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PROBLEMS OF INTENSE SECONDARY PARTICLE BEAMS PRODUCTION

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Problems of Intense Secondary Particle Beams Production*)

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ABSTRACT

Discussed are the production problems of intense beams of secondary particles: positrons, antiprotons, and π- and K-mesons (to form the neutrino beams). Among these are the problems to provide the optimal focusing onto the target for primary beams and to collect the secondaries within a solid angle close to the production angle. At present the most effective systems for such a focusing are strong-focusing lenses of solid and liquid lithium. Considered are the desings based on the pumping of liquid lithium through the lenses which are intended for positron collection in a linear accelerator operating at a high repetition rates, as well as the parameters and the specialities of large lithium lenses used to collect the antiproton target stations. New problems dealing with the formation of the neutrino parents beams at TeV-range accelerators (Tevatron, UNC) and the designs of large-diameter solid- and liquid-lithium lenses intended for this purpose are considered as well.

The important problem one faces by the work with an intense primary beam are the heat removal and the protection of the target against the thermal failure at high densities of energy release. To solve the problem of heat removal the creating of mobile solid and jet liquid-metallic targets is suggested. To eliminate the target failure during the beam spill the scanning of primary beam on a target, or rarid exchange of the target substance are considered.

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In the optics of beams of secondary particles, three kinds of problems can be defined for which obtaining of a beam with maximum intensity is most urgent and requires the creation of special focusing systems with extremely high magnetic fields. The first problem involves systems of electron-positron conversion for which the need has recently arisen to attain a conversion factor above unity as, for example, in the projects of the positron sources SLC [1] and VLEPP [2] (in the latter case, a high degree of polarization, $P \gtrsim 0.6$, of the electron and positron beams is required as well). The second kind of problem is associated with an effective generations in the target stations of antiproton storage rings. In this case, it is necessary to achieve the maximum brightness of the source, which provides a high phase space density of antiprotons with the limited acceptance of a storage ring. Finally, the most complicated focusing apparatus is required for neutrino experiments, where the purpose is to ensure the most effective formation of a beam of neutrino «parents», π and K-mesons, in a broad energy range.

In all the above cases the intensity of the primary beam is a determining factor. In view of this, its focusing on a target of size unavoidably leads to a heavy thermal load of the target, so that the optimization of the secondary beam generation turns out to be directly connected with the thermal target problems.

In the present report we treat a few variants of the solution for these problems, using lithium lenses and utilizing liquid metals both in focusing elements and target devices.

1. SYSTEMS OF ELECTRON-POSITRON CONVERSION

In the conventional scheme of generating intense positron beams by converting high-energy electrons into low-energy positrons, which involves achieving a maximum output from a target, followed by further additional acceleration in a linac with an accompanying magnetic field, the basic problem is an effective quarter-wave transformation of the emittance of a positron beam, i. e. the transformation of its phase ellipse from small coordinate and a large angular sizes to a small angular spread. This is required for its matching to a paraxial focusing system accompanying the initial stage of acceleration. One should mention that the system of initial beam focusing should satisfy two conditions: a) to collect the positrons in a maximum angle of about ±0.6 rad corresponding to the r.m.s. angle of escape from the target at low energies and b) to transform the beam emittance in a short distance from the target, to avoid an increase of the longitudinal size of the beam, which is due to a large angular divergence of the beam, for its successful additional acceleration in the short-wave sections of a linac with a maximum rate of acceleration. These conditions can be satisfied only in systems with a strong magnetic field; for example, in the SLC project a solenoid is used with a longitudinal field equal to 6 T at the target and quadratically decreasing along the axis for a distance 10 cm. For the 33 GeV primary beam this provides a coefficient of positron collection of about 2, for the acceptance of the damping ring. To solve this problem, it has been proposed to employ, in the VLEPP conversion system, the most effective focusing system with a transverse-to-axis axisymmetric magnetic field — a short lithium lens of about 1 cm long with the gradient $G=200$ kOe/cm placed directly at the exit of the conversion target. In the project under discussion the generation of polarized electrons and positrons with a polarization degree of about 0.65, and a conversion factor of over unity, is assumed to be performed by impinging, on a target, the polarized γ-quanta produced in a helical undulator of about 150 m long. The primary beam of electrons (positrons) with an energy of 150—200 GeV passes through this undulator and deflects from the axis of the system. After the target, the spectrum of positrons is maximum at 20 MeV and the appropriate angle of multiple scattering in the lens substance, $\sim 5\cdot 10^{-2}$ rad, does not lead to a substantial increase in the beam emittance. The analysis in Ref. [3] concerning the aberration properties and the scattering shows that similar lithium lenses can be efficiently used for the transformation of the beam emittances directly near the target within the 10—20 MeV range (corresponding to a high phase density of positrons) at collection angles up to 0.6 rad, unattainable in systems with a longitudinal field.

To extend the possibilities of applying similar systems in positron sources of linear accelerators whose repetition frequency reaches hundred Hz, we have solved the problem of heat removal from the lens by using liquid lithium pumped through it as the current conductor. With a view to creating liquid lithium systems operating in the real conditions of an accelerating installation, work has been initiated on the creation of a conversion system for the positron source of the Kharkov linear accelerator LUE-2 operating a 250 MeV primary electron beam at a frequency of 100 Hz. In this case, a cone-shaped lens has been used. For the same optical characteristics this allows the decrease of the current amplitude and the average released energy by a factor of 1.5 (Fig. 1) [3].

