BEAM BUNCHING WITH STOCHASTIC COOLING

T. Katayama, GSI, Germany, R. Maier, D. Prasuhn, R. Stassen, H. Stockhorst, FZJ, Julich, Germany,
I. Meshkov, JINR, Dubna, Russia
T. Kikuchi, Nagaoka University of Technology, Nagaoka, Japan

Abstract

Beam bunching with RF field and stochastic cooling is investigated numerically and is compared with the experimental results. The formation of short bunch from the coasting beam is proposed in the heavy ion colliders.

INTRODUCTION

Bunched beam stochastic cooling is powerful means to suppress the beam heating due to the Intra Beam Scattering effects. It could contribute to prevent the degradation of beam luminosity at the collider experiments. Recently the concept was successfully attained at the BNL RHIC. [1] Another useful application of bunched beam stochastic cooling is to accumulate antiproton or heavy ion beams in the longitudinal phase space with simultaneous use of stochastic cooling and barrier pulses. In the concept, beams are accumulated in the storage ring from the injector synchrotron every repetition cycle up to the required intensity in the longitudinal phase space. Details of this concept is presented in the separate paper. [2]. Thus accumulated beam is a coasting one and then we need to make short bunches such as 1 nsec bunch length in the collider to attain the good luminosity. In the present paper, firstly the algorithm of the particle tracking code for the bunched beam stochastic cooling is briefly explained and the simulation results are compared with the bunched beam cooling experiments at COSY FZJ. Finally presented are simulation results of formation of short bunch of 3.5 GeV/u 197Au79+ beam at the NICA collider project at JINR.

COMPARISON OF SIMULATION AND EXPERIMENTAL RESULTS AT COSY

The theoretical model of stochastic cooling has been fully developed during two decades, being verified by the achieved experimental results at CERN, FNAL, GSI and FZJ. The cooling has been mainly applied to the coasting beam and the numerical results of Fokker-Planck solver well explained the cooling process. On the other hand, for the bunched beam cooling, evolution of cooling process with RF field, several authors tried to build up the theory of analytical way including the synchrotron motion. The recent success of 100 GeV/u gold beam momentum stochastic cooling at RHIC BNL stimulated the field of research of bunched beam cooling.

The simple way for the investigation of bunched beam cooling is so called CBA (coasting beam approximation) where the ring is assumed to be filled with particle number equal to the peak density of bunched beam. Thus approximated coasting beam could be analyzed with Fokker-Planck solver. The CBA is easiest way for the investigation of the bunched beam, but the effects of RF field is not taken into account and the assumption of peak intensity of bunched beam could be over estimated.

Present authors (TKs) have developed the particle (macro particle) tracking code for the study of bunched beam cooling. In the code the cooling force is derived as the similar way as for the coasting beam. The Schottky diffusion force includes the evolution of beam bunching where the required energy spectrum is calculated at each computing cycle from the particle distribution. Other diffusion terms such as IBS effects are included as well. Each macro particle receives the forces of RF field, cooling force and diffusion force as a particle kick.

To check the validity of the present theoretical model and the computing process we have compared the simulated results with the experimental ones performed at COSY FZJ. [3] The main parameters of beam and cooling system are as follows;

Proton beam: Kinetic energy=1.82 GeV, Intensity N=1.7e9, Initial Dp/p=4.4e-4 (rms), Initial bunch length=100 nsec (rms), Rimg slipping factor=-0.065,

Cooling system: Band width=1.8-3.0 GHz, Notch filter type, Electronic gain=~110 dB The electronic gain of cooling system is not clearly determined as usual in the stochastic cooling experiment, and is only a free parameter for the simulation.

The results of numerical simulation are presented in Fig. 1 where energy spectra, at time=0 sec, and 400 sec are illustrated as well as the coherent term obtained from the cooling parameters of electronic gain=110 dB. The particles are well inside the energy acceptance of the cooling system.

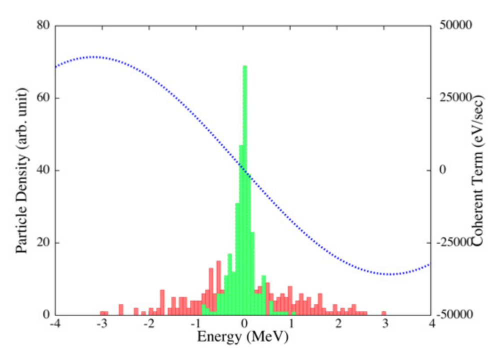

Figure 1: Initial particle distribution (red) and after 400 sec cooling (green). The coherent term (right scale) is obtained with stochastic cooling parameters with gain=110 dB.

