NEW GENERATION OF THE ELECTRON COOLING SYSTEMS

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Abstract

A new generation of the electron cooling systems will be used at ion storage rings with high requirements on beam parameters. The electron beam with variable profile of current density helps to obtain an ion beam with the emittance and intensity that needs for specific physical experiments.

INTRODUCTION

The idea of electron cooling method has a long history from the moment of its birth to the present day. The first experiments carried out in Novosibirsk in 1974 [1] showed the high efficiency of the method. During experimental work has been discovered that the time required for the cooling is shorter than was expected. Such a high cooling efficiency was the result of two factors. First, the magnetic field magnetizes the transverse electron motion, and as result, the heavy particle interacts with a Larmor electron circle, but not with the hot free electron. Second, the acceleration of the electron beam leads to significantly decreased longitudinal temperature of electron beam in the co-moving reference system. The obtained cooling efficiency was so high that the effect of crystallization of the proton beam was observed. It appeared as the abrupt degradation of the heat Schottky noise of proton beam to the zero level [2-4].

The detail study of the kinetics of magnetized electron cooling was investigated at the MOSOL device. In this device a very good straightness of the magnetic field lines was obtained. The experiment performed at MOSOL in the regime of single path of a particle through the electron beam showed the essential difference in the friction force for positively and negatively charged particles. The investigation of the longitudinal spread of the electron velocity showed a limit for effective electron beam temperature related to the IBS effect in the beam. High electron density and high flatness of the distribution function of the electron in the velocity space (the longitudinal temperature is much lower than the transverse temperature in the beam reference system) leads to high IBS rate that may be significant in single path yet.

Our experience obtained from experimental work had been used for the design and construction of the cooler for synchrotron SIS – 18 (GSI, Germany, 1998) [5]. This cooler was used for the accumulation of ion beams injected with energy of 11 MeV/u (2 kV, 0.5 A current). The number of stored ions was 10-20 times higher that of a single injection.

Electron cooling was applied to high charge ion beams. In this case the main loss came from the process of ion recombination on the electron beam and the charge exchange in the residual gas. The numerical estimation has shown that the storage factor of 20 is close to maximum due to recombination process. The typical storage cycle is shown in Figure 1.

Moreover the SIS experiment has confirmed the experimental fact of the extra-large recombination cross-section for certain type of ions [5-7]. The experiments carried out on LEAR, TSR and other devices [7,8] showed that the reason for the fast recombination might be the dielectronic recombination. A free electron is captured by an ion and the excessive energy is transferred to the bound electron that comes to an excited state.

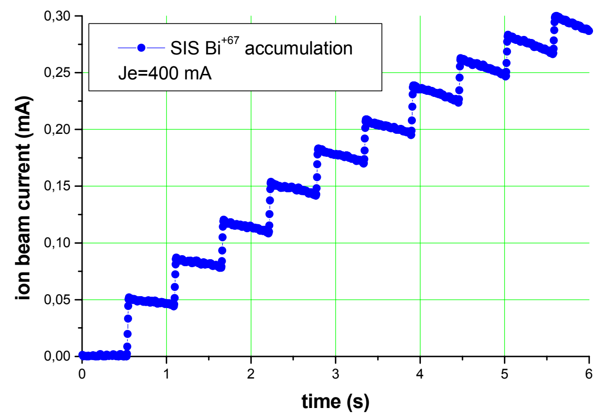

Figure 1: Accumulation of Bi ions at SIS-18. The degradation of ion beam current is related to the recombination losses.

ELECTRON HEATING

The experiment in CELSIUS device [9] revealed additional problem arising from the storage or just injection of high intensity ion beam. Figure 2 shows the proton beam current versus time for the different regimes:

a – no electron cooling;

b – electron beam current 50 mA, but the velocity of electron beam is detuned from the velocity of ion beam and the cooling force is actually absent;

c – the electron beam current is 50 mA and the velocities of electron and ion beams are equal.

