DYNAMIC EFFECT ON PASSAGE OF A CHARGED PARTICLE BEAM THROUGH SOLID BODIES

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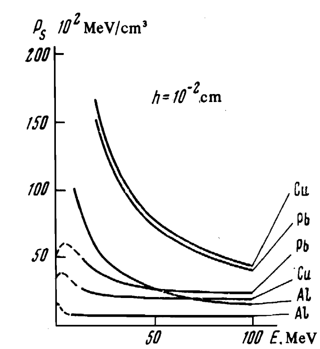
Dynamic loads in a solid body due to passage of charged-particle beams are determined. It is shown that at not very high energies the loads increase linearly with beam energy. At high energies (up to several hundred MeV) the loads are independent of energy in the case of an electron (positron) beam and decreases with increase of energy in the case of a proton beam. An experimental verification of the theory by measuring the amplitude of sound excited by the beam is proposed.

1. Theories of the interaction of fast particles with matter are the subject of an extensive literature. They deal principally with the fate of the beam itself or with the heating of the target material and the various defects that are produced in it. Yet it is no less well known[1-3] that when a beam of fast particles passes through matter dynamic loads are also produced and can lead, in particular, to excitation of elastic oscillations in the medium. The present paper is devoted to an investigation of the character of the dynamic loads and to their dependence on the beam parameters and on the target material[1)].

We determine the longitudinal load (with respect to the direction of the incident beam) in the case of electron (positron) and proton beams. Exact formulas are obtained for two limiting cases, a thin target ($\overline{\theta} \ll 1$, $\Delta E_t \ll E_0$) and a thick target ($h \gg l$), where $\overline{\theta}$ is the rms beam broadening angle, ΔE_t is the total energy lost by the beam particles in the plate, E_0 and l are the initial energy and mean free path of the beam particles, and h is the plate thickness.

At low beam energies (several hundred keV for a plate of thickness on the order of 0.01 cm), the pressure P_S exerted by the beam on the plate does not depend on the target material and increases linearly with energy, $P_S = n_0 p_0 v_0$, where p_0, v_0 and n_0 are the momentum, velocity, and density of the beam of incident particles. At high beam energies, the dependence of the pressure on the energy has a more complicated character. We present here numerical calculations for aluminum, copper, and lead plates 0.01 cm thick at energies starting with several MeV (see the figure). We have no exact formulas for the intermediate energy region. It is nonetheless easy to conclude that the function P_S, which increases at low energies and decreases at high energies, should have a maximum in this region.

We consider the case of beams of not too high a density, namely the energy released when the beam passes through the target material is insufficient for phase transitions or reactions that alter significantly the density and the elastic properties of the target



Dependence of the dynamic load on the beam energy. The ordinates represent the pressure on the plate (calculated for an incident beam of unit density). The lower (upper) curve pertain to an electron (proton) beam.

material (such as vapor production or chemical reactions).

2. We consider a thin plate, $h \ll d/\overline{\theta}$, on which a cylindrical beam of charged particles is normally incident (d is the beam diameter). Introducing the probability density for particle scattering in the target material $W(\theta, \omega)$, we obtain for the change in the beam momentum per unit time (per unit area of the beam cross section)

$$\mathbf{P}_s = J_0 \int_{\Omega} \int_0^E W(\theta, \omega)(\mathbf{p} - \mathbf{p}')\, do'\, d\omega, \tag{1}$$

where J_0 is the flux of the incident particles, p and p′ are the particle momenta before and after scattering by the plate, ω is the change of the particle energy, and θ is the scattering angle. Projecting (1) on the direction of motion of the incident beam and introducing the symbol $\Delta p = |\mathbf{p}| - |\mathbf{p}'|$, we obtain

$$\begin{gathered} P_s = P_{si} + P_{sd}; \\ P_{si} = 2\pi J_0 \int_0^{E_0} \int_0^{\pi} W(\theta, \omega)\, \Delta p \cos\theta\, d(\cos\theta)\, d\omega, \\ P_{sd} = 2\pi J_0 p_0 \int_0^{\pi} W(\theta)(1 - \cos\theta)\, d(\cos\theta), \end{gathered} \tag{2}$$

where

$$W(\theta) = \int_0^E W(\theta, \omega)\, d\omega.$$

We are interested in thin plates, passage through which alters the beam little

$$\overline{\theta} \ll 1, \quad \Delta E_t \ll E_0. \tag{3}$$

[1)]Excitation of elastic oscillations by fast particles was considered in a number of papers [4-6].

