WORK ON HIGH-CURRENT ACCELERATORS OF THE INSTITUTE FOR NUCLEAR PHYSICS OF THE SIBERIAN DIVISION OF THE USSR ACADEMY OF SCIENCES

I. HIGH-CURRENT PULSE ACCELERATORS WITH SPIRAL ELECTRON STACKING

By

E. A. Abramyan, I. E. Bender, L. N. Bondarenko, G. I. Budker, G. B. Glagolev, A. Kh. Kadymov, I. N. Meshkov, A. A. Naumov, V. E. Pal'chikov, V. S. Panasyuk, S. G. Popov, I. Ya. Protopopov, Yu. I. Rodionov, I. M. Samoilov, A. N. Skrinskii and L. I. Yudin

II. HIGH-CURRENT ACCELERATORS WITH A SINGLE-TURN CAPTURE OF INJECTED ELECTRONS

By

G. I. Budker, N. G. Kon'kov, Yu. A. Mostovoi, A. A. Naumov, O. A. Nexhevenko, G. N. Ostreiko, V. S. Panasyuk, V. V. Petrov, I. M. Samoilov, A. A. Sokolov, I. Ya. Timoshin and L. I. Yudin

(Inst. of Nuclear Physics of the Sib. Div. of the USSR Acad. of Sc.)

Introduction

Work on the design of annular high-current electron accelerators had been commenced by us in 1954 with the purpose of a study of the feasibility of the generation of relativistic stabilized beams. Four methods for the generation of high annular currents of relativistic electrons are being studied experimentally in the laboratories of the Institute:

1) Spiral method for stacking of electrons in assemblies of the betatron type with subsequent betatron or synchrotron acceleration [1].

2) Generation of extreme electron currents by means of the injec-

tion of electrons from a high-current linear accelerator into the annular chamber with a large aperture with subsequent synchrotron acceleration.

3) Electron stacking on tracks with a constant magnetic field by means of a repeated injection of electrons from a different lower-current accelerator. This method is used for a stacking of electrons and positrons in experiments with colliding beams and it has been described in detail in the report read by G. I. Budker [2].

4) Generation of high electron currents by means of an acceleration of the annular plasma electrons.

This report deals with the first two methods.

I. High-current pulse accelerators with spiral electron stacking

1. Nonferrous pulse betatron with a preliminary charge stacking (assembly B-2)

For the generation of high electron currents we constructed in 1955 the assembly B-2, which consists of a nonferrous betatron with a spiral stacking of electrons injected with an electron gun located at the internal wall of the chamber. The principle of the operation of the assembly and the basic parameters have been discussed in another publication [1] and will be repeated briefly during the discussion of the pulse synchrotron B-2C. We will mention only, that the extreme volume charge in assemblies of such a type is determined by the corelation

$$Q_{\text{extreme}} = \frac{(n - 0.25)\,\beta^2\gamma^3}{2(2 - n)}\,\frac{mc^2}{e}\left(\frac{r_f}{r_i}\right)^{2-n}\varkappa h,$$

where h is the beam height, r_i the injection radius, r_f the finite radius of spirally stacked electrons, β, γ the relativistic factors of the injected electrons; $\varkappa$ is a coefficient which indicates the shape of the beam, which lies in the interval between 1 and 2 and n is the index of the magnetic field decay.

The assembly B-2 has been designed for the generation of circulating currents of relativistic electrons of the order 100 amp. Initially, an annular current of the order of 10 amp. was produced in the B-2 assembly at a lowered injection energy.

In the following we succeeded in 1957 in raising the current at the internal radius (r_i = 14 cm) to 75 amp. at a value of r_f = 47 cm by means of increasing the injection energy to a magnitude of the order of 60 kv which yields a good agreement with the calculation. These results have been used in the development of the accelerators B-2C and B-3 described below.

2. High-current pulse synchrotron B-2C

In connection with positive results from work on the stacking of high electron currents in the pulse betatron B-2, work has been started in the Institute in 1956 on the construction of the assembly VEP-1 with colliding electron beams of an energy of 100 - 130 mev.

