COMPENSATION OF MEAN ENERGY LOSS DUE TO AN INTERNAL TARGET BY APPLICATION OF A BARRIER BUCKET AND STOCHASTIC MOMENTUM COOLING AT COSY

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Abstract

The High Energy Storage Ring (HESR) of the future International Facility for Antiproton and Ion Research (FAIR) at the GSI in Darmstadt will be built as an antiproton cooler ring in the momentum range from 1.5 to 15 GeV/c. An important and challenging feature of the new facility is the combination of phase space cooled beams with internal targets. Theoretical investigations have demonstrated that the strong mean energy loss due to an internal target can not be compensated by cooling alone. A barrier bucket cavity can be used for mean energy loss compensation while cooling will reduce the momentum spread. Experimental results at COSY to compensate the large mean energy loss induced by an internal pellet target similar to that being used by the PANDA experiment at the HESR with a barrier bucket cavity (BB) will be presented. Experimental cooling results using the Time-Of-Flight (TOF) method are shown in comparison with Filter cooling. TOF cooling is found to be very effective to cool the momentum spread prior to Filter cooling. Main focus of attention is the presentation of the experimental results.

HESR BEAM REQUIREMENTS

The High-Energy Storage Ring (HESR) [1] of the future International Facility for Antiproton and Ion Research (FAIR) at the GSI in Darmstadt will be built as an antiproton cooler ring in the momentum range from 1.5 to 15 GeV/c. Two operational modes will be available for the users. A pellet target with a thickness of $4 \cdot 10^{15}$ atoms cm^{-2} provides the high luminosity mode (HL) with 10^{11} antiprotons yielding the required luminosity $2 \cdot 10^{32}$ cm^{-2} s^{-1}. The HL-mode has to be prepared in the whole energy range and beam cooling is needed to particularly compensate beam heating by the beam-target interaction. Much higher requirements have to be fulfilled in the high resolution mode (HR) with 10^{10} antiprotons. The same target thickness yields here the luminosity $2 \cdot 10^{31}$ cm^{-2} s^{-1}. This mode is requested up to 8.9 GeV/c with an rms-relative momentum spread down to about $4 \cdot 10^{-5}$.

Both, transverse and longitudinal cooling is foreseen at the HESR. Transverse cooling is mainly applied to compensate a transverse beam blow up due to the beam-target interaction. The highest demands are made on longitudinal cooling, especially in the HR-mode. To fulfil this goal the bandwidth of the cooling system will be increased from (2 – 4) GHz to (2 – 6) GHz in the final stage. High sensitive pickup/kicker structures are being developed and tested at COSY [2]. The filter cooling technique [3] is applied for longitudinal cooling in the momentum range above 3.8 GeV/c. Below 3.8 GeV/c the Time-Of-Flight momentum (TOF-) cooling technique [4] will be used.

MOMENTUM COOLING METHODS

In the Filter cooling method a pickup in sum mode measures the beam current and the discrimination of particles with different momentum deviations is obtained by inserting a notch filter in the signal path before it drives a kicker in sum mode. The advantage of this method is that Schottky particle noise is substantially suppressed in the centre of the particle momentum distribution. A severe restriction in the practical cooling bandwidth comes from mixing between pickup and kicker. Large mixing from pickup to kicker will reduce the maximum momentum spread that can be cooled for a given upper cooling frequency without particle losses. Strong unwanted mixing from pickup to kicker especially prevents filter cooling below 3.8 GeV/c in the HL-mode. In the low momentum range 1.5 GeV/c up to 3.8 GeV/c TOF cooling is therefore envisaged. In this method the filter in the cooling chain is removed and the signal transit time from pickup to kicker is adjusted to the time-of-flight of a particle with nominal momentum. Mixing from pickup to kicker can now be used to discriminate between particles of different momenta. This method attains a larger cooling acceptance which is especially preferable for the HL-mode. Larger initial momenta can thus be cooled without particles losses. The main disadvantage of this method is however that due to the absence of the notch filter strong particle noise diffusion occurs in the distribution centre. The gain of the cooling system should be then reduced to avoid too much Schottky heating in the center of the distribution. Beam equilibrium values are consequently larger as for filter cooling.

