DEFLECTION ELEMENT FOR S-LSR

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Abstract

A dispersion-free storage ring can be realized by inserting electrostatic deflectors in the bending regions. This scheme is going to be applied to the compact ion cooler ring "S-LSR" at Kyoto University. An optimum design of electrostatic deflectors for the dispersion compensation has been done on the basis of detailed 2D and 3D field calculations, and its fabrication is now in progress. Beam dynamics in the dispersion-free lattice has also been studied theoretically.

INTRODUCTION

A small laser-equipped storage ring S-LSR is under construction by the I.C.R Kyoto University and National Institute of Radiological Science. The primary purposes of the S-LSR project are electron-cooling of a laser-produced ion beam with a very large energy spread and the generation of ultracold ion beams by means of the laser cooling technique. If a strong 3D cooling force and a properly designed storage ring are available, an ultimate low-temperature state of a charged-particle beam can be realized [1] [2]. Such a beam is supposed to have a unique structure physically equivalent to a Coulomb crystal in ion traps. S-LSR project also aims at the realization of *crystalline beams*.

In a conventional storage ring, there is a factor that seriously affects the stability of 3D crystalline structures. When an ultracold beam goes through a dipole magnet, particles travelling in radially outer positions fall behind to inner particles if all of them have the same longitudinal velocity. This effect will destroy an ordered structure with finite horizontal dimension [3]. The radially outer particles must, therefore, run slightly faster than inner particles, so that the 3D crystalline structure can be maintained.

The dispersion-free storage ring resolves this problem. Since the deflection element produces an electrostatic potential, it accelerates or decelerates particles. The amount of the energy gain depends on the radial position of each particle. Ideally, this effect equalizes the *angular* velocities of all particles, which greatly improves the stability of the crystal [4].

However, in order to realize the dispersion-free storage ring, there are some technical difficulties [5].

DYNAMICS IN THE DEFLECTION ELEMENT

We derive a Hamiltonian that describes the motion of a charged particle in a bending region of a dispersion-free storage ring. In the following, we use the notations employed in Ref. [6].

Choosing the path length s as the independent variable, we obtain the relativistic Hamiltonian of the form

$$H = -\left(1+\frac{x}{\rho}\right)\sqrt{\left(\frac{p_t+q\phi}{c}\right)^2 - m^2c^2 - p_x^2 - p_y^2} - q\left(1+\frac{x}{\rho}\right)A_s, \tag{1}$$

where $A_x = 0 = A_y$ has been assumed. By expanding the square root and leaving only low-order terms, Eq. (1) becomes

$$H = -\left(1+\frac{x}{\rho}\right)qA_s - \left(1+\frac{x}{\rho}\right)p + \frac{p_x^2+p_y^2}{2p}, \tag{2}$$

where $p = m\beta\gamma c = \sqrt{(p_t+q\phi)^2/c^2 - m^2c^2}$. The scalar potential of an electrostatic deflector vertically installed along the design orbit can be expressed as

$$\phi = -\kappa \cdot \ln\left(1+\frac{x}{\rho}\right) = \kappa \cdot \sum_{n=1}^{\infty}\frac{(-1)^n}{n}\left(\frac{x}{\rho}\right)^n, \tag{3}$$

where $\kappa \equiv V_0(=\text{const.})$ in the bending region and, otherwise, zero. The vector potential of a bending magnet is given by

$$\vec{A} = \left(0, 0, -\frac{B_y}{2}(\rho+x)\right) \tag{4}$$

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where B_y is a dipole magnetic field. The relation between kinetic momentum $p_0(\equiv m\beta_0\gamma_0 c)$ and radius of reference orbit ρ is

$$p_0 = qB_y\rho - \frac{qV_0}{\beta_0 c}. \tag{5}$$

The momentum deviation from the design value can approximately be written as

$$\Delta p \equiv p - p_0 \approx \frac{\Delta E - q\phi}{\beta_0 c} - \frac{1}{2p_0}\left(\frac{\Delta E - q\phi}{\beta_0 c\gamma_0}\right)^2. \tag{6}$$

Inserting Eq. (3), (4) and $p = p_0 + \Delta p$ into Eq. (2), neglecting some nonlinear terms, and using the relation (5), we find

$$\tilde{H} = -\frac{\Delta E}{\beta_0^2 E_0}\frac{x}{\rho}\left(1 - \frac{q\kappa}{\gamma_0^2\beta_0^2 E_0}\right) - \frac{\Delta E}{\beta_0^2 E_0} + \frac{1}{2\gamma_0^2}\left(\frac{\Delta E}{\beta_0^2 E_0}\right)^2 + \frac{\tilde{p}_x^2 + \tilde{p}_y^2}{2} + \left[1 + \frac{1}{\gamma_0^2}\left(\frac{q\kappa}{\beta_0^2 E_0}\right)^2\right]\frac{x^2}{2\rho^2}, \tag{7}$$

