COOLING STACKING INJECTION IN NICA BOOSTER

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Abstract

The multi cycling injection from the linear accelerator to the NICA booster is planned to use for storage of Au^{31+} ions at energy 3.1 MeV/u. The intensity of the stored ions is increased by 3-5 times at injection intensity of $5\cdot10^8$-10^9 ppp. The intensity of the stored beam is higher by one order of magnitude comparing with injection intensity of 10^8 ppp. The maximal intensity is restricted by the incoherent diffusion heating of the stack and the ion life time. The simulations of the cooling stacking injection were performed by BETACOL code. The coherent instability can be developed at a high ion intensity in presence of the electron cooling. The increment of instability essentially depends on the choice of the working point.

INTRODUCTION

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex is under construction at Joint Institute of Nuclear Research aimed to provide collider experiments with heavy ions up to gold at maximum energy at center of mass of $\sqrt{s} \sim 11$ GeV/u.

The complex NICA consists of three superconducting accelerators: booster, acting synchrotron-Nuclotron and collider which provides average luminosity of $10^{27}cm^{-2}s^{-1}$.

The collider NICA is proposed for study of baryon interaction in the hot and dense quark-gluon matter and search of mixed phase of that matter. The planed experiments will realize in colliding ion-ion beams.

The main goals of booster are connected with of $4\cdot10^9$ ppp gold ions Au^{31+} and its acceleration up energy of 600 MeV/u which is required for stripping of ion charge state Au^{79+}. Booster synchrotron has maximum magnetic rigidity of 25 Tm and the circumference of about 215 m. The Booster is equipped with an electron cooling system that allows to provide cooling of the ion beam in the energy range from the injection energy up to 100 MeV/u.

The multi cycling cooling stacking injection is planned to increase the stored ion intensity in booster NICA at injection energy of 3.1 MeV/u. The injection from the electron linac is repeated with frequency of 10 Hz. The intensity of gold ion beam at linac exit is equal to 10^8-10^9 ppp. The vacuum pressure in booster is $5\cdot10^{-11}$ mbar that corresponds to the ion life time of 3-5 sec at injection energy of 3.1 MeV/u. The average ion flax is the key booster characteristic, it is equal to $R=N/\tau$, where N is number of stored ions, τ is time duration of booster cycle. Average ion flax is equal to $R=2\cdot10^8$ sec^{-1} at number of stored ions $N=10^9$ ppp and time duration of booster cycle of $\tau=5$ sec.

The rms beam emittance $\varepsilon_{x,y}=\sigma_{x,y}^2/\beta_{x,y}$ at exit of the linear accelerator is equal to $\varepsilon_x/\varepsilon_y=3$ $\pi\cdot$mm$\cdot$mrad, here $\sigma_{x,y}$ – rms transverse beam size, $\beta_{x,y}$ is the beta function in injection area. The horizontal acceptance for stored stack ions is equal to $\varepsilon_{ac}=10$ $\pi\cdot$mm$\cdot$mrad. The equilibrium stack orbit is displaced relatively to the septum on a distance $(\beta_{inj}\varepsilon_{ac})^{1/2}$, where β_{inj} is the horizontal beta function in injection area. The bump of equilibrium orbit is displaced at single turn injection on a distance $2\sigma_x=2(\beta_{inj}\varepsilon_x)^{1/2}$. The angle spread of injected beam is equal to $(\varepsilon_x/\beta_{inj})^{1/2}$. The initial horizontal beam emittance corresponds to $\varepsilon_{inj-x}=2\varepsilon_x+(\varepsilon_x\varepsilon_{ac})^{1/2}=11{,}5$ $\pi\cdot$mm$\cdot$mrad in the booster.

The simulation of multi cycling cooling stacking injection were performed by the BETACOOL code [2] for gold ions Au^{31+}. The electron beam current is equal to 0.1 A, the beam has uniform density at radius less than 2 cm. The length of electron cooling section is equal to 1,94 m.

The efficiency of electron cooling is equal to ratio of amplitude of second injection pulse to amplitude of first injection pulse (Fig.1). The efficiency of electron cooling is equal to 40% at injection repetition frequency of 10 Hz. The maximal ion stored intensity corresponds to $4.6\cdot10^9$ ppp at injection intensity of 10^9 ppp and ion life time of 4.4 sec.

