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Traveling wave tubes: a history of people and fates

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Contents

Abstract. **The study of the interaction of electron beams with electromagnetic fields and of devices based on them is one of the central areas of the science of vibrations and waves. In the 20th century, *Physics–Uspekhi* published reviews devoted to the theory and description of new devices at that time. The theory and design of these devices and their place in the electromagnetic wave range have changed with time. Relativistic electronics has appeared. The terahertz range is being mastered. Some new facts related to the creation history of the traveling wave tube (TWT) have been discovered and are discussed in this paper. Events in the research biography of Andrei Haeff, Rudolf Kompfner, and John Pierce are described. Along with the TWT history of persons and their fates, the results of some modern TWT studies and developments for various purposes are presented.**

Keywords: traveling wave tubes, Haeff, Kompfner, Pierce, history

As for the novelty, there is no man who,
having learned science deeply
and observing the world, would not come to a firm
thought that "there is no new thing upon the Earth".
Francis Bacon

1. Introduction: from the past to the present

In 1948, *Physics–Uspekhi* published paper [1] by Lopukhin beginning with the words: "Recently, information about a new microwave amplifier appeared in the literature. Experiments have shown that the amplifier of this type offers a number of advantages compared to other microwave amplifiers used so far. The operation of the new amplifier is based on the witty use of the interaction of an electron beam with a traveling electromagnetic wave." In [1], the design of a traveling wave tube (TWT) and the main principles of amplification are described, and a brief analytic theory is considered (equations for the variable components of the current and electric field are derived and the solution of the dispersion equation is qualitatively analyzed). The operation characteristics of the tube known at that time are also presented: the power gain is 200, the bandpass at the carrier frequency of the amplified signal at 3600 MHz (wavelength $\lambda \approx 10$ cm) is about 800 MHz [2].

We briefly recall the essence of "the witty use of the interaction of an electron beam with a traveling electromagnetic wave," beginning with the elementary description of a spatial resonance (see, e.g., [3, 4]).

We consider a traveling wave $U(x, t)$ propagating with a constant velocity $v_{\rm ph}$ (t is time) in a one-dimensional medium along the direction x. The wave propagation can be described by the equation

$$\frac{\partial U}{\partial t} + v_{\rm ph}\frac{\partial U}{\partial x} = 0\,.$$

If the medium in which the wave propagates is subjected to a distributed external action $G(x, t) = G(x)\exp(\mathrm{j}\omega t)$ (ω is the circular frequency, $\mathrm{j} = \sqrt{-1}$), then, for $U(x, t) = U(x)\exp(\mathrm{j}\omega t)$, we have

$$\frac{\partial U(x)}{\partial x} + \mathrm{j}\,\frac{\omega}{v_{\rm ph}}\,U(x) = G(x)\,. \tag{1}$$

Under the condition that $U(0) = 0$, it is convenient to write Eqn (1) in the integral form

$$U(x) = \exp\left(-\frac{\mathrm{j}\omega x}{v_{\rm ph}}\right)\int_0^x G(\xi)\exp\left(\frac{\mathrm{j}\omega\xi}{v_{\rm ph}}\right)\mathrm{d}\xi\,, \tag{2}$$

where ξ is the moving integration variable. Assuming now that the external action is a wave with a constant amplitude, a frequency ω, and a phase velocity $v_{\rm ext}$, i.e., $G(x, t) =$

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$G(x)\exp(\mathrm{j}\omega t - \mathrm{j}\omega x/v_{\text{ext}})$, and integrating (2), we find

$$U(x,\,t) = G(0)\exp\left(\mathrm{j}\left(\omega t - \frac{\omega x}{v_{\text{ph}}}\right)\right) \times \frac{\exp\left(\mathrm{j}(\omega x/v_{\text{ph}} - \omega x/v_{\text{ext}})\right) - 1}{\mathrm{j}\left(\omega/v_{\text{ph}} - \omega/v_{\text{ext}}\right)}\,. \qquad (3)$$

