USAGE OF Li-RODS FOR IONIZATION COOLING OF MUONS

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Abstract

Four different schemes of final ionization cooling are discussed. The first scheme is the straight channel based on lithium rods, which can provide only 4-D cooling, but which can be modified to obtain 6-D cooling. The helical orbit scheme with decrement redistribution is one such modification. Two other modifications use emittance redistribution and emittance exchange procedures, respectively, to transfer phase-space volume from longitudinal to transverse degrees of freedom (where the transverse degrees of freedom alternate for each successive exchange or redistribution). By emittance redistribution is meant an arbitrary redistribution of phase-space volume from one degree of freedom to another and by emittance exchange is meant a symplectic operation of emittance swap. Estimates of the final emittance, calculations of the technical parameters and simulations of beam movement are presented. The study focused on the scheme with emittance exchange because it looks the most promising and simple, both conceptually and in terms of implementation, and it can also extend the cooling process to handle a larger initial emittance relative to the basic straight channel scheme.

INTRODUCTION

For the successful operation of a muon collider it is necessary to cool down the muon beams to reduce the 6-dimensional emittance by 5–6 orders of magnitude while preserving the intensity as carefully as possible. Such a progress in muon cooling is a must to reach sufficient luminosity.

The muon ionization cooling channel based on lithium rods (Li-rod) has been under consideration since the 1990s [1]. Li-rods provide muon energy losses due to ionization and simultaneously strong transverse focusing by carrying a very high current. While its technical realization is still in development, Li-rod usage may be a way to make the strongest focusing which is essential for the final cooling stage.

Unfortunately this scheme can provide only 4-D cooling, but it can be modified to obtain 6-D cooling. Three different modifications are discussed. The study focused on the scheme with emittance exchange because it looks the most promising and simple, both conceptually and in terms of implementation. The appropriate beam parameters for emittance exchange procedure and their dependence on transverse emittance and beam longitudinal parameters are discussed. Most simulations of muon beam cooling were performed using the specially developed software LyRICS (Lithium Rod Ionization Cooling Simulation). For numerical examples, we used muons around 200 MeV total energy since such energy is close to optimal.

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COOLING SCHEME UNDER CONSIDERATION

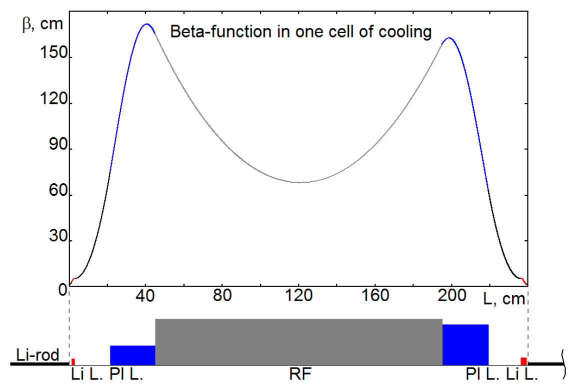

Figure 1: Example of the beta-function behavior in one period of the cooling channel.

The proposed cooling channel is based on Li-rods alternating with RF cavities. The matching between main elements is realized by the cascade of lithium and plasma lenses. The short lithium lenses (strong in comparison with plasma ones) make the beta-function a few times larger at the exit of lithium rods (smaller at the entrance) and weaken the low-aberration functioning of plasma lenses, which have longer focal length. An example of beta-function behavior along with parameters for one period of this cooling scheme are presented in Fig. 1 and Table 1 respectively, where the following abbreviations are used:

Li-r.	—	lithium rod
D.S.	—	drift space
Li l.	—	lithium lens
Pl l.	—	plasma lens
RF	—	RF cavity
E	—	energy at the exit of element, $[MeV]$
β	—	beta-function at the exit of element, $[cm]$
H	—	field on the surface, $[10^4 \times Gauss]$
I	—	current through the element, $[10^5 \times A]$
L	—	length of element, $[cm]$
D	—	diameter of element, $[cm]$

