Method of particle energy determination based on measurement of waveguide mode frequencies

A V Tyukhtin
Radiophysics Dep., St Petersburg State University
1 Ul’yanovskaya Str., St Petersburg, 198504, Russia
E-Mail: tyukhtin@bk.ru

Abstract. A new method of determination of charged particle energy is developed. This method consists in use of dependency of waveguide mode frequencies on Lorenz factor of particle. For this method it is principal that the particle bunch generates radiation in waveguide and the mode frequencies depend essentially on the Lorenz factor. Three variants of realization of such technique are considered. The first variant consists in use of a thin dielectric layer in a waveguide. The second variant is based on use of a waveguide containing a system of wires coated with a dielectric material. The third version consists in application of a circular waveguide having a grid wall. For all cases analytical solutions of the problems are obtained (in the case of grid waveguide we use the averaged boundary conditions). Some typical results of computations are given. Advantages and disadvantages of different variants are discussed. It is noted that the grid waveguide can be used as well for generation of microwave radiation.

1. Introduction
Cherenkov radiation is widely used for detection of charged particles [1]. However, as far as we know, there are no Cherenkov detectors using properties of radiation in waveguide structures. Meantime Cherenkov radiation in waveguide is no exotic effect. For example, it is actively used for wakefield acceleration of charged particles [2, 3]. In this technique, a large bunch (“driver”) excites Cherenkov radiation (so-called “wakefield”) in a waveguide loaded with a dielectric layer, and another (relatively small) bunch is accelerated in this field. Owing to this application, the techniques of Cherenkov radiation generation in waveguides are well-tested in present.

The bunch diagnostics method under consideration consists in use of dependency of the waveguide mode frequencies $\omega_m$ on Lorenz factor of the bunch particles $\gamma = \left(1 - \beta^2\right)^{-1/2}$ ($\beta = V/c$, $V$ is a bunch velocity, $c$ is a light velocity) [4–11]. Therefore, it is principal that the particle bunch generates Cherenkov radiation in waveguide. This can be achieved with different ways, but it is obvious that the waveguide can not be a simple regular structure with perfectly conductive walls. In the paper [4], the authors have offered to use a cylindrical layer of isotropic nondispersive dielectric in circular waveguide. A disadvantage of such variant is that the dependency of waveguide modes on the Lorenz factor is usually weak, therefore accuracy of Lorenz factor determination will be small especially for the ultra-relativistic case $\gamma >> 1$ (this peculiarity is typical for all known detectors based on Cherenkov phenomenon). However it is possible to overcome partly this imperfection.
We have offered several variants which give essential dependencies \( \omega_m(\gamma') \) both for predetermined narrow range of Lorenz factor values and for enough wide range. By our opinion, three versions are perspective for application. One of them is based on use of a thin dielectric layer in a waveguide [9]. Other variant is based on use of a waveguide loading with some metamaterial [5–10], for example, a system of wires coated with a dielectric layer [10]. The third variant is a circular waveguide having a grid wall [11]. Further the peculiarities of these versions are discussed.

2. Thin dielectric layer

In this section we consider the case of a circular waveguide loaded with a simple dielectric layer. This problem is well known in connection with the wakefield acceleration technique [2, 3]. Just this structure has been offered by Poliektov etc. [4] for determination of energy of particles in bunches. Our suggestion consists in using a thin dielectric layer instead a usual relatively thick layer [9].

It is assumed that some dielectric material forms a cylindrical layer in a circular waveguide with a radius \( a \). Vacuum channel has radius \( b \), and thickness of the medium layer is \( d = a - b \). The particle bunch possessing a charge \( q \) moves along the \( z \)-axis with a velocity \( V = c\beta \vec{e}_z \). The transverse dimension of the bunch is assumed to be negligible, and longitudinal distribution of the charge is determined by the Gaussian function \( \exp(-\zeta^2/(2\sigma^2)) \), where \( \zeta = z-Vt \) and \( \sigma \) is much less than the typical wavelength.

