# PARAMETER OPTIMIZATION FOR MULTI-DIMENSIONAL LASER COOLING OF AN ION BEAM IN THE STORAGE RING S-LSR*

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*Abstract*

S-LSR is a compact ion cooler ring built in ICR, Kyoto University, aiming at creating ultra-low temperature ion beam by laser cooling. In order to approach lowest possible temperature at S-LSR in an experiment, parameters of laser cooling should be carefully chosen by simulation. This paper mainly concerns optimization of laser cooling parameters and prediction of possible low limit of beam temperature at S-LSR. Firstly, the adiabatic capture process of ion beam is introduced and studied. Then, different laser profile parameters are compared and an optimized value is chosen. After that, optimized solenoid field strength for 3-D coupling is proposed. At last, by choosing the parameters proposed, the lowest beam temperature achievable for S-LSR is predicted to be 10 K in transverse direction and 0.05 K in longitudinal direction.

## INTRODUCTION

Cold beam, or low emittance beam, usually means less beam loss and smaller necessary beam aperture. Considerable effort towards ultra-cold beam was devoted in 1990's by two European teams (the TSR group at Max Planck Institute [1, 2] and the ASTRID group at Aarhus University [3, 4]). Both teams applied the laser cooling technique [5, 6] to various heavy ions and succeeded in reducing the longitudinal beam. However, the possible lowest emittance is limited by the linear coherent resonance crossing unavoidable in both TSR and ASTRID rings [4, 7, 8]. S-LSR [9], a compact ion cooler ring built in ICR, Kyoto University, has a potential to overcome the difficulties encountered by the European teams. For instance, we can reduce the betatron phase advance per single lattice period near or even below 90 degrees and avoid strong beam heating due to the linear resonance crossing. It is also possible to employ the resonant coupling method (RCM) [10, 11] and enables us to produce an ultimate ion beam that has a temperature near the absolute zero in all three dimensions [12, 13]. This paper mainly concerns optimization of laser cooling parameter and prediction of low limit of beam temperature at S-LSR.

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## BUNCHED-BEAM LASER COOLING

S-LSR is a compaction cooler ring with an electron cooling system and a laser cooling system. It has six-fold symmetric lattice and each lattice consists of a bending magnetic two quadruples and one 1.86 m long drift line, two of which are occupied by an electron cooler and a laser-beam interaction section as Fig. 1. A 40 keV $Mg^+$ beam is injected continuously into the ring and captured and bunched by a RF cavity. The laser is set co-propagating with the $Mg^+$ beam and is slightly tuned below the transmission frequency of the beam. With the synchrotron motion of bunched-beam, particles automatically falls into the cooling region of the laser, thus making bunched-beam cooling possible by single laser. [14]

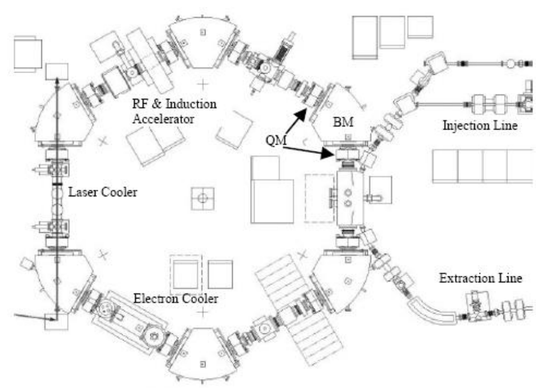


Figure 1: Layout of the ion storage ring [9].

In order to realize multi-dimensional laser cooling, the idea of RCM has been induced [10, 11]. In S-LSR, we adjust the working point around ($\nu_x$, $\nu_y$, $\nu_z$) = (2.075, 1.120, 0.075) for 2-D cooling and working point around (2.075, 1.075, 0.075) for 3-D cooling. Longitudinal direction and horizontal direction are coupled by dispersion; horizontal direction and vertical direction are coupled by solenoid field.

Simulations are specially designed for this single laser bunched-beam cooling experiment at S-LSR. The parameters are all chosen according to the data or past experiment result of S-LSR. A molecular dynamic simulation code, CRYSTAL, developed for the laser-cooling and crystalline-beam study, was used [12].



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An ideal cooling method would cool all the particles to a certain low temperature. However, simulation shows that there are always particles not captured by laser in the longitudinal phase space, making a hot corona existing together with a cold beam core. See Fig. 2 for a typical longitudinal phase space distribution after laser cooling.

