Istituto Nazionale di Fisica Nucleare

Accelerator R&D proposals

INFN input for the European Strategy for Particle Physics (ESPP)

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1 Introduction

The study of the next accelerator at CERN is fundamental to the future of particle physics in Europe for many reasons that have been outlined in some detail in the INFN National Input document.

INFN has encouraged and supported, with the adequate resources, a number of initiatives aimed at studying the feasibility of the FCC (Future Circular Collider) project at CERN, as well as R&D projects focused on innovative accelerator technologies.

The projects include R&D of radiofrequency cavities for future facilities, machine-detector interface studies for FCC-ee and Muon Collider, high-field magnets for future colliders and detectors, Cooling Cell technology and integration studies for Muon Collider and the plasma-based accelerator R&D related to EuPRAXIA.

Developments on both bulk-Nb and thin film accelerating cavities and superconducting magnets serve most collider concept designs; progress in this field has a significant impact on particle physics and its applications and bear a large energy saving contribution. A few research groups will provide specific contributions to the Future Circular Collider (FCC), in developing the interaction region mock-up, outlining the injector damping ring and contribution to beam dynamics investigations. For the muon collider, within the International collaborative effort which is in place, investigations of high electric fields embedded in high magnetic fields shall be conducted, which are an essential test for the feasibility of the cooling channel of the muons, after they have been produced by a proton driver. Leveraging on the experimental activity which is being carried out on EuPRAXIA, studies of the most crucial aspects of plasma-based-accelerator colliders will be analysed, including novel capillary systems for electron acceleration. Two specific topics with important impact shall be explored: improved positron sources based on oriented crystals and enhancements of the design and technological options for RF coupling windows, which are a known showstopper in the global development of future accelerating systems. Finally, a nationally distributed beam-based facility for material testing will be made available for future colliders R&D.

This paper summaries and discusses these activities.

2 R&D on superconducting cavities

Bulk Nb superconducting resonators for future colliders.
In this section we present two contributions dedicated to superconducting cavity studies. The first is carried on by the INFN LASA laboratory, a leading player in the field of bulk niobium superconducting cavities, and focused on the development of with high Q and high high gradient (G) SRF studies. The second effort is made in the INFN Laboratori Nazionali di Legnaro (LNL) and it aims at reducing the accelerator power consumption by means of thin-film cavities cooled at 4.2 K.
Most types of being investigated colliders rely on improved superconducting resonators for efficient particle acceleration (high gain, high quality factor). The activity proposed by the LASA team builds up on the current one and aims at specialising the so far acquired know-

how in SRF cavities (fabrication and treatment processes) to those structures operating at the reference frequency of the future HEP machine. Moreover, it is proposed to study those SRF structures, also operating in CW mode, allowing recovery of the beam energy to highly improve acceleration energy efficiency of beams with high average currents (needed for ERL and future linear collider projects such as ReLiC). The main overall goals are:

- to improve the currently achieved performance by improving the quality factor and therefore reducing cryogenic consumption with a view to energy saving (sustainability)
- to transfer this development towards industry production, an expertise for which LASA is at the forefront at present.

In this framework, the realisation of a horizontal cavity test cryomodule is proposed, filling the gap in the European landscape between large-scale horizontal cryostats (CEA, ESS, DESY) and simple vertical immersion cryostats.

The possibilities opened by this infrastructure are multiple and strategic:

- to optimise integration of cavity and helium tank
- to study cavity behaviour in its final configuration (horizontal, as in an accelerator), also equipped with a power coupler.
- to develop and qualify all RF ancillaries (frequency tuner, piezoelectric actuators, magnetic shield, etc.) for which LASA already has a consolidated experience.

Superconducting resonators with energy saving.

