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LONGITUDINAL PARTICLE DYNAMICS AND COOLING IN NICA COLLIDER

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Abstract

A feature of the NICA acceleration complex is high luminosity of colliding beams. Three types of RF stations will be used in the NICA Collider to reach the necessary beam parameters. The first type is for accumulation of particles in the longitudinal phase space with the moving barrier buckets under action of stochastic and/or electron cooling systems. The second and the third RF stations are for formation of the final bunch size in the colliding regime. This report presents brief description of three types of RF stations constructed in BINP and numerical simulations of longitudinal beam dynamics which take into consideration account the longitudinal space charge effect, cooling and IBS during the accumulation and bunching procedures.

INTRODUCTION

The goal of the NICA facility [1] in the heavy ion collision mode is to reach the luminosity level of 10^{27} $cm^{-2}s^{-1}$ in the energy range from 1 GeV/n to 4.5 GeV/n.

The RF systems of the Collider [1] have to provide accumulation of required numbers of ions in the energy range 1-3.9 GeV/n, accumulation at some optimum energy and acceleration to the energy of the experiment in the range of 1-4.5 GeV/n, formation of 22 ion bunches, and achievement of the required bunch parameters.

This can be done with the help of three RF systems [1], one of the broad-band type and two narrow-bands ones. The first one accumulates particles in longitudinal phase space with application of RF barrier bucket technique. The maximal voltage of the barrier is 5 kV, it has rectangular shape with phase length $\pi/12$. By applying additional voltage of 300 V, one can also use the meander between the barriers for inductive acceleration. The second RF system works on the 22nd harmonic of the revolution frequency and is used for formation of the proper number of bunches. The maximal RF2 voltage is 100 kV. The RF2 can also be used for beam acceleration or deceleration. The third RF system works on the 66th harmonic and is used for the final bunch formation and maintenance of the bunch parameters during the collision mode. The maximal RF3 voltage is 1 MV. The RF3 system is also used for ion beam acceleration or deceleration. All stages of the bunch formation as well as the collision mode are accompanied by a cooling process, either stochastic or electron.

Previous calculations modelling longitudinal beam dynamics were fulfilled in approach neglecting change of transverse emittance and cooling time during accumulation or bunching [2]. Now we take into account dependence of IBS and electron cooling force on transverse emittance which also changes in accordance with these effects in RMS model.

ACCUMULATION OF IONS

Moving Barrier Buckets

Accumulation is fulfilled with separated regions of injection and storage. Two pairs of voltage impulses form 2 separatrices, the 1st one for injection, the 2nd - for storage of ions (stack). After injection the impulses of injection separatrix move close to the stack, then impulses separating injected bunch from stack decrease, and separatrices join (Fig.1). If the length of combined separatrix exceeds half of the ring perimeter, it will be compressed.

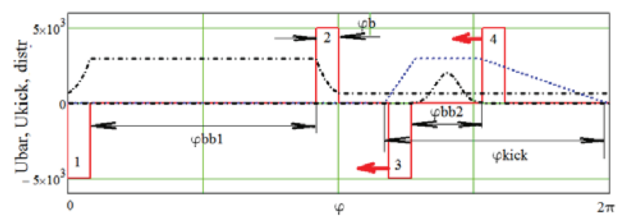

Figure 1: Barrier voltage (red line), density of stored and newly injected beam (black dash-dot line), impulse of kicker(blue dashes). φ_b, $\varphi_{bb1,2}$, φ_{kick} - phase lengths of voltage impulse, 2 separatrices and kicker impulse.

Calculation Model

At the calculation all the effects are separated (movement of barrier buckets, cooling, IBS, loss of ions at injection). All movements are slow, with conserved longitudinal emittance.

Electron cooling force is taken into account in a form of V.Parkhomchuk [3], with parameters of the electron beam (current, radius, transverse and longitudinal temperatures) $I_e = 1A$, $r_e = 1\,cm$, $T_{et} = 5\,V$, $T_{el} = 5\,mV$. We use in calculacion the longitudinal component of cooling force averaged over transverse velocities and averaged over all 3 velocities distributions values of longitudinal and transverse decrements.