At an intensity of the LUE-2 electron beam of about 10^{13} particles per second, the pulse heating of the target is insignificant, and to remove an average power of about 0.5 kW the target is placed directly in the inner volume of the lens and is cooled by liquid lithium. The flow of lithium reaches symmetrically the operating part of the lens, from the toroidal volumes on its faces. Liquid lithium circulates in a closed circuit consisting of the lens operating volume, two long tubes connected to at one end to this volume and, at the other end, to the electromagnetic pump outside the vacuum chamber. Current is supplied to the lens by a flat three-conductor strip line transforming into coaxial cylinders at the place of entrance into the vacuum chamber. Here there is a bellows connection, allowing the lens to be shifted in the transverse direction. The external, non-vacuum part of the lithium circuit, including the pump, is located on a movable plate connected to the current input. The lens is supplied by current pulses of 50 μs duration with an amplitude up to 60 kA from a matching transformer located on the same plate. The initial heating of the lithium circuit is performed by a special heating system. With the lithium melted in the whole volume, it starts circulating, and at a frequency of 100 Hz and at the nominal current the power of about 1 kW released in the operating volume of the lens is uniformly distributed throughout the system, where an equilibrium temperature of about 230°C is establiched.

The construction is radiation-resistant; the insulators in it are ceramic and insulating oxide coatings.

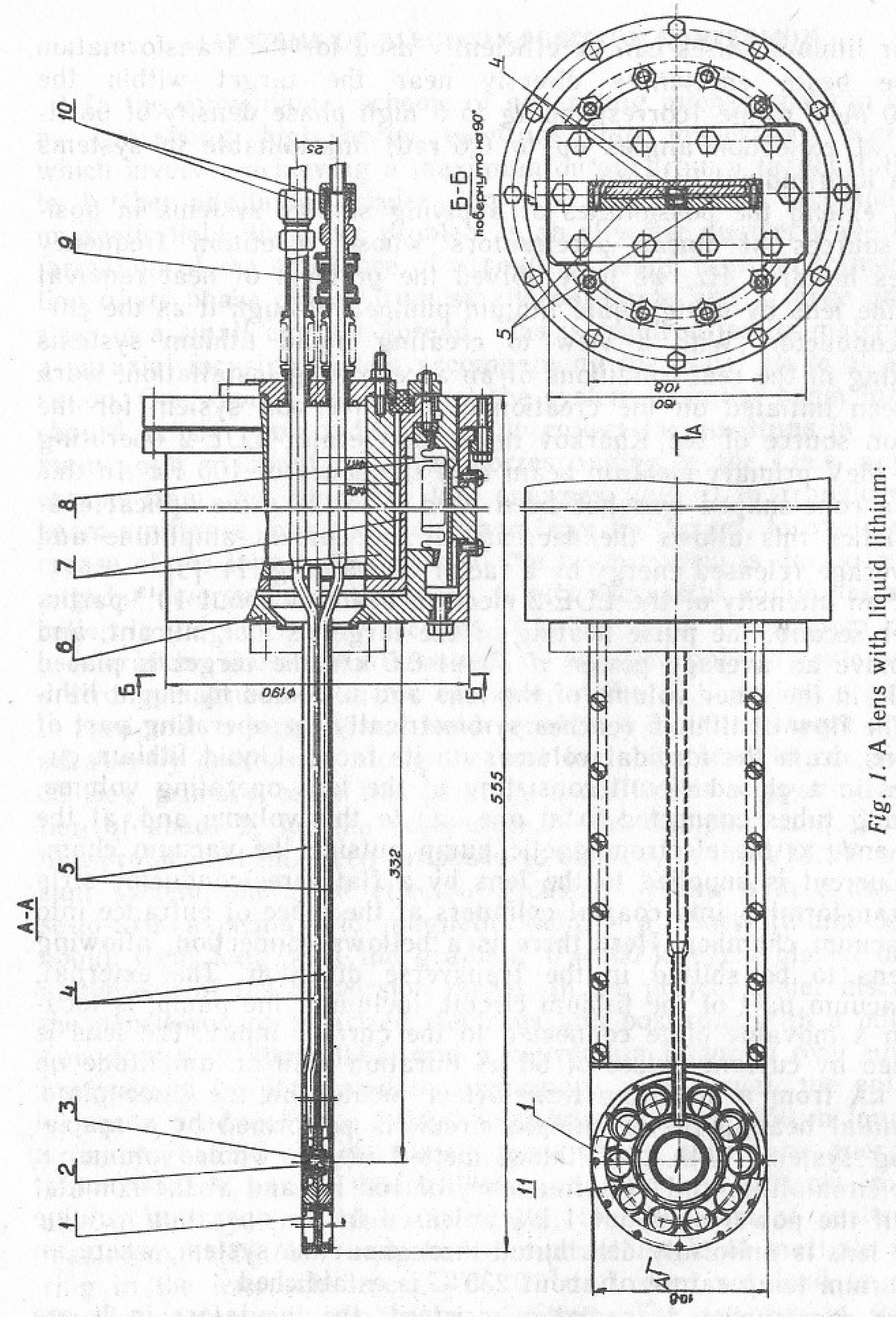

Fig. 1. A lens with liquid lithium: 1—cams of contact clamps; 2—conic lens; 3—W target; 4—titanium tubes for lithium supply; 5—flat current input; 6—vacuum chamber; 7—coaxial section of the current input; 8—bellows; 9—ceramic insulators; 10—conic sealings; 11—case of eccentric clamps.

