ELECTRON COOLING OF PROTON BEAM IN COSY AND S-LSR

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Abstract

Brief review of experimental studies of the electron cooling of a proton beam at COSY (Juelich, Germany) and S-LSR (Kyoto) are presented. Intensity of the proton beam is limited by two general effects: particle loss directly after the injection and development of instability in a deep cooled ion beam. Results of the instability investigations and the methods of the instability suppression, which allow increasing the cooled beam intensity, are described. Recent attempts of proton beam ordering in both rings are presented and discussed as well.

This work is supported by RFBR grant # 05-02-16320 and INTAS grant #03-54-5584.

Keywords: Electron Cooling, Beam Stability, Beam Ordering. PACS: 29.20.Dh; 29.27.Bd

INTRODUCTION

Electron cooling method is widely used to increase an ion beam density in the six dimensional phase space. One of the general limitations of the ion beam intensity at electron cooling is related to development of different kind instabilities of the stored and cooled down beam. Such phenomena were observed at a few coolers beginning with well known experiments at CELSIUS (Uppsala, Sweden) storage ring [1]. This instability leading to decrease of the ion beam life-time in the presence of an electron beam was named "electron heating". An explanation of this phenomenon given in [2] assumes a specific coherent interaction of particles in electron-proton (ion) plasma which is formed by both electron and proton beams in cooling section. Later detailed studies of intense proton beam stability at electron cooling performed at COSY had shown more complicated nature of the instabilities in such a system [3]. At least three effects play a key role in the instability development: “initial”, or “fast”, losses in a freshly injected proton beam due to nonlinearity of proton betatron oscillations in the field of cooling electron beam (“single particle” effect), interaction of an intense proton beam with cooling electron beam (collective “plasma” effect, or “electron heating”) and influence of residual gas ions (RGI) stored in cooling electron beam. The methods of these instabilities suppression were developed and applied at a few storage rings. The results obtained at COSY and S-LSR are discussed in the report as well.

The experimental observation in the 1970s of Schottky noise suppression in a cooled proton beam by V.Parkhomchuk et al. in 1979 [4] has been never repeated in any other cooler-storage ring and remained a “puzzle”, because similar phenomenon called “beam ordering” has been observed with heavy and “middle” weight ions in ESR, SIS, CryRing. Attempts to resolve the problem were performed in 2005-2006 at COSY and S-LSR. The results are reported here.

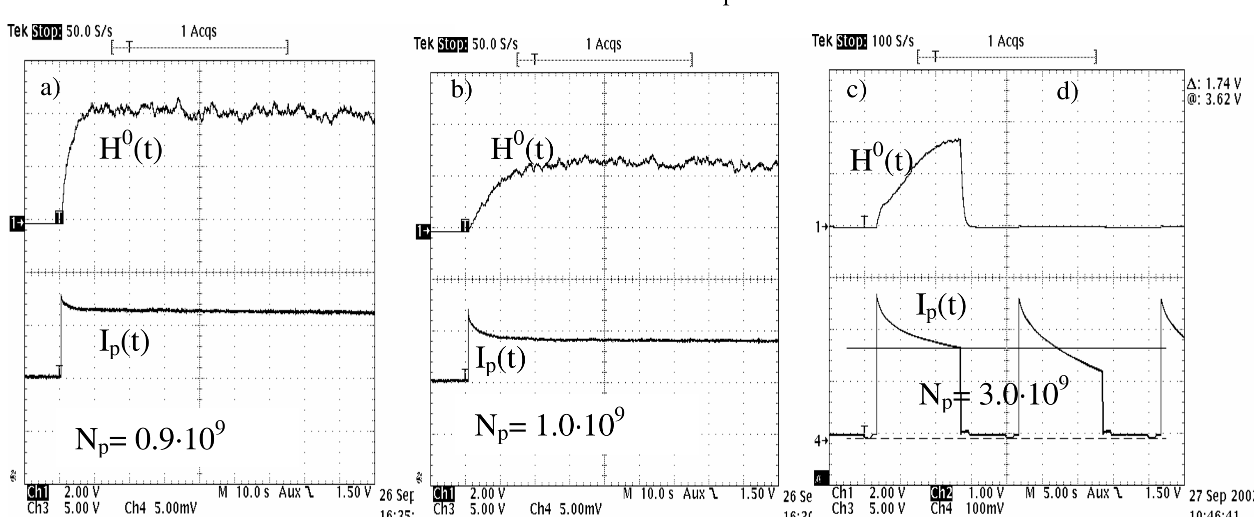

Figure 1: Dependence of neutral hydrogen flux $H^0(t)$ and proton beam current $I_p(t)$ on time at single injection shot in COSY at different injected proton number N_p and beam emittance values: $3\varepsilon_a \approx \varepsilon_b \approx \varepsilon_c$ when electron cooling is ON (a, b, c) and OFF (d, $H^0(t) \equiv 0$).

"INITIAL", OR "FAST", LOSSES

As experiments at COSY have shown the beam intensity loss rate at injection significantly increases with growth of the proton number N_p and the proton beam initial emittance ε (Fig. 1a, b, c) and electron current. The losses occur also when electron cooling is detuned (no cooling) but electron beam present in the ring (Fig. 1d). The proton loss rate is very sensitive to the ring sextupole magnets tuning that shows nonlinear character of proton oscillations.

