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POLARIZED DEUTERONS AND PROTONS AT NICA@JINR

A.D. Kovalenko, A.V.Butenko, V.D. Kekelidze, V.A. Mikhaylov, JINR, Dubna, Russia
A.M. Kondratenko, M.A. Kondratenko, STL "Zaryad", Novosibirsk, Russia
Yu.N. Filatov, MIPT, Dolgoprudny, Moscow Region, Russia

Abstract

The possibilities of NICA complex operation in polarized proton and deuteron modes were studied during the last few years. Several schemes of "Siberian Snakes" were considered and the most optimal one have been proposed for the future modeling and technical design. It was shown, average luminosity of polarized *pp*-collisions higher $1{\cdot}10^{32}$ $cm^{-2}s^{-1}$ at $\sqrt{s_{NN}} \geq 27$ GeV is reachable.

SCHEME OF THE COMPLEX

The NICA complex at JINR has been approved in 2008 assuming two phases of construction. The first phase realizing now includes construction of facilities for heavy ion physics program [1], whereas the second phase should include facilities for the program of spin physics studies with polarized protons and deuterons. In this paper we briefly describe the status of design the NICA technical concept in connection with polarized beams.

The main elements of NICA complex are shown in Fig. 1. They include: the heavy ion source and source of polarized ions (proton and deuteron), SPI, with corresponding linacs, existing superconducting accelerator, 6 A·GeV strong-focusing synchrotron – Nuclotron, new superconducting Booster synchrotron, new collider NICA with two detectors – MPD (Multi-Purpose Detector for heavy ion studies) and SPD (Spin Physics Detector), as well as experimental hall for fixed target experiments with beams extracted from the Nuclotron.

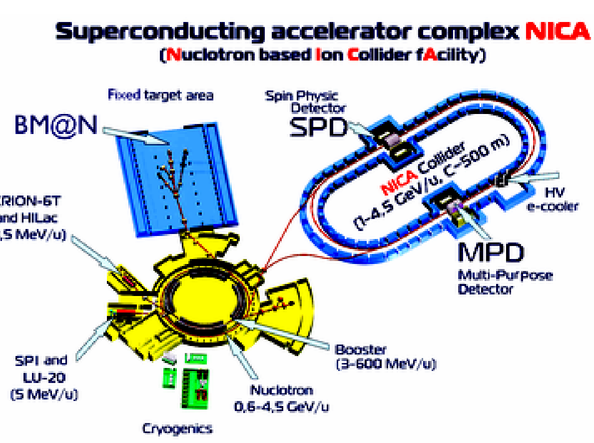

Figure 1: NICA complex at LHEP JINR.

The chain of beam injection to the collider rings in the case of polarized protons and deuterons includes: ions source SPI – modernized injection linac LU-20 with the new front-end part (PI) – Nuclotron – Collider. Heavy ion injection line includes respectively: ion source KRION-6T – HILAC – Booster – Nuclotron – Collider. It can be also used to inject any light ions, let say, deuterons to the collider. The main goals of the Booster are the following: 1) accumulation and acceleration of about $4{\cdot}10^9$ Au^{32+} ions; up to an energy required for effective stripping; 2) formation of the required beam emittance with electron cooling and 3) fast extraction of the accelerated beam.

The chain with using the booster in the case of polarized protons was proposed and considered also [2], nevertheless the approved scheme don't include direct beam extraction line from the booster to the collider at the first stage of the project realization.

The new polarized ion source is commissioning now. It was designed and constructed as an universal high pulsed intensity source of polarized deuterons and protons based on a charge-exchange plasma ionizer. The output $\uparrow D^+$ ($\uparrow H^+$) current of the source is expected to be at a level of 10 mA. The expected polarization will reach up to 90% of the maximum vector (±1) for $\uparrow D^+$ ($\uparrow H^+$) and tensor (+1, −2) for $\uparrow D^+$ polarization. The project is designed and constructed in close cooperation with INR of RAS (Moscow). The equipment available from the CIPIOS ion source (IUCF, Bloomington, USA) is partially used for SPI. The source will deliver to the linac 10 μs pulsed polarized proton or deuteron beam with intensity up to $(1\text{-}2){\cdot}10^{11}$ part./pulse and repetition rate of 1 Hz [3]. The description of the SPI have been published elsewhere, for example in [4]. The Alvarez-type linac LU-20 used as the Nuclotron injector was put into operation in 1974. It was originally designed as proton accelerator from 600 keV to 20 MeV. Later it was modified to accelerate ions with charge-to-mass ratio q/A>0.33 to 5 MeV/u at 2βλ mode. The pulse transformer voltage up to 700 kV is now used to feed the accelerating tube of the LU-20 pre-injector. The new pre-injector will be based on the RFQ section. The SPI is now commissioning at test bench, whereas the front-end linac section is under manufacturing [5].

