COSY Proposal

For Lab. use

Exp. No.:	Session No.

Title of Experiment

Measurement of the depolarizing pe cross section using co-moving electrons

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Collaborators: | Institute:

ANKE and PAX Collaborations

(Continue on separate sheet if necessary)

Spokesman for collaboration: Name: **Dieter Oellers (IKP-FZJ)**
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Is support from the LSF program of the EC requested?
Yes **No**

Date: **17.10.2007**

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Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second) minimum needed	Intensity or internal reaction rate (particles per second) maximum useful
p(pol), 10^9	**45 MeV (injection energy)**		
Type of target	Safety aspects (if any)	Earliest date of installation	Total beam time (weeks)
d	**none**	**Spring 2008**	**1MD 2 Data taking**

What equipment, floorspace etc. is expected from Forschungszentrum Jülich/IKP?

Summary of experiment (do not exceed this space):

The presently observed beam lifetimes at COSY are roughly a factor 10 too small to carry out experiment #169, although substantial progress has been made in understanding and overcoming some of the limitations. In order to make progress, we would like to continue our investigations addressing the role of electrons for the polarization of stored beam using the electrons in the electron cooler. Although much smaller in target thickness compared to the gas targets, the new calculations by Walcher and Arenhoevel suggest a very large cross section for the spin-exchange between protons and electrons of $\langle \sigma P_{zz} \rangle = 2\times10^{13}$ barn at small relative velocities v/c=0.001. This must be confirmed experimentally. The goal of the measurement proposed here is therefore to determine the spin-exchange cross section.

Attach scientific justification and a description of the experiment providing the following information:

For proposals:

Total beam time (or number of particles) needed; specification of all necessary resources

For beam requests:

Remaining beam time (allocations minus time already taken)

Scientific justification:

What are you trying to learn?
What is the relation to theory?
Why is this experiment unique?

Details of experiment:

Description of apparatus.
What is the status of the apparatus?
What targets will be used and who will supply them?
What parameters are to be measured and how are they measured?
Estimates of solid angle, counting rate, background, etc., and assumptions used to make these estimates.
Details which determine the time requested.
How will the analysis be performed and where?

General information:

Status of data taken in previous studies.
What makes COSY suitable for the experiment?
Other considerations relevant to the review of the proposal by the PAC.

EC-Support:

The European Commission supports access of new users from member and associated states to COSY. Travel and subsistence costs can be granted in the frame of the program Access to Large Scale Facilities (LSF).

Proposal to COSY
on

Measurement of the depolarizing $\vec{p}e$ cross section using co-moving electrons

(ANKE and $\mathcal{PAX}$ Collaborations)

Jülich, October 2007

Proposal to COSY
on
Measurement of the depolarizing $\vec{p}e$ cross section using co-moving electrons

(ANKE and $\mathcal{PAX}$ Collaborations)

Abstract

The presently observed beam lifetimes at COSY are roughly a factor 10 too small to carry out experiment #169, although substantial progress has been made in understanding and overcoming some of the limitations.

In order to make progress, we would like to continue our investigations addressing the role of electrons for the polarization of stored beam using the electrons in the electron cooler. Although much smaller in target thickness compared to the gas targets, the new calculations by Walcher and Arenhoevel suggest a very large cross section for the spin-exchange between protons and electrons of $\langle \sigma P_{zz} \rangle \sim 2 \cdot 10^{13}$ barn at small relative velocities $v/c \sim 0.001$. This must be confirmed experimentally. The goal of the measurement proposed here is therefore to determine the spin–exchange cross section.

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Contents

1 Introduction

In this proposal, the ANKE and PAX collaborations suggest to study the depolarization in a proton beam at the COSY injection energy of $T_p = 45$ MeV. The main objective of this experiment is the same as the one of the proposal which the collaborations submitted to the COSY PAC one year ago [1], namely to clarify the role of electrons for the polarization of stored beam.

The experimental task is to distinguish between the two theoretical scenarios that at present describe equally well the result of the spin filtering of a stored proton beam in the FILTEX experiment [2]. The first explanation was developed by H.O. Meyer [3], the second one by A. Milstein and V. Strakhovenko [4], and independently by N.N. Nikolaev and F. Pavlov [5]. The explanation by Meyer includes a transfer of polarization from the polarized electrons in the polarized Hydrogen gas target to the orbiting protons, while the theoretical approach by Milstein/Strakhovenko and Nikolaev/Pavlov is based solely on proton-proton scattering. In a recent publication T. Walcher and collaborators describe a new QED-calculation, which extends the calculation of Meyer to very low relative velocities of proton and electron. At an electron energy of 1 keV in the rest frame of the proton, i.e. at a relative velocity $v/c \sim 0.001$, the predicted spin–exchange cross section amounts to $\langle \sigma P_{zz} \rangle \sim 2 \cdot 10^{13}$ barn [6].

The goal of the measurement is to determine the spin–exchange cross section.

2 Machine Studies in June 2007

A detailed account of the results of the machine development run in June 2007 is given in Appendix A. Here we discuss only briefly the main findings:

1. With electron cooling the beam exhibits a purely exponential behavior, indicating that the losses are due to single Coulomb scattering.

2. A flat orbit is required. For a careful adjustment it is however necessary to calibrate the BPMs.

3. A machine acceptance of $\approx 30\,\pi$ mm mrad has been measured both with and without cell. The cell is not the limiting aperture in the machine, and an improved closed orbit correction is necessary to increase the machine acceptance.

4. In spite of the fact that higher beam lifetimes are expected in the region where horizontal and vertical tunes are equal, there is an area quite far away from the $Q_x = Q_y$ line, where the highest lifetimes were observed. This region should be studied in the upcoming machine development once again in more detail. Furthermore, the tune dependence of the beam lifetime near the line of equal tunes displays structures, which at the moment are not understood.

5. The beam lifetime is generally independent from the beam current, although the situation at high intensities of the order of 10^{10} particles per spill could not be examined yet.

6. A beam lifetime of 250 s was observed for a deuterium storage cell target thickness of 10^{14} cm^{-2}, which is substantially smaller than the predicted values. Such lifetimes make the proposed depolarization studies (# 169) almost impossible at the ANKE IP. Therefore, further machine development seems necessary.

7. In the current situation the use of ^{4}He target is not possible unless the pumping capabilities at the ANKE target location are substantially improved.

8. The beam lifetime at high beam currents has to be investigated. This requires the electron cooler to be set for two different energies, because it is needed both for stacking and for cooling on flat top.

2.1 Conclusion from the Machine Development

In order to investigate the role of electrons and to distinguish between the two theoretical scenarios a complementary approach of depolarizing an initially polarized beam with unpolarized deuterium or helium target has been proposed [1]. Experiment #169 requires a beam lifetime of about 3000 s in the presence of a dense deuterium gas target of $2 \cdot 10^{14}$ cm^{-2} at $T_p = 45$ MeV (see Table 1 in Sec. A.1 and our beam request 169.1 [7]) in order to reach the anticipated significance of five standard deviations. Although substantial progress has been made in understanding and overcoming some of the limitations, as discussed in Appendix A, the presently observed beam lifetimes are roughly a factor 10 too small to carry out the experiment. Taking into account the rest gas composition in the COSY ring, and the machine settings, the theoretical estimate of the beam lifetime, shown in Fig. 1, illustrates this finding. Shown there are two calculations of the expected beam lifetime and one data set with the background corrected values of the beam lifetime as function of the thickness of the D_2 storage cell target.

With the present beam conditions, simply by placing the target into the low-β section at TP1, one would gain about a factor of ten in beam lifetime. Therefore, one would conclude that the proposed experiment #169 using the electrons in the D_2 target could be carried out once the low-β section is implemented. It should be noted that the option, discussed in the proposal, of using a ^{4}He target seems very difficult to realize, because of the limited capabilities at ANKE to pump the gas (see also the discussion in Sec. A.8).

3 Physics Case for the Measurement with co–moving Electrons

In order to make progress, we would like to continue our investigations using the electrons in the electron cooler. Although much smaller in target thickness compared to the gas

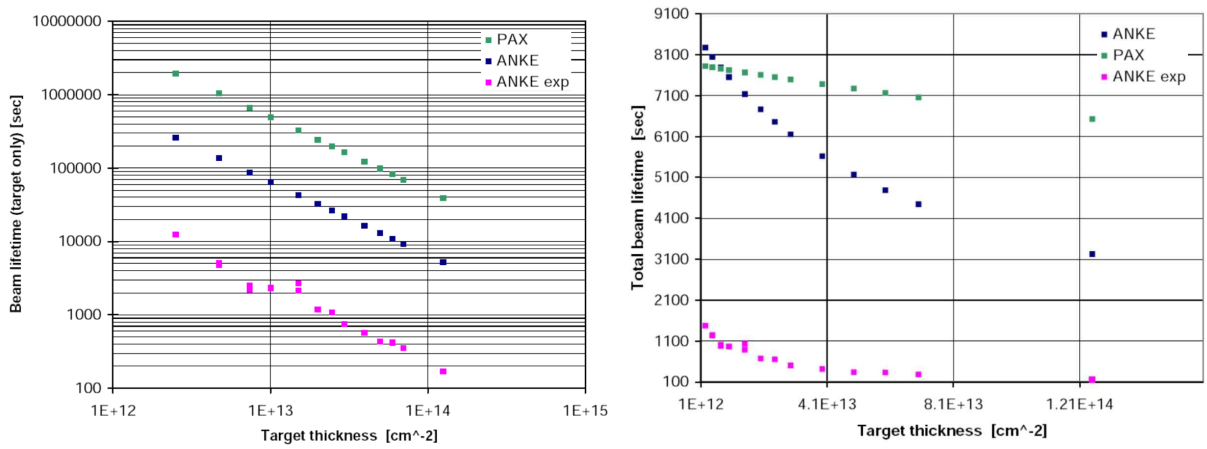

Figure 1: Measured beam lifetimes with (left panel) and without (right) background subtraction at the ANKE target location (magenta) using a D_2 storage cell target at $T_p = 45$ MeV. The other two sets are the result of a calculation of the expected beam lifetimes for ANKE (blue) and the location at TP1, where we anticipate to install the instruments for the spin-filtering studies (green PAX).

targets, as shown in Fig. 2, the new calculations [6] suggest a very large cross section for the spin-exchange between protons and electrons. This must be confirmed experimentally. Using the spin-exchange cross section $\langle \sigma P_{zz} \rangle$ from Ref. [6], the electron target thickness d_t

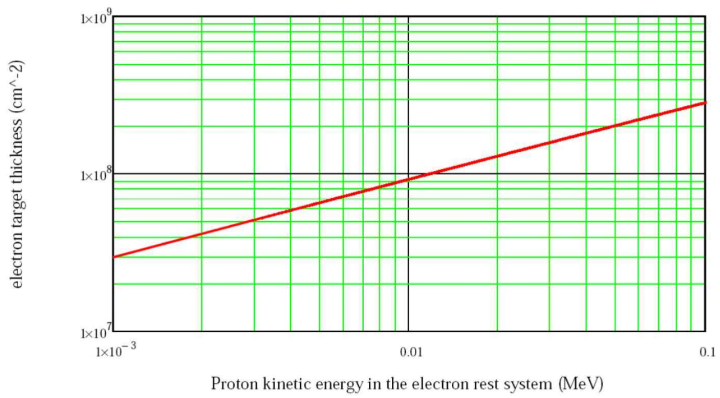

Figure 2: Calculated electron target thickness in the cooler for the proton energies of interest (I_e=240 mA, $\ell_{\text{Cooler}} = 2$ m, cross section of electron beam = 5 cm^2).

