NUMERICAL AND EXPERIMENTAL STUDY OF COOLING-STACKING INJECTION IN HIMAC SYNCHROTRON

E. Syresin, Joint Institute of Nuclear Research, Dubna, Moskow, Russia
K. Noda, National Institute of Radiological Sciences, Chiba, Japan
S. Shibuya, Accelerator Engineering Corporation, Chiba, Japan
T. Uesugi*, Reactor Research Institute, Kyoto University, Osaka, Japan

Abstract

The cooling-stacking injection at the HIMAC synchrotron was used to increase the intensity of Ar18+ ion beam. The beam stacking was realized in a horizontal free phase-space, which was created by the HIMAC electron cooler. The stack intensity of $(1.5 \sim 2.5) \times 10^9$ ppp was accumulated at an injection intensity of $(0.3 \sim 1.0) \times 10^9$. The lifetime of stack ions is determined by vacuum pressure. The new injected ions were slowly lost at multiple scattering on residual gas atoms at diffusion heating in the vertical direction caused by the acceptance of 30 πmm-mrad and a reduction of cooling force at large betatron amplitudes. The results of numerical simulations and experimental study of cooling-stacking injection on the HIMAC synchrotron are presented.

INTRODUCTION

The cooling stacking injection at the HIMAC synchrotron was used to increase the intensity of Ar^{18+} ion beam [1, 2, 3]. The beam stacking was realized in a horizontal free phase-space, which is created by the HIMAC electron cooler. The stack intensity of $(1.5 \sim 2.5) \times 10^9$ ppp was accumulated with the cooling stacking injection at injection intensity of $(0.3 \sim 1) \times 10^9$ ppp[1, 2, 3]. The stack gain is determined by two parameters: the cooling-accumulation efficiency and the ion-beam lifetime.

The cooling-accumulation efficiency is related to the ratio of the number of injected ions to the number of cooled ions which come inside of the available acceptance for the stack injection. This value characterizes the ion loss at bump orbit displacement at each injection cycle. The accumulation efficiency essentially depends on the electron current. It is increased typically from 50 % up 100 % at electron current variation from 25 mA up to 150 mA. However a transverse instability[1, 2, 3] restricts the formation of high intensive stack at a large electron current. In this paper, the electron current is restricted below the threshold of the transverse instability.

The stack gain depends on a ratio of the ion lifetime to the injection repetition time. The ion lifetime at the HIMAC synchrotron is determined by an interaction of ions with the residual gas atoms.

The ion-beam lifetime at very low intensity is around 10 s at the vacuum pressure of 10^{-10} Torr. However, by observing the slow beam-loss during stack-decay, it was found that the lifetime was reduced when ion-beam intensity was high. One possible source of the lifetime reduction is related to the increase of the heavy ion component of the residual gas. A large number of beam loss at high intensity causes the degradation of local vacuum pressure, and thus increases the beam loss by electron capture process and/or diffusion process. A similar effect was observed in LEAR cooler[5].

In addition, the large emittance of newly injected, uncooled part of the beam contributes to the lifetime reduction. At the beginning of the stack-decay, newly injected beam has a relatively large emittance and can be easily lost by some diffusion process, such as multiple scattering with residual gas atoms or cooler electrons.

In this paper, the cool-stacking injections were simulated with BECACOOL code, taking into account the lifetime reduction and accumulation rate.

Cool-Stacking Injection at a High Ion Intensity

The maximum intensity of 2.5×10^9 ppp was accumulated with cooling stacking injection[1, 2, 3]. The operation parameters are given in Table 1. The ion lifetime corresponds to $8 \sim 10$ s at an injected intensity of $(0.3 \sim 1) \times 10^9$ ppp. The lifetime of injected ions is by

Table 1: HIMAC parameters at cooling-stacking injection.

Ring	
Circumference	129 m
Acceptance	(264, 30)πmm-mrad
No. of injected ions	$(2 \sim 10) \times 10^8$ ppp
Stack intensity	$0.5 \sim 2.5 \times 10^9$ ppp
Particles	Ar^{18+} ,6 MeV/u
Betatron tunes Qx/Qy	3.69/3.13
Injection repetition time	1 s, 1.65 s or 3.3 s
Vacuum ion lifetime	$8 \sim 10$ s
Monitor betatron functions	(9,7) m
Cooler betatron function	(9.9,10.7) m
Electron cooler	
Current	$25 \sim 150$ m
Cathode diameter	35 mm
Magnetic expansion factor R	1.7, 2.8, 3.3, 3.8
Solenoid field	0.05 T , 1.2 m

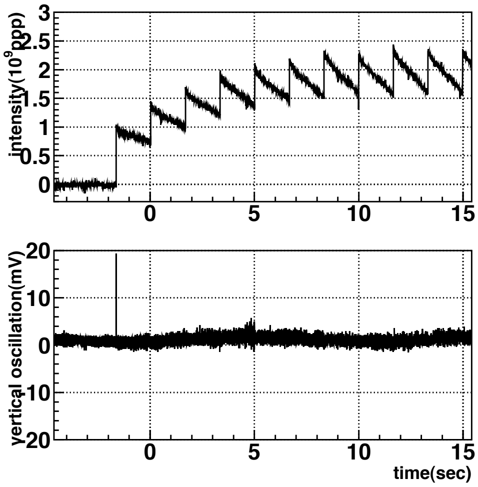

Figure 1: Cool stacking with $I = 120$ mA and R=2.

factor of 2 smaller than stack lifetime at high ion intensity. The stack size is by factor of 2 larger than it follows from equilibrium between IBS and cooling.

