SIMULATION STUDY OF STOCHASTIC COOLING FOR ACR AT RIKEN MUSES

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Abstract

We have made particle tracking simulation for a stochastic cooling system that will be installed in the accumulator cooler ring (ACR) at the RIKEN MUSES project [1]. This calculation strongly recommends us to design a lattice having dispersion asymmetry for the ACR to get shorter cooling time. It also shows that stochastic cooling system having variable frequency band is quite useful for faster beam cooling; typically half of cooling time is obtained compared with fixed band system. With this calculation, optimization of both the lattice of the ACR and stochastic cooling system is now in progress.

1 STOCHASTIC COOLING SYSTEM

In the stochastic cooling system assumed here, that is shown in Fig.1, strip line electrodes are used as both pickup and kickers, and the notch-filter method is adopted for longitudinal cooling. Every signal transport lines from the pickup to the kicker are made with 50-Ω impedance, and most of parameters in the system, for examples, sensitivity of electrode, gain of amplifiers, signal delay, pass band frequency, attenuation gain, etc. are variable in this calculation. Signals input to the kickers are originally produced at pickups by particles themselves when they pass through pickups. These signals are combined with thermal noise and transported to the kickers through every devices shown in Fig, 1. Particles feel not only longitudinal modulation potential but also transverse one at the longitudinal kickers, and that is the same at the transverse kickers.

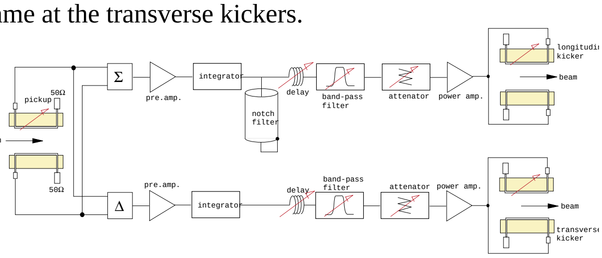

Fig. 1: Model of stochastic cooling system.

Origin of the pickup signal is beam current:

$$I_{pj}(t) = qef_j \sum_{n=-\infty}^{\infty} \delta(t - t_j - n/f_j) \qquad (1)$$

and the dipole current $d_j(t)=I_{pj}(t)x_j$ for longitudinal and transverse directions, respectively; they are coherent signal for the j-th particle, where f_j is revolution frequency, t_j arrival time at the pickup, and x_j transverse position at the pickup. The current is transformed to pickup voltage signal with coupling impedance $Z(\omega)$. After passing through all devices shown in Fig. 1, produced modulation potential in time domain for the i-th particle at the longitudinal kicker is

$$V_i^{Lcoh}(t) = -\frac{qe}{\pi}\sqrt{\frac{R_pZ_pZ_k}{R_k}}G_{tot}^L g_{ki}^L \sum_{j=1}^{N} g_{pj}^L \frac{1}{\tau_{pj}}$$
$$\times \sum_{n=-\infty}^{\infty} \frac{1}{n}\sin(n\omega_j\theta_{pj})\sin(n\omega_j\theta_{ki})\sin(n\omega_j/2f_0)e^{jn\omega_j(t-t_j-\theta_{pj}-\theta_{ki}-1/2f_j)} \qquad (2)$$

for coherent component and

$$V_i^{Linc}(t) = -j\frac{2qe\beta_i c}{\pi h_k}\sqrt{\frac{R_pZ_pZ_k}{R_k}}G_{tot}^L g_{ki}^T \sum_{j=1}^{N} g_{pj}^L \frac{1}{\tau_{pj}}$$
$$\times \sum_{n=-\infty}^{\infty} \frac{1}{n^2\omega_j}\sin(n\omega_j\theta_{pj})\sin(n\omega_j\theta_{ki})\sin(n\omega_j/2f_0)e^{jn\omega_j(t-t_j-\theta_{pj}-\theta_{ki}-1/2f_0)} \qquad (3)$$

