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Beam- and Spin Dynamics for Hadron Storage Rings

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High-precision physics experiments at hadron storage rings require highest beam intensity (or luminosity) and beam polarization. Advanced beam- and spin dynamics simulations are key tools to reach the anticipated performance. Hadron storage rings are used worldwide for various research topics and scientific applications (e.g., exploration of QCD physics in a wide energy range). In this paper the performance of polarized and cooled beams at the Cooler Synchrotron COSY, the layout of the High-Energy Storage Ring HESR at FAIR (Facility for Antiproton and Ion Research) and perspectives for high-precision beams of proposed storage rings for EDM (electric dipole moment) searches are discussed.

The Cooler Synchrotron COSY provides polarized and unpolarized proton (deuteron) beams in the momentum range from 300 (600) MeV/c to 3.7 GeV/c [1]. The COSY accelerator complex includes H^- and D^- ion sources and the cyclotron JULIC for pre-acceleration [2]. The negative charged ions are injected via charge exchange into the COSY ring. The layout of the COSY facilities is shown in Figure 1. COSY's lattice has a racetrack design, consisting of two 180° arc sections connected by straight sections. The total length of the ring is 183.47 m. The straight sections can be tuned as telescopes with 1:1 imaging, giving a 2π betatron phase advance. The super-periodicity (i.e. the number of magnetically identical periods in a storage ring) of the lattice can be adjusted to P = 2 or 6 [3]. Usually a P = 6 ion optics is applied at injection and changed to P = 2 during acceleration to avoid crossing the transition energy. To prepare high precision beams for experiments two different techniques of beam cooling are utilized: Electron cooling to increase phase space density at injection energy by means of stacking injection in combination with transverse feedback, and stochastic cooling to counteract beam heating of stored particles due to interaction with internal targets [4-7].

In a strong-focusing synchrotron like COSY two different types of first-order spin resonances are excited, namely imperfection resonances caused by magnetic field errors and misalignments of the magnets, and intrinsic resonances excited by horizontal fields due to the vertical focusing. In the energy range of COSY five imperfection resonances have to be crossed for protons. Vertical correction dipoles or a partial snake can be used to preserve polarization at imperfection resonances by exciting adiabatic spin flips. To preserve the polarization at the ten different intrinsic resonances, a rapid change of the vertical betatron tune and therefore a fast crossing of the spin resonance is applied. For this purpose, an air core copper coil quadrupole with a length of 0.6 m is installed in COSY. It is operated in pulsed mode, with currents of up to 3100 A, yielding a maximum gradient of 0.45 T/m, rise times of 10 μs, and fall times ranging between 10 and 40 ms [8]. Spin resonances are not crossed with polarized deuterons at usual vertical betatron tunes in the energy range of COSY. Since deuterons are spin-1 particles, they appear in three spin states (1,0,-1) relative to an arbitrary quantization axis, compared to two spin states (1,-1) of a spin-1/2 particle like the proton. Three vector components and five components of a second-rank tensor are required to describe spin-1 polarization. The polarized ion source at COSY is designed to provide a sequence of vector and tensor polarized beams, to be selected by the user out of the variety of possible combinations.

In recent years, vertically polarized proton and deuteron beams have been routinely accelerated in COSY and delivered to internal as well as external experiments at different momenta with polarization above 80%.