Although the 2K SRF technology based on bulk Nb cavities remains the state of the art for high energy physics accelerators, the need to make new accelerators more sustainable has led the SRF community to focus its efforts on searching a technology with higher T_c superconductors, to raise the working T to 4.2-4.5 K. This will allow to achieve a factor 3 reduction in cryogenic costs. Currently, PVD is the most promising technology to deposit Cu-based cavities with Nb_3Sn. Cu is also a cheaper material than Nb and this will reduce the primary cost item for cavity fabrication. INFN-LNL is a leader in the development of this technology, and the first prototype of a working 1.3 GHz cavity is foreseen in 2025. With the proposed continuation of this activity, it is expected:

- to industrialise the process and make it ready for mass production within the next 5 years; with a positive outcome, the team aims at scaling this technology to whatever frequency will be required by the next HE colliders, including the 400 MHz case for FCC;
- to setup the needed technology for finishing the Cu surface substrate, on which the SRF performance of superconducting films strongly depends; further development of the Plasma Electrolytic Polishing (PEP) is proposed, which promises 10 times quicker treatments, lower roughness than is achieved by so far developed methods and better sustainability, as it is using aqueous saline solutions, instead of concentrated acids.

3 High Field Magnets

High-field magnets are a cornerstone of future collider development. By achieving stronger magnetic fields, these magnets allow for more compact accelerator designs and higher collision energies, crucial for exploring new physics beyond the Standard Model at future collider such as FCC and multi-TeV Muon Collider. Additionally, advancements in high-field magnet technology, such as superconducting materials, improve energy efficiency and reduce operational costs, making them essential for the realisation of next-generation facilities.

The High Field Magnet project (HFM-I) is the Italian component in the wider European HFM R&D project on high-field magnets for next generation collider. The proposed program has already been discussed and agreed with the HFM management of CERN and a formal agreement is under preparation (approval expected by CERN FC in December 2024). The Italian groups in Genova and Milan-LASA sections are involved in the Falcon-D 12 T dipole project (based on Nb3Sn technology) spanning the period 2019-2026 and half-funded by CERN.

The aim is to develop high-field SC magnets (12-20 T), the fundamental technology for FCC-hh, already recommended in highest priority by the 2020 ESPP update. It is equally significative for a HE-LHC (as possible back-up of FCC-hh). This technology has strong synergy with the magnets for the Muon Collider. In the background, it is also useful for the Chinese SppC project, if this machine were approved. The high-temperature superconductor (HTS) part of the programme is also synergistic with the studies for the FCCee accelerator and for the related detector (IDEA).

Specific goal of HFM-I is, for Nb_3Sn, to demonstrate by 2030 that this technology, at 14 T (nominal value for FCC-hh), is ready for the pre-industrialization phase. The foreseen developments are:

- to design and build a Nb_3Sn dipole of the "Cosine theta" type in full scale in section, although of a reduced length, able to operate at 4.2K (instead of 1.9K) with significant energy saving.
- to build the first Two-In-One FCC dipole for FCC (i.e. hosting two beams, as in the LHC), based on the Nb_3Sn coils of the Falcon D project.

On the HTS technology, the HFM-I goal is to develop an accelerator-type magnet in HTS within early 2028, to verify whether HTS can achieve higher fields and operate at 20 K, yielding a ~ factor 10 energy saving factor and in particular:

- to investigate industrial scalability and cost reduction.
- to design and build a feasibility demonstrator, in 1:2 scale in section and about 1 m in length, aiming at 10 T, and 20 K operational temperature.
- To study of special Superferric Quadrupole-Sextupole lattice magnet in HTS, for lowering the dipole field in the main ring with a significant energy saving for FCC-ee.

4 Specific developments for the FCC

Interaction region design of FCC-ee

To achieve the required precision on the Physics reach at FCC-ee, it is of utter importance to control the material budget of the beam pipes and the vertex detectors which are intimately nested in the interaction region (IR) of the machine.

The unprecedented luminosity of FCC-ee, reached also through a very high beam current, together with the small vacuum chamber diameter, induces a considerable power dissipation in the chambers, up to about 500 mW/cm^2, which needs to be removed with cooling systems that are as light as possible in term of material budget.

