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Transformation of an ultra-wideband electromagnetic pulse in the process of its propagation through a large laboratory plasma

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ABSTRACT

The transformation of a subnanosecond ultrawideband electromagnetic pulse (UWB EMP) in a large-volume transparent plasma has been demonstrated experimentally using a large-scale KROT plasma device. The column of the plasma generated in the device chamber has a length of more than 4 m and a diameter of more than 1 m. This allows one to implement the regime of quasiuniform ionization, which is necessary to simulate UWB EMP propagation through the ionosphere. It is shown that the length of the wave propagation path in the plasma is sufficient for dispersion transformation of the pulse retaining the envelope of its frequency spectrum.

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I. INTRODUCTION

The advancement in the technology of generating ultrawideband (UWB) electromagnetic pulses (EMPs) and measuring their parameters1–5 makes UWB EMPs attractive tools for probing environmental media, encourages the development of testing and metering facilities, and contributes to perfecting the methods used to monitor and control parameters of pulsed technogenic events.6–12 The effects of the transformation of pulse wave forms and the nonlinear phenomena that arise when pulses propagate through plasmas13–16 are first and foremost interesting in the context of ionospheric applications, including new methods of active wave diagnostics of the ionosphere and analysis of the influence of lightning-generated EMPs and explosion-type phenomena on space equipment. A very promising approach to testing calculation instruments and creating test facilities is simulation of UWB EMP propagation using laboratory plasma devices. The first attempts of this kind were made in the 1970s,17 but limited plasma volumes and insufficiently mature pulse engineering hindered comprehensive analysis of the effects of pulse transformation. However, several large-scale plasma facilities, which had entered service globally by the beginning of the 21st century,18,19 have made such studies technically possible. Ionospheric propagation of some EMP types, e.g., microsecond pulses produced by lightning discharges, can be studied in large-scale plasma facilities by using scale modeling methods based on Alfvén’s similitude rules20 with the scaling factor γ ≈ 1000. In this case, generators of nanosecond pulses can be used as laboratory EMP sources. Ionospheric simulations require plasmas of at least 1 m length with the electron density ne ≈ 1012 cm−3, which is magnetized by the field B0 ≈ 1000 G. This corresponds to the operating parameters of such facilities as, e.g., LAPD.18

The problem of nanosecond and subnanosecond EMP propagation in the ionosphere, which is topical for many applications,13,15–17 can also be solved by using the method of laboratory scale modeling. However, direct application of the similitude rules in this case makes it necessary to use EMPs having the duration...
\( \tau \sim 0.1 \) ps, which is rather not feasible due to limited capabilities of the terahertz technology. On the other hand, a laboratory experiment on propagation of a nanosecond EMP can be performed using the so-called “limited” simulation scheme. In this approach, only basic characteristics of the ionospheric plasma are reproduced, where the properties of the dispersion that lead to a transformation of the EMP wave form being in the first place. Such a simulation can be performed with retention of the pulse duration \( (\tau \sim 1 \) ns) without scaling but with specific requirements imposed on the parameters of the laboratory plasma.

First, the plasma should be transparent for radiation, i.e., the lower boundary of the EMP frequency spectrum should be higher than the electron plasma frequency, i.e., \( f_{\text{lower}} \sim \tau^{-1}/2 > f_{pe} \), where \( \tau \) is the total pulse base duration. For \( \tau \sim 1 \) ns, this condition places an upper limit on the electron density, i.e., \( n_e \leq 10^9 \text{ cm}^{-3} \). Second, the plasma length \( L \) should be sufficient to ensure significant transformation of the pulse waveform due to dispersion, i.e., the delay in low-frequency spectral components relative to high-frequency ones for the time exceeding \( \tau \). Far from the cutoff, this condition can be written for a pulse, which has a spectrum width of the order of the magnitude of the central frequency, i.e., \( \Delta f \sim f_0 \sim \tau^{-1} \), as \( 2f_{pe}\pi L/c > 1 \), where \( c \) is the speed of light. Thus, the length of a plasma column with the electron density \( n_e = 10^9 \text{ cm}^{-3} \) for an EMP with \( \tau \sim 1 \) ns should be equal to at least 2 m. Third, the regime of propagation through the plasma should be close to the collisionless regime (i.e., \( v_0 \ll 2\pi f_{pe} \), where \( v_0 \) is the frequency of electron collisions with ions or neutral particles). Fourth, the radius of the plasma column should be sufficient for realization of the regime of the transversely unbounded plasma \( (R > 2.4c/2\pi f_{pe}) \). For \( n_e = 10^8 \text{ cm}^{-3} \), this corresponds to the condition of \( R > 0.4 \) m.