IBS is taken into account in a form of a diffusion coefficients calculated with a model of S.Nagaitsev [4], for NICA magnetic structure of 2018.

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After merging 2 separatrices till a new injection the RMS beam parameters change with account of averaged cooling decrements down till their stationary values, at which the times of cooling and IBS growth equal.

During injection the kicker injecting new portion of ions into stationary orbit simultaneously removes all ions of previously stored beam placed in the region of kicker impulse. The main goal of present calculations was an attempt to take into account nonlinearity of the cooling force and it's influence on the distribution function and hence on the losses at injection. For that we have used two models: gaussian distribution with current value of impulse spread σ_p (for linear cooling force) and the obtained as the first approach $f_1(\delta_p)$ ($\delta_p = \Delta p / p$) to the solution of the one-dimentional Fokker-Plank equation with account of diffusion coefficient and nonlinear averaged longitudinal cooling force (nonlinear distribution).

Outside of voltage barrier buckets the distribution is one-dimensional. We use obtained distribution $f_1(\delta_p)$ as a distribution inside the stack. But the losses at injection are difined by the one-dimensional distribution outside the stack $f_2(\delta_p)$, which is coupled with the distribution inside the stack $f_1(\delta_p)$ with the equation of motion along the phase trajectory and equation of continuity, resulting in $f_2(\delta_p) = f_1(\sqrt{\delta_p^{\,2} + \delta_{psep}^{\,2}})$, which is used for calculation of losses at injection.

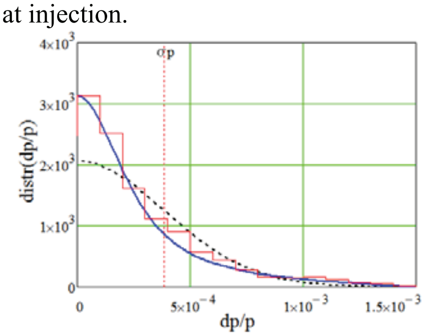

Figure 2: Stationary distributions. obtained with Betacool program (red steps), proposed nonlinear distribution (blue line) and gaussian distribution for the same impulse spread σ_p (black dashes).

Figure 2 presents stationary distributions obtained with Betacool [5] program (red steps), proposed nonlinear distribution (blue line) and gaussian distribution for the same impulse spread σ_p (black dashes). Stationary solutions for impulse spread and transverse emittance in dependence on number of ions also are in good accordance with Betacool RMS results. According to them the necessary number of ions $N_0 = 55 \cdot 10^9$ (at the energy $E_k = 3\ GeV/n$) can be accumulated in stationary regime (when the time between injections Δt_{inj} is much more than the averaged cooling time) at the electron beam currents $I_e > 0.65\ A$, with cooling time at stationary parameters being several tens of seconds. But for projected $\Delta t_{inj} = 8\sec$ the process of accumulation cannot be treated as stationary and one should take into account the dependence of RMS parameters on time.

Thus, the process of accumulation was modelled with account of next effects at each injection: averaging of RMS parameters at uniting separatrices; cooling and IBS; compression of the stack $\sigma_{p2} = \sigma_{p1} L_1 / L_2$ at conserved longitudinal emittance; losses of ions at injection.

Calculation of Ion Accumulation

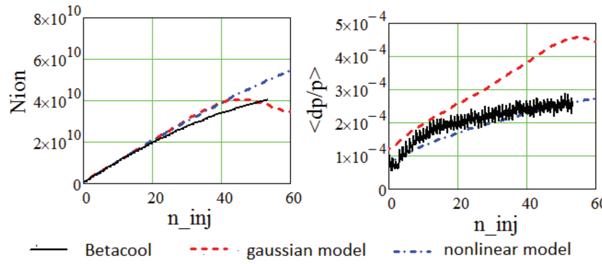

Figure 3: Number of accumulated ions, RMS impulse spread versus number of injections.

Calculations were done for the ions' energy E_k=3 *GeV/n*, the cooling electron current I_e= 1 *A*, parameters of injected bunch $\sigma_{si} = 10\ m$, $\sigma_{pi} = 1.2 \cdot 10^{-4}$, $N_i = 10^9$, $\Delta t_{inj} = 8$ sec, length of injection separatrix $\varphi_{bb2} = 6\sigma_{si}$.

