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STOCHASTIC OSCILLATORS

Formation of Turbulent Electron Beams for Generating Broadband Chaotic Oscillations

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Abstract—Oscillators of broadband chaotic oscillations, based on the use of intense turbulent electron beams, have been investigated. Different concepts of forming such beams are considered, and their structure is experimentally studied. The results of the experimental study of the oscillations generated by the broadband microwave sources developed are reported.

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1. INTRODUCTION

Currently, high-power broadband microwave sources are developed, produced, and studied not only to solve problems related to radio jamming [1]. Such sources are also needed for promising data transmission systems based on dynamic chaos and for noise radars [1, 2], as well as in manufacturing industry [3]. To date, chaotic signals are generated in different ways [1, 2]. Their main drawbacks are the difficulties of practical implementation; the presence of external feedback loop, which limits the band of generated frequencies; and low output power. Thus, an urgent task is to search for and develop methods for generating chaotic RF and microwave oscillations, which would be free of these drawbacks and make it possible to obtain broadband and ultra-broadband chaotic RF and microwave signals with a low irregularity of spectral characteristic and a high output power in a simple scheme, without an external feedback loop. We propose to use specially formed intense turbulent electron beams (TEBs) to this end.

2. TURBULENT ELECTRON BEAMS

The following concepts are used in electron optics [4]: laminar electron beams (where all electrons have the same velocity at each point of space), quasi-laminar beams (an electron beam is a superposition of a finite number of laminar beams), and regular beams (all electrons have the same energy). Real electron beams are non-laminar (turbulent) to a greater or lesser extent. Turbulent electrons [5] undergo unsteady chaotic motions along complex trajectories; the electron velocity and density at each point in an intense beam change chaotically, and the beam layers are intensively mixed. The turbulence of charged-particle beams is complicated by the peculiar character of interaction between beam particles, which are determined by long-range Coulomb forces; collective interaction of charged particles also manifests itself in such beams.

An electron beam composed of individual bunches (over length) acts as a current with higher harmonics. Under certain conditions this current can generate electromagnetic oscillations with the same frequencies as the current harmonics. An intrinsic potential (space charge Coulomb) field is formed in the electronic bunch, which contains both longitudinal and transverse (with respect to the mean current) components. The longitudinal-component forces increase the electron bunch length, while the transverse-component forces expand the beam. When slowed down, such intense non-laminar electron beams can emit radio waves.

These can be formed using combinations of electrostatic and space charge fields; magnetic and space charge fields; and electrostatic, magnetic, and space charge fields. A magnetron injection gun (MIG) can also be used as an electron source.

It was noted in [4, 6] that MIG devices are characterized by high noise.

A TEB-based structure has an internal electronic feedback, which is implemented through electrons leaving space charge bunches; as a result, the latter oscillate in space and time.

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3. SCHEMES OF TEB-BASED OSCILLATORS

Figures 1–4 show schematics of TEB-based chaotic oscillators. In the scheme in Fig. 1 TEBs are formed using an inhomogeneous electrostatic field by changing the diaphragm potential. Figure 2 presents a scheme of TEB formation by an inhomogeneous magnetic field. In this case, either amplitude or period of magnetic field increases, which leads to an increase in the magnetic focusing parameter α:

$$\alpha = 2\times10^8 \frac{B_0^2 L^2}{U}, \quad (1)$$

where B_0 and L are the magnetic field amplitude and period, respectively, and U is the accelerating voltage. The magnetic focusing parameter increases to 3–5, as a result of which the beam becomes unstable [7–9]. Note that the potential of energy receiver can be reduced in comparison with the accelerating voltage, as in Fig. 3, where TEB formation by combining

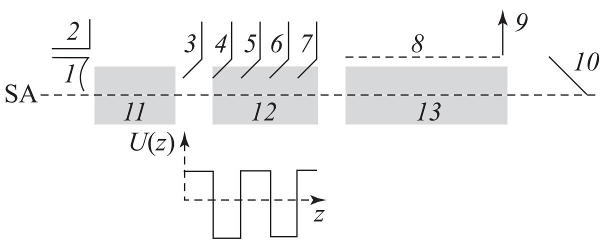

Fig. 1. Schematic diagram of ultrabroadband chaotic oscillator based on the formation of TEBs using electrostatic and space charge fields: (SA) symmetry axis, (*1*) cathode, (*2*) focusing electrode, (*3*) anode, (*4–7*) electrostatic focusing electrodes, (*8*) microwave energy receiver, (*9*) microwave energy extraction channel, (*10*) reflecting collector, (*11*) region of laminar electron beam formation, (*12*) region of electron beam modulation (space charge bunching), and (*13*) region of amplification of chaotic RF and microwave oscillations.

