Addendum to: The Muon Collider

Input to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

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Abstract

Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. A Muon Collider enables direct access to the underlying simplicity of the Standard Model and unparalleled reach beyond it. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider, yielding a physics potential significantly greater than the sum of its individual parts. A high-energy muon collider is the natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the many frontiers of the high energy community.

The last European Strategy for Particle Physics Update and later the Particle Physics Project Prioritisation Panel in the US requested a study of the muon collider, which is being carried on by the International Muon Collider Collaboration.

In this document, we directly address the questions listed in the guidelines for inputs for the large-scale projects by the European Strategy Secretariat.

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1 Stages and parameters

1.a The main stages of the project and the key scientific goals of each

IMCC is studying a site independent collider implementation to reach around 10 TeV collision energies. It is also studying site specific options that take advantage of existing infrastructure and limitations at CERN and FNAL.

At CERN, IMCC has developed a solution that reuses existing tunnels with an initial stage having 3.2 TeV centre-of-mass energy followed by an upgrade to 7.6 TeV centre-of-mass energy. Acceleration for 3.2 TeV would be achieved using a sequence of one Rapid Cycling Synchrotron in the SPS tunnel and a further RCS in the HL-LHC tunnel. The beam would be extracted to a collider ring. A further RCS would be installed in the HL-LHC tunnel to enable acceleration for 7.6 TeV. The beam would then be extracted to a collider ring.

IMCC considers that an initial lower energy collider can produce physics results earlier. A 3.2 TeV stage would enable an exquisite physics programme that explores collisions at the highest energy conceived for any lepton-antilepton collider. It would offer the first significant step beyond the HL-LHC in understanding the Higgs potential as well as testing Dark Matter candidates. The upgrade to 7.6 TeV would extend our understanding of EWSB even further allowing a differential test of EW restoration. Other energies, such as 125 GeV for resonant Higgs production and energies beyond 10 TeV have not been studied but are possible. A resonant Higgs factory may be important if no other low-energy Higgs factory were realised.

Table 1.a: Selected muon collider energy stages and corresponding luminosity ranges (depending on the collider ring and magnet technology circumference).

Parameter	Symbol	unit	Site independent		CERN	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	17.5	0.9–2.0	7.9–10.1
Collider dipole technology			Nb_3Sn	HTS	NbTi or Nb_3Sn	Nb_3Sn or HTS

1.b For each stage, the main technical parameters

IMCC is focusing on a collider that reaches around 10 TeV centre-of-mass energy. It also considers that a staged implementation can deliver physics earlier. The project has been studied for implementation at CERN and FNAL and for a site-independent implementation, assuming that no infrastructure can be reused. Four possible implementations are described here:

- A CERN-specific implementation with an initial 3.2 TeV stage followed by a 7.6 TeV stage where the collider ring is reused with a magnet upgrade.
- A CERN-specific implementation with an initial 3.2 TeV stage followed by a 7.6 TeV stage where a bespoke collider ring is used for each stage.
- A site independent option with an initial 3 TeV stage followed by a 10 TeV stage.
- A site independent option with an initial 10 TeV stage followed by a higher luminosity 10 TeV stage.

The different options are listed in tables 1.b and 1.c.

The collider dipole technology is a key bounding parameter. IMCC expects that HTS collider ring dipoles will not be available for a next-generation collider in 2050. Higher dipole fields would enable shorter collider rings and yield higher luminosity. The available magnet technology constrains the available dipole field and consequently impacts on the staging scenarios.

The implementation at CERN can use the SPS tunnel to house one RCS and the LHC tunnel to house two RCSs. This allows to reach a collision energy of $7.6\,\mathrm{TeV}$ with the technology studied for the site-independent scenario; to be developed fast-ramping HTS magnets in the final RCS might increase this energy. A natural maximum staging energy for this implementation would be $3.2\,\mathrm{TeV}$ since the final energy of the first RCS in the LHC tunnel is $1.6\,\mathrm{TeV}$.

Two example implementations for CERN are presented in table 1.c. The first uses the strongest dipole field available at the time and the smallest collider ring tunnel circumference for each stage and yields highest luminosity. The second has the lowest luminosity of the range of possible implementations. It uses the same 11 km collider ring tunnel for both stages. This implementation could reach $7.6\,\mathrm{TeV}$ with Nb_3Sn dipoles and $3.2\,\mathrm{TeV}$ with established NbTi technology.

For the site independent implementation two staging scenarios are considered, see table 1.b. They are based on the assumption that Nb_3Sn dipoles can be available for operation by 2050 but high-field HTS dipoles will be available only later. The first, energy staging, scenario consists of a $3\,\mathrm{TeV}$ stage, followed by a $10\,\mathrm{TeV}$ stage. The first stage uses three RCS and a 4.5 km-long collider with Nb_3Sn dipoles. The second stage adds an additional RCS and uses a new 11.4 km collider ring with HTS dipoles. The second, luminosity staging, scenario implements 10 TeV collider already in the first stage. This requires to use Nb_3Sn collider ring magnets and hence a longer tunnel. Later the luminosity can be upgraded with better interaction region magnets, similar to HL-LHC.

1.c The number of independent experimental activities and the number of scientists expected to be engaged in each.

The muon collider can naturally provide beams to up to two interaction points, with no loss of delivered luminosity compared to a single interaction point. In addition, it is expected to exploit the bright neutrino beams produced in the straight sections leading to the interaction points with dedicated stand-alone experimental facilities, located along the neutrino beam path. Two such facilities could be supported for each interaction point on the collider ring. Furthermore, a muon beam dump facility is being considered, targeting dark sector models. A suitably designed proton driver could enable a non-collider physics programme similar to the existing one at CERN. In particular, the Proton Synchrotron Booster and the Proton Synchrotron could continue to operate; continued operation of the SPS or its replacement with the first RCS is likely possible. The high-power proton complex for the muon production could enable additional opportunities.

It is expected to instrument each of the interaction points located on the collider ring with general purpose particle physics experiments. Because of the breadth of the muon collider physics programme, and because of the complexity of the experimental apparata, each experiment should require the engagement of a community with a size comparable to ATLAS, CMS, or general purpose detectors at future hadron colliders. Based on the ATLAS and CMS community size, this would likely correspond to about 6000 scientists. Each dedicated neutrino experiment will engage a community of up to several hundred scientists. The muon beam dump facility, if realized, can also attract about a hundred independent scientists. A suitably designed proton driver could support a programme similar to the existing CERN non-collider physics programme.

Table 1.b: Tentative target parameters for a site independent muon collider at different energies if target performances are achieved. Scenario 1 corresponds to Energy Staging, and Scenario 2 corresponds to Luminosity Staging.

