CRYSTALLINE BEAMS AT S-LSR

A.Smirnov[1], A.Noda[2], T.Shirai[2], M.Ikegami[2]
[1]Joint Institute for Nuclear Research, Dubna, Moscow region, 141980 Russia
[2]Institute for Chemical Research, Kyoto University, Uji-City, Kyoto 611-0011, Japan

Abstract

Simulation and experimental results for the achievement of the ordered state of the proton beam at S-LSR are presented. IBS heating rates were calculated for small temperature of the proton beam using Molecular Dynamics technique.

Different schemes of the laser cooling are proposed for generation of the crystalline magnesium beam. One laser system can be used together with RF-cavity and induction acceleration. Double laser system will be used in future for the formation of three dimensional crystals.

ORDERED PROTON BEAM

In present time the lattice structure of S-LSR has a non zero dispersion (Fig.1). This structure can be used for the achievement of ordered proton beams for the particle number up to 10^6 at energy of 7 MeV.

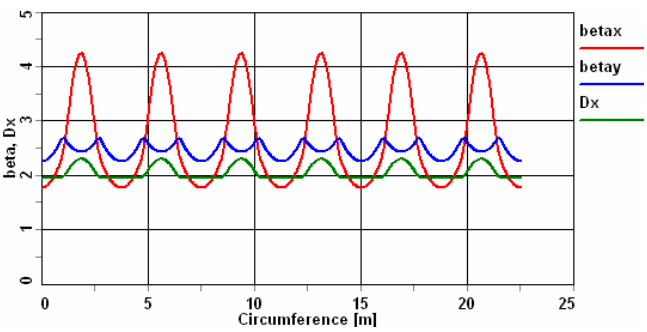

Fig.1. Non zero dispersion lattice structure of S-LSR.

The simulation of intrabeam scattering (IBS) heating rates with using of Molecular Dynamics (MD) techniques [1] shows a good agreement with theoretical calculation of IBS (Martini model [2]) in the range of large emittance and momentum and has a large differences in the range of small emittance and momentum spread (Fig.2) where ordered state of proton beam can be observed.

Ordered state of proton beam with particle number of 10^6 can be reached at very high cooling rates 10^5 sec^{-1} (black points on Fig.3a) and can not be reached for cooling rates of 10^4 sec^{-1} (red points on Fig.3a). For particle number of 10^5 the ordered state can be achieved for cooling rates 10^4 sec^{-1} (Fig.3b). The IBS heating rates are decreasing with particle number decrease (Fig.3a and b) and heating island of longitudinal component is shifted in the range of the smaller momentum spread.

The simulation shows that one and two dimensional crystalline state can be reached for proton beams: string (Fig.4a), zigzag (Fig.4b) and crystalline bunch (Fig.4c). Cooling rates in these simulations were 10^5 sec^{-1} that is impossible presently for real cooling systems.

Electron cooing of proton beam

The real electron cooling rates have values about $10^2 \div 10^3$ sec^{-1} and the ordered state can be reached for the particle number about a few thousands. The theoretical dependence of the longitudinal component of the friction force on the relative particle velocity (Fig.5a) has a good agreement with experimental results on S-LSR (Fig.5b).

The cooling force is measured by the induction deceleration of the proton beam (Fig.5b). The horizontal axis is the relative velocity and the vertical axis is a cooling force normalized by the effective cooler length. The maximum cooling force was 0.11 eV/m at the relative velocity of 4000 m/sec. The slope of the linear region is 3.3 x 10^{-5} eVs/m^2. When the induction force of 0.112 eV/m was applied the ion is not trapped in the cooling force any more.

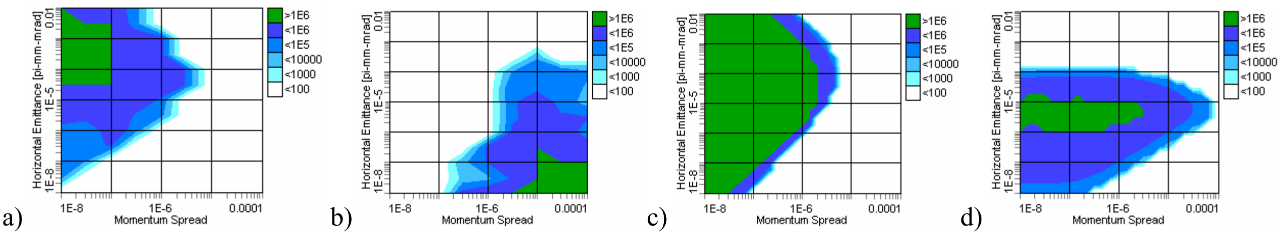

Fig.2. MD calculation of longitudinal (a) and transverse (b) components of IBS heating rates and theoretical calculation of longitudinal (c) and transverse (d) ones. $N_p = 10^6$.

