COSY Beam Time Request

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Exp. No.:	Session No. **13**

In cooperation with the JEDI collaboration

Proton polarization control at COSY in a Spin-Transparent mode at γG=2 integer spin resonance

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Is support from the LSF program of the EU requested?

[✓ Yes] ~~No~~

Total number of particles and type of beam (p, d, polarization)	Kinetic energy (MeV)	Intensity or internal reaction rate (particles per second)	
		minimum needed	maximum useful
Polarized protons	**~108 MeV**	**stored ~10^9**	**stored ~10^{10}**
Experimental area	Safety aspects (if any)	Earliest date of installation	Total beam time (No. of shifts)
JEPO detector, electron cooler, additional 0.04Tm solenoid in the arc	**none**	**QII 2022**	**2 weeks MD + 3 BT**

Proton polarization control at COSY in a Spin-Transparent mode at $\gamma G = 2$ integer spin resonance

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Abstract:

We propose an experiment to verify a method of proton beam polarization control at energies corresponding to integer spin resonances at COSY. The method supposes using one quasi-static solenoid in a straight section and one – in the bending arc. These solenoids allow to obtain any direction of proton polarization in the ring plane. The advantage of the method is using weak fields in solenoids and applicability to high precision experiments with polarized beams such as electric dipole moment (EDM) experiments. Special feature of the method is reaching integer spin resonance without polarization loss and staying in for measurements. Therefore, on the first stage of the experiment investigation of resonance strengths is foreseen to understand the properties of spin dynamics in vicinity of integer spin resonances. The program includes resonance crossings with different acceleration rates. On the second stage, the experiments with adiabatic capture of polarization in a spin resonance region and subsequent polarization control in a Spin-Transparent (ST) mode are foreseen. The measurements will be done with beam kinetic energy of 108 MeV which fulfils condition $\gamma G = 2$.

A. Scientific motivation and context:

The project for development of ST mode at COSY [1] is motivated by the search for new physics beyond the Standard Modell (SM), which is among most debated issues in particle physics. The SM is well known to be incomplete in several aspects. It is supposed that this issue can be resolved, if new sources of CP- and T-violation are discovered such as a nonvanishing EDM of neutral and charged particles [2]. However, this is not the only problem that can be addressed by spin experiments. Since the 1980's, there remains the unresolved problem of the spin structure of nucleons. Still another example of novel spin physics aspect for storage ring experiments is a search for axion-like particles [3]. All these spin experiments play a particularly important role in the quest for new physics and require new methods for high precision polarization control to resolve them and to overcome the experimental crisis [4].

The theoretical aspects of a new method for hadron polarization control – ST method – are presented in [5, 6, 7].

The idea of a ST method is based on manipulating beam polarization direction at an energy such that synchrotron lattice does not change particle spin orientation after one turn, i.e. spin-tune $\nu = 0$. The lattice becomes "transparent" for spin motion. A natural example of such a structure is a flat figure-8 ring. In "transparent" synchrotrons spin motion becomes degenerate: any spin direction at any place of an orbit repeats itself after each particle turn; in other words, the particles are in vicinity of a ST resonance. Spin motion in such situation is highly sensitive to small field perturbations along the orbit. On the other hand, one can use this sensitivity for realization of an ease and very effective spin control and manipulation in the entire energy range of the collider complex by using spin navigator (SN) solenoids – flexible devices with weak magnetic fields (constant or quasi-stationary) turning spin-vectors around a desirable direction by small angles.

A SN is characterized by the three principal parameters: resulting rotation axis direction $\vec{n}_N$ and angle $2\pi\nu_N$ of spin precession about $\vec{n}_N$. Note that ignoring synchrotron lattice imperfections, the stable polarization axis $\vec{n}$ in a straight section with a SN coincides with the SN axis $\vec{n}_N$, and the acquired spin tune ν is equal ν_N.

Strength of the applied SN field must be larger than all small perturbative fields arising from magnetic structure imperfections and beam emittances.

ST mode can be realized in a racetrack-shaped synchrotron by introducing two identical snakes in two opposite straight sections. In this case the spin-tune is independent on energy and it is equal to zero as well as in a figure-8 ring.

With certain limitations, the ST method of spin manipulation can also be expanded to stationary situations in the vicinity of spin resonance energies in racetracks without snakes when:

$$\nu = \gamma G = k, \tag{1}$$

where γ is the relativistic Lorentz factor, G is the anomalous part of the gyromagnetic ratio, and k is an integer.

