DEVELOPMENT OF HELICAL COOLING CHANNELS FOR MUON COLLIDERS

Katsuya Yonehara, Fermilab, Batavia, IL 60510, U.S.A.

Abstract

The biggest technical challenge problem for muon colliders is to cool of the six-dimensional (6D) muon beam phase sufficiently within the muons' short lifetime to permit acceleration. The Helical Cooling Channel (HCC) has been proposed as a means to obtain exceptional cooling performance in a short channel length. A number of experimental, design and simulation studies of the HCC have been completed recently. Results and current activities for the HCC are presented.

INTRODUCTION

The P5 committee compiled a road map for future facilities for high-energy physics (HEP) in May, 2008 [1]. According to their road map, muon colliders will be an appropriate long-term project for HEP community if progress is made on the necessary breakthrough technologies. Muons are an attractive for acceleration in future colliders because 1) muons emit no synchrotron radiation in circular accelerators even at TeV energies, whereas it severely limits the energies of circular electron-positron accelerators, and requires linear accelerators that are much larger than muon colliders, and 2) muon colliders have much less beamsstrahlung than electron-positron colliders, which results in better energy resolution, 3) muons have no internal structure, whereas that is a drawback in proton-proton and other hadron colliders. On the other hand, there are some challenges to make muon colliders. First, muons must be accelerated to high energy within their short lifetime. Half of the muons decay weakly into electron (positron) and anti-neutrino (neutrino) within 2.2 μs at rest. Second, rapid 6D muon beam phase space cooling is required to make practical muon colliders. Muons are generated in a pion decay channel. Without phase space cooling the initial muon beam phase space is too large to be accepted in a conventional RF accelerator system. A compact muon accelerating and cooling system is an essential requirement. Because high gradient RF is preferred for quick acceleration, SRF cavities are the most feasible solution for muon acceleration. To this end, the beam phase space needs to be cooled down to levels that are acceptable by the SRF system.

The most effective method of muon beam phase space cooling is by ionization cooling. Ionization cooling of a muon beam involves passing a magnetically focused beam through an energy absorber, where the muon transverse and longitudinal momentum components are reduced, and through RF cavities, where only the longitudinal component is regenerated. After some distance, the transverse components shrink to the point where they come into equilibrium with the heating caused by multiple Coulomb scattering. However, this process only makes 4D phase space cooling, called transverse cooling. Recently, a novel 6D phase space cooling channel based on ionization cooling called a helical cooling channel (HCC) was proposed [2]. It consists of a helical dipole and solenoid magnetic components to make a helical beam path as shown in Figure 1. The dense hydrogen gas is homogeneously filled in the beam path. In a helical dipole magnet, a high (low) momentum muon passes with longer (shorter) path length. As a result, the momentum distribution after the magnet with a continuous cooling absorber becomes uniform. This process is called emittance exchange. A helical quadrupole component is required to stabilize the beam phase space. To compensate for energy loss, a continuous RF acceleration field is needed. A high pressurizing hydrogen gas filled RF (HPRF) cavity can be used a homogeneous cooling absorber and a continuous acceleration at the same time. The HPRF cavity has been successfully tested and investigated for the cooling applications [3]. Integrating the HPRF cavity into the HCC is a major issue. The HCC is the most compact type of cooling channel of the various types of cooling channel.

In this paper, we discuss the latest results of 6D cooling simulation studies of the HCC. Then, we discuss the beam elements in the HCC. This study will lead to the question of how to incorporate the RF system into a compact helical cooling magnet.

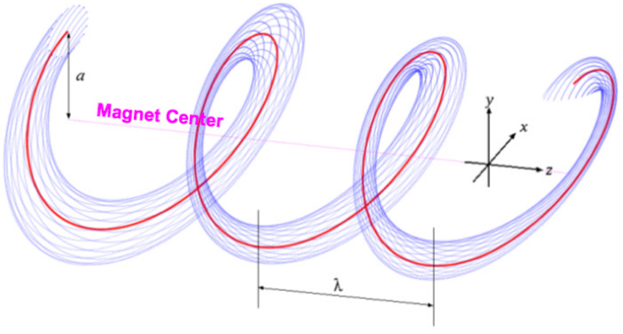

Figure 1: Helical particle tracking in the HCC. The red line indicates the trajectory of the reference design particle and the blue lines are the beam envelope. The particle track has a position offset from magnet center ("*a*" in picture). λ is a helical period.