In the case of a single-turn extraction of electrons from the cyclic accelerator and a single-turn capture into the storage rings, the synchrotron possesses a number of advantages over the linear accelerator, the main of which is that the beam extracted from the synchrotron possesses a small energy scattering and a small phase volume, and at the same time a great part of the electrons accelerated in the synchrotron can be captured into the storage ring.

For the storage rings of the VEP-1 the beam extracted from the accelerator-injector must possess the following parameters: energy 50 - 130 mev; number of electrons in the pulse not less than 10^9 at a frequency of repetitious once in 10 sec; pulse duration of the order of 10^{-8} sec; phase volume along the vertical and horizontal not worse than 3×10^{-2} cm x rad., energy scattering in the beam not over $\pm 3 \times 10^{-3}$. It was decided to construct at the base of the betatron B-2 a high-current 100 mev*) pulse synchrotron B-2C with a spiral electron stacking for the generation of an electron beam with such parameters.

The following changes have been introduced during the redesigning of the B-2 assembly: The constructive elements of the windings which generate the magnetic field in the chamber have been substantially reinforced; a split resonator has been developed which permits to carry out a spiral stacking of electrons; for purposes of a better utilization of the condenser battery and for a correction of the magnetic field, the commutation system of the windings has been made more complex; windings have been introduced for the control of the beam position, which generate harmonics in the azimuthal distribution of the chief magnetic field; a pulse deflector and a shielded channel for

*) It is planned to achieve an electron energy increase up to 130 mev in the storage rings.

the extraction of electrons have been introduced. All the other units of the betatron B-2 such as the system for split shields, the magnetic circuit which generates a turbulent electrical field, the chamber

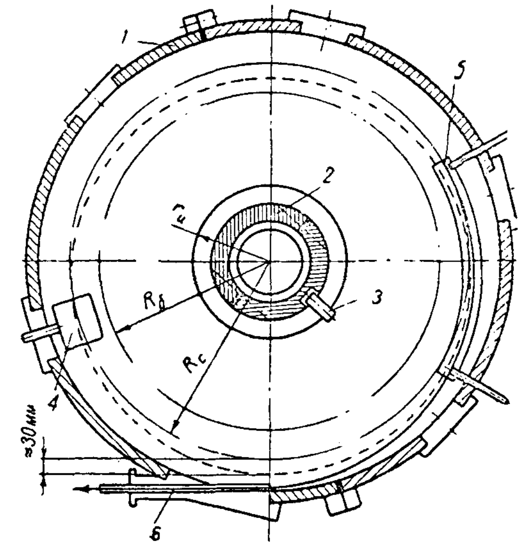

Fig. 1. Simplified cross-section of the acceleration chamber of the synchrotron B-2C. 1 - external shell; 2 - internal shell; 3 - injector "gun"; 4 - resonator; 5 - deflector; 6 - extraction channel; r_i - injection radius; R_σ - position of the betatron orbit; R_c - position of the synchrotron orbit; – – – extraction trajectory.

shells, the vacuum system and others have remained practically unchanged. In addition, at the tuning up of the synchrotron B-2C the methodology and the apparatus which were used at the adjustment of the experimental betatron B-2 were widely utilized. Together with a minimum expenditure we succeeded in constructing a high-current pulse synchrotron for the injection of electrons into storage rings.

The schematic cross-section of the assembly and the sequence of processes in the acceleration cycle are shown in fig. 1 and 2. The electron injection is carried out from a gun located at the internal shell, at an instant which corresponds to the maximum value of the chief field, generated by the discharge of a special condenser battery upon the loops of the electromagnet. The injected electrons are accelerated by the turbulent electric field and move along the spiral. After the electrons have filled the entire chamber, the condenser battery of the betatron field is switched on and the betatron acceleration of stacked electrons starts. Here the electrons are asymptotically constricted toward the equilibrium betatron orbit, whose position is chosen at the mean radius of the chamber.

