STOCHASTIC COOLING EXPERIMENTS AT NUCLOTRON AND APPLICATION TO NICA COLLIDER*

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Abstract

Stochastic cooling is the key element for the NICA accelerator facility that is presently under development at JINR, Russia. Beam cooling will work with the high-intensity bunched beams in the 3-4.5 GeV energy range; all three degrees of freedom will be treated simultaneously. The preparatory experimental work on stochastic cooling is carried out at accelerator Nuclotron (JINR, Dubna) since 2010. During this work hardware solutions and automation techniques for system adjustment have been worked out and tested. Based on the gained experience the overall design of the NICA stochastic cooling system was also developed. The report presents the conceptual design of the NICA stochastic cooling system and overviews the results of cooling experiments at Nuclotron and the developed adjustment automation techniques.

INTRODUCTION

Nuclotron-based Ion Collider Facility (NICA) is an intensively developing flagship project of Joint Institute for Nuclear Research (JINR) [1]. Stochastic cooling will be used in the collider ring during experiments with heavy ions for beam accumulation and intra-beam scattering (IBS) suppression to avoid luminosity reduction, which implies full 3D cooling of intense bunched beams. Beam accumulation process requires only longitudinal cooling and implies almost coasting beam with reduced intensities, therefore primary requirements for stochastic cooling systems arise from the IBS counteraction.

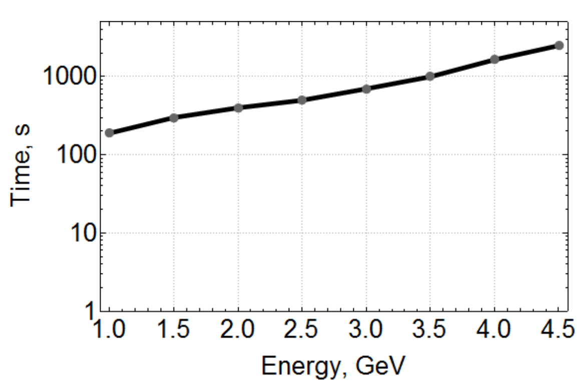

Figure 1: IBS heating times for Au^{79+}.

*Work supported by FAIR-Russia Research Center grant
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Stochastic cooling must provide cooling times lower than corresponding IBS heating times to prevent beam emittance growth and keep the luminosity, Figure 1 shows expected IBS heating times in the energy range of the collider operation.

At lower energies IBS process becomes much faster and accompanied with significant phase slip factor growth, which makes stochastic cooling hardly feasible at this region and therefore here electron cooling is foreseen. Nevertheless, it's highly advantageous to cover as wide as possible energy range with stochastic cooling, because it doesn't have additional beam losses unlike electron cooling (due to ion recombination).

The parameters of NICA collider are listed in Table 1:

Table 1: Parameters of the NICA Collider

Circumference, *m*	503		
Ions	Au^{79+}		
Number of bunches	22		
RMS bunch length, *m*	0.6		
γ_{cr}	7.088		
Energy, *GeV/u*	1	3	4.5
Bunch intensity × 10^9	0.2	2.4	2.3
$\Delta p/p \times 10^{-3}$	0.55	1.15	1.5
$\varepsilon_x, \pi \cdot mm \cdot mrad$	1.1	1.1	1.1
$\varepsilon_y, \pi \cdot mm \cdot mrad$	0.95	0.85	0.75
Phase slip factor η	0.215	0.037	0.009
IBS heating time, *s*	160	460	1800

LONGITUDINAL COOLING

There are three experimentally tested techniques to achieve longitudinal stochastic cooling – time-of-flight, Palmer and notch-filter methods. Further we shortly review the possibilities of implementation of these methods in the NICA collider.

Time-of-flight method provides the largest momentum spread acceptance for cooling system compared to the other methods. Time-of-flight method uses longitudinal pick-up and 90° phase shifter (which acts like differentiator) to make the signal to be proportional to the beam's momentum deviation. This method was recently experimentally tested at Forschungszentrum Jülich (FZJ) [2]. Unfortunately, time-of-flight method provides best

ISBN 978-3-95450-174-8

performance for beams with large momentum spread, and according to simulations with Fokker-Planck equation it will not provide enough efficiency in case of NICA collider parameters.