The limitations are in general due to the presence of the spin tune spread caused by the energy spread:

$$\Delta\nu = G\Delta\gamma = \gamma G \frac{\Delta\gamma}{\gamma}. \tag{2}$$

In practice, the relative energy spread can be maintained small through acceleration and storage while the absolute spread $\Delta\gamma$ grows with energy. With synchrotron oscillations of $\Delta\gamma$ in a conventional racetrack, there is a growing probability of depolarization by the satellite spin resonances:

$$\bar{\nu} \equiv \bar{\gamma}G = k + m_s\nu_s, \qquad \gamma = \bar{\gamma} + \Delta\gamma, \tag{3}$$

where ν_s is the synchrotron tune and $\bar{\gamma}$ is the relativistic factor averaged over the synchrotron oscillations.

The experimental investigation of the influence of synchrotron sidebands while reaching integer resonance is an obligatory step for ST mode preparation. Witness of adiabatic capture of polarization in a spin resonance without polarization loss and further polarization control by SN will prove the applicability of ST mode concept in accelerators. That will be a significant step towards high precision experiments with polarized beams.

The first-ever proof-of-principle experiment can be conducted at COSY ring at FZ Jülich. If successful, the method opens up new possibilities for COSY in the field of unique experiments with polarized hadrons. The method can be applied to enhance the scientific potential of the Relativistic Heavy Ion Collider (RHIC) and electron-Ion Collider (eIC) at the Brookhaven Laboratory in the US [8, 9], Nuclotron-based Ion Collider fAcility (NICA) in Russia [10], the Electron-ion collider in China (EicC), or the semi-electric and all-electric storage rings for the search for electric dipole moments.

The results of this project will contribute to better understanding of proton spin dynamics and development of proton Spin-Coherence Time (SCT) investigations at COSY [11]. The study is also relevant to Frequency domain method of EDM measurement in terms of experimental measurement of effective Lorentz factor γ_{eff}. That can also contribute to the design and construction of Prototype ring (PTR) [12] and other accelerators for EDM measurements.

B. Technical considerations:

B.1. Spin navigator based on two weak solenoids.

The operating mode of COSY for protons in $\gamma G = 2$ spin resonance is proposed [1]. To control proton polarization it assumes using SN based on two solenoids with longitudinal fields. One solenoid (2 MeV Cooler) should be located in one of the straight sections, and another – in the bending arc (fig. 1). The required field integral is 0.04 Tm for both solenoids.

SN based on two solenoids allows to obtain any polarization direction $\vec{n}$ in the detector and the navigator-induced spin tune $\nu_N \ll 1$:

$$\vec{n} = \frac{B_{z2} L_{z2} \sin\varphi_y \; \vec{e}_x + (B_{z1}L_{z1} + B_{z2}L_{z2}\cos\varphi_y)\; \vec{e}_z}{\sqrt{B_{z1}^2 L_{z1}^2 + B_{z2}^2 L_{z2}^2 + 2B_{z1}B_{z2}L_{z1}L_{z2}\cos\varphi_y}}, \tag{4}$$

$$\nu_N = \frac{(1+G)}{2\pi\, B\rho}\sqrt{B_{z1}^2 L_{z1}^2 + B_{z2}^2 L_{z2}^2 + 2B_{z1}B_{z2}L_{z1}L_{z2}\cos\varphi_y}\,, \tag{5}$$

where $\vec{e}_x$ and $\vec{e}_z$ are the radial and longitudinal unit vectors, respectively, $\varphi_y = \gamma G\, \alpha_y$ is a spin rotation angle, gained in arc dipoles with a total orbit rotation angle α_y between two navigator solenoids with longitudinal fields B_{z1}, B_{z2} and lengths L_{z1}, L_{z2}. $B\rho$ is a magnetic rigidity, $\nu_N = \nu - \gamma G$.

