ИЯФ

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И. Будкера СО РАН

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PROJECT OF SMALL-DIMENSIONAL 200 MeV PROTON SYNCHROTRON

BUDKERINP 93-66

НОВОСИБИРСК

Extension of application sphere of intermediate energy (0.1–1 GeV) proton accelerators makes an urgency for development of new types of accelerators which would be relatively cheap and available for serial production and whose design and run features allow to approach them at most to users. In this report a work led in INP at the development of such accelerators on a base of magnetic systems with field of order of 5–10 T is reflected.

The accelerator of 200 MeV energy being now developed has length of orbit of 5.1 m, acceleration time of 2.5 ms, repetition rate of 1÷5 Hz and estimated number of accelerated particles of 10^{10}. The power consumed at 1 Hz is equal to 40 kW, full weight of the accelerator is 5 t. Accelerator is assembled on a single platform which has wheels that permits to remove accelerator out of shielded room for preventive works and to supply it to a user in fully assembled and ajusted state.

Basic for magnetic system of the accelerator are dipole magnets of one turn structure with enlarged vertical aperture, $A_Z = 2A_R$. Field is formed by surfaces of current conductors and poles of lamenated magnetic core. At high induction the core becomes partly saturated thus resulting in a decrease of real aperture, but to this time the beam size is sufficiently reduced due to acceleration, whilst for an injection the whole aperture is available, keeping the necessary field homogeneity up to induction of 2 T.

Dependence of field inhomogenety in the median plane, expressed as a relative difference of field at the maximum radious from field at equilibrium one $\Delta H/H$, on induction is shown at Fig. 1 for several values of a relative aperture height $h = A_z/A_R$. Dashed lines indicate the values of $\Delta H/H$ for ironless magnet with the same value of h. In a chosen aperture of $A_R = 2$ cm and $A_z = 4$ cm by half-sine current pulse of 5 ms duration the field is good enough during the whole time of acceleration.

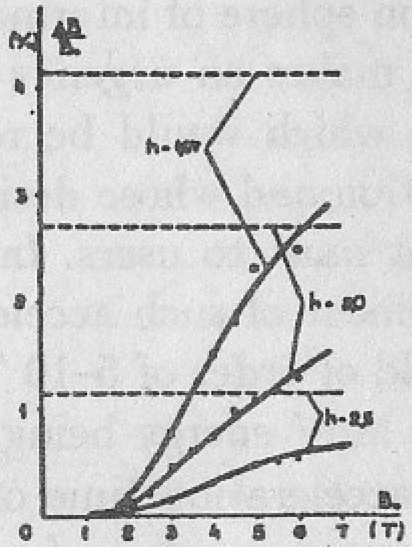

Fig. 1. Relative deviation of field in points $\Delta r = 1$ cm, $z = 0$ from field B_0 in aperture center.

The main problem in design development of the magnets is to provide the optimum field forming together with necessary mechanical stability. Distortion of field homogeneity at low and intermediate inductions is mainly due to a slit Δ between the iron pole and current conductor. The effective slit value is determined as $\Delta_{ef} = \sqrt{\Delta(\Delta + \delta)}$, where δ is the skin depth. To avoid this distortion the current conductors are densely pressed into the magnetic core whereas the insulating slit $\Delta = 0.1$ mm is

transferred to the core middle plane (Fig.2).

