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RECENT DEVELOPMENTS AND EXPERIMENTAL RESULTS FROM ELECTRON COOLING OF A 2.4 GeV/c PROTON BEAM AT COSY

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Abstract

The COSY control system as well as other subsystems are being upgraded. The 2 MeV electron cooler was recently extended with the EPICS control system and thereby integrated into the control and data acquisition system of the Cooler Synchrotron COSY. Taking advantages of the new software capabilities, studies of transverse and longitudinal magnetized electron cooling of a proton beam at 2.4 GeV/c were carried out. Electron and stochastic cooling were combined to reduce the cooling time while achieving lowest possible emittance and momentum spread. Results from experiments are discussed including cooling dynamics during operation of an internal cluster-jet target designed for the PANDA experiment at HESR. We present the results of probing the electron velocity distribution by means of the strongly cooled beam itself. The shape of the measured distibution may be caused by the galloping/scalloping effects within the electron beam. This effect plays a significant role in the strong dependence of the longitudinal and transverse electron cooling process on the proton beam size. Also discussed are the technical developments, achievements and further plans regarding the control system upgrade.

INTRODUCTION

The Cooler Synchrotron (COSY) is a storage ring operated at the Nuclear Physics Institute (IKP) at Forschungszentrum Jülich. Polarized as well as unpolarized proton and deuteron beams in the energy range 45 MeV to 2700 MeV can be delivered.It is equipped with a stochastic cooling system and two electron coolers. Currently a stochastic cooling system for the HESR is tested. While the 100 keV electron cooler operates mostly at injection energy, the 2 MeV electron cooler is designed for proton beam momenta beyond the COSY operating range of up to 4.5 GeV/c. The high energy electron cooler was developed at the Budker Institute of Nuclear Physics [1] and is being operated at COSY since 2013 [2].

TECHNICAL DEVELOPMENTS

EPICS Integration

The control system of the 2 MeV electron cooler was originally designed as a standalone-system. Six servers exist for control and diagnostics of the hardware components: the primary and secondary magnetic guiding system controlling the electron beam orbit, the beam position monitors (BPM) measuring the orbit, the electron gun and collector, the high-voltage accelerating sections as well as an interlock system for safety aspects. These systems are located in a separated environment with a custom control system.

In the course of upgrading the COSY control system to the Experimental Physics and Industrial Control System (EPICS) [3] it was decided to incorporate the 2 MeV electron cooler into the new control system. Having a common standard allows not only to further automate the beam cooling systems but also eases the handling of experimental data across various systems.

In order to integrate the 2 MeV electron cooler's control system into EPICS, an Input-Output-Controller (IOC) was developed. The IOC communicates with the cooler's systems using the EPICS modules *Stream* and *AsynDriver* while leaving the existing systems untouched. It provides the various parameters as process variables (PVs) to the EPICS control system, taking care of binary conversion and physical quantities. In addition, the EPICS alarm system is used to notify operators of critical values outside the normal operation ranges. [4]

Table 1 gives a statistical overview of the PVs made available. Currently the parameters of all systems are provided for readout and additional PVs exist to control the magnetic guiding system and electron gun. It is planned to further expand the control capabilities.

By having incorporated the 2 MeV electron cooler into the COSY control system EPICS, several advantages were achieved. The cooler's data is now centrally archived in a time correlated manner. This provides easier data-analysis after the experiments because all data is now saved continuously and stored in one single place. It is much easier to correlate the electron cooling data with other accelerator systems like beam diagnostics or timing. Furthermore a wide range of established tools designed for EPICS is used, e.g. to analyse data on-the-fly, producing physically meaningful displays which are vital for machine operation. Due to the

Table 1: Implemented Parameters

	Readout	**Control**
Analogue	610	63
DAC	*71*	*63*
ADC	*539*	
Binary status	381	60
Other	38	
Total	1029	123

