasma dynamics. The required milestones are:

2022: Setup of simulation tools for electron case studies ($\geq$ 2 stages) with certain approximations.

2023: Same for positron case study

2026: Study of spin preservation and beam-disruption mitigation strategies for a plasma-based collider.

2028: Demonstration of highly accurate (3D PIC, flat beams), stable and efficient numerical models.

2030: Start-to-end simulations of many plasma acceleration stages.

3.6 Facilities and Infrastructures

Here we summarize ideas and concepts for first particle physics experiments and facilities at intermediate (lower) beam energies. The advanced, compact Particle Physics collider is discussed in the following section, as a key element of our roadmap. In addition, we summarize required accelerator R&D facilities.

3.6.1 First Particle Physics Experiments and Facilities

As an intermediate step towards a linear collider at the energy frontier, we consider an accelerator capable of generating electrons with an energy of 15 to 20 GeV. One class of experiments that would profit from such an accelerator are fixed-target experiments aimed at the discovery of weakly interacting particles. A design for such a low energy HEP application facility involving plasma and dielectric accelerators does not exist beyond the idea stage.

3.6.1.1 Single electron tagging experiments

High-quality electron beams in the energy range 15–20 GeV are scarce, but have potential application in HEP. A case for an experiment to search for dark photons has been made based on electrons in the SPS. In order to tag each incoming electron, single electrons enter the experiment. Such a scheme allows for the full reconstruction of the event and hence the possible decay of dark photons to "invisible" dark matter candidates as well as e.g. e^+e^- pairs. For a possible list of parameters, see also Table 3.1.

A dielectric laser accelerator could be capable of generating such beams, possibly with a higher efficiency than conventional sources. The proposed particle energy is several orders of magnitude beyond present capabilities of dielectric laser accelerators.

3.6.1.2 Electron bunches experiments

In a bunched scheme, the individual incoming electrons cannot be tagged and signatures like the decay of dark photons to e^+e^- pairs in beam-dump mode are searched for. The AWAKE experiment has done a study of using such bunched electrons with energies of 50 GeV and above . At the lower energy of about 20 GeV, the sensitivity at higher masses of the dark photon will be reduced, but the possibility to investigate an as yet unexplored region remains. Other novel accelerator technologies should also study the possibility of providing such high energy bunched electron beams.

Table 3.1: Specification for an electron beam for fixed-target (FT) experiments, generated by a dielectric laser accelerator (inspired by the eSPS specifications) as well as for electron bunches for PEPIC , a low-luminosity LHeC-like collider , and for the LUXE experiment . Such bunches (for PEPIC and LUXE) can also be used for a beam-dump experiment to search for dark photons. Note that the number of bunches per train in the XFEL.EU is 2700, but for LUXE only one is used.

Parameter	**Unit**	**single e FT**	**PEPIC**	**LUXE**
Bunch charge	pC	few e	800	250
Final energy	GeV	20	70	16.5
Relative energy spread	%	<1	$2-3$	0.1
Bunch length	μm	-	30	$30-50$
Normalized emittance	μm	100	10	1.4
Number of bunches per train	-	1	320	1
Repetition rate	-	1 GHz	0.025 Hz	10 Hz
Luminosity	10^{27} cm^{-2} s^{-1}	-	1.5	-

The use of bunched electrons in the 15–20 GeV range is also proposed by the LUXE experiment using the European XFEL electrons . This experiment will investigate non-linear QED by colliding the electron bunches with a high-power laser. This is then a natural application for plasma wakefield acceleration and dielectric laser accelerators which could achieve similar parameters.

The AWAKE study also considered an electron–proton collider based on bunches of electrons at ~ 50 GeV, PEPIC, or 3 TeV (VHEeP). Using ~ 50 GeV electrons is akin to the proposed LHeC project. Typical parameters are shown in Table 3.1 Although a significantly shorter electron accelerator is expected, much lower luminosity is also expected in the AWAKE scheme. Aspects that should be further considered are:

- Further study and optimisation of the AWAKE scheme, in particular to increase the luminosity.
- Other novel accelerator schemes should consider application to the LHeC.
- Other electron beam energies could be considered and discussed with HEP as to their interest.

Another compelling application yet to be considered by any novel accelerator scheme is a $\gamma\gamma$ collider, with a centre-of-mass energy of 12 GeV . The current design is based on the use of the European XFEL electron beam but would require modifications/additions to the complex to run a collider.

3.6.2 Current Accelerator R&D Test Facilities

The ongoing R&D for advanced, high-gradient accelerators is being performed at accelerator or laser facilities that are located at research centers and universities. Access possibilities range from limited access, through collaboration-based access models to user facility operation with excellence-based access after committee review. We provide a preliminary work list of facilities:

- **Facilities at CERN:** AWAKE experiment at the SPS (collaboration-based access), CLEAR (user-facility access).
- **Major national facilities in CERN member states,** (facility defined access rules): **Laser facilities** (laser beam delivered to users): EPAC, CLF, APOLLON, PALLAS, DESY (LUX, *KALDERA*), Lund Laser Center, HZDR, LOA, Strathclyde, CALA, JuSPARC. **Accelerator facilities** (particle beam delivered to users): SPARC_LAB, DESY (FLASHForward, SINBAD/ARES), CLARA, SwissFEL.
- **European Research Infrastructures:** ELI-Beamlines (user-facility access), EuPRAXIA (user-facility access, placed on 2021 ESFRI roadmap update).
- **Large Non-European facilities:** : BELLA (collaboration-based access), FACET-II (user-facility access), facilities in China at Beijing and Shanghai (collaboration-based access), ImPACT program in Japan (collaboration-based access), Argonne Wakefield Accelerator (user-facility access) and Brookhaven's Accelerator Test Facility (user-facility access).

3.6.3 Possible Advanced Accelerator Test Facility for HEP Specific Aspects

A dedicated test facility for HEP-specific aspects of advanced acceleration concepts would greatly advance research in this area, as specific aspects of HEP relevant particle beams might not be fully addressed with existing facilities. These aspects include the generation and acceleration of positron beams, the generation and diagnostics of polarized beams, and detailed studies on energy efficiency. In addition, the scalability of the design, additional stages and accelerator lines should be studied, implemented and tested. The need and required technology for such a facility will be evaluated in the pre-CDR report in 2026. A dedicated test facility should include at least two accelerator lines, each one having two or three acceleration stages. Such a test facility will address issues and the R&D lines defined at the decision point after the pre-CDR. The facility might require lasers with a high repetition rate and sub-femtosecond synchronization for staged structures. Instrumentation for laser and particle beams and a fast feedback system would enable studies of the stability of the accelerator. Optionally, a connection to a conventional storage ring could be used to damp positron beams and re-inject them into the plasma.

The HEP collider solution requires a number of R&D developments to tackle different physical and technical challenges, which might require the use of an intermediate test facility targeting 15-20 GeV energy and a 100-200 pC charge in several stages. The following milestones could be envisaged for an intermediate facility:

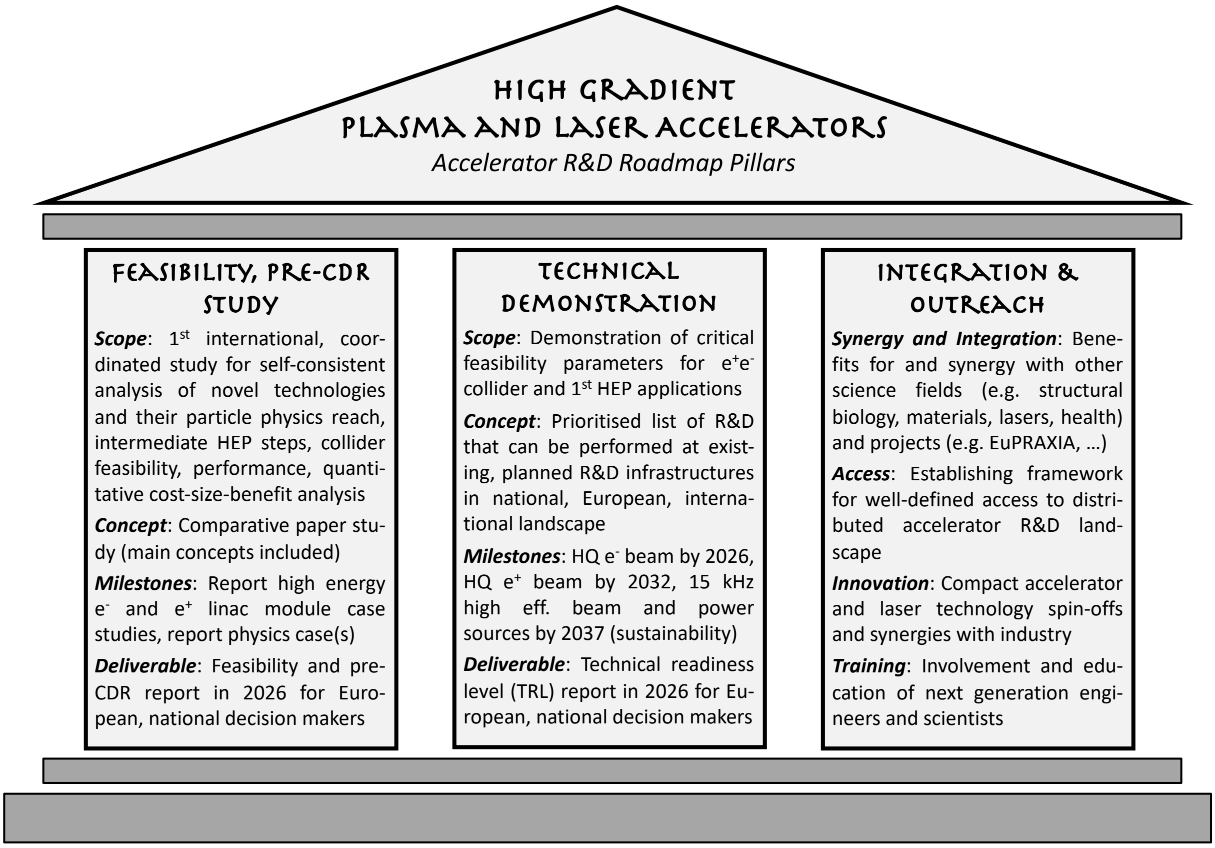
2026: Pre-CDR as part of the overall pre-CDR report.
2030: TDR.
2033: Completion of construction. Start of commissioning.
2035: Operation.

3.7 Key Points of the Roadmap

The key points of the roadmap are summarized and described in this section. It is noted that novel accelerators are a relatively young and diverse field and we present only an interim snapshot. Extensive consultations, discussions and iterations are ongoing and the presented roadmap components will be updated accordingly.

3.7.1 Three Pillars of Advanced Accelerator R&D Roadmap for Particle Physics

The panel has discussed and agreed on a roadmap that is based on three pillars that should be pursued in parallel (see Fig. 3.1). The three pillars of our roadmap are:



FEASIBILITY, PRE-CDR STUDY

Scope: 1st international, coordinated study for self-consistent analysis of novel technologies and their particle physics reach, intermediate HEP steps, collider feasibility, performance, quantitative cost-size-benefit analysis

Concept: Comparative paper study (main concepts included)

Milestones: Report high energy e^- and e^+ linac module case studies, report physics case(s)

Deliverable: Feasibility and pre-CDR report in 2026 for European, national decision makers

TECHNICAL DEMONSTRATION

Scope: Demonstration of critical feasibility parameters for e^+e^- collider and 1st HEP applications

Concept: Prioritised list of R&D that can be performed at existing, planned R&D infrastructures in national, European, international landscape

Milestones: HQ e^- beam by 2026, HQ e^+ beam by 2032, 15 kHz high eff. beam and power sources by 2037 (sustainability)

Deliverable: Technical readiness level (TRL) report in 2026 for European, national decision makers

INTEGRATION & OUTREACH

Synergy and Integration: Benefits for and synergy with other science fields (e.g. structural biology, materials, lasers, health) and projects (e.g. EuPRAXIA, …)

Access: Establishing framework for well-defined access to distributed accelerator R&D landscape

Innovation: Compact accelerator and laser technology spin-offs and synergies with industry

Training: Involvement and education of next generation engineers and scientists

Fig. 3.1: Visualization of the three pillars that are proposed to form the accelerator R&D roadmap for plasma and laser accelerators.

