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ACCELERATION OF DEUTERONS AT THE UNK (Proposal)

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In this article possible perspectives of using UNK for accelerating multicharged iones with minimal additions and changings in systems of complex UNK are considered. Deuteron accelerating is proposed as the minimum variant in which one supposes to reach energy till 1.5 TeV/nuc in one beam.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Ускорение дейтронов в УНК (Предложение)

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В данной работе рассмотрены перспективы возможного использования УНК для ускорения многозарядных ионов с минимальными изменениями и дополнениями в системах комплекса. В качестве минимального варианта в этом плане рассматривается дейтронный режим, в котором предполагается достигнуть энергии вплоть до 1,5 ТэВ/нуклон в одном пучке.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

1. Introduction

The acceleration-and-storage complex (UNK) to be built in the Institute of High Energy Physics (IHEP) is designed for acceleration of intense proton beams (up to $5 \cdot 10^{14}$ particles/pulse) in the synchrotron mode [1] and for investigations with secondary beams from the fixed target or with colliding proton-proton beams of energy up to 3 TeV. Totally, the complex consists of a 30 MeV linear accelerator with radio-frequency quadrupole focusing [2], a 1.5 GeV fast-cycling booster synchrotron (25 Hz) [3], a 70 GeV strong focusing synchrotron and three synchrotrons of the UNK proper with the orbit perimeter 20777.8 m and energy 400 GeV (600 GeV in the accelerating mode) and 2x3 TeV. The last two accelerators involve a magnet structure with superconducting elements. The first stages

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envisage construction of a 600 GeV accelerator and later one of the 3 TeV rings.

The present work deals with the possible use of the UNK for acceleration of multicharged ions with minimum modification of the UNK systems. Acceleration of multicharged ions was carried out at many high energy accelerators for investigations in the field of relativistic nuclear physics. For example, 9 GeV/c deuterium nuclei were accelerated for the first time at the JINR synchrophasotron in 1970 [4]. Later helium nuclei were accelerated there as well. In the 1970s, deuterons and α-particles were also accelerated at CERN, where they used the ISR facility designed for colliding proton-proton beams. In 1986—87, ^{16}O and ^{32}S with energy 200 GeV/nucleon were obtained there at the SPS. Similar research was carried out at the proton synchrotron AGS in Brookhaven (USA) (^{16}O of energy 15 GeV/nuclein and ^{28}Si of energy 14.6 GeV/nucleon). At present the growing interest in studying a new state of nuclear matter, which is quark-gluon plasma, results in construction of facilities for acceleration of heavy ions to ultrarelativistic energies. We mean the collider RHIC in Brookhaven, where experimenters will be able to work with particles from protons of energy 250 GeV and luminosity $\approx 10^{31}\ cm^{-2}s^{-1}$ to Au of energy 100 GeV/nucleon and luminosity $\approx 2\cdot 10^{26}\ cm^{-2}s^{-1}$. Besides, the large hadron collider (LHC) at CERN is known to allow not only proton-proton and proton-electron beams but also colliding ^{208}Pb —^{208}Pb beams of centre-of-mass energy 1312 TeV and luminosity $\approx 1\cdot 10^{28}\ cm^{-2}s^{-1}$.

From the aforesaid, it is clear why there arises interest in extending the capabilities and modification of the UNK, in construction of which large material resources are invested. As a maximum, we consider deuteron acceleration where energy up to 1.5 TeV/nucleon in a beam is supposed to be attained. Of great interest is also an investigation into a possibility of accelerating a beam of polarised deuterons. In ref. [5] the authors already touched upon the problem of conserving proton beam polarisation in the booster synchrotron U-1.5 and in the proton synchrotron U-70. However, for a deuteron beam the expected depolarisation effects seem to be less essential than for a proton beam.

2. General Physical Premises for Transition to the Deuteron Range

Since all the accelerators of the complex (except the injector linac) are alternating-gradients synchrotrons, transition to the deuteron range is determined by physical features of operation of this type of accelerator.

The main parameters of alternating-gradient synchrotrons are:

2.1. acceleration energy range,
2.2. acceleration frequency range,
2.3. dynamic characteristics and transition energy,
2.4. maximum charge density in a bunch,
2.5. maximum vacuum in a chamber,
2.6. luminosity.

It implies preserving the magnetic structure of the rings and the maximum induction of the magnetic field.

2.1. *Acceleration energy range.* The total energy of a particle is

$$E = \sqrt{[P^2c^2 + E_0^2]}, \tag{1}$$

where E_0 is the rest energy, P is the momentum of the charged particle,

$$P = \frac{eBk_f L_{e0}}{2\pi}, \tag{2}$$

L_{e0} is the length of a closed orbit, $k_f = \frac{R}{\rho}$ is the factor of filling the orbit with dipoles, $R = \frac{L_{e0}}{2\pi}$, ρ is the orbit curvature radius in dipoles, B is induction of the magnetic field in dipoles.

