STUDIES OF COLLIDING ELECTRON-ELECTRON, POSITRON-ELECTRON AND PROTON-PROTON BEAMS AT THE INSTITUTE FOR NUCLEAR PHYSICS, THE SIBERIAN BRANCH OF THE U.S.S.R. ACADEMY OF SCIENCES

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III. Colliding Proton-Proton Beams

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Studies of colliding beams of charged particles represent the basic program at the Institute for Nuclear Physics of the Siberian Branch of the U.S.S.R. Academy of Sciences. When the Institute was established, we did not consider construction of large accelerators requiring expenditure of large amounts of time and money to be expedient. The Institute's high-energy program provides for studies of colliding electron-electron beams, positron-electron beams, and colliding proton-proton beams. For this purpose three installations are being constructed, which are in various stages of readiness.

The study of colliding electron beams was initiated at the Institute (at that time the Laboratory of I.V. Kurchatov Institute of Atomic Energy) during the fall of 1956, following the Kerst report at the Geneva Conference on FFAG accelerators with proton colliding beams.

At that time we already had experience in obtaining large electron currents; in particular, an apparatus for spiral storage of electrons had been built and operated at the Laboratory;[1] at a later date it yielded circulating currents of the order of 100 amps.

In 1957 two systems were studied simultaneously. The first consisted of two accelerators with spiral storage and subsequent transfer of the particles into a synchrotron cycle in a relatively narrow region. The second, storage rings with constant magnetic field and multiple external injection depending on oscillation damping due to radiation.

The first system is more ponderous; the second contained a component undeveloped at the time: a 100 kw, 10 k-amp commutator with a nanosecond wave front. By the end of 1957, after initial positive results were obtained with a 100 kw resonator, we decided upon the system with storage rings.

Initially, construction of two installations was proposed: VEP-1 at 2 X 130 Mev energy and VEP-2 at 2 X 500 Mev energy. The VEP-1 was considered as the accelerator working model and also as an installation for tuning-up the components as well as setting up initial experiments at low energies. In 1958, after Prof. Panofsky's report on studies of colliding electron beams carried out at his laboratory at Stanford, we abandoned construction of the 500-Mev storage rings and continued only the work at 2 X 130 Mev. We had to build not only the storage rings but the accelerator as well. Besides, there was forthcoming the move to Novosibirsk, which would delay our work.

Instead of doing work on 500-Mev electron colliding beams, at the end of 1958 we outlined the study of positron-electron colliding beams and began the design of installation VEPP-2, containing as its basic components a high-current electron accelerator and a high-vacuum 700-Mev storage ring.

At present the VEP-1 and the VEPP-2 are installed at Novosibirsk. The VEP-1 is near its start-up stage and is scheduled for experimental use by the end of this year. The work on completion of VEPP-2 is trailing the VEP-1 by one year. Its assembly is being completed at present.

In order to obtain significant effect from using colliding proton beams, at least a 10-Bev accelerator is required. Since a conventional accelerator for such an energy represents an installation of considerable size, beyond the scope of our Institute, a decision was made to combine the idea of colliding beams with the construction of an air core pulsed accelerator of high field with a balanced central chamber; the latter work was reported by us at the Moscow Conference in 1956. By the end of that year a 17 cm model of such an accelerator produced 70-Mev electrons. Subsequently, this work was interrupted and seriously resumed only 18 months ago. The existence of two-directional field in an air-core machine with a central chamber permits acceleration of protons in opposite directions in a single unit; thus, with suitable configuration of the racetracks, collision of protons may be obtained in a single accelerating apparatus. At present we are developing a "proton-proton" apparatus of 2 m radius with a magnetic field of about 200 kilogauss and proton beam energy of 12 Bev, which corresponds to a relative energy of ~ 300 Bev.

At present design of the apparatus is under way, models are being tested, an effective method of injection by means of charge exchange of negative ions is being studied experimentally. Also under development are a system of pulsed power supply with 100 megajoules of stored energy and the high-frequency power supply system.

Since 1958 theoretical work has been in progress at the Institute investigating the limits of applicability of quantum electrodynamics,[2,3] computing the radiation corrections for electrodynamic sections,[2-6] and covering other problems of high-energy particle physics connected with preparation of colliding-beam experiments.[2,7-10]

I. Colliding Electron-Electron Beams

The studies of electron-electron colliding beams led to setting up of an electron-electron elastic-scattering experiment at 2 X 130 Mev energy. This will permit study of electron interaction at a magnitude of momentum transfer which cannot be obtained by other methods and with a 10% accuracy of measurements will permit a check on applicability of quantum electrodynamics at distances of the order of 0.1 fermi. Information existing at present on applicability of laws of quantum electrodynamics in this region of distances is based on two experiments. The first, study of elastic scattering of fast electrons on protons, gives evidence that the effective length characterizing violation of laws of quantum electrodynamics should be no greater than 0.3 fermi. The second experiment, measurement of anomalous magnetic moment of the muon, extends this boundary to a twice smaller value.

This experiment up until the present is of considerable interest despite the fact that evidently it will not disclose deviation from quantum electrodynamics and will not widen the limits of its applicability.

Our apparatus for colliding electron-electron beams consists of a high-current electron synchrotron B-2S, a paired system of two high-vacuum magnet rings, electron-optical channel for guiding the beam from the accelerator to the rings and a system of single-turn ejection from the accelerator and discharge to the rings.

The schematic arrangement of the VEP-1 components is shown in Fig. 1 and the general view in Fig. 2.

1. Accelerator Injector

A non-ferritic pulsed high-current synchrotron B-2S with spiral electron storage developed at our Institute is being utilized as an accelerator injector.

The synchrotron is designed to produce 100-Mev electrons. It is operating at present at 40 Mev. The current in the ejected beam pulse of less than 10 nsec duration is about 30 ma (in excess of 10^{10} particles). The energy scatter does not exceed 0.2%; repetition rate is one pulse in 30 seconds.

Despite the low mean intensity of the beam due to low repetition rate, such a synchrotron can successfully compete with a linear accelerator due to the short duration of the electron pulse and its good monochromatic properties.

It is possible that in the future a simpler air-core accelerator BSB of more reliable construction will be utilized as an accelerator injector for the VEP-1 installation. This accelerator, with an identical orbit radius, will have a greater terminal energy and the beam intensity such that a single pulse will be sufficient to fill the two storage rings with the required number of electrons.

The description of the two accelerators is given in a report presented at this Conference.[11]

2. Storage Rings

The storage apparatus consists of two circular magnetic rings of 43 cm radius, contacting each other at one side in such a way that the circular equilibrium orbits are tangent. Horizontal slits are positioned in the magnet poles opposite this point for emitting the electrons scattered from the region of the beam collision. The apparatus is arranged in such a way that the median plane of the storage rings is vertical and one ring is placed above the other. This permits the arranging of the scattered electron recording system in a horizontal plane around the storage apparatus.

In the common part of the rings (40° along the azimuth) the index of the fall of the magnetic field $n = 0$; the value of n outside this region is selected in such a way that the frequencies of betatron oscillations are remote from dangerous resonance values. On either side of uniform field are 20° long regions with $n = 1$; the field in the remainder of the ring has $n = 0.62$. Maximum intensity of the magnetic field: 10,000 oersted. Stability of magnet power supply: 0.03%.

The electromagnets are of a mushroom shape. The bodies of the magnet poles are integral with the walls of the vacuum chamber made of stainless steel. Inside the chamber are fastened the pole tips of semicircular shape. The working aperture of the chamber is 50 X 35 mm.

On all four faces the chamber has large rectangular openings covered by double flanges. Lead is used for the inner seal and rubber for the outer seal. The space between flanges is evacuated by means of separate oil-diffusion pumps to 5×10^{-6} Torr.

The main vacuum pump of Getter-ion type with titanium evaporation and nitrogen cooling provides limiting pressure of 10^{-8} Torr with a pumping speed of 10,000 liters/sec. In the working region of the chamber, vacuum of 3×10^{-8} Torr was reached. In order to secure such a vacuum, the chamber was baked out at 200°C.

Coaxial quarter-wave cavities were chosen as the accelerating elements. In order to reduce their physical size, second harmonic of rotation frequency is utilized. The feeds have a half-wave electric length.

During injection the amplitude of the high-frequency voltage is selected to secure the optimum capture of particles for storage. At 50 Mev injection energy the magnitude of the amplitude of high-frequency voltage is 5 kilovolts. During the holding period, in order to secure a longer life of the beam, the amplitude of high-frequency voltage may rise to 15 kilovolts. The output of the high-frequency generator is 2 X 6 kw.

Deviation from the optimum frequency results in radial displacement of the beam and disturbs the conditions for collision. This determines the tolerances for allowable frequency instability of the high-frequency voltage. A quartz crystal master oscillator provides the required stability of 0.01%.