Site independent muon collider parameters						
Parameter	Symbol	unit	Energy staging		Luminosity staging	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	17.5	4 (tbc)	13.8
Collider circumference	C_{coll}	km	4.5	11.4	15	15
Collider arc peak field	B_{arc}	T	11	14	11	11
Collider dipole technology			$\mathrm{Nb_3Sn}$	HTS	$\mathrm{Nb_3Sn}$	$\mathrm{Nb_3Sn}$
Luminosity lifetime	N_{turn}	turns	1039	1363	1039	1039
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transv. emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	5 (tbc)	1.5
IP betafunction	β	mm	5	1.5	5 (tbc)	1.5
IP beam size	σ	µm	3	0.9	1.6	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5	5	5
Protons energy on target	E_{p}	GeV	5	5	5	5

Table 1.c: Examples of tentative target parameters for a CERN implementation of the muon collider, reusing the SPS and LHC tunnels. Scenario 1 uses a 11 km tunnel for both stages, Scenario 2 uses optimal tunnel circumferences; the corresponding civil engineering studies remain to be performed.

CERN-specific muon collider parameters						
Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3.2	7.6	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.9	7.9	2.0	10.1
Collider circumference	C_{coll}	km	11	11	4.8	8.7
Collider arc peak field	B_{arc}	T	4.8	11	11	14
Collider dipole technology			NbTi	$\mathrm{Nb_3Sn}$ or HTS	$\mathrm{Nb_3Sn}$	HTS
Muons/bunch	N	10^{12}	2.2	1.8	2.2	1.8
Beam power	P_{coll}	MW	5.6	10.9	5.6	10.9
IP bunch length	σ_z	mm	4.7	2	4.7	2
IP betafunction	β	mm	4.7	2	4.7	2
IP beam size	σ	µm	2.8	1.2	2.8	1.2

2 Timeline

2.a The technically-limited timeline for construction of each stage

The muon collider concept requires significant R&D to achieve the maturity level needed for implementation. The timeline is largely driven by the progress of the R&D programme.

In Europe, hosting the collider is being considered either following a Higgs factory or as the next flagship project after the HL-LHC. In the United States, there is strong interest in hosting the collider to reassert leadership at the high-energy frontier. To guide the definition of the R&D programme, an ambitious technically limited timeline has been explored together by European and US experts. This scenario assumes a firm commitment to implementing a muon collider in Europe as soon as possible after the HL-LHC, with the goal of beginning operation around 2050 (see Figure 2.a). It prioritizes reuse of existing CERN infrastructure to minimize civil engineering costs and limits the collider's center-of-mass energy to approximately 3 TeV, consistent with realistic expectations for the development of high-field HTS dipole magnets.

The initial phase of the project focuses on advancing the design and the required technologies to a level that allows the feasibility of a muon collider to be demonstrated with confidence. The expected deliverables of this phase are listed in Table 5.b. The estimated resource requirements for this phase are approximately 320 million CHF in materials and 2700 full-time equivalent years (FTEy) in personnel, including 20 million CHF and 900 FTEy allocated to detector development. This phase is expected to last a minimum of 10 years.

Once feasibility has been established, the project preparation phase can begin, requiring at least five years. Although detailed resource estimates for this stage are not yet available, they are expected to exceed those of the initial phase. The subsequent construction phase would then require a minimum of nine years. The plan will have to be re-evaluated if the required resources are not available and/or if other considerations lead to a more stretched timeline for the implementation at CERN. The R&D timelines underpinning the overall timeline are given in 5.b and 5.c.

The U.S. community similarly targets operation in the early 2050s, with a focus on a single-stage 10 TeV collider. This timeline differs slightly in length and structure from the European plan, i.e. requiring 17 years to prepare a Technical Design Report, compared to 15 years in the European scenario.

At present, R&D progress is limited by available resources, both in Europe and particularly in the U.S., where organizational structures are still being established. It is therefore important to increase the design effort in order to complete a start-to-end design of the collider and to launch the technology R&D that has the strongest impact on the timeline. IMCC plans to review the Roadmap in 2028, following the results of the European Strategy for Particle Physics Update (ESPPU) and the subsequent mid-term review panel recommended by the P5 report. At that point, a decision can be made on the location of the demonstrator facility and it could be approved.

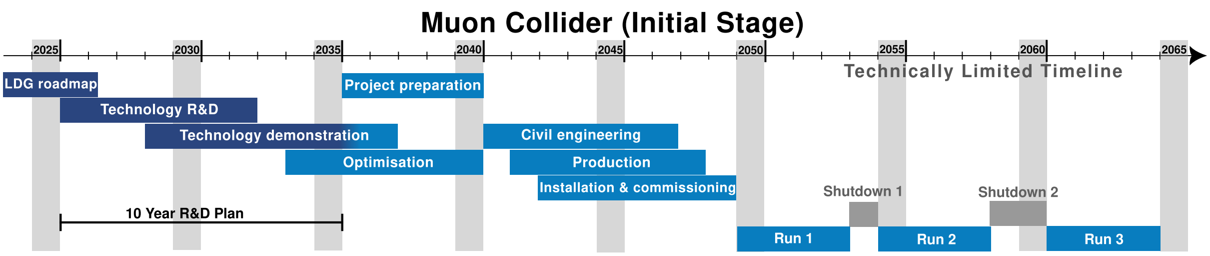

Fig. 2.a: Technically limited timeline for the initial muon collider stage, assuming a firm commitment to implement the project as soon as possible after the High-Luminosity LHC. The timeline of the project phases beyond the planned 10 years of R&D are affected by the siting choice and detailed planning by the host laboratory.

2.b The anticipated operational (running) time at each stage, and the expected operational duty cycle

No specific study has been performed to optimise the running time at each energy. Initial integrated luminosity goals have been set as $1\,\mathrm{ab}^{-1}$ and $10\,\mathrm{ab}^{-1}$ for 3 and 10 TeV. Operation time at the high energy is of the order of at least 10 years. For a 3 TeV stage, it will depend on the funding of the second stage and the technology development for the collider ring dipoles. A period of approximately 10 years of operation appears as a reasonable prediction.

The operation time per year is expected to be similar to other proposed projects, such as CLIC, and be in the range of $1 - 1.2 \times 10^7$s per year. Detailed studies will establish the margins and redundancies that are required to reach the necessary availability in the 70-80% range and the impact that this has on the cost.

3 Resource requirements

3.a The capital cost of each stage in 2024 CHF

The capital cost range is provided for the CERN scenario as compared to a Green Field realization in Figure 3.a

