STOCHASTIC COOLING OF A POLARIZED PROTON BEAM AT COSY

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Abstract

Future experiments at COSY with vertically polarized proton beams and internal targets at beam momentum larger than 1.5 GeV/c require stochastic cooling and barrier bucket operation to compensate the strong mean energy loss and beam momentum dilution due to the beam-target interaction. At the same time a long beam polarization life time is mandatory in these experiments. Albeit the electromagnetic fields in the kicker of the stochastic cooling system are small the question arises whether they can lead to de-polarization specifically in long time experiments. To investigate this question is also of great importance for the future challenging program at COSY to search for electric dipole moments of protons and deuterons.

INTRODUCTION

COSY is a COoler SYnchrotron and storage ring for medium energy physics [1]. The cooler ring delivers polarized or unpolarized protons and deuterons in the momentum range 270 to 3300 MeV/c. The COSY facility consists of an ion source, an injector cyclotron, a 100-m-long injection beam line, a 184-m-circumference ring and extraction beam lines. It has an electron cooling system that operates at injection, and a stochastic cooling system that operates at momenta between 1500 and 3300 MeV/c. A new 2 MeV electron cooler now being installed [2] will provide high energy cooling in future experiments.

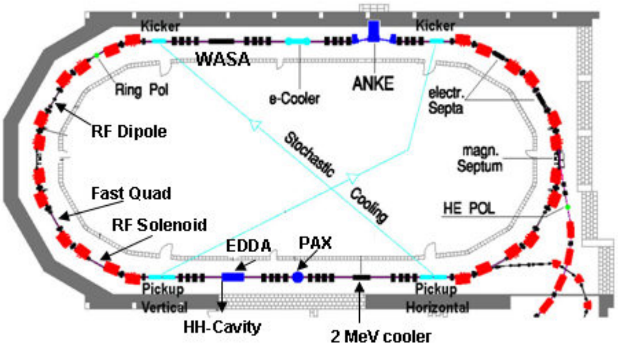

Figure 1: COSY layout.

Internal target experiments using gas jet targets, pellet targets or internal target cells are carried out at COSY. Stochastic cooling is necessary to improve the beam quality during these experiments and a barrier bucket cavity is used to compensate the strong mean energy loss induced by the beam-target interaction. Transverse stochastic cooling and Time-Of-Flight or Filter momentum cooling are routinely used [3].

Upcoming experiments with vertically polarized proton beams require long polarization life times. Since radial magnetic fields can depolarize the beam it is therefore necessary to investigate stochastic cooling as a source of depolarization through its electromagnetic fields in the kicker. In this experiment vertical cooling is applied since then radial magnetic fields in the kicker are present.

The COSY stochastic cooling system simultaneously works in two bands: Band I: 1 to 1.8 GHz, Band II: 1.8 to 3 GHz, and has separate signal paths for horizontal and vertical cooling, Figure 1. The electrode-bars of the pickups and corrector structures can independently be moved and allow an aperture change from 140 mm during the injection and a minimum of 20 mm during cooling. The design of the CERN AC tanks [4] had been adapted to the COSY requirements. The pickups consist of two tanks each equipped with 24 quarter wave electrode loops in band I and 32 loops in band II. Each of the two kickers consists of one tank each for band I and II. The interior of the PUs including the electrode terminations are cooled down to 40 K.

In this experiment vertical cooling with band II has been used. The distance between pickup and kicker is 94 m and the betatron phase advance is $\mu \approx 7/3 \cdot \pi/2$. The installed electronic power is 500 W/plane. The maximum voltage gain is 150 dB. Table 1 summarizes important parameters for the present experiment.

Table 1: SC Parameters

$\lambda/4$ **electrodes**		
Gap height d	50	mm
Loop width w	20	mm
Loop length l_P	22	mm
loop impedance Z_L	50	Ω
Pickup number of loops n_P	32	
Beta function β_P	11	m
Kicker number of loops n_K	8	
Beta function β_K	13	m
System temperature $T_R + T_A$	40	K

EXPERIMENT

During acceleration to the maximum flat top energy up to sixteen depolarizing resonances have to be cured for polarized protons in COSY. The strongest resonance occurs if the spin tune is $\gamma G = 8 - Q_z$. The gyromagnetic anomaly G is 1.79 for protons. During acceleration the vertical tune is kept at $Q_z = 3.62$ and the resonance

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appears at momentum $p = 2100\,MeV/c$. The momentum was chosen to be 1965 MeV/c in order to stay below this strong depolarizing resonance. Figure 2 shows the imperfection (bold) and intrinsic (semi-bold) resonances in the momentum range of COSY. The imperfection resonances appear as horizontal lines since they are independent of tune. The horizontal axis is the fractional vertical tune.