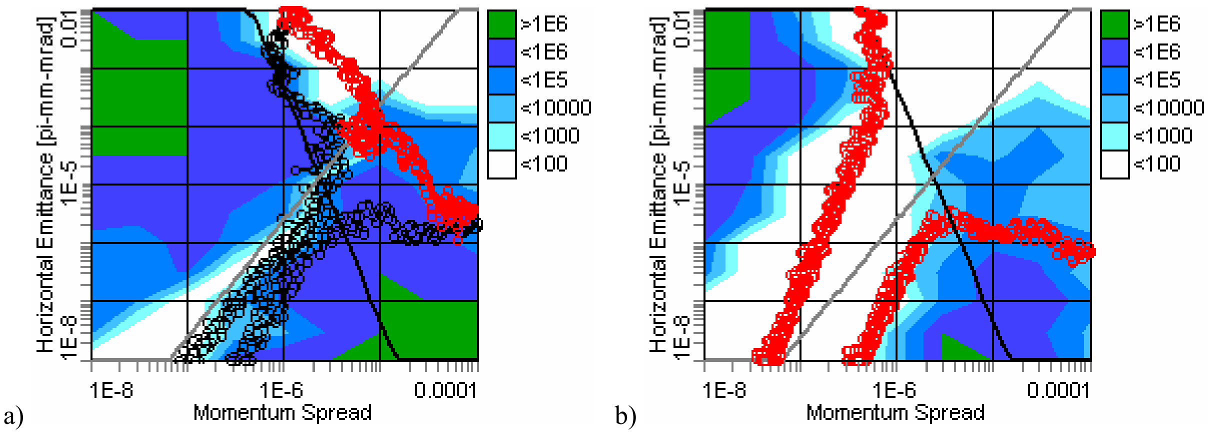

Fig.3. Overlapping of longitudinal and transverse components of IBS heating rates and particle dynamics for different Initial parameters of proton beam and different cooling rates: black – 10^5 sec^{-1}, red – 10^4 sec^{-1}, a) $N_p=10^6$, b) $N_p=10^5$. Black straight line corresponds to the ordered criteria, gray – equilibrium between transverse and longitudinal temperature of proton beam.

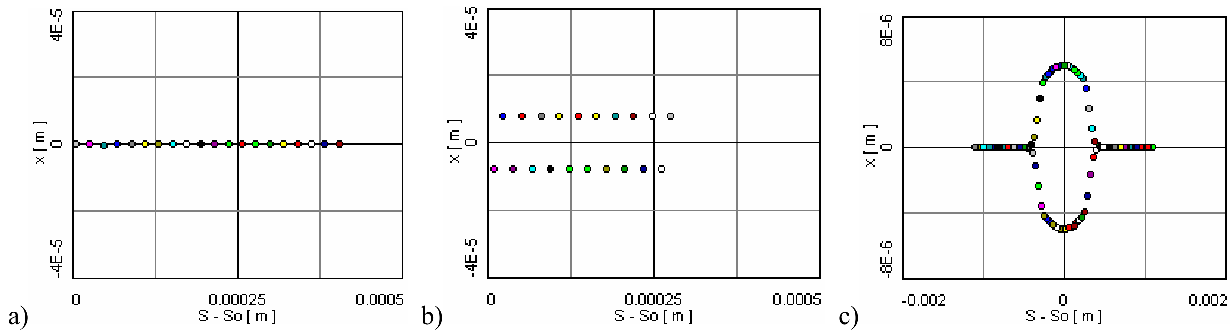

Fig.4. Simulation of crystalline proton beams for cooling rates 10^5 sec^{-1}: a) string for $N_p=10^6$, b) zigzag for $N_p=1.5\times10^6$, c) bunch for $N_p=100$.

