3 High-gradient RF structures and systems

3.1 Executive summary

Radio frequency (RF) systems are the workhorse of most particle accelerators and achieve high levels of performance and reliability. Despite five decades of improvement the community is still advancing RF performance with several novel developments. The next generation of particle accelerators will likely be still based on RF technology, but will require operational parameters in excess of state of the art, requiring an advanced R&D program. The R&D covers superconducting RF (SRF), normal conducting RF (NC RF) and ancillary systems such as RF sources, couplers, tuners and the systems that control them.

In SRF the development is focused in two areas, bulk niobium and thin-film (including high-Tc) superconductors. In bulk SRF new treatments are allowing niobium cavities to exceed previous record Q factors and avoiding degradation with increasing gradients. This includes nitrogen infusion and doping, and two-step baking processes. There is also an emphasis on limiting field emission. For thin-films the community is investigating creating coated cavities that perform as good as or better than bulk niobium (but with reduced cost and better thermal stability), as well as developing cavities coated with materials that can operate at higher temperatures or sustain higher fields. One method of achieving this is to use multi-layer coatings. Innovative cooling schemes for coated cavities are also being developed. Coupled to the cavity development is improvement in the cost and complexity of power couplers for SRF cavities.

Normal conducting cavities are also undergoing significant development both in the industrialisation and cost reduction of S, C and X-band (3, 6 and 12 GHz respectively) linacs, as well as novel developments to increase performance. There has also been a major leap forward in the understanding of RF breakdown and conditioning over the last decade, driven by improved test infrastructure and major R&D efforts, but much is still unknown and improvements are likely. To further increase RF performance novel developments in the use of cryogenically cooled copper, higher frequency structures and different copper alloys are under investigation. Finally for a muon collider significant R&D is required into the decreased RF performance in high magnetic fields (see e.g. Section 5.8.3).

It is expected that the energy consumption of particle accelerators will be a major driver in the next decade and the RF power is a significant fraction of that. Novel high-efficiency klystrons have been designed in the past few years, but this effort need to move to a prototyping phase. In addition fast ferro-electric tuners can reduce the required RF power for SRF accelerators, or NC RF accelerators with large beam transients. Artificial intelligence (AI) has started to show capability for classifying and potentially predicting RF faults making operating and conditioning linacs far simpler, and possibly allowing RF performance to be optimised. Low-level RF (LLRF) systems will also require R&D into standardising and simplifying hardware to decrease development costs and to aid collaborative efforts.

The panel notes there is significant overlap between the R&D required for energy-recovery linacs (ERLs) and muon colliders and the activities mentioned here. There is also requirements for RF to serve as injectors to novel accelerators. It is clear that improved RF system performance is both within reach and also critical to the development of any future high energy physics (HEP) accelerator, but such development will require appropriate investment.

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3.2 Introduction

All present particle accelerators used for HEP are based on RF technology to produce the high accelerating gradients required to achieve high energies of intense particle beams. Thanks to a continuous R&D activity conducted worldwide, tremendous progress was made in this area over the last 30 years, confirmed by the construction of several large scale facilities successfully operated since their commissioning.

Even though RF acceleration has been developed over decades, the requirements of future facilities to be considered for HEP are imposing new challenges are pushing forward RF acceleration technology. High gradient RF structures and systems is then one of the five key areas identified by the European Strategy for future HEP facilities where progress in R&D is needed.

At present, two main categories of RF accelerating structures are being used: accelerating cavities operating at room temperature and superconducting cavities operating at cryogenic temperature. The choice of either technology is dependent on the desired beam parameters and accelerator type. Both accelerating structure types have in common their need to be supplied by electromagnetic waves produced by high power RF sources and are transmitted to the structure by means of RF couplers, and their need for that electromagnetic wave to be controlled

The scope of this panel covers normal conducting and superconducting RF structures and their related systems (power couplers, frequency tuners, high-order mode couplers and dampers), high-power RF sources and LLRF. The main charge of the expert panel is to develop an R&D roadmap for the next 5 to 10 years for this technology taking into account the capabilities of the community.

3.3 Motivation

As a primary objective, increasing the accelerating gradient is an absolute necessity to keep the facility to a reasonable size while aiming at higher and higher particle energies. Then, economics always being a limiting factor, making progress towards more affordable accelerating RF systems at an industrial scale is also mandatory: engineering programs aiming at optimising the fabrication cost of some systems may gain in importance in the coming years.

Some key factors may see their importance growing with the size of HEP facilities or with the required beam parameters becoming more and more difficult to achieve. Energy efficiency is definitively a key parameter for future HEP facilities which will likely need to limit their electricity consumption. Efforts should be made on all systems and sub-systems, from the RF source to the RF structure, to optimise and thus limit their energy consumption. Another parameter of growing importance is the accelerator reliability: even though particle physics experiments are based on data accumulation over long periods, which can easily cope with short machine downtime, the overall effort to build and operate such large facilities impose the need to have a highly reliable accelerator and this may lead to technological choices not only driven by pure acceleration performance. For example large-scale facilities for photon science are expected to be operated with an availability well above 95% which leads to conservative goals with respect to accelerating gradients. HEP facilities can often accept somewhat lower availability but want the profit from highest possible gradients.

Each of the considered future facilities for HEP have specific challenges regarding RF acceleration technology and the proposed R&D plan, even if targeted towards generic R&D, addresses all of them. For instance, the proposed developments on superconducting acceleration at a temperature of 4.4 K to reduce the overall power consumption is of primary importance for high-current facilities operating in continuous-wave (CW) mode such as ERL-based facilities.

Even though novel acceleration concepts such as laser-plasma acceleration are promising for the long-term future, the actual or short-term potential for increased performances of RF acceleration is huge and could be exploited providing that R&D programs are well defined, oriented and coordinated among the different stakeholders, and this constitutes the main motivation to define and later on to implement an R&D roadmap for high-performing RF structures and systems.

3.4 Panel activities

The expert panel was fully constituted in April 2021 and held its first meeting on 6 May. The panel held several meetings afterwards, every two weeks in average. The first task was to precisely determine the technological domain covered by the panel and then to define its state of the art. Both superconducting RF and normal conducting RF international scientific communities are regularly exchanging about their progress through the TESLA Technology Collaboration (TTC) workshops for the former and through the recurrent High Gradient Technology Workshops for the latter, so information on the state of the art for each community is easily accessible.

The panel organised a dedicated workshop (held virtually) on 7 and 8 July 2021[5] with the double objective of understanding the requirements and challenges of future HEP facilities regarding RF acceleration and to define key technologies and developments which are essential on the way towards the construction of future accelerators for HEP. Presentations given and discussions held during this workshop have been the primary material used to produce this report.

Links and coherence with the international Snowmass process, and in particular with the topical group of the Accelerator Frontier AF7 (Accelerator Technology R&D) are ensured thanks to the participation of some members of our LDG expert panel to this AF7 group.

To produce the Roadmap, the panel worked in parallel over the three main topics: superconducting RF structures, normal conducting RF structures and high-power RF sources, ancillaries and control. In each area, we tried to identify where significant progress could be achieved and which are relevant for the whole panel of considered future HEP facilities.

3.5 State of the art and R&D objectives

3.5.1 SRF challenges and R&D objectives

3.5.1.1 Bulk niobium and the path towards high quality factors at high gradients

Bulk niobium technology for SRF cavities has been under constant optimisation for the last 50 years and today is still the main operational technology for the construction of SRF accelerators.

The definition of material standards, standard recipes for surface preparation and precise procedures for surface cleaning has set a very robust baseline allowing the construction of large scale SRF accelerators (examples being the European XFEL, LCLS-II at SLAC, SHINE in Shanghai, SNS and ESS).

Even though the hard fundamental limit of niobium has been close to being reached for the past 10 years, very specific and alternative surface and heat treatments have been investigated to tune the cavity performance to the very stringent specifications required by new projects and thus improve very specifically the driving parameters (Q_0, E_{max}, fabrication cost and reliability among others). Bulk niobium technology is still expected to be competitive for years to come, compared to the new alternative thin-film superconductors under investigation. Still many technical and technological challenges have to be tackled to allow their industrialisation.

The various new treatments under investigation and optimisation can be divided into three main focus areas:

- **Material structure**: The fine grain structure (FG), obtained from laminated ingots which were originally the only solution commercially available, has been surpassed in terms of both physical properties and cost by large grain structures (LG) obtained by sliced ingots. However, the latter LG structures suffer from technical limitations due to anisotropic mechanical properties. Challenges

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[5] https://indico.cern.ch/event/1052657/

with respect to pressure vessel regulations are under investigation. Medium grain structures (MG) are under investigation and development of these could offer the same physical properties (both superconducting and thermal) as LG with the improved mechanical properties compulsory for reliable cavity fabrication.

- **Heat treatments**: Baseline heat treatments often include an initial 800°C hydrogen degassing/recrystallisation treatment and usually also the so-called low temperature baking at 120°C during 48 h. These baseline treatments associated with advanced surface treatment (final electropolishing below 15°C), demagnetisation procedures, cooling procedures (high temperature gradients to promote magnetic flux expulsion) and magnetic hygiene revealed the efficiency and improvements offered by specific heat treatments such as nitrogen doping, nitrogen infusion and two-step baking. Nitrogen doping has allowed cavities to reach unprecedented Q_0 at the expense of the maximum achievable accelerating gradient. On the contrary, nitrogen infusion and two-step baking exhibit only a slight improvement of Q_0 but very high fields can be reached at low RF losses ($Q_0 > 10^{10}$ above 40 MV/m). Heat treatments at intermediate temperatures (between 200°C and 600°C) have recently been investigated and have revealed doping-like behavior (Q_0 rise versus accelerating gradient) but with a significantly simpler process.
- **Surface polishing**: For several years, the efforts made to reduce the temperature of electropolishing (EP) treatment below 15°C has led to unprecedented cavity performances. Low temperatures during chemical treatment are key to the promotion of optimum performance after the specific heat treatments described earlier. Alternative polishing techniques such as metallographic polishing (MP) and more recently electrolytic plasma polishing (EPP) are also under investigation. The ambition is to reduce the cost and eventually the ecological footprint of standard chemical processes. No real improvement of cavity performance is foreseen as achieving a surface roughness better than that achieved by EP does not seem to be a key parameter apart from for the future deposition of thin films.

