

DAMPING RING FOR TESTING THE OPTICAL STOCHASTIC COOLING METHOD

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Abstract

This paper describes a compact damping ring, which is able to demonstrate the optical stochastic cooling (OSC). In principle the OSC is a stochastic cooling method, but with the bandwidth extended to the optical range of the order 10^{14} Hz. The quadrupole and dipole wiggler serve as a pickup and a kicker. An optical amplifier is used for amplifying the transverse temperature signal from quadrupole wiggler. The bend between quadrupole wiggler and dipole wiggler, installed in this damping ring, satisfy the mixing requirements. The optical amplifier requirements for this scheme are considered also.

The Optical Stochastic Cooling (OSC) method [1], is a version of the well known stochastic cooling method [2] but with the carrier frequency in the optical range, with a corresponding optical bandwidth. The quadrupole wiggler and optical amplifier are the analogues of the ordinary pickup and broadband amplifier. Another important item in OSC is that the transverse kick arranged through the energy change in *dipole wiggler*, is positioned at a place of non zero dispersion. This is basically the same as the cooling with a longitudinal kicker. The reason for this is connected with the cancellation the transverse kick from electric and magnetic field of a *plane wave*, propagating co-directionally with the beam. The quadrupole and dipole wiggler have the same number of periods M , and the undulator factor of dipole wiggler is K .

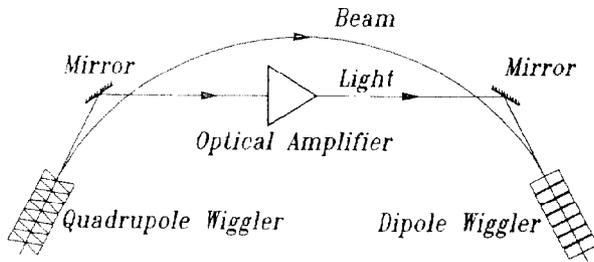


Fig. 1. The basis of Optical Stochastic Cooling Method

Considerations made [1] show that the amplification κ of radiated field must be

$$\kappa \cong \frac{1}{4} \frac{\varepsilon_1}{r_0} \frac{1}{N} \frac{\Delta f}{f},$$

where $r_0 = e^2 / mc^2$, $\varepsilon_1 = \gamma_b \Delta E / E$ is the invariant longitudinal emittance, N is total number of the particles and the cross-section of the beam S is estimated as

$S \cong \pi A_0^2 \cong 2\pi\lambda LM$. M - is the number of periods in the wiggler, L is a half period. In the last expression we used the optimal beam size as the transverse size of coherence. The dispersion function was also estimated $\eta \cong A_0 / (\Delta E / E)$, where A_0 is the amplitude of betatron oscillations, $(\Delta E / E)$ is the energy spread in the beam and $M \cong f / \Delta f$. If we substitute $N \cong 1 \cdot 10^8$, $l_b \cong 5$ cm, $M = 5$, $(\Delta E / E) \cong 1 \cdot 10^{-4}$ and $\gamma \cong 500$ (250 MeV), we obtain $\kappa \cong 1 \cdot 10^2$ for an electron damping ring which is well below the $\kappa \cong 10^5$, the typical amplification factor [3]. For the above parameters, the peak pulsed power required is $P_{mp} \cong 225$ W at an average power of $P_{av} \cong 0.75$ W, assuming a repetition rate of $f_0 \cong 20$ MHz. The number of the particles in the bandwidth will be $N_u \cong M\lambda N / l_b \cong 10^4$, and the damping time will be $\tau \cong N_u / f_0 \cong 5 \cdot 10^{-4}$ sec.

In our case the peak and average power is rather small. For amplification the Dye amplifier as well as Titanium Sapphire ($Ti:Al_2O_3$) pumped by Ar laser can be used. Considerations show, that three stages of amplification is enough for our purposes. The central wavelength of Titanium Sapphire amplifier is about $\lambda \cong 0.8 \mu m$. The wiggler period λ_u must correspond to this wavelength $\lambda_u \cong \lambda 2\gamma^2 / (1 + K^2)$, which for the parameters discussed above gives 20 cm. This is both for period of dipole and quadrupole wiggler (period of FODO structure). The field in dipole wiggler is ≈ 500 G.

Generally, the damping ring described below is a kind of isochronous ring. The difference is that the *only one part* of the damping ring is an isochronous one. This gives an advantage for keeping the desirable momentum compaction factor, and hence the length of the beam. The damping rings described in [7] are in line with the investigations of this paper.