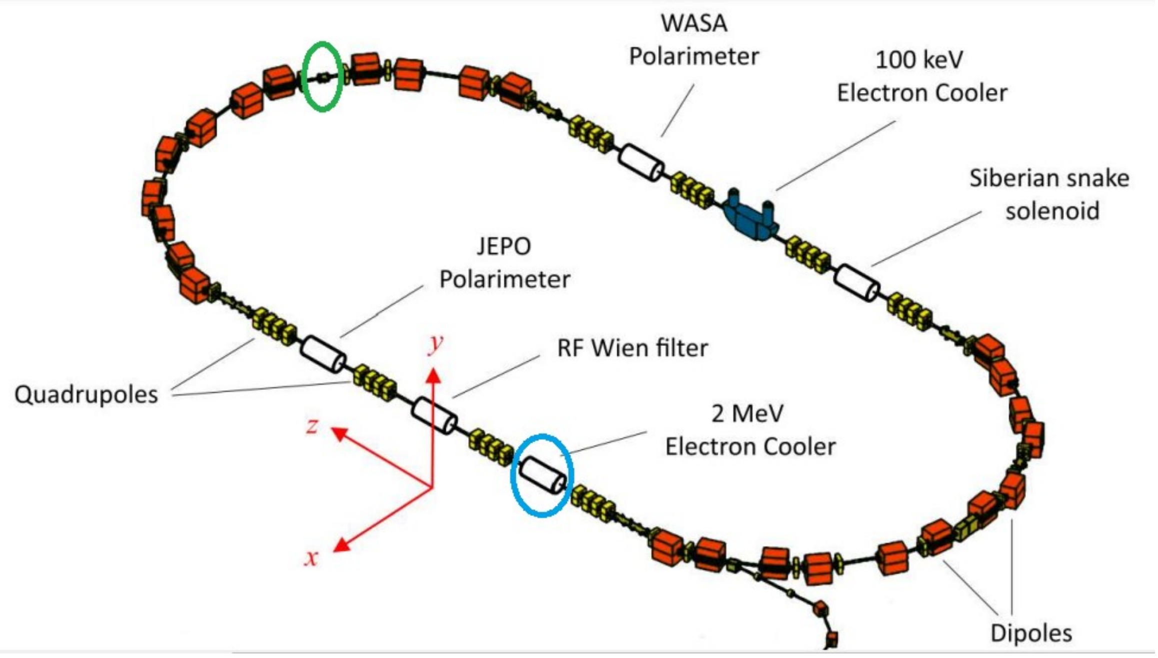

Figure 1. COSY layout. Circle in blue indicates the solenoid to be used in straight section. Circle in green indicates possible place for insertion of the second solenoid in the bending arc.

The second solenoid should be located in the bending arc but not in a straight section. In the latter case $\alpha_y = \pi$ and $\varphi_y = 2\pi$ for $\gamma G = 2$. Therefore, $n_x = 0$. That does not allow to change the $\vec{n}$ direction in the ring plane with solenoids.

B.2. Requirements for SN fields and tunes.

The spin tune ν_N induced by a SN must significantly exceed the ST resonance strength ω [5]:

$$\nu_N \gg \omega. \tag{6}$$

The ST resonance strength is a magnitude of the average spin field $\vec{\omega}$ determined by the deviation of the trajectory from the design orbit. This deviation is caused by construction and alignment errors of magnetic elements and beam emittances. In the absence of a navigator, the spin rotates by an angle $2\pi\omega$ about the $\vec{\omega}$ direction in one particle revolution along the closed orbit. Spin-vector completes its full rotation about $\vec{\omega}$ in $1/\omega$ orbital turns around the ring.

One must consider the constraints imposed on the navigator fields by synchrotron oscillations, which lead to satellite resonances. The strengths of the satellite resonances (3) decrease sharply, when $m_s \gg \Delta\nu/\nu_s$. Therefore, implementation of the additional condition

$$\nu_N \gg \max(\Delta\nu, \nu_s). \tag{7}$$

excludes the effect of satellite resonances on spin dynamics.

The estimated values of $\Delta\nu, \nu_s \sim 10^{-3}$ for $\gamma G = 2$ indicate that synchrotron resonances are closely located in the vicinity of an integer resonance and they act as the main source of depolarization. According to these estimates, polarization control is not influenced by synchrotron motion for SN field integral of 0.04 Tm. The latter is obtained assuming $\nu_N \sim 10^{-2}$.

Condition (6) is also fulfilled with a reasonable margin. The theoretical estimates of resonance strengths $\omega \sim 10^{-5} \div 10^{-3}$.

The fractional parts of betatron tunes should also fulfil:

$$\{\nu_\beta\} > 0.1, \qquad \{\nu_\beta\} < 0.9 \tag{8}$$

during the entire experiment to avoid crossing betatron spin-orbit resonances close to integer spin resonances.