One can see that the presence of electron beam leads to a beam instability but a threshold of the instability is defined by the value of the proton beam current. If the proton current exceeds 0.1 – 0.2 mA than the lifetime of proton beam is low for both cases with electron beam and high for the case when the electron beam is absent. After the proton current decreases less than 0.1 – 0.2 mA the current of proton beam degrades during time equaling to the lifetime at Je=0 mA. If the energy of electron beam is optimal for cooling, the lifetime of the proton beam remainder is very large. Let us note, that the proton beam in presence of detuned electron beam after loosing most part of protons and the rest protons having large amplitudes has lifetime about the lifetime of proton beam in absence of electron beam. It means that the non-linearity of the electrical field of electron beam space charge does not essentially influence the proton beam dynamics.

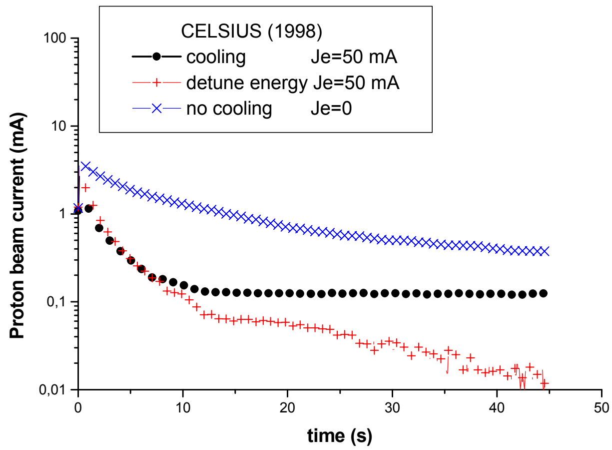

Figure 2: Decay of proton beam (48 MeV) current at CELSIUS without electron beam, with cooling and without cooling at detuned energy of the electron beam from the optimal value.

The interaction of ion and electron beams may be described by λ parameter [10]:

$$\lambda = \omega_{ii}^2 \omega_{ee}^2 \tau^4 , \qquad (1)$$

where ω_{ii} is plasma frequency of ion beam, ω_{ee} is plasma frequency of electron beam and τ is flight-time of electron through the cooling section. The physical meaning of this parameter is close to the parameter of beam-beam tune shift in collider ΔQ_{ee}:

$$\lambda = (4\pi \Delta Q_{ee} l_b / \beta^*)^2 , \qquad (2)$$

where l_b is the length of electron bunch, β^* is β-function at interaction point for a collider. It was shown in years-long experiments with colliding beams that maximum available value is ΔQ_{ee}=0.05-0.1 and λ≈1. Thus, decreasing of electron density ($\omega_{ee}^2 \propto n_e$) in the center of storage zone should lead to increasing of ion beam density ($\omega_{ii}^2 \propto n_i$). Figure 2 shows the rest of the proton beam current of 150 μA after cooling. The equilibrium diameter of proton beam was 0.6 mm. The Laslet tune shift was 0.1 and parameter λ=0.8. The increase of electron beam current to 200 mA leads to decrease of cooled proton beam current to less than 0.04 mA (but λ again close to 1).

NEW COOLER DESIGN

The new generation of cooling device has been produced by BINP for the IMP (Lanzhou, China, 2001-2004). They possess some properties to decrease the negative effects inherent to electron cooling process.

The electron gun is designed with variable beam profile [11]. The positive voltage on the Pears electrode increases electron emission at the edge of cathode and suppresses in the center as is shown in Fig.3.

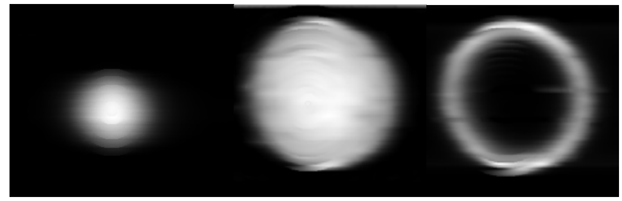

Figure 3: Electron beam profile for different voltage on control profile electrode: negative, zero and positive.

The idea of use electron beam with low density in the center comes from the strong dependence of electron cooling force on the amplitude of betatron oscillations of ions. By decreasing the electron density in the beam center it is possible to considerably decrease the recombination along with slight decrease of the cooling rate. Moreover, the proper radial profile of the electron beam enables obtaining uniform cooling of ions with various betatron amplitudes.