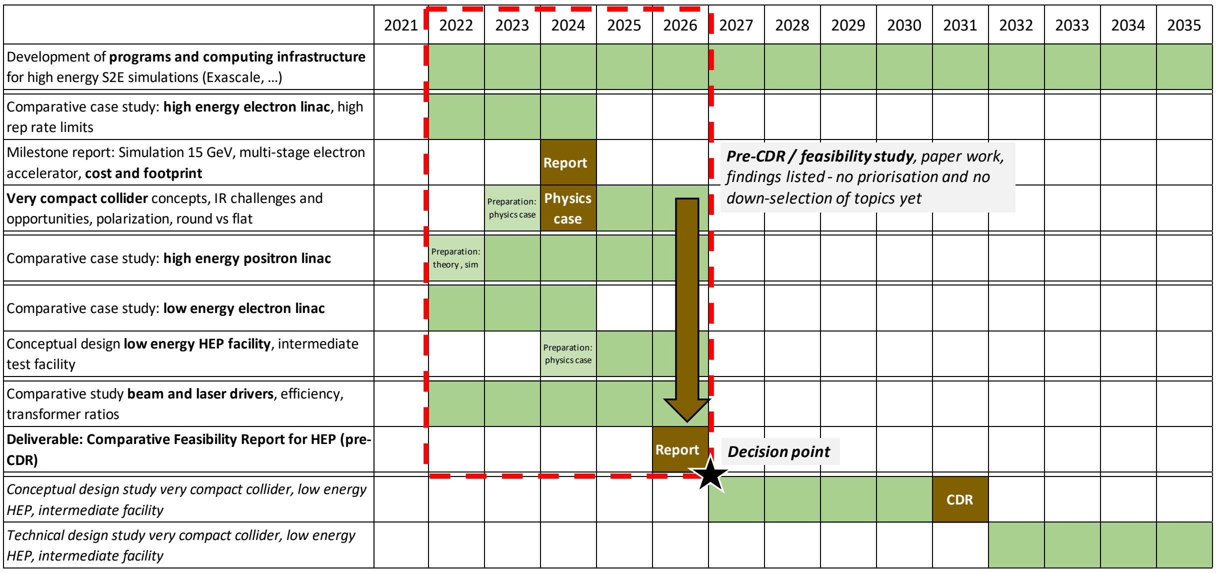
1. The first international feasibility and pre-CDR study for high gradient plasma and laser accelerators and their particle physics reach. This paper study will lead to a comparative report on various options, a feasibility assessment, performance estimates, physics cases, intermediate HEP applications and a cost-size-benefit analysis for high energy.
2. A prioritised list of technical R&D topics that will demonstrate a number of technical feasibility issues of importance for particle physics experiments.
3. Integration and outreach measures. This exploits and ensures the very high synergistic potential with other fields and large projects, like EuPRAXIA. It enables access to distributed R&D facilities under clear rules and supports innovation with closely connected industry. Finally, it connects to the next generation of scientists in close collaboration with other activities in IFAST and the European Network for Novel Accelerators (EuroNNAc).

3.7.2 Proposed components of feasibility and pre-CDR study (findings)

The proposed components of the feasibility and pre-CDR study are shown in Fig. 3.2. They are commented on in the following.

3.7.2.1 Theory and simulation

The proposed design study will include a strong effort on theory and simulation. A beam physics and simulation framework will be set up that addresses all system aspects of a high energy physics machine. The work will include the preparation of numerical and simulation tools, as required for simulating



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Development of **programs and computing infrastructure** for high energy S2E simulations (Exascale, ...)		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Comparative case study: **high energy electron linac**, high rep rate limits		🟩	🟩	🟩											
Milestone report: Simulation 15 GeV, multi-stage electron accelerator, **cost and footprint**				**Report**											
Very compact collider concepts, IR challenges and opportunities, polarization, round vs flat			Preparation: physics case	**Physics case**	🟩	🟩									
Comparative case study: **high energy positron linac**		Preparation: theory , sim	🟩	🟩	🟩	🟩									
Comparative case study: **low energy electron linac**		🟩	🟩	🟩											
Conceptual design **low energy HEP facility**, intermediate test facility				Preparation: physics case	🟩	🟩									
Comparative study **beam and laser drivers**, efficiency, transformer ratios		🟩	🟩	🟩	🟩	🟩									
Deliverable: Comparative Feasibility Report for HEP (pre-CDR)						**Report**									
Conceptual design study very compact collider, low energy HEP, intermediate facility							🟩	🟩	🟩	🟩	**CDR**				
Technical design study very compact collider, low energy HEP, intermediate facility												🟩	🟩	🟩	🟩

Fig. 3.2: Components and possible time line for the proposed common feasibility and pre-CDR study. This would be the first ever such study in the international context. No prioritisation or down-selection of the proposed components has been done yet.

multi-stage setups at high and low energy for the various options, both for electrons and positrons.

3.7.2.2 High-energy common study case

A high energy study case assesses the feasibility in the high-energy collider regime, for which CLIC has already established an optimized set of parameters. We use here the CLIC parameters of the final 15 GeV of the CLIC 380 GeV main linacs. The relevant study case is the design of an advanced accelerator module (two or more acceleration stages) accelerating electron or positron beams from 175 GeV (incoming) to 190 GeV (after acceleration in the advanced accelerator module). All required components for in- and out-coupling of the power drivers (e.g. laser, electron or proton pulses that drive the accelerating fields) shall be included, see Table 3.2. A collider based on plasma or dielectric accelerator technology is not expected to reproduce exactly the same parameters. Yet, the table indicates the parameter range of interest for particle physics, based on the example of an HEP-optimized RF-based machine. It can serve as the basis for a comparative study as proposed in this report. Parameters shall be adapted and modified to take into account constraints from plasma and laser accelerators.

3.7.2.3 Low-energy common study case

The potential for lower energy Particle Physics applications is assessed by considering a parameter regime for fixed-target experiments, which could be realized in the nearer future with more relaxed beam parameters compared to colliders. We use beam parameters for an electron beam as shown in Table 3.1, generated by a dielectric laser accelerator (inspired by the eSPS specifications) and for electron bunches for an LHeC-like collider and for the LUXE experiment .

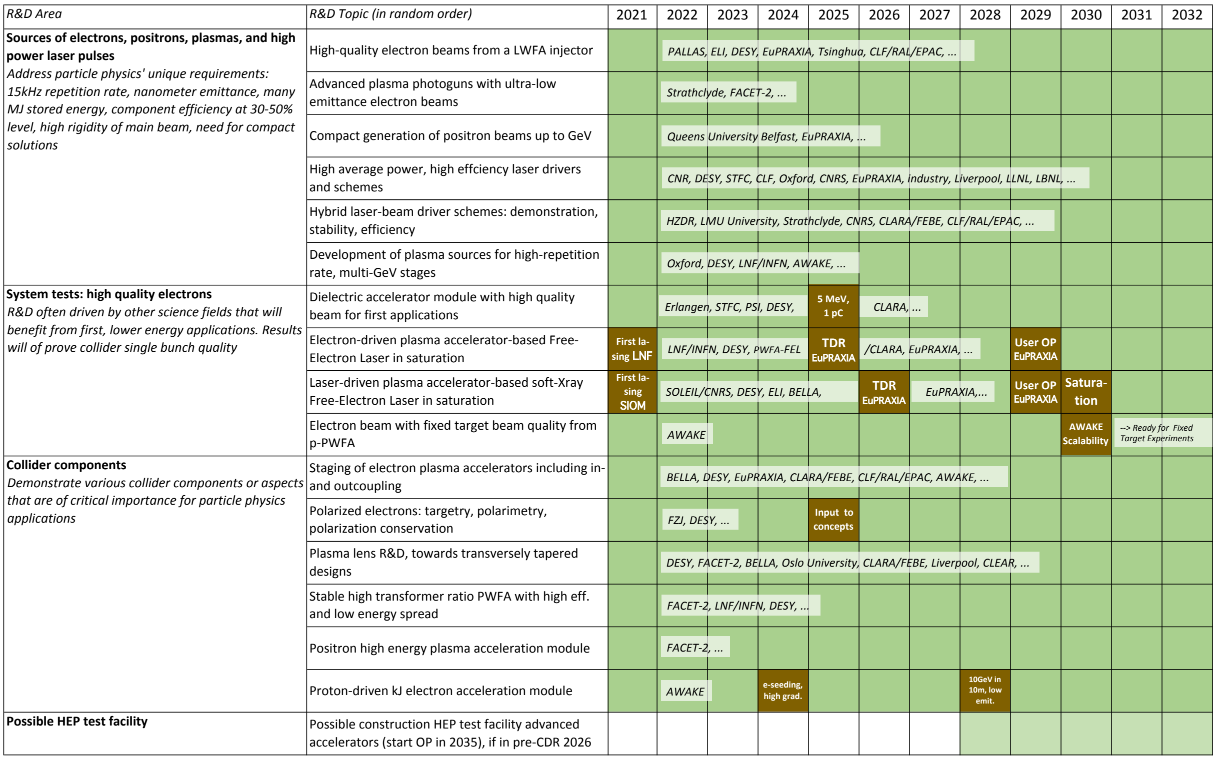
The relevant study cases are the design of an advanced accelerator (that can include the injector) to accelerate electrons to a final beam energy in the regime of 15 GeV to 50 GeV to be used for first HEP experiments as described in 3.6.1.

3.7.2.4 Collider pre-conceptual design and feasibility report in 2026

The relevant physics cases and collider concepts and solutions will be designed and calculated in detail once the case studies have established feasible accelerator modules for electrons and positrons. It is noted that there have been various sketches of possible colliders relying on plasma or dielectric technology. Those studies are valuable starting points for further design work but do not include realistic designs of the accelerator layout (including in- and out-coupling of power drivers) nor solutions for multi-stage positron acceleration nor performance assessments with realistic simulations. The various published sketches provide an understanding of the required parameters for constructing linear collider at the energy frontier, see Table 3.3. The proposed design work will include the first ever cost-size-benefit analysis for such an advanced collider that is based on simulation-based design work. A report in 2026 will provide decision makers with the results needed to decide on future directions and priorities.

3.7.3 Proposed technical demonstrations - areas and topics (findings)

The proposed feasibility and pre-CDR study must be complemented by technical demonstrations that establish the experimental state of the art and can be used to assess technical readiness levels (TRL). The present state of the art and the required work on various technical R&D issues have been listed and summarized in the previous sections. In Fig. 3.3 we provide an overview of the proposed technical demonstration areas and topics. Figure 3.3 includes a first preliminary matching with facilities where this work could or will be done (no down-selection). There is a consensus in our expert panel and through our consultation process that this is a rather complete list of challenges and work to be done. A prioritisation, scheduling and matching to facilities/resources will be done as the next step of our roadmap process.