from Fig. 2, and the frequency of the orbiting protons f_{rev}, the polarization lifetime

$$\tau_p = \frac{1}{\langle \sigma P_{zz} \rangle \, f_{\text{rev}} \, d_t} \tag{1}$$

for the proton kinetic energy in the electron rest frame is plotted in Fig. 3. It is interesting

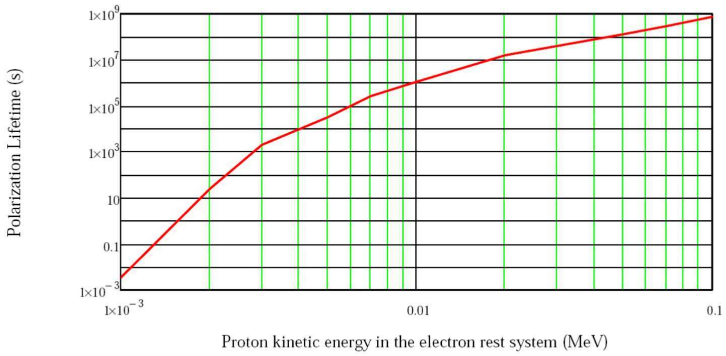

Figure 3: Polarization lifetime calculated using the spin–exchange cross section from ref. [6] as function of the proton kinetic energy in the electron rest system.

to note that with a proton kinetic energy of 1 keV the polarization lifetime amounts to a few ms only. At 6 keV, the calculated polarization lifetime exceeds already 10000 s. In order to obtain the necessary energies of the protons in the electron rest frame at a proton laboratory energy of $T_p = 45$ MeV, the electron cooler voltage must be detuned by a few hundred to a few thousand Volts, as indicated in Fig. 4.

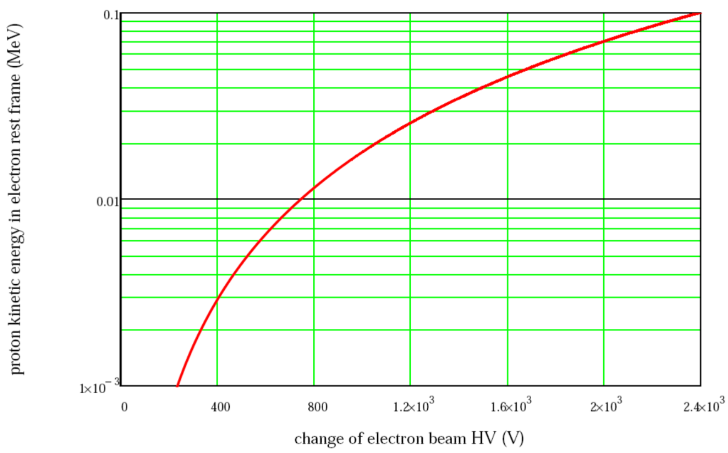

Figure 4: Proton energy in the electron rest frame as function of the necessary voltage change in the electron cooler.

3.1 Energy Resolution of Electron and Proton Beam

The longitudinal cooling force of the electron cooler was determined some time ago. It corresponds to an effective electron temperature of $T_{\text{eff}} \approx 0.020$ eV [8]. It is discussed in the literature [9] that the transverse electron temperature is much larger than the longitudinal one. A rough estimate given in ref. [9] yields 0.5 eV. Therefore, one would conclude that we do not have to worry much about the energy spread of the electron beam.

In a recent COSY measurement [10] the relative momentum spread of the proton beam was measured as function of the number of stored protons. The measurement shows that in order to stay below a proton beam momentum spread of 10^{-4}, the beam intensity should not exceed 10^9 particles, but this should be verified experimentally. The energy spread of the proton beam calculated from an assumed relative beam momentum spread of 10^{-4} is given by

$$\Delta T_p = \frac{\Delta p}{p} \cdot \frac{1+\gamma}{\gamma} T_p \,. \tag{2}$$

As shown in Fig. 5, the (absolute) energy spread of the protons in the electron rest frame assuming a beam intensity of 10^9 stored particles and a momentum spread of 10^{-4} is about an order of magnitude smaller than the proton energy itself.

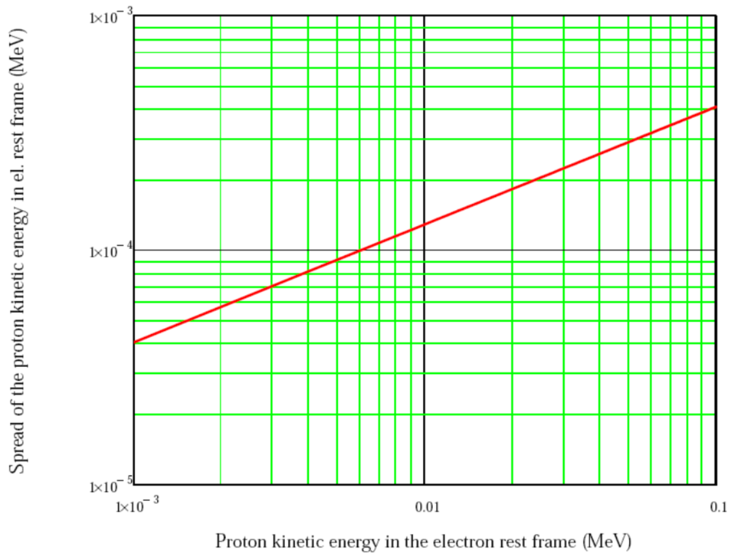

Figure 5: Absolute spread of the proton beam energy in the electron rest frame assuming a relative beam momentum spread of 10^{-4} as function of the proton kinetic energy in the electron rest frame.

3.2 Cycle Set-up

An additional complication arises from the fact that although the cooling force is small when the electron beam is detuned, the proton beam will nevertheless slowly change its momentum until again the velocities are matched. Therefore, one has to detune the cooler voltage for a short period of time, for instance for 2.5 s and then return to the nominal voltage for, say a period of 5 s to make sure the proton beam remains well-cooled. Alternating the cooler voltage between *nominal* and *detuned* leads to a cycle shown in Fig. 6. This procedure is repeated for, say for 150 s, during which the beam intensity decreases

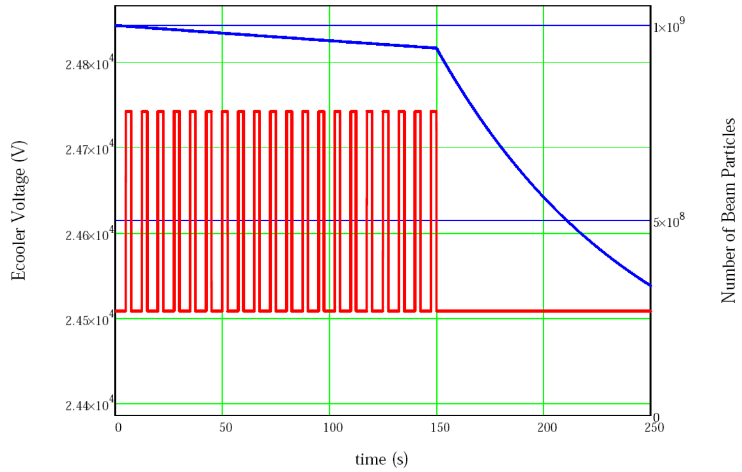

Figure 6: Cycle setup with alternating periods of detuned (2.5 s) and nominal (5 s) voltages of the electron cooler.

slowly, because there is no target in the beam. The assumed beam lifetime corresponds to the observed one: $\tau = 2500\ s$. After 150 s, the cooler voltage is set to the nominal one and the D_2 cluster target is switched on, resulting in a fast decrease of the beam intensity with $\tau = 100$ s.

3.3 Polarimetry

We plan to measure the beam polarization by making use of the analyzing power in elastic p-d scattering on a deuterium target. The generated asymmetry will be measured with the detector system, consisting of two ANKE STTs discussed previously in Refs. [1, 7]. With this detector system one can within 5 s obtain an error of the beam polarization of $\Delta P(\Delta t = 5\,\mathrm{s}) = 0.070$. Thus the statistical accuracy after one 100 s long measurement of the beam polarization is $\Delta P(\Delta t = 100\,\mathrm{s}) = 0.07/\sqrt{20 * 0.8} = 0.02$, where the factor 0.8 accounts for the decrease in beam intensity.

3.4 Determination of the depolarizing Cross Section

In order to quantify the depolarizing effect, one would perform measurements without detuning of the electron cooler to determine the injected beam polarization P_{initial}. When the electron cooler voltage is detuned for some time, in the above example shown in Fig. 6 for instance for a time period of $\Delta t_{\text{detuned}} = 50$ s, one obtains a second polarization value

$P_{\rm detuned}$. From these two numbers, one can derive the depolarizing cross section

$$\sigma_{\rm depol} = \frac{-\ln\left(\frac{P_{\rm detuned}}{P_{\rm initial}}\right)}{\Delta t_{\rm detuned}\, d_t\, f_{\rm rev}}\,. \tag{3}$$

In order to cancel systematic effects in the polarization measurement, we will use two identical STT's left and right of the beam. Near the injection energy of T_p = 45 MeV, there are precise data available of the differential cross section (T_p = 46.3 MeV [12]) and the analyzing power (T_p = 49.4 MeV [11]). It should be noted that for the determination of $\sigma_{\rm depol}$ an absolute determination of the beam polarization is not required, because only the ratio of polarizations enters in the numerator of Eq. (3). At the polarized ion source it is possible to adjust the ratio of beam polarization $P_\uparrow/P_\downarrow \approx 0.01$. The polarization measurement will utilize data from subsequent cycles with opposite beam polarizations, whereby detector efficiencies cancel, as well as differences in the luminosity to first order. A special effort is needed to determine the target thickness d_t. This can be achieved using the known cross sections, or using the Schottky energy loss method [13].

In Fig. 7 we show an estimate of the precision with which we can extract $\sigma_{\rm depol}$ for kinetic energies of the proton in the electron rest frame of 0.001, 0.01, and 0.1 MeV. Each point combines the statistics of a 2 h measurement. The different statistical accuracy at different energies reflects the effect of the relative proton-electron energy on the target density (cf. Fig. 2). The best limits one would observe in the absence of any depolarization, whereby, taking into account only the statistical precision $\sigma_{\rm depol} \approx 1 - 2 \times 10^7$ barn. This region is shown in Fig. 8 in more detail. From the count rate estimates we performed, it is obvious, that this investigation will not be limited by statistics. Systematic effects are difficult to control. Therefore, we have to be able to repeat the measurement often enough to obtain a reasonable understanding of the systematic errors.

4 Beam Request

1. **We request one week of beam time for machine development in the first half of 2008** to carry out again the necessary preparations with respect to electron cooling, possibly cooler–stacking, and to provide high beam lifetime and beam polarization lifetime.

2. **We request a total beam time of two weeks for data taking to carry out the proposed measurements.** The beam time should be preceded by the above requested machine development week.