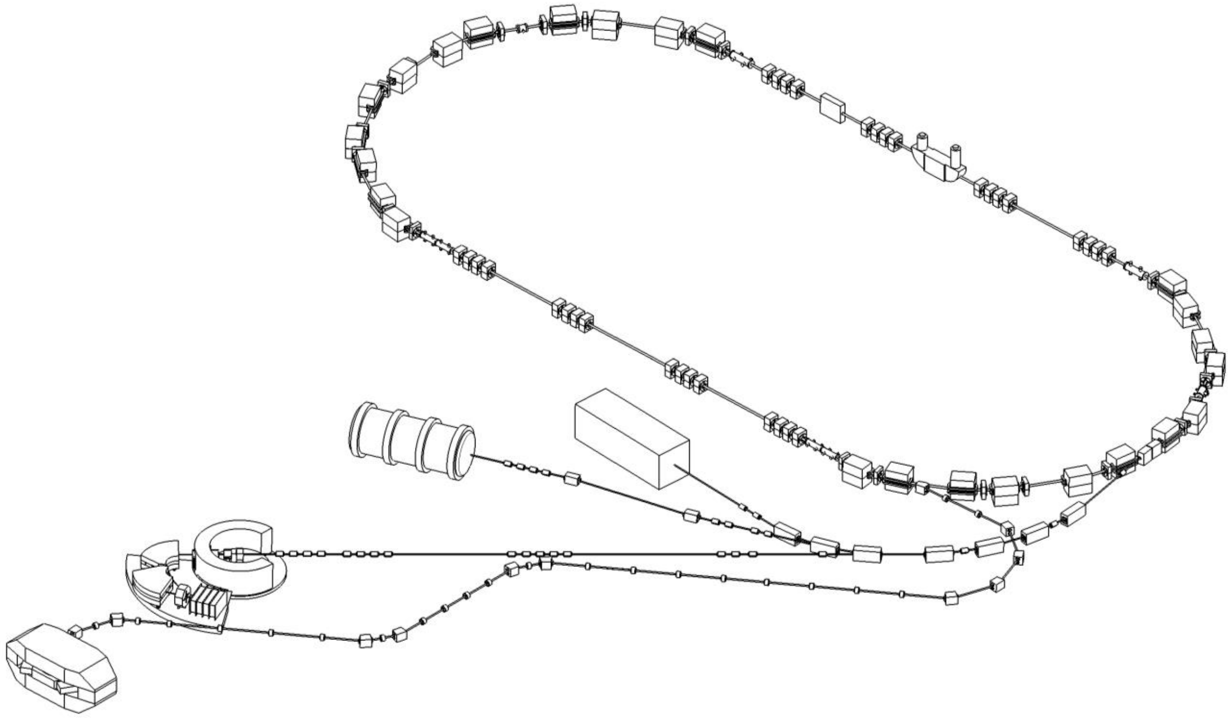

Figure 1. The layout of the accelerator complex COSY in Jülich, which includes polarized and unpolarized ion sources, the cyclotron JULIC and the Cooler Synchrotron COSY.

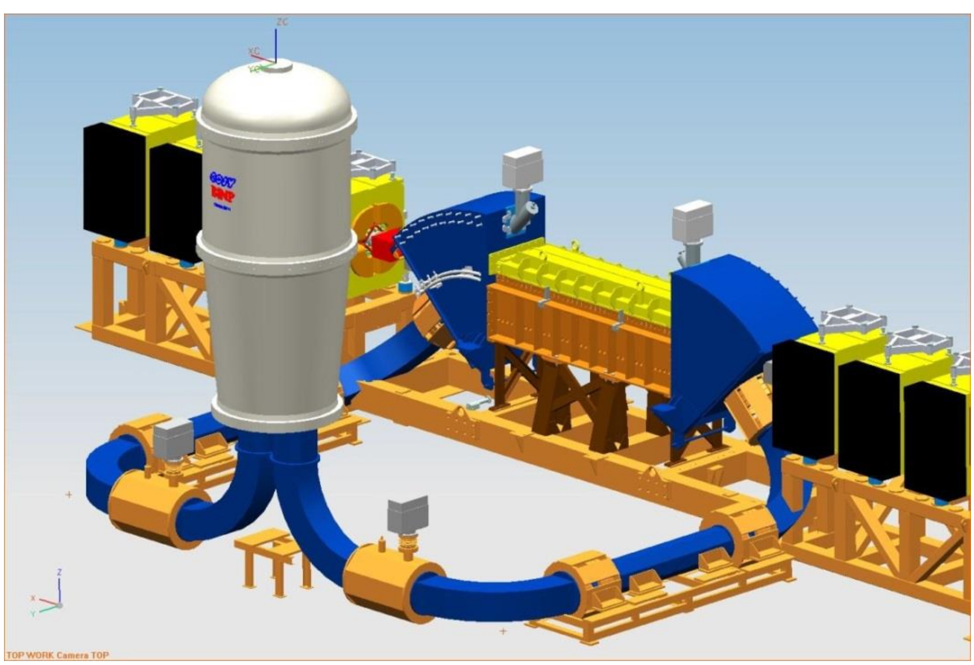

Figure 2. Layout of the new 2 MeV electron cooler at COSY. It consists of a high-voltage tank filled with up to 10 bar inert gas (Sulfur hexafluoride), electron transport lines and cooling section.