The particle distribution in the longitudinal phase space is given in Fig. 2.

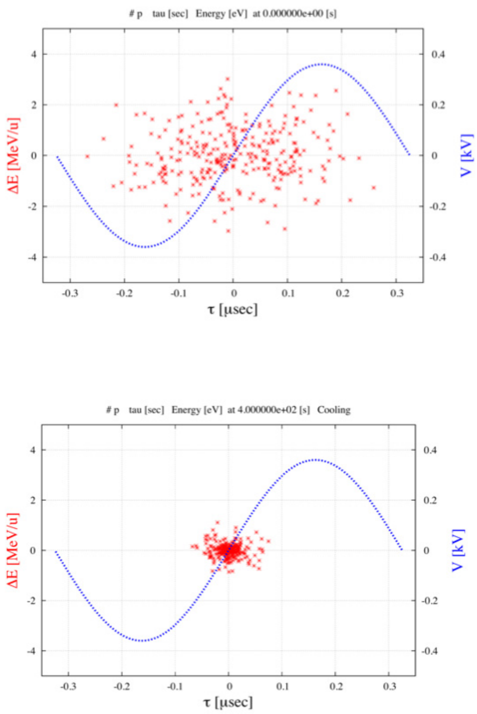

Figure 2: Numerical simulation results. Particle distribution (red points) at time=0 sec (top) and at 400 sec (bottom). The horizontal scale is time (micro sec) and the vertical scales the energy (left scale) and RF voltage. (right scale).

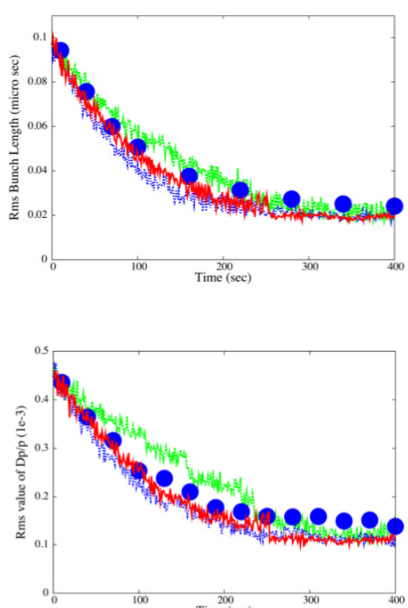

Figure 3: Evolution of bunch length (top) and *Dp/p* (bottom) with time. Red: simulation results for gain=110dB, green for 107dB and blue for 112dB, respectively. Blue points are measured ones. .

At the experiment, the evolution of bunch length was measured as a function of time as well as the relative momentum spread. In Fig. 3 the measured and simulated results of bunch length and *Dp/p* are illustrated.

Both results are in close agreement and the discrepancy between the measured and simulated ones (gain=110dB) of the bunch length are within around 20 % at the equilibrium.

The primary question is what is a main limiting factor to determine the bunch length or longitudinal emittance. The diffusion terms are composed of Schottky diffusion which proportional to the square of electronic gain and the spectrum density. The IBS diffusion term is proportional to the particle density in the six dimensional phase space. The thermal diffusion is proportional to the atmospheric and noise temperature and the gain squared. In the present cooling system the thermal diffusion is negligible comparing with Schottky term as the atmospheric temperature is as small as 80 K. In Fig. 4 the diffusion term including the Schottky noise, thermal noise and IBS effects are illustrated. Red line shows the initial diffusion term, and green line the one after 400 sec cooling. The increase of base line is due to the IBS term as the longitudinal phase space is reduced within 400 sec by factor 15. The Schottky term is around 8e9 [eV^2/sec] at the edge of particle distribution, order of magnitude larger than the IBS effect. Then we can deduce the conclusion that the main limiting diffusion term is Schottky term. As the Schottky diffusion is proportional to the square of the electronic gain and then we can expect that the shorter bunch is expected if we reduce the amplifier gain. As a matter of fact, the lower gain leads to longer cooling time.

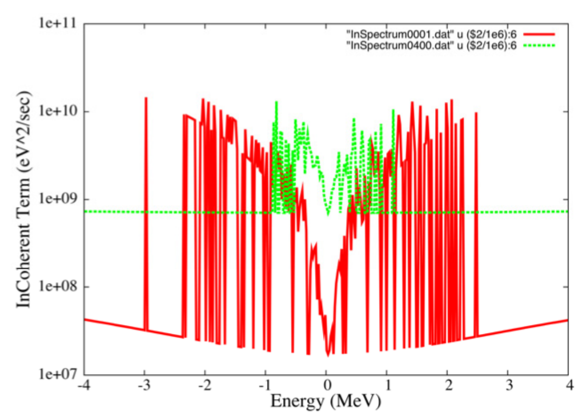

Figure 4: Diffusion term including the Schottky noise, thermal noise and IBS effects. Horizontal scale is prton energy and vertical scale the diffusion term. Red line shows the initial, and green line after 400 sec cooling.