HCC SIMULATION

From past HCC simulation studies, we noticed that an HCC with a lower RF frequency channel has larger longitudinal phase space stability [4]. The most plausible reason is because the momentum slip factor is not well

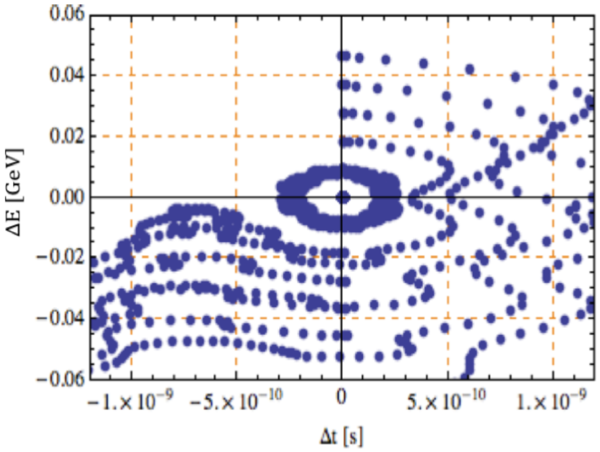

Figure 2: An RF bucket in a $E_0 = 16.0$ MV/m with $\phi_0 = 140.0^\circ$ at $\nu = 400.0$ MHz HCC.

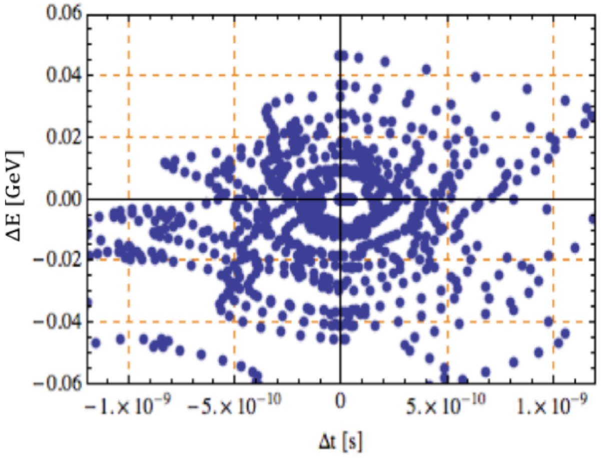

Figure 3: An RF bucket in a $E_0 = 31.4$ MV/m with $\phi_0 = 160.0^\circ$ at $\nu = 400.0$ MHz HCC.

matched to capture muons in the RF bucket, i.e. the time of flight of high (low) momentum muon traversing the HCC is too short (long) to stay in the RF bucket. The maximum RF bucket amplitude (ΔE_{max}) is given by

$$\Delta E_{max} \propto \left(\frac{1}{\nu} E_0 (\phi_0 \cos\phi_0 - \sin\phi_0)\right)^{1/2}, \qquad (1)$$

where ν is the RF frequency, E_0 is the amplitude of the acceleration field, and ϕ_0 is the RF phase, respectively. From this equation, one can expect that by applying a higher RF amplitude and setting a larger RF phase the RF bucket size becomes larger. Figures 2 and 3 show the RF buckets in an HCC with a small E_0 and ϕ_0 (Fig. 2) and with a large E_0 and ϕ_0 (Fig. 3), respectively. The former RF parameter is used in the conventional HCC design as in Ref.[4]. The plots in figures 2 and 3 clearly show an increase in RF bucket size.