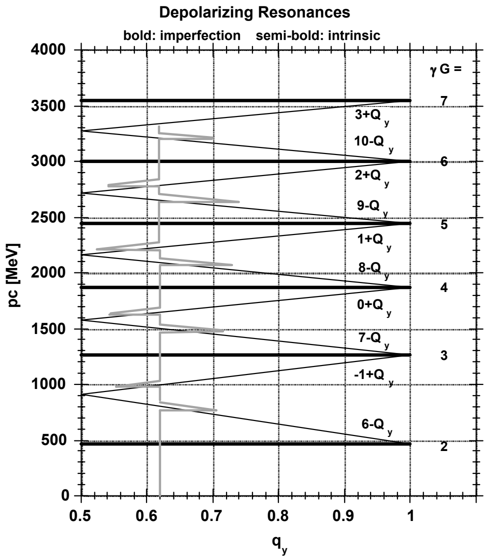

Figure 2: Depolarizing resonances in the momentum range of COSY. The experiment momentum 1965 MeV/c has been chosen below the strong 8-Q_z resonance.

There are three imperfection resonances below 1965 MeV/c. A loss of polarization at these resonances is avoided by artificially increasing the resonance strength, such that the polarization direction is completely reversed when the protons are accelerated across the resonance.

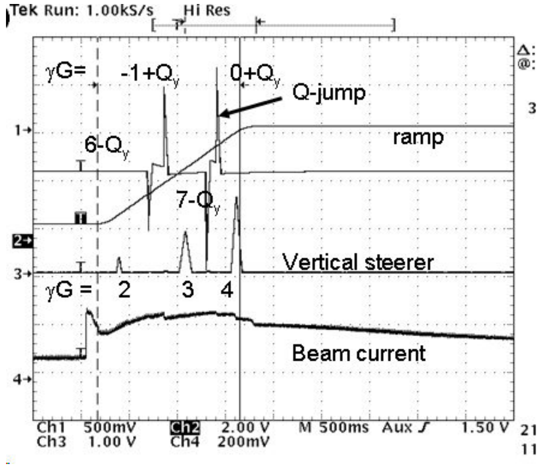

Figure 3: The acceleration ramp is shown together with the Q-jumper and the vertical steerer to compensate polarization losses during the acceleration ramp.

A vertical correction dipole located at a position with a large vertical beta-function is used to increase the orbit distortion that enhances the resonance strength. One method to conserve polarization at the four intrinsic resonances is a rapid vertical tune change (fast crossing). For this the fast tune jump system of COSY consisting of one air coil quadrupole with a length of 0.6 m and a gradient of 0.43 T/m is applied. It allows a rapid tune change of about 0.06 within 10 µs. Double crossing of resonances is avoided by a slow fall time of 40 ms. Polarization and particle losses due to an emittance increase can be kept low during acceleration if the beam position is carefully aligned in the acceleration ramp. The shaded zigzag line in Figure 2 at $q_z = 0.62$ symbolizes the change in working point (not in scale) during acceleration of the beam. The action of the vertical closed orbit distortion and tune jumps during the acceleration ramp are also visible in Figure 3.

The polarization versus momentum is shown in Figure 4. The spin flips are visible at the imperfection resonances. At the intrinsic resonances the polarization is conserved with the fast Q-jump.

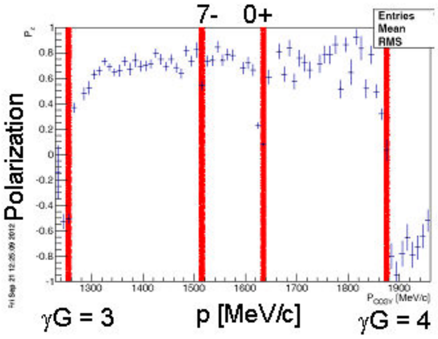

Figure 4: Polarization versus momentum.