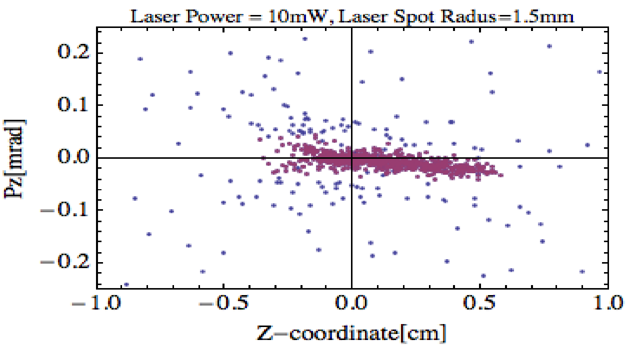



Figure 2: A typical phase-space plot after laser cooling. The magenta dots represent captured particles while blue dots shows hot beam corona.

## COOLING PARAMETER OPTIMIZATION

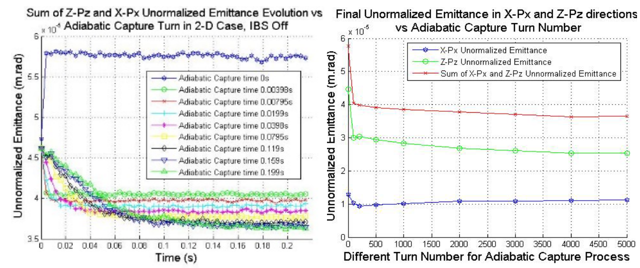
In order to maximize the cooling effect, various parameters should be optimized. Main experimental parameters are summarized in Table 1. Final detuning is chosen as minus half of the natural band width or $-\Gamma/2$, where the friction force is thought to be maximum. In our case, the frequency is 3.34 MHz or -1.1e-5 equivalent momentum spread. Laser scanning is applied in S-LSR to perform continuous laser cooling. Other parameters such as adiabatic capture time, laser spot size with saturation parameter, and solenoid field, should be carefully optimized by simulation. In this part, we assume that intra-beam scattering (IBS) effect is small enough and doesn't change the optimum value of each parameter, so we ignored the space-charge effect in the following simulations unless otherwise noted.

Table 1: Main S-LSR Parameters

| Parameter | Value |
|---|---|
| Circumference | 22.557 m |
| Average Radius | 3.59 m |
| Ion Species | $^{24}Mg^{+}$ |
| Kinetic Energy | 40 keV |
| Frequency | 25.145 kHz |
| Initial Momentum Spread | 7.0e-4 |
| Typical Laser Power | 10 mW |

### *Adiabatic Capture Process*

At S-LSR, $Mg^{+}$ beam is injected continuously in to the storage ring, forming a coasting beam circulating around the ring. To prevent emittance blowing up during the bunching, the adiabatic capture process is conducted in S-LSR. During the adiabatic capture process, the RF cavity voltage increases linearly from 0 to designed RF voltage decided by the synchrotron tune. So the only parameter needs to be optimized is the capture time. It can be easily seen from Fig. 3 that adiabatic capture process is a very effective procedure on preventing blowing up in emittance due to beam bunching process and even a very short period, would be far better than no adiabatic capture process. According to the result, an adiabatic capture time no less than 0.1s would be preferred by avoiding phase space dilution and strong emittance exchange.



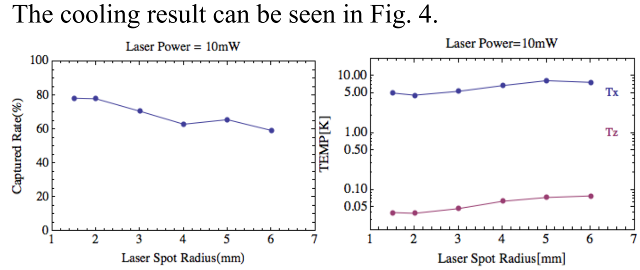

(a) (b)

Figure 3: (a) The sum of X-Px and Z-Pz un-normalized emittance evolution vs. different adiabatic capture time in 2-D case (b) Final un-normalized emittance in X-Px and Z-Pz directions vs. adiabatic capture turn number.

### *Laser Profile Parameter*

The total output power of laser available at S-LSR has now become the main constraint. A maximum output laser power of no more than 15mW is now available. On the other side, by maintaining a certain laser power, the laser profile parameters, namely laser waist radius R and centre saturation parameter S are able to adjust where $SR^2$ is kept constant.

As a result, optimizing laser cooling effect by optimizing laser waist radius and centre saturation parameter is important. In our simulation, laser waist radius varies 1.5 mm to 6 mm. IBS is turned on. And laser is kept at 10 mW. Laser cooling was maintained for as long as 5s. 2-D cooling is applied in these simulations. The cooling result can be seen in Fig. 4.




(a) (b)

Figure 4: Laser profile parameter optimization of certain power of laser in 2-D laser cooling. (a) Capture rate of laser cooling using different vs. laser spot radius, (b) The final temperature of captured particles vs. laser spot radius, IBS on, number of particles simulated is 300.

