Toward a Higgs Factory Muon Collider

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Abstract. Precise measurements of the parameters of the newly discovered Higgs boson candidate are needed to distinguish alternative theories. A muon collider operating near 126 GeV can create the Higgs boson by the s-channel resonance with a cross-section enhanced by a factor of 42,700 compared to an e+e- collider. By using beams with energy spread comparable to the predicted 4 MeV width of the Higgs boson, a muon collider can directly measure the width of the boson independent of theoretical models. This small energy spread centered on the boson mass implies that the event rate will be maximized. New muon beam cooling concepts and devices to achieve 4 MeV energy spread are being developed using analytical calculations, numerical simulations, and experiments, including the construction of a prototype cooling channel segment. A conceptual design of a Higgs Factory Muon Collider is the next step toward the realization of a new kind of machine that can do precision measurements as a lepton machine and has the potential to push the energy frontier beyond the LHC. Parameters for a compelling Higgs Factory are presented along with comments on their technical challenges. The fast track of the CERN proton-antiproton collider started over 30 years ago, that brought us the Z boson, W boson, and then the Top Quark at Fermilab, is a model to be emulated.

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INTRODUCTION

As a colliding beam particle, the muon offers many advantages to make up for its relatively short 2.2 μs lifetime. It is an elementary particle, so that all of its energy is available to create new states of matter such that a muon collider storage-ring can be ten times more effective than that of a hadron collider with the same diameter. It is 206.7 times more massive than an electron and therefore suffers little from electromagnetic radiation effects, which give an advantage over electron-positron colliders in the strength of bending magnets that can be used because of synchrotron radiation or in the initial-state energy resolution because of beamstrahlung.

The muon does not interact by the strong interaction, and its high mass relative to the electron means that it can pass through matter without hadronic or electromagnetic showers. Thus, it is the perfect candidate for ionization cooling [1], in which muons lose energy by passing through a low-Z material and only the longitudinal component is replaced by an RF cavity. This technique allows the angular spread of a beam of muons to be reduced in a very short time close to the limit determined by multiple scattering.

However, this will only work for transverse phase space and the longitudinal dimension requires emittance exchange. Effective longitudinal beam cooling in order to have a small beam energy spread can be the key to making a Higgs factory muon collider.

Precise measurements of the parameters of the newly discovered Higgs boson candidate are needed to distinguish alternative theories [2]. A muon collider operating near 126 GeV can create the candidate Higgs boson by the s-channel resonance with a cross-section enhanced by a factor of 42,700 compared to an e+e- collider. By using beams with energy spread comparable to the predicted 4 MeV width of the Higgs boson, a muon collider can directly measure the width of the boson, independent of theoretical models.

This small energy spread centered on the boson mass is needed to maximize the event rate. Muon beam cooling devices, inspired by analytical calculations and numerical simulations, are being developed, and a prototype of a cooling channel segment is being constructed that will achieve the required 4 MeV energy spread. A conceptual design of a Higgs Factory Muon Collider is the next step toward the realization of a new kind of machine that can do precision measurements as a lepton machine and has the potential to push the energy frontier beyond the LHC. The fast track of the proton-antiproton collider started at CERN over 30 years ago, that brought us the Z and W bosons, and later the top quark at Fermilab, is a model to be emulated.

MUON COLLIDER STRATEGIES

Muon beam cooling requirements for an energy-frontier muon collider are different from those of an s-channel Higgs factory muon collider. For the high-energy collider, the best approach is to cool the beams in all dimensions, which allows high-frequency RF acceleration. Then, using emittance exchange as the beams are accelerated, cause the transverse emittance to shrink and the longitudinal emittance to grow up to the point that the RF bunch length at the collision energy is comparable to the β* of the interaction point, where the luminosity is only slightly affected by the "hour-glass" effect at the IP.

For the s-channel resonance Higgs factory, the essential goal is to concentrate all the total energy of the muon beams at the mass of the Higgs. Well-controlled energy and small energy spread are needed both to maximize the event rate and to allow the Higgs boson mass and width to be measured precisely. The measurement and control of the beam energy can be accomplished by monitoring the precession frequency of the muons in the collider ring [3].

With hydrogen energy absorber using the scheme described below, ionization cooling will leave a 100 MeV/c beam with 2.6% energy spread. This scales to about 4 MeV at 63 GeV, almost the same as the width of the Higgs boson in the simplest model.

Thus, the key to a Higgs-boson Factory muon collider is first to use emittance exchange to cool the longitudinal emittance of each beam to its theoretical minimum and then to preserve that emittance through all transfers and acceleration stages. This preservation is the object of a proposed STTR project.

HELICAL COOLING CHANNEL (HCC)

In a Helical Cooling Channel (HCC) [4,5,6], a solenoid field is combined with a transverse helical dipole field that provides a constant dispersion along the channel as necessary for the emittance exchange that allows longitudinal cooling. The Hamiltonian that describes motion in this magnetic configuration is easily solved by a transform into the frame of the rotating helical magnet, where it is seen that the addition of a helical quadrupole field provides beam stability over a very large acceptance.