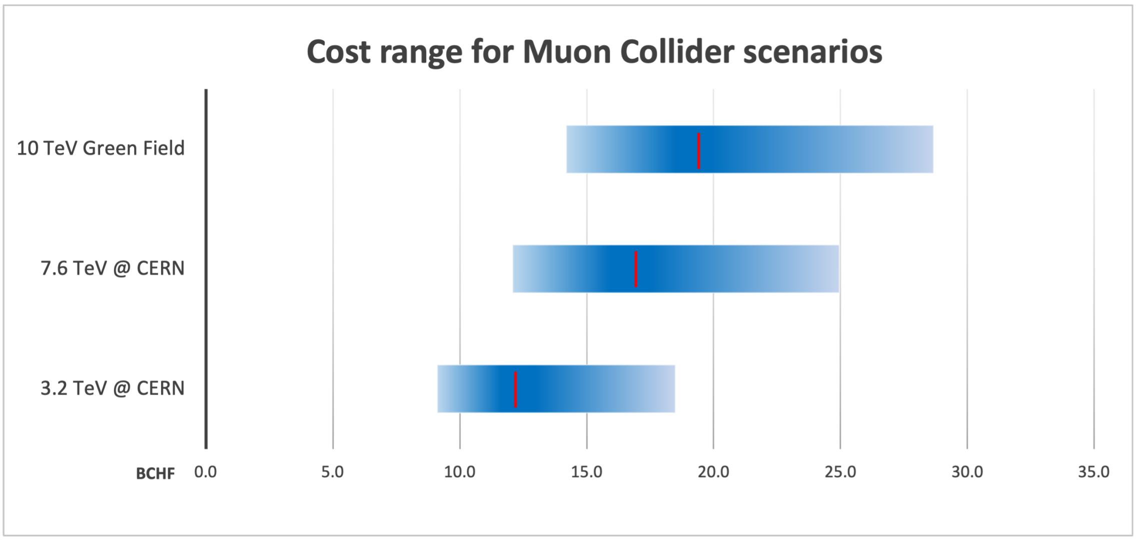

Fig. 3.a: The cost range is presented for the scenario of energy staging of the Muon Collider facility as compared to the Green Field realization. The cost for each stage represents the cost for a complete facility. The darkest part of the colour band identifies the most probable values, while the lighter sides of the band materialize the extension of the calculated uncertainty. Red markers show the position of the most probable value.

The Snowmass 2021 Collider Implementation Task Force [1] proposed a general formula for estimating the labour needed for construction:

$$\text{Explicit Labour} = 15.7 \cdot (Value)^{0.75}, \tag{3.a}$$

with Explicit Labour in FTE-years and Value in MCHF of 2010. This indicates that a CERN implementation requires around 18500 and 24000 FTE-years for 3.2 TeV and 7.6 TeV, respectively. An important part of these could be covered outside CERN, for in-kind deliverables.

3.b The annual cost of operations of each stage

The annual cost of operation is calculated on the basis of the investment cost and by considering the estimated needs in terms of spare parts. The following percentages are considered:

- 1% calculated for RF cavities, cryostats, magnets.
- 3% calculated for RF power and power converters.
- 5% calculated for CFS and cryogenics.

The replacement / operation cost will then be most likely around 200 MCHF for the low energy stage at 3.2 TeV and around 250 MCHF for the stage at 7.6 TeV.

In addition one has to consider the cost of energy for operation. In 4.a the estimated energy consumption is estimated for the different states of the machine and it is shown to be in the range of 0.78 - 1.12 TWh. The associated cost will then depend on the negotiated price of energy at that moment. A contract for the supply of energy for the LHC Run 4 has not been signed yet at the day of writing, for example, but we know that from 2026 CERN will make the transition from the ARENH price mechanism provided by the French supplier to market prices, with the associated uncertainty. It is generally assumed a cost of 80 CHF/MWh for energy as of today, which would imply an operation cost of about 90 MCHF for the 7.6 TeV stage.

3.c The human resources (in FTE) needed to deliver or operate each stage over its lifetime, expressed as an annual profile

The resources for operating the muon collider facility in the scenario of a CERN installation are expected to be very similar to those that are presently necessary for operating the CERN accelerator complex, however a detailed study would certainly be required. A detailed study performed by the ILC, which was also analyzed in the CLIC context, showed a need of 640 FTE. In the case of the muon collider, one can introduce some uncertainty in the estimate, also related to the operation of some innovative systems, like the long cooling channel, the target area for the muon production and the collider SC magnets in the presence of a high radiation load, and expect a need ranging between 700 to 900 FTE.

3.d Commentary on the basis-of-estimate of the resource requirements

At the time when the estimate is performed, the Muon Collider design is still in a pre-CDR stage, where the architecture has been developed to a certain level of detail and the main beam parameters are known with some accuracy, but still several options exist that may steer the project into different directions, with considerable impact on the final cost. For these reasons, the estimate is presented in the form of a cost range, which is justified partly by the level of maturity of the chosen technologies and partly due to the extrapolation of the cost information from other projects and studies.

An initial choice was made to consider the installation on the CERN site as a possible first configuration for the realisation of the Muon Collider, by also assuming that it would make the best use of the existing tunnels and technical infrastructure. That would certainly keep the environmental impact related to the civil engineering realisations on the low side, in spite of some initial limitations to the performance reach of the facility that may follow from this choice. The successive analysis looks into the cost variance introduced by the adoption of beyond state-of-the-art technologies that will push the overall performance and by configuration options that will allow the complex to deploy its full potential.

A project breakdown structure (PBS) was developed and for each area of the facility a few systems could be identified as the major contributors to the overall cost. The PBS considers four levels of complexity providing increasing detail starting from the Machine Sector down to Facility, System and Component. Work package leaders in charge of different technological areas were asked to provide their estimates of cost for equipment considered as the cost drivers, together with the level of maturity for the specific technology. The main cost drivers are represented by the civil engineering, the general technical infrastructure, the cryogenic system, the magnet system with power converters and by the RF system with the RF power generation. The cost of these main items is mostly estimated with a bottom-up approach by contacting recognised experts in the field and in some cases by soliciting cost estimates from industrial partners. Other sources of cost are extrapolated from previous projects.

The analysis presents the cost for each stage as a complete facility, rather than evaluating the incremental cost from one stage to the next, due to the significant error margin that affects any cost estimate at the moment. This kind of estimate will become possible after that the necessary R&D will have been produced and more accurate estimates will become possible.

Having considered the level of maturity of the project, the analysis aims at obtaining a rough order of magnitude (ROM) estimate for the different stages that have been considered, with a level of precision that combines Class IV and Class V estimates for different areas of the project. For the same reason cost uncertainties take into account technical uncertainties only and do not consider purchase uncertainties.

4 Environmental impact

4.a The peak (MW) and integrated (TWh) energy consumption during operation of each stage

The power consumption has been estimated for the two energy stages at CERN and it is summarized in Table 4.b together with the yearly energy consumption. In order to obtain the energy consumption a possible scheme for the operation time has been adopted as presented in Table 4.a with an assumed uptime efficiency of 77.5%. The stand-by state that has been used for the energy calculations corresponds to a state of accelerators when only cryogenics, magnets and the cooling and ventilation systems are powered and running.

Table 4.a: Muon Collider complex yearly operation time.

	Days
Operation	165
Luminosity	115.5
Technical stops	15
Machine development	20
Commissioning	40
YETS	125
	Hours
Operation	4509
Stand-by	1251
Off	3000

Table 4.b: Power and Energy consumption for the Muon Collider energy stages in the CERN scenario.

	Unit	**3.2 TeV**	**7.6 TeV**
Operation power	MW	117	182
Energy consumption	TWh	0.53	0.82
Stand-by power	MW	73	111
Energy consumption	TWh	0.09	0.14
Off state power	MW	58	69
Energy consumption	TWh	0.17	0.21
Yearly energy consumption	TWh	0.8	1.2

The facility wall-plug power requirement was estimated based on the sum of the estimated power consumption of each individual component. The estimate of power consumption for RF cavities was based on operation of known RF cavities and sources, including requirements for cooling of superconducting cavities. Power losses arising from operation of the pulsed normal conducting magnets was estimated based on comparison of calculation validated across three different codes and combined with loss estimates of both unipolar and bipolar pulsed resonance circuits as appropriate. All power estimates took advantage of the low duty factor required for the muon collider compared to other facilities. Additional heat load induced by the beam to RF cryostats in the RCSs was tentatively included into the operation power budget. In a worst case scenario, this power is of the order of 12 MW for the 3.2 TeV stage and up to 29 MW for the 7.6 TeV case. Collimation of the losses before and after the cavities will reduce the cooling requirements. We assume that the actual power is one third of the pessimistic case. However, the design and detailed study remains to be done. Further details of the estimated wall-plug power requirement of individual components may be found in Chapter 6 of Ref. [2].