In the VLEPP conversion system the thermal regime of the target is determined by the specific features of the generation of pairs by a pure beam of γ-quanta, for which the density of energy release grows practically linearly with the longitudinal coordinate in the target. Computer simulation [4] shows that with the following parameters: 150 GeV energy of the primary beam, 150-cm-long undulator with $\lambda=0.7$ cm and $P_\perp^2=0.1$, the density of secondary particles at the exit of a W target of 0.5 radiation length optimal length constitutes about 5 pairs in the whole spectrum in a circle of about 0.5 mm radius per one in the primary beam. At 10^{12} particles in a pulse in the primary beam and at a frequency of 10 Hz, the total power, released in the target, is 50 W, while the energy density at the exit achieves $q=400$ J/g and the temperature is $T\sim3000$°C during one pulse; this exceeds the magnitude permissible for repeated operation of the target. The first step in the solution of this problem is to eliminate the possibility of multiple arrival of the beam at one place by shifting the target. In this case, the target can be made, for example, in the form of a disc. A similar variant of the rotating target with intense water cooling has been designed for the SLC positron source, thereby solving the problem of removal of a large (about 5 kW) average power, by spilling the electron beam onto the target.

We have another engineering solution. In our variant the target is cooled by liquid metal, the gallium-indium alloy, and the metal is not only a heat-transfer agent but it sets in rotation the target, which is a freely-rotating disk about 50 mm diameter (Fig. 2). The target chamber is mounted on the input side of the lens so that the target exit is at a distance of 1—2 mm from its edge. It is located in the vacuum chamber with the lens and is connected a small pump through a long transport tube, the pump being outside the vacuum system. If the target exit surface is destroyed during long operation or from a single pulse (which will unavoidably occur with increasing energy of the primary beam), it is possible to proceed, without change of the construction, to a variant with the use of a liquid-metallic jet target (for example, a mercury target) (Fig. 2). In this case, the danger consists in splashes can be formed on the free exit mercury surface. These splashes may bombard the entrance wall of the lens which contains the liquid-lithium volume. To protect it, there are a protection titanium disk of about 0.3 mm thickness between the jet and the lens face, which is set into rotation by the mercury jet itself.

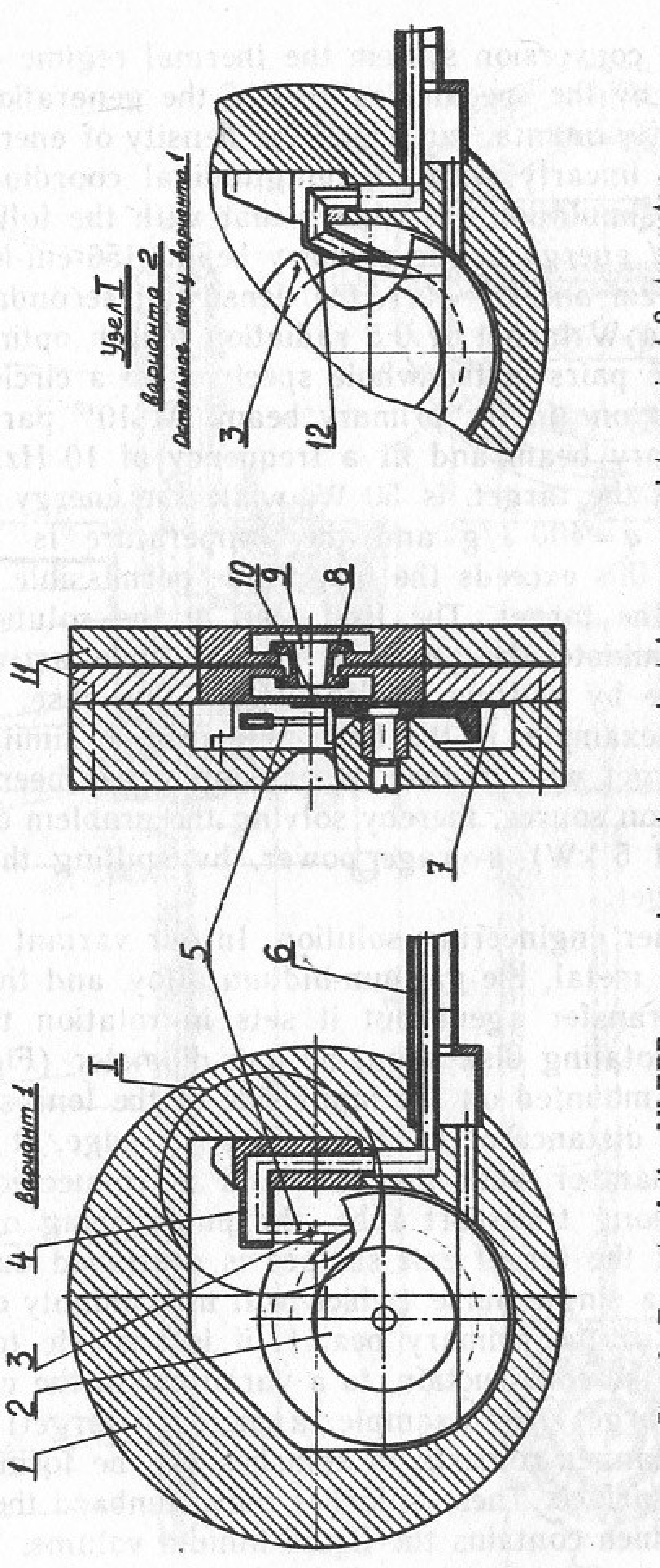

Fig. 2. Target of the VLEPP conversion system: variant 1: mercury jet; variant 2: tungsten disk; *1*—body; *2*—disk; *3*—beam axis; *4*—drain nozzle; *5*—mercury jet target; *6*—supply tubes; *7* guard titanium disk; *8*—body of a lithium lens; *9*—operating lithium volume; *10*—entrance flange of the lens; *11*—current input; *12*—drain nozzle for the gallium jet.

