HiSOR-II, Compact light source with a torus-knot type accumulator ring

Atsushi Miyamoto and Shigemi Sasaki
Hiroshima Synchrotron Radiation Center, Hiroshima University
2-313, Kagamiyama, Higashi-Hiroshima, 739-0046 Japan
E-mail: a-miyamoto@hiroshima-u.ac.jp

Abstract. We are designing a new ring based on the shape of a (11, 3) torus knot for our future plan ‘HiSOR-II’. This ring has eleven 3.6-m-long straight sections though the ring diameter is as compact as 15 m. The emittance reaches down to around 20 nmrad with the lattice having bending magnets with combined function. This level of emittance is as low as the conventional compact 3rd generation light source. On the other hand, there are a few potential problems. One of them is that the orbit radius varies in a bending magnet and hence the focusing force are not constant. However, precise calculations by dividing a bending into several sections show that it does not make serious influence to the stored beam. Detailed parameters survey of this ring and estimation of performance confirmed that this new scheme may plausible as a synchrotron light source ring.

1. Introduction
In comparison with third-generation light sources, the emittance of existing HiSOR[1] ring is quite large because it is a compact ring remodeled from an industrial use light source. There are as many as 15 beamlines available in the bending section, but there are only two straight sections for undulators which are obviously not enough as an active modern SR facility. Therefore, we are planning to construct a new compact storage ring ‘HiSOR-II[2] in which undulators are dominant light sources.

In accordance with this future plan, we proposed a torus knot type storage ring that the beam orbit is not closed with one turn but return to the starting point after multiple turns around the ring. The idea of this new scheme of accumulation ring was inspired based on the torus knot theory.

We are designing a new ring based on the shape of a (11, 3) torus knot for one of two choices of our future plan[3, 4]. This ring has eleven 3.6-m-long straight sections though the ring diameter is as compact as 15 m. The emittance can be reached down to around 20 nmrad with the lattice having bending magnets with combined function. This level of emittance is as low as the conventional low-energy 3rd generation light source.

2. Ring design for synchrotron light source

2.1. Basic design with torus knot
Figure 1 shows the schematic view of the ring based on the shape of a (3, 11) torus knot which we applied to a particle accelerator consisting of straight sections and bending sections. We tentatively named this architecture of the ring AMATELAS.
This ring has 11 straight sections inside and can place undulators effectively by placing elements of accelerator such as quadrupole magnets at the place near bending magnet, outside of the orbit crossing section. Further, this ring has about 3 times longer circumference in comparison with the conventional ring with the same diameter. The diameter of this ring is about 15 m, but its circumference is about 130 m long.

\[ \varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4} \]

Where \( C_q \) is the classical radius of the electron, and \( I_2, I_4 \) and \( I_5 \) are

\[ I_2 = \oint \frac{1}{\rho^2} ds, \quad I_4 = \oint \frac{1}{\rho} \left( \frac{1}{\rho^2} + 2K \right) ds, \quad I_5 = \oint \frac{\mathcal{H}}{\rho^3} ds. \]

In MAX-III of MAX-lab[6], they adopted the combined function type bending magnet with QD field and used the lattice that \( K \) in \( I_4 \) has negative value and achieved ultra low emittance. Therefore we decided to adopt the MAX-III type lattice in the AMATELAS ring. Figure 2 shows the lattice of unit cell used for HiSOR-II storage ring.

![AMATELAS schematic view](image)

**Figure 1.** Schematic view of the AMATELAS.

### 2.2. Low emittance lattice

Generally, Double Bend Achromat (DBA) is well known as a low emittance lattice, and it is often used for synchrotron light source rings. In late years, the lattice which introduced dispersion into the straight sections is engaged to achieve low emittance than that of DBA.

The natural emittance is written using radiation integrals as follows[5].

\[ \varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4} \]

Where \( C_q \) is the classical radius of the electron, and \( I_2, I_4 \) and \( I_5 \) are

\[ I_2 = \oint \frac{1}{\rho^2} ds, \quad I_4 = \oint \frac{1}{\rho} \left( \frac{1}{\rho^2} + 2K \right) ds, \quad I_5 = \oint \frac{\mathcal{H}}{\rho^3} ds. \]

In MAX-III of MAX-lab[6], they adopted the combined function type bending magnet with QD field and used the lattice that \( K \) in \( I_4 \) has negative value and achieved ultra low emittance. Therefore we decided to adopt the MAX-III type lattice in the AMATELAS ring. Figure 2 shows the lattice of unit cell used for HiSOR-II storage ring.