In order to compensate for possible phase shift of high-frequency voltage due to heating of cavities, an automatic system for adjustment of resonant frequency of the cavities is provided. Special phase shifting lines introduced into the lines to both cavities serve for controlling the position of the bunches and the point of their collision.

3. Electron-optic Channel

The beam deflected from its orbit is guided from the synchrotron chamber by means of a magnetic channel consisting of a circular iron screen in which the field intensity is near zero. With the aid of correcting magnets (see Fig. 1), the beam is guided through quadrupole lenses and then through a wedge-type bending magnet providing 48° bending of the beam. Additional ± 10° bend is secured by a switching magnet alternately guiding the beam into the upper or lower storage rings. Lenses form an intermediate focus in the bending magnet; the bending magnet, therefore, has only a small focusing effect upon the beam. The diverging beam beyond the bending magnet is focused again by means of quadrupole lenses.

Pulsed method of operation of the accelerator permits the use of pulsed focusing, compensating and bending systems. All components of the electron-optical channel with the exception of the bending magnet are thus pulsed.

Injection of the beam into the storage rings is accomplished by means of special compensating systems, in which pulsed magnetic field is formed, equal to but opposite in sign from the field of the storage rings. The compensating system is a "coaxial" of special form, carrying pulsed current of the order of 10^5 amps. By shaping the outer and inner electrodes it is possible to compensate the field of the storage ring magnet across the entire aperture of the "coaxial" with an accuracy of 1%.

4. Ejection and Injection Systems

In VEP-1, in order to inject into the storage rings electrons accelerated in the synchrotron, a pulsed single-turn beam control is used. Deflecting systems are placed at the equilibrium orbits of the synchrotron and of the storage rings, fed from a common pulsed generator. Time of establishment of controlling field (rise and fall) is less than half of the rotation period of particles in equilibrium orbits. The displacement of the beam in the deflecting systems is about 2 cm.

While passing through the ejection deflecting system, on the average, about half of the accelerated electrons receive a radial impulse sufficiently uniform in magnitude and, being displaced from the equilibrium orbit, find themselves in the ejection channel along which they leave the accelerator.

The deflecting injection system (the inflector) on the first turn damps out the beam oscillations that may arise at injection into the storage rings. The capture efficiency may be made to approach 100%.

The deflector consists of short-circuited sections of transmission lines and corresponds to the feeder in wave resistance. Due to sufficient uniformity of the deflector magnetic field along the path of the guided beam, the cross section and angular dispersion of the beam at ejection remain practically unchanged.

The inflector is a matched line, in which the voltage surge travels against the motion of electrons. The field (electric and magnetic) in the inflector is nonuniform, increasing nearly linearly with the radius. The amplitude of betatron oscillations of the stored beam, excited by the impulse, appears to be not over half the aperture of the storage ring.

In order to power the deflecting systems a special power supply has been developed, utilizing fast-acting overcharged spark gaps, the discharge gaps of which are in nitrogen, pressurized to 10-20 atmospheres. Structurally the spark gaps form a part of the transmission lines connected to them and are matched to them in impedance. With 13 ohm loading, the generator forms single rectangular voltage pulses of up to 100 kilovolt amplitude, the time of rise being 1 nsec and of 10 nsec duration. The power supply is synchronized with the starting pulse with an accuracy up to 0.3 microseconds. The power supply is powered by a 150 kw dc source. Oscillation of pulse amplitude is less than ± 3%.

5. First Storage Experiments

At present we started experiments at VEP-1 in storing electrons in a single ring. 40-Mev electron beam extracted from the synchrotron is guided without losses along the electron-optical channel and injected into the storage ring. During a single injection cycle up to 100 ma of electron current are successfully captured. Subsequent inflector pulses do not knock out the stored beam from the ring.

The work is carried out in a vacuum of the order of 10^{-7} Torr. The lifetime of the beam is 140 sec. This value is in good agreement with computations taking into account the single interaction between electrons and the atoms of residual gas, coulomb scattering of the nuclei, production of δ-electrons, and radiation loss. The long lifetime of the beam permits not associating the working energy of the storage apparatus with the energy of injection and storage. The required working energy is established by the rising magnetic field of the rings after storage. The possibility of such a working condition is confirmed experimentally: electron-beam energy in the storage ring rises to 140 Mev without any loss of its intensity. The lifetime of the electrons at the same time would rise to 10 minutes.

Large magnitudes of stored current diminish the lifetime of the beam due to effect of electron-electron scattering in the bunch, which causes a relativistic shift of a small transverse component of the momentum into a large longitudinal scatter (Touschek effect).[13] At conditions being investigated, the contribution of this effect to the lifetime of the beam becomes noticeable at a current of the order of 100 ma. In order to obtain currents of the order of 1 ampere without substantially reducing the lifetime of the beam it is sufficient to increase its radial dimension to 1 cm. This is possible to achieve by feeding the inflector electrode pulses deflecting the beam with a frequency of a greater magnitude, inverse to the period of damping of betatron oscillations. Rationality of such a procedure follows from consideration that lifetime increases as a square of radial (largest transverse) dimension of the beam, while the number of interactions (the basic effect) falls as the first power.

The program of further studies contemplates a three-fold increase in the lifetime of the beam by improving the vacuum, and increase of the repetition rate to 1 cycle in 10 seconds. At the rate of electron storage of about 100 ma ($\sim 5 \times 10^9$ particles) per acceleration cycle this will insure possibility of storage at each ring of currents of the order of 1 ampere.

6. Execution of the Experiment

The first experiment with colliding electron-electron beams consists of measuring the angular distribution of elastic scattering of electrons on electrons.

The recording apparatus consists of pairs of scintillation counters connected in coincidence with time resolution of $2\tau = 10$ nsec. The counters utilize photomultipliers FEU-33 and laminated scintillators of 60 and 90 mm diameter and 15 mm thick. The effective solid angle of a single recording channel is about 10^{-3} steradian.

The final dimensions of the interaction region establish definite requirements for detector size.[14] The effective length of interaction region from which two counters connected in coincidence are registering scattered electrons depends upon the angle at which the counters are placed. If the requirement is that the error connected with this effect is not to exceed 3%, then for the selected dimensions of the detectors, the effective length of interaction region should not exceed 2 cm.

The expected counting rate of the experiment and the background ratio depend on many parameters of the setup still insufficiently determined before the startup. At present, therefore, only approximate evaluation of experimental conditions is possible. The proposed working conditions of the setup at 100 Mev with ten pairs of counters placed at near 90° and with one pair each at angles of 30° and 150° respectively will permit a counting rate of one per minute for 90° angle of scatter and about five per minute for a 30° angle. The expected signal-to-noise ratio is of the order of 100.

II. Colliding Positron-Electron Beams

The investigation of positron-electron colliding beams contemplates experimental setup for study of positron-electron interaction at energies up to 2 X 700 Mev.

In the electron-electron experiment, the final state of two colliding electrons is determined only by Møller scattering. Existence of any other processes is less probable by two orders of magnitude and their study is considerably more difficult due to a complicated kinematic picture. In the positron-electron case neutrality of charge of the resulting system gives rise to many other processes with two-particle terminal state. Experiments studying these processes will be considerably richer in quantity of information obtained in regard to interaction between elementary particles as well as of its value.

Our setup for colliding positron-electron beams (VEPP-2) consists of a high-current electron synchrotron B-3M, high-vacuum magnetic racetrack, a converter for transforming the electron beam into a positron beam, electron-optical system for guiding the beam, and a system of single-turn extraction of the beam from the synchrotron and injection into the storage ring.

General schematic of the setup is shown in Fig. 3.

1. Accelerator Injector

Developed in our Institute, the high-current synchrotron B-3M with external injection from a so-called "amplitude" accelerator and a single-turn ejection system is utilized as an accelerator injector. Description of the two accelerators is given in reports delivered at this Conference.[11,15]

The proposed parameters of the B-3M synchrotron are as follows: energy, up to 350 Mev; duration of current pulse in emitted beam, about 20 nsec; pulse current, up to 10 amps ($> 10^{12}$ electrons per pulse); repetition rate of acceleration pulses, up to 12 cycles per sec.

Considering even the mean current (several microamperes) this synchrotron can compete with a linac. Utilization of such intense beam is required due to large losses of intensity during transformation of electrons into positrons.

2. Storage Ring

The storage apparatus consists of a weak-focusing racetrack with four identical rectilinear gaps. Two gaps are used for injection of electrons and positrons, the third gap contains a high-frequency cavity, and the last gap (opposite the cavity) is designated for experiments. The general view of the storage ring is shown in Fig. 4.

The quadrants are designed as electromagnets of a closed type. The slope of the pole planes is at an angle of $3^{\circ}35'$ with the horizontal and continues into the region occupied by the windings; this guarantees value of $n = 0.6$ with an accuracy better than ± 2% in the entire magnet gap. Maximum intensity of magnetic field at the equilibrium orbit is 15,000 oersted; stability of the magnet power supply 0.03%.