MOMENTUM COOLING EXPERIMENTS

At COSY momentum as well as transverse cooling is available. The system consists of two bands. Band I covers the frequency range (1 – 1.8) GHz and band II the range (1.8 – 3) GHz. The pickup and kicker electrode bars are movable to achieve a maximum in sensitivity. In these experiments only momentum cooling in band II is considered. The proton beam was accelerated to 2.6 GeV/c. To avoid transition crossing during acceleration the optics in the arcs is manipulated so that the transition energy is shifted upwards. When the flat top momentum is reached the acceleration rf-cavity is switched off and the optics is changed again so that now the machine is operated above transition energy. By this both straight sections of COSY attain zero dispersion. The pellet target of the WASA installation [5] is located at a dispersion free position in the target straight section. A flat top time of about 1000 was chosen and the particle number was about 1 to 2 $\cdot 10^9$.

TOF and Filter Cooling

Beam transfer function measurements have been carried out to optimize the gain and the delay of the momentum cooling system when the internal target was switched off and no cavity was operated. An example of an open loop gain measurement at harmonic number n = 1367 is shown in figure 1 for TOF-cooling operation.

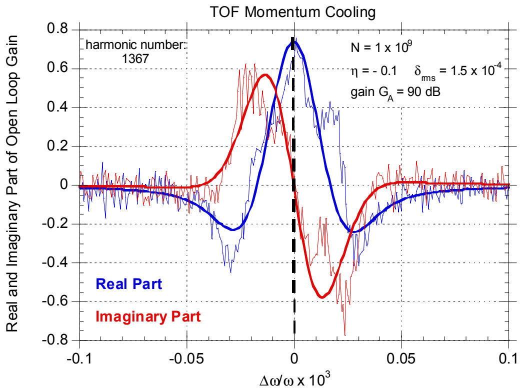

Figure 1: Open loop gain at n = 1367 for TOF cooling.

The imaginary part has a zero crossing and negative slope as desired for cooling. The real part is not zero as compared to filter cooling [6]. As a consequence Schottky noise heating is not suppressed in the center of the distribution. In comparison to the measurement a simulation result from a Fokker-Planck equation model [7] is shown in good agreement.

In order to benefit from TOF cooling the initial momentum spread of the beam was then increased from $\delta_{rms} = (\Delta p / p)_{rms} \approx 1 \cdot 10^{-4}$ to $\delta_{rms} = 1 \cdot 10^{-3}$ by applying band-limited white noise ($\Delta W = 500\,\mathrm{Hz}$) at harmonic number one with a momentum kicker. The nearly rectangular beam distribution was cooled with the TOF cooling method as depicted in figure 2. The figure shows the initial particle density at harmonic number 1000 as well as at time t = 200 s and 900 s where the beam is close to equilibrium. It is visible that the initially unsymmetrical distribution became more symmetric when the cooling time proceeded. The variance of the distributions exhibits an exponential decrease towards an equilibrium value $\sigma^2 = 805\,\mathrm{kHz}^2$. A relative momentum spread $\delta_{rms} \approx 1 \cdot 10^{-4}$ is deduced with the measured frequency slip factor $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2 = -0.1$.

In the above measurements the delay was adjusted so that the beam could be kept nearly at the center of the initial distribution. The measurements showed that a delay length change of 7.5 mm (≈ 30 ps delay change) resulted in a negative shift of the center of the equilibrium distribution of -150 kHz corresponding to the negative frequency slip factor.

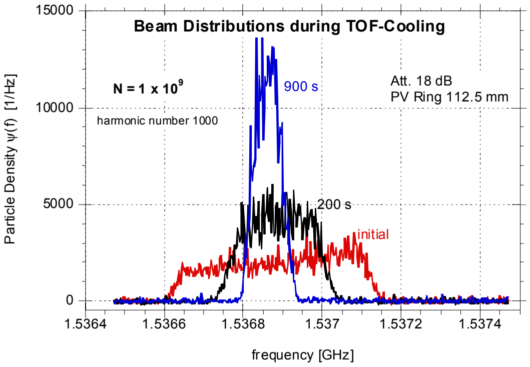

Figure 2: Particle densities at n = 1000 during TOF cooling.

In accordance to theoretical predictions this shift turned out to be linear in a delay change. This method allows to adjust the beam momentum in a range of $\delta \approx 1 \cdot 10^{-3}$.