Controlling the material budget requires the development of vacuum chambers of less than 0.5 % of a radiation length, comprising mechanical stability with embedded cooling, representing a considerable challenge compared to the state of the art. The LNF have led the IR design for the feasibility study, contributing among other topics with the design of the beam pipes. INFN is currently developing a full-scale mock-up of the IR, driven by LNF with the participation of Pisa and Perugia teams, and co-funded with CERN. In this framework, INFN is strongly interested to further develop this R&D activity in the pre-TDR phase by improving the following aspects:

- technical feasibility of IR thin vacuum chambers design and construction
- integrated solutions for vacuum chambers cooling;
- thermal and beam coupling impedance calculations;
- fully integrated lightweight vertex detectors and services;
- validation of assembly with full-scale IR mock-up.

This program is fully embedded within the ECFA DRD8 activity, carried out together with other international institutes.

Injector Damping Ring Design

FCC-ee, the future high-energy circular collider proposed for CERN, requires a high performances injector that, among other features, will include the most intense ever realized source of positrons providing a bunch charge of the order of 5 nC.

The FCC-ee injector complex must provide e- and e+ bunch trains for alternating bootstrapping injection during both top-up and filling-from-scratch operations.

The injector includes two separate linear accelerators, for e- and e+ (e-linac and p-linac), up to a beam energy of 2.86 GeV. Following the p-linac and e-linac, both species are injected/extracted into/from the Damping Ring (DR) by using four different transfer line (TL) branches.

The DR must accommodate beam trains consisting of 4 bunches separated by 25 ns, with a repetition rate of 100 Hz. It must also assure the largest possible acceptance of the incoming beams, and rapid damping, while maintaining good beam quality. All these features require dedicated and innovative solutions for the lattice design, for beam dynamics optimizations, and a comprehensive evaluation of the impact of collective effects.

Three different DR layouts, relying on different arc-cell configurations, are presently under study, the plan is to finalize the DR and TLs design in view of the TDR that should be delivered by 2028.

The design of the FCC-ee Injector Damping Ring and Transfer Lines and Energy and Bunch compressors are presently under the direct responsibility of INFN, and in particular of the INFN Laboratori Nazionali di Frascati (LNF), in the framework of a wider collaboration including PSI, CERN, CNRS-IJLab.

The INFN-LNF have all the competences and a strong interest in continuing to play a relevant role in the effort aimed at finalizing the FCC-ee injector TDR.

High intensity beam dynamics for Future Circular Collider

To reach the ambitious luminosity and beam intensities goals of both FCC-ee and FCC-hh, beam dynamics studies and vacuum chambers materials investigations are mandatory. FCC-ee will exploit the crab waist collision scheme with very small emittances and beta functions and a large Piwinski angle at the interaction points, while FCC-hh will require unprecedented magnetic field superconducting magnets where the beam-induced heat-loads have to be efficiently dissipated in the cryogenically cooled accelerator complex.

To preserve stability and good quality of the colliding beams of both accelerators, a thorough study of the collective effects and beam-beam interaction as well as an interplay of the different high intensity effects is required. In addition, mitigation strategies are to be elaborated to cope with beam instabilities.

5 R&D for the muon collider

Realising a multi_TeV Muon Collider involves overcoming several key technological challenges. Among these, the muon cooling channel is a critical component for producing a compact, high-quality muon beam, which is essential for the success of a muon collider.

Muons produced as tertiary particles from proton collisions impinging on a MW target are initially spread over a wide range of momenta and positions. To achieve the required beam brightness, the cooling channel must reduce the transverse and longitudinal emittance of the muon beam. High-field magnets and the embedded NCRF cavity constitute the elementary cooling cell to construct the muon cooling channel, addressing the crucial challenge of muon beam manipulation and energy restoration, reducing the beam emittance by several order of magnitudes before the fast acceleration stage. High-field magnets are critical for guiding, focusing, and compressing the muon beam as it passes through the cooling channel. Similarly, NCRF cavities are of paramount importance for reaccelerating the muons after they lose energy in the ionisation process.