It is assumed that the phase velocity of electromagnetic waves in the layer material is less than the charge velocity: \( c/\sqrt{\varepsilon} < V \) that is \( c\beta^2 > 1 \), where \( \varepsilon \) is a permittivity of material (dissipation and dispersion are assumed to be negligible, permeability is \( \mu = 1 \)). Expressions for the components of the wave electromagnetic field (so called “wakefield”) are well known [12]. In vacuum channel, they can be written in the following form (cylindrical coordinates \( \rho, \phi, \zeta \) are used):

\[
E_z = -4q(1-\beta^2)c^{-2}\beta^{-2}\theta(-\zeta) \text{Re} \left\{ \sum_{m=1}^{\infty} \omega_m \text{Res} \alpha(\omega) I_0(k(\omega_m)\rho) \exp\left[-\omega_m^2\sigma^2(2V^2)^{-1} + i\omega_m\zeta V^{-1}\right] \right\},
\]

\[
E_\rho = -4q c^{-2} \beta^{-1} \theta(-\zeta) \text{Im} \left\{ \sum_{m=1}^{\infty} k(\omega_m) \text{Res} \alpha(\omega) I_1(k(\omega_m)\rho) \exp\left[-\omega_m^2\sigma^2(2V^2)^{-1} + i\omega_m\zeta V^{-1}\right] \right\},
\]

\[
H_\phi = \beta E_\rho,
\]

where

\[
\begin{align*}
\alpha(\omega) &= \frac{s(\omega)K_1(k(\omega)b)\psi_1(s(\omega)) + \varepsilon k(\omega)K_0(k(\omega)b)\psi_0(s(\omega))}{s(\omega)I_1(k(\omega)b)\psi_1(s(\omega)) - \varepsilon k(\omega)I_0(k(\omega)b)\psi_0(s(\omega))}, \\
\psi_0(s) &= J_1(sb)N_0(sa) - J_0(sa)N_1(sb), \quad \psi_1(s) = J_0(sb)N_0(sa) - J_0(sa)N_0(sb), \\
k(\omega) &= \omega V^{-1}\sqrt{1-\beta^2}, \quad s(\omega) = \omega V^{-1}(c\beta^2 - 1), \\
\theta(-\zeta) &= 1 \text{ for } \zeta < 0, \text{ and } \theta(-\zeta) = 0 \text{ for } \zeta > 0.
\end{align*}
\]

Here \( \text{Res} \alpha(\omega) \) are residues of function \( \alpha(\omega) \) in poles \( \omega = \omega_m \), \( I_n(\zeta) \) and \( N_n(\zeta) \) are Bessel and Neumann functions correspondingly. The mode frequencies \( \omega_m \) are determined by the following dispersion equation:

\[
s(\omega)I_1(k(\omega)b)\psi_1(s(\omega)) - \varepsilon k(\omega)I_0(k(\omega)b)\psi_0(s(\omega)) = 0.
\]

Some results of computations of roots of this equation are shown in figures 1, 2. One can see that dependence of \( \nu_m = \omega_m/(2\pi) \) on \( \gamma \) becomes stronger with decreasing in the layer thickness \( d \).

For example, one can find from figure 2 that for the range 20 < \( \gamma < 30 \) the relative error of Lorenz factor \( \Delta\gamma/\gamma \) has the same order as the relative error of frequency \( \Delta\nu_1/\nu_1 \) in the case...
\[ d = 2 \text{ mm} \ (b = 98 \text{ mm}) \]. At the same time, these errors differ radically \( \left( \Delta \gamma / \gamma \gg \Delta v_1 / v_1 \right) \) for \( d > 10 \text{ mm} \). Thus the thin layer provides essential advantage in comparison of the thick one. Naturally, there is some limitation on value of \( d \) because the amplitude of the mode must be enough large for measurement. However computations show that this limitation is not essential for typical bunches with charges \( > 1 \text{pC} \).

**Figure 1.** Dependence of frequencies \( v_m \) (GHz) on \( \gamma \) in the case of non-dispersive isotropic dielectric layer for thick layer (above) and thin one (below). Channel radius \( b \) and the mode numbers \( m \) are indicated in pictures; \( a = 10 \text{ cm}, \ \varepsilon = 1.05 \).

**Figure 2.** Dependence of the 1st mode frequency \( v_1 \) (GHz) on \( \gamma \) for the channel radius values indicated near the curves (cm); \( a = 10 \text{ cm}, \ \varepsilon = 1.05 \).

