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One of the ways for increasing the efficiency in utilization of the high energy accelerator beams is to enlarge the angles of collection of the secondary particles up to the root mean square angle of their exit from a target. For the particles produced in hadron collisions, this angle is described by the expression $\langle\theta^2\rangle \cong \frac{2mm_\pi c^2}{p^2}$, where m and p are the mass of the particle and its momentum, m_π is the mass of the π-meson /1/ (for example, for antiprotons it is $\sqrt{\langle\theta^2\rangle} \cong 0.5/p$ (GeV/c). In the case when the angles of production are $\gtrsim$ 0.5 rad (at $p \lesssim 1$ GeV/c), the problem of collecting the secondary particles within the angle $\sim\sqrt{\langle\theta^2\rangle}$ can only be solved with the help of parabolic lenses /2/ because these lenses can be very powerful. But with an increase of energy and a narrowing of the production angle their use becomes low effective because of the current bridge of a finite radius which cuts the paraxial fraction of the beam. More promising in this energy range is the use of cylindrical lithium lenses which provide the focusing by a linearly growing magnetic field inside the conductor with uniform current density /3/.

The expressions for $\langle\theta^2\rangle$ and a focal distance $f \cong \frac{pc}{e\ell\frac{dH}{dr}}$ (ℓ is the lens length) enable one to derive the value for the field strength on the lens surface H_0. This value provides the collection of the root mean square production angle, i.e. $H_0 \cong \frac{c\sqrt{2mm_\pi}}{e\ell}$. If the losses, because of nuclear absorption in the lens substance, are taken to be equal to 10-15%, then the length of the lens made of lithium should be about 15 cm (λ_{Li} = = 120 cm). Thus, a collection of the antiprotons will be effective if a field on the lens surface is about 100 kOe. This requirement derived on a field value does not depend neither on the particle momentum nor the focal distance. With the same field and a given collection efficiency this allows one to have the lenses with the same focal distance for the particles of any energies. In our case this distance turns out to be $f \sim 10 \div 15$ cm. An increase in the particle momentum results only in decreasing the lens aperture, total current and its duration. An increment of the beam emittance because of both the multiple scattering in the lens and the chromatic aberration is determined by . The value of f is independent of the momentum. This means that the relative value of the increment is constant. With the lens of 15 cm long the multiple scattering angle in Li is $\sqrt{\langle\theta^2_{scat}\rangle} \cong \frac{5 \cdot 10^{-3}}{p(GeV/c)}$ that is equivalent to the appearance of a $\sqrt{\langle r^2\rangle} \cong \frac{0.05}{p(GeV/c)}$ cm effective source in its focus. In major cases, this is less than the source sizes determined both by the primary beam and a target length.

Application of the cylindrical lenses for collecting the particles with a momentum of a few GeV in the full production angle requires the creation of the lenses with large apertures. This application is complicated by a necessity to commute high pulsed currents. For example, in order to collect the antiprotons with p = 2 GeV/c within the θ ±0.2 rad angle, the lens of 15 cm long with the focal distance f = 14 cm has the aperture $2r_0$ = 5.6 cm and should be supplied by the current pulse of ~ 8 μsec duration and J_0 = 1.2 mA amplitude. In this case, the cylindrical shape of the lens is inappropriate since a significant part of its operating region near the entrance turns out to be outside the beam. If one manufactures the lens with a variable cross section, thereby nearing the surface generatrix to the beam envelope, the average current density becomes larger that leads to a decrease in the necessary total current value.

In the case when the generatrix of the lens surface coincides with the beam envelope, an equation of the envelope $r(z)$ is the following:

$$\frac{d^2r}{dz^2} - \frac{\varepsilon^2}{r^3} + \frac{K r_0^2}{r} = 0 \qquad (1)$$

Here $K = \frac{e G_0}{pc}$, where $G_0 = \left.\frac{\partial H}{\partial r}\right|_{z=0}$ is the field gradient at the lens entrance, r_0 is the entrance radius, ε is the beam emittance. If $r_0 \gg \Delta r$ (Δr is the beam size in its focus), the term with ε can be neglected that enables one to integrate the equation analytically. And finally, depending upon z_0, the main focal distance f, the exit radius r_{ex} and the lens length ℓ are obtained to be equal to: $\ell = \sqrt{\frac{\pi}{2K}} \cdot \frac{r_{ex}}{r_0} \; erf \frac{1}{z_0\sqrt{2K}}$,

$$f = z_0 \cdot exp\left(\frac{1}{2Kz_0^2}\right), \; r_{ex} = r_0 \cdot exp\left(\frac{1}{2Kz_0^2}\right) \qquad (2)$$