Assuming that $\omega/v_{\text{ph}} \approx \omega/v_{\text{ext}}$ ($v_{\text{ph}} \approx v_{\text{ext}}$), we obtain secular growth along the coordinate x, i.e.,

$$U(x,\,t) = G(0)x\exp\left(\mathrm{j}\left(\omega t - \frac{\omega x}{v_{\text{ph}}}\right)\right)\,. \qquad (4)$$

The main conclusion of the elementary analysis is that to obtain growth of a harmonic wave in space under the action of an external wave, the wave numbers of these waves must coincide, i.e., spatial resonance should take place. Of course, both the frequencies and wave numbers are in resonance, because there is just one frequency ω and $v_{\text{ph}} \approx v_{\text{ext}}$. The last equality is usually called the synchronism condition. The understanding of these conditions made the creation of TWTs possible in due time.

We now assume that $U(x,\,t)$ is the longitudinal component of the electric field strength E of a wave in a waveguide system and $G(x,\,t)$ is an alternating current wave I in the electron flow (up to a constant dimensional coefficient). In this case, Eqn (1) is a differential equation for excitation of the waveguide by a specified current (see, e.g., [4, 5]):

$$\frac{\mathrm{d}E}{\mathrm{d}x} + \mathrm{j}\,\frac{\omega}{v_{\text{ph}}}E = -\,\frac{1}{2}\left(\frac{\omega}{v_{\text{ph}}}\right)^2 KI(x)\,, \qquad (5)$$

where K has the dimension of resistance and is called the coupling resistance. If a rectilinear electron flow with a low current density is represented as a flow of noninteracting particles moving at a velocity v_0, the high-frequency perturbations have the form of the current wave

$$I(x,\,t) = I(0)\exp\left(\mathrm{j}\left(\omega t - \frac{\omega x}{v_0}\right)\right)$$

with the phase velocity v_0 ($v_0 = v_{\text{ext}}$). Therefore, the simplest synchronism condition is the equality of the electron velocity in the flow and the phase velocity of the wave. To achieve the synchronism condition for nonrelativistic electron velocities, the electromagnetic wave should be slowed down. A huge number of systems used for slowing down waves have been invented, but only few have survived: first of all, a spiral in broadband TWTs, a chain of coupled resonators in high-power TWTs, and a winding waveguide in short-wavelength amplifiers. We return to slowing down systems below when describing the history of TWTs.

We note that in hindsight, we consider only the effect of an external wave on the intrinsic wave. This is not usually the case. Under the synchronism condition, the problem is self-consistent because the field changes the current. In a TWT, for example, the field of the decelerating system modulates the beam in velocity and groups electrons into bunches. What are the features of electron bunching in a traveling wave and the interaction of electrons with the wave? A qualitative explanation already exists in paper [1] and textbooks. However, it is unlikely that the reader would seek a journal from the past years or flip through a textbook. Therefore, we allow ourselves one more look back.

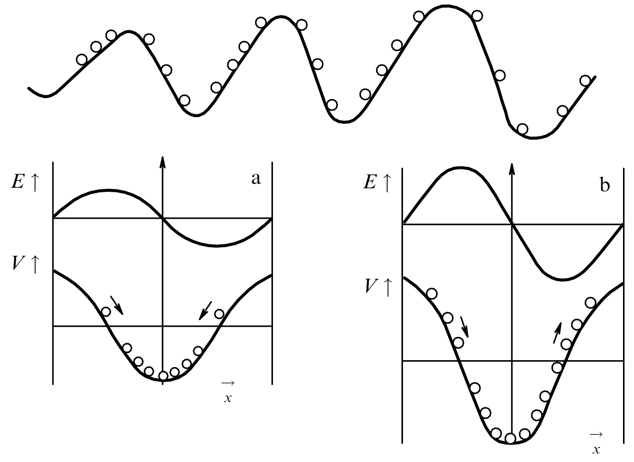

Figure 1. Illustration of electron bunching processes in a traveling wave and interaction of electrons with a wave in a mechanical model [4]: (a) at the beginning of the interaction range $v_0 = v_{\text{ph}} = v_{\text{h}}$ and (b) at the end of the interaction range $v_0 > v_{\text{h}}$.