The shortcoming of this technique consists in its limitation on \( \gamma \). For example, if \( b = 98 \text{ mm} \) the range \( \gamma \leq 10 \) corresponds to frequencies \( v_1 > 50 \text{ GHz} \) (figure 1). The typical bunches with \( \sigma \geq 3 \text{ mm} \) generate mode with very small amplitude because of the exponential factor in (1). On the other hand for \( \gamma > 30 \) the precision of \( \gamma \) is essentially lower in comparison with the precision of the frequency measurement. These defects can be partially overcome with the help of different structures.

### 3. The wire metamaterial

Besides the layer of simple dielectric, different variants of waveguide structures can be used for determination of particle energy. Some of them are connected with use of metamaterials which are artificial periodic structures with small periods. Such structures can be characterized by macroscopic parameters such as permittivity and permeability. One of known metamaterials is a system of parallel wires with coating [13, 14].
Let us consider a periodic system of perfect cylindrical conductors which have a nonconductive cylindrical coating with permittivity $\varepsilon_1$ and permeability $\mu_1$. A radius of conductor is $r_0$, and a radius of coating is $r_d$. The surrounding medium is characterized by permittivity $\varepsilon_2$ and permeability $\mu_2$. Let the $z$-axis be parallel to wires. The periods of system along $x$- and $y$-axis are equal to $d$. It is assumed that the following conditions are fulfilled:

$$r_d << d << \Lambda,$$

where $\Lambda = \min(\lambda, \Delta)$, $\lambda$ is a typical wavelength, $\Delta$ is a distance of variation of an “incident” field (i.e. the field in the case of absence of the structure).

For determination of “effective” permittivity of such structures, we have developed a new method [14] which is similar to method of averaged boundary conditions for planar structures [15]. Result of approximate analytical calculation of permittivity tensor can be written in the following form [14]:

$$\tilde{\varepsilon} = \begin{pmatrix} \varepsilon_\parallel & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_c \end{pmatrix}, \quad \varepsilon_\parallel = \varepsilon_c, \quad \varepsilon_\perp = \varepsilon_c, \quad \varepsilon_1 = \varepsilon_c \left(1 - \frac{\omega_p^2}{\omega^2 - \chi \omega^2_0 \kappa^2 / (\varepsilon_2 \mu_2)}\right),$$

where

$$\omega_p^2 = \frac{2\pi c^2}{d^2 \varepsilon_c \mu_2} \left[ \ln \left( \frac{d}{r_d} \right) + \frac{\mu_1}{\mu_2} \ln \left( \frac{r_d}{r_0} \right) \right] - 1.0487,$$

$$\chi = 1 + \frac{\left(\varepsilon_2 / \varepsilon_1 - \mu_1 / \mu_2\right) \ln(r_d/r_0)}{\ln(d/r_d) + \mu_1 \mu_2 \ln(r_d/r_0) - 1.0487}.$$

$\varepsilon_c$ is some constant which is close to $\varepsilon_2$ (it can be estimated more exactly with the Garnett’s formula). “Effective” permeability of structure is some constant $\mu_c$ which is close to $\mu_2$. One can see that this “medium” has both frequency and spatial dispersion. The role of spatial dispersion is connected with the parameter $\chi$. We can vary this parameter owing to varying magnitudes of $\varepsilon_1 / \varepsilon_2$, $\mu_1 / \mu_2$, and $r_d / r_0$. Increase in any of these parameters results in decreasing the role of spatial dispersion [14].

We consider a circular waveguide containing the structure under consideration (the main axis of structure ($z$-axis) coincides with the waveguide axis). It is assumed that $\mu_1 = \mu_2 = 1$. As above, a charged particle bunch moves along the $z$-axis with velocity $\vec{V} = c \beta \vec{e}_z$, the transverse dimension of the bunch is negligible, and longitudinal distribution of the charge is determined by the Gaussian function. Using analysis basing on the mode expansion of the wave field one can obtain the following expression for the mode frequencies:

$$\omega_m \equiv 2\pi \nu_m = \beta \sqrt{\frac{c^2 \kappa_m^2}{a^2 (\beta^2 e_c - 1)} + \frac{\varepsilon_c \omega_p^2}{\beta^2 e_c - \chi}},$$

where $a$ is a waveguide radius, $\kappa_m$ are roots of Bessel function ($J_1(\kappa_m) = 0$).

