Report to LDG and CERN Council by the RF Coordination Panel

November 2023

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Introduction

In the follow up process of RF activities, the RF Implementation Panel has surveyed all teams working in Europe in the 6 Working Group (WG) theme areas, as this analysis was not reported in the European Strategy for Particle Physics - Accelerator R&D Roadmap (CERN-2022-001). It is only through the outcome of such survey processes, focusing on the reported achievements, on-going activities and needs in terms of resources and infrastructures, that a consistent request to the national funding agencies can be appropriately defined and promoted. The action towards the funding agencies is the next planned strategic interaction of the RF Coordination Panel for the roadmap implementation process.

This report summarises the main outcome of the surveys, which are broken down for each WG into the following sections:

1. The specific RF needs of the proposed future colliders;
2. The working teams involved across Europe;
3. The main progress achieved since the Accelerator R&D Roadmap was approved, at the beginning of 2022;
4. The remaining critical areas and needed infrastructures.
5. A section is also left for general comments, which are appropriate for future development expectations.

This detailed survey outcome, one per WG and still pending some replies at the date of this report, can be found in Appendix 1. It has been carried out by the individual working groups of the RFCP, supervised by the coordinators G. Bisoffi (INFN-I) and P. McIntosh (STFC-UK). The coordinators of the RFCP working groups are the following:

- **WG1 - Bulk Nb**: M. Baylac (CNRS-F), C. Madec (CEA-F), L. Monaco (INFN-I).
- **WG2 - Thin Film SRF:** Claire Antoine (CEA-F), Oleg Malyshev (STFC-UK).
- **WG3 - Couplers (FPC and HOM):** Frank Gerick (CERN-CH), E. Montesinos (CERN-CH), Axel Neumann (HZB-D).
- **WG4 - NC Very High Gradient:** Walter Wuensch (CERN-CH), David Alesini (INFN-I).
- **WG5 - RF Power Sources and High Efficiency**: Igor Syratchev (CERN-CH) Graeme Burt (U Lancaster-UK); Morten Jensen (ESS-Swe).
- **WG6 - LLRF, AI and ML:** Zheqiao Geng (PSI-CH), Wojciech Cichalewski (Uni-Lodz-PL).

With M. Baylac and A. Neumann acting as link persons towards the ERL Panel and G. Burt acting as link person towards the Muon Collider Panel.

In Appendix 2, a snapshot analysis is provided, for the progress status with respect to the prospective milestones which are published in the Roadmap document: it assembles them respectively as 5 and 10-year delivery expectations.

1. WG1 - Bulk Nb

1.1 Needs of Future Colliders

The main goals driving the development of future colliders are to increase the quality factor Q_0 and the accelerating field (E_{acc}) in a reproducible way, to contain both capital and operation operational costs of future colliders.

With a higher E_{acc}, the same beam energy can be reached with fewer cavities, since the energy gain is directly proportional to the field (energy gain E_{acc} L_{acc}). Reducing the length of the accelerator (L_{acc}) and its capital cost is of particular interest for **ILC**. It would also lead to a shorter acceleration time, as would be required by the **Muon Collider**. A higher quality factor Q_0 reduces power losses in the cavities (P_{loss} $\propto 1/Q_0$) and therefore minimizes the required refrigeration power and associated costs for **all types of Superconducting RF (SRF) accelerators**, with a huge impact for operation at 2 K. For example, the high Q_0 demonstrated and measured for the ESS medium beta cavities operating at 704.4 MHz ($Q_0 > 10^{10}$) reduces the cryogenic power by a factor >2 compared to the specified $Q_0 > 5 \times 10^9$.

To increase Q_0 and E_{acc}, R&D efforts are pursued on Nb material, surface polishing (HPR, BCP, EP), surface treatment (N doping) and heat treatments (low/mid/2-step baking, H degassing). In addition to pushing the limits of cavity performances, it is essential to confirm them in large series production by industry and to maintain them in time. Reproducibility is enabled by both reducing contamination during assembly via robots in clean room and recovering from field emission with in-situ plasma processing.

1.2 The Working Teams

In Europe, mainly ten labs are involved in R&D on bulk Nb: CEA, CERN, CNRS-IJCLab, DESY, ESS, Hamburg-University UHH, HZB, INFN-LASA, INFN-LNL, STFC. Full details can be found in the attached Appendix 1 (in worksheet WG1-Bulk Nb).

1.3 Main Progress Achieved

In 2021, the roadmap inception highlighted four main areas on which R&D should focus: niobium material structure (medium grain and large grain), heat treatment with or without gas (N_2 doping, N_2 infusion, …), surface polishing and field emission reduction. In the following sections, the main progress in each area is briefly described. All details can be found in the "Reference" (Appendix 3).

1.3.1 Improving the Nb material structure (large/medium grains)

In a two-year long project, the large grain (LG) structure is under study at SHINE (China) in collaboration with DESY and the main goal is still material qualification with respect to pressure vessel code.
Studies carried out by different labs (e.g. KEK, JLab), also in collaboration with one Nb producer, show that medium grain (MG) Nb is promising compared to fine grain (FG) on 1-cell and 3-cells cavities at 1.3 GHz, from both a mechanical point of view and the final performances achieved with different treatments (cold EP, two-step bake, furnace baking). Developing MG Nb would lead to a cost reduction w. r. t. FG of about 35% for the material, translating into a ~5% cost reduction on the full cavity.

1.3.2 Adopted heat and surface treatments

E_{acc} and Q_0 improvements have been obtained optimizing the production cavity process, mainly with annealing treatments (annealing for H_2 degassing and mechanical stress release, Mid-T, two-step baking) and surface treatments (N_2 doping, N-infusion, cold Electro-Polishing-EP).

N_2 doping was industrialized and applied to LCLS-II cavities. Other heat treatments (N_2 infusion and 800°C) are also applied in some projects. The R&D is focused (Hamburg University and ICCLab) on understanding the material modification lowering the surface resistance and slightly increasing E_{acc}. Another R&D path is Nb-doping via ALD thin film deposition, controlling the surface oxide layer and mitigating multipacting.

Plasma EP (PEP) is safer as it works with dilute salt solutions (no acids, no HF). Erosion rates are 10 times higher than in standard EP. Minimum roughness obtained is R_a =10 nm (on Cu). PEP was tested at INFN-LNL on planar samples, on QPR's and on 6 GHz cavities. The next step is scaling the process to a 1.3 GHz cavity.

1.3.3 Field emission reduction

Field emission (FE) is one of the main reasons for the degradation of accelerator cryomodules, as field emitted current tends to become more severe during the beam operation. Precise diagnostic and analysis tools are required to gain more information.