The large-scale KROT plasma device designed to model wave processes in the ionosphere and the magnetosphere allows one to fulfill the requirements stated above. The present paper contains a demonstration of EMP waveform transformation in a large plasma column using this device and is organized as follows: Section II describes the experimental apparatus used, and Sec. III contains the preliminary results obtained. The results are briefly discussed in Sec. IV along with future plans and perspectives.

II. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

The scheme of the experiment described herein is shown in Fig. 1. EMP propagation was studied in a quiescent decaying plasma produced by a pulsed RF inductive discharge in argon under the pressure \( p_0 = 2 \) mTorr. The discharge was ignited in the absence of the magnetic field, i.e., the studies were performed in the regime of an isotropic plasma. The power of RF generators was reduced relative to the nominal one, and the electron density at the breakdown moment did not exceed \( n_e = 10^{11} \text{ cm}^{-3} \). The characteristic duration of the diffusion plasma decay was equal to approximately 1 ms [Fig. 2(a)], and the electron temperature at the decay stage was equal to \( T_e = 0.3 \) eV. A pair of probes with microwave resonators, which were based on quarter-wave sections of double lines with eigenfrequencies of 850 MHz and 7.5 GHz, was used to measure and control the density of the decaying plasma in the range \( n_e = 10^9 \text{ cm}^{-3} \). The length of the plasma column in the device exceeded 4 m, and its diameter at the half-maximum was 1 m [Fig. 2(b)].

The dimensions of the plasma were more than sufficient to meet the above-specified criteria for laboratory modeling.

UWB EMPs were excited by a GIN-40 generator of high voltage pulses, which was based on fast ionization diode (FID) switches and producing pulses with the following output parameters at a matched load of 50 \( \Omega \): a voltage amplitude of 22–45 kV, a pulse rise time (at the level of 0.1–0.9 of the peak value) of not more than 150 ps, and a total pulse duration of less than 1.5 ns. The generator...
loaded the vertically polarized TEM horn designed for emission of a 1 ns long bipolar pulse via a vacuum-tight high-voltage coaxial 16 mm/9 mm connector. EMPs were detected by an ultrashort pulse converter\(^\text{24}\) installed inside the vacuum chamber at the axis of the plasma column. Such a converter allows one to directly measure the intensity of the electric field orthogonal to the plane of the sensor (strip line) directed to the emitter as a time function without preprocessing of the signal. A short rise time of the transitional characteristic of the converter (35 ps) makes it possible to reproduce details of the pulse waveform, and the time constant (4.5 ns) is sufficient to reproduce the entire pulse without distortions. The signal at the converter output was recorded by a Tektronix digital oscilloscope with a band of 12.5 GHz. The length of the path between the emitter and the receiver was 5.6 m. To lower the level of undesired reflections, the elements of the chamber along the signal propagation path were coated with mats of a radiation-absorbing Mylar-film material.

III. EXPERIMENTAL RESULTS

Figure 3 shows the waveform of a voltage pulse fed to the emitter and waveforms of the electric field of the EMP, which were obtained under the conditions of an anechoic chamber and in the chamber of the KROT device. Here, the time delay of 19 ns between the high voltage pulse and EMP received is removed; the signals are simply combined at a single panel for demonstration purposes. The pulse formed by an emitter in a vacuum chamber of the KROT device differs significantly from the pulse in the anechoic chamber. This difference is attributed to several reasons. First of all, the absorber used is partly transparent to electromagnetic radiation, especially at frequencies below 1 GHz. While high-frequency reflections are well suppressed by the absorber, low frequencies are partly reflected by metallic chamber parts. The waveguide dispersion, which is induced by the metal chamber, 3 m in diameter, and its internal elements (about 1.5 m in diameter), results in a loss of waveform simplicity and low-frequency spectral components. Second, the absorber located at a distance of about 1 m from the emitter affects the electromagnetic field distribution in the near zone, changing emitting antenna properties. Note that even on such a large facility as the KROT device, the waveform of the UWB EMP is distorted due to the finite size of the chamber.

Figure 4 presents the results of experiments on EMP propagation through a plasma for various values of the electron density \(n_e\). In this measurement series, the amplitude of a high-voltage pulse applied to the emitter was about 35 kV. The value of \(n_e\) was controlled by the change in the EMP emission delay with respect to the ionization pulse [Fig. 2(a)]. The influence of the plasma on the pulse

\[ n_e (\text{cm}^{-3}) \]

\[ 10^9 \]

\[ 10^8 \]

\[ 10^7 \]

\[ 10^6 \]

\[ 10^5 \]

\[ 10^4 \]

\[ 10^3 \]

\[ 10^2 \]

\[ 10^1 \]

\[ 0 \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ 4 \]

\[ 5 \]

\[ t (\text{ms}) \]

\[ n_e (10^4 \text{ cm}^{-3}) \]

\[ 0 \]

\[ 20 \]

\[ 40 \]

\[ 60 \]

\[ r (\text{cm}) \]

\[ U (\text{u}) \]

\[ 0 \]

\[ 2 \]

\[ 4 \]

\[ t (\text{ns}) \]

\[ \text{GIN-40 output pulse} \]

\[ \text{EMP: anechoic room} \]

\[ \text{EMP: KROT chamber} \]
FIG. 4. Waveform of an UWB EMP in the chamber of the KROT device in the absence and presence of a plasma at different values of the electron density $n_e$, where the amplitude of the voltage pulse at the output of GIN-40 is $U = 35$ kV.