The basic interest of a damping ring with OSC equipment is the possibility to generate small emittances for electrons and positrons as well as for μ mesons and heavy ions.

The total number of radiated photons in the bandwidth per one pass is $\Delta N \cong \alpha N_u$ [5], where $\alpha = e^2 / \hbar c$ is the fine structure constant. The noise of an amplifier is of the order of one photon per volume of coherence. This corresponds to one photon per bandwidth.

The equations which define the equilibrium emittance in the damping ring are as follows

$$\frac{d\varepsilon_{x,y}}{dt} \cong \left\langle \left(H_{x,y} + \frac{\beta_{x,y}}{\gamma^2} \right) \frac{d}{dt} \left(\frac{\Delta E}{E} \right)^2 \right\rangle - \varepsilon_{x,y} \left(\frac{1}{\tau_s} + \frac{1}{\tau} \right)$$

where τ_s, τ is the time of cooling by synchrotron radiation and OSC correspondly,

$$H_{x,y} = \frac{1}{\beta_{x,y}} \left(\eta_{x,y}^2 + (\beta_{x,y} \eta'_{x,y} - \frac{1}{2} \beta'_{x,y} \eta_{x,y})^2 \right)$$

$\beta_{x,y}$ is the envelope functions, $\eta_{x,y}$ is the dispersion function, and $\eta'_{x,y}$ its derivative. The averaging ($\langle \dots \rangle$) is made over the longitudinal distance, while x and y denote two transverse coordinates.

The energy spread is defined by the relation

$$\frac{d}{dt} \left(\frac{\Delta E}{E} \right)_i^2 = \frac{d}{dt} \left(\frac{\Delta E}{E} \right)_{IBS}^2 + \frac{d}{dt} \left(\frac{\Delta E}{E} \right)_{QE}^2.$$

composed of two definite components, denoted by the subscripts QE - quantum excitations and IBS-intra-beam scattering. Due to cooling

$$\frac{d}{dt} \left(\frac{\Delta E}{E} \right)^2 = \frac{d}{dt} \left(\frac{\Delta E}{E} \right)_i^2 - \left(\frac{\Delta E}{E} \right)^2 \left(\frac{1}{\tau_s} + \frac{1}{\tau} \right).$$

The increase in the energy spread due to IBS can be expressed as

$$\frac{d}{dt} \left(\frac{\Delta E}{E} \right)_{IBS} \cong \frac{N r_0^2 \sqrt{\epsilon_x \beta_x} L n_c \cdot c}{\gamma^3 \epsilon_x \sqrt{\epsilon_y \beta_y} \sigma_l \sigma_x}$$

where $\sigma_x = \sqrt{\epsilon_x \beta_x + \eta_x^2 (\Delta E / E)^2}$, $L n_c$ is the Coulomb's logarithm, $\sigma_l \cong l_b / 2$. The increase in the energy spread attributable to QE can be approximated by [5]

$$\frac{d}{dt} \left(\frac{\Delta E}{E} \right)_{IBS} \cong \frac{55}{48 \sqrt{3}} \frac{r_0^2 c \gamma^5}{\alpha |\rho|^3},$$

where ρ is the bending radius. The equilibrium emittance is defined by the conditions

$$\frac{d}{dt} \left(\frac{\Delta E}{E} \right)^2 = 0, \quad \frac{d\epsilon_{x,y}}{dt} = 0.$$

Thus, as the energy is lowered, the source of excitation of the transverse emittance from synchrotron radiation is also reduced by $1/\gamma^3$ for fixed radius, and the effective time

$$\frac{1}{\tau_s} + \frac{1}{\tau} \cong \frac{1}{\tau},$$

is the time of OSC. The formulas represented above are used for numerical calculations of the emittances.

The primary source of heat for the beam is intra-beam scattering (IBS). Because the damping times with OSC are practically independent of the envelope functions in the damping ring, the optimization of this ring must be done at relatively lower energy in order to minimize of IBS.