Magnet poles and brass shells form the outer vacuum chamber. Its junctions are sealed by means of rubber gaskets. Evacuation of the outer chamber is performed by means of two oil-diffusion pumps.

The inner chamber is of rectangular cross section 160×135 mm^2 and is made of copper. V-groove-type seals with copper gaskets are used. The chamber is baked to a temperature of 400°C. On test, by means of oil-diffusion pump with a nitrogen trap of special design, pressure of 5×10^{-10} Torr was obtained in the working region of the chamber.

The cavity of the storage ring is operating at the first harmonic of the particle rotation frequency of 25 megacycles. It consists of two quarter-wave coaxial lines loaded by a two-disc condenser and its $Q \approx 3000$. A 250 kw generator is used for excitation of the cavity. With an additional cascade connection it is proposed in the future to increase this power to 750 kw, which will permit up to 300 kw at the cavity loaded by the beam.

3. Electron-optical Channel

By means of a system of quadrupole lenses and bending magnets (see Fig. 3), the electron beam emitted from the synchrotron is guided directly into the storage-ring chamber or into the electron-positron converter. In the latter case the first bending magnet is not energized.

The converter consists of a tungsten plate, about one radiation unit thick. In order that the conversion would not introduce significant increase of phase volume of the beam, the converter is placed in the focal plane of two short-focus lenses. With sufficiently large "candlepower" such a system insures capture into the storage apparatus of a major part of positrons of such energy range that satisfy the conditions of capture. The bandwidth of this range is 1.5% of injection energy. By selecting the positron energy to be one-half of the electron energy, it is possible to obtain a conversion coefficient of 3×10^{-4}.

For the short-focus lenses it is proposed to use magnetic lenses, which may be called "parabolic". Such a lens (Fig. 5) consists of two paraboloids of revolution made from 0.1 - 0.2 mm thick aluminum (or beryllium) joined at their vertices. Pulsed current of the order of 10^5 amps, with about 1 microsecond pulse, is fed into the lens by means of a symmetrical low-inductance line in such a way that in the space between the paraboloids is created an axially symmetrical pulsed magnetic field, falling off in transverse direction as $1/r$. In case the beam axis is directed along the axis of symmetry of the lens, then a charged particle will traverse a path in the magnetic field proportional to r^2. Thus, the integral of the field along the trajectory rises linearly with the distance from the axis, which insures linear focusing of the beam.

Injection of the beam into the storage ring is accomplished in the vertical plane; the median surfaces of the accelerator and of the storage apparatus are, therefore, separated 68 cm vertically. The beam is injected by means of pulsed air-core magnets having the thickness of the field forming conducting surfaces greater than the skin depth.

4. Ejection and Injection Systems

Single-turn ejection of electrons from the accelerator and injection of electrons and positrons into the magnetic racetrack are accomplished by means of electromagnetic systems of the deflector and of two inflectors (without ferrites), which are fed by special synchronized high-voltage generators of nanosecond pulses. All generators have dual outputs.

The deflector is designed as a section of short-circuited flat line with an opening for introduction of electrons.

The positron and electron inflectors are each arranged in the second quadrant from the point of injection. The inflectors are copper sheets arranged along the entire magnet quadrant above and below the beam. The voltage wave in the inflector propagates in the direction of motion of the particles, which permits injection of one beam without perturbation of the beam of opposite charge. The wave impedance of each inflector plate is 10 ohm. Maximum plate voltage is 50 kilovolt.

At present there has been built a model of a generator of high-voltage pulses based upon a three-electrode segmental spark gap (with thyratron start) working in nitrogen pressurized to 25 atmospheres. The model has the following parameters: pulse repetition rate, 25 cycles; maximum voltage at 50-ohm load, 25 kilovolt; pulse length, 30 nsec; risetime and accuracy of synchronization with an external trigger, 1 nsec.

5. Proposed Working Procedure

It is proposed to execute the positron storage at 150 Mev. To this energy and at a vacuum of 10^{-9} Torr corresponds the fractional beam lifetime with single interaction processes with residual gas of about 3×10^4 sec. In order that the Touschek effect would not substantially reduce the lifetime it is necessary artificially to maintain a greater transverse dimension of the beam. It is possible to prove that 1×3 cm^2 size of the beam will permit storage of a current greater than 1 ampere.

The proposed rate of positron storage is about 1 ma ($\sim 3 \times 10^8$ particles) during one cycle of acceleration. Betatron oscillation damping for 150-Mev injection energy is rapid enough to permit operation at a repetition rate of 3 cycles per sec. At these conditions 1 amp current will be stored in 300 sec. Two orders of reserve in the lifetime (or in rate of storage) will facilitate overcoming any unknown difficulties in the future.

6. The Experimental Setup

In Fig. 6 are shown the energetic (for 90° angle) and angular (at 300-Mev energy) relations of cross sections of several processes in positron-electron interaction. The computations are carried out at the lowest order of perturbation theory in the consideration of validity of laws of quantum electrodynamics at small distances.

The difficulties of controlling the parameters of the region of interaction of the two beams reduce considerably the accuracy of measurement of absolute value of cross sections; therefore, their relative energetic and angular distributions will be the subject of measurements.

Evidently, the easiest to record and consequently the most convenient to use as a monitor will be the process of two-quantum annihilation with dispersion of γ-quanta along the line close to the line of collision. For this effect at 150-Mev energy, the beam cross-section areas of 3 cm^2 and 1 amp current in each beam, a counter with angular size of 1° will have a counting rate of the order of 10 counts per minute.

To insure such a counting rate while measuring elastic scattering and two-quantum annihilation at an angle of 90° to the collision line, it is necessary to have effective solid angle of recording of about one steradian.

With increase of energy the Touschek effect is getting weaker, and it is possible to reduce the cross-section size of the beam, still retaining the lifetime in excess of 10^4 seconds. This will permit increasing the counting rate, despite the fact that with increase of energy the cross sections of all processes are diminished. At 700-Mev energy the beam cross section may be reduced to 0.1×10 mm^2, which is close to its natural size. To these conditions, or a solid angle of 1 steradian and a counting rate of the order of 10 counts per minute will correspond recording of more rare events, such as $e^+ + e^- \rightarrow \mu^+ + \mu^-$ and $e^+ + e^- \rightarrow \pi^+ + \pi^-$. At this energy will also be observed the process $e^+ + e^- \rightarrow K^+ + K^-$ with a counting rate of about 3 counts per minute.

A system of spark chambers with acoustic means of information gathering is being developed for carrying out the positron-electron experiments. High geometric resolution of spark chambers will permit better estimate of measurement errors related to final size of interaction region, radiation effects and to the background. Acoustical system for obtaining information will also permit the primary processing of measurement results at an electronic computer.

III. Colliding Proton-Proton Beams

The utilization of the principle of colliding beams materially reduces the weight of an accelerator designed for experiments with assigned relative energy; however, an accelerator of this type cannot fully replace an ordinary accelerator for a corresponding relative energy since the latter serves as a producer of high-energy secondary particles. However, for proton-proton experiments, an accelerator with colliding beams has an advantage over an ordinary accelerator, since the dispersion angles of secondary particles are small even in the center-of-mass system. In the laboratory system, due to relativistic contraction, in many cases these angles cannot be measured at all. Besides, all secondary particles from a regular accelerator are extremely relativistic and are, therefore, hardly distinguishable.

Another method of reducing the accelerator weight is to utilize magnetic fields of higher intensity. We may assume that the practical limit of magnetic field in air-core accelerators is about 200 kilogauss. Such a field will create a pressure of 1600 atmospheres. At present it is difficult to imagine rational designs in which we could obtain magnetic fields of much higher magnitude with accuracies required for acceleration.

Our "proton-proton" setup combines the principle of colliding beams and utilization of high magnetic fields.

1. Setup Schematic

The "proton-proton" apparatus: a single-turn pulsed air-core proton synchrotron with weak focusing and balanced central conductor in which protons are accelerated simultaneously in opposite directions. Radius of equilibrium orbit is 2 meters; magnetic field about 200 kilogauss, which corresponds to energy of each beam of 12 Bev and relative energy of $\sim$ 300 Bev.

Cross section of the chamber and the magnet are shown in Fig. 7. Pulsed current flowing along the central conductor returns along the chamber wall. The latter simultaneously forms the vacuum chamber. The lines of magnetic force are shown dotted. With respect to magnetic forces the central conductor in its entirety is in a state of stable equilibrium. However, it is firmly secured for structural considerations. The chamber is built from non-magnetic steel from considerations of the internal pressure of the magnetic field. Due to the skin effect the currents are flowing along the surface, and thus the shape of the field is determined by the shape of the surfaces.