The correlation of the periods of the turbulent and chief magnetic field has been chosen in such a way, that after the acceleration of the

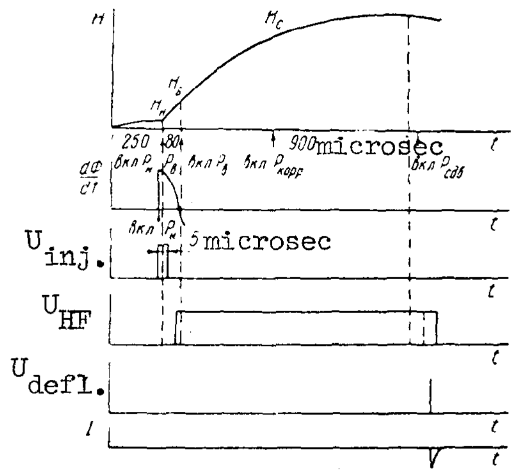

Fig. 2. Scheme of process sequence in the acceleration cycle of the assembly B-2C. H - chief magnetic field; $\frac{d\Phi}{dt}$ - turbulent voltage; $U_{inj.}$ - injection pulse; U_{HF} - high frequency pulse; $U_{defl.}$ - deflector pulse; I - particle current.

electrons to the energy of the order of 2 mev, the radius of the equilibrium orbit begins to grow, the electrons are introduced into the interior of the accelerating resonator and are captured into the synchrotron cycle upon the radius of the equilibrium orbit $R_c = 412$ mm (frequency 116 MHz) after which the synchrotron condenser battery is connected with the external part of the electromagnet loops.

At the end of the acceleration the equilibrium orbit is shifted toward the extraction channel by means of special loops, in order to facilitate the extraction conditions. The single-turn extraction is materialized by the transmission of a voltage pulse upon the deflector with a stacking time of 10^{-9} sec and an amplitude up to 100 kv (capacity in the pulse up to 10^9 watts).

At the present time the energy of 80 mev has been achieved in the synchrotron B-2C, which if required can be increased to 100 mev. The basic operating modes of the assembly and the beam characteristics have been investigated at an injection energy of 20 kev and a final energy of 40 mev, at which the first experiments on the stacking of electrons upon a single track were carried out. Here in the accelerator an annular current of approx. 0.5 amp. (3×10^{10} electrons in the pulse)

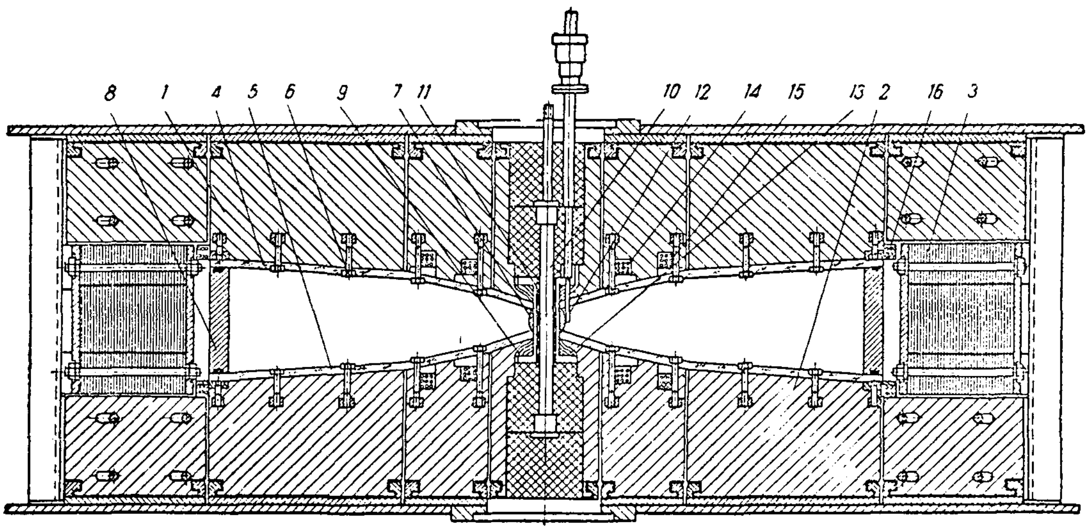

Fig. 3. Schematic cross-section of the first variant of the assembly B-3. 1, 2 - magnet poles; 3 - locking yoke; 4, 5 - vacuum chamber covers; 6 - vacuum cover bolts; 7 - internal shell; 8 - external shell; 9, 13 - shielding system; 10 - core; 11 - core winding; 12 - injector; 14, 15 - "slot" windings; 16 - chief field winding.