POLARIZED PROTONS AND DEUTERONS ACCELERATION AT NUCLOTRON

Polarized Deuterons

Acceleration of polarized deuterons at the Synchrophasotron was done for the first time in 1984 [6] and at the Nuclotron in 2002 [7]. There are no dangerous spin resonances at polarized deuteron acceleration up to an energy of 5.6 GeV/u. This limit is practically very close to the maximum design energy of the Nuclotron (6 GeV/u

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for the particles with charge-to-mass ratio q/A = 1/2), thus centre-of-mass energy up to $\sqrt{s_{NN}} \approx 13$ GeV can be provided. Any additional spin control insertions into the Nuclotron lattice are not necessary (vertical spin direction of deuterons is supposed). The only problem in case of deuterons is changing the polarization direction over large angles, say $\pi/2$, in the collider.

Polarized Protons

According to the NICA project, experiments with polarized protons should be carried out up to the maximum energy $\sqrt{s_{NN}}$ of 27 GeV and at desired average luminosity $L \geq 1 \cdot 10^{32}$ cm^{-2}s^{-1}. The NICA operation in polarized proton mode will need additional acceleration of protons from 5 to 12.5 GeV in the collider, because it is impossible to keep the beam polarization over the total energy range in the Nuclotron. For the preservation of beam polarization in Nuclotron, "Siberian snake" insertions will be installed into one of the straight sections of the accelerator ring. The snake eliminates crossing of numerous dangerous spin resonances. Due to limitation of free space in Nuclotron, we consider Siberian snake based on solenoids with pulsed magnetic field [8]. The insertions containing transverse magnetic fields would lead to very big closed orbit distortions especially at low energies. Helix snake is much complicated and gives no profit also in the considered case. The comparison of different "snakes" is presented in [9]. Orbital parameters of polarized proton beam in Nuclotron with solenoid Siberian snake without compensation of the betatron oscillation coupling is presented and analyzed in [10,11]. The maximum magnetic field integral of the "Snake" solenoid depends on the particle momentum and approximately equal to 21 T·m at the proton Lorenz-factor $\gamma = 6$. Taking into account available empty space for the solenoid within the existing straight section (about 2×3.05 m without compensating quadrupoles) one can find the needed amplitude of the solenoid magnetic field $B \approx 3.6$ T. Superconducting pulsed solenoid with the field ramp $dB/dt \approx$ 2-3T/s can be manufactured based on the Nuclotron-type hollow high-current NbTi composite superconducting cable cooled with two-phase He flow. The main necessary parameters of the solenoid are shown in Table 1.

Table 1: Snake Solenoid Parameters

Aperture diameter, mm	100
Number of turns per meter	111
SC cable outer diameter, mm	9
Length of section, m	3.05
Number of layers	2
Supply current at B = 3.6 T, kA	12
Supply current for half-snake, kA	6

Based on the previous experience of the design and long-term tests of Nuclotron magnets and cables we can estimate the parameters as feasible. Necessary operation current levels were provided, namely: for the Nuclotron (~6 kA) and for NICA booster test magnet (~ 11 kA).

COLLIDER IN POLARIZED PROTON AND DEUTERON MODES

The novel scheme of the polarization control at NICA collider, suitable for protons and deuterons, based on the idea of manipulating with polarized beams in zero spin tune vicinity. This approach is actively developed at JLAB for the 8-shaped ring accelerator project. To provide zero spin tune regime at the collider of a racetrack symmetry, it is necessary to install two identical "Siberian snakes" (SOL, $\pi/2$) in the opposite straight sections (Fig. 2). In this scheme any direction of the polarization is reproduced at any azimuth point after every turn. But, if one fixes the longitudinal or transverse polarization at SPD then the polarization direction at MPD will obtain some angle in respect to the particle velocity vector. This angle depends on the beam energy and *vice-versa*: if the polarization directions are fixed at MPD area, some arbitrary polarization angle will occurred at SPD. Solenoid magnetic field integral in a single (Sol $\pi/2$) - rotator at the maximum energy is reached of 25 T·m and 80 T·m for proton and deuteron case respectively.

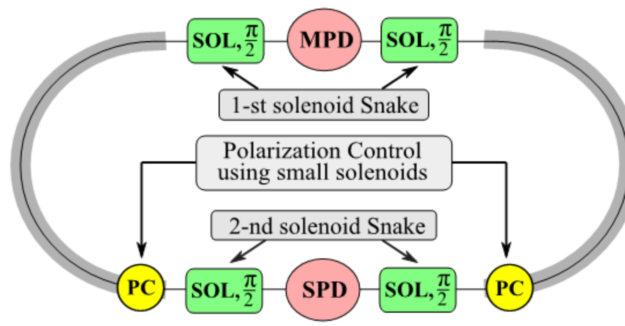

Figure 2: Preliminary positions of the polarization control elements in the collider lattice.