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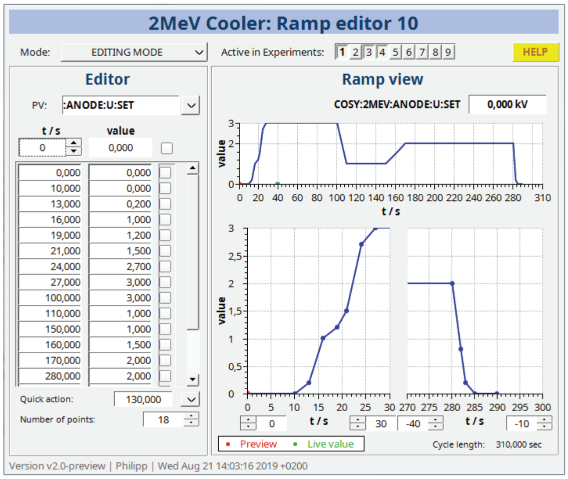

Figure 1: Screenshot of the ramp editor CSS-GUI.

common control system an enhanced interaction between the accelerator and electron cooler is possible, e.g. by means of automation (see also next section).

In addition to the 2 MeV electron cooler's EPICS integration, the most important parameters of the 100 keV cooler were also made available as PVs just recently. We are currently working on integrating the stochastic cooling system as well.

Ramp Editor

In order to automate the operation of the electron cooler a ramp editor was developed. Figure 1 shows a screenshot of the user interface. Based on the EPICS control system the editor allows to define arbitrary waveforms for a given parameter. The values are then interpolated based on the specified waveform and synchronised to the COSY timing system. This allows an automated, synchronous ramping of any desired parameter. For example, the electron current can be ramped up with the lowest possible beam loss by fine-tuning the voltage ramps of the electron gun. Once set up according to the experimental requirements, the system will provide reproducible cooling properties for every machine cycle.

COMBINED ELECTRON AND STOCHASTIC COOLING

Stochastic Pre-Cooling

Taking advantages of the new control system components, studies of transverse and longitudinal magnetized electron cooling with a proton beam at 2.4 GeV/c were carried out [5]. Thereby the electron cooling was combined with the stochastic cooling system at COSY. The stochastic cooling works best at high beam emittance where electron cooling is comparatively slow while the electron cooler performs better at low emittance. Figure 2 shows a typical setup where stochastic pre-cooling is followed by electron cooling. The equilibrium momentum distribution reached for the given setup of the stochastic cooling is shown by the black spectrum. Afterwards fast electron cooling is observed at low beam emittance. The 2 MeV electron cooler is capable of further reducing the momentum uncertainty by a factor of 6.6 (as shown by the blue spectrum) as well as the emittance by a factor of 2 compared to the stochastic cooling system.

Our experiments show that not only the equilibrium momentum spread but also the cooling time can be reduced by using stochastic pre-cooling compared to electron cooling only. Stochastic cooling was only required in the transverse direction, reducing the initial beam emittance of about 0.3 mm mrad to 0.09 mm mrad (horizontal) and 0.8 mm mrad to 0.12 mm mrad (vertical). This leads to a faster electron cooling not only in transverse direction but also longitudinally. The momentum cooling time is reduced from $\tau = 20.2(10)$ s to 7.7(3) s due to the lower emittance. At the same time the equilibrium momentum uncertainty is reduced from $\Delta p/p = 6.1(2) \times 10^{-5}$ to $3.0(2) \times 10^{-5}$ while showing a more symmetric shape.

This shows how cooling can be improved significantly by combining the advantages of both cooling systems.

