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Sub-terahertz gyrotron based on the use of external frequency-tunable mirror

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Abstract. We describe a concept of a sub-terahertz frequency-tunable gyrotron based on a combination of a low-Q irregular cavity and a frequency-tunable external reflector. Simulations predict possibilities for creation of gyrotrons with high (20% and higher) efficiencies provided in a wide (~10%) frequency band.
Keywords: gyrotron, terahertz cyclotron radiation.

1. Introduction

Numerous spectroscopic applications require compact and relatively inexpensive sources of continuous radiation of the sub-terahertz (hundreds of GHz) frequency range with relatively high (tens of Watts – units of kilowatts) power. Important (from the point of view of spectroscopy) requirements for such sources are, on the one hand, the narrow–band spectrum of the output radiation, and, on the other hand, the possibility of broadband tuning of the generation frequency. According to the set of key characteristics (frequency, power, compactness, continuity, narrowband), subterahertz gyrotrons are the most attractive sources for such applications. However, an important disadvantage of gyrotrons implemented according to traditional schemes is that the use of selective cyclotron excitation by electrons of high-quasicritical modes of open resonators in these generators significantly limits the possibilities of frequency tuning. The characteristic Q-factors of the operating modes of traditional gyrotrons correspond to the frequency band at the level of fractions of a percent. Such a band can be sufficient for precise adjustment to any band of the spectrum of the material under study. However, for spectroscopy, it would be ideal to have a source that provides a combination of stability (a narrow band) of the generated signal with the possibility of its smooth adjustment in a frequency band with a width of at least a few percent, which would make it possible to obtain a spectral picture in a relatively wide band.

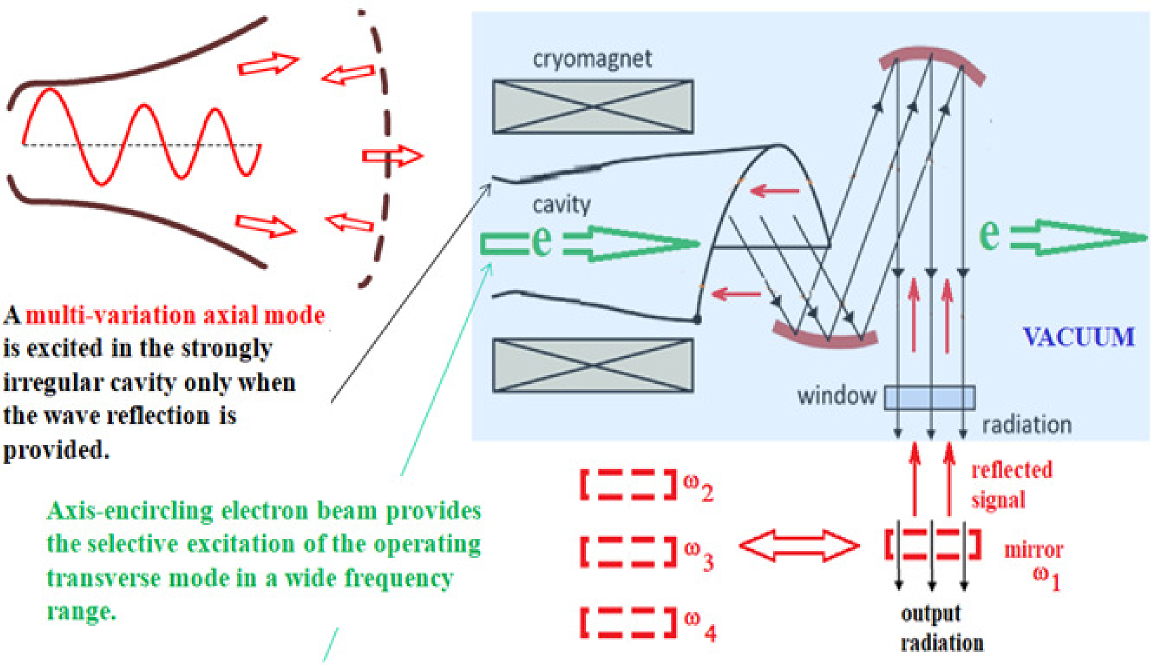

Fig.1. Illustration of the scheme of a gyrotron with frequency-tunable mirrors.

