INTENSIVE ION BEAM IN STORAGE RINGS WITH ELECTRON COOLING

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Abstract

Results of experimental studies of the electron cooling of a proton beam at COSY (Juelich, Germany) and an ion beam at HIMAC (Chiba, Japan) are presented. Intensity of the ion beam is limited by two general effects: particle loss directly after the injection and development of instability in a deep cooled ion beam. Methods of the instability suppression, which allow increasing the cooled beam intensity, are described.

INTRODUCTION

Electron cooling method is widely used to increase an ion beam density in the six dimensional phase space. To increase intensity of the stored beam the stacking- cooling procedure is applied: injected beam is cooled to small dimensions and thereafter a new injection can be performed into free part of the ring acceptance. Such a procedure is repeated to saturation of the stored beam current. At high phase space density one of the general limitations of the ion beam intensity is related to development of coherent instabilities of the stored beam. Different types of instabilities developing at a high beam phase density were observed at a few coolers [1]. Specific instability, which appears directly at electron cooling application, was firstly observed in CELSIUS storage ring [2]. This instability leading to decrease of the ion beam life-time in the presence of an electron beam was named “electron heating".

Both types of instabilities were observed at COSY since beginning of the electron cooling system operation. Coherent instability of the stored ion beam limits the beam intensity at HIMAC storage ring. Results of the instability investigations performed at COSY and HIMAC during last years are presented in this report in comparison with previous results from CELSIUS and LEAR. At COSY the experiments were done with coasting proton beam at injection energy (45 MeV), at HIMAC – on coasting beam of Ar^{18+} at energy of 6 MeV/u. Aspecial attention is paid to study of an influence of the electron beam neutralization on stability of the circulating ion beam.

“ELECTRON HEATING”

The initial particle losses are resulted from strong diffusion process which power is proportional to the electron beam current. To investigate the diffusion at most clear conditions the ion beam lifetime can be measured at detuned electron beam energy. In this case the electron cooling does not work, but the electron beam noise acts on the injected beam and so called “electron heating” processes can play a role also. An example of results of such measurements at COSY is presented in the Fig. 1, where the electron energy is detuned by 2 keV from the value required for cooling. The proton beam lifetime increases with decrease of the proton beam intensity (Fig. 2) and after about 10 sec reaches saturation at relatively long value.

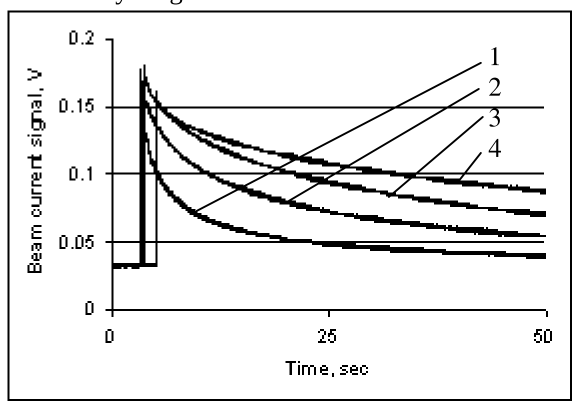

Fig. 1: Proton beam current as a function of time at electron beam current of 243 (1), 95 (2), 45 (3) and 0 (4) mA.

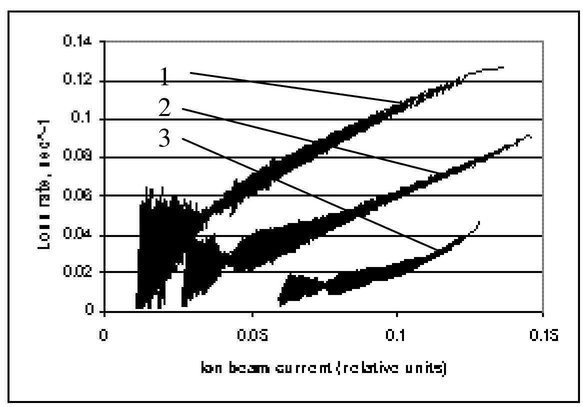

Fig. 2: Rate of the proton losses versus the beam intensity. Electron current is 243 (1), 45 (2) and 0 (3) mA.

Decrease of the beam intensity is related mainly to a loss of the particles with amplitude of betatron oscillations larger than electron beam radius. Nonlinearity of the electron beam self-fields can be a reason of the loss [2]. Other explanation proposed in [3] is based on assumption, that the interaction of the proton and electron beam leads to the proton beam coherent oscillations and electric field of these oscillations generate the proton beam heating.

