STUDY FOR STOCHASTIC COOLING AT NUCLOTRON, JINR

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Abstract

The experiment on stochastic cooling at Nuclotron, initiated two years ago as a preparatory work for the NICA collider, is progressing. New scheme of cooling system, which includes ring-slot couplers as pick-up and kicker (designed at FZJ), an optical notch-filter and a full remote-controlled automation of measurements and adjustments, was set in operation in autumn 2012. This report presents first results of the beam cooling achieved at Nuclotron in March 2013.

INTRODUCTION

A unique heavy-ion collider NICA is under construction at JINR (Joint Institute for Nuclear Research) [1]. One of the challenging technologies of the collider project is the stochastic cooling. Since the stochastic cooling had never been used before in JINR, it was decided to perform an experiment at Nuclotron, superconducting synchrotron at JINR, for the NICA team to get familiar with the cooling technique.

The stochastic cooling experiment started in 2010. During the first two years design of the cooling scheme, ordering the required equipment, assembling and adjusting the system components were completed. The present working system was set in operation in 2012.

As the pick-up is located in the straight section with small dispersion, the scheme utilizing the sum signal from the pick-up is advantageous. Thus notch-filter scheme was implemented for the first stage of the experiment.

COOLING SYSTEM

Main parameters of the Nuclotron and stochastic cooling system are presented in Table 1.

Table 1: Parameters of the Cooling System at Nuclotron

Circumference, m	251.5
Ions	D+
Intensity, particles	2×10^{9}-10^{10}
Energy, GeV	3
Rev. frequency, MHz	1.158
Flattop time, s	480
Phase slip factor, η	0.034
Initial $(\Delta p/p)_{RMS}$	0.55×10^{-3}
Cooling system	Long., notch filter
Bandwidth, GHz	2-4
ToF P-K, ns	431.88
Pick-up impedance, Ohm	144
Kicker impedance, Ohm	576
Power for the kicker, W	18

The design of cooling system is described precisely in [2]. Here are described only major features.

The pick-up and kicker are located at the opposite straight sections of accelerator ring (Fig. 1).

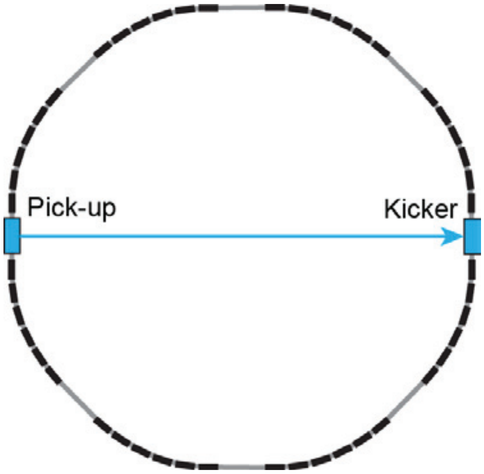

Figure 1: Pick-up and kicker location at the Nuclotron.

The pick-up is installed inside the cryostat at ~10 K, while kicker is in the section at room temperature. Both structures are of ring-slot couplers type (developed in FZ Jülich [3]) consisting of 16 rings with electrodes. Each ring has 8 electrodes, placed uniformly over the perimeter. Signals from each of 8 electrodes are transferred to combiner boards. It is possible to switch remotely between sum and difference modes by rearranging the outputs. In the experiment transverse signals were obtained by combination of 8 electrodes of pick-up in opposite pairs and further subtraction of appropriate signals in vertical or horizontal planes (Fig.2).

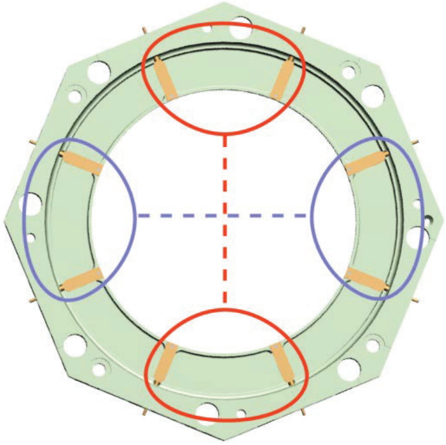

Figure 2: Combination of electrodes for horizontal (blue) and vertical (red) signals.

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The optical notch-filter was utilized in the experiment ([2], [4]). Notch depths are larger than 40 dB on the average and maximum frequency dispersion is 10 kHz (i.e. maximum deviation of notch position in pass-band).

