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DESIGN OF STOCHASTIC PICK-UPS AND KICKERS FOR LOW BETA PARTICLE BEAMS

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Abstract

The COSY facility hosts experiments for the JEDI (Jülich Electric Dipole moment Investigations) collaboration. Polarized deuteron beams with a momentum of 970 MeV/c are stored in the ring. To achieve polarization times in the order of several minutes, small emittances and momentum spread are crucial. Therefore, the beam is pre-cooled with the 100-kV electron cooler. To further improve the spin coherence time, cooling during the experiments would be desirable. That way, the beam blow-up due to intra beam scattering could be compensated. But since the focusing solenoids in the e-cooler may not be perfectly compensated, it cannot be used to cool during the experiments. The existing stochastic cooling (SC) system is not sensitive at low beam velocities. Thus, it is proposed to build a dedicated SC system for low beta beams. This work presents the proposed system. It emphasizes the design process of pick-up and kicker hardware. Starting from the slot-ring structures that have been developed for HESR, an optimization towards a high sensitivity at a beta of 0.46 is undertaken.

INTRODUCTION

The discovery of an electric dipole moment (EDM) of hadrons would constitute a breakthrough in the search for CP violations. Since the proposed values of less than 10^{-24} e·cm are hard to resolve, great effort is done to design high precision experiments.

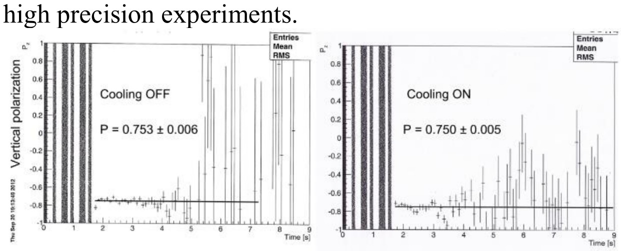

Figure 1: Vertical polarization measurement results after 30 minutes beam storage time, once without and once with vertical stochastic cooling.

The JEDI collaboration faces this task by investigating polarized beams in storage rings [1]. The precursor experiments currently done at COSY use vertically polarized deuterons at momenta of 970 MeV/c [2]. The goal is to increase the polarization lifetime up to the order of 1000 seconds. The beam is pre-cooled with the 100-kV electron cooler to reduce the beam emittances and momentum spread, and consequently increase the spin coherence time [3]. Unfortunately, the focusing in the e-cooler is done by a solenoid, which applies an unwanted longitudinal polarizing force to the beam. Thus, the solenoid is compensated by two additional solenoids before and after the beam intersection range. But this compensation is not perfect, and may not fulfil the desired accuracies.

To avoid such depolarization problems, the use of stochastic cooling (SC) instead of electron cooling is investigated. SC systems do not need focusing magnets at all. Thus, the cooling may be applied even during the experiment, counteracting the beam blow-up caused by intra-beam-scattering (IBS).

The influence of the SC system itself on the beam polarization was investigated in [4], concluding that no depolarizing influence is to be expected. To verify this result, vertical cooling was applied to a vertically polarized proton beam (1,965 MeV/c, $N = 3\times10^{8}$). Vertical cooling causes horizontal magnetic RF-fields, thus a horizontal polarization may build up. But after 30 minutes of cooled flat-top, no vertical polarization loss was investigated in comparison to an uncooled setup, as shown in figure 1. It is expected that this will be also true for low energy deuterons in EDM experiments.

PAST AND PRESENT STATE OF COSY COOLING SYSTEMS

The COler SYnchrotron (COSY) of the Forschungszentrum Jülich started its operation in 1993 [5]. Protons and deuterons are accelerated in the 184-m long ring and stored at momenta from 0.3 to 3.7 GeV/c. Remarkable features are polarized sources for both deuterons and protons, and the eponymous beam cooling systems.

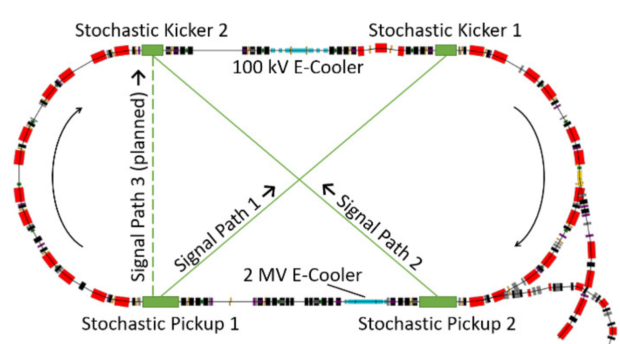

Figure 2: Cooling systems at COSY: Two electron coolers, the high energy SC system at signal path 1, the deprecated vertical and longitudinal system at path 2, and the planned low energy system at path 3.

