NUCLOTRON STATUS REPORT

A.M.Baldin, S.A.Averichev, Yu.D.Beznogikh, A.M.Doniagin, E.I.Djachkov, I.B.Issinsky, A.I.Govorov, A.D.Kovalenko, G.G.Khodzhibagijan, L.G.Makarov, A.I.Mikhailov, V.A.Mikhailov, A.I.Pikin, I.N.Semeniushkin, A.A.Smirnov, I.A.Shelaev, B.V.Vasilishin, M.A.Vojevodin, A.G.Zel´dovich, L.P.Zinoviev

Joint Institute for Nuclear Research, Dubna, USSR

A.A.Vasiliev
State Committee for Utilization of Atomic Energy, Moscow, USSR

Summary

An accelerator of relativistic nuclei at an energy of 6 GeV/u is presented in outline. The parameters of the accelerator and the characteristics of superconducting magnets with iron-shape magnetic field employed in it are given.

Introduction

Over the past years search for an optimal solution of the creation of an accelerator of relativistic nuclei, Nuclotron,[1] has been carried out at JINR. This Nuclotron is expected to exceed substantially, in its parameters, the Synchrophasotron and in future be able to replace the latter.

Present-day intensive studies in the field of relativistic nuclear physics, in particular, investigation of the multiquark nuclear model, search for a new state of nuclear matter, quark-gluon plasma, etc., require for the energy of nuclei to be not less than[2] 3.5 GeV/u. An energy of 4.2 GeV/u presently achieved on the Synchrophasotron, acceleration of the beams of "bare" nuclei from the Donets electron beam ion source, a new experimental hall with a wide network of channels of primary and secondary particles all these facilities explain a great demand of physicists for this accelerator. However this demand much exceeds at present the capabilities of the machine built more than 25 years ago. These requirements can be satisfied by a modern accelerator the dimensions of which permit one to install it into the existing Synchrophasotron building (Fig. 1).

Alongside with the study of superconducting magnets with higher (~5 T) fields since 1976 work aimed at the creation of low-field, low-cost superconducting magnets with iron-shape magnetic field[3,4] has been done at JINR. The concept of creating magnetic units makes it possible to decrease the cross section of the accelerator magnet coils and the energy consumption by about an order of magnitude. Four years ago[5] one has started to design magnets which cools by a forced liquid helium stream inside a hollow superconducting cable forming the coil. The cryostat consists of a nitrogen shield and a vacuum jacket. This construction is remarkable by its reliability, simplicity of mass production and small expenditure of superconductor. The vacuum chamber is eliminated due to cryogenic pumping. The total cycle duration of the accelerator magnetic field is provided to be within the limits of 1 sec. The duration of the beam extraction may be changed from tenths of a second to unlimited one. As the Nuclotron injector a heavy-ion synchrotron or directly an Alvarez-type linac with the Donetz electron beam ion source can be used which would make it possible to accelerate multi-charged ions without intermediate stripping.

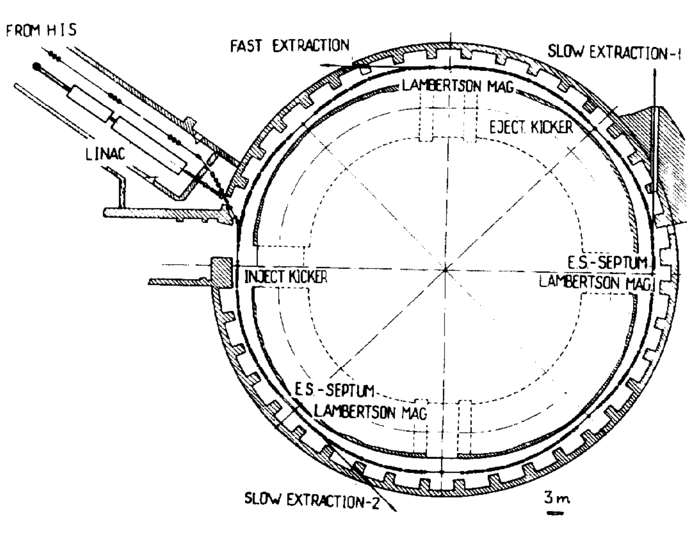

Fig.1. General Layout of Nuclotron.

Taking into consideration the facilities available at the Laboratory of High Energies of JINR (equipment, buildings, communications), our technology of production of superconducting magnets, their reliability, energy losses, stored energy as well as the physical program developed it is advisable and profitable to build the Nuclotron ring on the basis of the superconducting magnets of the mentioned type.