At COSY the proton beam life-time in presence of the electron beam decreases by about 10 times, at CELSIUS this effect is even more pronounced – the proton beam at injection (which practically coincides with injection energy at COSY) decreases by up to 100 times in presence of intensive electron beam. At HIMAC the ion beam life-time is not affected by the electron beam, but there the ion beam radius at injection is less than electron beam one.

COHERENT INSTABILITY

Single Injection

After fast losses caused by the "electron heating" and some period of the beam cooling new particle loss can appear due to coherent instability. After injection at COSY the initial losses take place during first 5 sec of the cooling process (Fig. 3, lower curve). The cooling process is accompanied by H^0 production in the cooling section (upper curve in the Fig. 3) and H^0 count rate increases during initial particle loss. It reflects the fact that the lost particles have an amplitude of betatron oscillations larger than electron beam radius. The H^0 count rate saturates at approximately the same moment as the proton beam intensity stabilizes.

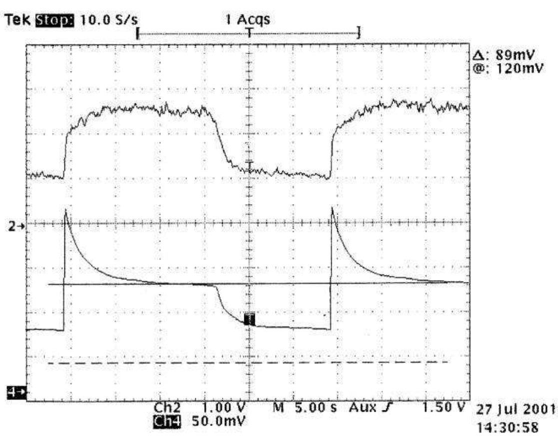

Fig. 3: Proton beam intensity at COSY during repeated injection at low frequency.

Coherent oscillations of the circulating beam starte after about 7 seconds of the cooling but initially do not lead to the particle loss. In the case presented in the Fig. 3 initially the dipole oscillations appeared in the longitudinal and horizontal plane. These oscillations were registered in the spectrum of the beam Schottky noise, or directly from pick-up electrodes using oscilloscope. After some period of time the horizontal oscillations were transformed to the vertical ones. The coherent oscillations of the beam in vertical plane lead to fast particle losses due to smaller value of the vertical acceptance.

Cooling - Stacking

The instability of the intensive proton beam in the cooling-stacking mode was investigated in details at COSY [4]. The instability nature is the same as in the case of single injection - coherent oscillations of the stored ion beam: initially in the longitudinal and horizontal degree of freedom and, after some time, the oscillations "jump" into the vertical plane. Coherent instability during stacking leads to random variations of the beam intensity near saturation and limits the stored beam intensity. More probably explanation of the instability origin is the plasma oscillations of the ion beam in accordance with the theory developed in [3]. The coherent oscillations appear when the ion beam density increase to the level corresponding to more than one plasma oscillation of the ions during passage of the electron beam. The transformation of horizontal coherent oscillations into the vertical ones leading to particle losses was observed also at HIMAC as well.

Instability Suppression

The instabilities of cooled ion beam can be avoided by preservation of "overcooling" of the beam core. For instance at CELSIUS and later at COSY an additional external heating of the beam in longitudinal and transverse degrees of freedom and/or misalignment of the electron beam were tested for instability suppression. However, both of these methods stabilize the stored beam but do not give a substantial increase of its intensity. The external heating leads to higher value of the particle loss after injection due to decrease of dynamic aperture of the ring. The misalignment of the electron beam leads to non-equilibrium distribution in the transverse degree of freedom and, in principle, can provoke a chromatic instability. The experience of the CELSIUS cooling system operation demonstrated that more effective way to suppress the stored beam instability is artificial increase of the electron beam energy spread. This was done by connecting the electrically insulated inner structure in the drift tube to a hi-fi amplifier, and modulating the voltage at this structure. For instance, at 115 keV electron energy at CELSIUS it was demonstrated that most effective is square-wave modulation at amplitude of 50 V [5].

Formation in the electron gun the hollow electron beam is another and, as one can expect, more effective way to avoid overcooling the ion beam core and related instabilities. The results of experimental investigations of the electron beam profile in such a gun were presented in [6].

The instability threshold depends not only on the beam current and on the magnitude of the transverse machine impedance but also on the particle momentum spread. Therefore to avoid beam losses the chromaticity should be negative below transition. Stabilization of the proton beam by adjustment of the chromaticity accomplished with sextupoles was demonstrated at COSY [7].