In the next experiments the beam was initially heated by applying band-limited white noise with $\Delta W = 700\,\mathrm{Hz}$ at harmonic number one in order to show the larger cooling momentum acceptance of TOF cooling as compared to Filter cooling. In figure 3 the result of only Filter cooling is displayed. After 200 s the distribution is cooled but exhibit still tails towards lower and higher frequencies. This indicates that Filter cooling is more effective in the center. Particles with lower or higher frequencies in the tails see a wrong sign in the cooling force and are driven further out of the center.

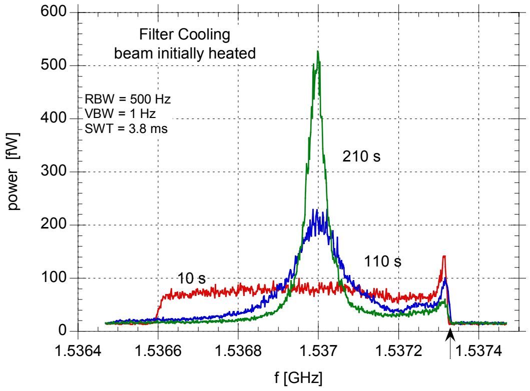

Figure 3: Filter cooling of an initially heated beam.

As a result a part (28 %) of the beam particles in the tails is heated by the cooling system and is lost at the momentum acceptance of the machine.

At 1.53734 GHz a small peak (see arrow in figure 3) is visible which is due to a vanishing local frequency slip factor. The available particle frequency attains here a maximum value. Particles which loose energy due to the heating can not have frequencies beyond that value. They enhance the density in the vicinity of this value leading to asymmetric distributions. As seen in figure 3 the tails are reduced by cooling and heating as time proceeds.

In order to avoid initial particles losses the beam was pre-cooled with the TOF method for 200 s. After pre-cooling the cooling system was switched to Filter cooling: The Filter part that contains the delay by one revolution was closed and the gain was inverted.

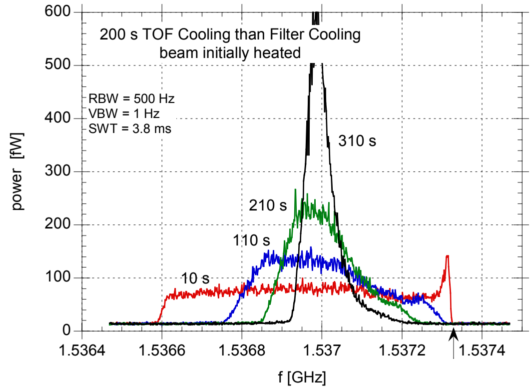

Figure 4: Power spectra at n = 1000 during cooling. The beam is pre-cooled with TOF cooling for 200 s. Cooling is then switched to the Filter cooling method.

The result is shown in figure 4 where one observes that the tails are reduced by only cooling. Particles are moved to the center during pre-cooling (t = 210 s). Also the particle enhancement at the small peak is reduced by TOF cooling. In this case almost no particle losses were observed. The final relative momentum spread after 900 s of cooling was $1 \cdot 10^{-4}$ (FWHM).

Filter Cooling with Synchrotron Motion

Theoretical predictions [7] have shown that the mean energy loss due to the beam-target interaction can be compensated by a barrier bucket cavity. Experimental tests of stochastic momentum cooling of particles subject to the synchrotron motion induced by a barrier bucket [2] or h = 1 cavity have been therefore carried out. Figure 5 compares from top to bottom Filter cooling without synchrotron motion and cooling with a barrier bucket cavity and the h = 1 cavity operation.

The maximum available barrier bucket peak voltage $U_0 = 175\,\mathrm{V}$ was used. The h = 1 cavity was operated with $U_0 = 200\,\mathrm{V}$. The target was switched off for this study. Figure 5a shows Filter cooling of the initially not heated beam. A significant cooling is visible after 310 s. The filter frequency is slightly above the initial center frequency. The influence of the synchrotron motion of the protons in a barrier potential becomes visible in figure 5b. After 310 s the beam width is reduced by cooling. The resulting width is however broader as compared to only Filter cooling in figure 5a. While in figure 5a the filter determines the center of gravity of the distribution it is determined by the barrier frequency.