In plan, the apparatus consists of an asymmetrical racetrack with four gaps (Fig. 8). Direction of the current flow in the central chamber in the left and right halves is in the opposite direction. In the upper and lower rectilinear gap the particles are transposed from the inner track to the outer one and vice versa. A cavity installed in the left or the right gap accelerates the particles in both directions and while operating at any odd harmonic guarantees collision of bunches at the points of orbit intersection.

In the "proton-proton" apparatus the particles are colliding during the entire acceleration cycle, whereupon the limiting energies have an advantage since they are in correspondence with the apex of the sine wave of the feed current. Relatively short duration of the time of operation compared to that in a usual accelerator is compensated by greater beam intensity resulting from the small size of the apparatus. With other conditions being equal (injection energy, relative aperture, etc.), the beam intensity is here more in the ratio of the squares of the radii.

In order to obtain a well-observed effect of the proton collision, it is necessary to drive the beam intensity practically to its limit defined by space charge or by sufficiently high injection energy.

Evaluations indicate that at 2-Mev injection energy and 1-millibarn cross section it is possible to obtain several interaction events during a single acceleration cycle. It is proposed to achieve injection by means of charge exchange of negative ions or neutral atoms inside the chamber. In order to study such injection mechanism we are carrying out experimental investigations to which is devoted a separate report presented at this Conference.[16] (See Fig.9)

2. Electron Models

In 1956 we built and started up an electron model of an air-core accelerator with a balanced central chamber. Acceleration was performed in a single ring. The radius of equilibrium orbit was 17.4 cm, aperture 2.5×3 cm^2, magnetic field index $n = 0.6$.

Energy of 70 Mev was reached with this model and it was shown that in radial direction the entire racetrack was suitable for acceleration.

Construction of an electron synchrotron with an orbit radius of 23 cm for 1-Bev energy is being carried out during the second stage of work. At present the construction and assembly of the accelerator are completed; the tune-up is in progress. In a single quadrant of the accelerator, 130-kilogauss field has been obtained of required configuration and of an accuracy required for acceleration.

3. Development of the Magnetic System

The success of constructing a "proton-proton" machine to a large extent depends on a successful development of the magnet power supply -- an impulse generator of 250 million joules energizing the magnet in 0.02 seconds. Due to difficulty of this problem and in order to develop all components with greater care, it is proposed to initially construct an accelerator with reduced parameters (orbit radius, 1.3 meters; magnetic field intensity of the order of 100 kilogauss, corresponding to beam energy of about 3 Bev and relative energy of 30 Bev). The design of this accelerator is being carried out at present.

The investigation of stability of the motion of particles in an asymmetrical racetrack has shown that, in comparison with an ordinary case, the prohibitive resonance zones are widened and there appears a certain azimuthal asymmetry in the curved trajectories.

The difference in the radii of curvature of the orbit in the inner and outer racetracks is compensated by the difference of their magnetic fields. In the version selected, this is secured by both racetracks being of equal width, even at the end of the acceleration cycle, when the width of each track for the magnetic flux is increased over its geometrical value due to penetration of the magnetic field into the metal of the chambers.

All dimensions of the magnetic path in the models were selected from the condition of equality of magnetic resistances at all cross sections at any time. This problem is complicated by the fact that the magnitude of magnetic resistance varies considerably during the time of acceleration. The configuration of the central chamber is selected in a way to insure its equilibrium with respect to forces of magnetic field. It has been shown that the required manufacturing tolerances are within the accuracy of usual machining. Requirements have been also determined of the uniformity of electric conductance of the chambers and the effect of temperature of the chambers upon the accuracy of the magnetic field was established.

A number of other problems arising during the design were investigated: strength and rigidity of components, selection of contact surfaces at the points of current transfer from chambers to flanges and vice versa, etc.

4. Development of Power Supplies

High frequency excitation of a pulsed air-core accelerator is considerably more complicated than usual, since at considerably higher power a higher frequency is required and its variation occurs in a shorter time. Despite the fact that total energy storage of the magnetic field at a given particle energy is decreasing inversely proportional to the intensity, the system of electrical excitation of air-core magnets is also more complicated since this energy has to be introduced in a shorter time. At greater than 10 megajoules energy of the magnetic field, special apparatus is required since use of condensers in this case becomes economically irrational. Solution of these two problems is facilitated due to pulsed operation of the accelerator with a low repetition rate.

A resonant circuit with variable natural frequency is proposed for particle acceleration. Tuning of the circuit is carried out by magnetizing the ferrite core of the circuit. To insure frequency tuning in a very short time a special ferrite was developed, permitting high rate of frequency tuning without loss of Q. The model of the cavity develops up to 20 kilovolts at the accelerating gap and permits acceleration of particles with a 9:1 variation of their rotation frequency. The cavity is fed by a broad-band amplifier with a power output of greater than 100 kilowatt.

For the magnet excitation, at present is being developed an impulse generator, based upon sharp deceleration of rotating masses in a magnetic field.

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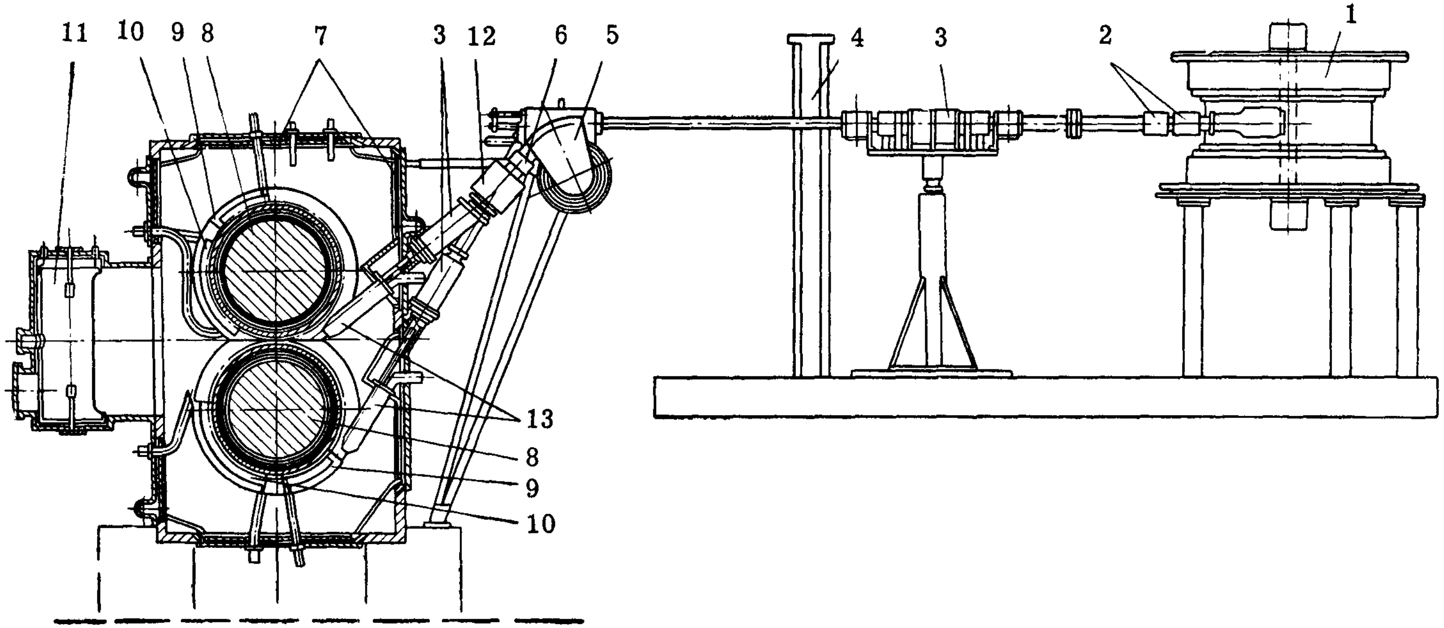


Fig. 1 - Schematic of arrangement of components in the VEP-1 machine.

(1) Synchrotron B-2S; (2) correcting magnets; (3) quadrupole lenses;
(4) radiation and magnetic screen; (5) bending magnet; (6) correcting coil;
(7) interflange space; (8) storage racetrack magnets; (9) cavity;
(10) inflector; (11) high-vacuum pump; (12) switching magnet;
(13) compensating systems.