APPLICATION TO THE HEAVY ION COLLIDER

The heavy ion collider NICA is planned at the JINR Dubna where 197Au79+ ion beams at energy of 1-4.5 GeV/u will collide with each other to perform the research on the mixed phase of quark–gluon and hadron states of strongly interacting matter. It requires the average luminosity 1e27/cm2.sec and the bunch length 1 nsec with ion number of 1e9/bunch. The number of bunch in the ring is around 20 . This number could be changed after the more optimization process.

The scheme of beam injection is a barrier bucket accumulation method from the injector synchrotron Nuclotron. Thus accumulated beam is a coasting one and has to be bunched in the collider from the coasting one to the short bunch condition. The initial momentum spread of coasting beam is 1.5e-3 (rms) which is deduced from the analysis of barrier bucket accumulation in the NICA collider in the separate paper [2]. In the beam bunching simulation the initial energy spectrum is assumed as Gaussian with +/- 3 sigma truncated.

First step of the bunching is to apply the stochastic cooling and RF field, 200 kV of harmonic number 20 for the number of 2e10 ions/ring. Thus created 20 bunches contain 1e9 ions/bunch and the *Dp/p* (rms)=6e-4 and bunch length (rms)= 3 nsec. This equilibrium condition is attained within the time period of around 100-150 sec depending upon the cooling gain. Typical gain control is to start from 90 dB and is reduced to 75 dB within 250 sec to suppress the Schottky diffusion. The required microwave power is mainly due to the Schottky power and is depending upon the gain. Typical values are 1kW for 90 dB gain and 10 W for 70 dB gain. The trade-off is the microwave power and the bunching time. When we reserve the bunching time as around 500 sec, the gain 70 dB could be chosen.

The required bunch length 1ns (rms) is achieved with the second step of beam bunching. The pre-bunched beam created in the 1st step is re-captured by the RF field of 500 kV RF field (harmonic number=100). This voltage is adiabatically increased within 1 sec when no significant dilution of the longitudinal emittance is observed in the simulation. The bunch length is reduced by factor two with the adiabatic voltage increase.

After further application of stochastic cooling 100 sec, the bunch length reaches to the equilibrium state of 1.2 nsec. In Fig. 5 are illustrated the evolution of bunch length in the 2nd step. The red line is corresponding to the case with stochastic cooling. Without stochastic cooling, due to the IBS effects, the bunch length increases gradually. The stochastic cooling system, gain=80 dB is continuously applied and the required microwave power is 30 W. In the real cooling system the required power is factor 3~5 larger than the calculated power.

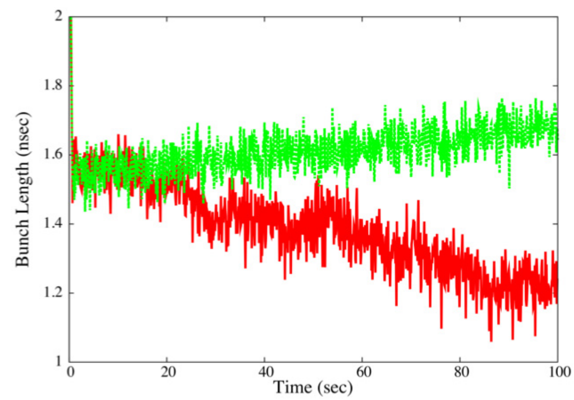

Figure 5: The simulated evolution of beam bunch length with time. Red line shows the case with stochastic cooling and green line without cooling.

The expected beam parameters in the collider are: 20 bunches/ring, 1e9 ions/bunch, *Dp/p*(rms)=9e-4, bunch length=1.2e-9 sec, longitudinal emittance (rms)=0.0045 π eV.sec. For the high dense and short bunch heavy ion beam, further investigations on the beam feed back effects in the stochastic cooling loop and the space charge repulsion force are main concern.

Thanks are due to F. Caspers, D. Moehl and L. Thorndahl for the useful discussions and comments.

REFERENCES

[1] M. Blacskiewicz, J.M. Brennan and F. Severino, Phys. Rev. Lettt. 100 (2008) 174802, In this article covered all important papers related with this subject.
[2] T. Katayama et al., “Beam Accumulation with Barrier Voltages and Stochastic Cooling”, in this Proc.
[3] H. Stockhorst et al., “Stochastic Momentum Cooling with a barrier bucket cavity”, in this Proc.