Formation of dense plasma on the surface of a stainless steel conductor in superstrong magnetic fields

V A Kokshenev, R K Cherdizov and N E Kurmaev

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia

E-mail: vak@oit.hcei.tsc.ru

Abstract. In experiments on the GIT-12 megaampere generator, the characteristics of conductors made of AISI 321 stainless steel were investigated in the microsecond regime of increasing superstrong magnetic fields. In this regime, a skin explosion of the conductor material takes place with the formation of a dense plasma and its expansion into the interelectrode gap of the vacuum transmission line. The values of the characteristic magnetic field $B_0 \equiv 100$ T are determined, above which there is the effect of nonlinear diffusion of the magnetic field into the conductor, and the critical magnetic field $B_{cr} \equiv 260$ T, the excess of which leads to the formation of dense plasma on the surface of the massive conductor. A method is proposed for increasing the critical magnetic field on the surface of a conductor up to 1.5 times by choosing the optimal thickness of the conducting surface, and criteria for its determination are given. The effect of increasing the critical magnetic field on the surface of a two-layer sample and creating a pressure in the Mbar range until the moment of formation and expansion of explosion products of an inner conductor with high conductivity has been tested.

1. Introduction
On the GIT-12 generator, experiments were continued [1] to determine the limiting values of magnetic fields on the surface of the conductors, above which there is a skin explosion of the conductor material with the formation of dense plasma and its expansion into the interelectrode gap of the vacuum transmission line. In such regimes, the time of energy input into the conductor is less or comparable to the time of diffusion of the magnetic field. Joule heat release occurs in the surface layer of a substance with a size of the order of the thickness of the skin layer $\Delta = (\rho \tau / \mu_0)^{1/2}$. At this stage of research, the characteristics of AISI 321 stainless steel, which is the main structural material of the central unit of the GIT-12 generator, have been investigated. For pure metals (Cu, Al, Ti, Fe), their behavior in superstrong magnetic fields was studied in detail and the values of the characteristic and threshold magnetic fields for a current front of $\sim 100$ ns were determined (MIG generator, [2]). For stainless steel, these characteristics are either unknown or assumed to be equal to those for iron, which may not be entirely obvious when going to characteristic current rise times of $\sim 1 \mu$s (GIT-12).

2. Experimental results
The experiments were carried out on a GIT-12 generator at a charging voltage of 50 kV at a current amplitude in the samples up to 4.3 MA with a rise time of $\sim 1.8 \mu$s. The design of the load unit is
shown in figure 1. Samples of stainless steel (SS) had a continuous galvanic contact at the cathode up to a diameter of 320 mm. A tight sliding contact was used at the anode in a smooth transition with a depression of 5 mm, since as a result of vacuum pumping, a slight decrease in the interelectrode gap of the radial line occurs. The experiments were carried out with AISI 321 stainless steel samples in the form of rods or tubes with an outer diameter of 3, 4 and 6 mm and a wall thickness of 0.25, 0.5, 0.9 and 1 mm. In addition, we investigated two-layer conductors with an outer layer of stainless steel with a wall thickness of 0.25, 0.5, and 1 mm, and inside a tightly inserted copper conductor with diameters of 2, 3 and 3.5 mm. The samples either had a uniform structure along their entire length, or were composite. The upper anode half of the cylinder remained solid, while the lower half was a stainless steel layer with a copper insert.

![Figure 1](image_url)

**Figure 1.** Scheme of the load node of the generator GIT-12. SS4/3 - stainless steel conductor, 
$U_l$ - voltage sensor, $M_g$ and D1-D3 - inductive grooves for measuring the generator current $I_g$ and load current $I_z$, NG1-2 - two-frame electro-optical complex "Nanogate Frame-9".