Table 1: Example of Element Parameters for One Period of the Cooling Channel

	Li-rod	D.S.	Li lens	D.S.	Pl. lens	RF	Pl. lens	D.S.	Li lens	D.S.	Li-rod
E	190	190	190	190	190	220	220	220	220	220	190
β	1.11	2.52	5	75.28	165	158	63.19	5	1.39	1.1	1
H	20	—	14.7	—	0.31	—	0.79	—	13.9	—	20
I	5	—	7.81	—	0.5	—	2.6	—	8.18	—	4
L	30	1.25	1.63	18.7	23.37	150	24.6	17.05	2.84	0.56	30
D	1	—	2.14	—	6.3	—	13.32	—	2.34	—	0.8

EXTENSION TO 6-D COOLING

6-D Cooling Schemes

In general, there are several ways how to organize 6-D cooling:

- The helical orbit scheme with *decrement redistribution*: analytical calculations show that the density gradient in Li-rod helix is not enough for 6-D cooling realization.
- *Emittance redistribution* usage for phase-space transferring from longitudinal to transverse degrees of freedom: at this moment this scheme is not clear and looks too complicated [2].
- *Emittance exchange* usage for phase-space transferring from longitudinal to transverse degrees of freedom where the transverse degrees of freedom alternate for each successive exchange: this scheme looks more promising and is discussed in more details below.

Limitations for Emittance Exchange Usage

The final value of full emittance is determined by the equilibrium value of the transverse emittance and how much phase-space volume is transfered from the longitudinal to transverse degrees of freedom during cooling. Therefore, the wish to redistribute as much as possible is natural, but there is a certain limitation. If the longitudinal second moment values are too small, the “diffusion’ process (a fluctuation of ionization losses) begins dominating and longitudinal heating goes faster (Fig. 2).

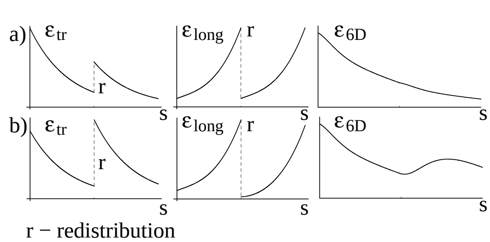

Figure 2: Behavior of full transverse, longitudinal and 6-D emittances as functions of the length passed in matter during cooling with the optimal redistribution from the longitudinal to transverse degrees of freedom (a.) and excessive redistribution with undesirable full emittance increment (b.).

Therefore, a proper value for the longitudinal emittance after redistribution, or rather a beam position on the $(c\Delta t, \Delta E/E_{eq})$ plane, and the dependence of that value on the transverse motion should also be determined for further simulations (Fig. 3).

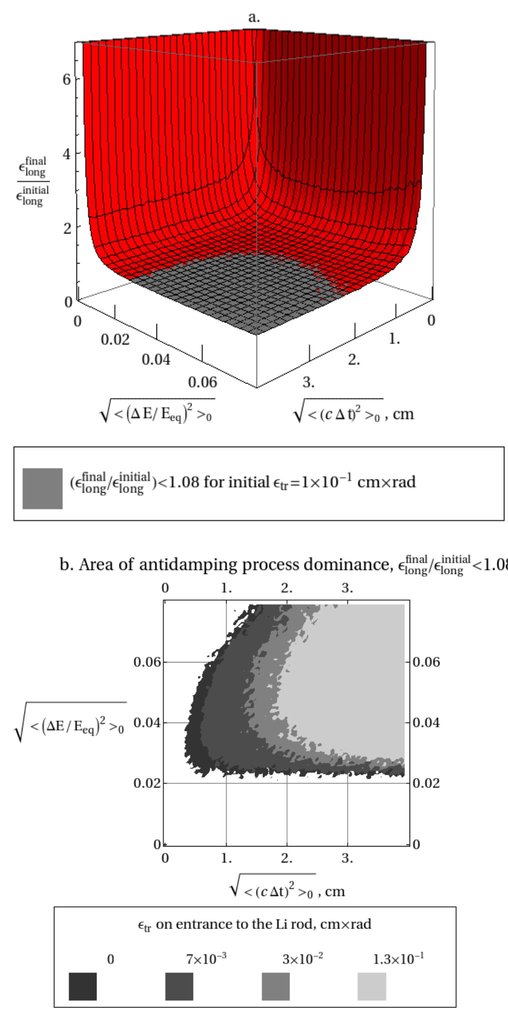

Figure 3: a. Growth of the longitudinal emittance as a function of the initial root-mean-square energy and arrival time spreads after passage through one lithium rod for a fixed value of initial ε_{tr}. b. The region in which the anti-damping process dominates over the fluctuation of ionization losses for different values of the initial transverse emittance after passage through one lithium rod.