had been generated and the extracted beam possessed the following parameters:

a) average number of electrons in the pulse - 1×10^{10};

b) energy scattering $\frac{\Delta E}{E} = \pm 2 \times 10^{-3}$;

c) radial phase volume 10×10^{-3} cm x rad. at a radial dimension $\pm$ 0.5 cm;

d) vertical phase volume 6×10^{-3} cm x rad. at a vertical dimension $\pm$ 0.3 cm;

e) duration of the electron pulse 3 - 4 n-sec;

f) frequency of repetition: once in 20 sec.

3. High-current pulse betatron with spiral stacking (assembly B-3)

The betatron pulse assembly B-3 with a spiral stacking of electrons, designated for the generation of currents above 100 amp. at an energy of the order of 50 mev has been constructed on the basis of results obtained from the assembly B-2.

For the generation of high circulating currents according to the corelation discussed in chapter I. 1, it is of importance to use a maximum injection energy and the highest possible ratio $\frac{r_f}{r_i}$. The maximum radius of the acceleration area r_f is limited by the dimensions and the weight of the assembly and the minimum radius by the dimensions of the core. In contrast to betatron B-2 in the assembly B-3 for purposes of an increase of the stacked current the core is used for the generation of a turbulent electric field only for the period of stacking and for the initial period of constriction. In the following special windings, located in the slots of the magnetic poles ("slot" windings, fig. 3) have been used for the establishment of the betatron ratio 1:2, which generate a supplementary current in the central area when the electrons have moved to larger radii during the constriction process. This permitted a decrease of the radius r_i, regardless of a considerable increase of the final energy of the electron beam as compared with the betatron B-2.

The application of "slot" windings determined the choice of the ferrous system of poles and of the magnetic circuits. The poles of the magnet (see fig. 3) consist of packets of transformer steel layered along the radius, 12 of which are positioned uniformly, locked by the yoke in the vicinity of the poles. The vacuum chamber is formed by two organic glass covers of a radius of 100 cm, fastened to the poles by means of bolts, and by two shells, an internal and an external one. The core with the shields and with parts of the poles represents a separate construction. Two variants have been worked out for the central part of the assembly. The first variant has been designed for the use of the internal electron gun with a voltage up to 100 kv, at an injection radius of $r_i = 5.5$ cm. The second variant takes care of the considerable increase of the injection energy from the application of a high-voltage injector positioned on the outside.

