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CHALLENGES OF LOW ENERGY HADRON COLLIDERS

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Abstract

NICA (Nuclotron-based Ion Collider fAcility) collider complex [1-3] is under construction at JINR (Dubna, Russia). The initial configuration of the collider will support collisions of fully stripped heavy ions, ^{209}Bi, for a study of phase transition in the quark-gluon plasma in the energy range 1÷4.5 GeV/u per beam. Commissioning of the collider injection chain has been recently started. The complex includes two linacs, two Booster synchrotrons (Booster and Nuclotron to support the beam injection to the collider at the collision energy less than 3.9 GeV/u), and 2 collider rings with 503 m circumference. The design luminosity is ~10^{27} cm^{-2}·s^{-1} at 4.5 GeV/u. The heavy ions are generated in the ESIS-type ion source with intensity ~$5\cdot10^8$ per pulse. Then they are accelerated into the linac and Booster and directed to stripping target. Next, fully stripped ions are accelerated in Nuclotron and injected into Collider. Electron cooling at 65 MeV/u in Booster will be used to increase the beam phase space density. The electron and stochastic cooling are used in each of collider ring to support beam accumulation and to prevent emittance growth due to intrabeam scattering. Three RF systems are used for longitudinal phase space manipulations: RF-1 — barrier bucket RF for the beam accumulation, RF-2 makes initial bunching creating 22 bunches from a continuous beam, and RF-3 at the 66th revolution harmonic operating at the collisions.

An achievement of design luminosity requires overcoming many technological and beam physics problems which are shortly discussed in this paper.

INTRODUCTION

In the course of last 50 years the growth of beam energy was the major focus of hadron collider development. The next highest priority was maximizing the collider luminosity. To achieve maximum collision energy the protons and antiprotons were the particles of the choice. This road profoundly affected the development of the high energy physics and fundamentally changed our understanding of the world. However, recent developments in the nuclear physics have required a study of collisions of heavy ions in a range of relatedly small collision energy (< ~10 GeV/u) for a study of phase transitions in the quark-gluon plasma. The first attempt of such studies has been carried out at RHIC in the BNL [4]. The collider luminosity was relatively small since its operation was at the energy well below the design energy. It had two drawbacks: too large ring circumference which greatly reduced the cooling rates; and too small bending field which negatively affected the ring dynamic aperture and beam control. NICA collider complex is designed to address these challenges. It is currently under construction at JINR.

LUMINOSITY LIMITATIONS

The choice of main parameters was driven by the following considerations.

We account that: Eq. (1) the beam luminosity depends on the bunch population, N, and the beam emittance, ε, as $L \propto N^2/\varepsilon$; Eq. (2) the betatron tune shift is as $\Delta\nu \propto N/\varepsilon$. Then, excluding N one obtains that the luminosity is $L \propto \varepsilon\Delta\nu^2$. Typically, the betatron tune shifts are limited by a single particle stability to ~0.05, consequently the luminosity is proportional to the beam emittance. Thus, an increase of beam emittance to its limit is our first essential requirement.

An increase of beam emittance is limited by intrinsic non-linearity of the interaction region focusing. The edge field of quadrupoles creates non-linear kicks [5] in both transverse directions. For x-plane we have:

$$\Delta x = \frac{k}{12}(x^3 + 3xy^2)$$
$$\Delta P_x = -\frac{k}{4}((x^2 + y^2)P_x - 2xy \cdot P_y)$$

where k is the quadrupole gradient normalized to the magnetic rigidity, $P_x = dx/ds$, and $P_y = dy/ds$. The expression for y-plane is obtained by cycling permutation of x and y and by change of sign for k. In a thin lens approximation, the above equations yield the relative change of focusing strength for a particle passing through a quadrupole lens:

$$\frac{\partial\Phi}{\Phi} \approx \frac{x^2 + 3y^2}{4LF}, \qquad (1)$$

where L is the quadrupole lens length, and $\Phi = 1/F$. In a low energy collider with collision optics in the interaction region (IR) the main non-linearity comes from the IR quadrupoles where local beta-functions are at least one order of magnitude larger than ones in the rest of the ring. Note that although formally this is a cubic nonlinearity it cannot be easily compensated by octupoles which make kicks proportional to $(x^2 - 3y^2)$. To make a rough approximation we assume that F is equal to the distance from the interaction point to the lens; and that the beta-function in the lens is: $\beta \approx F^2/\beta^*$, $F \gg \beta^*$. Here β^* is the interaction point (IP) beta-function. Then the betatron tune shift due to lens non-linearity at the aperture boundary is:

$$\delta\nu \approx F\varepsilon/\beta^{*2}. \qquad (2)$$

Typically, the distance from IP to the IR quads, F, is set by the space required for the detector. In this case a reduction of the IP beta-function quadratically reduces the ring acceptance. Particle tracking in the real NICA optics shows

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that the focusing non-linearity is mainly driven by this intrinsic non-linearity in quad edge focusing. For β^*=60 cm tracking yields the dynamic aperture of 90 μm. It drops to 28 μm for β^*=35 cm.