The Palmer method for longitudinal cooling also provides quite large momentum spread acceptance. In this method the horizontal pick-up is placed in the region with high dispersion and small beta-function values, so that the resulting signal would be proportional only to the momentum deviation. Thus to have effectively operating Palmer cooling one has to have

$$\sqrt{\epsilon_x \beta_x} \ll D_x \frac{\Delta p}{p_0},$$

where ϵ_x, β_x, D_x – horizontal emittance, beta-function and dispersion correspondingly, $\Delta p/p_0$ – momentum spread.

The implementation of Palmer method in the NICA collider encounters two difficulties. First, dispersion in the whole ring is quite small and has a maximum value of only ~2.5 m. Second, the maximal values of dispersion function are always accompanied by the betatron motion of the same order (Fig. 2):

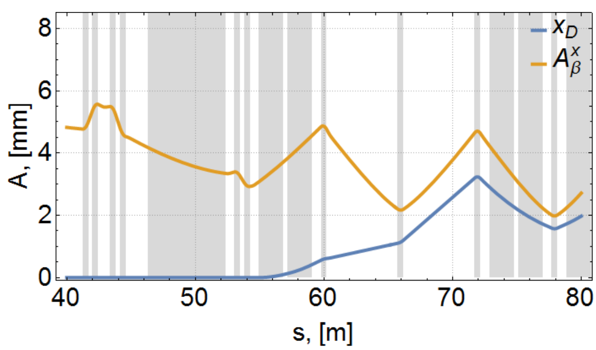

Figure 2: Deviation due to dispersion $D_x\Delta p/p_0$ (blue) and amplitude of betatron motion $\sqrt{\epsilon_x \beta_x}$ (orange).

Presence of transverse signal will cause cross-heating between two degrees of freedom unless the kicker is placed with a proper distance from the pick-up, so simultaneous longitudinal and horizontal coolings would be possible. This modification of Palmer method is known as *Palmer-Hereward* method [3]. The theoretical and particle tracking simulations show that Palmer-Hereward method wouldn't provide the required cooling times for both degrees of freedom.

The Palmer method alone (simulation without additional transverse signal) provides sufficient cooling rates for wide energy range 3-4.5 GeV. So it is advantageous still to consider it. Non-integer parts of betatron tunes in the NICA collider are close to 0.5, and in the frequency domain corresponding betatron sidebands would be located in between of the longitudinal Schottky bands (no overlap occurs), so it is also possible to discuss a special comb-filter to filter out the transverse signal. This approach requires further experimental investigation.

Lastly the **notch-filter method** is a well-known and dispersion-independent method for longitudinal stochastic cooling. In this method the signal from the longitudinal pick-up is being filtered out by a notch-filter (comb filter to be more exact) with notches and phase inversions at the harmonics of revolution frequency. The main disadvantage of this method in the frame of NICA is that is has considerably narrower momentum spread acceptance due to additional one-turn delay line in the filter. Consequently, this limits the energy range for stochastic cooling only to 4-4.5 GeV/u, so it's advantageous to look for other solutions.

MÖHL'S METHOD FOR LONGITUDINAL COOLING

Another method, in which two longitudinal pick-ups are used, could be proposed for longitudinal cooling at NICA. This method was firstly proposed by D. Möhl [4], and respecting this further we will refer to this method as Möhl's method. The basic idea of this method is very similar to the Filter method, which uses the difference of two longitudinal signals, separated by revolution period. In Möhl's method, instead of dividing the original signal, longitudinal signals are obtained from two separated longitudinal pick-ups (Fig. 3):

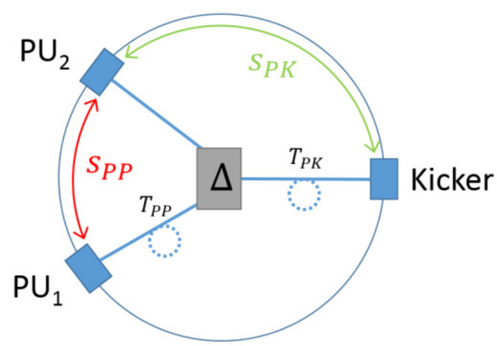

Figure 3: Möhl's method layout.

Eventually the difference of these signals with additional 90° phase shift will also produce a correctional signal proportional to the particles' momentum deviation.