BETACOOL Simulations

The calculations of cooling stacking injection by BETACOOL code [6] are given at considerations of the following effects: the cooling of injected ions, intra-beam scattering (IBS), ion interaction with residual gas atoms and a diffusion heating. The ion losses are related to ion interaction with residual gas atoms, the bump height displacement at each injection cycle and ring acceptance. A part of ions are lost caused by bump orbit displacement if during injection cycle they do not come to a space available for the stack ions. The multiple scattering on residual gas atoms and a diffusion ion heating are sources of slow ion losses because of the relatively small vertical acceptance and weak cooling at large betatron amplitudes. The initial distribution of the macro-particles were defined with the rms emittance of (10,5)πmm-mrad and 0.1% momentum spread.

SLOW BEAM-LOSS

Observing the slow beam-loss during stack-decay, it is found that the lifetime became higher at higher ion-intensity [2]. In Fig. 2 the lifetime was plotted as a function of ion-intensity, which is related to the time after stopping stack-injection. The lifetime was $4 \sim 5$ s at the beginning of the stack-decay, while it was 8 s after several seconds.

Lifetime vs CO Partial Pressure

The ion lifetime related to electron capture is reduced at an increase of partial pressure of the heavy residual gas components. The BETACOOL simulations were performed with different partial pressure of CO-gas. The lifetime of stack ions were $7 \sim 8$ s

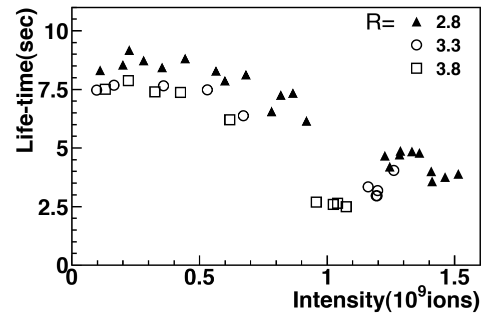

Figure 2: Lifetime reduction at high intensity.

Simulation with Two Component Lifetime

The stack gain is defined by the ion lifetime and the injection repetition time. We recalculate the stack gain at any cooling accumulation efficiency in case when the lifetimes of injected (τ_{inj} and stack ions (τ_{st} are different. The number of injected ions, which came to the stack at each injection cycle, is equal to

$$N_1 = \eta N_{inj} \exp(-\frac{T_{inj}}{\tau_{inj}}) \ . \qquad (1)$$

where N_{inj} is the number of injected ions and η is the accumulation efficiency. The input of i-th injection batch in the intensity of stored ions after K injection batches corresponds to

$$N_i = \eta N_{inj} e^{-\frac{T_{inj}}{\tau_{inj}}} e^{-\frac{(K-i)T_{inj}}{\tau_{st}}} \ . \qquad (2)$$

The total number of stored ions after K-injection batches is equal to

$$N = N_{inj}\left[1 + \eta e^{-\frac{T_{inj}}{\tau_{inj}}} \frac{1 - e^{\frac{(K-1)T_{inj}}{\tau_{st}}}}{1 - e^{\frac{-T_{inj}}{\tau_{st}}}}\right] \qquad (3)$$

The stack gain $G = N/N_{inj}$ is decreased at injected ion lifetime reduction for a constant τ_{st} . This reduction is large when the cooling efficiency is high. The stack gain corresponds to G=5.4 at η=1 and τ_{inj}=τ_{st}=8 s. These conditions correspond to the cooling-stacking injection presented on Fig. . However at cooling-stacking injection given on Fig. 1 the measured stack gain is only of $G_{meas} = 2.5$ at η=65%, τ_{st}=8 s and τ_{inj}=4 s. The measured stack gain has a good agreement with simulated one.

COOLING ACCUMULATION EFFICIENCY AND BUMP LOSSES

The cooling-accumulation efficiency (η is defined as the survival ratio of an injected number of ions at the next bump-orbit excitation. New ions injected with large betatron amplitudes are lost at a bump orbit displacement when the injection pulse is over if they do not came to a space available for the stack. The efficiency can be found from the amplitudes of first and second injection batches. The

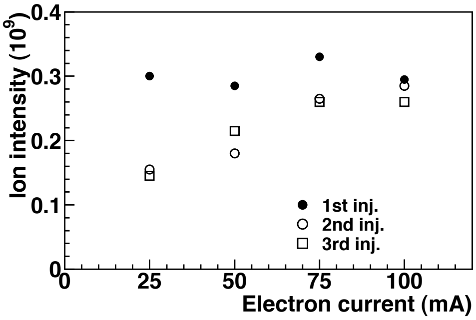

Figure 3: Injected no. of ions at 1st, 2nd and 3rd injections.