The beam with $N = 3 \cdot 10^8$ protons is accelerated from injection momentum 294.5 MeV/c to the experiment momentum 1965 MeV/c in 1.7 s. In flat top the working point is changed to $Q_x = 3.54$ and $Q_z = 3.56$ in a region far away from higher order depolarizing resonances. The frequency slip factor was measured to be $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2 = 0.15$. The relative momentum spread of the beam is then derived from a measurement of the protons's longitudinal frequency distribution which gives $(\Delta p/p)_{rms} = 1.3 \cdot 10^{-4}$. The beam polarization was measured with the EDDA polarimeter [5] at the beginning of flat top. A polarization $P = 75\ \%$ was found, see also Figure 4. At the end of a flat top time of 5 minutes and 30 minutes the polarization was measured again and no polarization loss was observed as shown in Figure 7.

Vertical stochastic cooling was then carried out and the beam profiles during cooling were measured using a ionization profile (IPM) monitor [6], Figure 5. The figure shows from top to bottom the beam current (BCT) the horizontal and vertical rms beam width as well as the horizontal and vertical beam position at the location of the IPM monitor. In addition the beam profiles are shown. The green distributions are measured at the beginning of flat top.

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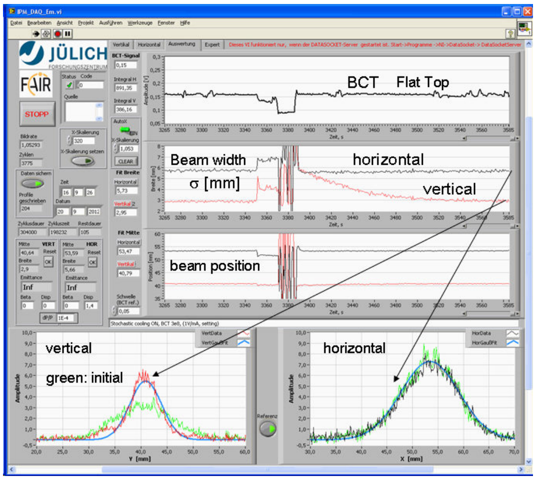

Figure 5: Ionization profile monitor (IPM) measurements. The green profiles are at the beginning of flat top.

Figure 6 clearly shows that the beam is only cooled in the vertical plane. The horizontal plane is not affected. Also the beam position is not changed. After 160 s the vertical rms beam size is reduced by a factor of two from $\sigma_z = 6\,mm$ to $\sigma_z = 3\,mm$. With the beta function at the IPM position, $\beta_x = 64\,m$ and dispersion $D_x = -13\,m$ as well as $\beta_z = 8\,m$ one finds at the start of cooling the rms emittances $\varepsilon_x \approx 0.5\,mm\,mrad$ and $\varepsilon_z \approx 5\,mm\,mrad$.

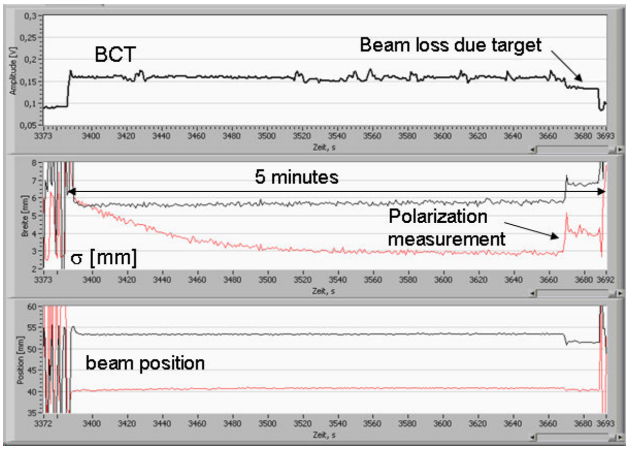

Figure 6: Beam current (BCT), rms beam size and beam position versus time. At the end of flat top the EDDA target is inserted in the beam to measure the beam polarization. Clearly the beam size is suddenly increased.

During cooling the vertical emittance is decreased and attains an equilibrium value $\varepsilon_z \approx 1.3\,mm\,mrad$ in 160 s. At the end of the flat top the beam polarization was again measured, see Figure 6, with the result that no polarization loss was observed. Figure 7 displays the polarization measurement at the end of flat top when cooling is OFF compared to the case when cooling is ON. Within the statistical error the beam polarization is on both cases $P = 75\,\%$.