for incoherent one. In the same way, those at the transverse kicker are

$$V_i^{Tcoh}(t) = -\frac{qe\beta_i c}{\pi h_p h_k}\sqrt{\frac{R_pZ_pZ_k}{R_k}}G_{tot}^T g_{ki}^T \sum_{j=1}^{N} g_{pj}^T \frac{A_j}{\tau_{pj}}$$
$$\times \sum_{n=-\infty}^{\infty}\left[\begin{array}{l}\frac{1}{(n+Q_j)^2\omega_j}\sin\left((n+Q_j)\omega_j\theta_{pj}\right)\sin\left((n+Q_j)\omega_j\theta_{ki}\right)e^{j\left((n+Q_j)\omega_j(t-t_j-\theta_{pj}-\theta_{ki})+\phi_j\right)} \\ +\frac{1}{(n-Q_j)^2\omega_j}\sin\left((n-Q_j)\omega_j\theta_{pj}\right)\sin\left((n-Q_j)\omega_j\theta_{ki}\right)e^{j\left((n-Q_j)\omega_j(t-t_j-\theta_{pj}-\theta_{ki})-\phi_j\right)}\end{array}\right] \qquad (4)$$

$$V_i^{Tinc}(t) = j\frac{qe}{2\pi h_p}\sqrt{\frac{R_pZ_pZ_k}{R_k}}G_{tot}^T g_{ki}^L \sum_{j=1}^{N} g_{pj}^T \frac{A_j}{\tau_{pj}}$$
$$\times \sum_{n=-\infty}^{\infty}\left[\begin{array}{l}\frac{1}{n+Q_j}\sin\left((n+Q_j)\omega_j\theta_{pj}\right)\sin\left((n+Q_j)\omega_j\theta_{ki}\right)e^{j\left((n+Q_j)\omega_j(t-t_j-\theta_{pj}-\theta_{ki})+\phi_j\right)} \\ +\frac{1}{n-Q_j}\sin\left((n-Q_j)\omega_j\theta_{pj}\right)\sin\left((n-Q_j)\omega_j\theta_{ki}\right)e^{j\left((n-Q_j)\omega_j(t-t_j-\theta_{pj}-\theta_{ki})-\phi_j\right)}\end{array}\right] \qquad (5)$$

where Z and R are characteristic impedance of electrode and line impedance of feed through, G_{tot} total amplitude along the signal transport line including pre- and power amplifiers, attenuation, cable loss, and gain loss at signal combinations, g a geometric factor related to relative position between electrodes and beams, τ a transit time of beam at the pickup electrode, θ is expressed by $l/2(1/v_s+1/\beta_i c)$ with length of electrode l and signal velocity v_s on the electrode, A a betatron amplitude, Q a tune value, h is gap height of electrode pair, and we

Table 1: Parameters set used in the calculation

Number of pairs of electrode	16
Length, width, and gap of electrode [mm]	50/60/100
Impedance Z and R [Ω]	50/50
Preamplifier: temp.[K], Nf[dB], gain [dB]	100/1.2/37
Power amplifier gain [dB]	160
Cable loss and attenuation [dB]	variable
Ring circumference C [m]	139.87
Distance between pickup and kickers (L/T) [m]	59/52
β functions at pickup and kickers (L/T) [m]	21.0/4.0/18.0
α functions at pickup and kickers (L/T)	-0.694/0.0/0.595
Betatron tune Q	3.225
Betatron phase advance from pickup to kickers	0.904/0.731
Chromatisity ξ	0.0

assumed here that every gain factor included in G_{tot} is constant over whole frequency range, electrodes of pickup and kicker are exactly the same type. Suffixes p and k means values at pickup and kicker, respectively; L and T values in longitudinal and transverse directions, respectively.

Following calculations have been curried out for RI beam with A/q=100/40, the energy of 300 MeV/u (γ=1.322) and the number of circulating particles of 10^3. Parameters set typically used here are listed in Table 1; especially machine parameters are taken from present design of the ACR [2]. Thermal noise coming from somewhere in the system is also taken into account. Calculations for both longitudinal and transverse directions are simultaneously done; they affect something to each other; only horizontal (x) direction is taken into account as transverse effect in the present calculation.

