THE STUDY OF A Li LENS SYSTEM AS A FINAL COOLER FOR A MUON COLLIDER*

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Abstract

Study is ongoing to find a final cooling channel using the Lithium lens in the muon collider. The goal is to achieve the transverse emittance $\varepsilon_{x,y}$ less than 0.1 mm-rad as required for injection into the muon collider. The final cooling channel is to incrementally cool the beam from about 0.5 to 1 mm-rad. We present here previous studies on ring structures which show cooling in the transverse emittance to the goal level and preliminary results of the ongoing work.

INTRODUCTION

Lithium lens has been studied for ionization cooling by UCLA members prior to this work [1-3]. The strong focusing and its low-Z property are the reasons for use in ionization cooling. The Li lens was developed in the 1980s by Dr. Silvestrov et al. at BINP in Russia [4]. The technology was transferred to CERN and Fermilab subsequently. We mention briefly here the solid Li lens at the Fermilab. The solid Li lens has been currently in use in the beam line of the anti-proton source for the Tevatron collider at the lab. The solid lenses are of the dimensions of 2 cm dia. × 15 cm length and were designed and developed at the Fermilab [5]. The azimuthal direction B field focuses the charged antiprotons axially downstream from the target for increased particle collection.

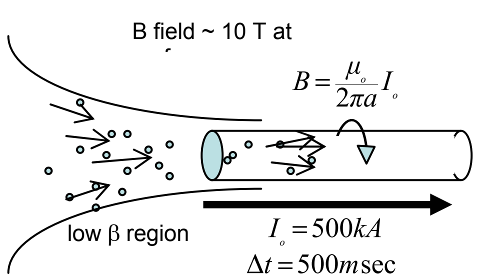

Figure 1: Lithium lens focuses the beam by the azimuthal B field generated by a pulse of 500kA current of a few hundred msec duration.

Liquid Li lens was also first developed by G. Silvestrov at BINP. He developed the liquid Li lens also for the Fermilab in 1990s for use in the anti-proton source beam line. The advantages of the liquid lens option over the solid lens are the expected longer life time and the higher pulse rate of operation. The current Fermilab solid lens operates only at the ~2 Hz and for no more than 6 months. However, due to complexities involved in the system over the solid system and the time constraint allowed by collider run II startup, work was stopped in 2001 after some initial success [4].

Here, we briefly summarize the history of Li lens work relevant to the current work. Ionization cooling studies were performed using Li lens early in 2000's in ring structures to achieve 6-D beam cooling. In the studies by A. Garren and Y. Fukui in 2002-2004, transverse cooling was achieved in the simulation of the ring structures [1,2]. In subsequent studies by Y. Fukui from 2004-2008, curved Li lens ring was shown 6-D cooling [3]. While UCLA members have considered Li lens for ionization cooling, we are currently taking on the simulation study in the final cooling stage. The larger muon beam size at the upstream stages might exclude the use of the Li lens with the existing ones at only at 2 cm diameter.

SIMULATION STUDY

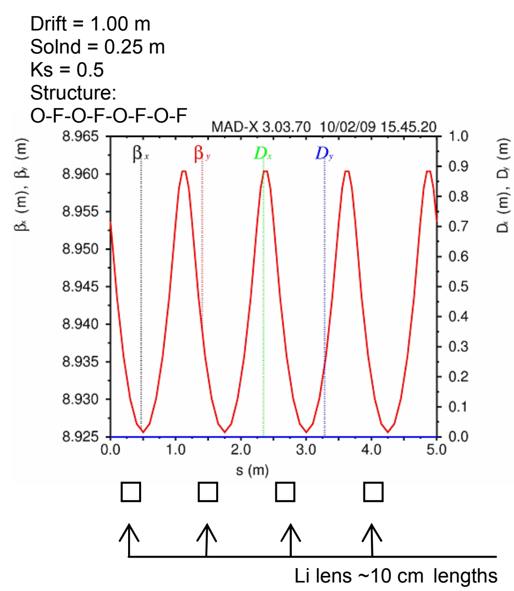

Figure 2: Beta function of the solenoidal channel as calculated using the MADX code.

Our study is ongoing to find a final cooling channel using the Lithium lens in the muon collider. The goal is to achieve the transverse emittance $\varepsilon_{x,y}$ less than 0.1 mm-rad as required for injection into the future muon collider, from the emittance of about 0.5 to 1 mm-rad [6].