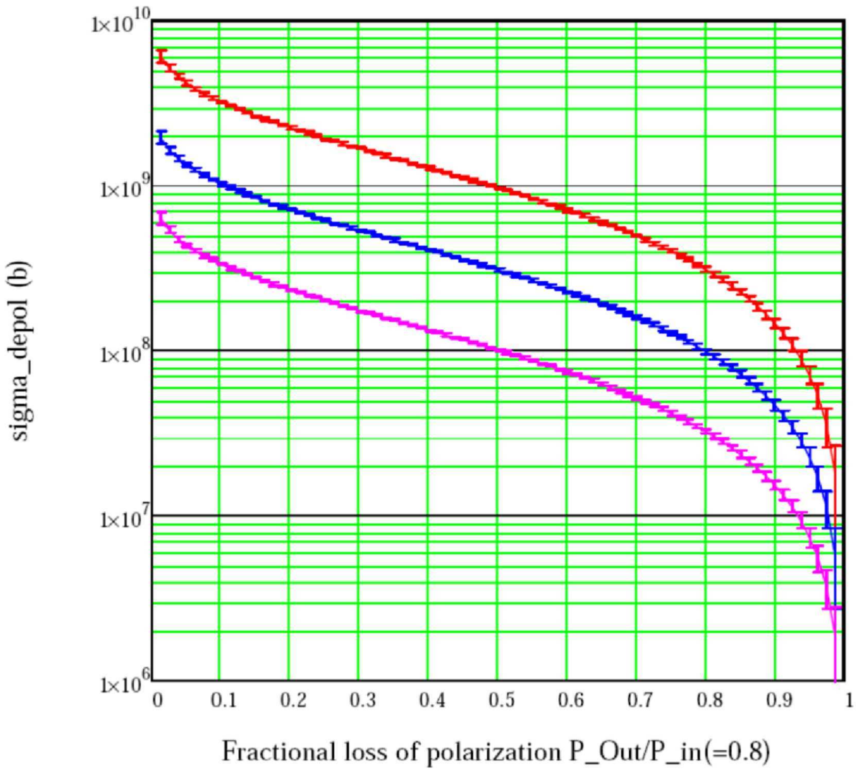

Figure 7: Estimate for the measurement of the depolarizing effect of the co-moving electrons of the cooler versus the fractional loss of beam polarization. The three curves are for kinetic energies of the proton in the electron rest frame of 0.001 (red curve), 0.01 (blue), and 0.1 (magenta) MeV. Each point reflects a 2 h measurement.

References

[1] Proposal #169 to the COSY PAC on *Do unpolarized electrons affect the polarization of a stored proton beam?*, ANKE and PAX Collaborations, spokesperson: Dieter Oellers (Forschungszentrum Jülich), available from the PAX website `http://www.fz-juelich.de/ikp/pax`.

[2] F. Rathmann *et al.*, Phys. Rev. Lett. **71**, 1379 (1993).

[3] H.O. Meyer, Phys. Rev. E **50**, 1485 (1994).

[4] A.I. Milstein and V.M. Strakhovenko, Phys. Rev. E **72**, 066503 (2005).

[5] N. N. Nikolaev and F. F. Pavlov, Buildup of stored protons and antiprotons: FILTEX Result and Implications for PAX at FAIR, available from `arXiv:hep-ex:0601184`.

[6] T. Walcher *et al.*, *A surprising method for polarising antiprotons*, `arXiv:0706.3765`, available from `http://xxx.lanl.gov/abs/0706.3765`.

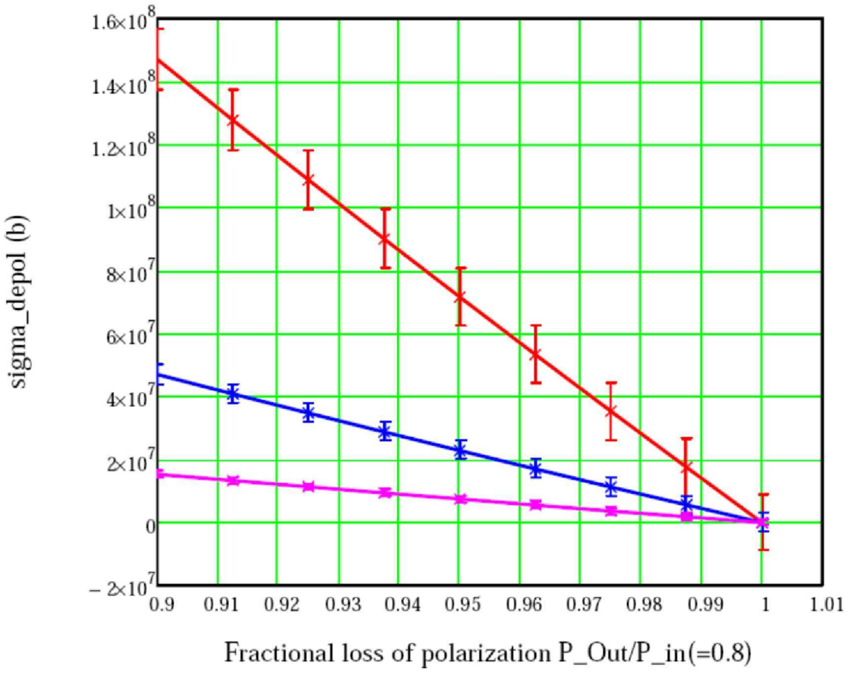

Figure 8: Estimate for the measurement of the depolarizing effect of the co-moving electrons. The color code is the same as for Fig. 7.

[7] Beam Request #169.1 to the COSY PAC on *Do unpolarized electrons affect the polarization of a stored proton beam?*, ANKE and PAX Collaborations, spokesperson: Dieter Oellers (Forschungszentrum Jülich), available from the website `http://www.fz-juelich.de/ikp/anke`.

[8] H. J. Stein, private communication.

[9] A.W. Chao and M. Tigner, Handbook of Accelerator Physics and Engineering (3rd printing), Sec. 2.8.2 (Electron Cooling, p.190).

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[11] N.S. King *et al.*, Phys. Lett B **69**, 151 (1997).

[12] S.N. Bunker *et al.*, Nucl. Phys. A **113**, 461 (1968).

[13] H. J. Stein *et al.*, in preparation.

[14] J. Dietrich *et al.*, IKP Annual Report 2004, *Characteristic Features of Electron Cooling at COSY*, p. 77, available from `http://www.fz-juelich.de/ikp/publications/AR2004/documents/AR2004_Articles.pdf`

A Summary of the Machine Development, June 18 - July 1, 2007

A.1 Goal and Status

In order to distinguish the two scenarios described in Sec. 1, a depolarizing study of a stored polarised proton beam with an kinetic energy of $T_p = 45$ MeV was proposed at COSY-PAC in autumn of 2006 [1]. With electrons in a ^{4}He or a D_2 target it should be possible to measure the electron contribution to spin filtering. To achieve 4-5 σ significance in 4 weeks of data taking the following beam requirements are needed:

Parameter	Value
Target Thickness	$2 \cdot 10^{14}\,\mathrm{cm}^{-2}$
Beam Intensity	$2 \cdot 10^{10}$ stored protons
Initial Beam Polarisation	0.8
Beam Lifetime with target	2700 s
Beam Lifetime without target	10000 s
Beam Polarisation Lifetime	45000 s
Beam Energy	45 MeV

Table 1: Set of parameters to evaluate the depolarizing effect of the electrons in a deuterium cluster target with 4-5 σ accuracy.

The goal of this machine development was to improve the beam lifetime at injection energy to reach the necessary lifetime of $\sim$10000 s without target and $\sim$ 2700 s with target. Prior to this investigation, beam lifetimes of only $\sim$ 800 s [14] were reported at the injection energy of 44.83 MeV without target.

A.2 Machine Setup

A change in the magnet settings at injection energy can lead to a complete loss of the injection as the matching conditions for the injected beam are defined by the quadrupole setting in the ring. Lattice functions x, x′, $\beta_{x,y}$, $\alpha_{x,z}$ of the beam line have to match the ring parameters. By changing the ring focussing elements these parameters also change. To keep the injection one would then have to re-adjust the beam line to match the new ring parameters. To avoid frequent re-adjusting, which is a time consuming process, we worked at “flat top” after the smallest possible acceleration. For the unpolarized proton beam a ramp from $p = 293.48$ MeV/c up to $p = 295$ MeV/c was introduced. This is equivalent to beam kinetic energies of $T = 44.83$ MeV and $T = 45.28$ MeV, respectively.

It is extremely important to know which contribution to the beam lifetime is due to the residual gas. Therefore, at the beginning of the beam development each of the mass spectrometers installed in the ring was read out. From these data, combined with the total

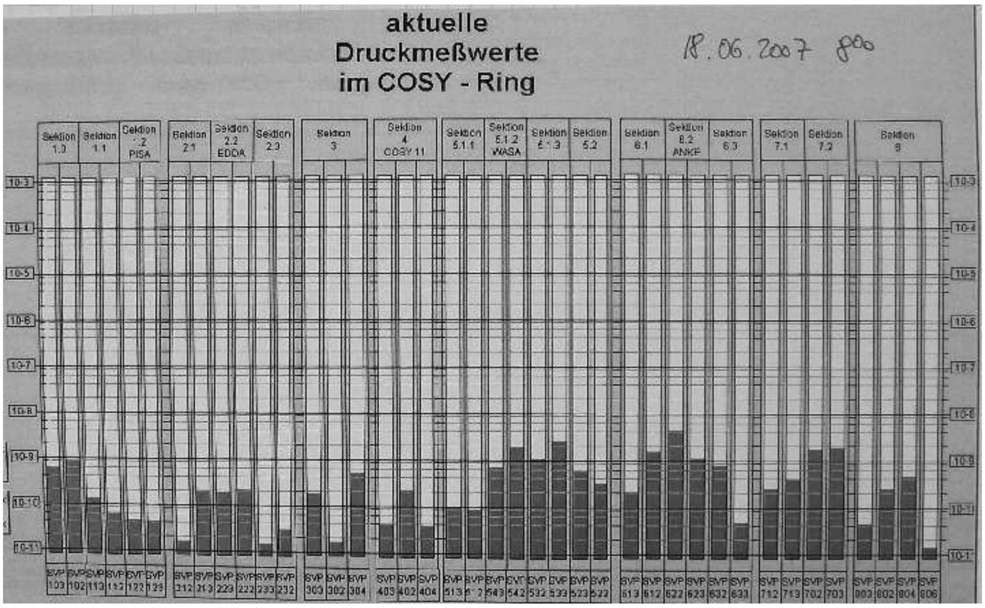

Figure 9: Pressure distribution of the COSY ring on 18th of June 2007.

pressure in each section, the partial pressures of the most prominent gases in all sections of the ring was calculated.

In Fig. 10 one can clearly see, that H_2 is the dominating gas in the COSY ring. In section 7, there is a big contribution from nitrogen, which is an indication for a leakage. The nitrogen contribution to the residual gas produces roughly the same amount of Coulomb scattering losses as the H_2 contribution due to the Z^2 dependence. Additionally, one should mention that the residual gas monitor (RGM) from GSI, which was installed for test purposes in section 7 was producing a lot of residual gas of every kind every time the voltage was switched on. In the whole ring, the titanium sublimation pumps (TSP) were switched on, and the vacua were quite good. Nevertheless, the TSP's were heated up every 5 hours, which caused a temporary pressure increase. The improvements, like closing the leakages and removing the RGM should lead to higher beam lifetimes.

