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SUPERSTRONG QUADRUPOLES OF LIQUID METAL FOR FINAL FOCUSING AT LINEAR COLLIDERES

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To solve the problem of linear collider final focus, i. e. the problem of accelerated beams focusing to the interaction point into small size with beta-function value of about 1 cm [1], an extremely strong lens is to be used as the last focusing element. Besides the condition $\beta_0\beta = F^2$, which determines the lens focal distance F versus beta-function values on the interaction point β_0 and on the lens β, an additional limitation to F arises in a form $F \cdot \Delta p/p < \beta_0$ as a demand of small increase of interacting beam spot sizes due to particle energy spread $\Delta p/p$. The value of $\Delta p/p$ in an accelerated beam is of the order of 1% [1], that for $\beta_0 = 1$ cm leads to restriction $F < 100$ cm. If quadrupoles are considered for such a focusing their field gradient for a beam of 1 TeV energy is to be of the order of 10 T/mm or more. By that the ultimate field available for forming by iron poles is exceeded already at a distance of 0.1 mm from lens axis. With a small value of beam emittance such an aperture could be enough to let pass the beam but should not garantee the lens protection from the radiation from the interaction point. Besides a danger for lens safety it would produce an extremely hard background conditions for a detector. Moreover a small error in beam alignment could result in the whole beam caught by the lens body that should lead to an instant destroy of the lens.

Looking more adequate to the problem is an ironless quarupole with comparatively large, of $\sim\pm 1$ mm, aperture and high magnetic field, up to 10 T or more, at the aperture periphery, fed with current pulses of short duration. Notion «ironless» is considered here as conditional only. Laminated iron could be used as it will be shown below for current conductors fixation and for back magnetic flux guiding but its participation in a field forming within the aperture is negligible due to the saturation at high inductions.

Field forming is fulfilled with current conductors only. Small size of a particle beam reduces requirements to a forming accuracy but keeping its significance is a ratio of field gradient G to the maximum field value on the conductor surface $H_{\max}$ restricted by a possibility of metal destruction under field pressure. An increase of this ratio is one of the ways of conductor shape optimization including a rounding of angles and a proper choice of transverse sizes. Shown in Fig. 1 is a ratio $G/H_{\max}$ dependence on transverse size of conductor cross section. By infinitely thin skin depth in conductor this dependence occures to be the same for round conductor and for rectangular with rounded angles (see Fig. 3). Maximum value of $G/H_{\max}$ by that equals to 0.74 and takes place by a conductor radious R equal to 0.55 of an aperture radious A. Finite skin depth makes more flat the dependence of $G/H_{\max}$ on R and slightly increases its maximum, up to 0.79 at $\delta = 0.36\,A$.

Skin type of field distribution inside the conductor is resulted from small current pulse duration necessary to reduce the Joule heating. Heat amount per pulse Q in the case of thin skin depth $\delta \ll R$ is proportional to δ, i. e. depends on pulse duration as

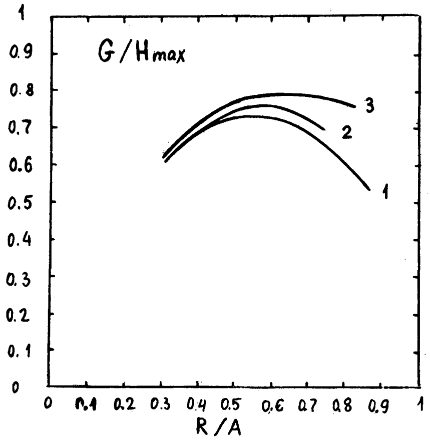

FIGURE 1. Ratio $G/H_{\max}$ versus R/A for round conductors with skin depth equal to: *1*—0, *2*—0.09*A*, *3*—0.36*A*.

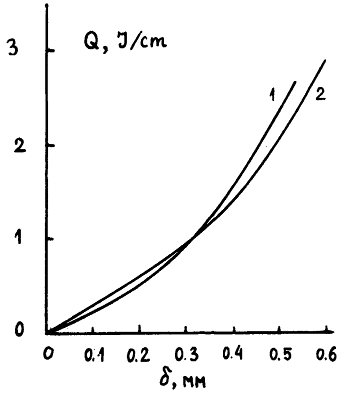

FIGURE 2. Joule heat Q per pulse and 1 cm conductor length in round conductor of radious 0.53 mm (*1*) and 0.75 mm (*2*) at field gradient 10 T/mm and aperture radious 1 mm versus skin depth.