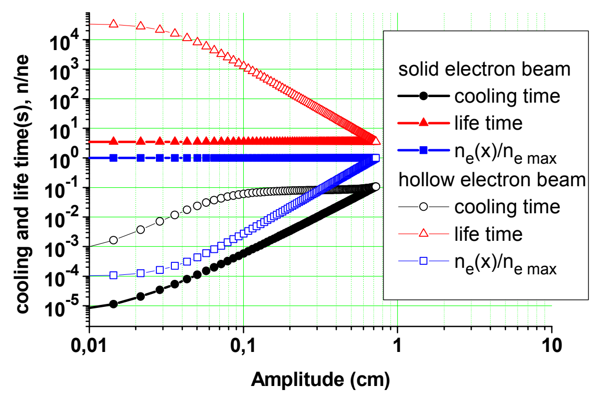

Figure 4: Cooling time and lifetime vs. amplitude for solid (solid symbols) and hollow electron beam (open symbols).

This fact allows to avoid the formation of super - dense core of ions in the beam center and to ease the problem with ion space charge [12].

In order to bend the electron in the Toroid section a transverse magnetic field is usually used to compensate the centrifugal drift motion. In this case an electron reflected from the collector will have two times more displacement by drift at bending part. Finally, they fall on the vacuum chamber and become lost. In case of use the electrostatic field for the creation of centrifugal force the dynamics of electrons passing to the collector and reflected back are same.

$$\vec{F} = e\vec{E} + e\frac{\left[\vec{V} \times \vec{H}\right]}{c} = -\frac{\gamma\beta^2 mc^2}{R^2}\vec{R} . \qquad (3)$$

Electrons leaving the collector have few attempts to be absorbed in it during their oscillations between cathode and collector. It leads to good values of recuperation rate (10^{-6} or better). As the pressure of the residual gas strongly depends on this parameter, the vacuum conditions in the cooling section will be improved essentially (p .≈ 4 x 10^{-11} Torr) [13].

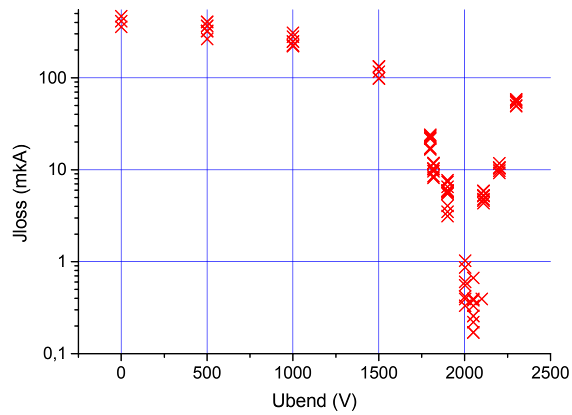

Figure 5: The electron beam loss versus electrostatic voltage on bending plates. The position of electron beam stays the same – with increasing electrostatic bending magnetic bending field decreases (according to Eq.3).

Main solenoid of the cooling section consists of 68 pancake coils connected in series. All of them are adjustable by slightly rotating at three points of support. After several iterations of measurement and adjustment sufficient level of magnetic field straightness ($\Delta B_{\perp}/B \approx 10^{-5}$) has been achieved.

CONCLUSION

The electron coolers with variable electron beam profile open new ways for optimisation of cooling, accumulation of ions and compensation of scattering of ions on internal targets.

The combination of the electron gun with changing beam profile and the modulation of electron beam enable regulation of the distribution of cooled ions in 6-dimensional phase space. Testing this ideas at CSR (IMP Lanzhow) and LEIR (CERN) will be useful for new projects of high voltage coolers.

Scientific efforts in BINP and others laboratories promote the progress in development of new high-technology electron coolers for accelerator techniques. Authors are thankful to A.N.Skrinsky, M.Steck, D.Reistad, G.Trankvile, Y. Xiaodong and Wenlong for very productive discussions of new electron cooling systems.

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