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CONCEPTION OF HIGH INTENSIVE POLORIZED PROTON BEAM FORMATION IN NICA COLLIDER

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Abstract

NICA (Nuclotron-based Ion Collider fAcility) is a new accelerator complex being assembled at JINR to search for the mixed phase of baryonic matter and to investigate the nature of nucleon/particle spin. The polarized proton beams will be operated at the energy range of 5-12.6 GeV, the beam intensity in each ring of $2.2\cdot10^{13}$ and the luminosity of $1\cdot10^{32}$ $\mathrm{cm^{-2}\cdot s^{-1}}$. The conception of formation of high intensive proton beams is discussed for two different schemes. In first scheme the protons are injected from Nuclotron to Collider at an energy of 2-2.5 GeV to provide the cooling and the storage at this energy and then they are accelerated up to energy of experiments. In the second scheme the cooling of protons is realized in one from accelerators of the injection chain and the protons are injected from Nuclotron to Collider at energy of experiments, where they are stored up required intensity.

INTRODUCTION

The accelerator facility of the NICA collider [1-3] has the following configuration for formation of polarized proton beams: the light ion linac LILAC, the acting superconducting synchrotron Nuclotron and two collider storage rings with two interaction points at the maximal energy E=13.5 GeV.

LUMINOSITY AND KEY PARAMETERS OF PROTON BEAMS

The main parameters of the NICA accelerator complex for the proton-proton collision mode are given in Table 1. The colliding beam luminosity [4] is determined by the beam stability conditions. The strongest limitations are the effects of the beam space charge — the so-called “Laslett effect” and “beam-beam effect”. Both of them lead to shifts Δq and ξ in the frequencies of betatron oscillations of particles in the collider focusing system, bringing them closer to the frequencies of the nonlinear resonances. At luminosity simulations the total shift of the betatron frequency corresponds to $\Delta Q=\Delta q+2\xi=0.05$ for two IP, but the Luminosity is given for one IP (Fig. 1).

The longitudinal normalized rms emittance of a bunched beam is $\varepsilon_c=N_b\gamma_{exp}\beta_{exp}\sigma_s\sigma_p=0.27$ m. The rms momentum spread after the LILAC debuncher corresponds to $\sigma_p=10^{-3}$. On injection from LILAC into the Nuclotron, the beam occupies the orbit with the circumference $C_N=251.52$ m, which corresponds to the rms bunch length $\sigma_s=C_N/2\cdot3^{1/2}=74.4$ m.

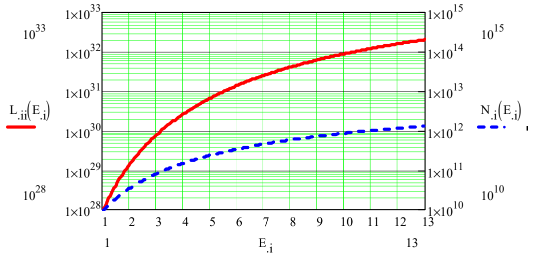

Figure 1: Dependence of the luminosity and the number of protons per bunch on the proton kinetic energy.

The normalized longitudinal emittance of the bunch in the Nuclotron is $\varepsilon_b=\gamma_{inj}\beta_{inj}\sigma_s\sigma_p=0.012$ m, where $\beta_{inj}=0.166$ at injection energy $E_{inj}=13$ MeV. The Nuclotron proton bunch intensity corresponds to $N_p=5\cdot10^{10}$, and the total intensity in the Collider ring is $N=2\cdot10^{13}$. As many as $N_{inj}=400$ injections from the Nuclotron to each Collider ring are required. Typical repetition injection time is $\tau_{rep}=3$ s. The total longitudinal emittance of all bunches at N_{inj} injections from the Nuclotron to each Collider ring corresponds to $\varepsilon_N=N_{inj}\gamma_{inj}\beta_{inj}\sigma_s\sigma_p=4.8$ m at the proton energy of 2.8 GeV. This value is a factor of 17.8 higher than the longitudinal emittance of the proton bunched beam in Collider experiments. The effective cooling system is obligatory to reduce the longitudinal emittance of the accumulated proton beam at the injection energy.

The Collider stochastic cooling could not be used for so intensive proton beams. The electron cooling can be

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applied only at a relatively low proton injection energy of 2-2.8 GeV. The longitudinal cooling time τ_{cool} increases as $\tau_{cool} \propto \gamma^2$ with growing proton injection energy. The polarized proton beams are extracted from the Nuclotron into the Collider at this energy, accumulated in the Collider by the RF barrier bucket technique, and then accelerated up to E=6-13.5 GeV for Collider experiments [5].