Inductive grooves were used to measure the shape and amplitude of the current pulse. The currents were measured at the collecting electrode of the central unit $M_g$ ($I_g(t) = \int M_g(t) \, dt$) and on the coaxial transition to the radial line D1-3 ($I_z$), in the center of which the samples were installed. To determine the symmetry of the current injection into the conductor under study at the input of the load unit, the signal from the inductive groove was recorded at 3 points (D1, D2, D3) located symmetrically in azimuth at 120°. In addition, magnetic probes (B-dot) were installed at radii of 6 and 9 cm. The voltage divider recorded the voltage $U_l(t)$ at the collecting electrode of the GIT-12 central unit. The resulting oscillograms made it possible to calculate the inductance of the circuit section from the collection electrode to the short-circuited load $L_v(t) = \int U_l(t) \, dt / I_z(t)$, the voltage on the sample $U_z$, as well as the value $L(t) = U(t) / dI_z / dt$, which is sensitive to small changes in parameters in the load circuit. From the oscillogram of the current, the integral of the total action was calculated $J = \int I_z^2 \, dt$. Parameter $J$ uniquely determines both the energy released in the sample volume and its resistance. The recording of the intrinsic radiation of the surface plasma of the conductors in the optical range was carried out using a two-frame electro-optical complex "Nanogate Frame-9" (NG 1-2) with a frame exposure time of 10 ns. The frames from the cameras NG1 and NG2, synchronized with the oscillograms of the current, voltage and, accordingly, the values of $L(t)$, $U_z(t)$,
J(t), made it possible to record the change in the sample size at different times from the beginning of the current. The oscillograms of the current I(z) and the parameter J(t) in all shots had practically the same shape, at least up to t = 1.5 μs from the beginning of the current.

In figure 2 shows the typical diagnostic results used in the experiment, in this example for shot #2761 (4/3 mm diameter stainless tube). It can be seen that by the maximum voltage U_z, the outer diameter of the tube remained practically unchanged (an increase of ≤ 10%, frame 1), the current by this moment is distributed over the entire wall thickness (ΔSS ≈ 1 mm > Δtube = 0.5 mm) and the integral of the total action J corresponds to the cross-sectional area of the tube S = 0.055 cm². Joule heating reaches the sublimation energy, which leads to the explosion of the tube with ionization of material vapors and their expansion at a speed of v ~ 6 mm/μs and a voltage drop across the sample. The moment of explosion corresponds to \( J = hS^2 \sim 4 \times 10^9 \text{ A}^2\text{s} \), hence the integral of the specific action \( h = J/S^2 \sim 1.3 \times 10^9 \text{ A}^2\text{s/cm}^4 \). The onset of an increase in the voltage U_z is associated with the onset of a nonlinear increase in the resistivity ρ and the appearance of nonlinear diffusion of the magnetic field into the conductor. The magnitude of the magnetic field corresponding to this moment is called the characteristic magnetic field \( B_0 \) and in a given shot it is equal to \( B_0 \sim 100 \text{ T} \). Analysis of experiments with sample diameters of 3 and 6 mm with wall thicknesses of 0.25 and 1 mm eventually made it possible to establish the following values of the integral of the specific action \( h_{SS} \sim (1.2±0.1) \times 10^9 \text{ A}^2\text{s/cm}^4 \) and the characteristic magnetic field \( B_0 \sim 100±10 \text{ T} \) for steel AISI 321. Estimates are made for the temperature coefficient of resistance \( \alpha_{SS} \sim (7.8±0.1) \times 10^{-4} \text{ K}^{-1} \) and the thermal coefficient \( \beta_{SS} \sim 2.5 \times 10^{-10} \text{ m}^3/\text{J} \).

Figure 2. Shot # 2761. Stainless steel tube with an outer diameter of 4 mm and a wall thickness of 0.5 mm. The main quantities used to analyze the characteristics of stainless steel, the current in the sample I_z, the voltage across the sample \( U_z(t) = U_I(t) - L_0dI/dt \), associated with an increase in resistance with increasing temperature of the sample material, the integral of the total action \( J \), \( L_0 \) is the initial inductance of the load node. On the right, time-lapse images of the sample obtained with the cathode-optical cameras NG 1, 2, squares 1, 2 show the moments of exposure.