In the conventional muon collider cooling scheme, the initial cooling channel must have a low frequency RF structure, i.e. usually starting with a 200 MHz RF system. By increasing the longitudinal phase space acceptance, the HCC will start with 400 MHz RF system. Figure 4

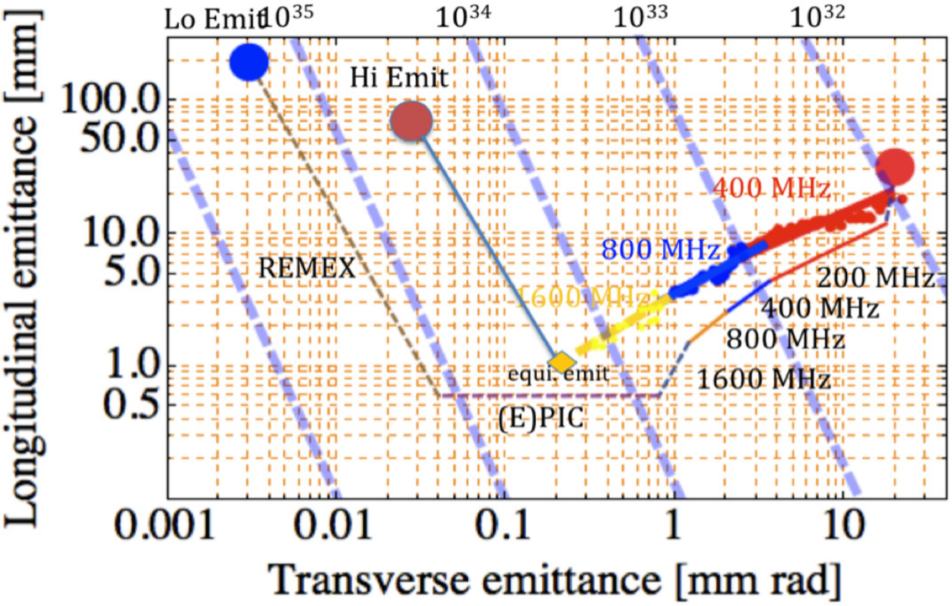

Figure 4: Fernow-Neuffer plot of transverse and longitudinal emittance evolutions in a series of HCCs for a muon collider. A thin line shows the result in an old HCC design while a thick line shows the result in a new HCC one with the optimized RF parameters. The big red point is the initial phase space after the frontend channel. The beam phase space goes down to the diamond point, which is the equilibrium emittance in the HCC. The big brown and blue points show the goal in “high emittance” and “low emittance” schemes, respectively [5]. To realize the low emittance scheme, some extra cooling channel is required. We propose to add (Epycyclic) Parametric Resonance Ionization Cooling channel (PIC) and Reverse Emittance EXchange channel (REMEX) [6]. The light blue broken line shows the expected luminosity under the assumption of no beam loss.

shows the plot of an evolution of transverse and longitudinal phase spaces (Fernow-Neuffer plot) in a series of HCCs, i.e. a 400 MHz HCC, an 800 MHz HCC, and a 1600 MHz HCC, respectively. The idea of incrementing the frequency in the series of HCCs is that more RF power can be put into higher frequency RF cavities. In the cooling simulation, optimizing the HCC parameters, the cooling factor for a 300 meter long HCC is ~ 3×10^5 in 6D phase space. This amount of cooling corresponds to a beam luminosity of more than 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for a muon collider, assuming that there is no beam loss in the entire system, including cooling, acceleration, and beam storing in a collider ring.

Table 1: HCC Parameter in Design Simulation

Parameter	**Unit**	**Value**		
RF frequency	MHz	400	800	1600
Helix period	m	1.0	0.6	0.3
Helix tangential pitch		1.0	1.0	1.0
Helix dipole field, b	Tesla	1.60	2.67	5.33
Helix quadrupole, b’	T/m	-0.55	-1.53	-6.10
Solenoidal field	Tesla	-5.30	-8.84	-17.7
RF field amplitude	MV/m	31.5	32.5	32.5
RF phase	Degree	160	160	160
RF cavity length	mm	100	60	30

Table 1 shows the beam element parameter in a series of HCCs as shown in Figure 4. These parameters are for a positive muon beam with a left-handed (anticlockwise) helicity beam, hence the sign of the field is sensitive. The mean momentum is 250 MeV/c. The direction of acceleration field is the global z direction, i.e. solenoid direction of the magnet. It should also be paid attention that the strength of the fields is stronger at higher RF frequency. A smaller beam phase space can be achieved in a stronger magnetic field because it makes a lower beta function. Stronger magnetic fields can be generated more easily in smaller bore magnets, which accommodate the smaller higher frequency RF cavities. This is another reason why a series of HCCs is needed to make lower emittance beams. Integrating of RF cavities into the helical magnet will be discussed later.

