PROCEEDINGS OF SCIENCE

Hybrid 6D cooling channel: Status, challenges and future plans

Diktys Stratakis[1]
Brookhaven National Laboratory
Upton, NY 11973, USA
E-mail: diktys@bnl.gov

Experimental and numerical studies have shown a decline on the maximum achievable rf gradient when the cavity is exposed in multi-Tesla magnetic fields. In this study, we describe a cooling technique that simultaneously reduces all six phase-space dimensions of a muon beam without facing this challenge. In this process, cooling is accomplished by reducing the beam momentum through ionization energy loss in wedge absorbers and replenishing the momentum loss only in the longitudinal direction by using gas-filled rf cavities. Here we present the latest results in modelling this channel and show that the final transverse emittance satisfies the cooling criteria for a Muon Collider. Furthermore, we preliminary discuss some engineering challenges associated with this new design. Finally, we outline our plans for future studies.

16th International Workshop on Neutrino Factories and Future Neutrino Beam Facilities
25 -30 August, 2014
University of Glasgow, United Kingdo

[1]Speaker

PoS(NUFACT2014)084

1. Introduction

Lepton (e+e-) colliders have the valuable property of producing simple, single-particle interactions with little background, and this property is essential in the exploration of new particle states. However, extension of (e+e-) colliders to multi-TeV energies is performance-constrained by radiative effects and cost-constrained because two full energy linacs are required [1]. Since radiative energy losses for a lepton of mass m are inversely proportional to m^4, radiation difficulties may be circumvented by use of a heavier probe. For this reason, it seems prudent to begin investigating muon beams as primary probes in high-energy collisions, since they combine an electron-like nature with a large mass which is sufficiently immune to radiation [2, 3].

The initial muon beam occupies a relatively large phase-space volume which must be compressed by several orders of magnitude to obtain high-luminosity collisions [4]. Furthermore, this phase-space reduction must be done within a time that is not long compared to the muon lifetime (2 μs in rest frame). Ionization cooling is currently the only feasible option for cooling a muon beam [5]. This technique is not very practical for protons, which would have frequent nuclear interactions, or electrons, which would have bremsstrahlung, but is practical for muons, and cooling rates compatible with muon life times are possible.

While ionization cooling seems a straightforward method from theoretical point of view, in reality it will require extensive simulation and hardware development for its optimization. Over the last year, significant progress on the design and simulation of an ionization cooling with vacuum rf cavities has been made. Specifically, it was shown numerically [6] and theoretically [7] that by using a multi-stage stage channel the 6D emittance can be cooled by more than 5 orders of magnitude with high transmission. A key requirement of that design is that it requires vacuum rf cavities to operate at 5 T or greater magnetic fields. This can become a technological challenge since the performance of a normal conducting cavity may degrade when the cavity is exposed in a strong axial magnetic field [8].

The goal of this work is to present a fast cooling scheme that simultaneously reduces all six phase-space dimensions of a charged particle beam. Our lattice design is based on a rectilinear channel that in view of its simple geometry offers substantial technological advantages over previously considered schemes. To mitigate the possible problems in high magnetic fields we investigate a hybrid approach wherein we incorporate gas-filled high pressurized (HP) cavities along with discrete absorbers. We note that a similar approach was successfully implemented [9] for the Neutrino Factory 4D cooler which we now extend to 6D. With the aid of simulation codes, we compare its performance against an equivalent channel with vacuum rf cavities and show that the achieved emittances of the final beam match the cooling criteria for Muon Collider.