The interaction of electrons with an electromagnetic wave can be illustrated best with the help of the known mechanical model [5] in which balls move over some surface under the action of gravity (Fig. 1). In this case, the balls are analogs of electrons, and the surface profile corresponds to the longitudinal distribution of the electromagnetic field potential at a given moment of time. We note that in the coordinate system comoving with a 'cold' wave, the crests and troughs of the potential surface are at rest.

We assume that the wave velocity v_{ph} in a contour without a beam coincides with the unperturbed electron velocity v_0. Initially, the energy exchange between electrons and the wave is small. The analog of this in the mechanical model is the same height of crests and troughs of the profile under study. Under the action of gravity, balls (electrons) roll down to the center of troughs, i.e., group near the zero phase of the electric field strength. As a result, the grouped beam current outpaces the 'cold' wave field by $\pi/2$ (it is said that the interaction is a reactive type). This interaction reduces the 'hot' wave velocity v_{h}. Then the balls displace from the troughs to the right, decelerating slope of the potential surface (the longitudinal component of the wave field here is different from zero). The energy exchange them leads to an increase in the amplitude (the height of crests and the depth of troughs in the mechanical model increase).

If we assume that the initial electron velocity slightly exceeds the phase velocity of the wave, and the wave is increasing, the electrons (balls) moving over the surface experience repeated ascents and descents. As a result, the balls are grouped in decelerating regions (the 'right' slope), forming bunches in this phase, and are disaggregated in accelerating regions (the 'left' slope). Because the wave is increasing, deceleration effects dominate over acceleration effects. If the electrons (balls) pass over the entire decelerating slope, the interaction is the most efficient. Due to a constant removal of small energy portions from the electron flow, the electromagnetic wave is amplified over the total length of the tube.

If the initial electron velocity is smaller than the phase velocity of the wave, and the electrons 'lag behind' it, then the balls (electrons) predominantly group on the acceleration slopes of the surface, which corresponds to the energy transfer from the wave to the electron flow. Then the electromagnetic wave can decay or the input signal can be completely suppressed, as we discuss in Section 4.

It is known that an electron moving rectilinearly and uniformly in a vacuum produces no emission. When it moves in a transparent medium with the velocity exceeding the phase velocity of an electromagnetic wave $v_{\rm ph} = c/n$, where c is the speed of light in a vacuum and n is the refractive index of the medium, Vavilov–Cherenkov radiation is possible. In this case, a conic wave diverges at an angle θ (determined by the known relation $\cos\theta = v_{\rm ph}/v_0$) to the axis coinciding with the electron motion direction. Individual electrons with random phases emit incoherently, which corresponds to spontaneous radiation. Coherent radiation can be observed when the phases of fields emitted by different electrons match. This is possible if electrons are properly grouped into bunches.

Radiation is also possible when an electron flies in a vacuum near a periodic structure having a period l along the electron trajectory. A set of spatial harmonics with the wave numbers $k_n = \omega/v_0 + 2\pi n/l\,(n = 0, \pm 1, \pm 2, \ldots)$ is then excited. A wave is formed in the environment with the phase velocity (or the phase velocity of one of the spatial harmonics along the electron motion direction) exactly equal to v_0. However, grouping is absent and the wave goes away with no back reaction on the electron flow. If the wave is kept in the system (for example, the flow moves inside a spiral), it groups the electron flow. Such a longitudinal bunching occurs in a TWT, resulting in induced Cherenkov radiation.

We note that the theory of spontaneous and induced radiation of free electrons applied to resonance self-oscillators is described in detail in papers by Vainshtein [6–8]. The author emphasizes that the classical theory for such devices allows induced radiation in the background-field approximation, while spontaneous radiation is obtained in the fixed-current approximation.

We end the brief discussion of the spontaneous and induced radiation of free electrons with a quotation from book [9]:

"A reader educated in the spirit of the traditional approach to the microwave electronics will probably assume that the consideration of spontaneous and induced radiation is artificial and superfluous. Indeed, spontaneous and induced radiations are the basic concepts of the quantum radiation theory without which quantum electronics cannot be considered. However, classical electronics describing the motion of electrons in the vacuum did not use these concepts until recently because it did not give any instructive and new results. The situation changed with the advent of devices with curvilinear beams, whose theory can be developed in two ways: in the spirit of classical electrodynamics considering the motion of electrons... and in the spirit of quantum electronics considering an electron beam as an active medium consisting of nonlinear oscillators... the latter approach proves to be both fruitful and physically illustrative."

