DESIGN OF NEW COMPACT COOLER RING FOR CRYSTALLINE BEAMS

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Abstract

The compact ion cooler ring project (LSR) has been started in Kyoto University from 2001. LSR will have an electron cooler and a laser cooling system. The circumference is 20.997 m and the maximum magnetic rigidity is 1 Tm. One of the research subjects is a realisation of crystalline beams by cooling techniques. LSR has 6 superperiods and satisfies the so-called "maintenance condition", which is necessary for the beam crystal. It can also be operated with the betatron phase advance below 90 degrees per superperiod to avoid the envelope instability. We also plan to test the three-dimensional laser cooling in this ring.

1 INTRODUCTION

In Institute for Chemical Research, Kyoto University, we are constructing a new generation ion cooler ring (Laser equipped Cooler Ring, LSR) [1]. The most important feature of LSR is a high superperiodicity and a small phase advance per superperiod. It is essentially important to suppress an effect of the non-linear resonance and to achieve a very high-density beam. The ultimate case of this high-density beam is a crystalline beam.

The main scientific interests of LSR are,

(1) Realisation of the crystalline beam using the three dimensional laser cooling and the electron beam cooling,
(2) Development of the new electron cooling technique for hot ion beams, especially for high intensity laser produced ions [2].

To achieve a crystalline beam, laser cooing experiments have been carried out in TSR (MPI, Heidelberg), ASTRID (Aarhus University) and PALLAS (LMU München) [3], [4], [5]. In parallel, many analytical and numerical studies were carried out to show the condition of the crystalline beam. Some required conditions are derived from the study of a Hamiltonian for cooled beams in the storage ring [6]. One condition is that the beam energy must be lower than the transition energy. The other is that the phase advance per superperiod must be lower than 127 degree. It is necessary to ensure the stability of the ground state of the crystalline beam. These are called as "maintenance condition". We made simulation studies of the crystalline beam using TARNII lattice parameters in INS, Tokyo University [7]. TARNII satisfies this condition and the molecular dynamics (MD) simulation shows the possibility of the beam crystal [8].

On the other hand, particle in cell (PIC) simulations shows that the strong beam heating occurs during the cooling process when the phase advance is larger than 90 degree. It comes from the effect of the non-linear resonance (the envelope instability) [9], [10].

2 DESIGN OF LSR

In order to obtain the crystalline beam, the storage ring should satisfy not only the small betatron phase advance in the above discussions, but also some other conditions. The following conditions are design issues of the LSR lattice,

(1) Small betatron phase advance (< 90 degree),
(2) Smooth beam envelope,
(3) Long straight sections for the electron and the laser cooling,
(4) Small non-linear components of the magnetic field,
(5) Small alignment error of the magnets and the small magnetic field error.
(6) Small chromaticity without the sextupole magnet correction.
(7) The diameter of LSR must be less than 7 m.

The last condition comes from the restriction of the available area in the accelerator building. In this limited area, the superperiod number of 8 is impossible because

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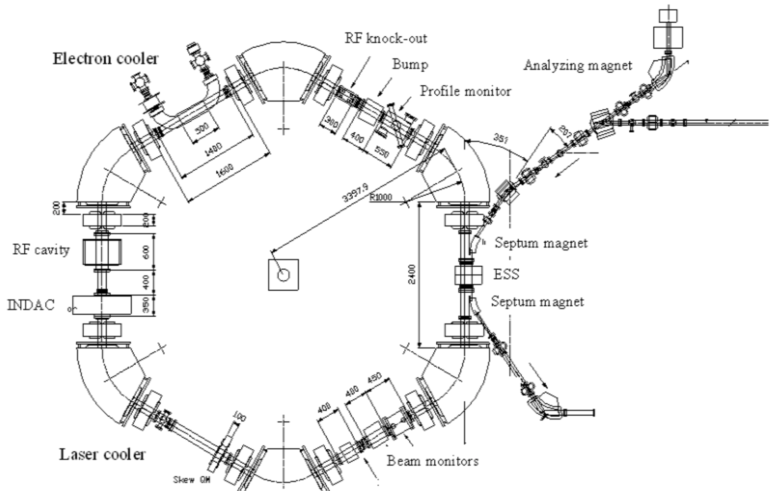

Figure 1 Layout of LSR

the length of the straight section is not enough. The superperiod of 6 is a natural choice. Due to the condition (1), the operating tune in the crystalline mode must be less than 1.5 in the horizontal and the vertical directions.

In order to satisfy the conditions, we adopt a following lattice structure,

Drift/2-QD1-BM-QD2-Drift-QD2-BM-QD1-Drift/2.

BM is a bending magnet and QD1(2) is a quadrupole magnet. QD1 and QD2 have identical geometry and only the field gradient is different. Drift is a drift space to place the cooler devices, a RF cavity and beam monitors. This is one third of LSR lattice and the basic number of superperiod is 3. When the field gradient of QD1 and QD2 are equal, the number of superperiod becomes 6, which is called as a crystalline mode. In the ring, there is no QF, because the radial focusing power of the bending magnet is enough strong. The length of the drift section is determined from the compromise between the required length for the electron cooler and the restriction of the available building space.

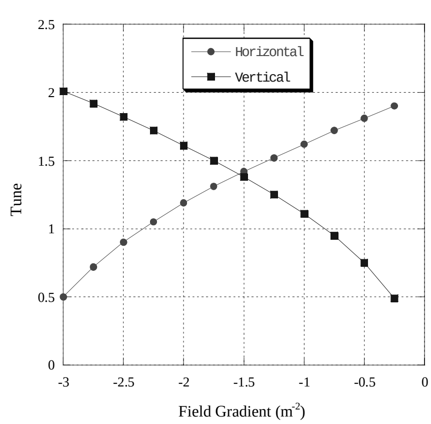

Figure 2 Horizontal and vertical betatron tune with the various field gradient of the quadrupole magnet in the crystalline mode.

