СИБИРСКОЕ ОТДЕЛЕНИЕ АН СССР
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ

B.F.Bayanov, G.I.Budker, G.S.Villevald,
T.A.Vsevolozhskaya, L.L.Danilov,
V.N.Karasyuk, G.I.Silvestrov,
V.A.Tayursky, A.D.Chernyakin

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A.D.Chernyakin

Institute of Nuclear Physics,
630090, Novosibirsk, USSR

Optimization of the conditions for producing the secondary particle beams (positrons, antiprotons, π -mesons of low- and high energies) has resulted in the studies (Institute of Nuclear Physics, Novosibirsk) concerning the creation of optical devices with large (50÷300 kOe) pulsed magnetic fields and with a wide range of parameters determined by a sort of secondary particles, their energy and also by the requirements on the beam characteristics.

This subject covers two directions: a) creation of the so-called parabolic lenses which are the thin-wall rotation envelopes through which the current flows, their shape provides aberrationless focusing of the particles, in practice, for any angles of collection; and b) creation of the cylindrical lenses made of light metals (lithium, natrium) with the uniform (over the cross section) distribution of current density, these lenses are designed for short focusing of the beams.

1. Electron-Positron Conversion Systems

The optimal formation of a phase volume of the positron beam in the electron-positron conversion requires the minimal size for focusing the primary electrons onto a target until the angles of electron convergence are smaller than those at which the positrons leave the converter. It is also required the aberrationless collection of positrons within the root mean square angle of their exit from the target. In the case of a high enough energy of positrons ($E_+ \sim \frac{1}{2}E_- \gtrsim$ 100 MeV) and optimal target length ($\sim$ 1 radiation length unit), an effective positron source, if the electron beam is infinitely narrow, is characterized by the mean square of the linear exit angle $\langle\theta^2\rangle \cong \frac{125T}{E_+^2}$ and by that of the particle coordinate $\langle r^2\rangle \cong 0.08\langle\theta^2\rangle \cdot T^2 \cdot X_o^2$ where the energy E is taken in MeVs, T (the target thickness) in radiation length units, X_o is the radiation length unit in cm /1/. Thus, a β-function of the positron beam β_o is $\beta_o \cong 0.3TX_o$, i.e. $\sim$ 0.1 cm if the target is made of tungsten. With a finite phase volume of the electron beam, the positron beam emittance is minimal if the β-function of electron beam β_e on the target is equal to the β-function of positron source β_o. This condition requires a power of the lens focusing the electrons be equal to $\pi\varepsilon_e/\beta_o$, where ε_e is the electron beam emittance. For example, if $\varepsilon_e \sim$ 1 cm·mrad, it is $\sim$ 0.035 ster.

At present, the short-focusing cylindrical lenses made of lithium operate at the facilities VEPP-2 and VEPP-3. These lenses are used both for focusing the electron beam onto a target and for collecting positrons. Such a lens is a thin-wall cylindrical tithanium container of spool-like shape at the ends.

On this container the copper cut-in-half bandage is put and the bandage is wound up by a thin steel wire. In addition, the bandage is isolated from tithanium by a layer of electrotechnical mica and impregnated with epoxide resin under pressure. On a special bench the container is filled with melted lithium under the pressure of several hundreds atmospheres, that provides a good electrical contact with tithanium. As a container material, tithanium is chosen because of the high ohmic resistance and corrosion hardness relative to lithium. At the lens sides lithium is coated by protecting berillium foils of 0.2 mm thickness, after that the lens is inserted into the coaxial cylindrical current-connections which are compressed through the berillium foil to tithanium, thereby providing axial compression of the construction and also electrical contact on the lens sides throughout. The current-connections have the holes necessary both for the exit and entrance of the beam. These holes in the lenses with up to 50 kOe fields remain open but at higher fields they are closed with the conic berillium plugs which protect the foil from flexion when lithium is pressed out under a magnetic field. The lens is supplied by the unipolar pulsed current of sinusoidal shape. The pulse duration is determined by the optimal ratio between the skin layer and the lens radius r_0 at which, on the one hand, a sufficiently uniform distribution of current density over the cylinder cross section is established for its maximum and, on the other hand, the lens heating is minimum. Close to the optimum is the relation $\delta/r_0 \sim 0.7$ at which the current density is uniform over the cross-section with an accuracy better 0.5%, while the heating temperature is not 1.5 times higher than the surface heating in the skin case ($\delta \ll r_0$) $\Delta T = \frac{H^2}{8\gamma c}$, that

is $\Delta T = 72°$ for lithium at $H = 100$ kOe.