The most important thing for OSC in the lengthening of the trajectory from the pick up to the kicker. The lengthening Δl in the first order can be expressed as following [8]

$$\Delta l = - \int_0^s \frac{x}{\rho} d\sigma = -x_0 \int_0^s \frac{C}{\rho} ds - x'_0 \int_0^s \frac{S}{\rho} ds - \frac{\Delta \gamma}{\gamma} \int_0^s \frac{D}{\rho} ds,$$

where $D(s)$ is the dispersion, and the trajectory expressed as

$$D(s) = -S(s) \int_0^s \frac{C}{\rho} d\sigma + C(s) \int_0^s \frac{S}{\rho} d\sigma,$$

$$x(s) = x_0 C(s) + x'_0 S(s) + D(s) \Delta \gamma / \gamma =$$

$$= x_{00} C(s) + x_{00}' S(s) + (\eta(s) C + \eta'(s) S + D'(s)) \Delta \gamma / \gamma$$

$$x'(s) = x_0 C'(s) + x'_0 S'(s) + D'(s) \Delta \gamma / \gamma.$$

$\rho(s)$ is the actual bending radius of the trajectory in the magnets used in the system. $C(s), S(s)$ are cosine and sinelike trajectories and η is the dispersion function of the ring. In the expression for $x(s)$ these were separated for the betatron and dispersion components of the damping ring. For both the transverse horizontal and longitudinal cooling simultaneously, following [4] one need to satisfy the condition $D(s_x) = 2\eta$ which yields $\Delta l \approx -2x'_0 \eta$. Namely for eliminating this effect of initial emittance we used here a soft focusing damping ring with a scraper at the extraction point.

In our calculations we have taken into account only the first order over $\Delta \gamma / \gamma$ due to very small energy spread of injected beam, with the second order terms being out of possible resolution ($\approx 10^{-8}$).

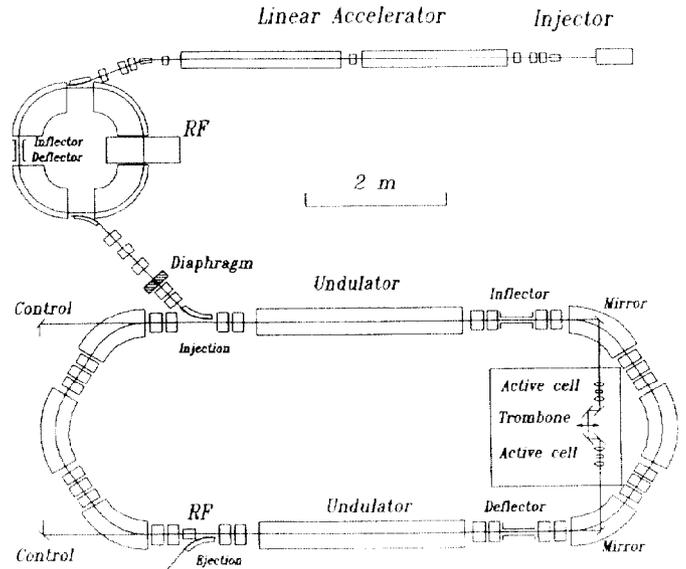


Fig. 2. Damping ring with injection complex.

In conventional schemes, all particles in the sample get the same kick. In optical stochastic cooling, the particles get a kick, dependent on the phase of the electromagnetic wave, produced by the sample, and time of entering of the particle in the kicker.

For optical stochastic cooling the mixing problem does not cause any additional difficulties due to the short length of the sample, corresponding to the bandwidth, and the remaining synchrotron radiation.

The damping ring complex is represented in Fig. 2. Here the Injector is a thermionic gun producing the beam, which is accelerated in the Linear Accelerator. After that the beam goes into the soft focusing synchrotron. The extracted beam, which is scraped in a diaphragm, goes to the main ring. The main ring is basically a racetrack type with three magnet bends. The bending magnets are interlaced by triplets. On one bend is positioned the optical bypass, which includes mirrors, active cells and a trombone for adjusting the general delay.

The one turn injection system consists of pulsed injection septum and inflector, placed at a quarter of a wavelength of betatron oscillation. The damping ring also contains the one turn extraction system for further possible utilization.

