Generation of THz-radiation in the Cherenkov decelerating structure with planar geometry at frequency ~ 0.675 THz

I A Ashanin and S M Polozov
Department of Electrophysical Facilities, National Research Nuclear University - Moscow Engineering Physics Institute, Kashirskoe shosse, 31, Moscow, 115409, Russia
E-mail: ilya.ashanin@mail.ru; SMPolozov@mephi.ru

Abstract. One of the ways to generate THz-radiation is by the relativistic electron bunches travelling through Cherenkov decelerating dielectric filled capillary channel. Sapphire or other dielectric materials can be used for the internal surface coating of the capillary. Relativistic electron bunches of ~100 μm in diameter and pulse durations of 1 ps or shorter are capable to produce substantial power of THz-radiation. The aperture of Cherenkov decelerating structure should be comparable with the sub-mm wavelength (0.05-3 mm). Such type of decelerating system allows providing of the wide range of operating parameters at the various geometrical sizes. But it is necessary to consider that such capillaries are difficult in production as there is a requirement to drill a small aperture in a long crystal of high hardness but brittle. In this regard it would be desirable to offer transition option from the axial to the planar geometry. Furthermore the ribbon beam has some advantages as focusing at low energies and possessing smaller expansion in the drift space. The authors present design and results of electrodynamics study of the decelerating planar dielectric filling Cherenkov channel at frequency 0.675 THz in this article. It is also delivered characteristic comparison with axial geometry channel. A horn antenna attached to such channel at 0.675 THz resonant frequency is considered.

1. Introduction
At present facilities for THz-radiation can be used in such areas as introscopy of large objects, medicine (THz tomography for survey and determination of cancer neoplasm), pharmacy (definition of medical product composition). Such facilities can be realized based on sufficiently powerful radiation source.

As it is known Cherenkov decelerating capillary channel or corrugating channel with dielectric filling and horn antenna can be used for THz-radiation generation with relativistic electron bunches passing through [1, 2]. RF photo injectors can provide high-brightness relativistic electron bunches with pulse durations of 1 ps or less and are capable to produce substantial power of THz-radiation. The basic components of a RF photo injector are RF-gun with photocathode (Cu, Mg, Cs2Te, GaAs, Ba etc.), laser and optical system producing the desired pulse structure, a RF source, timing and synchronization system [3].

High-brightness relativistic electron bunch of mm-sub-mm length and 100 μm in diameter travelling through decelerating structure can produce a coherent Cherenkov radiation. The aperture of such Cherenkov decelerating structure shall be compared with the mm or sub-mm wavelength (0.1-3 mm). Different dielectric materials as quartz, sapphire, diamond, barium tetratitanate can be used for the internal surface coating of the dielectric capillary channel of mm-sub-mm cross-section. There is a need to use a dielectric material with higher dielectric permittivity (5 and higher), such as diamond or sapphire for obtaining the best results on the radiation generation. THz-radiation in a broad band of...
frequencies possesses low penetration because of its high absorption in water. In this case the frequency of 0.675 THz was considered as one of the high transparency window for THz-radiation transmission in atmosphere [4].

In the article [5] it was suggested to use sapphire as dielectric filling material for decelerating Cherenkov capillary structure, because of its high durability, ε~9.9, thermal stability up to 1600° C and with almost no conductivity. Electrodynamic and geometrical characteristics of capillary channel were analyzed and simulation results of main parameters of such structure were obtained.

It is necessary to consider that such capillaries are very difficult to produce as a small aperture must be drilled in a long crystal of high hardness. In this regard it would be desirable to offer transition option from the axial to the planar geometry and to use a ribbon beam. Planar structure is easier for manufacturing, for preparation and it is still of high dielectric permittivity. Moreover using ribbon beams has such features as smaller expansion in the drift space, slight impact of spatial charge and more simple focusing at low energies.

For transformation of bunch symmetry from axial to the ribbon quadruple lens can be used. Axial beam passing through contracts in one, and stretches in another plane and acquires a tape form.

In this paper design and results of electrodynamics study of the planar metallized sapphire decelerating Cherenkov channel are presented. Horn antenna integrated to such decelerating channel at 0.675 THz resonant frequency is considered. Electrodynamic characteristics comparison with axial geometry channel is presented as well.

2. Geometrical and electrodynamics characteristics of dielectric loaded planar structure

CST Microwave Studio was used to simulate the decelerating planar structure with sapphire filling and to calculate the main electrodynamics characteristics [6]. Electrodynamic model of decelerating sapphire planar structure at resonance frequency 0.675 THz is shown in Figure 1. Geometrical and electrodynamic characteristics of decelerating planar channel with sapphire coating at resonance frequency 0.675 THz are presented in Table 1.

![Figure 1](image)

**Figure 1.** Electrodynamic model (front view) of decelerating sapphire planar structure at resonance frequency 0.675 THz. 1 – vacuum; 2 – dielectric coat; $H_{\text{cap}}$ – channel height; $H_{\text{die}}$ – dielectric coat height; $H_{\text{vac}}$ – vacuum channel height; $W_{\text{cap}}$ – channel width.