2. OBTAINING INTENSE ANTIPROTON BEAMS

Among the major problems concerning effective production of antiprotons for injection into storage rings, there are the optimal focusing of the primary beam on a target, and the efficient collection of antiprotons up to angles close to the maximum production angle. The most effective optical systems for such problems are cylindrical lithium lenses. The technology of their manufacture was developed at the INP in the late 70's and is being applied successfully at the accelerator centres FNAL (USA) and CERN, where similar lenses have been created for their application to antiproton target stations of the Tevatron-I and AA-ACOL facilities.

The main characteristics of the lenses, which determines the possibility of the collection of particles of r.m.s. production angle $\langle\theta^2\rangle = \frac{2mm_\pi c^2}{P^2} \simeq \frac{\langle P_\perp\rangle^2}{P^2}$, i. e. with transverse momentum equal to $R_\perp \lesssim 0.5\,\mathrm{GeV}/c$ for antiprotons, is the field integral over the trajectory of a boundary particle, which gives the bending angle $\alpha_c = \frac{300}{P}\int_0^l H(l)\,dl$. With the r.m.s. angle of collection $\alpha_c = \sqrt{\langle\theta^2\rangle}$, the maximum field integral at the aperture boundary should be $H_{\max}\cdot l = \frac{P_\perp}{300} = 1.7\cdot 10^6$ Oe cm, irrespective of the total energy of antiprotons. Since the storage ring acceptance, ε_{st}, is somewhat lower than the r.m.s. emittance of the antiproton beam, $\varepsilon_{st} < \varepsilon_{\bar p} = \frac{Z\langle\theta^2\rangle}{2\sqrt{3}}$, ($Z$ is the length of the target) and the optimal angle of collection into the acceptance ε_{st} is equal to $\alpha_c = 1.65\left(\frac{\varepsilon_{st}\langle\theta^2\rangle}{\lambda_i}\right)^{1/4} \leqslant \sqrt{\langle\theta^2\rangle}$ (λ_i is the length of nuclear absorption of the target material), the characteristic parameters of the lens will be $H_{\max} \simeq 100$ kOe at $l \simeq 15\,\mathrm{cm} \ll \lambda_{\mathrm{Li}}$, for any energy of antiprotons. For the FNAL project, at $P_{\bar p} = 8.9\,\mathrm{GeV}/c$ and $\varepsilon_{st} = 20\pi\,\mathrm{mm\cdot mrad}$, a lens with such parameters and aperture $R = 1$ cm have an optimal angle of collection $\alpha_c = 0.046$ rad ($\sqrt{\langle\theta^2\rangle} = 0.057$) and the total distance $F = R/\alpha_c = 22$ cm, while a lens for the CERN project at $\varepsilon_{st} = 200\pi\,\mathrm{mm\cdot mrad}$ $\alpha_c = 0.134$ ($\sqrt{\langle\theta^2\rangle} = 0.145$) and $F = 7.5$ cm, at $P_{\bar p} = 3.5\,\mathrm{GeV}/c$, i. e. in this case the source (target output) should be placed either near the entrance face of the lens, or the lens should have a large aperture with the same field on its surface.

The major technical problems associated with the creation of reliable large-diameter lenses with ~ 100 kOe fields consists in the containing the pressure from the thermal expansion of lithium, which leading to considerable stresses in the thin-wall envelope, and in providing adequate heat removal from lithium. At present there are two methods in manufacturing the lenses under discussion, from a construction point of view. The lenses manufactured at the INP and FNAL are elastic systems (Fig. 3a) where lithium in the operating part of the lens is limited by a thin-wall titanium cylinder with a free outer water-cooled surface. With increasing the lithium volume during the pulse heating, the envelope expansion and the lithium compressibility in the non-heated parts result in a decrease of the pressure in the system, while the stress in the envelope walls is expressed as [5]:

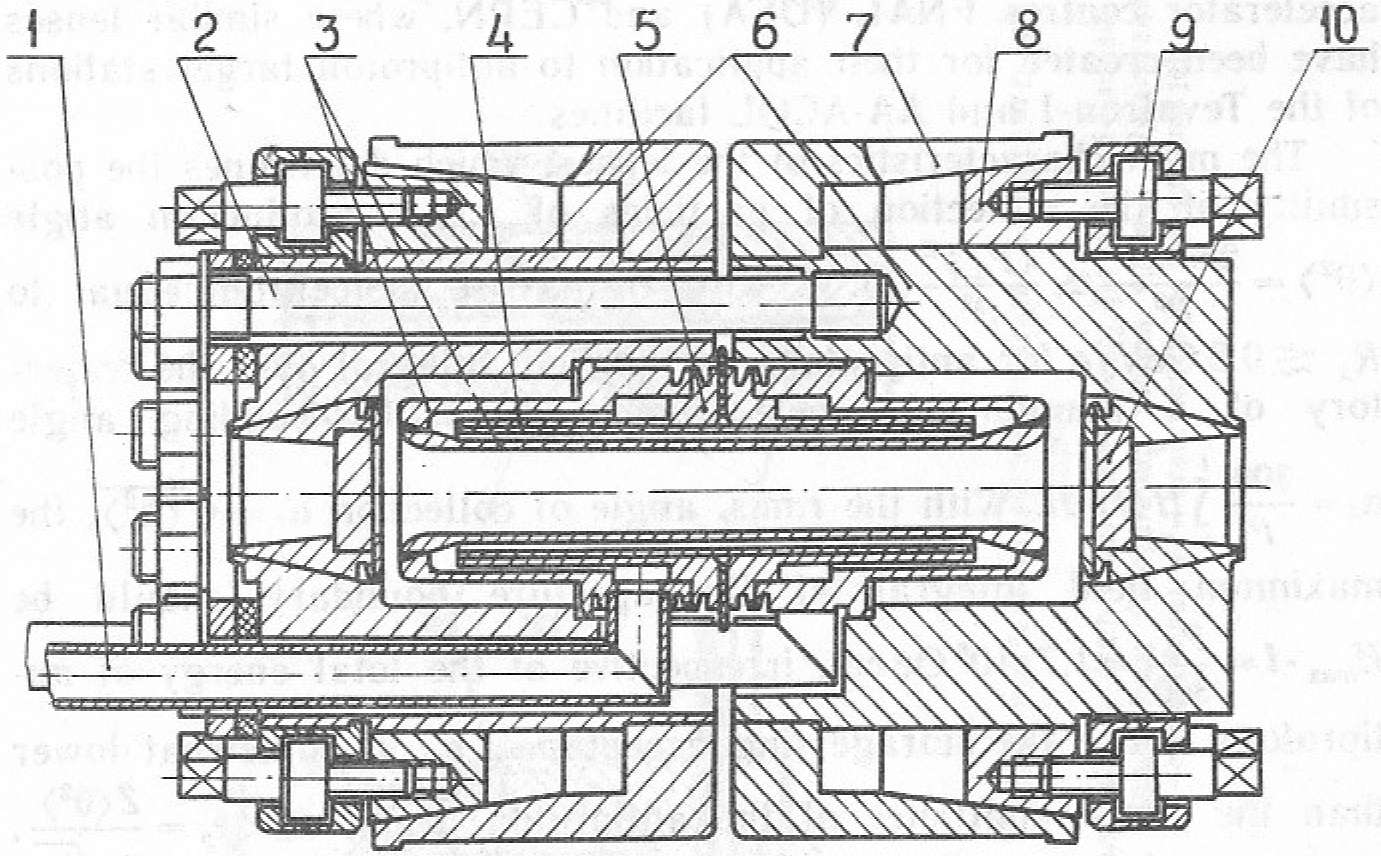

Fig. 3a. Lens with elastic wall:

1—water supply; *2*—retaining bolts; *3*—titanium body of the lens; *4*—distribution pipes of the water system; *5*—flanges of the distribution pipes; *6*—steel body of the lens; *7*—collet contact; *8*—conic clamps; *9*—bolts; *10*—berillium windows.

$$\sigma = \frac{\alpha T}{\chi_{\mathrm{Li}} \frac{\Delta}{R}\left(1+\frac{V_b}{V_n}\right)+\frac{2}{E_{\mathrm{Ti}}}}.$$

Here α is the factor of volumetric expansion of lithium, χ_{Li}—its compressibility, Δ—the wall thickness, R—the cylinder radius, E_{Ti}—the modulus of titanium elasticity, V_n—the operating lithium volume being heated, V_b—the non-heated section of the lithium volume in the current feeds, which is subjected to the pressure from the operating part of the lens. In the CERN lenses (Fig. 3b), the stainless steel envelope of the lithium is supported by a large number of ceramic balls. This lens is a rigid construction capable of withstanding a maximum pressure close, to $p=\frac{\alpha}{\chi}T$, in the given case; this constitutes $p=1200$ atm at $T=60°$.

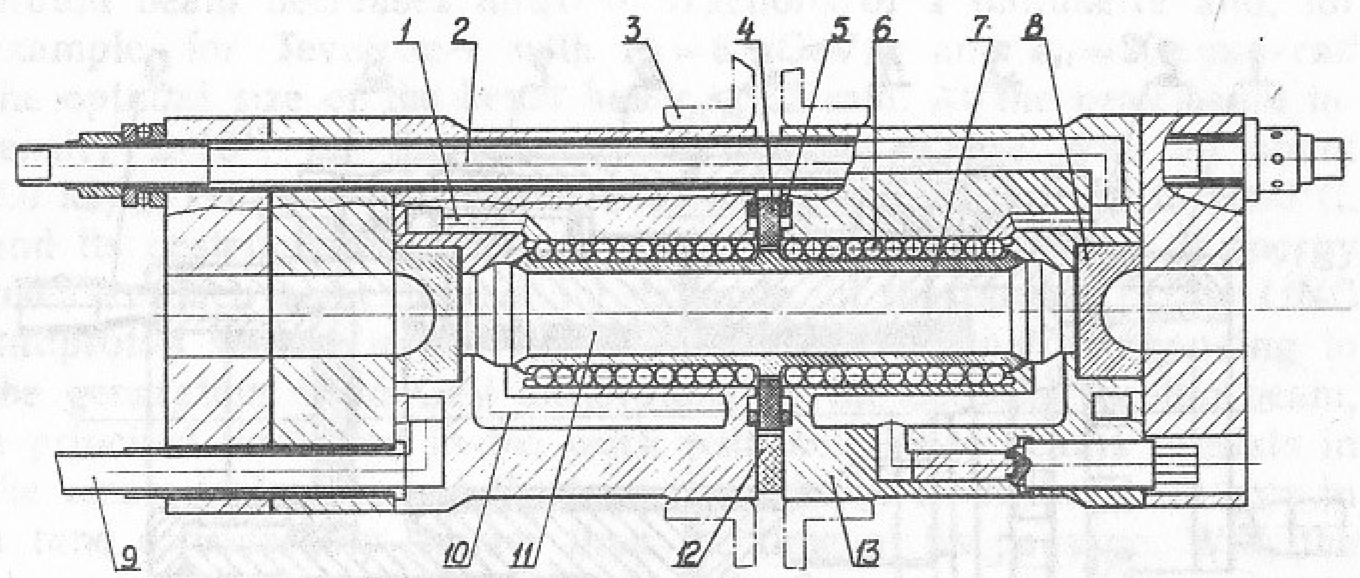

Fig. 3b. CERN lens:

1—water supply; *2*—retaining bolts; *3*—current input; *4*—sealed insulator; *5*—seals; *6*—ceramic balls; *7*—body of the lens; *8*—titanium windows; *9*—water supply tubes; *10*—cooling channels; *11*—operating lithium volumes; *12*—insulator.