C. Experimental technique:

The investigations for polarization control in ST mode include:

- Experimentally measure spin resonance strengths which limit the permissible field integrals in SN solenoids.
- Provide adiabatic capture and delivery of polarized protons into the region of a spin resonance $\gamma G = 2$.
- Polarization manipulation by SN at spin resonance $\gamma G = 2$.

C.1. Measurement of a resonance strength for $\gamma G = 2$.

In an accelerator with magnetic guiding field $\vec{B}$ the invariant spin axis $\vec{n} \parallel \vec{B}$ that coincides with Y-direction in a non-resonant case. The detuning factor from k-th spin resonance (1) is $\varepsilon = \nu - \nu_k$. The relation between vertical polarization before (P_i) and after (P_f) the resonance crossing is described by Froissart-Stora (FS) formula [13]:

$$P_f = P_i \left[2 \exp\left(-\frac{\pi \omega_k^2 \Omega_0}{2 \left| \frac{d\varepsilon}{dt} \right|} \right) - 1 \right], \tag{9}$$

where $\frac{d\varepsilon}{dt} = G \frac{d\gamma}{dt}$ is a constant detuning speed, Ω_0 is the particle revolution frequency at COSY and ω_k is a resonance strength. In a case of a fast resonance crossing ($\left|\frac{d\varepsilon}{dt}\right| \gg \omega_k^2 \Omega_0$) the depolarizing influence of neighboring synchrotron resonances can be neglected and the relative change of polarization (D) is:

$$D = \left| \frac{P_f - P_i}{P_i} \right| = \frac{\pi \omega_k^2 \Omega_0}{|d\varepsilon/dt|}. \tag{10}$$

Measuring the dependence of depolarization degree D on $d\varepsilon/dt$, defined by acceleration rate of COSY, one can deduce resonance strength ω_k. The measurements should be done for different crossing rates fulfilling condition $D \leq 0.1$.

C.2. Adiabatic capture of polarization in a resonance $\gamma G = 2$.

Spin dynamics at COSY with one solenoid in a straight section is determined by the latter in an integer resonance and can be simply described in a rotating frame with $\nu_k = 2$ around the vertical axis. The direction of $\vec{n}$ in a straight section is longitudinal ($n_z = 1$) when $\gamma G = k$. In a situation when non-zero detuning is present $\vec{n}$ lies in vertical Y-Z plane with an angle $\varphi = \arctan\left(\frac{\varepsilon}{\nu_N}\right)$ relative to particle velocity and the spin-tune $\nu = \sqrt{\varepsilon^2 + \nu_N^2}$.

When the conditions (6, 7, 8) are satisfied, one can adiabatically arrive at an ST resonance by ramping the average energy $\bar{\gamma} mc^2$ at a rate meeting an additional condition [5]:

$$\frac{d\bar{\gamma}}{dt} \ll \frac{\Omega_0}{G} \nu_N^2. \tag{11}$$

It represents the requirement $\dot{\varphi} \ll \Omega_0 \nu_N$, i.e. during the change of $\vec{n}$ direction the spin-vector makes many turns around $\vec{n}$ and follows its direction. For $\Omega_0 \sim 10^6$ Hz the change of $\varepsilon = d(\bar{\gamma} G) = 0.1$ should be done much slower than during $dt \sim$ 1ms, where $\nu_N \sim 10^{-2}$. In this case, the spin oriented vertically far from the resonance adiabatically tilts into the synchrotron plane until it lies along the spin field induced by the SN, i.e. occurs adiabatic capture of polarization by SN. In another case, when condition (11) is not satisfied, the resonance is reached quickly, particle spins have no time to change their orientation and remain vertical, i.e. transverse to the SN field, at the ST resonance point. As a result, the polarization is lost due to spin tune spread.

In the experiment one can change ε (beam energy) and scan vertical polarization while the field in a straight section solenoid is switched on for adiabatic capture. If one finds effective Lorentz factor γ_{eff} so that vertical and radial polarizations vanish, it means that $\varepsilon = 0$. The fact that the resonance state was approached without polarization loss can be checked by changing ε, escaping the resonance region and comparing polarization degree with the preceding value before approaching the resonance.

