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**SPIE.**

Event: SPIE Defense, Security, and Sensing, 2012, Baltimore, Maryland, United States

# Possible standoff detection of ionizing radiation Using high-power THz electromagnetic waves

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## ABSTRACT

Recently, a new method of remote detection of concealed radioactive materials was proposed. This method is based on focusing high-power short wavelength electromagnetic radiation in a small volume where the wave electric field exceeds the breakdown threshold. In the presence of free electrons caused by ionizing radiation, in this volume an avalanche discharge can then be initiated. When the wavelength is short enough, the probability of having even one free electron in this small volume in the absence of additional sources of ionization is low. Hence, a high breakdown rate will indicate that in the vicinity of this volume there are some materials causing ionization of air. To prove this concept a 0.67 THz gyrotron delivering 200-300 kW power in 10 microsecond pulses is under development. This method of standoff detection of concealed sources of ionizing radiation requires a wide range of studies, viz., evaluation of possible range, THz power and pulse duration, production of free electrons in air by gamma rays penetrating through container walls, statistical delay time in initiation of the breakdown in the case of low electron density, temporal evolution of plasma structure in the breakdown and scattering of THz radiation from small plasma objects. Most of these issues are discussed in the paper.

**Keywords:** THz radiation, standoff detection of radioactive sources, gyrotron, breakdown

## 1. INTRODUCTION

Recently, a new method of remote detection of concealed radioactive materials was proposed [1, 2]. This method is based on focusing a high-power short wavelength radiation in a small volume of air where the wave electric field exceeds the breakdown threshold and, therefore, in the presence of free electrons an avalanche discharge can be initiated. When the wavelength is short enough, such a breakdown-prone volume can be much smaller than a cubic cm, while the ambient density of free electrons in the absence of additional radioactive materials is about one electron per cubic centimeter. So, the probability to have a breakdown in such conditions in short enough pulses is low. Hence, a high breakdown rate will indicate that in the vicinity of this volume there are some materials causing ionization of air.

For realizing such method of remote detection of radioactive materials a number of issues should be addressed. First of all, a high-power source of electromagnetic (EM) waves should be developed. Then, this high-power radiation should be transformed into a wave beam and focused to a small spot where the electric field strength exceeds the breakdown threshold. The wave attenuation and scattering on the way from a transmitter to the focus should be taken into account. If the radioactive material produces enough free electrons, in a breakdown-prone volume the avalanche ionization will start. So we should be able to characterize the EM source frequency, power and pulse duration as well as production of free electrons by radioactive materials and issues important for characterizing the plasma in the breakdown. Below, we describe the progress in our studies of these issues. This paper partially overlaps with the invited talk given at the 4th International Workshop on Far-Infrared Technologies (7-9 March, 2012, Fukui, Japan).

## 2. HIGH-POWER SOURCE OF ELECTROMAGNETIC RADIATION

In Figure 1 reproduced from Ref. [3] available sources of microwave, millimeter- and submillimeter-wave EM radiation are shown together with the solid lines indicating the power required for creating a given breakdown-prone volume (solid lines) and the range normalized to the size of the antenna dish depicted by dashed lines.

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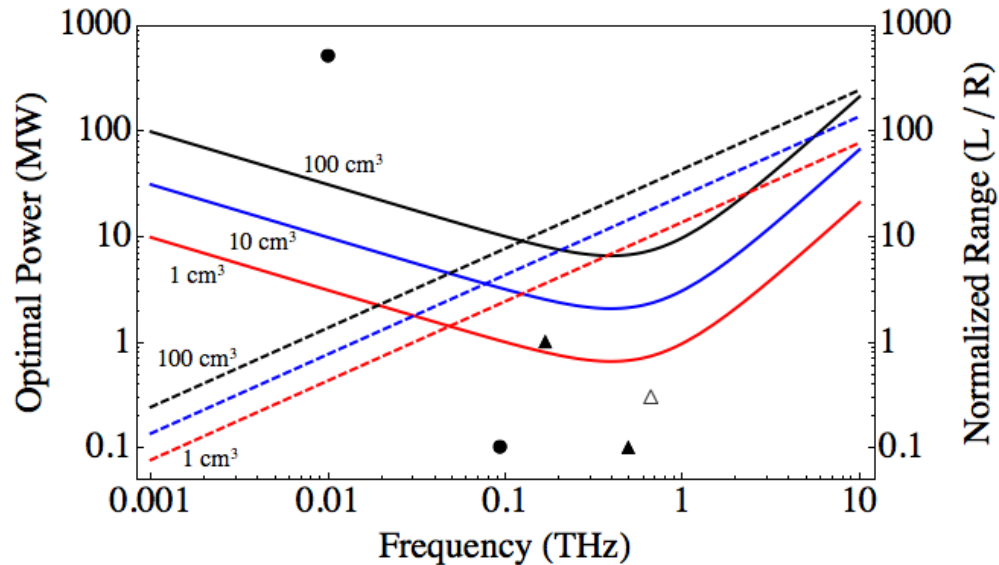


Figure 1. Optimal power required for creating a breakdown-prone volume and corresponding range normalized to the radius of the antenna dish as functions of wave frequency. Solid black dots show the X-band (frequency 10 GHz) backward-wave oscillator built for the nanosecond GW radar (NAGIRA) [4], the W-band (94 GHz) gyro-amplifier built for the NRL radar WARLOC [5]; solid triangles show a 170 GHz, 1 MW continuous-wave gyrotron built for the international thermonuclear reactor ITER [6] and the submillimeter-wave gyrotron with a pulse solenoid producing 100 kW at the 0.5 THz frequency [7]. An empty triangle shows design parameter of a gyrotron presently under development [8].