where the transverse momenta and the Hamiltonian have been scaled to be dimensionless; namely, $\tilde{p}_{x(y)} = p_{x(y)}/p_0$. From the Hamiltonian (7) the horizontal equation of motion in the bending region can be derived

$$\frac{d^2x}{ds^2} \approx -\left[1 + \frac{1}{\gamma_0^2}\left(\frac{q\kappa}{\beta_0^2 E_0}\right)^2\right]\frac{x}{\rho^2} + \left(1 - \frac{q\kappa}{\gamma_0\beta_0^2 E_0}\right)\frac{1}{\rho\beta_0^2}\frac{\Delta E}{E_0}. \tag{8}$$

Specifically, the first term in the right hand side of Eq. (7) gives rise to linear dispersion. When the relation

$$\frac{qV_0}{\gamma_0^2\beta_0^2 E_0} = 1 \tag{9}$$

is satisfied, dispersive effects are suppressed. Equation (5) gives the relation between required strength of the magnetic field and the electric field under the dispersion-free condition (9):

$$\left(1 + \frac{1}{\gamma_0^2}\right)\frac{V_0}{\rho_0} = B_y\beta_0 c \tag{10}$$

The horizontal equation of motion in the bending region can be written, with this condition satisfied, as

$$\frac{d^2x}{ds^2} \approx -\frac{1+\gamma_0^2}{\rho^2}\cdot x. \tag{11}$$

which looks like a equation of motion in a focusing quadrupole magnet.

Consider now an ion beam strongly cooled by some dissipative force. The energy spread eventually vanishes, i.e. $\Delta E = 0$, at low temperature limit where the beam is Coulomb crystallized. In this situation, the momentum spread of a beam in a conventional storage ring simply becomes zero, which does not meet the stability requirement of a 3D crystal. On the other hand, in a bending region with the deflection element, the momentum deviation of a particle naturally has a radial-position dependence because of the electrostatic field. In fact, we have

$$\frac{\Delta p}{p_0} \approx \frac{1}{\beta_0^2}\frac{\Delta E - q\phi}{E_0} \approx \frac{q\kappa}{E_0\beta_0^2}\frac{x}{\rho} \tag{12}$$

Under the dispersion-free condition, the velocity ratio between the reference particle and the others can be given by

$$\frac{v}{v_0} \approx 1 + \frac{x}{\rho}, \tag{13}$$

where v_0 is the design velocity, and v denotes the velocity of a particle at the horizontal position x. It is now evident that the angular velocities of all particles are approximately the same in the dispersion-free lattice.

APPLICATION TO S-LSR

The circumference of S-LSR is 22.557 m and the curvature radius of the bending section is 1.05 m. The lattice structure is shown in Fig. 1.

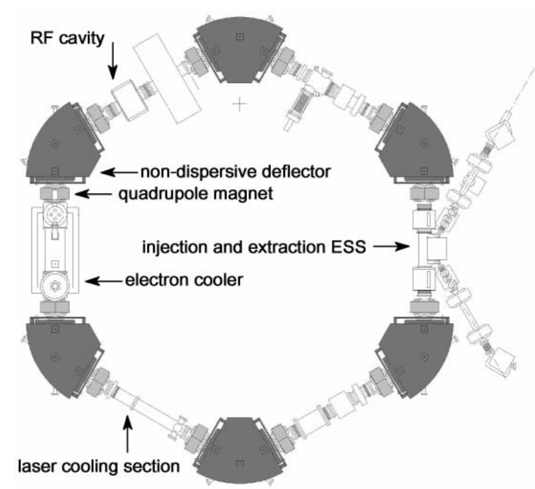

Fig. 1. Lattice structure of S-LSR

If the field gradient of the quadrupole magnets are equal, the number of superperiod becomes 6. The non-dispersive deflector can be used as a dipole magnet, if the electrostatic deflector is removed. The main case using the non-dispersive deflector is the storage of a 35 keV $^{24}Mg^{+}$ beam. In this case, the needed field strengths for the dispersion-free deflectors are 6.7×10^4 V/m and 0.252 T, respectively, which are in a reasonably attainable range. When the field gradient of the quadrupole magnets are equal, the relation between horizontal and vertical betatron tune and field gradient becomes as shown in Fig. 2. When the field gradients of all quadrupole magnets are 0.69 T/m, the horizontal beta function becomes minimum (Fig. 2).