As to optical properties, the cylindrical lenses are inherent of aberrations due to non-uniformity of the current distribution along the cylinder crosssection with a pulsed-current supply, side effects, and spherical aberrations. At $\delta/r_0 = 0.7$ the first aberration gives the root mean square increment of the coordinate in the focus $\sqrt{\langle \Delta r_{ab}^2 \rangle} \cong 4\cdot 10^{-3} r_0$. The side effect results in a non-uniform current distribution at the input places even in the case of their axial symmetry. This leads to a dependence of the effective length of the lens on the distance to the axis. The aberration increment of the angle of particles at the edge is maximum in the extreme case of an infinitely thin current-connection and is $\langle \alpha_{ab}^2 \rangle = 4\cdot 10^{-3} \frac{\alpha_0^2 r_0^2}{Z^2}$ where α_0 is the trajectory bend angle at a maximum radius r_0 on a length Z. The root mean square angular increment, because of spherical aberration, is expressed, depending upon the collection angle θ_m, as $\sqrt{\langle \alpha_{ab}^2 \rangle} = \frac{\xi}{6}\sqrt{\frac{l}{F}}\,\theta_m^3$ where ξ depends on the ratio l/F (l is the lens length, F is its focal distance). At $l/F \ll 1$ the value of ξ is maximum and equal to 1/2.

A general view of the electron-positron conversion unit is given in Fig.1. This unit consists of a pair of lithium lenses with current-inputs and adjustment systems. The lenses are supplied by the current pulses of $T_0 = 50 \div 100$ μsec duration and their amplitude J_0 is 50÷100 kA from the step-down transformers through flexible current-connections. The lenses are mounted in the current-collecting bars placed on the coordinate mechanisms. The coordinate mechanisms enable one to adjust mutually the lenses at a long distance with an accuracy of $\sim$ 0.05 mm.

The main parameters of the lenses are listed in the Table.

Energy E(MeV)	Focal distance (cm)	Length of a lens (cm)	Aperture 2a(cm)	Maximum field H (kOe)	Current amplitude (kA)	Pulse duration (sec)	Scattering angle (mrad)
E=430	5.3	1.7	0.6	63	95	120	4.4
E=250	4	1.7	0.5	40	50	90	7
E=270	1.7	1.7	0.5	100	125	90	8
E=120	1.4	1.1	0.6	110	165	120	12.6

These parameters provide the conversion conditions close to the optimum in the case of producing the positrons within the above ranges of energy.

2. An Effective System of Proton-Antiproton Conversion

With the analogous principle of focusing, i.e. with the use of a magnetic field of direct current, develeopment of focusing systems to optimize the conditions for producing the antiproton beams injected into a magnetic ring requires a number of more complicated technical problems to be solved. This is due to high energy of the primary and secondary beams, large angles of production of antiprotons and also to a large longitudinal size of a target which is necessary for an effective use of the proton beam, that results in a great magnitude of the root mean square emittance of antiprotons. The emittance depends linearly on a target length $\varepsilon_{\bar{p}} \cong \frac{\langle\theta^2\rangle l}{2\sqrt{3}}$. Here $\langle\theta^2\rangle$ is the mean square of the angle of production of the antiprotons and it is equal to $\langle\theta^2\rangle \cong \frac{2 m m_\pi c^2}{p^2}$ (m and m_π are the masses of the proton and π -meson, respectively). So, for the antiprotons with the momentum p = 2 GeV/c at a 7 cm length corresponding to the maximum exit from the target made of tungsten, the antiproton beam emittance is $\sim$ 140 π rad/cm. This is significantly larger than the acceptances of the antiproton storage rings under development. The capturing coefficient in the acceptance which is ε in both transverse directions depends on a target length l as $F \sim \frac{\varepsilon}{\langle\theta^2\rangle} exp\left(-\frac{l}{\lambda} - \frac{1.6\varepsilon}{l\langle\theta^2\rangle}\right)$, where λ is the length of inelastic nuclear interaction and reaches its maximum at $l = l_{opt} \cong 1.3\sqrt{\frac{\lambda\varepsilon}{\langle\theta^2\rangle}}$. In the existing projects /2,3/ this is much more less than $7 cm$. In this case, the root mean square of an effective antiproton source located in the middle of a target, $\langle r_{\bar{p}}^2\rangle \cong \frac{l_{opt}^2\langle\theta^2\rangle}{12}$, turns out to be small and, as is the case of electron-positron conversion, the problem arises of focusing the primary beam onto a size equal to fractions of a millimeter.

