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BEAM COLLIMATORS

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INTRODUCTION

The continuous increasing of particles energy and intensity in linear colliders require to pay more and more attention to the problem of the energy absorption of the spent beam and of that particles, which for some reasons are lost during the acceleration or the beam transfer. This problem should be solved to exclude the activation and the destroying of the accelerator equipment. It is specially important in the case of superconducting resonators or lenses application, as for example, in the TESLA- project [1]. For the absorption of the most part of the spent particles energy in the linear colliders in specially shielded places main beam dumps are installed. That incoming to IP particles, which have parameters inappropriate for the collisions or that of the spent particles, which can not be transferred to the main dump should be intercepted by collimators. It is desirable to reduce the number of collimators to a minimum and their layout and sizes should ensure the maximum energy absorption of the intercepted particles.

The geometry and the material choice of collimators, the calculation of the energy deposition distribution caused by the intercepting particles, the determination of the temperature regime, the definition of acceptable particles number per a collimator are described. We restricted ourselves by the consideration only of the collimators for lepton beams like used in TESLA- project.

THE CHOICE OF MATERIAL FOR COLLIMATORS

The choice of the construction and of the materials of collimators in an essentially degree are defined by the parameters of the intercepting particles and by the features of processes of their interaction with the collimators substance. Let's note the main moments, which define this choice.

The collimators are intended basically for the interception of the peripheral part of the beam. It means that they should have a rectangular (elliptic) aperture, when the beam is symmetric in the transverse planes relative its axis, as for example, in the beam delivery system before IP. But in the ejection line there is a long tail in the particles distribution along one direction of one transverse coordinate because of the large momentum deviation of the spent particles. Therefore the collimator can have one jaw to intercept the particles of the tail.

The particles distribution in the peripheral part of the beam essentially depends on the collimator position and can be very complicate.

The time structure of the beam has usually a form of macro pulses, the duration of which is few hundreds of micro seconds with a repetition frequency of few Hz. The macro pulses consist of high-frequency bunch sequence. For TESLA-project these data are 800 μs, 5 Hz and 1.3 GHz accordingly.

The energy deposition distribution in collimators depends on the initial particles density distribution in the beam, on the particles energy determining the form of the electromagnetic cascade inside the collimators body, on the material type of the collimators, on the geometry of its jaws.

Because of the rather complex geometry of the collimators and of the initial particles density distribution it is practically impossible in general case to find analytically the energy density deposition and accordingly the temperature distributions, their dependence on the material characteristics. Therefore we shall make it by two consecutive steps. At the first stage by the analytical estimations using a simplified geometry we choose the material type and define the main geometrical collimator sizes and on the second one by the numerical calculations we find the distribution of the energy deposition and of the temperature for the concrete chosen geometry.

As a simplified configuration for the first stage we choose an infinite in the longitudinal direction cylinder of the large section, along the longitudinal axes of which a point like beam is passed. The main reasons at the choice of the materials for the collimators are as following:

- they should sustain arising thermal heating;
- they should have necessary vacuum properties;
- the arising mechanical stresses should not lead to a destroying of the collimators.

Here we shall not concern the last problem as it consideration is possible only for the case of a concrete construction with an exact known sizes. The second requirement can be satisfied if we limited ourselves by known materials with good vacuum properties like, for a example, as metals Al, Fe, Cu, W etc. Hence at a choice of the material we shall concern in the first order to satisfy the requirements of its heat resistance.

The temperature growth in a collimator body is a result of the energy deposition transmitted by a beam at the interaction of its particles with structural elements of substance. The main types of high energy leptons interactions with the substance leading to a development of a electromagnetic cascade are: the ionization processes, the generation of bremsstrahlung and the conversion of the last to electron-positron pairs with the further recurrence of the same processes. If the energy of primary particles or created at interactions exceeds the critical energy the two last processes prevail what leads to a significant losses of the particles energy, but the energy transferred to the substance is small. If the energy of the particles interacting with the matter decreases up to a critical one and below the main part of the particles in the electromagnetic cascade becomes electrons, the predominant processes become ionization, at which the main energy is transferred to the elements of the substance. This is the point with the maximum energy deposition. The distance from the entrance of a primary particle in the substance to this point is [2]:

$$z_{max} = \ln(E/E_c) - 0.5 \qquad (1)$$

where: z_{max} is expressed in terms of radiation lengths, E is the initial energy of the particles, and E_c is the critical energy of the substance, which in turn is equal to:

$$E_c = 610 / (Z + 1.24)\ \text{MeV} \qquad (2)$$

where: Z is the charge of the substance nucleus.