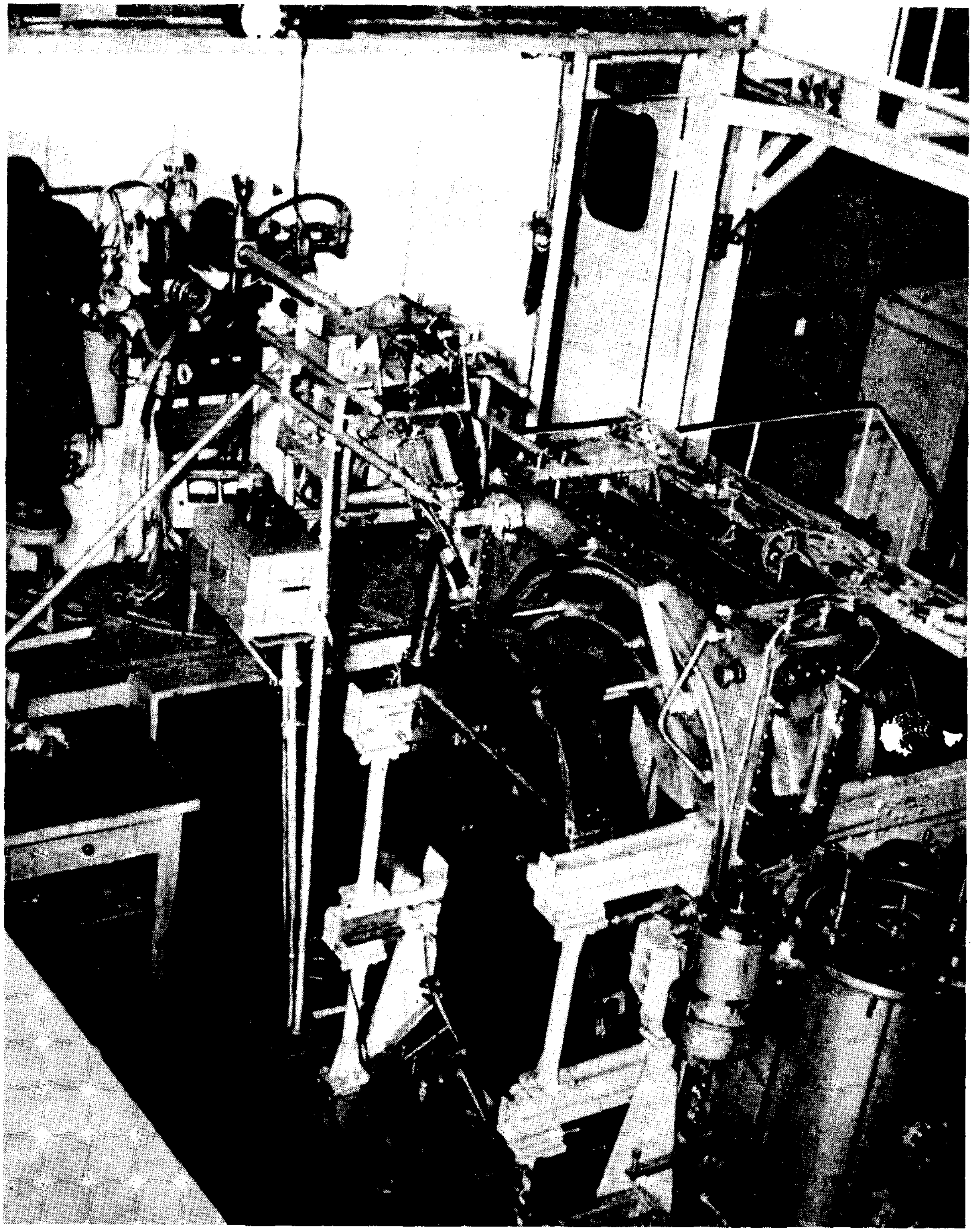


Fig. 2 - General view of storage racetracks and part of electron-optical path of the VEP-1. Synchrotron B-2S is behind the screen.

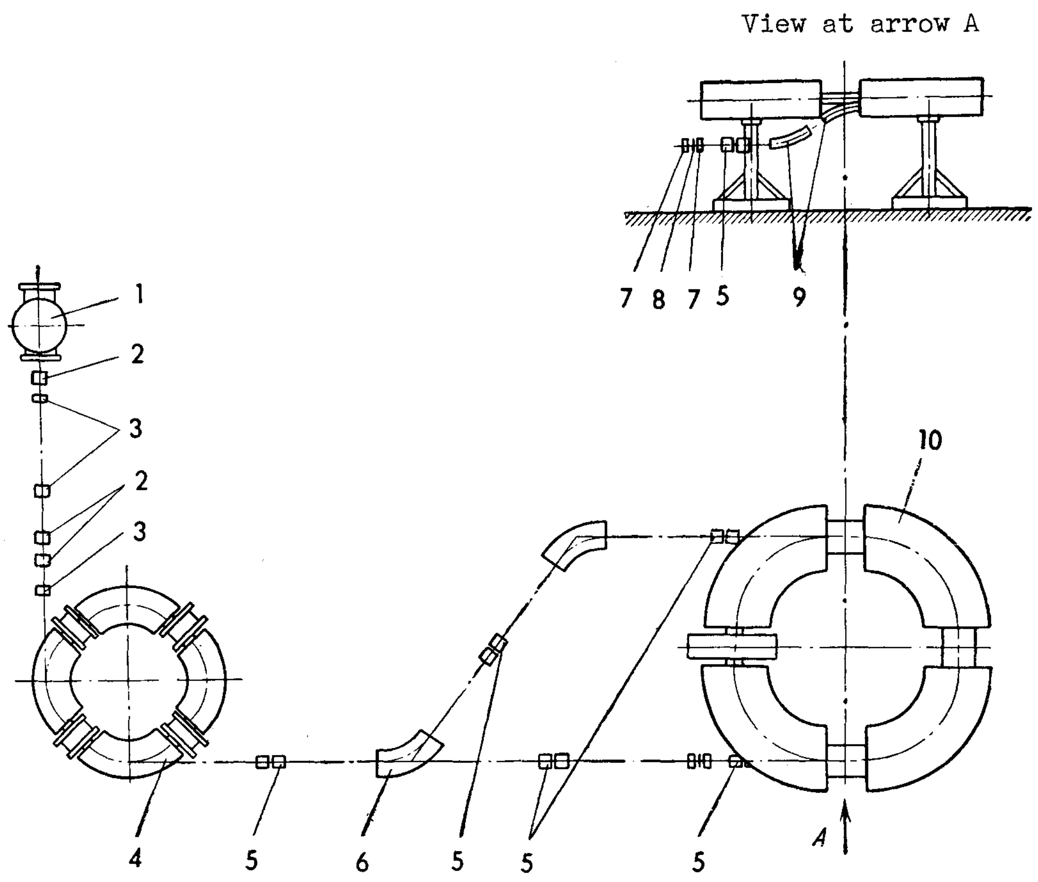


Fig. 3 - **General schematic of the VEPP-2 machine.**

(1) Injection accelerator; (2) correcting lenses; (3) cylindrical lenses; (4) synchrotron B-3M; (5) quadrupole lenses; (6) bending magnet; (7) "parabolic" lenses; (8) converter; (9) system for parallel displacement of the beam; (10) storage ring.

