Studies of Beam Dynamics in Cooler Rings

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Abstract. This report describes the numerical simulation of the crystalline proton beam formation in COSY [1] using BETACOOL code [2]. The study includes the description of experimental results at NAP-M [3] storage ring where the large reduction of the momentum spread was observed for first time. The present simulation shows that this behavior of proton beam can not be explained as ordered state of protons. The numerical simulation of crystalline proton beams was done for COSY parameters. The number of protons when the ordering state can be observed is limited by value 10^6 particles and momentum spread less then 10^{-6}. Experimental results for the attempt to achieve of ordered state of proton beam for COSY is presented. This work is supported by RFBR grant # 05-02-16320 and INTAS grant #03-54-5584.

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NAP-M EXPERIMENTS

The dependence of momentum spread on ion number in a cooled beam has very specific character: at certain conditions the momentum spread drops up to very low value and remains constant with the decrease of the ion beam intensity.

For the first time such a “disappearance” of the beam momentum spread was observed in experiments on NAP-M, where the suppression of the Schottky noise of the cooled proton beam up to very low level was registered (Fig.1) [3]. Then the assumption of some orderliness of the cooled beam was declared and soon the idea of the crystalline beam was proposed [4].

TABLE 1. Parameters of storage rings.

	NAP-M	COSY
Circumference, m	47,25	183,5
Proton energy, MeV	65	45,6
Gamma transition, γ_{tr}	1,069	2,4
Betatron tunes, Q_x/Q_y	1,34 / 1,24	3,62 / 3,68
Dipole field stability	$\sim 10^{-5}$	$\sim 2\times 10^{-5}$
Electron cooler		
Cooling section length, m	1,0	1,4
Beam current, A	1,0	0,05 ÷ 1,0
Beam radius, cm	0,5	1,27
Magnetic field, kG	1,0	0,8
Electron energy stability	$\sim 10^{-5}$	$\sim 2\times 10^{-5}$

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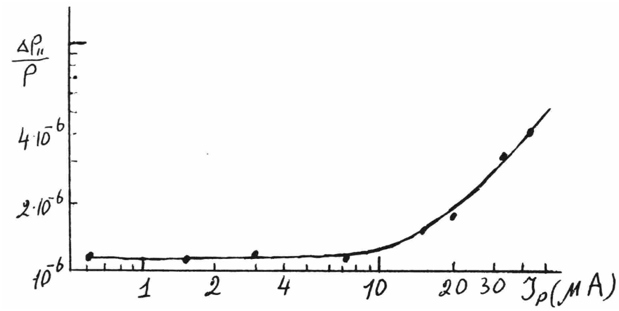

FIGURE 1. NAP-M experiment (1979). The dependence of momentum spread on proton number (1 μA = 2,64·10^6 protons).

