# A SPHERE COOLER SCHEME FOR MUON COOLING

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*Abstract*

Muon cooling is the greatest obstacle for producing an intensive muon beam. The frictional cooling method holds promise for delivering low-energy muon beams with narrow energy spreads. We outline a sphere cooler scheme based on frictional cooling to effectively produce such a “cold” muon beam. As an example source, we take the parameters of a surface muon source available at the Paul Scherrer Institute. Simulation results show that the sphere cooler has an efficiency of 50% to produce a “cold” muon beam with an energy spread of $0.9\ \mathrm{keV}$. This high quality beam could potentially meet the requirement of a neutrino factory or a muon collider.

## INTRODUCTION

Intense muon sources are important for many experiments in particle physics and material research [1]. A muon collider [2] and neutrino factory [3] also require high-quality muon beams. Muon beams are produced in the decay of pion beams that are produced by proton beams hitting targets. They initially have large phase space volume that must be reduced. This process, called “cooling,” is important for all the experimental endeavors described above.

Frictional cooling [4] is one promising method to produce a “cold” beam. Some cooling schemes based on frictional cooling were outlined in our previous work [5], in which a surface muon was cooled to a slow muon with an efficiency of more than 1%. In this paper, we outline a sphere cooler scheme, which is modified from the previous scheme. As an example input source, we use a surface muon beam such as the one available at the Paul Scherrer Institute (PSI), Switzerland [6]. Simulation results show that the sphere cooler has an efficiency of 50%, which is 3 to 4 orders of magnitude higher than the moderator technique.

## SPHERE COOLER SCHEME

Figure 1 shows the block diagram of a cooling scheme based on the sphere cooler. The sphere cooler is a spherical shell section with an inner radius of $20\ \mathrm{cm}$ and outer radius of $200\ \mathrm{cm}$. The shell has a substended angle of $120°$. Helium gas is filled in the sphere cooler. An electric field is applied in the radial direction in the sphere cooler, pointing to the center of the sphere. The realistic issue and the breakdown of such a field in gas will be discussed in the discussion section. The inner sphere has an entrance window, which is a $20\ \mathrm{nm}$ thin carbon foil, to let the muons pass through and to keep the gas pressure. Another $20\ \mathrm{nm}$ thin carbon foil is put $2\ \mathrm{cm}$ away from the entrance window in the sphere cooler. It separates the sphere cooler into two parts: the bigger volume has a helium pressure of $0.01\ \mathrm{mg/cm^3}$, and the smaller volume has a pressure of $0.001\ \mathrm{mg/cm^3}$.

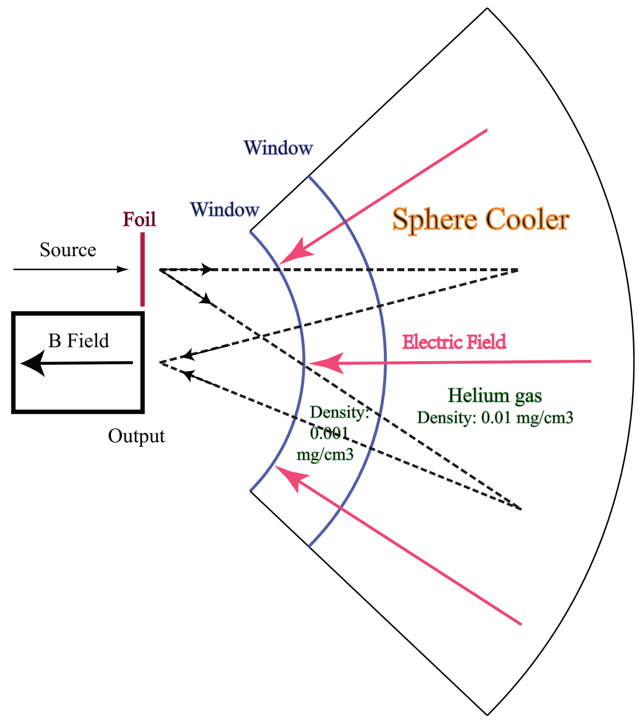


Figure 1: The block diagram of the sphere cooler scheme (not to scale), and two sample trajectories (dashed lines).