The most essential is possibility to manipulate with the polarization vector direction by means of relatively small fields. The maximum field integral of the small solenoid does not exceed of 0.5 T·m for proton and deuteron case. It allows one to manipulate of the particle spin during an experiment without affecting the beam orbital properties, which provides a capability of carrying out polarized beam experiments at a new precision level. Moreover, such polarization design allows for easy adjustment of the spin dynamics to meet any experimental requirements, which may arise in the future. Design of the final scheme is continuing. Additional analysis of the polarization control at the MPD area will be fulfilled. It is necessary also to define composition of the solenoids, namely: stationary and dynamic parts. The final scheme will be approved at the later stages of the project.

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THE LUMINOSITY ESTIMATES

The NICA peak luminosity in the proton mode is calculated (Fig. 3) for the proton kinetic energy range from 1 to 12.7 GeV [12]. The maximum value at the curve is corresponds to the total *pp*–collision energy of $\sqrt{s}$ = 27 GeV (the equivalent fixed target beam kinetic energy E_{kin}= 388 GeV respectively).

The luminosity and the total number of stored particles have been calculated taking into account the space charge limits and the other parameters listed in Table 2.

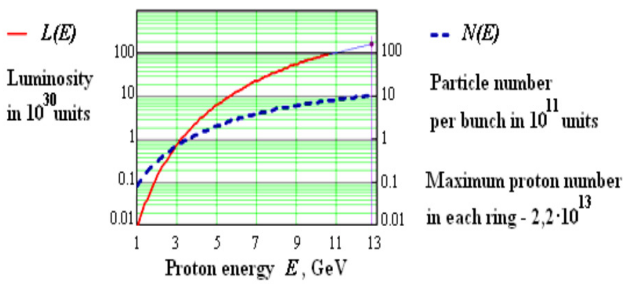

Figure 3: NICA collider *pp* luminosity in units 10^{30} (left scale, solid line) and maximum number of particles per bunch (right scale, dotted line).

Table 2: Main Parameters of NICA Collider in *pp*-mode

Circumference, m	503
Number of collision points (IP)	2
Beta function β_{min} in the IP, m	0.35
Rms bunch length, m	0.5
Incoherent tune shift, $\Delta_{Lasslett}$	0.027
Beam-beam parameter, ξ	0.067
Number of protons per bunch	~$1\cdot10^{12}$
Number of bunches	22
Beam emittance (normalized) ε_{nrm} at 12.5 GeV, π mm mrad	0.15

As it follow from the calculations, the peak luminosity of L_{peack} = $2\cdot10^{32}$ cm^{-2}s^{-1} is reached at the beam kinetic energy of 12.7 GeV. From the other hand, the ring filling time will depend on the Nuclotron pulse intensity and cycle duration. The expected proton beam intensity at the Nuclotron output is limited by the SPI source current and particle losses at different stages of the accelerator/collider work cycle. Taking the SPI design current (10 mA) and estimate particle loss coefficient between the source and the Nuclotron (0.5), RF capture (0.8), extraction efficiency (0.86) and the other factors in the synchrotron (0.9), we can expect up to $1.6\cdot10^{11}$ polarized protons per pulse from the Nuclotron. Thus, the necessary number of injection cycles is about 200 per each ring. The cycle duration depend on the magnetic field ramping time (up and down), the peak value of the magnetic field and necessary pause between the cycles. For our case we suppose B = 1 T, dB/dt = 0.7 T/s and t_p = 1 s, i.e. the total cycle duration T_c = 5 s and obtain the ring filling time T_f = 2000 s for the both rings, if a double-spin process is studied. To estimate the average luminosity, one should take into account necessary beam cooling (stochastic) time, the luminosity life time, the machine reliability coefficient. Assuming the cooling time T_{cool} = 500 s, and the luminosity life time T_{Llf} = 10000 s it is possible to calculate the average luminosity as L_{aver} = η L_{peack}, where η = T_c/T_o the ratio of the luminosity life time to the total data taken time and beam preparation time. In the considered case: L_{aver} = $0.8\cdot L_{peack}$. Thus, the average luminosity of $1.6\cdot10^{32}$ cm^{-2}s^{-1} can be reached. Rough estimates of *dd*-collisions luminosity gives the level of $1\cdot10^{31}$ cm^{-2}s^{-1}. Of course, the collider operation reliability coefficient should be also taken into account.

The bunch parameters shown in the Table 2 will be optimized at the technical design stage of the facility. So, an increase of the bunch intensity allows increasing the luminosity at the same value of the tune shift. To keep the constant tune shift the beam emittance has to be increased proportionally to the bunch intensity and the luminosity is scaled linearly with the ion number.

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