A MAD[1] calculation aimed at estimating the beam lifetime has been performed. The area occupied by particles in phase space at the beginning of a beam transport line allows to determine the location and distribution of the beam at any other place along the transport line. In phase space this is an ellipse and the area is a constant at any point of the ring. Its shape and orientation are fixed by three parameters α, β and γ (see Fig. 11). The acceptance is computed from the relation:

$$A_{x,y}(s)/\pi \,\mathrm{mm\,mrad} = \frac{r^2_{x,y}(s)/\mathrm{mm}}{\beta_{x,y}(s)/\mathrm{mm}},$$

and leads to a result of A = 42.35 π mm mrad for the six-fold symmetry of the ring. The

[1]**M**ethodical **A**ccelerator **D**esign

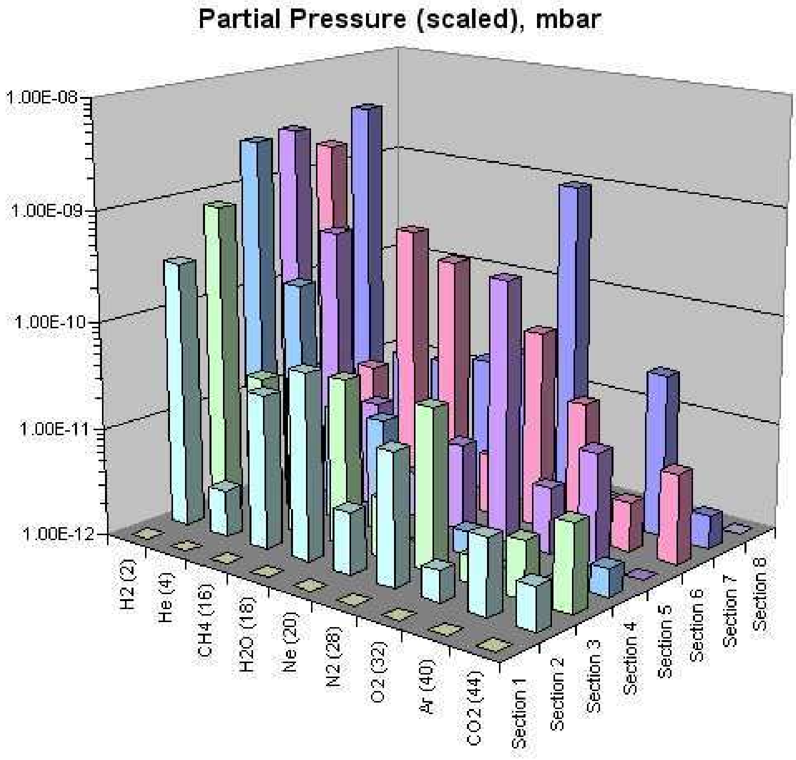

Figure 10: Main residual gas components in all COSY section at the beginning of the beam development.

acceptance limit is located in the arcs.

With this number, the γ parameter at each point of the ring and the single Coulomb scattering loss cross section, and therefrom, the lifetime contribution from each residual gas component is calculated. The total lifetime of COSY without target should be about 11000 s.

During the beam development the lifetime has been determined online using a fit of the BCT (beam current transformer) signal available in the data stream. Several exponential fits to the BCT have been made available. Data from the Schottky spectra have been monitored to ensure that the revolution frequency and energy spread remained stable. In the electron cooler protons recombine with electrons to H^0. These atoms can be detected to measure the beam profile. The detection system comprises 2 proportional chambers with wires placed horizontally and vertically, and 2 scintillation counters giving the integral flux of H^0s. Since the MWPCs were not working properly, the beam profile could not be measured during this beam development, although the rate of H^0s has been permanently monitored. The H^0 rate should be proportional to the beam current, provided that the conditions of the electron beam and the stored beam do not change. For two cycles the rate of H^0/I is shown in Fig. 12.

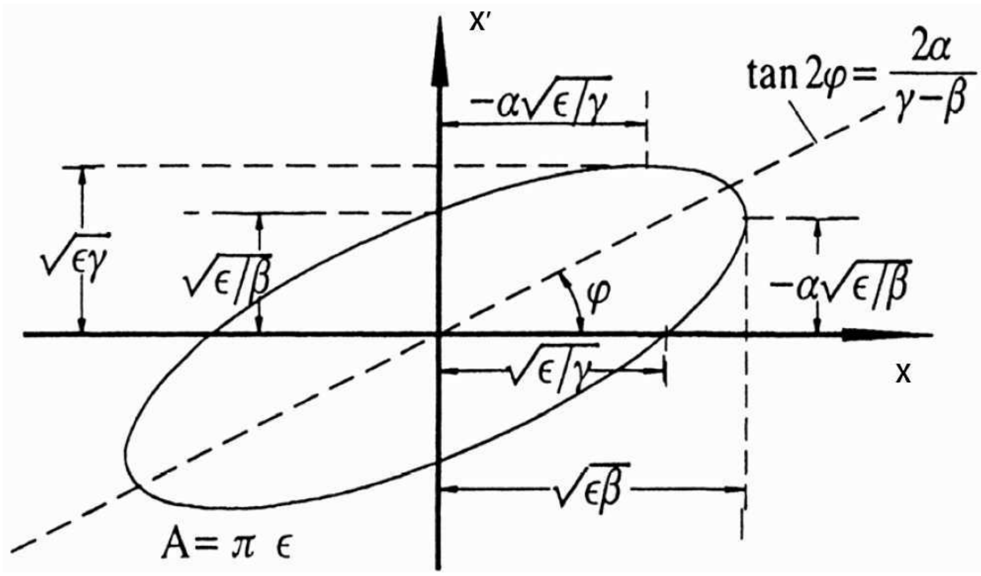

Figure 11: Phase space ellipse.

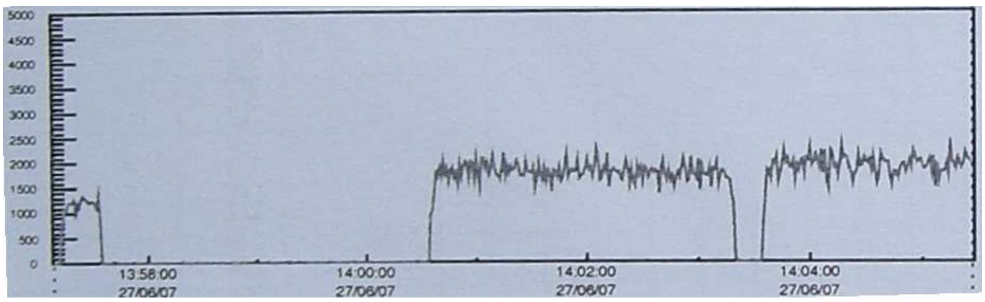

Figure 12: Counting rate of H^0 divided by the beam intensity in arbitrary units as a function of time.

For studies of the target effect on the beam lifetime, a storage cell has been prepared. The cell could be filled with different gases. The gas inlet was calibrated to provide based on the known cell conductance a known target thickness. The calibration plots for different gases are shown in Fig. 13[2].

A.3 Closed Orbit Manipulations and Acceptance Measurement

Initial closed orbit ranged within ±7 mm vertically and ±18 mm horizontally. The largest machine acceptance is achieved, if the orbit is in centre of the beam pipe. In order to reach

[2]The calibration for N_2 plotted here is not correct as different settings for a valve opening have been used and led to a changed device conductance.

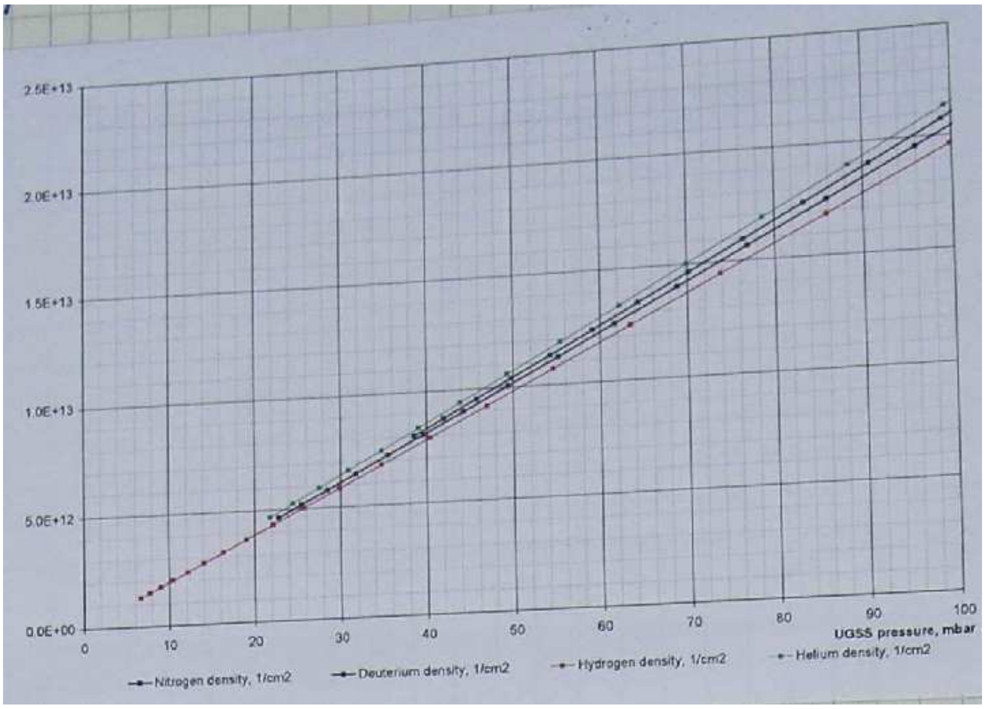

Figure 13: Calibration curve: Target density in particles / cm^2 *versus* pressure in the unpolarized gas supply system (UGSS).

the best orbit with the storage cell and the electron cooler a 3-step approach has been chosen:

1. Optimization without electron-cooler magnets switched on (see Fig. 14), where the orbit remained within 5 mm, both vertically and horizontally.

2. Optimisation with electron-cooler magnets on. The orbit has also been flattened, down to 12 mm, although not being as good as without the cooler (see figure 15).

3. Optimisation with the storage cell. This worked without any problems, and no changes to the orbit were needed.

An attempt to further improve the orbit with the help of the orbit response matrix method, based on the BPM reaction to local orbit kicks has been carried out. But there was only very limited time to test this method. It has also been found out, that some of the BPMs and kickers could possibly be wrongly connected. In addition, the BPMs have never been exactly calibrated, thus they can have an offset of the central position. It is worthwhile to have an additional look into this.

To measure the acceptance, a fast kicker has been used. Since the kicker is capable to kick only in the horizontal plane, this measurement can only give an upper limit for the machine acceptance. For each kick the beam emittance ϵ is calculated as $\epsilon = \Theta^2/\gamma$,

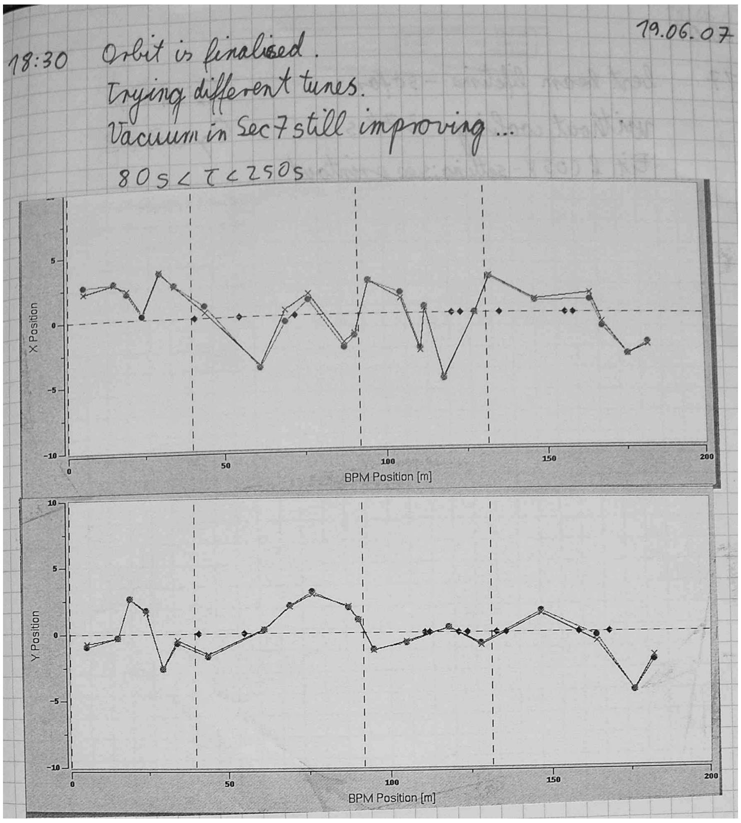

Figure 14: Beam orbit after closed orbit manipulations with all electron-cooler magnets switched off.

with the kick angle Θ and the beta function at the kicker of $\gamma = 0.1797\,/\mathrm{m}$. A calibration curve of the kicker (see Fig. 16) is used to get the kick angle from the voltage at the kicker. From the voltage one can calculate the current and the magnetic field. The kick angle Θ is calculated from $\Theta = \frac{\int BdL}{B\rho}$, with the magnetic rigidity $B\rho = 984.002$ mT m and $\int BdL$ is the integral of the magnetic field along the kicker.