1.1 Motivation

High intensity, low emittance muon beams are essential requirements for a future Muon Collider and/or Neutrino Factory. Low emittance muon beams can be produced by ionization cooling. This consists of passing muon beams through low-Z absorber material, to reduce all components of the momentum and replacing only longitudinal momentum with accelerating fields using rf cavities. At the same time, to keep the muon beam focused, both the absorbing material and rf cavities are placed inside a strong magnetic field provided by a superconducting solenoid. The ionization cooling process is most efficient if both the accelerating fields and magnetic fields are high. To study the interactions of a static magnetic field with operation at high accelerating fields, two 805 MHz rf cavities e.g. (i) LBNL-Pillbox (ii) All-Season have been tested in a multi-Tesla magnetic field at the Fermilab MuCool Test Area (MTA). During operation with high magnetic field B = 2 - 5 T, the cavity's accelerating field degrades significantly, dark current and X-rays are produced and interior surfaces suffer severe breakdown damage [10].

A rf cavity filled with high pressure hydrogen gas was proposed to overcome the above mentioned problem. The gas provides the necessary momentum loss as a cooling material and also increases the breakdown gradient of the cavity. Since the collision frequency of electrons with H_2 molecules at 100 atm in rf fields is much higher than the cyclotron frequencies in the ambient magnetic fields fields, any effects of B are eliminated. Experiments have demonstrated that a breakdown gradient of 65.5 MV/m could be achieved in a 3 T magnetic field with 70 atm hydrogen gas [11].This cavity was letter sucesfully tested with an ionizing beam in the parameter range of interest [12].

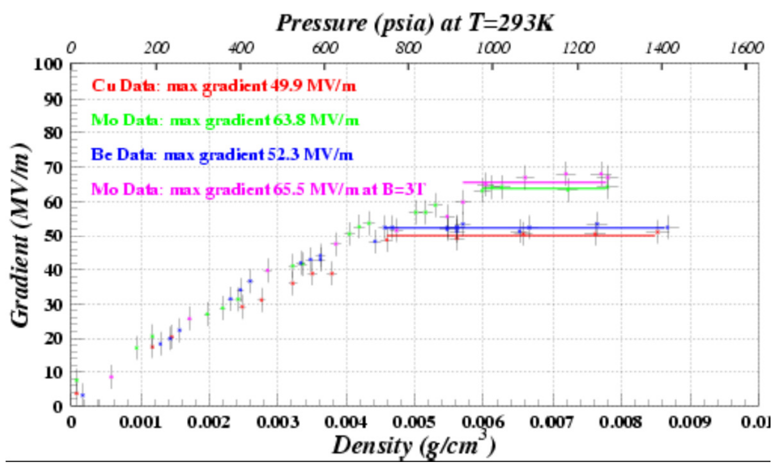

Figure 1:(a) Measurements of the maximum stable gradient as a function of hydrogen gas pressure at 800 MHz with no magnetic field for three different electrode materials, copper (red), molybdenum (green), and beryllium (blue). As the pressure increases, the mean free path for ion collisions shortens so that the maximum gradient increases linearly with pressure. At sufficiently high pressure, the maximum gradient is determined by electrode breakdown and has little if any dependence on pressure. Unlike predictions for evacuated cavities, the Cu and Be electrodes behave almost identically while the Mo electrodes allow a maximum stable gradient that is 28% higher. The cavity was also operated in a 3 T solenoidal magnetic field with Mo electrodes (magenta); these data show no dependence on the external magnetic field, achieving the same maximum stable gradient as with no magnetic field. More details can be found in Ref. 11.

1.2 Lattice Design

There are key differences between a conventional helical cooling channel [13] with HP rf cavities and a channel with vacuum rf. In a helical cooling channel, the energy loss is distributed throughout the channel, rather than localized at discrete absorber regions. While the addition of high-pressure hydrogen to the rf cavity likely increases the maximum allowable gradient, it is not obvious that replacing all of the lithium hydride (LiH) absorbers with gaseous hydrogen is the ultimate solution. It requires 160 atm of gas at room temperature which gives rise to substantial engineering challenges [14]. Inspired from the work in Ref. 9, we propose here to apply a hybrid approach so that to convert a vacuum rf 6D cooling channel to an HP rf version. The scheme we describe will use HP gas to avoid cavity breakdown, along with discrete LiH absorbers to provide the majority of the energy loss. Since our primary purpose is to avoid degradation of the cavity gradient to high magnetic field we use only enough gas to accomplish this task. The desired gradient of a 650 MHz cavity is 26-28 MV/m. We assume that a pressure of 34 atm at room temperature will be enough to satisfy that goal.