This paper describes a scheme for the implementation of frequency-tunable gyrotrons of the subterahertz frequency range (Fig.1). It is proposed to abandon the traditional scheme of gyrotron operation based on the excitation of high-Q near-cutoff modes of regular cavities. Instead, it is proposed to work on low-Q far-from-the-cutoff longitudinal modes of an irregular cavity, the selective excitation of which by an electron beam is provided only by reflecting part of the output signal from a narrow-band mirror located outside the window of the gyrotron (that is, outside the vacuum zone).

In fact, it is proposed to implement a "traveling wave resonant tube" scheme in which selectivity and frequency tuning are carried out due to (1) the use of replaceable or tunable external narrow-band reflectors and (2) the absence in an irregular electrodynamic system of high-Q near-cutoff gyrotron modes that could be excited without external reflection. The use of an irregular cavity with an optimized profile provides the possibility of highly efficient excitation by an electron beam of a wide range of different longitudinal modes of the system. In this case, the frequency of the excited mode is "dictated" by the frequency of reflection of the external mirror, and the tuning of the frequency of the generated wave is provided by a mechanical adjustment of the operating frequency of the reflector.

2. Preliminary experiment

The idea of a scheme for implementing a frequency-tunable gyrotron arose after analyzing the results of experiments with a continuouswave large-orbit gyrotron (LOG) operating in the third cyclotron harmonic at a frequency of 0.39 THz with the parameters of the operaitng electron beam of 30 keV / 0.7 A [1, 2].

In a special series of experiments [3], a wave beam formed in the regime of excitation of the $TE_{3,7}$ mode of a circular cross-section cavity was fed into a focusing quasi-optical system. To visualize the distribution of the wave field using a breakdown pattern, a gas flow injected into the compression point was used. In the experiment, a discharge was obtained, but from the "picture" of this discharge it was clear that the gas breakdown occurred in the antinodes of the standing wave electric field (Fig.2), which was explained by the reflection of radiation from the gas flow input system. In the regimes of the brightest discharge, the wavelength measured from the discharge image (about 2.5 mm) turned out to be close to the wavelength (2.28 mm, frequency 132 GHz) of the corresponding generation at the fundamental cyclotron harmonic. The closest to the operating mode TE_{37} among the modes of the spectrum of the operating cavity excited by an axial electron beam at the fundamental harmonic is the mode TE_{13}. This mode in the operating magnetic field of about 5 Tesla at a wavelength of 2.28 mm corresponds to a cut-off radius of 3.1 mm. This means that during the experiment, the conditions for the excitation of the TE_{13} mode were provided not in the regular part of the operating cavity (whose radius was less than 3 mm), but in its irregular cone section of the diffraction output of radiation.

This fact was confirmed by subsequent theoretical analysis and calculations, which showed that in the absence of reflection, a complex multivariate wave of the output section of the cavity cannot be excited. At the same time, however, in the presence of reflections, it is excited with a sufficiently high efficiency (tens of percent) even when the excitation of this wave in the output section of the resonator is carried out by an electron beam that interacted with the working wave in the regular section of the resonator and, accordingly, has a sufficiently large velocity and energy spread.

So, this experiment, together with the corresponding calculations, showed that:

- stable single-frequency generation of a complicated wave structure of an irregular cavity can be ensured by reflecting a part of the signal from even a broadband reflector;

- calculations show that under different conditions (operating magnetic fields and reflector frequencies), waves at different frequencies can be excited in different parts of an irregular cavity;
- the efficiency of generating such waves can be very high (tens of percent) even under the conditions of the experiment described above, when the profile of the cone section of the cavity was not optimized from the point of view of using it as a radiating system, and the electron beam acquired an additional velocity and energy spread as a result of the excitation of the operating wave in the regular section of the cavity.