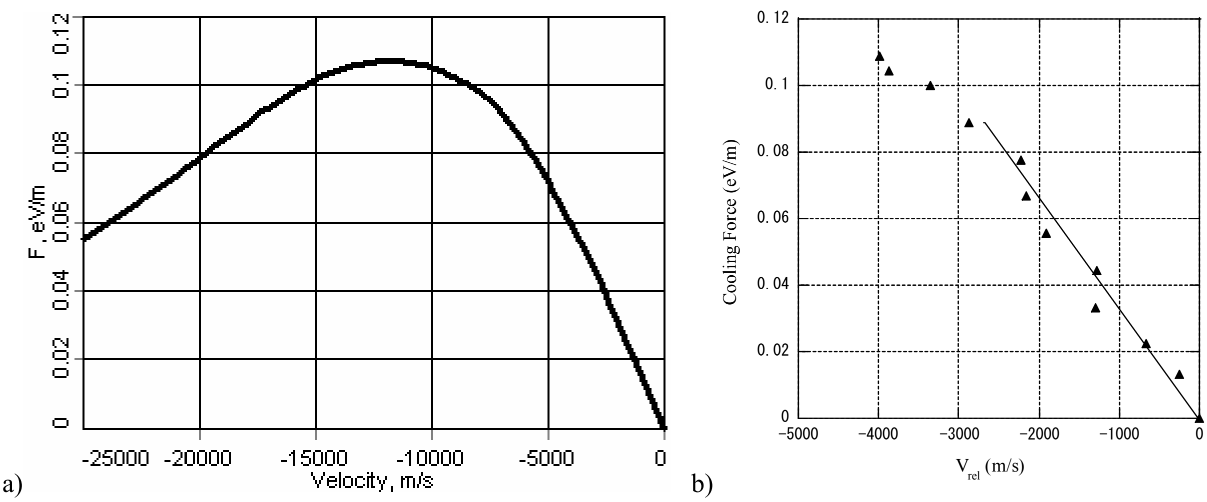

Fig.5. The longitudinal component of friction force vs the relative proton velocity: a) simulation with Derbenev-Skinsky model, b) measurements on S-LSR. $I_e = 0.05$A, a=2.5cm, $T_\perp/T_\parallel$=40meV/0.3meV.

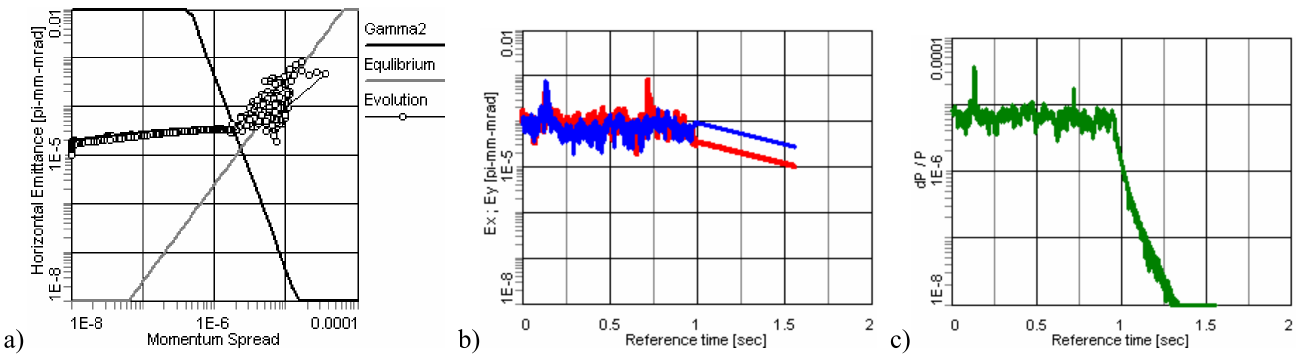

Fig.6. MD simulation of cooling process, N_p=3000.

The simulation of particle dynamics with real cooling force shows that for the real parameters of electron beam which are presented in Fig.5, the ordered state can be reached for particle number about 3000 (Fig.6). The transition point to the ordered state is defined by ordered criteria [1] and the transition value of momentum spread for the proton beam is $\Delta P/P=2\times10^{-6}$ (cross point between black and gray straight lines on Fig.6a).

