THE STOCHASTIC COOLING SYSTEM AND ITS APPLICATION TO INTERNAL EXPERIMENTS AT THE COOLER SYNCHROTRON COSY

R. Stassen, U. Bechstedt, J. Dietrich, K. Henn, A. Lehrach, R. Maier, S. Martin, D. Prasuhn, A. Schnase, H. Schneider, H. Stockhorst, R. Tölle, Forschungszentrum Jülich GmbH, D-52425 Jülich

Abstract

The COSY stochastic cooling system operates in the frequency range from 1 to 3 GHz divided into two bands, I: 1 to 1.8 GHz and II: 1.8 to 3 GHz. All components are installed and have come into operation. Two pickup tanks each 4 m long for the horizontal and vertical plane are available. They are cryogenically cooled down to nearly 60 K to increase the signal-to-noise ratio especially at low proton numbers. Uncooled preamplifiers having a noise temperature below 50 K are mounted outside the vacuum tanks. The positions of the electrode bars are independently adjustable. Programmable delays permit a momentum adjustment from 1.5 GeV/c to the maximum momentum of 3.3 GeV/c. Two kicker tanks of length 2 m are installed for the horizontal and vertical plane, respectively. Similar to the pickups the electrode bars are independently movable. An adjustable notch filter is available for longitudinal cooling. We report on gain adjustments and computer-controlled BTF measurements to optimise the phase. Cooling in all phase space planes of a beam with up to $2*10^{10}$ protons at about 2.6 GeV/c is discussed. The beam quality enhancement for an internal gas target experiment is presented.

1 FIRST RESULTS OF THE STOCHASTIC COOLING SYSTEM

We've started to adjust the stochastic cooling system of COSY at the beginning of 1997. The first results have been documented by the capability of the internal experiment EDDA [1]. This experiment is able to measure directly the vertical profile of the COSY beam. A beam of $2*10^9$ protons at 2.6 GeV/c has been cooled using the vertical Band I system only. The beam diameter has been reduced from initially 3 mm (FWHM) to 0.8 mm. The cooling time to reach this final value was about 1200 s, gain and phase were only roughly set.

After optimising the cooling system we reached cooling times at different momenta as aspected by the theoretical calculations. Some results are presented in table 1.

Momentum	p = 3,39	p = 2,6	GeV/c
Revolution frequency	f_0 = 1,6	f_0 =1,5355	MHz
Width of the frequency distrib.	Δf_0 = 54	Δf_0 = 147	Hz
Phase slip factor	η = -0,08	η = -0,1	
Number of protons	$1,5*10^{10}$	$4*10^9$	
Bandwidth of the cooling system	W = 800	W = 800	MHz
Mixing	M = 43	M = 15	
optimum cooling time τ_{opt} = N*M/W	τ_{opt} = 780	τ_{opt} = 80	s
measured signal suppression	SS = 4	SS = 3	dB
measured cooling time	t > 750	t = 90-100	s

Table 1: stochastic cooling times

In order to remotely adjust the system we used the possibility to tune the phase and amplitude measuring a list of definite parameters. The stochastic cooling system consists of about 100 amplifier and about 120 additional active RF components. Each component and each connection of different components has been tested with respect to amplitude and phase behaviour over the desired frequency range. A beam-simulation set-up has been used to measure the signal sensitivities of the beam coupling structures and the signal transmission within the cooling tank. After installing all cooling tanks into the COSY ring, we have begun the optimisation by adjusting the electrical lengths of the cooling system, regarding the resulting phase difference between beam and cooling system and the open and closed gain of the cooling system

2 BEAM TRANSFER FUNCTION

Stochastic cooling of the COSY beam requires adjustments of electrical lengths and gains in the order of 10^{-5}. Therefore a series of individual transfer-function measurements with and without beam were performed.

The measurements of the transfer function of the RF hardware without beam (HTF) showed no deterministic signal [2]. This confirms that the ferrite attenuators installed in the cooling tank end elements and along the beam coupling structures are sufficient.

The measurements of the transfer functions with beam (BTF) present mainly the betatron sidebands. The RF signals of an network analyser excited the beam at the kicker station. At the pickup station we have measured the beam response including the whole RF signal path of the cooling system. We have generated a computer program to measure a series of betatron sidebands in the desired frequency range. The program automatically determines the phases and amplitudes of the betatron sidebands and plots the phase behaviour over all sidebands. Linear increases or decreases of the phases in respect to the frequency range is caused by an unmatched electrical length between pickup and kicker.

