Polarized Negative Light Ions at the Cooler Synchrotron COSY/Jülich

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The polarized ion source at the cooler synchrotron facility COSY of the research centre Jülich in Germany delivers negative polarized protons or deuterons for medium energy experiments.
The polarized ion source, originally built by the universities of Bonn, Erlangen and Cologne, is based on the colliding beams principle, using after an upgrade procedure an intense pulsed neutralized caesium beam for charge exchange with a pulsed highly polarized hydrogen beam. The source is operated at 0.5 Hz repetition rate with 20 ms pulse length, which is the maximum useful length for the injection into the synchrotron. Routinely intensities of 20 µA are delivered for injection into the cyclotron of the COSY facility. For internal targets the intensity of 2 mA and a polarization up to 90% have been reached. Reliable long-term operation for experiments at COSY for up to 9 weeks has been achieved. Since 2003 polarized deuterons with different combinations of vector and tensor polarization were delivered to experiments.

Introduction

The accelerator facility COSY [1,2] consists of the injector cyclotron and the synchrotron and storage ring. Polarized and unpolarized protons and deuterons in the momentum range between 0.3 and 3.65 GeV/c are accelerated for the research of production and interaction of strange mesons.

The operation close to the production threshold benefits from the effective use of beam cooling methods. Electron cooling increases the phase space density at injection momentum. At high beam momentum a stochastic cooling system is used for internal experiments to conserve the beam emittance. Polarized beams for fundamental research is provided by negative ion sources especially adapted for the use at the COSY facility. Figure 1 shows the floor plan of the facility with the internal and external experimental areas.

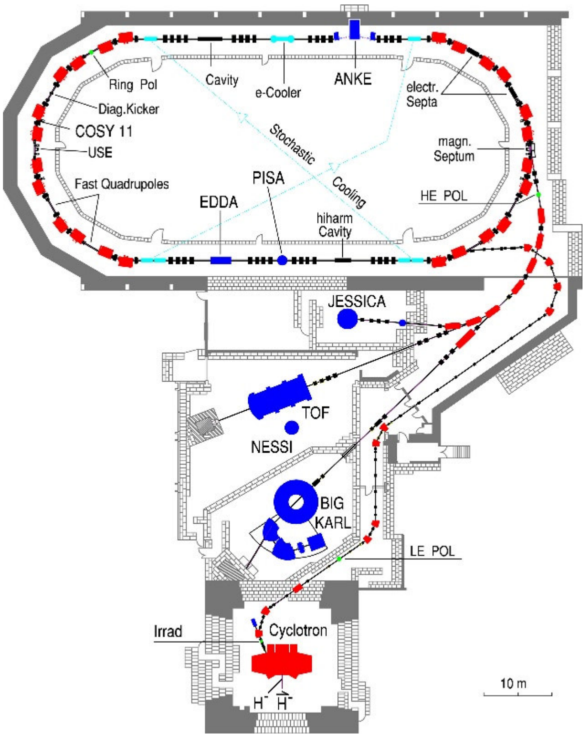

Fig. 1: The COSY floor plan.

The polarized ion source

The polarized colliding beams source at COSY [3,4] comprises three major groups of components, the pulsed ground state atomic beam source [5-8], the caesium beam source and the charge exchange and extraction region. The setup is shown schematically in figure 2.

The highly nuclear polarized atomic $\vec{H}^0$ beam meets inside the charge exchange region the fast neutral Cs^0 beam and charges are swapped according to the reaction $\vec{H}^0 + Cs^0 \rightarrow \vec{H}^- + Cs^+$. The negatively charged $\vec{H}^-$ ions are extracted from the charge exchange region by electric fields and are deflected magnetically by 90° into the beam line to the injector. The ions are transferred to the cyclotron, passing a Wien Filter to provide the proper spin alignment for injection into the cyclotron.

