NEW EXPERIMENTAL RESULTS ON ELECTRON COOLING AT COSY-JUELICH

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Abstract

Recent results of electron cooling of proton beams at COSY-Juelich are reported. Cooling at an electron energy of 70 keV has been studied for the first time. At the injection energy level of COSY, corresponding to 24.5 keV electron energy, the features of the cooled proton beam at extremely low intensities have been investigated in order to find out whether an ordering of the proton beam can be achieved. Such investigations are motivated by the results of a numerical simulation of the ordering process by the BETACOOL code.

INTRODUCTION

The COSY synchrotron accelerator and storage ring provides unpolarized and polarized proton or deuteron beams for internal or external hadron physics experiments in the momentum range from 300 MeV/c to 3.7 GeV/c [1]. Electron cooling is applied at low energies, preferably at injection energy, to prepare high-brilliance coasting beams to be used after acceleration and extraction for external experiments. Stochastic cooling, covering the momentum range from 1.5 GeV/c up to the maximum momentum, is used to compensate energy loss and emittance growth at internal experiments. The merits of the electron cooler for internal experiments, where duty cycle aspects are not as critical as in external applications, is the possibility to increase the ion beam intensity by a cooling-stacking process [2]. This procedure can be helpful in the cases of low-intensity ion sources or low-acceptance devices as storage cell targets.

The design of the existing COSY electron cooler represents the state-of-the-art in the eighties [3]. Originally, the COSY electron cooler had been designed for up to 100 keV electron energy. The capability to produce a 3 A, 100 keV electron beam was clearly demonstrated during the commissioning tests in 1992. At present, only 24.5 keV electron beam energy is necessary for the proton injection energy of 45 MeV. Electron beam currents in the range from 50 to 440 mA have been used for cooling tests. Higher electron currents are not useful because the advantage of shorter cooling times is foiled by drastically increasing proton beam losses [7]. Currents of 170 to 250 mA have turned out to be appropriate for the physics experiments. The typical cooling time of about 10 s can be tolerated in view of the duty cycle. Important diagnostic tools to adjust and characterize the cooling process are the beam current transformer (BCT), two x-y beam position monitors in the drift solenoid, a FFT vector analyzer with integrated storage capacity as a versatile instrument to analyze and record the time evolution of longitudinal or transverse Schottky spectra and a neutral particle (H^0) detector placed 24 m downstream of the electron cooler. Total H^0 rates and H^0 beam profiles in both planes are measured. The profiles represent the divergence of the ion beam at the electron cooler. Based on beta function values, emittances of the cooled beam can be determined.

ELECTRON COOLING AT 70 KEV ELECTRON ENERGY

Despite the fact that during the commissioning tests in 1992 100 kV/ 3 A electron beams were produced, HV sparking above 70 keV occurred in later years In September 2005 we tried successfully to operate the electron cooler at 70 keV in order to study the cooling process at higher proton energies.

Fig. 1 shows the behavior of proton beam current (lower curve) and H^0 rate (upper curve) observed in cycles of 2 min duration. The electron beam with a current of 250 mA was switched on only after the proton beam was accelerated from the injection energy level of 45 MeV to 129 MeV, corresponding to 70 keV electron energy.

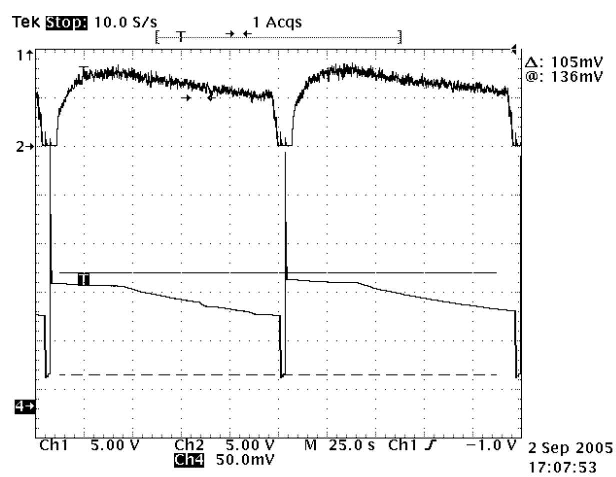

Figure 1: Electron cooling at 70 keV electron energy with 250 mA electron current. The electron beam is switched on only after the proton beam is accelerated and debunched. In contrast to cooling at injection energy, initial losses during the cooling process are negligible. However, more than 50% of the injected coasting beam is lost during bunching before acceleration. The remaining cooled beam intensity (lower curve) is 0.9 mA= $7x10^9$ circulating protons (a 100 mV BCT signal corresponds to 1 mA proton beam current). The corresponding H^0 rate (upper curve) is 2300 counts/s (10 V correspond to $3x10^3$ H^0 particles).