$\tau^{1/2}$, while Q is proportional to τ if $\delta \gg R$. Dependence of Q on R in round conductor remains lenear up to about $\delta = 0.5R$ (Fig. 2). By that the value of Q could be good enough defined by an expression $Q = \frac{\delta}{16}\int H^2 ds$ (*1*), where the squared field integral over conductor surface is calculated in the infinitely thin skin depth approximation. This expression might be as well applied to other geometries with the above correlation of δ to a curvature radious of conductor surface.

Shape of conductor cross section is determined by the requirements of conductor fixation and of heat removal. Transfer from round conductor to rectangular with round angles though results in current increase (Fig. 3) does not lead to a significant growth of Joule heat and in voltage. Value of voltage determines the minimum current pulse duration. At chosen lens parameters it is about 1 mcs. In copper conductor by that the skin depth is 0.09 mm and Joule heat is 0.22 *J* per 1 cm conductor length with the field gradient $G = 10$ T/mm and aperture radious $A = 1$ mm. Thus at a repetition rate of 100 Hz the heating power will be 22 W. With transverse size of conductor cross section of ~1 mm the heat removal seems to be a very complicated problem. Its solution requires first of all the extention of conductor cross section in transverse direction so as in radial by change its shape into a triangular one (Fig. 4). This change results in some increase of Q value but it is the only way to dispose the cooling water channels inside the conductor. It is particularly applied to a case where the back magnetic flux is guided by a magnetic core so that there are no restrictions for cross section extention into a region where iron is not saturated. Such a quadrupole with field gradient of 10 T/mm and aperture radious of 0.5 mm having a complicated cooling system is now under development in CERN [3] For more aperture or maximum field value such type systems do not look perspective.

As a cardinal solution of cooling problem we consider the use of conductors of liquid metal, pumped through with a high speed. Could be used for this purpose is an alloy of gallium and indium having low melting temperature $T_m = 18.5°C$, or lithium ($T_m = 186°C$) whose small density allows to have a high speed of metal pumping. Certainly the change for conductors of liquid metal leads to an increase of Joule heating due to the specific resistance increase by 15 times as compared to copper conductor. However Q increase is not so large, by 4-5 times only, by benefit of skin type (though close to violation with $\delta = 0.36$ mm and $r = 0.5-0.75$ mm) field distribution in conductor.

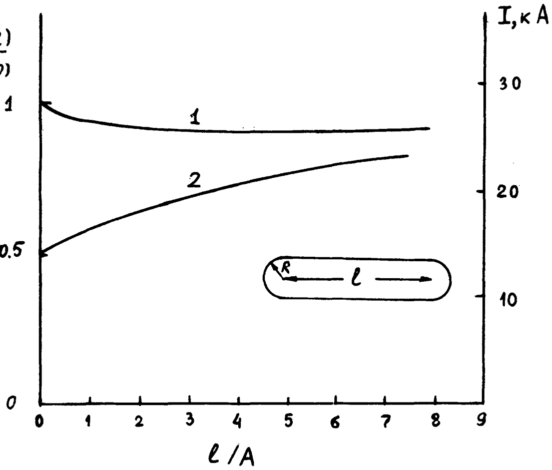

FIGURE 3. Joule heat (*1*) and current (*2*) dependence on the longitudinal size of cross section in a rectangular conductor with rounded angles and equal to ±0.53 of aperture radious the transverse cross section size.

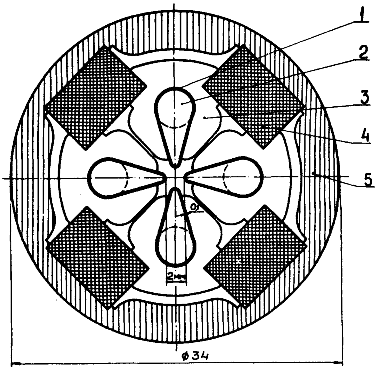

FIGURE 4. Cross section of quadrupole. *1*—titanium envelope, *2*—liquid metal, *3*—laminated iron, *4*—ceramic bars, *5*—cylindric bandage.