However the measurements of the dependence of the momentum spread on the particle number shows that the ordered state was not achieved in this experiment (Fig.7). For the particle number less than 10^4 the momentum spread reached the constant value. It means that for small number of particle the equilibrium with cooling force is defined by some another additional heating which does not depend on the particle number.

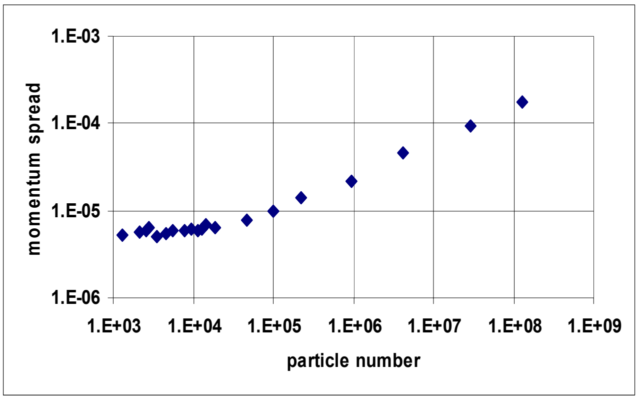

Fig.7. The experimental dependence of the momentum spread on the particle number with electron cooling.

Additional heating can be defined by the homogeneity of the magnetic field of electron cooling section, the stability of power supplies of electron cooling system and optics element of the storage ring. The study of the additional heating nature is the main goal of the further studies for the achievement of the ordered state for proton beams.

Dispersion free lattice structure

The special design of bend magnets permits to get the dispersion free lattice structure at S-LSR [3]. This lattice structure (Fig.8) is a candidate for the achievement of two and three dimensional crystalline beams of magnesium ions under action of the laser cooling.

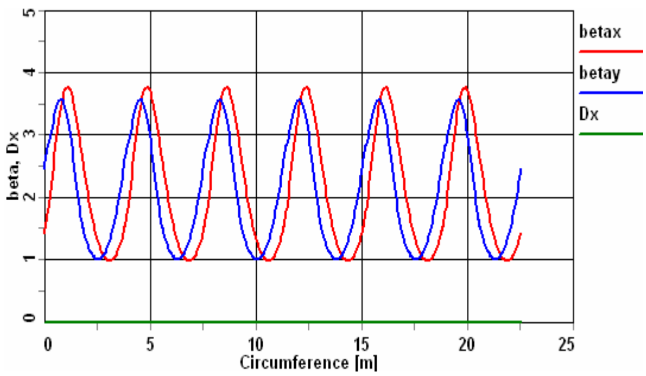

Fig.8. Zero dispersion lattice structure of S-LSR

The same lattice structure was used for the simulation of the ordered state for the proton beam. The results of simulation show that the dispersion free lattice structure does not bring a new advantages in comparison with usual lattice structure for the achievement of the ordered state of proton beams (Fig.9).

LASER COOLING OF MAGNESIUM BEAM

The laser cooling of magnesium ions in the dispersion free lattice structure is proposed for formation of two and three dimensional crystalline beams [3]. Initially one laser will be used for the study of the cooling process and achievement of the ordered state of the magnesium beam.