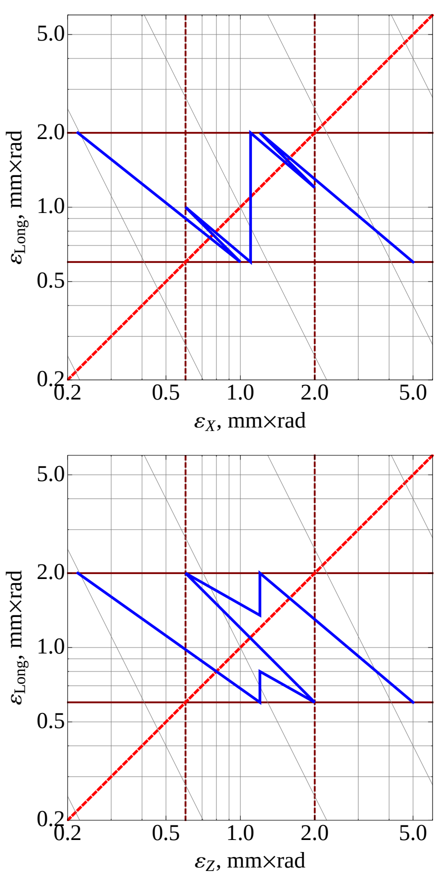

Figure 4: Idea of emittance exchange usage for Li-rod cooling scheme.

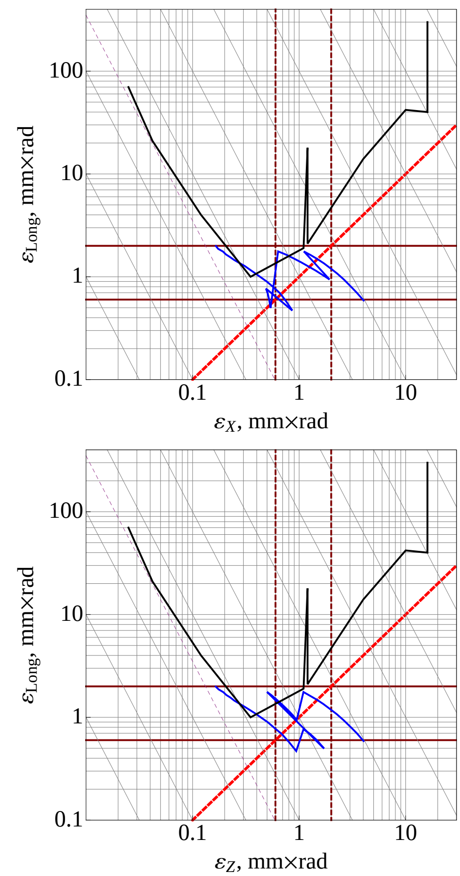

Figure 5: Preliminary simulation of cooling with emittance exchange usage.

PRELIMINARY SIMULATION WITH THIN EXCHANGE

The idea of emittance exchange usage is presented in Fig. 4. Since the cooling process is not symmetric with respect to x and z, there are two plots ε_{Long} vs. ε_X and ε_{Long} vs. ε_Z. Three emittance exchanges are used as follows: Long with X, Long with Y and then Long with X again. Diagonal gray lines are the levels of a full 6-D emittance for the case of equal transverse emittances. The brown horizontal lines approximately show the range of longitudinal parameters where Li-rods can be used: the bottom bound is referring to a "diffusion"-dominance region which was described above, and the top bound is referring to the RF-system parameters). The emittance exchanges let to map a point on this plots relative to a main diagonal (red dashed line). Therefore the intersection between horizontal and another one vertical bands (which is a flip image of a first one) is an area where emittance exchange procedure can be used. Otherwise, after the exchange the longitudinal emittance will be out of range of an adequate for this scheme parameters).

The simulation of this ideal case is presented in Fig. 5. The emittance exchange, RF and matching were simulated as ideal thin processes, but all Li-rods were simulated with taking into account all main effects such as dissipation, scattering and energy fluctuation. Black line is a general scenario of a full cooling process considered in many articles (e.g. [3]). *It seems that if emittance exchange parameters will have resonable values, this scheme can be included to the general scenario starting from the first exchange.*

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