The feeding system of the core windings, of the chamber and of the

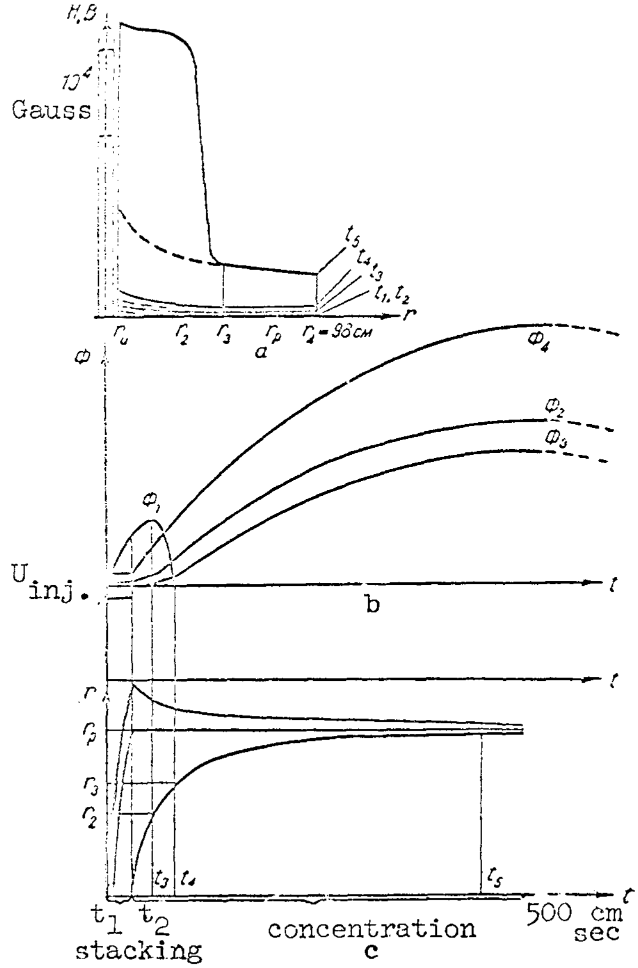

Fig. 4. Operation mode of the assembly B-3 (for explanations, see the text).

"slot" loops permits an independent control of the instant of the switching on and of the magnitude of the current in each winding. One of the possible operation modes of the assembly B-3 is shown in fig. 4.

In fig. 4, a is the distribution of the magnetic field along the radius at different instants of time (r_i - injection radius, r_2 - the radius where the magnetic field of the first "slot" winding practically does not distort any more the chief field; r_3 is the same as r_2, only that it applies to the second "slot" winding; the dashed lines indicate the chief magnetic field without the switching on of the "slot" windings; t_1 - t_5 correspond to the analogous instants of time in fig. 4, b and c).

In fig. 4, b is the variation of the magnetic fluxes in time (Φ_1 - magnetic flux of the core; Φ_2 - magnetic flux of the first "slot" winding; Φ_3 - magnetic flux of the second "slot" winding; Φ_4 - magnetic flux of the chief field of the chamber; $U_{inj.}$ - pulse of the injection voltage).

In fig. 4, c is the electron motion along the radius during the stacking and the constriction. In the general case the equilibrium radius r_p can vary during the constriction in a previously fixed manner.

In Moscow in 1961 the units of the first variant of the assembly were laid aside. At an injection energy of 50 kv there was achieved a circulating electron current of approx. 15 amp. per a radius of 80 cm 1.5 x 10^{12} electrons) at an energy of 35 mev. Studies on the possibility of a stacking of high currents have not been carried out for the first variant of the central part of the assembly, since by attempting to decrease the initial radius down to the limit, we were not able to shield the chamber from scattered magnetic fields which generate an accelerating field, as thoroughly as was the case in the assembly B-2, and this made the stacking process of electrons very difficult.

During the relocation of the assembly from Moscow to Novosibirsk, it was decided, for purposes of a further increase of the current to materialize the second variant of the central part of the assembly, by using an accelerating tube with a pulse voltage generator after the scheme by Marks as an injector, and to improve the shielding of the accelerator chamber from magnetic fields of the core by a total separation of the magnetic fluxes of the core and of the chief field of the chamber. For this purpose shields have been used, analogous to the shields of the assembly B-2 which permit an extraction of the magnetic flux of the core beyond the limits of the poles of the assembly. At the same time with the reconstruction of the shielding system a number of supplementary technical improvements of the assembly B-3 were carried out.

The assembly is being mounted at the present time in Novosibirsk. According to the corelation from chapter I. 1, at an injection energy of 500 kev it is possible to obtain a circulating current of approx. 10^3 amp. at a radius of 80 cm, with an energy of approx. 40 mev. In this assembly, however, a decrease of the magnitude of the extreme current is possible, because of reflexions in the poles.

II. High-current accelerators with a single-turn capture of injected electrons

1. Nonferrous single-loop high-current synchrotron (BSB)

The pulse synchrotron BSB designed for a repetition frequency of 2 - 3 times per minute belongs to the second group of high-current synchrotrons which are being developed by us. The design of the synchrotron based on the concept of a nonferrous single-loop magnetic system simplifies considerably power problems as compared with the conventional multi-loop nonferrous machines. The synchrotron under discussion possesses the following singularities: a) the betatron mode of acceleration is absent; b) a high-voltage, high-current injector is used, which safeguards currents up to 200 amp; c) a single-turn capture by means of deflecting plates is applied whose voltage is stripped by fast-action dischargers, synchronized with the injector; d) the chamber possesses an enlarged cross-section.