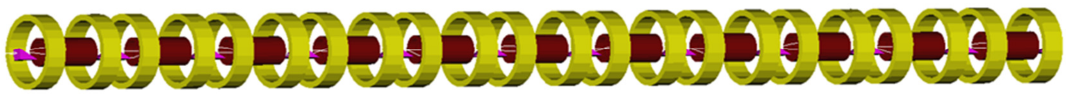

Figure 2: Conceptual design of the proposed hybrid rectilinear channel with gas filled cavities.

A schematic layout of our proposed channel is shown in Fig. 2. The lattice consists of a sequence of identical cells with two or four coils (yellow) in each cell with opposite polarity to provide transverse focusing. The relative amount of cooling can be adjusted by changing the opening angle and transverse location of the wedge-shaped absorber (magenta). A series of rf cavities (dark red) are used to restore the momentum along the longitudinal axis. As depicted in Fig. 2, essentially the same cells from a helical channel [6] (commonly known as a "Guggenheim" channel), including their coil tilts and resulting upward dipole fields, are laid out in a straight (rectilinear) geometry. The solenoid focusing is so strong, compared with the dipole deflections that the closed orbits are merely displaced latterly, but continue down the now straight lattice. Previously conducted studies [15], showed that the cooling performance of a rectilinear is essentially the same as with a "Guggenheim" channel. At the same time, its simplified geometry offers less engineering challenges. Therefore, this will be considered our baseline cooling lattice and will be analyzed in more detail within the next paragraphs. Recent studies showed numerically that good cooling efficiency requires the channel to be tapered. In this scheme, parameters such as cell length, focusing strength, rf frequency and gradient progressively change from stage to stage based on the emittance reduction rate and transmission with the purpose to maintain a beam emittance that is always larger from the equilibrium emittance. As a result, each subsequent stage will have a lower beta than the previous one. The required lattice parameters are summarized in more detail in Ref. 16.

Figure 3 exhibits the equilibrium transverse emittance at different stages. One can see that, at least in theory, our proposed scheme can cool the beam to the required [17] transverse emittance of 0.30 mm. The transverse beta function varies from 39.70 cm to 3.26 cm, while the on-axis magnetic field increases from 2.8 T to 15.0 T. A technical challenge may arise as the operating current on the conductor should not exceed the critical current corresponding to the peak field in the coil. Note that there is an increase of the magnet operating current with stage number. This is a direct consequence of the low β_T lattice design which is needed to cool towards micron scale emittances. Our preliminary findings indicate that even with inclusion of reasonable safety factors, the needed fields are consistent with the critical limits of existing conductor technology. However, the last four stages are barely within the limits of Nb_3Sn and therefore it is critically

PoS(NUFACT2014)084

important to the development of a Muon Collider that a well thought-out test program to be continued.

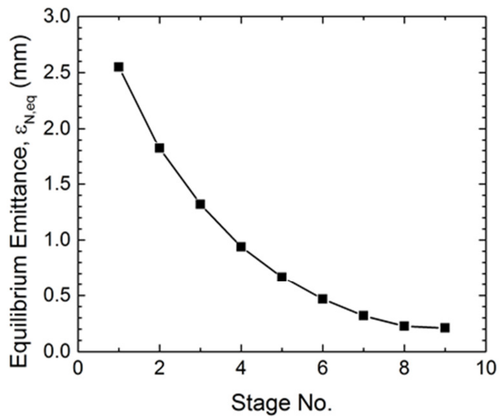

Figure 3: Equilibrium emittance vs. stage number. This plot shows that our channel is capable to cool to 0.3 mm transversely, as required for a Muon Collider [17].