Table 1: Proton Beam Parameters at the Storage and Bunching in the Collider

Parameter	Value		
Ring circumference, C, m	503.04		
Number of bunches, N_b	22		
Rms bunch length, σ_s, m	0.6		
Rms σ_p=dp/p, 10^{-3}	2.2	1.75	1.5
Rms ε, π mm·mrad	1		
Beta-function in the IP, m	0.6		
Betatron tunes, Q_x/Q_y	9.44/9.44		
Proton energy, GeV	9	11	13.5
Proton number per bunch, N_p	$6\cdot10^{11}$	$8\cdot10^{11}$	$1.2\cdot10^{12}$
Luminosity, $cm^{-2}\cdot s^{-1}$	$5.5\cdot10^{31}$	10^{32}	$2\cdot10^{32}$

As an alternative to low-energy injection, high-energy injection is considered with proton energy, corresponding to Collider experiments [6]. Protons extracted from the Nuclotron are stored in the Collider rings, bunched, and used in the experiments without acceleration. In this case, the cooling should be realized in the injection chain before the beam extraction from the Nuclotron. The first option in realization of the high-energy injection mode is related to modification of the injection chain and construction of an additional transfer line from light ion linac LILAC to the Booster [7, 5]. Application of the Booster electron cooling at the LILAC injection energy of 13 MeV permits providing fast longitudinal cooling and then bunching. The Booster electron cooling permits the longitudinal emittance of the beam injected from LILAC to be reduced by a factor of 20 at the injection repetition time of about 10-15 seconds. The Booster will be used for injection in the Nuclotron. The second option is connected with the Nuclotron longitudinal stochastic cooling, which can be used for cooling the proton beam with the intensity of $5\cdot10^{10}$ and the repetition injection time of 85 seconds [5].

INJECTION FROM NUCLOTRON TO COLLIDER AT LOW PROTON ENERGY

The proton injection energy of 2.8 GeV in the Collider rings is defined by the cooling time at this energy. To fill half of the Collider ring by stack protons with the injection repetition time of $2\tau_{rep}$=6 s, the number of injection cycles should be $n_{inj}=0.5C/(2\cdot3^{1/2}\sigma_s)\cong8$. The cooling is rather effective at accumulation of protons during N_{inj}=400 injections, if cooling time $\tau_{cool}\cong$25-30 s is less than $\tau_{cool}<2n_{inj}\tau_{rep}$. It permits one to accumulate the proton stack in the half of the ring with the intensity $N=2\cdot10^{13}$ and the rms momentum spread $\sigma_p=4\cdot3^{1/2}\varepsilon_c/(\gamma_{inj}C)=1.2\cdot10^{-3}$. The stored stack has the transverse rms emittance $\varepsilon=r_{pN}/(2\pi\Delta q\gamma^3\beta^2)$=4.8 π mm·mrad at the Laslett tune shift Δq=0.05. The COSY longitudinal cooling time was τ_{cool}=18.6 s at γ=2.78 for protons.

To accumulate the proton beam with the intensity $N=2\cdot10^{13}$, the rectangular RF barrier bucket is used at the RF voltage V_{RF}= 5 kV and the phase width φ=π/12. The proton beam space charge effects lead to a 26% reduction in the RF barrier bucket capacity $V_{RF}\cdot\varphi$ and a 13% decrease in the height of the separatrix, which corresponds to the proton momentum spread $\sigma_{p-s}=1.25\cdot10^{-3}$. The threshold rms momentum spread is $\sigma_{p-th}=6\cdot10^{-4}$ at the development of longitudinal instability. The height of the separatrix is 2 times larger than the threshold momentum spread, which leads to longitudinal ion losses. To avoid ion losses, the RF barrier bucket should have the RF voltage V_{RF}= 5 kV and the phase width φ=π/6. This RF barrier bucket system can be used for storage of a proton beam with the intensity $N=2\cdot10^{13}$ and E=2.8 GeV. The RF1 induction acceleration corresponds to U=300 V per revolution period T_{rev}. The time of proton acceleration from the injection energy to the experiment energy $\tau_{ac}=T_{rev}(\gamma_{exp}-\gamma_{inj})\cdot mc^2/eU$=50 s.