4.b The integrated carbon-equivalent energy cost of construction

A life-cycle assessment of the ILC and CLIC accelerator facilities performed by ARUP to evaluate their holistic global warming potential (GWP), has so far provided the most detailed environmental impact analysis of construction. The components of construction are divided into classes: raw material supply, material transport, material manufacture, material transport to work site, and construction process. These are labelled A1 through A5, where A1-A3 are grouped as materials emissions and A4-A5 are grouped as transport and construction process emissions. The approximate construction GWP for the main tunnels are 6.38 kton CO_2e/km for CLIC (5.6m diameter) and 7.34 kton CO_2e /km for ILC (9.5m diameter); the Muon Collider tunnel design is similar to that of CLIC, so 6.38 kton CO_2e/km is used here for the calculation of emissions.

While a comprehensive civil engineering report is unavailable for the Muon Collider, we estimate the concrete required for access shafts, alcoves, caverns, klystron galleries, etc. to contribute an additional 30% of emissions, similar to what is anticipated for other colliders. The analysis indicates that the A4-A5 components constitute 20% for CLIC and 15% for ILC. In the absence of equivalent life cycle assessment analysis for the Muon Collider, we account for the A4-A5 contributions as an additional 25%. For a greenfield site, a 3 TeV or 10 TeV Muon Collider would require approximately 30 km and 70 km of tunnels, respectively. However, a site reusing existing infrastructure such as CERN for 7.6 TeV center of mass would only need 15 km of tunnels primarily limited to the muon source, cooling channel and the collider ring. For these three cases the emissions in kton CO_2e is on the order of 700, 300 and 150 for decreasing tunnel length, including A1-A5 contributions as described above.

4.c Any other significant expected environmental impacts

Tentative studies indicate the potential for the neutrino flux to have a negligible impact on the environment, similar to LHC. Initial studies focus on two main challenges:

- The experiments as well as beam injection and extraction are placed in straight insertions. Along the projection of these straights, the neutrino flux can be quite high. For CERN a first orientation of the collider has been identified whereby the neutrino flux emerges in two non-built-up spots in the Jura mountains, which would allow to fence the area and place experiments as appropriate. The other exit points would be in the Mediterranean Sea. Potential other orientations remain to be explored.
- The flux from the arcs is mitigated with a mover system. The system will avoid significant localised neutrino flux by systematically changing the beam angle between $-1\,\mathrm{mrad}$ and +$1\,\mathrm{mrad}$. If applied in the horizontal and vertical plane, this would yield a negligible neutrino flux at the surface. Detailed studies of the impact of the system on the beam remain to be performed.

Further optimisation and expansion of the studies to the full complex are required.

5 Technology and delivery

5.a The key technologies needed for delivery that are still under development in 2024, and the targeted performance parameters of each development

By 2036-37, the muon collider project aims to achieve readiness for a staged implementation, requiring R&D resources around 300 MCHF and 1800 FTE-years for the accelerator and 20 MCHF and 900 FTE-years for the detector between 2026 and 2036. A breakdown of the resources is provided in Table 5.a.

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Table 5.a: Summary of R&D resources, divided by area, over a ten year period. Personnel is given as average Full Time Equivalent (FTE), where students count as 50% FTE. Material is given in millions of CHF (MCHF). The total is the sum of the four areas.

This R&D investment would enable a first operational stage around 2050. Key milestones include construction and testing of essential magnets and demonstrating cooling technology, both of which drive the schedule. Readiness requires a mature baseline design, TRL 6+ technologies, comprehensive site and environmental studies, and advanced cost, power, and schedule assessments. Further progress is also needed in physics and detector studies. Part III of the supplementary report contains a detailed description of the R&D [2]. The main elements for the accelerator design are listed in Table 5.b and are grouped as follows:

- **Magnet technology developments:** HTS solenoids for muon production and cooling; and collider ring dipoles and fast-ramping magnet systems.
- **RF technologies:** components such as klystrons; cavities working in high magnetic field and with high beam loading; and test infrastructure.
- **Muon cooling technology:** the technologies for muon cooling and their integration into the 6D cooling and the final cooling system.
- **Design and technologies:** study of key design challenges, including collider modelling; lattice optimization; advanced simulations; site impact studies to balance cost, efficiency, and risk; and technical developments as target, RF and MDI.
- **The muon cooling demonstration programme:** integration and test of cooling technologies; performance verification; and development of key components like HTS solenoids and RF systems.
- **Detector R&D priorities:** simulation; technology; and software to enhance physics output while reducing beam-induced backgrounds, which are not included in the table.

Table 5.b: Key deliverables of the proposed R&D programme.

Technologies	**Deliverables**	**Key parameters and goals**
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	$1\,\mathrm{m}$ inner / $2.3\,\mathrm{m}$ outer diameters, $1.4\,\mathrm{m}$ length, $20\,\mathrm{T}$ at $20\,\mathrm{K}$
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	$510\,\mathrm{mm}$ bore, gap $200\,\mathrm{mm}$, $7\,\mathrm{T}$ at $20\,\mathrm{K}$
Final cooling solenoid	Build and test HTS prototype	$50\,\mathrm{mm}$ bore, $15\,\mathrm{cm}$ length, $40\,\mathrm{T}$ at $4\,\mathrm{K}$
Fast-ramping magnet system	Prototype magnet string and power converter	$30\,\mathrm{mm}$ x $100\,\mathrm{mm}$, $1.8\,\mathrm{T}$, $3.3\,\mathrm{T/s}$
LTS collider dipole	Demonstrate $\mathrm{Nb_3Sn}$ collider dipole	$160\,\mathrm{mm}$ diameter, $11\,\mathrm{T}$, $4.5\,\mathrm{K}$, $5\,\mathrm{m}$ long
HTS RCS dipole	Demonstrate RCS HTS dipole	$30\,\mathrm{mm}$ x $100\,\mathrm{mm}$, $10\,\mathrm{T}$, $20\,\mathrm{K}$, $1\,\mathrm{m}$ long
HTS collider dipole	Demonstrate HTS collider dipole	$140\,\mathrm{mm}$ diameter, $14\,\mathrm{T}$, $20\,\mathrm{K}$, $1\,\mathrm{m}$ long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long
	Radiofrequency	
Muon cooling RF cavities	Design, build and test RF cavities	$352\,\mathrm{MHz}$ and $704\,\mathrm{MHz}$ in $10\,\mathrm{T}$ field
Klystron prototype	Design/build with Industry $704\,\mathrm{MHz}$ (and later $352\,\mathrm{MHz}$) klystron	$20\,\mathrm{MW}$ peak power, $704\,\mathrm{MHz}$ / $352\,\mathrm{MHz}$
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 $\mathrm{MV/m}$, $704\,\mathrm{MHz}$–$3\,\mathrm{GHz}$ cavities in 7–$10\,\mathrm{T}$
SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	$352\,\mathrm{MHz}$, $1056\,\mathrm{MHz}$, $1.3\,\mathrm{GHz}$, $1\,\mathrm{MW}$ peak power (FPC)
	Muon Cooling	
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 µm emittance, 40 T field
	Design & Other Technologies	
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O($\pm 1\mathrm{mradian}$)
Beam Instrumentation	Instrumentation component designs	Protoype components and tests as needed
Target Studies	Target design and test of relevant components	$0.4\,\mathrm{MJ}$/pulse, $5\,\mathrm{Hz}$
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

5.b The critical path for technology development or design

The IMCC has identified several items that are critical for delivery of the muon collider on a next-generation time scale.