The theoretical investigation of the Möhl's method could be thoroughly performed by solving the corresponding Fokker-Planck equation. The latter includes coherent and incoherent terms, which could be expressed via transfer functions of the elements of cooling system [5]. To figure out the transfer function for Möhl's method let us write the correction signal of a test-particle at the kicker:

$$S_n \propto j[delay_n(T_{PK}) i_n(T'_{PK}) \\ - delay_n(T_{PK}+T_{PP}) i_n(T'_{PK}+T'_{PP})]$$

where $delay_n(t) = \exp(-j\omega_n t)$ – system signal delay of t sec at harmonic n, $i_n(f,t) \propto \exp(j\omega'_n t)$ – test-particle's current at harmonic n, $\omega_n = 2\pi f_0 n$, $\omega'_n = 2\pi f'_0 n$, where

ISBN 978-3-95450-174-8

f_0, f_0' - nominal and particle's own revolution frequencies, T_{PK}, T_{PK}' – pick-up to kicker travelling times for nominal and off-momentum particles, T_{PP}, T_{PP}' – 1st pick-up to 2nd pick-up travelling times for nominal and off-momentum particles.

After mathematical transformations the correctional signal could be expressed as

$$S_n \propto e^{j\omega_n \Delta T_{PK}} \cdot j(1 - e^{-i\omega_n \Delta T_{PP}}),$$

where $\Delta T_{PK} = T_{PK}\eta_{PK}\,\Delta p/p_0$, $\Delta T_{PP} = T_{PP}\eta_{PP}\,\Delta p/p_0$, η_{PK}, η_{PP} – local slip-factors between pick-up and kicker or two pick-ups correspondingly.

The first factor $e^{j\omega_n \Delta T_{PK}}$ represents a regular mixing between the second pick-up (that is closer to the kicker) and the kicker, accordingly the expression

$$M_n = j(1 - e^{-i\omega_n \Delta T_{PP}}) = j\left(1 - Exp[-i\omega_n \frac{s_{PP}}{\beta c}\eta_{pp}\frac{\Delta p}{p}]\right),$$

where s_{PP} – distance between two pickups, could be regarded as the transfer function for Möhl's method. As can be seen for Möhl's method slip-factor η_{PP} between two pick-ups should have a non-zero value. The new parameter – distance between the pick-ups s_{PP} – directly controls the momentum acceptance range of the system. The provided range could vary between two extremities – first, if the pick-ups are very close to each other the Möhl's method would have the same acceptance as Palmer method, and second, if the pick-ups are separated by the whole ring, then the acceptance will be similar to the notch-filter method (Fig. 4). Eventually it would be advantageous for NICA to have both pick-ups possibly closer to each other in order to widen the momentum acceptance range.

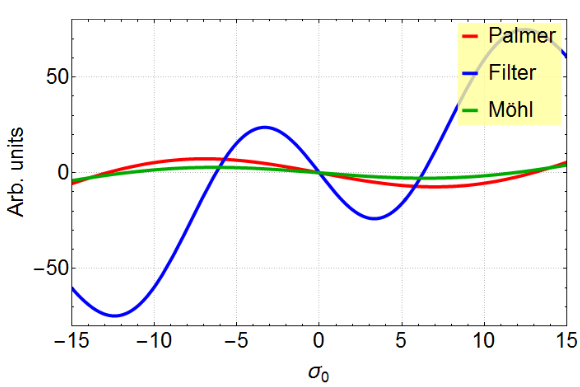

Figure 4: Coherent term of Fokker-Planck equation for Palmer (red), notch-filter (blue) and Möhl (green) methods for NICA at 4.0 GeV/u.

This method has three main advantages: it's dispersion-independent, utilizes strong sum signals from pick-ups and could provide wide momentum acceptance. Möhl's method can also help to reduce the strong coherent signal of bunched beam due to subtraction of longitudinal signals.

To provide best performance the pick-ups should be as identical as possible as well as all electronics before the subtractor.

At the NICA collider the Möhl's method theoretically is capable to cover whole IBS-dominated regime 3-4.5 GeV/u. But this method has not yet been tested experimentally, so additional theoretical and experimental studies are required, dedicated experiments are foreseen at the Nuclotron.