3.5.1.2 Field emission reduction is a must for all accelerators

Field emission is one of the main reasons for the degradation of a superconducting cavities' quality factor. Its presence can limit the ultimate performance of superconducting RF cavities and hence the cryomodule in which the cavities are assembled. In general, the field emitted current tends to become more severe during beam operation. Hence, it can affect the entire accelerator's final performance. Dust particles on the cavity surface are the most common sources of contamination leading to field emission during cavity operation.

For this reason, it is essential to better understand how this phenomenon is created and evolves from SRF cavity preparation, starting in the clean room, to the cavity assembly into the cryomodule, the final accelerator module test and during machine operation.

The field emission issue can be addressed at three different levels:

- **Clean room preparation**: A clean environment is mandatory to preserve the cavity package's high performance. Improvement in manipulation, pumping/venting procedures and automation can be valuable assets for both high performance and mass production. The introduction of robots in the assembly line can relieve operators from tedious, time consuming and heavy work while ensuring robustness and reproducibility. It can also have a beneficial impact on the cost of mass production.
- **Diagnostics**: Analyzing X- and γ-ray patterns emerging from the cryomodule is a valuable method to diagnose field emission; with a proper detector system it is possible to evaluate recovery or mitigation methods. Specific diagnostic tools need to be developed for cryomodule testing and operation.

- **Mitigation and recovery**: There are ongoing efforts to develop in-situ treatments capable of cavity performance recovery or the mitigation of detrimental effects due to field emission in the most cost-effective way. Plasma cleaning and dry-ice rinsing are very promising and need further development.

Finally, field emission is a long-standing issue in the SRF field and will become even more relevant for the future high gradient and high-performance superconducting cavities, hence for future HEP facilities' operation.

3.5.1.3 Thin superconducting films for superconducting radiofrequency cavities

SRF cavities are one of the cornerstone infrastructures of particle accelerators. As mentioned in the previous chapter, for the past 50 years great advances have been made with bulk niobium technology which is now reaching with a high level of reproducibility $\sim$35 MV/m, Q$\sim$2–5 10^{10} at 2 K. Nibbling on the last cavity performance improvements to reproducibly reach the intrinsic limits of niobium will become increasingly difficult and exponentially expensive. In order to overcome this roadblock, a technological leap is needed to produce next generation SRF cavities with cost-effective means and reliable production methods scalable to mass industrialisation. Practical solutions are:

1. **Reduced amount of superconducting materials**: The SRF performance is dominated by the superconductors' properties within the surface layer of a few penetration depths. Hence, micron-thick films should be able to replace the more expensive bulk material while still maintaining bulk equivalent SRF cavity performances. Furthermore, the much higher heat conductivity of copper substrates reduces the risk of quenches. Recent remarkable results obtained at CERN with Nb/Cu have demonstrated the feasibility of this approach. This approach also suppresses the need for chemical etching of niobium and replaces it with a chemical surface preparation of copper which does not use hydrofluoric acid. In addition, the chemical recipes used can be transformed into processes that only leave a small amount of "dry" waste, which is a lot easier to deal with than large amounts of liquid waste. Once elaborated it can work for bulk Nb and Cu. The cooling procedures of thin superconducting films on Cu cavities have to be optimised in order to avoid thermoelectric trapped flux.
2. **Increased operation temperature for the same Q**: Higher T_c materials such as A15 compounds (Nb_3Sn, Nb_3Al, V_3Si) and MgB_2 with critical temperatures two to four times higher than niobium would enable operation at a temperature of 4.2 K or higher and significantly reduce operational costs while still preserving the required SRF cavity Quality factor ($> 10^{10}$). Well-established results obtained at Cornell and Fermilab with Nb_3Sn synthesised on bulk niobium cavities have demonstrated quality factors of 10^{10} at 4.2 K up to 22–24 MV/m. The major challenge is now to reproduce these results on Cu substrates and cavities. An increase in the operation temperature to 4.2 K represents an energy saving of a factor of three in the cryogenic system with respect to 2 K operation and significantly simplifies the helium distribution network. This is of primary importance for high current CW facilities such as ERL-based accelerators for which huge savings in the operation costs could be achieved (see e.g. Section 6.6.2.2).
3. **Increased maximum operation gradient (E_{max})**: To that end new multilayer hetero-structures with higher critical fields than niobium have been proposed. The multilayer approach composed of nanometric superconducting (50–200 nm) and insulating (5–10 nm) thin-film stacks has the potential to significantly increase E_{max} by 20 to 100% as compared to Nb. This solution can be applied to any optimised thin film mentioned in the points above. The major challenge is to demonstrate the feasibility of this solution for higher gradients i.e. > 50 MV/m. A 50% increase in the maximum accelerating gradient implies a construction cost saving for an XFEL-scale accelerator of about 100 M€ and a 50% lower cryomodule operational cost.

An ideal solution would merge all three approaches. To that end complementary deposition techniques and efforts must be pursued in Europe. For a few microns thick film (points 1 and 2) techniques such as chemical vapour deposition (CVD), hybrid physical–chemical vapor deposition (HPCVD), high-power magnetron sputtering (HIPIMS), etc. are well adapted and have demonstrated high quality superconducting materials (Nb, NbN, Nb_3Sn, MgB_2, etc.) on coupon scales. For the multilayer approach (point 3) however a nanometre-scale uniformity has to be achieved on complex shaped structures. To reach this goal the use of a deposition technique with demonstrated industry-scale production capability and nanometre-scale conformality and thickness control over arbitrary shapes has to be selected.

Priority should be given to the deposition techniques that can be scaled up to complex geometric shapes such as SRF cavities; i.e. optimised structural, chemical and electrical properties obtained on flat coupons have to be homogeneous and reproducible on a 1.3 GHz cavity shape. Vapor phase—CVD, atomic layer deposition (ALD) and physical vapour deposition (PVD), plasma-assisted deposition (HIPIMS, custom DC/AC sputtering) and electrodeposition are promising methods that meet the complex geometric requirements.

In addition to the deposition methods and superconducting alloys mentioned above, the thin-film R&D program relies on the success of three key factors common to the three mentioned research thrusts:

1. **Normal metal (Cu and Al) substrates**: The structural and chemical substrate properties are a crucial aspect of thin-film deposition with bulk-like superconducting properties. In particular, substrate roughness needs to be reduced well below the film thickness (1–5 microns), and the role of surface chemical properties (oxides, impurities) needs to be better controlled and understood. Investment on seamless cavity fabrication (mechanical, electrodeposited or 3D printed) is needed to reduce the impact of welds on SRF performance. The cavity geometry itself could be designed and optimised to facilitate the coating process. Chemical surface treatments such as HF-free electropolishing, buffered chemical polishing (BCP) and/or passivation layer deposition are methods of choice that could enable stable Cu surface preparation in one laboratory and deposition in another laboratory. This aspect should reinforce laboratory collaboration and speed up R&D outcomes.

2. **Innovative cooling techniques**: High T_c superconducting thin films will enable a higher SRF cavity operation temperature (>4.2 K), and hence will open the way for new conduction cooled accelerating structures using new cooling techniques (cavity wall with integrated liquid helium cooling circuit or pulsating heat pipes, etc.) and cooling channels instead of helium tanks. Indeed, one of the major problems is the evacuation of the energy inhomogeneously deposited inside the cavity towards the cold source. Regardless of the superconducting film used, improved heat transfer is essential. It is therefore necessary to offer innovative solutions that use existing and available technologies to ensure optimal heat transfer. Additive manufacturing of metals (Cu and Al alloys or elemental) becomes an option for designing optimised thermal links and structures cooled by cryo-coolers. Several conditions are necessary for this: (1) materials with optimised thermal conductivity (> superconductors); (2) increase in heat transfer and helium consumption by optimising the exchange links and surfaces; (3) optimised mechanical properties, both on the material and on the geometry of the cavity; (4) compatibility with ultra-high vacuum and low surface roughness.

3. **Infrastructures and manpower**: High-throughput characterisation methods on samples with demonstrated predictive capability for cavities RF performances are an absolute necessity for a successful R&D program prior to cavity scale-up. Besides all the usual structural (diffraction, scanning electron microscope—SEM, transmission electron microscope—TEM, etc.), chemical (spectroscopy, secondary ion mass spectrometry—SIMS, etc.) and electronic (transport) characterisation techniques applied to samples, special effort should be dedicated to reinforce means and efforts on the development of tunneling spectroscopy, magnetometry and RF tests on samples with quarter wave resonators (QWR). In a second step, cavity scale-up is mandatory to demonstrate

project feasibility. To that end, the SRF community research programs need: (1) a sufficiently large number of RF cavities (mono-cell and multi-cell for relevant project frequencies) at various frequencies (400 MHz, 600 MHz, 700 MHz, 1.3 GHz); (2) an RF testing facility dedicated to R&D at cryogenic temperature (down to 1.8 K), that can handle a large spread of frequencies (400 MHz to 6 GHz). This capability should handle 2–3 tests per week at least with in-situ metrology (magnetic field and temperature mapping, X-ray detectors, etc.). In addition, a reinforced international collaboration framework (collaborative agreements) and an international student program should be implemented to provide the necessary task force for a competitive and accelerated R&D throughput.

3.5.1.4 Challenges regarding the construction of SRF couplers

Superconducting cavities cannot be operated without fundamental power coupler (FPC) and higher-order mode (HOM) couplers. Both types of RF couplers play a fundamental role with respect to the R&D objectives for future HEP facilities. Whenever the community invests in better SRF cavities, driven by new challenging beam parameters, the FPCs and higher-order mode couplers (HOMCs) will also require effort. The worldwide expert community has long since addressed design and technology issues: RF & multipacting simulations, the maximum RF power, the number of couplers per cavity, the choice of ceramic, its surface preparation (e.g. TiOx or TiN layers), possible discoloration, the copper coating of stainless-steel parts (bellows are critical), diagnostics, and last but not least coupler conditioning and testing in dedicated infrastructures. All major laboratories and projects (including non-HEP large-scale facilities) have their own FPC and HOMC history, but many problems were and are shared. Key items like the ceramics for the windows (be it disk, cylindrical or coaxial) are of utmost importance. Heat transfer and the suppression of multipacting, by coating or DC voltage polarisation, has to be studied, and the qualification of cleanroom handling and cryostat integration are a must. Finally, mass production for large scale facilities requires perfectly qualified vendors, who typically have the challenge that almost each project triggers a fabrication re-start after a longer break between projects.