In Table 1 the Synchrophasotron parameters are compared with the Nuclotron parameters for two versions of the magnetic system, the warm and the superconducting ones.

Table 1

	Synchrophasotron	Nuclotron Warm magnets	Nuclotron SC magnets
Max.energy, GeV/u	4.2	6	6
Repet.rate, cycle/sec	0.1	0.5-1	0.5-1
Max.duration of extraction per 10 sec, sec	0.5	5	9
Intensity (part./cycle)			
d	10^{11}	3×10^{12}	3×10^{12}
C^{6+}	10^{6}	$\sim10^{10}$	$\sim10^{10}$
U^{82+}	-	$\sim10^{9}$	$\sim10^{9}$
Beam emittance (mm mrad)			
Ex	110π	4π	4π
Ez	26π	3π	3π
Power consumption (MW)	8.5	4	0.7
Mass (tons)	36000	320	80

Ion Sources

The Nuclotron project makes it possible to use any source in which the ionization state of atoms is high enough ($0.3 \leq q/A \leq 1$) as to be able to perform acceleration without intermediate stripping. This source may also be a duoplasmotron and a Penning-type source for relatively light nuclei, a laser and so on.

However, in our project we suggest to use the Donets electron beam ion source[6] as a basis of high charged ions which is known, on the basis of the results obtained, to provide the highest ionization state of atoms. This source has successfully been working on the Synchrophasotron since 1977, one of its versions has been used to produce Ar^{18+}, Kr^{34+} and Xe^{52+} ions. Although the sources where a 0.1 A electron beam is employed give the ion intensity $10^{10}/q$ per pulse the calculations show that further improvement of the ionizer and an in-

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crease of the electron beam current up to a few amperes can provide an increase of the particle intensity up to $(0.5-1)\times10^{12}/q$.

There is also no limitations of principle in producing highly charged ions of heavy elements up to uranium. The estimations and experiments carried out by Donets show that the electron beam ion source can be used to produce the uranium ions, in particualr, from U^{72+} (q/A=0.3 which corresponds to a minimum allowed value of this parameter in the Alvarez linac) to U^{82+} (q/A=0.34). The latter value may turn out to be optimum since for an appropriate mode of operation of the ionizer there is a possibility of keeping the electron K and L shells to be completely populated with an intense ionization of the all foregoing ones. To this end, the electron beam energy is chosen to be sufficiently high but not much exceeding the L shell ionization potential. In so doing, the 82+ ion intensity is expected to be maximum since the charge spectrum width is 2-3 units compared to the 72+ ion intensity for which the spectrum width is much larger (about 10 units).

Sources of the duoplasmotron type will be employed for proton, deuteron and He^{2+} beam.

Injector

According to the earlier suggested scheme[1] of the Nuclotron the beam should come to its main ring from an intermediate one for which a linear accelerator of an energy of 10 MeV/u or higher should serve as an injector.

Although the high degree of ionization obtained in the Donets source makes it possible, in principle, to start accelerating ions with q/A=0.3 directly in the Alvarez linac, progress achieved lately in particle acceleration by the Kapchinsky-Tepliakov method gives a favorable opportunity of using it in the low-energy part of the injector[7]. The particle energy after the RFQ linac is equal to 1.5 MeV/u.

When the acceptance is completely filled the emittance at output of the linac is in the limits of 30π mm mrad. The emittance value of the beam from the Donets source is expected to be not larger than 4π mm mrad at the linac output.

The main parameters of the Alvarez linac are given in Table 2.

Table 2

Output energy	12 MeV/u
Input energy	1.5 MeV/u
Frequency	145 MH z
Number of cavities	2
Minimum q/A	0.3
Normalized acceptance	5π mm mrad.

Booster

The intensity of beams, at the first stage of lightest nuclei such as D and He^{2+}, is planned to be increased by means of a booster, the Heavy Ion Synchrotron, TIS[8], the acceptance of which (A_x=500π mm mrad, A_z = = 100π mm mrad) much exceeds that of the main ring of the Nuclotron. This accelerator with repetition frequency up to 3 Hz will also be of an independent value as a source of ions and nuclei in a wide range of masses with an energy up to 800 MeV/u.

For a five-turn injection into TIS of a beam from a linac with an energy of 12 MeV/u and a 30π mm mrad emittance the intensity of the beam injected into the main ring will be $\approx 6\times10^{12}$ particles/pulse, the Coulomb limit corresponding to the deuteron current 60 mA from the linac.

Main ring

The particular features of the magnets, the winding dimensions of which are much smaller compared to the warm magnets and which do not require a traditional internal vacuum chamber (see below), make it possible to use effectively the accelerator perimeter and install the magnets close to one another.