In figure 2, an overview of the installed cooling systems is given. The initial configuration of COSY consisted of a 100-kV e-cooler for low energies, and a 3D SC system for the upper energy range.

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The e-cooler has a typical beam current of 250 mA, and can cool momenta up to 0.6 GeV/c per nucleon [6]. The original SC system is meanwhile disassembled to make space for new installations. It was designed for fast particles starting from 1.5 GeV/c [7]. It consisted of two separate sub-systems, one for the vertical plane at position “1”, and one for the horizontal at “2”. Furthermore, filter cooling was implemented as well at position 1 for the longitudinal plane. The roughly four-meter-long pick-up (PU) tanks and two-meter-long kicker (KI) tanks contained quarter-wave couplers as electrodes. They could be moved to increase the aperture for low energies, and the coupling impedance during cooling at high energies. The PUs were cooled below 30 K to increase the signal-to-noise ratio. The system was split to two frequency bands, i.e. 1 to 1.8 GHz and 1.8 to 3 GHz.

In 2013, the cooling capabilities of COSY were extended by a second e-cooler [8]. It covers to a wide voltage range from 0.025 to 2 MV, which corresponds to the complete energy range of COSY.

Figure 3: PU / KI of the high energy SC system for HESR. Right: One stack of 16 slot rings. Center: eight combiner boards are attached to the electrode lines. Right: Two stacks, boards are combined pairwise.

The original SC system was disassembled to make space for the new high energy system [9]. It was developed for the High Energy Storage Ring (HESR) at the Facility for Antiproton and Ion Research (FAIR) [10], and was successfully tested at COSY [11].

The PU and KI hardware was newly developed. Instead of quarter-wave couplers, it consists of slots that resemble iris-loaded linac cells [12]. This static aperture approach is possible due to the small HESR aperture of only 89 mm. The simulated longitudinal shunt impedance per length is more than twice as high as of a comparable quarter-wave structure.

Each cell is equipped with eight electrodes which couple to the magnetic field of the beam. Every electrode loads the slot with 50 ohms, resulting in a large bandwidth of one octave, i.e. from 2 to 4 GHz. The single cells are manufactured separately and stacked afterwards in groups of 16 (figure 3, right). Then, 16-to-1 combiner boards are attached directly onto the stack, combing the electrodes of each row with static delay lines corresponding to a beam velocity of $\beta = 0.93$. Finally, adjacent rows are combined in pairs, which can be connected from the outside via four outlets.

Each tank consists four such stacks, combined to one large shaft (figure 3, left). A network of hybrids and delay lines outside of the tank allows to adjust the delay between the stacks to fit an antiproton momentum range of 3.8 to 15GeV/c. The hybrids combine the opposing pairs, so that the horizontal and vertical plane can be operated in push-pull configuration separately, or all electrodes in sum mode. This allows for a simultaneous cooling of all three planes in one single structure, reducing the needed length additionally by a factor of two.

Since the system is designed for HESR, it is not suited for slow particles at all. The combiner boards are not very broadband since they have static delay lines. For $\beta = 0.46$, the combination loss is more than -13dB. Furthermore, the shunt impedance of the single slot rings drops below 1 Ω in the frequency band of 2-4 GHz. Thus, an additional dedicated system for slow particles is inevitable.

All HESR tanks are tested at COSY before they get shipped. One pair of PU and KI at a time is installed at signal line 1. Thus, line 2 is now free for new installations. Nevertheless, it was decided to install a new signal path for a low energy SC system, labelled “3” in the floor plan. That is because the sensitivity of the slot-rings strongly depends on the aperture. PU position 2 is too close to the injection point, and the full COSY aperture of 150 mm is needed during injection. At position 1, the high energy system already reduces the aperture. Since the new PU is much shorter than the old one, sufficient space is left for a second PU at the same position. The phase advance between the two kickers is almost exactly 2π, thus the transverse cooling condition is met between PU 1 and KI 2 as well. Furthermore, the deuterons are comparatively slow, so they still do not outrun the signal despite the shorter orbit length.

DESIGN OF NEW PICK-UP AND KICKER HARDWARE

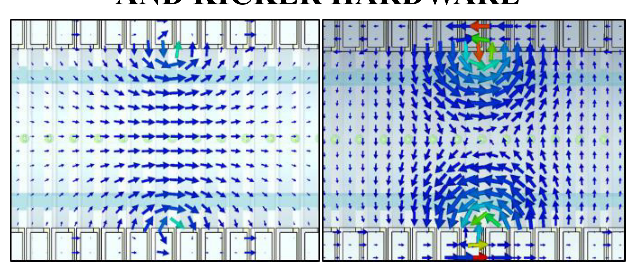

Figure 4: Transverse cut through a slot-ring kicker, with electric field of one excited cell. Left: All electrodes in phase (longitudinal). Right: Top and Bottom electrode in push-pull (vertical).