The charge of the RF power coupler community, in view of future large scale HEP (and other e.g. free-electron laser—FEL—and ERL) projects is to have sufficiently strong R&D activities and to address technology improvement but also a sustainable production. Expertise in the laboratories can be preserved by addressing identified main potentials of performance improvement, reliability, cost-effectiveness and energy efficiency. Young researchers need to be trained in existing, and in some cases also new, technical infrastructures. Expertise, knowledge and infrastructure can be shared for many large-scale projects, the latter to be evaluated on a case-by-case basis.

3.5.2 NC RF challenges and R&D objectives

High-frequency NC RF

High-gradient acceleration through NC, high-frequency structures (S-C-X band) provides at present the highest accelerating fields on a scale suitable for a high energy physics facility like an e^+/ e^- linear collider. In this respect NC high-frequency structures are the best option where the facility compactness is of primary concern. To further improve the operational gradients simplifying the construction process of all components, reducing the conditioning time, reducing the cost and delivery time of the RF power sources (klystrons), transferring expertise to industry to allow production of all components over orders of magnitude larger scale are the main challenges for building a HEP facility based on this technology. Gradients at the level of or in excess of 100 MV/m have been demonstrated in many CLIC-type X-band accelerating sections, even those incorporating HOM dampers. Larger gradients have been demonstrated in tests of prototypes made of hard copper or copper alloys.

However, reaching the highest gradients at an acceptable breakdown rate requires a long-lasting conditioning process, with a typical duration of several months. In addition, the peak RF power required to reach the highest gradient is substantial, this results in it being impractical to design a facility where sections are driven close to their physical limits by external RF power plants. In fact, the gradient baseline for all projects based on X-band klystrons driving accelerating modules is in the 60–80 MV/m range, well below the demonstrated physical limits that are mostly exploited only in two-beam configurations. To operate sections closer to the present and (hopefully improved) future breakdown limit it is necessary to increase either the available RF peak power in the tubes or the intrinsic efficiency of the sections themselves. Obviously, the latter would be preferable for cost and sustainability considerations. Clever design, such as distributed input coupling, or suitable technologies, such as the use of cryogenic copper, dielectrics and maybe even high-temperature superconductor (HTS), are promising roads to be explored in this respect. Cryogenic copper has been mainly tested in C-band so far, showing an efficiency increase allowing in principle to conceive a linear collider based on this technology.

At present, high gradient experimental R&D is carried out in a limited number of test facilities around the world, with a testing capability of few tens of structures per year. The number of the klystrons installed in these test facilities is also limited. Since a HEP infrastructure based on this technology would require a number of RF modules of the order of $> 10^3$, it is clear that scalability, in view of mass production, and industrial involvement are crucial issues to be addressed.

Low frequency NC RF in strong magnetic fields for a muon collider

To date, a muon collider is the only viable solution for a lepton collider with center-of-mass collision energy at the scale of 10 TeV. The Muon Accelerator Program (MAP) developed the concept where a short, high-intensity proton bunch hits a target and produces pions—see Section 5.2.2 of this report. The decay channel guides the pions and collects the muons produced in their decay into a beam. To provide the required luminosity several cooling stages then reduce the longitudinal and transverse emittance of the muon beam using a sequence of absorbers and RF cavities in a high magnetic field. The accelerating cavities are key to cooling efficiently with limited loss of muons. The RF cavities need to operate in the frequency range of 300 to 700 MHz and provide a high gradient in a strong magnetic field, up to 30 MV/m in 13 T. It has been shown experimentally at Fermilab's MuCool Test Area that the achievable accelerating gradient in RF cavities based on conventional copper technology is strongly reduced when operating in a strong magnetic field which makes the use of cavities limited to low gradient and dramatically reduces the efficiency and increases the size of the muon cooling complex. The main challenges are to show the feasibility of stable operation at high gradient in a strong magnetic field and to develop practical RF cavities suitable for mass production.

Two approaches have been considered in MAP, high-pressure hydrogen filled cavities and beryllium wall cavities. Although the dedicated test program in the MuCool Test Area has demonstrated that both approaches result in cavities operating up to 50 MV/m in 3 T, this remains an unconventional technology with potential risks and hazards. It is necessary to experimentally develop it further before applying it to a muon cooling test facility and ultimately to a muon collider.

This R&D program includes:

- consolidation of achieved results (50 MV/m) and pushing it to stronger magnetic fields up to 13 T;
- investigation of other materials (Al, AlBe, CuBe, and other alloys) which may show similar or better performance and are better suited for RF cavity fabrication;
- investigation of operation parameters including lower temperatures, down to cryogenic, and shorter RF pulse lengths.

To perform this program, a dedicated RF test stand is mandatory. In addition to a MW level peak RF power source, it must have high field ($\sim$10 T) solenoid. After the MAP has been stopped and the MuCool Test Area is decommissioned no similar test stand will be available anywhere in the world. There is a strong and urgent need to build a replacement in the near future to facilitate the development of RF technology for muon cooling.

In addition, synergy with other ongoing high gradient R&D programs should be exploited including for example the CLIC study and the CERN L4-RFQ spare project where, in addition to RF test stands, high voltage DC test setups have become an integral part of the R&D program. It offers fast and cost-effective way to investigate the high-gradient properties of many different materials in a large parameter space including operating at cryogenic temperatures.

3.5.2.1 General NC RF studies covering new geometries, breakdown studies, conditioning, dark current modelling and simulations

Despite its importance to the maximum gradient of an RF structure, breakdown is still poorly understood. For decades it was believed that it was a phenomena entirely down to surface electric field and surface geometry, since 2000 we have known that the magnetic field also plays a role related to pulsed heating but in the past decade there has been a real leap forward in understanding, with models related to mechanical stress leading to tip formation and models involving local power flow and field emitted beam loading coming forward. This is leading to new figures of merit in the design of RF structures and hence new geometries designed to avoid breakdown.

As well as breakdown modelling there has also been recent studies into conditions with the development of statistical conditioning models that can be used to optimise the best routing for conditioning. The long held belief that breakdowns condition a structure has been replaced with a work hardening model based on number of pulses. Studies of the role of dislocation dynamics in breakdown and conditioning is a fast developing field.

While significant progress has been made, full understanding is not complete but is expected to increase significantly over the next five to ten years.

3.5.2.2 NC RF manufacturing technology

Accelerating structures are made with ultra-precision diamond machining involving tolerances in the µm range and surface roughness in the range of 1/10 to 1/100 of a micrometer. Subsequent bonding and brazing operations need to be carried out in an inert atmosphere to avoid surface pollution. Several months of conditioning is needed per structure to reduce the breakdown limits. For large facilities like Compact Linear Collider (CLIC—see Section 7.3), the production cycle needs to be simplified and the reliability of the assembly of full modules, with damping, absorbers and wakefield monitors, needs to be improved while the quality of the assembled structures needs to be maintained or even improved. At present, structures are measured and tuned by hand, which is a time-consuming process not applicable to large-scale fabrication. State-of-the-art gradients of 100 to 120 MV/m have been achieved in modules that often require repeated mechanical corrections in order to be qualified.

Performance improvement. For industrialisation, vacuum brazing has already been applied at some labs and needs to be studied further. The production of two halves with subsequent electron beam welding (EBW) has been tested once and promises to reduce the production and conditioning time. The use of hard copper and of rectangular integrated discs deserves further R&D.

Technical infrastructure. High-precision milling, vacuum brazing and ultra-precision metrology are available at various suppliers but the knowledge of using this infrastructure efficiently often hinges on a few technical experts, which quickly disperse in case of longer production breaks. It is important to keep this expertise at least in a few laboratories. Structure assembly and handling may profit from chemistry, procedures and clean-room environments as used for SRF cavities. This approach should be studied further.

3.5.2.3 MM-wave & higher-frequency structures

Millimeter-wave (MM-wave) and Terahertz (THz) acceleration is a growing area of research worldwide. As part of the Compactlight program novel Ka-band (36 GHz) travelling and standing wave structures have been developed [1]. While initially aimed at an intermediate gradient lineariser system, there is scope for such technology to operate at higher gradients than X-band technology.

Main challenges and requirements for HEP facilities. With the higher frequencies come smaller apertures making transverse dynamics and short-range wakefield much more challenging. To be useful for HEP we must be able to transport higher charges with less drift space taken up by focussing systems. As the wavelength is also smaller it takes electrons several tens of mm-wave periods to become relativistic making longitudinal dynamics more complex, similar to proton linacs. In the long term mass production of high-frequency structures needs to be developed to minimise the cost.

MM-wave accelerators are useful as short bunch injectors, where the small period allows tight bunching, linearisers as part of a bunch compressor, short pulse diagnostics or as main accelerators. For a main accelerator the advantage is the higher gradients (200 MV/m or more) possible due to the operation at higher frequencies and shorter filling times, allowing shorter accelerators. However, the beam dynamics issues would have to be overcome to allow either higher bunch charges ($\sim$nC) or higher repetition rates (10 kHz or more).

State of the art and performance improvement. At Ka-band, a design was developed for Compactlight that used a 3 MW RF source to drive a 30 cm travelling wave structure at 38 MV/m, while previous studies at CERN used a two-beam accelerator to demonstrate gradients of 152 MV/m for an 8 ns pulse. At higher frequencies (100–300 GHz) high gradients have been demonstrated with wakefield-driven structures with a maximum gradient of 400 MV/m demonstrated and electrons have been accelerated by up to 200 keV while Gyrotron-driven structures have achieved 150 MV/m, however 3 MW laser-based sources are now available allowing gradients in excess of this. The bunch charges are typical tens of pC.