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The main diagnostic device to measure polarization of the internal COSY beam is the EDDA detector [9], primarily designed to measure the pp-scattering excitation functions during beam acceleration. The polarization is determined by measuring the asymmetry of scattering events between the circulating COSY beam and carbon or CH_2-fiber targets.

In a dedicated shutdown in the year 2013 a new 2 MeV electron cooler has been installed at COSY. The system has been built in close collaboration with the Budker Institute of Nuclear Physics in Novosibirsk (Russia). The layout of the whole system is shown in Figure 2.

In a high-voltage tank a DC electron beam with up to 1 A current and 2 MeV kinetic energy is produced, guided via a transport line to the cooling section, where it interacts with the circulating COSY beam, and guided back to the high-voltage tank to recover its kinetic energy. The principle of electron cooling is based on a heat exchange of a “cool” electron beam with a “hot” ion beam by Coulomb interaction.

In Figure 3 a picture of the cooling section of the electron cooler taken after installation inside the COSY tunnel is shown. At the end of the year 2013 first electron beams has been produced up to a current of 300 mA. Acceleration voltages of 1.3 MV could be reached. First Electron cooling was achieved for roughly 10^8 protons at a kinetic energy of 200 MeV [10].

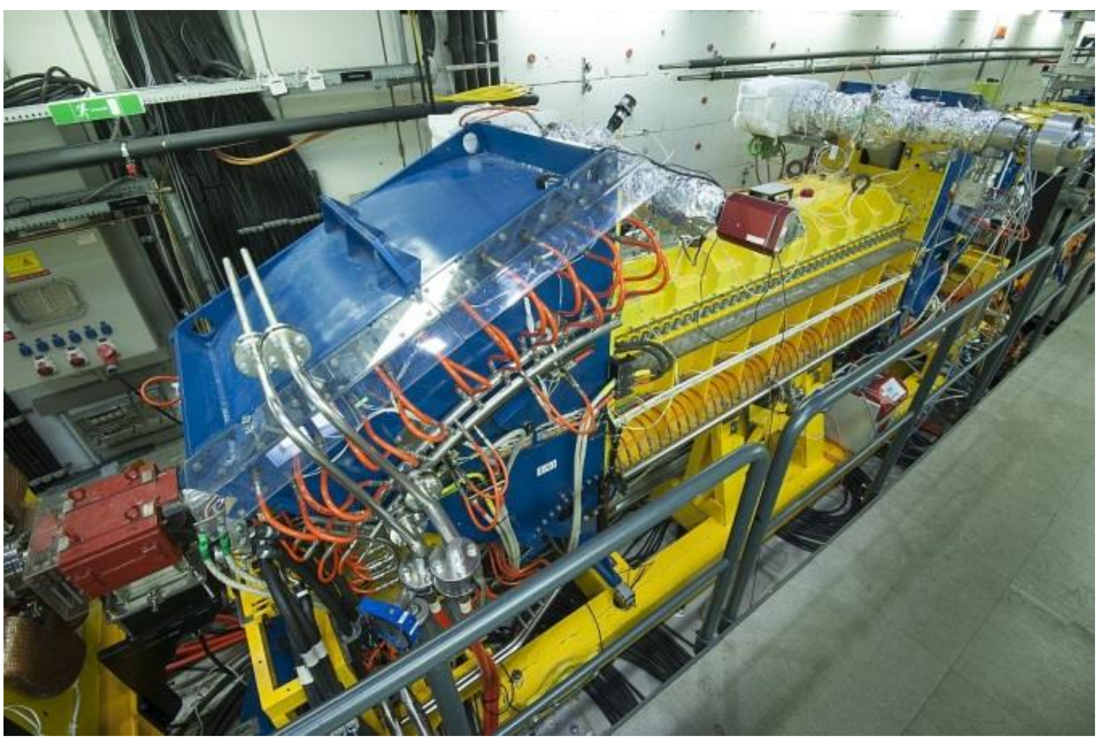

Figure 3. Cooling section of the new 2 MeV electron cooler after installation inside the COSY tunnel.

