INFLUENCE OF INJECTION KICKER POST-PULSES ON STORAGE OF ION STACK IN NICA COLLIDER

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Abstract

The peculiarity of the injection kicker power supply in the NICA Collider is related to same post-pulses of the magnetic field that is appeared after a regular injection pulse. The magnetic field of these post-pulses leads to an increase of the stack ion angle spread during each injection cycle. When the stack ion angles reach the acceptance angle the ions are lost in the Collider. Influence of the injection kicker post-pulses on the storage of the ion stack is considered in this paper in presence of the electron cooling and the ion electron recombination losses.

INTRODUCTION

The project luminosity of Collider NICA corresponds to 10^{27} cm^{-2}c^{-1} at collisions of Au^{79+} ions [1]. To reach this luminosity it is required to store N=6,6×10^{10} ions in each ring [1]. The number of ions injected from Nuclotron is equal to $N_b=10^9$ per one injection cycle. The number of injections in Collider depends on stored intensity and the ion losses during accumulation. Transverse losses are related to the ion transverse motion of ions and their recombination with electrons in the electron cooling system.

A peculiarity of Collider kicker main magnetic field pulse generated by thyratron with forming line is connected with parasitic post-pulses at an amplitude by 50 times smaller than amplitude of main pulse. The kicker parasitic post-pulses of magnetic field considerably affect the transverse ion motion (Fig. 1). The kicker parasitic post-pulses lead to the transverse loses during ion accumulation. At the injection the stored ions pass through the kicker under action of parasitic post pulses, which increases the ion angle spread. When the ion angles reach a critical angle θ_{cr} defined by Collider acceptance these ions are lost.

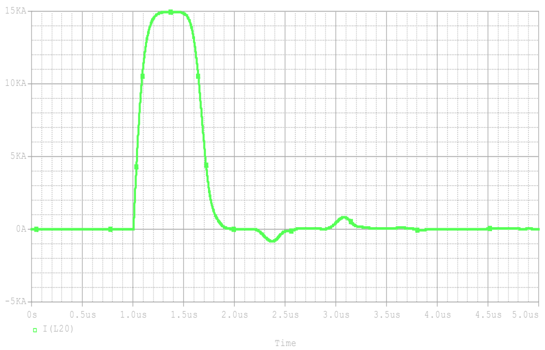

Figure 1: The kicker pulse with parasitic post pulses.

The transverse beam dynamic is defined by the kicker magnetic field of parasitic post pulses, the electron cooling and the ion betatron motion. The electron cooling damps betatron oscillations and reduces the ion angle spread. When ions pass through the electron cooling system they recombine with electrons and then are lost. The betatron stack ion phase is random at kicker entrance for each new injection cycle. As result, the increase of ion angle spread has diffusional character.

ION STORAGE IN COLLIDER

The initial spread of ions injected from Nuclotron to Collider corresponds to:

$$\frac{dN_b}{d\theta} = \frac{N_b}{\pi^{1/2}} exp\left(-\frac{\theta^2}{\theta_0^2}\right), \tag{1}$$

where θ_0 is the ion rms angle spread at the kicker entrance. The ions are deflected on an angle at pass through kicker at magnetic field B_p of the parasitic post pulses

$$\Delta\theta = \frac{ZeB_p l_k}{A\beta m_p c^2}, \tag{2}$$

where l_k is the kicker length, Z и A are charge and atomic number of ions. The time of the parasitic post-pulses is comparable with the stored stack revolution time. As a result the magnetic field of kicker parasitic post-pulses leads to the angle increase for η= 40% of the stored ions. The amplitude of ion angle at kicker exit is defined by an initial angle at kicker entrance $\theta_n=\theta$, deflection angle $\Delta\theta$ of parasitic post pulses and phase of betatron oscillations φ_b:

$$\theta_{kn}^2 = \theta^2 + 2\theta\Delta\theta\cos\varphi_b + \Delta\theta^2. \tag{3}$$