1.3 Numerical Studies

The performance of the cooling channel was simulated with ICOOL. For each stage, we generated 3D cylindrical field maps by superimposing the fields from all solenoids in the cell and its neighbor cells. The rf cavities were modeled using cylindrical pillboxes running in the TM010 mode and a reference particle was used to determine each cavity's relative phase. The absorber material was lithium hydride for all stages.

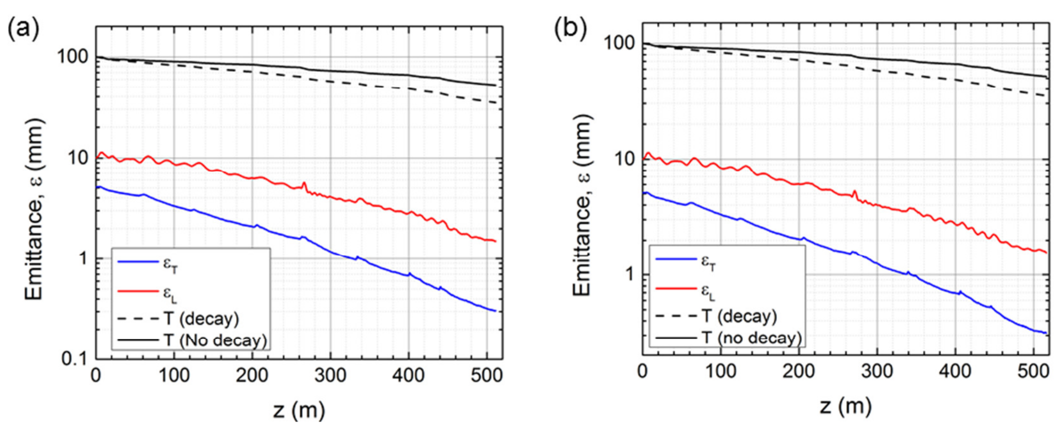

Figure 4: Transmission and cooling performance vs. distance: (a) Using vacuum rf cavities, and (b) using gas filled cavities. The gas pressure is set at 34 atm at room temperature

The transverse and longitudinal emittance and the transmission are shown as function of distance along the channel in Fig. 4. Note that the dashed curve shows the transmission of muons with the decay option disabled in the simulation. It is worth noting that after a distance of 515 m (9 Stages) the 6D emittance has fallen by a factor of 1000 with a transmission of 35% (52% with the decays disabled). In addition, at the end of the channel the transverse emittance decreased by a factor of ~17, while the longitudinal emittance shrank by more than a factor of ~6. Note that a transverse emittance $\varepsilon_T \approx 0.3$ mm is the baseline requirement for a Muon

Collider at the end of the 6D cooling sequence [17]. We can conclude from the results in Fig. 4, that 9 Stages are enough to fulfill this requirement since the transverse emittance of the final beam at z=515 m is 0.3 mm.

1.4 Future Plans

Plasma loading: In a hybrid 6D cooling channel, cooling is accomplished by reducing the beam momentum through ionization energy loss in wedge absorbers and replenishing the momentum loss in the longitudinal direction with gas-filled rf cavities. While the gas acts as a buffer to prevent rf breakdown, gas ionization may also occur as the beam passes through a HP rf cavity. The resulting plasma, may gain substantial energy from the rf electric field which it can transfer via collisions to the gas, an effect known as plasma loading. In our future work, we like to investigate the influence of plasma loading on the cooling performance of a rectilinear hybrid channel. With the aid of numerical simulations we like to examine the sensitivity in cooling performance and plasma loading to key parameters such as the rf gradient and gas pressure.

Theoretical framework development: We are interested to line out the theoretical framework to predict and evaluate the performance of hybrid cooling channels and discuss its application to our specific case. This will enable us to investigate in detail the parameter dependencies and compare our results with numerical simulations.