At 100–300 GHz the first challenge is to demonstrate > 100 MV/m operating gradients and acceleration of 1 MeV, this should be accessible with current technology. Little research has been done on beam transport between accelerating stages and longitudinal dynamics in the injection stage, and this should allow the development of full linacs. The shorter filling times could offer improved energy efficiency of future accelerators as you waste less energy filling the structure, however this would need the development of more efficient mm-wave sources.

Technical infrastructures. MM-wave accelerators can currently be tested at the CLARA accelerator for fully relativistic beams but beam time is currently limited. At lower energy 100 keV level DC guns and THz-driven guns exist at several labs.

3.5.3 High RF power and LLRF: challenges and R&D objectives

3.5.3.1 High-efficiency klystrons and solid-state amplifiers

Main challenges. High-gradient operation of NC structures reduces the footprint of the accelerator, but increases the RF power requirements quadratically, leading to klystrons with up to 50 MW peak power being employed. CLIC uses two-beam schemes, which effectively reduces the peak klystron power but requires two accelerators for one physics beam. Even if larger gradients become possible in the future, they may not be usable because the RF sources become prohibitively expensive. Higher-efficiency tubes can reduce the voltage of the modulators, reduce the size of the RF stations, and provide higher output power. For CW or long-pulse acceleration mostly superconducting cavities are used with gradients up to around 30 MV/m already in operation. Here it is not so much the peak power but the average power, which determines the cost and size of RF power sources. Solid-state amplifiers have gained ground on vacuum tubes in recent years but the volume, overall efficiency, power combination techniques and reliability can pose a challenge.

Main requirements for HEP facilities. Efficient generation of high peak powers in the X-band range is needed for NC accelerators, while efficient high average power devices up to ∼2 GHz are typically needed for SC accelerators. The first requirement is unique to HEP facilities and some medical applications, light sources, and screening technologies, which means that the market is very small. With the broadcasting industry moving to smaller power devices in the GHz range, the market for high average power devices is also declining. Muon collider RF systems are expected to use a large variety of frequencies with high peak power and high efficiency requirements.

State of the art and performance requirements. High-efficiency klystrons have made important progress in the last five years and successful prototypes have shown that the technology works with a frequency coverage from a few 100 MHz to tens of GHz [2]. Solid-state amplifiers have made the step into the MW range with the installation and operation of the CERN SPS solid-state plant at 200 MHz, a frequency so far not covered by klystrons. The R&D on high-efficiency klystrons needs to continue and several suppliers have shown interest and are ready to collaborate with laboratories in the production of prototypes. While solid state is set to take over the market of tetrodes for lower-frequency high-power RF amplifiers, the technology needs to improve efficiency. The combining networks are of crucial importance as they define the fault tolerance and maintainability. Improved efficiency at the transistor or amplifier module level is expected to be driven by industry. Combining networks or combining cavities, reliable operation, packing factor and overall efficiency are areas where laboratories can contribute R&D.

Technical infrastructures. Testing RF power stations with peak power in the range of several tens of MWs, as well as CW power stations in the MW range need significant infrastructure which is often not available at the manufacturer. Larger industrial production will likely need lab-based test stations in order to keep the cost down. Prototyping of solid-state combining technologies and the development of high-efficiency klystrons in the labs are vital to enable industrial production, and to moderate the cost of the production of high-power RF systems in industry.

3.5.3.2 MM-wave and gyro-devices

A key issue in the development of higher-frequency accelerators is the shortage of higher power RF sources, where klystron and gyro-klystron devices are currently being developed. Gyro-devices are capable of delivering high powers at significantly higher frequencies so are critical for mm-wave linac development. At the boundary between RF and mm-wave at Ka-band there is scope for both klystron- and gyrotron-based sources [3, 4]. As part of the compactlight program a novel Ka-band (36 GHz) RF system has been studied including the development of Ka-band RF sources.

Main challenges and requirements for HEP facilities. The main challenges are the development of high-power, high-efficiency short-pulse mm-wave sources, and the beam dynamics (both transverse and longitudinal). Currently the power available in short pulses is tens of kW, while MW are required for HEP applications. MW-level sources do exist but tend to be long-pulse. Both laser-based and electron-beam based sources are under development with two 3 MW, 36 GHz sources designed already. Laser-based sources can deliver GV/m fields in free space with instantaneous powers of a up to 30 MW but in very short picosecond pulses that are difficult to synchronise, and have had little development so far.

State of the art and performance improvement. At Ka-band, the 3 MW sources should be build and proven to work. Coaxial Gyro-Klystrons offer the potential of 10 MW sources in the future. At present laser-based sources are well suited to very short pulses, and low repetition rates, while electron-beam based sources such as gyro-devices tend to be long pulse and high repetition rate but neither currently deliver the intermediate-length pulses required here.

3.5.3.3 Technologies to reduce RF power needs for acceleration

The frequency control of high-Q superconducting cavities is an area for power savings that has further potential [5]. Two areas are of particular interest: very low beam-loading, and operation with rapidly changing beam currents.

Low beam-loading case. Low beam-loading results in a very small intrinsic cavity bandwidth down to a few Hz or a few 10s of Hz. Keeping the frequency of the cavities controlled to such a level is challenging due to the small vibrations, coming from the cryogenics, the vacuum system or other external sources, known as microphonics. Therefore the fundamental power coupler is usually over-coupled, resulting in a larger bandwidth of the cavity-coupler system. However, in doing so the power requirements are often increased tenfold with respect to the power needed for acceleration and replacing the surface losses of the cavities. Correcting the cavity frequency fast enough to compensate these microphonics has the potential to reduce the power needs for low beam-loading machines by up to a factor of 10 (e.g. LHeC, PERLE, HIE-ISOLDE, etc.).

High beam-loading case. For high beam-loading cavities with rapidly changing currents, such as the LHC cavities (e.g. at injection), the cavity frequency is usually adjusted to be optimum for either the full beam current or 50% of the beam current (half-detuning scheme) in order to optimise the peak power needed from the RF system. Changing the cavity tune during transients (no beam to full beam) could significantly reduce the peak power needs. In the case of HL-LHC the peak power needs during injection could be reduced by 50% or more.

Technology for rapid cavity tuning. With the rise of purpose-designed low-loss ceramics it became possible to design tuning devices for SC cavities that do not rely on mechanical deformation. Instead a fraction of the stored RF power is coupled out, sent through a ferroelectric fast reactive tuner (FE-FRT), which shifts the phase as a function of externally applied voltage. The electromagnetic wave is then reflected back into the cavity, thereby changing its frequency. The proof-of-principle has been done and R&D for a full-scale tuning device, applicable to the LHC has started. Further work for ERLs and future circular colliders should follow.

3.5.3.4 Low-level RF

Today's low-level RF & controls infrastructure (electronics & software) is mostly developed within the different laboratories for highly specific machine requirements. This means that each lab is putting aside resources for its own design and development of electronic cards, firmware and software, which are not interchangeable. In recent years some laboratories have started using commercial off-the-shelf (COTS) components in order to reduce the in-house electronics effort and in order to standardise their equipment. This development must be encouraged so that existing resources can be used towards higher-performance software (e.g. machine learning) instead of machine-specific hardware.

Main challenges and requirements for HEP facilities.

- High-current colliders: minimising RF power through more advanced algorithms for beam-loading compensation. Development of very low-noise demodulators/modulators.
- Very large machines: instantaneous signal transmission to a large number of distant RF stations.
- Standardisation/compatibility: development of standard electronics modules (ideally COTS), which will enable standardised firmware and software blocks that can be exchanged between labs.
- Archiving: maintenance of growing firmware and software libraries for existing machines such that ageing software can still be edited and deployed on newly made spares.

State of the art and performance improvement.

- Use of deterministic links (such as White Rabbit, Update Link, etc.) for synchronising several RF stations and injectors has been proven to be effective and should be developed further.
- More structured design methodologies can save programming time, ease archiving, and make code blocks more exchangeable between different labs.
- System on chip: the combination of field-programmable gate arrays (FPGAs) with digital signal processors (DSPs) and even with analogue-to-digital converters (ADCs) can drastically reduce the manpower effort: all communication between these different elements needs to be defined and programmed today, while system-on-chip architectures would make this effort obsolete.
- Development and deployment of new platforms such as micro telecommunications computing architecture (µTCA), advanced TCA (ATCA), etc. together with industry and in coordination with other laboratories to enable the use of advanced algorithms.

Technical infrastructures.

- A centralised and powerful synthesis machine for all firmware developments and archives should be available in each lab.
- Test infrastructures for COTS components.
- Tools for code testing and development. Tools for simulation of entire FPGA design.

3.5.3.5 Artificial intelligence and machine learning

Machine learning is being developed in several labs for use in RF conditioning and operation of accelerators. This involves a computer algorithm being trained to identify the difference between a good RF pulse, a bad RF pulse and anomalies. The algorithm then constantly analyses RF traces and characterising them. This can be used to identify advance triggers or warnings of failures or real-time detection in order to take corrective actions. This is a new field but expertise exists in many labs like CERN, STFC and JLab.

Main challenges and requirements for HEP facilities. Initial studies suggest it is possible to predict and avoid SRF and RF faults, but it is a new field. Typical expected gain could be the minimisation of field emission, arcs and trips of RF systems. In some cases, the time window between fault prediction and the fault may be short, so we need considerations of what targeted mitigations are possible (such as turning cavity voltages down temporarily for instance).

To make progress in this field, there is a need to access large volumes of the right data recorded at the right time to train the algorithm. This requires a fundamental shift in how accelerators take data and make them available for machine learning.

State of the art and performance improvement. Currently studies are performed in retrospect analysing past data. On tests the breakdowns can be predicted a little before it happens but work is required to assess if that's an artifact of the data. Work has also been done on fault classification and this has been very successful separating normal pulses from arcs in different components, outgassing, multipactor, abnormal klystron pulses, etc. The algorithms were able to find rare breakdown events in the decay of the pulse that were being missed in traditional detection methods.