In the section of the maximum energy deposition the number of created secondary electrons by one entering will be [3]:

$$M = 0.31\cdot(E/E_c)\cdot(\ln(E/E_c) - 0.37)^{-1/2} \qquad (3)$$

Then the energy transferred to the substance in this section can be find as:

$$(dE/dz) = M\cdot(dE/dz)_{max} \qquad (4)$$

where: $(dE/dz)_{max}$ is the energy lost by an electron in the ionization processes in the section at z_{max} on an unity path.

Taking into account that the beam has a pulsed character at the defining of the temperature distribution inside the collimator it is necessary to distinguish two different processes: the instant temperature jump because of the instant energy deposition during the action of a beam pulse occurring without the heat conductivity and the established one, at which the instant temperature jump per a pulse is compensated during the pause between the pulses by the heat conductivity due the existing temperature gradient. The dividing of a complicated process in two more simpler ones is expedient by two reasons: the allowable temperatures limit for these two modes are different and so an approach simplifies the mathematical calculations. In both cases the arising temperatures depend on the energy density deposition distribution over the collimator volume. As at large energies for a dot beam (at analytical estimations we shall limit ourselves by this case) the longitudinal sizes of the electromagnetic cascade is considerably more than the transverse one it is tolerable in the section of the maximum energy deposition to neglect of its dependence on the longitudinal coordinate. The transverse energy density deposition distribution we shall accept according to [4] satisfying to the law:

$$(dW/dV) = a \cdot R^2 \cdot (dE/dz) / (r^2 + R^2)^2 \qquad (5)$$

where: r is the current radius and the parameters a and R should be found or experimentally or from other reasons. For their definition we shall use that established experimentally and confirmed by many numerical calculations (see for example [5]) fact that inside a cylinder limited by one and two Molier's radiuses in the section at z_{max} about of 90 % and 95 % of the electromagnetic cascade energy is correspondingly concentrated. Thus solving the equations

$$\int_0^{R_m} \frac{2\pi a R^2 r}{(r^2+R^2)^2} dr = 0.9 \quad \text{and} \quad \int_0^{2R_m} \frac{2\pi a R^2 r}{(r^2+R^2)^2} dr = 0.95$$

we get: a = 0.309, R = $0.275R_M$.

Taking into account that in the agreement with (5) the maximum of the density energy deposition take place at r = 0 we find that the maximum number of particles in the beam pulse couldn't be more than

$$N = 6.4 \cdot 10^{12} \cdot C_p \cdot \rho \cdot \Delta T \cdot R_M^2 / (dE/dz) \qquad (6)$$

where: ΔT is the allowable heating at pulsed energy deposition, C_p and ρ are the specific heat and the density of the substance.

Bearing in the mind that for various substances the figure $(1/\rho) \cdot (dE/dz)_{max}$ is approximately the same and using (2) and (3) we come to the conclusion that the number N is proportional to the value

$$k_1 = C_p \cdot \Delta T \cdot R_M^2 / M, \qquad (7)$$

Hence, the most heat resistant materials, i.e. most suitable for pulsed loadings are that having higher C_p and ΔT and lowest nuclear charge. As allowable ΔT usually is chosen the least one between two quantities [1]

$$\sigma_{0.2} /(E \cdot \alpha) \text{ or } 0.2 \cdot (T_m - 20^o C), \qquad (8)$$

where: $\sigma_{0.2}$ is the plasticity limit, E is the elastic modulus, α is the coefficient of linear thermal expansion and T_m is the melting temperature.

In table1 the parameters of the materials, which can be considered as candidates for collimators are given.