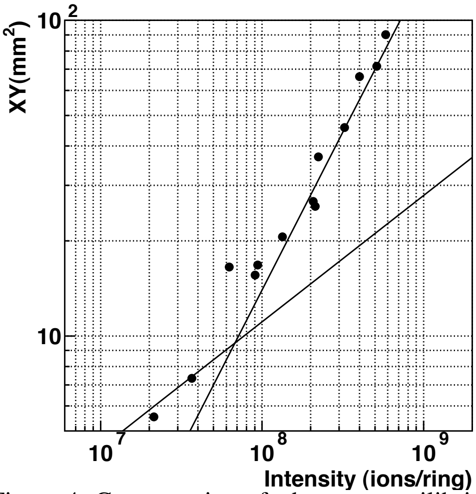

Figure 4: Cross-section of a beam at equilibrium.

stack intensity depends critically on a bump height. It is reduced to half when the bump height is shifted from optimum by 20% [2]. The cooling efficiency corresponds to 65% at stacking given in Fig. 1. The cooling accumulation efficiency depends on the electron current (Fig. 3). The ratio of first and second injection batch amplitudes is fast reduced at an electron current decrease (Fig. 3). The cooling efficiency is about 100% at electron current of 100 mA and it is reduced to 50% at electron current of 25 mA.

THE EQUILIBRIUM STACK SIZE

The behavior of the stack equilibrium ion size indicates a diffusion realized at high ion intensity. This ion diffusion heating is related to ion multiple scattering on residual gas atoms and an additional transverse diffusion . At small ion intensity the ion beam cross-section is proportional to $N^{2/5}$ [2] as shown in Fig.—4. The size of ion beam is defined by equilibrium between electron cooling and IBS. However at ion intensity larger than 10^8 ppp the ion beam cross-section is increased linearly with ion intensity grow at a constant ion density of 0.9×10^7 ions/mm^2. This density corresponds to the Laslett tune-shift of 0.03. The linear behavior of the ion beam cross-section versus ion intensity is characterized by a diffusion noise and ion multiple scattering on residual gas atoms.

At a high intensity ion-beam the equilibrium stack

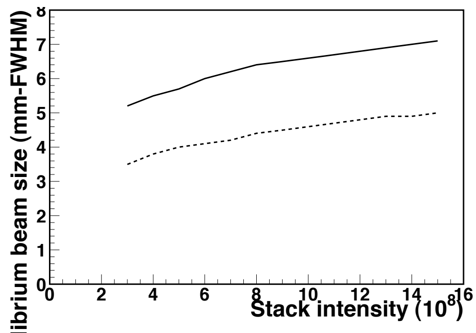

Figure 5: FWHM beam-sizes vs ion intensity

size is defined by the cooling rate λ_{cool} and a diffusion heating rate. The diffusion heating rate is estimated as $\epsilon' \sim \lambda_{cool}\sigma_v^2/\beta_v$ ~2 πmm-mrad/s at a stack rms size of σ_v ~5 mm, beta function of β_v=7 m at the profile monitor, and cooling rate of λ_{cool}=0.5 s^{-1}. The behavior of measured stack size at its decay is given in Fig. 4. The cooling-stacking injection is shown on Fig. 1 at same parameters.

The equilibrium stack size estimated by the BETACOOL simulation (Fig. 5) agree with the experimental results (Fig. 4) at a low intensity of $\sim 3 \times 10^8$ ppp. However, the equilibrium stack size at its decay is twice larger at high ion intensity of 1.5×10^9 ppp than that expected by the BETACOOL simulations at equilibrium between IBS and electron cooling. A good coincidence of simulated and measured FWHM stack sizes is realized at the vertical heating rate of $\epsilon'_v \sim 5$ πmm-mrad/s and horizontal one $\epsilon'_h \sim 3$ πmm-mrad/s at ion intensity of $(0.5 \sim 1.8) \times 10^9$ ppp. The sources of these heating rates are ion multiple scattering on residual gas atoms and a transverse noise generated by a high intensive stack.

CONCLUSION

The stack intensity of $(1.5 \sim 2.5) \times 10^9$ ppp was accumulated with cooling stacking injection at injection intensity of $(0.3 \sim 1) \times 10^9$ ppp. The stack gain corresponds to 3~4 at these intensities and stack lifetime of 8~10 s. The maximal stack intensity is restricted by a transverse instability and ion lifetime reduction. The ion lifetime is mainly defined by electron capture losses at ion interaction with heavy residual gas components. The IBS, ion multi scattering on residual gas and a transverse diffusion lead to lifetime reduction by factor 2~3 for new injected ions comparing with stack ones.

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