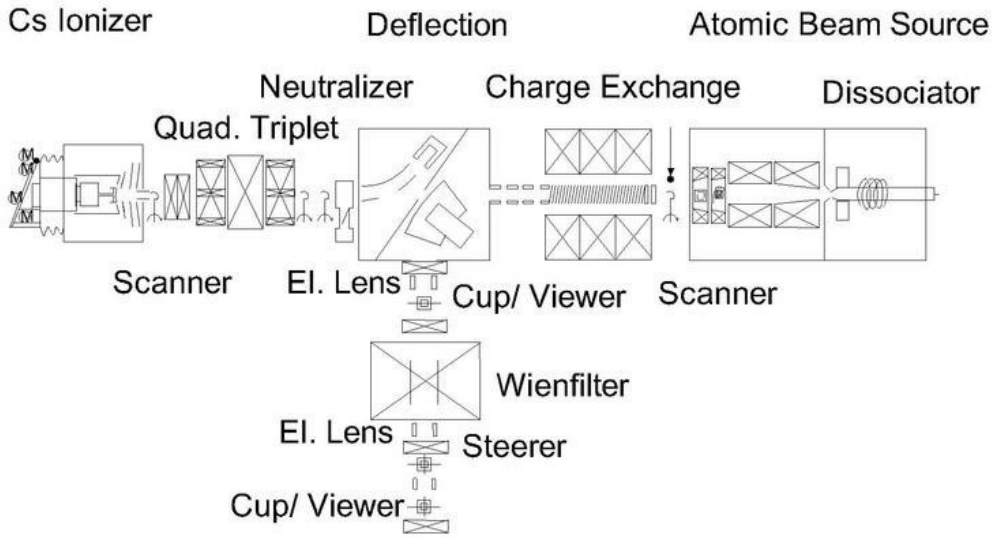

Fig. 2: Scheme of the polarized ion source.

The ground state atomic beam source produces an intense pulsed polarized atomic hydrogen or deuterium beam. The gas molecules are dissociated in an inductively coupled RF discharge. The atoms are cooled to about 30 K by passing an aluminium nozzle of 20 mm length and 3 mm diameter. A high degree of dissociation is kept by special admixture of small amounts of nitrogen and oxygen, reducing surface and volume recombination. The current output of the source depends sensitively on the relative fluxes of the gases and on their timing with respect to the dissociator radio frequency. The cooled beams are focussed by an optimized set of permanent hexapoles into the charge exchange region. By cooling down the supersonic atomic beam the acceptance of the hexapole system and the dwell time in the charge exchange region are increased in proportion to the decrease of the beam velocity. Gas scattering in the vicinity of the nozzle reduces partly these beneficial effects. A peak intensity of $7.5 \cdot 10^{16}$ atoms is measured in a diameter of 10 mm at the exit of the hexapole chamber [9].
The fast neutral Cs^0 beam for the charge exchange reaction is produced in a two-step process. Caesium vapour is thermally ionized on a hot porous tungsten surface at a beam potential around 45 kV. The beam is focussed by a quadrupole triplet to the charge exchange region. Space charge compensation of the intense beam is improved by feeding 10^{-3} mbar l/s Argon to the beam tube following the extraction system. The neutralizer, a chamber filled with caesium vapour, is placed between the quadrupoles and the Cs deflector. The neutralizer comprises a caesium oven, a cell filled with caesium vapour and a magnetically driven flapper valve between the oven and the cell. The remaining Cs^+ beam is deflected in front of the solenoid to the Cs cup. Routinely a neutralizer efficiency of over 90 % was measured.
The highly selective charge exchange ionization produces only little unpolarized background that would reduce the nuclear beam polarization. In the charge exchange solenoid various beam properties can be adjusted. The transversal emittance can be traded for polarization by varying the solenoids magnetic field. The magnitude of the electrical drift field inside the solenoid can be tuned to optimize the energy spread of the beam. A monotonous gradient in combination with a double buncher system in the injection beam line to the cyclotron led to an improved bunching factor.

Operational experiences

Long-term operation revealed that several components limited the effectiveness for routine experiments. In order to provide reliable operation for experiments at COSY prototype parts, mainly of the caesium beam section [10] of the source were replaced through an improved design. Caesium sputtering and contamination is generally impeding long-term reliability. Therefore pulsed operation of the caesium ionizer has been included in the source [11]. The caesium pulses reached peak intensities of over 10 mA with reduced width around 10 ms. For routine operation caesium pulses with 5 mA flat shape of 20 ms width and a repetition rate of 0.5 Hz are used [8].