R&D Area	*R&D Topic (in random order)*	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Sources of electrons, positrons, plasmas, and high power laser pulses *Address particle physics' unique requirements: 15kHz repetition rate, nanometer emittance, many MJ stored energy, component efficiency at 30-50% level, high rigidity of main beam, need for compact solutions*	High-quality electron beams from a LWFA injector		*PALLAS, ELI, DESY, EuPRAXIA, Tsinghua, CLF/RAL/EPAC, ...*										
	Advanced plasma photoguns with ultra-low emittance electron beams		*Strathclyde, FACET-2, ...*										
	Compact generation of positron beams up to GeV		*Queens University Belfast, EuPRAXIA, ...*										
	High average power, high effciency laser drivers and schemes		*CNR, DESY, STFC, CLF, Oxford, CNRS, EuPRAXIA, industry, Liverpool, LLNL, LBNL, ...*										
	Hybrid laser-beam driver schemes: demonstration, stability, efficiency		*HZDR, LMU University, Strathclyde, CNRS, CLARA/FEBE, CLF/RAL/EPAC, ...*										
	Development of plasma sources for high-repetition rate, multi-GeV stages		*Oxford, DESY, LNF/INFN, AWAKE, ...*										
System tests: high quality electrons *R&D often driven by other science fields that will benefit from first, lower energy applications. Results will of prove collider single bunch quality*	Dielectric accelerator module with high quality beam for first applications		*Erlangen, STFC, PSI, DESY,*			**5 MeV, 1 pC**	*CLARA, ...*						
	Electron-driven plasma accelerator-based Free-Electron Laser in saturation	**First lasing LNF**	*LNF/INFN, DESY, PWFA-FEL*			**TDR EuPRAXIA**	*/CLARA, EuPRAXIA, ...*			**User OP EuPRAXIA**			
	Laser-driven plasma accelerator-based soft-Xray Free-Electron Laser in saturation	**First lasing SIOM**	*SOLEIL/CNRS, DESY, ELI, BELLA,*				**TDR EuPRAXIA**	*EuPRAXIA,...*		**User OP EuPRAXIA**	**Saturation**		
	Electron beam with fixed target beam quality from p-PWFA		*AWAKE*								**AWAKE Scalability**	*--> Ready for Fixed Target Experiments*	
Collider components *Demonstrate various collider components or aspects that are of critical importance for particle physics applications*	Staging of electron plasma accelerators including in- and outcoupling		*BELLA, DESY, EuPRAXIA, CLARA/FEBE, CLF/RAL/EPAC, AWAKE, ...*										
	Polarized electrons: targetry, polarimetry, polarization conservation		*FZJ, DESY, ...*			**Input to concepts**							
	Plasma lens R&D, towards transversely tapered designs		*DESY, FACET-2, BELLA, Oslo University, CLARA/FEBE, Liverpool, CLEAR, ...*										
	Stable high transformer ratio PWFA with high eff. and low energy spread		*FACET-2, LNF/INFN, DESY, ...*										
	Positron high energy plasma acceleration module		*FACET-2, ...*										
	Proton-driven kJ electron acceleration module		*AWAKE*		**e-seeding, high grad.**				**10GeV in 10m, low emit.**				
Possible HEP test facility	Possible construction HEP test facility advanced accelerators (start OP in 2035), if in pre-CDR 2026												

Fig. 3.3: List of technical demonstration topics that have been proposed as part of the roadmap. No scheduling, prioritisation or down-selection of the proposed components has been done yet. Milestones or deliverables are indicated by brown boxes.

Table 3.2: Specification for an advanced high energy accelerator module, compatible with CLIC. Additional CLIC design values are listed for reference in the second part of the table.

Parameter	**Unit**	**Specification**
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	$\geq$2
Efficiency wall-plug to beam (includes drivers)	%	$\geq$10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	$\leq$0.35
Bunch length (entry/exit)	μm	$\leq$70
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h \epsilon_v}$)	nm-rad	$\leq$135
Emittance growth budget	nm-rad	$\leq$**3.5**
Polarization	%	80 (for e^-)
Normalized emittance h/v (exit)	nm-rad	900/20
Bunch separation	ns	0.5
Number of bunches per train	-	352
Repetition rate of train	Hz	50
Beamline length (175 to 190 GeV)	m	**250**
Efficiency: wall-plug to drive beam	%	58
Efficiency: drive beam to main beam	%	22
Luminosity	10^{34}cm^{-2}s^{-1}	1.5

Table 3.3: Required parameters for a linear collider with advanced high gradient acceleration. Three published parameter cases are listed. Case 1 (PWFA) is a plasma-based scheme based on SRF electron beam drivers. Case 2 (LWFA) is a plasma-based scheme based on laser drivers. Case 3 (DLA) is a dielectric-based scheme.

Parameter	**Unit**	**PWFA**	**LWFA**	**DLA**
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h \epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%	$\leq$0.35		
Polarization	%	80 (for e^-)		
Efficiency wall-plug to beam (includes drivers)	%	$\geq$10		
Luminosity regime (simple scaled calculation)	10^{34}cm^{-2}s^{-1}	1.1	1.0	1.9

4 High-gradient RF Structures and Systems

5 Bright Muon Beams and Muon Colliders

T. Arndt[a], *A. Chance*[b], *J. P. Delahaye*[c], *A. Faus-Golfe*[d], *S. Gilardoni*[c], *P. Lebrun*[c], *K. Long*[e,f], *E. Métral*[c], *M. Palmer*[g], *N. Pastrone*[h], *L. Quettier*[i], *T. Raubenheimer*[j], *C. Rogers*[f], *D. Schulte*[c], *M. Seidel*[k], *D. Stratakis*[l], *A. Yamamoto*[m]

[a]Karlsruhe Institute of Technology (KIT) and Institute for Technical Physics (ITEP)
[b]CEA Saclay, France
[c]CERN, Switzerland
[d]University of Valencia, Spain
[e]Imperial College London, United Kingdom
[f]STFC Rutherford Appleton Laboratory, United Kingdom
[g]Brookhaven National Laboratory, United States of America
[h]INFN Torino, Italy
[i]CEA Lorraine, France
[j]Stanford University, United States of America
[k]Paul Scherrer Institute, Switzerland
[l]Fermi National Accelerator Laboratory, United States of America
[m]KEK, Japan

5.1 Executive Summary

Muon colliders have been identified as being uniquely well-suited to deliver high energy collisions with overwhelming potential in discovery searches and precision measurements to study fundamental physics. The muon collider has the potential to deliver physics reach at the highest energies on a cost, power consumption and time scale that may improve significantly on other proposed facilities. To understand the research required to deliver a muon collider, the Laboratory Directors' Group (LDG) initiated a muon collider collaboration and formed a panel to determine the required R&D programme to deliver a muon collider .

The Muon Beam Panel has confirmed that the muon collider is a promising path to highest energy lepton collisions and has identified the study of colliders having a centre-of-mass energy of 3 TeV and around 10 TeV as being of particular importance. A 10-14 TeV muon collider, accumulating 10-20 ab^{-1} respectively, has a physics reach comparable to a 100 TeV hadron collider with a footprint comparable to the LHC. A 3 TeV collider accumulating 1 ab^{-1} could be constructed by 2045 as an initial stage, given sufficient resources; this makes it suitable to follow on from the end of the HL-LHC if so required. The footprint would be considerably smaller than the LHC. Studies for staging between these facilities seem promising and very likely only the 4.5 km-long collider ring could not be reused for the full energy stage.

The initial goal is to establish, within the next five years, whether the investment into a full programme is scientifically justified. To this end the collaboration plans to provide a sufficiently detailed design of the key systems of the complex to demonstrate that the beam parameters required for luminosity can be achieved and that the cost and power consumption scales are sustainable. In parallel it will develop an R&D programme that will demonstrate the functional specifications where they are beyond the state of the art. In particular, a Demonstrator test stand will be developed to establish the muon cooling system, eventually including beam tests. A limited experimental programme to address technologies that are unique to the muon collider, such as fast-ramping magnets and the muon cooling RF, will help

---

This contribution should be cited as: Bright Muon Beams and Muon Colliders, DOI: 10.23731/CYRM-2021-XXX.33, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold, CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 33.

to support the assessment of performance predictions. This will allow the next ESPPU to make fully informed decisions and support similar strategy processes in other regions. Based on these decisions a significant ramp-up of resources could be made to accomplish construction of the collider by 2045.

Potential synergies between the collider complex in general and the demonstrator in particular with other projects will be explored and additional collaborative connections will be formed where they are beneficial to the study.

A number of key challenges have been overcome by previous R&D efforts. The panel has identified several remaining R&D challenges that need to be addressed in the next 5 years in order to enable subsequent prototyping. All of the challenges have viable solutions. The study of these challenges will enable timely development of the muon collider.

5.2 Motivation

Muon colliders offer enormous potential for exploration at the particle physics frontier. Muons, like electrons, are fundamental particles, so the full energy of the particle is available when they collide, whereas protons are composites of quarks and gluons so only a fraction of the energy is available. Unlike electrons, the high mass of the muon tends to suppress synchrotron radiation so that muons can be accelerated to high energy in rings. This results in a facility footprint that can be rather small compared to other proposed future facilities while yielding comparable results.

5.2.1 Physics Potential of the Muon Collider

A muon collider with 3 TeV center-of-mass energy would be likely to have similar or greater physics potential compared to an electron-positron collider such as CLIC, the physics reach of which is well established and documented . A muon collider with a centre-of-mass energy of 10 TeV or more would open radically new opportunities for the exploration of fundamental physics. On the one hand, it would feature a mass-reach for the direct discovery of new particles that vastly surpasses the HL-LHC exclusion potential and that, in certain cases, is superior to future hadron collider projects. On the other hand, it would enable precision measurements through which new physics could be discovered indirectly, or the validity of the SM confirmed at a currently unexplored scale of energy. Detector studies indicate that the potential of the muon collider can be exploited with the present state-of-the-art technologies at 3 TeV and further R&D for a 10 TeV facility, as discusssed in the Detector R&D Roadmap.

5.2.2 Sustainability

As compared to other frontier particle accelerators and colliders under consideration, the Muon Collider shows particular advantages in terms of sustainability: a compact footprint, efficient electrical power consumption even at high collision energy and potential for phased construction with physics at each stage.

The accelerator complex is compact because a more modest energy is required for physics reach comparable to a proton collider and linacs are not required. For a collision energy per elementary constituent around 10 TeV, the footprint of the Muon Collider does not exceed linear dimensions of order 10 km, well below those of electron and hadron colliders of comparable physics reach.

The muon collider has a relatively small electrical power consumption per unit of luminosity. The luminosity that can be achieved per unit of beam power is shown in Fig. 5.1. For energies at or below 1 TeV, the power requirements of the muon production and cooling tend to dominate resulting in a less efficient facility. At energies above 1 TeV, the muon collider is expected to consume far less power for a given luminosity than equivalent electron or proton machines. For e^+e^- colliders Beamstrahlung dominates the uncertainty of collision energy but for muon colliders the limitation is given by the intrinsic energy spread of the beam. With increasing energy and under the condition of keeping the relative energy spread unchanged, the muon beam bunches can be reduced in length. Shorter bunches can be focused more strongly at the interaction point which leads to a gain of luminosity per grid power in proportion to the kinetic energy. Furthermore, the collision rate in the collider ring increases through the circulation frequency with stronger bending field B. The main parameters affecting the luminosity are summarised in the following scaling formula:

$$L \propto \gamma B P_{\text{beam}} \frac{N \sigma_\delta}{\varepsilon_n \varepsilon_l}. \tag{5.1}$$

P_{beam} denotes the beam power, N the particles per bunch, σ_δ the relative energy spread, ε_n the normalised transverse beam emittance and ε_l the normalised longitudinal beam emittance.

From this relation the advantageous scaling of luminosity with energy is evident. However, the absolute value of the power consumption for a certain center of mass energy has not been studied or optimised in detail. In particular the energy efficient design of rapid cycling synchrotrons with recovery of the magnetic field energy from cycle to cycle, and the reduction of large unrecoverable losses from eddy currents, are important topics for optimization. Other aspects include minimizing beam induced heat load at cryogenic temperatures and efficient RF acceleration systems.

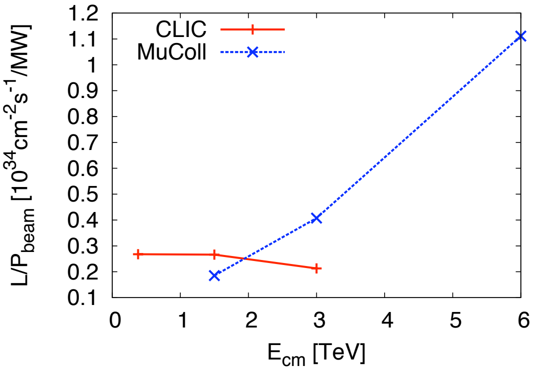


Fig. 5.1: Estimated luminosity of the muon collider and CLIC per MW of beam power, compared with the centre of mass energy at the collision point.