The main problem in working out the liquid metal quadrupoles consists in a precise forming of surviving 400 bar pressure from 10 T field the current carring surface of liquid metal which determines the magnetic field forming accuracy. Principal design idea of such a quadrupole is clear from Fig. 4. Profile of liquid metal conductor is determined by a thin, of 0.1 mm, titanium or steinless steel envelope (*1*), leaned by its most part on surrounding laminated iron (*3*). Remained free is only a small part of envelope within the lens aperture. Laminated iron is simultaneously guiding the back magnetic flux. In Fig. 4 the envelope is shown only schematically. In real structure its thickness is small outside the iron and increases fluently along the surface of tangency to it up to 1 mm on the opposite to aperture side of conductor. Envelope is brazed to iron along all surface of tangency. Four such laminated iron blocks with brazed conductors are precisely fixed by means of rectangular ceramic bars in cylindric bandage (*5*).

With current pulse duration of 1 mcs the skin depth in titanium and steinless steel is 0.5 mm. Thus the free part of envelope outside iron is almost transparent for magnetic field and does not suffer from its pressure which is transmitted into liquid metal. The mechanic loading of thin part of envelope will arise with a pressure pulse reflected from an opposite rigid envelope wall. Even if this reflected pulse amplitude would be equal to an initial pressure pulse, i. e. to about 400 bar, the tention in envelope material should be about 200 kg/cm^2 only. That is several times less than the limit value and allows to hope that the ultimate magnetic field could considerably exceed 10 T.

As it was shown above with 10 T/mm magnetic field gradient and 1 mcs current pulse duration the full Joule energy per 1 cm conductor length is equal to about ~1 J per pulse. Although the maximum temperature rise in the adjoining aperture part of conductor will be 60°C, being averaged over whole conductor cross section (~20 mm^2) it will be less than 3°C. With conductor lenght of 20 cm and speed of liquid metal pumping of 10 m/s the time of matter exchange in conductor will be $2 \cdot 10e^{-2}$ s. Thus even with a repetition rate of 1 kHz an average temperature will not exceed $60°C + T_m$.

Besides the solution of heat removal problem another cardinal advantage of liquid metal lens consists in an absence of a problem of conductor surface destroy under repeated thermal stresses which is the main restriction of magnetic field amplitude in solid conductors.

Final focus quadrupole system will consist of a few independently fed elements of about 20 cm length. Main restriction to element length is a reasonable voltage drop which can not exceed 10 kV. With 10 T/mm field gradient and 1 mcs current pulse duration such a voltage corresponds to 20 cm length of element.

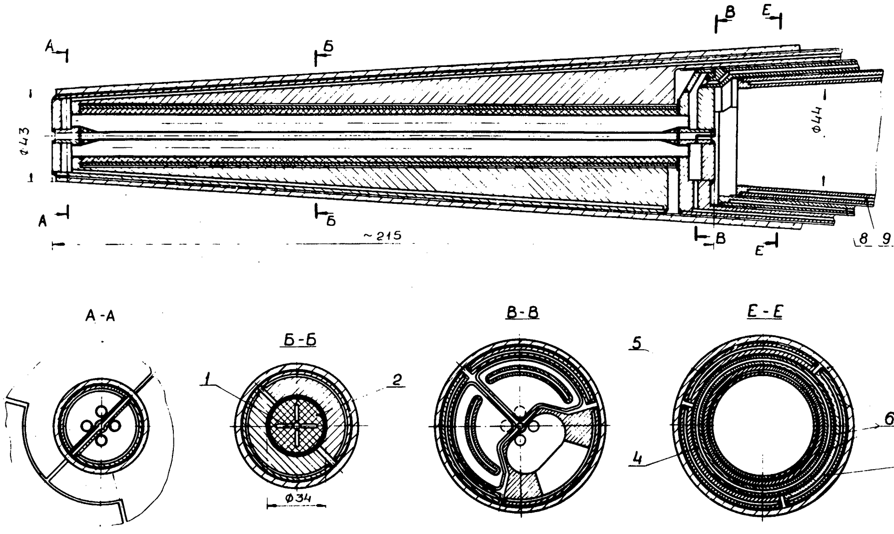

FIGURE 5. Longitudinal section of the lens with coaxial conic current input. Central cross section (Б — Б) is shown in schematic view: *1* — liquid metal conductor, *2* — ceramic insulator.

Shown in Fig. 5 is the structure of one quadrupole element with coaxial conic current input which serves simultaneously for liquid metal supply. It feds four conductors with current in series and with liquid metal in parallel. Such a supply of liquid metal shortens by four times its way through the conductors with corresponding increase of the pumping speed. Conic shape of current input allows to insert coaxially one element into another and to obtain a sequence of independently fed such quadrupole elements.

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