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A MUON BEAM FACILITY AT CERN TO DEMONSTRATE MUON IONISATION COOLING *

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Abstract

The International Muon Collider Collaboration (IMCC) has been formed following the 2020 European Strategy for Particle Physics Update, with the goal of studying the feasibility of a muon collider at a centre of mass energy of around 10 TeV. One of the most challenging sections of a muon collider is the initial cooling before acceleration, due to the necessity to apply intense magnetic and electric fields to reduce the 6D emittance of the muon beam by 5 orders of magnitude in a very short time, to cope with the limited lifetime of muons (2.2 µs at rest). The IMCC proposes to build a Demonstrator to prove that all the involved technologies (RF, magnets, absorbers, beam instrumentation) can be built at the required specifications, and integrated in order to limit the length of the cooling sections to an acceptable value. Several options are being considered in different laboratories within the collaboration. This paper describes possible implementations at CERN.

INTRODUCTION

Since the last European Strategy for Particle Physics upgrade (ESPPU) in 2020 [1] and the publication of the report of the conclusions of the Particle Physics Project Prioritisation Panel (P5) [2] in 2023, interest is growing in the study of a Muon Collider at around 10 TeV in the center of mass. The showstoppers that were blocking its endorsement in the past have in fact been overcome by the technology developments in several areas, initially promoted by the Muon Accelerator Program (MAP-US) in the United States, and later by the IMCC Collaboration established at CERN. In particular high magnetic fields generated by High Temperature Superconductors (HTS), High Efficiency Klystrons (HEK), surface studies to suppress breakdown in magnetic fields and new mitigation strategies for neutrino radiation on the Earth's surface, have convinced a large community of physicists and engineers that the main showstoppers for such a collider are no longer insurmountable. One of the most challenging sections of a Muon Collider chain is the initial muon ionisation cooling section, due to the requirements on high RF fields immersed in high magnetic fields (which increase the RF breakdown rate), in a very limited space. Ionisation cooling is based on a well-known and easily described physics process (ionisation in H_2-rich materials), however uncertainties are raised by the coexistence of multiphysics processes that are necessary to reduce the 6D emittance as required to achieve the target luminosity. Those processes require the perfect integration into a tight space of an absorber (providing the ionisation effect) with RF cavities, solenoids and dipoles that are necessary to select the muon energy, reducing the energy spread and the 6D emittance while preserving the muon bunch intensity. The MICE experiment confirmed the ionisation cooling principle [3], however in a configuration with only magnetic fields.

A complete R&D programme proposal has been submitted as an input to the new update of the ESPPU that will be submitted to CERN council in 2026, that aims at demonstrating first of all that the various components (RF, magnets and absorbers) can be built and integrated at the required specifications, and then test them with a muon beam to prove that the technology is compatible with the requirements of operation in a real beam environment. Such programme foresees construction and test of one cooling cell (the assembly of solenoids, a cavity and an absorber), then of a 5 to 10 cells assembly, and finally the construction of a facility with up to 30 cooling cells. Several locations have been investigated to implement a facility to host this programme at CERN, and similar proposals are being elaborated in the US, in particular at Fermilab. This paper gives some details of two possible locations at CERN, the one hosted in the TT7 tunnel, and the one hosted in the CLIC Test Facility (CTF3) (formerly the building of the Linear Injector of LEP).

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IMPLEMENTATION IN TT7

A muon ionisation cooling facility starts from the impact of a proton beam, ideally in the energy range from a few GeV (say 5) to about 20 GeV in order to profit from the high cross-section of muon production from the impact of protons onto a graphite target (ideal material for the intensity that can be generated with present CERN beams). At CERN the PS complex is the best placed to provide a beam with such an energy range, and in the next 10 to 15 years there is also for the time being a sufficiently high production to provide enough protons to a new facility. Competition would be much harder at the SPS complex, that would anyway provide beams at a much higher energy (~400 GeV).