A staged scenario can be developed by constructing additional acceleration stages that would accelerate the beam to higher energies after the initial facility is constructed. An initial facility could have 1.5 TeV beam energy with 3 TeV centre-of-mass energy. Further acceleration to 5 TeV or more beam energy could then be constructed to reach 10 TeV centre-of-mass energy. This scheme allows first physics to be reached earlier and with less investment. The overall risk would be more evenly spread across the project as the requirements for the collider ring technology are less demanding at lower energy. Acceleration is achieved in a different ring to collisions, so the integrated cost would only increase by the cost of the 3 TeV collider ring, which initial studies indicate could have a circumference of 4.5 km.

Finally, the modularity of the Muon Collider complex will allow synergy with other accelerator projects through reuse of subsystems, e.g. the high-intensity proton driver which could also serve a neutrino factory.

5.3 Muon Beam Panel Activities

The muon beam panel is employing closed, fortnightly meetings of the panel, meetings of the broader muon collider collaboration and dedicated community meetings and workshops that draw on the worldwide expertise to develop the input for the roadmap. Three open community meetings have been held in 2021 with strong attendance from the international community and at least one more is planned.

This approach combines the expertise of the panel members, the participants in the new collaboration, as well as the participants in the earlier efforts. Contributions from the US community are necessarily limited pending the outcome of the ongoing US strategy process.

5.4 Muon Collider State of the Art

The Muon Accelerator Programme collaboration (MAP) developed the concept shown in Fig. 5.2. The proton complex produces a short, high-intensity proton pulse that hits the target and produces pions. The decay channel guides the pions and collects the muons produced in their decay into a buncher and phase rotator system to form a muon beam. Several cooling stages then reduce the longitudinal and transverse emittance of the beam using a sequence of absorbers and RF cavities in a high magnetic field. A linac and two recirculating linacs accelerate the beams to 60 GeV. One or more rings accelerate the beams to the final energy. These rings can be either fast-pulsed synchrotrons or fixed-field alternating-gradient accelerators (FFAs). Finally the two single-bunch beams are injected at full energy into the collider ring to produce collisions.

LEMMA is an alternative scheme to produce a muon beam with a very small emittance. Novel ideas are required to overcome limitations in muon beam current and luminosity so LEMMA is not considered as a baseline in this report.

5.4.1 Status of the Concept

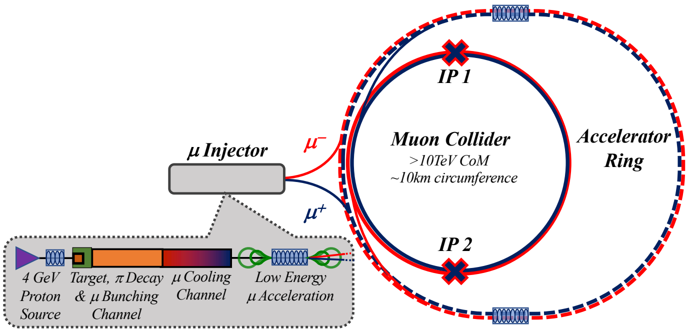


Fig. 5.2: A conceptual scheme of the muon collider.

MAP focused on demonstrating the feasibility of the key sub-systems required to deliver an energy frontier collider . The test program at Fermilab's MuCool Test Area demonstrated operation of gas-filled and vacuum pillbox cavities with up to 50 MV/m accelerating gradients in strong magnetic fields ; a 6D cooling lattice was designed that incorporated reasonable physical assumptions to meet the 6D cooling targets ; a Final Cooling Channel design, which implemented the constraint of a 30 T maximum solenoid field, came within a factor of $\sim$2 of meeting the transverse emittance goal for a high energy collider and current development efforts appear poised to deliver another factor of $\sim$1.5 improvement; while further R&D is required, fast-ramping magnet concepts exist that could deliver muon beams to the Terascale. Following the end of MAP, acceleration in a recirculating linear accelerator with FFA arcs was demonstrated by CBETA .

In Europe, significant investment into muon accelerator R&D was made in neutrino factory design through the EuroNu and neutrino factory International Design Study . The International Muon Ionization Cooling Experiment (MICE) completed a detailed measurement of the ionization cooling process for lithium hydride and liquid hydrogen absorbers and a number of different beam conditions . Rapid acceleration in a fixed field accelerator was demonstrated by EMMA . Schemes for high power targetry using liquid metal and fluidised powder jets were demonstrated, indicating potential for managing proton beam powers even beyond those required for the muon collider.

The MAP and European studies made sufficient progress to demonstrate a viable path forward to realisation of a muon collider.

5.5 R&D Objectives and Challenges

The International Muon Collider (IMC) Collaboration aims to deliver a start-to-end concept for the muon collider and to evaluate the cost and performance of the facility. This effort will include development of the detector concepts and an evaluation of the physics potential.

In particular, the study will focus on the design of a machine with centre-of-mass energy of initially 3 TeV followed by a machine of at least 10 TeV. Potential synergies between the collider complex and other projects will be explored and additional collaborative connections will be formed where they are beneficial to the study. Currently, parameter sets based on scaling from MAP are investigated as starting

Table 5.1: Tentative target parameters for a muon collider at different energies based on the MAP design with modifications. These values are only to give a first, rough indication. The study will develop coherent parameter sets of its own.

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_{L}	$\mathrm{MeV\,m}$	7.5	7.5	7.5
Transverse emittance	ϵ	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

points for 3, 10 and 14 TeV with the goal to reach luminosities, integrated over 5 to 10 years, of 1, 10 and 20 ab^{-1} respectively. This increase in luminosity compensates the decrease of the s-channel cross sections.

To achieve the maturity that allows commitment to the construction of a collider an R&D programme is required that includes the development of key collider technologies as well as the construction and operation of a demonstrator.

The initial goal of the collaboration is to establish, within the next five years, whether the investment into this R&D programme is scientifically justified. It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power-consumption drivers. It will also identify the R&D path to develop a full conceptual design for the collider and its experiments. This will allow fully informed decisions to be made at the next ESPPU and support similar strategy processes in other regions.

Given appropriate resources, the design can be optimised in the next stage and a demonstration programme can be implemented. The latter contains one or more test facilities as well as the development and testing of individual components and potentially dedicated beam tests. The resulting conceptual design will demonstrate the performance, cost and power consumption of the collider facility, making it possible to technically commit to the collider. In this case a technical design phase will follow to prepare for the approval and ultimate implementation of the collider.

The Panel endorses the goals of the collaboration. The focus on high energy develops the unique capability of the muon collider and avoids diluting efforts on energy ranges that are accessible with more mature technologies. The Panel also agrees that the muon collider concept should be further developed, including a start-to-end simulation, to assess whether it is a credible option for the future of particle physics. The proposed R&D programme mitigates the risk that the next ESPPU is not in a position to include the muon collider in its considerations and to make fully informed choices.

5.5.1 Key Challenges

Based on the MAP design, target parameter sets have been defined for the collider as a starting point, shown in Table 5.1. If all design goals are met, these parameters would deliver the desired integrated luminosities within five years from the end of commissioning. These design goals serve to clarify the critical design issues and, once detailed studies are available, operational budgets that account for sources of beam quality degradation will be added.

The parameter sets have a luminosity to beam-power ratio that increases with energy. They are based on using the same muon source for all energies and a limited degradation of transverse and longitudinal emittance with energy. This allows the bunch in the collider to be shorter at higher collision energy and the use of smaller beta-functions. The design of the technical components, such as the final focus quadrupoles, to achieve this goal are a key element of the muon collider study.

A 3 TeV muon collider would be highly novel while a 10 TeV lepton collider is uncharted territory and poses a number of key challenges, described below.

5.5.2 Neutrino Radiation

Muon decay produces a large flux of high-energy neutrinos in a very forward direction. In particular in the plane of the collider ring this can lead to a high local flux of neutrinos, which have a small likelihood of producing showers when exiting the ground at a distance from the facility. The insertions produce a very localised flux in a limited area; the arcs in contrast produce a ring of flux around the collider.

Minimising the flux in public areas is a prime goal of the study; this implies staying well below the legal limit for off-site radiation, for example at a level consistent with LHC operation. Estimates indicate that a 10 TeV collider in a 200 m deep tunnel approaches the legal limit for the neutrino flux.

The proposed solution is a system of movers to deform the beamline periodically in the vertical plane so that narrow flux cones are avoided. Flux from insertions can be further minimised by acquiring the concerned land and by using a large divergence in the focusing triplets. This solution improves on a previous, less performant, proposal to move the beam within the magnet apertures. The system could achieve radiation levels similar to the LHC. The development of a robust system is the key to siting the collider in a populated area. Impact on the ring performance must be minimised. Proper consideration for vacuum connections and cryogenics systems must be made. Management of the neutrino flux is a critical issue for the muon collider. The panel endorses the proposed strategy to reduce flux to levels consistent with LHC operation.

5.5.3 Machine Detector Interface (MDI)

Detector design at a muon collider has to be performed together with the machine-detector interface due to the presence of the huge flux of secondary and tertiary particles coming from the muon beam decay. Integrated studies of the detector and the collider are needed to ensure a properly optimised performance. Beam-induced-background, arising both from muon decays and incoherent e^+e^- pair production, is a serious concern for the detector performance. The current solution to mitigate the background arriving at the detector consists of two tungsten cone-shaped shields (nozzles) in proximity to the interaction point, accurately designed and optimized for each specific beam energy. A framework based on FLUKA has been developed to optimise the design at different energies . Studies performed so far demonstrate that, given reasonable assumptions of detector performance, it will be possible to perform the most challenging physics measurements . Optimisations, for example using improved pixel timing on the tracker detector and novel trigger algorithms, are in progress and may yield improved performance. This requires further studies at higher energies. Combined interaction region, detector shielding and detector design should be performed to confirm physics performance at 3 TeV and 10 TeV.

5.5.4 High-energy complex

Cooled muons are accelerated through a sequence of accelerators. MAP envisioned initial LINACs and recirculating LINACs (RLA) to reach energies below 100 GeV followed by a series of Rapid Cycling Synchrotrons to reach energies of 100s to 1000s of GeV.

Collider designs were developed for an s-channel Higgs Factory, as well as 1.5, 3.0 and 6.0 TeV centre-of-mass energies . There are several notable features associated with the design of a muon collider ring. First, the luminosity performance of a muon collider is proportional to the dipole field that is used in the ring. Next, muon decays within the collider ring require large aperture superconducting magnets with shielding around the beam-pipe to prevent excessive radiation load on the magnets themselves. Finally, the use of straight sections in the ring must be minimized to prevent tightly focused beams of neutrinos from creating off-site radiation issues.

In the collider and accelerator rings of the high energy complex both muon beams will pass through the same magnet apertures moving in opposite directions; single aperture magnets are sufficient.

Longitudinal beam dynamics is the key to high luminosity. Each muon beam consists of one high-charge bunch and the accelerating cavities must be designed to have an acceptable single-bunch beam loading. This is more demanding at high energies where shorter bunches are required to boost the luminosity. A global lattice design for the high energy complex should be developed, including start-to-end simulations of key systems, taking into account the need to move the magnets in order to mitigate neutrino radiation. Particular attention should be paid to longitudinal collective effects such as beam loading. Consideration should be made of RF cavity design and effective beam loading compensation schemes.

In the baseline scheme, acceleration to 10 TeV centre-of-mass energies requires $\sim$30 km of 2 T fast-ramping normal-conducting magnets, which are interleaved with fixed-field superconducting magnets. The magnets for acceleration to 3 and 10 TeV are a large-scale system that can have significant impact on the cost and power consumption of the facility. Design and prototyping should be performed for these magnets. Alternative options based on high-temperature superconductors (HTS) should be explored.

The collider ring arc magnets have to combine high dipole field, to maximise the collision rate, and large aperture, to allow shielding in the magnet bore to protect the cold mass from the 500 W/m of high energy electrons and positrons produced by the muon beam decay around the ring. Combined function magnets are essential to minimise the neutrino flux and the field-free gap between magnets must be minimised for the same reason. Shielding of the collider ring magnets from muon decay products drives the aperture and consequently the maximum field that can be achieved. Particular attention needs to be given to optimise the aperture in order to yield the best performance.