The momentum spread and the beam emittance reduce as $\Delta p/p\propto1/\gamma$, $\varepsilon\propto1/\gamma$ at proton acceleration. After acceleration from 2.8 GeV to 13.5 GeV the stack rms emittance ε=4.8 π·mm·mrad and the momentum spread $\sigma_p=1.2\cdot10^{-3}$ reduce to ε=1.1 π·mm·mrad and $\sigma_p=2.7\cdot10^{-4}$. If the RF2 and RF3 stations are used for stack bunching, the rms bunch length corresponds to σ_s= 60 cm. The momentum spread increases to $\sigma_p=\sigma_{p-}\cdot C/(4\cdot3^{1/2}N_b\sigma_s)=1.5\cdot10^{-3}$ at beam bunching. The Laslett tune shift reduces as $\Delta Q\propto1/(\gamma^3\varepsilon)\propto1/\gamma^2$ at proton acceleration. Formation of a coasting beam at the energy of experiment leads to a further 2 times reduction in Laslett tune shift. The Laslett tune shift increases again $\Delta Q\propto C/(N_b(2\pi)^{1/2}\sigma_s)$=0.02 at stack bunching. The luminosity of proton-proton colliding beams at the energy of 13.5 GeV corresponds to $L=2\cdot10^{32}$ cm−2·s−1.

The above-presented regime of proton acceleration from the energy of 2.8 GeV to 13.5 GeV is realized when the critical energy is higher than the proton energy of Collider experiments. However, the present Collider ring lattice optics used for the heavy ion mode has the critical energy E= 6.65 GeV, which is lower than the proton energy corresponding to Collider experiments. Effects of longitudinal instability restrict the formation of highly intensive beams at transition through the critical kinetic energy during proton acceleration in the Collider, which leads to a reduction in the luminosity of the colliding protons beams. Transition through the critical energy and effects of longitudinal instability at this transition are discussed in the next paragraph.

To avoid transition through the critical energy at proton acceleration, special super symmetrical lattice optics with modulation of dispersion function [8] is developed for the proton mode. The critical energy corresponds to 17 GeV, and it is higher than the maximal energy of experiments of 13.5 GeV for this lattice. The power supplies of F quadrupole lenses are modified in comparison with the ion mode. Two additional power supplies with the current of 3 kA for F1 arc lenses and 1.1 kA for F2 arc lenses will be installed for realization of this lattice optics.

TRANSITION THROUGH CRITICAL ENERGY AT PROTON ACCELERATION

Longitudinal instability is developed at transition through the critical energy during proton acceleration ($\gamma=\gamma_{tr}$) due to reduction of the compaction factor to $\eta=0$ at γ_{tr}. The rate of proton acceleration by the RF1 station corresponds to $d\gamma/dt=0.2\ s^{-1}$. This rate is small to avoid development of longitudinal instability with an increment when γ is close to γ_{tr}. To prevent development of longitudinal instability at small γ-γ_{tr}, the fast jump of γ_{tr} is realized. To provide a fast variation of gamma transition by a value $\Delta\gamma_{tr}$, the current is rapidly varied in the power supply, which provides a current difference between the F and D lenses. The maximal possible variation of current differences between the F and D lenses leads to the maximal betatron tune shift $\Delta q \cong 0.05$ caused by variation of dispersion and therefore to the maximal variation of the gamma transition $\Delta\gamma_{tr} = 1.8\cdot\Delta q \cong 0.09$. The maximal rate $d\gamma_{tr}/dt=8.5\ s^{-1}$ is defined by the maximal rate of the lens gradient $dG/dt=14.3\ T/(m\cdot c)$ [1] or its maximal current rate $dI/dt=6.4$ kA/c. Fast variation of the gamma-transition is realized during the time $t_0=\Delta\gamma_{tr}/(d\gamma_{tr}/dt)=10.5$ ms. Variation of the current difference between the F and D lenses $\Delta I=67$ A leads to the variation $\Delta K=0.075$ produced by 24 lenses and to the betatron tune shift $\Delta q=\beta\Delta Kl/4\pi=0.05$. An additional power supply with the fast current variation $dI/dt=6.4$ kA/s, current of 67A and voltage of 14.5V will be used for fast variation of the gamma-transition at the total arc quadrupole lens inductance $L_Q=2.3$ mG.