It is interesting that the study of the synchronization principle and electron bunching effect, which are typical for TWTs, had a considerable impact on the development of the theory of cyclotron-resonance masers and free-electron lasers (FELs). On the other hand, the study of processes occurring in these devices allowed understanding that from the standpoint of quantum physics, TWTs also use induced radiation mechanisms, as in masers and lasers.

We note that at present the electronic industry is mainly dealing with the development and manufacturing of relatively low-power TWTs. But one of the avenues of fundamental investigations is still the study of devices using high-current relativistic electron beams. They can be used for generating and amplifying gigawatt pulses. It is assumed that prerequisites for the development of relativistic microwave electronics already appeared in the late 1940s [10]. First of all, its origin is related to theoretical papers by Ginzburg [11, 12]. The first experimental attempts to create relativistic microwave radiation sources based on usual accelerators were unsuccessful [13]. In reality, the energy of relativistic electrons can be taken away if a sufficiently strong microwave field exists in a sufficiently large region. "...The relativistic microwave electronics became a reality only after the advent of high-current accelerators" [10].

Petelin [10] compared the similarity laws for weakly relativistic and ultrarelativistic microwave devices to find whether the use of intense relativistic electrons would result in qualitative changes in the design of microwave devices. In the weakly relativistic case, the system of equations for the motion of electrons was obtained in the form

$$\begin{cases} \dfrac{d\mu}{d\zeta} = \mathrm{Re}\left[G(\zeta)\exp(\mathrm{j}v)\right], \\ \dfrac{dv}{d\zeta} = \dfrac{1}{\sqrt{\mu}} - 1, \end{cases} \qquad (6)$$

where $\mu = v^2/v_0^2$ is the dimensionless kinetic energy, v_0 is the electron velocity at a device input, $G = -2eE_{\parallel}^{\omega}/(\omega m_0 v_0)\exp(\mathrm{j}\,\zeta)$, $\zeta = z\omega/v_0$ is the dimensionless longitudinal coordinate, $E_{\parallel}^{\omega}$ is the complex amplitude of the longitudinal component of an alternating electric field at the frequency ω, and e and m_0 are the electron charge and mass. An ultrarelativistic electron flux is described by the system of equations

$$\begin{cases} \dfrac{d\mu}{d\zeta} = \mathrm{Re}\left[G(\zeta)\exp(\mathrm{j}v)\right], \\ \dfrac{dv}{d\zeta} = \dfrac{1}{\mu^2}, \end{cases} \qquad (7)$$

where $\mu = \varepsilon/\varepsilon_0$ is the dimensionless total energy, ε_0 is the total electron energy at the device input, and

$$G = -2\gamma_0\left(\frac{e\lambda\!\!\!^{-} E_{\parallel}^{\omega}}{\varepsilon_{\rm rest}}\right)\exp\left(\frac{\mathrm{j}z}{\lambda\!\!\!^{-}}\right), \quad \zeta = \frac{z}{\lambda\!\!\!^{-}}\,\frac{1}{2\gamma_0^2},$$

$$\lambda\!\!\!^{-} = \frac{\lambda}{2\pi} = \frac{c}{\omega}, \quad \gamma_0 = \frac{\varepsilon_0}{\varepsilon_{\rm rest}},$$

where $\varepsilon_{\rm rest} = m_0c^2$ is the rest energy.

A comparison of results has shown, for example, that to preserve constant electron efficiency and the constant function $G(\zeta)$ characterizing the relation between the electron energy and the real field structure with increasing electron energy, it is necessary:

(i) in the weakly relativistic case (6), to increase the relative length L/λ of the device proportionally to the electron velocity or to increase the product $\lambda E_{\parallel}^{\omega}$ proportionally to the electron velocity;

(ii) in the ultrarelativistic case (7), to increase the ratio L/λ proportionally to the electron energy squared or to decrease the product $\lambda E_{\parallel}^{\omega}$ inversely proportionally to the electron energy.

