LATTICE DESIGN AND COOLING SIMULATION AT S-LSR

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Abstract

A compact ion cooler ring, S-LSR is under construction in Kyoto University. It has an electron beam cooling device and a laser cooling system. The circumference is 22.557 m and the maximum magnetic rigidity is 1 Tm. One of the important roles of S-LSR is a test bed to examine the lowest temperature limit of the ion beams using cooling techniques. The ultimate case is a crystalline one. The ring optics of S-LSR has a high super periodicity and a low phase advance to reduce the beam heating from the lattice structure.

INTRODUCTION

In Kyoto University, a new ion cooler ring (S-LSR) is now under construction for the beam physics related to the beam cooling [1]. Figure 1 shows the layout of S-LSR. It has an electron beam cooler with the electron energy of 5 kV and the laser cooling system using a Dye laser and a sub harmonic generator. S-LSR has three kinds of ion injectors. A 7 MeV proton linac and a laser produced ion source [2] are used for the electron beam cooling experiments. Especially, the technical developments of the accumulation and the cooling of the laser produced ions are the important subjects of S-LSR. A direct injection from 50 keV heavy ion source is used for the laser cooling. The purpose of the laser cooling experiment is a physics of an ultra-cold beam, especially the study of the crystalline beams. Many analytical and numerical studies predict the crystalline beam and the required condition of the formation [3-5]. This is one of the goals of S-LSR project.

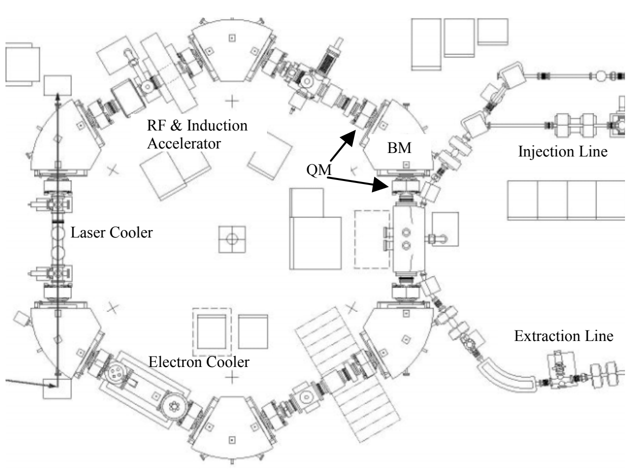

Figure 1: Layout of S-LSR.

The circumference of S-LSR is 22.557m and the maximum magnetic rigidity is 1 Tm, which is enough high to accept the beams from above ion injectors. Table 1 shows the major parameters of S-LSR. The applications of the cooled beam are also important subjects of S-LSR. S-LSR has a fast extraction system for the beam applications using the crystalline beam or an ultra-short bunch beam, which is formed by the electron beam cooling and the RF bunch rotation.

LATTICE DESIGN

The key issue of the lattice design is to adopt the super-period number of 6. It is a minimum number to achieve the phase advance less than 90 degrees in the period. It is important to avoid the envelope instability, which is severe during the deep cooling process [5]. In the other hand, the length of the drift space becomes shorter compared with the super-period number of 4. To maximize the drift space in the limited space, a bending magnet and two quadrupole magnets are closely placed with each other. Figure 2 shows the one unit of the bending magnet and the quadrupole magnets. The distance between them is 0.20 m and an iron plate is installed to eliminate the field interference.

The bending magnet has a deflector electrode in the vacuum chamber [6]. It works for the low energy heavy ion beams. This ring has both features of the magnetic ring and the electrostatic ring.

Table 1: Major parameters of S-LSR

Ring	
Circumference	22.557 m
Average radius	3.59 m
Length of straight section	2.66 m
Number of periods	6
Bending magnet	6 unit
Maximum field	0.95 T
Curvature radius	1.05 m
Gap height	70 mm
Quadrupole magnet	12 unit
Length	0.20 m
Bore radius	70 mm

The length of the drift space is determined by that of the cooling devices. In the final design, the length of the drift space is 1.86 m. The total length of the electron beam cooler is 1.63 m and the effective cooling length is 0.50 m, which corresponds to the 2.2 % of the ring circumference. The effective cooling length of the laser cooler is 2.66 m and it occupies the 12 % of the ring.