With respect to power, the synchrotron has been designed for an energy up to 400 mev. The assembly BSB is designated for the acceleration of extreme currents which originate from the effect of the volume charge upon the process of capture and the synchrotron acceleration of electrons.

The diagram of the design*) of the accelerator is shown in fig. 5. The chamber consists of two Duralium rings: the internal 1 and the external 2, tightened by the top 3 and bottom 4 covers made of organic glass. The external ring is shortcircuited and the internal one which is cut along the diameter forms a loop at which the condenser battery is discharged. For the generation of a magnetic field with the configuration required for focusing the sides of the rings which set boundaries for the particle track have been profiled along the radius. The mean radius of the track is 41 cm and the gap between the rings 10 cm. Thickness of rings: internal - 6.5 cm; external - 15 cm. Height of the rings - 30 cm. The chamber is located between two Duralium shields 11 and 12.

At a radius of the synchrotron orbit of 43 cm a magnetic field of 30 k-oersted is required in order to generate an electron energy of 400 mev; here the pressure of the magnetic field upon the rings is 40 atm. The index of the magnetic field decay $n = 0.4$. The internal loop with the current can be balanced exactly by subjecting it only to a multilateral compression. In the assembly the compensation of power in the internal ring is maintained with an accuracy of 5%.

*) Construction work has been carried out by P. I. Medvedev.

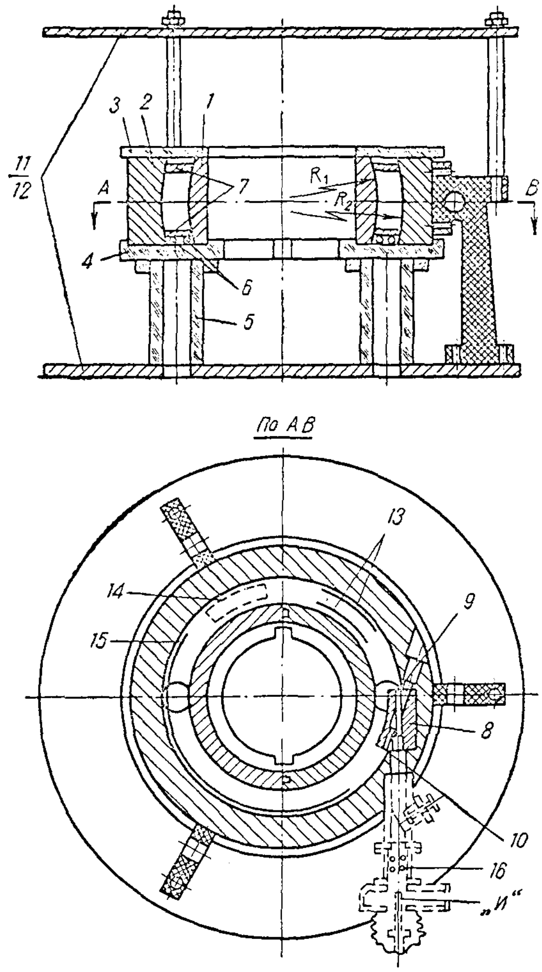

Fig. 5. Design of the synchrotron BSB:
5 - porcelain pumping tubes; 6 - annular glass traps, cooled with liquid nitrogen; 7 - shields covered with Aquadag. Others: see in the text.

For the injection of the electrons into the chamber and the extraction of accelerated particles the external ring has been provided with a Duralium insertion piece 8 profiled along the radius in which together with the external ring the input channel 9 and the output channel 10 have been milled. The arrangement of the capture plates 13 and extraction plates 15 in the resonator chamber 14 is shown in fig. 5.

All elements located in the chamber have been designed in such a manner that the size of the aperture amounts to 8 x 10 cm.

During the mounting of the assembly an injector is used which possesses the shape of a section of the coaxial line 1 (fig. 6) designed under the direction of B. G. Erosolimskii with the participation of L. N. Bondarenko and G. I. Yasnov. The section of the line has been shortened from one end, and at the other open end a cathode loop is positioned which is heated from the inside of the central tube of the coaxial line. A low-resistance coaxial line 2 is connected with the center of this line through the discharger P_0 which is charged from the pulse voltage generator 3 (GIN) which has been assembled according to the Marks scheme.