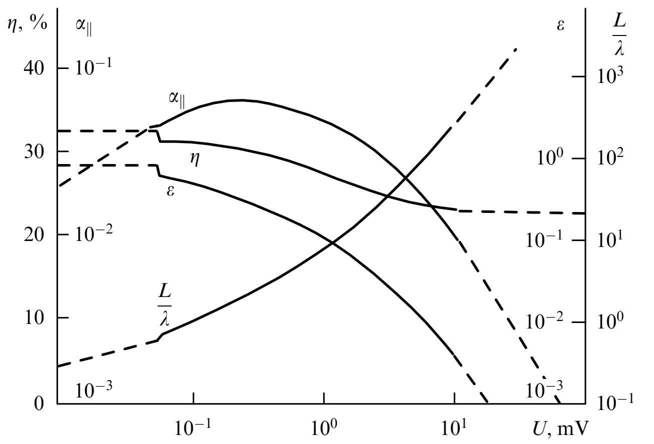

Figure 2. Dependence of the maximum efficiency and the optimal values of the parameters $\alpha_{\parallel}$, ε, and L/λ on the electron energy [10].

Thus, the similarity laws for classical and relativistic devices derived in [10] are substantially different and in some sense even opposite to each other (Fig. 2 [14, 10]). Figure 2 presents the dependences of the maximum efficiency and the optimal values of the parameters $\alpha_{\parallel} = (e\bar{\lambda}E_0)/\varepsilon_{\text{rest}}$, $\varepsilon = (v_0 - v_{\text{ph}})/v_0$, and L/λ on the electron energy in the case of the interaction of an electron beam with a wave with the constant amplitude E_0 and the phase velocity v_{ph}.

It is interesting that equations for the motion of the electron flow and equations for the FEL mentioned above have a similar structure. The universal asymptotic equations of motion of an electron in an FEL presented in [15] have the form

$$\begin{cases} \dfrac{\mathrm{d}w}{\mathrm{d}t'} = \kappa \operatorname{Re}\left[\alpha \exp\left(\mathrm{j}\theta\right)\right], \\ \dfrac{\mathrm{d}\theta}{\mathrm{d}t'} = \delta + \mu w, \end{cases} \tag{8}$$

where $t' = \omega t$, $w = 1 - \gamma/\gamma_0$, $\gamma = \sqrt{1 - v^2/c^2}$, $\alpha = (eE_0^{\omega})/(\omega c m_0 \gamma_0)$ is the dimensionless amplitude of the wave, δ is the initial resonance mismatch, μ is the bunching parameter, and κ is the electron–wave coupling parameter characterizing the projection of the electron velocity vector on the electric field of the wave.

The fact that the equations of motion of electrons in 'O'-type FELs coincide up to constants with universal asymptotic equations for devices with the inertial electron bunching is also emphasized in [16].

One of the variants of FELs uses the induced radiation of a relativistic electron beam with high-energy particles whose transverse oscillations are excited during their propagation in the spatially periodic magnetic field of an ondulator (or a wiggler) in the form of a bifilar wire spiral. As correctly pointed out in [17], electrons in FELs are not completely free: to interact efficiently with an electromagnetic wave, they move in the magnetic field along a curvilinear trajectory, i.e., with acceleration. To use induced radiation in an FEL, the synchronization of individual emitters is necessary, which is achieved, as in a TWT, due to the longitudinal bunching of electrons. We can then say that the difference between TWTs and FELs lies in the use of different types of induced radiation: ondulator radiation in FELs and Cherenkov radiation in TWTs.

Paper [1] ends with the words: "One can assume that a traveling wave tube will be commonly used with time in radio engineering in the centimeter wavelength range."