- The **Demonstration of an integrated rectilinear cooling module** is necessary in order to verify that the technology can be realised and to inform a decision making process on the muon collider facility at the conceptual design stage. The proposed cooling cells are very compact so that integration of equipment poses significant challenges in thermal and force management which must be verified in hardware. Delivery of a beam test will follow to inform the technical design and eventual operation of the facility. As part of the Demonstration of Cooling, a **prerequisite RF Test Programme** is required to demonstrate that the proposed RF gradients are achievable even in the presence of strong magnetic fields. The cooling system RF gradient requirement is about 25% lower than that achieved in a test programme in the US in relevant conditions but IMCC still considers this an important risk. Higher gradients would improve performance.
- Several critical **magnet** technologies require advanced prototypes to be sure that the design criteria can be met, in particular for the high-field HTS solenoids required for muon production and cooling which have fields up to 25% higher than currently available solenoids. Delivery of solenoids having capabilities beyond those proposed would improve the performance.
- A **start-to-end design of the facility** is required to improve the reliability of the existing power, cost and performance estimate in order to approve the muon collider project. Several design areas rely on previous studies which are not fully integrated and carry risks which must be mitigated. A start-to-end design would improve understanding of the relative trade-off between different sub-systems which may yield an improvement in power, cost or performance.
- The high-energy muon collider **detectors** must be optimized for physics in the challenging environment created by machine-induced backgrounds. Most detector components must simultaneously optimize position resolution, timing capability, radiation hardness, data transmission, and on-detector background rejection, all while maintaining low mass and low power consumption. Research and development must focus on developing the necessary detector technologies, tools, and crucial expertise to construct state-of-the-art detectors for this future machine.

The estimated timeline is shown in Figure 2.a. The timeline for the Demonstrator is shown in Figure 5.a and for the magnet development in Figure 5.b.

5.c A concise assessment of the key technical risks to the delivery of the project

The proposed R&D program is designed to address the key risks in delivering collision energy and luminosity as well as good experimental conditions and site options within an appropriate cost and time envelope. Table 5.a details the key components and the target performances when they are not based on already achieved values. Risk to each of these parameters may be mitigated in the following ways:

- **Siting:** neutrinos arising from muon decay may create a weak neutron shower near to the surface. Neutrinos may arise from decay of muons in the straight sections near the interaction point or the arcs. An implementation has been identified that mitigates the neutrino flux risk from the interaction point straights. Neutrinos emerge in two non-built-up sites in the Jura mountains and Mediterranean sea, which could provide an ideal location for neutrino physics experiments. In the arcs a system of movers will change the beam angle between -1 mrad and +1 mrad in order to make a negligible impact, consistent with the equivalent impact from operation of the LHC. IMCC must demonstrate that the movers can operate remaining within alignment constraints. As the project matures, appropriate permitting and consents must be established for the proposed remote sites.
- **Experimental Conditions:** Muon decay products can impinge on the detectors creating electro-magnetic showers that lead to Beam-Induced Background. Tungsten masks protect the detector

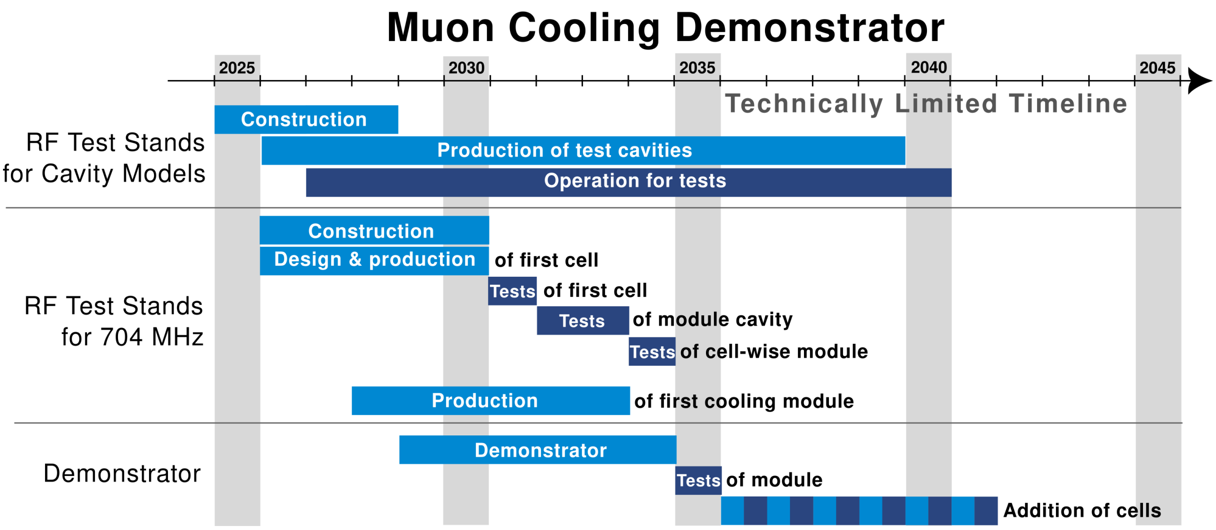

Fig. 5.a: Technically limited timeline for the Muon Cooling Demonstrator programme, including the prerequisite RF R&D.

