Instability phenomena of electron-cooled ion beams at COSY

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Abstract

At the cooler synchrotron COSY electron cooling is used after stripping injection of $H^-$ or $D^-$ ions in order to prepare phase-space-dense ion beams before acceleration to a requested energy. The electron-cooled beam has been successfully applied for specific external experiments. In addition, stacking of an electron cooled beam at injection could significantly increase the stored beam intensity. Transverse coherent instabilities due to beam–wall interaction occurring at higher intensities could be cured through chromaticity correction either by introducing more Landau damping or by applying an active transverse feedback system. This led to an increase in intensity and stability of a cooled beam.

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1. Introduction

The cooler synchrotron COSY \cite{1} delivers unpolarized and polarized protons and deuterons in the momentum range 300 MeV/c up to 3.65 GeV/c. Electron cooling at injection level and stochastic cooling covering the range from 1.5 GeV/c up to maximum momentum are available to prepare high precision beams for internal as well as external experiments in hadron physics. The beam is fed to external experiments by a fast kicker extraction or by stochastic extraction.

The achievable beam intensity is however limited by instabilities during the cooling process. Besides initial losses after injection \cite{2}, as long as the beam still has large emittances, the self-excitation of coherent betatron oscillations due to beam–wall interaction in the horizontal and vertical plane turned out to be the dominating beam loss mechanism.

In several machine runs the loss mechanisms have been studied and different cures have been tested: Operating the machine at different working points, controlling the chromaticity by sextupoles and applying a new transverse feedback system \cite{3}. A significant stable increase in beam intensity was found if the feedback system was employed during stacking. This improvement is especially important...
for internal experiments that run with polarized proton beams and long cycle times.

2. Chromaticity correction

It is known that below transition energy, as is the case at injection of COSY, the beam may become considerably unstable in the horizontal or vertical plane if the chromaticity $\tilde{\zeta} = (\Delta Q/Q)/(\Delta p/p)$ is positive [4]. The instability threshold not only depends on beam current and on the magnitude of the transverse machine impedance but also on momentum spread. To avoid beam losses the chromaticity should therefore be negative below transition [4]. An adjustment of the chromaticity can be accomplished with sextupoles, preferably those located in the arcs of COSY. The increased tune spread will then supply sufficient Landau damping to stabilize the cooled beam.

Fig. 1 shows two machine cycles during a physics experiment run. The injected proton beam ($\approx 2$ mA) with 293.8 MeV/c is electron cooled for 10 s and is then accelerated within 1.8 s to flat top momentum (FT) 2085 MeV/c. In the first cycle, a strong vertical oscillation occurs (Fig. 2) leading to beam loss immediately after injection. In this case, the tunes and chromaticities were measured after 8 s to be $Q_x = 3.587$, $Q_y = 3.696$ and $\tilde{\zeta}_x = -2.8$, $\tilde{\zeta}_y = 0.3$, respectively. Note, that this and all other measurements were made at an electron current 170 mA in 5 cm$^2$ electron beam area.

The corresponding transverse Schottky spectra in Fig. 2 were measured with a combined pickup for the horizontal and vertical plane. The electrodes were tilted around the longitudinal axis by 45° so that both horizontal and vertical betatron oscillations are simultaneously visible in one spectrum. The upper trace gives the linear spectrum at the instant marked in the figure by an arrow. Here, the horizontal tune is $Q_x = 3.609$. The lower trace represents Schottky power spectra versus time in a linear scale, the spectrogram mode. The gray level denotes the magnitude of the spectral lines.

The measurements were carried out at injection level, i.e., the measuring time is about 10 s. One
clearly observes strong vertical betatron oscillations just after injection leading to fast particle losses. They die out and horizontal oscillations come up responsible for a further slow beam loss as can be seen in Fig. 1. The horizontal tune is now shifted to $Q_x = 3.587$.

In the second cycle, the sextupole family mxg located in the arcs was only powered after injection until acceleration started with $1.7\%$ to shift the vertical chromaticity $\xi_y$ from +0.3 to -0.6 within 100 ms. By this means the coherent vertical betatron oscillations at injection could be significantly suppressed (Fig. 1). The stabilizing effect of the sextupoles is also obvious in the measured Schottky spectra (Fig. 3). It covers the same frequency span and the line spectrum (upper trace) is measured on the same scale as in Fig. 2. The vertical oscillations are strongly suppressed. The remaining horizontal oscillations, being significantly reduced in amplitude, are less harmful, leading to almost no beam loss, due to the larger horizontal size of the beam pipe and the lower beam emittance after cooling in both planes $\varepsilon_2 \approx 0.5 \mu m$.