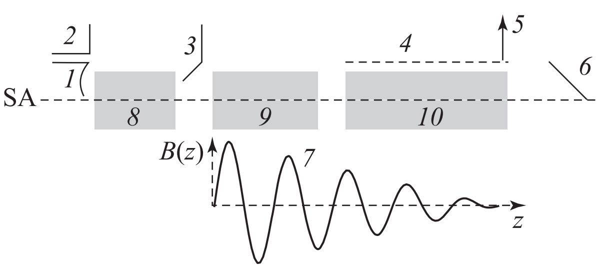

Fig. 2. Schematic diagram of oscillator based on the formation of electron beams using magnetic and space charge fields: (SA) symmetry axis, (*1*) cathode, (*2*) focusing electrode, (*3*) anode, (*4*) microwave energy receiver, (*5*) microwave energy extraction channel, (*6*) reflecting collector, (*7*) possible types of ac magnetic field, (*8*) region of laminar electron beam formation, (*9*) region of electron beam modulation (space charge bunching), and (*10*) region of amplification of chaotic RF and microwave oscillations.

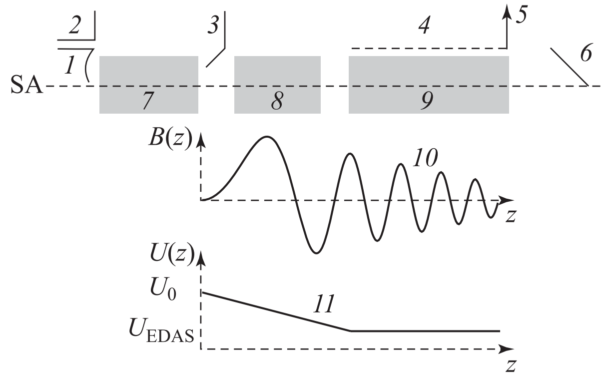

Fig. 3. Schematic diagram of oscillator based on the formation of electron beams using inhomogeneous magnetic, electrostatic, and space charge fields: (SA) symmetry axis, (*1*) cathode, (*2*) focusing electrode, (*3*) anode ($U = U_0$), (*4*) electrodynamic amplification system, (*5*) RF and microwave energy extraction, (*6*) reflecting collector, (*7*) region of laminar electron beam formation, (*8*) region of electron beam modulation (space charge bunching), (*9*) region of amplification of chaotic RF and microwave oscillations, (*10*) possible types of ac magnetic field, and (*11*) distribution of inhomogeneous electric field between the anode and electrodynamic amplification system ($U_{EDAS} < U_0$).

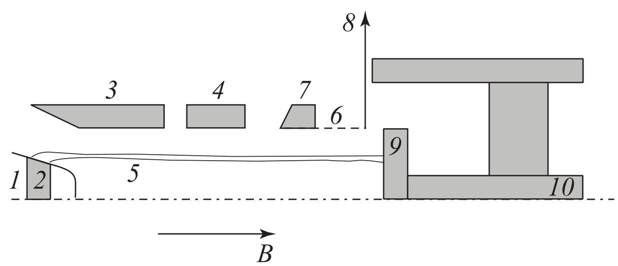

Fig. 4. Laboratory model of MIG oscillator (of gyrotron type): (*1*) cathode, (*2*) emitting zone, (*3*) control electrode, (*4*) anode, (*5*) electron beam, (*6*) helical segment, (*7*) absorbing insert, (*8*) energy extraction, (*9*) RF probe (collector), and (*10*) central conductor of the RF probe.

inhomogeneous magnetic fields, electrostatic fields, and space charge fields is schematically shown.