The special software for the filter adjustment was developed. The program measures notches' positions in bandwidth to estimate the notch frequency error and then automatically corrects the delay of long branch of notch filter. In the sequel it scans the notches once again for adjusting the attenuation to have notches as deep and uniform as possible. The adjustment procedure takes only several minutes and easily can be used for the remote automatic filter adjustment for any particle energy at a given range.

The delay line was the part of optical link and consisted of fibres and precise optical delay module with 0.01 ps accuracy. The total delay of all system elements was quite large and only about 15 ns was inserted with additional cable length.

The gain level was around 110-114 dB (see cooling simulation section for details). Total power for the kicker was 18 W that is maximum output power of main amplifier used in the experiment.

OPEN-LOOP MEASUREMENTS

Open-loop measurements is a standard procedure of measurement the response from the beam excited by the kicker. This procedure is typically used for system delay adjustments.

Due to various defects of developed stochastic cooling system we had experienced invalid amplitude and phase behaviour of open-loop measurements during previous runs.

After numerous system revisions open-loop measurements yielded very nice and clear amplitude/phase response signals (Fig. 3), so the system delay could be properly adjusted.

For the system delay adjustment long branch of notch-filter was broken during measurements to take into account only own device delay.

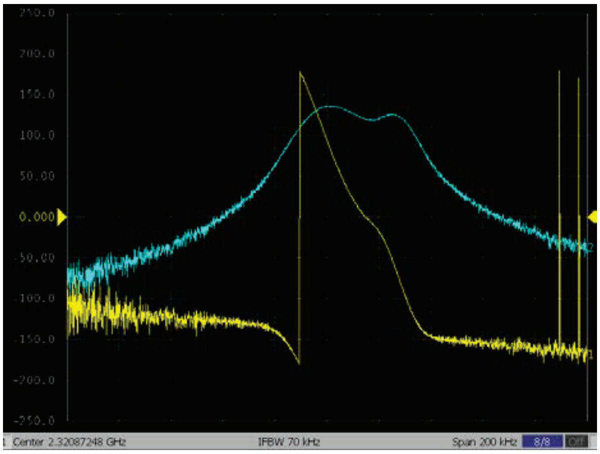

Figure 3: Open-loop measurements taken at 2004th harmonic. Blue/yellow curves – amplitude/phase responses.

EXPERIMENTAL RESULTS

Main experimental results are the following: momentum cooling of deuteron beam and transverse Schottky noises measurements.

Beam Cooling

The momentum cooling of coasting beam of deuterons was obtained (Fig. 4). The beam intensity was 2×10^9 and energy 3 GeV/u. The RMS momentum spread was reduced by approximately a factor of 2.2 within 480 s. The initial momentum spread was 0.55×10^{-3} and the final one was 0.25×10^{-3}.

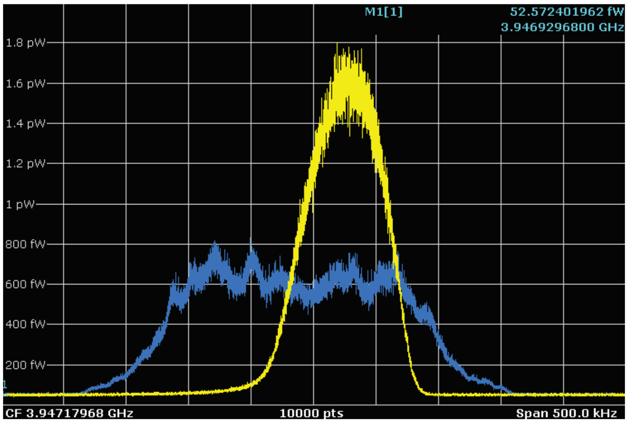

Figure 4: The Schottky signals at 3048th harmonic. The initial signal (blue) and final one at time = 480 s (yellow).

Transverse Schottky Noises Measurements

Transverse signals of the beam were measured. Due to small charge of ions (D+) and short pick-up structure the betatron side-bands are almost at noise level, but signals were discernible. Horizontal and vertical noises are shown in Fig. 5 and 6. Fractional parts of the betatron numbers are estimated from these measurements as:

$$q_x \approx 0.28,\ q_y \approx 0.32\,.$$

The beam was not centred correctly in the pick-up as longitudinal harmonics of revolution frequency are not completely rejected.