In the relativistic case ($E >> E_0$) we have

$$E \approx Pc. \tag{3}$$

It directly follows from (2) and (3) that the maximum total energy of an accelerated particle in the given structure of the magnetic field ($B_{\max} k_f L_{e0}$ = const) is proportional to the charge of a particle undergoing acceleration (e), i.e., the proton ring corresponding to the energy 3 TeV will also hold 3 TeV deuterons.

2.2. *Acceleration frequency range.* Since the revolution frequency on a closed orbits is

$$f = \frac{\beta c}{L_{e0}}, \tag{4}$$

the frequency range is only determined by the velocity of an ion (βc) at injection and at final energy.

In a non-relativistic case ($\gamma = \frac{E}{E_0} \approx 1$)

$$f \approx \sqrt{\frac{W}{m}}, \tag{5}$$

where W is the kinetic energy and m is the mass of a particle. Here and on the symbol «~» indicates that under the given conditions the proportionality constants are the same for protons and deuterons.

At the relativistic energy ($\gamma >> 1$)

$$f \sim 1 - \frac{1}{2\gamma^2}. \tag{6}$$

In this case the frequency band width is

$$\delta f = \frac{\gamma_k^2 - \gamma_i^2}{2\gamma_k^2 \gamma_i^2} \frac{c}{L_{e0}}, \tag{7}$$

where γ_k, γ_i correspond to the final energy and injection energy.

2.3. *Dynamic characteristics and transition energy.* Within the single-particle theory (without allowance for space charge) betatron frequencies only depend on the magnetic field structure and do not depend on the charge and mass of the particle undergoing acceleration in the synchrotron mode.

The difference occurs in the transition energy, which, at the given expansion coefficient of closed orbits $\alpha = \frac{P}{L_{e0}} \frac{\delta L_{e0}}{\delta P}$, is found from

$$E_{tr} = \frac{E_0}{\sqrt{\alpha}}, \tag{8}$$

i.e., for the given magnetic structure the kinetic energy increases by a factor of A as compared with protons, where A is the number of nucleons of the given ion. There are several methods of overcoming or elimination of transition energy [6,7,8]. It should be considered in each particular case, which of them is the best.

2.4. *Maximum charge density in a bunch.* The maximum charge density in its transverse effect at the fixed length of the closed orbit L_{e0} and the frequency of free oscillations (Q_z, Q_r) is

$$k \sim \frac{E_0 \gamma^3 \beta^2}{e^2} \sim \frac{EP^2}{E_0^2}, \tag{9}$$

where the values of γ, β, P correspond to the energy of injection in the ring, $P = \frac{E_0 \beta \gamma}{c}$.

With the injection energy from the non-relativistic region ($\gamma \approx 1$) and unchanged particle revolution frequency ($\beta_d = \beta_p$), expression (9) becomes simpler:

$$k \sim E_0, \tag{10}$$

i.e., the maximum density of a deuteron beam in a bunch will be twice as large.

For relativistic injection energies ($E \approx Pc$) and the same magnetic rigidity ($P_d = P_p$) we obtain

$$k \sim \frac{1}{E_0^2}, \tag{11}$$

which decreases the maximum density of the deuteron beam by a factor of four.

However, it is not always possible to satisfy the condition $\beta_d = \beta_p$ or $P_d = P_p$. In this case (9) is transformed to

$$k \sim \frac{EB_i^2}{E_0^2}, \tag{12}$$

where B_1 is induction in dipoles at injection. From (12) a possibility of an intermediate variant between (10) and (11) follows. Longitudinal effects under the phase stability, as a rule, do not impose additional limitations on the beam charge density.

2.5. *Maximum vacuum in a chamber.* The multiple Coulomb scattering effects in annular accelerators for protons and deuterons can be compared by the root-mean-square increase in the amplitude of betatron oscillations. At a fixed length of the closed orbit, the same dynamic characteristics (Q_r, Q_z) and vacuum for this relation can be written as [9]

$$\langle a^2 \rangle \sim \frac{\mathfrak{L}}{P\beta^2}, \tag{13}$$

where $\mathfrak{L} = L_{e0}\nu$, ν is the number of revolutions necessary to double the injection (kinetic) energy, P and β are taken at the injection energy.

If the equality $P_d = P_p$ is observed in injection, then at the non-relativistic energy it follows from (13) that $\langle a_d^2 \rangle = 2\langle a_p^2 \rangle$ owing to a decrease in the deuteron velocity at injection and a decrease in the number of revolutions at energy doubling for the same energy gain per revolution.