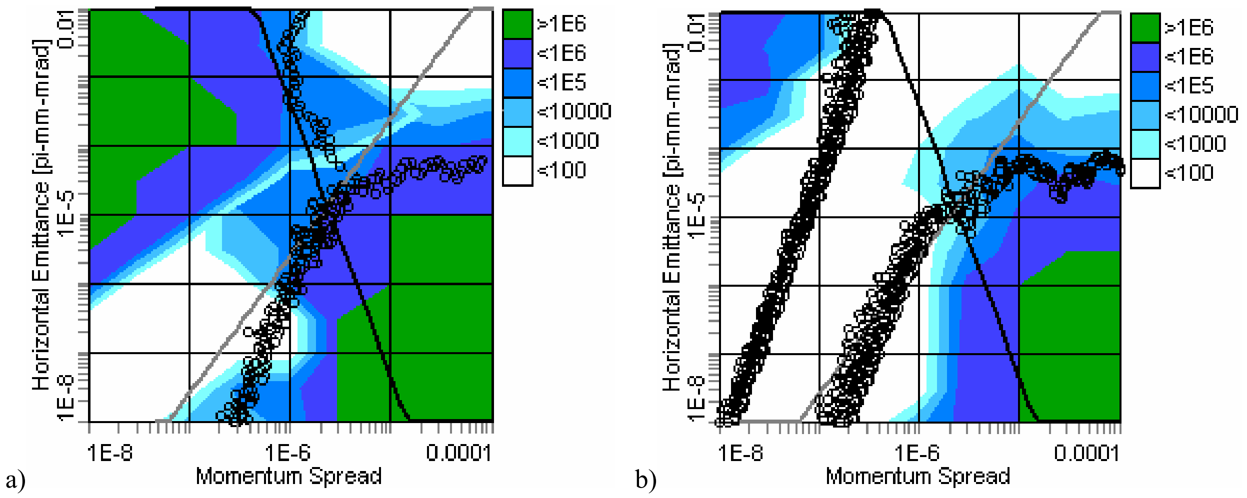

Fig.9. Overlapping of longitudinal and transverse components of IBS heating rates and particle dynamics for different initial parameters of proton beam: a) $N_p=10^6$, cooling rates 10^5 sec^{-1}, b) $N_p=10^5$, cooling rates 10^4 sec^{-1}.

Model of laser cooling

The spontaneous laser force can be calculated with formula [4]:

$$F = \frac{h\nu}{c} \cdot \frac{\Gamma S}{1 + S + (\Delta / \Gamma)^2},$$

where h is the Plank constant, ν - laser frequency, c – speed of light, $\Gamma = 0.2857\times10^9$ Hz - inversed lifetime for upper state of Mg^+ ions, S = 10 - saturation parameter which is defined by ratio of laser intensity and saturation density, Δ - frequency detuning equal to

$$\Delta = 2\pi\gamma_0 \nu(1 + v_{\|} / c) - 2\pi\nu_0 .$$

Here γ_0 is Lorenz factor, $v_{\|}$ - ion velocity in the laboratory rest frame, ν_0 - resonance frequency in the ion rest frame. For Mg^+ ions the resonance wavelength equal to 280 nm.

$$v_{\|} = \frac{P_i}{\gamma_i m} = \frac{P_0 + \Delta P_i}{\gamma_i m} = \frac{P_0}{\gamma_i m}\left(1 + \frac{\Delta P_i}{P_0}\right) \approx v_0\left(1 + \frac{\Delta P_i}{P_0}\right),$$

where index i corresponds to ion parameters, index 0 corresponds to beam parameters, P – momentum, m – particle mass. In the program longitudinal momentum of each particle is described as $\Delta P/P$. Correspondingly we have

$$\Delta = 2\pi\gamma_0 \nu\left[1 + \beta_0\left(1 + \frac{\Delta P_i}{P_0}\right)\right] - 2\pi\nu_0 .$$

Maximum of cooling force corresponds to the laser frequency when Δ=0. Then for $\Delta P/P = 0$ one can write the optimum laser frequency:

$$\nu = \frac{\nu_0}{\gamma_0[1 + \beta_0]}$$

For the simulation of the deviation of the laser frequency from the ion resonance frequency we can introduce the deviation of the momentum spread δ. Finally the frequency detuning in the simulation is

$$\Delta = \nu_0\left[\frac{1 + \beta_0(1 + \Delta P_i / P_0 - \delta)}{1 + \beta_0} - 1\right]$$

The dependence of spontaneous laser force on the ion velocity is presented in Fig.10.

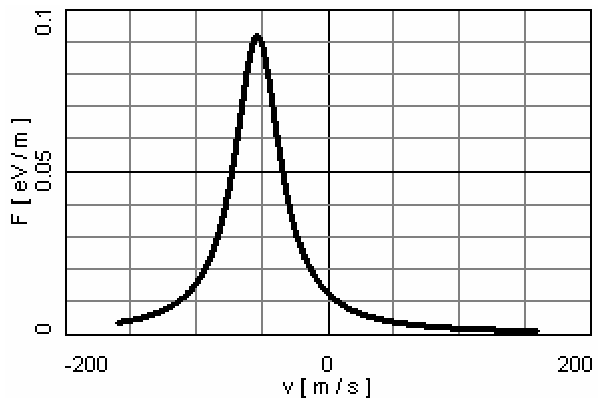

Fig.10. The spontaneous laser force vs the relative ion velocity $\Delta P / P = -3\times10^{-4} \div 3\times10^{-4}$, $\delta = -1\times10^{-4}$, .