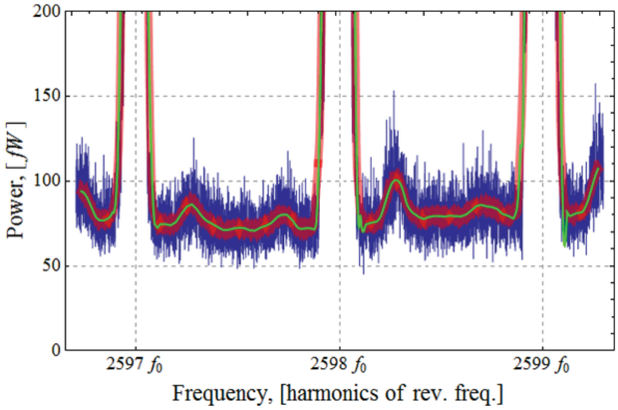

Figure 5: Horizontal Schottky noise (blue) with averaging

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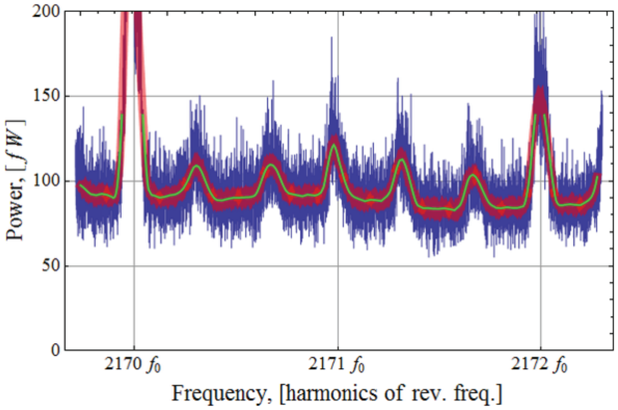

Figure 6: Vertical Schottky noise (blue) with averaging.

COOLING SIMULATION

The longitudinal cooling process was calculated by solving the Fokker-Planck equation. The FP equation was written with the same approach as in [5] and [6]. Numerical solving was implemented both with the Wolfram Mathematica standard solver (which utilizes method of lines) and with C++ using different methods (e.g. adaptive method of lines [7] and CIP method [8]).

In the modelling of the longitudinal stochastic cooling following parameters are necessary: notch-frequency, system delay, transition gamma γ_{tr} and system gain. Also the coupling impedance and kicker shunt impedances are critical parameters. However in the real experiment, these values could not be definitely determined. Typically the model is also quite sensitive to notch-filter imperfections such as amplitude and frequency dispersions.

The main amplifier was in saturation during the cooling experiment and then the exact gain level was unknown. It can be roughly estimated with known output power of saturated amplifier, system transfer function in pass-band and initial distribution function. Thus estimated gain value is around 114 dB. Simulation with this gain value and "ideal" system gives the final momentum spread of 0.1×10^{-3} which is 2.5 times lower compared to the experimental value 0.25×10^{-3}.

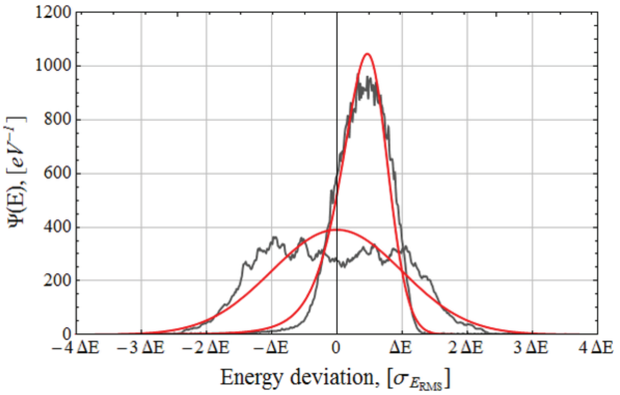

Figure 7: Cooling simulation with gain 110 dB, system delay error 20ps and filter delay error 10ps. Experimental (gray) and theoretical (red) initial and final distributions.

On the other hand after the adjustment of gain to 110 dB as well as the delay error of 20 ps and the filter delay error of 10 ps, the beam profile by the simulation is given in Fig. 7.

The simulation and experimental results are in reasonable agreement which proves that the developed model adequately describes the cooling process.

CONCLUSION

The first stage of stochastic cooling experiment at Nuclotron has finished successfully. New developed scheme was set in operation and proved to be reliable and effective. With the developed software for remote control and adjustments the system can be easily operated and adjusted. Optical delay and notch-filter showed good performance together with high accuracy and compact size. Ring-slot couplers have been proven to be operated well both as pick-up and kicker, including transverse modes of operation.

During the Nuclotron run in March'13 the momentum cooling of deuteron beam was achieved for the first time and fractional parts of the betatron numbers were measured.

Concerning the further steps it is planned to have C^{6+} beam during December run. This will give much stronger beam signal, which is especially important for difference/transverse signals. This should allow us the chromaticity measurements from the transverse Schottky noises and in principle make possible the Palmer and betatron cooling experiments.

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