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INITIAL DESIGN OF A PROTON COMPLEX FOR THE MUON COLLIDER*

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Abstract

The proton complex is the first piece in the Muon Collider, it comprises a high power acceleration section, a compressor and a target delivery system. For the International Muon Collider Collaboration (IMCC) we are investigating the possibility of having a full energy 5-GeV linac followed by an accumulator and a compressor ring and finally a target delivery system. In this paper, we present the initial studies for the complex and derived initial beam parameters at each interface.

INTRODUCTION

The proton complex is the first piece in the Muon Collider complex. It comprises of a high power acceleration section, an accumulator and compressor, and a target delivery section. The high power acceleration section can take many shapes as shown in Fig. 1. The first section is responsible for delivering high power, high intensity bunches to the accumulator and compressor section. At the end of the high power acceleration section, the pulse total charge is distributed among a high number of bunches with a small energy spread. Such a long train of bunches does not reach the desired instantaneous power for intense pion production on the target.

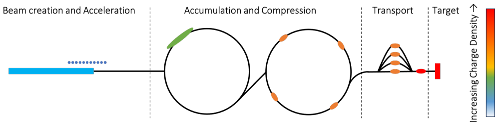

Figure 1: Schematic layouts for the proton complex section. The bunch density as the proton travels through the complex, increasing steeply all the way to the target. Thus reaching high densities is one the main challenges in the design of this part of the Muon Collider.

In order to achieve the high proton intensities in a short pulse, an Accumulator and Compressor ring will be used to combine and compress the protons into very short bunch, with a length of the order of ~ 2 ns rms. The first storage ring, the Accumulator, accumulates the protons via charge stripping of the incoming H^- beam from the linac section, preserving the energy spread. The incoming beam is chopped to allow a clean injection into the ring circumference. The second storage ring, the Compressor, accepts between 1 and 6 intense bunches from the Accumulator and performs a 90°-bunch rotation in longitudinal phase space, shortening the bunches to the limit of the space-charge tune shift just before extraction. The Compressor ring must have a large momentum acceptance to allow the storage of the beam with a momentum spread of a few percent, which arises as a consequence of the bunch rotation.

The target delivery section transports the final intense short bunches from the compressor to the target, ensuring that neither the transverse nor longitudinal properties of the beam are compromised in the process. To achieve optimal luminosity, the final collider will work in single bunch colliding mode. Therefore, in the multi-bunch solution, short bunches extracted from the Compressor must be recombined and hit the pion production target simultaneously.

The primary requirement of the Proton Complex is to enable the production of a high number of useful muons at the end of the decay channel after the target. The production rate, to good approximation, is proportional to the primary proton beam power, and (within the 5–15 GeV range) only weakly dependent on the proton beam energy.

BASELINE DESIGN

In our baseline design, the idea is to keep the Proton Complex as simple as possible. The initial design will have a full energy linac for beam creation and acceleration and will move forward to find the parameters that will allow accumulation and compression in a single bunch. This baseline setup is illustrated in Fig. 1, without the recombination in the transfer line to target, and the main parameters are described in Table 1. This is the baseline and simplest case, not in the sense of beam physics simplicity but in number of sections and transfer lines. The results from the parametric studies to verify the feasibility of this setup will be presented and discussed in the following sections. From the baseline parameters derived for this scenario, further studies will dictate the need to further expand the proton driver into more complex setups.

Table 1: Beam Parameters to be Delivered to Target

Beam Power	2 MW
Repetition Rate	5 Hz
Beam Energy	5 and 10 GeV
accumulated bunch length	120 ns
compressed bunch length	2 ns

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HIGH POWER ACCELERATION

The particle creation and acceleration in a full energy linac with a final energy of 5 GeV and 10 GeV was studied. Table 2 shows the necessary single pulse intensities for the Muon Collider for the 5 GeV case assuming a 2 MW case and equivalently for the 10 GeV and 4 MW final power. Values required for pulse length and current of the H^- source, as can be seen, are not far from already achieved quantities in other facilities under operation and should not present large technical difficulties for the Muon Collider needs.

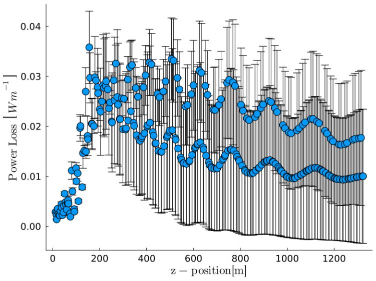
Table 2: Single Pulse Intensities Requirements for a Muon Collider (MC) H^- Source and Other Facilities in Operation.