Fig. 4 shows two cycles of the COSY beam. The injected proton beam (current of 2 mA) with 293.8 MeV/c (45 MeV) is electron cooled for 10 s and then is accelerated within 1.8 s to the flat top momentum of 2085 MeV/c. In the first cycle a strong vertical oscillation occurs leading to beam loss immediately after injection. In this case the tunes and chromaticities measured after 8 s were equal to Q_x = 3.587, Q_y = 3.696 and ξ_x = -2.8,

$\xi_y = 0.3$, respectively. In the second cycle the sextupole family located in the arc section of the ring was powered only after injection until acceleration started with –1.7 % to shift the vertical chromaticity ξ_y from +0.3 to –0.6 within 100 ms. By this measure the coherent vertical betatron oscillations at injection could be significantly suppressed and intensity of the accelerated beam was increased by two times.

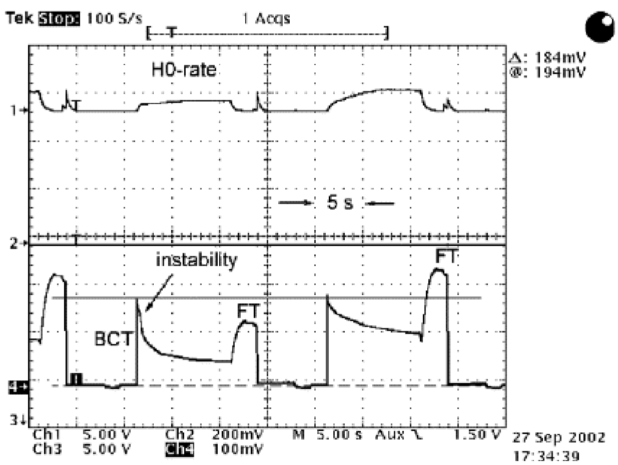

Fig. 4: In the first cycle, without sextupole, a strong beam loss after injection due to a coherent vertical betatron oscillations (instability) is visible in the beam current signal (BCT). This beam loss is compensated by the sextupole family in the next cycle. The flat top (FT) intensity is doubled. The horizontal line in the lower trace points at the same number of injected protons in both cycles. (100 mV BCT signal corresponds to 1 mA proton current).

Results of a feed back system application to increase stored beam intensity was demonstrated, for instance, at LEAR [1]. There strong transverse instabilities occurred once the intensity exceeds a few 10^8 protons. A large number of modes was observed at all energies accessible with electron cooling (5.3 - 50 MeV). Therefore, a feedback system of the bandwidth of 0.1 - 70 MHz was implemented, to stabilise the first 100 or so dipole modes. It was then possible to store up to about $3\text{x}10^9$ protons with the small emittances given by the equilibrium between intrabeam scattering and cooling in the energy range accessible. Higher intensities, up to $8\text{x}10^{10}$ protons, could be cooled to the intra beam scattering limit, when the stochastic cooling system of a reduced gain with a bandwidth up to 500 MHz was used as additional dipole damper.

At COSY the vertical feed back system was designed and implemented after investigations of the particle loss nature. Its bandwidth up to 70 MHz was chosen to suppress all the exiting modes. The system application made it possible to stabilize the cooled proton beam at a level of $2\text{x}10^{10}$ particles (1,8 mA) after a single injection. With the stacking technique a maximum of $1{,}2\text{x}10^{11}$ cooled protons (9,2 mA) at injection energy were stored without instability, which is about two times higher than without a feed back system application [8].

ION CLOUD IN AN ELECTRON COOLING SYSTEM

The ions of residual gas are trapped in the electron beam in transverse direction by the electron beam electric field. When the vacuum chamber radius is varied along the cooling system from cathode to collector the condition of the ion trapping in longitudinal direction can be also met. The trapped ions partially compensate the electron beam electric field and this effect leads to so called "natural neutralization" of the electron beam. The level of the natural neutralization in COSY is measured by two independent methods and is about 37%, that is in good agreement with estimations based on geometry dimensions of the vacuun chamber [9]. In HIMAC level of the natural neutralization is about 15%.

Thus in the cooling section the circulating ion beam interacts with the primary electron beam, secondary electrons and different species of neutralizing ions, which can lead to various types of multi-stream instabilities [10]. The stability of antiproton beam at HESR ring of FAIR project (GSI) in presence of neutralizing ions was descussed in [11] where was shown that even a few percent of the neutralization level can lead to sufficient decrease of the instability threshold. Influence of the neutralizing ions on the circulating beam stability was experimentally investigated at HIMAC [12] and later at COSY.