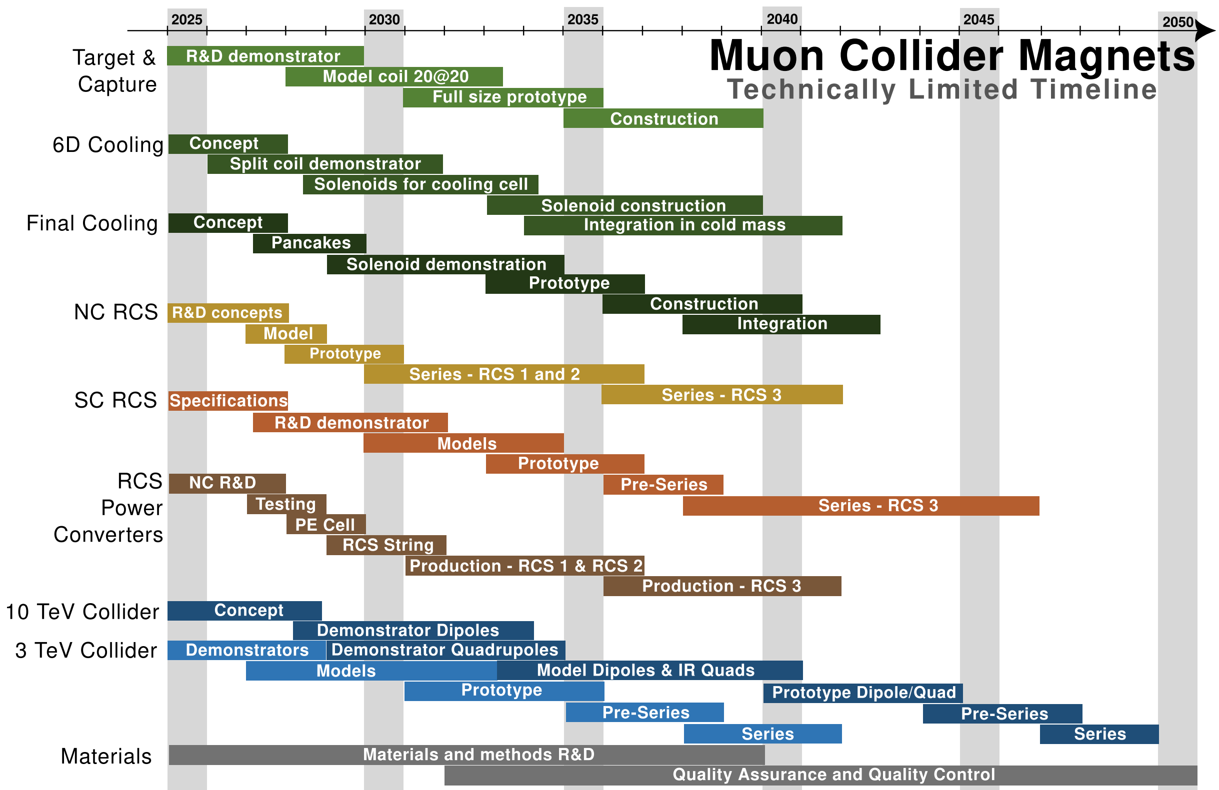

Fig. 5.b: Technically limited timeline for the Muon Magnet programme.

from the BIB and detector components with high time and space resolution further reduce this impact. Dedicated studies indicate that the radiation in the detector region is roughly similar to HL-LHC, even if not uniformly distributed.

– **Integrated Design:** IMCC has designed key components but a number of other components have not yet been designed. Sufficient accelerator physics resources are required to complete and optimise the lattice design, which can profit from several iterations in difficult cases, and to guide the technology development. The mitigation of collective effects and imperfections along the whole chain is essential to avoid a bottleneck for the bunch charge or emittance growth; an assessment of the component availability and the impact on integrated luminosity is essential. The start-to-end model presents an opportunity; optimisation may yield performance improvements and allows trade-offs between different systems and technologies to be made. It can also uncover risk, which must be managed by further design work.

– **Muon Cooling:** The muon cooling system requires close integration of absorbers, magnets and RF cavities. Large forces between neighbouring magnets must be managed while allowing sufficient space for services to RF cavities. RF cavities must operate at high gradients despite the intense solenoid fields. The IMCC has developed a full engineering design of a typical cooling cell that adequately manages the forces. Previous experiments have demonstrated RF gradients that are 25 % higher than the requirements for the cooling system, but the response to parameters (frequency, magnetic field, etc) has not been fully characterised. Experimental verification of the cell performance, ultimately with beam, is important and detailed in section 5.b.
– **Superconducting Magnets:** A new systematic analytical approach has allowed specification of target parameters for all the magnets and concepts exist. Experimental verification is needed to establish that the HTS solenoids and Nb_3Sn dipoles can achieve performance that pushes beyond already achieved values. The feasibility of HTS dipoles has to be established for the second project stage. IMCC seeks to leverage development in magnet technology to improve performance. IMCC plans to use high field solenoids throughout the muon production system. HTS, which is coming online commercially, will be fully exploited. Solenoids with fields up to 25 % higher than the current state of the art will need a strong R&D programme to realise. In other areas solenoids having significant forces, stored energies and stresses will need R&D to deliver. Further work is foreseen for dipoles, quadrupoles and combined function magnets in the high energy complex. Development of final focus magnets and collider ring dipoles will be particularly important to yield the ultimate luminosity.
– **Fast booster magnets and power converter:** Concepts for the fast booster magnets and the power converters exist that can reach the required performance. Further optimisation and experimental demonstration is required.
– **RF systems:** Concepts for the cavities along the complex are required. In particular an optimisation of the beamloading and the couplers is required to minimise the overall cost and power consumption while maintaining good beam quality. Power losses induced by muon decay products heating the superconducting RCS cavities should be minimised, as they could in the worst case require up to almost 30 MW of electric power to cool.
– **Schedule, Cost and Power:** The comprehensive R&D program will minimize risks to the project's schedule, cost and power consumption. The key R&D that is most critical for the schedule is given in section 5.b. The R&D programme covers the important cost and power drivers and will inform future cost estimates and power consumption assessments.

Sufficient resources in terms of personnel and material are key to mitigate the **risk for the schedule**. A coherent strategy to secure the resources is essential for timely implementation of the R&D programme and requires a centralised process. An important part of the resources could be provided through the CERN MTP and be complemented with resources from other institutions with commitments taken in a coherent agreement, for example through the LDG or a similar organisation.

6 Dependencies

6.a Whether a specific host site is foreseen, or whether options are available

IMCC is developing a site independent design, which could be realised at any location. It is also exploring two main specific implementations at this moment, one at CERN and one at FNAL. The proposed layouts are shown in Figure 6.a. At these sites the muon collider can potentially benefit from existing infrastructure, e.g. at CERN from the SPS and LHC tunnels. For CERN this would impact the energy choices, currently 3.2 TeV for the first and 7.6 TeV for the second stage. The site specific studies also allow addressing the neutrino flux.

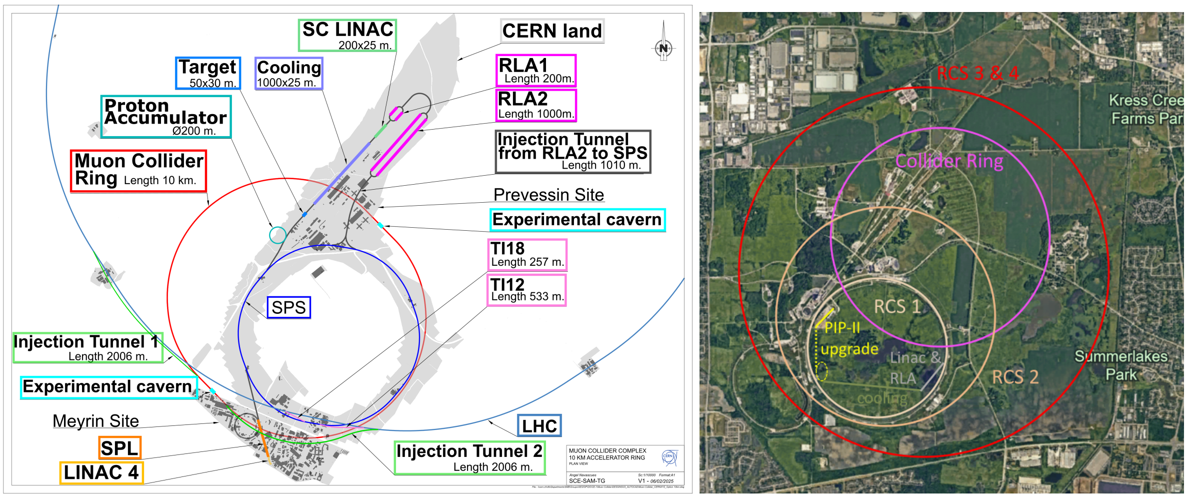

Fig. 6.a: Conceptual layout of the muon collider at CERN (left) and Fermilab (right).