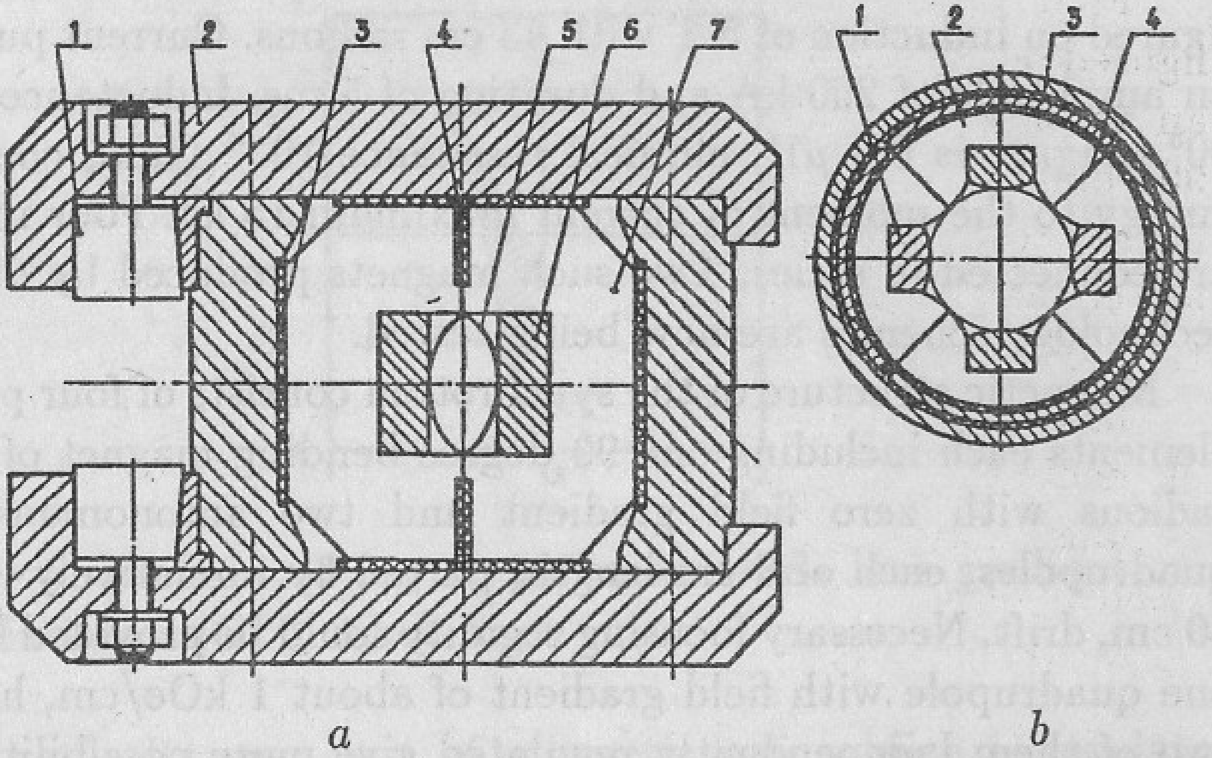

Fig. 2. *a*—magnet cross section: *1* — conic clamps, *2* — tightening bandage, *3, 4* — insulators, *5* — vacuum chamber, *6* — current conductors, *7* — magnetic core; *b* — lens cross section: *1* — current conductors, *2* — magnetic core, *3, 4* — insulator slits.

The magnetic core in such a design is electrically connected to the current conductors. That allowes to solve more reliably a task of their fastening by transfer an insulator, which accepts the magnetic field pressure, to expansed surface of outer side of the core. Set at different potentials two core halves with an insulator between them (Figs 2,*a*, 4) are tightened by powerful bandage which by means of conic clamps provides a preload in system exceeding the magnetic field pressure.

We use such a design scheme for production of different types of magnets as with organic insulators on the base of epoksy compaunds so with radiationly firm — on the base of oxide coating and cements [1]. With these magnets the magnetic field forming in different geometries at inductions up 5–10 T was studied and testing runs for millions pulses were worked out.

First version of the synchrotron is based on use of magnets figured on induction of 5 T with 43 cm radious. Current pulse has an amplitude of 200 kA and duration of 5 ms. Inductance of one 90° magnet is 0.6 μH, ohmical resistance 10^{-4} Ohm, consumed energy to the moment of current maximum 15 kJ. Four magnets are connected in series. Two such magnets produced by different technology schemes are now being tested.

Magnetic structure of the synchrotron consists of four periodic elements each including one 90 degree bending magnet of 43 cm radious with zero field gradient and two autonomously fed quadrupoles, each of 8 cm length, parted by a relatively long, of 30 cm, drift. Necessary focusing regidity could be provided by only one quadrupole with field gradient of about 1 kOe/cm, however two of them independently regulated give more possibility for a control of betatron frequencies. Such a regulation could be fulfilled directly in acceleration process due to an extremely small energy capacity of the quadrupoles. Fig. 3 shows the domain of ν_R and ν_z variation when field gradients of the quadrupoles having an opposite polarities are changed up to 3 kOe/cm. The left hand boundary of domain represents the case of one lens or of two lenses of same polarity with a sum of gradients equal to one-lens gradient. The drift length is equal to 30 cm. Its change shifts the domain along the axis ν_R. Chosen as an operating point are $\nu_R = 1.4$ and $\nu_z = 0.45$. Beam envelope in synchrotron is characterized by a sufficient, of about 3 times, modulation of radial beta function due to long stright sections as compared to magnet radii. The maximum values of β_R and β_z are 1 m and 2 m. At the apertures of $A_R = \pm 1\ cm$ and $A_z = \pm 1.8$ cm the admittances are $\epsilon_R = 100\pi$ mm·mrad and $\epsilon_z = 160\pi$ mm·mrad.