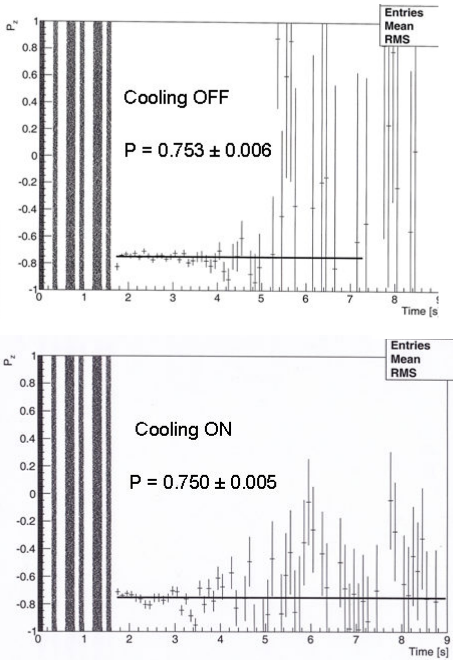

Figure 7: Polarization measurement at the end of flat top time 5 minutes with cooling OFF and cooling ON.

The same result was found when the flat top time was increased to 30 minutes.

Since at longer flat top times in the order of hours the polarization measurements require an inconvenient large run time a basic model has been developed to estimate the influence of the kicker fields on beam polarization.

THEORETICAL DISCUSSION

Cooling Results

The emittance reduction during transverse stochastic cooling of a beam with N particles having charge Qe and revolution frequency f_0 is found from the differential equation [7]

$$\frac{d\varepsilon}{dt} = -\frac{W}{N}\left(2gM^* - g^2 M\right)\cdot\varepsilon + g^2\frac{W}{N}(U\varepsilon) \qquad (1)$$

for the beam emittance ε. The cooling bandwidth is W. The electronic delay has been adjusted to the nominal particle velocity and the vertical betatron phase advance between pickup and kicker is $\mu \approx 7/3\cdot\pi/2$. The unwanted mixing from pickup to kicker is then $M^* \approx 1$. The wanted mixing is $M = \dfrac{f_0}{2\sqrt{2\pi}\,\eta\,\delta\,f_C}$ with $\delta = \Delta p/p$ and the center frequency of the cooling system is $f_C = 2.4\,GHz$.

The correction *g* in Equation 1 is related to the electronic voltage gain G_A of the cooling system by

$$g = N(Qe)^2 f_0\sqrt{\beta_P\beta_K}\,Z_P G_A\frac{K_\perp}{p_0\beta c}\,. \qquad (2)$$

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The beam momentum is p_0 and the velocity is βc. The beta function at the pickup and kicker, β_P and β_K, are given in Table 1. The pickup coupling impedance Z_P and kicker sensitivity $K_\perp$ of the quarter loop electrodes of COSY are approximated by [8]

$$Z_P \approx \sqrt{n_P}\sqrt{\frac{Z_L Z_C}{2}}\frac{\sigma}{h} \text{ and } K_\perp \approx \sqrt{n_K}\,\frac{2}{\pi}\sqrt{\frac{Z_L}{2Z_C}}(1+\beta)\frac{\sigma}{h}\ell \tag{3}$$

for n_P pickup and n_K kicker loop pairs. The length of an electrode is ℓ. The electrode impedances is Z_L and the characteristic line impedance is Z_C. In the experiment the gap height h of both pickup and kicker are equal and are kept constant during cooling. The pickup and kicker geometry factor is $\sigma = 2\tanh(\pi w/2h)$.

The noise-to-signal ratio U of the cooling system is calculated from

$$U=\frac{P_{th}}{P_S}=\frac{k(T_R+T_A)\cdot G_A^2\cdot W}{N(Qe)^2 f_0\dfrac{|Z_P|^2}{Z_C}\cdot G_A^2\cdot W\cdot\beta_P\cdot\varepsilon}. \tag{4}$$

The Boltzmann constant is k and the system temperature is T_R+T_A, see Table 1. Numerically the coupling impedance amounts to $Z_P = 4455\,\Omega/m$ and the kicker sensitivity is $K_\perp = 1.2$. The wanted mixing is $M = 6.4$.