With a small value of the antiproton beam emittance nuclear efficiency of a target can be increased through the use of a strong focusing of the antiprotons in the conversion process. In this case, the emittance of the antiproton beam becomes independent of a target length and this length can be increased up to a value comparable with $7 cm$. One of the ways for carrying out such a focusing is to use several short targets and to place the very strong cylindrical lenses in between. These lenses transfer an image of the beam from one target to another one. Then the transverse phase volumes of antiprotons from all the targets superimpose and their total emittance does not exceed the emittance of the beam from one target, so that the collection efficiency in a first approximation grows proportionally to the number of target. For example, in the project /3/ (p = 1.8 GeV/c, $\Delta p/p$ = $\pm 2.5\%$, $\pi\varepsilon$ = 8 mrad/cm) the optimal cascade target contains 4 targets, each of 3.5 mm length, with the 10 cm cylindrical lenses of 1cm in diameter. The lenses occupy a whole gap between the targets and their field on the surface is 300 kOe. Two factors limits the length of the system: an increase of the antiproton emittance due to chromatic aberration and also a necessity to obtain the proton beam of small size along the whole length of the system.

Unlike the considered above cylindrical lenses whose fields are ranging within ~ 100 kOe when the average temperature of lithium is lower than the fusing temperature ($T_{mLi}= 186°$), when designing the lenses with ~ 300 kOe fields a number of serious problems arise which are due to heating of a cylinder ($\Delta T \sim 800°$ per pulse). One of the problems is to design a closed sealed system which is capable of undergoing huge mechanical loads resulted from the volume expansion of metal during pulse heating and from the magnetic field pressure. The second problem is connected with heat removal since at the indicated temperatures about 2 kJ are absorbed in each cm^3 and to remove such an energy in the certain design of the lens even with the ~ 0.1 Hz cycle frequency seems impossible. We overcome these difficulties by using, as a conductor, the molten metal fastly pushed out from the system after every pulse and circulating in the closed circuit with heat exchanger.

The lens design is given in Fig.2. Two thin-wall tithanium tubes with the flanges at the ends are pressed in the steel cylinder and then they are pressed vacuum-tight on the tithanium tube with internal diameter equal to that of the lens. All the tithanium elements are coated with an insulating oxide layer so that the steel cylinder has a reliable thermal-resistant insulation at a 1 kV voltage. Two side flanges constrict tighten the system in the axial direction with the help of a ring hydraulic bag under the pressure of 1000 atm and unclamping the metallic packings these flanges allow a simultaneous sealing of the new container and axial-symmetric current-input to molten metal filling the system. The lens is inserted into the coaxial current-input and is clamped to the contact surfaces by the same hydraulic bag. This bag provides both the axial and radial clamping of the intermediate contact element. As in the previous construction, the cone berillium plugs are pressed in the side elements at the points of exit and entrance of the beam. The operating volume of the lens is communicated with the special cavities which have a much larger volume compared to that of the heating portion of the metal. This provides the damping of pulsed pressure due to volume expansion and a magnetic field. The internal lens volume is connected with the molten metal circulation system which contains the pulse electromagnetic pumping of coaxial design, heat-exchanger, devices for producing preliminary pressure and for heating the molten metal. The time necessary for a full replacement of the metal in the operating lens volume is less than 0.1 sec and can be shortened by increasing a power of the pump. Hence, the frequency of operating cycles of the system is determined by the power of auxiliary equipment: the pump, heat-exchanger, pulsed generator etc.

As a metal, we use the molten natrium whose fusing temperature is lower than that of lithium ($T_{m\ell t}= 97°$) and whose resistance is 2.5 times lower after melting ($\rho_{Na}(97°) = 9.6 \cdot 10^{-6}\ Om.cm$), that allows a proportional decrease in both the pulse duration and reactive power of the pulsed generator. The lens is supplied with the unipolar current pulse (its duration is 250 μsec and the amplitude is 750 kA) from the step-down transformer with the transformation coefficient N = 10. The 30 kJ capacitor battery is discharged in the primary circuit of this transformer through the system of tyristor switches in series and parallel connections.

Such the lenses are assumed to be applied to focusing the beam onto a target and also to intermediate focusing the antiprotons onto a cascade target. In the latter case, these lenses are placed in the same current-wrapper but separated between each other with the flanges wherein the targets are mounted. The lenses are on in series.