Subst	ρ	C_p	λ	ΔT	T_m	R_M	$L_{99\%}$	M	k_1	k_2
	g/cm^3	J/g×K	W/cm×K	deg	^{o}C	cm	cm			
W	19.34	0.134	1.685	660	3380	0.93	10	3007	0.021	0.098
Cu	8.93	0.388	3.896	150	1083	1.62	35	1338	0.070	0.348
Fe	7.88	0.440	0.744	240	1535	1.78	42	1233	0.156	0.119
Al	2.7	0.896	2.093	60	660	4.8	190	671	0.387	0.768

Table 1: The parameters of materials (*E*=250 GeV).

In the steady state we accept that the energy deposition and the temperature do not vary in the time, i.e. we replace pulsed energy deposition and sawtooth changing of the temperature with the averaged in the time values. Then for the accepted energy density deposition distribution the heat equation will be:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr} \right) = -\frac{4.09 \cdot dE/dz}{\lambda R_M^2 (1+(3.64r/R_M)^2)^2} \qquad (9)$$

where: λ is the heat conductivity.

Taking into account the boundary conditions, which mean that on the axis of the cylinder the temperature should remain restricted and at r = R_k (R_k –collimator radius) its value is equal to T_0 the solution of this equation can be written as

$$T = T_0 + (1.02 /\lambda)\cdot(\ln ((R_M^2 + (3.64\, R_k)^2) / (R_M^2 + (3.64\, r)^2)) \cdot (dE/dz) \qquad (10)$$

The highest temperature take place at r = 0 and it should not exceed the melting one of the collimator substance. Therefore the number of particles per second, which can be intercepted should not be more than

$$N = 0.26\cdot10^{14}\cdot\lambda\cdot(T_m – T_0) / (\ln (1+ (3.64\cdot R_k/ R_M)^2)\cdot(dE/dz)) \qquad (11)$$

With the same remarks as for the instant energy deposition case and remembering that usually for any substances it is necessary to take the same relation of R_k/R_M we come to the conclusion that in (11) only the figure

$$k_2 = \lambda\cdot(T_m - T_0) / \rho\cdot M \qquad (12)$$

depends on the substance parameters.

The more this figure is the higher beam intensity sustains the collimator. These dates for the chosen materials are presented in the table1 too. Comparing the factors for various materials for two approaches one can conclude that the most suitable materials for collimators for the instant energy deposition are Fe or Al but for the steady state regime only Al has the preference. Of this reason in the further we shall consider collimators manufactured of Al.

All above made discussions were carried out to find a simple criteria for the comparison of the heat resistance of different materials at two heating stage at the simplified geometry. Quantitative dates of the energy deposition distributions and accordingly of the temperature in real construction will be essentially different from the considered one. Nevertheless the found ratio between the heat characteristics for different materials for different heating stage shouldn't change very much.

RECTANGULAR COLLIMATOR

At the choice of the longitudinal and transverse collimators dimensions fig.1 we shall proceed from the following reasons. The longitudinal path of particles in the substance should be such that they loose at least 99 % of initial energy. For this purpose the collimators length should be not less, then [1]

$$L = (\ln (E^{1.52} / E_c^{4.1}) + 17.6)\cdot L_r.$$

where: L_r is the radiation length of substance.

The thickness of a collimator jaw, which intercepts the beam should be equal or more

$$\Delta x = \Delta x_b + 2R_M$$

where: Δx_b is the effective size of the intercepting beam.

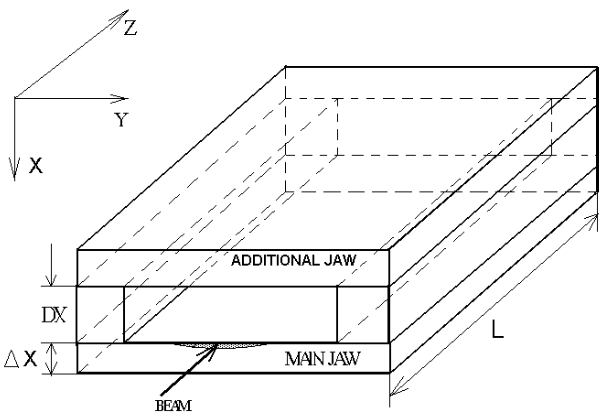


Fig.1: Rectangl collimator (variant A).

