Synchronizing the Proton Beam RF with the Muon Cooling RF

Charles M. Ankenbrandt
Rolland Johnson

Abstract

A proposed site for the MUCOOL experiment uses the Fermilab 8 GeV Booster proton beam to generate muons which are used to probe the cooling parameters of the ionization cooling channel. The cooling channel consists of liquid hydrogen absorbers interspersed with 200 MHz or 805 MHz RF accelerating cavities. In the experiment's original conception, these frequencies of the cooling RF are not harmonics of the 52 MHz Booster beam and the produced muons randomly hit the 5% acceptance of the cooling RF, leading to a 5% capture efficiency. We propose that the Booster harmonic number be lowered to reduce the Booster RF frequency such that the cooling RF becomes its harmonic. Then, by phase locking the two RF systems and also making the bunches short in time, one can improve the fraction of muons which fall within the acceptance of the cooling channel. To the extent that short proton bunches can be made and short muon bunch structure preserved, RF synchronization can improve the fraction of muons in the RF acceptance window of the cooling channel. This can improve the rate of good events at least by a factor of 16 for the 200 MHz channel or a factor of 4 for the 805 MHz channel. Methods for producing short proton bunches and preserving short muon bunches are discussed. The needed equipment to allow cycle-to-cycle changes in the Booster harmonic number is discussed.

Introduction

In cascaded accelerator systems, where the beam from one synchrotron is transferred to a second synchrotron for storage or more acceleration, the RF frequency of the two machines is locked in frequency and phase. This allows bunches from the first accelerator to be put into the centers of the waiting RF buckets of the second accelerator. To be able to do this usually takes careful planning so that the RF frequencies of the two machines at the time of transfer are matched appropriately. Not only should the RF frequency of the receiving machine be equal to or an harmonic of the RF frequency of the first machine, but the frequencies must be those that define stable RF buckets in each machine. That is, the harmonic number must be an integer in each machine.

The harmonic number, h, is the number of RF buckets in a machine. If all the buckets are filled, it is also the number of beam bunches. For a given beam speed, v, it depends on the length of the closed orbit, L, since the revolution frequency is v/L. Then h times the revolution frequency is the RF frequency, f. Thus the harmonic number is simply related to the RF frequency,

$$h = f\,L\,/\,v\,.$$

The MUCOOL Experiment

In the case of the MUCOOL experiment, we also have a cascaded accelerator system. The first accelerator is the 8 GeV Fermilab Booster and the second is the ionization cooling channel which is accelerating the muons to compensate for the deceleration caused by the LH2 absorber.

Two options for the RF frequency for the MUCOOL cooling channel are 200 MHz or 804 MHz. The 200 MHz option is appropriate for earlier stages of cooling in a muon collider or for a neutrino factory. The 805 MHz option is to simulate the later stages of cooling for a muon collider, where the transverse beam dimensions are smaller. In each case, the exact frequency of the cooling rf is determined by availability of materials, expertise, and other economic factors, which limit the ability to match the Booster parameters. Luckily, the Booster parameters can be manipulated to match these cooling channel RF frequencies.

The Booster operates with h = 84 at a kinetic energy near 8 GeV. The field of the permanent-magnet 8-GeV transfer line presently determines the exact Booster energy at extraction. The following table contains solutions to the harmonic equation above, where the first row is the present Booster operating condition.

h	f (MHz)	4*f (MHz)	16*f (MHz)
84	52.8114	211.2456	844.9824
83	52.1827	208.7308	834.9231
82	51.5540	206.2159	824.8638
81	50.9253	203.7011	814.8046
80	50.2966	201.1863	804.7451
79	49.6679	198.6715	794.6858

The harmonics that best match the cooling channel RF occur with the 80th Booster harmonic. These frequencies should be in the tuning range of the cooling RF, or can be made so, if specified in advance.

Experiments with the Booster have demonstrated proton bunch lengths at extraction of 300 ps. At the low intensities required of the MUCOOL experiment, lengths this short or shorter should be relatively easy to obtain. For the sake of argument, we assume that the muon bunch structure is the same as the proton bunch structure and that the RF is phase locked such that the muon bunches fall in the center of the cooling RF bucket. With the 60 ps acceptance of the 805 MHz cooling RF, roughly 60/300 = 1/5 of the muons will be captured by the cooling channel. This is 4 times better than if the muons were uniformly distributed in time over the 1.2 ns period of the cooling RF.

In the case of the 200 MHz cooling RF, the acceptance is four times larger and we can do much better. That is, 80% of the 300 ps bunch overlaps the 240 ps cooling acceptance. This compares to the 1/20 = 5% that would be accepted in the case of a uniform beam distribution or the case with no RF synchronization. Running the Booster at the 80th harmonic can lead to an increase of a factor of 16 in good event rate.

Luckily, the Fermilab Linac upgrade from 200 to 400 MeV raised the injection RF frequency of the Booster from 30.2 to 37.8 MHz. The tuning range which is now unused can be taken advantage of to allow running at a lower harmonic. Injection at the 80th harmonic requires a frequency of 37.8 * 80 / 84 = 36 MHz. All the hardware is still compatible with lower frequency operation, and it may only take a few hours to set up operation at the 80th harmonic.

To allow cycle-to-cycle switching between operation at h = 84 and h = 80 is a bit more difficult. The Booster RF function generator tables are clock event driven except for one which creates the cavity tuner Bias (1024 points) and one which generates the RF frequency (10,000 point, VXI crate). These two can be augmented cheaply by using the old analog generators, which are now used as spares. To make them clock event driven is a matter of one engineer-day and two technician-weeks.

Creating and Preserving Short Muon Bunches

We have considered methods to create short proton bunches and to preserve the bunch structure in the muon beam. Some suggestions to optimize the design of the beam line follow. A short beam line with narrow momentum bite is an advantage, since the muons at 187 MeV/c have a significant velocity spread. After 10 meters, a muon momentum spread of +1% will add 93 ps in quadrature to the 300 ps of the proton bunch width. The narrow momentum bite is a necessary condition for the use of RF synchronization, and the low event rate required by the MUCOOL experiment allows such restrictions.

Another trick to be used to preserve the proton bunch structure in the muon beam is to match the velocities of the decaying pions with the muons. This condition is that the ratio of the pion to muon momentum be equal to the ratio of pion to muon mass. If the parent pion momentum is 245 MeV/c, a daughter muon of 187 MeV/c will have the same velocity as the pion. The time of flight from the target to the muon cooling channel will be independent of where the decay took place.

We have also considered extracting the Booster beam at the time (and energy) of transition. At transition, the proton bunch is infinitesimally short in time and this would make the bunch-shaping problem rather easy. However, other problems arise which make this choice difficult: extracting on the ramp makes operation of the extraction devices difficult, especially if other Booster cycles are interspersed with MUCOOL cycles, phase lock at transition is complex, and the lower-energy beam (5.2 GeV) produces fewer muons. Nevertheless, operation at the 81st harmonic would be a reasonable match to the cooling RF if the Booster beam were extracted at transition.