THE NICA FACILITY IN POLARIZED PROTON OPERATION MODE

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Abstract

Basic goal of the planned NICA facility at JINR is focused on the studying of heavy ion collisions over the energy range $\sqrt{s_{NN}}$ ~ 4…11 GeV. Capabilities of the proposed scheme were carefully analyzed in this case and reaching of the average luminosity, $L = 1\cdot 10^{27}$ cm^{-2} s^{-1} for gold-gold collisions at $\sqrt{s_{NN}}$ = 9 GeV, have been confirmed. The other important NICA research domain is the experiments with polarized proton beams at the highest possible energy, the highest luminosity and polarization degree as well. The main aim is to provide $\sqrt{s_{NN}}$ ~ 25 GeV and L ~ $1\cdot 10^{31}$ cm^{-2} s^{-1}. The unsolved aspects of the problem are discussed, possible solutions are analyzed and necessary modifications of the NICA scheme are considered as well.

INTRODUCTION

The flagship project in high energy physics of the Joint Institute for Nuclear Research (JINR) in Dubna is the NICA/MPD started in 2007 [1,2]. This project is based on the existing superconducting (SC) synchrotron Nuclotron that is in operation since 1993 [3] and was modernized recently [4]. The facility aimed to provide, for the first time, collider experiments with heavy ions (gold ions as reference) at centre of mass energy in the range from 4 to 11 GeV/u, with light ions and different ions in asymmetric mode. Operation in polarized deuteron and polarized proton collisions is also an important NICA regimes, because the studies of the nucleon spin structure is the first priority task for many scientific collaborations. since the famous "spin crisis" in 1987. It is supposed, that the NICA facility should provide polarized pp- and dd – collisions at the maximum centre of mass total energy $\sqrt{s_{NN}}$ up to about 26,7 GeV and 12,7 GeV respectively and at average luminosity of ~ $1\cdot 10^{31}$ $cm^{-2}s^{-1}$ (for protons). Acceleration of polarized deuterons at the Nuclotron has been tested in 2002 and analyzed theoretically earlier [5]. There are no dangerous spin resonances up to the energy of 5.6 GeV/u. This is practically very close to the maximum design value (6 GeV/u for the particles with charge-to-mass ratio q/A = ½) and there are no doubts about the realization of the project target in this case. The only problem in the case of deuterons is changing of the polarization vector direction (from vertical to horizontal or backward), namely: the field integral should be twice as larger in comparison with the proton case, whereas operation in polarized proton mode meet some problems and limitations that dictate necessary changes in the NICA scheme and operation scenario. These are due the following: 1) limitation of the Nuclotron magnetic rigidity; 2) transition energy; 3) spin resonances, 4) spin direction matching at injection to the collider. The first two points are valid for both non-polarized and polarized proton beams and are essential for reaching peak energy and the highest possible beam intensity. It was supposed that the use of a spin resonance transparent crossing method will give a chance to overcome all dangerous spin resonances in the Nuclotron over the total energy range. Nevertheless, careful calculations [6] have shown: 1) the beam should have momentum spread of ~10^{-5} (i.e. additional beam electron cooling in the Nuclotron ring is necessary), 2) a fast ramped "warm" dipoles (rise time of ~ 1ms) should be integrated with the Nuclotron superconducting ring and 3) spin matching at injection to collider will need large integrals of the magnetic field of the spin control elements. Thus more optimal scheme of the NICA operation should be found and used in this case.

STRUCTURE OF THE FACILITY

Recent composition of NICA site is shown in Figure 1.

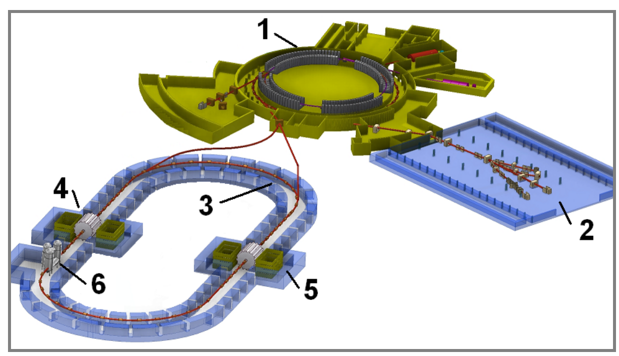

Figure 1: The NICA facility: 1 - the existing accelerator building; 2 - fixed target experimental hall; 3 – collider ring; 4 and 5 - the MPD and SPD detector facilities respectively; 6 – high voltage electron cooling system.