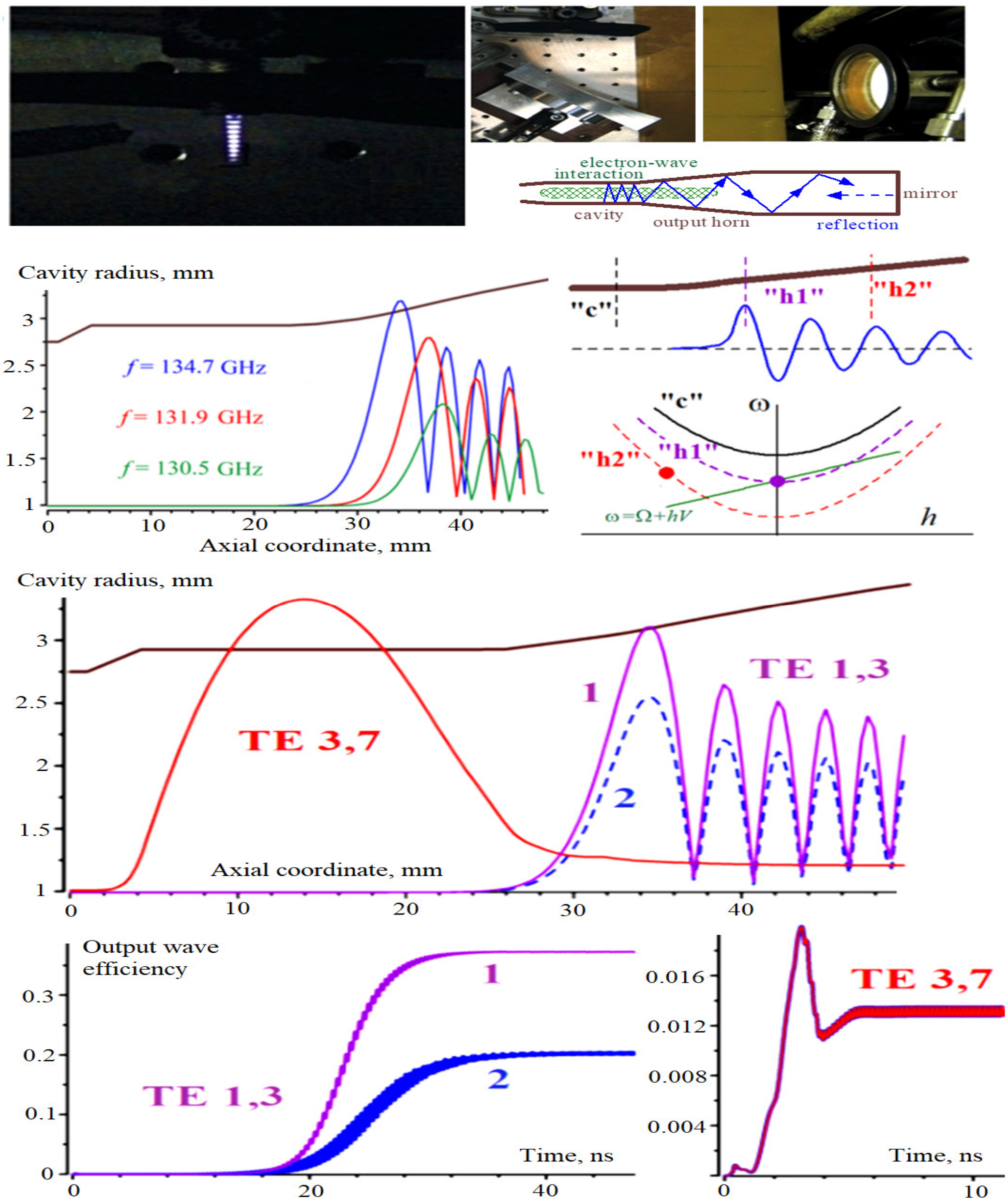

Fig.2. An experiment in which wave excitation was observed at the fundamental cyclotron harmonic in the output cone section of the cavity. Photo of the breakdown in the area of the external reflector. Dispersion characteristics of the excited transverse mode in the regular and conical parts of the cavity, as well as the calculated structures of waves excited at different frequencies. Results of two-wave modeling: calculated longitudinal wave structures at the third and first harmonics (modes TE_{37} and TE_{13}), as well as the radiation power of two waves measured in electronic efficiency as a function of time.