6.b The dependencies on existing or required infrastructure

The muon collider can benefit from existing infrastructure but does not depend on it.

An initial exploration of a muon collider **implementation at CERN** has been carried out. It concludes that

- There is at least one implementation of the collider ring that enables an exquisite neutrino physics programme while also mitigating the neutrino flux from the experimental insertions.
- The proton complex could be implemented on the CERN site, for example on the Meyrin site, using a layout planned for the SPL.
- The muon production target could be installed on the Prevessin site.
- The muon cooling complex could be installed in a cut-and-cover tunnel in the Prevessin site; the klystrons and modulators could then be conveniently placed in a building above the beam tunnel.
- Similarly the initial linacs and recirculating linacs could be installed at Prevessin.
- The beam can then be injected into the SPS tunnel, which can house one (baseline) or two (alternative) RCS rings. The RCS would be a normal design where the magnets are only ramped up in field.
- From the SPS the beam can be injected into the LHC tunnel that would house one RCS to accelerate the beam to 1.6 TeV and a second stage that could accelerate to 3.8 TeV. The first stage would use pulsed normal conducting dipoles, while the second stage would be a hybrid RCS comprising fixed superconducting dipoles and pulsed normal conducting dipoles.
- The collider ring is conveniently located to facilitate injection from the LHC.

– All surface construction can be located on CERN land except for the experimental sites. These could also be moved onto CERN land if necessary.

This scenario would enable collision energy as high as 7.6 TeV with the baseline technologies. It could be envisaged to increase the energy by using higher field HTS fast-ramping magnets in the last RCS in the LHC. Alternatively, a second hybrid RCS could be installed in the SPS and the first RCS in the LHC could be hybrid. A detailed study will enable validation of these implementation concepts.

The initial 10 TeV **Muon Collider Fermilab site-filler** concept has been studied and a very preliminary design has been developed. The PIP-II linac will be used as the initial part of the proton source. Ongoing Fermilab proton intensity upgrade plans involve a new proton linac with energy of 0.8 GeV. To get to higher energies (8-16 GeV) needed for the muon collider proton driver, options for a linac or a linac and RCS are being studied. This is followed by a muon collection and bunching section that leads into the 6D muon cooling channels that can deliver exquisite low emittance beams. The collection and cooling channel will be 1-2 km long. Muon acceleration is achieved in multiple stages. The team is considering a 4-stage hybrid RCS scenario. The RCS is constrained to fit within the Fermilab site, restricting the circumference of the largest tunnel to 16.5 km. The first RCS is chosen to include only NC magnets (up to 1.8 T) and to fit a 6280 m circumference so that it could potentially use the existing Tevatron tunnel. Its peak energy would be 450 GeV. The second RCS takes the beam energy up to 1.725 TeV and requires a new tunnel with circumference of 10.5 km. RCS3 and RCS4 are housed in the longest tunnel, which will be 16.5 km long. The 5 TeV beams will be injected into a 10 TeV collider ring which is expected to have a circumference of 10.5 km.

6.c The technical effects of project execution on the operations of existing infrastructures at the host site

At CERN, the muon collider would follow after the completion of HL-LHC. It requires the LHC to be dismantled. However, it is likely possible to maintain the current SPS or to replace its functionality with the new RCS. If the current SPS is kept, operation of the ring will be interrupted during installation of the RCS. Both cases will lead to additional power consumption and an additional overall operations budget.

7 Commentary on current project status

7.a A concise description of the current design / R&D / simulation activities leading to the project, and the community pursuing these

The growing **collaboration** is based on a Memorandum of Cooperation (MoC). The number of signatories has increased to 58 and several more institutes are in the process of joining the collaboration. IMCC succeeded in receiving funding for an EU cofunded design study, MuCol, which started 1.3.2023. The US Particle Physics Project Prioritization Panel recommended in December 2023 to consider hosting a muon collider in the US and joining the IMCC. Discussions with US partners including the Department of Energy's bureau of high-energy physics are on-going. The US community already collaborates strongly in developing the R&D plan for the next decade and is in the process of setting up their national organisation. An inaugural US muon collider community meeting took place at Fermilab in August 2024 with close to 300 participants.

The overall IMCC goal is to carry out the R&D together and to develop options to host the collider at CERN or at FNAL and potentially also other sites. On the 2050 timescale, the muon collider is an important option as an alternative to low energy Higgs factories, that can also deliver energy frontier measurements. At this point progress in several areas is limited by resources and additional resources are being sought across the collaboration, in parallel with the above-mentioned processes to include new partners.

IMCC has improved the status of the muon collider design and the relevant technologies since the last ESPPU mostly by using analytic methods and simulations. Work has focused on the following key areas:

- **Physics Potential.** The unique physics potential of the collider has been further explored. Studies have been performed of the collider's exquisite precision in electroweak physics as well as the potential to explore physics beyond the standard model.
- **Environmental impact.** Beyond the unique physics potential, the compact footprint, limited cost and power consumption have been investigated including a first estimate of cost and wall plug power consumption. This will form the basis for optimisation. A scheme to mitigate the impact of neutrino flux mitigation has been developed.
- A **second detector design study**, MAIA, has started in addition to the existing MUSIC detector design at 10 TeV. Both experiments' design is constrained by beam induced background. Shielding reduces the radiation to levels similar to HL-LHC. Full simulation studies with background including beam-beam pair production indicate that the most relevant physics channel can be studied with near-future technology, in many cases thanks to developments for HL-LHC. Further improvement will be possible with more computing power, improved algorithms and better technology.
- **Machine-detector interface and detector.** Electrons and positrons from muon decays in the collider create showers in the region of the interaction points, referred to as beam induced background (BIB). Tungsten masks protect the detector from the BIB, and detector components with high time and space resolution further reduce this impact. Dedicated studies indicate that the radiation in the detector region is roughly similar to HL-LHC, even if not uniformly distributed.
- **Proton complex.** In the baseline, 2 MW of 5 GeV proton beam at 5 Hz is used for muon production. Proton facilities with larger power are under construction. Lattice designs exist for the two main challenging components, the accumulator and combiner ring that compresses the proton pulses to 2 bunches of 2 ns length. Optimisation is ongoing to minimise collective effects, which could also be addressed by slightly increasing the beam energy.
- **Muon production.** Key challenges for the high-power target have been addressed and showed that a graphite target will survive the shock waves of the incoming beam pulses and the temperature gradients resulting from the removal of the deposited heat. The solenoid surrounding the target is feasible and can be shielded. Work now concentrates on the removal of the proton beam and

mitigation of losses downstream of the target area.

