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PLASMA MUON BEAM COOLING FOR HEP

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Abstract

Ionization cooling has the potential to shrink the phase space of a muon beam by a factor of 10^6 within the muons short lifetime (2.2 µs) because the collision frequency in a cooling medium is extremely high compared to conventional beam cooling methods. Ionization cooling inherently produces a plasma of free electrons inside the absorber material, and this plasma can have an important effect on the muon beam. Under the right circumstances, it can both improve the rate of cooling and reduce the equilibrium emittance of the beam. This can improve the performance of muon facilities based on muon cooling; in particular a future muon collider. We describe how plasma muon beam cooling can be applied to both the basic Helical Cooling Channel (HCC) and extreme Parametric-resonance Ionization Cooling (PIC) techniques. This new approach to muon cooling can achieve significantly reduced muon beam emittance.

HELICAL COOLING CHANNEL

A helical muon cooling channel consists of a helical magnet, RF cavities filled with dense hydrogen gas [1, 2]. The gas reduces the dark current flow and therefore suppresses RF electric breakdown even when the cavity is operated in a strong magnetic field. In addition, dense gaseous hydrogen works as an ionization cooling medium. A helical cooling channel (HCC) is designed to maximize the advantage of utilizing gas-filled RF cavities for a six-dimensional (6D) ionization cooling channel. The beam trajectory is a spiral by solenoidal and helical magnetic components (Fig. 1). To avoid any pressure gap along the beam path, hydrogen gas is distributed homogeneously in the channel. RF cavities are located along the helical beam path. A thin RF window is located between adjacent cavities to electrically isolate them. Solenoidal and helical dipole magnetic field components are applied to generate continuous dispersion. Emittance-exchange occurs during the cooling process due to dispersion, which induces 6D phase space cooling. A helical magnetic field gradient continuously focuses the beam and stabilizes the phase space. Large acceptance of the channel is achieved because there is no betatron resonance in a continuous focusing channel. The HCC channel length is shorter than other ionization cooling channels.

A pictorial representation of a helical cooling channel is shown in Fig. 2. Compact dielectric loaded RF cavities are designed to fit inside the magnet. The magnet coils and RF windows are aligned along the helical beam path. The helical dipole component and the helical field gradient are generated by the stray field of the adjacent coils.

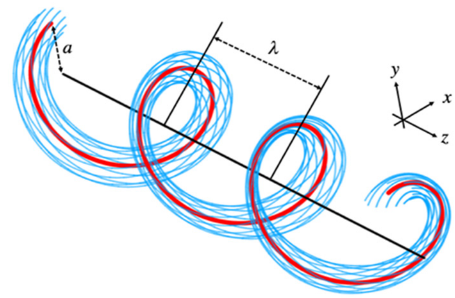

Figure 1: Typical beam paths in a HCC (blue), around a design reference orbit (red).

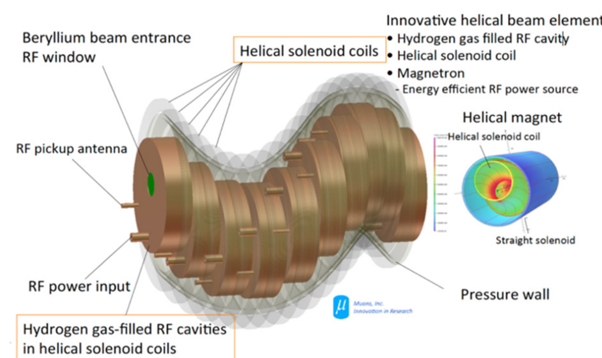

Figure 2: Pictorial drawing of an HCC channel.

Figure 2 also shows that the smaller inner radius of coil and thicker coil are required to generate stronger dipole fields and field gradients. This is an intrinsic limit to design the HCC with the helical solenoid coils. All of these details, including the construction of helical solenoid coils, were developed in SBIR/STTR projects of Muons, Inc. Several helical solenoid coils were made, and the geometry constraints were experimentally verified. Extensive beam simulations have been carried out for limited sections of HCCs as well as for complete cooling channel studies for multi-TeV muon colliders.