In a result of calculations for 50 injections (Fig.3) we have $4 \cdot 10^{10}$ ions (Betacool); $4 \cdot 10^{10}$ ions (gaussian model) / $5 \cdot 10^{10}$ ions (nonlinear model). Necessary number of ions $5.5 \cdot 10^{10}$ can be obtained in ~80 injection (extrapolation of Betacool results); in 55 injections (nonlinear model); can not be reached (gaussian model). For gaussian model this number of ions can be accumulated at higher electron current I_e=*1.25A*, in 60 injections.

Impulse spread for gaussian model is significantly larger than for nonlinear model and for Betacool. Thus, the nonlinear model of one-dimensional code seems to be more close to Betacool solution than the gaussian model, but with some overestimated cooling (~30%) .

ADIABATIC CAPTURE AND BUNCHUNG OF ION BEAM

Preparation of beams for ion-ion collision is performed in two stages. Firstly 22 bunches are produced using adiabatic capture technique at slowly increasing RF voltage.

Starting voltages of RF2, RF3 were chosen with the account of conditions of minimal required power of generator at the maximal voltage and of absence of static instability at the start of increase of the voltage of RF3: $U_{2\min} \approx 1.5kV$, $U_{3\min} \approx 22.5kV$.

When RF2 voltage reaches the maximum of 100 kV, the electron cooling is switched on for some time (Fig.4, [t1,t2]). When the bunch length becomes short enough due to cooling and RF2 maximal voltage, the voltage of the

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RF3 system working on the 66th harmonic (after a time of cooling) starts adiabatically increasing from 22 kV.

The maximal RF2 voltage together with cooling should provide conditions when the final longitudinal bunch length at interception into RF3 system voltage must be equal to the length completely fitting into the bucket of the RF3 system. However, a small number of ions at interception can be captured in the parasitic side separatrix of 66th harmonic. This leads to parasitic collisions in the Collider. The ratio of the number of captured ions in the side parasitic separatrix to the total number of bunch ions strongly depends on the RMS bunch length after the RF2 bunching and cooling. Further adiabatic increase in the RF3 voltage together with following cooling time (Fig.4, t>t4) provides formation of an ion bunch with the length of 60 cm and momentum spread of 10^{-3} required for colliding experiments.

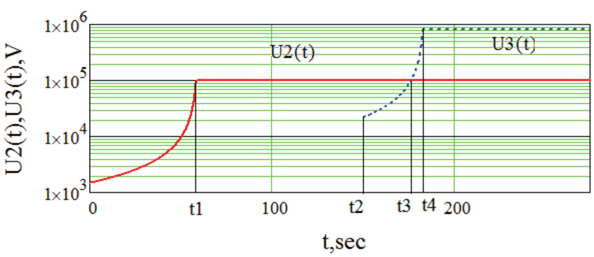

Figure 4: Amplitudes of voltages RF2, RF3 versus time.

One-dimensional Longitudinal Tracking

For estimation of capture and bunching a one-dimensional tracking code was developed. It implies a model of macroparticles for modelling the beam in the limits of one separatrix of 22-nd harmonic; numerical integration of equations of motion (4-th order Runge-Kutta method); variable time step proportional to the period of small synchrotron oscillations. At each time step we use arbitrary kicks $\sqrt{D(\sigma_p,\sigma_s)\Delta t}\cdot rnd_i$ (for σ_p, σ_s calculated over current distribution of macroparticles) to each macroparticle to modell IBS. The averaged longitudinal component of cooling force is taken into account in the same way as at accumulation. Change of transverse emittance is taken into account in RMS approach (1). While the generators of RF3 are still switched off, the induced by the ion beam voltage on the cavities of RF3 is taken into account. To speed up the calculation we use compression of the process time by the factor 0.1-0.001, together with times of cooling and IBS growth time, while synchrotron frequencies being unchanged. It means decrease of the number of fast oscillations by this factor, keeping them still fast in comparison with slow processes of cooling, IBS growth and adiabatic increase of voltage amplitudes.