3. Frequency-tunable gyrotron

Based on these experimental results, we propose a scheme of frequency-tunable LOG with an irregular cavity and an external reflector (Fig.1). Its idea is based on the following principles. Firstly, it is proposed to use a cavity with an inhomogeneous (in the longitudinal coordinate) profile, in which, unlike a traditional regular gyrotron cavity, there are no near-cutoff modes with high diffraction Q-factors. The cavity should be strongly irregular that in the absence of external reflections, so that the operating electron beam could not provide the start of self-oscillations of any of the waves of the system.

Secondly, in order to ensure the start of the operating oscillation at a given frequency and the subsequent output to a stable stationary generation regime, it is assumed to use the reflection of a significant part of the gyrotron output signal from an external (located outside the gyrotron window, i.e. outside the vacuum zone) narrow-band mirror. Thus, the operating frequency of the oscillations excited in such a system is "dictated" by the frequency of reflection of the external mirror. In such a system, frequency tuning is carried out by changing the eigenfrequency of the external cavity; that is, either by simply replacing one mirror with another (as shown in Fig.1), or by using narrow-band mirrors with a smooth mechanical adjustment of the reflection frequency. Since the mirror is located behind the exit window of the gyrotron, that is, outside the vacuum zone, any mechanical manipulation with it is not a problem. An additional adjustment of the operating magnetic field of the gyrotron will ensure the optimal mode of electron-wave interaction at each of the operating frequencies. The use of an axial electron beam significantly increases the selectivity of the system, and also ensures maximum interaction of electrons with the "correct" operating transverse modes (whose azimuth index coincides with the number of the operating cyclotron harmonic) when using various replaceable cavities.

Fig.3 illustrates the results of calculations of such a scheme. The cavity profile was optimized from the point of view of ensuring broadband frequency tuning when the same $TE_{1,3}$ mode is excited at the first cyclotron harmonic at a frequency of about 135 GHz. The profile of the working cavity, the calculated longitudinal structures of waves excited at different frequencies under the condition of using a narrow-band (i.e., fixing the operating frequency) mirror with a characteristic reflection coefficient of 50%, as well as the dependence of the efficiency of the electron-wave interaction on the generation frequency are given. Calculations predict generation with an electronic efficiency of 20–40% in the frequency band of the order of 10%. For an electron beam of 0.7 A / 30 keV, this corresponds to a power of 4–8 kW in continuous generation regime. Naturally, these calculations took into account the real characteristics of the electron beam used in this LOG (i.e., velocity and position spread).

4. Reflectors

A separate problem is the creation of external reflectors, which should have the following properties:

- operation in the sub-terahertz frequency range (about 130 GHz in the gyrotron on the main cyclotron resonance and 260 GHz on the second cyclotron harmonic);
- smooth adjustment of the frequency of reflection in the band of the order of 10%;
- a narrow (less than 1%) frequency band when operating at a given frequency.

As one example of solving this problem, the figure below illustrates a reflector based on a Bragg structure (corrugated surface). For a given period of corrugation, the frequency at which this corrugation provides a connection between the incident wave and the wave reflected back (in the anti-mirror direction) is determined by the angle of incidence of the wave on the surface. In the example shown in the Fig.4 below, the angle of incidence of 45 degrees corresponds to a frequency of 135 GHz, while a change in this angle within 42–48 degrees corresponds to a realignment of the frequency of the reflector in the band of more than 10% without noticeable changes in the reflection coefficient. At the same time, with a fixed angle of incidence (and, accordingly, the center of the frequency band of reflection of the reflector), the width of this band is no more than 1%.