When a muon beam with an angular and energy divergency gets into the sphere cooler from the center, each muon is facing to an electric field directly toward it. The muons will be slowed down by the electric field and turn back to the center of the sphere. When they turn back, the muons reach a kinetic energy below $50\ \mathrm{keV}$, so that they are in the frictional cooling range [5]. The gas and the electric field bring the muons to the equilibrium energy around $2\ \mathrm{keV}$. Muons with such a kinetic energy would be greatly

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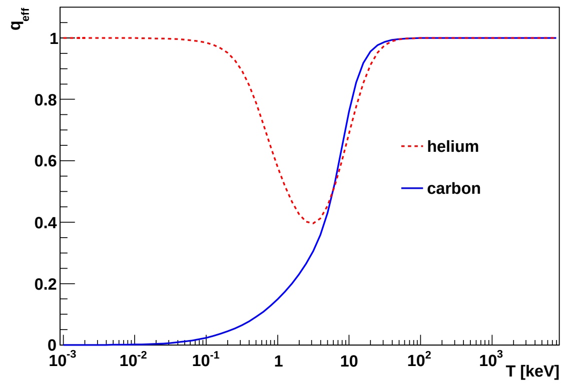


Figure 2: The effective charge of $\mu^+$ in helium and carbon.

neutralized by a carbon window [7]. Figure 2 shows the effective charge of the muons in helium and carbon. The effective charge of a 2 keV muon in carbon is around 0.15, which means 85% of the cooled muons will be neutralized when they exit the carbon window. In order to avoid the neutralization, we accelerate the muons in a helium gas to 20 keV before they exit the sphere cooler. Accelerating the muons in gas will bring an energy spread to the beam, because when the beam energy is higher than the ionization peak (around 10 keV) the muons with higher energy loses less energy than the lower-energy muons. We limit this spread out by lowering the density of the helium gas in the last 2 cm before the muons exit the sphere cooler. In this 2 cm the muons are accelerated and their effective charges rise up to 1 gradually. After exiting from the window, the muons will travel to the center of the sphere and then be collected by a solenoid magnet. We evaluate the beam energy and spatial distribution at the entrance of the solenoid as the output.

## SIMULATIONS

Table 1: Mean kinetic energies and the $\mu^+$ rates of the input and output beam, and the RMS values for the six-dimensional ingredients of the emittance.

| | Input | Output |
|---|---|---|
| $\mu^+$ rate | $4 \times 10^8$ /s | $2 \times 10^8$ /s |
| Mean energy | 3.7 MeV | 22 keV |
| Energy spread | 0.32 MeV | 0.90 keV |
| $x$ | 2.9 cm | 2.1 cm |
| $y$ | 1.4 cm | 2.1 cm |
| $P_x$ | 1.8 MeV/c | 0.70 MeV/c |
| $P_y$ | 3.5 MeV/c | 0.73 MeV/c |
| $P_z$ | 1.3 MeV/c | 0.24 MeV/c |

As an example input source, We take the parameters of the μE4 surface muon source at PSI (Table 1). We put the source 10 cm offset to the center of the sphere, so that the input and output beam can be separated. To reduce the required electric potential in the sphere cooler, the beam first passes through a foil for an initial energy loss. For a fixed electric field, lowering the mean energy decreases the distance that the muons traveled in the cooler, thereby reducing the loss from decay.

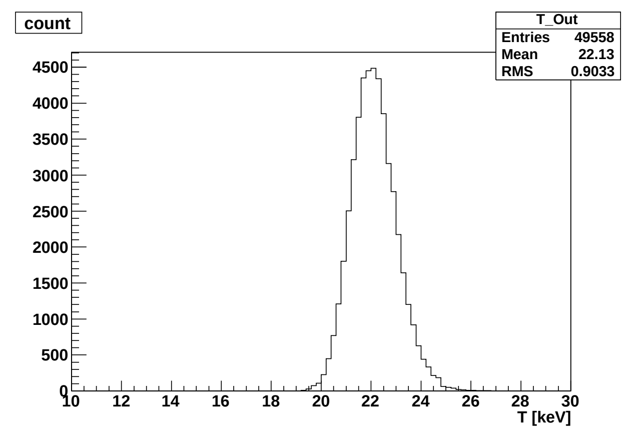


Figure 3: The energy distribution of the output $\mu^+$.