2 REQUIREMENT FOR ACR

We have started calculation with only coherent signal to obtain requirements for ACR especially the lattice structure. One of the important results from the study is that the ACR lattice should be asymmetric. This means that the lattice consists of two parts which have different types of lattice; one is a part of approximately isochronous ring and the other is a strong focus type of ring having large transition gamma compared with γ (1.1-1.4: ACR case) of beam. The lattice structure from pickup to kickers should be the former and the reverse should be the latter. In the other words, the ring has partially different slipping factor η defined by $\eta\Delta P/P=\Delta T/T$, where T is time of flight; the factor η_{pk} is for from pickup to kickers and η_{kp} for from kicker to pickup. The requirement of asymmetric lattice is shown in Fig. 2; this shows contours of cooling rate obtained from average with the first 100 turns in (η_{pk}, η_{kp})-plane for the case of use of two different frequency band in which initial momentum spreads $\Delta P/P$ are 0.5 % and 0.04 % (rms), respectively. If we define γ_{pk} as $\eta_{pk}=1/\gamma_{pk}^2-1/\gamma^2$ and γ_{kp} as $\eta_{kp}=1/\gamma_{kp}^2-1/\gamma^2$, range of ($\gamma_{pk}$,$\gamma_{kp}$) in Fig. 2 corresponds to 1.0-6.0.

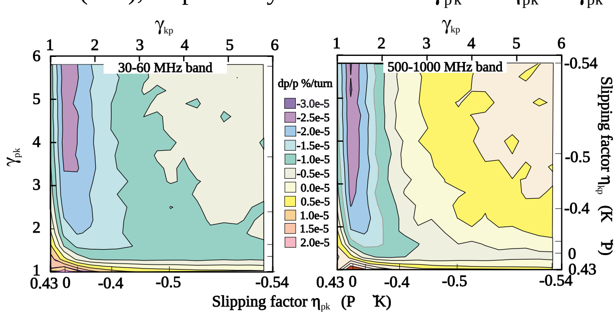

Fig. 2: Momentum cooling rate in (η_{pk},η_{kp})-plane.

This behavior can be qualitatively understood as follow: since energy modulation rate is proportional to difference of the revolution frequency Δf_j in the notch-filter method, larger slipping factor in negative direction is desirable, many particles, however, are out of cooling phase due to phase shift by notch filter and breaking synchronism between transported modulation signal and traveling particles from pickup to kicker. In the other words, Fig. 2 tells us that mixing factor from pickup to kickers should be large but small from kicker to pickup as well known.

Even if we take into account incoherent modulation and thermal noise, this property is maintained as shown in Fig. 3; changes of rms momentum spread and rms emittance obtained in long time tracking calculation are shown for several cases of (γ_{pk},γ_{kp}). As expected from Fig. 2, in the case of asymmetric lattice (γ_{pk},γ_{kp})=(1.5,5.0), which corresponds to (η_{pk},η_{kp})=(-0.128,-0.532), the cooling time is shorter than those of the other symmetric cases. In the case of symmetric lattice with large transition gamma, momentum cannot be cooled down up to our target momentum 0.1 %; this means that lower frequency band should be used. For faster cooling time and final momentum spread which we can reach, higher frequency band is desirable. Asymmetric lattice, therefore, is suitable for stochastic cooling.

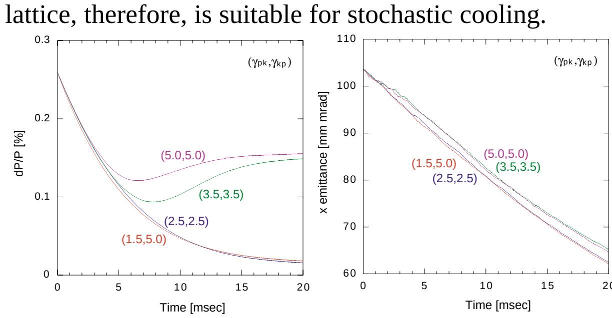

Fig. 3: Changes of $\Delta P/P$ and ε_x for several (γ_{pk},γ_{kp}).

Since it is a mission for the ACR to cool down hot RI beams as soon as possible, design of the lattice should be dedicated to the beam cooling. One of the solutions is presented in ref. [2].

3 VARIABLE BAND SYSTEM

To get faster cooling, we have to optimize not only the lattice structure but also the stochastic cooling system itself. Present calculation tell us that the frequency band of the system should be continuously changed as decreasing $\Delta P/P$ of the beams. Once lattice design is established, frequency band used in the cooling system depends on the momentum spread of circulating beams.