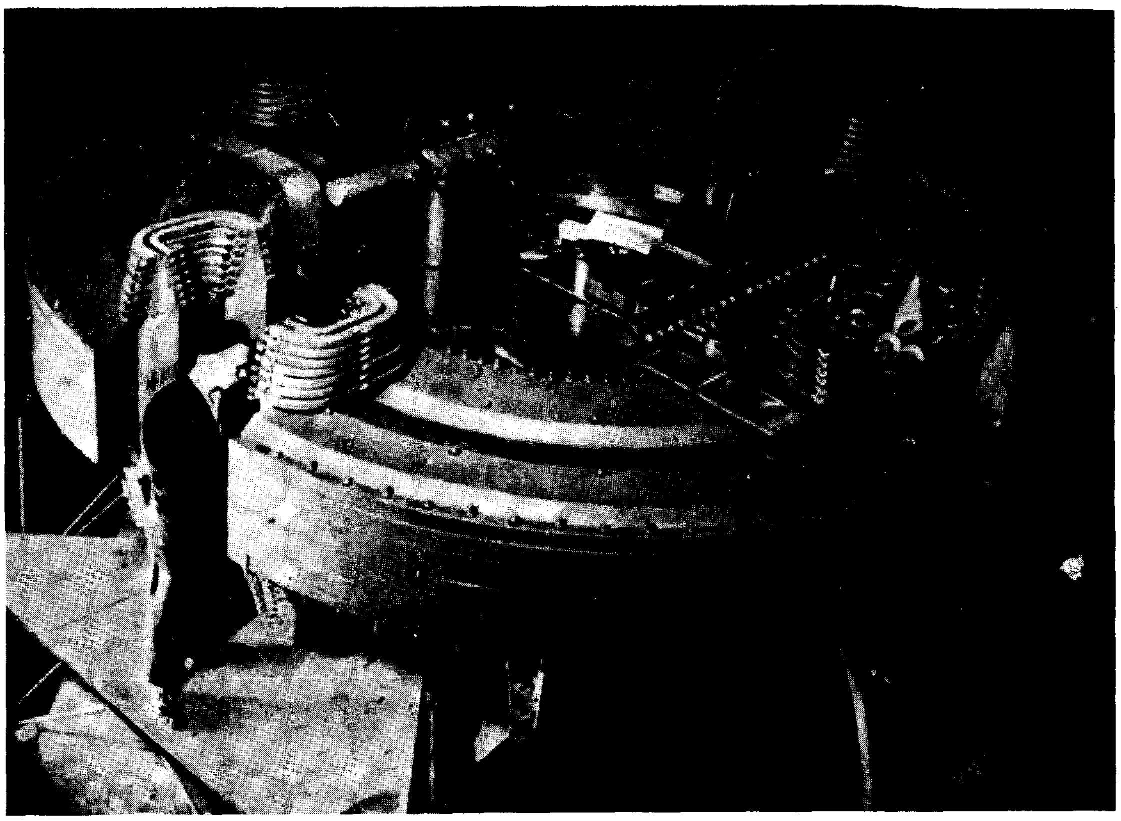


Fig. 4 - General view of the storage apparatus

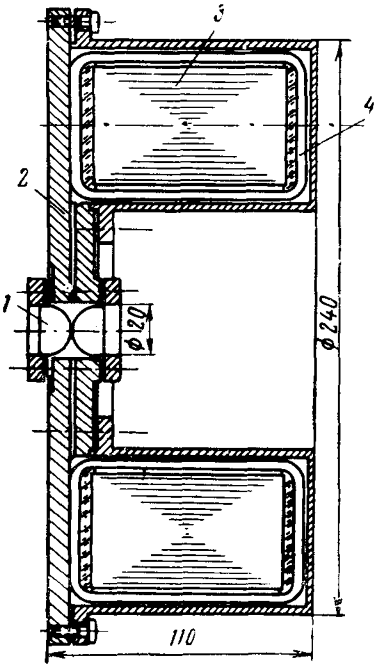


Fig. 5 - "Parabolic" lens.

(1) Parabolic electrodes of the lens
(2) current leads;
(3) current transformer core;
(4) primary transformer winding.

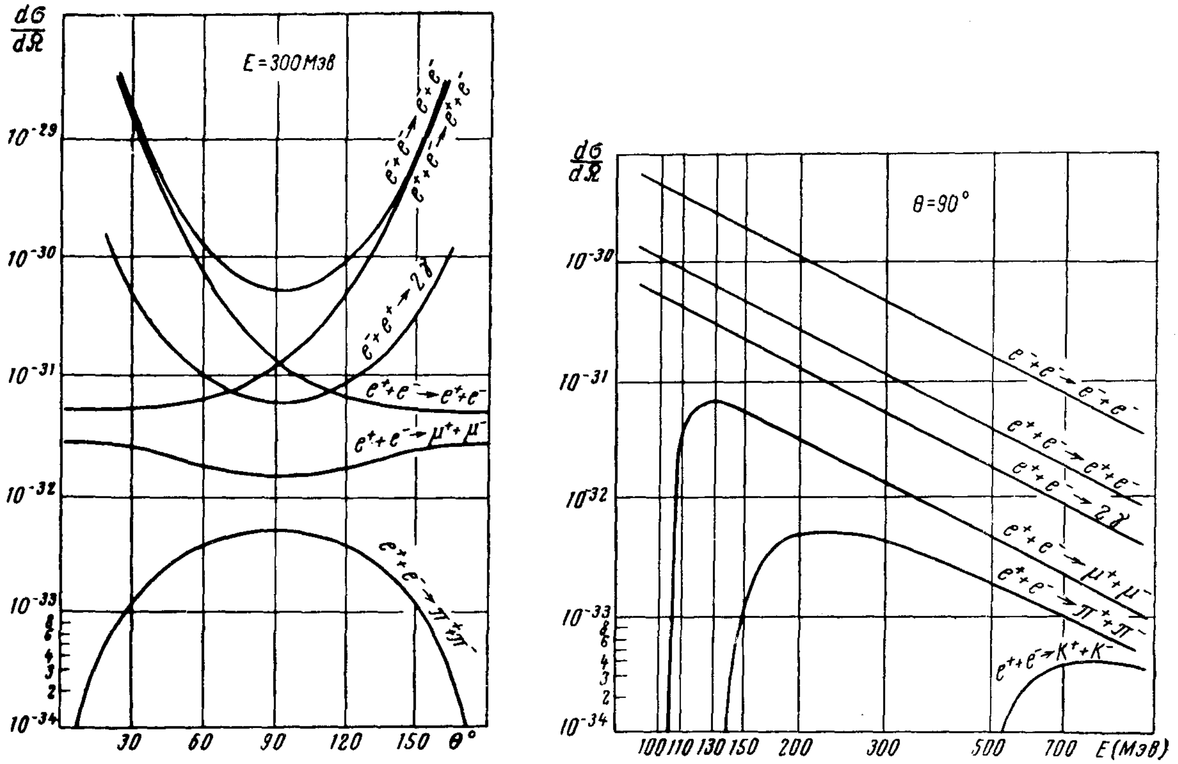


Fig. 6 - Energetic and angular relationships in Møller cross section and cross sections of processes at electron-positron interaction.

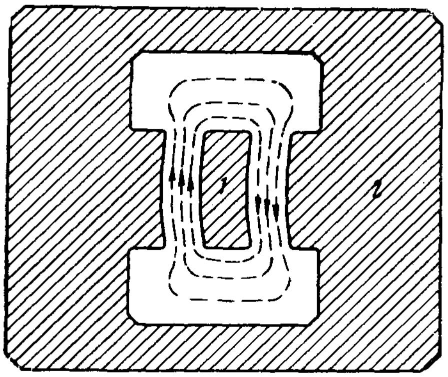


Fig. 7 - "Proton-proton" machine, magnet cross section. Force lines of magnetic field are shown. (1) Central balanced conductor; (2) outer chamber - framework.

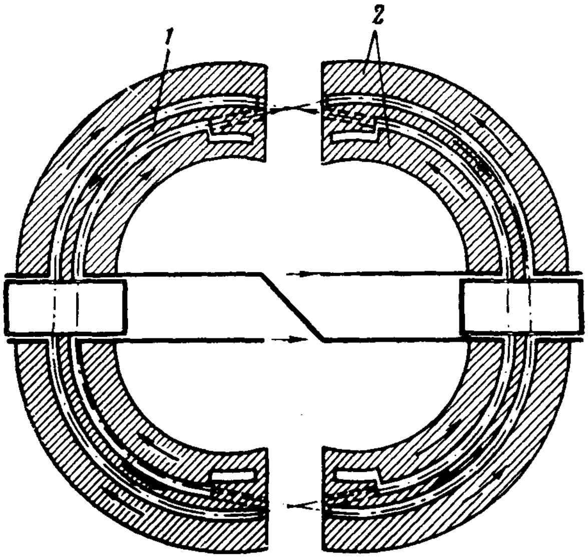
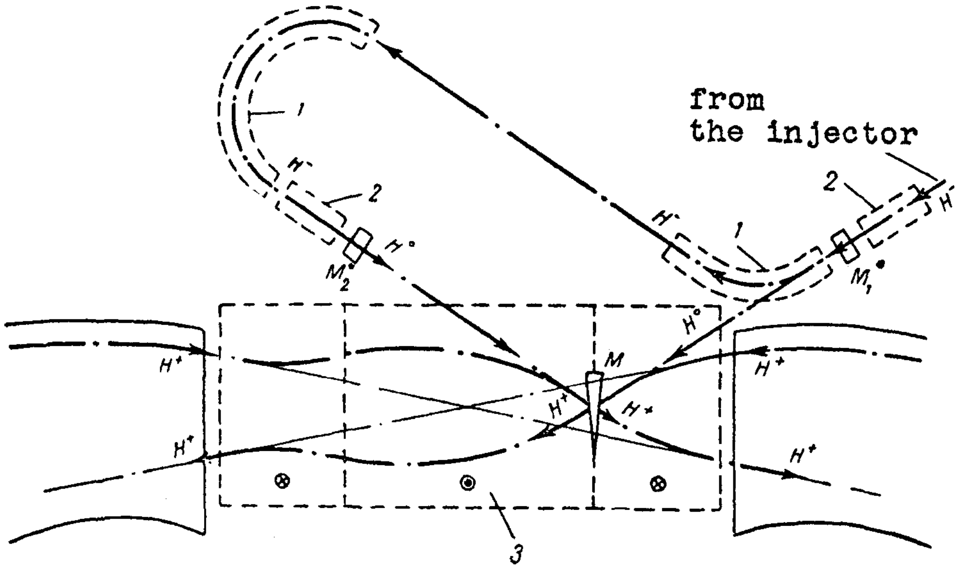


Fig. 8 - Plan view of "Proton-proton" machine. The arrows indicate directions of current flow. (1) Central balanced conductor; (2) outer chamber - frame work.