In the particular case of wires without coating ($\chi = 1$) the modes frequencies are real only for $\beta^2 e_c > 1$, i.e. Cherenkov radiation is generated only for superlight speed of charge as in an usual medium. In this situation we do not have preferences as compared with the ordinary media. Principally different result takes place in the case of wires with coating. As earlier the ordinary modes are generated for $\beta^2 e_c > 1$. However there are additional (“anomalous”) modes which are generated under condition $\chi < \beta^2 e_c < 1$. Frequencies of these modes decrease with increase in the mode number and with increase in $\gamma$ (figures 3, 4). One can see that there are strong dependence $\nu_m(\gamma)$ in some narrow range of $\gamma$. In this range the relative error of Lorenz factor $\Delta \gamma / \gamma$ can be much less than the relative error of measurement of frequency $\Delta \nu_m / \nu_m$. Thus, this structure is convenient for high-precision
determination of relatively small values of $\gamma$ in some predetermined range. However it is not good for wide range of $\gamma$ and for big values of $\gamma$.

4. The grid waveguide

Here we consider a structure that allows determining relatively big values of $\gamma$: a circular waveguide which has a grid wall with rectangular cells (figure 5). As usual, the $z$-axis coincides with the waveguide axis. The grid is characterized by period $d_z$ for “$z$-wires” (which are parallel to the $z$-axis) and period $d_\phi$ for “$\phi$-wires” (which are orthogonal to the $z$-axis).

\[ \frac{d_z}{d_\phi} \]

Figure 5. Geometry of the problem.

The grid wires are perfect, and the following conditions are assumed to be fulfilled:

\[ r_0 \ll d_{z,\phi} \ll \Lambda \equiv \min(a, c/\omega). \] (10)

Owing to these inequalities we can use method of the averaged boundary conditions (ABC) [15]. In the case under consideration (where only TM-field is generated), the ABC has the form

\[ E_{\omega z}|_{r=a} = -\frac{i\omega d_z}{2\pi c} \ln \left( \frac{d_z}{2\pi r_0} \right) \left( 1 + \frac{c^2}{\omega^2 \beta^2 \delta^2} \right) \left( H_{\omega \phi}|_{r=a+0} - H_{\omega \phi}|_{r=a-0} \right), \] (11)

Figure 3. The mode frequencies depending on $\gamma$ for the medium parameters $\varepsilon_2 = \mu_2 = \mu_1 = 1$, $\varepsilon_c = 1.0027$, $\nu_p = 4.17$ GHz, $\chi = 0.887$ corresponding to the wire structure with $d = 10$ mm, $r_0 = 0.2$ mm, $r_1 = 0.3$ mm, $e_1 = 5$; the mode numbers are indicated in figure.

Figure 4. The 1st mode frequency depending on $\gamma$ for $r_0 = 0.3$ mm (curve 1), $r_0 = 0.4$ mm (2), $r_0 = 0.6$ mm (3), $r_0 = 1$ mm (4); other parameters are the same as in figure 3.
where $\delta = (1 + d_\phi / d_z + \kappa) / (d_\phi / d_z + \kappa)$. Parameter $\kappa$ is charged with contact between conductors in points of their intersections. In case of perfect contact $\kappa = 0$, and $\delta = (d_z + d_\phi) / d_\phi$, i.e. $\delta = 1$ for grid from $z$-wires only ($d_\phi = \infty$), $\delta = 2$ for grid with square cells ($d_z = d_\phi$), and $\delta \approx d_z / d_\phi > 1$ in the case $d_\phi << d_z$.

Omitting derivation we write expressions for wave field ("wakefield") in the case of Gaussian bunch moving along the waveguide axis. The non-zero components of wakefield (existing only behind the charge) are

$$E_r^W = \frac{4q\gamma}{a^2} \frac{k_0 a}{W(k_0 a)} \exp\left(-\frac{\omega^2 \sigma^2}{2V^2}\right) \sin\left(\frac{\omega_0 \zeta}{V}\right) \left\{K_0^2(k_0 a)I_0(k_0 r) \text{ for } r < a, \right. $$