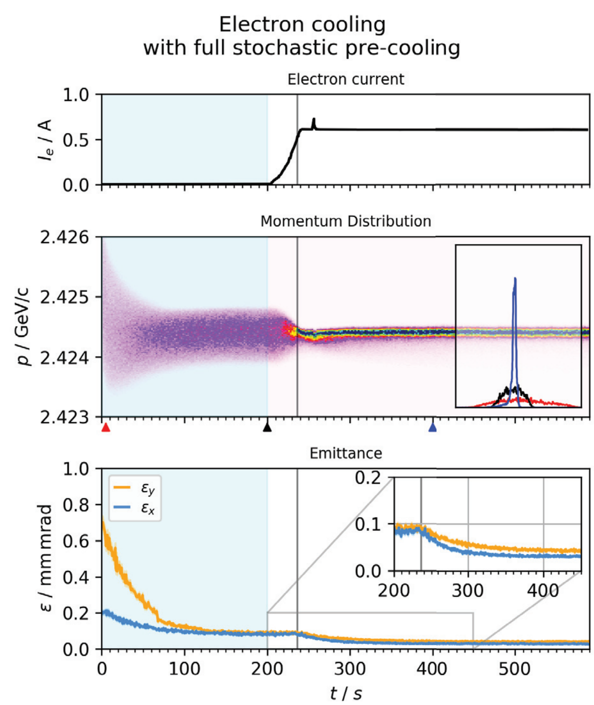

Figure 2: Momentum distribution (middle plot) and emittance (lower plot) of a 2.425 GeV/c proton beam consisting of $3 \cdot 10^8$ particles. The beam is cooled with longitudinal and transversal stochastic cooling for the first 200 s. Afterwards electron cooling is applied. The electron current of 0.73 A at 907.9 keV is shown in the upper plot. The initial momentum spread of $\Delta p/p = 5 \cdot 10^{-4}$ (red marker and spectrum) is reduced to $2 \cdot 10^{-4}$ (black) and finally $0.3 \cdot 10^{-4}$ (blue).

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Counteracting Adverse Target Effects

Additional experiments with the electron cooler were carried out while a target was installed in the ring. The PANDA Cluster-Jet Target [6] generates hydrogen clusters with an effective density of $1 \times 10^{13}\,\mathrm{cm}^{-2}$ to $2 \times 10^{15}\,\mathrm{cm}^{-2}$. Measurements at a density of $1 \times 10^{15}\,\mathrm{cm}^{-2}$ showed that the emittance control in the present set-up is not strong enough to compensate the emittance growth due to beam-target-interaction. The mean energy loss can be compensated for by the barrier bucket system.

However, at an average target density of $2 \times 10^{14}\,\mathrm{cm}^{-2}$ the most emittance growth can also be compensated by electron cooling. It is again useful to combine the electron cooling with transverse stochastic cooling so a low emittance is reached faster. With electron cooling only, the momentum distribution is broader and energy loss due to the target is clearly visible (see Fig. 3). By using transverse stochastic pre-cooling and therefore having a lower emittance we were able to enhance the electron cooling process. This results in narrower and more symmetric momentum distribution and fewer beam losses (see Fig. 4).

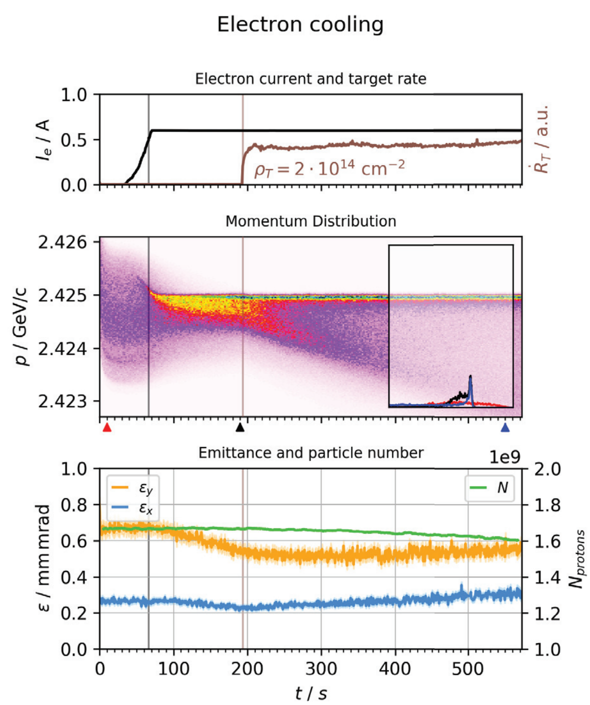

Figure 3: Momentum distribution (middle plot) and emittance (lower plot) of a 2.425 GeV/c proton beam consisting of $1.7 \cdot 10^9$ particles. The beam is cooled with electron cooling only. The electron current of 0.6 A at 908 keV is shown in the upper plot along with the target-beam-interaction event rate. The initial momentum spread of $\Delta p/p = 6 \cdot 10^{-4}$ (red marker and spectrum) is reduced to $2 \cdot 10^{-4}$ (black) before target operation. The target is switched on at 190 s.