The plots shown in Figure 1 are made for the atmospheric pressure. At this pressure, the optimal power has its minimum in the sub-THz frequency range (close to 0.6 THz) where the wave frequency is close to the frequency of electron collisions with air molecules, and that corresponds to the bottom of the Paschen curve. As follows from Fig. 1, there are some microwave sources which can produce power necessary for the atmospheric breakdown, but at such frequencies the breakdown-prone volume is so large that there are always some free electrons present even in the absence of radioactive materials. For realizing our concept we should have a volume smaller than one cubic centimeter.

Bearing in mind that in the sub-THz frequency region there is an atmospheric window at 670 GHz, the decision was made to develop a high-power source delivering radiation at this frequency. The required power of this source was determined by the necessity to have the amplitude of the electric wave field in the focal plane exceeding the threshold value [9]  $E_{th}(MV/m) = 3.2\sqrt{1 + \omega^2 / \nu_{coll}^2}$ . At the given frequency (the wavelength is about 0.45 mm), this corresponds to the threshold power density close to 2.7 MW/cm<sup>2</sup>. Hence, to realize the power density in the focal plane on axis of a wave beam two times the threshold density and focus the wave beam in a spot of a 1 mm radius, we need about 170 kW power.

Such power can be provided by a table-top gyrotron with a pulse solenoid similar to one described in Ref. 7. Since gyrotrons operate under condition of cyclotron resonance between the wave and electrons gyrating in the external magnetic field, to realize 0.67 THz radiation at the fundamental cyclotron resonance, magnetic field about 27 T is needed. Such fields can be obtained in pulse solenoids. As the design study [8] shows, it is possible to develop a gyrotron with such solenoid delivering up to 200-300 kW power in 10-100 microsecond pulses with single-shot operation. A photo of a gyrotron designed in collaboration with Russian team led by Dr. M. Glyavin and fabricated by Russian consortium GYCOM is shown in Figure 2.



Figure 2. A photo of a 670 GHz gyrotron with a pulse solenoid. The solenoid producing 2 millisecond pulses of 27 T magnetic field should be cooled by liquid Nitrogen for reducing its joule heating and stabilizing solenoid parameters.

. At present, experiments with this gyrotron are ongoing at the University of Maryland and, in parallel, by M. Glyavin's team. The THz power measured calorimetrically is at the 80-100 kW level in about 7 microsecond pulses. The total energy per pulse is more than 0.5 Joule. This corresponds to the efficiency about 10-12%. The waveforms and calorimetric response are shown in Figures 3 (a) and (b), respectively.

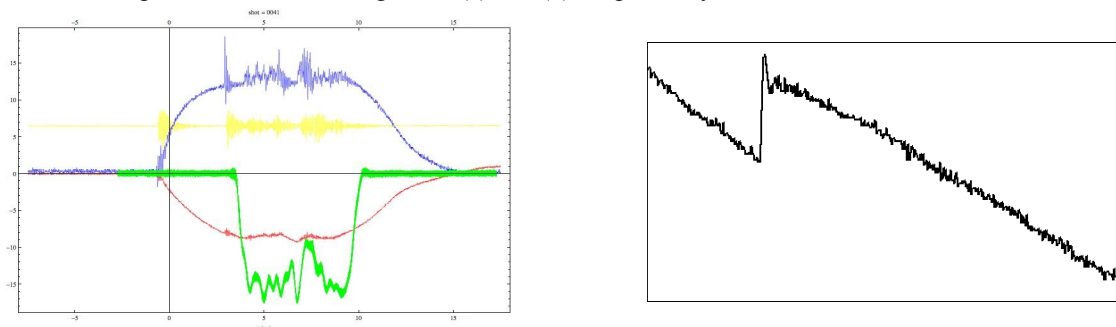


Figure 3: (a, left) traces of the voltage (brown), current (blue) and the detector signal (green); (b, right) calorimetric response indicating absorption of 0.54 J.

The gyrotron operates in a high-order  $TE_{31,8}$ -mode. By using standard quasi-optical means described elsewhere [10], it is planned to transform the radiation of this mode in a Gaussian wave beam. Corresponding components (a so-called Vlasov coupler and quasi-parabolic mirror) have already been designed and fabricated.