In the current work, we consider repeated structure of solenoids with Li lens in between and also simple repeated structure of Li lens. The former was motivated by a previous work by P. Spentzouris [7]. In the solenoidal channel we considered, the solenoids are positioned 1 m apart to form low beta waist regions in the

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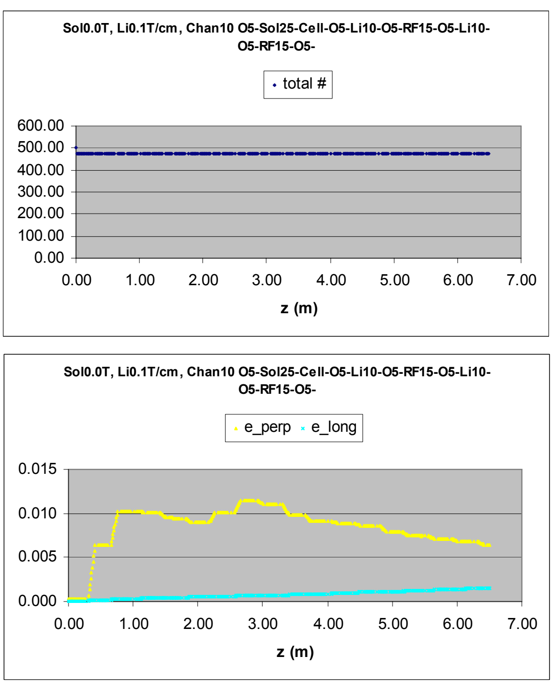
channel where the Li lens can operate, where cooling is maximal [8]. The simulation study has been carried out using the MADX code, the ICOOL code v.3-10 and ICOOL associated codes such as EMITCALC.

The ICOOL simulation results show that the focusing strength by the Li lens with field gradient ~ 1 T/cm is comparable to that of the solenoids of 25 cm length and ~15 T B field. Due to the comparable focusing strengths, the addition of the Li lens components as suggested in Figure 2 into the straight channel of the solenoids modifies the original beta function significantly. Simply positioning the Li lens into the narrow waist regions of the original beta function did not result in beam matching. With many iterations of the ICOOL run tweaking the field gradient of the Li lens, beam matching was eventually achieved. For the strong solenoid field of 18 T, the Li lens field gradient was correspondingly of 1.86 T/cm. While beam matching appears to be achieved in Fig. 5a for this channel, there remain many slight mismatches, and overall beam cooling was not achieved.

A straight channel of only a series of Li lens and RF cavities was also studied. The solenoids were either removed from the channel or the field was set to zero. For a parallel initial beam profile, beam matching was achieved with a weaker focusing strength of only 0.1 T/cm. In both channel configurations, field strengths were uniform for all components of the same kind.



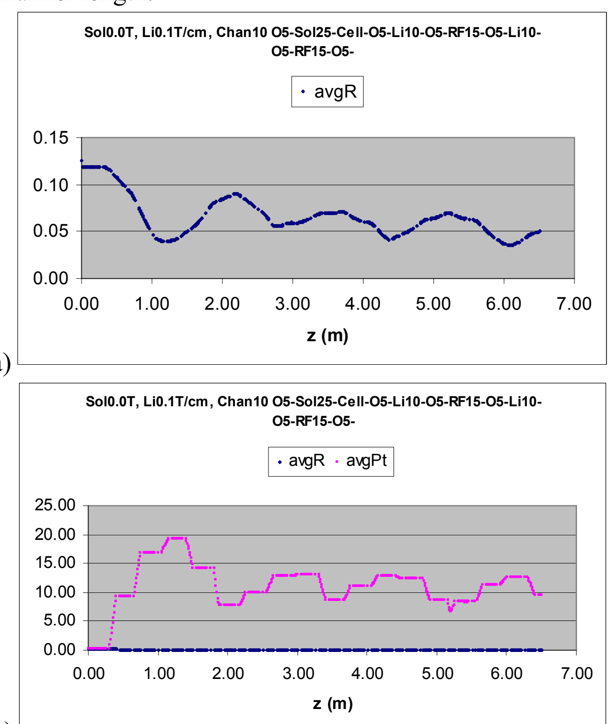
a)

b)

Figure 3: In a) is the particle number in the channel tracking over the 6.5 m length. In b) the plot shows decrease in transverse emittance after 3 m.

In Figure 3 are results of the channel with only Li lens and RF cavities. The channel structure is described in the title line at the top of the plots. O5 means a drift length of 5 cm and Li10 means a Li rod length of 10 cm. The Li rods are of 20 cm in diameter. In this channel, the solenoid field is turned off. The Li lens gradient is 0.1 T/cm. The transverse emittance at the channel entrance is ~$2.5\times10^{-5}\pi$ m-rad or 0.08 mm-rad. The entrance beam is nearly parallel with a spot size of 10 cm radius. In the future, we will use more realistic beam profiles for the studies.