Figure 3 shows the energy distribution of the output beam. About 49.6% of the initial muons enter the output solenoid with a mean kinetic energy of 22 keV and an RMS of 0.9 keV. This efficiency of producing the low-energy muon beam is 3 to 4 orders of magnitude higher than the moderation technique. The spatial distribution of the muons entering the solenoid is shown in Fig. 4. The RMS diameter of the beam is 2.1 cm, which is comparable with the input beam size.

The average time of flight from the source to the output solenoid is 442.2 ns, which is mainly spent when they turn backwards in the sphere cooler at low energies. The higher energy muons spend more time because they travel longer distance in the cooler (Fig. 5). This correlation can benefit the cooling for a muon collider, because the higher-energy muons after the decay channel in a muon collider arrive earlier at the cooling section. In this way the time distribution of the beam can also be reduced.

The parameters of the output beam are summarized in Table 1 in comparison with the input beam parameters.

## DISCUSSION

For reflecting a MeV muon beam, a total potential difference of 4 MV is needed in the sphere cooler, which requires a Van der Graff generator. High voltage grids in a spherical shell shape in the sphere cooler can be used to maintain a constant (or nearly constant) strength of the electric field in a radial direction. However, these grids in the helium gas would cause an electrical breakdown. How to realize a constant radial electric field in the sphere cooler without having electrodes in the gas needs to be investigated.

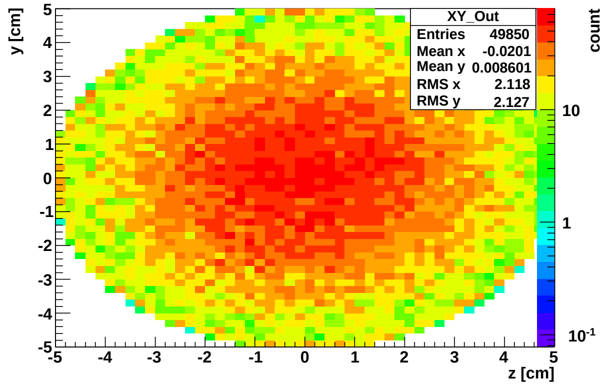


Figure 4: The transverse distribution of cooled muons entering the output solenoid.

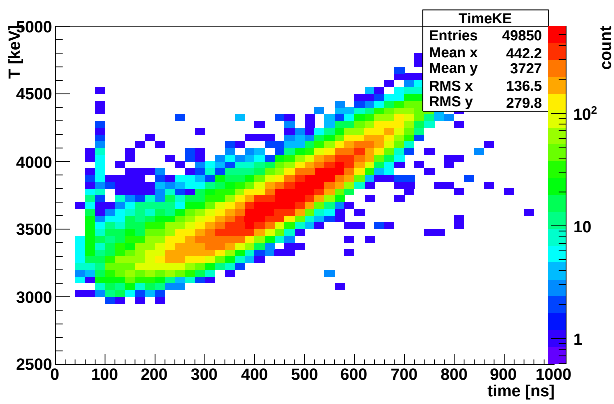


Figure 5: The distribution of the time of flight from the source to the output solenoid of the cooled muons and their initial energies.

One possible solution is to divide the sphere cooler into a series of cylindrical cells, which are arranged in a radial direction. In this way the high-voltage grids can be put outside the gas cells to provide a constant field. We are investigating such a "porcupine" scheme.

Differential pumping technology may provide a windowless cooling cell, so that the neutralization in the window can be avoided without accelerating the muons in gas, and the energy spread of the output can be reduced further.

The sphere cooler scheme can cool negative muons as well. Thin Foils can be used to provide the constant radial field and as the retarding material at the same time for negative muons, so that the breakdown problem could be avoided by having a ultra-high vacuum cooler.

The sphere cooler has a large acceptance of angular and energy spreads, but the required potential difference limits the maximum energy of the muon source. For application on a muon collider, precooling is needed to reduce the initial energies of the muons.

## CONCLUSION

Frictional cooling holds promise for producing low energy muon beams with small energy spreads. Our simulation shows that a sphere cooler scheme can cool a surface muon beam to a mean energy of $22\ \mathrm{keV}$ with an energy spread of $900\ \mathrm{eV}$. The efficiency for low-energy muon production is 50%, which is 3 to 4 orders of magnitude higher than the moderation technique. If such a scheme is experimentally successful, it could provide a muon collider with high quality muon source and reduced costs.

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