The ions trapped in the electron beam oscillate in the longitudinal magnetic field of the cooler solenoid and electric field of the electron beam with frequency determined by the following formula

$$\omega = \sqrt{\omega_i^2\left(1-\eta_{neutr}\right)+\omega_B^2/4} \pm \omega_B/2, \qquad (1)$$

where $\omega_B = \dfrac{ZeB}{Am_p}$ is the cyclotron frequency of the ion at mass of Am_p and charge Ze in the magnetic field B, $\omega_i^2 = \dfrac{Ze^2 n_e}{2Am_p}$ is the ion plasma frequency in the electron beam of the density of n_e. To control the neutralization level and to clear the electron beam from one of the ion spesies one can use resonant excitation of the ion oscillations with transverse sinusoidal electric field. This field is applied to pair of electrodes, so called "shaker electrodes", wich are, for instance, position pick-ups in the cooling section. At shaker frequency equal to the ion oscillation frequency the ions leave very fast the electron beam and neutralization level is changed. That leads to a change of potential at the electron beam axis and, as result, to a change of the revolution frequency of the ions circulating in the ring. This change of the revolution frequency can be compensated by change of the electron gun cathode potential. Dependensies of the cathode potential at constant ion beam revolution frequency on the shaker frequency measured at HIMAC and COSY are presented in the Fig. 5, 6.

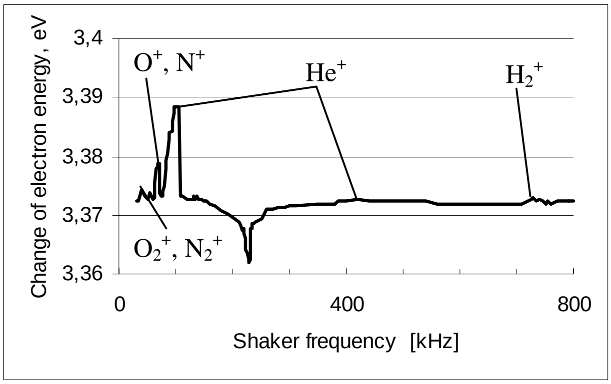

Fig. 5: Spectrum of resonance shaker frequencies measured at HIMAC cooler.

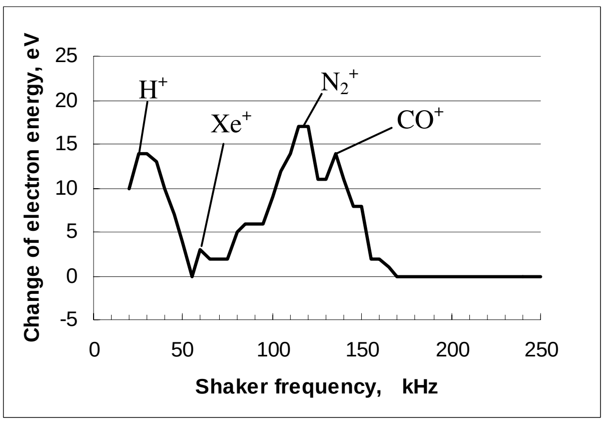

Fig. 6: Spectrum of resonance shaker frequencies measured at COSY cooler.

The measurement were performed at different shaker voltage, which was varied in the range from 10 to 60 V. Width of the resonant peaks increases with increase of the voltage (Fig. 7). The peak shape is typical for nonlinear resonance and at a high value of the shaker voltage a hysteresis behavior appears. At increase of the shaker frequency the neutralization level decreases monotonically, but at some frequency it jumps to initial value. At decrease of the shaker frequency the opposite jump of neutralization level takes place at smaller value of the frequency.

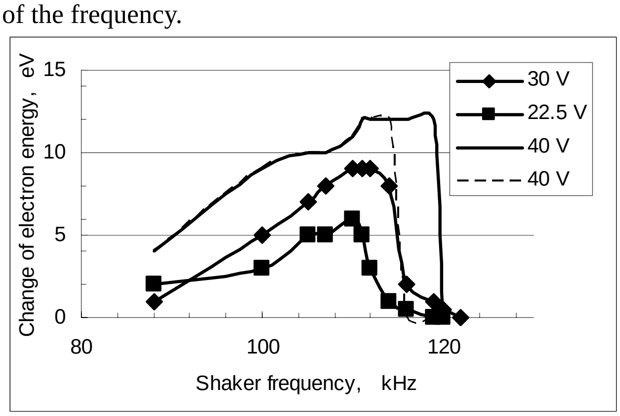

Fig. 7: Shape of the resonant peak at 90 – 120 kHz as function of the shaker voltage amplitude. At 40 V there is a hysteresis effect – solid line corresponds to an increase of the shaker frequency, dashed line – to a decrease.