The quadrupoles of the 3 TeV final focus pose similar challenges to the ones of High-Luminosity LHC (HL-LHC) or the hadron collider of the Future Circular Collider (FCC-hh). At 10 TeV larger aperture and higher magnetic field in the aperture are required and call for HTS. The design of the correction system to achieve the required bandwidth for the final focus system is a key challenge to ensure that the luminosity per beam power can increase with energy. The final focus magnets should be developed, paying attention to the needs of the detector and any beam-induced-background.

5.5.5 Muon Production and Cooling

Muons are produced via tertiary production ($\mathrm{p} \rightarrow \pi \rightarrow \mu$) by delivering a multi-MW proton beam onto a target. Proton energy in the 5-15 GeV range yields a production rate proportional to beam power . The proton beam strikes a target enclosed in a high-field, large-bore solenoid magnet to enable simultaneous capture of both positive and negative species . RF cavities capture the muons into a bunch train. An Initial Cooling channel , capable of cooling both species of muons simultaneously, reduces the 6D phase space of the beam by a factor of 50. The two muon species are subsequently separated into parallel 6D cooling channels to continue reducing the beam emittance to the levels required for luminosity production in a collider. The intermediate sections of cooling require high-gradient RF cavities operating in strong solenoid fringe fields. The final sections require state-of-the-art high field solenoids to reach the lowest emittances, and hence highest luminosity.

The system of solenoids around the target requires 15-20 T fields and large bores to accommodate shielding material. The short proton bunch length and 5 Hz operation result in a large instantaneous power which may cause significant damage to a solid target. A liquid metal or a fluidised tungsten target are alternative solutions. A preliminary engineering study of the target magnet should be performed, including consideration of radiation arising from beam interaction with the target. Studies of stress and heat load on the target should be performed and appropriate alternative solutions may be studied.

The overall design has to be optimised; further improvements would facilitate the machine design in the high energy complex. Alternative options have been proposed and need to be evaluated. In addition, the collective effects and beam-matter interactions should be explored further to validate the overall emittance performance. Integration of the muon production subsystem designs should be performed. Optimisation should be performed, paying particular attention to those areas that can significantly improve facility performance and current and expected future availability of high-gradient RF and high-field solenoids.

5.5.6 Proton Complex

Based on MAP calculations, the average proton beam power required in the target is in the range of 2 MW, but this needs to be fully validated by an end-to-end design of the facility. The proton beam energy should be in the range of 5-15 GeV. The power appears very feasible; spallation neutron sources like SNS and J-PARC already operate in the MW regime and others like ESS and PIP-II are in construction. The Superconducting Proton Linac (SPL), an alternative injector complex considered for the LHC, would have provided 4 MW of 5 GeV protons. The collector and compressor system merges the beam into 2 ns long pulses with a repetition rate of 5 Hz. Alternatively the use of an FFA or pulsed synchrotron could be considered, profiting from synergies with the next generation of spallation neutron sources in the UK. In this case the magnet design and collective effects needs studies and R&D. Scaling from existing and planned facilities is expected to give a good indication of required parameters. Eventually development of an accumulator and compressor system will be necessary, taking into account existing H^- ion sources and capability of H^- stripping systems for injection into the ring.

5.5.7 Physics and Technology Synergies

The ambitious programme of R&D necessary to deliver the muon collider has the potential to enhance the science that can be done at other muon-beam facilities.

nuSTORM and ENUBET offer world-leading precision in the measurement of neutrino cross sections and exquisite sensitivity to sterile neutrinos and physics beyond the Standard Model. nuSTORM in particular will require capture and storage of a high-power pion and muon beam and management of the resultant radiation near to superconducting magnets. The target and capture system for nuSTORM and ENUBET may also provide a testing ground for the technologies required at the muon collider and as a possible source of beams for the essential 6D cooling-demonstration experiment.

The next generation searches for charged lepton flavour violation exploit high-power proton beams impinging on a solid target placed within a high-field solenoid. The technological issues of target and muon capture for these experiments are similar to those present in the muon collider design.

The potential to deliver high quality muon beams could enhance the capabilities of muon sources such as those at PSI and ISIS. The use of frictional cooling to deliver ultra-cold positive and negative muon beams is under study at PSI and may be applicable to the muon collider.

FFAs have been proposed as a route to high proton beam power for secondary particle sources such as neutron spallation sources, owing to the potential for high repetition rate and lower wall plug power compared to other facilities. An FFA is under study as a possible means to upgrade the ISIS neutron and muon source.

High-power short-pulse proton drivers are in use throughout the world, for example at SNS and

JPARC. In Europe ESS and ISIS are both studying options for upgrades to MW-class short-pulse proton production. Opportunities to learn from these facilities may be exploited.

The underlying technologies required for the muon collider are also of interest in many scientific fields. The delivery of high field solenoid magnets is of great interest to fields as wide ranging as particle physics, accelerator science and imaging technology. Operation of RF cavities with high gradient is of interest to the accelerator community.

5.6 Facilities and Infrastructure

A test stand is required to demonstrate the ability of the muon collider to deliver the requisite luminosity, initially to demonstrate engineering integration of RF, magnets and absorbers, and eventually incorporating beam tests. Achieving high luminosity rests on the solution of two critical issues; the ability to create a high-flux muon beam from pions created at the target, and the ability to efficiently cool the beam in all six phase-space dimensions. This technology represents the single most novel system of the muon collider and requires unique customization of key accelerator technologies. A demonstrator may be able to contribute to a cutting-edge physics programme and this possibility should be exploited.

The construction and operation of the demonstrator that can explore the full bandwidth of relevant accelerator technologies will be required. The test facility could be placed at any laboratory that can provide a proton beam having a sufficiently high instantaneous beam power or can afford to construct a new proton complex. Initial explorations are ongoing at CERN to identify a site with access to appropriate beam. Preliminary studies indicate that construction of a junction cavern may be required in the next long shutdown in order to meet the timeline of a muon collider by 2045. A design for the demonstrator should be developed. Detailed study of required preparatory activities should be performed and approval sought in order that, should the demonstrator be deemed necessary by the particle physics community, the programme is not delayed.

In addition, a dedicated programme of key component development will have to be executed. The cooling systems require normal conducting RF cavities that can operate with high gradient in strong magnetic fields, which can cause conventional cavities to break down. Test cavities have been developed that can exceed the required performance. The existing R&D should be exploited to develop and test production cavities for the cooling systems that can operate in the desired range. Such development will require an RF test stand with significant available RF power in an appropriate frequency range and a suitable high field, large aperture magnet.

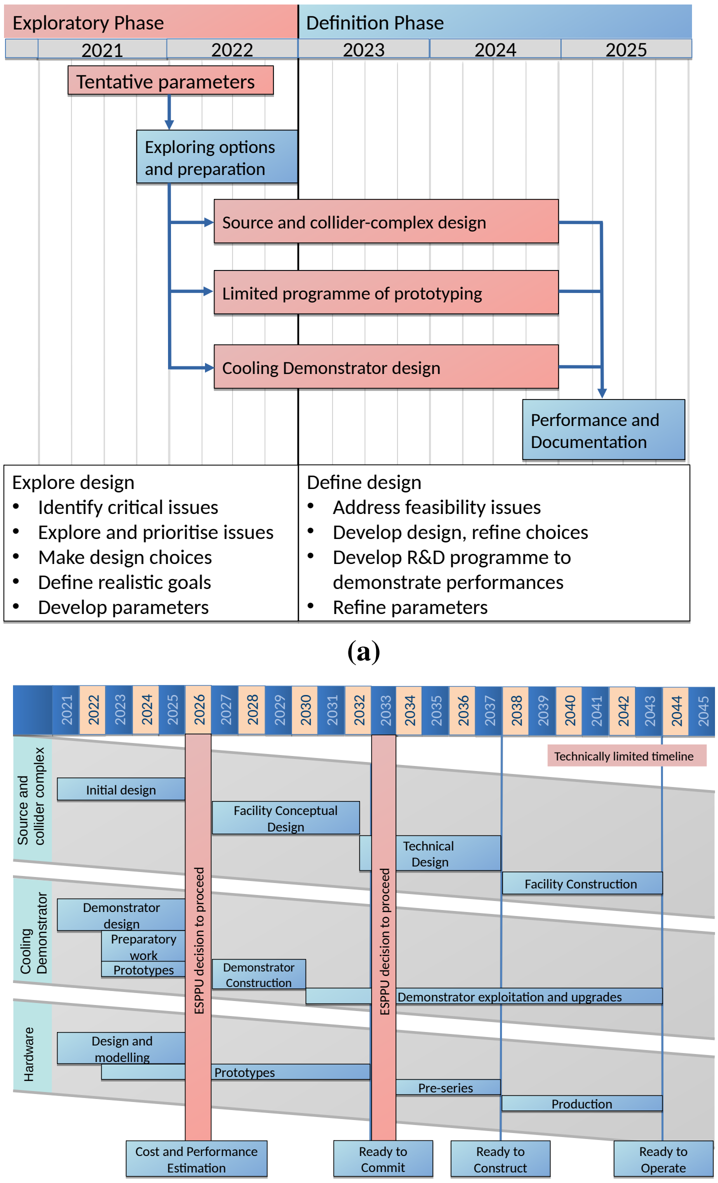
High-field superconducting solenoids and accelerator magnets are key to the muon collider performance. This includes the target solenoid, cooling solenoids, collider ring magnets, the fast ramping magnet and powering system. Specific challenges arise from the combination of high field and large aperture that lead to stress in the magnets. Design studies of key magnets are required to translate the magnet technology progress into estimates of performance of magnets appropriate to the muon collider.

Development of efficient superconducting RF with large accelerating gradient is essential for the high energy complex. Existing RF infrastructure should be sought in order to perform tests of superconducting RF cavities.

The proposed power density in the target and surrounding magnet is significant. Damage to both the target itself and also the superconducting wires is a possibility. Tests of components in a high radiation environment should be carried out using existing facilities such as HiRadMat to establish the sustainability of the required power density.

5.7 Key Points of the Roadmap

The muon collider R&D programme will consist of the initial phase followed by the conceptual and the technical design phases. The initial phase will establish the potential of the muon collider and the required R&D programme for the subsequent phases. A technically limited timeline for the initial phase would need five years and is outlined in Fig. 5.3. Two sub-phases phases have been identified: the Exploratory Phase and the Definition Phase.



(a)

(b)

Fig. 5.3: Muon collider R&D roadmap (a) leading to the next ESPPU and (b) for the muon collider programme, assuming full resourcing.

In the Exploratory Phase existing studies will be identified and early stage design work will be performed leading to a tentative parameter set. Design choices will be made and critical issues will be identified so that tasks can be prioritised. Additionally resources will be sought to perform more involved studies. The exploratory phase is on-going and will continue until the end of 2022.

In the Definition Phase more involved design work will be performed. A complete baseline will be established including start-to-end simulation. Concepts for managing key technical issues and technologies which can drive the performance of the facility will be studied, where necessary including prototyping of the underlying equipment. In particular, a design of a facility to demonstrate an engineered muon ionisation cooling channel will be prepared. A more detailed parameter set will be established enabling an estimate for the performance, cost and power consumption to be performed. The R&D programme required to deliver a conceptual design report will be established. The Definition Phase will be completed by the end of 2025 so that a fully informed decision may be made during the next European strategy update.

The consecutive R&D programme will depend on the Strategy Decision. The most ambitious programme timeline leading to construction of a 3 TeV muon collider by 2045 is outlined in Fig. 5.3. Subject to the prioritisation made by the next European Strategy, the project could enter a conceptual design phase. The performance and cost of the facility would be established in detail. A programme of test stands and prototyping of equipment would be performed over a 5 year period, including a cooling cell prototype and the possibility of beam tests in a cooling demonstrator. This programme is expected to be consistent with the development of high field solenoid and dipole magnets that could be exploited for both the final stages of cooling and the collider ring development. A technical design phase would follow in the early 2030s with a continuing programme focusing on prototyping and preseries development before production for construction begins in the mid-2030s, to enable delivery of a 3 TeV collider by 2045. The programme is flexible, in order to match the prioritisation and timescales defined by the next ESPPU.