3.6 Delivery plan

In order to address the R&D objectives depicted in the previous chapter, the panel has defined corresponding work programs for each of the topics and sub-topics. In the large majority of cases, three different investment (budget and effort) scenarios are proposed:

- the nominal plan is roughly based on the actual effort of European labs in generic R&D dedicated to RF acceleration in terms of allocated full-time equivalent-years (FTEy) and budget;
- the minimal scenario is obtained either by a reduced ambition in some programs or by putting priorities between programs and then removing the one with the lowest priority;
- the aspirational scenario is the full sum of all programs, but with reasonable or affordable ambition: in any case, for a short to medium term plan, effort just cannot be infinitely increased because these R&D plans require already trained and skilled people.

The proposed plan is addressing a generic R&D program for RF acceleration. The corresponding estimated cost is the required budget to develop technologies and solutions that could be later adapted to targeted HEP projects which could benefit from the scientific and technological outcomes. The required budget for the specific adaptation or optimisation for a given facility is not accounted for here, as we consider it as direct project funding.

The generic R&D budget is to support development of new concepts, new ideas and to prove their feasibility. The complete demonstration of the operational performance of a given objective (project) could sometimes only be performed on a full scale prototype (for instance a full cryomodule). This development phase should also be funded directly by the projects and are not accounted for in our estimates.

Regarding infrastructure and equipment costs, where we have analysed that specific equipment is globally missing in our European labs, its cost has been integrated into the program. But we consider that the existing infrastructure is already supported in terms of operation and maintenance, such that the corresponding cost and effort (operators) is not integrated into the presented program budget.

3.6.1 Superconducting RF

3.6.1.1 Bulk niobium and the path towards high quality factors at high gradients

1. Push forward the development and validation of large/medium grain material.
   (a) Milestones at five years:
      i. Operational CW cryomodule at gradients > 20 MV/m.
      ii. Develop new vendors of LG/MG ingots to allow mass production.
   (b) Milestone at ten years: scale to lower frequencies than 1.3 GHz (larger cavities).
2. Continue R&D on vacuum heat treatment and doping.
   (a) Milestones at five years:
      i. Push further investigation of the so-called mid-T baking (300–600°C) and doping.

      ii. Fine tuning of parameters of advanced heat treatments as mid-T baking, doping, etc.
      iii. Demonstrate improvements and applicability of these advanced heat treatment for other frequencies than 1.3 GHz.
   (b) Milestone at ten years: apply advanced heat treatments as standard treatment for new accelerator projects.

3. Improvement of surface polishing and characterisation techniques: standard techniques (EP, BCP) and developing new techniques (EPP, MP, etc.).
   (a) Milestones at five years:
      i. Develop new infrastructures for large cavities (multicells, low beta, etc.): extra-cold EP, rotational BCP.
      ii. Investigate and identify new polishing techniques compatible with SRF requirements and industrialisation.
   (b) Milestone at ten years: new and advanced polishing techniques mature for new accelerator projects.

Table 3.1: Costing scenarios for bulk niobium R&D.

Scenario	Minimal	Nominal	Aspirational
Scope	Reduced (1&2)	Full (1&2&3)	Full (1&2&3)
Cost for five years[a]	3 MCHF	4 MCHF	6 MCHF
FTEy for five years[b]	60	75	100

[a] Includes dedicated and specific facilities for R&D needs, prototypes, consumables. Does not include cost of standard SRF infrastructures required for cavity test (clean rooms, etching labs, vacuum furnace, cryostats, cryogenics, etc.).

[b] Includes dedicated R&D FTE. Does not include FTE required to operate standard SRF facilities.

3.6.1.2 Field emission reduction is a must for all accelerators

1. Develop robotisation/cobotisation (human-robot collaboration) for surface processing/cleaning of SRF components.
   (a) Milestone at five years: operational robot in clean rooms and demonstrate improved cleanliness.
   (b) Milestone at ten years: apply as standard for new accelerator projects.
2. Pursue R&D effort on particle counting in clean room and X-rays diagnostics capabilities.
   (a) Milestone at five years: show improved efficiency and yield of surface preparation.
   (b) Milestone at ten years: apply as standard diagnostics for new accelerator projects.
3. Intensify R&D on field emission mitigation/in-situ recovery techniques (dry-ice, plasma).
   (a) Milestone at five years: deployment and show efficiency of these techniques for accelerator in operation.
   (b) Milestone at ten years: apply as standard pre-treatment or recovery treatment for new accelerator projects.

Table 3.2: Costing scenarios for field emission reduction R&D.

Scenario	Minimal	Nominal	Aspirational
Scope	Reduced (1 & 2)	Full (1 & 2 & 3)	Full (1 & 2 & 3)
Cost for five years	3 MCHF	4 MCHF	5 MCHF
FTEy for five years	30	40	50

3.6.1.3 Thin superconducting films for superconducting radio frequency cavities

The thin-film research and development efforts in Europe should pursue three main goals with the following roadmap and milestones:

1. **Continue R&D niobium on copper—construction cost saving and securing supply:** fabrication cost reduction for cavity fabrication with frequencies < 700 MHz. The goal is to reach RF performances (Q and E_{max}) similar to bulk niobium. As a standard for the ongoing R&D efforts, 1.3 GHz cavities will be used with performance targets of $Q = 10^{10}$ at 20 MV/m, followed by $Q = 10^{10}$ at 30 MV/m. In parallel, high performance will be established on lower frequency cavities (400 MHz to 800 MHz) and multicellular cavities in order to demonstrate the performances potential for HEP projects based on low-frequency cavities (ERLs, FCC).
    (a) Milestone at five years: reach bulk niobium performances on 1.3–0.4 GHz elliptical and various cavity shapes (WOW, SWELL).
    (b) Milestone at ten years: scale up process to multicellular cavities (1.3–0.6 GHz).
2. **Intensify R&D of new superconductors on Cu—**4.2 K **operational cost saving:** operation cost reduction (higher operation temperature > 4.2 K). Such superconductors are selected A15 compounds (Nb_3Sn, Nb_3Al, V_3Si) and MgB_2. Proof of principle has been achieved with Nb_3Sn on niobium cavities, the goal is now to achieve the same performance on Cu cavities at 1.3 GHz: $Q = 10^{10}$ at 15–18 MV/m and 4.2 K. Scaling to lower frequencies (600 MHz) cavities will also be investigated to cope with the need of ERLs and FCC.
    (a) Milestones at five years:
        i. A15 (Nb_3Sn, V_3Si, etc.): reach same performance as Nb_3Sn on Nb at 4.2 K on several cavity geometry (1.3–0.6 GHz).
        ii. MgB_2: feasibility (critical temperature > 30 K) on 1.3 GHz cavity.
        iii. Study the influence of mechanical deformations and induced strain (~0.1 %) of cavities on the RF performances of A15 and MgB_2 alloys.
    (b) Milestones at ten years:
        i. A15: reach same performances at 4.2 K as bulk Nb at 2 K, scale to other frequencies (elliptical) and investigate the potential for multicell cavities.
        ii. MgB_2: reach same performances at 4.2 K as bulk Nb at 2 K.
3. **Pursue multilayers—push for high gradient:** operation and construction cost reduction by increasing the maximum accelerating gradient and the quality factor. The goal is to demonstrate improved performance on a 1.3 GHz superconducting RF cavity, i.e. 30–50% increase in the maximum accelerating field and a factor of two in Q_0.
    (a) Milestone at five years: demonstrate increased acceleration on 1.3 GHz bulk Nb and thin-film Nb/Cu 1.3 GHz elliptical cavity.
    (b) Milestone at ten years: scale up to various cavity shapes and multicell elliptical cavities.

In addition to the mentioned deposition methods and superconducting alloys, the thin-film R&D

Table 3.3: Costing scenarios for thin superconducting films R&D.

Scenario	Minimal	Nominal	Aspirational
Scope	Reduced (1 & 2) 2–3 years slower than aspirational scenario	Full (1 & 2 & 3) 2–3 years slower than aspirational scenario	Full (1 & 2 & 3)
Cost for five years	10 MCHF	15 MCHF	30 MCHF (25 + 5 for cavity-scale coating facilities)
FTEy for five years	40	100	140

program relies on the success of three key factors common to the three mentioned research thrusts:

4. **Intensify Cu cavity production and surface preparation.**
   (a) Milestones at five years:
      i. Seamless elliptical Cu substrates (mechanical or electro-deposited) starting at 1300 MHz down to 400 MHz.
      ii. Optimise air stable chemistries (EP-BCP/without liquid waste, heat treatment, passivation layers, etc.) for Cu surface preparation.
   (b) Milestones at ten years: scale up processes to multicell cavities (1.3 GHz).
5. **Develop 3D printing and innovative cooling techniques.**
   (a) Milestones at five years:
      i. Develop proper substrate Cu/Al alloys (monocellular cavity 3.9 and 1.3 GHz) for thin-films deposition with optimised density (> 99.8%), cooling power and mechanical response (similar to Nb at 4.2 K).
      ii. Demonstrate substrate (cavities) surface roughness <1 µm.
      iii. Demonstrate conduction cooled cavities with selected and optimised innovative heat links and a cryocooler.
   (b) Milestones at ten years: deposition of thin superconducting films.
      i. Demonstrate bulk Nb performances with thin Nb film on 3D printed/electro-deposited cavity at 4.2 K.
      ii. Demonstrate bulk Nb performances with new superconductors (A15, MgB_2) film on 3D printed/electro-deposited cavity at 4.2 K.
      iii. Develop proper substrate multicell cavities.
6. **Infrastructures and manpower—high-throughput testing.**
   (a) Milestones at five years:
      i. Dedicated building with thin-film specific state-of-the-art infrastructures (clean rooms, chemistry, rinsing/washing, assembly).
      ii. Improved surface characterisation methods (spectroscopy, QPR) and cold test diagnostics (temperature mapping on Cu, automated optical inspection, etc.).
      iii. Reinforced International Student and collaboration effort program.
   (b) Milestone at ten years: high-throughput RF testing facility to establish repeatable and reliable performance needed in preparation of series production.

This ambitious plan (points 1 to 6) is the basis for SRF cavity development towards future European SRF needs (FCC, muon collider, etc.) and will position Europe as the leader in thin-film SRF cavity

Table 3.4: Costing scenarios for key technologies.