3. A Parabolic Lens For Collecting the Antiprotons from a Target

The parabolic lenses are optic devices most suitable for powerful collection of the secondary particle beams from a target and their phase volume can be transformed in a shape convenient for transportation by the paraxial systems and for matching with the storage ring acceptance /4/. If the current and energy of the particles are given, the shapes of the current surfaces of the lenses are due to the absence of spherical aberrations and a linear dependence of the particle exit coordinate on an entrance angle at a point source. These conditions provide the minimum distortion of the beam emittance at a non-point source. In this case, distortion of the beam emittance is mainly caused by scattering in the walls and its influence can be reduced to the minimum if the lens is made short-focusing so that the scattering angles will be smaller than the phase angles in the beam $\Delta\alpha$ on the lens surfaces, i.e. $\sqrt{\langle\alpha^2_{scatt}\rangle} < \Delta\alpha = \frac{\Delta r}{l}$, where Δr is the source semi-size, l is the distance from the source to the point of intersection with the lens surface. At a given energy the focal distance can be made shorter if one can increase a length of the lens and also the magnetic field up to the ultimate value determined by the mechanical strength of the lens.

The lens created for focusing the antiprotons with the momentum of 2 GeV/c, linear collection angle $\theta_m = \pm 0.18$ rad and focal distance $f = 20$ cm is an example of such a lens. The lens length is 25 cm, the entrance surface is barrel-shaped, the diameter of the narrowest part, the neck, is 1.6 cm. With the indicated collection angle this corresponds to the particle losses on the neck which are less than 5%. The maximum field on the lens surface is 140 kOe. The lens is manufactured from aluminium alloy D16T or from berillium and the thickness of the lens walls is varied with its length from 1 to 3 mm, so that the average parth of particles in the substance is ~ 2 cm and the corresponding angle of multiple scattering is ~ 3 mrad. The thickness of the lens walls was chosen according to the calculation results and experimental studies of their mechanical properties with a given geometry of the lens, which are confirmed by the operating tests of hundreds thousands of pulses /5/. The lens is supplied by the current pulse with an amplitude $J_o = 550$ kA and duration ~ 100 μsec through the step-down transformer in the primary circuit of which a 55 kA current is commuted by the system of tyristor switches.

Water cooling of the lens body is carried out with two methods. At a cycle frequency of ~ 0.2 Hz the water is pulverized on the internal surface of the lens. At a frequency of up to 3 Hz, a more intensive cooling system is used, namely: two aluminium envelopes with the walls of 0.5 mm thick are inserted into the lens. These envelopes have the same shape as that of the lens surface and the gap between them and the lens is 0.5÷1 mm through which a water flows. The lens is inserted into the coaxial wrapper (Fig.3) and connected with it with the help of ring hydraulic clamps under the pressure of 1000 atm which provide a reliable, long-distance controlling contact and enable one to replace immediately the lens in the wrapper in the case of its breaking.

The analogous technique of long-distance disconnected hydraulic contacts is applied in all the elements of the proton-antiproton conversion system which operates at a very high level of radiation. This gives the possibility, if the breakdown occurs, to disconnect, evacuate and replace any element at a long distance. To this end, the universal coaxial inputs /6/ have been designed which connect each element with the stationary current-connections of the transformers through hydraulic contacts and, if pressure is absent, the long-distance adjustment is allowed.

4. Development of the Methods of Wide-Angular Beam Focusing

The absence of spherical aberration is entirely due to a shape of the current surfaces of the parabolic lenses. It may be chosen so that the spherical aberration is completely eliminated and, in practice, the lenses with any angles of collection may be created. The possibility to vary a shape of the profiles makes it possible to use another feature of such lenses, namely: if a ceratin non-linearity of focusing is given, one can redistribute the transverse and longitudinal components of the phase volume, that leads to reducing the transverse phase volume of the

beam within some limits /4/. Such a system with wide-angular non-linear focusing can be examplified by the lens for collecting low-energy positrons corresponding to the maximum of conversion factor at energies close to the ultimate ones (10÷20 MeV for heavy targets) and have the exit angle from the target of the order of one steridian. Due to scattering, application of similar lenses at these low energies is limited. However, the small focal distance and a special shape of profiles enable one to reduce the emittance increment to the minimum.