Recent development of dedicated detectors for FE radiation, with larger solid angle and lower energy threshold sensitivity, are being combined with simulations to identify electron emission sites. In-situ FE processing methods (with high voltage, or plasma with various gases, or dry ice) are being developed to improve the operational gradients and the energy margin of linear accelerators. Finally, cobots are being developed for clean room assembly to reduce particles contamination and painful work.

1.3.4 3D-printed cavities

Additive manufacturing (AM) aims at lowering both cavity production cost and environmental footprint (through enhanced cooling efficiency). While the main challenges for vibration mitigation remain (scaling to 1.3 GHz and lower frequencies), proof of principle on 3.9 GHz and 6 GHz cavities however has been made (with Cu). Micrometric R_a, RRR up to 80, with successful leak tightness and cryogenic tests represent encouraging results. Still open challenges are AM development on Nb cavities and demonstration that the Cu bases are appropriate for thin film coating.

1.3.5 Performance improvements since 2021

Improvements of the series production process on LCLS-II-HE increased the accelerating gradient by ~5 MV/m (with a $Q_0 \sim 3 \times 10^{10}$) versus LCLS-II results, overcoming specifications also in series production.

Other meaningful achievements, mainly on surface and annealing treatments R&D, have been obtained on single and multi-cells cavities at different frequencies for several projects. For ILC (1.3 GHz), cold EP and 2-step bake processes allowed to achieve $<E_{acc}>$ = 41.0 MV/m, $Q_0 = 1 - 1.5 \times 10^{10}$ on 9-cell cavities to be installed in a High-Gradient Cryomodule (HGC). Various heat and surface treatments allowed progress on accelerating cavities for: the CW European XFEL (on 1.3 GHz 9-cell cavities, with mid-T treatment studies on LG and FG); for CEPC (on 1-cell and 2-cell cavities at 650 MHz, on 9-cell cavities at 1.3 GHz, with studies on mid-T, BCP and N-infusion), for PIP-II (on 5-cell cavities, 650 MHz, CW mode, β = 0.61 and 0.92, with studies on high-T bake, mid-T bake).

1.4 Critical Areas and Needed Infrastructures

1.4.1 Material structure

Nb bulk FG material remains the best candidate to achieve the high performances needed for the future HEP machine, still with margin for improvement. To reduce manufacturing costs, LG and MG are studied, also considering compliance with vessel pressure code needed for cold operation. Cavity manufacturing via AM or spinning is being carried out at Uni-Padova and INFN-LNL respectively, while DESY is specialized in Eddy Current Scanning (ECS). Investigations on LG cavities are done at INFN-LASA (3.9 GHz 9-cells, 704.4 MHz 6-cells) and DESY (1.3 GHz, 9-cell).

Needed infrastructures, to speed up R&D, are another ECS installation (candidate: IJCLab) and a station for material characterization (candidate: UHH).

1.4.2 Heat treatments

Experience in heat treatments is rather widespread. Infrastructures are available in labs and in industries (superscript "I" indicates availability of an infrastructure): UHH^{I}, IJCLab^{I}, INFN (LNL and LASA), CEA, DESY^{I}, CERN^{I}. More specifically: on mid-T UHH, IJCLab, DESY, INFN-LASA; on high T annealing IJCLab, DESY, INFN-LASA; on baking and 2-step baking DESY and INFN-LASA.

Additional ovens for cavity treatments (high temperature, candidate: CEA; single cell, candidate: INFN-LASA) would speed up overall R&D.

1.4.3 Surface treatments

Experience in surface treatments is diffused. Available infrastructures at various lab are indicated hereafter in parenthese, while the others use facilities of industrial companies or other labs: UHH (BCP, EP, HPR), IJCLab (BCP, EP, HPR), INFN-LNL (BCP, EP, PEP, HPR), CEA (BCP, EP, HPR), DESY (BCP, EP, HPR), INFN-LASA (HPR), CERN (BCP, EP, HPR, N-doping).

Expertise by items is: mechanical polishing (IJCLab), BCP (UHH, IJCLab, INFN-LNL, CEA, DESY, INFN-LASA, CERN), EP (UHH, IJCLab, INFN-LNL, CEA (vertical), DESY, INFN-LASA, CERN), PEP (INFN-LNL), N-infusion (IJCLab), N-doping (CERN), HPR (UHH, IJCLab, INFN-LNL, CEA, DESY, INFN-LASA, CERN).

1.4.4 Field emission (detection and in situ mitigation)

Several labs have experience in clean room assembly (and also the facility in house). Cobotization is studied only at CEA site. FE diagnostics is widely present (in labs that have the cold test facility). Expertise in clean room assembly is available at STFC, IJCLab, CEA, DESY, INFN-LASA, CERN. Expertise in cobotization is available at CEA. Expertise in FE studies is available, with either cavity or cavity+cryomodule, at IJCLab, CEA, ESS, DESY, INFN-LASA and CERN. Experience in FE recovery is available at IJCLab (plasma processing TEM cavity), CEA, ESS, DESY, CERN.

R&D would be speeded up by novel infrastructures for CM assembly (candidate: ESS), cobotization (candidate: IJCLab), in-situ plasma processing (candidate: CEA).

1.4.5 Industrial manufacturing capability is jeopardised

There is a strong need for industrial partners for HEP accelerators (FCC ~1000 cavities, ILC - 8000 cavities) and also for large non-HEP machines. There is a risk that the very limited number of industrial cavity suppliers, for both the Nb material (only 1 supplier in China, perhaps 2 in Japan/USA) and cavity production (2 qualified suppliers in Europe, 2÷3 in China, 1 in Japan), becomes critical. The situation is worsened by the decreased number of projects foreseen in the coming years. This means that it is mandatory, for Europe, to maintain SRF technology skills at an adequate level in both labs & industry.

1.5 General Comments

The survey among the labs shows that personnel averages at 2 - 3 FTE/lab with an average yearly budget between 100 and 300 k€. Both figures are insufficient for the scopes of the above-mentioned R&D themes, the main problem being the low level of FTE's. Most labs declare involvement in both HEP and non-HEP projects, i.e. the time available to R&D is strictly linked to carrying out projects, which use most of FTE's and budget.

Work on bulk Nb is not HEP-specific, except for R&D dedicated to **ILC**. Outside Europe, the main labs with the same R&D objectives are KEK, JLab, Fermilab, Cornell, SLAC, ANL, IHEP Beijing, SHINE, CAS. While several international frameworks for SRF R&D exist (TTC meeting, SRF conference, AMICI, Linear Collider workshop, SLHIPP), the European accelerator R&D program will be strengthened by a stronger link with the **ERL** theme, with the development of a cryomodule for 800 MHz cavities. Injection of partnerships with external expertise (e.g. robotisation in clean room for cavity preparation, chemistry experts for plasma processing for FE recovery) would be of significant help.