In a relativistic case with $P_d = P_p$ or for non-relativistic energy at $\beta_d = \beta_p$ at injection, it directly follows from (13) that $\langle a_d^2 \rangle = \langle a_p^2 \rangle$.

Within this model of scattering by residual gas, the distribution over amplitudes of betatron oscillations follows the Raleigh law:

$$F(a) = \frac{a}{\langle a^2 \rangle} e^{-\frac{a}{2\langle a^2 \rangle}}. \tag{14}$$

Thus, for injection with $P_d = P_p$, only the non-relativistic part of the complex must be checked for multiple scattering effect in transition from a proton to a deuteron beam.

2.6. Luminosity. One can estimate the luminosity (L) for deuterons assuming that the root-mean-square dimensions of beams at collision points, revolution frequencies of particles and the number of bunches in a circulating beam are the same for both variants. In this case we have

$$L \sim N^2, \tag{15}$$

where N is the number of particles in a circulating beam.

3. Estimation of Deuteron Mode Parameters

Proceeding from the considerations of section 2 we shall estimate parameters of UNK operation in the deuteron mode. The results are given in the table compared with the proton variant. For deuterons, there are only values of those parameters that differ from the proton variant.

The energy of injection into booster was calculated with the given minimum revolution frequency of protons $f_p = 0.7467$ MHz. Thus, the field induction at injection could be found from (1) and (2). The maximum number of particles in a circulating beam, determined by the shift of the frequency of axial free oscillations due to Coulomb repulsion, can be calculated in accordance with (9) by the formula [10]

$$N_d = \frac{r_p}{r_d} \frac{\gamma_d(\gamma_d^2 - 1)}{\gamma_p(\gamma_p^2 - 1)} \frac{f_d}{f_p} N_p, \tag{16}$$

Table

LINAC	Protons	Deuterons
Output energy (MeV)	30	60
Current pulse amplitude (mA)	67	76

BOOSTER	Protons	Deuterons
Final energy (kinetic) (GeV)	1.5	1.05
Intensity in pulse (particles/cycle)	$9x10^{11}$	$1.0x10^{12}$
Circulating current (mA)	425	483
Transition energy (kinetic) (GeV)	2.55	5.096
Magnetic field induction in injection (T)	0.139	0.278
Frequency variation range (MHz)	0.747—2.79	0.747—2.32

U-70	Protons	Deuterons
Final energy (kinetic) (GeV)	70	69
Intensity in cycle (particles/cycle)	$1.1x10^{13}$	$1.2x10^{13}$
Circulating current (mA)	357	405
Transition energy (total) (GeV)	8.876	17.738
Frequency variation range (MHz)	5.56—6.1	4.66—6.06

UNK-I and UNK-II (collider mode)	Protons	Deuterons
C.m.energy (TeV)	2.2	2.19
Full required intensity (particles/cycle)	$2.4x10^{14}$	$6x10^{13}$
Circulating current (mA)	554	139
Luminosity ($cm^{-2} s^{-1}$)	$1x10^{32}$	$6x10^{30}$
Transition energy (GeV)	42	84

UNK-I	Protons	Deuterons
Maximum energy (GeV)	600	599
collider mode	400	399
Planned intensity (particles/cycle)	$6x10^{14}$	$1.5x10^{14}$
Circulating current (mA)	1385	347

UNK-II	Protons	Deuterons
Maximum energy (GeV)	3	3
Planned intensity (particles/cycle)	$6x10^{14}$	$1.5x10^{14}$
Circulating current (mA)	1385	347

UNK-II and UNK-III (collider mode)	Protons	Deuterons
C.m.energy (TeV)	6	6
Full required intensity (particles/cycle)	$2.4x10^{14}$	$6x10^{13}$
Luminosity ($cm^{-1} \cdot s^{-1}$)	$2.8x10^{32}$	$1.7x10^{31}$

where r_p and r_d are the classical radii of the proton and deuteron. It is assumed that the permissible frequency shift, beam emittance and bunching factor are the same in both cases. The estimation was done with the energy of injection in the facility. The decisive factor for the beam intensity in the whole chain of accelerators of the complex (linac, booster, U-70, UNK-I, UNK-II) is the maximum number of particles attained in U-70 now. Yet, after the updating of U-70 an almost 5-fold increase in the number of ejected beam particles is expected. This fact was taken into account in calculation of deuteron intensities given in the table. It was also assumed that the efficiencies of acceptance, transmission, re-bunching (U-70) and beam extraction are the same for protons and deuterons and have the values achieved at present.