$$K_0^2(k_0 a)I_0(k_0 r) \text{ for } r > a, \right\},$$

$$E_z^W = \frac{4q}{a^2} \frac{k_0 a}{W(k_0 a)} \exp\left(-\frac{\omega^2 \sigma^2}{2V^2}\right) \cos\left(\frac{\omega_0 \zeta}{V}\right) \left\{K_0^2(k_0 a)I_0(k_0 r) \text{ for } r < a, \right. $$

$$K_0^2(k_0 a)I_0(k_0 r) \text{ for } r > a, \right\},$$

$$B_\phi^W = \beta E_r^W,$$

where $W(x) = I_1(x)K_0(x) - I_0(x)K_1(x)$, $k_0 = \omega_0 V^{-1} \gamma^{-1}$, $\gamma = (1 - \beta^2)^{-1/2}$, $\beta = V/c$, $\zeta = z - Vt$. Here $k_0$ is a real positive solution of the following dispersion equation:

$$I_0(ka)K_0(ka) = \chi_\phi,$$

where $\chi_\phi = \frac{\delta \beta^2 - 1}{\delta} \frac{d_z}{2\pi a} \ln\left(\frac{d_z}{2\pi \eta_0}\right)$. This equation can have only a single real root $k = k_0$. This root exists under condition $\chi_\phi > 0$, that is $\beta > \delta^{-1/2}$. Thus, propagating mode can be generated only in the case $\delta > 1$. It means that generation of radiation (wakefield) is possible only in the case of grid possessing both $z$-wires and $\phi$-wires. This fact can be seemed wonderful because only current in $z$-wires are excited. However the distribution of the charge on the grid depends on the orthogonal $\phi$-wires too. This circumstance is reflected in the ABC (11) owing to presence of the parameter $\delta \neq 1$.

**Figure 6:** The mode frequency depending on $\gamma$; $a = 3$ cm, $r_0 = 0.5$ mm, $d_z = 2\pi a / 38 \approx 5$ mm; magnitudes of $d_\phi$ (cm) are given close to the curves.

**Figure 7:** Amplitudes of components $E_z^W$ (solid curves) and $E_r^W$ (dotted ones) depending on $r$; $q = 1\mu$C, $\sigma = 3$ mm, $a = 3$ cm, $r_0 = 0.5$ mm, $d_z = d_\phi = 2\pi a / 38 \approx 5$ mm, magnitudes of $\gamma$ are indicated near the curves.
One can obtain simple approximations for the propagating mode frequency in two particular cases:

\[ \omega_0 \approx \frac{V \gamma}{(2a \chi_g)} \text{ for } \chi_g \ll 1 \text{ (not very large } \gamma) , \]

(14)

\[ \omega_0 \approx \frac{2C}{a} \sqrt{\frac{\gamma^2 - 1}{\exp(-C - \chi_g)}} \text{ for } \chi_g > 1 \text{ (} \gamma \gg 1 \), \]

(15)

where \( C = 0.577... \) is Euler constant. According to (15) the dependency of \( \omega_0 \) on \( \gamma \) for large values of \( \gamma \) can be significant due to factor \( \exp(-\chi_g) \) strongly decreasing with increase in \( \gamma \). This fact is especially attractive for determination of particle energy.

Figures 6–9 show some results of computation of wave field. One can see that dependency of the mode frequency on Lorentz factor is essential for enough large range of magnitudes of \( \gamma \) (figure 6). For waveguide with radius of the order of several centimeters this range can be several decades. One can show that relative accuracy of determination of Lorentz factor \( \Delta \gamma/\gamma \) has the same order as relative accuracy of measurement of frequency \( \Delta \nu/\nu \) in some range of \( \gamma \). The radial component of electric field on the outward surface of waveguide is the most convenient for measurement because it is much more than longitudinal component (figure 7). Dependency of the radial component on \( \gamma \) is shown in figure 8. One can see that its values for bunch with the charge of 1 pC is enough large for measurements. Figure 9 shows typical wakefield. Note that this computation was performed with account of finite conductivity of wires. Consequently, exponentially decrease of wakefield with increase of \( |\xi| \) occurs.

![Figure 8](image_url)

**Figure 8.** Amplitude of the component \( E_{r}^W \) on the outward surface of waveguide \( (r = a + 0) \) depending on \( \gamma \); magnitudes of \( d_\phi \) (cm) are indicated near the curves, other parameters are the same as in figure 7.