During our experiments an artefact appeared in the schottky-spectrum when electron and transverse stochastic cooling were applied at the same time. The artefact is clearly visible in the momentum distribution calculated from the schottky-signal measured at the stochastic cooling pick-up in Fig. 4. The reason for its appearance in the schottky-signal is not yet fully understood. One can also see a disturbance in the horizontal emittance at the same time. However this is purely an effect of calculation when obtaining the emittance from a beam profile measurement (dispersion). The beam profile measured with an Ionisation Profile Monitor (IPM) does not show the disturbance in either plane. Therefore it is possible that the observed artefact is a coherent effect rather than a beam instability. It might possibly be related to the pick-up used, which is part of the stochastic cooling loop.

ELECTRON VELOCITY PROFILE

Method

We describe a method of measuring the electron velocity distribution within the electron beam by probing it with the pencil proton beam. Therefore the beam is well cooled in advance of the measurement. Making use of the new EPICS software components the electron orbit is then shifted in the cooling section by keeping it parallel to the proton beam. Thereby the relative position of the pencil proton

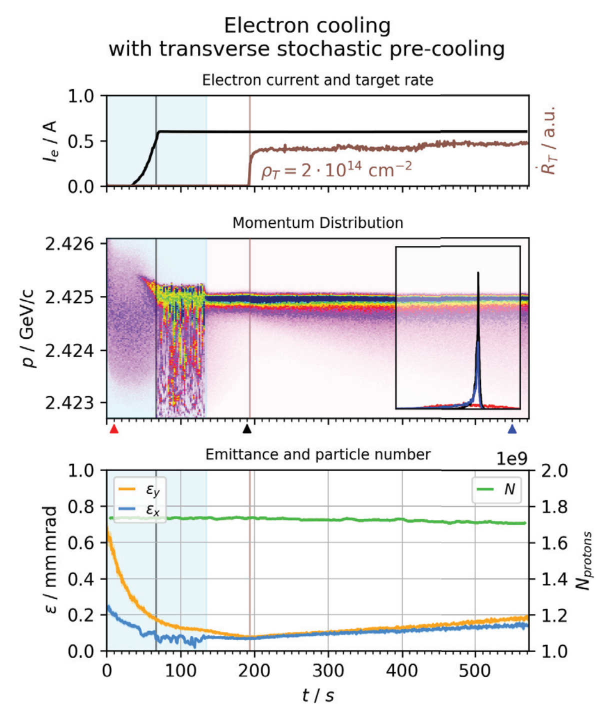

Figure 4: Beam properties as in Fig. 3. Here the beam is cooled with transversal stochastic cooling for the first 135 s and electron cooling starting at 50 s. The initial momentum spread of $\Delta p/p = 6 \cdot 10^{-4}$ (red marker and spectrum) is reduced to and kept at $3 \cdot 10^{-5}$.

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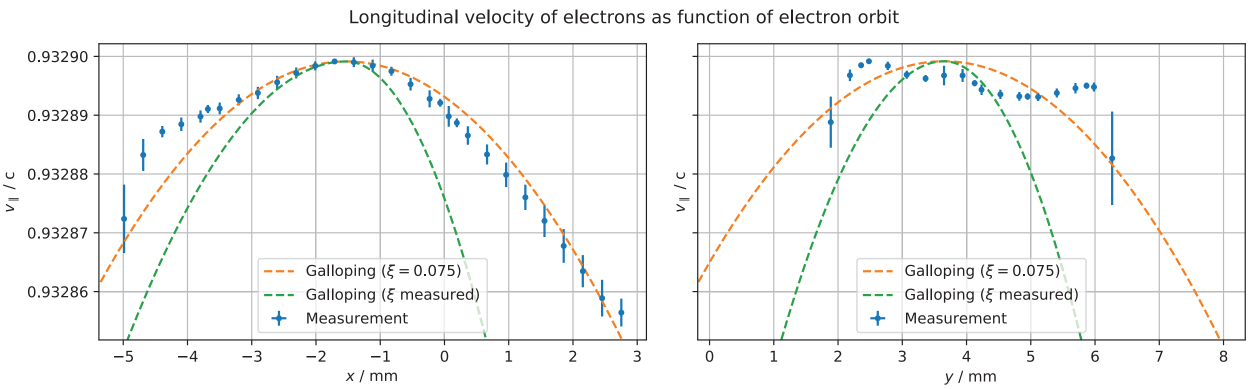