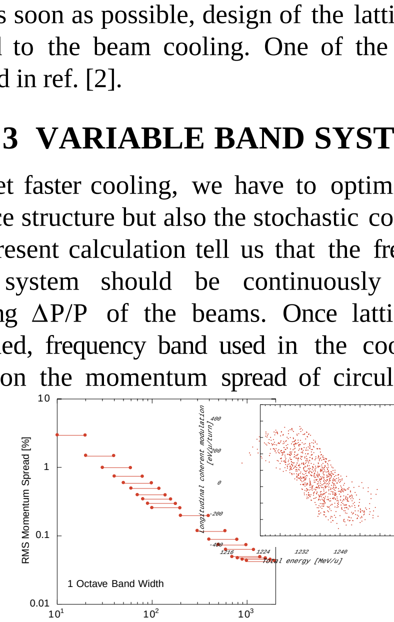

Fig. 4: Optimum frequency band for given momentum spread (rms).

Assuming that we have asymmetric lattice with $(\gamma_{pk},\gamma_{kp})=(1.5,5.0)$, relations between rms $\Delta P/P$ of the beam and the suitable frequency band is shown in Fig. 4, we assume here the band width for all bands to be a octave. The criterion is that particles in 6-rms $\Delta P/P$ feel approximately linear modulation by coherent signal in longitudinal direction as shown in right part of Fig. 4; this corresponds to the mixing factor from pickup to kickers of about 20.

Assuming momentum spread at the starting point of cooling to be $\Delta P/P$=0.5 % (rms), we should used the frequency band of 60-120 MHz. If cooling system can change the frequency band electrically by means of some ways, we should sweep the band to higher frequency as decreasing the momentum spread. This effect on cooling time is shown in Fig. 5. Obviously the momentum cooling time in variable band system is much shorter than that of fixed band system. In the case of fixed band system, cooling force is gradually decreases as decreasing $\Delta P/P$. On the other hand, since we change not only frequency band but also the characteristic of sensitivity of the pickup and kickers, delay and attenuation gain in signal transport line, etc., as shown by red arrows in Fig. 1 so that the system is always optimum for used band, cooling rate in longitudinal direction dose not have so big change and beam is cooled down linearly with time. Variable band system gives us shorter cooling time at our target $\Delta P/P$ of 0.1 % by a factor of about 2 compared with fixed band one.

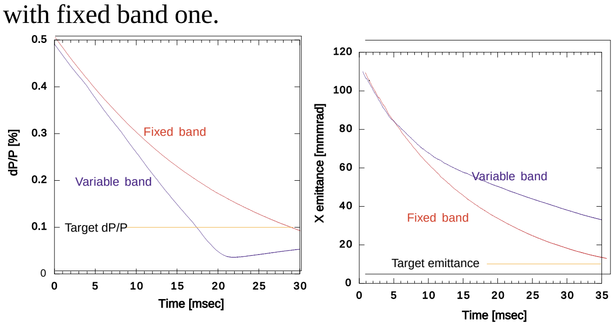

Fig. 5: Comparison of beam cooling between with fixed and with variable bands system.

For emittance cooling, it seems from Fig. 5 that the variable band system in not so effective. The reason is that the transverse coherent signal amplitude is approximately proportional to $1/n^2$ as shown in eq. (4), nevertheless amplifier gain dose not change in every band in the calculation of Fig. 5. So this problem can be avoided by controlling the gain during cooling process.

4 CONCLUSIONS

We have made particle tracking simulation code for stochastic cooling to help the optimizations of the ACR lattice and the cooling system itself. In this paper, we present two important results quantitatively. The lattice of the ACR should be asymmetry; it should consists of two parts which have different slipping factor, i.e. negatively small slipping factor from pickup to kickers and negatively larger one from kickers to pickup. This structure makes cooling time shorter and obtains colder beam compared with normal strong focusing lattice. In the other words, asymmetric lattice allow us to use higher frequency band to cool down the beam having the same momentum spread.

Another recommendation is that the stochastic cooling system should be able to sweep the frequency band continuously during cooling process. This system prevents the decreasing of cooling rate as decreasing momentum spread and cools the momentum of beams linearly with time. Consequently beam cooling is faster by a factor of 2 than the fixed band system.

Since we accumulate and cool down RI beam having short lifetime in the ACR, faster beam cooling is top priority in designing the ACR. We are now making more detail calculations for optimization of the system and studying how can such system be realized.

REFERENCES

[1] T.Katayama, et al., “Storage Rings of Ions and Radioactive Beams”, This proceedings.

[2] K.Ohtomo, et al., “New Lattice Design of Accumulator Cooler Ring for MUSES”, This proceedings.