5.8 Conclusion

The muon collider presents enormous potential for fundamental physics research at the energy frontier. Previous studies, in particular the MAP study, have demonstrated feasibility of the facility across the parameter range required. A number of proof-of-principle experiments and component tests, such as MICE, EMMA and the MuCool RF programme, have been carried out to practically demonstrate the underlying technologies.

The muon collider is based on novel concepts and is not as mature as some other lepton collider options such as ILC and CLIC. However, it promises a unique opportunity to deliver physics reach at the highest energies on a cost, power consumption and time scale that may improve significantly on other proposed colliders on a footprint that is consistent with the LHC. It is the only practical technique to deliver lepton collisions at energies beyond 3 TeV. At this stage the panel did not identify any showstopper in the concept.

The panel has identified a viable baseline parameter set and a development path that can address the major challenges and deliver a 3 TeV muon collider by 2045. The panel will propose the R&D effort that it considers essential to address these challenges during the next five years to a level that allows estimation of the performance and cost with greater certainty. Execution of this R&D is required in order to maintain the timescale described in this document. Ongoing developments in underlying technologies will be exploited as they arise in order to ensure the best possible performance. This R&D effort will inform the decision-making process at the next ESPPU. Based on these decisions a significant ramp-up of resources could be made to accomplish construction by 2045, or a continued base level of investment could enable development on a longer time scale. This would enable Europe to exploit the enormous potential of the muon collider.

5.8.1 Acknowledgement

We would like to thank the conveners of the community meetings as well as the speakers and participants of the community meeting, the meeting on muon collider testing opportunities and of the regular muon collider meetings. Special thanks go to Andrea Wulzer and Donatella Lucchesi for valuable comments on the physics and detector. We would also like to thank Alexej Grudiev and Roberto Losito for valuable contributions.

6 Energy-Recovery Linacs

D. Angal-Kalinin[a], *K. Aulenbacher*[b], *A. Bogacz*[c], *G. Hoffstaetter*[d,e], *A. Hutton (Co-Chair)*[c], *E. Jensen*[f], *W. Kaabi*[g], *M. Klein (Chair)*[h], *B. Kuske*[i], *F. Marhauser*[c], *D. Kayran*[e], *J. Knobloch*[i], *O. Tanaka*[j], *N. Pietralla*[k], *C. Vaccarezza*[l], *N. Vinokurov*[m], *P. Williams*[a], *F. Zimmermann*[f]

[a]STFC Daresbury Laboratory, United Kingdom
[b]Mainz University, Germany
[c]Jefferson Lab, United States of America
[d]Cornell University, United States of America
[e]Brookhaven National Laboratory, United States of America
[f]CERN, Switzerland
[g]IJCLab, Orsay, France
[h]University of Liverpool, United Kingdom
[i]Helmholtz-Zentrum Berlin, Germany
[j]KEK, Japan
[k]Technical University Darmstadt, Germany
[l]INFN Frascati, Italy
[m]BINP, Novosibirsk, Russia

6.1 Executive summary of findings to date

The fundamental principles of energy recovery linacs (ERLs) have been successfully demonstrated across the globe. There can no longer be any doubt that an ERL can be built and achieve its goals. The panel has drafted a long write-up as an introduction to "The Development of Energy Recovery Linacs" and held an ERL Symposium . It is currently evaluating recent electron-positron collider ERL concepts and moves towards the development of a Roadmap on ERLs—to serve future colliders as well as low-energy particle and nuclear physics. ERLs promise a luminosity increase for physics applications by orders of magnitude at a power consumption comparable to classic, low-luminosity solutions, which is a necessary step towards the sustainability of high-energy physics, as interaction cross sections fall with rising energy. ERLs are also near utilisation in several industrial and other applications.

The novel high-energy ERL concepts targeted at energy-frontier electron-hadron, electron-positron and electron-photon colliders, as well as further physics and other applications, require the development of high-brightness electron guns and dedicated SRF technology as prime R&D objectives. Moreover, "it needs a facility comprising all essential features simultaneously: high current, multi-pass, optimised cavities and cryomodules and a physics-quality beam eventually for experiments" (Bob Rimmer).

Europe's next endeavours are MESA at Mainz, a polarised beam facility for experiments, bERLinPRO, an accelerator R&D facility at Berlin with the potential to reach 100 mA of electron current, and a dedicated high-power, multi-turn facility, PERLE at Orsay, which is being developed by a large international collaboration. Moderate investments, compared to other accelerator R&D projects, will be required to have this programme adequately supported. Globally, ERLs deserve coordinated cooperation, with the developments of high-current ERL facilities at BNL, BINP and KEK, with a forthcoming high-energy experiment at CEBAF as well as plans for next-generation facilities. High-current ERL

This contribution should be cited as: Energy Recovery Linacs, DOI: 10.23731/CYRM-2021-XXX.45, in: European Strategy for Particle Physics - Accelerator R&D Roadmap (Interim Report), Ed. D. Newbold,
CERN-2021-XXX, DOI: 10.23731/CYRM-2021-XXX, p. 45.

operation causes major challenges, such as beam breakup instabilities or RF transients, requiring collaborative efforts across the various facilities. In summary, the panel notes with much interest that the ERL technology is close to its high-current and high-energy application, requiring dedicated and coordinated R&D efforts, with the stunning potential to revolutionise particle, nuclear and applied physics as well as key industry areas, at a time where caring for energy resources is a prime necessity for this planet, not least big science. ERLs are therefore primed for inclusion among the grand visions our field has been generating, and for dedication of adequate support to it for this unique potential to bear fruit.

6.2 Motivation

6.2.1 Sustainability

Energy efficiency and sustainability have received a lot of attention over recent years. The concerns about climate change and global warming have to be taken especially seriously, also by the accelerator community. To quote F. Bordry : "There will be no future large-scale science project without an energy management component, an incentive for energy efficiency and energy recovery among the major objectives." It is a prime goal for the panel to evaluate the power economy of ERLs and to emphasise techniques being developed to further minimise the use of power. The accelerator community drives research and development at the cutting edge of technology for a greater purpose than just making the next accelerator better: Society expects a return from the investment in this research, which includes other applications of accelerators and further spin-offs. Innovation in accelerator technology, often linked to energy frontier physics, has been a prime attraction to new talents, the training of whom is an important part of the sustainability program followed here.

6.2.2 Accelerator Development

Energy-Recovery Linacs are an extremely efficient technique for accelerating high-average-current electron beams. In an ERL, an intense electron beam is accelerated to relativistic energies in (typically) a superconducting RF linear accelerator operating in continuous-wave (CW) mode. The beam is then used for its intended purpose, i.e., providing a gain medium for a free-electron laser, synchrotron light production, or a cooling source for ion beams. In high-energy physics, the interest is on an intense, low-emittance beam for colliding against hadrons (eh), positrons (e^+e^-) or photons (eγ). They all rely on the provision of high electron currents (of I_e up to $\sim 100\,\mathrm{mA}$) and high-quality cavities ($Q_0 > 10^{10}$).

Energy Recovery is at the threshold to become a major means for the advancement of accelerators. Recycling the kinetic energy of a used beam for accelerating a newly injected beam, i.e., reducing the power consumption, utilising the high injector brightness and dumping at injection energy: these are the key elements of a novel accelerator concept, invented half a century ago . The potential of this technique may indeed be compared with the finest innovations of accelerator technology such as by Wideroe, Lawrence, Veksler, Kerst, van der Meer and others during the past century. Innovations of such depth are rare and their impact only approximately predictable.

6.2.3 ERL-based Physics Prospects

ERLs provide maximum luminosity through a high brightness source, high energy through possible multi-turn recirculation, and high power, which is recovered in the deceleration of a used beam. It is most remarkable that following the LHeC design from 2012 (updated in 2020), all these avenues have been followed: for $\gamma\gamma$ collisions , further for eh with the FCC-eh in 2018 , for e^+e^- in 2019 (an ERL concept for FCC-ee termed CERC) and in 2021 (an ERL version of the ILC termed ERLC) and very recently a concept for the generation of muon pairs through high-energy, high-current eγ collisions .

A common task for these colliders is precision SM Higgs boson measurements dealing with a small cross section (of 0.2/1 pb in charged current ep interactions at LHeC/FCC-eh and similarly of 0.3 pb in Z-Higgsstrahlung at e^+e^-). This makes maximising the luminosity a necessity to profit from the clean experimental conditions and to access rare decay channels while limiting power. High luminosity and energy are expected to lead beyond the Standard Model and are essential for precision measurements at the corners of phase space.

At low energies, the luminosity is similarly crucial for several physics applications, such as polarised ep scattering for weak interactions, elastic form-factor measurements or dark-photon searches as are planned for MESA and had been pursued at JLab. Very high ERL intensity may permit to use internal targets, which avoids external target acceptance uncertainties. In backscattered photon scattering, the luminosity available exceeds that of ELI by a few orders of magnitude, paving the way to nuclear photonics, an area possibly comparable with the appearance of lasers in the sixties. A further fundamental interest regards the exploration of unstable nuclear matters with intense electron beams of O(500) MeV energy as is characteristic for PERLE and envisaged for GANIL in France. This follows the recognition of the field by NuPECC in their strategic plan in 2017: “Ion-electron colliders represent a crucial innovative perspective in nuclear physics to be pushed forward in the coming decade. They would require the development of intense electron machines to be installed at facilities where a large variety of radioactive ions can be produced”.

6.2.4 Industrial and other Applications

The range of further applications, beyond particle and nuclear physics, is very remarkable. Examples include high-power lasers, photolithography, and the use of inverse Compton scattering (ICS) . An ERL-FEL based on a 40 GeV LHeC electron beam would generate a record laser with a peak brilliance similar to the European XFEL but an average brilliance which is orders of magnitude higher than that of the XFEL.

The industrial process of producing semiconductor chips comprises the placing of electronic components of nanometre scale onto a substrate or wafer via photolithography. For advancing this technology to a few nm dimension, the FEL must be driven by a superconducting ERL. An ERL with electron beam energy of about 1 GeV would enable multi-kW production of extreme-ultraviolet (EUV) light. This would benefit the global semiconductor industry by allowing study of FEL capabilities at an industrial output level. Initial surveys and design studies were undertaken by industry some years ago. If the economic viability may be underpinned by large scale high reliability, ERLs might well reach into the market, which in 2020 was 400 B Euro.

A third example, interesting due to its applications for nuclear physics but also exotic medical isotope generation and transmutation, is the process of very intense inverse Compton scattering. An about 1 GeV energy superconducting ERL operating at high average electron current in the 10 to 100 mA range would enable a high-flux, narrowband gamma source based on ICS of the electron beam with an external laser within a high-finesse recirculating laser cavity. The production of 10 to 100 MeV gammas via ICS results in properties of the gamma beam fundamentally improved with respect to standard bremsstrahlung generation. This ICS process would be a step change in the production of high-flux, narrowband, energy-tunable, artificial gamma-ray beams. They will enable quantum-state selective excitation of atomic nuclei along with a yet-unexploited field of corresponding applications.

6.3 Panel activities

The ERL Roadmap Panel was recruited and its membership endorsed by the LDG in early 2021. It has 18 members, representing leading institutions and major ERL facilities (past, operational or in progress), and assembles key expertise such as on injectors, superconducting RF, operation and management. Supported by the LDG, the panel decided early on to write a baseline paper on ERLs for publication , from which a Roadmap would naturally emerge in a second phase of activity. Today, a draft of 220 pages exists citing 350 references, which is being completed in the coming weeks. The write-up, besides the panel, currently has about thirty further authors for covering the field with the necessary expertise.

On Friday 4th of June, an extended Symposium on the Development of Energy Recovery Linacs was held , introduced by Dave Newbold for the LDG. With up to 100 participants, and including an hour-long discussion, this was an important consultation with a community of interested accelerator, particle and nuclear physicists. Max Klein was invited to present to a TIARA meeting (29.6.21), while Andrew Hutton talked at the subsequent Particle Physics Symposium (9.7.21).