2. WG2 - Thin films

2.1 Needs of Future Colliders

2.1.1 Higher quality factor Q_0

In application to **FCC**, **ERL**, **ILC**, **etc.**, higher Q_0 means lower RF losses and so **cryogenic power is minimised**.

Cavities with superconducting thin films deposited on copper, working at 4.2 K with moderate accelerating gradients will be probably the first step to be reached. Niobium films with properties closer to bulk Nb are already close to being realised, but still far from being applied on a production scale. Depositing higher critical temperature (T_c) materials on multi-cell copper cavity substrates requires further R&D, after completing the refined optimisation conducted on samples and single-cell cavities (see § 2.4). Several different compounds need to be explored in parallel to determine the most optimum solution for the development of larger production requirements.

2.1.2 Higher accelerating gradients E_{acc}

In application to **FCC**, **ERL**, **ILC**, **etc.,** higher E_{acc} means shorter linacs and/or RF installation, i.e. **lower capital cost.**

Higher accelerating gradients are more likely expected to emerge from multilayer structures, which demand that deposition of thicker films are first fully mastered. The achievement of deposition of multilayers with similar properties as bulk Nb, is foreseeable in the next 2-3 years at the prototyping stage. The need to further improve SRF thin film cavity performances will require a substantial investment, beyond what is currently being made available across Europe.

2.1.3 Others: Reproducibility, Cost, Industrial Manufacturing

Mastering deposition of superconducting thin films on copper cavity substrates and being able to operate at 4.2 K will provide tremendous benefits in reducing both cavity fabrication and infrastructure costs. Operation at 4.2 K instead of 1.9 K (required for best performance of Nb bulk and coated cavities), reduces both the cost of fabrication due to simplification of design and infrastructure and the cost of operation. Operational energy efficiency and cost reduction are fundamental requirements for all types of accelerators and so developments are not just specifically important for HEP accelerators.

2.2 The Working Teams.

In Europe, up to ten organisations are involved in R&D on SRF thin films: CEA, CERN, DESY, Hamburg U, HZB, HZDR, INFN, IEE, Riga Technical U, STFC/CI and USI. A full list of details can be found in the attached Appendix 1 (in WG2-Thin Films).

2.3 Main Progress Achieved

Continue R&D Niobium on Copper. *Bulk niobium performance to be reached on 0.4 - 1.3 GHz elliptical and other cavity geometry shapes*. CERN has a systematic program for depositing cavities at various frequencies and shapes, with INFN, STFC/CI and USI also having activities in that domain. From which, a better understanding has been established for the role of the copper substrate quality, in terms of its smoothness, surface treatment (CERN, INFN, HZDR and RTU), its interlayers (CEA) and of the film density to ensure success. R&D is, however, still necessary to fully optimise the process and increase production yields.

Intensify R&D of New Superconductors on Cu. *Nb_3Sn on bulk niobium at 4.2 K on several cavity geometries has also matched bulk niobium performance for single cell cavities at 0.6 - 1.3 GHz*. Efforts have been established to deposit Nb_3Sn (CERN, INFN, STFC), or NbTiN and NbN (CEA, Hamburg U., USI, STFC) on copper substrates. STFC is the only lab that has attempted to work on MgB_2. Several difficulties still need to be resolved, such as for tin diffusion into the copper substrate, or tin evaporation during heat treatments. Several routes are expected to be further explored (e.g. interlayer between copper and the superconducting layer at CEA, or compounds from -V_3Si- which should be less sensitive to evaporation at STFC). The influence of mechanical deformations and trapped flux sensitivity also requires extensive evaluation. First attempts to deposit inside cavities (split cavities, 6 GHz) are ongoing at both STFC and INFN.

Pursue Multilayers (ML). *Developments to demonstrate increased acceleration on 1.3 GHz bulk Nb and thin-film Nb/Cu 1.3 GHz elliptical cavity.* CEA, Hamburg U., STFC and USI have deposited and characterised ML samples. CEA and Hamburg U have developed cavity deposition set-ups based on atomic layer deposition (ALD) and are adapting the technology to deposit a first prototype cavity.

Intensify Cu Cavity Production and Surface Preparation*. Optimisation of air stable chemistries (EP-BCP/without liquid waste, heat treatment, passivation layers, etc.) for Cu surface preparation is underway.* CERN is exploring several fabrication routes, whilst INFN has developed an automated production process (by spinning) with the company Piccoli. INFN is also involved in surface treatment by plasma EP with promising results. Other surface treatments are being explored (laser treatment at RTU, Flash annealing at HZDR, mechanical-chemical polishing by IJCLab and CEA), but these activities are at small scale.

Develop 3D Printing and Innovative Cooling Techniques. *To provide substrates (cavities) with effective surface roughness and to demonstrate conduction cooled cavities.* Additive manufacture activities are being undertaken at CEA, CERN and INFN. CEA has demonstrated a Cryocooled 3D printed, doubled walled 3.9 GHz cavity, with 1 µm roughness on samples, but has been recently halted due to lack of resources. INFN has developed a protocol to produce 6 GHz cavities with surface treatment and final roughness below 400 nm. CERN and RTU are also undertaking AM activities, however these are not directly related to thin film deposition objectives.

Infrastructures and Manpower, High-Throughput Testing. Most of the SRF thin film labs have been commissioning their deposition set-ups for 6 GHz cavities and have each started development for 1.3 GHz deposition: HIPIMS at CERN, HPCVD, DCMS, HIPIMS in STFC, DCMS at INFN, HIPIMS at USI, and 1.3 GHz ALD set-ups at CEA and Hamburg U. Specific measurement set-ups have been developed or further improved (e.g. full field penetration experiments at STFC, tunnelling microscopy at CEA). Concerning sample RF characterisation, a new Quadrupole Resonator (QPR) cavity has been commissioned at DESY (Hamburg U), a 7.8 TM GHz choke-mode cavity has been developed at STFC, and a TM020 4.8 GHz cavity has been developed at HZB in addition to their already extensively utilised QPR cavity. Construction of a dedicated building (surface preparation, thin film deposition, cleanroom…) is being foreseen for the end of the decade at CERN.

2.4 Critical Areas

Since the publication of the 2020 update (CERN-2022-001), budgets supporting the thin film community are mostly internal (institutes, few national calls) and EC funding programmes, such as IFAST (May 2021 - April 2025), equating to ~50 k€/year/lab for IFAST. This amounts to ~50% of the minimal budget presented in the CERN report. Additional money has been proposed in a special INFN accelerator innovation program (valid only in Italy) and in the EC funded ISAS project (2024-2028). For thin films, it involves only 4 European labs and amounts to <100 k€/year/lab. Without additional funds, it is expected that most of the identified milestones in the report cannot be realistically met in 2025. Some will indeed be met with some delay, while other topics will be abandoned if no alternative support is found post-IFAST.

Here are two examples which illustrate this difficulty.