ELECTRON BEAM COOLING

Figure 3 shows the design of the electron beam cooler. The length of the central solenoid is 0.8 m and the effective cooling length is 0.5 m. For the installation into the limited drift space, the troid has a bending angle of 90 degrees and discrete coils. One feature of this cooler is that the horizontal steering magnets are set in the troid coils (see Fig.3). They cancel the horizontal kick from the troid coils and reduce the beam heating by the kick. The maximum COD is 3 mm for 7 MeV proton beam.

The required lattice conditions for the electron cooling are the adequate dispersion, the small chromaticity and

Table 2: Lattice parameters in two operation points

Betatron tune	(1.70, 1.11)
Field gradient of QM1	-1.02 m^{-2}
Field gradient of QM2	-1.02 m^{-2}
Chromaticity	(-0.64, 0.62)
Max. β-function	(3.87, 3.42 m)
Max. horizontal dispersion	1.71 m
Transition γ	1.46
Moment. Compaction	0.467
Central solenoid length	0.80 m
Eff. cooler length (design)	0.50 m
Field in the central solenoid	500 Gauss
Cathode voltage	1-5 kV
Electron beam diameter	30-50 mm
Gun perveance	2.2 μP

Figure 2: One unit of the bending magnet and the quadrupole magnets.

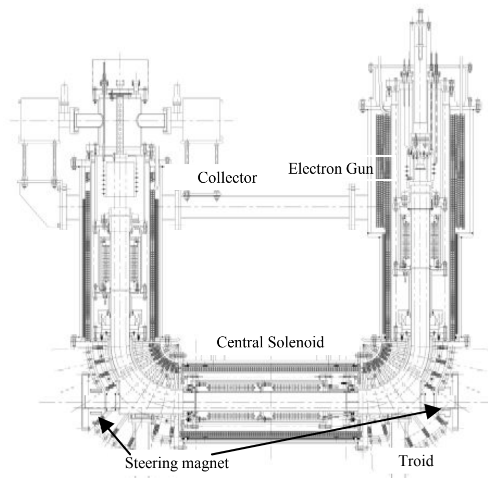

Figure 3: Design of the electron beam cooler. The length of the central solenoid is 0.8 m.

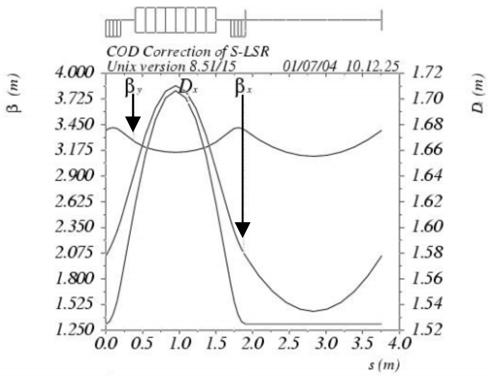

Figure 4: Lattice parameters in one period when the betatron tune is (1.71, 1.11).

the high injection efficiency rather than the low phase advance, because the cooling force of the electron cooler is not enough high to create the high density crystalline beams. The design operating point is (Qx, Qy) = (1.70, 1.11) in the electron cooling mode. The calculated Twiss parameters by MAD8 [7] is shown in table 2 and Fig.4. Table 2 also shows the major parameters of the electron cooler.

LASER COOLING

The laser cooling can reduce the ion velocity spread until the natural width of the atoms in the ideal case. It means the strong cooling force is expected and it is suitable for the study of the ion beam crystal. The laser system consists of a 532nm solid state laser, a Dye laser and a sub harmonic generator. For Mg^+ ions, the required wavelength is 280 nm and the expected laser power is 100 mW. The cooled beam is measured by fluorescence monitors, such as photo multipliers and a highly sensitive cooled CCD (EB-CCD) camera.