COHERENT INSTABILITY

After injection at COSY the initial losses take place during first 5-10 sec of the cooling process (Fig. 2, the curve "a"). The cooling process is accompanied by H^0 generation in the cooling section (upper curves in the Fig.1) and H^0 count rate increases during initial particle loss. It reflects the fact that the lost particles have amplitudes of betatron oscillations larger than electron beam radius and weakly recombine with cooling electrons. The H0 count rate saturates at approximately the same moment as the proton beam intensity stabilizes. After about 10 seconds one can see beginning of coherent horizontal oscillations (Fig.2, curve "c") that does not lead to the particle loss. These dipole oscillations are accompanied with oscillations in longitudinal degree of freedom (not shown in Fig.2). These oscillations can be observed in the spectrum of the beam Schottky noise as well. After certain time the horizontal oscillations transform into the vertical ones (at t ≈ 18 s after injection in Fig.2, the curve "b" at t ≈ 18 s after injection in Fig.2), which cause the particle losses (the "dog-leg" in the curve "a"). It happens due to smaller vertical acceptance size.

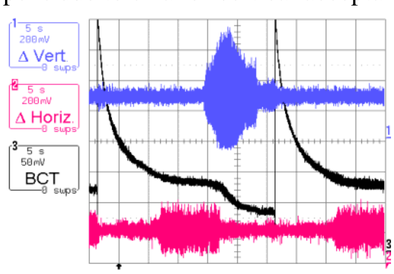

Figure 2: Rare repetition of injection at COSY (two shots are shown): proton beam (a) and signals of vertical (b) and horizontal (c) PU-monitors vs time (5 s/div).

Both described phenomena limit proton beam intensity at stacking [3].

ION CLOUD IN AN ELECTRON COOLING SYSTEM

As it was found in experiments at HIMAC and COSY [3], the residual gas ions (RGI) trapped in the electron beam of n_e density can partially neutralize its space charge field (neutralization coefficient η) that makes an influence on the coherent instability development. Cleaning the cooling electron beam from RGI was provided with so called "shaker method" - resonance exitation of RGI oscillations at the frequency

$$\omega = \sqrt{\omega_i^2(1-\eta)+\frac{\omega_B^2}{4}} \pm \frac{\omega_B}{2},$$

$$\omega_B = \frac{ZeB}{Am_p}, \quad \omega_i = \frac{Ze^2 n_e}{2Am_p} \qquad (1)$$

where Am_p and Ze are the ion mass and charge, B is the magnetic field in cooling section. This procedure allows to prolong the stable state of an intense and cooled proton beam before coherent losses start (Fig.3).

INSTABILITY SUPPRESSION

The "standard" method of coherent instability suppression is an application of feed back system (FBS). At COSY the vertical FBS made it possible to stabilize the cooled proton beam at a level of 2×10^{10} particles (1.8 mA) after a single injection. With the stacking technique a maximum of 1.2×10^{11} cooled protons (9.2 mA) at injection energy were stored without instability.

Applying additionally the horizontal FBS did not bring any essential effect. Application of FBS at S-LSR showed its very high sensitivity to proper choice of time delay between PU and kicker [5].

Another way to suppress instability is based on idea to avoid of "overcooling" of the beam core. 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. As it was demonstrated at CELSIUS, more effective way is an artificial increase of the electron beam energy spread by its modulation. Another method developed recently [6] and tested preliminary at LEIR is formation in the electron gun the hollow electron beam.

PROTON BEAM ORDERING

Experiments on proton beam ordering performed at COSY (2005-2006) and S-LSR (2006) have given very similar results. To compare them with the results of pioneering experiments at NAP-M and the experiments on heavy ion beam ordering at ESR the parameter - linear beam density in the particle rest frame multiplied by factor Z^2 [7] - is used (Fig.4):

$$\rho_{ordering} = \frac{\gamma Z^2 N}{C_{Ring}} \qquad (2)$$

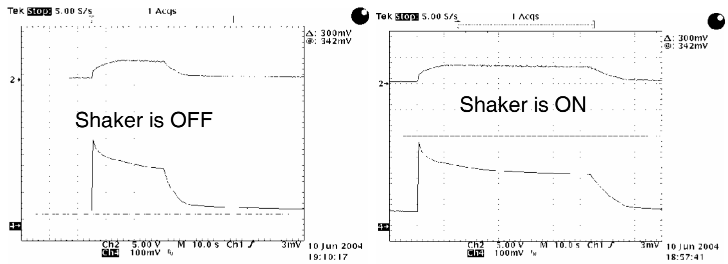

Figure 3: The shaker effect. Upper curves – $H^0(t)$, lower curves – $I_p(t)$.

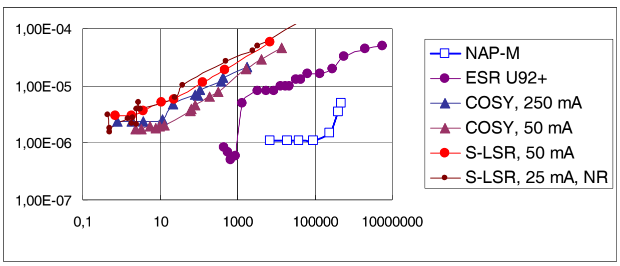

Figure 4: Comparison of the beam ordering experiments at NAP-M, ESR, COSY and S-LSR: particle momentum spread vs the "ordering parameter".

The comparison shows that the ordering state of the cooled proton beam was not formed in the experiments with protons beams, because no distinct and abrupt decrease of particle momentum spread and Schottky noise power (that is so typical for heavy ion beam behavior) have been observed *.

CONCLUSION

The experimental studies of electron cooling process at COSY have shown the limitation of the ion beam intensity due to a few phenomena related each to other. The methods of cooled beam instability suppression have been proposed and developed during recent years.

* After the report submission new experiment at S-LSR has shown a distinct "phase transition effect" in proton beam at $N_{proton} < 3\cdot10^3$

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