Figure 5: Measurement of the horizontal and vertical distribution of the electron's longitudinal velocity component within the electron beam. The fitted theoretical shape due to galloping effects is indicated for comparison (orange dashed lines). The rate was also obtained by measuring the larmor radius as function of the magnetic field (shape in green dashed lines).

beam within the (larger) electron beam is changed systematically.

Due to the cooing dynamics the protons adjust to the local velocity of the electrons. When moving the electron beam around the fixed pencil proton beam stepwise, the proton velocity changes accordingly. This yields a distribution of the effective electron velocity component parallel to the proton orbit. The velocity change of the protons can be deduced from the frequency change visible in a schottky-spectrum measurement. This way the electron velocity distribution within the electron beam (*velocity profile*) can be obtained.

Measurement Results

Figure 5 shows the measured velocity distribution within the electron beam. It is clearly visible that there is a maximum point from where the longitudinal velocity decreases with distance. The horizontal profile shows a nearly parabolic shape where the velocity at the edge of the electron beam is reduced by a factor of about $5 \cdot 10^{-5}$. However the vertical profile has a complex shape where the velocity component is only reduced by a factor of $1 \cdot 10^{-5}$.

The reduced longitudinal electron velocity suggests an increased velocity component transverse to the particle motion. This can be explained by larmor oscillations due to the strong longitudinal magnetic guiding field in the cooling section (magnetized cooling). The effect is called galloping (or scalloping in some papers) as the transverse motion and therefore larmor-radius increases with distance from a maximum point [7].

The dashed curves in Fig. 5 indicate the theoretical distribution due to galloping with a fitted and measured galloping rate. The distribution seems to be dominantly caused by these effects, but the asymmetry especially in the vertical profile suggest an additional cause. This might be a higher order beam motion which can also explain the asymmetry in the vertical plane compared to the horizontal distribution. Also space charge effects have not been considered in the theoretical deliberations.

The presence of larmor oscillations impairs the transverse cooling. This is particularly critical for large diameter proton beams (high emittance) because interaction with the hot electrons at the outer region can not be prevented. Therefore much better cooling results are obtained for narrow proton beams.

SUMMARY AND OUTLOOK

Based on the EPICS integration of the 2 MeV electron cooler and related systems, measurements of combined stochastic and electron cooling were carried out. These show a significantly faster electron cooling and a lower equilibrium momentum spread for low beam emittance due to stochastic pre-cooling. This way we were able to combine the advantages of both cooling systems.

During simultaneous operation of the stochastic and electron cooling an artefact in the schottky spectrum was observed. We suspect that this might be a measurement-induced effect and intend to study the cause in the next beam time. Therefore it is planned to measure the schottky signal with an independent pick-up and also to check possible dependencies on the stochastic cooling loop and electron energy.

Additionally a measurement of the velocity distribution within the electron beam was performed. This indicates an issue with the transverse electron temperature mainly caused by larmor rotations. In order to improve the cooling process it is of high importance to compensate this transverse motion wherever possible. Space charge effects as well as the influence of the beam density profile were not yet taken into account. It is further planned to also consider asymmetric effects in the bending sections of the electron beam transport channel. These might give a possible explanation for the difference between the horizontal and vertical profile.

The present experiments prove that the combined use of stochastic and electron cooling is useful to obtain a small momentum spread and transverse emittance even while an internal target of high density is inserted in the ring. It is

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strongly suggested to use this kind of beam cooling method for the PANDA experiment and future HESR operation up to an anti-proton beam energy of about 3 GeV. The electron cooling will also be very effective for cooling of highly charged ion beams and therefore inevitably necessary to reach similar experimental conditions for ions in the HESR.

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