In experiments with samples consisting of two sections, the upper one is a solid cylinder 4 mm or 6 mm in diameter, the lower one is a tube with a wall of 1 mm or 0.9 mm, the value of the critical magnetic field \( B_{cr} \), at which the surface of a massive conductor explodes, is determined. The \( B_{cr} \) value with an error ±5% is for AISI 321 stainless steel \( B_{cr} \sim 260 \text{ T} \). The effect of the presence of an optimal conductor thickness, at which the magnitude of the magnetic field on the surface can exceed \( B_{cr} \) by a factor of 1.2-1.3, has been established. The effect is associated with the appearance of a wave of nonlinear diffusion in superstrong magnetic fields \( B(t) \) is significantly greater than \( B_{cr} \).
into the depth of the conductor, the current density on the surface and, therefore, the energy released in the subsurface layer grows in proportion to the energy density of the magnetic field on the surface. As a result, if the wave penetrates through the thickness (or radius) of the conductor before the magnitude of the magnetic field on the surface reaches $B_0$, the current density over the cross section of the conductor will level out and the parameter $J_0 = \frac{h_0}{4\pi}$ will take effect. In figure 3 shows frames 1-3 of optical shooting with NG 1, 2 cameras for an experiment with a sample consisting of two sections, the upper one is a solid cylinder 6 mm in diameter, the lower one is a tube with a wall thickness of 0.9 mm. The oscillogram of the current $I(t)$ and the parameter $J(t)$ correspond to those in figure 2. The characteristics of the presented frames are as follows; frame 1 - current $I_s = 3.7$ MA with rise time 1280 ns, $B(t) = 250$ T, $J = 6.3$ kA²/s, frame 2 - current $I_s = 4.1$ MA with rise time 1500 ns, $B(t) = 275$ T, $J = 11$ kA²/s, frame 3 - current $I_s = 4.25$ MA with rise time 1900 ns, $B(t) = 282$ T, $J \sim 18$ kA²/s. The photographs clearly show that at the beginning (frames 1, 2), when the magnetic field $B(t) = 250$ T ~ $B_c$ is reached, plasma formation occurs on the surface of a solid conductor 6 mm in diameter, but there is no plasma on the tube. The value of the skin-layer of nonlinear diffusion $\Delta_0$ is greater than the thickness of the tube wall, but less than the radius of the conductor (3 mm). The optimal wall thickness can be defined as: $\Delta_{tube} \leq \Delta_0 + \delta$, where $\Delta_0$ is the value of the skin-layer of linear diffusion until the moment $B_0$ is reached on the surface. The dimension $\delta$ is the distance traveled by the nonlinear diffusion wave during the time in the magnetic field from the value $B_0$ to $B_{cr}$ ($\Delta_{cr} = \Delta_{cr} - \delta$). The values of $\delta_t$ and $\tau_{cr}$ depend on the law of increasing magnetic field $k = f(B(t))$. For a linear increase in the magnetic field $B(t) = kt$ and under the assumption of a constant propagation velocity of the nonlinear diffusion wave $v_{cr} = (\frac{\rho}{2\mu_0})^{1/2}$ [3], the quantity $\delta$ can be defined as $\delta = (B_{cr} - B_0)v_{cr}/k$. For steel AISI 321, we obtain the following expression for the tube wall $\Delta_{tube} \leq \Delta_0 + \delta = (B_{cr} - B_0)v_{cr}/k + \Delta_0 \cong 16/k^{1/2}$. In our experiments on the GIT-12 generator, the average rate of increase of the magnetic field is $k \cong 3 \times 10^8$ T/s, and for the optimal tube wall thickness, we can write $\Delta_{tube} \leq 16/k^{1/2} \cong 1$ mm.