Intra-Beam Scattering (IBS) of charged particles in a beam brings another principal limitation on the luminosity of the low energy colliders [6]. The IBS increases fast with energy reduction, and, in the absence of cooling, may degrade luminosity within few minutes or tens of minutes depending on the beam energy. In difference to the high energy colliders, which operate well above transition, the IBS significantly reduces if collider operates below transition. The overall emittance growth may be additionally reduced if the beam is in a quasi-equilibrium state when temperatures in all three degrees of freedom are approximately equal, *i.e.*

$$\theta_x \approx \theta_y \approx (\delta p/p)/\gamma . \qquad (3)$$

Here γ is the relativistic factor. In this case the emittance growth rates for all degrees of freedom are equal, and the emittance growth is driven by beam lumped focusing which changes local temperatures along the ring resulting in the overall 6D emittance growth. Computation of IBS growth rates, which uses the algorithm suggested [7], shows that for NICA lattice the overall emittance growth in this quasi-equilibrium is ~3.5 times slower than the time of temperature exchange between degrees of freedom. Figure 1 shows sizes of major axes of velocity ellipse in the space of velocities along the ring. The blue line shows the vertical rms velocity spread. The horizontal and longitudinal planes are coupled. That causes variations in the green line which represents the ellipsoid size in the direction close to the longitudinal direction. The right side of the plot shows velocity variation in the section with regular focusing in the arc, while the left side presents velocity variations near IP. As one can see the IR optics results in very large difference between "transverse" and "longitudinal" velocity spreads which greatly increases the growth rates. In the absence of the IR focusing the emittance growth rates in a quasi-equilibrium would be much slower. IBS determines the required cooling times, which for NICA parameters are in the range 5-30 minutes. Thus, in addition to the beam cooling during beam accumulation the beam cooling during collisions becomes necessary.

BEAM COOLING

A low beam energy and a usage of highly charged ions enable an application of both electron and stochastic cooling. Both methods have been used at large number of different machines. However, up to now cooling at collisions was only used in RHIC in BNL for cooling of dense bunches of heavy ions [8]. Electron cooling looks preferable at low energy. Up to now the highest energy cooling was used in Fermilab during Tevatron Run II where 8 GeV antiprotons were cooled [9]. The electron cooling in NICA is designed to cover the entire range of its energy. Stochastic cooling operates better at relativistic energies where the slip-factor is reduced thus creating a possibility to use microwave frequencies. For NICA it can be used for energies above ~2.5 GeV/u.

Magnetized electron cooling enables very deep cooling of the ion velocity spread. However, the electron beam temperatures need to be increased to reduce cooling force for small amplitude particles and the beam loss due to radiative recombination.

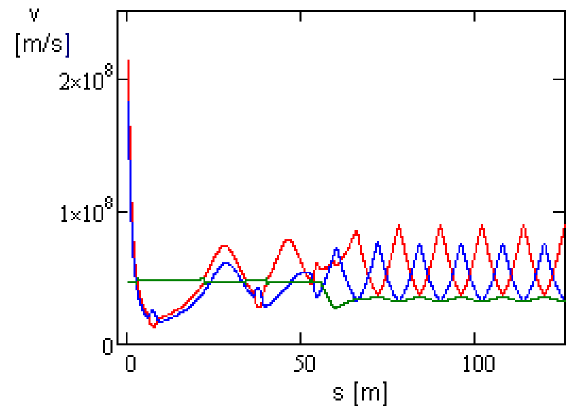

Figure 1: Rms values of the velocity ellipse for quarter of NICA circumference for the case when the beam is in a quasi-equilibrium.

Presently we believe that the betatron tune shifts due to beam-beam effects and the beam space charge represent the major limitation on the collider luminosity. For estimates we assume that the total tune shift should not exceed 0.05 (relatively conservative constraint since the tune shift of 0.1 was achieved in RHIC operation at low energy, although with bad beam lifetime [10]). This requirement together with the dynamic aperture limitation, considered in the previous section, determine the number of particles per bunch, and, consequently, the luminosity. Corresponding values are presented in Table 1. For operation at the maximum luminosity the beam cooling strength has to be sufficient to compensate for the IBS.