At γ-$\gamma_{tr}=\Delta\gamma_{tr}$ the threshold current of longitudinal instability $I=2\pi mc^2\beta^2\gamma\eta\sigma_{p\text{-}tr}^2/eZ_{imp}$ depends on the stack rms momentum spread $\sigma_{p\text{-}th}$ and the compaction factor $\eta=2\Delta\gamma_{tr}/\gamma_{tr}^3=5.2\cdot10^{-4}$. To increase the threshold current, the rms momentum spread should be maximal possible. The longitudinal acceptance of the Collider rings corresponds to $\Delta p/p=10^{-2}$. To avoid proton losses at transition through the critical energy, the maximal rms momentum spread is chosen to be $\sigma_{p\text{-}tr}=(\Delta p/p)/3=3.3\cdot10^{-3}$. The RF barrier bucket system shrinks the stack length to $L_{tr}=\gamma_{inj}\beta_{inj}C\sigma_p/(2\gamma_{tr}\beta_{tr}\sigma_{p\text{-}tr})=32.3$ m. The threshold current at $Z_{imp}=20$ Ohm is $I=11.2$ A, which corresponds to the accumulated proton stack intensity $N=2.3\cdot10^{13}$.

After proton acceleration to the energy of 13.3 GeV and further bunching, the number of protons per bunch is $N_b=1.2\cdot10^{12}$, and the rms transverse emittance corresponds to $\varepsilon=1.06\ \pi$ mm·mrad. The rms bunch length is $\sigma_s=1.08$ m, 1.8 times larger than the IP beta function $\beta_{Ip}=0.6$ m. The luminosity is reduced by 20% in comparison with the case of $\sigma_s=\beta_{Ip}$ (Table 1) [4] due to the hourglass effect, and it is $L=1.65\cdot10^{32}$ cm−2·s−1. The decrease of the experiment energy leads to the reduction of the luminosity (Fig. 2). The luminosity reduction is faster at the proton energy reduction for the effects of the longitudinal instability in comparison with space charge effects of bunching beam.

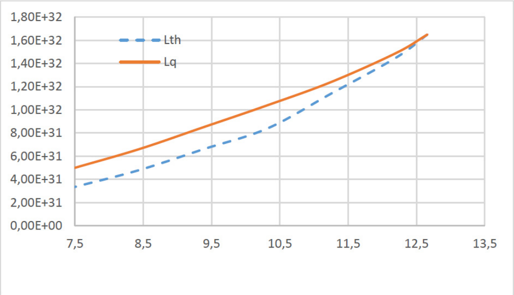

Figure 2: Dependence of luminosity on the relativistic factor γ corresponding to the proton energy of experiment, L_{th} is the luminosity defined by the longitudinal instability, L_q is the luminosity defined by the Laslett tune shift and the beam-beam effects.

REFERENCES

[1] Technical Project of NICA Acceleration Complex, Dubna, 2015.

[2] A. D. Kovalenko *et al.*, "Polarized Protons and Deuterons at NICA@JINR", in *Proc. IPAC'14,* Dresden, Germany, Jun. 2014, pp. 1000-1002. `doi:10.18429/JACoW-IPAC2014-TUPRO004`

[3] Yu. Filatov *et al.*, "Spin transparency mode in the NICA collider", *EPJ Web of Conferences* vol. 204, 2019. `doi:10.1051/epjconf/201920410014`

[4] I. N. Meshkov, "Luminosity of ion collider", *Phys. Part. Nucl.*, vol. 50, pp. 776-811, 2019.

[5] E. Syresin, O. Kozlov, I. Meshkov, N. Mityanina, "Formation of intensive proton beams in NICA Collider", NICA Machine Advisory Committee 2019, Dubna, Jun. 2019.

[6] Yu. M. Shatunov, I. A. Koop, A. V. Otboev, S. R. Mane, P. Yu. Shatunov, "About possibility of polarized proton acceleration in synchrotron Nuclotron", *Phys. Part. Nucl. Lett*, vol. 7, no. 219, pp. 755-760, 2019.

[7] A. D. Kovalenko *et al.,* "The NICA Facility in Polarized Proton Operation Mode", *in Proc. IPAC'11*, Santa Sebastian, Spain, 2011, p.1804-1806, paper TUPZ004.

[8] Yu. Senichev and A. Chechenin, "Theory of "Resonant" Lattices for Synchrotrons with Negative Momentum Compaction Factor", *J. Exp. Theor. Phys.,* vol. 105, no. 5, pp. 1127-1137, 2007.