In the tuning of the channel to achieve beam matching, it was helpful to view the graphs of the RMS R transverse position and the RMS Pt transverse momentum as in Figures 4 and 5. They were used to achieve minimal beam envelope in each channel type. The Li lens field gradient was adjusted as best possible until the RMS R curve comes out of the Li lens component with the zero slope. With zero slope entering in the subsequent drift space or the RF cavity, the beam RMS R then does not grow. In order to achieve a decrease in the transverse emittance, both the RMS R and the RMS Pt must decrease over the channel length.



a)

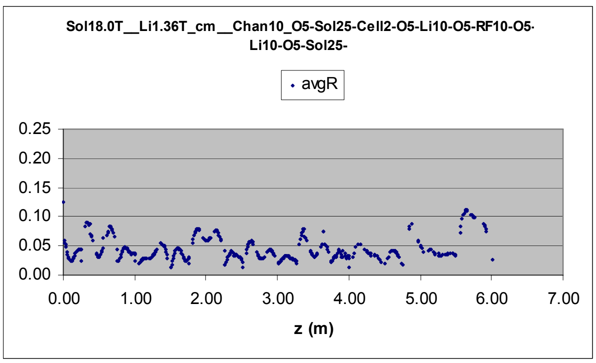
b)

Figure 4: Plots of the RMS R and Pt over the channel of a series of only the Li lens and the RF cavities. The steps in the RMS Pt plot correspond to the Li lens focusing by the 0.1 T/cm field. The anti-correspondence is seen between the RMS R and Pt. The steps also correspond to structures in the emittance plot in Fig. 3b.

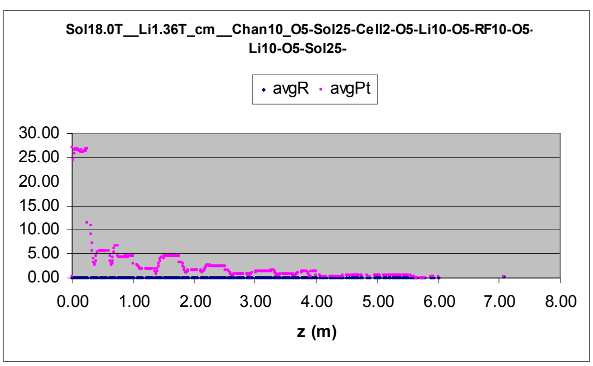
A parallel beam profile was used for its ease in achieving cooling in the channel. For a non-parallel initial beam profile, stronger focusing fields were required to contain the beam against the non-zero momentum spread. The channel then had to be highly tuned and consequently has less tolerance for field errors. With stronger focusing strength of the components, the RMS R curve was seen with many cusps as in Fig. 5a, indicating slight mismatches. The mismatches cause growth in the RMS R and subsequently no beam cooling with beam loss.

CONCLUSION

Although, the study has not achieved the 0.1 mm-rad for the final cooling stage, the decreasing trends indicate the continued decrease beyond the 6 m length in the channel with only a series of Li lens and RF cavities. The ‘cooling’ observed provides motivation for further optimization of the Li lens channel to include beam profiles of no parallel beam. We plan to continue with the simulation effort to achieve final cooling emittance of fewer than 0.1 mm-rad, also using realistic profiles at the channel entrance.



a)



b)

Figure 5: Plots of the RMS R and Pt over the channel of a series of solenoids, Li lens and RF cavities. The steps in the RMS Pt plot correspond to the focusing by the 1.86 T/cm field gradient of the Li lenses and by the edge field of the 18 T solenoids.

REFERENCES

[1] Y. Fukui, et al., "Progress in Designing a Muon Cooling Ring with Lithium Lenses," Proceedings of the 2003 Particle Accelerator Conference.

[2] Y. Fukui, et al., "A Muon Cooling Ring with Curved Lithium Lenses", Proceedings of the 2005 Particle Accelerator Conference, IEEE01591401.

[3] Y. Fukui, et al., 6 Dimensional muon phase space cooling using curved lithium lenses, Proceedings of the 2007 Particle Accelerator Conference.

[4] http://www-bdnew.fnal.gov/pbar/Projects/liquidlilens/liquidli.htm ; B.F. Bayanov et. al, “Large Cylindrical Lenses with Solid and Liquid Lithium,” EPAC 1988, http://epaper.kek.jp/e88/PDF/EPAC1988_0263.PDF

[5] J.P. Morgan and T. Leveling at Fermilab, private communication.

[6] R. Palmer et al., “A Complete Scheme of Ionization Cooling for a Muon Collider”, Proceedings of the 2007 Particle Accelerator Conference.

[7] P. Spentzouris, "DPGeant Simulation and Design Studies of Ionization Cooling using lithium lenses and solenoid transport channels", MuCOOL note 47.

[8] D. Neuffer and B. Palmer, "Progress Toward a High-Energy, High-Luminosity $\mu^+\mu^-$ Collider," Sausalito 1994 workshop on Physics Potential and Development of $\mu^+\mu^-$ Collider, AIP Conference Proceedings 352.