With sufficiently durable construction, it will be reliable, but for lenses of large diameter, 4—6 cm, the development of elastic systems seems more promising. On this path the cardinal solution is a transition to the constructions with liquid lithium, which has several times higher the compressibility. In systems with flowing liquid lithium the problem of heat removal is solved also, which in large lenses with 50—100 kJ energy release this problem turns out to be practically insoluble with the use of water cooling.

The first experiments with the models of liquid-lithium lenses of large, 2—3 cm diameter, were performed in Novosibirsk in 1984 and demonstrated that the main problems determining the service reliability of the system are associated with fluid shocks arising during pulse heating. This requires a proper strengthening of the pumping elements: a pump, a heat exchanger and transport tubes. Fig. 3c shows the working variant of a 4-cm-diameter lens under test. Using this construction we plan to test the system with stop valves located at the entrances to the buffer volumes (*1*). The latter are connected to the operating volume of the lens by the distribution channels (*2*) and this is assumed to reduce the pulse pressure transmitted to the pumping system of the lithium. The lens power is supplied through a toroidal matching transformer with radiation-resistant ceramic insulators and is intended for work with about 3 ms duration current pulses and with an amplitude up to 1 MA.The lens is connected with a pump which is assumed to be placed behind the radiation shelding, using transfer tubes of about 4 m long. The methods of studying stresses in the lens as well as the apparatus and technological problems associated with liquid lithium can be found in [5, 6].

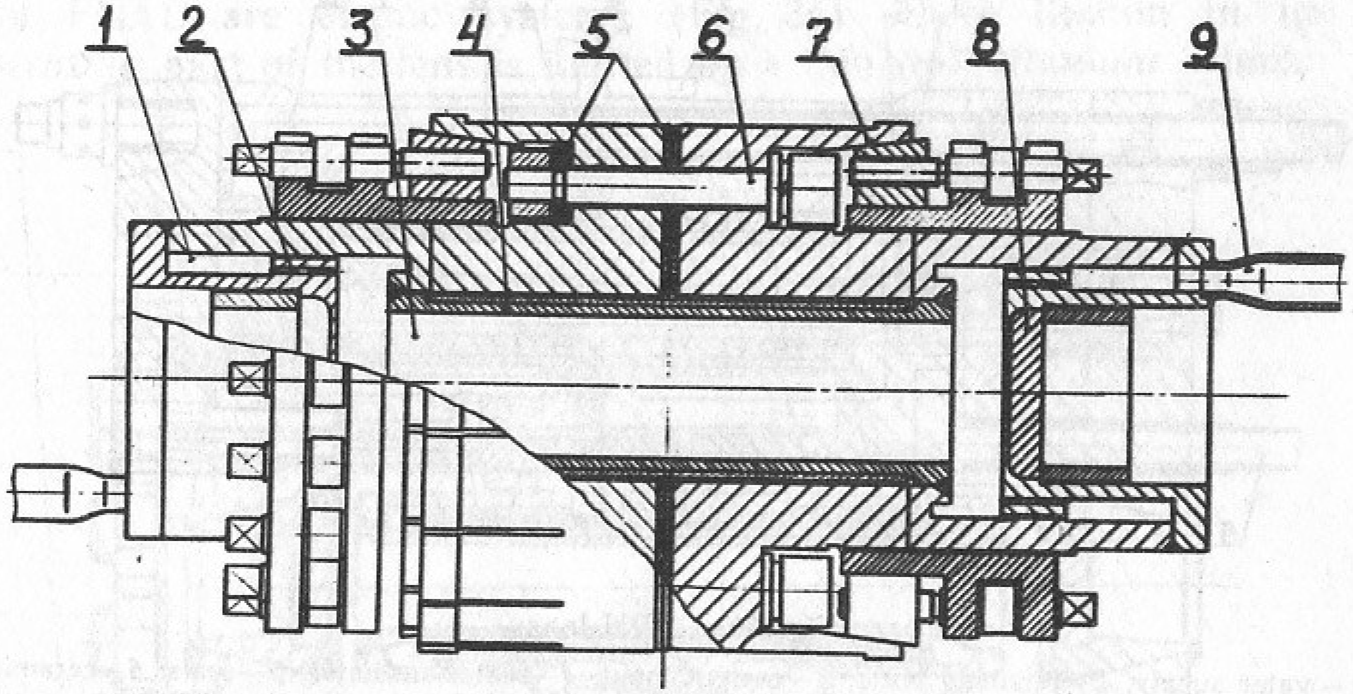

Fig. 3c. A lens with liquid lithium:

1—buffer volumes; *2*—supply channels; *3*—operating lithium volume; *4*—thin-wall envelope of the operating lithium volume; *5*—oxidized titanium insulators; *6*—retaining bolts; *7*—collet contacts; *8*—beryllium windows; *9*—supply tubes for liquid lithium.