Laser cooling with RF-cavity

The harmonic electric field of RF-cavity produces the rotation of ions in the longitudinal phase space and the bunching of the ion beam. In the case of one laser cooling system the final distribution of the ion bunch depends

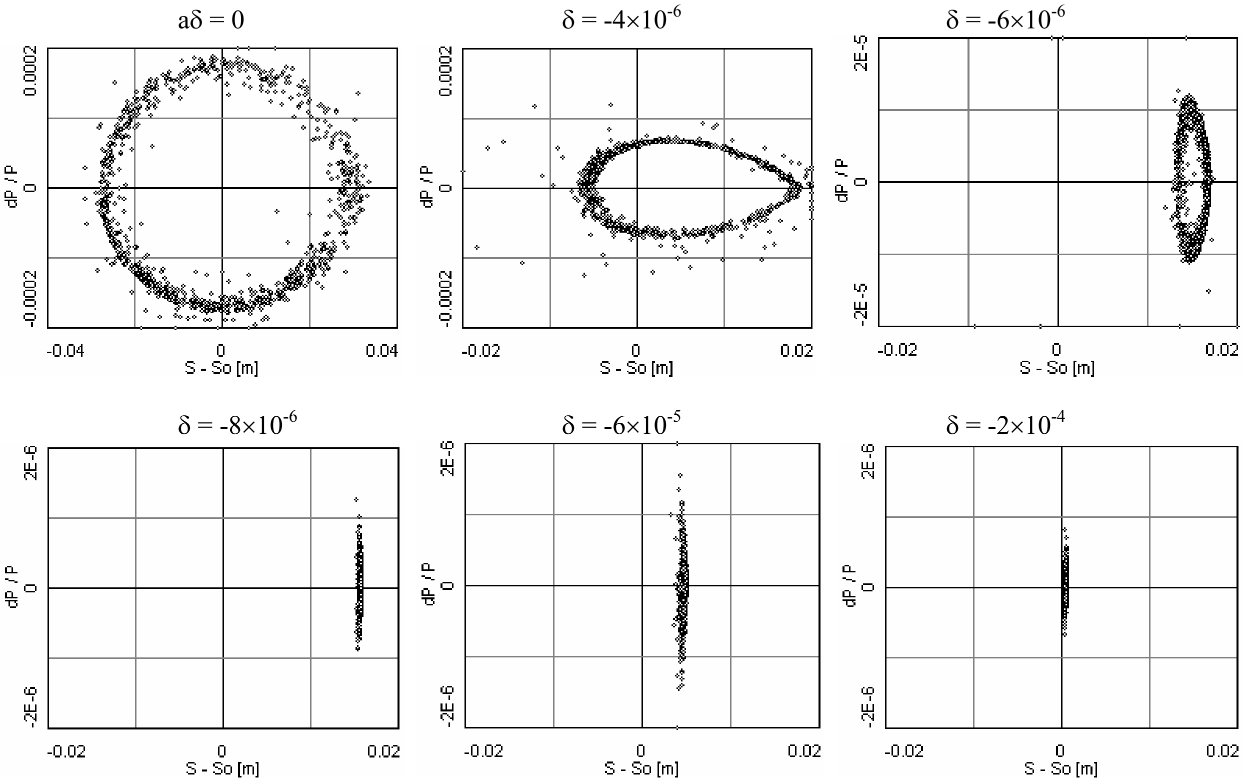

Fig.11. Longitudinal phase space for different deviation of laser frequency without IBS. U_{rf} = 1 V, harmonic number 100.

significantly on the deviation of the laser frequency from the magnesium resonance frequency (Fig.11). For δ = 0 all ions have the same invariant in the longitudinal phase space and travel along the longitudinal separatrix. For the negative deviation of the laser frequency the center of the ion bunch has the positive displacement. Increasing of the frequency deviation leads to the decreasing of the bunch size and momentum spread.