The GIN operates by the triggering pulse and charges under aperiodic working conditions the line 2 after approx. 4×10^{-7} sec. through a low-induction wire resistance 4. Here the gap of the discharger P_0 is exposed in such a manner, that the delay time during its operation is of the order of the charging time of the line 2. The breakdown of the overcharged discharger P_0 permits to obtain a steep leading edge (approx. $(1 \div 2) \times 10^{-9}$ sec) of the voltage transmitted to the basic line 1. The voltage wave which moves to the open end of the line doubles at the terminal and generates the operating voltage of the injector in the shape of a rectangular pulse. For an increase of the electrical stability and a shortening of the lengths of the lines 1 and 2 they have been covered with transformer oil. The injector generates a pulse of the duration of approx. 1.2×10^{-8} sec; according to measurements the front of the injection pulse amounts to $(2 \div 3) \times 10^{-9}$ sec.

The loop of the electron-optical system of the injector is separated from the space filled with oil by an organic glass insulator 5, 6. For purposes of shielding against prolonged over-voltages connected with repeatedly reflected pulses, at the lines 1 and 2 a shortcircuiting discharger P_1 has been positioned near the insulators, whose gap is adjusted in such a way that the delay time of its breakdown is of the order of the duration of the injection pulse. At the right part of the line 1 plate 7, a capacitance divider of the injector has been positioned, whose pulse is transmitted to the dischargers of the capture plates.

The single-turn electron capture is materialized by means of capture plates, whose voltage is stripped by the dischargers over a period of $(1 - 2) \times 10^{-9}$ sec. The preliminary adjustment of the synchrotron is carried out at an injection energy of 700 kev and therefore a low-capacity high-frequency generator is used for the feeding, whose frequency varies within the limits from 104.5 to 116 MHz, in correspondence with the energy increase of accelerated electrons.

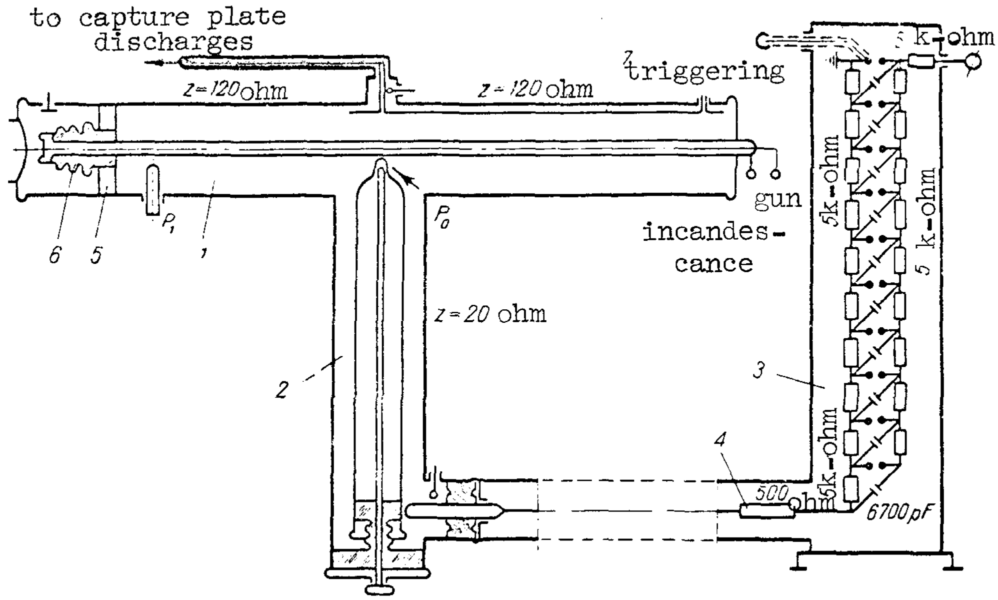

Fig. 6. Injector diagram.