Optimization of the focusing of a proton beam onto a target corresponds to obtaining its size r_p, smaller than the effective size of the antiproton source (which is determined by the target length z and the production angles as $\sqrt{\langle r_{\bar{p}}^2\rangle}=\frac{z\theta}{2\sqrt{3}}$, under the condition on the proton beam radius $r_p^2 \ll \frac{8}{3}\frac{\varepsilon_{st}^2}{\langle\theta^2\rangle}$, for beam captured into the acceptance ε_{st} less than the effective emittance of the antiprotons [7].

As the energy of antiprotons grows, the necessary size of the proton beam decreases down to fractions of a millimetre and, for example, for Tevatron-1 with $P_{\bar{p}}=8.9\,\mathrm{GeV}/c$ and $\varepsilon_{st}=20\pi\,\mathrm{mm\cdot rad}$ the optimal size of the beam has $r_p \leqslant 0.2$ mm. At the peak beam intensity $2\cdot10^{12}$ *pp* the density of energy release will be about 0.8 kJ/g. For a W target this corresponds to heating up to 6000°C, and its destruction during one pulse. At highest densities of energy release which are expected, for example, in the targets of the UNC antiproton source, in the variant under discussion corresponding to the generation of 15 GeV antiprotons by the 600 GeV proton beam, a principal limitation in the work with small-size beams consists in the «massdepleshing» of the target substance from the beam axis in a time considerably shorter than the time of its passage. With the characteristic times of beam spill, 1.5—2 μs, beam scanning across the target surface is likely to be the only possibility for eliminating the thermal destruction effects without a loss in phase space density of the antiprotons. Such a scanning reduce the local density of energy release with an appropriate synchronous shift of the acceptance of the antiproton section of the focusing system behind the target. This method has been suggested in [8] and discussed in detail in [9, 10] including versions of optical systems and the technical parameters of the system. At present we have completed the manufacturing of the first variant of the system which comprises four alternating magnets of vertical and horizontal deflection. These magnets are fed by phase-shifted sinusoidal current pulses of 5 μs period in order to achieve circular scanning of a 70 GeV proton beam, on the target stand of the Institute of High Energy Physics [11] with a spill time of 5 μs. The magnets have the aperture $A_r=A_z=1.6$ cm and, at a field of 20 kOe, provide beam scanning over a circle of 3 mm radius at the focal point of a lithium lens whose focal distance is about 70 cm. The parameters and the description of the system can be found in [10]. During the experiments various systematic problems will have to be solved, and studies will be parformed to determine the ultimate densities of energy release, which do not result in a destruction of a targets during a single beam spill under the scanning conditions. The data obtained should provide the basis for the choice of the parameters of the operating version of similar systems.

3. FORMATION OF THE BEAMS OF NEUTRINO «PARENTS» FOR NEUTRINO EXPERIMENTS

In the consideration of projects of neutrino channels on TeV accelerators, and the increasing requirements for the parameters of neutrino beams, the necessity arises to search for new methods of focusing the beams of neutrino parents. This is associated with the fact that in the range of meson energies, 0.1—1 TeV, the angle of their escape from a target becomes very small $\left(\theta \sim \frac{P_\perp}{P} \simeq \frac{0.4}{P(\text{GeV})}\right)$, so that the application of conventional focusing systems such as magnetic horns and parabolic lenses for their formation proves to be ineffective because of the connecting «neck» and the absence of focusing in the near-axis region. This gives rise to reduced particle collection and to generation of a high level of background caused by the opposite-sign particles. Moreover, the growth of the amount of neutrino events in a detector necessitates working with millisecond beams which in turn leads to complicated problems of cooling systems composed of thin-wall envelopes, and to problems of stresses in them caused by pulsed thermal expansion. To overcome these difficulties, one apply cylindrical lithium lenses with a large, 3—6 cm, aperture which should be fed by long, several-millisecond current pulses. In particular, a project has been accepted for the UNC neutrino channel for work with 3.6 TeV protons. Its focusing system includes a telescope composed of three lithium lenses with the following parameters: ∅ 1.8 , 3.4 and 6 cm; length ~15 cm; fields 80, 60 and 40 kOe; distances to the target of 10, 30 and 150 m, respectively. As has been demonstrated in [12], such lenses will allow one to reduce, by a factor of 2—3, the length of the focusing system in comparison with a similar variant based on parabolic lenses and reduce, by one order of magnitude, the background level. The mode of operation of the UNC is assumed to be the following: with $6 \cdot 10^{14}$ protons stored and their energy increased up to 3.6 TeV, separate portions of the beam, with $5 \cdot 10^{13}$ particles in each, will be extracted to the target with the 4 s interval. Each cycle of extraction will last up to 1 ms. So the lenses will be supplied by current pulses with flat tops of about-1-ms and with an amplitude of up to 500 kA.

The major problems concerning the creation of lithium lenses with such parameters has been treated above and we intend to solve them of developing the technology of utilizing liquid lithium pumped through the system.

At the proton beam energy and intensity under consideration, the thermal regimes of the targets become complicated and the total energy release in them, depending on their substance and geometry, can achieve 100 kJ and higher. Using short-focus and small-aperture lithium lenses to collect secondary particles requires focusing the proton beam on a target, to a small, about 1—2 mm size. The second argument in favour of the work with a small-size beam is connected with increasing the nomber of secondaries emerging from the side of the target which belong to a nuclear-electromagnetic cascade developed in it. These particles are responsible for an increase of the total energy release; it can be decreased under the condition that as the size of the beam is reduced, a simultaneous reduction of the transverse size h of the target can occur, the quantity $h=4\sigma$ being conserved. In the limiting case, at $\sigma=0.1-0.2$ mm the energy release will be only determined by ionization losses and by the losses due to nuclear excitation of the primary beam and will be practically energy-irrespective. For example, in a lithium target of about 150 cm long the energy release will be reduced to a magnitude lower than 1 kJ. However, as the beam size decreases, the peak energy release density grows fast, and a stationary target can operate only in an explosive regime. At a spill time of the beam of about 1 ms this problem can be solved by a rapid exchange of the substance in the heating region, that is by using a flat liquid-metallic jet crossing the beam axis with a velocity of several tens of metres per second, thereby offering simultaneously the possibility of solving the heat removal problem. This possibility has been discussed earlier [13, 14] and at present we start work on its technical realization.