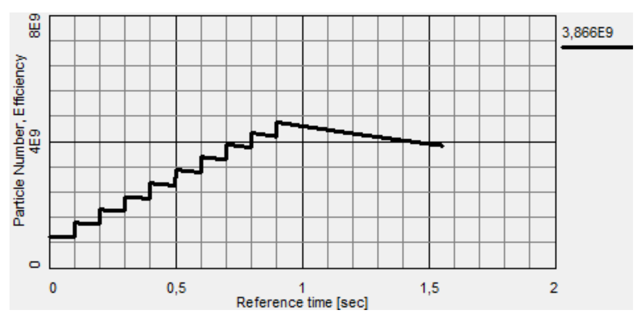

Figure 1: Dependence of stored ion intensity on time at 10 cycle injection.

The average ion flax is equal to $R=7.6\cdot10^8$ sec^{-1} at an number of stored ions of $N=4.6\cdot10^9$ ppp and time duration of booster cycle of $\tau=6$ sec. Cooling stacking injection increases by 3.8 times the average flax in comparison with single turn one cycle injection.

The maximal stack ion intensity is restricted by several effects: the incoherent stack noise, the instability of cooled ion stack and the ion life time at interaction ions with residual gas atoms and molecules.

The emittance of cooled ion stack is defined by number of stored ions N_{st} and betatron tune shift ΔQ

$$\varepsilon_v=(r_pZ^2N)/(4\pi A\beta^2\gamma^3\Delta Q),$$

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where Z is the nuclear charge, A is the atomic number, β and γ - are the relativistic factors, r_p is the proton radius. The equilibrium between sack noise incoherent heating and electron cooling determinates the ion stack emittance. The incoherent stack heating reduces the electron cooling efficiency and finally it became to reduction of stored ion intensity. The emittance rate at diffusion heating is proportional to number of the stack ions N normalized on number of the injected ions N_{inj}: $d\varepsilon/dt=kN/N_{inj}$ [3]. The maximal stack intensity corresponds to $N=5{,}5\cdot10^9$ ppp at time duration of cooling stacking injection of 2 sec and emittance heating rate $d\varepsilon_h/dt=d\varepsilon_v/dt= 0.3N/N_{inj}$ sec^{-1} for 20-cycle injection with repetition frequency of 10 Hz.

Coherent instability or "electron heating" is developed at storage of the high intensive ion beams in presence of the electron cooling [4]. To avoid stack instability the hollow electron beam is formed in the electron cooling system [5]. The hollow beam with low density in central region is used for stack cooling; the high density for the boundary electrons is applied for cooling of new injected ions with the large betatron amplitudes. The increment of beam instability can be essentially reduced in case of hollow electron beam and ion stack life time can be increased.

The internal radius with the low electron density $n=5\cdot10^6$ cm^{-3} is equal to 0.5 cm. The electron density in boundary region corresponds to $n=2\cdot10^7$ cm^{-3}, the electron beam current is equal to 0,095A. The hollow electron beam provides similar stack intensity as uniform electron beam when the ion life time is same for both cases. However for hollow beam electron heating is weak and ion life time is larger than for uniform electron beam. Finally it became to increase of the stack intensity.

The stack intensity is defined by incoherent emittance rate at electron heating. The presence of diffusion heating with emittance rate $d\varepsilon_h/dt=d\varepsilon_v/dt=0.1N/N_{inj}$ became to reduction of stack intensity from $6.3\cdot10^9$ ppp to $5.7\cdot10^9$ ppp. An increase of emittance heating rate up $d\varepsilon_h/dt=d\varepsilon_v/dt=0.3N/N_{inj}$ sec^{-1} leads to reduction of stack intensity from $6.3\cdot10^9$ ppp to $4.1\cdot10^9$ ppp (Fig.2).