Scenario	Minimal	Nominal	Aspirational
Scope	reduced (4)	reduced (4 & 5)	full (4 &5 & 6)
Cost for 5 years	2 MCHF	5 MCHF	30 (8 + 20 + 2) MCHF[a]
FTEy for 5 years	10	15	55 (25 + 25 + 5)[a]

[a] Includes 20 MCHF + 25 FTEy for R&D dedicated cavity-scale testing facility and 2 MCHF for green laser 3D printing machine + 5 FTEy.

R&D worldwide. The aspirational scenario is mandatory for a real, internationally competitive, thin-film R&D effort toward project-scale application. Existing testing and handling infrastructure (DESY, CEA, CNRS, CERN) is not sufficient because they each focus on very specific testing frequencies, mostly on bulk Nb cavities, their use is dominated by project needs over R&D and they often suffer from insufficient metrology capabilities and manpower. The example of the USA R&D program on SRF cavities is eloquent; about hundred million dollars have been invested over the last decade in JLab and in Fermilab R&D infrastructure, respectively, to achieve their current success.

3.6.1.4 Challenges regarding the construction of SRF couplers

The state-of-the-art power fundamental couplers for SRF cavities peak power handling capability exceeds 1 MW both on high-power test stands and on complete cryomodules. However, this applies to pulsed operation up to 10% duty cycle. In the case of CW operation, reaching 1 MW has only been demonstrated on room temperature test benches, and represents a two fold increase of the current FPC performance in cryomodules in the lower half of the frequency range considered here (from ∼200 MHz to 1.3 GHz), and is a much greater challenge on the higher frequency side. A challenging performance goal for pulsed FPCs with up to 10% duty cycle would be to transfer a power in excess of 2 MW.

Beside the ubiquitous parasitic phenomena which can deter the performance of any power coupler (i.e. multipactor, cleanliness issues), CW operation above 1 MW on a SRF cavity with existing FPCs is compromised by:

- the RF losses in the critical areas constituted by the RF window dielectric material (e.g. alumina) leading to thermally induced stress;
- the thermal stability of cold FPC parts (which can be a cold window, the RF bellows or the thin thermal barriers) when generating an excessive heat load to the cryogenic system;
- the breakdown phenomena in the dielectrics, the air on the mode converter between the high-power waveguide network and the upstream RF window or the window material itself.

Although each of these limitations balance differently at the lower and upper ends of the RF frequency range and duty cycles considered here, advances in these areas are required for future couplers. They require both generic R&D when materials, high-performance coatings or manufacturing processes are concerned, and case-specific design and optimisation for a given cavity application.

- **Assessing the effective improvement of high performance ceramics.**
    - High purity alumina is an attractive window material: it could reduce the RF losses and stress in RF windows, and ultimately enable the design of cold windows for high average power applications. High purity alumina is notoriously more difficult to braze to copper than commonly used 95 to 97.5% purity alumina materials. The improvement in terms of RF losses and thermo-mechanical behavior has to be demonstrated on actual RF windows. In particular, the thermal conductivity of the combined material layers between the alumina and window RF body should not get in the way of increased power handling capabilities.

  - Low secondary emission yield (SEY) ceramic materials have been proposed by companies for almost a decade now (e.g. Kyocera). The improvement expected by FPC designers is to eventually get rid of the anti–multipactor coating (Ti, TiN) which is applied to the vacuum side of ceramic windows on current FPCs. The efficiency to complexity and cost ratio of this delicate step in FPC window manufacturing is often debated in the community. However, even if the exact composition and thickness choices for the layer vary among the laboratories, all high power FPCs require this form of SEY reduction in order to prevent the development of charge build-up and breakdown in FPC windows. One should stress that industrial production of windows have been put in jeopardy more than once in recent years when the Ti/TiN deposition system and process specific to a particular window was not developed and transferred to industry beforehand. The alternative offered by the new low SEY compounds can be a game-changer provided the brazing process is developed and transferable to industry, and the performance improvement is demonstrated.

- **R&D topics on architecture and components of FPCs.**
  SRF FPC designs are strongly dependent on the cavity and the cryomodule they are assembled on. However, several FPC options or features can be studied separately or in combination with each other in order to come up with novel architectures:
  - waveguide and mode converter types,
  - variable or fixed coupling,
  - DC biasing,
  - single-window or dual-window FPCs,
  - rigid or flexible connection to the SRF cavity.

  The FPCs of interest for future HEP applications at high CW power cannot skip the added complexity of featuring variable coupling and DC biasing:
  - FPCs must sustain a number of wave reflection conditions when running on a SRF cavity with varying loading by the beam. This is mitigated with a variable coupler which provides the correct matching, with the benefit of the minimisation of the local RF field maxima inside FPC components and associated localised heat loads. DC biasing of the antenna for multipactor suppression makes things more challenging by adding the DC voltage across air gaps on top of the peak RF voltage.
  - The breakdown field on the air-side of the room temperature window is a limitation which can be overcome by increasing the window dimensions, within boundaries usually imposed by the high power RF waveguide types under consideration. Loading the air side with a pressurised gas aiming at a greater dielectric strength can also improve the breakdown threshold. More open options can be studied, such as exploring alternative combinations of waveguides and corresponding methods for coupling electromagnetic modes between the high power network and the main waveguide of the FPC. Conceptual studies of new architectures combining elliptical and rectangular waveguide exist in literature. Such studies should be resumed and broadened to alternate geometries for FPCs and coupling ports on SRF cavities. The selection of a particular architecture can be triggered by several criteria than the potential increase of power handling, for instance the possibility of variable coupling, the compatibility with clean room assembly, the simplification of manufacturing process and cost reduction.

- **Test stands.**
  The high-power RF test stands are a key element in FPC development. Currently, dedicated FPC test stands are in operation in European laboratories, and share the common characteristics of being tied to a given RF frequency and type of operation (pulsed or CW). Developing concurrent designs at two or more laboratories at a given frequency and power target is a must. This has often been the way the FPC community has proceeded and is the preferred one for obvious reasons. The model

of a single test place and several laboratories producing FPC variants for one project is known to work during the R&D phase if the host laboratory is able to provide a team with high-level skills in SRF, FPC instrumentation, vacuum, cryogenics and clean room activities.

In the particular case of 1 MW and higher CW power test stands for future HEP projects, the choice of the target RF frequency and power should be made as early as possible in order to start to equip the high power RF part of the test stand. In many cases, the RF source is simply the prototypical version delivered to the accelerator project when a new industrial development has to be started early. One should keep in mind that the widely accepted testing technique in the high power FPC community is to start all power tests in pulsed mode before switching to CW. The RF source and its control system should therefore be compatible with this requirement. A promising alternative is to use an existing power source extending its power range using a resonant ring, a tuned waveguide structure recirculating the RF wave constructively.

Since an unprecedented level of SRF CW power is expected in this R&D program, the testing of FPCs should not be limited to room temperature conditioning in a pair arrangement, but should include a complete instrumentation to monitor the coupler behavior and compare it against the design criteria. If a FPC fails during the test, the root cause must be identified, so short-term, faster time-stamped data acquisition should be available.

In addition to the instrumentation dedicated to vacuum, electronic activity and arc detection, a dedicated realistic cryomodule-like environment should be available for demonstration of the thermal behavior of the FPCs. The demonstration of the designed thermal behavior and the efficiency of the links between the FPC and cryomodule, as well as the associated targeted heat loads can only be demonstrated in a properly instrumented cryogenic test stand.

Milestones. The goals, expressed in terms of CW power, are mostly related to CERN-related future machines. If the need for a pulsed power high-duty cycle (>10%) FPC emerges with power levels above 2 MW peak, the same development phases apply, only the performance goal is changed.

M1: Build or upgrade a fully equipped bench for room-temperature high-power RF testing of 1 MW class CW FPCs.

M2: Demonstrate the feasibility of room temperature windows with equivalent power handling as the current state of the art, based on both high-purity and low SEY ceramic.

M3: Demonstrate the feasibility and assess high-power RF performance in a realistic cryogenic environment of a high average power cold window.

M4: Conceptual studies of novel FPC architectures and selection of the more promising ones for further prototyping.

M5: Demonstrate the performance at room temperature of a power coupler at 1 MW CW.

M6: Demonstrate the performance in cryomodule-like conditions of a power coupler at 1 MW CW.

M7: Start industrialisation for series production.

The number of participating laboratories is expected to range from 2 to 5, which is the current number of European FPC teams participating in the World Wide FPC (WWFPC) community hosted by CERN. The WWFPC networking activity facilitates technical exchange between FPC experts on FPC design, technology, test stands and operational experience. Since the FPC community in Europe is reduced to a few individuals, the continuation of the WWFPC meetings is fundamental to keep it dynamic.

Ultimately, technological developments in this field should be transferable to industry if mass production is considered, or co-developed with industry within the time-frame of the Roadmap. A clearly identified risk is that the skill level of the very few industrial partners known today is not maintained due to a reduction of their activity linked to FPCs in the current decade.

Table 3.5: Roadmap scenarios for SRF couplers.

	Minimal	Nominal	Aspirational
Goal at five years	M1 + M3 + M4 + M5 with current materials, simple design to assess the limit of power handling	Minimal scenario + M2 + M1 with resonant ring + power testing of components from M4	Nominal scenario + M1 + cryogenic test conditions M6
Goal at ten years	M5 with updated materials or architecture	Minimal + M6 + M7 + M5 with updated materials and architecture	Nominal + demonstration of power margins of nominal scenario + M6 with updated materials and architecture + M6 on a prototype cryomodule

Table 3.6: Estimated resources for SRF couplers.

	Minimal	Nominal	Aspirational
Five-year programme	10 FTEy + 3 MCHF	16 FTEy + 4 MCHF	20 FTEy + 7 MCHF

3.6.2 Normal conducting high-gradient structures

3.6.2.1 General NC RF studies covering new geometries, breakdown studies, dark current modelling and simulations

The nominal scenario includes:

- RF design of an accelerating structure for the klystron based CLIC RF module with the new type of cells with integrated HOM damping loads, 'rectangular disks'. RF design of RF pulse compression system with correction cavities for the klystron based CLIC RF module. RF design study of accelerating structures for CLIC main linac with distributed coupling.
- Optimisation of electromagnetic constructive design of X-band high-gradient structures to be operated with klystrons and pulse compression for EuPRAXIA project, synergic with similar linac projects. Modelling dark current production and transport, and benchmark it against experimental data.