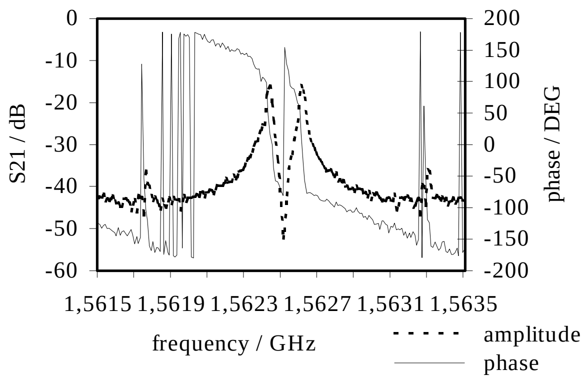

Fig. 1: Beam Transfer Function

After adjusting this length we got a nearly constant phase behaviour over the whole frequency range reaching nearly the optimum phase without further phase shifting.

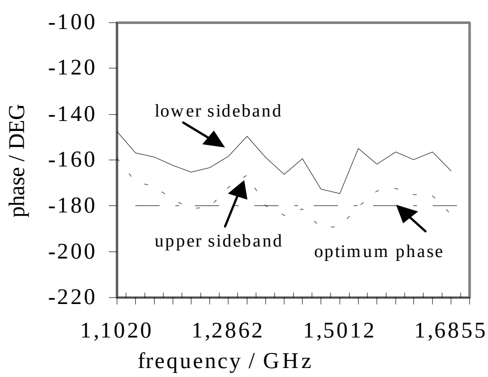

Fig. 2: phase behaviour of betatron sidebands

The ion-optical phase advance $\Delta\mu$ between pickup and kicker is ideally an odd multiple of 90°. Deviations of this value could directly be measured as a phase difference between the upper and lower sidebands. The phase difference $\Delta\Phi$ is related to the phase advance $\Delta\mu$ by $\Delta\Phi = 2\Delta\mu+180°$ modulus 360°. If the phase advance $\Delta\mu$ is exactly an odd multiple of 90° both curves collapse.

A simplified expression for betatron cooling of N protons can be derived if all betatron sidebands in the cooling band have identically weighting function. In this case, each term can be added to give the cooling rate $1/\tau$ for the emittance ε [3].

$$\frac{1}{\tau} = \frac{1}{\varepsilon}\frac{d\varepsilon}{dt} = \frac{W}{N}\left\{2\frac{g}{1+g/g_0} - \left(\frac{g}{1+g/g_0}\right)^2 (M+U)\right\}$$

thereby g: open loop gain, $g_0=2/M$.

The bandwidth of the cooling system is W. The mixing factor M is estimated by

$$M = \frac{3}{4}\frac{f_0}{W * |\eta| * \delta} \quad \text{where} \quad \eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^{\ 2}}$$

and δ denotes the relative momentum spread of the protons. The gains of the systems have been adjusted by measuring the open/closed loop signal suppression. If the cooling loop is open the spectrum analyser will measure the peak power S_{open}. If the cooling loop is closed S_{open} will change to S_{close} by feedback via the beam. The measured ratio S_{open} / S_{close} gives the signal suppression SS. The normalized system gain $x=g/g_0$ can be directly measured by observing this signal suppression SS [dB] = 10 lg (S_{open} / S_{close}) = 20 lg (1+x). In our case with M>>U we get an optimum cooling rate:

$$\frac{1}{\tau_{opt}} = \frac{W}{N * M}$$

This optimum cooling rate is reached if we were measuring a signal suppression of 6 dB.

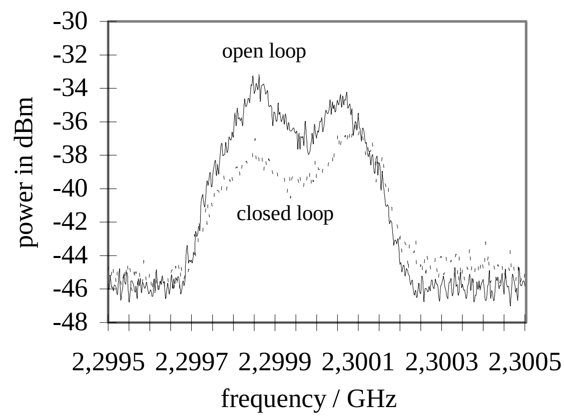

Fig. 3: open/closed loop signal suppression

Fig. 3 represents a signal suppression measurement of the vertical band II system. The system gain could be further increased to get the desired signal suppression of 6 dB.