A model MIG-based oscillator is presented in Fig. 4. The MIG includes a conical cathode with an emitting dispenser hot zone from 1 to 3 mm wide, control electrodes, and anode. The anode–collector gap was 3 mm wide. The angle of inclination of the cathode surface to the axis was 15°. The magnetic field in the oscillator was formed by a permanent magnet; the maximum magnetic field strength was 0.15 T.

4. EXPERIMENTAL STUDY OF THE STRUCTURE OF INTENSE NON-LAMINAR ELECTRON BEAM

The electron beam envelope along the z axis, current density distribution in the cross section, and the longitudinal electron velocity distribution were investigated by placing a mobile probe with a 50-μm diaphragm [10] in the drift channel.

The probe had a Faraday cup collector, to which a retarding potential was applied [10]. The laminar electron beam, formed by the gun, entered the rising magnetic field in the z_0 plane to be compressed by the field in the z_1 plane. A change in the transverse angular momentum of electrons in inhomogeneous magnetic field may lead to a spread in electron velocities. According to the Bush theorem, the electron angular momentum in an increasing magnetic field is proportional to the difference in magnetic induction fluxes through the cross section under consideration. As a result the azimuthal and transverse electron velocities increase, while the longitudinal velocity decreases. At the same time, the paraxial electrons change their longitudinal velocity only slightly, whereas the peripheral electrons, which initially had a lower longitudinal velocity, are slowed down even more; hence, the spread of electron velocities in the cross section increases (Fig. 5). Pulsations are displaced in different layers, as a result of which pulsations with pronounced maxima are absent in the beam envelope. Thus, the beam becomes turbulent due to the layer mixing.

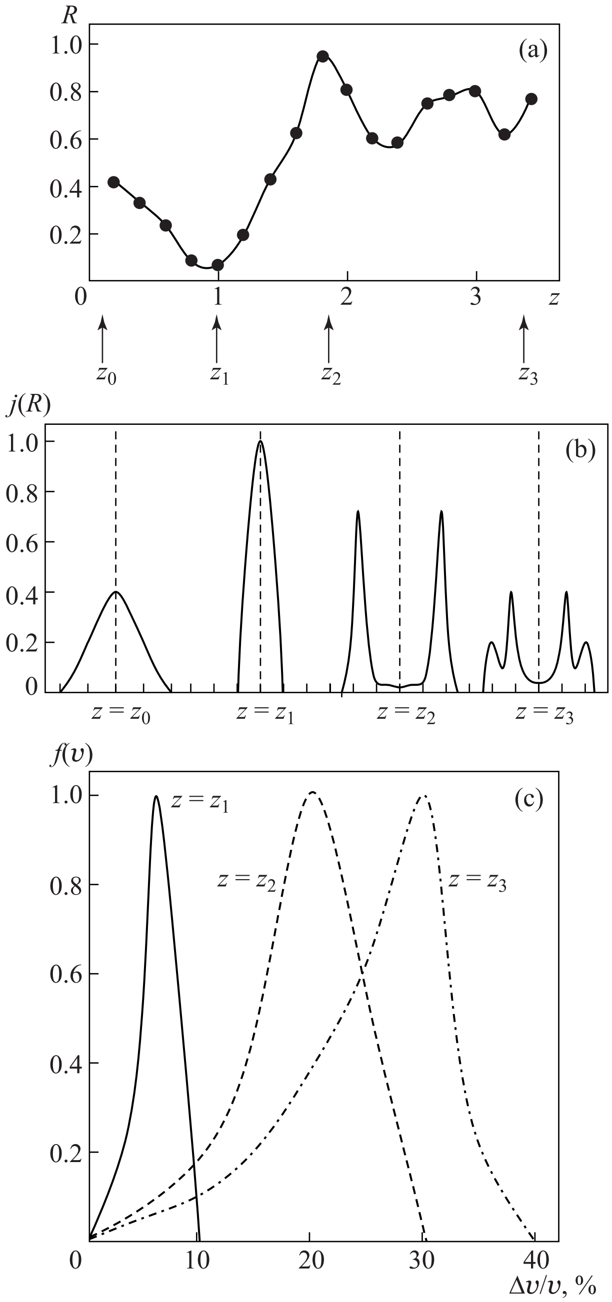

Fig. 5. Structure of non-laminar electron beams: (a) electron beam profile in dimensionless coordinates (z, R), (b) current-density distributions in different beam cross sections, and (c) velocity spectra in the region of space charge bunches.