Matching between stages: As we noted earlier, in the tapering concept the beam leaves a stage with high beta and enters a stage with lower beta function. In our model, we assume a "infinite" periodic lattice in both ends. In reality, matching between the transition regions is required and this needs to be investigated.

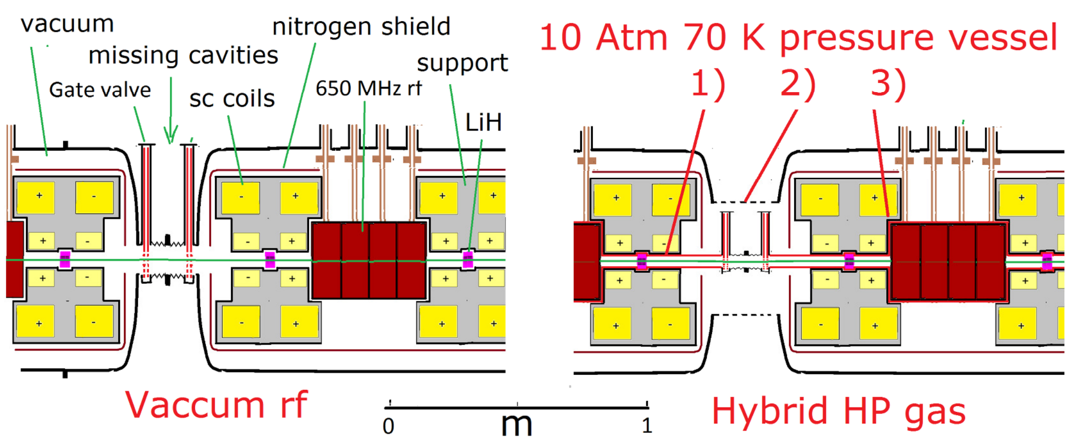

Figure 5: Enginnerring challenges of a hybrid 6D cooling channel. In a hybrid chanel there are numerous challenges: 1) There is no space between beam and inner coils; 2) It is not clear how one can open vaccuum to get at gate HP valves, and 3) HP flange will be thick. All those challenges require additional room at this may hurt performance. A feasibility study is of great importance.

Engineering feasibility: Having a continuous pipe filled with high pressure hydrogen will have safety implications and may not be acceptable. In this configuration, any problem encountered would involve the entire hydrogen inventory. For these reason, a modular system, with independent gas supplies, seems desirable. Unfortunately, such a system comes with the obvious drawback of more isolation windows which can harm performance. Although operating the channel at liquid-nitrogen temperature will reduce the pressure requirements, it may also complicates the engineering of the channel. Finding the suitable operation tempearture requires a detailed study. The effect of isolation windows in the performance (especially transmission) needs investigation. Additinal challeges are shown in Fig. 5 and discussed in the figure caption.

Front-End: A key requirement in designing intense muon sources is operating rf cavities in multi-Tesla magnetic fields. In this task, we like to use rigorous simulation to investigate the performance of an intense muon source (front-end) with gas filled cavities. Our desire is to present a new lattice design and compare our results against conventional schemes. A conceptual design is illustrated in Fig. 6. Pressurized rf cavities may enable higher gradient rf within magnetic fields than is possible with evacuated cavities, providing more options in the front-end. The status of designs of the capture, phase rotation, and precooling systems of muon beams in pressurized cavities will be analyzed.