1 -- Rotary magnet; 2 -- corrector; 3 -- entrance magnet. M -- Common charge exchange target; M_1^* -- bisecting neutralizing target; M_2^* -- neutralizing target for the second beam.

Fig. 9 - This figure has been added from reference 16. It represents the proposed injection method for the "proton-proton" accelerator.

PHYSICAL INSTITUTE OF THE USSR ACADEMY OF SCIENCES - MOSCOW

LEBEDEV INSTITUTE

D. V. Skobeltsyn	- Director
N. A. Dobrotin	- Deputy Director of Institute; Director, Cosmic-Ray Laboratory
A. Baldin	- Head of Theoretical Section, 250 Mev Synchrotron Laboratory
P. H. Cherenkov	- Director, 250 Mev Synchrotron Laboratory
I. M. Frank	- Director, Laboratory of Nuclear Physics
A. A. Kolomenskiy	- Director, FFAG Laboratory
Ye. P. Ovchinnikov	- Director, Radio astronomy Laboratory
V. A. Petukhov	- Director, 660 Mev Synchrotron Laboratory
I. Y. Tamm	- Director, Theoretical Department
V. S. Vavilov	- Deputy Director, Semiconductor Laboratory
B. M. Vul	- Director, Semiconductor Laboratory

Yu. M. Ado
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Kannunikov
A. N. Lebedev
Yu. N. Metalnikov
E. M. Moroz
M. S. Rabinovich
B. N. Yablokov

PHYSICAL INSTITUTE OF THE USSR ACADEMY OF SCIENCES - MOSCOW (LEBEDEV INSTITUTE)

This Institute was founded in 1934 and has many branches. These include Theoretical Physics (Tamm), Radio Physics, Solid State Physics, Radio Astronomy, Optics, and Observatories.

1944 saw the start of atomic physics. Veksler was at Lebedev when he discovered the synchrotron principle.

1947. The first synchrotron was constructed at Lebedev with the help of Moscow factories. It was a 30 Mev machine, the first synchrotron in the USSR and one of the first in the world. It is still in operation doing photonuclear work. The person in charge is a woman physicist (Lazareva).

1949. A 270 Mev electron synchrotron was built which is still in operation doing work in the photo meson field. Have recently done some beam stacking in it. Cherenkov and Baldin are in charge. This was reported on at Dubna.

1953. A 180 Mev proton synchrotron built by the Komar Institute was added to the facilities at Lebedev Institute. This was an operating model for the 10 Bev synchrophasotron and investigations were carried out on it of (a) resonance phenomena, (b) synchrotron oscillations and (c) betatron oscillations. It has since been converted to a 660 Mev electron synchrotron and a special laboratory has been built up around it doing pion physics.

The intensity of the 660 Mev electron synchrotron is 3-4 x 10^{10} e/pulse with a pulse rate of 1 per 5 seconds. The pulse has a 0.5 to 0.7 second flat top. Work proceeds on a 5 day experimental, 1 day preventative maintenance schedule. Injection is at 800 kev.

The machine is still being improved as illustrated by plans for a high current microtron injector at 5 Mev to replace the impulse transformer at 1 Mev, the use of multiple turn injection, and provision for a long flattop (½ second).

1948 to 1957. The Lebedev Laboratory did all the work of initiating and designing the 10 Bev synchrophasotron. After it was finished, the machine was given to the JINR. The actual construction of the machine was done by the Komar Institute. The JINR is now an independent laboratory.

1953 to present. Work has been done on FFAG theory and models. Recently a 30 Mev symmetrical ring phasotron has been built. This is in Kolomenskii's laboratory and under the direction of Komeelikov.

Work on a plasma acceleration method is also being pursued at the Lebedev Institute. Some of the experimental work here was reported at the Dubna Conference.

Much accelerator theory research is also done at the Lebedev Institute.

The activities of the institute are primarily concerned with the study of basic accelerator design. One of the major past efforts was the design of the 10 BeV accelerator at the Joint Institute. At present the projects appear to be advanced accelerator development such as storage problems, plasma acceleration, and FFAG. No large accelerators are under construction or development. Recent efforts of the institute have been concerned largely with attempts to bring into operation a 30 MeV alternating sector FFAG synchrotron similar to the MURA model. The accelerator has not yet operated because of difficulties at injection.

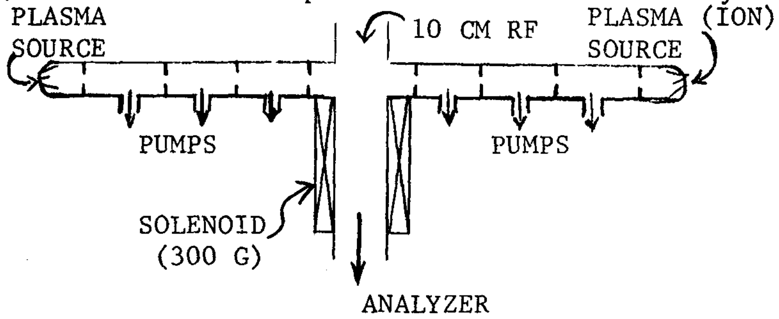
The current situation at the 30 MeV FFAG is as follows. The magnets are in place but the "nonscaling pole" is not complete. The current regulation problems caused by choosing the magnet back leg too small have been solved. The vacuum chamber which employs diffusion pumps is in place. The injector is an improved Kerst-type gun with good optics and sufficient current but with no electrostatic deflector to provide a narrow septum thickness. The mounting and positioning mechanism of the gun is elaborate and well done. The RF station is constructed and delivered but not yet installed.

The RF system actually consists of two separate RF systems, a low power system to accelerate the electrons from injection to roughly 1 Mev, and a high power system to accelerate them over transition to 30 MeV. The latter system produces some 2 kv per turn and utilizes a cavity similar to those on the MURA 50 MeV electron synchrotron. In view of the very high accelerating voltage, it would appear that high intensity through high repetition rate (possibly 250/sec) is an objective. The low power system develops one or two hundred volts across the other gap with no cavity, i.e. the gap is driven as a capacitor as on the first MURA FFAG electron model. Both systems had been successfully tested, that is, that they produced the required number of volts over the frequency range of interest.

This accelerator also had provisions for betatron acceleration over the full energy range from injection to final energy. This has not been successful as yet because of excessive flux leakage from the betatron core into the injection energy orbit. However by injecting at the proper time on the core flux wave a beam lasting for a few hundred turns had been achieved. They hope to change to RF acceleration as soon as possible.

The use of radiofrequency acceleration should allow acceleration of the particles to some energy. However, this energy will be considerably less than the nominal design energy (30 MeV) since as yet no shaping or compensation windings have been applied to the nonscaling pole region of the magnets.

The plasma accelerator is a most novel project. Plasma is pulsed into a wave guide and accelerated by the radiation pressure from an electromagnetic wave. The plasma was accelerated to 10 KeV average energy, 50 KeV peak energy. They are now working on better plasma sources (and incline toward Bostick-type sources), and greater purity (pure hydrogen) in the plasma. At the present, the guide is at 10^{-6} - 10^{-7} torr, the spark plasma generator gives 10^{15} - 10^{16} ions of hydrogen, the plasma is confined by a 300 gauss field, about 10^{12} ions are accelerated to about 10^{8} cm/sec. The plasma is formed in 10^{-2} mm Hg of hydrogen. This work was reported at the Conference by Hecker.



The difficulty at the present is that the plasma density is too large. Therefore the mass is too large and the acceleration is small. This work is being done by Rabinovitz.

THE RESEARCH INSTITUTE OF ELECTROPHYSICAL EQUIPMENT - LENINGRAD

Some personnel at the Institute are:

E. G. Komar - Director
Y. G. Basargin - Chief, Isochronous Cyclotron
V. M. Levin - Medical Accelerators
A. M. Stolov - Chief, high field impulse testers
F. G. Zheleznikov - Chief, Injector Section of 70 Bev Accelerator

E. A. Dmitriev
Filipov
O. A. Gusev
I. F. Malyshev
N. A. Monoszon
V. N. Nadgorny
A. V. Popkovich
A. I. Solnyshkov
I. A. Shukeylo
V. A. Titov
A. S. Temkin
V. B. Zalmanzon
G. A. Zeytlenok

THE RESEARCH INSTITUTE OF ELECTROPHYSICAL EQUIPMENT
LENINGRAD

This Institute started in 1946 and has provided (or is providing) the design and components for the three accelerators at Dubna, the 7 Bev proton synchrotron at Moscow, the 70 Bev proton synchrotron at Serpukhov, the 6 Bev electron machine at Yerevan, and 2 Bev linac at Kharkov, together with many 1 to 1.5 meter cyclotrons, and several Van de Graaff generators; some of the latter two types have been made for other countries such as Czechoslovakia and Rumania. No tandem Van de Graaffs have yet been constructed. The Institute is also doing design studies for a 1000 Bev proton synchrotron.