The survival probability p is calculated using $p = \frac{BCT_f}{BCT_i}$, where BCT_f and BCT_i denote the BCT signal before (i) and after (f) the kick. The acceptance is the value, where the survival probability reaches zero. Two measurements were carried out: one with the beam passing through the storage cell, and a second one with the storage cell moved out of the beam. Both results are shown in Fig. 17.

For both measurements with and without storage cell, the measured acceptance is very similar and amounts to $\approx 30\ \pi$ mm mrad. Therefore, the storage cell was not limiting the machine acceptance. In order to study the machine acceptance and to determine the beam lifetime that can be reached, a MAD-calculation has been carried out. For horizontal and vertical direction the beam position was randomly varied from the beam pipe centre and the acceptance was calculated. The dependence of the acceptance on the different

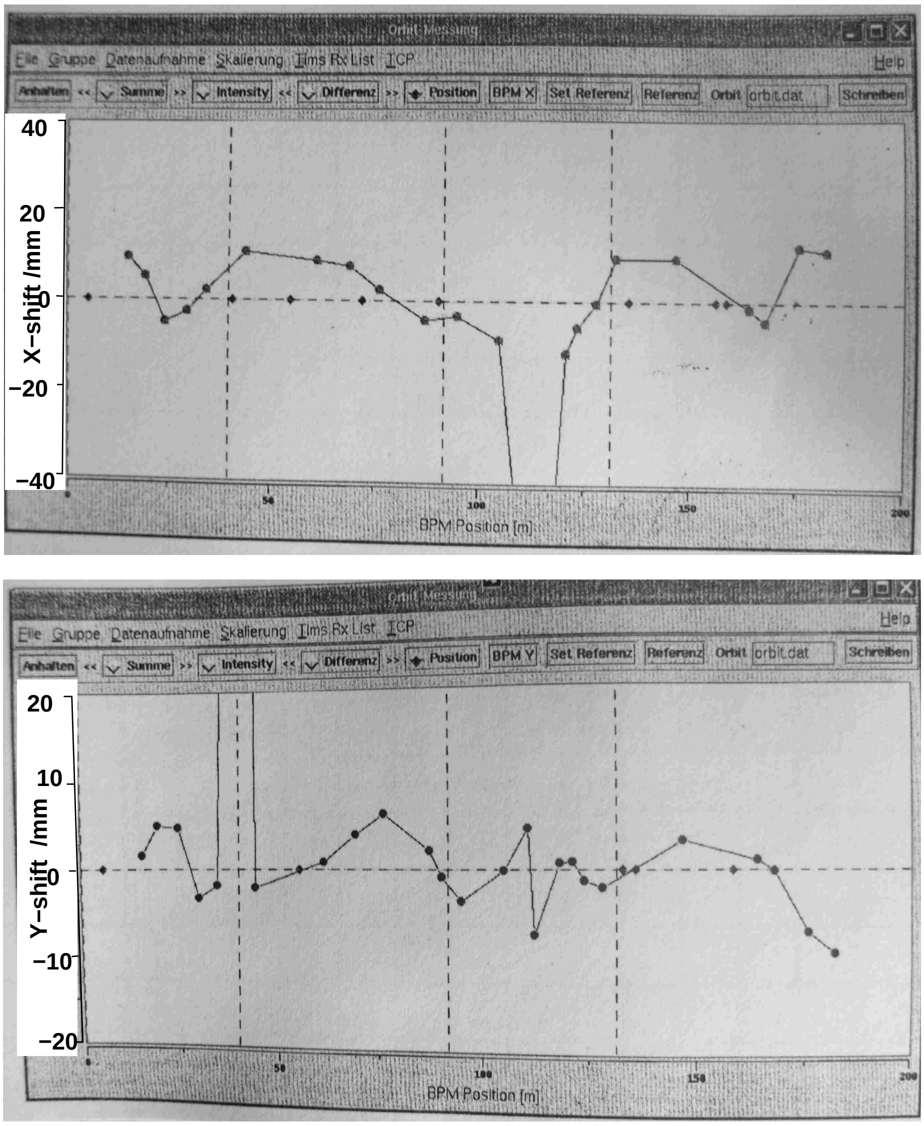

Figure 15: Beam orbit with electron-cooler magnets switched on.

maximum deviations is plotted in Fig. 18 for each plane with and without a storage cell. For all calculations it was assumed, that the beam was in the centre of the storage cell.

For the horizontal plane one can clearly see, that the storage cell is the acceptance limit. The acceptance drops from $\approx 160\ \pi$ mm mrad to $36\ \pi$ mm mrad. The acceptance with storage cell shows no dependence on the orbit deviation. From this one concludes that even with an orbit deviations of 10 mm, the storage cell is limiting the acceptance. For the vertical plane things are different. The acceptance is $\approx 42\ \pi$ mm mrad without storage cell and about $28\ \pi$ mm mrad with storage cell. The vertical machine acceptance

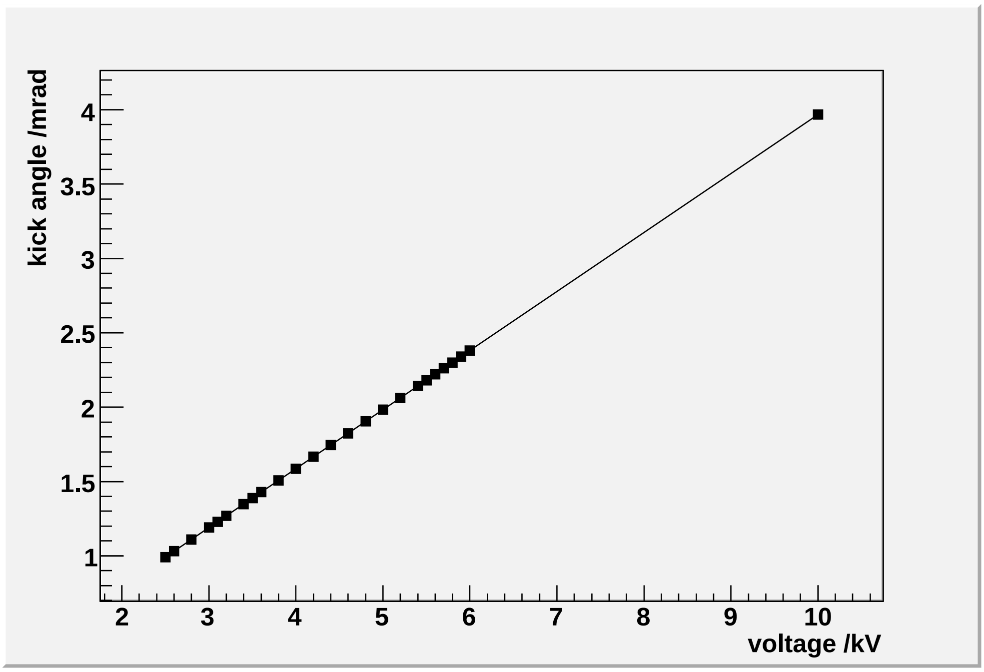

Figure 16: Calibration curve for the horizontal kicker. Voltage at the kicker *versus* kick angle Θ. The markers show the points used for the acceptance measurement.

is much smaller than in the horizontal plane. The kink in the plot with the storage cell indicates, that with orbit deviations of 6 mm or more the acceptance limitation moves from the storage cell to the ring and drops to 20 π mm mrad at 10 mm orbit deviations. This is in good agreement with the acceptance measurement performed with the kicker. The uncalibrated BPM measurements show an orbit with roughly 12 mm deviations. Further calculations show that with the storage cell the beam lifetime drops from 7400 s to 5400 s because of the orbit deviations (see Fig. 19). It becomes clear, that the orbit limited within 12 mm leads to a serious acceptance limitation, and, therefore, has to be improved in the future.

A.4 Tune Scans and Beam Lifetime

The beam lifetime strongly depends on the chosen machine tunes. Ideally the tunes should be irrational numbers, while in practice one just tries to stay away from the machine resonances, plotted in Fig. 20 up to 10th order.

In order to change the tunes, the current in two families of quadrupoles (Quad 1-3-5 and 2-4-6, due to the 6-fold symmetry) was varied to map the region of the tune diagram around $Q = 3.61$, and the beam lifetime was recorded for each tune combination. The result of the measurements is presented in Fig. 21.

The gap around $Q_x = Q_y$ is a clear indication for coupling between the x and y planes

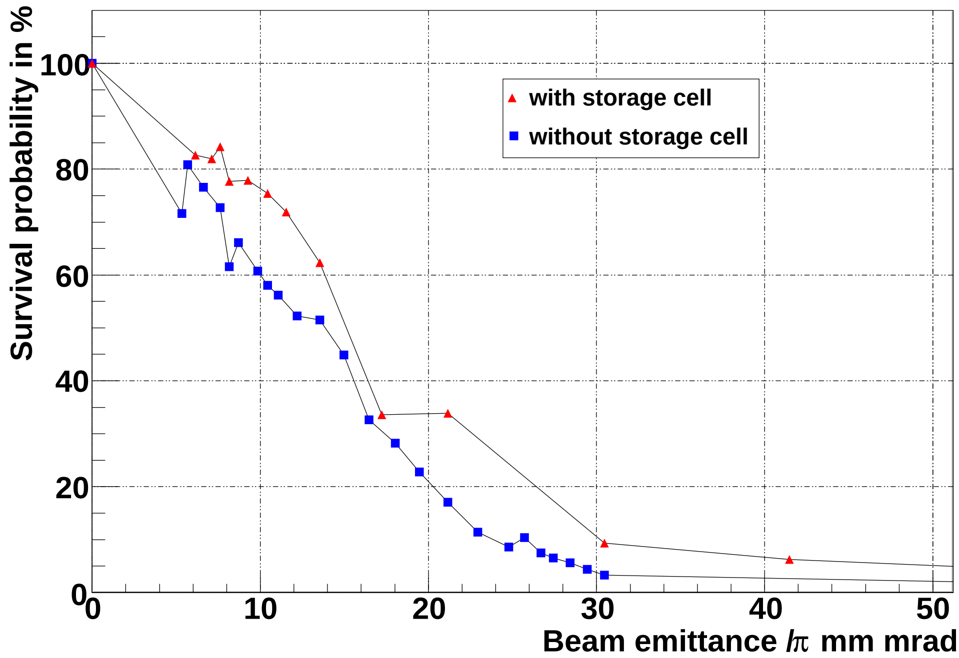

Figure 17: Survival probability *versus* emittance.