The lens with a 0.5 rad angle of collection (Fig.4) which is based on this principle has the focal distance of 1.5 cm, its entrance surface is strongly elongated to the source (nearly ellipsoide) and the plane exit surface. The lens is made of berillium and has a 0.2 mm thickness of the walls, so that the average path of the particles in the substance is ~ 1 mm. At an energy of 20 MeV this corresponds to the scattering angle ~ $3.5\cdot10^{-2}$ rad. Since the lens entrance surface is close to the source, with the indicated energies the phase angles which are determined by the spread of coordinates in the source are approximately equal to the scattering angles on the lens surface. Hence, the emittance increment of the beam does not exceed ~ 1.5 because of scattering and, in practice, is compensated by its decrease due to non-linear focusing, which makes up in a given geometry also ~ 1.5. At an energy of 20 MeV the lens should be supplied by a 100 kA current, that corresponds to the magnetic field H_m = 130 kOe on the neck of 3 mm in diameter. Mechanical strength of such thin-wall envelopes at so high fields is due to their properties of inertia in dynamical regimes of loading if the current pulses are very short (microsecond). These properties have been studied experimentally in the previous work devoted to the parabolic lenses /7/. This lens is supplied by the current pulses of τ = 0.8 μsec duration from the toroidal transformer of cable construction with N = 6 and very large scattering (Fig.4). At the voltage V_1 = 20 kV the current (J_1 = 17 kA) is commuted in the primary circuit by the generator on hydrogen tyratrons TGNI-1000/25 operating in the croubar regime.

To collect the π-mesons of low energies which are produced nearly isotropically within the 50-100 MeV range in the total splid angle, a much wider angular focusing is required. Further development of the parabolic lens principle enables one to create the focusing systems analogous to a parabolic mirror and capable of collecting the particles in a solid angle close to 4 π rad.

The example of such a system is the lens with the collection angle of 10 ster, which has been developed in the Institute of Nuclear Physics (Novosibirsk) /8/. This lens transforms the beam produced by the point source (its angles are $30^\circ \leq \theta_m \leq 150^\circ$) into the beam converging on the axes of the system at the angles of ±25° at a 65 cm distance from the source (Fig.5).

The entrance surface of the lens is of a shape of the cone on the axis of which the source is located, whereas the exit one has such a shape which provides the focusing conditions. If the energy is 30 MeV (pc=100 MeV/c), the necessary current is 1.4 MA, the maximum field of the narrowest part of the lens is 112 kOe. The lens body is manufactured from thermal-treated aluminium alloy and, for mechanical strength, the maximum thickness of the wall of entrance surface is 5 mm, the exit one is 2 mm. Scattering in the walls leads to appearing an additional size in the image plane. With the above parameters the root mean square radius determined by scattering is $\sqrt{\langle r^2 \rangle} \cong$ 5 cm. As the lengthy target located on the system axis serves as a source, its longitudinal size is transferred in the image plane with an enlargement approximately equal to the ratio of the angles of collection to those of convergence, $u \approx 2.4$. The image size coincides with the root mean square one at the target length l = 2 cm, so that, in practice, at large sizes of a target the scattering can be neglected. The drift space behind the lens is restricted by a cone hole in the shielding and a cone tungten plug which absorbs the main flux of background particles behigh the target and is a force element of the construction. This element protects the lens body from longitudinal displacement under the magnetic field. The pulse spectrum in the image is ranging within the interval $\frac{\Delta p}{p} \sim$ ±15% because of the drift space behind the lens formed by cone surfaces.

A general view of the lens with the current-wrapper, transformer and cooling system is given in Fig.5. In our cooling system a water flux flows through two-layer body. When the lens is supplied with the current pulse of τ = 100 μsec duration, such a system allows the operation with up to 10 Hz cycle frequency. The inductance of the lens is ~ 50 cm, its power supply is W = 50 kJ, the active losses are ~ 20 kW at ~ 10 Hz frequency. The lens is supplied from the toroidal transformer of cable construction with the transformation coefficient N = 10. In the primary circuit of this transformer the current (J_1 = 140 kA) is commutated by a switch consisting of a great number of tyristors on in series and in parallel. The analogous generator has been designed in the INP and at present one of its sections is being tested which comprises 24 parallel branches, each consists of 10 tyristors TD-200 in series connection.

The construction under discussion is a sketch project of one feasible variant of a similar system with the extremely high parameters (a field, current, thermal loads) which can be decreased in the case of choosing the parameters of certain devices. The up-to-date level and the experience dealing with strong pulsed magnetic fields ($\gtrsim$ 100 kOe) and high pulsed currents ($\gtrsim$ 1 MA) enable one to choose the parameters of fields and currents for such systems within the above ranges without fearing principal technical difficulties.

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FIGURE CAPTIONS

Fig.1 A general view of the conversion unit: 1 - tithanium container, 2 - copper bandage, 3 - steel wire, 4 - lithium, 5 - current-connections, 6 - berillium plugs, 7 - flexible current-connections, 8 - current-collecting bars, 9 - coordinate mechanisms.