BEAM-INDUCED PLASMA FOCUSING

Beam-induced plasma in dense hydrogen gas opens many interesting subjects. Ionization electrons are quickly thermalized by momentum exchange with molecular hydrogen. The plasma regains kinetic energy from RF fields. This energy is transferred to the hydrogen gas via thermalization of the electron. As a result, RF power is transformed into the gas temperature at a rate proportional to the plasma

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density. This process is called the plasma loading effect, which can be mitigated by doping a small amount of electronegative gas in the cavity. Other plasma process parameters have also been measured experimentally [3, 4], and have been used in a numerical plasma simulation to evaluate the collective effect in a cavity for intense muon beam applications. The space charge of the beam is neutralized by the motion of the plasma and the tail of the bunched beam is strongly focused by the self-induced axial magnetic field (Fig. 3).

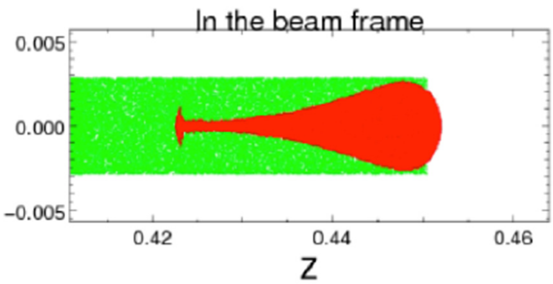

Figure 3: Muons (red) passing through hydrogen gas leave a beam-induced plasma trail (green).

This phenomenon is similar to a plasma lens that has been studied for the electron-positron collider at SLAC [5]. This new focusing mechanism can produce an extremely cold muon beam.

PLASMA FOCUSING IN A HCC

The geometry constraints of helical solenoid coil become more crucial to achieve smaller beam emittance. In order to overcome the geometry constraint, a plasma focusing is considered. The beam-induced plasma in the hydrogen gas filled RF cavity is polarized by the space charge field and forms a plasma sheath along the beam path. As a result, the self-induced toroidal magnetic field focuses the beam. The field polarity is always focusing the beam. From a simple model, the estimated toroidal field strength is

$$b_{plasma} = \frac{\mu_0 I \cdot (0.68)^2}{2\pi r},$$

where 0.68^2 is a correction factor to take into account the gaussian distribution. The field strength is determined from the beam current ($I = en_\mu v/2\sigma_z, 2\sigma_z = 2\varepsilon_{L,N}/(\beta\gamma \cdot (dp/p))$) and the RMS beam spot size ($r = \sqrt{\beta_T \cdot \varepsilon_T/\beta\gamma}$). Those are changed continuously in the cooling channel. For example, in the segment 2 the estimated beam current is 2000 amps and the RMS beam spot size is 20 mm, the toroidal field strength is 9 mT and the field gradient is 0.46 T/m. The helical solenoid coil should generate a field gradient 0.50 - 0.46 = 0.04 T/m. On the other hand, after the segment 4, the beam current and the RMS beam spot size are 20,000 amps and is 2 mm, respectively. The estimated toroidal field strength is 0.92 T and the field gradient is 460 T/m. The obtained field gradient is two orders of magnitude from the required field gradient in the HCC. note that the field gradient generated by the plasma is comparable to the quadrupole field of superconducting magnets at LHC. We never included this field gradient in the HCC cooling simulations. Thus, helical lattice tuning is needed and there is significant potential for improved cooling.

Most parameters of the beam-induced gas plasma are measured in the past experiment. Figure 4 shows the transverse focusing of the beam in a pure 100-atm hydrogen gas that is produced by the space charge neutralization effect by using the measured plasma parameters. A straight solenoid field is applied for the beam focusing. The front-end beam generates plasma, which neutralizes the space charge in the rest of beam, and the self-induced toroidal field pinches the back-end beam. The time constant of space charge neutralization is estimated by using a simple formula

$$\tau = \frac{\varepsilon_0}{(n_e/n_b)} \cdot \mu E.$$

The simulation provides τ = 20 ps. The neutralization time is longer with lower electron density. The electron density is adjusted by doping a small amount of O_2.

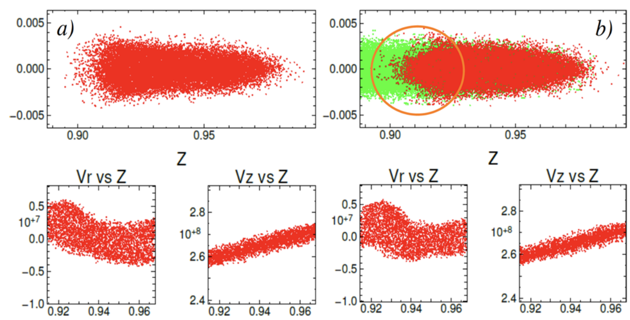

Figure 4: WARP simulations show the plasma lens effect without gas (a) and with gas (b). A red point is an incident particle and a green one is an ionization electron. Only a straight solenoidal magnetic field and RF field are applied, with no dispersion in this simulation. The orange circle shows that the beam is focused by the plasma lens.