Starting from the design of the high energy slot ring kicker, the geometry was optimized for slow particles. For cooling band, the frequency range from 350 to 700 MHz was chosen. This is a comparatively small bandwidth, but simulations showed a Schottky band overlap starting from

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800 MHz. Furthermore, higher frequencies lead to low transit time factors for such slow particles.

The electromagnetic fields have been simulated with CST Microwave Studio 2016/2017 [13]. The structure was optimized for longitudinal shunt impedance. Therefore, structures with many cells, typically 31, have been modelled. The ends of the structure are connected to beam pipes, and terminated with waveguide ports. Only the center cell, in this example cell number 17, is excited. All electrodes of the cell are fed with signals of the same phase. The pulses are mostly reflected at the shorted ends of the electrodes, but some field reaches the beam axis, accelerating, or decelerating the beam (figure 4, left).

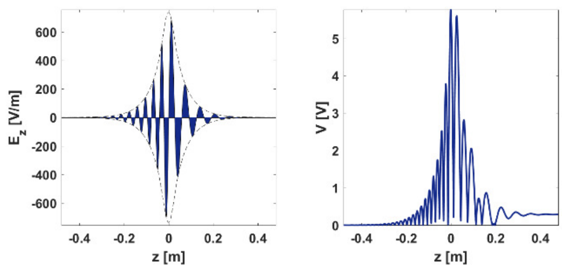

Figure 5: Left: Electric field observed by a slow particle passing through the HESR kicker, excited with 4 watts at 3 GHz. Right: cumulated voltage.

Although the frequency is far below cut-off of the aperture, a strongly damped TM_{01}-mode propagates along the structure, absorbed by the electrodes in the neighboring cells. The simulated structure length was chosen such that virtually no field reaches the beam pipe, to neglect end-effects. It is assumed that those end-effects are comparatively small, thus the quantities simulated for this center cell can be multiplied by the number of cells of the final structure to calculate the performance of the whole tank.

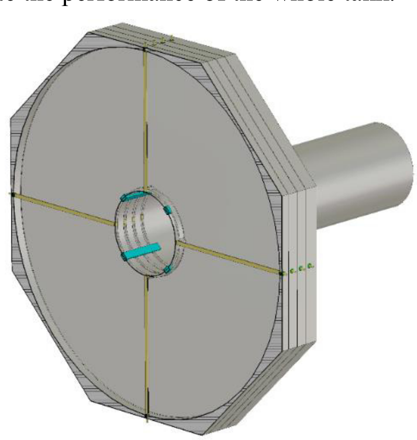

Figure 6: Low energy SC kicker as resulting from the optimization process.

The complex electric filed along the beam axis was used to calculate the longitudinal shunt impedance according to [14]. The particles passing the structure observe an effective accelerating voltage,

$$V = \int e^{j\omega\frac{z}{\beta c_0}} E_z(z)\mathrm{d}z. \tag{1}$$

This voltage is maximized for indefinitely fast particles. But since the electric field is oscillating during transit, its value drops strongly with transit time. To illustrate this, figure 5 shows the electric field that a particle with $\beta = 0.46$ experiences in the HESR KI at 3 GHz. The field changes its direction multiple times while the particle passes, and accelerating and decelerating periods almost cancel out. The cumulated voltage oscillates, resulting in a very small net acceleration. This shows that the HESR system is not suited for slow particles.

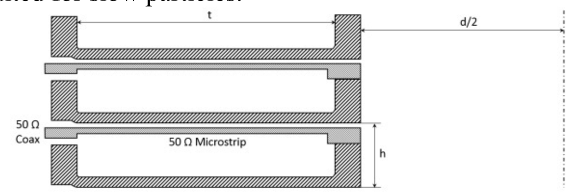

Figure 7: Cut through the cells of a slot ring coupler.

A cut through the slot of a cell is shown in figure 7. Thinking in terms of pick-ups, the image current of the beam must flow perpendicular to the slots, resulting in a voltage drop over the gap of the slot. This voltage is measured by the electrode, which forms a 50 ohms microstrip line with the upper neighboring cell and leads the signal to a coaxial transmission. Higher frequencies lead to bigger induced voltages over the slit, until the stray capacitances counteract this behavior.