- A key milestone is: "MgB_2: feasibility (critical temperature > 30 K) on 1.3 GHz cavity". For now, only STFC has made some attempts on sample deposition, but its priorities rely first on Nb/Cu, Nb_3Sn, V_3Si and NbTiN materials. A lack of manpower does not allow them to actively pursue this topic. MgB_2 could open the route to cryocooling and 10 K (lower cost!) operation.
- For additive manufacturing, CEA has conducted a successful 2-yr programme, demonstrating feasibility of a highly original cooling system. Due to lack of staffing resources, this programme is now stopped, with no obvious future opening opportunity.

Most of the contributing European Labs are now able to proceed to the first steps of development, including deposition set-ups for samples and small cavities and provisioning of specific characterisation tools. Their immediate needs are for manpower (PhD students and PostDocs), along with sufficient funds to outsource material characterisation and RF testing, with both STFC and INFN requiring refurbishment of their cavity tests stands for improved thin film testing.

With adequate work force, alternative routes can be explored if unforeseen difficulties appear. For instance, significant expectation is placed on the success of Nb_3Sn. Up to now, it has only been tested on individual Nb cavities. As a brittle material, the largest risk is that it cannot stand deformations due to tuning, which is anticipated to be explored in the ISAS project starting in 2024.

Adaptation of deposition set-ups to various size of cavities needs to be prepared, requiring increased investment and the budget to RF test those larger cavities must also be considered. A comparable initiative to that conducted by INFN at a European level, with a clear program and key collaborators, beyond the smaller perimeter of 4 years European calls, would be ideally suited.

2.4.1 List of Risks and Teams Involved:

The main risk for thin film R&D is lack of resource and manpower, with each topic having its own specific technical risks:

- **Continue R&D niobium on copper** - Lack of reproducibility, limited accelerating gradient, Nb/Cu interface issues (CERN, INFN, STFC, USI for deposition; RTU, HZDR for superficial heat treatments, CEA for interlayers)
- **Intensify R&D of new superconductors on Cu** - Diffusion (e.g. of tin) in the copper substrate, difficulties to get the exact composition and crystalline structure, higher sensitivity to trapped flux, brittleness. (CERN, INFN, STFC, USI for deposition; RTU, HZDR for superficial heat treatments, CEA for interlayers)
- **Pursue multilayers** - Adaptation of processes assessed on samples to cavities, no visible improvement on bulk Nb (Nb is already very good!). (CEA, Hamburg U for cavities deposited using ALD, STFC and USI on planar samples by other deposition techniques)
- **Intensify Cu cavity production and surface preparation** - Ongoing (CERN, INFN)
- **Develop 3D printing and innovative cooling techniques** - Surface quality not good enough for thin film deposition (Activities at CERN and INFN, stopped at CEA).
- **Infrastructures and manpower -** high-throughput testing, with bottlenecks for samples and prototype characterisation (all labs concerned).

2.5 General Comments

Thin film developments are not HEP specific, though highly needed by this community for energy efficiency and cost reasons. In addition to accelerators, superconducting thin films present a strong interest in the domain of quantum computing, Q-bit achievement and quantum sensing.

2.5.1 International Situation (non-exhaustive):

There are global thin film activities in USA, Japan and China. Jlab has published very encouraging results on Nb layers on Cu, they also have activities on Nb_3Sn and multilayers. Jlab, Cornell and FNAL have had successful activities on Nb_3Sn on Nb. They are now exploring routes to achieve deposition on copper. Temple University, LANL and KEK have activities on MgB_2. KEK has activities on Nb_3Sn and multilayers. Between Peking University and IMP Lanzhou, China has activities in all these domains. All these groups try to coordinate collaborations using mechanisms such as; TTC-thin film sub-group or SNOWMASS initiatives, which propose similar programmes to the IFAST activity in Europe.

3. WG3 Fundamental Power Coupler and HOM Couplers

3.1 Needs of Future Colliders

For **ILC** the needs and technical solutions for couplers are well understood and available. For the **Muon Collider**, cavity designs and specifications are still under development, hence it is too early to start specific R&D activities in the field of couplers. **EiC** is a US project hosted by BNL, with some involvement of European Labs, e.g. scientific exchange with CERN in the field of couplers (+ cavities and RF amplifiers).

Cavity designs and power requirements for **FCC** are fairly mature and R&D activities need to be started. For 400 MHz a power of 1 MW, CW is anticipated, which will require an adjustable coupler design. For 800 MHz a power level of ~200 kW, CW is expected, also requiring an adjustable coupler. For HOM couplers some basic designs exist but the challenge will be to extract 10s of kW per coupler and today no verified solution exists for FCC-type HOM couplers. Another R&D line is on fast reactive tuners, which will allow fast frequency tuning without mechanical deformation of the superconducting cavities: this technology can compensate microphonics, reduce power demands during cavity transients (transient detuning), and be used as non-mechanical cavity tuners.

The R&D activities presently in progress include the following:

<u>FPC R&D towards FCC</u> (today mostly at CERN): water-cooled ceramics, highly adjustable coupler designs using 2 windows, new mounting methods ensuring a high cleanliness level, development of resonant rings (for efficient testing and conditioning with small RF power sources). FPCs need to be developed, tested, and conditioned, for tests at 400 and 800 MHz in horizontal test cryostats or in cryomodules expected for 2029.

<u>HOM coupler R&D</u> (FCC, CERN). The electrical design must be finalized at CERN, followed by mechanical realization and testing (not started), to be ready for anticipated horizontal tests in 2029.

<u>Fast reactive tuners</u> (CERN, Lancaster, HZB). Demonstration of transient detuning for 400 MHz cavities (CERN, Lancaster) is expected in 2024. A prototype demonstration of microphonics compensation for 1.3 GHz cavities (HZB) is expected in a horizontal test stand in 2025. In 2026 - 27 the integration into a dedicated 1.3 GHz ERL Linac cavity design is foreseen. Additional funding is required to prototype a FRT Linac module with optional 4 K operation.

Microphonics compensation and transient detuning for 400 and 800 MHz FCC-type cavities are required before finalization of the cryomodule design, ideally in 2028 –32.

3.2 The Working Teams

In Europe, up to four organisations are involved in R&D on FPC and HOM couplers: IJCLab, DESY, HZB and CERN. A full list of details can be found in the attached Appendix 1 (WG3-Couplers).

3.3 Main Progress Achieved

Concerning FPCs for FCC there was basically no progress at CERN due to lack of manpower.

Microphonics compensation with a FRT on a 400 MHz cavity was demonstrated at CERN. A transient FRT detuning demonstrator was designed and assembled and is ready for a cold test at CERN. HZB is on the way to procure a ferro-electrical characterization test stand to test the given FE-FRT materials for frequencies at 1.3 GHz.; in addition, an FE-FRT expert was hired to start working at HZB starting in January 2024.