The effect of increasing the critical magnetic field on the surface of a conductor [2] was tested in experiments with a two-layer sample: an outer layer of stainless steel with a wall thickness of 0.25, 0.5 and 1 mm, and inside a tightly inserted copper conductor with diameters of 2, 3 and 3.5 mm. The maximum magnetic field without a registered increase in the diameter of a stainless steel tube (measurement error $\leq 10\%$) reached 370 T, which is $\sim 1.5$ times higher than $B_{cr}$ for a massive conductor. By the time the parameter $L(t)$ grows rapidly with a simultaneous increase in the sample diameter, the resistance of the stainless tube can exceed the resistance of a copper conductor with a skin layer thickness for nonlinear diffusion by $\sim 15$ times. The main part of the current flows in the copper conductor and the magnitude of the magnetic field pressure $p_m = H^2/8\pi$ on the surface of copper conductors with a diameter of 3 or 2 mm can reach 1.2-1.5 Mbar. In figure 4 shows images from NG cameras for options with a stainless conductor with an outer diameter of 4 mm. Frame 1 - a stainless steel tube with a wall thickness of 0.5 mm with a copper cylinder 3 mm in diameter nested inside. In frame 2, for comparison, the top of the load is a solid stainless steel cylinder. The shape of the current pulse $I(t)$ and the parameter $J(t)$ practically corresponds to that shown in figure 2. For frame 1 - current $I_s(t) = 4.1$ MA with rise time 1500 ns, $J = 10$ kA²/s, for frame 2 - current $I_s(t) = 4$ MA with rise time 1430 ns, $J = 9$ kA²/s. The expansion velocity of explosion products for a solid rod made

![Figure 3. Images taken with NG 1, 2 optical cameras at different times from the beginning of the current: 1 – 1280 ns, 2 – 1500 ns, 3 – 1900 ns. On the right, the structure of a sample made of AISI 321 stainless steel is shown.](image-url)
of stainless steel AISI 321 was $v \sim 6.3$ mm/μs. Thus, in a two-layer structure of a conductor with an outer layer of lower conductivity, higher values of the magnetic field induction on the surface of the conductor are achieved without its explosion. This is due to the appearance of the effect of nonlinear diffusion of the magnetic field deep into the conductor in superstrong magnetic fields of several hundred T with a microsecond front, which leads to a decrease in the Joule heating of the surface layer due to the redistribution of the current density over the cross section.

![Figure 4](image)

**Figure 4.** Images taken with NG 1, 2 optical cameras at close time moments from the beginning of the current for two-layer samples with an outer layer of AISI 321 stainless steel 0.5 mm thick with a copper conductor 3 mm in diameter embedded inside. In frame 2, the top of the load is a 4 mm diameter solid stainless steel cylinder.

3. **Summary**
The work investigated the behavior of samples made of stainless steel AISI 321 in superstrong magnetic fields. The experimental technique [1] made it possible to determine the characteristic values of this material and the critical values of the magnetic field at which the surface of the stainless steel conductor explodes. The possibility of increasing the critical magnetic field on the surface of a conductor with an optimal conductive layer thickness is shown. The increase in the critical parameters is due to the non-monotonic distribution of the current in the sample volume due to the interaction of competing skin-effect processes and nonlinear diffusion of the magnetic field into the conductor.

**Acknowledgements**
The work was performed under State Assignment of the Ministry of Science and Higher Education of the Russian Federation (project No. FWRM-2021-0001).

**References**
[1] Kokshenev V A, Kurmaev N E and Fursov F I 2018 *Izv. Vuz. Fiz.* [in Russian] 61 171–5
[2] Chaikovsky S A, Oreshkin V I, Datsko I M, Labetskaya N A and Ratakhin N A 2014 *Phys. Plasmas* 21 042706
[3] Shneerson G A 1973 *Sov. Phys. Tech. Phys. – U.* 18 268