Because of the high facility use by the COSY user community only little experimentation on the sources is possible. Specific ion source development stands has been constructed to allow specific work for improvements. A dissociator stand is used for preparation of replacement parts, study of efficient cooling schemes and atomic beam production. An atomic beam part is in operation for the test of atomic beam focussing with PM-hexapoles and transition units for improving efficiency and polarization. On a common test bench a Cs - ionizer with beam line and diagnostic elements is in use for technical improvements.

A high degree of polarization for proton beams was achieved by working out a special tune of the machine so that jump quadrupoles were able to shrink losses to a negligible amount. The polarization inside COSY is depicted in figure 3. The polarization is measured during the acceleration ramp by the EDDA group [12,13]. Modifications of the colliding beams source contributed too to this high degree of polarization. A 90° bending magnet replaces the former electrostatic deflection system used to bend the ions into the beam line for injection into the cyclotron. The new alignment of the spin in this beam line reduced depolarising effects and resulted in a polarization of over 90%
after the cyclotron.

Extraction magnet design and construction

Convinced by this improvement for the proton beam a hybrid magnet, employing Fe-ND-B permanent magnets, has been designed. Using permanent magnets with a high-energy product results in a superior field shape.

The colliding beams source provides either 4.5 keV polarized H^- or 7.6 keV polarized D^- in pulsed mode for axial injection into the injector cyclotron. For extracting the beam a C-shaped 90° bending magnet is located in the CBS vacuum chamber. The magnet coil is water-cooled. This electromagnet as well as a proposed hybrid design, which in addition makes use of permanent magnets, was analyzed numerically with the aim to evaluate and compare their excitation and bending characteristics [14]. The complexity of the different magnet configurations warranted the use of finite-element analysis and particle tracking [15]. Figure 5 shows the result of a simulation performed with the finite element program package TOSCA/ VECTORFIELDS. An indexed field has been chosen to get about the same spin rotation for all particles. The iron edges have been shaped to give a very good linear radial dependence of the field over the size of the beam.

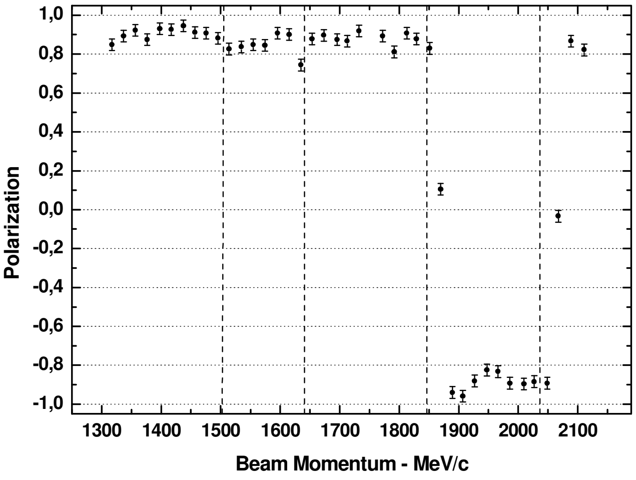

Fig. 3: Polarization during the acceleration ramp with spin flips around 1.88 and 2.08 GeV/c.