Technical developments for this new electron cooler are important steps towards the 4.5(8) MeV electron cooler planned for the High-Energy Storage Ring (HESR) [11,12] of the International Facility for Antiproton and Ion Research (FAIR) [13] at the Helmholtzzentrum für Schwerionenforschung (GSI) in Darmstadt. The HESR electron cooler layout will strongly benefit from the experiences of the high-energy electron cooler operation at COSY. The measurement of beam cooling forces and other features

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of magnetized electron cooling at high energies are also essential for the planed HESR electron cooler. For the startup phase of FAIR this 2 MeV electron cooler is well suited for beam cooling and accumulation at HESR injection energy.

An important feature of the HESR (see Figure 4) is the combination of powerful phase-space cooled beams and thick internal targets (e.g., pellet targets) to reach the demanding requirements of the internal target experiment PANDA [14] in terms of beam quality and luminosity. A consortium consisting of Forschungszentrum Jülich (as leading institution), GSI in Darmstadt, Helmholtz-Institute Mainz, University of Bonn and ICPE-CA Bucharest is in charge of HESR design and construction.

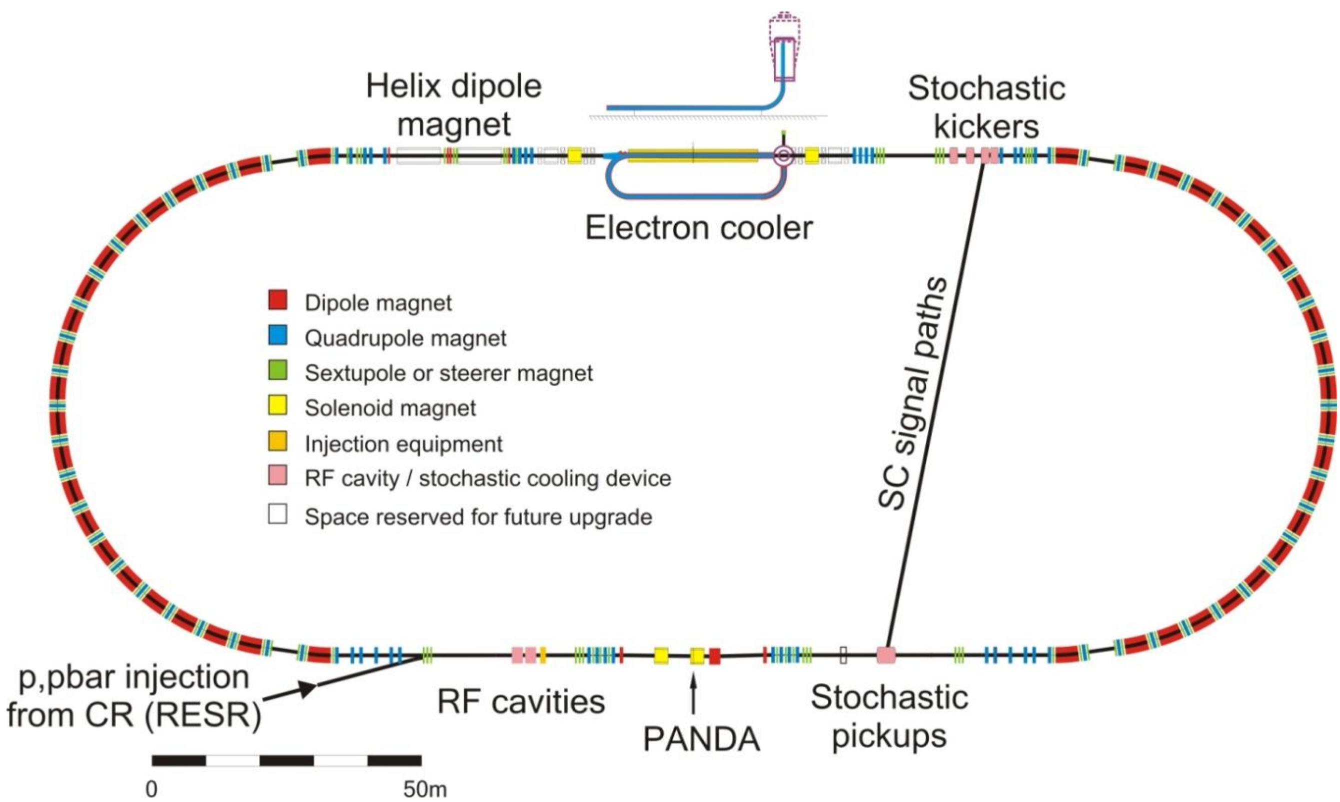

Figure 4. Schematic view of the HESR. Positions for injection, cooling devices and experimental installations are indicated. The upper straight is housing the electron cooler, stochastic kickers and includes space for a future upgrade. The lower straight contains injection, RF cavities, the PANDA detector, and stochastic pickups. The total length of the ring is roughly 574 m.