We assume first that the beam energy is not very large, $E_0 \ll \epsilon_c$, where ϵ_c is the critical energy (the energy at which the radiative and ionization losses of the particle in the medium become equal). The calculation of the expressions in (2) is then much simpler. Indeed, in the expression for P_{si} we can put $\cos\theta = 1$ and $\Delta p = \epsilon_{ion}(h)/v_0$, where $\epsilon_{ion}(h)$ are the ionization losses in a plate of thickness h. Further, we can substitute for $W(\theta)$ in the expression for P_{sd} the particle angular distribution function for multiple scattering[7]

$$W(\theta)=\frac{2}{\bar{\theta}^2}\exp\left\{-\frac{\theta^2}{\bar{\theta}^2}\right\}. \tag{4}$$

As a result we obtain

$$P_{si}=J_0\varepsilon_{ion}(h)/v_0;\quad P_{sd}={}^1/_2J_0p_0\bar{\theta}^2. \tag{5}$$

The quantity P_s is obviously the pressure exerted by the beam on the plate. The term P_{si} describes the pressure connected with the ionization deceleration of the beam particles in the target material; the term P_{sd} describes the pressure due to the angular broadening of the beam.

If the condition $E_0 \ll \epsilon_c$ is not satisfied, then P_s is only part of the pressure on the target, since it is necessary, generally speaking, to take into account in this case the pressure exerted on the target by the bremsstrahlung photons. In the considered case of a thin target, satisfying the inequality (3), the bremsstrahlung photons are emitted from the target without transferring to the matter appreciable energy or momentum. The contribution made to the pressure by the bremsstahlung photons can obviously be disregarded.

The final expression for the pressure is obtained by substituting in (5) the well-known Bethe formula for the ionization losses and the Moliere formula for $\bar{\theta}$ (see, for example,[7]):

$$P_s=n_0\frac{2\pi e^4nz}{v_0}h\left\{\frac{2\Lambda_B}{mv_0}+\frac{\Lambda_M(z+1)}{p_0}\right\}, \tag{6}$$

where z and n are the atomic number and the number of atoms per unit volume of the target material; Λ_B and Λ_M are factors that depend logarithmically on the energy and are of the order of 2–10.

The dependence of the pressure on the beam energy for aluminum, copper, and lead plates of thickness $h = 10^{-2}$ cm is shown in the figure. We see that in the case of an electron (positron) beam the pressure is independent of the energy in a wide range of energies; only in the region of relatively low energies should a certain decrease of pressure be observed with increasing energy. In the case of a proton beam, the pressure decreases monotonically with increase energy. We note that according to (6) the value of P_s is proportional (with logarithmic accuracy) to the plate thickness h. Therefore in the region where the theory is applicable (i.e., for $h < 10^{-1}$–10^{-2} cm) the presented diagrams make it easy to determine the pressure in the case of plates of arbitrary thickness.

3. We consider now the case of a thick target, in which the beam is completely absorbed, $h \gg l$ (l is the cascade length in the substance). In this case the pressure exerted on the target is obviously equal to the total momentum introduced by the beam particles per unit time into the interior of the target (per unit beam area).

$$P_s=n_0p_0v_0. \tag{7}$$

Of course, this formula is valid for sufficiently broad beams $l\theta_0 \ll d$, where θ_0 is the average divergence angle of the cascade particles. If this inequality is not satisfied, then the momentum transferred to the target (per unit time) is equal, as before, to $(^1/_4)n_0p_0v_0\pi d^2$; in this case, however, it is distributed not over a region $(^1/_4)\pi d^2$, but over a larger region, since this pressure is no longer determined by formula (7).

Since the range of the particles in the target material increases with increasing energy, formula (7) is valid for a plate of definite thickness in the case of low beam energies. In the case of high energies, conditions (3) are satisfied, and then formula (6) holds. For the intermediate energy region we have no exact formula, but it can be concluded nevertheless that P_s, which increases at low energies and decreases at high energies, should have a maximum in this region.

4. The dynamic loads produced in a solid passage of a beam should lead, in particular, to excitation of elastic oscillations in the solid. The amplitude of the excited elastic oscillations is obviously proportional to the dynamic load, and therefore the change of the amplitude should serve as an experimental check on the theory of dynamic loads. It is particularly easy to trace the dependence of the load on the density, type of particle, and beam energy. To this end it suffices to compare the amplitudes of the sound excited by different beams in one and the same target.

It is somewhat more difficult to verify the dependence of the dynamic loads on the target material. It is apparently easiest to do so by using scaling considerations. Namely if two substances have close Poisson coefficients σ, then plates made from these substances, with linear dimensions l having the same ratio as $(E/\rho)^{1/2}$,

$$l_{1x}:l_{2x}=l_{1y}:l_{2y}=l_{1z}:l_{2z}=(E_1/\rho_1)^{1/2}:(E_2/\rho_2)^{1/2},$$

are acoustically equivalent in the sense that the amplitudes u of the sound excited in them are related like the corresponding loads

$$u_1:u_2=P_{s1}:P_{s2}$$

(E and ρ are Young's modulus and the density; the subscripts 1 and 2 pertain to the two substances).

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