Our experiments showed that the pattern is even more complicated when the beam electrons at the input (z_0 plane) have a larger spread of longitudinal velocities ($\Delta v/v = 0.1-0.15$). The initial velocity spread can be caused by the cathode heating (mode of current temperature limitation) or the effect of inhomogeneous field in the control-grid cells. In this case, the magnetic field compresses beam to a lesser extent, and it becomes nonlaminar, with a weakly pulsating boundary.

Let us now consider the results of studying the MIG-beam structure and the dependencies of the output integral power and generation band on the magnetic field. An analyzer (segment of a helical slow-wave system, mounted on the screen with the aid of ceramic rods and matched with the energy output) was used to investigate the vibrational phenomena and measure the noise spectral density in MIG beams. An electron collector (RF probe) was located behind the analyzer and connected to the energy output through matching elements. The electron beam structure was experimentally studied using a demountable vacuum system [10], which included a hollow cylindrical chamber (a flight channel with MIG elements inside), a segment of slow-wave system, and a collector. The residual gas pressure in the flight channel was $10^{-6}-10^{-7}$ Torr. The current density distribution in the MIG beam was analyzed by replacing the collector in the flight channel by a mobile probe with a diaphragm and a Faraday cup collector. The diaphragm had a 50-μm hole. The probe moved in three mutually perpendicular planes at a distance of 150–200 mm from the gun. The maximum current density j_{max} was measured in each beam cross section and compared with the corresponding value at the MIG output (see Fig. 5). The demountable vacuum system we used made it possible to move the probe in both longitudinal and transverse planes. The

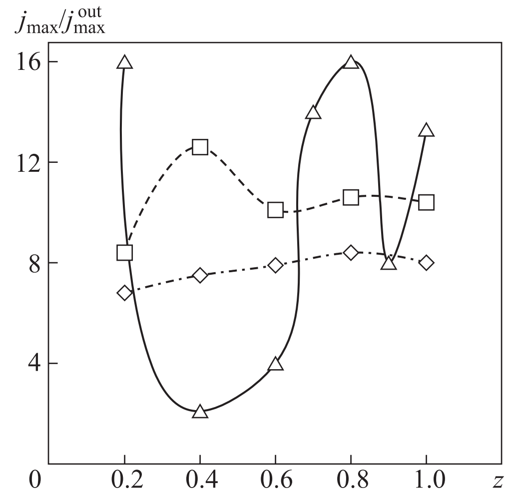

Fig. 6. Change in the maximum beam-current density along the drift length at different magnetic inductions: $B = 0.04$ (□), (◇) 0.02, and (△) 0.056 T.

current density at different points of the cross section was measured by displacing the probe (using an ShD-4 stepper motor) in the beam cross section with an error of ±0.05 mm. The experimental technique was described in [10].

The results in Figs. 6 and 7 were obtained for a hot zone 1 mm wide. The distribution of the maximum current density along the flight channel, measured at different magnetic fields, is shown in Fig. 6. One can see that both the maximum current density and its variations along the flight channel increase at some magnetic field values. This fact indicates formation of intense space charge bunches.

Figure 7 shows the distribution of space charge density in the beam cross section at a distance of

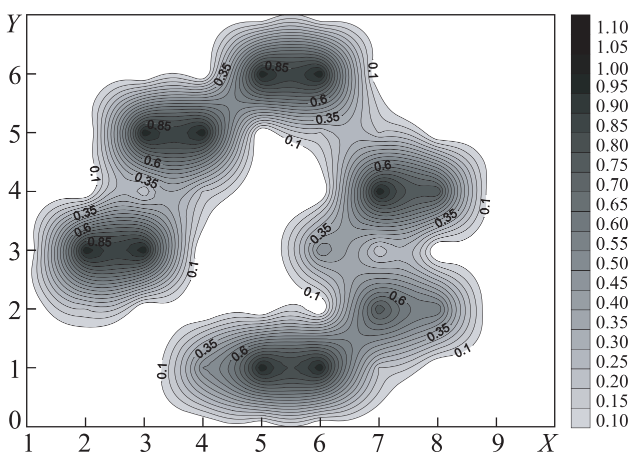

Fig. 7. Schematic image of electron bunches in the beam cross section (dimensionless coordinates X, Y) at a distance of 4 mm from the cathode. The space charge density is shown in gray gradations (dimensionless units; the calibration scale is on the right).

