Project: Muon Collider Feasibility Studies

Muon Collider Feasibility Studies: Collective effects and muon cooling

Team:

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Introduction

Based on the beam dynamics challenges identified in 2021 within the new International Muon Collider Collaboration (IMCC):

https://indico.cern.ch/event/1041985/contributions/4377185/attachments/2253375/3825390/SummaryOfChallenges_BD-WG_27-05-21_EM-TR.pdf.

The muon collider project started in February 2022 with the hiring of a post-doc at CERN, Dr D. Amorim. In parallel at EPFL-LPAP we have started a selection for the hiring of a PHD student that will hopefully join the team early summer 2023.

In general, this project focuses on the transverse collective effects after the critical phase of the necessary muon ionization cooling, starting first from the highest energy (the collider ring) and going down in energy through the several other machines (Rapid Cycling Synchrotrons (RCS), Recirculating Linacs (RLAs) and Linac) to check that the very quick acceleration phase is indeed feasible when high-intensity effects are considered.

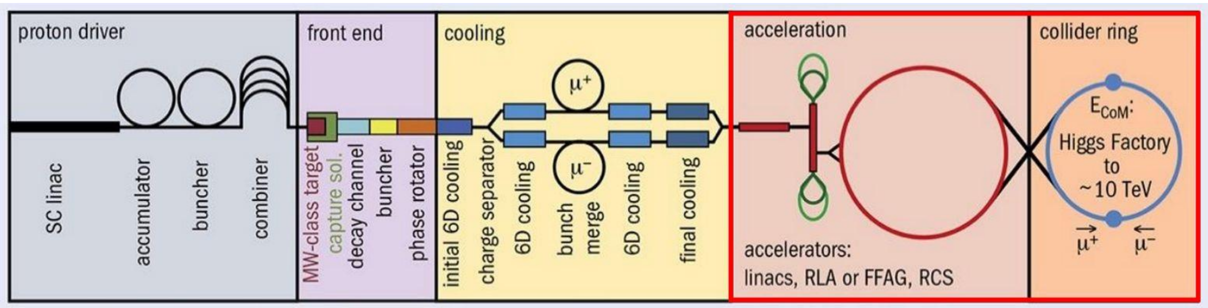

Figure 1: Proposed layout for a muon collider accelerator complex. The stages investigated are highlighted in red.

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A staged implementation of the muon collider is foreseen, with first collider at 3 TeV center-of-mass energy that would require three Rapid Cycling Synchrotrons for the final acceleration stage.

The second step would be a 10 TeV center-of-mass collider that would require four RCS for the final acceleration. The first three RCS of the 3 TeV collider would be reused for the 10 TeV collider.

In more details, in the last reporting period the following points have been addressed:

Computation of the resistive-wall impedance and wakefield for the 3TeV and the 10 TeV muon collider ring, and for the first Rapid Cycling Synchrotron (RCS 1).

Impedance and wakefields are computed using analytical formulas and simulation codes such as ImpedanceWake2D. All evaluations have been stored in an impedance repository and available for the collaboration on GitLab (https://gitlab.cern.ch/damorim/muc-impedance/) allowing the replication and extension of the results. A preliminary webpage with all the collected information can be found here: https://muc-impedance.docs.cern.ch/. In this webpage all components impedance and wakefields calculations will be stored during the project. As a basis we will use the same standards as what has been done in the past for the impedances and wakefields (and optics) of all the CERN machines.

Study of the impact of RF cavities wakefield for the RCS 1.

The RCS 1 is the first Rapid Cycling Synchrotron in the high-energy acceleration, that would accelerate muons from an energy of 63 GeV to 300 GeV. To provide the large acceleration gradient, O(700) RF cavities will be needed in the accelerator. These cavities will create High Order Modes (HOMs) that can drive the beam unstable.

A general stability criterion was derived from simulation studies and applied to a proposed ILC type superconducting RF cavity. The R_S/Q of the most critical HOM created by this type of cavity was found to be 8 times below the stability threshold using this general criterion, as shown in Figure 2. This threshold was also confirmed with specific simulation using this HOM.

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The effect of chromaticity in the RCS 1 was also studied to investigate if the machine could be operated with negative chromaticity. A small emittance growth over the short acceleration time is predicted from simulations.

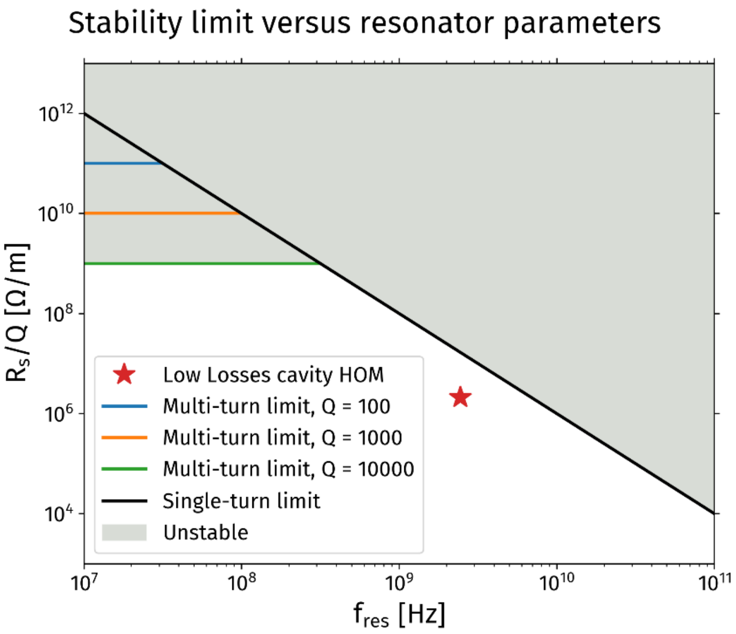

Figure 2: General stability criteria for a resonator wakefield with resonance frequency f_{res}, shunt impedance R_s and quality factor Q. The star denotes the most critical HOM generated by 670 ILC type cavities.