By definition, the cooling time is determined by the time when the H^0 rate reaches its maximum and the H^0 profiles reach their minimum width (Fig. 2), was about 25 s and of course longer than the 10 s, which are typical for cooling at injection [4]. Proton beam losses occurred in the first seconds due to bunching and acceleration, but there were practically no initial losses during the cooling process, which were always present when the proton beam is directly cooled after injection [4]. The continuous decrease of the proton beam intensity starting at about 40 s is due to a horizontal coherent oscillation after the beam is fully cooled. These oscillations are seen as betatron frequencies on the transverse Schottky FFT analyzer [5]. From time to time the horizontal oscillation jumped to the vertical plane but soon back to the horizontal plane (see also Fig. 4, second cycle). The stepping down of the proton current is due to these short periods of a vertical oscillation causing increased losses because the vertical acceptance in COSY is smaller than the horizontal one.

Without applying our feedback system [6], the instability could be avoided by i) reducing the electron current down to 130 mA (Fig. 3) or ii) by slightly misaligning the electron beam horizontally by 0.35 mrad (Fig. 4). Reducing the electron current resulted in a longer cooling time of about 50 s, the misalignment yielded a larger horizontal emittance as observed by the H^0 profile monitor (Fig. 5).

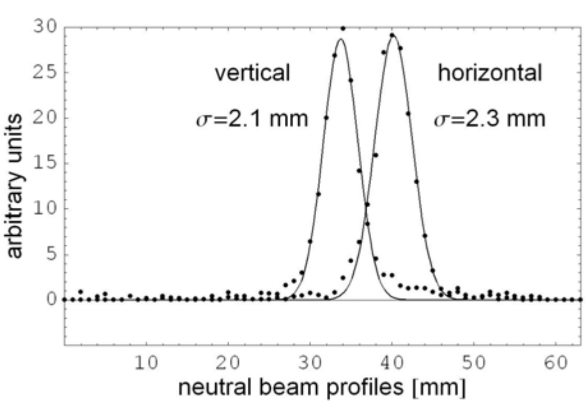

Figure 2: H^0 beam profiles corresponding to the well cooled beam in Fig. 1 measured at about 30 s after injection before onset of the horizontal oscillation. Lattice model based optical functions at the position of the electron cooler (β_x = 9 m, β_y = 18 m, D= -6 m) yield 2σ emittances of ϵ_x = 0.28 µm and ϵ_y = 0.35 µm.

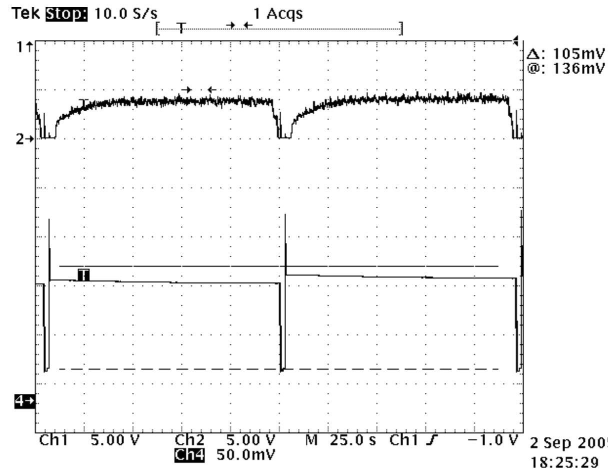

Figure 3: Electron cooling at 70 keV electron energy with 130 mA electron current. No coherent oscillations at all. The slight, exponential decrease of the proton intensity within the 2 min cycle is interpreted as single scattering beam loss due to the residual gas in the 183 m long COSY ring, which had a mean pressure of about $2x10^{-9}$ mbar.