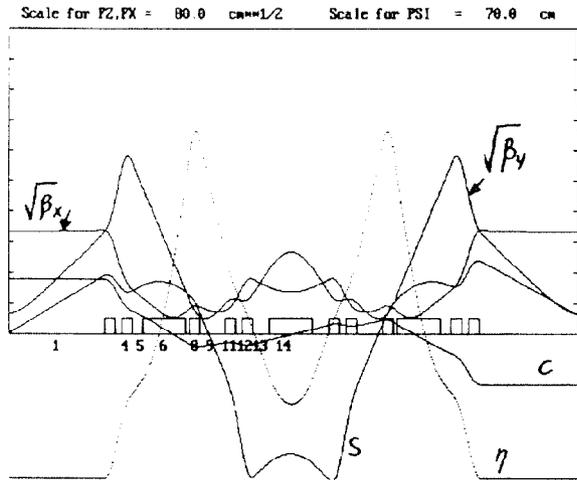


Fig.3. The Floquet functions, the dispersion function, $C_x(s)$, $S_x(s)$ for horizontal motion. The wigglers are not represented.

Parameters of the soft focusing damping ring are the following:

E	300 MeV	Circumference.....	460 cm
f_0	65 MHz	$\gamma\epsilon_x$	$8.2 \cdot 10^{-4}$ m rad
$Q_x \approx Q_y$	0.88	$\gamma\epsilon_y$	$1.1 \cdot 10^{-9}$ m rad
$(\Delta E / E)_{QE}$	0.00037	N	$3 \cdot 10^{10}$
τ_z	0.006 sec	U_{RF}	2.2 kV

The number of the particles, mentioned above, corresponds to the current 300 mA. Further the number of the particles will

be $N \approx 10^8$ after the scraper. Parameters of the main damping ring are the following:

E	300 MeV	Circumference.....	1596.0 cm
f_0	18.8 MHz	$\gamma\epsilon_x$	$4.4 \cdot 10^{-5}$ m rad
$Q_x \approx Q_y$	2.98, 2.69	$\gamma\epsilon_y$	$2.5 \cdot 10^{-10}$ m rad
$(\Delta E / E)_{QE}$	0.00032	N	$1 \cdot 10^8$
τ_z	0.025 sec	U_{RF}	3.0 kV

Emitances for both damping rings are calculated taking into account IBS both for vertical and horizontal directions. These calculations made numerically, take into account the real envelope functions in the damping ring. For the main ring the damping time due to OSC was taken as 1 millisecond. The physical restriction for coupling of transverse motion is IBS, which has a level $\sqrt{\epsilon_y / \epsilon_x} \leq 5 \cdot 10^{-4}$. The envelope functions of main damping ring are represented in Fig.3. The OSC could be a first test for vertical emittance, where the lengthening limitations are weaker.

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References

- [1] A.A.Mikhailichenko, M.S.Zolotarev, "Optical Stochastic Cooling", Phys. Rev. Let., vol. 71, n 25, 1993.
- [2] S. van der Meer, "Stochastic damping of betatron oscillations", Internal report, CERN/ISR PO/73-31. D.Möhl, G.Petrucci, L.Thorndhal and S.van der Meer, Physics and Technique of Stochastic cooling, Phys. Reports 58, No.2 (1980), 73-119.
- [3] R.Wallenstein, "Pulsed Dye Lasers", in Laser Handbook, vol.3, p.289, Edited by M.L.Stitch, North-Holland PC, 1979.
- [4] H.G.Hereward, "Statistical Phenomena", in Proc. First Course Int. School on Accelerators, Erice, 1976: Theoretical Aspects of the behavior of beams in Accelerators and Storage Rings (CERN 77-13 Geneva, 1977), p.281.
- [5] D.E.Alferov, Yu.A.Bashmakov, k.A.Belovintsev, E.G.Bessonov, P.A.Cherenkov, "The Undulator as a source of electromagnetic radiation", Particle accelerators, 1979, vol.9.p.223.
- [6] H.Bruck, "Accelérateures Circulaires de Particules", Press Universitaires de France,1966.
- [7] F.Nolden, G.Berthes, D.Bohne, B.Franzke, A.Schwinn, "Stochastic precooling of Heavy Fragments in the ESR", EPAC-1988, proceedings, vol.1,p.579. S.Y.Lee, K.Y.Ng, D.Trbojelvic, "A design of quasi-Isochronous Storage Ring", 1993 Part. Acc. Conf., p.102. L.Lin, C.E.T.Gonsalves da Silva, "A quasi-Isochronous Oper. mode for the LNLS UVX Stor. Ring", ibid, p.252. W.Wan, M.Berz, Four Cell Third Order Achromatic and Their Application to Multi-Pass Time of Flight Spectrometers, bid, 155.
- [8] K.Steffen, "High Energy Beam Optics", Interscience Pub., 1964.