![Figure 9](image_url)

**Figure 9.** Component \( E_{r}^W \) on the outward surface of waveguide depending on the distance \( \xi = z - Vt \) for \( \gamma = 15 \) (solid curve), \( \gamma = 20 \) (dotted curve), \( \gamma = 25 \) (dashed curve). Conductivity of wires is \( 5 \cdot 10^7 \text{(ohm m)}^{-1} \) (copper), other parameters are the same as in figure 7.

Note that the structure under consideration can be examined as generator of monochromatic microwave radiation too. It is important that radiation has single propagating mode in our model where the averaged boundary conditions are used. Really, radiation has some spectrum of shorter waves with wavelengths \( \leq d_\phi \). However these waves can be filtered out, and we will obtain almost monochromatic radiation with frequency \( \omega_0 \) that can be varied with variation of the bunch velocity.
5. Conclusion
We have considered different variants of realization of new method of particle energy determination. This method consists in use of dependency of waveguide mode frequencies $\omega_m$ on Lorenz factor $\gamma$. For this method it is principal that the mode frequencies depend essentially on $\gamma$.

The first version consists in use of a thin dielectric layer. Decrease of the layer thickness results in increase of dependency of $\omega_m$ on $\gamma$ and in some extension of the Lorenz-factor range which is suitable for measurement. The important advantage of this structure is that it is relatively simple for realization. But this method has essential limitations on $\gamma$ (both above and below).

The second variant is based on use of a waveguide containing a system of parallel wires coated with a dielectric material. Periods of the structure are assumed to be small, therefore it can be considered as some “medium” (metamaterial). In the waveguide with such filling, the bunch can generate not only the ordinary modes but also additional (“anomalous”) modes. These modes allow the energy determination with high accuracy. But this is possible only for some narrow range of $\gamma$, and the values of $\gamma$ can not be large.

The third version consists in application of a circular waveguide having a grid wall with small rectangular cells. Analytical solution of the problem has been obtained with use of the averaged boundary conditions. It has been shown that such structure gives essential dependency of frequency on Lorentz factor in wide range of its values. As well this structure can be used for generation of monochromatic microwave radiation with tunable frequency depending on the particle energy.

Acknowledgments
This research was supported by the Saint Petersburg State University.

References
[1] Zrelov V P 1970 Vavilov-Cherenkov Radiation in High-Energy Physics (Jerusalem: Israel Program for Scientific Translations)
[2] Power J G, Conde M E, Gai W, Kanareykin A, Konecny R and Schoessow P 2000 Phys. Rev. ST-AB 3 101302
[3] Kanareykin A 2010 J. Phys.: Conf. Ser. 236 012032
[4] Poliektov V V, Vetrov A A, Trukhanov K A and Shvedunov V I 2008 Instruments and Experimental Techniques 51 191
[5] Tyukhtin A V, Antipov S P, Kanareykin A and Schoessow P 2007 Proc. Particle Accelerator Conf. PAC’07 (USA, Albuquerque, 2007) p 4156
[6] Tyukhtin A V 2008 Tech. Phys. Lett. 34 884
[7] Tyukhtin A V 2009 Tech. Phys. Lett. 35 263
[8] Tyukhtin A V, Schoessow P, Kanareykin A and Antipov S 2009 AIP Conf. Proc. 1086 604
[9] Tyukhtin A V, Antipov S P, Kanareykin A and Schoessow P 2009 Proc. Particle Accelerator Conf. PAC’09 (Canada, Vancouver, 2009) p 4033
[10] Tyukhtin A V, Doli’ntitsina E G and Kanareykin A 2010 Proc. Int. Particle Accelerator Conf. IPAC’10 (Japan, Kyoto, 2010) p 1071
[11] Tyukhtin A V 2011 Proc. Int. Particle Accelerator Conf. IPAC’11 (Spain, San-Sebastian, 2011) p 1302
[12] Bolotovskiy B M 1961 Physics – Uspekhi 75 295
[13] Demetriadou A and Pendry J B 2008 J. Phys.: Condens.Matter 20 295222
[14] Tyukhtin A V and Doli’ntitsina E G 2011 J. Phys. D: Applied Physics 44 265401
[15] Kontorovich M I, Astrakhhan M I, Akimov V P and Fersman G A 1987 Electrodynamics of grid structures (Moscow: Radio i svyaz’; in Russian).