3.4 Critical Areas

At CERN the development of FPCs and HOMCs is limited by the available manpower. The infrastructure at CERN is largely adequate but needs an additional high-power test stand. Two engineers will be hired, who will work part-time on couplers and who will need support by 1 - 2 dedicated postdocs. An additional staff member is required, to achieve the goal of having a full set of 400 and 800 MHz FPCs and HOMCs available for 2029. Collaborating partners can contribute with design studies, requiring marginal financial support. FPC and HOM development usually receives a boost as soon as a dedicated accelerator project is funded.

3.5 General Comments

Overseas, FNAL developments for the PIP-II project face highly challenging microphonics controls for their low-current, high-Q cavities, which may become relevant for some HEP machines, especially for ERLs. JLAB develops couplers for high-current, high-power cavities of the **EIC** project (BNL), which are of interest for **FCC**. SLAC work may be interesting for **CLIC** (but details not known). KEK mainly designed couplers for their B factory and, in the following years, for the compact ERL C-ERL at 1.3 GHz for injector and linac. The injector high power FPC did not reach their design goal. The designs are mainly variants of single window fixed coupler type.

The main international community reference meeting is the Worldwide FPC Workshop organized by CERN. Other networks are those of **FCC** and **CLIC** studies. The TTC workshops are focused on SC technology for all types of accelerators, as the SRF conference is. Developments on both FPC and HOM couplers, specific for PERLE, with FE-FRT at 800 and 1300 MHz, are foreseen in the ISAS European program, comprising an ERL module.

4. WG4 High Gradient NCRF

4.1 Needs of Future Colliders

High-gradient normal conducting technology is important for most the proposed future high-energy colliders. In the cases of **CLIC** and **C^3** a high accelerating gradient is a crucial for the overall cost, energy efficiency and performance of the facilities. For the **Muon Collider** a high-gradient in the muon capture section is crucial for the performance of the facility. The technology and R&D needs for the **FCC** are listed in more detail below:

CLIC – The main focus of the CLIC project in the period leading up to the next strategy update is to carry out technical work related to refinements of the design and complete a project readiness document. The technical work includes luminosity improvements, power consumption reductions and injector and source optimization. Long-term high-gradient system operation will continue in the Xbox test stands at CERN. Experimental and simulation of high-gradient limitations will also continue.

Muon Collider – The primary need for the Muon Collider in the area of NCRF is the development of the muon capture RF system. This requires operation of a high-gradient, few hundred MHz accelerating cavity in a strong, 16 T or more, external magnetic field. Dedicated high-gradient test stands are required and the search for host laboratories and associated funding is underway. This infrastructure has strong synergies with CLIC and C^3.

FCC-ee – The FCC-ee injector complex requires approximately 16 GeV of acceleration. The injector complex is very large but is envisaged to be largely conventional. It has strong similarities to the CLIC injector complex and RF system design expertise that overlaps with CLIC and other high-performance linacs is required.

C^3 – The C^3 effort is largely based in the US. The high-gradient testing carried out in the programme is relevant to CLIC and the Muon Collider. The beam dynamics of C^3, along with alignment and vibration tolerances, are similar to those of the CLIC main linac.

HALHF – The HALHF project will likely have significant overlap with the CLIC project in both the conventional positron linac and in the drive beam accelerator. Specific R&D topics will be elaborated once the HALHF project definition is further defined.

4.2 The Working Teams

A focus for R&D on normal conducting high-gradient has been provided for many years by the CLIC study. In recent years the resources available for CLIC has been significantly reduced but collaborative connections have remained through personal contacts and workshop series such as the High-Gradient and MeVArc. In addition, high-gradient normal conducting technology is being adopted by numerous non-high energy physics applications and the community remains extremely dynamic as a consequence. In Europe, up to eight organisations are involved in R&D on High Gradient NCRF activities: INFN, Elettra, DESY, CERN, Cockcroft Institute, Uppsala U, PSI and U Valencia. A full list of details can be found in the attached Appendix 4 (in WG4-High Gradient NCRF).

Currently about half of the contributing institutes have some HEP involvement, the majority of which being for non-HEP activities. Overall, such developments represent a total of >€70M investment and >5 - 6 FTE/yr of staffing activity, with an expectation for this to grow in future, however this is anticipated to be more extensive for non-HEP activities.

4.3 Main Progress Achieved

CLIC – Continued testing at Xbox test stands at CERN and initiated testing at the TEX test facility at INFN has progressed the develop the performance verification capabilities for high gradient X-band linac structures. Progress on fabrication techniques has developed, which is also an important scope of work for accelerating structure fabrication within the IFAST WP7 and for INFN EuPRAXIA linac structure prototypes.

Muon Collider – As a relatively new initiative, its primarily areas of research and development are at the early planning stage.

FCC-ee – The current design study focus does not specifcally address high-gradient issues yet, although high average power for S and C band structures operating at up to 400 Hz repetition rate is a principal challenge, the expectation for higher gradients may emerge in the future.

C^3 – Further testing at SLAC being conducted, and pulsed DC testing at Uppsala U is planned.

HALHF – As a very recent initiative, the requirements for NCRF are not yet fully defined, although linac gradient expectations are anticipated to be relatively modest at ~25 MV/m for the 31 GeV NC linac stage.

4.4 Critical Areas

The most significant new infrastructure request is for high-gradient cavity in magnetic field test stands. The test stand is driven by the **Muon Collider** but has strong overlap with **CLIC** and **C^3**. An ultimate test stand for the **Muon Collider** is for a 350 MHz RF system but a 3 GHz system could be an important first step. No resources are currently however available for such a test stand.

4.5 General Comments

The normal-conducting, high-gradient community activity focus is primarily for Xray FEL or compact accelerator technology developments, with CLEAR and eSPS at CERN, CompactLight, XFEL at INFN Frascati, SmartLight at Eindhoven and Xara at Daresbury Lab being the most prominent, in addition to activities at SLAC, Arizona State U and Tsinghua U more broadly.
The high-gradient community meeting, as was recently held at INFN Frascati, the HG2023 workshop https://agenda.infn.it/event/34253/, is a primary mechanism for the main international actors in the NCHG field to represent their respective progress and future ambitions, typically encompassing a broad range of perspectives from design to operation. In Europe, the IFAST WP7 activity is developing demonstrated capabilities for the design of two different C-band (5.712 GHz) RF electron guns operating at very high gradient cathode peak field, in addition to building and testing prototypes of the X-band (12 GHz) accelerating structure for the CompactLight (XLS) project.