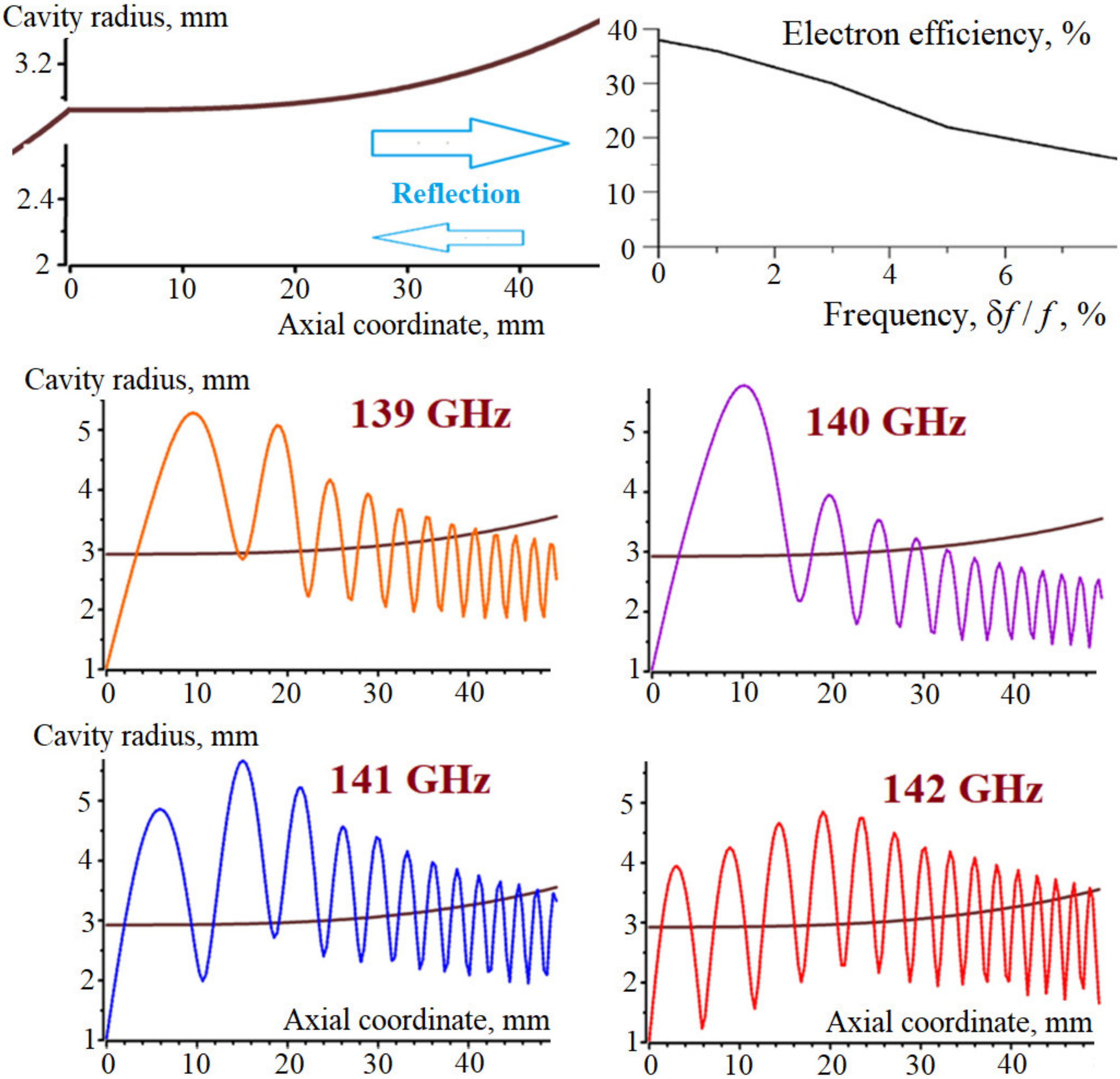

Fig.3. Calculations of a gyrotron with an irregular cavity and reflection from the output mirror. The cavity profile, calculated longitudinal structures of waves excited at different frequencies, as well as the dependence of the efficiency of the electron-wave interaction (counting from the frequency f_0, corresponding to the cutoff frequency in the narrowest region of the cavity).