Here z_0 is the distance between focal plane and lens entrance. An equation for the envelope of the lens surface has the form:

$$z = z_0 + \ell - \frac{r_{ex}}{r_0}\sqrt{\frac{\pi}{2K}} \; erf \sqrt{ln \frac{r_{ex}}{r_0}} \qquad (3)$$

In a careful consideration, because of the conic geometry, the field distribution in such a lens is not strongly linear even at constant current. However, the non-linearity eppeared at the divergence angles $\theta \lesssim 0.3$ does not exceed that arising from the finite thickness of the skin-layer δ at $\delta \sim r_0$ and has the opposite sign. In comparison with the cylindrical lens, a gain in the current depends on the ratio r_{ex}/r_o . This ratio cannot be made much more larger than 2, at least, for two reasons: on the one hand, because of overheating the lens entrance cross section at $\delta/r_o > 1$ and, on the other hand, because of the field non-linearity on the lens exit at $\delta/r_{ex} < 0.5$ /4/. Compared to the considered above cylindrical lens for collecting the antiprotons with p = 2 GeV/c and θ =±0.2 rad, the lens with optimized (according to (3)) profile should be supplied with the current J_o = 0.765 mA in the case of the same length (ℓ = 15 cm) and focal distance (f = 14 cm) at the ratio $r_{ex}/r_o = 2$, i.e. the gain in current value is 1.58. The maximum aperture of the lens decreases down to 2 A = 5.34 cm, the pulse duration can be decreased nearly by a factor of 3 because of a considerably less mean cross section.

The considered previously designs of the strong-field lithium lenses for focusing narrow beams /3,5/ have turned out to be inappropriate for creation of the powerful lenses with large lithium volumes. For this reason, a new version of the lens has been designed and tested (see Fig.1). With the help of a two-side hydraulic bag (2) wherein a pressure is about 1000 atm, two steel cups (1) with an effective water cooling system (3) are pressed to the contact surfaces of the coaxial current-connections (7) and simultaneously they are packed, thereby creating a sealed cylindrical volume filled with lithium. A thin-wall two-layer tithanium shield of the cylindrical, conic, or any given shape is inserted into the cylinder. The outer coating of this shield consists of two parts which go into the disks at the centre and are clamped with the metallic vacuum seals between the sides of the cups. The surfaces of the coatings and disks which touch each other are separated by means of the oxidized tithanium and

electrically connected only at the welding points on the sides. The fraction of lithium inside the shield is an operating volume of the lens which is supplied with the current through the peripheral fraction of lithium the lithium contacting with the internal surfaces of the current-connecting cups. The injection and extraction of the beam is carried out through berillium plugs 6 and 9.

The distinctive operational feature of this construction under intense thermal conditions is due to a large extension of lithium upon heating. This can lead to the loss of sealing at the points of packings and contacts so that application of hydraulic bags keeping up the constant contact stress is of principal importance. When varying the regime of average heating the excess of lithium, because of extension, is passed through the channel (8) into a special buffer volume. For the tests a 15 cm conic lens whose entrance diameter is 2 cm and whose exit one is 5 cm was manufactured. This lens was supplied by the unipolar sinusoidal current pulse of $\sim$ 1.5 μ sec duration that corresponds to δ/r_o = 0.8 on the entrance diameter at the temperature of lithium T = 20°C. The operating-life tests were carried out at the repetition frequency ν = 1 Hz with a further increasing of the current amplitude from J_o = 500 kA by 100 kA in each 100 thousands pulses up to the amplitude J_o = 900 kA corresponding to the field on the entrance diameter H_o = 180 kOe.

Based on these tests, three types of lenses have been designed for different focusing conditions. These lenses have the same layout.

1. The first lens is the considered above lens with optimized profile described by eq.(3) which has been designed for col-

lecting the antiprotons. Its momentum is 2 GeV/c and the linear angle is 0.2 rad in the project of antiproton storage rings with electron cooling on the electron energy.