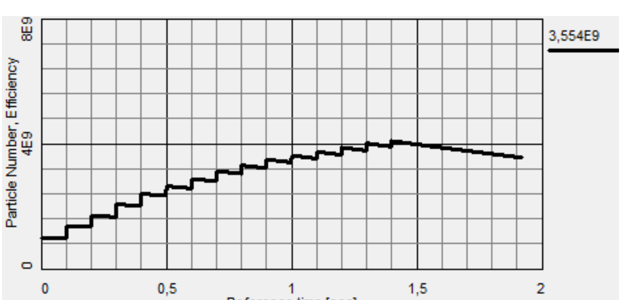

Figure 2: Dependence of stored ion intensity at 15-cycle injection on time for hollow beam at presence of incoherent stack heating.

The equilibrium emittance is defined by internal radius of hollow beam at a high incoherent emittance heating rate. Therefore the cooling stacking injection provides by 4-5 times increase of stored stack intensity in comparison with one cycle single turn injection.

The stored ion intensity depends on the ion life time. The ion life time is defined by its interaction with residual gas atoms and molecules. The ion life time depends on two parameters: the pressure and the charge-mass spectrum of residual gas [6,7].

Dependence of stored ion intensity on the ion life time is given in Fig.3 for parameters presented in Fig.2. The ion life time reduction from 4.4 sec to 0.65 sec became to ion intensity reduction from $4.1\cdot10^9$ ppp to $2.2\cdot10^9$ ppp.

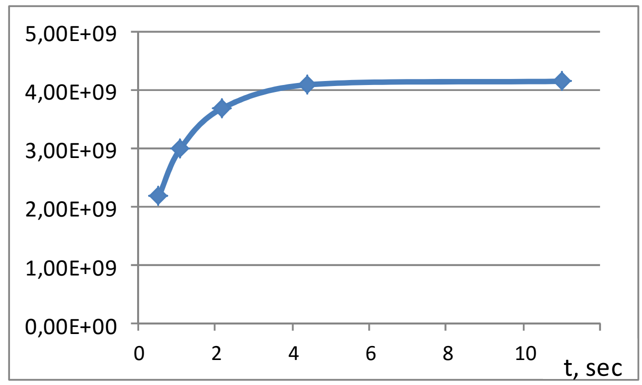

Figure 3: Dependence of stored ion intensity on ion life time at injection repetition frequency of 10 Hz.

The intensity of stored ion beams Au^{31+} can increased by 10-15 times at low injected ion intensity of 10^8 ppp during 50 cycles with repetition frequency of 5-10 Hz (Fig.4).

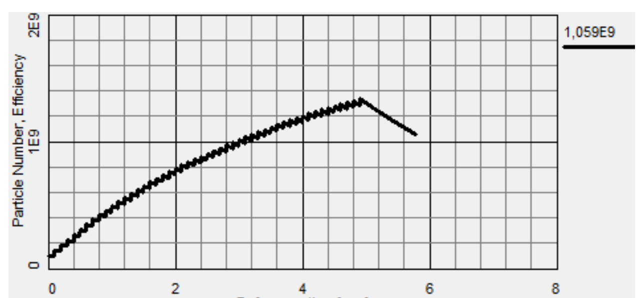

Figure 4: Dependence of the stored ion intensity on time at 50-cycle injection with repetition frequency of 10 Hz.

Reduction of the repetition frequency from 10Hz to 5Hz leads to decrease of the ion intensity from $1.3\cdot10^9$ ppp to 10^9 ppp caused by short ion life time of 4.4 sec.

INSTABILITY OF ION BEAM AND CHOICE OF WORKING POINT

Coherent instability or so called "electron heating" [5] is developed for high intensive ion beam in presence of electron cooling. The ion losses are rapidly increased when the ion intensity reaches the critical value. The space charges of electron and ion beams together with solenoid magnetic field in cooling section provide

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connection between horizontal and vertical coherent oscillations. The transverse motion of the ion and the electron beam center gravities are given by following equations [4]:

$d^2z/dt^2+i\omega_c dz/dt+\omega_i^2 z=\omega_i^2 z_e$, $dz_e/dt+i\omega_d z_e=i\omega_d z$,

at initial conditions $z(0)=z_0$, $dz_{(0)}/dt=(dz/dt)_0$, $z_e(0)=0$, $dz_e(0)/dt=0$, where $\omega_c=ZeB/\gamma m_i$ is the ion cyclotron frequency, $\omega_i^2=Ze^2n_e/2\varepsilon_0\gamma m_i$ is the ion plasma frequency in the electron beam field, $\omega_d=\omega_e^2/\omega_{ce}$ is the drift electron frequency, $\omega_e^2=Ze^2n_i/2\varepsilon_0\gamma^3 m_e$ is the electron plasma frequency, $\omega_{ce}=eB/\gamma m_e$ is the electron cyclotron frequency, B is the magnetic field of solenoid, n_e and n_i are electron and ion densities, correspondently. Centre gravity motion can represented in matrix form $X=M_{cool}X_0$ [5], where M_{cool} is 4×4 matrix of cooling section. Matrix M_{cool} corresponds to unstable motion caused by $\det M_{cool}\neq 1$ [4]. Ion motion outside of cooling section is characterized by Twiss matrix. Single turn booster matrix M_{ring} with electron cooling is equal $M_{ring}=L_{dr}\cdot R_{Twiss}\cdot L_{dr}\cdot M_{sol}^{-1}\cdot M_{cool}\cdot M_{sol}$ [4], where L_{dr} is matrix of drift cooling section with negative length $-L/2$ and M_{sol} is solenoid matrix. The peculiarity of booster matrix M_{ring} is related to that module of its Eigen values do not equal to 1: $\Delta\lambda_{1,2,3,4}=|\lambda_{1,2,3,4}|-1\neq 0$ [4]. At small value the $\Delta\lambda$ characterizes the increment of instability $\gamma_{ins}=|\lambda|-1$ in number of booster turns. Two dipole modes are exited with increment γ_1, and other two modes with decrement γ_2. The dipole modes have resonance character at $Q_x-Q_y = 0$. The values γ_1 and γ_2 change the signs at transition through the resonance $Q_x-Q_y = 0$.

The unstable modes are exited before resonance. The damp mode are exited after transition through resonance. Therefore there are exited modes all time in the system. The increment is asymmetric in relation to difference resonance $Q_x-Q_y=0$ and sum resonance $Q_x+Q_y=9$. Increment has maximum at difference resonance and it has minimal value around sum resonance [7]. The dependence of increment and decrement on the vertical betatron tune is given in Fig.5 at fixed value of horizontal betatron tune $Q_x=4.8$ for hollow electron beam with density in central area of $n_e=5\cdot 10^6$ cm^{-3} and number of stored ions Au^{31+} of $3\cdot 10^9$ ppp.

The hollow electron beam is planned to use for reduction of increment. The density in central region is by 4 time smaller in comparison with boundary electron density. However for hollow electron beam is possible development of instability at high ion intensity. The instability increment essentially depends on choice of working point [7].

The booster working point $Q_x/Q_y=4.8/4.85$ is close to difference resonance $Q_x-Q_y=0$ and it corresponds to increment closed to maximal value. The horizontal betatron tune will fixed in booster and vertical tune will changed at variation of current in quadrupole lenses. The choice of the working point in area closed to sum resonance permits to reduce the increment of the instability. New working point $Q_x/Q_y=4.8/4.15$ is displaced from sum resonance $Q_x+ Q_y=9$ and high orders resonances $2Q_y+Q_x=13$ и $4Q_x=19$. The simulated increment for working point $Q_x/Q_y=4.8/4.15$ is by several times smaller than increment for booster working point $Q_x/Q_y=4.8/4.85$.

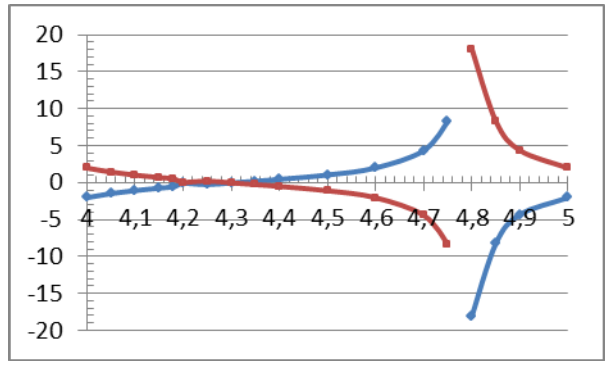

Figure 5: Dependence of increment and decrement of instability on vertical betatron tune at horizontal betatron tune of $Q_x=4.8$.

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