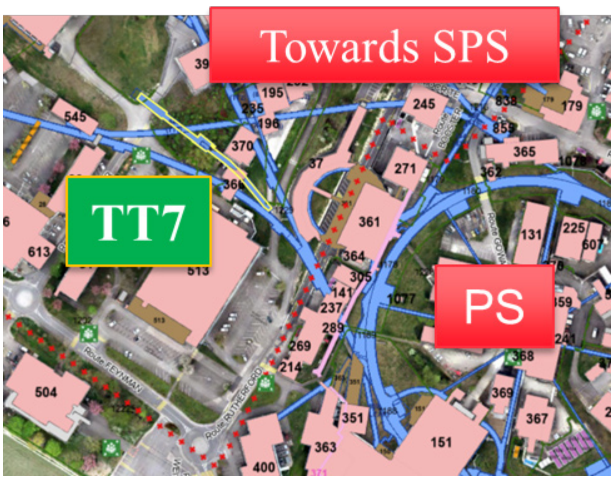

Figure 1: The TT7 tunnel (in yellow) on the CERN Meyrin site.

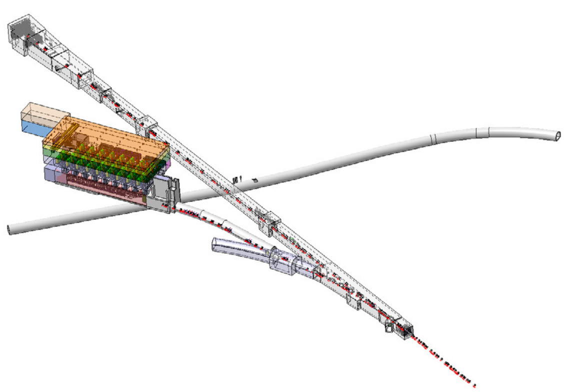

Figure 2: A sketch of the beam lines from the PS, with the facility and the klystron building on the left.

We investigated possible extraction points from the PS, and identified TT7 (Fig. 1) as a possible site since it would allow to extract a beam with the already existing fast extraction that sends PS beams towards the SPS, and to install simply a dipole on the PS-SPS transfer line to deflect the beam towards TT7 [4]. The beam characteristics are described in another paper in this conference [5], the main being the number of protons per bunch (~10^{13}), the bunch length (currently about 10 microsec long pulses are extracted from the PS towards the n_TOF facility at 20 GeV), and the repetition rate of 4 to 5 pulses per minute, which should not impact the present beams extracted from the PS Injection to LHC and fixed target experiments, both in the PS and the SPS complex.

A full study was performed to assess the feasibility of installing the facility in TT7. Although there were no critical issues, it was found that it is necessary to enlarge the existing tunnel to host a chicane after the target for selection and collimation of the beam. A civil engineering pre-study was performed, confirming the feasibility of such a solution. In addition, a new building to host klystrons and power converters plus all the control electronics would have to be built on top of the tunnel. A possible configuration is shown in Fig. 2. Though feasible, this solution will require more civil engineering works than hoped initially and would also oblige to deviate the present access to the Anti-proton Decelerator Facility (AD) with an impact to be evaluated.

IMPLEMENTATION IN CTF3

For the reasons mentioned in the previous paragraph, we started in March 2025 a new pre-study to implement the facility in the CTF3 building. This option had not been analysed in the first place since it implied that a new extraction system should be installed in the PS. In the sector foreseen for this purpose there is presently one of the RF cavities used to prepare the LHC beams in the PS, that will have to be moved to another sector.

The CTF3 site has on the other hand several advantages that makes it sufficiently attractive to study this option further:

- There is already a path to transfer the proton beam to CTF3, only the vacuum pipe and beam line elements have to be installed.
- There is enough space in what was the delay loop building of CTF3 to build the target area with sufficient shielding to manage the intensity of the PS.
- Following the target, there is more space to allow a decay line to allow the pions to decay and capture a higher fraction of muons than with the TT7 option, where only about 50 m are available overall for the entire facility from the target to the dump. As explained in [5] we expect therefore a factor of up to ~10 more muons than in TT7.
- There is more longitudinal space to install cooling cells, and eventually even space to use the 200 MeV beam for possible experiments or test beams. Some groups of experimental physicists are investigating the possibility for experiments or test beam usage in this area.
- The existing klystron gallery can host the klystron needed for 30 cooling cells. An optimisation of the RF powering scheme will be necessary. Knowing that each RF cavity requires about 15 MW of RF power and that HEK can provide 24 MW, we will feed 3 cavities with 2 klystrons, or 4 cavities with 3 if the margin is too low. A complete integration study will clarify whether an extension or further optimisation is needed to also include power and control electronics.

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It is worth highlighting that although the CTF3 facility is on surface, we do expect fulfilling the Radiation Protection requirements with an adequate shielding design for the target, muon capture and dump area. Some preliminary sketches are shown in fig. 3, 4 and 5.