TRANSVERSE COOLING

It's planned to use slot-ring couplers for pick-ups and kickers of the NICA stochastic cooling systems [6]. These devices are capable to work simultaneously with all degrees of freedom, hence it is desirable to find solutions, when same pick-ups and/or kickers are used in several systems. The most beneficial scheme for NICA would be using same pick-up and kicker for transverse systems, this is favorable from the lattice point of view (beta-function and dispersion values), this will also reduce the dissipated power at the electrodes of the kicker, because transverse systems have separated feeding electrodes.

The main restriction for the transverse systems (betatron cooling) is the proper phase advance between the pick-up and the kicker ($\Delta\psi_{PK} = \pi/2 + \pi n$). For this reason the pick-up and the kicker, which are used simultaneously for horizontal and vertical systems, should be located in the ring so that both horizontal and vertical phase advances would have optimum values. To determine optimum pick-up and kicker locations it is convenient to draw the dependence of an optimum phases from its' positions, which is governed by the solutions of the equation $\Delta\psi(s_P, s_K) = \pi/2 + \pi n$, where s_P, s_K – positions of pick-up and kicker (Fig. 5).

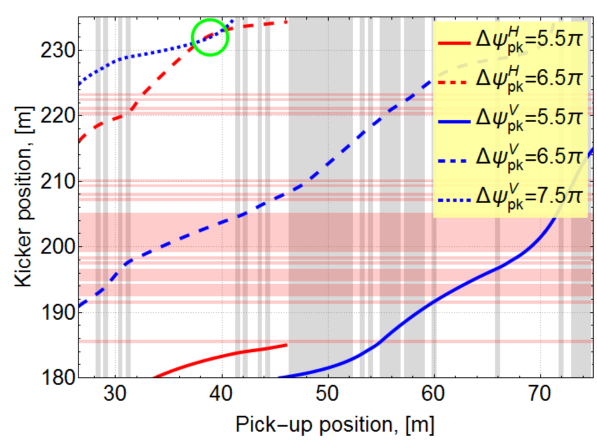

Figure 5: Optimum phase curves for horizontal (red) and vertical (blue) systems, semi-transparent red and grey – lattice elements, distances are counted from IP1.

To have optimum phases for transverse systems with merged pick-up and kicker the corresponding optimum phase curves should intersect. There exists only one region with such intersection (see Fig. 5), which implies

ISBN 978-3-95450-174-8

feasibility of having "merged" pick-up and kicker for transverse systems at the NICA collider.

STOCHASTIC COOLING SYSTEM FOR THE COLLIDER

Finally, each ring of the collider will have three stochastic cooling systems (6 in total), transverse systems will use same pick-ups and kickers (Fig. 6):

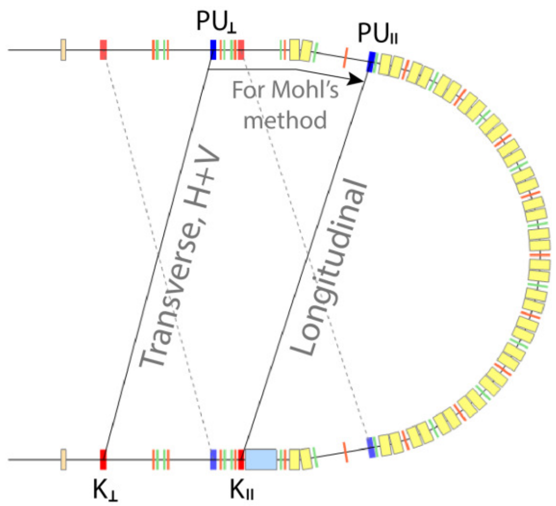

Figure 6: Stochastic cooling systems for NICA collider.

The longitudinal system will have enough spare system delay to install the cable from first pick-up to the second simply along the beam-pipe for Möhl's method (thick arrow at Fig. 6). The pick-ups and the kickers will be the slot-ring couplers of the same type, that will be used at the HESR facility of FAIR [7]. It's strongly desirable for Möhl's method to have the pick-ups as identical as possible, so the length of the pick-ups will be determined by the transverse sensitivity of the devices (in our case 64 rings, ~1 m).

The bandwidth of all systems is 2-4 GHz. The estimated CW power depends on the energy, its maximum is ~ 1 kW, including safety factor 10. The power will be provided by a series of amplitude- and phase-optimized 80 W solid-state amplifiers.