Table 3 shows the lattice parameters for the laser cooling. The mode 1 gives the lowest phase advance per period, which is less than 90 degree to avoid the envelope instability. The mode 2 is used for the three dimensional laser cooling experiment using the coupling resonance [8]. The synchrotron tune is 0.07 at this experiment. The phase advance is larger than the 90 degree but the lower than the 127 degree, which is determined by the maintenance condition.

To study the structure of the beam crystal, a molecular dynamics simulation code, SOLID is used [9]. The cooling process is calculated in the following way,

$$\delta\vec{p} \rightarrow \delta\vec{p} - \alpha \cdot \delta\vec{p} \qquad (1)$$

where δp is the momentum spread and the momentum of αδp is subtracted every turn. We assume that α is 0.1 in the SOLID simulation. The ion species is 35 keV Mg^{+}. Table 4 shows the crystal structure and the total ion number in the ring. The horizontal tune is 1.45 and 2.08. Figure 6 shows two examples of the crystal structures. The crystal structure depends on the betatron tune, because the focusing force of the quadrupole magnets affects the crystal structure. In both cases, there is no difference of the particle number at the transition point of the beam crystal.

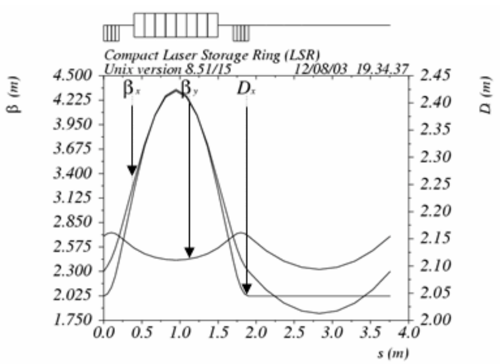

Figure 5: Lattice parameters in one period when the betatron tune is (1.45, 1.44).

Table 3: Lattice parameters in the laser cooling mode

Betatron tune	(1.45, 1.44)	(2.08, 1.07)
Phase advance /period	(86.9, 86.3 deg)	(125, 64.2 deg)
Field gradient of QM1	-1.58 m^{-2}	1.42 m^{-2}
Field gradient of QM2	-1.58 m^{-2}	-2.55 m^{-2}
Chromaticity	(-0.10, 1.26)	(-1.21 -0.18)
Max. β-function	(4.33, 2.74 m)	(4.20, 5.32 m)
Max. hori. dispersion	2.42 m	1.32 m
Transition γ	1.23	1.76
Moment. Compaction	0.658	0.321

Table 4: Crystal structure by the MD simulation. The ion species is 35 keV, Mg+

Particle number	Crystal Structure (Qx=1.45)	Crystal Structure (Qx=2.08)
1.8 x 10^5	String	String
4.0 x 10^5	Horizontal Zigzag	Vertical Zigzag
5.3 x 10^5	Horizontal 3-line	Vertical 3-line
7.8 x 10^5	Horizontal 4-line	Single Shell (3D)
1.6 x 10^6	Single Shell (3D)	Single Shell (3D)

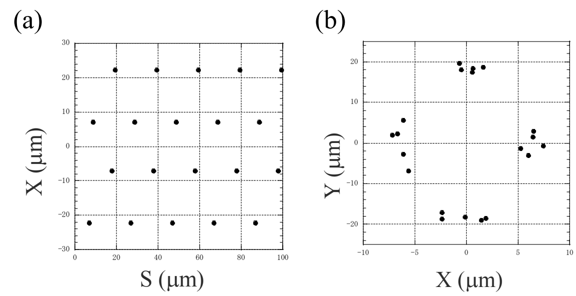

Figure 6: Example of the crystal structure. 6(a) is the side view of the horizontal 4-lines crystal at the particle number of 7.8x10^5. 6(b) is the front view of the single shell at the particle number of 1.6x10^6.

SUMMARY

S-LSR is designed to achieve the ultra-cold beam. Not only the lattice structure, also the magnets are fabricated on the same policy. Many of the fabrications of the ring components have already finished. In this autumn, the alignment will start and the first beam test is scheduled at the first half of the next year.

ACKNOWLEDGMENTS

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