Since the absolute value of the electronic gain G_A in Equation 2 is not known it has been varied to achieve a good agreement between prediction and experimental data.

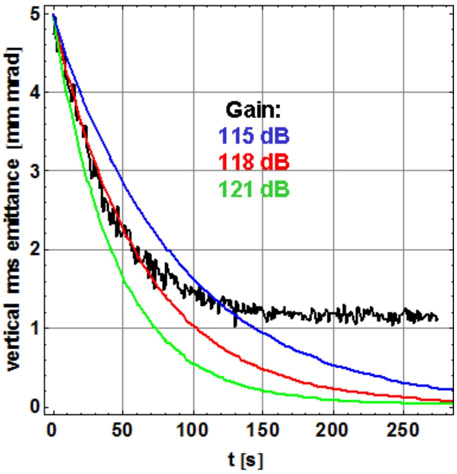

Figure 8: Comparison of cooling model predictions at different gains with the experimental data (black).

The result is shown in Figure 8 for three different gains as indicated. The best agreement is found with $G_A = 118\,dB$. The sum of particle Schottky and thermal noise power as well as the noise-to-signal ratio U are depicted in Figure 9 during cooling.

Figure 8 shows a good agreement for the first 70 s. The experimental data show a significant larger equilibrium value. The discrepancy between data and prediction can not be explained by either IBS or by residual gas scattering. A possible explanation could be that the beam was not centred in the kicker. This would lead to additional heating effects which are not included in the present model.

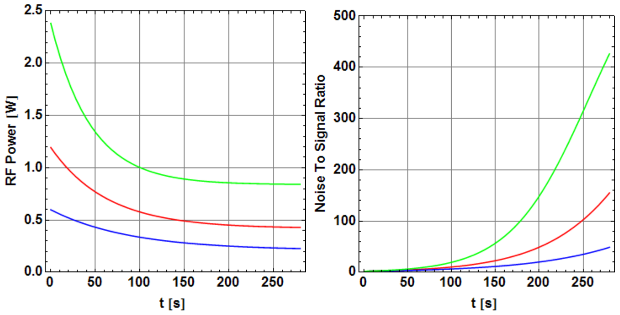

Figure 9: RF power (Schottky plus thermal) and noise-to-signal ratio versus time for three different gain settings 115 dB (blue), 118 dB (red) and 121 dB (green).

Spin Resonance Discussion

The spin motion under the influence of the kicker fields with the electronic gain of 118 dB deduced from the cooling experiment is now discussed to find the resonance frequencies and the order of magnitude of the resonance strength. A detailed description is in work.

Generally, the spin motion of a particle with rest mass m_0, charge Qe and gyromagnetic anomaly G moving with velocity $\vec{v}$ is governed by the Thomas-BMT equation [9]

$$\frac{d\vec{S}}{dt} = \vec{S}\times\vec{\Omega} \tag{5}$$

with the spin precession angular velocity vector

$$\vec{\Omega} = \frac{Qe}{m_0\gamma}\left[(1+\gamma G)\vec{B}_\perp + (1+G)\vec{B}_{//} + \left(\gamma G + \frac{\gamma}{\gamma+1}\right)\frac{\vec{E}\times\vec{\beta}}{c}\right] \tag{6}$$

wherein the electromagnetic fields $\vec{E}$ and $\vec{B}$ are given in the laboratory system and the spin vector $\vec{S}$ is in the particle's rest frame. With respect to a co-ordinate frame that moves with the particle velocity $\vec{\beta} = \beta\vec{v}$ the magnetic field is decomposed into a component $\vec{B}_\perp$ perpendicular to $\vec{v}$ and one along the particle's velocity, $\vec{B}_{//}$. It is assumed that the only perturbation results from the kicker fields and that they can be described by pure TEM waves. In this case the relation $B_x = \frac{1}{c}E_z$ holds. The machine is a perfect planar ring and in the absence of the perturbing fields the beam is vertically polarized. In the moving Frenet-Serret frame, with unit vectors $(\hat{x},\hat{s},\hat{z})$ for the radial outward, longitudinal and vertical direction the electromagnetic field is then given by

$$\vec{E} = E_z\hat{z} \text{ and } \vec{B} = B_x\hat{x} + B_z\hat{z} = \vec{B}_\perp \text{ with } \vec{B}_{//} = 0. \tag{7}$$

The vertical bending field of the dipoles is $B_z \hat{z}$.