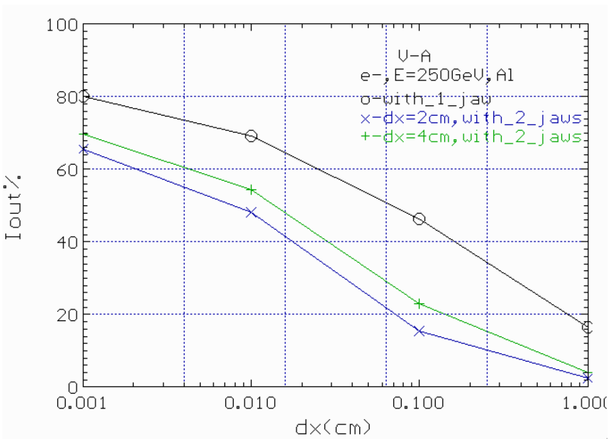


Fig.2: The collimator efficiency versus dot beam position.

As will be shown later using only one jaw, which direct intercepts the beam isn't effective because about 50 % or more of beam energy escapes. To exclude this on the other side of the beam is

reasonable to put an auxiliary jaw. The thickness of such jaw is accepted equal $2R_{M.}$ At such approach the absorption up to 95 % of the beam energy is provided. We believe that 5 % of the intercepting beam energy will be absorbed by the water cooling system if it will be foreseen. Without it instead of the size $2R_M$ it is necessary to take $3R_M$.
High energy electrons or positrons (250 GeV and higher, as in the TESLA- project) create an electromagnetic cascade of a complex spatial structure, which defines the distribution of the energy density deposition over the volume. The electromagnetic cascade structure becomes still more complicate if it is necessary to take into account the geometrical configuration and sizes of the collimator, the different particles density distribution of the intercepting beam. It is quit obvious that defining of the temperature distribution in a collimator with real boundary conditions on its surfaces, bearing in the mind the temperature dependence of the substance heat parameters is possible only by the numerical calculation. For this purpose the program [6], which allows by Monte Carlo methods to simulate processes of the electromagnetic cascades development in three-dimensional structures, to find the energy density deposition and the temperature distributions were used. We start with a rectangular collimator, in which the jaw can be located along one, two opposite, three or four sides. The outside part of the jaw can be joined to a cooling system.

The expedience of the collimators using depends on their efficiency. As an efficiency we understand the relation of the beam energy absorbed directly inside the collimator body to the total energy stored in the intercepting beam. It is obvious, that the collimator efficiency depends basically on three circumstances: from the particles density distribution in the intercepting beam at the collimator entrance, from the collimator geometry and from the electromagnetic cascade shape in it. In fig.2 the dependence of the leaked from a collimator energy as a function of doted beam position relative the collimator edge in the transverse plane is presented. Using it in principle it is possible to define the leaked energy for any particles density distribution in the beam. From fig.2 it follows: as closer to the collimator edge the particles enter the more part of their energy is leaked. It is clear that the escaped energy will be dissipated by other accelerator elements what significant decrease the efficiency of the collimator using. It means that it is necessary to attempt to install it there where the dimension of the intercepting part of the beam is more and to undertake additional steps for the increasing of its efficiency. One of such possible step is to use of an additional jaw installed parallel to the main one on the opposite side of the beam axis. The data of fig.2 show that the effect of use of an additional jaw is higher as farther from the edge of the collimator the particles enter and as less the distance between the jaws is.

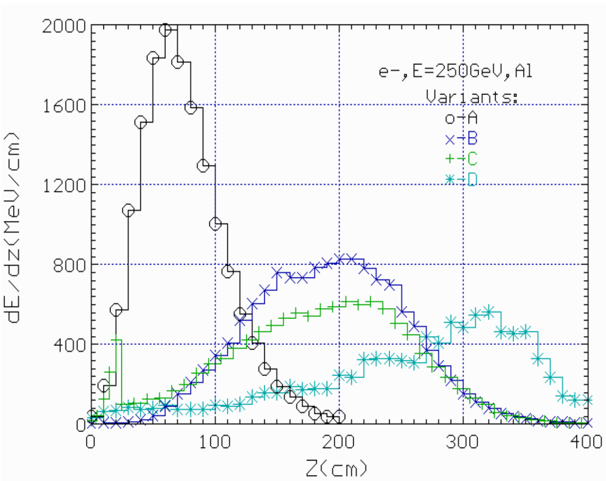


Fig.3: The longitudinal changing of the integrated energy deposition.