The electron cooling is used for reduction of the ion angle spread, produced by parasitic post- pulses. The ion angle is reduced between injection cycles in accordance with equation:

$$\frac{d\theta_{cn}^2}{dt} = -\frac{\theta_{cn}^2}{\tau_{lcool}}, \tag{4}$$

where $\tau_{lcool}=\tau_{cool}\times(\theta_{ef}^2+\theta_{cn}^2)^{3/2}/(\theta_{ef}^2+\theta_0^2)^{3/2}$ is the electron cooling time, which also depends on the ion angle θ_{cn}, τ_{cool} is the cooling time for the ion with the angle θ_0, $\theta_{ef}^2=(v_{ef}^2/\beta^2c^2+\sigma_p^2)/\gamma^2$ is the effective angle related to the longitudinal electron temperature, and σ_p is the ion rms momentum spread. The ion angle at cooling is reduced from θ_{cn} to θ_{cn+1} during the injection time T_{inj} as:

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$$F(\theta_{cn}) - F(\theta_{cn+1}) = \frac{T_{inj}}{\tau_{cool}}\left(\theta_0^2 + \theta_{ef}^2\right)^{\frac{3}{2}}, \qquad (5)$$

$$F(\theta_{cn}) = \frac{2}{3}\left(\theta_{cn}^2 + \theta_{ef}^2\right)^{3/2} + 2\theta_{ef}^2\left(\theta_{cn}^2 + \theta_{ef}^2\right)^{1/2} + \theta_{ef}^3 \ln\left\{\left[\left(\theta_{cn}^2 + \theta_{ef}^2\right)^{1/2} - \theta_{ef}\right] / \left[\left(\theta_{cn}^2 + \theta_{ef}^2\right)^{1/2} + \theta_{ef}\right]\right\}.$$

The ion intensity is reduced by recombination of ions with electrons at electron cooling during injection time T_{inj} as:

$$N_{n+1} = N_n exp\left(-T_{inj}/\tau_{rec}\right), \qquad (6)$$

where τ_{rec} is the recombination time, which is

$$\tau_{rec} = \frac{\eta_{cool}\gamma^2}{\alpha_{rec} n_e}, \qquad (7)$$

here $\eta_{cool}=l_{cool}/C$, $l_{cool}=6$ m is the length of the cooling section, C=503 m is the Collider circumference, $n_e=I/\pi e v r_c^2$ is the electron density, I=1 A is the electron beam current, $r_b=5$ mm is the electron beam radius, and α_{rec} is the recombination coefficient. Approximation of the recombination coefficient by the experimental data [2] is given by

$$\alpha_{e-rec} = 10^{-13} Z_2 T_e^{-0.385}\, cm^3/s. \qquad (8)$$

In accordance with the Bell formulas, the recombination coefficient $\alpha_{B\text{-}rec}$ (cm^3/s) is [3]

$$\alpha_{B-rec} = 10^{-13}\frac{Z^2}{T_e^{1/2}}\left[\ln\left(5.66\frac{Z}{T_e^{1/2}}\right) + 0.196\frac{T_e^{1/3}}{Z^2}\right]. \qquad (9)$$

The ion storage rate dN_n/dt is defined by the rate of injected ions from the Nuclotron dN_b/dT_{inj}, the rate of recombination losses N_n/τ_{rec}, and the rate $\Delta N_n/T_{inj}$ of lost ions having an angle under the action of the kicker post-pulses θ_n larger than acceptance angle θ_{cr}:

$$\frac{dN_n}{dt} = \frac{N_b}{T_{inj}} - \frac{N_n}{\tau_{rec}} - \frac{\Delta N_n}{T_{inj}}. \qquad (10)$$

COMPUTER CODE FOR SIMMULATION OF ION STORAGE

A computer code was developed for simulation of the ion storage, which involves effects of the kicker post-pulses, the electron cooling, and the betatron motion. This computer code consists of several blocks for simulations. The first block is connected with input of initial data given in Table 1.

