R&D on Extreme Six-Dimensional Cooling for a Muon Beam

Authors: K. Yonehara (Fermilab), D. Summers, and T. L. Hart (University of Mississippi)

We propose to investigate extreme six-dimensional (6-D) cooling for a muon beam. A collider luminosity gains inversely with the 1-D beam size at a collision point. A narrow energy spread makes a precise s-channel measurement at a collision point. The first approach of the extreme cooling is extending the conventional ionization cooling channel by using a cutting-edge high field magnet technology. The second approach is applying a conceptually new cooling scheme.

The strengths of our helical and rectangular muon cooling channels are simulated longitudinal and transverse cooling, respectively. The helical cooling channel uses an increased momentum slip factor to reduce ϵ_z to 890 microns [1]. The rectilinear channel uses short, low beta regions (β^*) to reduce ϵ_{xy} to 280 microns [2, 3]. The xyz emittances in the two channels are (610, 610, 890) and (280, 280, 1570) microns. A final cooling channel might both increase momentum slip and reduce β^* with strong focusing. This would increase muon collider luminosity by a factor of three. Two 57 m long cooling stages with short 21 and 28 T High Temperature Superconductor (HTS) solenoids have recently been added to the 969 m long rectilinear cooling channel and simulated. The result is ϵ_{xyz} = (140, 140, 1050) microns as shown in Figure 1. Our next goal is to increase momentum slip to further reduce ϵ_z. A 14 T HTS (RE)$Ba_2Cu_3O_{7-x}$ (REBCO, RE = Rare Earth) coil has been inserted into a 31 T solenoid to generate a 45 T magnetic field in Florida [4].

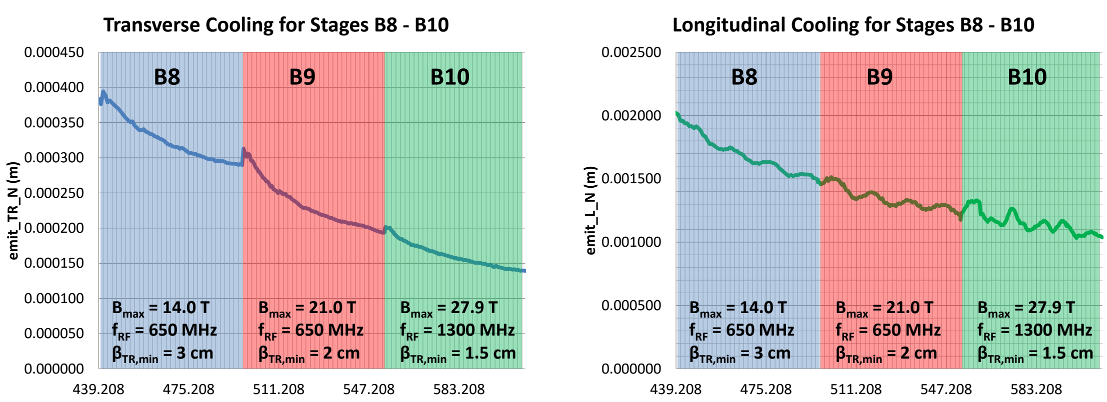

Figure 1: Additional rectilinear channel transverse and longitudinal muon cooling.

Parametric-resonance Ionization Cooling (PIC) has been proposed as the final 6-D cooling stage for a high-luminosity muon collider [5, 6, 7]. Combining muon ionization cooling with parametric resonant dynamics should allow an order of magnitude smaller final equilibrium transverse beam emittances than conventional ionization cooling alone. In this scheme, a half-integer parametric resonance is induced in a cooling channel causing the beam to be naturally focused with the period of the channel's free oscillations. Thin absorbers placed at the focal points then cool the beam's angular divergence through the usual ionization cooling mechanism where each absorber is followed by RF cavities. One of the PIC challenges is the compensation of beam aberrations over a sufficiently wide parameter range while maintaining the dynamical stability with correlated behavior of the horizontal and vertical betatron motion and dispersion.

Table 1: Expected PIC parameter

Parameter	Unit	Initial	Final
Muon beam momentum	MeV/c	250	250
Number of particles per bunch	10^{10}	1	1
Absorber thickness	mm	20	2
Normalized transverse emittance (rms)	μm	230	23
Beam size at absorbers (rms)	mm	0.7	0.1
Angular spread at absorbers (rms)	mrad	130	130
Momentum spread (rms) $\Delta p/p$	percent	2	2
Bunch length (rms) σ_z	mm	10	10

Plasma dynamics by interacting with a charged beam in a dense hydrogen gas filled RF cavity has been studied in experiment [8, 9, 10], and in numerical simulation [10] for evaluating the RF cavity as an ionization cooling device. The study suggests that a beam-induced plasma forms a plasma sheath along with a beam path, which is excited by the space charge of the incident beam. The space charge is neutralized by the plasma sheath. As a result, an azimuthal magnetic field is induced along the beam path, and the field focuses the beam. It is different from the conventional plasma lens because the plasma temperature is cold. A stronger focusing field is induced by a smaller beam size, which makes a colder beam by ionization cooling. In case of a simple rectangular beam, a 280-micron transverse emittance beam with 2×10^{12} muons may be able to generate a field of 425 T/m and a transverse beta function of 4 cm [11]. Further study is required in a Particle In Cell simulation for a muon beam [12] by using the High Performance Computer (HPC) to validate and improve the concept, and find out the theoretical limitation of cooling.

As a consequence, a goal of the proposed R&D is following.

- Optimize a cooling performance of the conventional cooling channel. Especially, a practical beam element will be added in the channel.
- Proof-of-principle of the PIC simulation. Especially, a non-linear component needs to be treated to compensate higher order aberrations.
- Validate and improve a concept of the plasma focusing by using HPC.

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