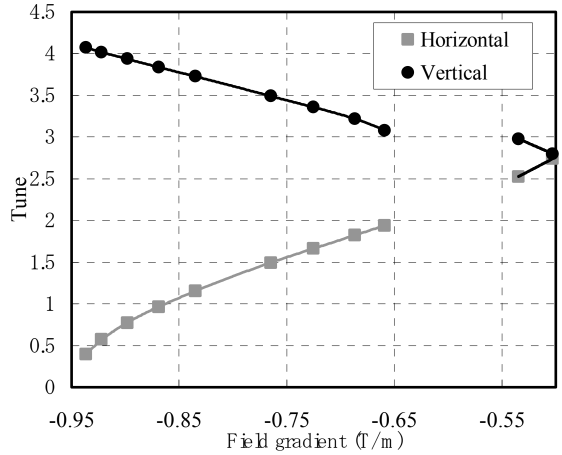

Fig. 2. The relation between betatron tune and field gradient of the quadrupole magnets, when all field gradient of quadrupole magnets are equal.

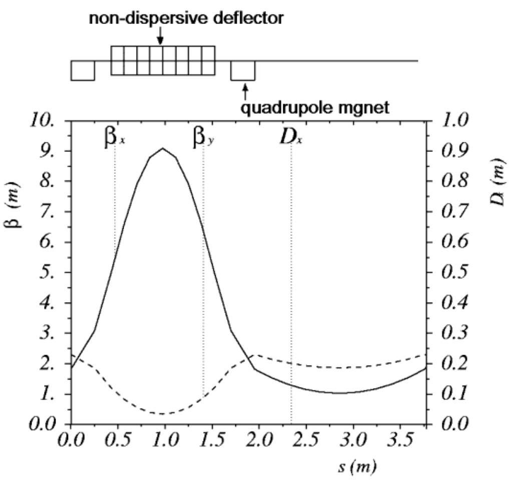

Fig. 3. The lattice parameters at one superperod. In this case, the field gradient of the quadrupole magnets are 0.69 T/m, and the horizontal and vertical betatron tune are (1.82, 3.23).

The horizontal beta function becomes larger compare to the case using only a magnetic field in the deflectors [7]. Therefore, we want to secure the widest possible horizontal aperture of electrostatic deflector.

DEFLECTION ELEMENT

4.1 Dipole magnet

The design of the dipole magnets was fixed by using 2D and 3D magnetic-field calculation codes POISSON and TOSCA. The magnet has a gap of 70 mm and a pole width of 371 mm. The measured field uniformity is a few times 10^{-4} in the inner side of the gap. The individual difference of the effective length is less than $\pm 2.5 \times 10^{-4}$.

4.2 Electrostatic deflector

Since the electrostatic deflector is inserted to the vacuum vessel in the small gap of the dipole magnet, its size is limited and the quality of its electrostatic field becomes worse (Fig. 4). In order to secure the good quality of the electrostatic field and a wide aperture of the electrostatic deflector, intermediate electrodes are introduced [5]. Eventually, the horizontal and vertical aperture became to 30 mm and 26 mm, respectively, with a few times 10^{-3} of deviation from the ideal value of the field. The $^{24}Mg^{+}$ beam will be produced from an ion source and injected into the storage ring directly. The maximum emittance of the beam which can be circulated in the dispersion-free storage ring is about 8 π mm mrad. The emittance of the injected beam will be adjusted by using a double slit. We can get sufficient intensity of the beam even by this method

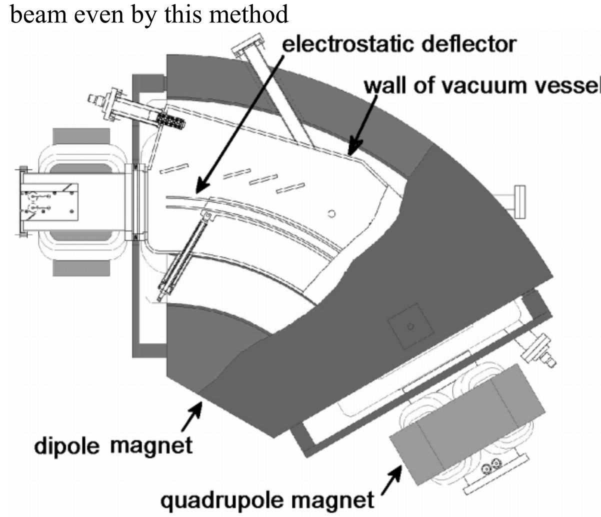

Fig. 4. Structure of non-dispersive deflector.

PROSPECT

In the present calculation, the effect of fringing field of the non-dispersive deflector is not taken into account. The lattice parameters may be shifted by the fringing field effect. The field error of the electrostatic field is expected to be larger than that of the magnetic field. Nevertheless, the horizontal aperture of electrostatic deflector is only 30 mm. Therefore, we should estimate the closed orbit distortion induced by the electric field error correctly and should consider a method of COD correction. The performance test of a constructed non-dispersive deflector will be performed in 2004 by using a directly injected beam from an ion source.

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