The International Muon Collider collaboration, since the recommendation of the previous ESPPU (June 2020), was formed and hosted at CERN to study the multi-TeV baseline facility. The required R&D plans were approved to be implemented by the Accelerator R&D Roadmap outlining the need for the construction of a cooling demonstrator. The INFN Milano LASA Laboratory, is leading the effort to design and integrate the cooling cell and to develop a final baseline design for the demonstrator with the INFN Southern National Laboratories (LNS).

More recently the US Particle Physics Project Prioritisation Panel (P5) recognized the shared interest for a multi-TeV Muon Collider reaching the highest energy frontier, which could be hosted on Fermilab site, aiming to revitalise US HEP research.

Radiofrequency studies in High Magnetic Field for Muon cooling channel towards a Demonstrator Facility

A muon cooling channel consists essentially of absorbers, focusing magnets and RF cavities.

In this scheme the performance of the RF cavities is critical since, in the presence of a strong magnetic field, they become much more susceptible to the breakdown phenomena.
Limits have never been explored experimentally at the field levels required by the muon cooling cells (>30 MV/m). The lack of experimental data and, consequently, the difficulties to develop and verify theoretical models of the involved phenomena must be addressed on a short timescale.
In such framework, there are different lines of R&D activities of INFN interest:

- test of RF cavities at different frequencies with electric field larger than 30 MV/m embedded in strong (> 7 T) magnetic field to develop BDR models.
- design and fabricatation of single and multi-cells structures and fabrication of SC HTS solenoids, starting from a single coil at 5 T with a useful bore of the order of at least 200 mm up to large bore, diameter of the order of 400 mm.

The use of HTS magnets (20K) is mandatory for reason of performance and sustainability.

6 Activities for future plasma-based colliders

Plasma accelerators are capable of accelerating extremely short bunches with electric fields larger than 10 GV/m. These properties make plasma accelerators a promising technology for a more compact, less expensive and more sustainable high-energy linear collider or injectors for circular colliders.

There are several large, international projects at various levels of development that explore some accelerator schemes and address issues relevant for application to particle physics, such as EuPRAXIA@SPARC_LAB at INFN-LNF, AWAKE at CERN, HALHF in Europe, FACET II in the US.

EuPRAXIA and beyond

The EuPRAXIA@SPARC_LAB facility is the new project under implementation at the INFN Laboratori Nazionali di Frascati (LNF). This is the beam driven pillar of the EuPRAXIA project which is expected to provide, by 2029, the first European Research Infrastructure dedicated to demonstrating usability of plasma accelerators delivering high brightness beams up to 1-5 GeV for users. EuPRAXIA (https://www.eupraxia-facility.org/) is actually the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts driven by innovative laser and linac technologies. It is included in the ESFRI roadmap since 2021.

With the advent of the EuPRAXIA project, INFN received funding from the Minister of University and Research (MUR) for the construction of this new facility at LNF. This facility will realize the first short-wavelength Free Electron Laser (FEL) driven by a plasma accelerator. By itself EuPRAXIA will be a fundamental stepping stone towards any plasma-based particle physics collider. Consequently, INFN is strongly motivated to pursue R&D activities toward plasma-based linear colliders (LC).

An intense R&D program is needed to demonstrate a plasma-based LC design, which, as previously mentioned, can be developed in the framework of the EuPRAXIA project.

INFN is particular interested in developing these activities and in the proposed methodology to design and build advanced plasma components based on:

- development of theory and simulations for multistage acceleration and muon acceleration;
- realization of high repetition rate capillary prototypes to operate in a kHz regime;
- beam manipulation for high efficiency acceleration to reach high transformer ratio;
- positron production and acceleration;
- scalable laser driver technology;
- demonstration of staging.