Currently we are working on the design of a phase space matching channel in the HCC simulation study. The action angle and canonical variables are well known from analytical investigation [2]. Now the issue is how to translate these parameters from one canonical coordinate system to the other by using the conventional beam elements.

STUDY OF BEAM ELEMENT IN HCC

In the rest of the paper, we discuss the beam elements, which consist of the helical magnet and the RF system. These modules cannot be designed separately because they will be integrated into the 6D cooling channel. This task is the main goal current HCC design study.

Helical Magnet

The design of helical magnet has already been created and prototyped at Fermilab. Figure 5 shows an innovative design for an optimum helical field by using coils arranged along a helical axis, a helical solenoid (HS). The HS coil can produce the required helical dipole and solenoidal fields, and can be tuned. The coil diameter is an additional parameter, which can be used to adjust the helical quadrupole component. However, this geometric effect is too weak to optimize the field gradient. Besides, an 80 mm gap requirement for infrastructure limits the maximum field gradient. Adding the helical correction conductors around the HS structure is currently the main activity of optimization of the helical field. A detailed description is represented in Ref. [7]. A four coil test section of a helical solenoid has been made (see Figure 6) and it has been confirmed that the field simulation is accurate enough to design the HS coil of a full-length HCC magnet [8].

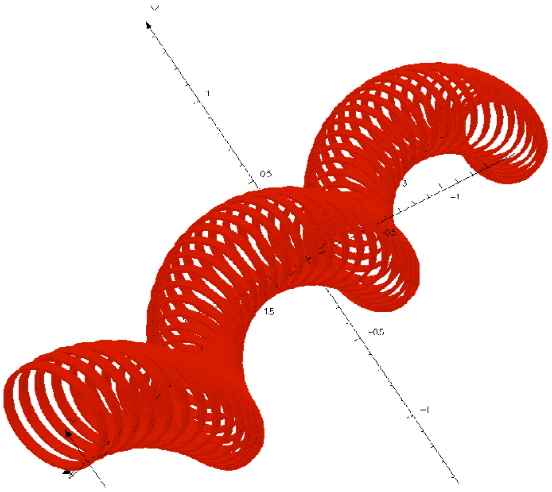

Figure 5: Design of helical solenoid magnet.

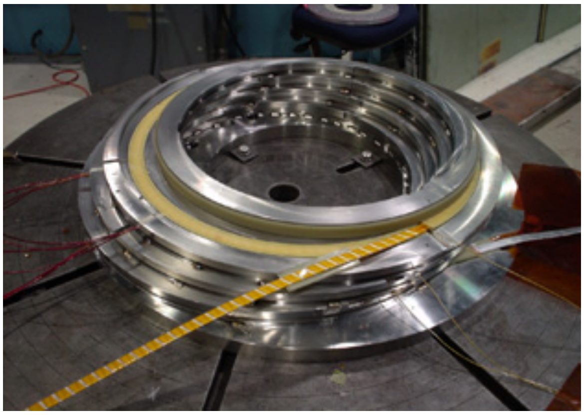

Figure 6: Winding the helical solenoid coil.

RF Cavity

As discussed above, the size of HS coil is fixed so as to generate the optimum helical magnetic field. Also the size of the RF cavity is inflexible. The radius of a pillbox type RF cavity is inversely proportional to the resonant frequency, which is determined by a boundary condition in the solution of Maxwell equations. In order to make a flexibly sized RF cavity, a high dielectric material loaded RF cavity has been proposed [9]. In this cavity, the velocity of light in the dielectric material is reduced and, as a result, the radial distribution of field in the dielectric material shrinks in the radial direction.