2. The second lens is the lens for collecting the antiprotons within the root mean square production angle $\sqrt{\langle\theta^2\rangle} \cong 0.06$ rad with the momentum p = 6÷8 GeV/c corresponding to their maximum output from the target at the primary proton beam energy $E \sim 100$ GeV. With such angles of entrance the lens' aperture is not large, therefore, it is of cylindrical shape, its diameter is 2 cm and the length is 12 cm. At a current of 750 kA the field on the surface is 150 kOe and the focal distance of the lens is 12 cm. Due to scattering the effective beam size in the focus is $\sqrt{\langle\Delta r^2\rangle} \cong 0.1$ mm.

3. The third lens is the lens for creating optical structures comprising several objectives for shaping the beams of π - and K -mesons which are the parents of neutrino in the energy range higher 100 GeV where the application of the lenses compared to the magnetic horn and parabolic lenses an essential gain in the integral neutrino flux, the antineutrino background level in the netrino beam and inversely, as well as in the possibility to increase the duration of the extracted proton beam up to several milliseconds /7/. For such systems the lens of 15 cm long and 5 cm diameter with a maximum field on the surface of 60 kOe has been manufactured. This lens is supplied by the current pulse of 750 kA amplitude and 6 μsec duration which provides a sufficient homogeneity of the current density over the cross section /4/.

All the lenses are placed in the same coaxial current-wrappers connected to the stationary current-connections with the help of hydraulic contacts /1,8/. These contacts allow the long-distance switching-off of the lenses and their evacuation from the active zone if the damage occurs.

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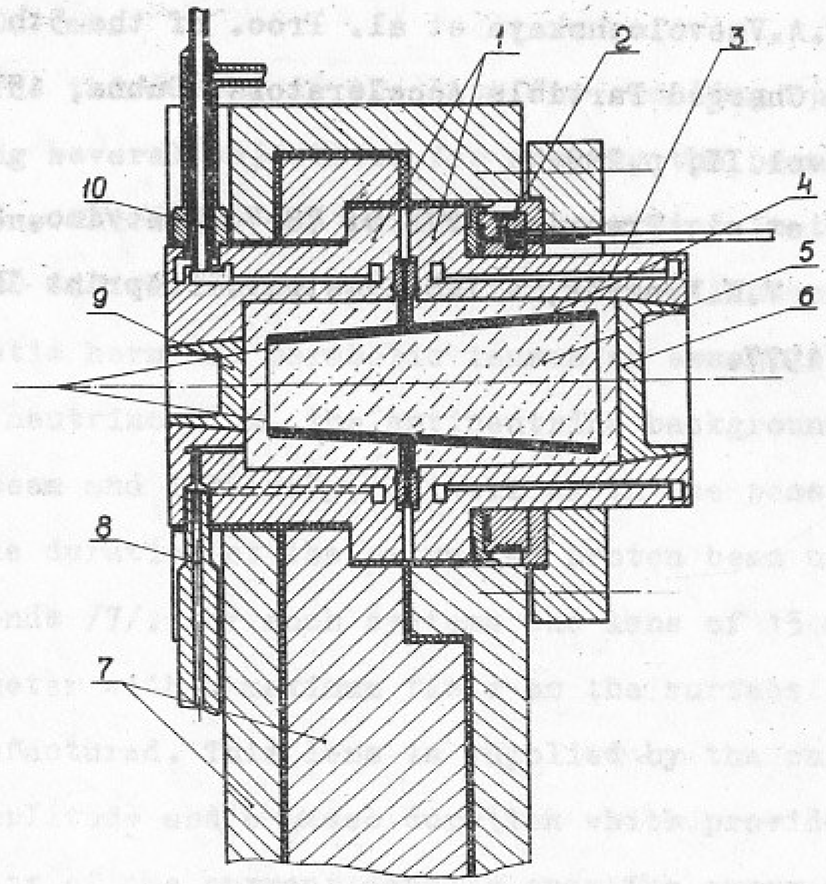
FIGURE CAPTION

Fig.1 Cross section of the lens with current-wrapper:
1 - current-connecting cups, 2 - hydraulic bag,
3 - water cooling channels. 4 - tithanium body of the lens,
5 - operating lithium volume; 6,9 - berillium plugs,
7 - coaxial current-connections, 8 - entrance channel for
lithium, 10 - entrances for the water cooling system.



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