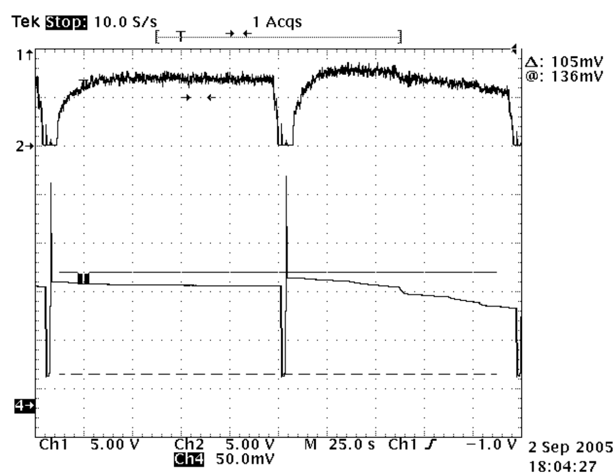

Figure 4: Electron cooling at 70 keV again with 250 mA electron current but in the first cycle with a slightly 0.35 mrad horizontally misaligned electron beam. No coherent oscillations at all. In the following cycle the misalignment was removed resulting again in coherent oscillations as observed by the betatron frequencies seen in the transverse Schottky signal.

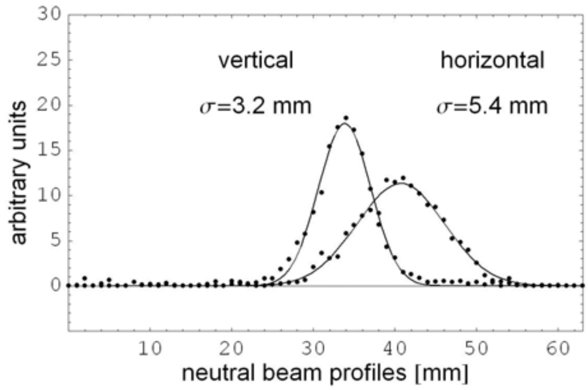

Figure 5: Horizontal and vertical H^0 profiles with a 0.35 mrad horizontally misaligned electron beam. Electron beam current 130 mA. Here, the 2σ emittances are ϵ_x = 1.6 μm and ϵ_y = 0.8 μm.

The proton intensity after acceleration without cooling electron beam is the same. Also here one sees a slight beam decrease due to single scattering losses but they are not of exponential nature as in Fig. 3 or Fig. 4. The reason is that the beam size grows due to multiple scattering with the consequence that the acceptance angle of the ring is getting smaller with increasing beam size. Obviously, the emittance growth due to multiple scattering is fully compensated by electron cooling maintaining a constant beam size.

Besides the details of the above observations we like to make an important conclusion in view of the "initial losses", cf. [4] and [7]. The fact that at 70 keV cooling no initial losses (of incoherent nature) were observed are a strong indication that right after injection the initial losses are caused by the large emittance (and large $\Delta p/p$) so that in this case the ion beam is larger than the electron beam. In the case of cooling after acceleration the ion beam has lost tails in ε and $\Delta p/p$ by the preceding bunching and shrinks during the acceleration

INVESTIGATION OF ORDERED BEAM FORMATION AT COSY

It is presumed that in a cooled beam the dependence of momentum spread on the ion number has a very specific character: at certain conditions the momentum spread suddenly drops down to very low value and remains constant with further decreasing ion beam intensity. Such a behavior is named beam ordering.

Simulations show that the ordered state should be observable if the proton number is less than 10^6 and the momentum spread is less than 10^{-6} [8].

The goal of the experiments is to achieve such an ordering of the proton beam.

Simulations with BETACOOL

At injection the COSY ring has parameters which are similar to the Novosibirsk NAP-M ring [9]. So COSY should be suited for the study of the ordering of proton beams. The main difference between the two rings is the super-periodicity of the lattice. NAP-M has the super-periodicity S = 4, but COSY has only S = 1.

The longitudinal components of intrabeam scattering (IBS) growth rates at COSY (Fig. 6a) are largely different from NAP-M. The longitudinal IBS component for COSY has a very specific island of growth rates in the range of the transition point to the ordered state. The same island was found in simulation for other ring with small super-periodicity. The physical reason for the existence of this island is not yet clear. The experimental verification of this behavior of IBS growth rates at low temperature of ion beams is a very interesting and important task. The numerical simulation with Molecular Dynamics techniques of the cooling process shows that the ordering state for COSY parameters can be reached if the proton beam has specific initial parameters: large transverse emittances and small momentum spread (Fig. 6c) [8].