To do this, an experimental device (Fig. 4) has been built with a stationary freely-flowing jet of gallium-indium alloy. This jet is 20 cm wide (along the beam axis) and its transverse size is $h=1\div2$ mm. The device is assumed to be mounted on the IHEP target stand and we intend to investigate maximum admissible densities of energy release at which the substance density on the beam axis does not decrease, with the 76 GeV proton beam, focused to 1mm, incident on it. This will give information about how many

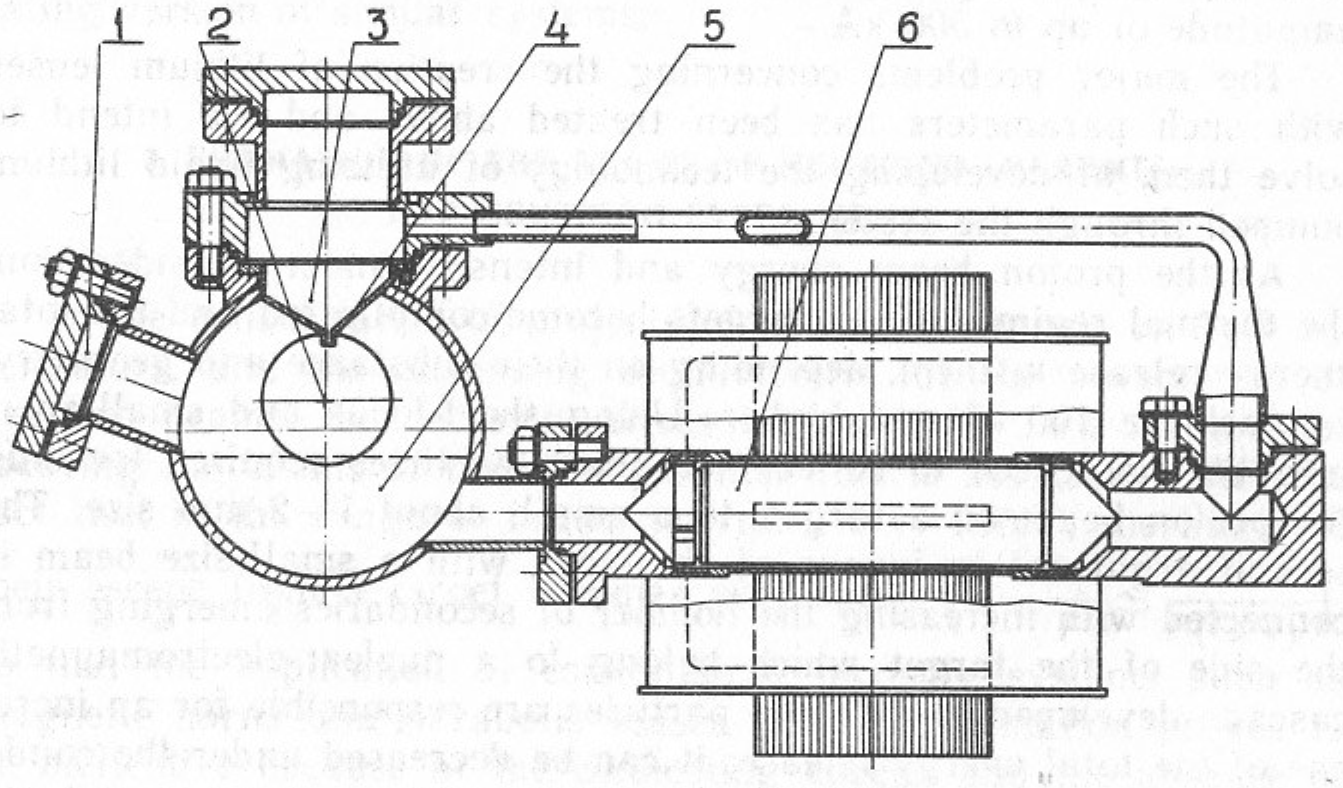

Fig. 4. A stationary jet target:

1—observation hole; *2*—beam axis; *3*—nozzle of the drain chamber; *4*—liquid metal; *5*—pump.

times the substance should be exchanged in more intense UNC targets, and about the required velocity of a jet. It is more rational to design liquid-metallic jet targets (the jet velocity is about 100 m/s) for the pulse mode of operation, using for this purpose the electromagnetic method of accelerating a liquid metal. To analyse these possibilities, a device has been designed in which a narrow, ~2-mm gap between two flat current 20-cm-wide conductors is short-circuited by a stationary flow of liquid metal. When passing through the conductor a current pulse of about 2 MA amplitude, the metal will be pushed out from the gap under the pressure of the magnetic field whose magnitude is above 100 kOe. Using this device, the parameters of a liquid-metallic jet will be studied and the optimal regimes will be chosen, which provide the maximum velocity.

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Problems of Intense Secondary Particle Beams Production

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Проблемы получения интенсивных пучков вторичных частиц

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