The elements placed in building 1 are the following: the injector facility; the new superconducting booster synchrotron (is supposed, to be located inside the yoke of the decommissioned Synchrophasotron); the Nuclotron and the new beam transfer channels. Building 2 is the Nuclotron fixed target experimental area. The collider tunnel, two new superconducting storage rings, the buildings for the detectors and beam transfer channels to collider are the part to be newly built.

The injector facility consists of the four different types of different particle sources (ESIS, laser, duoplasmatron, polarized protons and deuterons), modernized DTL linac LU-20 and the new heavy ion linear accelerator (HILAC) aimed at accelerating ions with q/A ≈ 0.12 to an energy of 3.5 MeV/u. 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 system and 3) fast extraction of the accelerated beam. The present layout was optimized to place the ring of 211 m length inside the yoke window of the Synchrophasotron. The booster description was presented in [7]. Some of the booster parameters important for our consideration are listed in Table 1.

Table 1: The booster main parameters

Fold symmetry	4
Number of the FODO cells per arc	6
Number of large straight sections	4
Large straight sections, m	2×4
Small straight sections, m	1.2/0.6
Betatron tunes	5.8/5.85
β-functions, m	14.3
Maximum dispersion function, m	2.9
Momentum compaction factor	0.039
$\gamma_{\text{transition}}$	5.064
Critical energy, GeV/u	~ 3.81
Acceptance (h/v), π·mm·mrad	138 /40
Cycle without electron cooling, s	~ 3.0
Maximum magnetic rigidity, T·m	25
Dipole magnetic field, T	1.8
Dipole magnetic field ramp, T/s	1.2

The collider rings contain the two detector facilities: **MPD** - **M**ulti **P**urpose **D**etector - for heavy ion physics mainly and **SPD** – **S**pin **P**hysics **D**etector – for spin physics research. The Siberian Snake insertions installed in the opposite with respect to the SPD straight sections and spin rotators installed directly in front of the SPD setup are used to change spin orientation from longitudinal to transverse (Fugure:2).

The use of the Nuclotron as a basic element of the NICA injection chain, i.e. acceleration of ions up to necessary energy of the NICA collider experiment is reasonable, nevertheless, in the case of polarized protons such scheme will not operate perfectly. The Nuclotron was never designed as proton machine. The transition energy of this machine corresponds to $\gamma_{tr} \approx 7$ at the main work point Q ≈ 6.85 and $\gamma_{tr} \approx 11$ at Q ≈ 7.42. Thus, in any case, we should cross γ_{tr} and, moreover, the increased field gradient at Q ≈ 7.42 will reduce safety margin of the superconducting lattice quadrupoles. It will definitely lead to unstable accelerator operation near the maximum level of the magnetic rigidity, i.e. in the most important domain for physics data taking. To solve this and other above-mentioned problems, the new operation scenario of the facility is proposed.

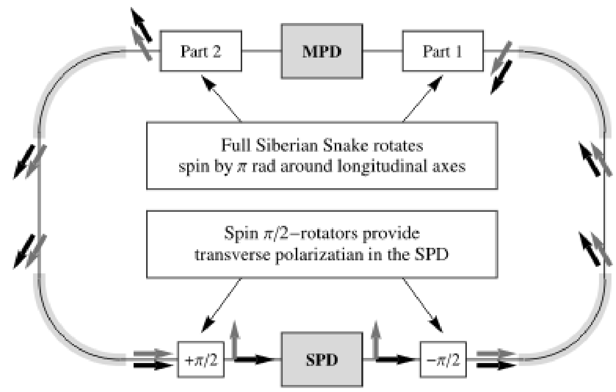

Figure 2: The polarization direction control in the NICA collider (black arrows are correspond to longitudinal and grey ones – to transverse directions respectively).

POLARIZED PROTON MODE

The NICA elements chain in polarized proton mode is proposed to be the following:

- the new ion source with the intensity of $1{\cdot}10^{10}$ polarized (and non-polarized) protons per pulse [8];
- linak LU-20M with the new RFQ section;
- the booster with the spin control insertion and accelerating RF station suitable for protons;
- fast extraction system from the booster and injection of the beam directly to the collider rings;
- the collider rings of 503 m long with magnetic rigidity up to 45 T·m equipped by the RF stations for proton beam acceleration/deceleration.

