MAGNITUDE OF THE SUPERSTRONG MAGNETIC FIELD PRODUCED IN SELF-DESTRUCTIVE SINGLE-TURN SOLENOIDS

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The amplitude of the induction in a superstrong magnetic field becomes much smaller than its theoretical value, owing to the rapid increase of the inside radius of the solenoid during the course of the discharge of the high-power capacitor bank. In this paper a simple estimate is derived for the amplitude of the induction B_m in the limiting case when the effective internal radius of the solenoid r increases noticeably before the current reaches its maximum value I_m. In such conditions B_m is much smaller than its theoretical value [1 - 3].

To find the asymptotic character of the relation $B_m = f(I_m, \tau)$, where τ is the current growth time, it is necessary to analyze the possible growth mechanisms of the effective inside radius with allowance for the similarity conditions. The most important process is the flow of metal in the radial and axial directions under the influence of magnetic pressure. This process can be described in the approximation of an ideal incompressible fluid, since the influence of the strength is negligible in megagauss fields, and the effects connected with the compressibility of the material and with the formation of a shock wave does not play a noticeable role in short solenoids, where $\ell/c < t_m$ (ℓ is the length of the solenoid, c the speed of sound, and t_m the time taken by the induction to grow to its maximum). Two other processes are the diffusion of the field in the conductor [4, 5] and the electric explosion of the skin layer [3, 4]. The most probable mechanism of the electric explosion in short solenoids is the ejection, in the axial direction, of metal heated above the melting point. Then, as shown by calculations, the thickness of the layer of molten metal is close to the thickness of the skin layer, provided $B^2/2\mu_0 >> Q_s$ (Q_s is the melting heat). Taking the foregoing into account, we arrive at the following functional relation for B_m:

$$B_m = f(r_0, \ell_0, I_m, \tau, \gamma, \rho_0, \beta, \mu_0), \quad (1)$$

where ρ_0 is the resistivity under the initial conditions, β the thermal coefficient of resistivity [5], r_0 and ℓ_0 the initial inside radius and length of the solenoid, respectively, γ the density of the material, and μ_0 the magnetic constant. It is further possible to eliminate four quantities with independent dimensionalities [r_0, γ, μ_0, and $(di/dt)_0 = \pi I_m/2\tau$]:

$$B_m = \mu_0^{3/4} \gamma^{1/4} (di/dt)_0^{1/2} \phi(q_1, q_2, q_3, \eta), \quad (2)$$

where

$$q_1 = (\tau^{3/4}/r_0)(di/dt)_0^{1/2}(\rho_0\beta)^{1/4}, \quad q_2 = (\mu_0/\gamma)^{1/4}(\tau/r_0)(di/dt)_0^{1/2},$$
$$q_3 = \rho_0 \tau/\mu_0 r_0^2, \quad \eta = \ell_0/r_0,$$

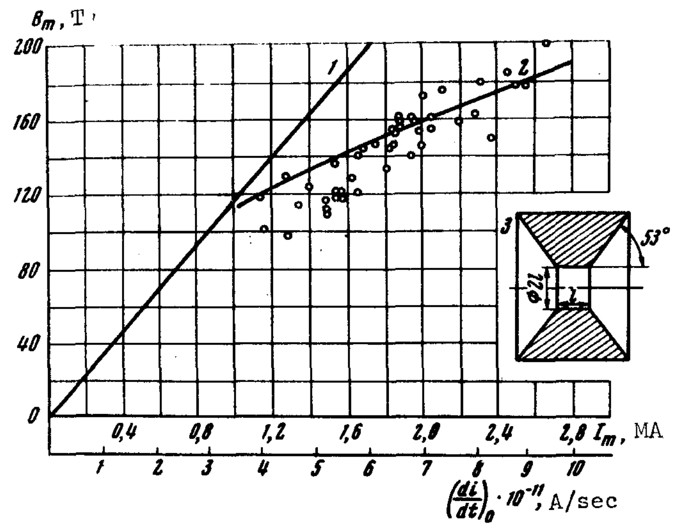
and $(di/dt)_0$ is the initial current growth rate.

The parameter q_3 is connected with the diffusion of the field in the cold metal and plays no role in strong fields.