Momentum cooling becomes less effective with synchrotron motion induced by the h = 1 cavity. Particle losses occur and the momentum spread is only slightly reduced (figure 5c).

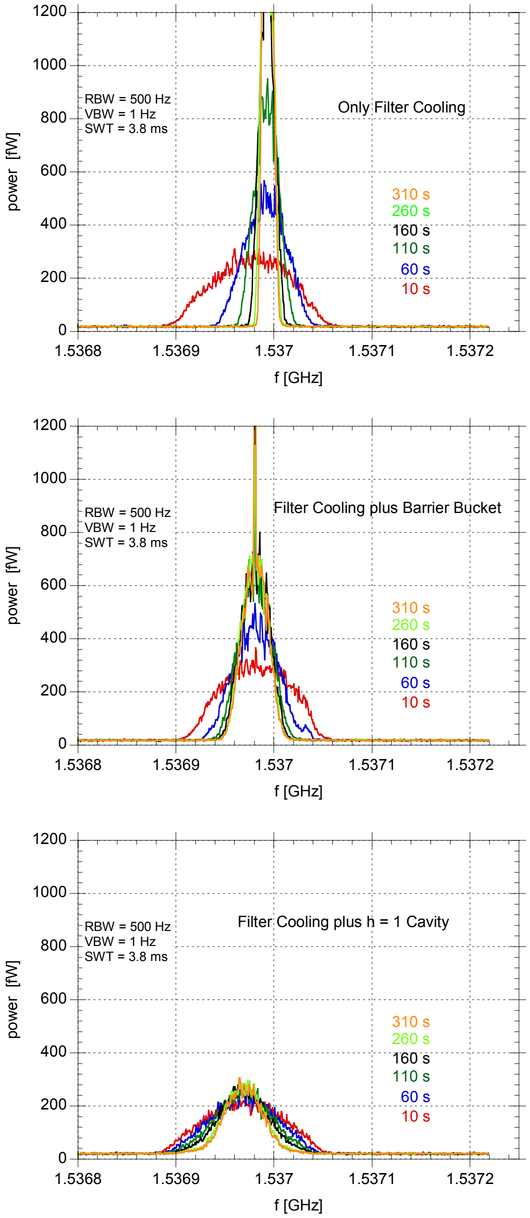

Figure 5: Filter cooling without/with synchrotron motion.

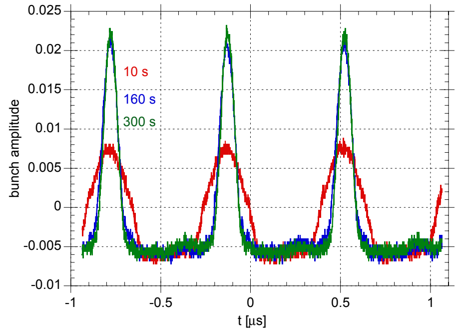

Figure 6: Bunch evolution during Filter cooling.

While in the barrier bucket case the bunch is nearly DC the beam is bunched when the h = 1 cavity is operated. The bunches become shorter during cooling (figure 6).

Mean Energy Loss Compensation

First the mean energy loss in the pellet deuterium target of the WASA installation [5] has been deduced by measuring the linear time dependence of the frequency shift of the spectral Schottky line at n = 1000. The mean energy loss ΔE is determined from a measurement of the linear frequency shift per unit time and the frequency slip factor $\eta = 1/\gamma^2 - \alpha$: $\Delta E \approx$ -12 meV/turn. The effective target thickness is then calculated with the Bethe-Bloch formula yielding $N_T \approx 2 \cdot 10^{15} \text{atoms}/\text{cm}^2$. The target thickness is thus comparable to that in the PANDA experiment at the HESR. The cooling result is displayed in figure 7. The target is switched on at t = 14 s. The barrier extends from 1.53692 GHz to 1.537015 GHz. It is seen that at t = 10 s a fraction of 29 % of the particles visible as a hump are outside the barrier. At t = 110 s this hump becomes smaller and is moved closer to the center. At the same time the density in the barrier is increased (figure 8) and the width of the distribution is reduced by cooling. For t > 300 s the peak density attains a maximum for a while and then drops down. The maximum is reached when the particle losses start to become stronger than the increase in peak density due to cooling, figure 8. Figure 7 shows that the particles losses can only be due to a transverse emittance increase caused by the beam-target interaction. Particle losses in the longitudinal phase space would be visible in a similar enhancement of particles as in figure 3 at frequency 1.5374 GHz, see arrow in figure 7. Note that the center of gravity of the distributions keeps the same which means that the mean energy loss is compensated.