While the panel started to work, the ERLC concept was put forward to build the ILC as an energy-recovery twin collider, with the prospect of a major increase of the e^+e^- luminosity as compared to the ILC default. Similarly, the CERC concept had been published to configure the FCC-ee as a circular energy-recovery collider, with very high luminosity extending to large cms energy, maximally 600 GeV. This caused the formation, in agreement with the LDG, of a sub-panel[3] to evaluate the luminosity prospects, the involved R&D, schedule and cost consequences for both ERL-based e^+e^- collider options. It is intended to document the findings of the sub-panel in an Appendix to the ERL baseline paper, which will be published in early autumn 21.

The panel is moving towards the genuine ERL Roadmap document, based on its insight from the long ERL write-up and corresponding to its mandate.

6.4 State of the art

6.4.1 Current Status

A long way has been paved since the first SRF ERL at Stanford. Key parameters of an ERL are the electron beam current I_e ($\propto$ luminosity) and energy E_e. The beam power is simply $P = I_e E_e$. Through recovery of the energy, it is related to the required externally supplied power P_0, which then gets augmented by a factor $1/(1-\eta)$ where η is the efficiency of energy recovery. This way, for example, the LHeC can be designed to reach $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ luminosity, for which a GW of beam power would be required without energy recovery. The current state of the art may thus be characterised by a facility overview, presented in Fig. 6.1, as an E_e vs I_e diagram with constant beam power values P drawn as diagonal lines. The plot includes three completed ERL facilities, the first European ERL facility ALICE at Daresbury, CEBAF (1-pass), which, with 1 GeV, reached the highest energy so far, and the JLab FEL, which reached the highest current, of 10 mA. Larger currents have been achieved in the normal-conducting, lower-frequency ERL facility at BINP (the Recuperator). There are three SC facilities (dark green) currently operational, S-DALINAC at Darmstadt, CBETA at Cornell and the compact ERL at KEK in Japan.

Five facilities in progress, three of which are in Europe, marked in dark blue, have complementary goals intending to reach higher energy in five turns (CEBAF 5-pass) or high current (bERLinPRO and the coherent electron cooler, CeC at the EIC), in a single pass. MESA at Mainz will serve a number of low-energy experiments, the only facility with polarised beams so far. PERLE is designed for high current (20 mA), 3-turn operation leading to 500 MeV beam energy.

Figure 6.1 also displays the parameters of the by now five design concepts for ERL applications at the energy frontier with electron beam energies between 50 (LHeC) and 200 GeV (EXMP). CERC has a low current but a rather large number of beam lines. LHeC and FCC-eh are 3-turn linacs with about 20 mA current delivered by the gun. ERLC and EXMP are single pass linacs, with possibly twin-axis cavities. There follows a common demand on SC cavities to tolerate about 100 mA current load, which is the goal of PERLE (in 3 turns) and, in a single pass, of an upgraded bERLinPRO and the CeC at BNL in its most challenging configuration.

---

[3] **Sub-Panel on e^+e^- ERLs**: Chris Adolphsen (SLAC), Reinhard Brinkmann (DESY), Oliver Brüning (CERN), Andrew Hutton (Jefferson Lab, Chair), Sergei Nagaitsev (Fermilab), Max Klein (U Liverpool), Peter Williams (STFC Daresbury), Kaoru Yokoya (KEK), Akira Yamamoto (KEK), Frank Zimmermann (CERN).

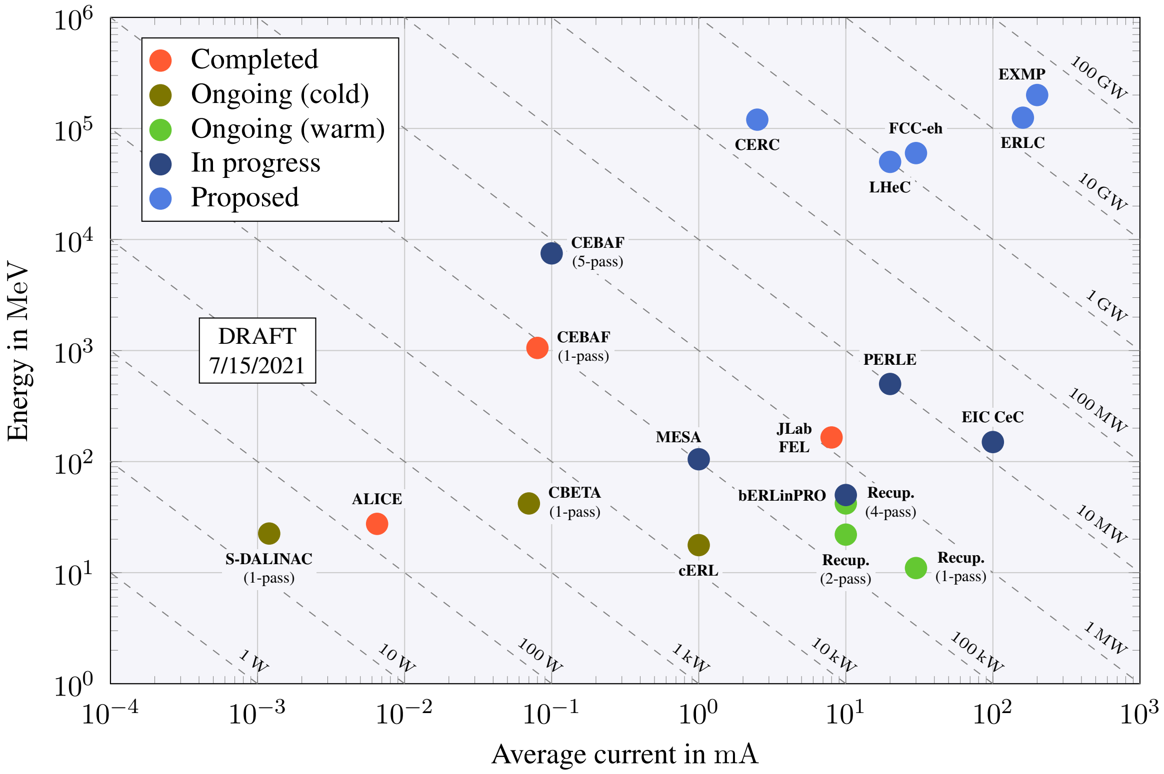


Fig. 6.1: Electron energy vs. current for ERL facilities .

6.4.2 *Plans for the Next Years—Operational Facilities*

The existing and forthcoming facilities have specific development plans. These activities and plans underpin to quite some extent the common, main R&D objectives, which are detailed in Section 6.5.

- S-DALINAC (TU Darmstadt)
  - establishment of a multi-turn SRF-ERL with high transmission (up to 70 MeV and 20 µA);
  - quantification of phase-slippage effects in multi-cell-cavity ERLs and countermeasures;
  - characterisation of potential operating points of individually recirculating ERLs.
- Recuperator (BINP Novosibirsk)
  - The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved;
  - Plans are to install this gun in the injector, while the existing electrostatic gun will be kept there. The RF gun beamline has already been manufactured and assembled on the test setup. The beam parameters were measured after the first bending magnet and at the beamline exit.
- CBETA (Cornell)
  - improve transmission, which includes investigating better optics solutions;
  - developing improved diagnostics for the decelerating passes;
  - reducing halo by using a low-halo cathode, possibly in conjunction with beam collimation.
- bERLinPRO (HZB Berlin)
  - Present activities are focused on the high-current SRF photoinjector and associated technologies. A dedicated diagnostic line capable of handling 10 mA is installed to characterise the beam;

  - Following the upcoming booster installation, the beam can be transported through the merger to the high-power beam dump following the splitter section, allowing studies of emittance preservation, beam loss, and bunch length manipulation.
- cERL (KEK)
  - Development of a 10 kW-class powerful ERL-based EUV-FEL;
  - Realisation of 100 % energy-recovery operation with a beam current of 10 mA at cERL and FEL light production experiment;
  - Development of an irradiation line for industrial applications (carbon nanofibers, polymers and asphalt production) based on CW cERL operation;
  - Further, planning to develop a high-efficiency, high-gradient Nb_3Sn acceleration cavity to realise a superconducting cryomodule based on the compact freezer.
- MESA
  - Improving electron beam polarimetry to an accuracy of $\mathrm{d}P/P \leq 0.5\,\%$ in order to support the first physics measurements of electroweak observables, possibly including Hydro-Moeller polarimeter;
  - Installing a second photo-source at the MESA injector with the potential to provide bunch charges > 10 pC with good beam quality;
  - Improving the cavity higher-order mode (HOM) damping capabilities, for instance by coating of the HOM antennas by layers of material with a high critical temperature.

6.5 R&D objectives

As the state-of-the-art section above indicates, the development of ERLs has been a complex challenge regarding several interrelated technology issues. The panel identified three key research and development objectives of particular importance: i) the provision of electron beams of high brightness, ii) the development of high-quality SRF technology designed for ERL use, and iii) the development of supportive technology including software and simulation techniques. It is characteristic for the field that its eventual progress relies on complete ERL facilities, for which a new generation is forthcoming, presented in Sect. 6.7.

6.5.1 High-Current Electron Sources

Injectors for high-energy physics ERLs, which require high average current in combination with complicated temporal beam structure, are typically based on photocathode guns. These guns rely on photocathodes, e.g., semiconductor materials, which for high average current are based on (multi)alkali antimonides, or GaAs-based systems for polarised beams, in combination with a photocathode drive laser and extremely-high-vacuum accelerating structure.

The quality of the photocathode is relevant for the performance of the photoinjector in terms of emittance and current, and a long photocathode lifetime is essential for photo-injector operation. Reproducible growth procedures have been developed and months-long lifetimes under operational conditions have been achieved. For high-current operation, photocathodes with high quantum efficiency are necessary and are usually developed in-house. Quantum efficiencies above 10 % at the desired laser wavelength have been achieved in the laboratory.

One critical aspect is to preserve demanding vacuum conditions ($< 10^{-10}$ mbar) on the whole way from the preparation system, via the complete transfer line to the photo-injector and the photocathode gun itself. The photocathode substrates (usually made from molybdenum) are optimised regarding their cleanliness and surface finish ($<$ 10 nm rms surface roughness) to achieve low emittance and to avoid field emission.

Especially in SRF photoinjectors, the superconducting cavity is extremely sensitive to any kind of contamination; therefore, the photocathode exchange process is very critical.

For weak interaction physics experiments, polarised electron beams are needed. These can be based on GaAs photocathodes, but their lifetime has still to be improved, e.g., by using newly developed activation processes.

Ongoing research topics in the field of photocathodes are the understanding of the photocathode materials (e.g., electronic properties), the photoemission process, and their intrinsic emittance. New growth procedures of high quantum efficiency, smooth, mono-crystalline photocathodes or multi-layer systems, and the screening of new photocathode materials are crucial for future electron accelerators.

A main research topic in the field of gun development relies on design of accelerator structure, which can provide a high cathode field in combination with extra-high vacuum conditions. Major efforts are concentrated on development of DC guns (Cornell University), VHF NCRF (LBNL), and lower- (BNL) and high-frequency SRF guns (bERLinPRO). Important insight can be gained from operating smaller facilities with high-current thermionic guns (BINP).

In brief, the field of laser systems for electron injectors, the technology of lasers with sufficient power to operate with antimonide-based photocathodes has been rather well developed. Major efforts are concentrated on the generation of laser pulses with elliptical temporal profile, which are necessary to deliver high charge bunches with ultra-low emittance.

6.5.2 Superconducting RF Technology

Superconducting RF is the key technology for energy-efficient ERLs. A vibrant global R&D program has aptly demonstrated the routine operation of SRF systems in many large-scale accelerators. Future developments must now push the technology to meet the stringent demands of next-generation ERLs while making strides in improving further the energy sustainability of the systems.

The focus for a linear collider is the high accelerating gradient, achievable in pulsed operation. CW ERLs, however, must handle very high beam currents. Simultaneously, they must balance the requirement for high cryogenic efficiency and beam availability, with the need for a reasonably compact and cost-efficient design. Presently, operation at moderate gradients (around 15–20 MV/m) provides the best compromise between these competing requirements.