As another approach, it is proposed to investigate the possibility of using a complex Bregg reflector scheme in a gyrotron, described in [4]. It is a planar system (a planar waveguide formed by two corrugated metal planes) based on a complex three-wave process of Bragg reflection (traveling incident wave → quasicritical wave → traveling reflected wave). As shown in the work mentioned above, a narrow-band reflector of this type can operate in the sub-terahertz frequency range. At the same time, a smooth adjustment of its frequency is provided by changing the distance between the metal planes forming this reflector.

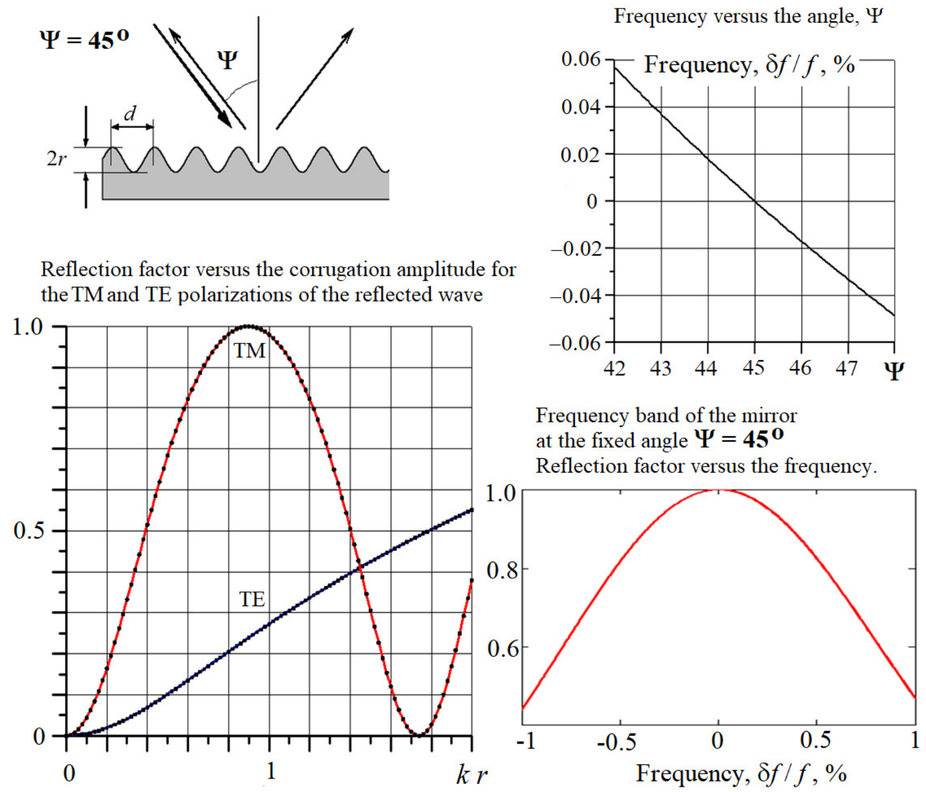

Fig.4. Geometry of the Bragg type reflector, the dependence of the reflection coefficient for TE and TM polarization waves on the size of the corrugation when the wave falls at an angle of 45 degrees, the change in the operating frequency of the reflector when the angle of incidence of the wave changes, and the frequency band of the reflector at a fixed angle of incidence of the wave.

5. Conclusion

The concept described in this paper can become the basis for the implementation of gyrotrons of the subterahertz frequency range with unique characteristics. The combination of high efficiency in these devices with the possibility of continuous broadband frequency tuning makes them very attractive for modern spectroscopy applications.

As a first step, we consider a gyrotron operating on the fundamental cyclotron harmonic. Clear, that the transition to higher harmonics in this scheme is possible as a way to increase the operating frequency. At the same time, naturally, competition with the now parasitic fundamental cyclotron harmonic will impose its limitations on the bandwidth of frequency tuning. This problem will be the topic of our future research.

Acknowledgement

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