Estimated resources for the nominal plan: 27 FTEy over 5 years.

The aspirational scenario integrates the nominal plan and in addition:

- development of high-gradient, high-duty cycle RF cavities;
- RF Breakdown studies using flat samples.

Estimated resources for the aspirational plan: 36 FTEy and 300 kCHF.

3.6.2.2 NC RF manufacturing technology

The program plan of the nominal scenario includes:

- Supervision and qualification of copper-cells manufacturing companies, assembling and brazing in-house complete structures. Study and test of alternative, brazing-free construction process.
- Design and fabrication of prototypes of the new type of cells with integrated HOM damping loads,

’rectangular disks’. Fabrication of an accelerating structure prototype for the klystron based CLIC RF module. Design and fabrication of RF pulse compression system with correction cavities for the klystron based CLIC RF module.

- Development of ’rectangular disks’ and work with companies to manufacture X-band cavities including RF testing.

Estimated resources for the nominal plan: 30 FTEy and 2.5 MCHF over 5 years.

3.6.2.3 MM-wave and higher frequency structures

The program plan consists of:

- Minimal—development of beam dynamics for scalable mm-wave linacs: 3 FTEy over 5 years.
- Nominal—demonstration of scalable staging of mm-wave acceleration (including beam dynamics): 15 FTEy and 0.2 MCHF over 5 years.
- Aspirational—demonstration of Ka-band high-gradient acceleration: 25 FTEy and 0.5 MCHF over 5 years.

3.6.3 High RF power and low-level RF

3.6.3.1 High-efficiency klystrons & solid-state amplifiers

The minimal program plan consists of:

- simulations & design of high-efficiency klystrons;
- prototype of LHC plug-compatible high-efficiency klystron;
- design of power combining cavities.

Estimated resources for the minimal plan: 7.5 FTEy and 550 kCHF over 5 years.

The nominal program plan consists of the minimal plan and in addition:

- conceptual designs for high-efficiency klystrons;
- 1 FCC CSM or 2 stage L-band klystron prototype (400–800 MHz);
- X-band 50 MW high-efficiency klystron prototype;
- X-band 1.6 kW prototype solid-state klystron driver amplifier;
- low-power prototypes of solid-state power combining systems;
- RF power system concept for muon collider.

Estimated resources for the nominal plan: 20 FTEy and 5.5 MCHF over 5 years.

The aspirational program plan consists of the nominal plan and in addition:

- CERN high-efficiency klystron replacements for LHC before end-of-lifetime of existing devices to increase power into cavities (16 klystrons in total).
- More likely: $\sim$6 new klystrons + gradual replacement towards end-of-lifetime.
- High-power prototypes of various solid-state power combining systems.
- Develop RF power sources concept for muon cooling complex RF system. Set target specifications and address potential issues (frequencies, peak power, efficiency).

Estimated resources for the aspirational plan: 37 FTEy and 6.5 MCHF over 5 years.

3.6.3.2 MM-wave & gyro-devices

The program plan consists of:

- Minimal scenario: Scoping study of short pulse mm-wave gyro-devices for linacs. Estimated resources are 1 FTEy.
- Nominal plan: perform an electromagnetic design of mm-wave gyro-devices. Estimated resources are 5 FTEy.
- Aspirational plan: development of Gyrotron prototypes at 36 and 300 GHz and development of a 36 GHz klystron prototype. Estimated resources for this scenario are 15 FTEy and 1.2 MCHF.

3.6.3.3 Technologies to reduce RF power needs for acceleration

The minimal program consists of performing conceptual studies adapted specifically to LHC, FCC, muon colliders and ERLs. Estimated resources are 4 FTEy.

The nominal plan consists of the minimal plan and in addition design and build prototypes for the LHC transient detuning. Estimated resources are 6 FTEy and 400 kCHF.

The aspirational program is based on the nominal plan and in addition:

- design and build prototypes for ERL operation (e.g. FCC-eh, PERLE);
- design and build prototypes for FCC-ee transient detuning.

Estimated resources for the aspirational plan: 9 FTEy and 0.8 MCHF over 5 years.

3.6.3.4 Low-level RF

The nominal proposed plan consists in:

- Development and implementation of µTCA based LLRF & control system for the HL-LHC superconducting crab cavities. Improved methodology + infrastructure. Continued development of white rabbit framework and components (5 years).
- Development of µTCA based LLRF & control system for the LHC elliptical superconducting accelerating cavities (10 years).

The corresponding estimated resources are 25 FTEy, already budgeted in the HL-LHC project and potentially in the LHC consolidation budget.

The aspirational plan consists in:

- Implementation of centralised computing infrastructure for FPGA design.
- Development and installation of standardised System-On-Chip LLRF prototypes for new machines and as replacement of legacy Versa Module Eurocard (VME) systems. Increased use of machine learning algorithms for operation.
- Use RF test stands as development beds for new LLRF modules (e.g. µTCA, system on chip, etc.).
- LLRF networking events and increased coordination effort between European laboratories.

The corresponding estimated resources are 20 FTEy, and 1 MCHF for this 5 years program.

3.6.3.5 Artificial intelligence and machine learning

The minimal plan consists of several work program developed at CERN, STFC and DESY. For CERN, the effort is embedded in operation and commissioning. For STFC, the plan is to perform further studies on X-box & CLARA data and start SRF studies (develop predictive AI to detect breakdown and other trips). For DESY, the program is to perform SRF studies:

- provide a complementary AI algorithm to detect SRF cavity quenches along with other anomalies observed within the LLRF systems;
- classify anomalies;
- implement a demonstrator for live data analysis (i.e. running with live data).

The corresponding estimated resources are 14 FTEy and 100 kCHF.

The nominal plan has in addition the following tasks:

- test on-line running and control via AI on test stand: decrease conditioning time on test stands using AI;
- running detection live on the entire EuXFEL;
- automatic categorisation / labelling of trips for SRF cavities.

The corresponding estimated resources for this nominal plan are 26 FTEy and 600 kCHF.

The aspirational plan has in addition to the nominal plan:

- Demonstration of an operating machine of AI control: decrease machine trips of an operating machine using AI.
- SRF:
    - extending the AI monitoring to other subsystems (klystrons, cryogenics);
    - extending the functionalities of the online AI to self-calibration of LLRF systems, predictive diagnostics and automatic preventive countermeasures.

The corresponding estimated resources for the aspirational plan are 41 FTEy and 800 kCHF.

3.7 Facilities, demonstrators and infrastructure

In the development plan of RF technologies, once basic performance demonstration is performed on prototypes, it may be required to have a complete demonstration and validation of fully equipped RF structures in their nominal operation conditions. Thus, availability of large-scale test stands equipped with nominal RF power could be considered as mandatory to perform a complete demonstration of an RF structure performance, possibly with a beam to accelerate. This chapter is dedicated to these large-scale test stands and indicates either the required effort to operate and develop the already existing stands or the effort to build new ones.

3.7.1 NC RF test stands

Consolidating and expanding the activities carried out at the present existing high-gradient test stands, as well as promoting the implementation of new ones, are crucial actions. An increased capability of testing and conditioning a large number of components, in particular accelerating structures of various kinds, is required to push further up the breakdown limits, and to qualify different materials and/or design approaches. Experimental optimisation of the conditioning process, to increase the effectiveness and reduce the duration, is also a collateral strategic goal that should be pursued, guided by conditioning process modeling to be elaborated and refined iteratively on the base of theoretical considerations benchmarked on existing data. Number and location of existing test stands:

- CERN: X-box #1 #2 #3;
- INFN Frascati: TEX;
- PSI: C-band test stand for structures/modules;
- Valencia: S-band test stand for structure;
- Cockcroft Institute: S-band test stand under construction.

The nominal plan for such test stands is:

- Operation, maintenance and upgrade of CERN Xboxes: #1, #2 and #3. High-gradient testing of X-band RF structure prototypes: CLIC super accelerating structure, structures fabricated from two halves, structure from ’rectangular disks’, deflecting cavities as well as new RF components: RF pulse compressor, RF windows.
- Construction of High gradient test stand at Daresbury. Study of RF breakdown on flat samples. Testing of new structure types.
- Valencia and INFN-TEX: test of 5 X-band devices/year for the next 5 years, including EuPRAXIA type structures, CLIC structures, pulse compressors, waveguide components (splitters/directional couplers/loads/variable phase-amplitude shifters).

The corresponding estimated resources for the nominal plan are 40 FTEy and 5.3 MCHF over 5 years.

The aspirational has in addition to the nominal plan:

- Increased capacity of the Daresbury test stand.
- INFN TEX: adding capability to operate power tests also in S/C bands for expanded high gradient activities. High cathode peak field tests of RF guns ($\approx$200 MV/m goal, C-band).

The total effort estimated for the aspirational plan is 75 FTEy and 8.8 MCHF over 5 years.

3.7.2 Test stands for new materials resilient to beam losses and RF breakdown in vacuum

Activities conducted on these tests stands (Lancaster, CERN, Uppsala) have strong synergy between high-gradient RF for muon collider, as well as for both electron and hadron high-gradient high-intensity linacs. The scientific objectives are the following:

- Identification of a set of materials with potential better performance than oxygen-free (OFE) copper in terms of resilience to the RF breakdown in vacuum and to effect of beam irradiation. Investigate experimentally the effect of irradiation by H^- or similar beams.
- Investigate experimentally maximum achievable strength of electric field on the surface in a DC test setup and compare it to OFE copper.
- Develop new assembly techniques for the new materials.

The nominal plan consists in:

- Cryogenic DC test of copper electrodes down to 30 K.
- Testing different irradiated materials.
- Study of conditioning.
- DC testing of electrodes from different material including: OFE Cu, CuCrZr, TiAl6V4, Nb, Ta, CuBe before and after irradiation. Fabrication, preparation and evaluation of electrodes.

- Upgrade cryogenic DC test system to reach temperatures below 10 K.
- DC test of superconducting electrodes (niobium).
- Equipped DC test system with portable clean room for electrode installation.

The corresponding estimated resources for the nominal plan are 17 FTEy and 0.7 MCHF over 5 years.