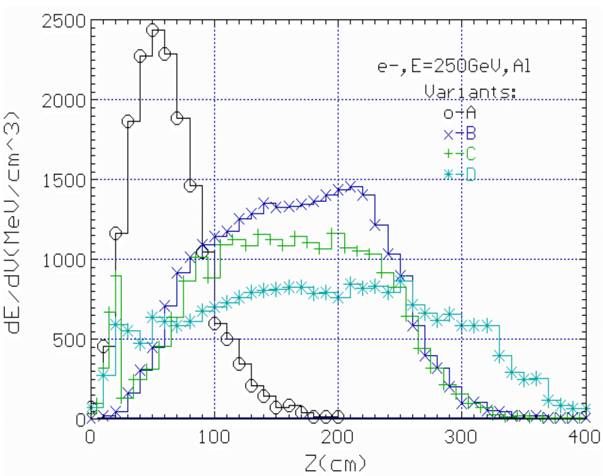


Fig.4: The longitudinal changing of specific energy deposition.

The changing along the collimator length of the energy density deposition and the integrated over the transverse coordinate energy deposition are given in figs.3 and 4. One can do two important conclusions. As specific as integrated energy depositions are rather non-uniform on the collimator length that naturally results a significant non-uniformity also in the temperature distribution. Both distributions are rather similar, though their maximums are a little bit shifted one relative other. In fig.5 the transverse changing of the specific energy deposition in the point of a maximum longitudinal distribution for different beam dimensions is represented. As well as it could be expect the maximum specific energy deposition takes place on the collimator edge and is as more as less the beam sizes are. It is necessary to note that by more detailed consideration it appears that the maximum take place not direct on the edge but is a little bit of few tenth of mm shifted inside the collimator and the value

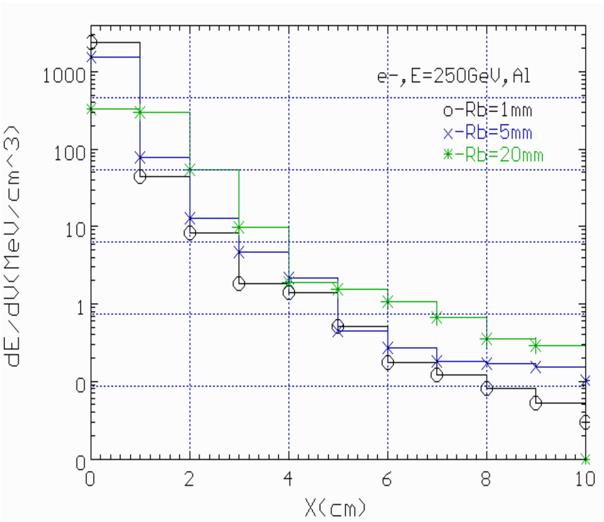


Fig.5: The transverse changing of the specific energy deposition.

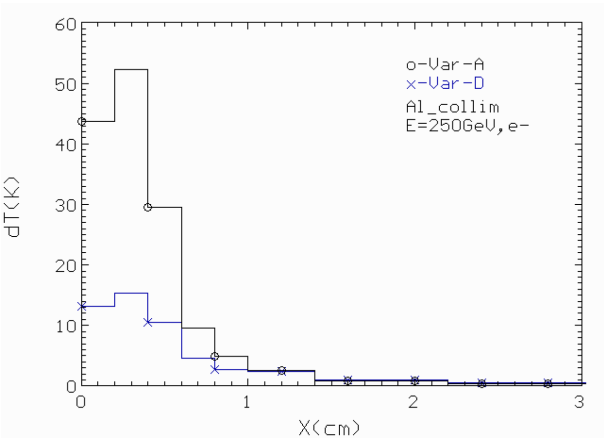


Fig.6: Instant transverse temperature distribution.