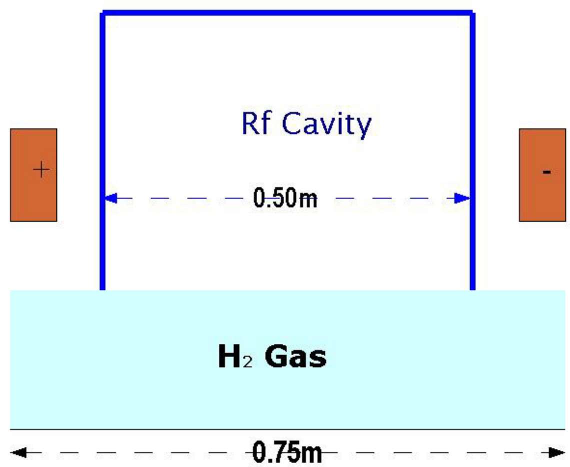

Figure 6: A cell of the gas-filled cooling system (radial cross-section view). This contains 0.5 m long “pillbox” 201.25 MHz rf cavities, with 0.25m gaps between cavities containing coils for magnetic fields. The H_2 gas fills the center of the transport with a uniform density. More details can be found in Ref. 18.

1.5 Summary

In this paper we have discussed a hybrid approach for a 6-dimensional cooling scheme wherein gaseous Hydrogen provides protection to the cavity from the focusing magnetic field and discrete LiH absorbers are the primary loss of energy loss medium. We implemented this approach to a conventional rectilinear 6D cooling channel. Results from numerical simulations indicate that the transmission is comparable to that of an equivalent channel with vacuum rf cavities. In addition, the emittances of the final beam satisfy the cooling requirements for a Muon Collider. While we mainly considered for this study a 34 atm pressure at room temperature, preliminary simulations suggest a loss in performance if we increase the gas pressure. For a future study, it would interesting to examine more systematically the cooling sensitivity to various gas pressures and perhaps different gas types.

References

[1] M. Tigner, AIP Conference Proceedings **279**, p. 1 (1992).

[2] N. Skrinsky, V.V. Parkhomchuk, Sov. J. of Nucl. Phys. 12, (1981).

[3] G. I. Budker, Proceedings of the 7th International Conference on High-Energy Accelerators, Yerevan, 1969 (Academy of Sciences of Armenia, Yerevan, 1970), p. 33.

[4] R. B. Palmer et al., Proceedings of the 2007 Particle Accelerator Conference, Albuquerque NM, p. 3193.

[5] D. Neuffer, Part. Accel. 14 75 (1983).

[6] D. Stratakis et al., Phys. Rev. ST Accel. Beams 16, 091001 (2013).

[7] D. Stratakis and D. V. Neuffer, Proceedings of IPAC 2014, Dresden, Germany, p.1392 (2014).

[8] D. Stratakis et al., Nucl. Instrum Meth. A 620, p. 147 (2010).

[9] J. C. Gallardo and M. S. Zisman, AIP Conference Proceedings 1222, 308 (2010).

[10] A. Moretti et al., Phys. Rev. ST Accel. Beams 8, 072001 (2005).

[11] P. Hanlet et al., Proceedings of EPAC 2006, p. 1364 (2006).

[12] M. Chung et al., Phys. Rev. Lett. 111 184002 (2013).

[13] D. Y. Derbenev and R. P. Johnson, Phys. Rev. ST Acce Y. Derbenev and R. P. Johnson, Phys. Rev. ST Accel. Beams **8**, 041002 (2005).

[14] R. Fernow and J. Gallardo, Neutrino factory/ Muon Collider Document 311 (2005) [http://nfmcc-docdb.fnal.gov/cgi-bin/DocumentDatabase.

[15] D. Stratakis et al., Proceedings of the 2014 IPAC, Dresden, Germany, p. 1389 (2014).

[16] D. Stratakis, Proceedings of the 2014 IPAC, Dresden, Germany, p. 1401 (2014).

[17] Jean-Pierre Delahaye, Robert B. Palmer, Thomas J. Roberts, Robert Ryne, Michael J. Syphers, and Katsuya Yonehara, "Criteria for comparing and assessing 6-D cooling channels," (2014), Muon Accelerator Program internal document, version dated Feb. 10, 2014.

[18] D. Neuffer et al., Proceedings of PAC 2009, Vancouver, Canada, p. 2712, (2009).

PoS(NUFACT2014)084