The minimum momentum spread at the level of $\Delta P/P$ ~3×10^{-7} is defined by the equilibrium between the spontaneous laser force and RF voltage. Due to the specific cooling scheme when laser system and RF cavity are placed in the different points of the storage ring the magnesium beam every time will get some additional kick. It means that this scheme can be used for the generation of one dimensional crystal of the bunched ion beam.

Simulation of the particle dynamics with IBS is presented in Fig.12 for different numbers of ions. The result of simulation shows that the transition point to the ordered state (cross point between black and gray straight lines in Fig.12) can be reached for ten ions per bunch only.

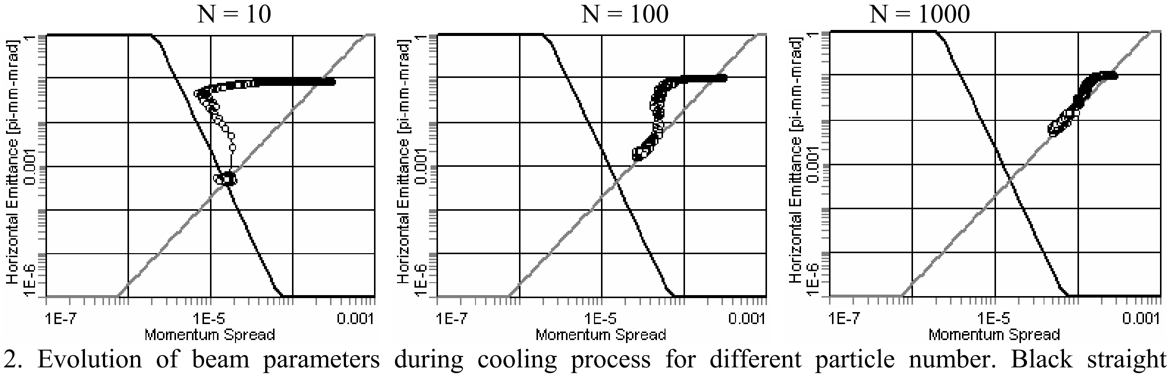

Fig.12. Evolution of beam parameters during cooling process for different particle number. Black straight line corresponds to the ordered criteria, gray – equilibrium between transverse and longitudinal temperature of proton beam.

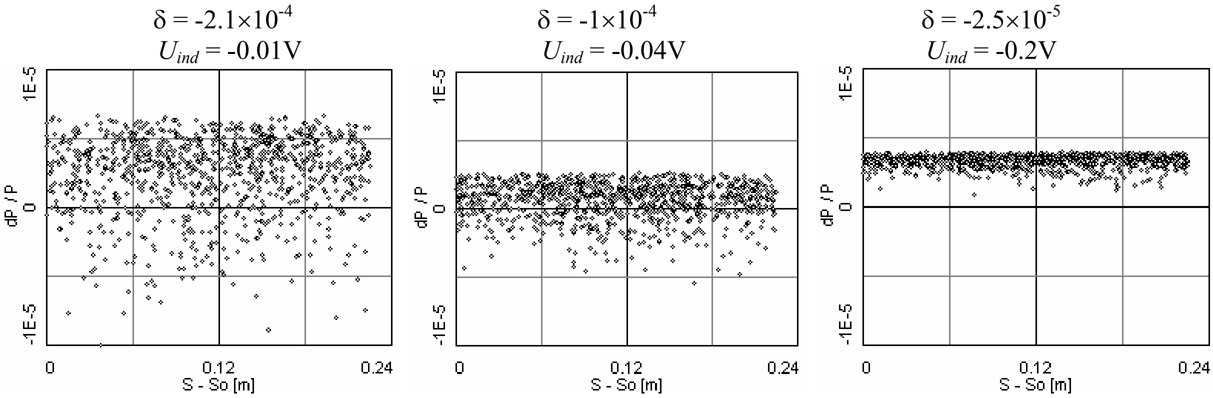

Fig.13. Longitudinal phase space for different deviation of laser frequency and voltage of induction acceleration without IBS.

Laser cooling with induction acceleration

Induction acceleration was used for measurement of electron friction force and can be used also for the single laser cooling scheme. The minimum of momentum spread is defined by the equilibrium between the spontaneous laser force and induction acceleration. This cooling scheme can be used for the formation of one dimensional crystal of the coasting ion beam.