LNS, in collaboration with LNF, will actively contribute to this field in synergy with the EUPRAXIA activities, focusing on advancing the charge and energy of laser-driven electron beams. This work aligns with EUPRAXIA's objectives by optimizing the capillary discharge technique and the gas-jet approach. These efforts will be further supported by the new high-power laser at LNS, which is a key resource within the EUPRAXIA framework.

7 Developments benefitting several collider options

This chapter outlines key technological developments benefiting multiple collider designs. It expands into innovative solutions for positron sources, advancements in RF windows and couplers, and material studies for vacuum chambers, addressing critical challenges in achieving the high performance and reliability required for future accelerators.

Positron Sources for Future Colliders

Future colliders require high-intensity, low-emittance positron sources to achieve the luminosity and precision levels necessary for future experiments. Severe heat load and high energy density deposited in the target represent a crucial constraint for the achievable intensity in conventional systems. One possibility to overcome such limitations is to exploit the intense radiation due to lattice coherent effects in oriented crystals to achieve a high rate of e+e- pair production in a thinner target, thereby strongly decreasing the deposited energy and the peak deposition density (PEDD) in the target, while also permitting to decrease the electron beam current.

The development of positron sources based on oriented crystals represents a significant technological advancement, with substantial impacts on both particle physics and collider design.

INFN is strongly interested in developing these activities. They are focused on:

- study of hybrid sources that combine the use of oriented crystal radiator with an amorphous converter;
- prototyping granular and/or rotating converter targets to distribute the thermal load;
- study of single crystal sources for circular collider, allowing to insert the crystal target directly into the matching device used to capture the highly divergent positron beam;

- development of advanced simulations integrated into the Geant4 toolkit and RF-track;
- irradiation test to assess the target's durability and the resilience of its crystalline structure.

R&D on RF windows and couplers

All RF cavities (normal or superconducting) are fed by RF power couplers. To transmit 100's kW into SRF cavities reliably (with only W's left in the cold mass) through thin ceramic windows is a delicate R&D topic for future colliders: couplers are the interface between the RF distribution network (in air) and the rf cavities (in ultra-high vacuum). Moreover, in the SRF case the couplers are also at the transition between room and cryogenic temperatures. For FCC, in particular, 400 MHz, 1 MW CW and 800 MHz, 250 kW CW SW couplers are foreseen, which is twice the present state of the art. INFN has strong competencies in several fields which are crucial for the development of high-power couplers. At LNL, it can leverage on a set of high-power RF amplifiers which enable high-power tests in realistic conditions.

The proposed R&D lines are:

- RF design and studies of the sensitivity of the coupler geometries to multipacting (MP), to be conducted in an optimization loop between RF ad particle tracking loop.
- a qualification process for the Ti(N) coating of different shapes of alumina windows (discs, coaxial, cylinders);
- setup of a sputtering facility to perform high quality coating on larger size alumina;
- to develop the brazing process ceramic-to-metal, a key asset for the coupler production and nowadays one of the most time-demanding steps on the procurement chain;
- to perform the coupler high power RF test, to give the final demonstration of the RF coupler compliancy.

Vacuum chamber material studies

Vacuum is a ubiquitous item, important tfor all the aforementioned projects. It requires not only specific competences, such as the detailed knowledge of material vacuum behaviour (e.g. their desorption properties), but also the ability to tackle unconventional issues that can have severe impact on the accelerator performances. Experimental analysis of such properties for all the materials to be used in the future accelerators must be performed with specific UHV spectroscopic tools. For the FCC-hh, the FCC-ee and for the Muon colliders, for instance, study of some of the electronic properties of the surfaces inside the vacuum chamber may become crucial R&D aspects. One example is given by their ability to produce secondary electrons if hit by other electrons or photons, since such electrons may interact with the circulating beam causing detrimental instability issues. This activity is already ongoing at LNF , where such studies have been successfully performed on, among others, LHC and FCC-hh cryogenic walls, EIC (the Eletron Ion COllider, to be built in USA) beampipes and on some candidate materials expected to be used in the FCC-ee