For the Van de Graaffs and small cyclotrons, all the construction, including preliminary design and final putting into operation at the location, is done by this Institute's personnel. However on "experimental" accelerators and large experimental equipment such as bubble chambers, the Institute works in collaboration with physicists at the other Institutes. But for items such as bending magnets, only the bending angle and size is provided by others and the design, procurement and testing is done here. Complete engineering drawings, including those for the required tooling are made here but no manufacturing of the components. However, a new workshop is being constructed and it is expected that after its completion, about 1965, some items will be manufactured here. Staff of the Institute visit various factories where the parts are fabricated and they also supervise assembly at the site. However, they usually do not remain with a machine after it begins operation.

The RIEE has not been building the machines for Budker at Novosibirsk. Although they have built traveling-wave linacs, the RF systems for standing-wave linacs and the Dubna, Kharkov, and Moscow linacs have been done by Mints of the Radiotechnical Institute in Moscow.

This Institute is undergoing quite a sizeable expansion. A new building for dc accelerators is completed, a new building for making RF components is not quite finished, a cryogenic building is under construction where it is planned to have a department making studies on superconducting items, a new cafeteria and several warehouses are planned. There is also considerable thermonuclear work going on and the director expects that the future will see this greatly expanded. Of the staff of about 2,000, half are technical staff and of these 70% are doing research work and investigations and the other 30% are builders of equipment.

For the Serpukhov 70 Bev machine, the ion source and preinjector (this is a 750 kv pulse transformer) are being built here and also the drift tubes for the linac injector. The rest of the linac is being built at Mints Institute (The Radio Technical Institute in Moscow).

The 700 Kev preinjector is certainly an interesting piece of development work. Most of the details known about it are contained in a report by A. I. Solnyshkov, et.al. The beam is reported to have a transverse emittance of π x 25 mm mrad at 400 ma, which would give it a current density within this emittance that is about ten times greater than that of preinjectors at CERN, Brookhaven, and LRL. The most important feature of this design is the use of a plasma expansion cup as large as 10 cm. This is followed by a short accelerating column in which the high gradients and large cross-section are intended to avoid the usual emittance blow-up in other high current preaccelerators. Until now, their emittance measurements have been based on beam cross-section measurements. They are now preparing equipment to measure more precisely the beam characteristics. More detail about the preinjector is given in the section on Serpukhov.

A dc magnet model for a 1000 Bev machine has been built that has an aperture 4 cm by 7 cm (supposedly full-scale), about 60 cm long and of exterior size some 30 to 40 cm on each side. This has had suitable fields up to about 15 kilogauss on the central orbit with $n = 5700$ and the measurements are in a paper on the 1963 High Energy Accelerator Conference Proceedings. Work on this model has been done by Dr. Manoson.

For historical interest, there is an ALPHA thermonuclear machine. Also available is a plasma device with a toroidal discharge chamber. This machine was used to gain knowledge of plasma diagnostic devices. A bank of capacitors was discharged via ignitrons in the primary winding. Total storage 1.5 M joules. With 3 to 5 amps discharges in the plasma electron temperatures of 10^5 to 10^6 °C have been reached. Medium ion temperatures for different ion impurities are 10^6 - 10^7 °C. The plasma configuration is a force-free, quasi-stationary configuration. Pulsing at the rate of 1 to 3 pulses per minute is possible, with pulse lengths of 3 msec. Ion densities of 10^{14} ions/cm^3 were cited, the evidence being the reflection of the 8 mm wavelength. Future plans include improvement of vacuum, improvement of field distribution and the use of neutral hydrogen beams as probes.

Work on very high magnetic fields is being done by Dr. Stolov. A 2 megajoule bank of capacitors is available for pulsing currents up to 10^6 amps. Firing is done via spark gaps which are carefully synchronized. After firing 500 to 1000 pulses the spark gaps have to be serviced. With a one-turn coil 12 cm inside diameter and 14 cm long a field of 100,000 gauss could be obtained. The field rise time is 20 sec of which 70% is due to the coil and 30% is due to inductance in the feed cables. Schematically the circuit arrangement is as shown in Fig. a; also indicated is the firing sequence. The pulse system employed two condenser banks, two coils, and three spark gaps, such that the two banks were dumped into the two coils, and then the third gap fired to short circuit the two coils into one short circuited inductor. This arrangement gave them a one millisecond flat top to the field pulse. A device for the study of the influence of very high magnetic fields on the properties of metals is nearing completion. Two discs of 40 cm diameter and 1 cm apart are connected as shown in Fig. b.

Current feed-in and take-off is radially distributed over both discs, resp. The field as a function of r is also shown in Fig. b. Because the field strength varies in a known fashion as a function of radius, certain properties can be studied as a function of magnetic field with single or multiple discharges at one total current value only. Fields up to 1.5 10^6 oersted are being planned.

Beam current measurements are done in the standard way with both properly biased Faraday cups and calorimetric methods. The grids used in the preaccelerator are of a mesh of about 3/16" x 3/16" with tungsten wires. Penetration factor for this gauze was 90%. Work on RF sources was also being carried out here. Some of this work is carried out by Dr. Zhepakhin who is also concerned with the Serpukhov preinjector. One set-up was for neutral beams for a tandem Van de Graaff system. Duoplasmatron parameters were studied in one set-up without actually using an expansion cup. A Faraday cup was used immediately opposite the ion source hole. With only 800 v across a 1 to 2 cm gap a very weak extraction field was obtained. Nevertheless, it seemed possible to study certain parameters of the duoplasmatron in this fashion.

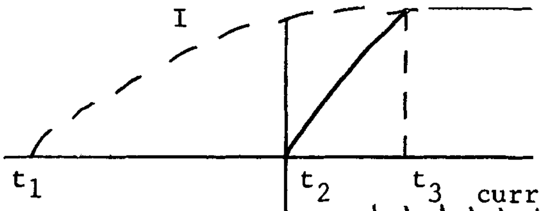
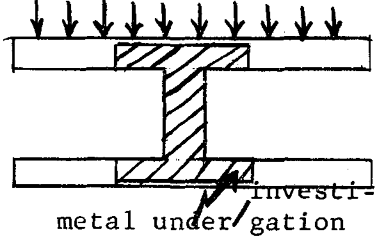


FIGURE a



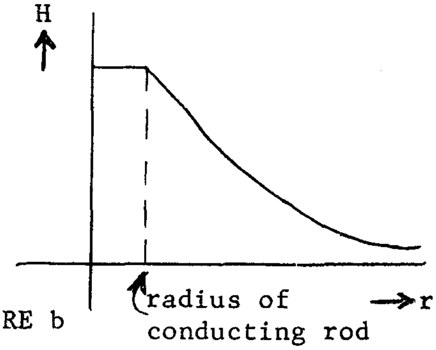


FIGURE b

A group is now set up to do particle-orbit calculations and will use a computer at the Mathematics Department at the Leningrad Academy of Sciences; also a new RF group will start studying such problems. Komar hoped that large-scale design for a super-energy machine would be starting very shortly but there has not yet been any discussion of possible location. In order to get rid of problems of stray fields, he would like to see an injection field of 300 to 500 gauss but this group has not yet considered the question of a linac as an injector. Vladiminsky and Mints also have designs for multi-hundred Bev accelerators which are different from those of Komar.

DISCUSSION

C. Bernardini

How do you measure the stored intensity?

G. I. Budker

The beam intensity was measured by the synchrotron radiation with the aid of a photomultipler. The signal from the photomultiplier was first calibrated with respect to current with the aid of a Rogowsky loop.

C. Bernardini

Can you write down the data concerning the beam of your synchrotron-injector?

G. I. Budker

The beam characteristics of the B2-S accelerator were given in the text of the report.

C. Bernardini

I want to remark that 2 γ bremsstrahlung $(e^+ + e^- \to \to e^+ + e^- + 2\gamma$ dominates over 2γ annihilation $(e^+ + e^- \to 2\gamma)$ when the energy resolution of γ detectors is of the order of 20% (around 500 MeV). As a consequence the monitor problem is not so easy.

F. Amman

How will it be obtained, in your storage ring for electrons and positrons, the vertical height quoted?

G. I. Budker

In the VEPP-2 device, we intended to increase the dimensions of the beam by continuously oscillating it in the electric field of the inflector.

I. B. Enchevich

Did you make a comparative estimate of the cost of the proposed accelerators for a given energy in the center of mass system?

G. I. Budker

An equivalent accelerator for electrons has, in general, not been discussed since it would have a diameter of the order of the Earth's. The comments may only be applied to proton accelerators.

We can imagine such an ordinary 300 GeV accelerator. An ironless accelerator with counter beams has a radius of 2 m. It is obvious that the creation of such an accelerator contains many technical difficulties which, however, are not measured in rubles or dollars.