If initial parameters of the proton beam do fit to the equilibrium temperature (upper points of the gray straight line on Fig. 6c) the proton beam reaches the equilibrium between cooling and heating and can not come into the ordered state region.

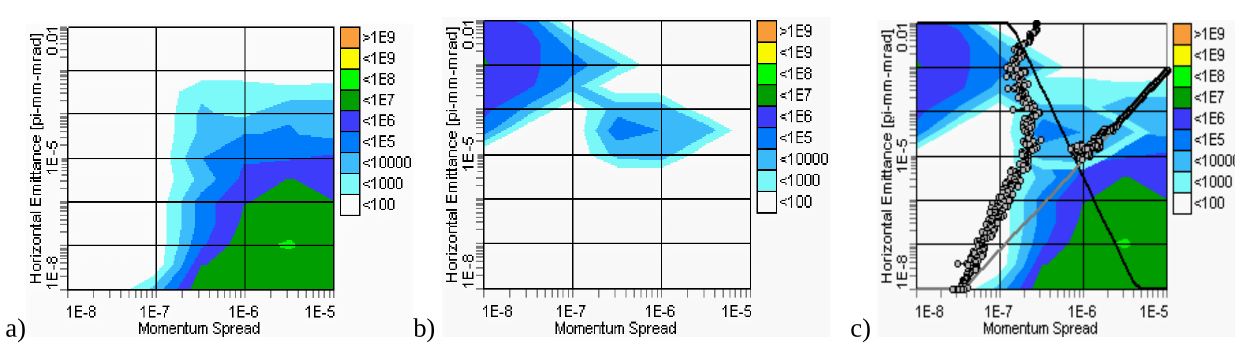

Figure 6: Growth rates (1/s) for COSY (Molecular Dynamics), $N_p = 10^6$.
a) horizontal component of IBS, b) longitudinal component of IBS, c) overlapping of a) and b) pictures and beam evolution during cooling process for different initial conditions.

Experiments

Here, we report on two cooling runs at COSY, one in August 2005, the second in March 2006. Electron cooling of the proton beam in COSY was performed with various electron beam current values (Fig. 7). The momentum spread was determined as FWHM (full width on half maximum) of the longitudinal Schottky signal as long as only one peak in the frequency spectrum is observed. This holds true for proton numbers below 10^8. At larger proton numbers the well known plasma waves propagating along the beam produce two more or less expressed peaks in the longitudinal Schottky spectrum. In this case a sophisticated method is needed to calculate the momentum spread.

The cooling experiments were done after a single injection into COSY. The initial proton number was about $2\text{-}5\cdot 10^9$. To speed up the process of proton losses the horizontal scraper was used, decreasing the ring aperture and, therefore, shortening the proton lifetime. After a few minutes the proton number reached a value less than 10^8 and the longitudinal Schottky signal showed up as a single peak. Then the scraper was taken out resulting in a longer lifetime enabling the measurements as a function of the proton number.

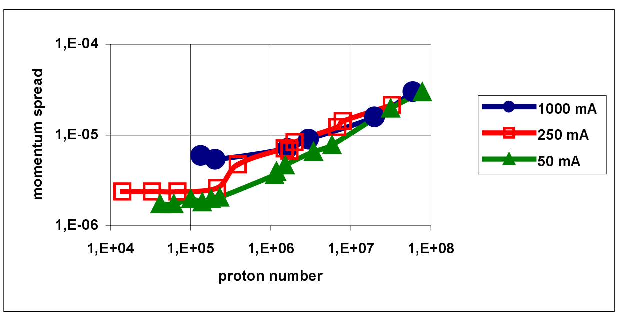

Figure 7: Cooling run 2005: Dependence of momentum spread on the proton number for different values of electron beam current (vacuum pressure 10^{-9} mbar).

When in the 2005 run the proton number reached the value less than 10^5 the momentum spread stopped to decrease and remained constant (Fig. 7). No sudden reduction of momentum spread was observed. We have to conclude that the proton beam did not achieve an ordered state under the conditions of the experiment.

In the cooling run 2006 we found the same qualitative behavior (Fig. 8). The dependence of the momentum spread is practically the same for electron beam currents in the range 168-487 mA (Fig. 8). However, there are important differences between the two runs. First, the minimum momentum spread was achieved for good vacuum conditions (Fig. 7). Second, the minimum momentum spread in the case of good vacuum is reached at a proton number of 10^5, in the case of poor vacuum at a proton number of 10^7.