### 3. PRODUCTION OF FREE ELECTRONS BY GAMMA QUANTA

Since only gamma rays can penetrate via the walls of metallic containers, it is necessary to analyze the process of producing thermal electrons by these gammas. This analysis was presented in Ref. 11 and described in more detail in Ref. 12. Here, a brief review of this work is provided. Gamma rays penetrating via container walls undergo Compton scattering with air molecules. In the course of this process, secondary gammas appear together with primary energetic electrons whose energies typically range from 0.1 to 1 MeV. (An example of corresponding Monte Carlo simulations for Cobalt-60 is given in Ref. 8.) These energetic electrons, however, have low attachment rates and, hence, cannot cause substantial ionization of air. Each of these primary electrons produces a huge number of secondary electrons whose

energies can be on the order of 1 eV or less. Such electrons (called ‘thermal’) have high attachment rates and, therefore, can initiate an avalanche breakdown. A typical production rate of free electrons is shown in Figure 4 reproduced from Ref. 12 as the function of the distance from the radioactive container. Here the red dashed line shows the production rate due to the primary gammas only, while the black solid line takes into account also the role of secondary gammas which becomes important at distances over 50-60 meters. Note that the production rate in the ambient conditions is in the range of 10-30 pairs per cubic cm per second. So one Curie of Cobalt-60 can be detected at the distances up to 80-100 meters. (This estimate, of course, implies the unshielded case. In the case of shielding, the detectable amount of radioactive material should be increased accordingly.)

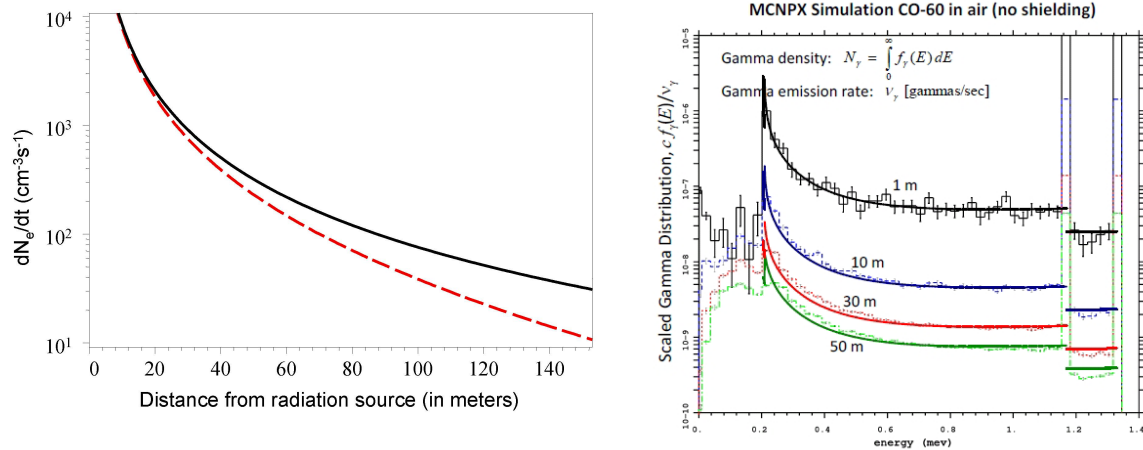


Figure 4 (left). Production rate of free electrons caused by 1 Curie of Cobalt-60 as the function of the distance from a container.

Figure 5 (right). . Energy distribution of gammas calculated with the use of the MCNPX code and results of the analytical theory. The latter results are shown by solid lines. Calculations are done for several distances from the source; the distances are given in the figure.

It should be noted that results of the analytical theory agree well with results of Monte-Carlo simulations performed by Dr. J. Penano of NRL. Both results for the case of unshielded material are shown in Figure 5 reproduced from Ref. 11, 12. The theory developed, however, cannot accurately describe the energy distribution in the presence of shielding.

#### 4. STATISTICAL WAITING TIME

When a THz wave beam is focused in a spot with dimensions on the order of a wavelength the breakdown-prone volume is small. Correspondingly, in the absence of radioactive materials in the vicinity of this volume, the probability of having at least one free seed electron for initiating an avalanche discharge there is low. Thus, the probability of the breakdown which should indicate the presence of radioactive material has a statistical nature and should be described accordingly. A corresponding theory was developed several years ago [13]. By using this theory we were able to estimate the detectable amount of radioactive material as the function of the distance of the breakdown-prone volume from the radioactive source for given power and pulse duration of a THz source. This study is described in Ref. 14. It is also shown there that the use of efficient active pulse compressors with high enough compression ratio can significantly reduce the detectable level of radioactive material.

#### 5. SUMMARY

The status of our research program is presented above. In the first experiments, a record power level 80-100 kW at the 670 GHz frequency was demonstrated. Because of the operation in a very high-order mode having relatively small ohmic losses, the efficiency of operation was at the record level of 10-12%. Experiments with this gyrotron are ongoing. When reproducible shot-to-shot gyrotron operation at a sufficiently high power level is achieved, experiments on focusing the THz radiation for initiating breakdown will begin. In these experiments, a number of issues will be addressed, including plasma characterization (its spatial structure, temporal evolution, possible filamentation) and the

scattering of THz waves from saturated plasma blobs for registering the breakdown by receivers located close to the gyrotron transmitter.

## ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research under Grant No. 000140911190.

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