Table 1: Tentative NICA Parameters

	2 GeV/u	**4.5 GeV/u**
Number of ions, 10^9	0.71	3.25
Rms vertical emittance, μm	0.7	
Rms momentum spread, $10^{-3}Q$	0.82	1.6
Space charge tune shift, $\delta Q_x/\delta Q_y$, 10^{-2}	4.2/4.7	2.1/2.8
Beam-beam tune shift/IP, $\delta Q_x/\delta Q_y$, 10^{-3}	1.3/1.3	2.5/2.6
Beta-function in IP, cm	60	
IBS emittance growth times, min	6.5	24
Luminosity, 10^{26} cm$^{-2}\cdot$s^{-1}	0.86	16.7

For a relativistic beam the cooling rates in relativistic electron cooling decrease fast with beam energy increase. The same is justified for IBS. However, IBS heating rates

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decrease slower than the cooling rate. Consequently, an energy increase requires an increase of the electron beam current. The NICA electron cooler is designed to cover the entire range of NICA beam energy. The cooler should operate up to 2.5 MeV electron beam energy with up to 1 A beam current. To provide the design luminosity simultaneous operation of electron and stochastic cooling systems is anticipated. Such operation with both stochastic and electron cooling on were demonstrated in Fermilab in the course of Tevatron Run II [9].

For a bunched beam the stochastic cooling rate of transverse cooling at the optimal gain is:

$$\lambda_{\perp} \approx \frac{2\pi|\eta|\sigma_p}{f_0 N}\frac{\sigma_s}{C}\left(f_{\max}{}^2 - f_{\min}{}^2\right). \tag{4}$$

Here $\eta = \alpha - 1/\gamma^2$ is the slip factor of the ring, N is the number of particles in the bunch with length σ_s, C is the ring circumference, σ_p is the relative rms momentum spread in ion beam, f_0 is the revolution frequency, f_{max} and f_{min} are the upper and low frequencies of stochastic cooling band and we assume that the gain of stochastic cooling system is linearly growing with frequency. The latter maximizes the cooling rate for a given band. Equation (4) is justified when $B = |\eta|\sigma_p f_{\max} / f_0 \le 0.15$. With further increase of this factor the cooling rate stops to grow [11]. Up to now the transverse cooling systems typically operate without overlap of longitudinal and transverse bands which corresponds to $B \le 0.07$. For NICA operating at 4.5 GeV/u we choose f_{max}=3.5 GHz which corresponds to B≈0.09. That enables to suppress the IBS without electron cooling. To avoid the band overlap at lower energies the total band of NICA stochastic cooling 0.7-3.5 GHz is split into 4 bands. That enables to extend the stochastic cooling reach to about 2.5 GeV/u by a reduction of upper boundary of the band.

A usage of the only stochastic cooling, if possible, is highly desirable, since recombination of heavy ions with electrons in the electron beam considerably reduces the beam lifetime.

Note that the momentum spread of the ions is smaller in the course of ion beam accumulation. Therefore, the stochastic cooling can be effective for the beam energy below 2.5 GeV.

OTHER CONSIDERATIONS

NICA magnetic system is based on superconducting magnets. This choice was driven by the following considerations: (1) available technology which was already well tested in the Nuclotron ring built in JINR in 1993 [12], (2) a cryogenic vacuum chamber enables obtaining exclusively good vacuum so that to avoid the beam loss due to particle interaction with residual gas, and (3) minimization of consumed power.

At maximum energy the average beam current in NICA is about 0.5 A, with peak current of about 10 A. It presents considerable challenge for suppression of beam instabilities and will require both the transverse and longitudinal dampers. The problem is driven by the separation of coherent and incoherent frequencies by the beam space charge.

For the longitudinal degree of freedom this problem is well understood in the absence of longitudinal beam damping. Below transition, the space charge interaction in the longitudinal plane results in a loss of Landau damping [13, 14]. That results in the beam being unstable even in the presence of small impedances. Note that usually it does not result in the beam loss since the instability is self-stabilized by non-linearity of bunch self-interaction. It was experimentally observed in the Tevatron during its Run II [15]. However, a presence of such instability during collisions is unacceptable since it will amplify the beam-beam effects.

The situation for the transverse plane is much more complicated and requires both theoretical and experimental studies. Considerable efforts were done in recent years [see Ref. [16] and references there). However, predictive power of these studies is insufficient for NICA.

In conclusion we need to state that the IBS is expected to be an important mechanism for beam stabilization as it was observed in RHIC [17].

CONCLUSION

In this paper we described the main ideas and limitations which led us to a creation of NICA conceptual design and, consequently, to the machine design and construction.

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