The intensity of the circulating beam is

$$I_c = \frac{eNf_{rf}}{q}, \qquad (17)$$

where q is the ratio of the accelerating field frequency f_{rf} to the particle revolution frequency.

As the given magnetic rigidity of the rings ($B\rho$) one determines the final energy of accelerators in accordance with (1), the revolution frequency by (4) and the transition energy by (8). A new thing, as compared with the proton variant, is the transition energy in the range of UNK-I energies in acceleration of deuterons. The methods of overcoming the transition energy were mentioned in section 2.

The centre-of-mass (c.m) energy of colliding beams was estimated by the well-known formula [11]:

$$E_{\text{c.m.}} = c^2 \sqrt{[m_{01}^2 + m_{02}^2 + 2m_{01}m_{02}\gamma_1\gamma_2(1 - \beta_1\beta_2)]}, \qquad (18)$$

where m_{01}, m_{02} are the rest masses of particles; β_1, β_2 are taken algebraically, i.e., with their signs.

The dynamic characteristics of the transverse motion of deuterons (interval frequencies, envelopes, etc.) in the accelerating chain from the booster to UNK-I are fully equivalent to the proton mode characteristics. So, with the same emittance of proton and deuteron beams injected from the linear accelerator and with the deuteron intensity at which the Coulomb shift of betatron frequencies is equal to or smaller than for protons, the transverse emittance of the deuteron beam and the acceptance of the accelerators of the complex can surely be matched.

4. Technical Realization

As seen from the aforesaid, the deuteron mode of the UNK operation is possible with the existing and planned equipment without essential changes.

The only facility to be built is a linear accelerator for deuterons to inject them in the booster. As is known, however, while making U-70 into an injector of the UNK, one intends to increase the injection energy from 30 MeV to 60 MeV [12]. To this end, a new linear accelerator is supposed to be built. While the new accelerator, one could take into account the requirements imposed by the deuteron mode and experience of IHEP in designing a heavy-current linear accelerator for deuterons [13].

Besides, it is necessary to allow for a system for overcoming the transition energy in the UNK-I. The final considerations for selection of its parameters will be formulated later in the course of elaboration of this proposal.

5. Conclusion

The deuteron mode of acceleration can be regarded as the initial step of the programme for acceleration of ions heavier than hydrogen at the UNK.

Implementation of this programme will require development of the necessary ion sources and upgrading of several systems of the complex, especially the injection section, the beam indication system and some others. Suitability of this programme and the rate of its implementation will depend of the experiments proposed with allowance for the status of ion acceleration activity at large accelerating complexes in European centres and in the USA. We think that it will be undoubtedly useful to develop the relevant techniques and technologies in advance.

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References

1. Ageev A.I. — Accelerator-Storage Complex of IHEP. In: Proc. of 10th All-Union Conf. on Charged Particle Accelerators, JINR D9-87-105, Dubna, 1987, v.2, p.430.
2. Kapchinsky I.M. et al. — In: Proc. of 11th All-Union Conf. on Charged Particle Accelerators, JINR 9-89-52, Dubna, 1989, v.1,p.37.
3. Aleev E.A. et al. — In: Proc. of 9th All-Union Conf. on Charged Particle Accelerators, Dubna, 1985, v.1, p.14.

4. Baldin A.M. et al. — JINR P9-5442, Dubna, 1970.
5. Azo Yu.M. et al. — In: Proc. of 8th All-Union Conf. on Charged Particle Accelerators, Dubna, 1983, v.1, p.212.
6. Vladimirsky V.V. et al. — Proton Synchrotron on Energy 60—70 GeV. In: Proc of Int. Conf. on Accelerators, Moscow, 1964, p.197.
7. Myae E.A., Pashkov P.T. — In: Proc. of 8th All-Union Conf. on Charged Particle Accelerators, Dubna, 1983, v.1, p.231.
8. Trboevic D. — Design Method of High Energy Accelerator without Transition Energy. In: Proc. of 2nd European Particle Accelerator Conference, Nice, France, Editions Frontieres, 1980, v.11, p.1536.
9. Blachman N., Courant E. — Rev. Sci. Intsr., 1953, 24, p.836.
10. Kolomensky A.A. — Physical Bases of Methods of Charged Particles Accelerations. Moscow, 1980, p.249.
11. Bovet C. et al. — Selection of Formulae and Data Useful for the Design of A.G. Synchrotrons, CERN, 1970, p.6.
12. Gurevich A.S. et al. — Upgrading 70 GeV IHEP Accelerator as UNK Injector, in Proc. of 2nd European Particle Accelerator Conference, Nice, France, Editions Frontieres, 1980, v.1, p.415.
13. Budanov U.A. et al. — IHEP, 90-126, Protvino, 1990.

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