Table 1 Major parameters of LSR

Ring	
Circumference	20.997 m
Average radius	6.69 m
Length of straight	1.6 m
Number of superperiod	3 or 6
Bending magnet	H-type
Number	6
Maximum field	0.95 T (Bρ=1.0)
Curvature radius	1.05 m
Bending angle	60 degree
Gap height	70 mm
Edge angle	0 degree
Quadrupole magnet	
Number	12 (2 groups)
Length	0.20 m
Bore radius	7.0 cm
Maximum field gradient	5 T/m

Table 2 Lattice parameters in the crystalline mode

Tune	(1.41, 1.39)
Number of superperiod	6
Betatron phase advance	(85 deg, 83 deg)
Field gradient of QM	-1.5 m^{-2}
Natural Chromaticity	(-0.11, 1.14)
Maximum β-function	(4.0 m, 2.6 m)
Maximum dispersion function	2.32 m
Transition γ	1.22
Momentum Compaction Factor	0.677

Table 1 shows the parameters of LSR and Fig.1 shows the layout. The circumference is 20.997 m and the length of the straight section is 1.6 m. The maximum magnetic rigidity is 1.0 Tm. The corresponding maximum beam energy is 48 MeV for proton, 145 MeV for $^{12}C^{6+}$, 121 MeV for $^{40}Ar^{10+}$ and 2.0 MeV for $^{24}Mg^{+}$.

Figure 2 shows the horizontal and vertical betatron tune with the various field gradient of the quadrupole magnet in the crystalline mode. It is calculated by the computer code MAD8 [11]. The field gradient of QD1 and QD2 are identical. When it is 1.5 m^{-2}, the betatron tune has almost minimum value of 1.41 and 1.39 in the horizontal and the vertical direction, respectively. Table 2 shows the calculated lattice parameters in this condition. Figure 3 shows the horizontal and vertical β-function and the dispersion function in one sixth of LSR. The operating point is close to the coupling resonance to control the horizontal and vertical coupling each other. The distance from the coupling resonance is controlled by the quadrupole magnets in order to maximise the cooling force and minimise the beam temperature.

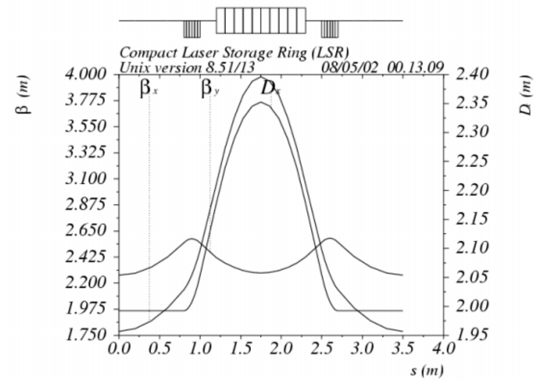

Figure 3 Lattice parameters in one sixth of the ring when the horizontal and vertical tune is 1.41 and 1.39, respectively. The field gradient of the quadrupole magnet is -1.5 m^{-2}.

3 LASER COOLING

The possible ion species for the laser cooling are Li^+, Be^+, Mg^+, Ca^+, for example. Most of the ion species requires two kinds of lasers because of the level splitting. Only Mg^+ needs the single wavelength of 280 nm. It is a big advantage for the laser cooling in the storage ring, because we can simplify the alignment between the ion beam and the laser at the interaction region in the storage ring. One problem of Mg^+ beam is a lifetime. In LSR, the maximum energy of Mg^+ is 2.0 MeV (83 keV/u). In this energy range, the beam lifetime is a few seconds and the ions with lower energy have a longer lifetime [12], [13]. In the present plan, we will use 30 keV beams (1.3 keV/u). The expected lifetime is longer than 20 seconds when the vacuum pressure is a few times of 10^{-11} Torr. The beam is injected to LSR from an ion source, directly.

The present laser cooling works mainly in the longitudinal direction. But in order to obtain the crystalline beam, a three-dimensional cooling is necessary, otherwise, the cooled beam grows up in the uncooled direction. The basic idea of the three dimensional cooling is a sharing of the cooling force using coupling resonance [8]. Table 4 shows the operating parameters for this cooling. The operating point is close to the horizontal and vertical coupling resonance. It is also close to the horizontal and longitudinal coupling resonance (synchro-betatron coupling). In order to enhance the coupling, the RF cavity is placed at the dispersive section and skew quadrupole magnets also will be installed.

Table 4 Beam and lattice parameters for the three-dimensional laser cooling.

Ion species	$^{24}Mg^+$
Beam energy	30 keV
Betatron tune	(1.41, 1.39)
Synchrotron tune	0.40
RF voltage	120 V
RF frequency	27.7 MHz
RF harmonics	1000

4 SUMMARY

We have already started the construction of the new compact cooler ring. We expect that it is able to cool the ion beam to the colder temperature and obtain the higher density beam than those in the existing cooler rings, We hope to obtain the crystalline beam in this ring. The construction of LSR will be finished in 2005. We will start the beam circulation test and the cooling experiment at that time.

ACKNOWLEDGEMENTS

This project is performed as a part of "Advanced Compact Accelerator Research Project" with the collaboration of National Institute for Radiological Science, Kansai Research Establishment of Japan Atomic Energy Research Institute, KEK, Hiroshima University and Tokyo University.

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