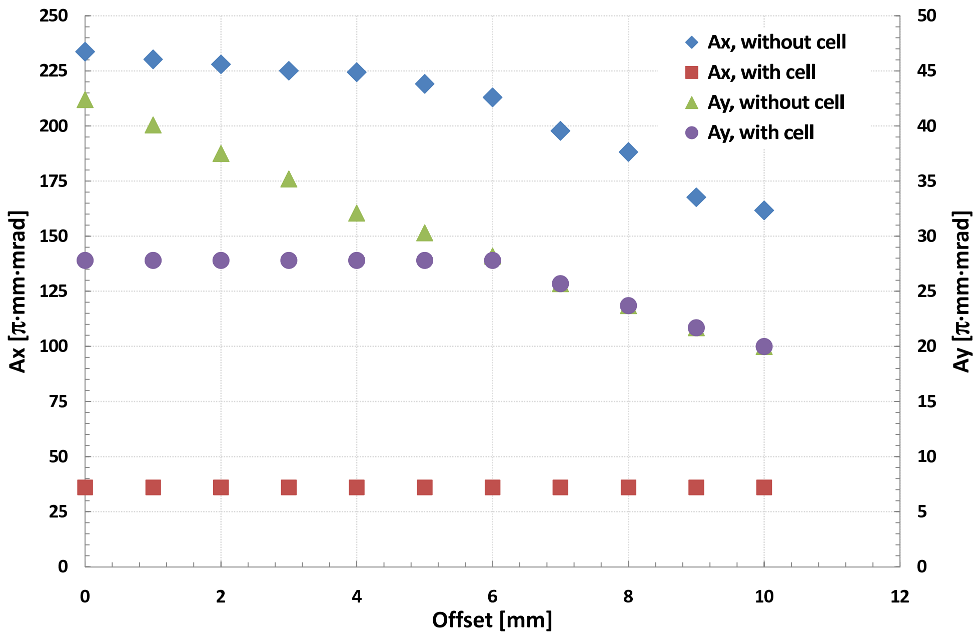

Figure 18: The plot shows the orbit deviations *versus* the vertical and horizontal acceptance with and without the storage cell.

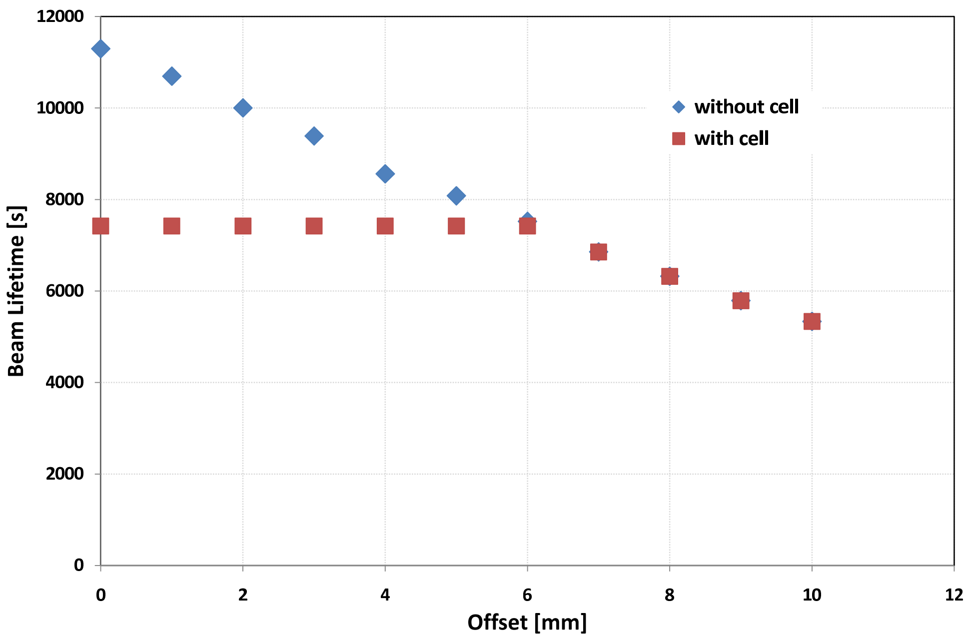

Figure 19: Beam lifetime as a function of orbit deviations.

of the machine, but also a region where higher lifetimes are expected. The determined lifetimes plotted *versus* the tune difference are shown in Fig. 22.

Here the two measurements near $\Delta Q = -0.4$ show the highest lifetimes. Further investigations close to these points should be performed during the upcoming beam development period at injection energy. Reducing the coupling to reach the region closer to $Q_x = Q_y$ has been achieved by adjusting the sextupole magnets of COSY. After this change the gap in the tune plot became smaller. These results are included into the plot with brown points. They do not show an increase in lifetime, and are even not stable without any explanation for it. The lifetime of all measurements is shown in Fig. 23.

With the properly electron cooled beam, a pure exponential behaviour of the beam current has been observed (see Fig. 24). Therefore, the beam losses are mainly due to single Coulomb scattering.

The second plot in Fig. 24 shows the $dBCT/dt$ signal, and the beam lifetime is calculated by $\tau = -\frac{BCT}{\frac{d(BCT)}{dt}}$. Here one can see the points representing the beam lifetime grouped into lines. A Fourier analysis is needed to clarify the observed structure.

A.5 Coupling with Electron Cooler Solenoids

By kicking the beam with different frequencies in the x and y direction and measuring the amplitude of the beam oscillations, the tunes show up as narrow peaks in this spectra. Tunes with $Q_x = Q_y$ are not reachable due to the coupling of the x and y planes. This coupling leads to a rotation of the eigenvectors of the transversal oscillations with respect

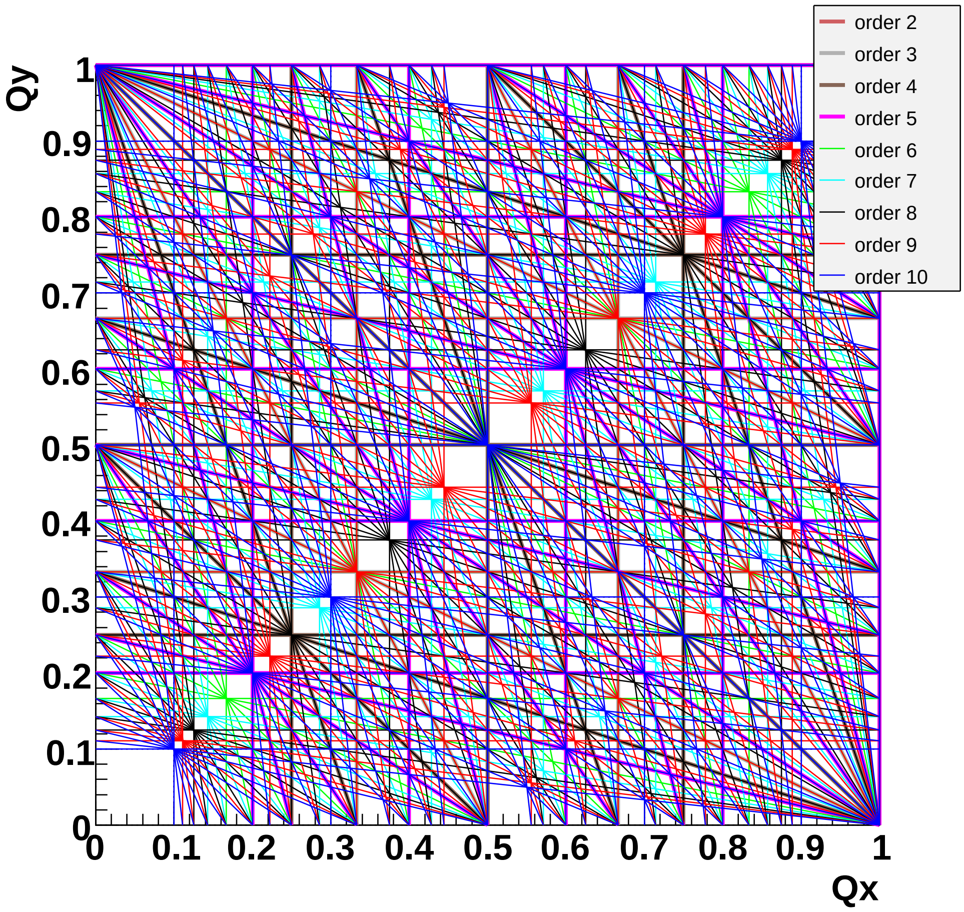

Figure 20: Fractional machine resonances up to the 10^{th} order.

to the x and y planes. Therefore one observes both frequencies in both x and y spectra. Only from the amplitudes of each peak one could associate one frequency to a plane. But sometimes this does lead to an ambiguity which cannot be resolved. Two reasons for coupling are:

- Sextupole magnets.
- Not compensated solenoid field.
- Torodial field (in E-Cooler).

The solenoid of the electron cooler has compensating magnets, with which the overall solenoidal field of the cooler should be zero. From the minimum difference the coupling strength could be calculated in terms of a bending power $(B \cdot dL)$. A measurement of the coupling strength in terms of the minimal tune difference as a function of the current in the compensating solenoids has been performed (see Fig. 25). This measurement shows,

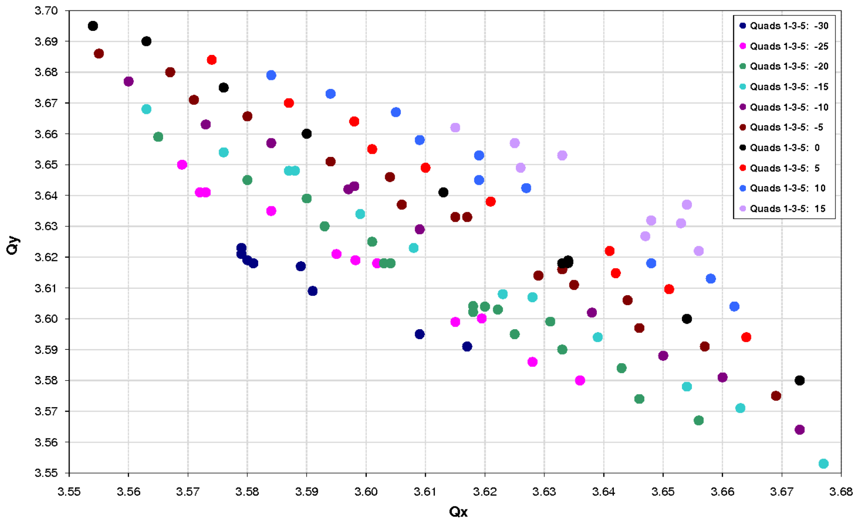

Figure 21: Tune occupancy plot.