5. WG5 RF Power Sources & High Efficiency

5.1 Needs of Future Colliders

Future large scale HEP colliders like **FCC_{ee}**, **ILC**, **CLIC**, **Muon Collider** and **HALHF** will require 100-200MW average RF power for operation. Thus, a major component of the overall efficiency regards RF power conversion from the electrical grid to the accelerator. To reduce power consumption and carbon footprint of these installations, development, prototyping, and industrialization of high efficiency RF power sources is mandatory. Proposed layouts of almost all future colliders suggest operating them in CW or pulsed regimes with frequencies 0.3 - 1.3 GHz (UHF-L-band). In such a frequency range, a single novel technological solution for high efficiency (HE) RF power sources can suit different HEP applications, thus reducing the short-term (until 2025) development scope to a single HE demonstrator design, prototyping, and testing. In this context, **HL-LHC** and **FCC_{ee}** were identified as the primary objectives of such development.

5.1.1 RF power amplifiers technologies for HEP.

The klystron amplifier technology covers almost all RF frequency/power demands for different accelerators. Klystrons have been used in particle accelerators for more than 8 decades. In L-band, modern commercial klystrons can reliably reach 65% RF power efficiency. However, recent klystron development at CERN in collaboration with ULAN and industry promises that an ambitious efficiency improvement – up to 85% for 1 MW, 0.4 GHz CW FCC_{ee} klystron - is feasible and can be demonstrated by 2025 - 2026.

Solid State RF Power Amplifies (SSPA) is another available UHF - L-band technology which relies on massive use of individual commercial components, the combination of which can provide the required RF power. Typically, in this frequency range, individual transistors generates ~0.2 - 1 kW RF power. Thus, up to several 100.000 of such devices should be combined to reach a 100 MW RF power level. Together with low voltage power converters, such a system, if constructed today, requires significantly more space in underground tunnels (dependent on individual power levels) compared to a klystron solution. New developments, however, have already succeeded in making solid state amplifiers more compact. The efficiency of modern SSPA is lower than what is expected for high-efficiency klystrons. Future efficiency reach with different transistor technologies will be largely driven by industrial demand, while HEP laboratories can contribute on power combination technologies & control systems. Up to several 10's of kW, solid state amplifiers are already available as an alternative to the tubes and are used in several new accelerator projects. It is likely that this will extend to 100's of kW in a not too far future.

5.1.2 High frequency RF power amplifiers for beam diagnostics and beam manipulation.

While no current HEP machine requires higher frequencies for beam acceleration, such devices have significant advantages in ultra-short bunch injectors, short-bunch longitudinal diagnostics, and bunch phase space linearizers. In the future, such applications in a frequency range up to 300 GHz will require longer pulses, higher RF power and higher efficiency, thus Gyrotron based sources are being developed. In the Ka-band frequency (~30 GHz) range there are no suitable tested sources, but klystron- and gyrotron-based sources have been designed.

5.2 The Working Teams

The HE klystron project is led by CERN (2.2 FTE) in collaboration with ULAN (1.1 FTE) and industrial partners associated with each specific development: Thales (France), CPI (USA) and Canon TED (Japan). A HE SSPA L-band (1kW) module is under development at Uppsala (1 FTE): it is funded by European project IFAST (100 k€ over 2 years). CERN is likely to continue its work on combining cavities in the frame of FCC. MM-wave sources are being developed by KIT, Strathclyde U, INFN, ULAN and CERN. More information is available in Appendix 1 (WG5-RF Sources and high efficiency).

5.3 Main Progress Achieved

The HEP specific high efficiency klystrons project at CERN.

- HE (70%) CSM 350 kW, 400 MHz klystron for HL-LHC. Klystron prototype is in fabrication at Thales as a retrofit of the existing tube (60%): factory acceptance tests will be done in May 2024. It is planned that production flow of 4 klystron per year will continue at Thales, to be ready to install 16 operational devices at CERN by 2029.
- New 2-Stage klystron technology for HEP colliders. Design of the RF and auxiliary systems of TS HE (>85%) MBK (1MW, 400MHz, CW) FCC_{ee} klystron is completed at CERN. The klystron prototype fabrication will be contracted to industry in 2024, followed by 2÷3 years of technical design and production, with acceptance tests expected in 2025-2026. RF design of TS HE MBK klystrons for CLIC and ILC are completed (published) and are ready for technical implementation stage (if requested).

General high efficiency klystrons project at CERN (non-HEP accelerators applications)

- Development and maintenance of the CERN home-made fast and accurate klystron computer code KlyC.
- X-band 10 MW HE (56%; cf. 42% in existing commercial devices) klystron was designed at CERN and fabricated at Canon TED. Two tubes arrived at CERN in 2023, installed in X-band test facility and put in operation. This is the first commercial demonstrator of HE klystron technology developed at CERN.
- X-band 50 MW HE (65%; cf. 38% in existing commercial devices) klystron was design at CERN and communicated to CPI. The tube is currently in fabrication, and it is planned to be tested at the end of 2024. The project is funded by INFN (Frascati, Italy).

High Efficiency SSPA L-band module development at Uppsala (HEP specific).

- First 1.1 kW, 750 MHz SSPA module (x6 GaN transistors) prototype has demonstrated 82.5% drain RF efficiency. This strongly indicates that at 800MHz, required by FCC_{ee}, 10 combined modules will deliver 10kW RF power with efficiency above 75% in a compact arrangement (without cavity combiner).

Mm-wave RF power sources:

- KIT is developing a Ka-band 5 MW Gyro-Klystron for future compact accelerators and a D-band 2 MW Injection locked synchronised Gyrotron. Strathclyde is developing a 2 MW Ka-band Gyro-klystron for mm-wave bunch linearisers and mm-wave undulators. INFN is developing a 3rd harmonic Gyrotron up-converter to generate 30 MW at Ka-band. ULAN and CERN developed a 2 MW HOM-Klystron at Ka-band for compact light, but that project is now on-hold.

As part of the implementation phase of the accelerator R&D roadmap a survey of existing RF sources, current developments, and future requirements of all accelerators projects in Europe was carried out by WG5 convenors. Later, it was coupled with a dedicated feedback meeting with RF sources experts at every major European laboratory. This has created a unique database giving a snapshot of the current state of RF sources in Europe.

The Workshop series on "Efficient RF sources", as a part of the IFAST initiative for "Sustainable concepts and technologies", is a new and unique international platform, where RF experts can present and discuss the new development towards improving efficiency and performance of various RF power sources. The first WS took place in Geneva (Switzerland) [https://indico.cern.ch/event/1138197/] in July 2022, and the next one is scheduled to be held in Europe in Autumn 2024.

5.4 Critical Areas

High efficiency klystron development at CERN currently covers the short-term need for HE RF source for HEP large accelerators. On a longer term, it is foreseen to develop 500 kW, 800 MHz klystrons for the FCC booster using the same TS technology as used for 1 MW, 400 MHz tube (2024 - 27). Another

S-band 80 MW HE (60%) klystron needed for the FCC injector will be developed on the same time scale, based on experience gained at CERN during development of X-band HE klystrons.