The staging is foreseen for the NICA collider – it will start operation with so-called start-up configuration, which involves significantly reduced intensities, momentum spreads, IBS rates; consequently, the requirements for the cooling times will be much less severe [8]. Such start-up scenario requires only longitudinal cooling and system with a notch-filter would be capable to provide the necessary cooling times. Thus start-up configuration will include only one pick-up and kicker per ring for longitudinal cooling with the notch-filter method. A prototype of such channel was developed and tested at the Nuclotron facility in collaboration with FZJ. Later on during start-up period it is planned to install second pick-up for experimental study of the Möhl's method. Also for start version it's planned to use 200 W TWT power amplifiers, that was kindly loaned to JINR by FNAL from the decommissioned cooling systems of Tevatron, which should significantly reduce the initial commissioning costs.

STOCHASTIC COOLING AT NUCLOTRON

As a preparatory work for the NICA collider dedicated experiments at Nuclotron facility were carried out. The developed Nuclotron stochastic cooling system is longitudinal 2-4 GHz system with optical notch-filter and fiber system delay [9]. During experiments the prototype slot-ring couplers were tested for different operational regimes and powers. In 2014 a new 60W power amplifier was installed. This amplifier was not optimized for phase and group delay, but the performance was sufficient for first tests and significantly improved the performance of the system compared to previous 16W power amplifier (Fig. 7):

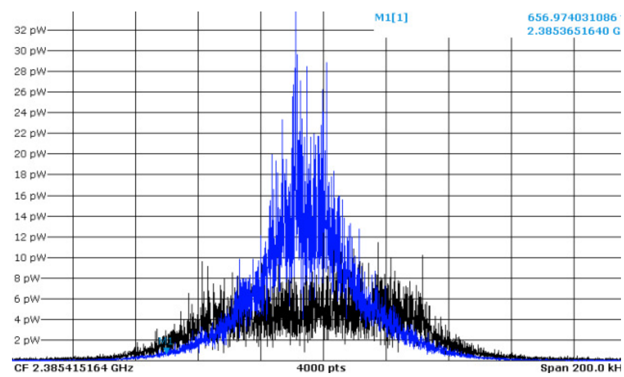

Figure 7: Cooling of 2×10^{8} C^{6+} ions within 20s. Screenshot from spectrum analyser taken at 2078th harmonic.

The software for control and adjustment automation of the stochastic cooling systems is also developing. This software could be seamless integrated into NICA control system, based on the TANGO.

A number of automation techniques and algorithms were developed for fast system adjustment, like automatic notch-filter adjustment, automation of open-loop measurements and system delay adjustment, etc. The algorithm for the notch-filter allows fully automatic adjustment of filter's frequency and amplitude within a very short time. The basic idea is to downsample the filter frequency response signal from VNA to get the maximum number of notches within a single sweep, which is then analyzed locally with a simple PC. All developed software is universal and could be seamlessly integrated into NICA or FAIR control systems.

CONCLUSION

Stochastic cooling of 3D intense bunched beams at the NICA collider represents a challenging task, which

ISBN 978-3-95450-174-8

requires deep theoretical and experimental researches. A dedicated experimental stochastic cooling system was developed at the Nuclotron facility in collaboration with Forschungszentrum Jülich. The experiments at Nuclotron proved the developed theoretical approaches and provided the basis for developing a stochastic cooling system of NICA collider – both for hardware and software. The hardware developments include tests of prototype pick-up and kicker, switching and amplification schemes, precise notch-filter and optical system delays. The software developments engage control, diagnostic and different automation techniques for fast system adjustments. The developed software is universal and also is planned to use at the HESR facility of FAIR.

The investigation of possible implementations of the stochastic cooling at NICA revealed the advantage of the different approach for longitudinal cooling, Möhl's method, which was theoretically studied and proposed for the collider.

Based on detailed theoretical research and experience with stochastic cooling at Nuclotron the CDR for the NICA stochastic cooling system had been worked out.

ACKNOWLEDGMENT

Authors are very grateful for invaluable help, advise and support to a large international collaboration: I. Meshkov, H. Stockhorst, L. Thorndahl, F. Caspers, V. Lebedev, S. Nagaitsev, V. Parkhomchuk and R. Maier

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ISBN 978-3-95450-174-8