In hadron storage rings the complex interplay of different processes like beam cooling, beam-target interaction and intra-beam scattering determines the final equilibrium distribution of the beam particles [15,16]. Electron and stochastic cooling systems are required to ensure the specified beam quality and luminosity for experiments at HESR [17,18]. The construction phase of the HESR has already been started together with FAIR construction.

Different approaches to measure electric dipole moments (EDMs) of proton, deuteron and light nuclei are pursued at Brookhaven National Laboratory and Forschungszentrum Jülich with an ultimate goal to reach a sensitivity of 10^{-29} $e{\cdot}$cm in dedicated hadron storage rings [19,20]. Full spin-tracking simulations

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of the entire experiment are absolutely crucial to explore the feasibility of the planned storage ring EDM experiments and to investigate systematic limitations. For a detailed study of particle and spin dynamics during the storage and build-up of the EDM signal, one needs to track a large sample of particles for billions of turns. Existing spin tracking programs like COSY Infinity [21] have been extended to properly simulate spin motion in presence of an electric dipole moment. In addition, benchmarking experiments are performed at the Cooler Synchrotron COSY to check and to further improve the simulation tools [22]. Finally, the layout of a dedicated storage ring has to be optimized by a full simulation of beam and spin motion.

References:

[1] R Maier, Nucl. Instr. Meth. A **390** (1997), p. 1.
[2] R Gebel *et al*, European Particle Accelerator Conference EPAC2006 (2006) p. 1705.
[3] A Lehrach *et al*, Nucl. Instr. Meth. A **439** (2000), p. 26.
[4] H Herr and D Möhl, Workshop on Phase Space Cooling of High Energy Beams (1978).
[5] S van der Meer, CERN Accelerator Note, CERN/ISR-PO/72-31 (1972); S. van der Meer, Rev. Mod, Phys. **57** (1985), p. 689.
[6] H Stockhorst *et al*, AIP Conf. Proc. **950** (2007), p. 239.
[7] D Prasuhn *et al*, Workshop on Beam Cooling and Related Topics, Bad Honnef (2001), Matter and Material (Forschungszentrum Jülich) **13** (2001).
[8] A Lehrach *et al*, AIP Conf. Proc. **675** (2003), p. 153.
[9] D Albers *et al*, Phys. Rev. Lett. **78** (1997), p. 1652.
[10] N Alinovskiy *et al*, International Particle Accelerator Conference IPAC2014 (2014) p. 765.
[11] R Maier, Particle Accelerator Conference PAC2011 (2011) p. 2104.
[12] A Lehrach *et al*, Int. J. Mod. Phys. E (IJMPE) **18** (2009), p. 420.
[13] "FAIR - Facility for Antiproton and Ion Research", Green Paper - The Modularized Start Version, October 2009.
[14] PANDA Collaboration, FAIR Baseline Technical Report **3B** (2006).
[15] O Boine-Frankenheim *et al*, Nucl. Instr. Meth. A **560** (2006), p. 245.
[16] A Lehrach *et al*, Nucl. Instr. Meth. A **561** (2006), p. 289.
[17] D Reistad *et al*, Workshop on Beam Cooling and Related Topics COOL2007, Bad Kreuznach, MOA2C05 (2007) p. 44.
[18] H Stockhorst *et al*, Workshop on Beam Cooling and Related Topics COOL2007 (2007) p. 30.
[19] srEDM Collaboration, http://www.bnl.gov/edm/files/pdf/Proton_EDM_proposal_20111027_final.pdf
[20] JEDI Collaboration, http://collaborations.fz-juelich.de/ikp/jedi/documents/proposals.shtml
[21] K Makino and M Berz, Nucl. Inst. Meth. A **558** (2005), p. 346.
[22] M Rosenthal, "Investigation of Beam and Spin Dynamics for EDM Measurements at COSY", in these proceedings.