The major identified critical issue is availability of the klystron development capacity in industry. Only 3 qualified vendors are active on the market worldwide. The accelerator community is already facing unexpected delays with tube fabrication and repairing, rather steep price increase and even a reduction of their quality and reliability. This situation forces some users to migrate (where possible) to SSPA solutions, despite extra cost and complexity. Large HEP installation will run for decades; hence, ensuring continuation of industrial support with this time scale is very important. It is not clear which measures will be required, to strengthen the relationship between accelerator community and industry. One possible way, in the prototyping and small series phase, is to increase the laboratory participation in the fabrication process, while outsourcing component fabrication to non-klystron companies: this would facilitate monitoring cost, schedule and quality control. Another way could be in-lab development of the new HE RF power sources, which will have added market value: a good example is X-band klystron activity at CERN, where the new power sources designs are transferred to industry and can be used for medical applications (e.g., flash therapy) and in different compact accelerators (e.g., Compton sources, X-FEL).

Efficient SSPA development shows good progress in Uppsala. However, GaN technology appears to be still rather expensive (~7 €/W – almost 10 times more compared to the klystrons). Uppsala is ready to provide further development and study different approaches, like LDMOS, targeting cost optimized and efficient solution for 10 kW 800 MHz units compatible with FCC requirements. It will require 1 FTE for 3 years and ~ 300 - 400 k€. SSPA industrialization efforts faces long-time scale challenges, similarly to klystrons. Transistor development will be solely an industry development, with accelerator labs focusing on ways to configure, combine and operate them. Transistor technology is evolving so rapidly that the original devices soon become obsolete and irreplaceable: this implies significant logistics problem in the long term (large stock of selected components, expensive adaptation of power supplies to the new specs or to the expected next transistor generation).

It might be appropriate to reconsider the option of alternative electrovacuum devices with moderate RF power (10 - 20kW) in L-Band, such as IOT's.

5.5 General Comments

Efficient RF power sources development for HEP in Europe is on a good and dynamic track, albeit with a limited number of labs involved (CERN, ULAN and Uppsala). This development is conducted in a strong collaboration with industrial partners. RF power sources operational issues in existing large facilities, like **LHC** and ESS, were reported and are being considered by HE klystron teams to improve the efficiency of entire power system (including modulators and LLRF). The new klystron technology developed at CERN has been implemented not only for HEP, but also for other user facilities, namely X-band medical, light sources etc.

The new 2-stage klystron technology developed at CERN promises record efficiency of 85%. At present, this technology is mostly advanced for **FCC** application. However, RF designs of similar devices for **CLIC** and ILC are already completed. In connection to **Muon Collider** expected requirements, we anticipate that frequency scaling of **CLIC** TS MBK klystron from 1 GHz down to 0.7 GHz and 0.35 GHz is a straightforward process, whilst preserving pulsed peak RF power at 25 MW level. Such study will be done at ULAN (in collaboration with CERN).

Currently, **CEPC** (IHEP, China) is the only one project outside Europe investing significant resources in HE RF power sources for HEP. In their work, they adopted CERN's original concept (CSM technology, like in HL-LHC Thales klystron) and they are now in a prototyping stage of 650 MHz 800 kW MBK klystrons, expecting to reach ~80% efficiency. Their recent reported progress strongly indicates that their goal will be fulfilled in early 2024.

6. WG6 LLRF-ML-AI

6.1 Needs of Future Colliders

Future colliders impose strict requirements for the performance and operation of the RF system. Several key points are listed below:

- Future colliders have multiple accelerator sections with different beam patterns and RF frequencies. To operate the RF systems across these sections, **high-level intelligent automation and optimization are required for the LLRF systems.** For example, the relative phases between different cavities should be synchronized and optimized to maximize the beam quality and beam transfer efficiency between different sections. For such applications, machine learning (e.g. surrogate models to predict the beam performance with different RF voltage and phase settings) could be beneficial.
- Saving electricity energy is becoming a critical topic for large-scale colliders. With **optimized LLRF control strategies and operational procedures,** the required RF power to provide the desired accelerating voltage and stability can be minimized. For example, by applying fast reactive cavity tuners and intelligent control strategies for different beam patterns, we can reduce the required RF drive power.
- Due to the long construction and operation cycles, future colliders require **RF control systems to be sustainable with long-term supported standard hardware/software,** and with **optimal architecture and framework** for system integration/upgrade.
- Machines like **ILC/FCC/MC** employ superconducting RF cavities, which impose difficulties in RF field control in the presence of strong mechanical vibrations, heavy beam loadings, and with critical electrical/mechanical characteristics of the cavity. To handle these difficulties, **LLRF may need to adopt advanced control algorithms, including machine learning algorithms** (e.g. model predictive control based on a ML model of a Cryomodule) and other artificial intelligence techniques.

As a summary, a comprehensive, intelligent, highly automated, and standardized LLRF system is essential for the success of the RF systems of future colliders. The working teams interest in the above-mentioned areas has been expressed in the survey results.

6.2 The Working Teams

In Europe, at least fourteen organisations are involved in R&D on LLRF systems: CERN, PSI, DESY, HZB, CNRS, ESRF, INFN, Elettra, DMCS, Lodz Uni, ISE, Warsaw Uni, Diamond, STFC, ESS and ITAINNOVA, along with a number of industries such as MicroTCA Technology Lab (DESY, Germany), Struck Innovative Systeme (Germany), Instrumentation Technologies (Slovenia), IOxOS Technologies (Switzerland), Cryoelectra GMBH (Germany). A full list of details can be found in the attached Appendix 1 (in WG6-LLRF-ML-AL).

6.3 Main Progress Achieved

The primary achievements of the LLRF R&D include:

- MicroTCA has become the most widely used platform for LLRF system construction, benefiting from the big success of the European-XFEL LLRF system. A group of high-quality MicroTCA hardware (e.g., the Struck SIS8300 digitizer board) was developed, and standardized firmware and software frameworks were built upon it. All these are great steps to standardize the LLRF system platform. Standardization is helpful for gaining long-term support from the industry and encouraging wider collaborations between different labs and the industry.
- Driven by the progress of telecommunication industry, advanced digital hardware, such as high-resolution fast ADCs (e.g., 16-bits ADCs with > 250 MSPS sampling rate) and high-performance fast digital processors (e.g., large-scale FPGA, multi-core CPU, GPU), is ready to implement complex real-time RF controllers for stabilizing the cavity field and advanced automation and optimization algorithms for operating the RF systems.