The operation cycle consist of the following stages: 1 – storage of the maximum number of the particles in the collider rings (stochastic cooling is switched on); 2 – formation of the necessary beam emittance and momentum spread; 3 – acceleration at reasonable bunch factor; 4 – adiabatic bunching (increasing of the RF amplitude); 5 – physics data taking (experiment); 6 – decreasing of the RF, partial de-bunching; 7 – beam deceleration to the injection energy; 8 – the next injection cycle to compensate the particle losses during the phase (5), the beam phase space formation and so on. The initial storage will not reduce the average luminosity since the storage time will be much less then the luminosity life time and the collider operation in phase 5. The filling factor is defined by the linac operation cycle, ion source beam intensity and the time of the collider magnetic system necessary ramp up/down time. The linac cycle is not shorter than 7 s (limited by the RF system). Thus, the collider rings filling ramp rate of ~ $1.4{\cdot}10^9$ c^{-1} is reasonable. Assuming necessary number of injection pulses as 50 per ring and possible ramp, we obtain the total refilling time of 700 sec and the total additional number of the injected particles $0.7 \cdot 10^{11}$ per ring. The luminosity life time in the case of polarized protons will be limited mainly by higher order spin resonances in the collider magnetic rings. For rough estimate the value of 10 hours can be used.

The pp-collider peak luminosity at proton kinetic energy E_p = 12.66 GeV, which corresponds to the total collision energy $\sqrt{s}$ = 27.06 GeV and the equivalent fixed target beam kinetic energy E_{kin_equi} = 388.5 GeV respectively, was estimated at the level of $6 \cdot 10^{30}$ $cm^{-2}s^{-1}$ per one collision point. The parameters values were the following: normalized beam emittance ε_{norm} at 12.5 GeV 0.15π mm mrad, the number of protons per bunch $1 \cdot 10^{10}$, Lasslet tune shift $\Delta_{Lasslett}$ = 0.027 and beam-beam parameter ξ = 0.067. Nevertheless, this estimate will be further improved at the next stage of the system design. During technical design the bunch parameters will be optimized depending on the experiment energy. So, an increase of the bunch intensity will allow increasing the luminosity at the constant 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 changed linearly with the ion number.

PRESERVATION OF POLARIZATION

The use of Siberian Snake (Figure: 3) with longitudinal magnetic fields is proposed to suppress dangerous spin resonances in the booster.

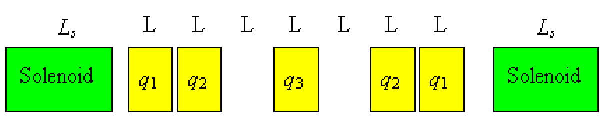

Figure 3: Structure of the Siberian Snake insertion.

To provide necessary effect of the snake over the total energy range (up to proton energy of 6 GeV) the longitudinal magnetic field integral should be $B_{\|}L_{\|}$ = 21.5 T·m. If the field in solenoids to limit to, let's say, 10.5 T, the total length of the insertion L_{tot} will be about 4m. This number is well correlated with the booster straight section length. Five quadrupoles are used for compensation of the betatron motion coupling [9]. The quadrupoles parameters in this case are chosen from the condition to keep the matrix of vertical particle motion through the insertion and the matrix of open section of length L_{tot} equal to each other. The matrix of horizontal motion M_x under such condition is equal to $-M_y$, i.e. additional phase advance of π - radians due to this procedure will occur.

Matching at Injection

As it is well known, if the only one Siberian Snake is used in the accelerator, the periodical spin precession axis, i.e. stable direction of a beam polarization vector, is correspond to the beam orbit plane. At this condition, the opposite in respect to the snake placement "empty" section beam polarization vector is directed along the particle velocity vector (see Figure 2). Thus, it is necessary to take care about matching of the polarization vector at the stage of polarized beam transportation to the collider NICA. The ideal place of the beam injection in the collider would be opposite in respect to the Snake, because the polarization direction at this place doesn't depend on the beam energy. There is no such possibility in the case of the beam injection from the existing Nuclotron. The problem of matching spin direction should be solved for proper injection of the beam to the collider magnetic arc. Remind, polarization vector direction in the Nuclotron is traditional – vertical. Thus, at first, it is necessary to put it horizontally, in the beam orbit plane and after that to turn it at the needed angle in the orbit plane. Practically it will lead to additional spin rotator, i.e. additional system of forming strong enough magnetic fields, because the available space is very limited.

SUMMARY

Preliminary analysis has demonstrated the advantages of the new concept of the NICA facility operation in the polarized proton collision mode. The use of Nuclotron as final stage of the collider injector chain and the collider system without RF acceleration system doesn't provide all of the project research goals. Moreover, any reconstruction of the Nuclotron ring will take the time and will lead to limitations of the annual beam time. Detailed design and analysis of the proposed modification will be continued.

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