The helical dipole magnet creates an outward radial force due to the longitudinal momentum of the particle while the solenoid magnet creates an inward radial force due to the transverse momentum of the particle, according to

$$F_{h-dipole} \approx p_z \times b; \quad b \equiv B_{\perp}; \qquad F_{solenoid} \approx -p_{\perp} \times B; \quad B \equiv B_z$$

In these expressions, B is the field of the solenoid, the axis of which defines the z axis, and b is the field of the transverse helical dipole. By moving to the rotating frame of the helical fields, a time- and z-independent Hamiltonian is used to derive the beam stability and cooling behavior [4]. The motion of particles around the equilibrium orbit is shown schematically in Fig. 1.

$$k = 2\pi/\lambda \qquad \kappa = ka \qquad \kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

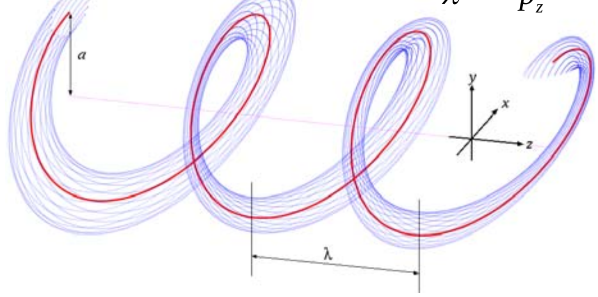

FIGURE 1: Schematic of beam motion in a helical cooling channel.

The equilibrium orbit shown in red follows the equation that is the Hamiltonian solution:

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{\kappa} b\right]$$

The dispersion factor $\hat{D}$ can be expressed in terms of the field components B, b, and the transverse magnetic field radial gradient $\partial b/\partial a$ on the particle's orbit:

$$\hat{D} = \frac{p}{a}\frac{da}{dp} = \left(\frac{a}{p}\frac{dp}{da}\right)^{-1}; \qquad \hat{D}^{-1} = \frac{\kappa^2 + (1-\kappa^2)q}{1+\kappa^2} + g;$$

$$g \equiv \frac{-(1+\kappa^2)^{3/2}}{pk^2}\frac{\partial b}{\partial a}$$

where g is the effective field index at the periodic orbit.

The magnetic field ratio on the equilibrium trajectory satisfies the condition

$$\frac{b}{B} = \frac{\kappa}{1+\kappa^2}\left(1 - \frac{k}{k_c}\right) = \frac{\kappa}{1+\kappa^2}\left(\frac{q}{q+1}\right),$$

with $q \equiv \frac{k_c}{k} - 1$ and $k_c = B\sqrt{1+\kappa^2}/p$.

For stability, the following condition has to be satisfied

$$0 \quad < \quad G \equiv (q-g)\hat{D}^{-1} \quad < \quad R^2 \equiv \frac{1}{4}\left(1 + \frac{q^2}{1+\kappa^2}\right)^2.$$

Use of a continuous homogeneous absorber (e.g. H_2 gas) takes advantage of the positive dispersion along the entire cooling path, a condition that has been shown to exist for an appropriately designed helical dipole channel. We have also shown that this condition is compatible with stable periodic orbits.

G4beamline HCC Simulations

The analytic relationships derived from this analysis were used to guide simulations using a code based on the GEANT4 [7] toolkit called G4beamline [8] and using ICOOL [9], developed at BNL. Simulation results [10] show a 6-D cooling factor of 190,000, where the reference orbit radius is decreased and fields are increased as the beam cools. Results of more recent studies using analytical field expressions [11] show the cooling of longitudinal and transverse emittances at the end of 8 HCC segments that are plotted as red dots in Figure 2. The peak RF field is 27 MV/m, and 60 μm Be windows make the cavities true pillboxes. The gas pressure is 160 atm at 300 K.

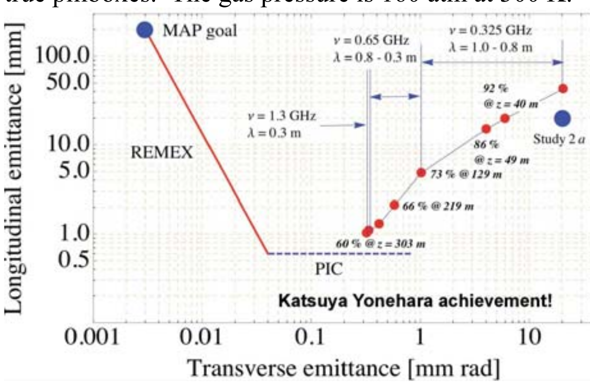

FIGURE 2: G4beamline simulation of the emittance evolution along a HCC with three sets of RF frequencies, showing a MAP goal for a high-energy muon collider.

The less effective 1.3 GHz segment in Figure 2 is a limitation for the Higgs Factory Muon Collider since analytic calculations imply that 100 μm should be possible. Smaller, dielectric-loaded 800 MHz cavities may be the solution to this problem.

HCC Hardware Component Developments

Pressurized RF cavities filled with hydrogen gas have been tested with beam and in magnetic fields in the Mucool Test Area (MTA) at Fermilab. Recent results indicate that ionization electrons can be neutralized fast enough to prevent significant degradation of accelerating gradient by the addition of a small amount of oxygen dopant [12].