3.7.3 RF design and implementation of low/medium energy high-gradient linacs

An important intermediate step between test stand facilities and a future high energy collider is the design and realisation of low/medium-energy (a few GeV) electron linac facilities based on high gradient NC RF. This will drive the design and integration of full RF modules, the realisation over larger scales of components, and ultimately will test the reliability of the technology as a user facility backbone. The EuPRAXIA program at INFN Frascati and the AWAKE e-linac at CERN are examples.

The nominal plan consists in:

- operation of CERN facilities (AWAKE, CLEAR, eSPS);
- realisation of a full RF module prototype for the EuPRAXIA@SPARC_Lab project (INFN);
- realisation and test of a high-gradient, high-repetition rate C-band RF gun (INFN).

The corresponding estimated resources for the nominal plan are 20 FTEy and 3 MCHF over 5 years.

The aspirational scenario has in addition to the nominal plan the design and realisation of structures for high-gradient 400 Hz operation. The total effort estimated for the aspirational plan is 25 FTEy and 4 MCHF over 5 years.

3.7.4 RF test stand and test cavities for R&D on high-gradient NC RF in strong magnetic fields

The main goal of this test stand is to identify and set-up an infrastructure for testing RF cavities in strong magnetic fields: RF power source, SC solenoid, etc. The aspirational tasks consist of:

- design and build a RF test stand based on the available infrastructure and specific requirements;
- develop a test program adapted to the test stand, considering possible limitations in terms of available frequency, power, magnetic field strength and size of a SC solenoid;
- design, build and test the prototype cavities.

This has some synergy with RF guns and positron capture linacs operating in moderate magnetic fields which report increased breakdown rates when the solenoid is set at high field. Resources to build the above mentioned test stands within 5 years (2025):

- At CEA:
  - design studies for cavities and pulse compressor;
  - design studies for bunker and electronics layout;
  - RF Infrastructure construction (bunker, magnet installation, control room, wave guides, etc.;
  - construction and testing of cavities.
- At STFC:
  - study of breakdown in moderate magnetic fields for RF guns;
  - construction of high-gradient test stand with large superconducting magnet;
  - study of breakdown in high magnetic fields.

The corresponding estimated resources for the aspirational plan are 18 FTEy and 3.3 MCHF over 5 years.

3.7.5 Technical infrastructure for fully dressed superconducting cavity testing

In SRF acceleration, the usual development plan to reach a full assessment and validation of the performance of a new cavity concept or preparation/material is the following:

- Develop an R&D program on bare cavities (even sometimes even on simplified geometry such as monocell cavities, or reduced size cavities for cost efficiency reasons).
- Develop an R&D program for the associated ancillaries systems (power couplers, tuners, HOM) specifically adapted to the need and geometries of the cavity. This part integrates separated tests of each sub-system for their individual validation.
- Assess the overall performance of the fully dressed cavity (cavity equipped with its ancillaries) at the nominal operation temperature and RF power.
- Perform the engineering design of the complete cryomodule integrating the outcomes of the preceding program and build a prototype cryomodule.
- High power test of the prototype cryomodule for the full assessment of its performances.

Steps one and two are meant to be supported by a generic R&D budget, whereas steps four and five are usually integrated into the project budget as they incorporate system designs which are specific to a given project. In this development plan, and despite the critical milestone it represents, step three (fully dressed cavity test) is often abandoned due to the lack of adapted available infrastructure to perform this test. The price to pay is a late assessment of the overall SRF cavity package performance obtained only during the prototype cryomodule test at a late stage of development (strong negative impact on cost and schedule in case of failure).

A fully dressed SRF cavity test requires a horizontal cryostat and adapted RF sources. In Europe, a few of them exist (CHECHIA in DESY, HNOOS in Uppsala, CRYHOLAB at CEA, HobiCat in HZB), but they are either adapted only for a given cavity geometry (often 1.3 GHz multicell) or not available. The upgrade of some of these facilities or the construction of a new versatile horizontal cryostat (as already studied and designed in the TIARA project) capable to test fully equipped SRF cavities of various geometries would constitute an important and useful piece of equipment for several future HEP facilities, and in particular for ERLs and FCC for which this test is a major milestone.

The corresponding estimated resources are 10 FTEy and 0.9 MCHF for the upgrade of two existing facilities (nominal plan) and 15 FTEy and 1.9 MCHF for a new versatile horizontal cryostat (aspirational plan).

3.8 Conclusion

This Roadmap clearly states the priorities for RF development required for the next generation of HEP accelerators. Currently there are several different directions for the next HEP machines and hence the RF development plan must cover a wide variety of RF technologies. While the Roadmap has focused on generic RF R&D there is a clear link between this R&D and the project specific R&D already budgeted for in many labs. However what we have shown is in many cases the lack of flexibility in the project infrastructure limits the ability to fully study and develop technology and there is a requirement for funds directed at generic R&D that is coordinated across European labs and universities.

The nominal investment scenario given in this document is the future committed R&D at the present time, however with significant RF improvements required to meet the needs of future HEP machines and to meet expected improvements in energy consumption additional funding will be required.

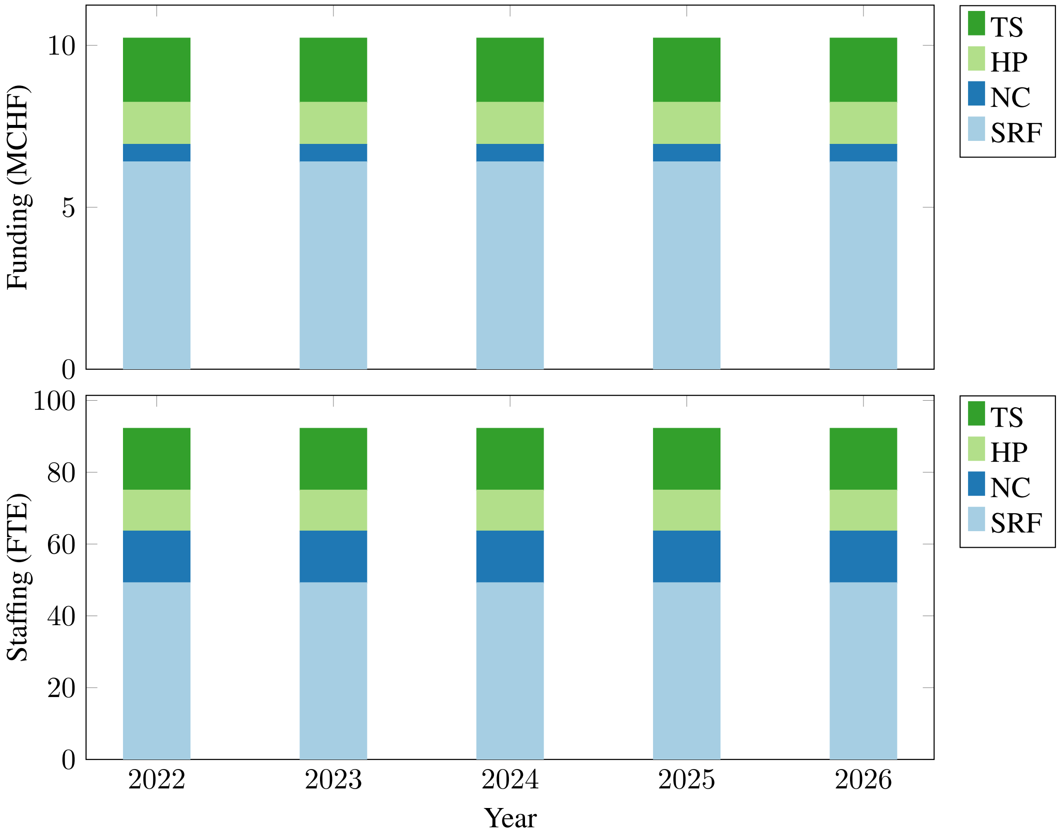

Fig. 3.1: Resource-loaded schedule for the RF nominal plan.

We have presented an aspirational scenario that represents a reasonable amount of investment to meet those needs.

While this Roadmap is focused of HEP, it should be noted that similar R&D is required for light sources and medical accelerators, which are already taking advantage of R&D initially developed for HEP machines, such as Compactlight, and proton-therapy linacs. Further development of SRF systems making them lower cost and more robust will enable penetration further into accelerator application sectors. In this respect much of the money invested in R&D may create a return in that investment.

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Table 3.7: Tasks breakdown for high-gradient RF structures and systems (nominal plan).

Tasks	Begin	End	Description	MCHF	FTEy
RF.SRF.BKNb	2022	2026	Superconducting RF: bulk Nb	4	75
RF.SRF.FE	2022	2026	Superconducting RF: field emission	4	40
RF.SRF.ThF	2022	2026	Superconducting RF: thin film	15	100
RF.SRF.INF	2022	2026	Superconducting RF: infrastructure	5	15
RF.SRF.FPC	2022	2026	Superconducting RF: power couplers	4	16
RF.SRF			**Total of superconducting RF**	32	246
RF.NC.GEN	2022	2026	Normal conducting RF: general NC studies	0	27
RF.NC.MAN	2022	2026	Normal conducting RF: NC manufacturing techniques	2.5	30
RF.NC.HF	2022	2026	Normal conducting RF: mm wave & high frequency	0.2	15
RF.NC			**Total of normal conducting RF**	2.7	72
RF.HP.HE	2022	2026	High-power RF: high-efficiency klystron & solid state	5.5	20
RF.HP.HF	2022	2026	High-power RF: mm-wave & gyro devices	0	5
RF.HP.TUN	2022	2026	High-power RF: reduced RF power needs (tuners)	0.4	6
RF.HP.AI	2022	2026	AI and machine learning	0.6	26
RF.HP			**Total of high-power RF**	6.5	57
RF.TS.NCRF	2022	2026	NC RF test stands	5.3	40
RF.TS.MAT	2022	2026	Test stand: new materials	0.7	16
RF.TS.BEAM	2022	2026	Beam test	3	20
RF.TS.SRF	2022	2026	Test stand: SRF Horizontal cryostat	0.9	10
RF.TS			**Total for test stand**	9.9	86
			Total	**51.1**	**461**

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