Fig.2 The lens with molten metal: 1 - steel cylinder, 2 - composed tithanium tubes, 3 - tithanium cylinder, 4 - side sealing flanges, 5 - hydraulic bag, 6 - molten metal, 7 - berillium plugs, 8 - coaxial current-wrapper, 9 - damping cavities.

Fig.3 The parabolic lens: 1 - the lens body, 2 - thin-wall envelopes, 3 - coaxial current-wrapper, 4 - hydraulic clamps, 5 - coaxial current-connection, 6 - hydraulic contacts, 7 - stationary current-connections.

Fig.4 The lens with transformer: 1 - the lens body, 2 - transformer, 3 - primary winding outputs, 4 - magnetic circuit, 5 - grip slamps of contacts, k - converter.

Fig.5 A general view of the lens: 1 - transformer, 2 - coaxial current-wrapper, 3 - exit surface, 4 - shielding, 5 - current-connection, 6 - contact grips, 7 - entrance surface, 8 - target, 9 - tungsten plug, 10 - water cooling body.

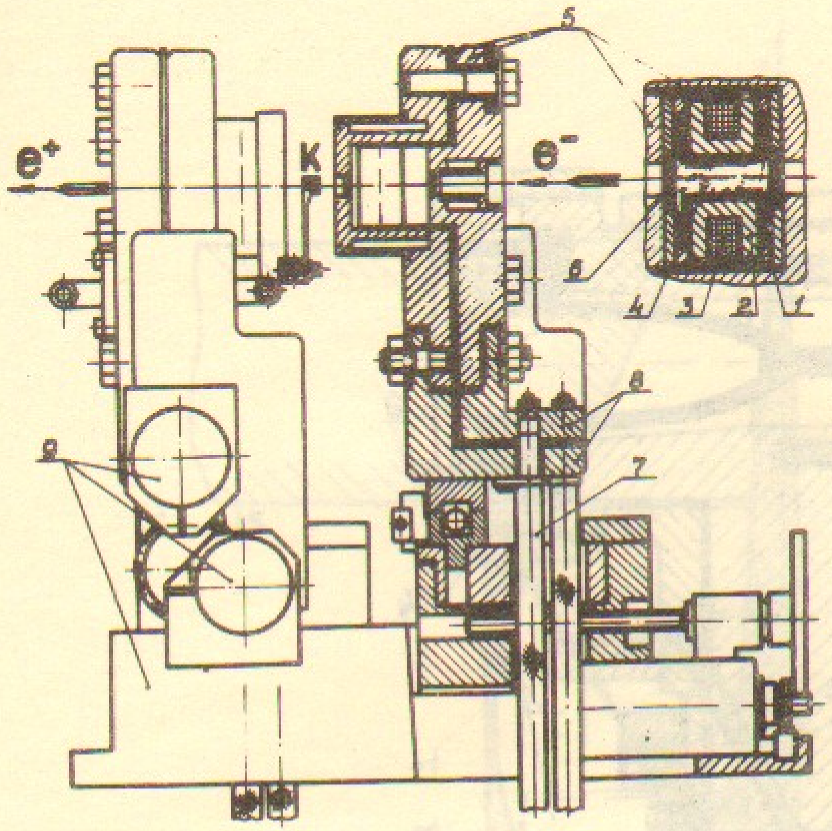

Fig. 1.

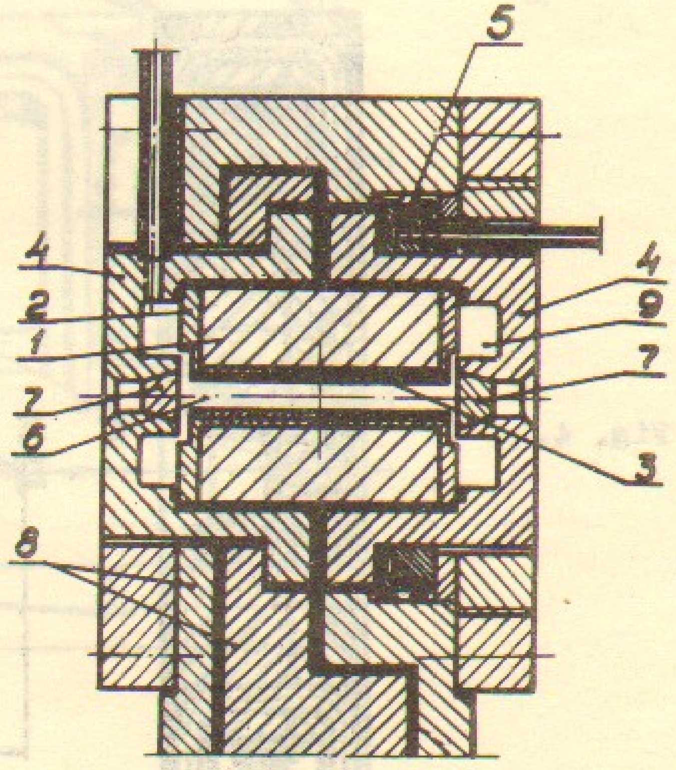

Fig. 2.