The second code block describes the initial angle distribution of ions injected from the Nuclotron. The third code block is related to the influence of the kicker post-pulses magnetic field. The fourth block describes the ion losses if the ion angle is larger than the acceptance angle. The fifth block calculates the ion angle reduction at electron cooling. The sixth code block is connected with the losses to the ion–electron recombination. The seventh code block represents the betatron motion at which the stored ions that passed through the kicker at parasitic after pulses have an a random betatron phase at each new injection cycle. The eighth block describes the ion storage under the action of the kicker post-pulses and the recombination and injection of a new ion portion. The ninth code block calculates the angle distribution function for stored ions.

Table 1: Initial Dates

Parameter	**Value**
Acceptance, π×mm×mrad	40
Relativistic factor, γ	4.26
Rms emittance, ε, π×mm×mrad	0.4
Kicker	
Acceptance angle, θ_{cr}, mrad	1.5
Magnetic field, kG	1.3
Length, m	3.9
Ion deflection angle, mrad	12
Kicker parasitic post- pulses	
Magnetic field, G	23
Deflection angle, Δθ, mrad	0.18
Percentage of ions affected by post-pulses, η, %	40

ION STORAGE SIMULATION RESULTS

The electron cooling and recombination (Table 2) are defined by the transverse electron temperature T_e and the ion momentum spread which increases with the number of stored ions as $\sigma_p=\sigma_{p0}\times(N/N_b)^{1/3}$, where $\sigma_{p0}=1.7\times10^{-4}$ is the initial ion momentum spread at the extraction from the Nuclotron. The cooling and recombination times at θ_0 and energy 4.5 GeV/n are given in Table 2. The reduction of electron temperature to value of 1 eV leads to fast decrease of the recombination time and a reduction of the stored ion intensity.

Table 2: Cooling and Recombination Time

T_e, eV	**$V_{ef}/\gamma\beta c$**	**τ_{cool}, s**	**$\tau_{B\text{-}rec}$, s**	**$\tau_{e\text{-}rec}$, s**
10^3	2.6×10^{-4}	55	17000	6800
10^2	2.5×10^{-5}	40	4843	2800
10	4.5×10^{-6}	28	1115	1740
1	3.7×10^{-6}	21	209	717

The stack ion angle distribution function after 30 injections is presented in Fig. 2 at $\Delta\theta=1.04\times10^{-4}$, $\theta_0=1.54\times10^{-4}$, $\tau_{cool}=28$ s, and $\tau_{inj}=8$ s. The dependence of the number of stored ions on the number of injections is given in Fig. 3. One macroparticle corresponds to 10^5 ions in these simulations.

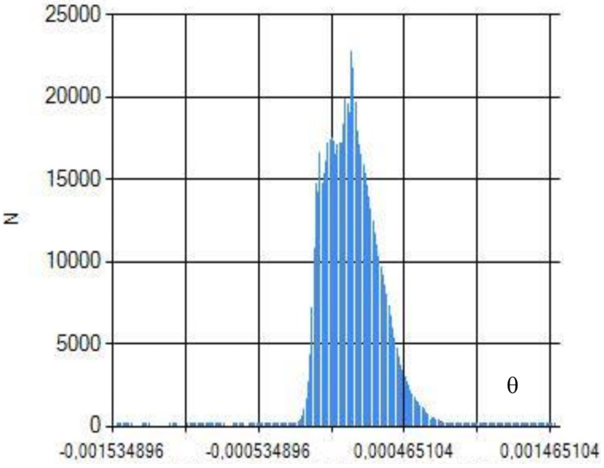

Figure 2: The stack ion angle distribution function after 30 injections.

The dependence of the FWHM square angle spread on the number of injections is presented in Fig. 4. The FWHM square angle spread is linearly increased with number of injections. The dependence of the number of stored ions on the kicker post-pulses deflection angle is shown in Fig. 5. The losses for this post-pulses deflection angle are relatively low and the ion intensity is increased practically linearly with the number of injections.

The critical kicker post-pulses deflection angle corresponds to $\Delta\theta=1.8\times10^{-4}$, at which the intensity of stored ions is equal to the project value 6.6×10^{10}. The magnetic field amplitude of parasitic post-pulses Bp=23.4 Gs corresponds to 1.8% of the main magnetic field of the kicker pulse. The intensity of stored ions exponentially decreases with increasing kicker post-pulses deflection angle when the rms stack ion angle spread θ is comparable with the acceptance angle θcr.