Figure 7 shows a conceptual picture of a dielectric-loaded RF cavity. The field calculation has been done in Superfish. In this example, the radius of the dielectric-loaded 400 MHz cavity can be about 9 cm, which is less than half the radius of a conventional vacuum RF cavity. The big issue for the dielectric loaded RF cavity is the RF power dissipation in the dielectric material. This issue may be resolved by using state of the art ceramics. There are many ceramics that have very low dielectric loss rates, around 10^{-5}. The required RF power will be a couple of MW. Finding the proper ceramics and doing the demonstration tests are planned in the dielectric loaded RF cavity R&D.

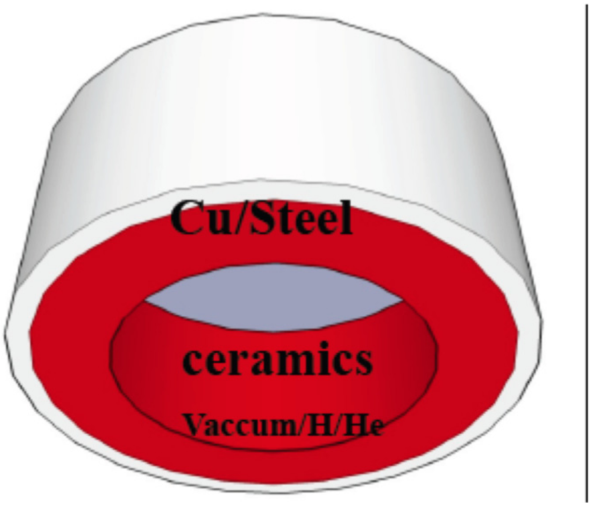

Figure 7: Conceptual drawing of dielectric-loaded RF cavity.

Figure 8 shows a series of dielectric-loaded RF cavities designed to be inside the HCC. Each RF cavity is a high-pressure pillbox-type, with a window between cavities and an RF power feed-through to the high pressure interior. The size of the RF power coupler will be determined when we optimize the RF parameters in simulation, which will be tested in the demonstration test in the current R&D.

The possibility of employing traveling wave helical RF structure is also being studied. Figure 9 shows a helical RF system within the HS coil magnet. A big advantage in the traveling wave RF structure is that there is no window between RF cells. Hence, the interference of the helical field caused by the RF power port will be minimized. The wedge shape RF cavity can generate an electric field along the helical beam path. The RF cavity has a coupling port to adjust the phase velocity in the RF cell to match to the beam velocity. In addition, the coupling port is needed to reduce the RF power by magnetic coupling. To this end, the coupling port can be located far from the cavity center, which is the beam path area. Hence, it can have a large aperture at the beam entrance and exit. A detailed discussion for this design is in Ref. [10].

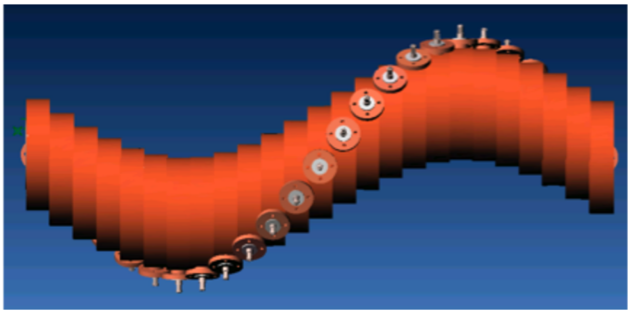

Figure 8: Conceptual design of RF cavities in arranged in a helical structure for use in an HCC.

HPRF cavity under high radiation conditions

RF cavities that are pressurized with hydrogen gas have been shown to operate at higher electric gradients in strong magnetic fields than vacuum cavities. The dense gas in the cavity absorbs the dark currents and suppresses breakdown. In addition the hydrogen gas acts as the energy absorber needed for ionization cooling, and occupies the same space as the RF cavities for a more compact cooling channel. This clever idea was first brought up by Muons Inc. and now the project is promoted by Muons Inc., NFMCC, and Muon Collider Task Force (MCTF).