The ring with a circumference of 250 m consists of 8 superperiods each of which includes 4 cells with FODO configuration (Fig. 1). The effective dipole length is 3.020 m and the quadrupole one is 0.4 m. There are two long straight sections in each superperiod which are due to the elimination of two dipole magnets. Correcting magnets are installed into short 0.4 m long spacings between quadrupoles and dipoles. The betatron frequencies are chosen to be about $Q_x \approx Q_z \approx 6.75$. The quadrupole gradients are G_F=37.4 T/m and G_D=37.9 T/m for the dipole field of 2 T. Then the particle energy obtained in the Nuclotron is expected to be 6 GeV/u.

The initial condition in the determination of the aperture of the magnetic elements of the main ring is taken to be the values of the emittance of a beam from TIS: E_x=30π mm mrad and E_z=20π mm mrad. The factors of the increase of the effective phase-space volume of the beam in the process of injection are estimated to be 1.3 for the horizontal emittance and 1.5 for the vertical one which correspond to the beam acceptance values in the main ring A_x=40π mm mrad and A_z=30π mm mrad.

Fig. 2 shows a typical use of apertures in dipoles and quadrupoles.

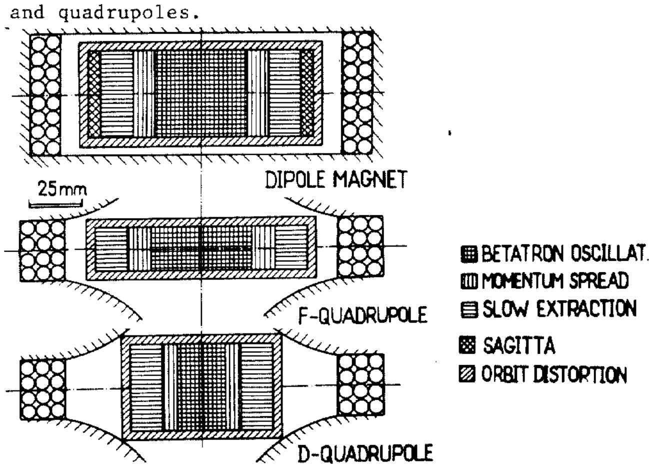

Fig. 2. Typical filling of apertures.

There was also considered a possibility of a direct injection of a beam from a 12 MeV/u linac to the Nuclotron main ring. The calculations show that this suggestion is quite acceptable at the first stage of construction of the complex. The magnetic field level in the ring will be B_i=0.0632 T for uranium and B_i=0.0435 T for nuclei with q/A=0.5 which does not lead to troubles from the point of view of residual fields. The Coulomb limit for deuterons will be 1×10^{12} or in the general case, 5×10^{11} A/q^2.

The injection, slow and fast abort extraction are performed in the vertical plane. Lamertson magnets with superconducting coils are used. Such a scheme enables one to extract the beam on the level of experimental halls, as well as to exclude a warm current-carrying septum and, thus to provide high-vacuum conditions. The estimated extraction efficiency is not less than 99%.

Superconducting magnets

In designing superconducting dipole and quadrupole magnets of the Nuclotron the following conditions have been satisfied: (a) The frequency of repetition of accelerating cycles is 0.1 - 1.0 Hz; (b) There is no special vacuum chamber; (c) Cryogenic security is provided by a small amount of helium in the system; (d) The total heat leaks per meter in magnets of the accelerator should not exceed 5 W/m.

Starting from the abovementioned considerations we have chosen a window frame dipole magnet and a superconducting cable forming the coil with a maximum field of 2.0-2.1 T. The dipole has an aperture of 130 mm x x 56 mm size and consists of two identical half-units of 1.5 m long. The external dimensions of the dipole are 300 mm x 200 mm. The saddle-shaped winding is made of a hollow superconducting cable which is fabricated as follows: thirty one filaments are spirally wound on a cupro-nickel pipe 5 x 0.5 mm in diameter with a twist of 47 mm. The interturn insulation consists of four layers of mylar tape 0.02 mm thick and 10 mm wide and of two layers of fibre glass 0.08 mm thick and 10 mm wide impregnated with epoxy-resin.

The superconducting cable is designed to operate at the rates of increase of the magnetic field $\dot{B}$ = = 4 T/sec. The cooperative losses per meter of the cable length are, in this case, of the order of 0.172 W/m when NbTi wires 0.5 mm in diameter with a copper matrix and superconducting 10 µm filaments are used. These losses can considerably be reduced by employing superconductors with a copper-nickel matrix.