PARAMETRIC-RESONANCE IONIZATION COOLING OF PLASMA COOLED BEAMS

The limit on the minimum achievable emittances in muon ionization cooling comes from the equilibrium between the cooling process and multiple Coulomb scattering in the absorber material. The concept of Parametric-resonance Ionization Cooling (PIC) is to push this limit by an order of magnitude in each transverse dimension by focusing the muon beam very strongly in both planes at thin absorber plates. This creates a large angular spread of the beam at the absorber locations, which is then cooled to its equilibrium value resulting in greatly reduced transverse emittances. Achieving adequately strong focusing using conventional magnetic optics would require unrealistically strong magnetic fields. Instead, PIC relies on a resonant process to provide the necessary focusing. A half-integer parametric resonance is induced in

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a cooling channel, causing focusing of the beam with the period of the channel's free oscillations. The resonant perturbation changes the particles' phase-space trajectories at periodic locations along the channel from their normal elliptical shapes to hyperbolic ones as shown in Fig. 5.

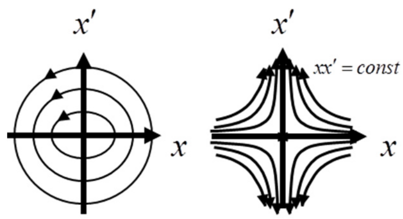

Figure 5: Parametric-resonance ionization cooling.

Thus, at certain periodic focal positions, the beam becomes progressively narrower in x and wider in x' as it passes down the channel. Without damping, the beam dynamics are not stable because the beam envelope grows with every period as illustrated in Fig. 6. Placing energy absorbers at the focal points stabilizes the beam motion by limiting the beam's angular divergence at those points through the usual ionization cooling mechanism. These dynamics then result in a strong reduction of the beam spot size at the absorber locations leading to transverse beam emittances that are an order of magnitude smaller than without the resonance. The longitudinal emittance is maintained constant against energy straggling by emittance exchange occurring due to dispersion or its slope at the locations of wedge or flat absorbers.

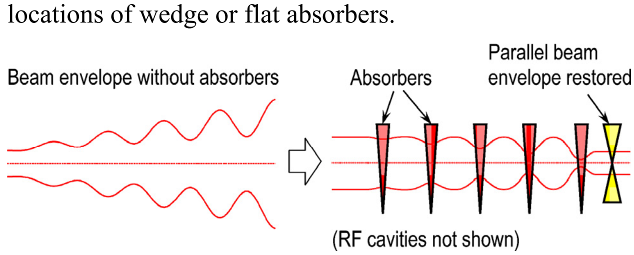

Figure 6: Stabilizing effect of ionization cooling energy absorbers in a channel with a half-integer resonance.

Cooling in a PIC channel was successfully demonstrated with stochastic effects ignored. To proceed to cooling simulations including stochastic effects, compensation of beam aberrations is required. But it is difficult to find a set of multipoles sufficient for aberration compensation that does not cause beam instabilities. The Skew PIC concept was developed to overcome this issue. Skew PIC introduces coupling into a cooling channel in such a way that the periodic focusing is preserved, but the canonical betatron tunes are shifted from the resonant values that caused issues in the PIC channel. The plasma focusing technique described in this proposal provides much stronger focusing magnetic fields than can be provided by conventional superconducting magnets. It allows for significant reduction of the beam size at the beam expansion points. This reduces the size of the aberrations and therefore greatly simplifies their compensation.

CONCLUSIONS AND FUTURE WORK

Plasma cooling is an important aspect of muon beam cooling. There are challenges in performing accurate and realistic simulations, because it combines multiple physics processes in a unique way:

1. A muon beam propagating in a magnetic lattice consisting of dipoles, quadrupoles, and higher-multipole magnets.
2. A muon beam being accelerated in RF cavities.
3. A muon beam interacting with the matter in the absorbers.
4. The electron plasma generated by #3 being affected by the magnets, the RF cavities, and the muon beam.
5. The muon beam being affected by the electron plasma.

Modeling item #5 is a major goal, but that cannot be done accurately without a self-consistent approach incorporating all five items. At present no beam-simulation code includes plasma physics, and no plasma-physics code includes beamline magnets, RF cavities, or a muon beam. We plan to investigate existing codes and determine how best to develop a simulation tool that has all the capabilities required by this project.

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