Figure 5 shows stationary bunch RMS length at 3 significant moments of bunching,in dependence of electron beam current. Red line corresponds to $U_2 = U_{2\max}, U_3 = 0$. It defines minimal bunch length before increasing U_3; at $I_e = 1A$ $\sigma_{s1st} = 1.425\,m$. Blue dash-dots correspond to $U_2 = U_{2\max}, U_3 = U_{2\max}$ (arising the side separatrices). Comparing this bunch length with $\lambda_{66}/6 = 1.27\,m$, 1/6 of the wavelength of 66-th harmonic defines the number of ions in side separatrices. ($\sigma_{s2st} < \lambda_{66}/6$ at $I_e > 0.3A$). Black dashes correspond to $U_{2\max}, U_{3\max}$. These stationary parameters define final parameters after cooling and should be $\sigma_{s3st} < 0.6\,m$ - necessary for experiment. It can be achieved at $I_e > 0.5A$.

Stationary Parameters

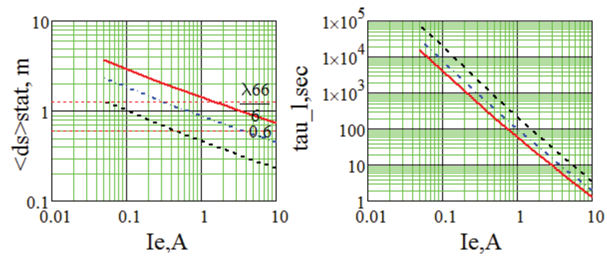

Figure 5: Stationary RMS length versus electron beam current; averaged longitudinal cooling times at stationary parameters.

Beam Capture with RF2

Below there are the results of calculation of capture and bunching of ion beam with described above 1-dimentional tracking code . Initial parameters $\sigma_{p0} = \left(\delta_{p\,sep}\right)_{RF1}/3$, $\varepsilon_{x0} = 0.1\pi\cdot mm\cdot mrad$ correspond to these values after accumulation of ions, $I_e = 1A$.

The calculations are fulfilled for the rate of detuning change $da/dt = 3\sec^{-1}$ time of tuning for RF2 ~60 sec and for RF3 - ~30 sec (Fig.4). After reaching maximal voltages of RF2 and RF3 cooling is switched on to reach necessary stationary parameters (Fig.5, left), for the time estimated by cooling times at Fig.5 (right) .

Figure 6 shows the results of the ion beam capture by RF2. Induced by the ion beam current voltage on the cavities of RF3 while switched off appears to be small in comparison with voltage of RF2, so it practically does not influence the dynamics of the ions.

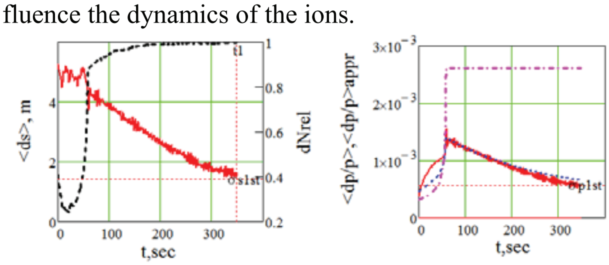

Figure 6: Left: RMS bunch length versus time (red line) and relative number of ions captured into separatrix. (black dashes). Right: RMS impulse spread versus time, tracking (red line) and approximation (blue dashes); separatrix amplitude (pink dash-dotes).

A beam can be cooled to $\sigma_{s\,st} = 1.425\,m$ with the electron beam current $I_e = 1A$.

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Further Bunching with RF2+RF3

Increase of voltage of RF3 leads to formation of 3 separatrixes of 66-th harmonic instead of 1 separatrix of 22-nd harmonic, with further compression of the bunch length, ideally to $\sigma_s < \lambda_{66}/6$, so that the bunch as a whole is located in the cenral separatrix, and the side separatrices contain a small share of ions. The goal is to minimize this share.

Figure 7 shows the results of further bunching of ions by RF3 together with RF2. Figure 8 shows relative number of particles outside the central separatrix versus RMS bunch length at the start of increasing voltage of RF3 and minimal electron beam current at which this length could be reached. At $\sigma_{s0} = 1.5m$ 2.5% of ions are outside the central separatrix. In order to decrease this number, one should increase the electron current. At $I_e = 1.5\ A$ $\sigma_{s1st} = 1.2m$, ~1% of ions are outside the central separatrix.