Dielectric loaded RF cavities allow their smaller diameter to fit inside high field superconducting magnets and their cryostats [13]. Tests in the MTA will be to demonstrate that breakdown of the dielectric will be suppressed by the pressurized gas.

Superconducting Helical Solenoid segments have been made using NbTi and YBCO. A new design based on Nb3Sn conductor is being designed and a four-coil segment is funded to be built next year [5].

An **Engineering design of a prototype 1-m segment** is underway, based on the concept shown in figure 3. Smaller diameter cavities will allow the coaxial waveguides to run parallel to the axis of the segment so they can exit between 1-m long magnet cryostats rather than have to penetrate them as implied by the figure.

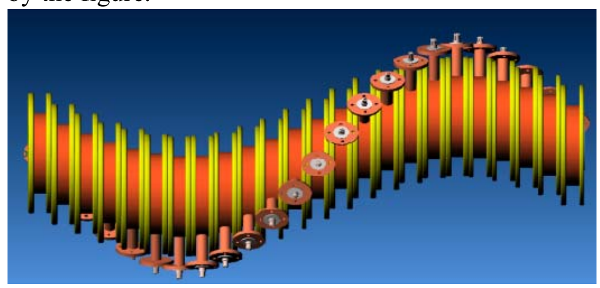

FIGURE 3: An STTR project is underway (Muons, Inc. and Fermilab) to design a 1-m long Helical Cooling Channel Segment – complete with a 10 T Superconducting Helical Solenoid magnet (coils in yellow), twenty 805 MHz RF Cavities (copper colored), each dielectric-loaded, pressurized with doped hydrogen gas, and powered by a phase and frequency locked magnetron power source.

HIGGS FACTORY MUON COLLIDER

TABLE I – Ultimate Performance Parameters

Cross section cm^2	40.0E-36
Higgs/10^7s (two detectors)	500,000
Collider Ring	
E (GeV COM)	126
Average dipole field (T)	10
Length of Straight Sections (m)	50
Circumference (m)	232
Revolution frequency (MHz)	1.2934
Number of IPs	2
Number of mu+ bunches	1
bunch intensity	2.5E+12
tune shift parameter	0.016
beta star (cm)	1.0
bunch length (cm)	0.65
Beam energy spread (MeV)	4.12
Norm trans emittance (μm)	200
Norm long emittance (μm) (=0.89eV-s)	100
Peak Luminosity	1.89E+34
mu lifetime (s)	1.30E-03
rep rate (Hz)	60
Average Luminosity	1.26E+33
Proton Driver	
Proton Energy (GeV)	8
mu+ or mu-/sec at 63 GeV	1.5E+14
p/sec	3.17E+15
proton power (MW)	4

Table I shows a set of parameters for a muon collider Higgs factory that could produce over a million Higgs bosons in a real year using two intense bunches of muons cooled to the limits implied by hydrogen energy absorbers. In the table, we assume that each proton produces 0.15 positive and 0.15 negative muons that are captured by a transverse precooling system. Of these captured muons, we estimate 31% survive cooling in the HCC and acceleration to 63 GeV.

Technical challenges to this set of parameters include overcoming limitations to the brightness of the beam due to space charge effects and the effects of RF cavity beam loading. One idea under consideration is that the hydrogen-pressurized HCC will allow compensation of space charge effects.

Another technical challenge is to reduce the costs of the proton driver, cooling channels, and muon accelerators and storage rings. We are addressing these by developing less expensive magnetron power sources, power couplers, and cryostats as well as new concepts for multiturn magnetic return arcs and aberration corrected low beta insertions.

PBAR-P MOTIVATIONAL EXAMPLE

The CERN pbar-p project [14] started with van der Meer's 1972 stochastic cooling concept [15], confirmed in a 1977 experiment [16]. Nobel prizes were awarded to Rubbia and van der Meer in 1984.

Although the 7-year interval from proof of principle experiment to Nobel Prize is amazing, the analogy between that feat and what could be done to realize a Higgs Factory Muon Collider is worth considering. In the 4 years following the demonstration experiment, CERN turned the Super Proton Synchrotron into a 340 GeV colliding beam storage ring with low beta insertions and new transfer lines. They also designed, built, and commissioned a sophisticated antiproton accumulator ring with several state of the art high frequency RF cooling devices.

Assuming that the project-X proton driver has been built, the Higgs Factory Muon Collider has technological problems to solve that are similar to those that CERN had for the pbar-p collider.

Instead of retrofitting the CERN SPS accelerator to be a 240 GeV storage ring, Fermilab will need to build a relatively small collider ring, which because of superconductivity needs less than a 30 m radius of curvature. Instead of CERN's pbar target, collection system, and accumulator/cooling ring, Fermilab needs a pion/muon production target, collection system and two muon cooling-channels. The acceleration can be much like that developed for a neutrino factory [17].

Most important of all, the s-channel Higgs Factory is on a direct path to an energy-frontier muon collider that would fit on the Fermilab site.

ACKNOWLEDGMENTS

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