Abstract. A compact ion cooler ring, S-LSR is under construction in Kyoto University. One of the subjects of S-LSR is a realization of the crystalline beams using the electron beam and the laser cooling. The ring is designed to be satisfied several required conditions for the beam ordering, such as a small betatron phase advance, a small magnetic error and a precise magnet alignment. The design phase advance per a period is less than 127 degree. The calculated closed orbit distortion and the stopband is less than 1 mm and 0.001 without correction, respectively.

Keywords: Ion Cooler Ring, Electron Cooling, Crystalline Beam.

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INTRODUCTION

In Kyoto University, a new ion cooler ring (S-LSR) is now under development. Figure 1 shows the layout of the ring and the table 1 shows the main parameters of the ring. The circumference of the ring is 22.557 m and the maximum magnetic rigidity is 1 Tm. S-LSR has an electron beam cooling system and a laser cooling system [1]. The maximum electron energy is 5 kV and the maximum electron beam current is 400 mA. The laser cooling system consisted Dye lasers excited by a solid state green laser, and sub-harmonic generators. The system covers from the visible light to ultraviolet light.

The peculiarity of the ring is that it is optimized for the beam cooling, especially the realization of the ultra-cold beam. One of the goals of S-LSR project is a realization of the crystalline beams. Many analytical and numerical studies predict the possibility of the crystalline beam and the required condition of the formation. S-LSR is designed and the technical developments have to be carried out to be satisfied these conditions.
The strategy to achieve the crystalline beam is step by step. The first step is to achieve the 1-D crystal (string) of the 7 MeV proton beam using the electron beam cooling. The second step is to achieve the 1-D crystal and 2-D crystal (zigzag) of the low energy Mg\(^+\) beam using the 3 dimensional laser cooling [2]. Even with the shearing force, the zigzag structure can be stable in the molecular dynamics (MD) simulation. The third step is that the formation of the simple 3-D crystal (1 shell) using the laser cooling and an electrostatic deflector in the vacuum chamber of the bending magnet, which has a role to cancel the shearing force [3].

![FIGURE 1. Layout of S-LSR.](image)

<table>
<thead>
<tr>
<th>TABLE 1. Main specification of S-LSR.</th>
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<tbody>
<tr>
<td><strong>Ring</strong></td>
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<tr>
<td>Circumference</td>
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<tr>
<td>Average radius</td>
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<tr>
<td>Length of straight section</td>
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<tr>
<td>Number of periods</td>
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<td>Max. magnetic rigidity</td>
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**Development of the Cooler Ring**

The key issues of the design of S-LSR is reduce the beam heating as small as possible in order to realize the ultra cold beam and the crystalline beam. Even if the electron beam cooling and the laser cooling are used, it is difficult to overcome the strong beam heating from the ring itself. The following items are considered in the design stage and the development has been carried out.

1. High symmetry of the ring lattice. This is important to reduce the phase advance per a superperiod. In S-LSR, the number of the superperiod is 6 to keep the reasonable length of the straight section for the cooling.
2. Small phase advance per a superperiod. It is less than 127 degree in the normal operation mode, even in the zero-dispersion mode using the electrostatic deflector in the bending magnet chamber [4]. The minimum phase advance is less than 90 degree in the special mode. This condition is necessary to avoid the beam heating due to the linear resonance.
3. Small individual differences among the magnets. The differences of the magnets break symmetry of the ring and increase the stop band of the resonance, which is the source of the beam heating. The all magnets are made from the block irons and fabricated precisely.

4. Precise alignment of the magnets. The alignment errors also create the magnetic field error and have the same effect as above.

5. Compensation system of the shearing force. Even if the beam crystal is created, the complicated crystal is destroyed by the shearing force in the bending magnet. In order to cancel the effect, an electrostatic deflector is placed in the vacuum chamber of the bending magnet [5].

**Lattice Design**

Figure 2 shows the twiss parameters of one period for the crystalline modes. The betatron tune is (1.45, 1.44) at the left figure. The phase advance in this mode is 86 degree, which is less than the important criteria of 90 degree. It is important to avoid the envelope instability. The electron cooling is possible but we do not find the suitable method of the three dimensional laser cooling in this mode.

The right one in the figure 2 shows the twiss parameters when the betatron tune is (2.08, 1.07). In this mode, if we set the synchrotron tune of 0.07, we obtain the strong transverse-longitudinal resonance coupling and the three dimensional laser cooling becomes possible. The phase advance per a period is still lower than the 127 degrees at this tune value.

![FIGURE 2. Twiss parameters in one period of S-LSR. The operating tune is (1.45, 1.44) in the left, (2.08, 1.07) in the right figure.](image)

**Magnetic Field Measurement**

The figure 3 shows the bending magnet and the quadrupole magnet for S-LSR. They are made from the block ion and fabricated carefully to reduce the individual differences. The differences enhance the closed orbit distortion and the stop band of the resonance. One more important point is to reduce the nonlinear magnetic field. It induces the nonlinear resonance and it leads to the beam heating with the high tune
depression. The design of the magnets were done by the three dimensional magnetic simulation code (TOSCA) and optimized to minimize the high order component [6][7].

We measure the magnetic field of the bending magnet using the three Hall probes (Group3 TP141) and the field gradient of the quadrupole magnets was measured by a shift coil method. The difference of the BL products among 6 bending magnets is shown in the figure 4 (left). It is within +/-2x10^-4 without corrections. The difference of the GL products among 12 quadrupole magnets is shown in the figure 4 (right). It is within +/-2.5x10^-3.

The resultant closed orbit distortion is 1 mm and the stop band is 0.001 due to the above differences. It will corrected by the correction current or correction coils in the operation.

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**FIGURE 3.** View of the bending magnet (left) and the quadrupole magnet (right).

**FIGURE 4.** Layout of the S-LSR.
Magnet Alignment

The precise alignment of the dipole and quadrupole magnets is also important to suppress the closed orbit distortion and the stop band. It was carried out using the laser tracker (LEICA, LTD800) and the level (LEICA, N3). The measurement accuracy of the laser tracker is 40 mm in this situation. After the fine alignment, we measured the position of the alignment targets on the magnets again by the laser tracker. The results are shown in figure 5. The left one shows the results of the bending magnet and the right one is quadrupole magnets. In the both cases, 65% of the alignment targets on the magnets are placed within the error of +/-50 μm and all targets are placed within +/-100 mm.

The effect of these alignment errors on the closed orbit distortion and the stopband is smaller than that from the differences of the magnets which is discussed in the previous section.

FIGURE 5. Alignment error of the bending magnets (left) and the quadrupole magnets (right).

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REFERENCES