The concept of effective Lorentz factor γ_{eff} [12, 14] is used because particles perform betatron oscillations, and due to orbit lengthening and synchronous acceleration principle the effective energy (γ_{eff}) of particles increases relative to a reference particle (γ_{ref}):

$$\gamma_{eff} = \gamma_{ref} + \Delta\bar{\gamma}. \tag{12}$$

The γ_{eff} determines the spin resonance condition:

$$\gamma_{eff} G = k \tag{13}$$

and has to be measured experimentally.

C.3. In-plane polarization control in ST mode.

After performing adiabatic capture of polarization by *one* solenoid (see C.2.) one can experimentally verify formula (4) for $\vec{n}$ direction depending on fields of *two* solenoids.

To preserve the polarization, the rate of change of polarization direction must satisfy the adiabaticity condition that can be written in terms of polarization reorientation time (τ) [5]:

$$\tau \gg \frac{1}{\Omega_0 \nu_N}. \tag{14}$$

From this condition it follows that polarization direction should be changed much slower than during 0.1 ms.

If one wants to set the spin direction along or against the particle velocity – it depends on the sign of B_{z1}. The fulfilment of adiabaticity condition (14) depends on how we change fields form their initial configuration (B_{z1}, B_{z2}) to the final one. If B_{z1} is changed slowly while $B_{z2} = 0$ the adiabaticity condition is violated at the point ($B_{z1} = 0$, $B_{z2} = 0$) where the navigator spin tune becomes zero. However, one can achieve the final configuration while maintaining the adiabaticity condition by getting around the resonance point with no change in the spin tune at all. This requires moving along an ellipse in the (B_{z1}, B_{z2}) parameter space (see eq. 5) [5]:

$$B_{z1}^2 L_{z1}^2 + B_{z2}^2 L_{z2}^2 + 2 B_{z1} B_{z2} L_{z1} L_{z2} \cos \varphi_y = const. \tag{15}$$

This avoids beam depolarization due to the spin resonance crossing. The method allows to set any polarization direction in the ring plane starting from the point $(B_{z1}, 0)$ obtained at the end of adiabatic capture while transferring control to the second solenoid in a way described in (15).

D. Running time request:

This running time request is for 5 weeks including first 2 weeks for machine development and 3 weeks for measurements. During all the measurements particles from the beam are moved to the polarimeter target using white noise heating to measure polarization at JEPO polarimeter. It has reasonable analyzing power for 108 MeV beam energy [11].

So far, the experimental program at COSY has focused on deuterons. The time for machine development (MD) stage is mostly determined by the time for optimization of COSY machine settings for protons (polarized source, quadrupole settings, dispersion matching, etc.). After these activities the proposed experiment can be started. The machine setup will not require sextupole scans to find better SCT, using RF Wien filter and RF solenoid. That will simplify the MD stage.

Measurement Week 1:

FS resonance crossing experiments assume measuring the depolarization degree for at least 10 crossing speeds. The synchronous phase of COSY RF will be varied to set a required constant acceleration rate. To acquire reasonable statistical data at least 3 measurement cycles of about 100 seconds per cycle (80 sec. for preparation and 20 – for measurements) are supposed to be done for every crossing speed. After each cycle the beam is dumped and reinjected.

Adiabatic capture measurement cycle implies beam acceleration until the resonance point, then acceleration rate is set to zero to check if polarization is longitudinal. If it is not, the beam is accelerated up to a new flattop energy. When the resonance point is reached the beam is accelerated again to exit the resonance region and verify the preservation of polarization degree. When the energy corresponding to a resonance point is found, at least 3 cycles of about 300 sec. each (100 sec. for approaching, staying in and exiting resonance) for 10 crossing rates should be done to verify the efficiency of polarization transfer into the resonance region without losses.

Measurement Weeks 2-3:

Polarization control measurements imply the previously proven method of adiabatic capture of polarization in a resonance region first and then – changing fields in SN solenoids to set a desired polarization direction. The latter will be scanned in 30-degree increments (12 full measurements).

After the feasibility of the method of polarization control is shown one has to investigate the long-term preservation of polarization. One has to estimate the time when polarization drops by 10% for a fixed direction of $\vec{n}$ and for the case of rotating $\vec{n}$.

The next step is to check the stability of the method by decreasing the fields in the solenoids from 0.04 Tm integral to the situation when $\nu_N \sim \max(\Delta\nu, \nu_s, \omega)$ to find the lowest acceptable fields in SN.

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