An experimental model of such a dipole (Fig.3) of a full-scale length and with a somewhat smaller aperture had been constructed and tested (Table 3). There is a good agreement between the characteristics obtained and the requirements imposed. The dipole and its installation in a cryostate are shown in Fig. 4. In the construction of quadrupole magnets use is made of the same hollow superconducting cable as for the dipoles. The quadrupole magnet yoke has hyperbolic poles wound by a double row superconducting winding with six turns on the pole.

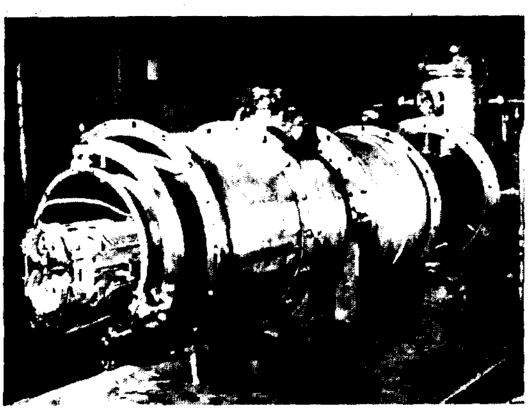

Fig. 3. The experimental dipole magnet.

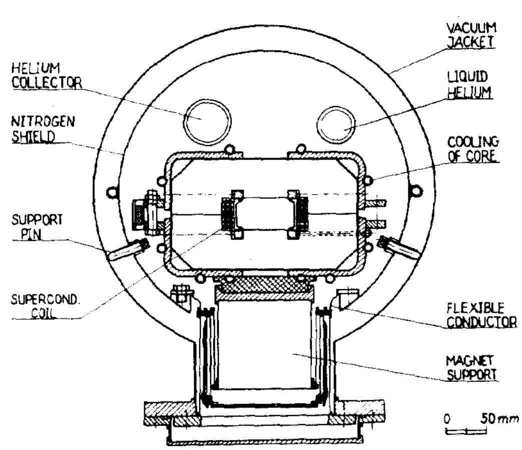

Fig.4.Layout of the dipole installation in cryostate.

Table 3

Aperture	90 mm x 42 mm	Number of s.c. filaments in the wire	1045
Length	1.5 m	The copper to the supercond.ratio	1.39/1
Number of turns	12	Twist pitch of filaments	3 mm
Cable length	42 m	Maximum current	6 kA
Outside diameter of cable	6.7 mm		

Vacuum in the Nuclotron ring

The acceleration volume is mainly restricted by the inner walls of magnets with a temperature of (4-5) K. In this region the residual gas must consist mainly of H_2 and He. To pump the latter constituents cartridges with charcoal can be installed on the surface of the magnets and connectors.A tight sealing of adjacent magnets with one another and a hermetization of the magnet yokes make safe the acceleration volume against penetration of gas molecules from the insulation volume. All these measures must enable one to reach a pressure of $P=1.10^{-10}$ Torr in the acceleration volume.

Cryogenic system

As far as cooling is made by means of forced circulation of two-phase helium in the hollow composite superconductor,the helium vessel of the cryostat need not be used and the access to the magnetic system thus becomes easier.The cryostat is a "warm" vacuum vessel of a cylindrical shape inside which a copper shield cooled with liquid nitrogen is located.The vacuum vessel has telescopic connections.

It seems to be possible to design the scheme of cryogenic supply as follows (Fig.5).Liquid and gas collection headers are embedded in the cryostats. All the magnets of the superperiod have parallel feeding by the cryogenic liquid.The headers of two neighbouring superperiods are supplied with helium from one of the four satellite refrigerators located along the accelerator ring. An apparatus with a refrigerating capacity of 1800 W at 4.5 K and an energy consumption of about 350 W/W is suggested to be used as a helium liquifier.

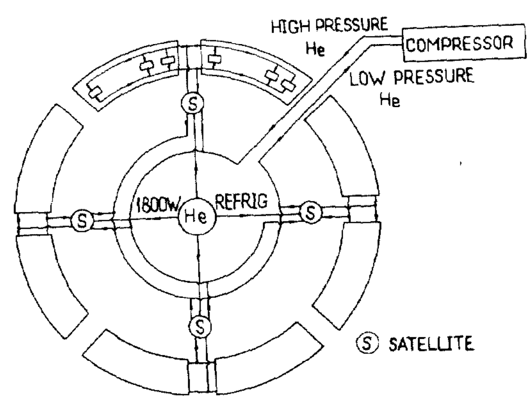

Fig. 5. Layout of the cryogenic system.

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