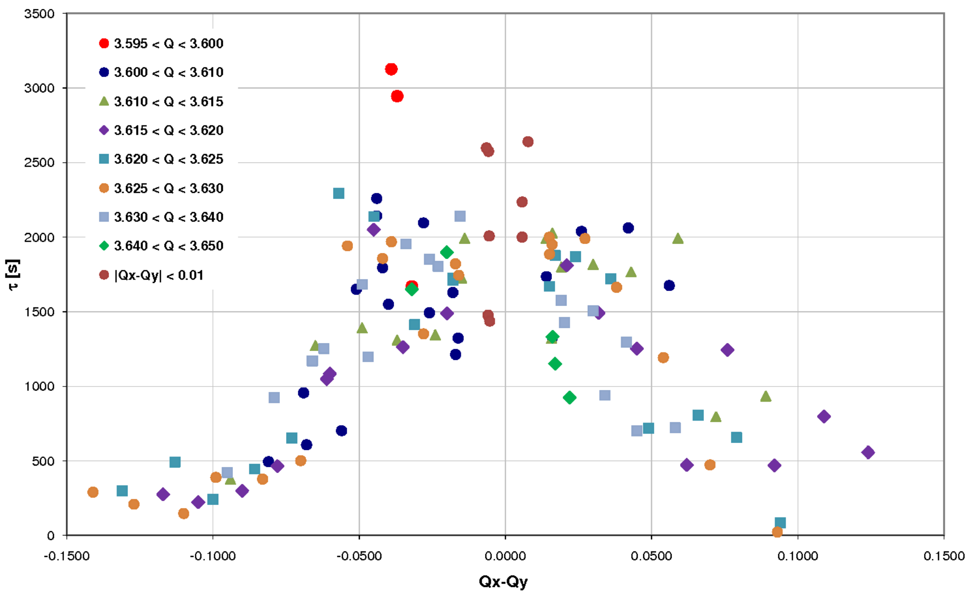

Figure 22: Beam lifetime as a function of tune difference. Each colour denotes a constant tune $Q = \sqrt{\frac{Q_x^2+Q_y^2}{2}}$.

that the coupling cannot be generated by the electron-cooler solenoid alone. After this measurement the coupling was reduced by tuning the sextupole magnets of the ring (see also Fig. 22).

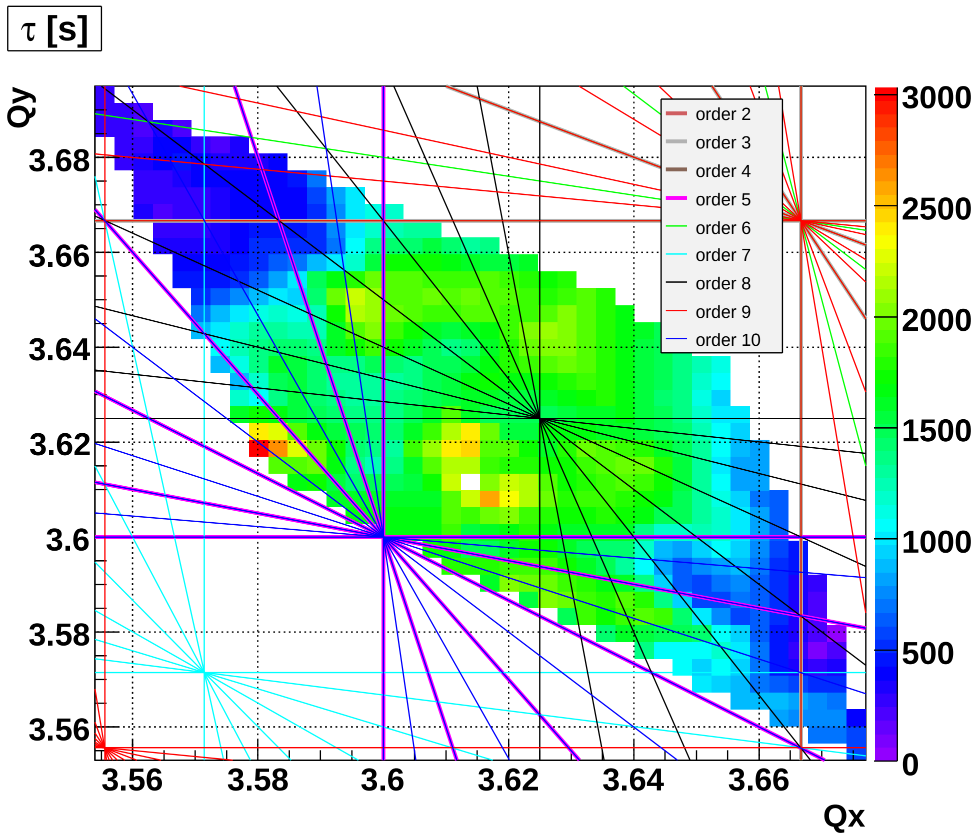

Figure 23: Lifetime as a function of the tune.

A.6 Target Density and Beam Lifetime

In order to check up to which target density the electron cooler could compensate the multiple Coulomb scattering, the lifetime was measured with different gases and different target densities. As the time dependence of the beam current is purely exponential the lifetimes resulting from different effects τ_i lead to a total lifetime τ_{total} of:

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_1} + \frac{1}{\tau_2},$$

where τ_1 is the contribution from the target and τ_2 is the lifetime, which is due to the residual gas. In order to disentangle the two contributions, the measurement has been performed in two cycles: one with the target switched on and one with the target off.

Each cycle was been organized as follows:

- Injection: 0 s
- Cooling on: 6 s
- Target on: 26 s, (later 66 s)

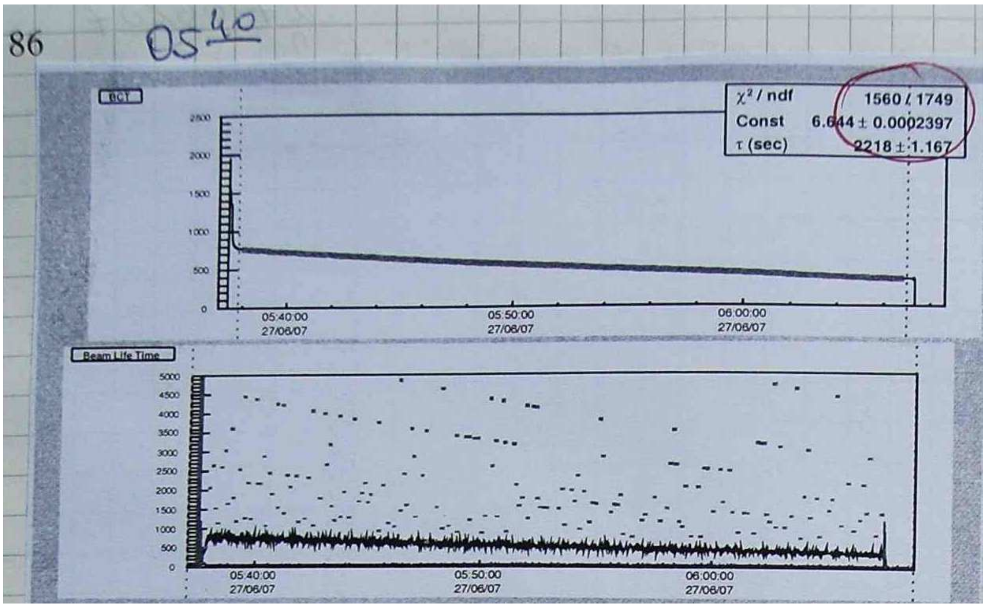

Figure 24: Beam current with exponential fit in upper plot, $\frac{d(BCT)}{dt}$ and local beam lifetime in plot below.

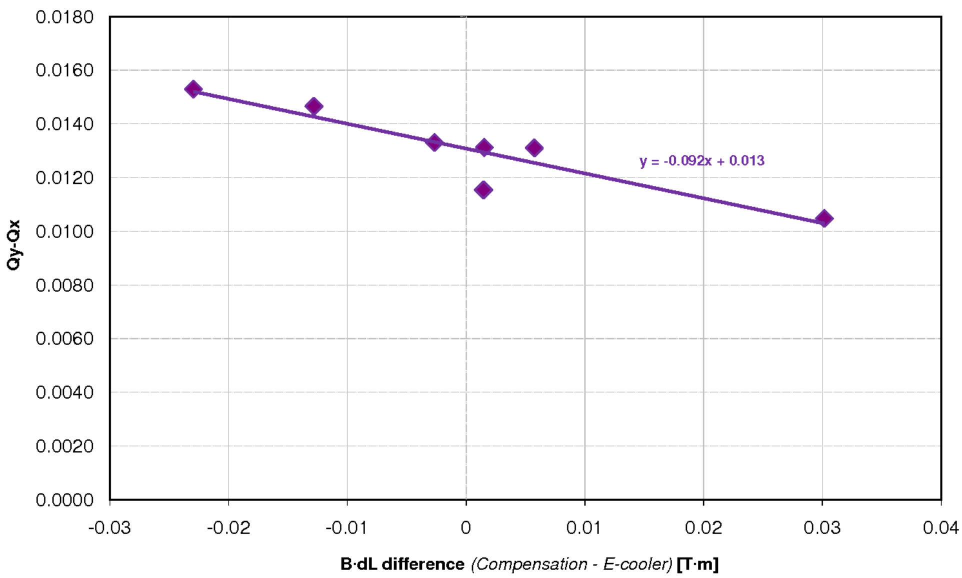

Figure 25: Tune difference as a function of the magnetic field in electron-cooler.

- Target off: 1740 s
- Cooling off: 1790 s

For higher target densities, the target-on signal was shifted to a later time. This became necessary because of the observed higher beam losses just after switching the target on, as shown in Fig. 26. With the shifted target-on timed, these beam losses did not occur anymore. The only explanation for this effect would be that the beam needs more time to

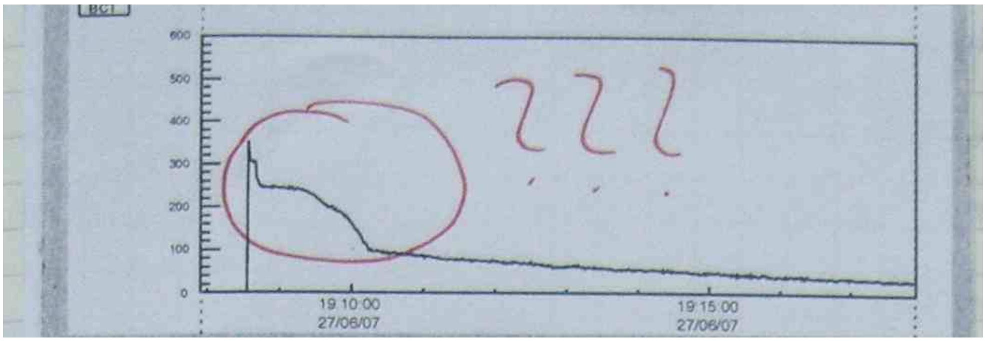

Figure 26: Initial beam loss after switching the target on.

be cooled down.

For every gas type, several target densities have been measured. As the single Coulomb scattering losses increases linearly with the target density ρ, the lifetime should be proportional to $\frac{1}{\rho}$.

For each target density the lifetime caused by the target effect was calculated using the lifetime from the cycle with target and one cycle without target nearby. This was done to minimize the influence of the varying residual gas and other effects in the ring.

A.7 Deuterium

In the deuterium case the target density dependence was measured during two nights. All results are shown in Fig. 27. The plotted fit-curve shows an exponent of -1.01, which is in perfect agreement with the expected value of -1. The lifetime with the target density of $\approx 1.2 \cdot 10^{14} \frac{1}{\mathrm{cm}^{-2}}$ was only 150 s, which has to be improved by at least an order of magnitude.

A.8 Helium

As helium is pumped very badly (see Fig. 28), it was not possible to measure the target density dependence with helium. The helium gas travels around the ring and the lifetime without target was strongly varying from cycle to cycle.

This shows that there is no way to use helium as a target with the existing pumps. Only a decrease of the temperature for the cryo pumps from 10 K to 7 K (see Fig. 29) or replacing the cryo pumps with turbo pumps could improve this.