To verify the idea of ordering proton beam on NAP-M the numerical simulation of beam dynamics was done for NAP-M lattice structure (Fig.2) which was reconstructed from original articles. The main parameters of NAP-M are presented in Table 1. The example of input file for MAD program is the following:

```
dr1: drift, l=7.1
sb1: SBEND, L=4.7124, ANGLE=1.5708, E1=0.415, E2=0.415
NAPM: line=(dr1,sb1,dr1,sb1,dr1,sb1,dr1,sb1)
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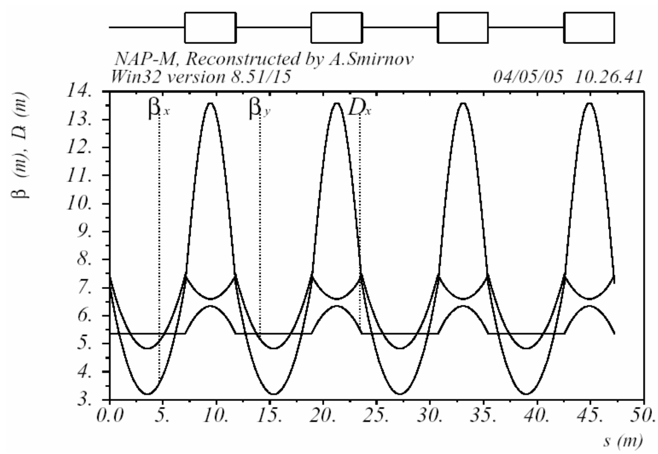

FIGURE 2. Lattice structure of NAP-M.

Fig.3 shows the result of simulation for NAP-M using Molecular Dynamics technique [5] for proton number of 10^6 at constant cooling time 20 μsec. If one overlaps transverse and longitudinal component of IBS (Fig.3,a,b) one can find the particle number when the ordering state can be reached. In the case of particle number of 10^6 the summary picture (Fig.3,c) has the "channel" between of heating growth rates. The simulation results using Molecular Dynamics technique shows that the proton beam can reach the ordered state in NAP-M.

In the case of the proton number of 2×10^6 the "channel" disappears in the summary picture and the ordering state can not be reached. These results show that the ordered state of proton beam on NAP-M can be observed for particle number less then 10^6. Therefore the experimentally observed large reduction of the momentum spread (Fig.1) can not be explained by the ordering process.

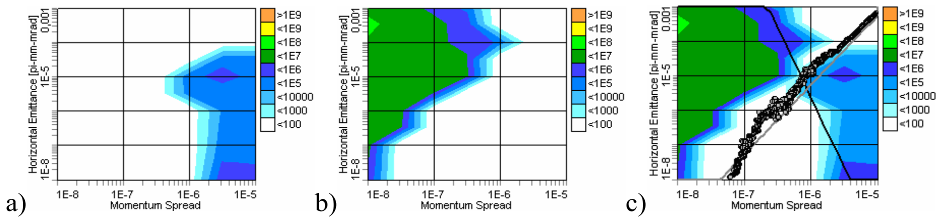

FIGURE 3. Growth rates (1/sec) for NAP-M (Molecular Dynamics). $N_p = 10^6$.
a) horizontal component of IBS, **b)** longitudinal component of IBS, **c)** overlapping of **a** and **b** pictures and beam evolution during cooling process. Gray straight line corresponds to equilibrium between transverse and longitudinal temperature, black straight line – ordering state criteria [6].

COSY SIMULATION

COSY ring has parameters at the injection energy a similar to NAP-M (Table 1). This ring can be used for the study of the ordering proton beams. The main difference from NAP-M is the superperiodicity of the lattice structure. NAP-M has 4 superperiodicity but COSY has only one.

The longitudinal components of IBS growth rates (Fig.4,a) have a large difference from NAP-M lattice structure. The longitudinal component has a very specific island of growth rates in the range of the transition point to the ordered state. The same island was found in simulation for other ring with small superperiodicity. The physics of this island existence is not explained yet. The experimental verification of this behavior of IBS growth rates at low temperature of ion beams is a very interesting and important task.

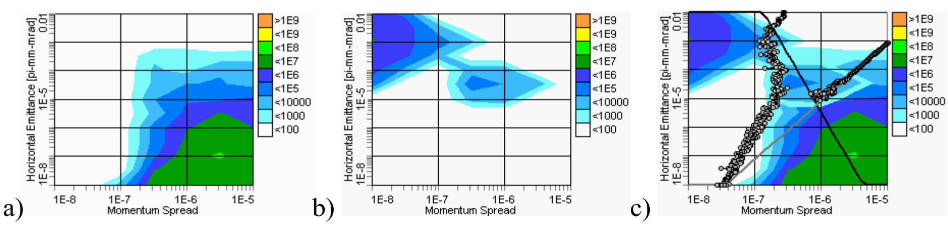

FIGURE 4. Growth rates (1/sec) for COSY (Molecular Dynamics). $N_p = 10^6$.
a) horizontal component of IBS, **b)** longitudinal component of IBS, **c)** overlapping of **a** and **b** pictures and beam evolution during cooling process for different initial conditions.

The numerical simulation with Molecular Dynamics techniques of the cooling process shows that the ordering state for COSY parameters can be reached if the proton beam has specific initial parameters: large transverse emittances and small momentum spread (Fig.4,c).