From the result, we can see that the capture rate goes down while the final captured particle temperature goes up with laser radius going up, indicating smaller laser radius would be more effective in suppressing IBS effect in cold beam cores. If our goal is to get lowest possible captured beam temperature while maintaining a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reasonable capture rate in real case, a smaller laser radius of 1.5 mm would be preferred.

### *Solenoid Field*

In 3-D laser cooling process, solenoid field should be turned on to couple horizontal direction and vertical direction. However, an optimized solenoid field for S-LSR remains unknown. In this part, solenoid field is changed from 50 Gauss to 400 Gauss and 3-D laser cooling is put forward and the cooling effect is then checked. The result can be seen in Fig. 5.

According to the calculation, if our final target is to get a cold particle core instead of getting the lowest total emittance, we can find out that the best solenoid field would be around 100 Gauss. And no matter too big or too small solenoid field is not good for coupling condition. Low solenoid would reduce the coupling between vertical and horizontal direction and high solenoid field would break the coupling condition between longitudinal and transverse direction. So a suitable solenoid field should be chosen to attain good cooling effect.

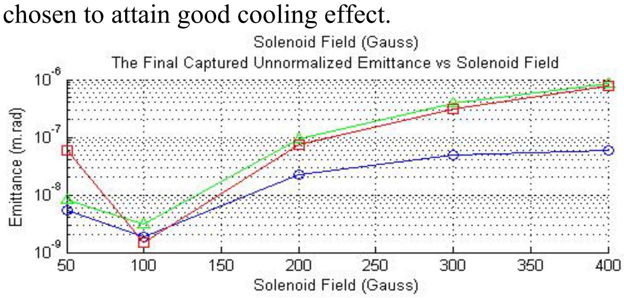


Figure 5: Result combination of cooling result vs. different solenoid field.

## PREDICTION OF LOW- TEMPERATURE LIMIT AT S-LSR

Up to now, we have been talking about the optimum choices in bunched-beam laser cooling at S-LSR. Long term study shows that in order to achieve transverse laser cooling, differential resonance condition should be imposed. Laser scanning should also be imposed to increase particle capture. And it has also been suggested that in order to gain a more satisfactory cooling result, adiabatic capture process is needed. With very limited laser power, the laser profile should be adjusted and a small laser radius as 1.5 mm is preferable for compressing IBS heating effect. For 3-D laser cooling, a solenoid is opened to couple X and Y degree of freedom and the optimum solenoid field would be 100 Gauss.

To see how far we can actually go under this real situation, IBS effect is considered in the following simulations. The simulated number of particle is varied from 200 to 1000 to see the particle number dependence of IBS heating in S-LSR. According to the simulation result, capture rate drops, final rms beam radius, normalized cold beam core emittance and temperature goes up with the number of initial particles. This is because IBS effect gets enhanced by larger number of particles. Thus we prefer lower number of particles to reduce IBS heating effect. However, around 1000 particles per bunch are near the limit of detection. At that circumstance, we can achieve around 600 particles cooled. The final temperature of cold beam core would be around 10 K in transverse direction and 0.05 K in longitudinal direction, as shown in Fig. 6.

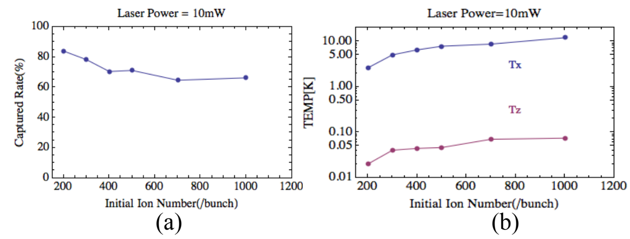


Figure 6: S-LSR real situation laser cooling simulation with IBS on. Cool effect of different number of particles. (a) Final rms beam radius vs. number of particles; (b) Final transverse and longitudinal temperature vs. number of particles.

## CONCLUSION

The power of the cooling laser currently available in S-LSR is quite limited. We then expect the achievable beam temperature to be much higher than the Doppler limit even with the RCM. Nevertheless, considering the high potential of S-LSR, according to the simulation study, even with this limitation in the laser system, it seems feasible to break the world record of lower limit of the beam temperature. This paper gives useful insights for the laser-cooling experiment under a practical situation. By carefully choosing laser cooling parameters, we can finally arrive in a cold ion beam with temperature around 10 K in transverse direction and 0.05 K in longitudinal direction. However, the result is a theoretical lower limit achievable by current S-LSR system and recent experiment results still arrive in higher temperature after cooling [15]. And we also expect that with an upgrade of the laser system in S-LSR in the future, a colder beam with an even lower temperature would be possible to be realized.

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