Introducing the particles azimuthal angle $\theta = s/\rho$ with bending radius ρ and using Equation 7 the Thomas-BMT equation can be written as

$$\frac{d\vec{S}}{d\theta} = \vec{S} \times \vec{\Omega} \text{ with } \vec{\Omega} = \left[w\hat{x} + (\gamma G)\hat{z} \right]. \qquad (8)$$

The radial component of the spin precession angular velocity vector is given by

$$w(\theta) = \alpha \frac{B_x(\theta)}{B} \qquad (9)$$

where the abbreviation $\alpha = \left\{ (1+\gamma G) - \beta\gamma (G + \frac{1}{\gamma + 1}) \right\}$ has been introduced. Note, $B_z = -B$. Equation 8 shows that in the absence of the kicker fields, $w = 0$, the spin precession is around the vertical axis and the spin tune, the number of spin rotations around the vertical axis when the particle moves for one turn in the ring, is γG.

Taking into account the beam's Schottky signals in the cooling loop which are sampled once per turn by a circulating beam particle the resonance driving term, Equation 9, can be estimated as

$$w(\theta) = \frac{\alpha}{4\pi} \frac{\hat{B}_x \ell}{B\rho} \sum_{n=-\infty}^{\infty} \left\{ e^{i[(n+q_z)\theta + \varphi]} + e^{-i[(n+q_z)\theta+\varphi]} \right\}. \qquad (10)$$

where φ is a uniformly distributed phase between 0 and 2π. The resonance strength is

$$|\varepsilon(K)| = \frac{\alpha}{4\pi} \frac{\hat{B}_x \ell}{B\rho} \qquad (11)$$

and resonance occurs if the spin tune γG equals

$$\gamma G = K = n \pm q_z \qquad (12)$$

where n is an integer.

The kicker fields thus essentially induce intrinsic resonances. No polarization loss could therefore occur due to stochastic cooling since the working point is adjusted far away from intrinsic resonances.

The magnetic field magnitude $\hat{B}_x$ can be found from

$$\hat{B}_x = \frac{1}{c} \frac{2}{d} \sqrt{\frac{Z_L}{n_K}(P_S + P_{th})} \qquad (13)$$

where the gap height is $d = 50\ mm$ and the number of kicker loop pairs is $n_K = 8$, Table 1. The total power for $G_A = 118\,dB$ is initially $P_S + P_{th} = 1.2\,W$ and decreases due to cooling to nearly 0.4 W, Figure 9. Using $\ell = n_K \cdot 22\,mm \approx 180\,mm$ for the length of 8 kicker loop pairs and $B\rho = 6.6\,Tm$ at $p = 1965\ MeV/c$ one finds from Equation 11 with $\alpha = 0.8$ that the resonance strength induced by the kicker fields is very weak, $|\varepsilon(K)| \approx 5.2 \cdot 10^{-10}$. Note that the resonance strength decreases with the emittance reduction during cooling according to Equation 13.

SUMMARY AND CONCLUSION

The polarization life time during stochastic cooling of the vertical beam emittance has been investigated experimentally. A cooling model has been applied to deduce the electronic gain of the cooling system. The gain is then used to estimate the electromagnetic TEM kicker fields. A basic model for the spin motion under the influence of the kicker fields during stochastic cooling of the vertical beam emittance has been applied. The model prediction is in agreement with the experimental outcome that no polarization loss has been observed. According to the model the kicker fields for vertical cooling essentially induce intrinsic resonances. Since the resonance condition was not met in the experiment no polarization loss could thus occur during cooling. Moreover, the estimated resonance strength induced by the kicker of the stochastic cooling system, $|\varepsilon(K)| \approx 5.2 \cdot 10^{-10}$, is extremely small. For comparison, the strongest intrinsic resonance strength in COSY, the 8-q_z resonance, amounts to $2 \cdot 10^{-3}$ [10]. One can thus expect that the stochastic cooling system will also not influence the polarization life time in longer run times as planned for the upcoming internal target experiments.

So far vertical cooling has been examined. It is expected that the conclusions made above also hold for horizontal and longitudinal cooling.

Concerning the challenging future program of the electric dipole moment (EDM) search at COSY a dedicated investigation of the electric kicker fields on EDMs will be carried out.

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