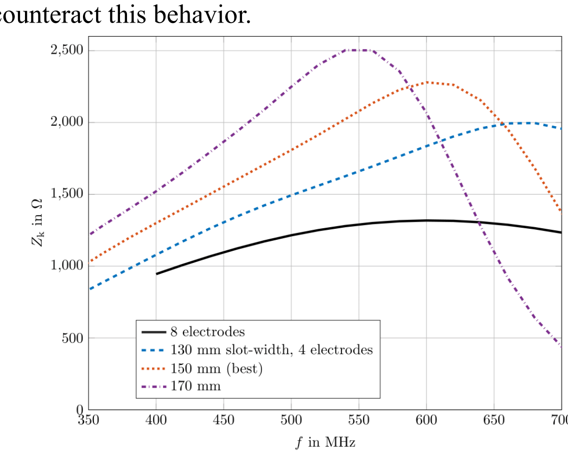

Figure 8: Longitudinal shunt impedance of a slot ring kicker for some variations of the tuning parameters. The longitudinal shunt impedance Z_k is given for a 64-cell long structure.

The longitudinal shunt impedance is a measure for the beam voltage that is achieved by a given input power. It is defined by

$$Z_\mathrm{k} = \frac{1}{2}\frac{|V|^2}{P_\mathrm{in}}. \tag{2}$$

The kicker geometry was optimized for Z_k by variation of different parameters. The result is displayed in figure 6. The aperture was set to 90 mm, to not further reduce the value given by the high energy PU. The most sensitive parameter is the slot width t. It defines the additional length for the image current and thus can be used to tune the resonant frequency to the desired band, as can be seen in the diagrams in figure 8.

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The cell height h is sensitive as well. Slimmer cells have a smaller impedance, but a higher impedance per length. Very slim cells are not advisable, because the combiner boards get more complex. As a trade-off, we stuck to 12.5 mm as for the high energy kicker.

The number of electrodes per ring was reduced to 4. The diagrams show that the bandwidth is still sufficient, and besides, the peak sensitivity is higher. Furthermore, the number of combiner boards is reduced by a factor of two. This gives space for the larger Wilkinson combiners and longer delay lines that are needed for the low frequencies.

The structure is comparatively huge with a diameter of approx. 40 cm. The stiffness was adjusted by increasing the thickness of the base plates to 2 mm, and adding plastic supports between the rings and around the electrode outlets. Simulations showed a negligible influence on the electromagnetic properties.

After optimization of the longitudinal shunt impedance, the transverse impedance was checked. The cell was excited in push-pull mode. The transverse impedance can be derived from the gradient of the beam voltage by utilizing the Panofsky-Wenzel-theorem [14]:

$$Z_{k,x} = \frac{1}{2\overline{P}_{in}k^2}\left(\frac{\partial \tilde{V}}{\partial x}\right)^2 \quad \text{with } k = \frac{\omega}{c_0} \tag{3}$$

Values of 1.6 kΩ or more were found for the whole band. This is sufficient for transverse cooling, thus no further optimization was done.

SYSTEM SIMULATION

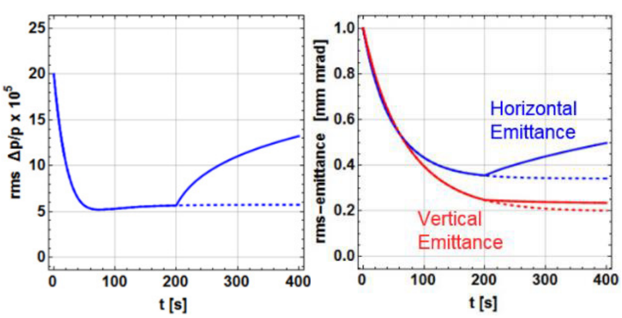

Figure 9: Momentum spread, horizontal and vertical emittance during 3D-cooling for 200 s, and beam blow-up when cooling is turned off.

The field simulation results have been used to simulate the cooling performance of the proposed system. A beam of 10^9 deuterons at 970 MeV/c was cooled in all three planes simultaneously, with filter cooling for the longitudinal plane. As can be seen in figure 9, an equilibrium state of 6×10^{-5} is reached for the momentum, and 0.35 or 0.2 mm mrad for the horizontal and vertical emittance. The longitudinal time constant is roughly 30 s and the transverse 80 s. When cooling is turned off, the strong influence of intra beam scattering is observed. This shows that permanent cooling during the experiment is desirable.

Another remarkable result of the simulation is the amount of RF cooling power, which turned out to be comparatively low. Of-the-shelf 5-watt power amplifier are sufficient for operation, thus an essential cost factor is omitted.

OUTLOOK

A set of test rings is under construction. The aim is to find out if the stiffness is sufficient, or whether the large plates will warp during the milling process. In parallel, new combiner boards will be developed that are suited for the new frequency band.

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