In the experiments at HIMAC the clearing of the electron beam from the residual gas ions led to increase of the stored beam intensity after stacking by about 2 times. Simultaneously the Schottky noise power of the circulating beam was of sufficiently less level [12].

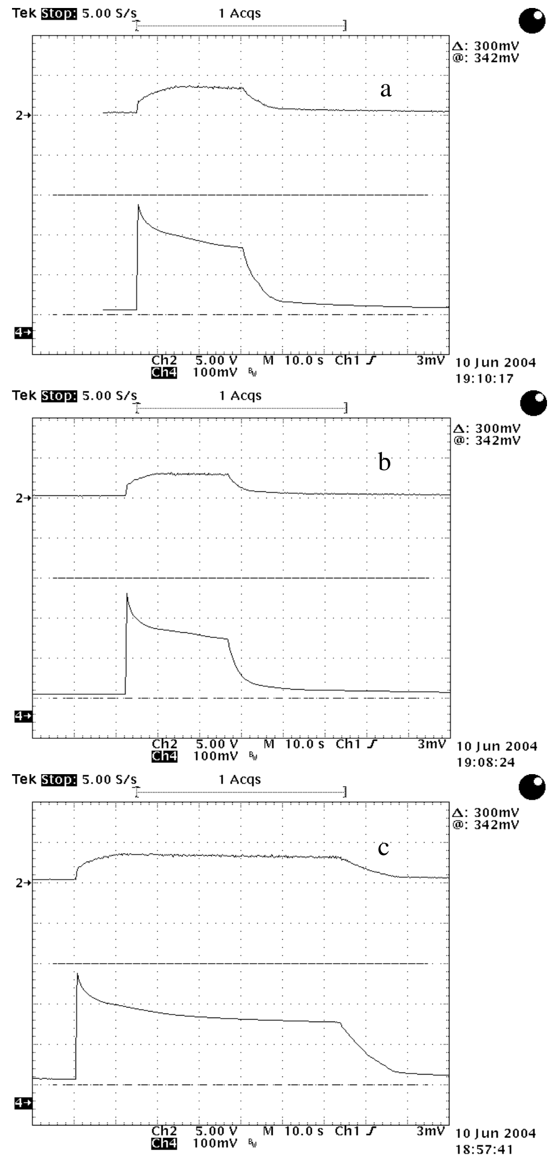

Fig. 8: Ion current versus time: a) shaker is off, b) non resonant excitation, c) excitation on resonant frequency of 114 kHz.

Influence of the neutralization on the proton beam stability at COSY is well illustrated in the Fig. 8. Without shaker or at nonresonant shaker frequency a coherent instability leading to fast particle losses appears after approximately 25 s (Fig. 8 a, b). At clearing the electron beam from one specie of the ions (the frequency of 114 kHz, which corresponds to molecular nitrogen ions) the instability develops after about 70 s and the ion loss rate at instability decreases by about 3 times (Fig. 8 c). This indicates that the threshold ion beam phase space density increases and instability increment decreases. However, in the cooling-stacking process the maximum beam intensity is slightly affected by the shaker in the case of monochromatic excitation. It means that at high proton beam intensity the beam stability can be determined by interaction with the ion cloud consisting of other species.

CONCLUSIONS

The experimental studies of stacking process at COSY and HIMAC cooler-synchrotrons have shown the limitation of the ion beam intensity due to three phenomena related each to other:

1) fast losses directly after injection,
2) slow losses in the cooled proton beam caused by a coherent instability with transformation of horizontal oscillations into vertical ones,
3) trapping of residual gas ions in the cooling electron beam.

The fast initial losses are supposed to be a result of an influence of the electron beam field nonlinearity. Another explanation is related to plasma oscillations in the ion and electron beams, which lead to noise of big amplitude reducing the ion lifetime.

The second stage of the loss takes place when coherent oscillations appear in the cooled ion beam. The transformation of horizontal coherent oscillations into the vertical ones leads to particle losses due to smaller value of the vertical acceptance. One of the more effective ways for coherent instability suppression is a feedback system application.

Comprehensive explanation of these effects was not done yet and they have to be studied in more details. Last results of the experiments at both rings – COSY and HIMAC demonstrated importance of the electron beam neutralized state control especially at cooling of intense beams. At low ion beam intensity neutralization of the electron beam can decrease the cooling time, at high intensity the ion cloud in the cooling section can provoke instability of the cooled beam.

AKNOWLEGMENTS

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