In its design the quadrupoles are one turn structures of the same principle scheme as the magnets — with current conductors connected to core without any slit (Fig. 2,*b*). Each of four conductors of hyperebolic profile is densely pressed in having the same profile its own part of magnetic core whjich is insulated from others by a thin, of ~ 0.1 mm, slit. Four conductors are fed in series by a current pulse, synchronous to a pulse feeding the magnets. Current input and commutation take place at the outer lens surface thus resulting in the most symmetry of current distribution at an edge as well as of edge field. The lens has 8 cm length, 2 cm aperture radious, 0.3 μH inductance and 10^{-4} Ohm resistance. Current amplitude is 3.2 kA for field gradient of 1 kOe/cm. Power consumed at such a current and repetition rate of 10Hz is 25 W. Every four lenses of the same position in periodic magnetic structure are fed in series through a matching transformer from a transistor amplifier. Each lens is attached to magnet edge by means of a device which allows to ajust lens location in all three directions independently.

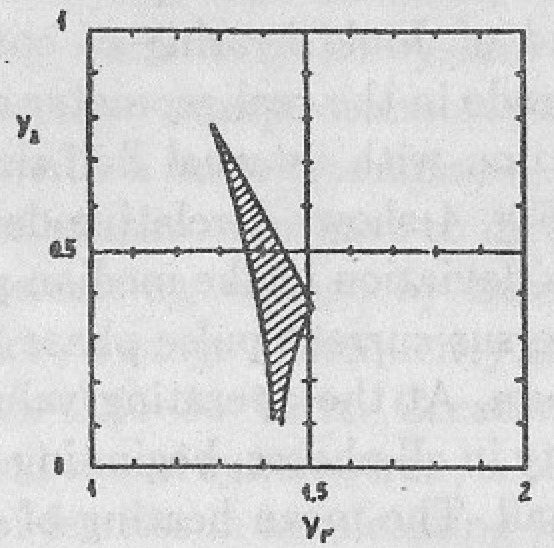

Fig. 3. Domain of ν_R, ν_z variation when lens gradients are varied in limits $|G| \leq 3$ kOe/cm.

Vacuum chamber of the accelerator is made of thin, 0.2 mm sheet of stainless steel. Such a decision in spite of high rate of field growth seems to be optimum at small magnet aperture. Use of ceramics or glass would leed to sufficient loss in aperture, to technology complication and to reliability decrease.

Before the decision to be accepted the chamber behaviour in alternative magnetic fields was investigaten from points of view of field distortion and of Joule heating of chamber wall. Field measurements were made in the real geometry of chamber, which has an oval cross section with internal half-sizes of ±1 cm and ±1.8 cm (Fig. 2,*a*). Fig. 4 shows a relative deviation of field at the maximum radious deviation in the median plane from field in the aperture center versus current pulse phase for different times t_m to current maximum. At the operating value of $t_m = 2.5$ mc the field inhomogeneity in all phases, beginning from the injection phase $\phi = 3.6°$, is small. The mean heating of chamber does not exceed several tens of degree by operation with repetition rate of 10 Hz.

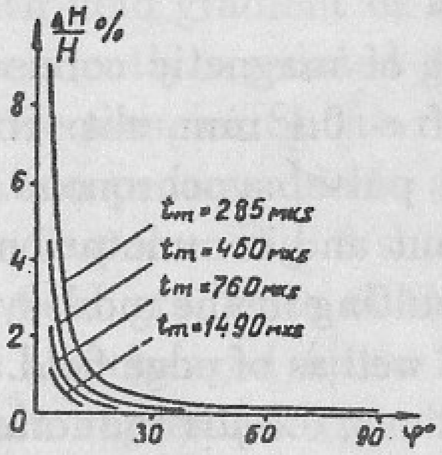

Fig. 4. Field distortion due to vacuum chamber influence at difierent pulse durations by unsaturated iron ($B < 2T$).