The employment of sextupoles not only stabilized the cooled dense proton beam from cycle to cycle but also the beam intensity at flat top momentum could be doubled to $1 \times 10^{10}$ protons (Fig. 1).

3. Active transverse feedback

The new feedback system [3] to damp vertical betatron oscillations use one of the beam position monitors (electrostatic, diagonally cut) to measure the beam position deviation with 70 MHz bandwidth covering about 150 beam harmonics. This signal is delayed by means of a very well-shielded coaxial cable and fed into a 180$^\circ$ splitter. Two power amplifiers drive the stripline kicker wired in differential mode. Each of the downstream ports of the kicker is terminated with 50$\Omega$. The betatron phase advance from the pick-up to the kicker at typical tunes was about $97^\circ$.

The beam position monitor (BPM) signals of the vertical and horizontal plane are shown together with the BCT signal in Fig. 4 over a cooling duration of about 30 s. The figure clearly demonstrates an increasing strong vertical coherent betatron oscillation with a rise time of about 5 s that is accompanied by a significant beam loss. This oscillation dies out in about 10 s due to the decreasing beam intensity. The visible fast occurr-

Fig. 2. FFT spectrograms of the transverse Schottky noise recorded during the 10 s cooling before acceleration starts. The frequency covers the first three harmonics of the revolution frequency $f_0 = 488.25$ kHz. The longitudinal lines are visible because the COSY orbit is displaced at the Schottky detector. The horizontal and the vertical betatron sideband frequencies are $f_x$ and $f_y$, respectively. At the instant marked by the horizontal line in the spectrogram (lower trace) the tunes are $Q_x = 3.609, Q_y = 3.694$. The upper trace gives the line spectrum at that instant. The outset of the vertical oscillation corresponds to the first kink of the BCT curve in Fig. 1.
ring coherent horizontal oscillation here appears prior to the vertical instability (cf. Fig. 2) which is again less harmful.

Such a characteristic beam loss effect at COSY had been observed already in July 2001 during an electron cooling experiment run [5].

Fig. 3. FFT spectrograms of the transverse Schottky noise recorded during cooling before acceleration starts. The frequency covers the same frequency span as in Fig. 2. The sextupole family mXg is powered after injection within 100 ms from 0% to −1.7% keeping that value for the time of cooling. Before acceleration the sextupoles were turned off. As compared to Fig. 2, the strong vertical oscillations disappeared and the horizontal oscillations are significantly reduced leading to a stable and almost loss-free cooling and acceleration to flat top where the beam intensity is now doubled, Fig. 1, second cycle. The vertical chromaticity, measured at 8 s, is now negative, \( \xi_y = -0.6 \). The horizontal chromaticity has slightly changed from \( \xi_x = -2.8 \) to \( \xi_x = -2.4 \). The corresponding betatron tunes marginally moved to \( Q_x = 3.598 \) and \( Q_y = 3.636 \).

Fig. 4. Vertical/horizontal BPM \( \Delta \)-signals and BCT. Time scale is 5 s/div.
Fig. 5. BCT and $H^0$ count rate signals with feedback on and off. In this example the injected intensity and initial losses are larger due to different injection parameters [2].

Fig. 6. Stacking process over 320 s with feedback on and off. Here the single injection intensities were reduced to 0.4 mA to simulate the lower current from the polarized source (vertical axis BCT 200 mV/div, horizontal 50 s/div) [3].
The stabilizing effect of the vertical feedback action is clearly seen in Fig. 5. Without feedback the beam current drops nearly to zero due to the instability (horizontal line). It is illustrated that with feedback on for about 30 s at injection momentum the vertical instability is suppressed leading to a nearly stable 1.5 mA cooled proton beam current.

As compared with feedback off stacking the intensity at flat top momentum is now increased by a factor of four. However, the emittance at this attained intensity of about $5 \times 10^{10}$ protons is increased to about $\varepsilon_{2\sigma} \approx 3 \mu m$ (horizontal) and $\varepsilon_{2\sigma} \approx 6 \mu m$ (vertical) (Fig. 6).

4. Summary and conclusion

Detailed studies of instability phenomena leading to strong beam losses of an electron cooled beam have been carried out. Cures to stabilize and to enhance the cooled beam intensity have been successfully applied either by introducing sufficient Landau damping or by damping these coherent oscillations with an active feedback system.

Depending on the working points, however, a feedback system may be the presumably favored choice if the additional tune spread induced by sextupoles might lead to cross a harmful resonance in the tune working diagram.

References