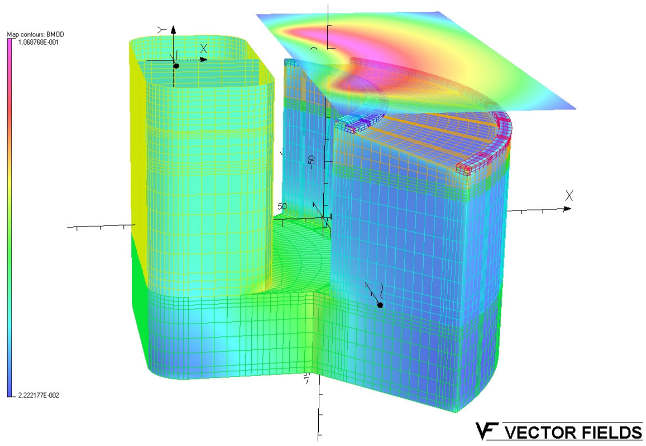

Fig. 5: The shape of the lower iron yoke with a Fe-Nd-B permanent magnet layer with a height of 3 mm. The magnet has an indexed pole gap, slanted at 8.84° over the full radial width of the pole from R= 80 mm to R= 140 mm, without shims. The gap is 40 mm at the central radius of 110 mm. The magnet is excited by a 160 mm high coil with 29 turns of hollow copper wire around the back yoke. The radial field gradient was linearized using shims (5 mm wide and 1 mm high).

The excitation of the magnet coil, and thus the heat transfer to the surrounding, can be considerably reduced by inserting permanent-magnet material at suitable symmetrical locations of the pole geometry above and below the median plane. These layers of permanent magnet material should be chosen such that the field without coil is about halfway between the field values required for H^- and D^-. The coil is then only used to add or subtract field.

The results of the analysis showed that NdFeB with a remanence of 1.12 T and a layer thickness of about 3.1 mm would fulfill these requirements. In fact, such permanent magnets are commercially available in the form of blocks of 31.75 mm × 14.224 mm × 3.175 mm (- easy axis). The analysis showed that a minimum pole-tip thickness of 5 mm is adequate for this purpose, and that without coil current a field value of almost 108 mT can be expected at the center of the pole gap. Even at a short distance from the pole faces, the field ripple is still insignificant.

The calculated fields were used for the final assessment of the bending properties of such a hybrid magnet configuration. The results show that the effective field boundaries are here much closer to the physical edge of the pole gap than for the electromagnet, but they differ by almost 20 mm for the two coil excitations. The final position of the magnet in the extraction chamber is fixed close to the calculated position.

Conclusion

The colliding beams type negative ion source can provide negative polarized hydrogen and deuteron beams without modification in comparable intensities. To prepare polarized deuterons with the desired combinations of vector and tensor polarization the atomic beam part of the source needed to be equipped with new high frequency transitions. These transition units are operated at the magnetic fields and radio frequencies to allow exchange of occupation of the different hyperfine states in deuterium. A set of three installed devices, RFT1 to RFT3, allows a large number of combinations to be delivered to experiments. Table 1 summarizes the deuteron polarization states and compares the measured polarizations to the theoretical limits for these states. Parts of the EDDA detector were used to monitor the polarization in COSY [16,17]. The unpolarized mode is used for normalization and no polarization is given in the table.

Mode	P_z	P_{zz}	RFT1	RFT2	RFT3	Measured P_Z	Measured P_{ZZ}
			Transition			EDDA@1042MeV/c	
D1	0	0	Off	Off	Off	-0.002±0.003	
D2	-2/3	0	Off	Off	On	-0.533±0.004	0.057±0.051
D3	+2/3	0	Off	On	Off	0.438±0.014	
D4	+1/3	+1	Off	On	Off	0.285±0.032	0.594±0.050
D5	-1/3	-1	Off	On	On	-0.294±0.003	-0.634±0.051
D6	+1/3	-1	Off	On	Off	0.285±0.039	
D10	+1	+1	On	On	Off	0.764±0.022	0.545±0.050
D11	-1	+1	On	Off	On	-0.701±0.032	-0.537±0.052
D16	-1/2	-1/2	On	On	On	-0.349±0.022	-0.499±0.053
D17	1/2	-1/2	On	Off	Off	0.378±0.036	-0.282±0.052
P 1	+1	-	Off	On	Off	0.914 ± 0.022 ± 0.03 average in COSY	
P 2	-1	-	Off	Off	On		

Table 1: A subset of Polarization Modes for the polarized ion source for deuterons and protons. Modes P1 and P2 show the performance for polarized protons in COSY. All Data are taken from online measurements with the EDDA detector [16,17] at a beam momentum of 1.024 geV/c.

For experiments at the cooler facility COSY the polarized ion source delivers reliable polarized protons with increased intensities and a high degree of polarization close to the technical limit. The experimental options are successfully extended by a diversity of vector and tensor polarized deuterons.

Acknowledgments

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