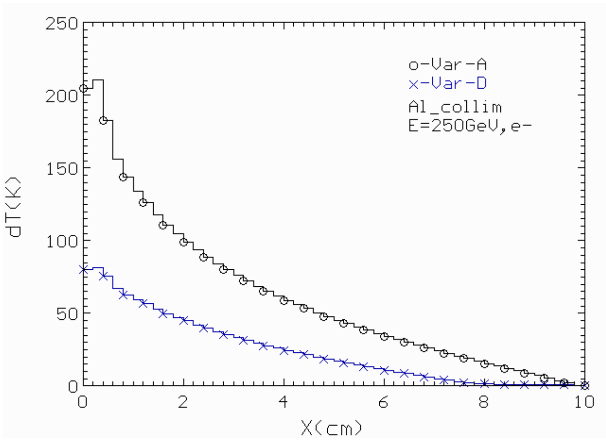


Fig.7: Steady state transverse temperature distribution.

of the specific energy deposition on the edge is of few percent lower than in the maximum (compare with the temperature distribution in figs.6 and 7) one. The explanation is: because the secondary particles having a transverse moment directed outside of the collimator escape it and do not participate in the energy deposition in the maximum of the electromagnetic cascade near the edge. Taking into account the above mentioned one can do a conclusion that both longitudinal and transverse as specific as integrated energy depositions are very non - uniform that results the occurrence of small areas with sharply expressed increased both instant and steady state temperatures. This conclusion is proved by figs.6 and 7 where the mentioned temperature distributions found by numerical solution of the heat equation in the section of the maximum

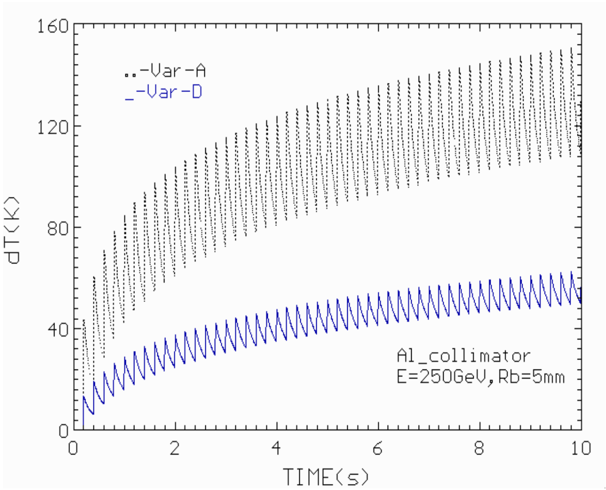


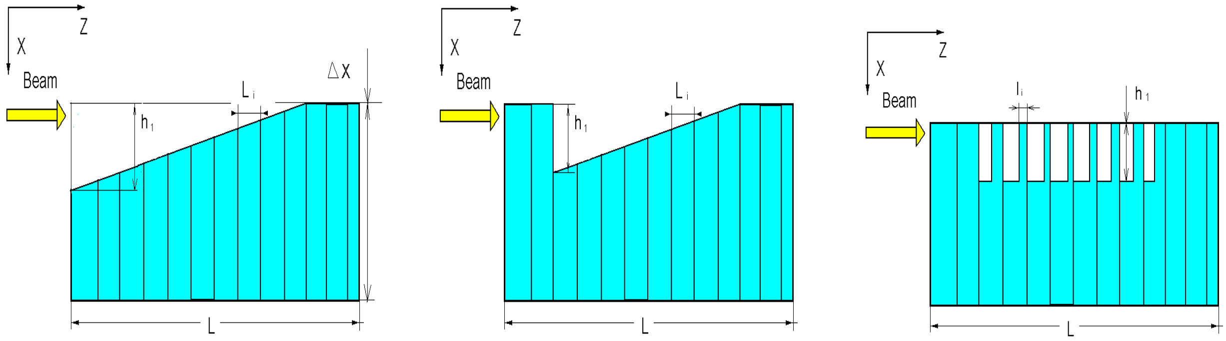
Fig.8: Changing of the temperature maximum in the time.

longitudinal energy deposition are shown. In fig.6 one can clearly see that the maximum instant temperature jump is a little bit shifted inside of the collimator what confirm the before made conclusion that the maximum of the specific energy deposition is not on the collimator edge.

In fig.8 the changing of the temperature in the maximum of energy deposition is presented.

OTHER COLLIMATOR TYPES

The presence of the sharp expressed maximums in the energy and temperatures distributions in rectangular collimator considerable reduce the tolerable level of beam intensity intercepted by it.