FIG. 5. Frequency spectrum of the received signal as a function of the plasma density $n_e$ along the UWB EMP propagation path.

FIG. 6. UWB EMP waveform in the case of the maximum voltage at the GIN-40 output ($U = 45$ kV) in vacuum and in the plasma of the density $n_e = 2 \times 10^9$ cm$^{-3}$. 

$w/o$ plasma

$6.0 \times 10^8$ cm$^{-3}$

$1.3 \times 10^9$ cm$^{-3}$

$2.0 \times 10^9$ cm$^{-3}$

$2.7 \times 10^9$ cm$^{-3}$

$4.0 \times 10^9$ cm$^{-3}$

$10$ V/cm

$S$ (a.u.)

$f$ (GHz)

$E$ (V/cm)

$w/o$ plasma

$n_e = 2 \times 10^9$ cm$^{-3}$
waveform becomes noticeable starting at \( n_e = 5 \times 10^9 \text{ cm}^{-3} \). At \( n_e = (1–2) \times 10^9 \text{ cm}^{-3} \), pulse transformations due to dispersion are observed clearly. In particular, the half-amplitude duration increases by about 2 times, and the waveform is transformed into a series of oscillations with an increasing period. The peak value of the electric field proves to be 2–3 times lower than that in the case of propagation in vacuum.

The frequency spectra of the signals shown in Fig. 4 are presented in Fig. 5. The plasma weakens the signal received at the chamber axis due, in the first place, to the refraction at the longitudinal and radial gradients of the electron density, when the pulse is injected into the ionized region. For the considered values of the electron density \( n_e = 6 \times 10^8–4 \times 10^9 \text{ cm}^{-3} \), the critical frequencies fall into the EMP frequency band. As a result, the signal spectrum becomes filtered from below. Note that the actual radiation cutoff frequencies (from 250 MHz to 900 MHz) prove to be 1.1–1.6 times higher than the calculated critical frequencies \( f_c = f_{pe} = 220–570 \text{ MHz} \) for the uniform plasma with density \( n_e \) corresponding to the center of the plasma column. This fact is also determined by the refraction since the radiation components with the wave vectors directed at an angle to the chamber axis undergo reflections even before they reach the central region of the plasma. At the same time, the position of the maximum in the spectral density of the EMP power, which corresponds to frequencies around 1.3 GHz, is retained up to the densities \( n_e \approx 3 \times 10^9 \text{ cm}^{-3} \). The spectrum envelope as a whole is retained as well.

Changing the GIN-40 output voltage changes the pulse rise time. For \( U \approx 45 \text{ kV} \), the pulse rise time is minimal, and the spectrum of the excited UWB EMP becomes wider. Therefore, dispersion effects are more pronounced. An example of this scenario is shown in Fig. 6. After the signal passes through a plasma of the density \( n_e = 2 \times 10^9 \text{ cm}^{-3} \), it tends to transform into a smooth enveloped pulse including about 7 oscillations of the electric field with a monotonically increasing period.

### IV. DISCUSSION AND CONCLUSIONS

Observing the transformation in the waveform of a pulse consisting of several cycles of microwave field oscillations became possible due to both the advancement in pulse engineering and the dimensions of the plasma in the large-scale KROT plasma device, which are above the standard for conventional laboratory setups. In this case, it becomes possible to apply greater-aperture EMP emitters, which have better radiation patterns than the small-size TEM horn used in this work.

Another promising approach seems to be designing a “giant” plasma dispersion line. As a variant of the engineering solution, one can consider a metal coaxial line filled with plasma, which has the electron density \( n_e = 10^8–10^9 \text{ cm}^{-3} \), being fed directly by an EMP source, which maintains propagation of TEM modes. Such a solution will ensure the possibility of avoiding radiation refraction losses at the radial gradient \( n_e \) and, if implemented in an appropriate manner, ensure excitation of an EMP in the form of a quasiplanar electromagnetic wave with minimal attenuation in the propagation direction. This structure, approximately 10 m long and about 1 m in diameter, on the one hand, opens the way for studying the effects of interaction of high-intensity EMPs with plasma; on the other hand, it can be used as a dispersion line for controlling EMP waveforms in basic plasma physics studies and equipment tests.

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