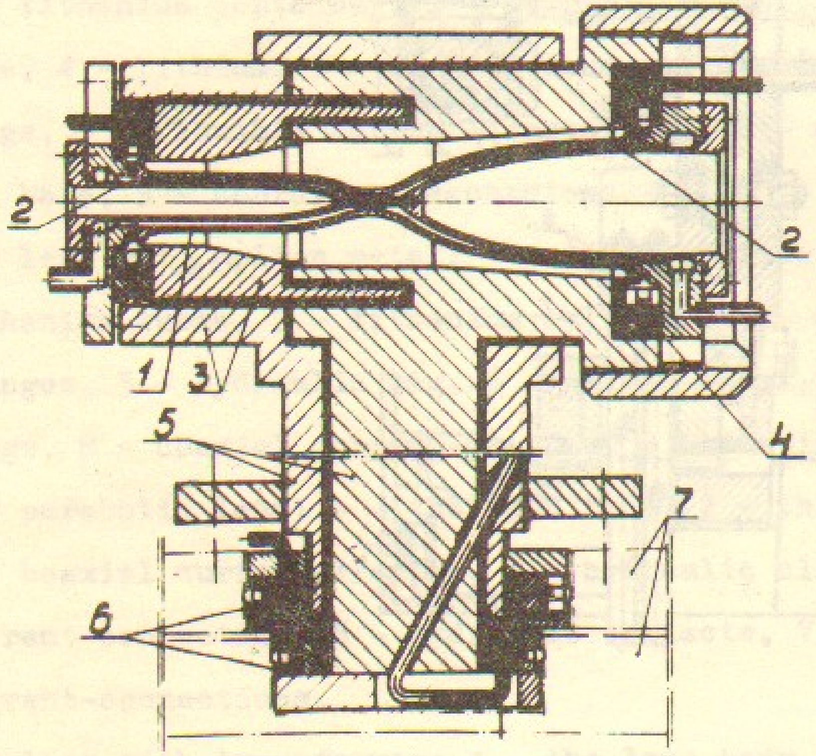

Fig. 3.