**Table 1.** Geometrical and electrodynamic characteristics of decelerating planar structure with sapphire coating at resonance frequency 0.675 GHz (geometrical characteristics are shown in Figure 1).

| Material | $\varepsilon$ | $H_{\text{cap}}$ ($\mu$m) | $W_{\text{cap}}$ ($\mu$m) | $Q$-factor | $R_{\text{sh}}/Q$ (kOhm/m) | Group velocity $\beta_{\text{group}}$ |
|----------|---------------|----------------------------|--------------------------|-------------|--------------------------|-------------------------------|
| Sapphire | 9.9           | 228                        | 500                      | 1133        | 61                       | 53.8                          | 0.62                          |
3. The radiating horn antenna integrated into the sapphire planar channel

As it is known an axial or planar decelerating channel radiating at the end into open space does not provide the high directivity of radiation, which was shown on the diagrams in the article [5]. Rectangular or circular cross section horn antenna can be used for increasing the radiation efficiency. This type of decelerating channel has rectangular cross section, therefore the most relevant variant shall be the rectangular antenna which will be directly integrated into the end of the planar channel. The main parameters of the antenna is its directivity, the angle between its axis and the direction of the main lobe, the angular width of the main lobe and the reflection coefficient of the horn, the radiation reflectivity of the horn and width of the operating frequency band.

Electrodynamic model of a copper antenna matched with the sapphire planar channel was tuned to the resonant frequency of 0.675 THz (fig. 2). Electrical field distribution simulated at 1 J of storage power in the structure is shown in Figure 3. This condition was used for parameters simulation. Geometrical characteristics and simulation results of radiating antenna matching with decelerating sapphire planar channel are submitted in Table 2. Directivity patterns of such extractor are shown in Figure 4. S11-parameters analysis results are shown in Figure 5. Here S11-parameter is interpreted as a wave reflection coefficient from the output side into the horn antenna.

![Electrodynamic model (side view) of the rectangular horn matched with decelerating channel: 1 – vacuum; 2 – dielectric coat; 3 – copper; \( H_{cap} \) – channel height; \( H_{vac} \) – vacuum channel height; \( H_{diel} \) – dielectric coat height; \( H_{cop} \) – copper part height; \( H_{horn} \) – horn height; \( L_{cap} \) – channel length; \( L_{caphorn} \) – length channel with horn.](image)

**Table 2.** Geometrical characteristics and simulation results of radiating antenna matching with decelerating sapphire and copper capillary tuned at frequency 0.675 THz (geometrical characteristics are shown in Figure 2).

| \( H_{cap} \) (µm) | \( H_{vac} \) (µm) | \( H_{diel} \) (µm) | \( H_{cop} \) (µm) | \( H_{horn} \) (µm) | \( L_{cap} \) (mm) | \( L_{caphorn} \) (mm) | Directivity (dB) | Angular width (°) | Reflectivity (dB) | Operating frequency band width (THz (%)) |
|------------------|-------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 260              | 210               | 15               | 7.5              | 305.9            | 0.2              | 0.266            | 9.1              | 75.7             | -38.3            | 0.042 (6.2)      |
Figure 3. Electrical field distribution of decelerating planar channel with radiating antenna at frequency of 0.675 THz.

As in the case of axial structure angle reduces both directivity and operating frequency band width by increasing the horn beam. The width of the main lobe of the radiation and its angle contrary increase. Increasing the length of the horn and decreasing the beam angle lead to directivity increase. It is also worth to note that using the ribbon beam will allow to obtain higher directivity pattern values as the beam travelling through the planar dielectric structure will interact more with top and bottom of structure. Consequently it means a higher efficiency of THz-radiation output.

Figure 4. Circular (a) and three-dimensional (b) patterns of decelerating sapphire and copper planar channel at operating frequency of 0.675 THz matching with the horn extractor.

Figure 5. S11-parameters analysis results.
Comparison of electrodynamic characteristics of axial and planar Cherenkov structures are presented in Table 3.

Table 3. Comparison of electrodynamic characteristics of axial and planar structures.

| Geometry  | $\varepsilon$ | $R_{sh}$ (MOhm/m) | $R_{sh}/Q$ (kOhm/m) | $Q$ | $\beta_{gr}$ | F (THz) |
|-----------|---------------|-------------------|---------------------|-----|-------------|---------|
| Axial     | 9.9           | 50.2              | 32.7                | 1531| 0.43        | 0.675   |
| Planar    | 9.9           | 61.0              | 24.8                | 1398| 0.57        | 0.675   |

4. Conclusion

A model of planar Cherenkov radiating channel with horn antenna coated with sapphire and copper at the resonant frequency of 0.675 THz was designed. The group velocity is in the range of 0.5–0.6 c, the effective shunt impedance is $R_{sh}/Q = 20$–25 kOhm/m. Calculated horn antenna directivity provides $< -10$ dB, the reflection coefficient of the output of the capillary is less than -25dB, the width of the operating frequency band is $\sim 6\%$. Apparently as it follows from the results electrodynamic characteristics of axial and planar structure geometry do not differ significantly which allow to considering the planar Cherenkov decelerating structure as accepted for THz-radiation output. Planar Cherenkov decelerating channel with integrated radiating antenna allows achieving a wide range of operating parameters for different geometrical dimensions with axial structure.

References

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