3 CHROMATICITY MEASUREMENTS USING THE STOCHASTIC COOLING TANKS

Besides beam cooling, the pickups of the stochastic cooling system are used to determine the revolution frequency and the tune of the beam. Precision measurements of the betatron sidebands deliver the chromaticity in the following way :

If the fractional part of the tune is >0.5 (in the normal operating point of COSY), we can write for the upper and lower sidebands between the n and n+1 harmonics:

$f_- = (n+1-q_0) * f_0$ (lower sideband)

$f_+ = (n+q_0) * f_0$ (upper sideband)

f_0 denotes the revolution frequency. The widths of the sidebands could precisely be measured by the installed spectrum analyser. The widths of the sidebands are given by:

$|\Delta f_-| = |\{(n+1-q_0) * \eta - Q'\}| * f_0 * |\delta|$ (lower sideband)

$|\Delta f_+| = |\{(n+q_0) * \eta + Q'\}| * f_0 * |\delta|$ (upper sideband)

$Q' = Q_0 * \xi$ $\qquad$ Q_0: Tune, ξ: Chromaticity

We use the band I systems of the horizontal and vertical stochastic cooling pickups at a working frequency range of 1-1.8 GHz. At these high frequencies the expressions simplify to:

$|\Delta f_-| \approx |\, n * \eta - Q' \,| * f_0 * |\delta|$ $\qquad$ (lower sideband)

$|\Delta f_+| \approx |\, n * \eta + Q' \,| * f_0 * |\delta|$ $\qquad$ (upper sideband)

The optics of COSY have been adjusted to zero dispersion in the telescopes. This procedure crosses γ_{tr} at the fixed actual momentum and leads to a negative η value. The control program automatically measures the maximum frequencies f+ and f- and the widths of the betatron sidebands at a chosen harmonic n as well as the width of the harmonic itself. If the value of η is known we can determine the chromaticity in the following way:

$$\xi = \eta \frac{|\Delta f_+| - |\Delta f_-|}{2|\Delta f_0|} \frac{1}{Q_0} \quad ,$$

herein $Q_0 = 3+1/2*\{1+(f_+-f_-)/f_0\}$ is the normal COSY working point.

4 BEAM QUALITY ENHANCEMENT CAUSED BY LONGITUDINAL COOLING

Originally COSY had been planned for transverse cooling and longitudinal cooling as a future option. The vertical band I system has been installed with the possibility to switch between difference and sum mode of the pickup as well as of the kicker tank. This allows to use the vertical band I system for longitudinal cooling too. Both Hereward/Palmer [4,5] and Thorndahl/Carron [6] cooling methods were envisaged therefore. The characteristics of betatron and dispersion function at the installing position enabled only the filter cooling method. This method uses a filter between the preamplifier and the power amplifier having notches at all harmonics in the passband. The adjustments of the longitudinal signal path has been made in the same way as for the transversal cooling. The optimum phase in the center of the revolution harmonic is now zero degree [7] measured without notch filter. Besides momentum cooling the longitudinal cooling system was successfully used to compensate the energy loss of the beam caused by the internal gas target of the experiment COSY11 [8, 9]. The cycle length has been increased up to 60 min, only 7% of the protons were lost. Fig. 4 shows the resulting Schottky scan at the 2nd harmonic over the whole cycle. On the abscissa the frequency (proportional to momentum) is plotted. The momentum was 3.24 GeV/c with a proton number of 10^{10}. Without cooling the distribution would be shifted upwards in frequency due to the energy loss in the target.

However, the right hand side of the distribution is not affected because cooling which tends to decrease the frequency is in balance with the upwards shift in frequency due to the energy loss. The left hand side is compressed since cooling and energy loss increase the frequency. After 20 min the equilibrium is attained and the shape of the distribution remains unchanged until the end of the spill.

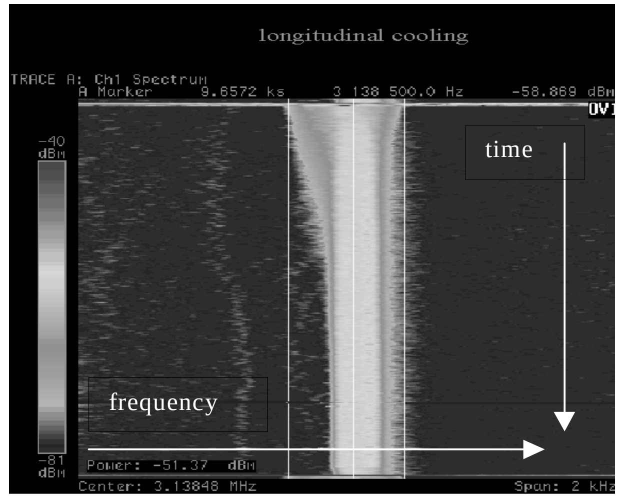

Fig. 4: longitudinal Schottky scan with cooling

Using stochastic cooling it is now possible to increase the cycle length to more than 1h and thereby the duty factor significantly. COSY is only be refilled for a next spill due to losses coming from reactions between target and proton beam.

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