If initial parameters of the proton beam do fit to the equilibrium temperature (upper points of the gray straight line on Fig.4,c) the proton beam reaches the equilibrium between cooling and heating and can not come onto the ordered state.

COSY EXPERIMENTS

The goal of the proposed experiments is an achievement of the ordered state of the proton beam. Simulation shows that the ordered state can be observed if the proton number less than 10^6 and the momentum spread less than 10^{-6}.

The electron cooling of the proton beam in COSY was done for the different electron beam current values (Fig.5). Momentum spread was measured as FWHM (full width on half maximum) of longitudinal Schottky signal when only one peak is observed. For larger number of protons after the cooling the longitudinal Schottky signal has two peaks (well known plasma waves propagated in the beam) and other method of calculation of momentum spread is needed.

In experiments the COSY ring was operated in a single injection mode. Number of protons at one injection cycle was about $2 \div 5 \times 10^9$. To speed up the process of proton losses the horizontal scraper was used. It decreased the ring aperture and shortened the proton lifetime. After a few minutes of cooling process with the inserted scraper the proton number reaches the value less than 10^8 and longitudinal Schottky signal is transformed to single peak. Then the scraper was returned to initial position and the proton number continues to decrease at constant lifetime.

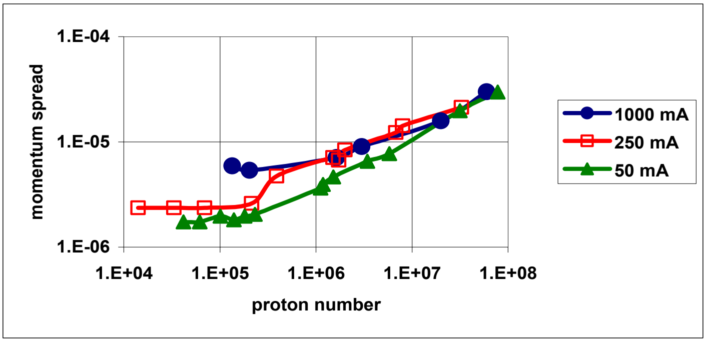

FIGURE 5. The dependence of momentum spread on the proton number for different values of electron beam current.

When the proton number achieves the value less than 10^6 the momentum spread stop to decrease and remains constant. No sudden reduction of momentum spread was observed in this experiment. It means that the proton beam does not achieve an ordered state at present parameters.

Results of COSY experiments are very similar to experiments at NAP-M (Fig.1). They show that the minimum momentum spread depends on the value of the electron beam current (Fig.6) and does not depend on particle number in the range of small number of protons below 10^5. It means that the equilibrium is defined by the parameters of the electron beam when intrabeam scattering disappears.

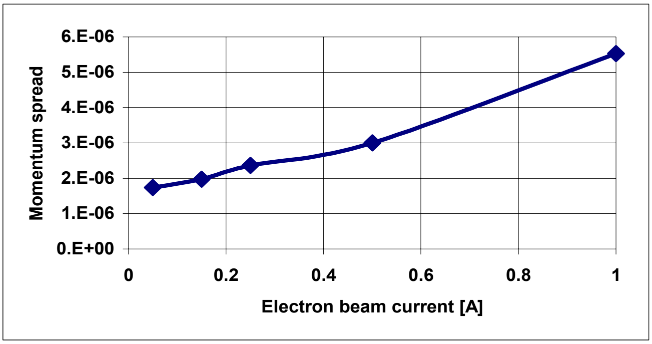

FIGURE 6. The dependence of minimum momentum spread on electron beam current.

To verify the simulation results which predicted the island of the longitudinal component of intrabeam scattering (Fig.4,c) the additional transverse heating with white noise was applied to the pick-up electrodes. In the experiment the additional heating leads to increasing of particle losses or to the excitation of beam selfmodulation in the longitudinal direction. No decreasing of the momentum spread is observed. The special method of transverse heating is needed to verify the break in the longitudinal component of IBS heating rates

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