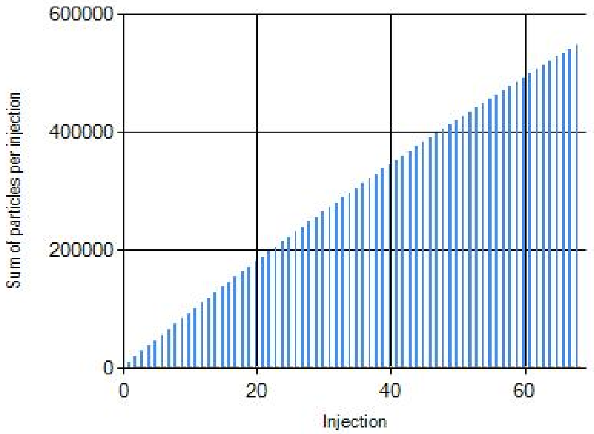

Figure 3: Dependence of the number of stored ions on the number of injections.

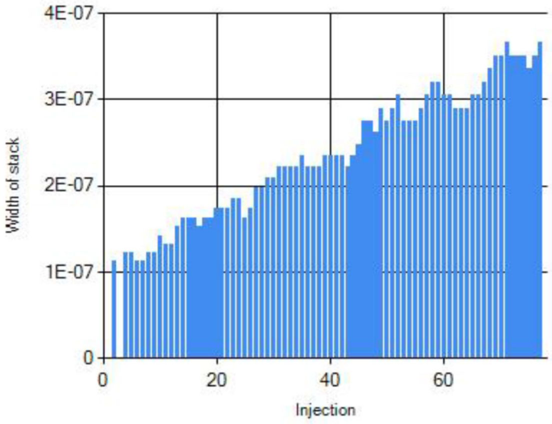

Figure 4: Dependence of the FWHM square angle spread on the number of injections.

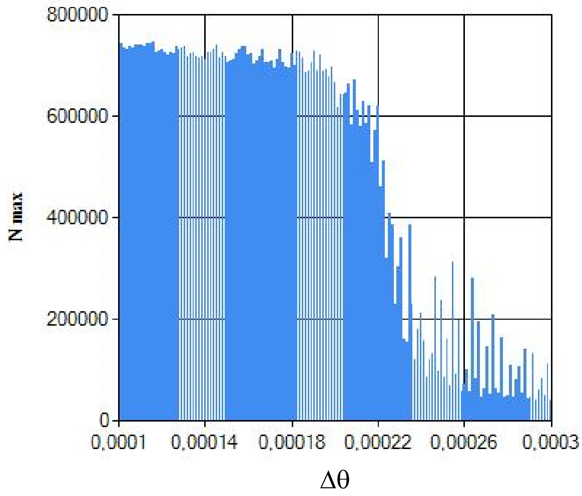

Figure 5: Dependence of the number of stored ions on the kicker post-pulses deflection angle at the electron temperature Te=10 eV.

The magnetic field action of kicker post-pulses may be partially compensating by the Collider feedback system [1]. The feedback system permits to compensate mismatching errors at ion injection during several tens of revolution turns. The feedback kicker at length of 1.08 m, voltage of 4 kV and operating at frequency 3 MHz will be used also for a partial compensation of the ion deflection angle produced by the magnetic field of the injection kicker post-pulses.

REFERENCES

[1] I.N. Meshkov and G.V. Trubnikov, “Technical Project of NICA Acceleration Complex”, JINR, Dubna, Russia, 2015.

[2] A. B. Kuznetsov, I. N. Meshkov, and A. V. Philippov, “Radiative recombination of ions and nuclei in electron cooling systems”, *Phys. Part. Nucl. Letters*, vol. 9, no. 4-5, pp. 346-351, 2012. doi:10.1134/S1547477112040218

[3] M. Bell and J. S. Bell, “Capture of cooling electrons by cool protons”, *Particle Accelerators*, vol. 12, pp. 49-52, 1982. doi:0031-2460/82/1201-0049$06.50/0

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