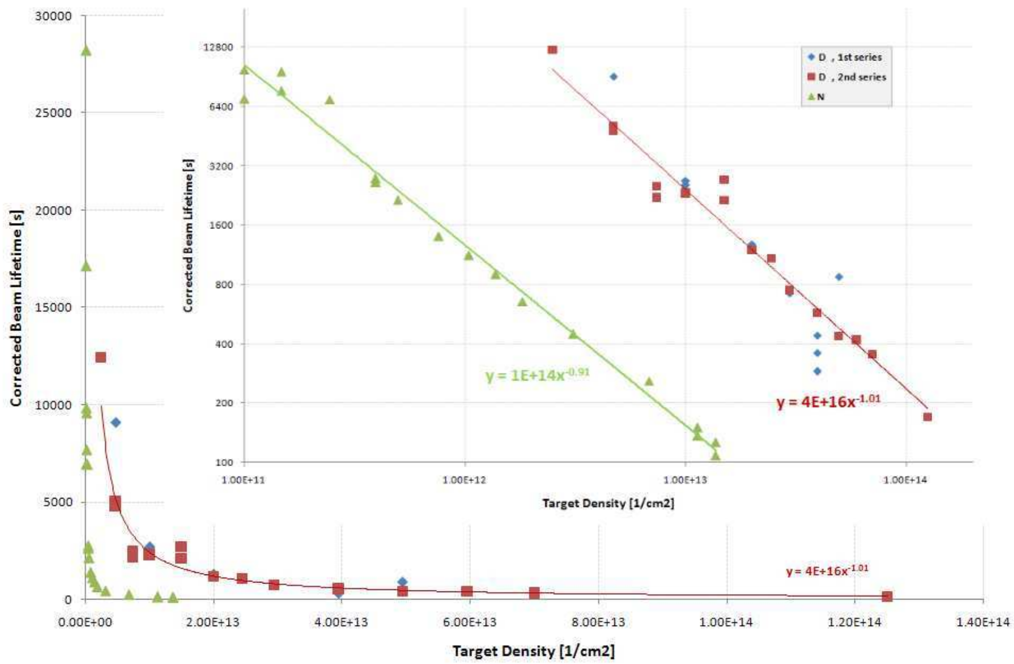

Figure 27: Beam lifetime dependence of the target density and a fit curve with the exponent as a fit variable for deuterium and nitrogen targets. The densities given here are atomic ones.

A.9 Nitrogen

For nitrogen the lifetime dependence on the target thickness is in good agreement with the expected $\propto 1/\rho$ behaviour (see Fig. 27). Like in the deuterium case, the reached lifetime with the target density of $\approx 1.0 \cdot 10^{13} \frac{1}{\mathrm{cm}^{-2}}$ was only 170 s. The ratio between the lifetime with deuterium and nitrogen should be 49:1, because nitrogen has $Z = 7$ and the beam lifetime is proportional to $1/Z^2$, although the observed ratio is roughly 20:1. There are several effects, which can cause this. First, for the two gases the gas inlet was calibrated separately. A small uncertainty in this calibrations can easily lead to a large change in the ratio. On the other hand it is possible, that the residual gas is different in the cycle with and without target. This would lead to a wrongly corrected lifetime resulting in a change of the ratio.

A.10 Beam Lifetime and Beam Intensity

At COSY we have a possibility to use stack injection in order to increase the beam intensity and micro pulsing to provide smaller intensities.

By using the micro pulsing the beam intensity has been adjusted between $4 \cdot 10^8 \frac{1}{\mathrm{cm}^2}$

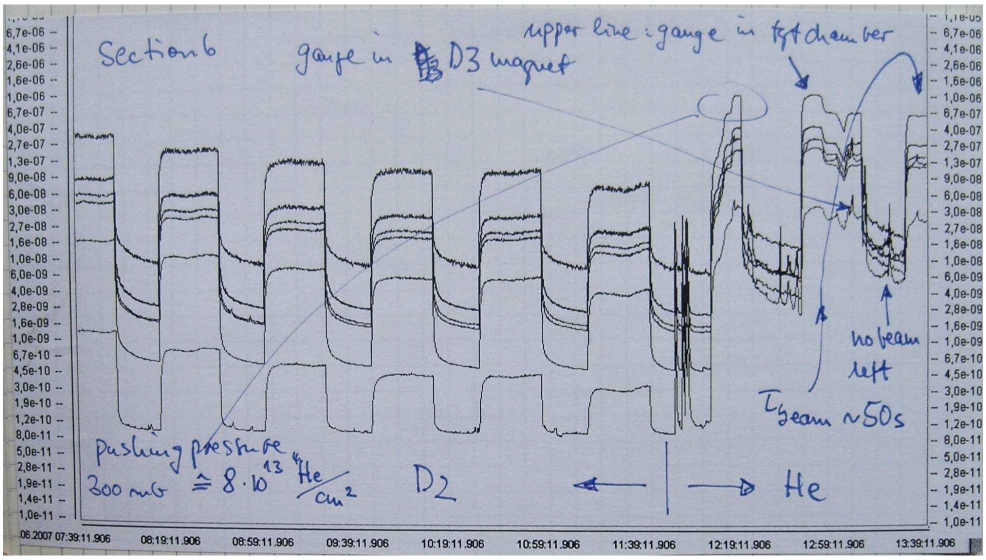

Figure 28: Pressure in section 6 with and without a deuterium and helium target.

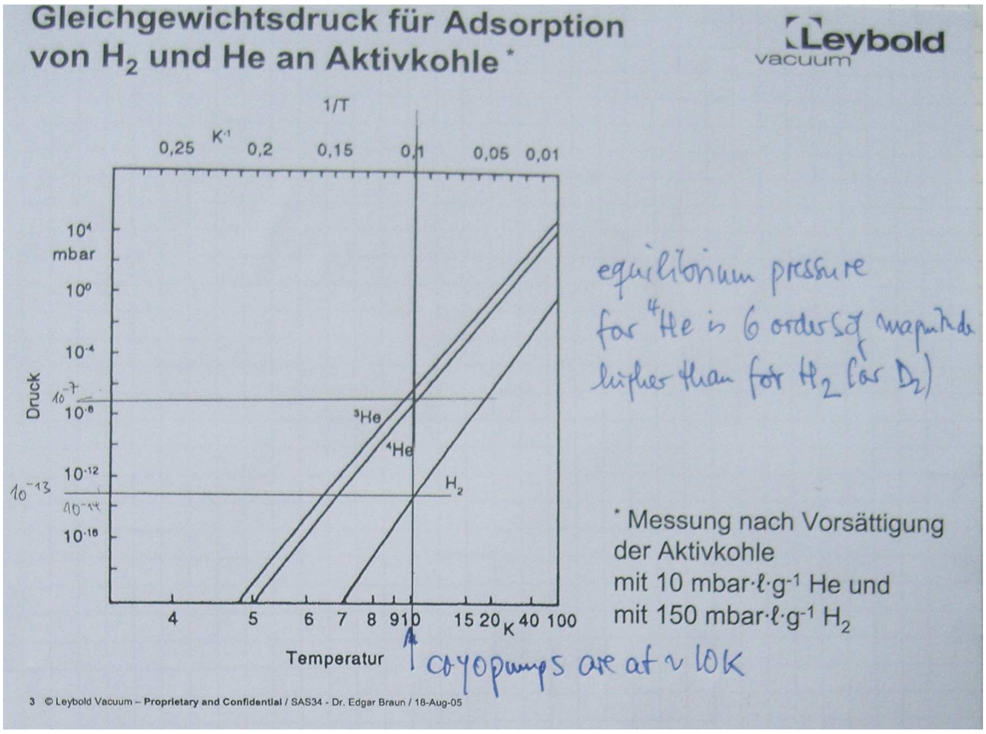

Figure 29: Equilibrium pressure for absorption of H_2 and He with active coal.

and $1.4 \cdot 10^9 \frac{1}{\mathrm{cm}^2}$. For all different targets the measured lifetime exhibits no dependence on the beam intensity (see Fig. 30).

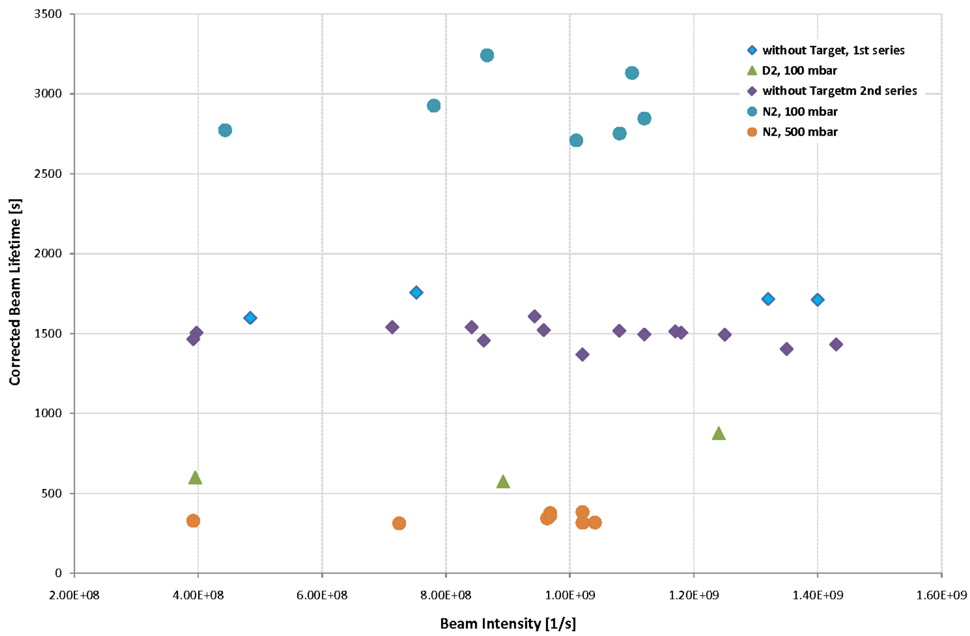

Figure 30: The lifetime dependence on the beam intensity for different gases and target densities .

A.11 Conclusions and Outlook

1. In the current situation the use of ^{4}He target is not possible unless the pumping capabilities at the ANKE target location are substantially improved.

2. With electron cooling the beam exhibits a purely exponential behaviour, indicating single Coulomb losses only.

3. A flat orbit is required. For a careful adjustment it is however necessary to calibrate the BPMs.

4. A machine acceptance of $\approx 20\ \pi$ mm mrad has been measured both with and without cell. The cell is not the limiting aperture in the machine and an improved closed orbit correction is necessary to increase the machine acceptance.

5. In spite of the fact that higher beam lifetimes are expected in the region where horizontal and vertical tunes are equal, there is an area quite far away from the $Q_x = Q_y$ line, where the highest lifetimes were observed. This region should be studied in the upcoming machine development once again in more detail. Furthermore, the tune dependence of the beam lifetime near the line of equal tunes displays structures, which at the moment are not understood.

6. The beam lifetime is generally independent from the beam current, although the

situation at high intensities of the order of 10^{10} particles per spill could not be examined yet.

7. A beam lifetime of 250 s was observed for a deuterium target thickness of 10^{14} cm^{-2}, which is much substantially than the predicted values. Such lifetimes make the proposed depolarization studies almost impossible at the ANKE IP. Therefore, further machine development seems necessary.

8. The beam lifetime at high beam currents has to be investigated. This requires the electron cooler to be set for two different energies, because it is needed both for stacking and for cooling on flat top.