Manufacture of chambers has required the development of special technology. Tubes of round cross section are formed by an oval set, then with Wood alloy bent by means of special device with simultaneous stretch to prevent the crumpling of chamber at its inner radious. In free state the chamber does not withstand to the atmosphere pressure however acquires the necessary firmness being rigidly restricted in vertical size by magnet poles. In such a state the chamber withstands to 0.5–0.7 of surplus atmosphere.

Chambers of magnets are welded through flexible connections to having round cross section lens chambers which then transit to drift chambers. The whole vacuum system of the accelerator is pumped out with one ion pump, connected to the drift chambers by means of tubes with a large transition section.

Rf system of the synchrotron have to meet next requirements: the maximum accelerating voltage by acceleration duration of 2.5 ms is to be 12 kV, a range of frequency tuning by acceleration at first harmonic is 2.95–36 MHz. Creation of such a system, consistent with small size of synchrotron, is based on stored in INP experience of use of ferrites in accelerating RF cavities with deep frequency tuning [2]. Schematically the cavity is a quarterwave coaxial line with entirely filled with ferrites inductive part, which is tunes by means of internal magnet. Field penetrates to ferrites through windows in longitudinally cut cavity body. Windows are shut with a thin foil transparent for magnetic flux. Removal of power dissipated in ferrites is due to good thermal contact to the body. Accelerating voltage is produced by means of two oppositely installed cavities with the opposite phase of voltage. To provide the system with chosen voltage the ferrites are to be of high quality factor. This contradicts to the deep tuning condition, which requires the ferrites of high permeability, which have low quality factor. The most suitable for this case are the ferrites of 200NN type. Chosen value of voltage is close to maximum for considered system. Could be considered as a spare are an increase of acceleration duration or use of one more accelerating structure in the opposite stright section of accelerator, kept spare to this purpose.

Particle injection into accelerator is carried out in a multirevotion scheme, based on time dependent shift towards an injection window of equilibrium orbit of particle motion inside the accelerator aperture. The window is located in upper part of aperture in one of the drifts that is near the maximum of vertical beta-function. The shift, equal to distance $\bar{z}$ between particle beam axis and accelerator median plane at the injection start, then linearly decreases down to zero for a time t_m of a few tens of particle revolutions. Such a shift is fulfilled by a pulsed magnet with linearly reduced in time field of radiall direction. The magnet is placed in a distance of half revolution length before the injection window. Location at the accelerator phase plane of a particle, flying through the injection window at a moment t_m, a distance to beam axis z_0 and an angle z_0' is determined in dependence on time t and azimuth coordinate s ($s = 0$ at injection azimuth, $-\pi R \leq S \leq \pi R$) as foolows

$$z + iz'\frac{R}{\nu} = \left(\bar{z}\left(1 - \frac{t}{t_m} + \frac{s}{vt_m}\right) - i\frac{\pi R\bar{z}\cos\nu\pi}{vt_m\sin\nu\pi}\right)\exp\left(-i\nu\frac{s}{R}\right) +$$
$$+\left(z_0 + \bar{z}\frac{t_0}{t_m} + i\left(\frac{z_0'R}{\nu} = \frac{\pi R\bar{z}\cos\nu\pi}{vt_m\sin\nu\pi}\right)\right)\exp\left(\frac{-i\nu v(t-t_0)}{R}\right).$$

Maximum value of field integral over a length of shifting magnet is determined through an initial value of orbit shift at injection azimuth, z, as $(HL)_{\max} = \bar{z}(2Pc\nu\sin\nu\pi/eR)$ and is equal to about 2.5 kOe·cm. Beam is brought into accelerator through a septum-magnet, which is moved into the aperture by a sum of injection window height and of septum thicknes which are equal to 2.7 mm and 0.3 mm, accordingly.

The computer simulation of injection in 30-revolution scheme, which provides close to maximum capture rate, gives an average capture efficiency F equal to 0.65 for an angular spread in a beam of $\pm 2 \cdot 10^{-3}$. Distributions of capture efficiency and of particle location at accelerator phase plane after the injection finish are shown against the time of fly into aperture in Fig. 5,*a* and in Fig.5,*b*, where time intervals, equal to revolution time τ_c, are numerated, starting from the second, in alphabetical order. In radial direction a capture efficiency of 1 is guarantied inside an emittanse of 26 mm·mrad and pulse interval of ±1%.