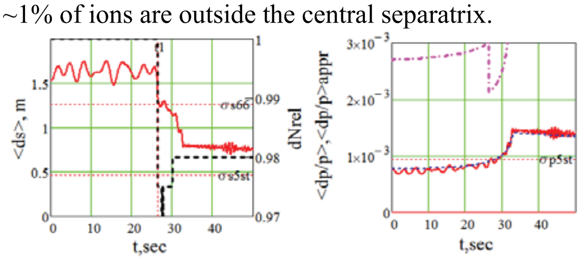

Figure 7: Left: RMS bunch length versus time (red line) and relative number of ions captured into the central separatrix. (black dashes). Right: RMS impulse spread versus time, tracking (red line) and approximation (blue dashes); separatrix amplitude (pink dash-dotes).

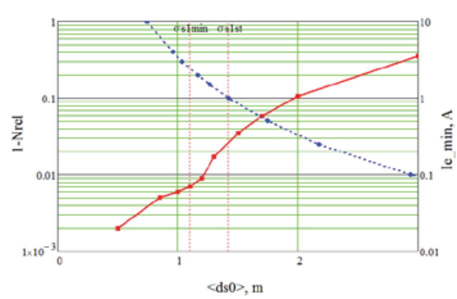

Figure 8: Relative number of particles outside the central separatrix versus RMS bunch length at the start of increasing voltage of RF3 (red line) and minimal electron beam current at which this length could be reached (blue points).

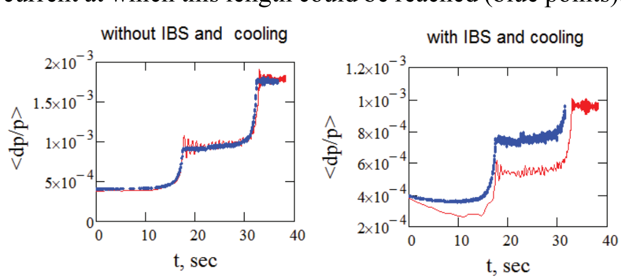

Figure 9: Impulse spread versus time at capture and bunching of ions. Red thin line - 1-dimentional tracking code, blue thick dashes - Betacool.

Comparison with Betacool

Figure 9 shows the results of one-dimensional tracking with Betacool results in comparison (here $da/dt = 10\ \mathrm{sec}^{-1}$). Left figure shows the impulse spread versus time without cooling and IBS, with times of calculation of one order; right figure shows the result with cooling ($I_e = 1A$) and IBS. Betacool calculation here requires ~15 times more time). One can see that the cooling in the one-dimensional tracking is overestimated. The result with $I_e = 0.6A$ coincides with the same Betacool result for $I_e = 1A$.

The Table 1 shows the relative number of ions left in side separatrices in these 3 calculations, which shows the same diference and coincidence of results as impulse spread at the Fig. 9.

Table 1: Number of Ions in Side Separatrices

	no cooling&IBS	with cooling&IBS
1-dim. tracking ($I_e = 1A$)	10.4%	3.2%
1-dim. tracking ($I_e = 0.6A$)		4.8%
Betacool	9.6%	5.1%

CONCLUSION

1. Different considered models show the possibility of accumulation of necessary number of ions at 3 *GeV/n* at the electron cooling current $I_e = 1\ A$ or at increased current $I_e = 1.25\ A$.

2. At $I_e = 1\ A$ 2.5% of ions are outside the central separatrix. In order to decrease this share till 1% the electron current should be increased at least up to $I_e = 1.5\ A$.

3. Final parameters ($\sigma_{sf} = 0.6\ m$) can be reached at electron current $I_e > 0.5\ A$.

4. At comparison with Betacool one can see that stationary solutions have sufficient accordance, but the time-dependent solutions have a certain difference. It looks like cooling in one-dimensional tracking is overestimated ~1.7 times. So, the one-dimentional approach code can be used for estimation of dependences on variating parameters, but final calculation requires more accurate (but rather slower) 3D calculation.

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