A theoretical analysis was performed for each of the three effective-radius growth mechanisms in the limit of large $(di/dt)_0$. In the case of purely hydrodynamic flow of an incompressible fluid with ideal conductivity ($q_0 = 0$) and $q_2 \gg 1$ we have $\phi = C_1$, and in the case of diffusion of the field without displacement of the field-conductor interface ($q_2 = 0$) and $q_1 \gg 1$ we have $\phi = C_2 q_2/q_1 = C_2(\mu_0\tau/\rho_0\beta\gamma)^{1/4}$. In the case of metal ejection under the condition $q_1^{2/3}q_2^{1/3} \gg 1$ we have $\phi = C_3(\mu_0\tau/\rho_0\beta\gamma)^{1/6}$, where the numbers C_1, C_2, and C_3 depend only on the geometric parameter η. In other words, at very large $(di/dt)_0$ the value of B_m increases, in accordance with each of the three models in proportion to $(di/dt)_0^{1/2}$, depends little on τ, ρ_0, or γ, and does depend on r_0. The same is to be expected if all three mechanisms act simultaneously:

$$B_m \approx C(\eta)\mu_0^{3/4}\gamma^{1/4}(di/dt)_0^{1/2}, \tag{3}$$

where C should not change strongly on going, for example, from copper to steel and when τ lies in the microsecond range. For solenoids of a given shape and made of a given material, we have in the strong-field limit $B_m \simeq A(di/dt)_0^{1/2}$, where A is a constant.



Amplitude of the induction in copper solenoids: o - experimental points; 1 - model measurements; 2 - $B_m = 0.53\ \gamma^{1/4}\mu^{3/4}(di/dt)_0^{1/2}$; 3 - section through solenoid.

The figure shows the results of measurements of the amplitude of the magnetic field in copper solenoids with initial aperture dimensions $r_0 = 1.7$ mm and $\ell_0 = 3r_0/2$. For the chosen shape of the solenoid (see the figure), the induction and the current are connected by the relation $B = bi/r$, where b is a constant. This has made it possible to find the rate of change of the radius by simultaneously reducing the current and induction oscillograms [3]. The quantity $dr/dt = f(t_m)$ varies in the investigated range of B_m (up to 200 T) between the limits 400 and 600 m/sec. The experiments were performed at a fixed current growth time $\tau = 4.5 \pm 0.2$ µsec. A comparison with the plots of formula (3) (using C = 0.53 for copper) shows that $B_m = f[(di/dt)_0]$ approaches the value in (3) asymptotically, and only when B_m decreases does it approach a linear relation. A similar result is obtained from an investigation of steel solenoids, for which C = 0.48. Although the geometry of the solenoid and the growth time in [1, 3] differed from the values indicated here, nonetheless the coefficient C has according to [3] the value 0.64, and the data of experiment H3 of [1] yield C = 0.52. It can therefore be assumed that formula (3) can be used for roughly estimating the field at various solenoid geometries if it is assumed that C = 0.5 - 0.6. In the experiments described in a recent paper [2] the field in copper solenoids was much lower than the calculated value, and therefore formula (3) is valid. It yields B_m = 170 - 200 T (at $(di/dt)_0 = 8.3 \times 10^{11}$ A/sec) and a measured value B_m = 200 T.

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RELATIVE ROLE OF VARIOUS IONIZATION PROCESSES IN SLOW COLLISIONS OF K^+ IONS WITH INERT-GAS ATOMS

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One of the methods of investigating various ionization processes occurring in collisions between atomic particles is to analyze the energy spectra of the electrons released as a result of such collisions. Investigations have shown (cf. e.g., [1]) that the electron spectra can contain two components. One of them is characterized by a continuous energy distribution and includes mainly the slow electrons (≲1 eV), and the other constitutes groups of electrons with discrete energies on the order of 10 eV. The origin of the groups of fast electrons can be attributed to the excitation of autoionization states of the target atom in collisions and subsequent decay of these states:

$$A^+ + B \to A^+ + B^* \to A^+ + B^+ + e \quad (1)$$

On the other hand, the appearance of slow electrons is connected with a number of processes: direct ionization

$$A^+ + B \to A^+ + B^+ + e, \quad (2)$$

ionization with excitation

$$A^+ + B \to A^+ + B^{+*} + e, \quad (3)$$

and multiple ionization

$$A^+ + B \to A^+ + B^{n+} + ne. \quad (4)$$

However, there are serious difficulties when attempts are made to assess the relative roles of even these two groups of ionization processes, namely (1) and (2) - (4), on the basis of the energy spectra of the electrons. These difficulties are connected with the determination of the intensities of the electron-spectrum components, which leads to the need for the study of the angular distribution and of determining with sufficient accuracy the yield of the slow electrons.

To determine the contributions of the different processes to the ionization energy in ion-atom collisions, we have used in this study the analysis of the kinetic energy of the incoming ions after they collide with the gas-target atoms. The experiments were performed with a setup that differed from that used by us in [2] to study electron-atom collisions in that the electron gun was replaced by a system consisting of a thermo-ionic source and a magnetic mass spectrometer with a sector field. We determined experimentally the dependences of the differential ion-scattering cross sections at fixed angles on the inelastic energy loss (inelastic-loss spectra) and the dependence of the differential cross sections on the scattering angle at fixed inelastic losses.