At the present time all the elements of the accelerator have been tested and an acceleration up to 20 mev has been achieved, which is determined by the capacity of the high-frequency generator. In all preliminary experiments the problem of the generation of extreme currents and energies has not been attacked. These investigations will start in the near future by using a more powerful high-frequency generator and a high-voltage injector.

At the first stage of work the synchrotron BSB will be used at energies between 150 - 200 mev and annular currents of several amp., as an injector for the tuning of the assembly with colliding electron-positron beams.

2. High-current pulse synchrotron B-3M

In 1958 work had been started in the Institute on the design of the assembly with colliding electron-positron beams VEPP-2. In 1959 we started with the construction of the high-current nonferrous pulse synchrotron B-3M with external injection designed for an electron energy of 350 mev at an annular current up to 10 amp. (approx. 10^{12} particles in the pulse). At the first stage of work a current of the order of 1 amp. has been contemplated.

A high-current linear accelerator (ILU) has been constructed in cooperation with the Institute for Technical Physics of the GKAE for use as an injector for the synchrotron B-3M, designed for the generation of currents of the order of 100 amp. in the pulse at an energy up to 3.5 mev.

In contrast to other experimental assemblies of the Institute described in this report the unit B-3M has been designed for a comparatively high frequency of repetitious, up to 12.5 times per second and correspondingly for relatively high mean capacities and thermal loads. In this connection particular attention has been paid to the choice of such a design of the assembly which would permit a best utilization of the magnetic field of the chief electromagnet. This circumstance forced us to abstain from the application of the method of spiral stacking of electrons and to limit ourselves to the construction of an accelerator with a single-turn capture.

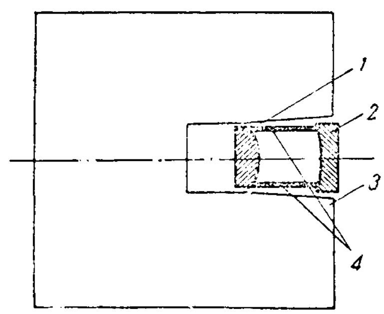

Fig. 7. Cross-section of the synchrotron B-3M electromagnet. 1 - internal bus of the electromagnet; 2 - external bus of the electromagnet; 3 - magnetic circuit; 4 - vacuum covers.

The annular, C-shaped electromagnet of the accelerator is divided by 4 rectilinear gaps in which the injection-, the extraction- and the control systems of the beam are located. The vacuum chamber together with the electromagnet is a total single unit. The radius of the equilibrium orbit amounts to approx. 1 m. The cross-section of the chamber is shown schematically in fig. 7. The magnetic field is generated by the current which flows along the bus bars 1 and 2 in opposite directions. The principal part of the magnetic flux is closed through the magnetic circuit 3, which consists of sheets of transformer steel. The required shape of the magnetic field in the working area is generated by the shape of the poles as well as by the corresponding profile of the bus bars which safeguard the calculated value of the index of the magnetic field decay $n = 0.6$. At such a design of the electromagnet scattered fields are practically nonexistent and almost the entire region between the bus bars and the poles is applicable for acceleration. The magnetic field behind the internal surface of the bus bars declines along the length of the order of the thickness of the skin-layer, which facilitates considerably the assignment of the injection and extraction of electrons. Such an electromagnet can be termed as ferrous-nonferrous.

An ignitron feeding system has been developed in cooperation with the V. I. Lenin Electrotechnical Institute for the excitation of the electromagnet which safeguards a generation of unipolar sinusoidal current pulses of a duration of 10^{-3} sec with a frequency of repetition up to 12.5 times per second at a current up to 150 k-amp.

The high-frequency generator operates at a frequency of 112.6 MHz which corresponds to the third harmonics of the frequency of electron revolution. The capacity in the pulse amounts to approx. 1 M-watt.

A synchronization system has been developed for the control of all processes, which safeguards a nano-second accuracy of the switching on of the injector and the deflecting plates. The injection and extraction of electrons is materialized by means of special pulse generators.

The assembly B-3M is at the stage of tuning up.

Literature cited

1. Budker, G. I. Cern Symposium, 1, 68 (1956).
2. Budker, G. I., See this collection, p. 274.