![Lattice of unit cell of the AMATELAS designed for HiSOR-II](image)

**Figure 2.** Lattice of unit cell of the AMATELAS designed for HiSOR-II.

### 2.3. Design of bending magnet

The combined function type bending magnets with QD fields are indispensable for MAX-III type lattice. Contrarily in AMATELAS, since the beam orbit crosses in the bending magnet, it is impossible
to overlay two bending orbit having the constant field gradient for entire length of beam orbit in a bending magnet. Therefore we consider one wide magnet which have field gradient along imaginary central orbit, and two orbit cross at the center of a bending magnet.

When we remove bending fields, this orbit is similar to the orbit passing a quadrupole magnet diagonally. However, it is necessary to consider that the bending radius and the focusing force change by the differences of the bending forces and changing the angle against the imaginary central orbit.

Therefore we calculated practical orbit passing through a bending magnet and the deviation of quadrupole field along trajectory with concrete parameters that a bending radius without gradient field is 1800 mm and defocusing force $K$ along the imaginary center is -0.98 m$^{-2}$. In this condition, it is found that the deviation of focusing force along beam orbit is smaller than 0.5%.

### 2.4. Determination of operating point

Because there are only four kinds of magnets in a unit cell of this ring, we surveyed each focusing magnet and calculated the natural emittance of the ring, determined the operating point that had a suitable optical functions. Firstly, we surveyed quadrupole field of QFS, QFL and Bend in the lattice shown in figure 2, and selected the operating points with the natural emittance less than 20 nmrad. In such a procedure, we decided to use the quadrupole field of -0.98 m$^{-2}$ of the bending magnet. However the quadrupole field along the beam orbit in the bending magnet is not constant, therefore the magnet is divided into 6 arcs to prepare for the linear matrix calculation, the stepped defocusing force is provided in each section.

Secondarily, we surveyed the natural emittance of the ring and the dynamic aperture at the center of a long straight section under the condition to choose the quadrupole field of SXD that the emittance became lowest when free parameters were given for two quadrupole magnet of QFS and QFL. We evaluated validities of calculated emittance, the focusing force $K$ of SXD and the dynamic aperture comprehensively, and the operation point of the ring was decided. The optical functions at the operating point are shown in figure 3.

![Figure 3. The optical functions of 1/3 of the ring.](image)

### 3. Performance of AMATELAS for HiSOR-II

The emittance of the AMATELAS designed for HiSOR-II reached 17.9 nmrad as the result of calculations described above by assuming the lattice of MAX-III. Also as mentioned above, this ring has 11 long straight sections. Therefore this design is advantageous in that we can install many insertion devices when it is used as a SR light source ring.

The HiSOR-II will have the injector for the top-up injection, and its details are under consideration. The latest parameters of the storage ring is shown in Table 1. Figure 4 shows expected radiation spectra of the light source in comparison with existing HiSOR. Because the beam energy does not change with from that of HiSOR, the energy region of SR covered by insertion devices is unchanged. However, it is expected that the brilliance increases drastically from the present by the effects of lower emittance and longer undulators.
Table 1. Main parameters of (11, 3) AMATELAS designed for HiSOR-II

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Ring shape                       | (11, 3) Torus knot         |
| Diameter [m]                     | 14.6                       |
| Perimeter [m]                    | 45.97                      |
| Total orbit length [m]           | 130.187                    |
| Beam energy [MeV]                | 700                        |
| Beam rigidity [Tm]               | 2.333                      |
| Straight sections                | 3.614 m ×11                |
|                                  | 1.728 m ×11                |
| Lattice type                     | MAX-III type               |
| Natural emittance [nmrad]        | 17.9                       |
| Betatron tune                    | (10.362, 7.807)            |
| Chromaticity                     | (+1.0, +1.0)               |
| Harmonic number                  | 88                         |
| RF frequency [MHz]               | 202.645                    |

Figure 4. The radiation spectra of HiSOR-II compared with HiSOR.

References
[1] See HiSOR Webpage, http://www.hsrc.hiroshima-u.ac.jp/english/index-e.htm
[2] Miyamoto A, Goto K, Sasaki S, Hanada S and Tsutsui H 2010 Proc of IPAC’10 2546
[3] Sasaki S and Miyamoto A 2011 Proc of IPAC2011 1467
[4] Miyamoto A and Sasaki S 2011 Proc of IPAC2011 1464
[5] Lee S Y 1999 Accelerator Physics (World Scientific) p 422
[6] LeBlanc G, Andersson A, Georgsson M, Lindgren L-J and Werin S 2000 Proc of EPAC2000 643