Double laser cooling

For the formation of two and three dimensional crystals the double laser cooling system is needed. In this case co-propagating and contr-propagating lasers accelerate and decelerate a magnesium ion in the same straight section of storage ring.

One dimensional crystals for ion number up to N=10^5 can be reached for double cooling system (Fig.14). For generation of two and three dimensional crystals the bunching process can be started after achievement of the ordered state. This idea is a task for further simulations.

CONCLUSION

The ordered state of the proton beam at energy 7 MeV can be reached for particle number up to 10^6 for very high cooling rates which are impossible for real cooling systems. Simulations shows that the real electron cooling system can be used for the formation of the ordered proton beam for the particle number a few thousand.

No ordered state was observed for proton beams in experiments on S-LSR. The momentum spread was reached a constant value at the particle number 10^4 and does not change with the particle number decreasing. It means that some additional heating exist in the storage ring which does not depend on the particle number.

Single laser cooling system with RF-cavity and induction acceleration can be used for the formation of one dimensional crystal for small number of particles. Double laser cooling system is proposed for generation of three dimensional magnesium crystals. Initially the string structure can be reached for the coasting magnesium beam for the large number of particles. Then one needs to

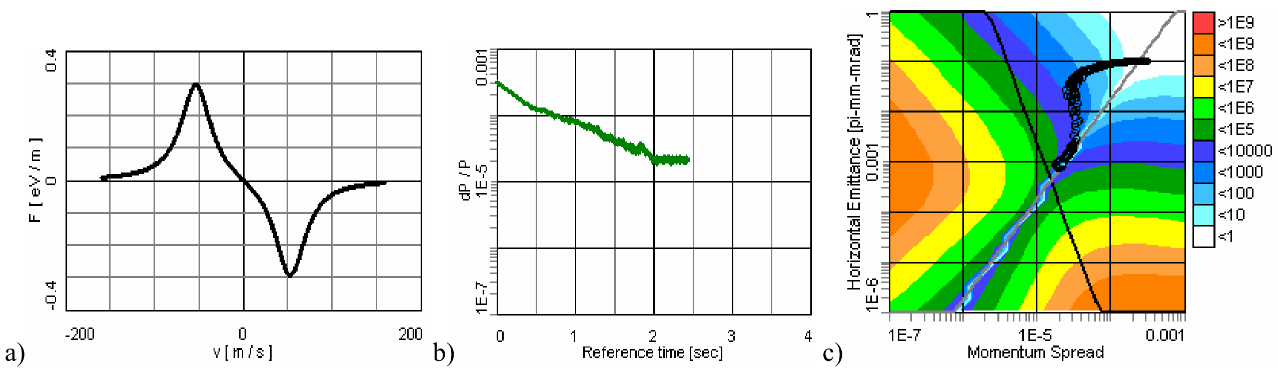

Fig.14. a) dependence of the sum of friction forces on the relative ion velocity for co-propagating and contr-propagating lasers, b) evolution of momentum spread in time, c) theoretical longitudinal and transverse components of IBS and beam evolution during cooling process. N=10^5.

switch on RF-cavity and increase linear density of ions in the bunch beam. The string will be transformed to the zigzag structure when the linear density of ions reaches the transition value from string to zigzag structure.

REFERENCES

[1] I.Meshkov, A.Sidorin, A.Smirnov, E.Syresin, T.Katayama, H.Tsitsui, D.Mohl. Simulation Study of Ordered Ion Beams. Preprint RIKEN-AF-AC-42, July 2003.

[2] M. Martini. Intrabeam Scattering in the ACOOL-AA Machines. CERN PS/84-9 AA, Geneva (1984).

[3] A.Noda et al. Laser Equipped Cooler Storage Ring, LSR at ICR. Proc. of the Workshop on Ion Beam Cooling – Toward the Crystalline Beam. World Scientific Publishing Co. Pte. Ltd, (2002).

[4] A.Noda, M.Grieser. Possible Scheme of Tapered Cooling by Combination of Laser Cooling and Wien Filter. Beam Science and Technology, vol.9, Activity Report 2003/2004, Laboratory of Particle Beam Science ICR, Kyoto University (2005).