- **Muon cooling technology.** The muon cooling system requires close integration of absorbers and RF cavities in a strong magnetic field. The operation of normal conducting RF cavities in a strong magnetic field can limit the gradient that can be achieved with no breakdown. The MAP study showed that gradients 25% in excess of the design target can be achieved by using cavities with beryllium endplates or by filling the cavities with hydrogen. A prime goal for the collaboration is to design and implement a new facility for further tests of RF cavities in high magnetic field. The collaboration has developed an engineering design of a cooling cell to explore the assembly of its components and their integration into one unit.
  The final cooling uses highest-field small aperture solenoids. The goal for the next generation HTS magnets is 40 T and we use this value in the current design effort for the final cooling. Studies of the physical limitations of the cooling design indicate that the emittance target can be reached.
  A tentative muon cooling system design now reaches the transverse emittance target of $22.5\,\mu\mathrm{m}$. This is a marked improvement compared to the performance of $55\,\mu\mathrm{m}$ estimated at the last ESPPU. The longitudinal emittance of $7.7\,\mathrm{meV\,s}$ is well below the target of $22.5\,\mathrm{meV\,s}$ and the MAP design of $26.7\,\mathrm{meV\,s}$; this excess performance will likely be used to modify the design parameters and ease the requirements for the collider ring energy acceptance.
- **Muon acceleration.** The muon beam acceleration takes place in a sequence of linacs, recirculating linacs and RCS. Due to resource constraint the focus has been on the RCS that accelerate from ($E_{init} > 60\,\mathrm{GeV}$) to full beam energy. In each RCS the magnet field is ramped up in proportion to the energy gain of the beam. Some synchrotrons are based on a hybrid design where the fast-ramping magnets are interleaved with static superconducting ones. Initial optics designs exist for the site independent RCSs and have been used to derive the component specifications. Conceptual designs for the fast-ramping magnets and associated power converters have been developed and reach the required ramp rates of up to 3.3 kT/s. The energy lost in the magnets is minimised to maintain a satisfactory wall-plug power requirement. An optimal, synchronised ramp shape has been developed for the RF and the magnet field.
  An alternative use of fixed field accelerators (FFAs) is also considered.
- **Collider ring.** A solution for 3 TeV collider ring lattice was developed previously and successfully addresses the challenges using Nb3Sn magnets. The collaboration has now developed a 10 TeV collider ring lattice design that reaches the small beta-function at the collision point using HTS magnets in the interaction region; the energy acceptance must be further optimised.
  Studies have determined the required thickness of the shielding to protect the magnets from the high-energy electrons and positrons from muon decay. Two conceptual magnet designs with the corresponding aperture and field are being developed.
- **Collective effects.** A very high muon bunch charge is required to achieve the luminosity goal and can potentially lead to significant collective effects. Initial studies have been performed for the RCSs and collider ring. They showed that impedance and beam-beam effects can be mitigated with careful beamscreen design and feedback. For the muon cooling section, the implementation of muon cooling physics into a CERN tracking code is ongoing and will allow the combination of single particle effects in matter with collective effects. Further efforts to implement all collective effects and develop a start-to-end model of the machine are planned. The impact of imperfections and their mitigation on the beam need to be studied.
- A **start-to-end study** of the beams along the whole complex remains to be done to make robust predictions of, and optimise for, performance, low risk, cost and power consumption. A first preliminary estimate of the total **transmission of muons** predicts 1.5×10^{12} at the collision point, which is 20% below the target. Further studies will address this aiming to improve the sub-system transmission and to increase the initial number of muons with a higher power target.
- **Superconducting magnet technology**, in particular HTS, is a key enabler of the muon collider

and has an important impact on the timeline. Growing use of HTS in society can potentially have an important impact on the cost. For all superconducting magnets studies have been performed taking stored energy, current limits and stress in the coils into account to determine the field levels that can realistically be obtained as a function of the superconductor used, the magnet aperture and cost. These limits have been integrated into the lattice designs. Several conceptual designs of magnets exist. An experimental programme has successfully been started several years ago and its continuation is now essential.

As mentioned above **the demonstrator design at CERN** is progressing and detailed studies of an implementation on CERN site - e.g. in the TT7 tunnel, or CTF3 building - are ongoing.

7.b A statement of any major in-kind deliverables already negotiated

The muon collider is still in the R&D phase and IMCC is developing the muon collider concept and technologies to a maturity level that enables a decision to be made on the implementation of a collider. The focus is thus on the funding of the R&D programme.

The partner institutions support the R&D programme with resources and in addition the European Union is co-funding a design study, MuCol, that has been instrumental in the timely start of the programme. Support has also been provided by the Snowmass process in the US and additional contributions from US partners have started. In particular FNAL plans a site study for the demonstrator and SLAC is building an RF test stand for 1.3 and 3 GHz frequencies. The integrated resources are shown in figure 7.a.

An initial ramp-up of the resources in Europe is instrumental to implement the technology R&D phase and maintain the muon collider as an option by around 2050. Following the ESPPU conclusions and considering global developments, the sharing of the efforts between the regions can be defined for the demonstration phase.

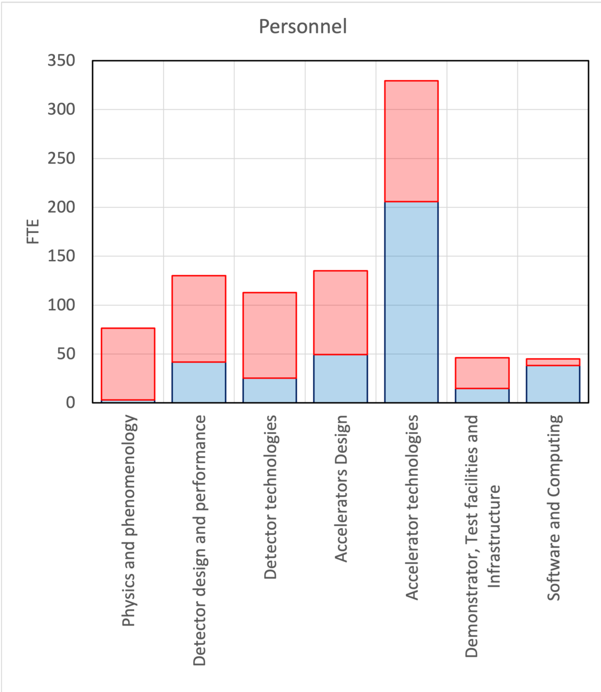

Fig. 7.a: IMCC-specific resources in FTE-years, integrated from 2023–2027 (secured in blue, potential in red).

7.c Any other key technical information points in addition to those captured above, including references to additional public documents addressing the points above.

Further, detailed information can be found in the supplementary report submitted to the European Strategy for Particle Physics [2] (also available at: `https://edms.cern.ch/document/3284682/1`).

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