4 mm from the cathode. One can see well azimuthal inhomogeneity, which is acquired by the beam at the gun output. The mechanism of space charge bunching in the beam cross section was described in detail in [4]. Thus, the analysis of our results shows that space charge bunches are formed in MIG systems not only in the (r, z) plane but also in the (r, φ) plane. The spatiotemporal oscillations of these bunches lead to generation of noise-like oscillations in such systems.

Thus, the electron beam in MIG systems is turbulent in essence, which is related to the features of its formation in the gun region. One might believe this beam inhomogeneity to be caused by the difference in the characteristics of the clusters of electrons emitted from different ends of the cathode hot zone. The clusters of electrons emitted from different ends of the hot zone acquire velocities that differ in modulus and direction. Thus, the electron beam is divided into layers: the emitted electrons had different velocities and directions, depending on the hot-zone part they were emitted from. Obviously, the difference in the characteristics of emitted electrons (velocity directions and moduli) should increase with the hot-zone width. The latter should lead to even higher inhomogeneity of the beam and enhance its stratification. An analysis of comprehensive experiments shows that an increase in the hot-zone width leads to an increase in the current density and number of space charge bunches. In other words, the wider the cathode hot zone, the more pronounced the electron beam turbulence is. The beam becomes significantly nonlaminar in the drift space, due to which many space charge bunches are formed.

5. RESULTS OF EXPERIMENTAL STUDY OF CHAOTIC MICROWAVE OSCILLATIONS

The dependencies of the output integral power and generation frequency band on the focusing parameter α are shown in Fig. 8. The parameter α was changed by varying the magnetic field amplitude. One can see that the power and band of generated frequencies increase with α. This can be explained by a significant increase in the number of independent bunches, which oscillate with different frequencies and phases.

The spatiotemporal oscillations of space charge bunches in the magnetic-field transition region are sources of RF and microwave oscillations, which can be enhanced in the amplification section.

Let us now analyze the results of studying the output characteristics of MIG oscillators. The plots in Figs. 9 and 10 were obtained at a hot-zone width of 1 mm. Figure 9 shows the dependence of the output integral power on the magnetic field value. The maximum power corresponds to $B = 0.05–0.06$ T, which is in good agreement with the results in Fig. 5. The

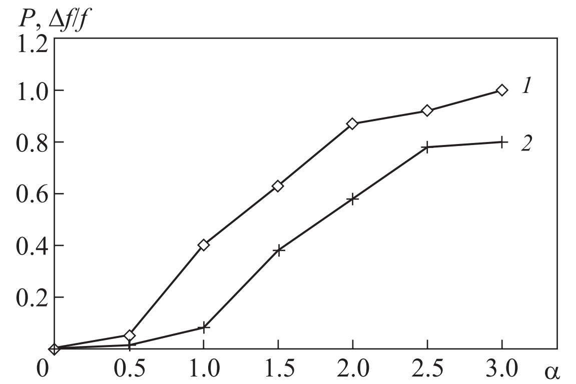

Fig. 8. Changes in (*1*) the output power P (normalized to maximum) and (*2*) the generation bandwidth $\Delta f/f$ of the chaotic TWT oscillator on the magnetic focusing parameter α.

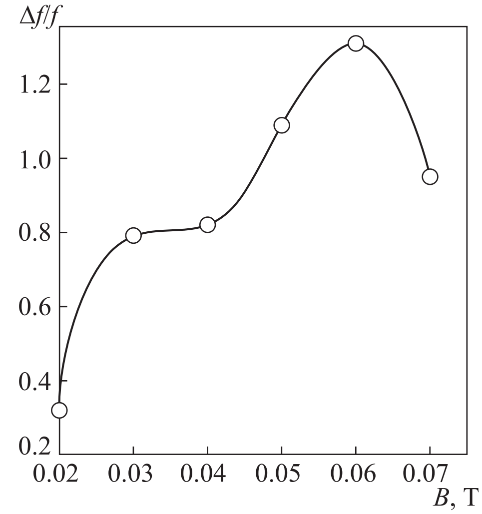

Fig. 10. Dependence of the generation bandwidth of MIG oscillator of noise-like microwave oscillations on the magnetic induction B.