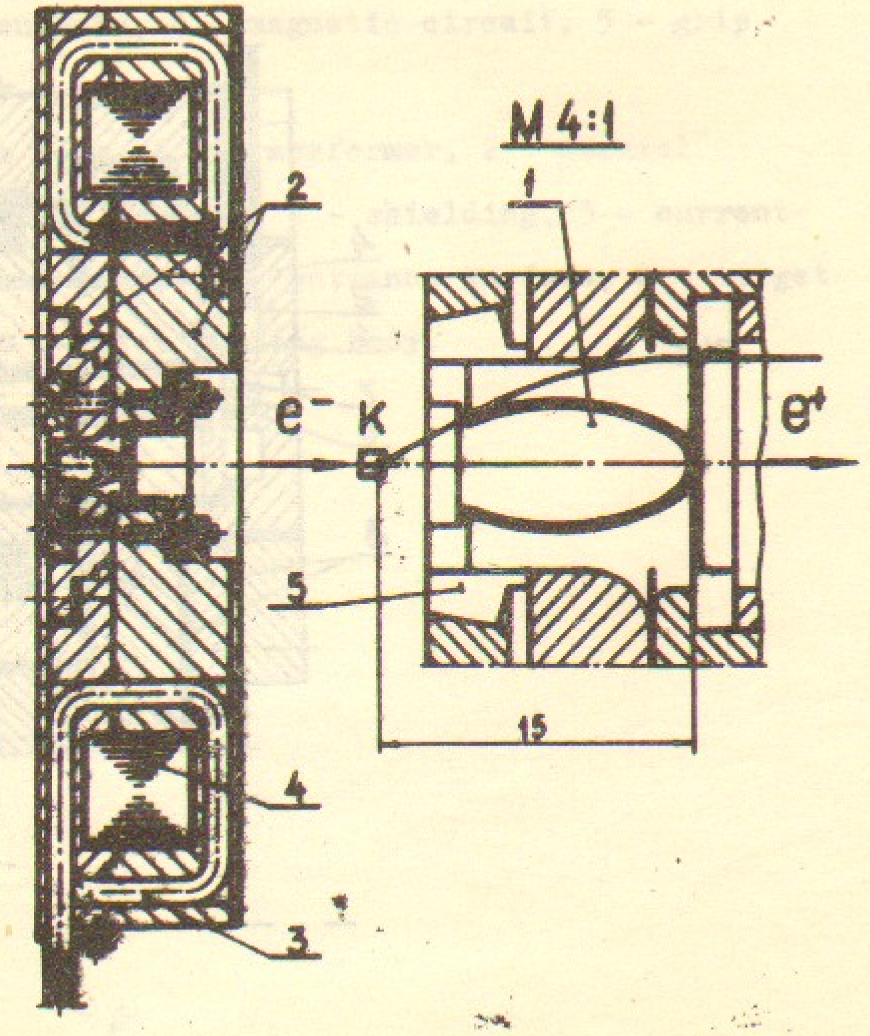

Fig. 4.

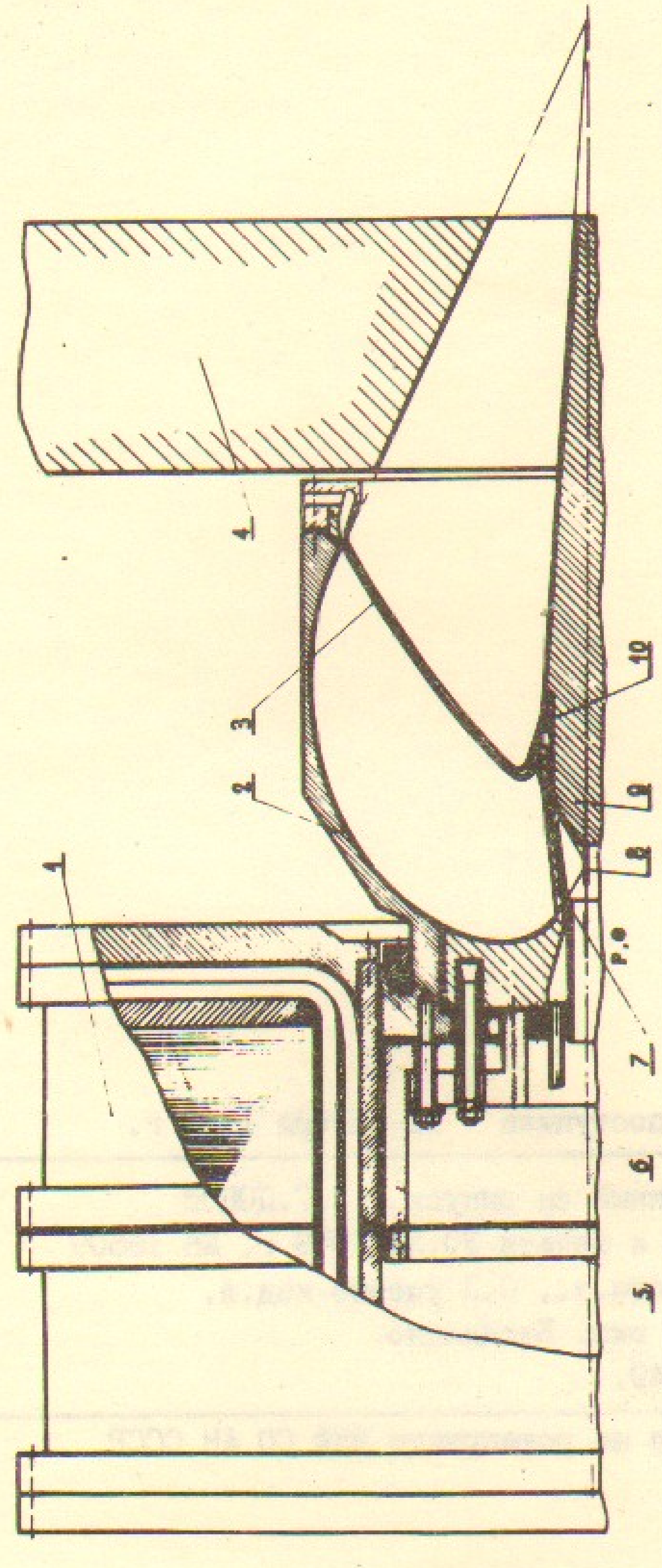

Fig. 5.