	Pulse length [ms]	**Current [mA]**
MC	2	40
LINAC4 [1]	0.4	35
J-PARC [2]	0.5	60
SNS [3]	1	38

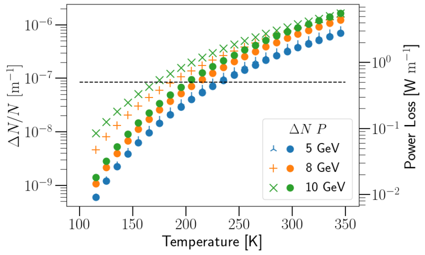
One of the main limitations for H^- linacs lies in the fact that the loosely bound electron can be stripped quite easily due to intra-beam scattering, interaction with magnetic fields present in the machine or with photons present in the vacuum chamber environment, also known as Blackbody radiation stripping [4]. An estimate of each of those effects for both possible final energies was done and is presented in Fig. 2. Lorentz stripping represents a very small effect on the total loss budget as long as the beam sizes throughout the linac are kept below 3 mm rms for both final energies. The limiting factor for higher energies is coming from Blackbody radiation stripping. This effect is particularly important in the warm sections of the linac, between cryomodules, and the transfer line to the rings. One solution would be to cool the vacuum chamber at around 200 K in those areas, which would bring stripping losses below a 0.5 W/m threshold.

ACCUMULATION AND COMPRESSION

A baseline lattice for the accumulator and compressor for the 5 GeV case, based on the studies for the Neutrino factory at CERN [5], was revised and ported to XSuite [6] and scaled up to 10 GeV for the accumulator ring. The accumulation for a 2 ms pulse length will occur during a 3250-turn period and the tune shift for such a case for both energies was simulated. The calculation was done for the full current case, which will be short-lived in the accumulator, and this can be interpreted as a worse case scenario. The tune shifts are 0.2 for 5 GeV and less then 0.1 for 10 GeV, both for an initial transverse geometrical emittance of 3π mm mrad.



(a) IBS



(b) blackbody

Figure 2: H^- stripping loss power components for a full energy linac. Top: Intra-beam scattering stripping for linac with a final energy of 10 GeV. Bottom: Black body radiation stripping loss and power loss. The dashed horizontal line represents the 0.5 W/m threshold.

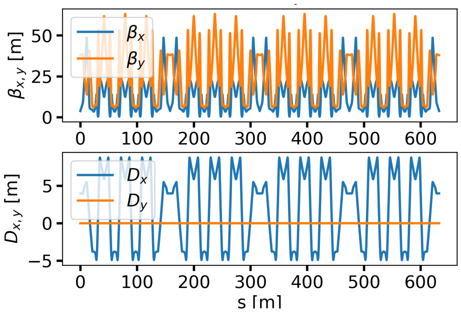


Figure 3: Twiss functions for the compressor lattice for the 10 GeV case. The designed tunes are 19.77 and 6.39 in horizontal and vertical planes respectively.

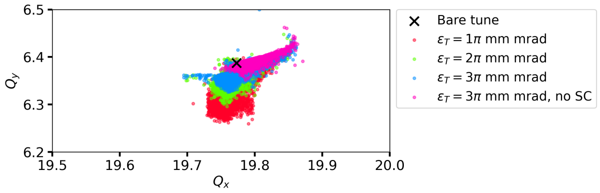
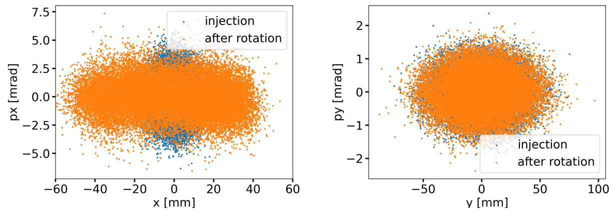


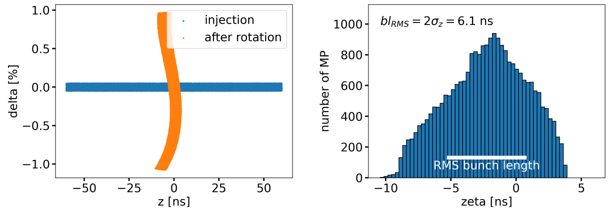
Figure 4: Tune spread for various emittances for the 10 GeV compressor lattice before rotation. Although space charge related tune shift is acceptable there are some strong chromatic effects that need to be addressed.