dependence of the generation bandwidth on the magnetic field is shown in Fig. 10. These data confirm that intense charge bunches expand the frequency range of noise-like oscillations and increase their power. Note that the maximum power can be as high as 47.25 W; at this value the beam microperveance $P\mu$, which is determined by the ratio of the beam current I_0 to the accelerating voltage V_0 ($P\mu = 10^6 I_0/V_0^{3/2}$), reaches 2.58, and the efficiency is 21%.

The results of the experimental study of the characteristics and parameters of MIG-based low-voltage oscillator with a virtual cathode (low-voltage vircator) are shown in Fig. 11 as dependencies of the integral output power P and relative generation bandwidth on the hot-zone width h. These results were obtained using a segment of slow-wave system; the collector potential was equated to the accelerating potential ($K = 0.4$, electron beam slowed down). An increase in the hot-zone width leads to a sharp increase in the current and output power and significantly expands the generation band. The power drops decrease with increasing the hot-zone width and the retarding potential (to $K = 0.5$). The hot-zone width affects significantly the characteristics of generated signals: an increase in this parameter leads to an increase in the power and frequency bandwidth of generated signals and in the maximum generation frequency. Moreover, it also reduces the power drop in the spectrum of the output signal. The reason is that an increase in the hot-zone width leads to an increase in both the current density and number of space charge bunches, whose spatiotemporal

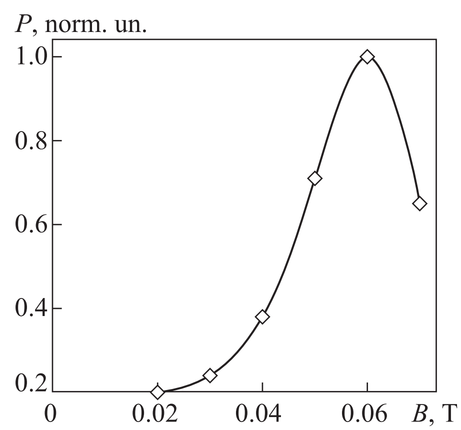

Fig. 9. Dependence of the output integral power of MIG oscillator (in dimensionless units, normalized to maximum) on the magnetic induction B.

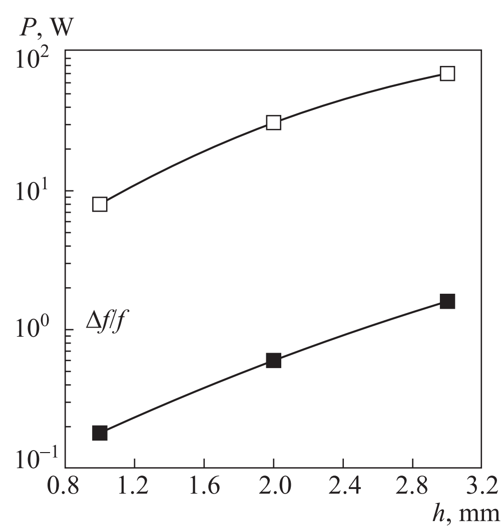

Fig. 11. Dependence of (□) the output integral power P and (■) the relative generation bandwidth $\Delta f/f$ of the MIG oscillator on the cathode hot-zone width.

oscillations are sources of high-power broadband microwave noise.

6. CONCLUSIONS

We investigated broadband chaotic oscillators based on the new principle: the use of intense TEBs. Our experiments confirmed the presence of space charge bunches in TEBs, which are unstable in both space and time; therefore, noise-like microwave oscillations arise in the system. The analysis of the results obtained showed that MIG oscillators can provide broadband noise-like microwave oscillations of high power. The anomalously high noise in MIG oscillators is caused by the formation of space charge bunches in the (r, z) and (r, φ) planes and the partition of the MIG-formed electron beam into regions characterized by different electron velocities and densities.

High-power broadband chaotic signals can be applied in information and telecommunication systems (promising data transmission methods based on the use of dynamic chaos properties), radio jamming systems, and noise radars. Such signals can also be used in manufacturing industry.

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