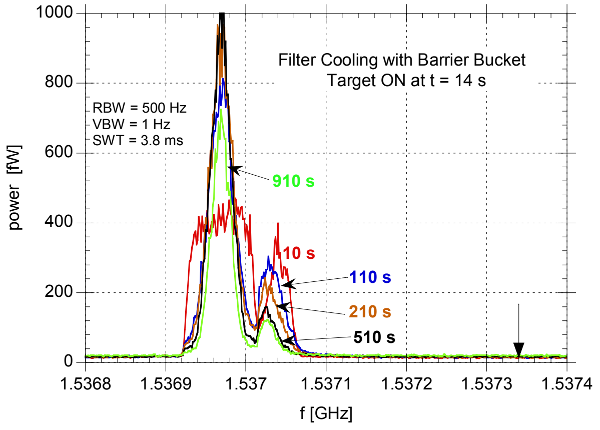

Figure 7: Power spectra at n = 1000 during Filter momentum cooling and barrier bucket operation. The pellet target is switched ON at t = 14 s.

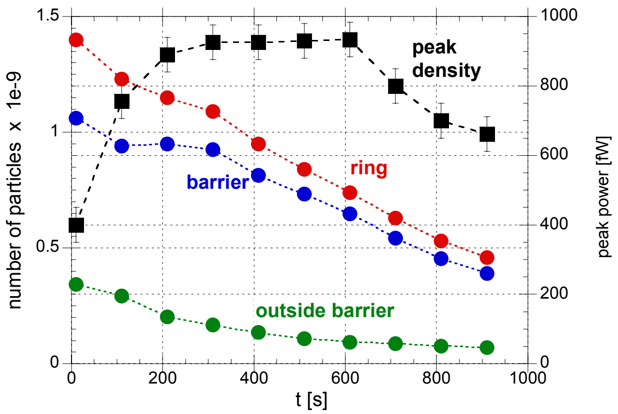

Figure 8: Peak power of particles in the barrier, number of totally stored particles and stored particles in as well as outside the barrier region during cooling.

SUMMARY AND OUTLOOK

The experiments have verified that the TOF cooling method as theoretically predicted is feasible and can be successfully applied to reduce the initial momentum spread for Filter cooling. The Filter or TOF technique for a proton beam with synchrotron motion induced either by a barrier or a h = 1 cavity has been investigated experimentally. Cooling with a barrier bucket turned out to be more efficient since the beam is similar to a DC-beam. The barrier bucket cavity was applied to compensate the mean energy loss induced by the WASA pellet target with a thickness comparable to that in the PANDA experiment at the HESR. The beam momentum spread could be cooled but particle losses probably caused by a transverse emittance increase reduced the life time of the beam. Further experimental and theoretical investigations are necessary to gain experience and to determine the optimal barrier voltage and cooling system quantities.

REFERENCES

[1] HESR, “Baseline Technical Report”, http://www.fz-juelich.de/ikp/hesr/2-11-HESR.pdf, and update April 2008

[2] R. Stassen et al., “COSY as Ideal Test Facility for HESR RF and Stochastic Cooling Hardware”, PAC09, Vancouver, Canada, May 4-8, 2009

[3] D. Möhl et al., Phys. Rep. Vol. 58, No.2, Feb. 1980

[4] W. Kells, “Filterless Fast Momentum Cooling”, Proc. of the 11th Int. Conf. on High-Energy Accelerators, Geneva, Switzerland, July 7-11, 1980, p. 777

[5] C. Ekstroem et al., Nucl. Instrum. Meth. Phys. Res. A 371, 572-574 (1996)

[6] J. M. Brennan et al., “Bunched Beam Stochastic Cooling at RHIC”, COOL07, Bad Kreuznach, Germany, Sept. 10-14, 2007, p. 25

[7] H. Stockhorst et al., “Stochastic Cooling for the HESR at the FAIR Facility”, PAC09, Vancouver, Canada, May 4-8, 2009