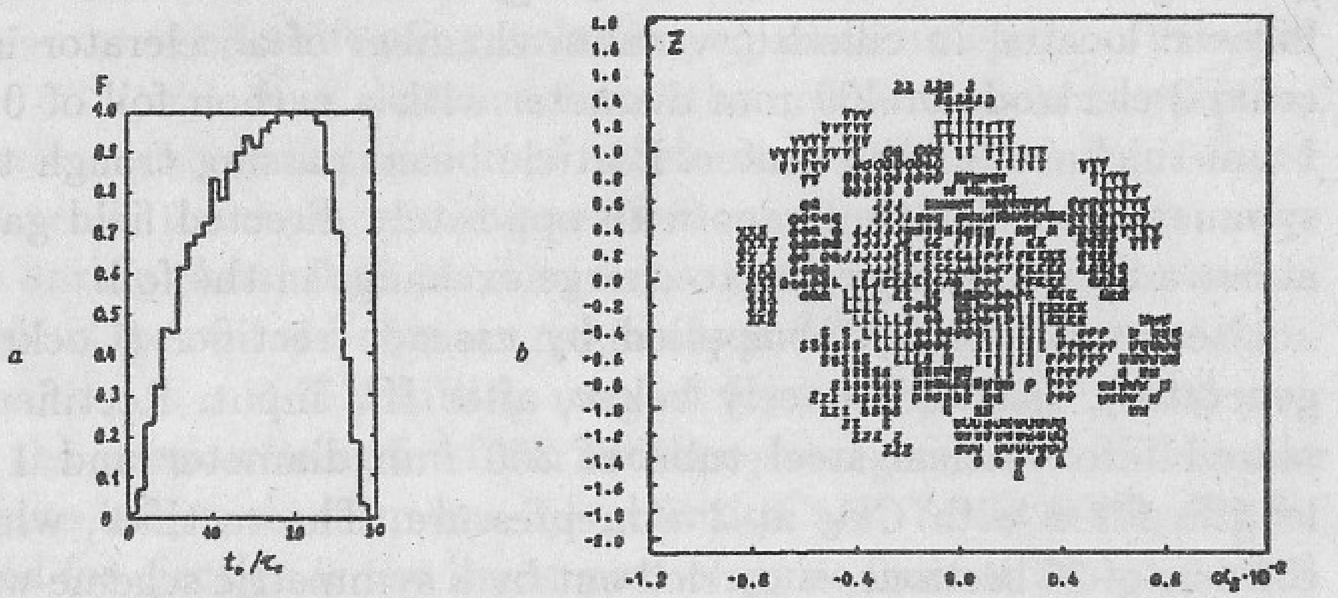

Fig. 5. Capture efficiency dependence on time of particle fly into accelerator arerture (*a*) and captured particles distribution upon accelerator phase plane (*b*).

To guaranty 10^{11} particles captured with an efficiency of 0.65 for 10 μs time of 30 revolutions the injection current is to be equal to 2 mA inside a vertical emittance of 3π mm·mrad.

Shifting magnet is a one turn system with laminated magnetic core. Its length is 6 cm and aperture size, $A_R \times A_z = 2 \times 3$ cm, is equal to that of accelerator drift. The magnet is fed with a current pulse of sine half-cycle form of 36 μs duration. Used for the injection is the linear part of pulse back side beginning with phase of 130°, where the field value is 400 Oe.

Injection septum-magnet has an aperture size of $A_R \times A_z = 1.2 \times 0.3$ cm and operating field of 6 kOe. Current pulse is to be of minimum duration to decrease the magnetic field penetrating through thin septum into accelerator aperture. To have as well a long enough flatt top of the pulse we make it of trapecidal form with 10 μs top and 5 μs sides.

Injector is a direct type accelerator with negative ions charge exchange to achieve the doubled energy. Schematically it looks as follows: located in cilindric vacuum chamber of accelerator is a coaxial electrode of 400 mm diameter with a carbon foil of 0.5–1 μm thickness at the center. Particle beam passing trough two symmetric accelerating gaps with oppositely directed field gains about a double energy due to charge exchange in the foil.

Necessary voltage is applied by cascade rectifier (Cockroft generator), situated spacely below, after HV input. Rectifier is placed into vertical steel tube of 350 mm diameter and 1 m length, filled with CF_6 at 3 atm pressure. The rectifier, which consists of 30 sections, is carried out by a symmetric scheme with an unobvious filter colomn, formed by a capacity of protective rings to outer tube.