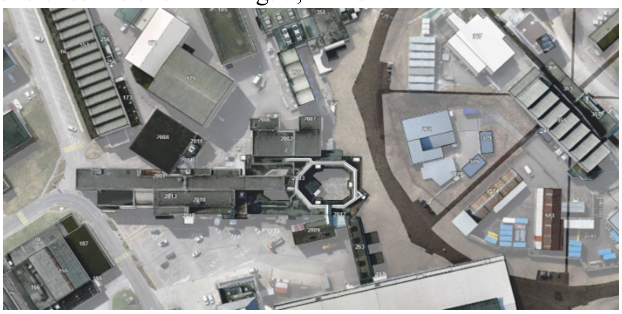

Figure 3: The CTF3 building close to the CERN PS.

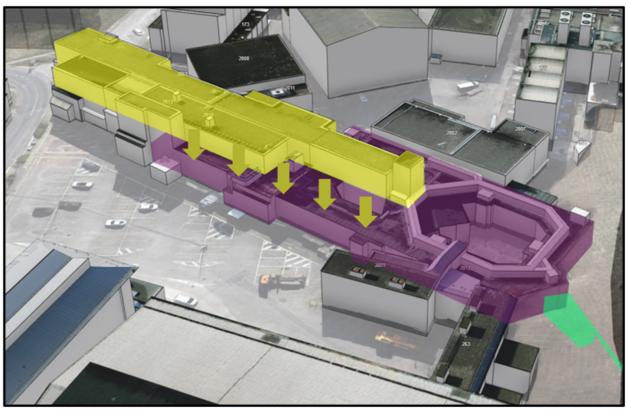

Figure 4: Isometric view of the CTF3 facility. In violet the proton and muon beam facilities, in yellow the klystron gallery, and in green the transfer gallery from the CERN PS.

TIMELINE

The demonstrator facility in both sites described above, requires interventions on the beam lines for TT7, and directly in the PS for the CTF3 option. Also, for both sites some civil engineering works will be necessary in the vicinity or inside the existing beam facility. For this reason, it is prudent to plan the start of the beams only after a long shutdown. With the present schedule of the HL-LHC, the first occasion realistically available is after the shutdown called LS4, that is presently planned for 2034. During LS3, due to start in 2026, all the resources of CERN groups are already committed to the already planned projects, and it would therefore be very challenging to obtain support for the construction of such facility. This fits well with the planning of development of the enabling technology, from HTS magnets to RF cavities equipped with mitigation measures (surface treatments or gas fillers) to improve the breakdown rate of RF in magnetic fields. This last issue will be studied in dedicated RF test stands. Moreover, given the selected RF frequency of 704 MHz (double of the frequency in the CERN LINAC4, that will generate the proton beam), we will need to develop a new high efficiency klystron, with the delivery of the first one presently foreseen between 2030 and 2031. Therefore, the first cooling cell would be fully tested by 2031, the 5-cell module by 2034, and the beam line would start operation with one module in 2035. The full R&D programme can be consulted in [6]

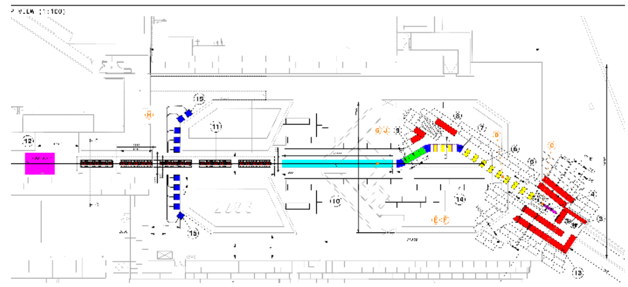

Figure 5: A sketch of the projected beam line. In red the target area, in yellow the muon capture, in cyan the section dedicated to beam matching and upstream beam instrumentation.

CONCLUSION

The IMCC is investigating possible sites at CERN to build a muon ionisation cooling facility. This is part of a larger R&D programme including the construction and test of a cooling cell as first item; of a train of 5 to 10 cells as second step, and finally the beam facility with up to 30 cells. The goal is to prove that the hardware works meeting the project requirements, and that it can be used in a real accelerator environment with beam. All options are today at the stage of pre-studies, where the main possible showstoppers have been analysed and mitigation measures proposed. CTF3 looks today as the most promising possible location.

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