Using the same basic idea of the 5 GeV compressor lattice, with negative bends to control dispersion, a 10 GeV lattice was designed. In both lattices the phase slip factor is high, 0.16 in the 5 GeV lattice and 0.11 in the 10 GeV lattice, allowing a full bunch rotation to happen in less than 45 turns. The Twiss functions for the 10 GeV lattice is shown in Fig 3. In order to be able to store the beam for the rotation gymnastics a parametric scan of the emittance looking at the injection bunch density was performed and is shown in Fig 4 for the high energy case. In these simulations the space charge induced tune spread was calculated using coasting beam simulations of equivalent line densities without the influence of RF cavitites. Geometric emittances of the order of 3π mm mrad are needed for the 5 GeV to constrain the tune shifts below 0.5 while for the 10 GeV case 1π mm mrad yield acceptable tune shifts of less than 0.25 (see Fig. 4).

A full rotation simulation for the 10 GeV case was performed (Fig. 5) showing that a final pulse length of 6.1 ns (3 ns rms) is achievable in 40 turns, assuming a RF total voltage of 4 MW working in the 6^{th} harmonic. The final bunch length can be improved by changing the initial beam energy spread and carefully picking the turn to extract the beam. Notice that some nonlinear effects, due to the RF harmonic used and lattice slip factor higher order terms, can also be seen in the final longitudinal distribution and should be fine-tuned. If the ”S” distortion is removed the beam full bunch length would be 3.6 ns (1.8 ns rms).



(a) horizontal (b) vertical



(c) longitudinal (d) long. histogram

Figure 5: Beam distributions before and after rotation in the compressor for the 10 GeV case with equal transverse geometric emittances of 3π mm mrad.

TARGET DELIVERY SYSTEM

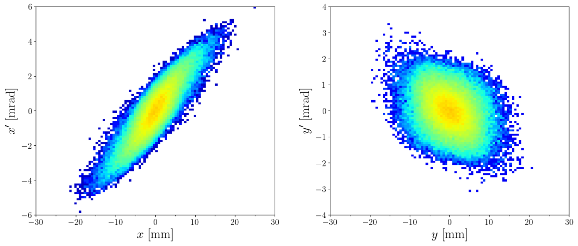
The full extraction design from the compressor ring is still to be designed, but the transport of a short pulse with high intensity over a FODO channel and a final focusing system was investigated. The longitudinal phase space does not suffer major changes even for a more than 100 m transport, however we do see some emittance growth on the transverse planes. The final focusing on the target surface is done with a triplet with moderate focusing forces where the maximum quadrupole gradient is bellow 20 T/m. The last element in the chain sits at 4 m from the Target surface, allowing enough room for the installation of a window and instrumentation.

The final beam on the target surface for a 10 GeV and 2 MW case is shown in Fig 6. The pulse length of 2 ns rms is conserved and the transverse rms size of 4.7 mm can be achieved. The final beam divergence is of the order of 1 mrad rms.

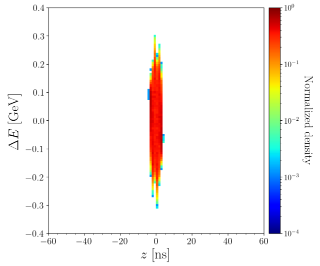
CONCLUSION

Results from simulations so far indicate that the baseline energy for the Proton complex should be 10 GeV or higher in order for the accumulator and compressor rings to be able to cope with the level of space charge effects present for the intensities needed for the Muon Collider. This will be especially true for the 4 MW case. For the single bunch, 10 GeV and 2 MW case, a beam emittance of the order of 3π mm mrad yields tunes shifts at injection that are acceptable for both accumulator and compressor rings. The transport of such a short and high-intensity bunch doesn’t represent a bottleneck however a more detailed design of the ring extraction regions should be done and studied in detail.

Although the lattice presented in this work has a proven potential to work with the intensities needed for the Muon Collider at 4 MW a study of alternative and more flexible lattices will be carried out in parallel. An investigation of lattices with flexible momentum compaction, similar to those from the J-PARC Main Ring was initiated. The lattice with negative bends requires very strong RF in order to perform the compression in just a few turns and we need to verify its feasibility. A initial investigation on instabilities thresholds and limitation on both rings should be carried out.



(a) horizontal (b) vertical



(c) longitudinal

Figure 6: Beam distributions after transport through 180 m and final focus on the target surface. Geometric transverse emittances are 3π mm mrad and bunch length is 4 ns (2 ns rms).

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