To produce the negative ion beam we use a plasma-surface source with Penning geometry of discharge and round emission hole of 1 mm diameter, described in [3]. With extractive voltage of 20 kV the source produces an ion beam with current of 20 mA and $3\cdot10^{-2}$ rad angular divergence. Beam is transported to the first accelerating gap of injector through a 90° separating magnet. Accelerated up to 1 MeV beam has an emittance of 2.5π mm·mrad in both transversal directions, that answers to the synchrotron acceptance. Concerning to the current there is a substantial reserve.

Injector is placed immediately near the synchrotron on a separate cart which is in hard clumping with the main synchrotron platform. After passing horizontally above the synchrotron magnet the beam is transported to the injection point by two magnets, the second of which is an injection septum-magnet.

The beam ejection is carried out by the same scheme as the injection. Shifting magnet with a linearly growing field creates a uniform motion of equilibrium orbit together with the beam towards the ejection window placed in a half revolution length after the magnet. The optimum ejection efficiency by the same geometry of ejection window, as of injection one, is achieved by the same orbit shift per revolution, equal at an ejection azimuth to 1/30 part of a distance from the median plain to ejection window center. Extraction of accelerated beam with its reduced size really takes place in five revolutions, from 23-d to 28-th, only, i.e. during about 0.14 μs. The r.m.s. spreaus of coordinate and of angle in extracted beam are ±0.6 mm and $6.0\cdot10^{-4}$, the extraction efficiency is ~ 0.75. Shifting magnet for the injection is used also for the ejection being fed from another pulse generator. Field pulse of sine half-cycle form has 3μs duration and 7.8 kOe amplitude. Used for ejection is the linear part of pulse front till to phase 50° where field has grown up to 6 kOe. Current amplitude is 12.5 kA by a voltage on the magnet of 1.5 kV. The small pulse duration requires the use of laminated magnetic core with 50 μm thick iron. Beam extraction takes place in the same drift as the injection at the opposite side of vertical accelerator aperture. By this the ejection window occures to be in a shadow of the injection one, resulting in no additinal reduction accelerator aperture. System of beam in-out thus occupates less than two whole drifts leaving in that with the shifting magnet space enough for correcting sextupole.

Ejection septum-magnet has an axial aperture altering with length that results in the altering field, equal to 20 kOe in 5 cm long part of magnet near thin septum and to 50 kOe at the rest 15 cm of magnet length, where the wall thickness becomes more than 1.5 mm. Current pulse is of 25 kA amplitude and of 10 μ s duration. Such a small duration is needed to guaranty the mechanic stability of the septum by 20 kOe magnetic field.

Power supple system for synchrotron magnets is based on a capacitpr discharge by current commutation with thyristor switchs with use of matching trasformer and with energy recuperation. Total inductance of connected in series magnets is equal to 2.5 μH. Storage battery of 70 kJ energy at 6 kV is composed of capacitor banks which allow to operate at a repetition rate up to 50 Hz. About a half of stored energy could be recuperated.

Matching transformer is of cable type in design with the transformation ratio of 12–14. Thyristor switch, commuting the primary current, is assembled in a bridge scheme so that the load connection is reserved just after the current maximum to avoid the capacitor polarity change.

An advantage of power system consists in a possibility to change the repetition rate of accelerator in wide interval from fractions to tens of Hz. Upper limit is determined by the heat flux coulde be removed from the magnets (~ 300 kW). In operation at low energy of 70 MeV the maximum repetition rate is equal to 10 Hz.

Charging system, designet and developed in INP, is based on three-phase thyristor invertors operating at 2 kHz and providing the charge of capacitor battery with efficiency better then 90% by constant power, thus excluding pulsations in outer power circuite during the operating cycle.

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Проект малогабаритного
200 МэВ протонного синхротрона

Ответственный за выпуск С.Г. Попов

Работа поступила июль 1993 г.
Подписано в печать 11.08 1993 г.
Формат бумаги 60×90 1/16 Объем 0,9 печ.л., 0,8 уч.-изд.л.
Тираж 200 экз. Бесплатно. Заказ N° 66

Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН,
Новосибирск, 630090, пр. академика Лаврентьева, 11.