Parametric studies for the 3 TeV and 10 TeV c.o.m colliders resistive wall impedance.

To protect the collider superconducting magnet coils from the radiation and heat induced by muon decay products, a 2 cm thick inner tungsten shield should be installed inside the cold bore. Depending on the magnet, vacuum, optics and beam stability constraints, the muon beam could be directly exposed to this tungsten shield or to a low electrical resistivity layer.

Parametric beam stability simulations were performed with:

- different materials for the beam chamber: copper or tungsten.
- different temperatures for the beam chamber: 80 K or 300 K.

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- a range of transverse feedback settings, from fast 2-turn feedback to a machine without feedback.

The minimum radius required to ensure transverse beam stability was found for all these cases. Figure 3 shows these results for the 10 TeV c.o.m collider. With a 100-turn transverse feedback gain, a 25 mm chamber radius is required with tungsten at 300 K, whereas this radius can be reduced to 17 mm if a copper coating or lining is applied. These values are used as inputs for the technical options discussed for the magnet design.

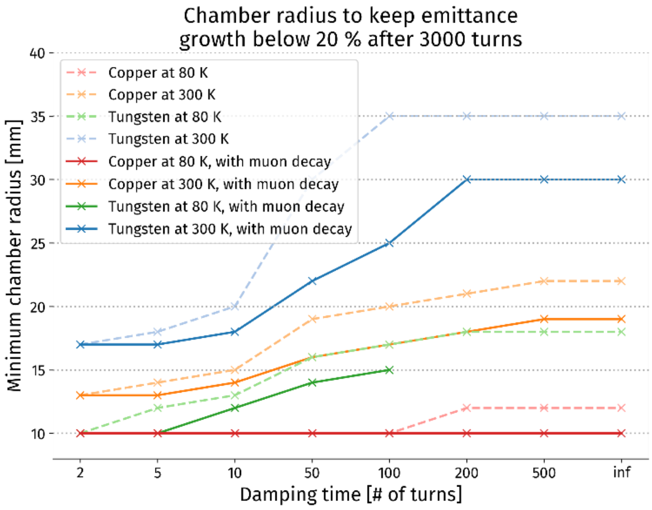

Figure 3: Minimum chamber radius versus damper setting required to preserve transverse beam stability in the 10 TeV c.o.m collider. The different materials investigated are represented with different colors. The dashed line shows simulation results not accounting for the muon decay effect, whereas solid lines account for it.

Extension and development of specific simulation software.

The simulation tools used for the impedance and beam stability simulations (ImpedanceWake2D, PyWIT, PyHEADTAIL) are already in use at CERN. However, phenomena specific to the muon beam must be included such as:

- the muon decay which leads to a beam intensity reduction over time, therefore mitigating transverse instabilities.
- the distribution of RF cavities along the ring in the RCS. Because of the large RF voltage, the synchrotron tunes in these machines are typically in the order of $Q_s \approx 1$, much

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larger than other synchrotrons. To preserve longitudinal stability the RF cavities must be distributed along the ring.

General contributions to code development such as with the impedance toolbox PyWIT (https://gitlab.cern.ch/IRIS/pywit/) were also made.

Publications and presentation of results:

- Collaboration Meeting of the Muon Collider Study, which took place at CERN from 11 to 14 October 2022 (see https://indico.cern.ch/event/1175126/contributions/5025351/attachments/2526430/4349940/2022-10-13_amorim_RCS_impedance_stability_v4.pdf
- Presentation at the Muon Collider Collaboration Annual Meeting on 12/10/2022 (see https://indico.cern.ch/event/1175126/contributions/5025354/attachments/2526431/4349946/2022-10-13_amorim_COLL3TeV_impedance_stability_v3.pdf
- Presentation at General Accelerator Design meeting on 21/11/22 (see https://indico.cern.ch/event/1219418/).
- Impedance models of the muon collider ring and the RCSs developed by David Amorin available at (https://muc-impedance.docs.cern.ch/).
- Several contributions at the HEMAC (High-Energy Muon Acceleration Chain) meetings (https://indico.cern.ch/category/14979/)
- Within the CERN BE/ABP group, status report of his activities during the CEI section meeting held on 10/11/22 (see https://indico.cern.ch/event/1212341/)
- Presentation at the CERN BE/ABP group information meeting on 12/01/2023 (https://indico.cern.ch/event/1235913/)
- Two proceedings proposed to IPAC 23:
    - Transverse impedance and beam stability studies for the Muon collider Rapid Cycling Synchrotrons
    - Transverse impedance and beam stability studies for the Muon collider Rings