Critical ERL SRF system developments must now focus on

- system designs compatible with high beam currents and the associated HOM excitation,
- handling of transients and microphonic detuning that otherwise require a large RF overhead to maintain RF stability,
- enhanced cryogenic efficiency of SRF modules.

To ensure beam stability in future ERLs operating with currents of O(100) mA, requires cavity designs and systems that minimise both the excitation and trapping of higher-order modes, facilitate HOM extraction and enables their efficient damping outside of the helium bath. Low-frequency cavities ($<$1 GHz) are typically favoured, having fewer cells to provide the same voltage and larger apertures. HOM damper solutions include space-efficient waveguide-coupled absorbers with high power capability or more readily implemented beam line absorbers between cavities. The ultimate efficacy of solutions must be put to the test in beam test facilities.

For CW operation, dynamic losses ($\propto E_{\mathrm{acc}}^2$) dominate the cryogenic load and pragmatically limit the gradient. In recent years a big improvement with Nb cavities was demonstrated with novel techniques such as nitrogen doping, effectively doubling the (typically) 2 K operating Q_0. A promising approach looks at the possible use of so-called A15 materials (like $\mathrm{Nb_3Sn}$) or $\mathrm{V_3Si}$ with higher T_{c}. First relevant tests with $\mathrm{Nb_3Sn}$-coated cavities, which can be operated at a higher temperature (4.2 K) and thus with significantly less power consumption for cryogenics, have reached encouraging results.

6.5.3 Supporting Technology, Simulations and Training

There are several important technology and development items to accompany the facilities in operation and those forthcoming. We provide here a non-exhaustive list of examples, which deserve further attention.

Fast Reactive Tuners

ERL cavities are essentially free of beam loading and in theory could be operated with negligible RF power. However, beam transients and the constant microphonic detuning of the resonance requires one to operate with an increased coupling and RF power overhead that can exceed the theoretical value by an order of magnitude and more. Most of the power is reflected and dumped. A side effect is that the RF stability and hence beam stability also suffers. This waste can be avoided if one can rapidly and continuously readjust the cavity resonance. Piezo-electric tuners have been investigated for some time, and, more recently, very promising ferro-electric BaTiO3 − SrTiO3-based fast reactive tuners are under development. Their suitability and longevity with full SRF systems without and with beam must be demonstrated to capitalise on their enormous potential.

Diagnostics developments

ERLs have specific diagnostics needs because of (a) the large beam power, (b) the small emittance that is to be preserved, and (c) the low beam loading that needs to be maintained in the main linac cavities. (a) The large beam power can lead to continuous beam losses that can easily damage vacuum components, magnets, and electronics; and it can create dark current in accelerating cavities. Halo diagnostics and radiation detection in critical regions is therefore essential. While existing ERLs have developed solutions, e.g., high-dynamic-range halo monitors at the JLab FEL or continuous radiation monitors along both sides of the beam pipe in CBETA, solutions for larger beam powers still have to be developed. Once loss regions have been identified with these devices, their sources can be addressed, e.g., by collimation of the beam at low energies. (b) The small emittances of ERLs have to be preserved to high energy. While the energy is subsequently recovered, the beam size has to remain small enough to keep loss rates low. View screens can be used when setting up the accelerating paths, but only in those return-loop regions where the accelerating beams of all turns can be separated. One source of emittance dilution can be Coherent Synchrotron Radiation (CSR), which may cause a microbunching instability. Such microbunching has been observed at CBETA and will have to be monitored to avoid the resulting emittance growth. Novel diagnostics that does not interrupt the beam has to be used for the decelerating passes. Effects that occur only at large beam currents—e.g., wake effects and beam-ion interactions—also require non-interrupting diagnostics that is yet to be developed. (c) In each cavity, the energy during all accelerating turns must match the energy that is recovered during all decelerating turns. Only then can each cavity be operated by the low drive powers installed in ERLs. This balance can only be maintained when the time for each accelerating and decelerating path is closely monitored by precise arrival time monitors.

Simulation Studies and Education

Before a facility may advance and hardware be built, it requires reliable simulations, based on collaborative efforts, experience and insight in the ERL beam physics and technology, from optimising guns through the injector, main loop onto the beam dump. Increasing beam brightness and energy requirements have to be met with advancements of simulation techniques requiring considerable CPU power. One can list a few specific beam dynamics studies related to ERLs:

- Study of CSR leading to microbunching and ultimately to beam quality degradation and emittance dilution. Simulations are instrumental in developing mitigation measures to suppress microbunch-

ing through appropriate lattice design. They are especially critical during the deceleration process, where the energy spread increases rapidly as the energy drops.
- Studies of wake fields and beam breakup (BBU) instability for multi-turn ERLs operating in CW mode, also addressing a long-standing question of BBU threshold scaling with the number of passes.
- Study of the longitudinal match to compress and decompress the electron bunch in order to optimise beam transport in energy-recovery mode. Implementation of second-order corrections to eliminate the curvature from the compressed bunch to further improve the longitudinal match without compromising the ability to transport the bunch in the decelerating passes.

The above selection of beam dynamics studies illustrates that the ERL accelerator technology represents a challenging training ground for a next generation of accelerator scientists. Many of these topics are dealt with in PhD theses, and all of the facility centres (and beyond) are engaged in forming and educating accelerator talents. The tasks to be solved are far from conventional, and the rather short time scales for building smaller facilities a plus in the attraction of young physicists.

6.6 Key points of roadmap

The panel is convinced that ERLs represent a unique, high-luminosity, green accelerator concept: for energy-frontier HEP colliders, for major developments in lower-energy particle and nuclear physics and industrial applications, altogether an innovative area with far-reaching impacts on science and society. With strongly enhanced performance, achieved with power economy and beam dumps at injection energy, ERLs are a most remarkable, vital contribution to the development of a sustainable science.

A peculiarity of the ERL development is that it needs operational facilities with complementary parameters and tasks to be successful. The global landscape of existing ERL facilities, including S-DALINAC in Europe, which are under further development, is rich, as has been outlined in Section 6.4.

A crucial next step towards the application of ERLs in high energy physics and elsewhere is to conquer the O(10) MW power regime with higher energy or/and high currents. This step requires to solve key technology challenges, described in Section 6.5, in particular for bright electron sources, dedicated ERL cavity and cryomodule technology ($Q_0 > 10^{10}$) as well as associated techniques. These technologies are partially available and under development for timely application and test in the existing and a forthcoming generation of ERL facilities.

The regime of high currents, in the range of 100 mA load to SC cavities, will be developed at BNL (EIC cooler CeC), KEK (cERL) and possibly HZB Berlin (bERLinPRO), and BINP Novosibirsk with normal-conducting, low-frequency RF. An order of magnitude increase in beam energy, to 10 GeV, is the goal of a new experiment at CEBAF. PERLE is the only facility designed to operate at 10 MW in a multi-turn configuration and the only one proceeding in a large international collaboration. MESA at Mainz will provide crucial insight in the handling of high beam polarisation in an ERL.

Four developments of high-energy and high-current facilities, presented in Section 6.7, are expected to provide major progress for the ERL field and a base for decisions due in the twenties on next generation HEP colliders, and their further development. For Europe, a roadmap focus will be on the utilisation of bERLinPRO for 100 mA developments and on a timely realisation of PERLE as a hub for accelerator developments and low-energy physics. These and further considerations will be the base for the European ERL Roadmap to be worked out in detail henceforth.

With appropriate financial support and enhanced attention to the European plans, complemented by the developments in the US and Asia, the road to powerful ERLs for application in energy frontier colliders, as well as for new generations of intense particle and nuclear physics experiments, can be timely followed with considerable confidence.

6.7 Facilities and infrastructure

The ERL roadmap is about R&D on key technology items and their use in complete facilities. The ERL development is reaching higher energies and currents in facilities which allow the in-depth study of associated technology and operation phenomena . Several facilities are in progress, their design parameters indicated in Fig. 6.1 and their programs described in what follows:

- **CEBAF 5-pass** (ER@CEBAF Jefferson Lab)
  Based on the large experience at Jefferson Lab, a novel project has been approved which has the target to study an ERL at highest energy, chosen to be 8 GeV, where effects such as coherent synchrotron radiation will notably occur. For the coming 4 years, the project has the following plans, also in collaboration with the University of Brussels and STFC Daresbury:
    - engineering design for a half-lambda delay chicane;
    - install dipoles for the delay chicane and the extraction dump;
    - continue ongoing beam dynamics studies;
    - finalise the Optics design, including sextupoles;
    - develop a step-by-step experiment run schedule (2024).
- **bERLinPro Upgrade** (Helmholtz-Zentrum Berlin)
  The beam transport and technical infrastructure for 100 mA, 50 MeV ERL operation has been set up at bERLinPro. The single-turn racetrack is closed, at high vacuum, in an underground building shielded to handle up to 30 kW continuous beam loss at 50 MeV. In 2022, the injection line will be completed and tested using an initial high-current SRF gun delivering up to 10 mA with an emittance better than 1 mm mrad. It is possible to upgrade the gun to 100 mA current and to complement the facility with a dedicated 1.3 GHz cavity-cryomodule for 50 MeV acceleration, designed to support a 2×100 mA load in CW operation and equipped with a Fast Reactive Tuner (FRT) system. The infrastructure at HZB exists for extensive cryomodule and FRT testing prior to installation in the ERL facility. This upgrade would transform bERLinPro into a key ERL facility providing experience with the highest current delivery and operation in the world. It will demonstrate the possibility to control the microphonic detuning of resonances leading to further, substantial power gains, and test the FRT system at currents suitable for future high-power multi-pass ERLs.
- **EIC electron Cooler CeC** (Brookhaven Nation Lab)
  Coherent Electron Cooling (CeC) is a novel but untested technique which uses an electron beam to perform all functions of a stochastic cooler: the pick-up, the amplifier, and the kicker. Electron cooling of hadron beams at the EIC top energy requires a 150 MeV electron beam with an average power of 15 MW or higher. This task is a natural fit for an ERL driver, while being out of reach for DC accelerators. Currently, BNL is developing two CeC designs. The first one is based on a conventional multi-chicane microbunching amplifier which requires a modification of the RHIC accelerator to separate the electron and hadron beams. Alternatively, the second CeC design is based on a plasma-cascade microbunching amplifier. Both CeC designs require an ERL operating with parameters beyond the state of the art.
- **PERLE** (Irène Joliot Curie Laboratory, Orsay)
  PERLE is a compact three-pass ERL project using SRF technology, pushing as a new generation machine the operational regime for multi-turn ERLs to around 10 MW beam power. PERLE will serve as a hub for the validation and exploration of a broad range of ERL accelerator phenomena in a so far unexplored operational regime serving for the development of ERL technology for future energy and intensity frontier machines. Particularly, the PERLE facility targets the LHeC configuration by featuring a 3-turn acceleration and 3-turn deceleration racetrack configuration, an 802 MHz SRF system, and beam currents of up to 20 mA (corresponding to a 120 mA cavity load). A first Nb cavity, realised at JLab in collaboration with CERN for FCC-ee and LHeC, had

a high Q_0 of 3×10^{10} up to a gradient of nearly 30 MV/m. The facility initially uses in-kind deliveries: of the gun (from ALICE at Daresbury), the booster cryostat (from JLab, using the module designed for JLEIC) and the main linac cryostat (from CERN adapting the SPL module). The Collaboration (BINP, CERN, U Cornell, IJClab Orsay, Jlab, U Liverpool, STFC Daresbury, with others expressing interest), has recently established an ambitious plan for first beam operation in the mid twenties. A second linac module, likely including FRT technology, and several electron-scattering experiments are in the early phase of planning.

7 Conclusion

A short summary of findings will appear here, alone with a description of the next stages of the roadmap process.

For the final report, the conclusions content will include:

- Summary of the key finding and recommendations in each area
- Cross-cutting recommendations
- R&D topics not included within the panel scope *If significant, this could form a short additional chapter*
- Timeline of proposed R&D activities and milestones
- Comparison of options and associated resources in each area