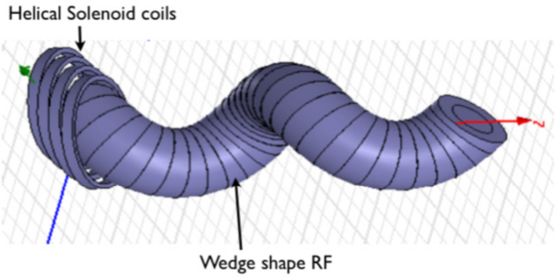

Figure 9: Traveling wave helical RF structure.

The results of these tests in the absence of beam have made a big impact, and continuation of the studies with high intensity proton beam now have a higher priority at Fermilab. The beam test will be done by 2010. One can expect that a high intensity charged beam will generate an electron swarm via the ionization interaction with a dense hydrogen gas, which will absorb a large amount of RF power and reduce the quality factor of the cavity. This process will be substantial if the recombination time is longer than the RF cycle [11]. By adding a very small amount of electronegative gas, this problem can be resolved. In last HPRF test without beam, 0.01 % of SF6 was mixed in pure hydrogen gas in the HPRF Test Cell. The observed maximum field gradient is increased about 20 % in the linear proportional region. Figure 10 shows that the experimental results are well reproduced in numerical simulation, in which the electron attachment by SF6 is added [12]. Further simulation efforts have been made for future beam tests and have shown that filling the HPRF cavity with 0.01 % SF6 dopant gas will allow the HPRF to operate with a 10^{12} protons/pulse beam [13], which is comparable with the muon beam intensity expected in a muon collider.

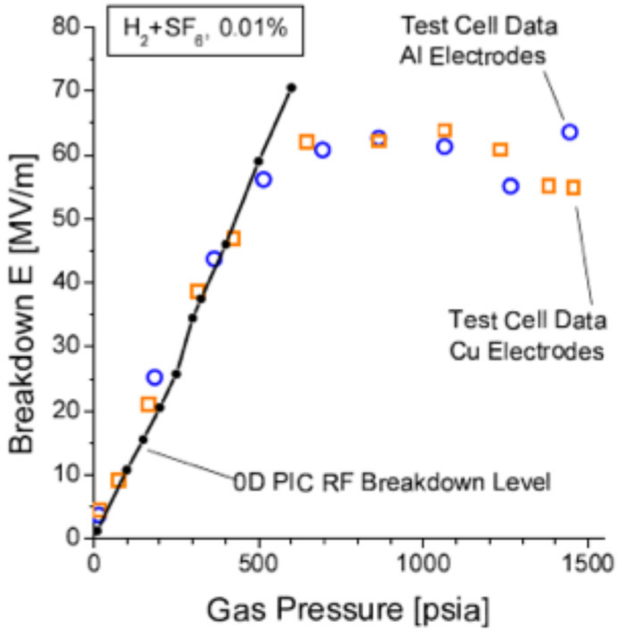

Figure 10: Comparison of experimental and simulation results. Square and circle points show the observed maximum electric field gradient with Copper and Aluminum electrodes in hydrogen gas with 0.01 % SF6 dopant gas and the solid line is the simulation result for this condition

SUMMARY

The HCC study has progressed in both experimental and simulation studies. In the simulation study, it is shown that the longitudinal phase space acceptance can be increased by tuning the RF parameters, with an initial RF frequency raised to 400 MHz. This can significantly mitigate the cost and space issues. One drawback in this design is that the HCC needs much greater RF power.

In experimental study, a 4-coil prototype of an HS has been built and tested and compared with the simulation results. The excellent agreement in both results shows that the HS coil magnet is feasible. Now, we endeavor to make a high field HS magnet, which will be used for the final HCC section as shown in Table 1.

HPRF testing without beam has been done in September, 2008. In this test, the effect of electronegative gas in high gradient RF fields was observed. The experimental results are well reproduced by the numerical simulation as shown in Figure 10. It indicates that the simulation tool will be able to predict the HPRF phenomena under high radiation conditions. According to the simulation study, the quality factor in the HPRF cavity with pure hydrogen gas will significantly drop, by two orders of magnitude. This reduction isl avoided if we add only 0.01 % of SF6 as a dopant gas. This will be tested at Fermilab in 2010.

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