- Benefiting from the LLRF R&D for free-electron laser machines, the achievable RF stability (0.01 % for amplitude and 0.01 degree for phase) keeps improving. The LLRF performance in terms of RF stability is sufficient for future colliders (e.g., ILC requires a stability of 0.07 % form amplitude and 0.24 degree for phase).
- Framework and algorithms (e.g., machine learning) are being developed to implement automation and optimization for operating the RF systems. High-level intelligent automation is critical for improving the availability, reliability, and operability of the machines like ILC and FCC, which consist of many RF stations and cavities (e.g., ILC main Linac has > 560 RF stations and 14500 cavities). Some applications of machine learning (e.g., SC cavity quench detection, RF faults classification) have been demonstrated.

6.4 Critical Areas

Considering the R&D status in different labs , the critical areas include:

- Standardization of LLRF hardware, firmware and software, for which PSI is planning to work on this topic.
- LLRF high-level applications for intelligent automation and optimization, for which DESY is conducting investigations on this topic.

6.5 General Comments

- LLRF systems are essential for all accelerators, therefore, outside EU, all accelerator labs have their own LLRF development teams and activities. For example, SLAC made considerable progress on applying machine learning to control superconducting cavities and Cryomodules, KEK have standardized their LLRF hardware with MicroTCA.
- The major framework for LLRF exchange is the LLRF workshop organized every two years. In addition, DESY hosts MicroTCA workshops in Germany, China and Japan to promote the MicroTCA standard as well as the firmware/software libraries they have developed.
- LLRF is an embedded topic for ERLs, which strongly relies on LLRF handling the control of narrow-band superconducting cavities. The Fast Reactive Tuner is a revolutionary component to improve LLRF performance with respect to cavity tuning control and RF drive power reduction.

7. Links with the ERL and Muon Collider Panels

RF activities in the various theme areas have domains of large overlap with the scopes of the ERL and Muon Collider panels, with which a strong liaison has been hence established.

WG2 Thin Films

Only Cu cavities have been considered for the ionisation cooling channel for a **Muon Collider**, because of the high static magnetic field. Thin film cavities with High B_{C2} superconducting materials could in turn be explored, similar to what has been done for axion cavities or FCC beam screens.

The scope of **ERLs** is to reduce power consumption and so operating at 4.2 K is an obvious benefit, which is of direct priority for the ISAS project, utilising SRF thin film techniques.

WG3 Fundamental Power Coupler and HOM Couplers

Regarding European teams, the CERN effort is strictly aimed at FCC specifications. The DESY and HZB efforts focus on 1.3 GHz cavities and have therefore a high relevance for ILC, **Muon Collider**, and **ERL-based** facilities with that frequency, e.g. LHeC. IJCLab is ready to engage if project funding becomes available. ESS is expected to join the collaboration effort in this field. Dedicated couplers for damping the so-called Higher-Order Modes (HOMs), excited by the passage of high-current beams in the superconducting cavities, are being developed as a collaboration activity between the RF and ERL coordination panels. In the same framework, novel tuners will be developed, to compensate cavity detuning from mechanical vibrations.

WG4 High Gradient NCRF

A key part of the **Muon Collider** R&D plan is development of the RF system. One particular area that needs research is RF breakdown under strong magnetic fields. Studies have shown that the breakdown probably increases significantly when under multi-Tesla level static magnetic field limiting the maximum gradient possible in the RF system used for ionisation cooling of muons, a requirement for any muon collider. Studies at Fermilab in 2020 demonstrated 50 MV/m level gradients in a 3 T magnetic field by using Be elements inside the cavity, which limits plastic deformation and pulsed heating thought to be part of the reason for the increased breakdowns. One or more tests stands are required to further study breakdown in strong magnetic fields and to find the optimum material to use in order to develop a future muon collider.

At present 4 such test stands are being considered. CEA is planning a UHF test facility using the same frequencies and fields as proposed for a muon collider, and such a facility is almost certainly required. INFN, CERN and Cockcroft are additionally planning to use existing infrastructure at higher frequencies, 3 GHz or 12 GHz, to understand the physics of the problem on a faster timescale and help guide future experiments.

In addition to RF test stands CERN and Cockcroft (and possibly Uppsala) are considering DC field breakdown test stands. Such facilities have been successfully used to understand breakdown without external magnetic fields as they can operate at significantly higher repetition rates than RF systems, as well as being far cheaper, more compact and do not produce X-rays. One drawback with using the DC test stands is they use very short gaps which may alter the physics of breakdown in strong magnetic fields.

WG5 RF Power Sources & High Efficiency

In addition to breakdown test stands new klystrons are required to meet the difficult requirements for a **Muon Collider**. The current plan calls for a 24 MW klystron to feed 8 cavities, at 325 and 650 MHz, with 30 microsecond pulses. This power could be reduced by feeding less cavities at the expense of space requirements. A more compact and efficient klystron design will be required to meet this requirement as discussed in WG3.

WG6 LLRF-ML-AI

LLRF system and the applications of AI and ML are common to all kinds of accelerators. There are no special topics for HEP-specific accelerators. In principle, the LLRF development is beneficial to the entire accelerator community.

8. Conclusions

The RF Coordination Panel (RFCP) started its activity one year ago, in fall 2022. In the handover from the panel which had written the accelerator R&D roadmap the RFCP revised, during the first six months, the needs of the future collider designs matching them to specific goals that the R&D European activity should fulfill in this domain.

In the last six months, a sizable effort has been made to identify – through ad hoc surveys - the European teams working in the various RF theme areas. Indeed, the identification of the working teams had not been reported on the roadmap and this was deemed essential by the RFCP to the very coordination purpose of the panel. This survey aimed at verifying: areas of expertise and interest for expanding them, workforce involved, yearly R&D budget, degree of interest in activities related to high energy physics applications, list of collaborating institutions, available and desired infrastructures. This document, with its attachments, summarizes the survey outcome.

The RFCP plans to use this report as a scientific-management tool to regularly monitor progress in the various theme areas.

The most relevant outcome of the survey is, however, to correlate the specific RF needs of future colliders to the particular labs which could best fulfill them, identifying critically where development and testing infrastructure might be lacking in support of future HEP technology performance demands. This will allow to better coordinate the requests of greater funding from such Institutions. Such requests are anticipated to be proposed to the LDG, which might decide to satisfy it in coherence with the needs and requests from the other roadmap panels.

The RFCP anticipates, moreover, that it will try to organize a sizable work-package in the to-be-prepared proposal of a joint European project on accelerator R&D, following I.FAST. The work-package content will consist in notable activities, pertaining to the various RF theme areas. This initiative is meant both to increase the level of consistency among the priorities of the RF disciplines and to achieve additional resources from the national funding agencies, in the form of co-financing of the European project.

Appendix1 – Surveys of the Working Teams

Excel file "RF Implementation Panel - Survey of the working teams", to be found in

https://ldg-rfcp.com/

Appendix2 – Progress on Roadmap Milestones

Excel file "Implementation Plan - Progress on Roadmap milestones", to be found in

https://ldg-rfcp.com/

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