It means that in the 2006 run the equilibrium was achieved between the electron cooling force and the scattering on the rest gas (Fig. 8). In the 2005 run the equilibrium was achieved between the electron cooling force and some other type of heating, presumably due to high voltage power supply ripple.

Third, the momentum spread for a proton number of 10^7 is less ($\Delta p/p = 4\cdot 10^{-6}$) for new measurements than for the old measurements ($\Delta p/p = 10^{-5}$). This fact supports the idea that using of additional transverse heating (from rest gas in our case) can decrease the momentum spread.

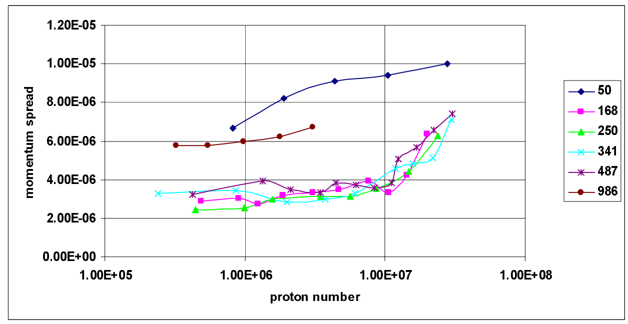

Figure 8: Cooling run 2006: Dependence of momentum spread on proton number for different electron beam current (higher vacuum pressure of 10^{-7} mbar in the target telescope section due to an air leak).

Results of COSY experiments are very similar to experiments at NAP-M [8]. They show that the minimum momentum spread depends on the value of the electron beam current (Fig. 9) and does not depend on the particle number in the range of small proton numbers below 10^5. It means that the equilibrium is defined by the properties (quality) of the electron beam when intrabeam scattering disappears.

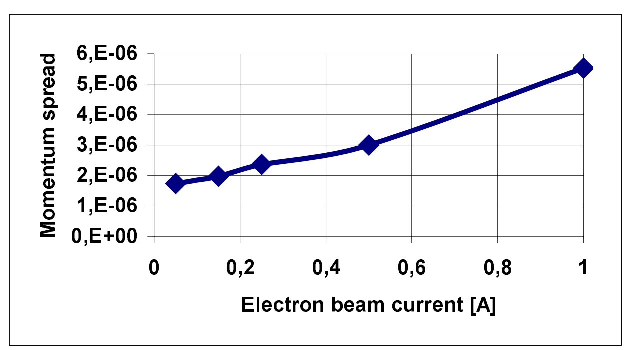

Figure 9: Dependence of minimum momentum spread on electron beam current.

DISCUSSION

The experimental studies with electron cooling at 70 keV electron energy indicate the reason for the fast initial losses which at COSY are always present when electron cooling is applied directly after injection. In contrast to the beam after bunching and acceleration, the proton beam size directly after injection is regularly larger than the electron beam diameter and is, therefore, exposed to electron beam field nonlinearities. A different explanation is related to plasma oscillations in the ion and electron beams, which may lead to big amplitude noise reducing the ion beam lifetime [10].

From simulations of the cooling process at COSY one should expect the transition to the ordered state at an rms momentum spread of about 10^{-6} and proton number below 10^6. The transition should occur when the equilibrium momentum spread is determined by the effective electron velocity spread only, and when other heating processes leading to longitudinal heating are negligible. To perform the transition at higher proton numbers one needs to provide large enough beam emittance, e.g., by additional heating of the beam in transverse direction. The obtained equilibrium beam parameters at COSY are close to the theoretical prediction for a transition of the proton beam into the ordered state. However, the sudden reduction of the momentum spread was not observed. Probably the minimum achievable momentum spread of the proton beam is determined by thermal equilibrium with cooling electrons. Earlier friction force measurements at COSY had indicated that the effective electron temperature lies in the range of a few meV.

The effective electron velocity spread is determined by the stability of the cathode voltage power supply and the straightness of the longitudinal magnetic field lines in the cooling section. At low electron currents the present stability of the cathode voltage corresponds to a longitudinal electron temperature below 0.5 meV. More probably that the electron beam effective temperature is restricted by the magnetic field inaccuracy which should be improved in the future experiments by using correction coils.

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