B C D

Fig.9: The possible variant of collimator configurations of lowed energy deposition density.

Therefore it is very important to look about other collimator configurations, which permit to get more uniform energy and temperatures distributions and their lower maximum value. Some possible variants are sketched in fig.9. Compare the energy distributions of the presented types with that ones of rectangle collimator shown in figs.3 and 4 one can remark the essentially difference of the data of each type. It happens because the particles having different transverse coordinates create the maximum energy deposition of the electromagnetic cascade in different longitudinal coordinate as in case B and C or due the changing of the effective substance density along the particle path as in case D. It is obvious that the degree of the energy deposition uniformity substantially depends on the ratio of the geometric dimension of different collimator elements and the beam dimension (the curves in figs.3, 4, 10 and 11 for the variants B, C, and D are evaluated for $L_B = Lc = L_D = 2L_A = 4$m, $h_1 = R_b = 5$mm, l is changed from L_1 to $0.1 \cdot L_1$, L_1=10 cm). In fig.10 the relations of the maximum of the specific energy deposition in the rectangle collimator to the same ones of other types are shown for different beam dimensions. It follows that the more decreasing of $(dE/dv)_{max}$ can be get by the using of the variant D.

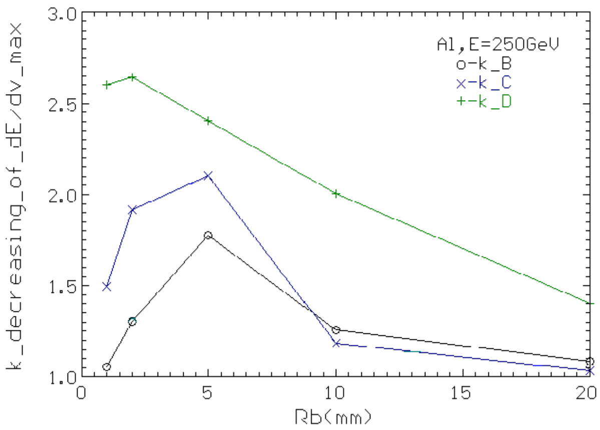


Fig.10: The influence of the beam dimension on the specific energy deposition.

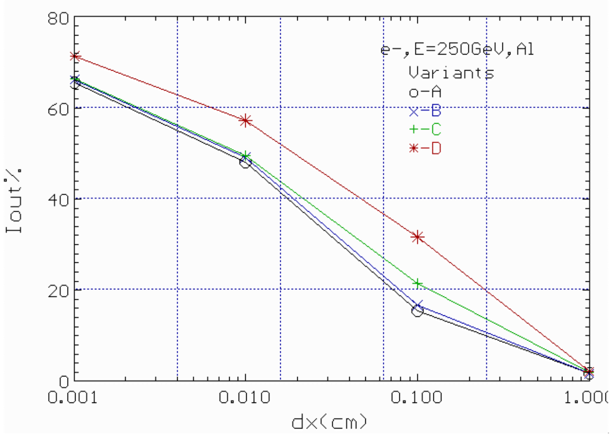


Fig.11: The dependence of the leaked energy as a function of dot beam position.

The penalty for the decreasing of $(dE/dv)_{max}$ and the more uniform energy distribution in the modified collimator configurations is their less efficiency. It came evident if we compare using fig.11 the leaking energy of all considered variants.

CONCLUSION

The possibility of collimator using to intercept the high energy leptons (up to 250 GeV as in TESLA-project), which can not be transferred to the main dump or are not be suitable for the collision is discussed. Is found an approach to compare the tolerable intercepting intensity depending on collimator material characteristics for the instant and steady state temperature regimes. Is shown that for TESLA beam one of the best suitable material for collimators is Al. Using a numerical calculation the energy depositions and temperature distributions are defined in a rectangular collimator. It is found that for the collimator efficiency increasing an installation of an auxiliary jaw is very useful. To get more uniform energy deposition and temperature distribution and consequently to lower their maximum value and to increase the tolerable intercepting intensity few types of collimator configurations are proposed. The penalty for the increasing of the tolerable intercepting intensity of these collimator types is the reducing of their efficiency. The concrete choice of the collimator configuration and dimensions can be done only taking into account the real detailed parameters of the intercepting beam.

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