More than seventy years have elapsed since that time. The evolution of TWTs has been impressive. The programs of the two last International Vacuum Electronics Conferences in 2018 and 2019 (IVEC 2018 and IVEC 2019) clearly demonstrate that TWTs are being extensively studied and widely used in different fields, from the standard telecommunication systems, TV, and digital radio broadcasting to the modern digital Internet and multimedia services. Traveling wave tubes of different designs with different powers are used in ground, air, or sea communication systems. They are used in radiolocation stations and on-board radars, as well as for radio electronic suppression. High-power and efficient TWTs can be used in a satellite global positioning system (GPS, Galileo) on a low-Earth orbit and for their continuous updating. Some examples of ground or on-board communication systems using microwave tubes (Thales Electron Devices, TED, France) are DirecTV, EchoStar, and Astra for DBS, Iridium for commercial systems, and Milstar, Syracuse, Stentor, and SBIRS for military systems [18].

In addition, a TWT is an indispensable device in satellite communication systems. There are a number of requirements regarding amplifiers for their successful operation in space. Among them are a high signal-to-noise ratio, a wide bandpass, and the ability of the device to withstand the rocket launch and to operate for a few years in space. Traveling wave tubes satisfy these requirements in one way or another.

A talk devoted to the Cassini mission was presented at the IVEC 2018 conference [19]. The Cassini–Huygens mission was an international project of NASA, ESA (European Space Agency), and ASI (Italian Space Agency). The aim of the mission was the investigation of Saturn and its rings and moons. The Cassini spacecraft was launched in October 1997, and the mission took about 20 years. In September 2017, the control command terminated the mission. The spacecraft had been in Saturn's orbit for almost 13 years and during this time sent 635 Gb of data and 453 thousand photos to Earth. For 20 years, all the data on the spacecraft state and research data were sent with the help of continuously operating 20 W, 8.40–8.45 GHz amplifiers.

The data collected over the 20 years (cathode current, spiral current, etc.) and presented in [19] confirm the operation stability of the TWT developed and manufactured by the Hughes Aircraft Company Electron Dynamics Division (presently, L3-Communication Devices, USA). Of course, this was only one of the many well-known examples.. We can also mention the Rosetta space probe [20] for studying the 67P/Churyumov–Gerasimenko comet (launched 26 February 2004, flight duration more than 12 years), where the data were also communicated using a TWT. The New Horizons spacecraft was launched in 2006 to study Pluto and its natural moon Charon [21], its signals being amplified by a 12 W TWT (the overall program was planned for 15–17 years). In addition, we note the Voyager program [22] to study the distant planets of the Solar System. Voyager-1 and Voyager-2 spacecraft were launched in 1977 and have been in flight for more than 41 years.

The parameters of TWTs developed recently for space applications are described in [23–31]. They include, for example, a compact 1250 W, 12–14-GHz TWT [26, 27] developed by Communications and Power Industries (CPI, USA), a 170 W, 17–20-GHz TWT [28] produced by the L3 Technologies Electron Devices Division (L3 EDD, USA), and a 40 W, 37.5–42.5 GHz TWT [29] developed by Thales Electron Devices (TED) supported by the French Space Agency CNES, France.

Relativistic TWTs demonstrate high power and efficiency and seem to be promising radiation sources for developing accelerators of high-energy charged particles [32]. Relativistic TWTs have been studied in numerous papers. However, these studies are predominantly theoretical or present the results of numerical simulations (see, e.g., [33–38]).

During the development of relativistic electronics, some experimental relativistic TWTs were also created [39, 40]. The authors of [41] presented experimental studies of single- and two-cascade sectioned relativistic TWT amplifiers. The TWT self-excitation problem is solved by using a sectioned deceleration system (see, e.g., [42]). In an 8.8 GHz single-cascade amplifier for 850 keV electrons and a 1.6 kA current, the maximum amplification was 33 dB, and the output power was 110 MW in the 0.2% band. The output power of a two-section TWT under otherwise identical conditions was 400 MW, the efficiency was 45%, and the gain band was 1.5%. Sections were separated by graphite inserts, which introduced a decay of about 30 dB. The authors of [41] pointed out that the disadvantage of such a variant of a relativistic TWT was excitation of oscillations in the side frequency bands.

The more efficient sectioning method proposed in [43] provided 1 GW of the output power with a 47 dB gain and 45% efficiency in the range 8–12 GHz. The electron beam energy and current were 0.8 MeV and 6 kA. It is interesting that a microwave pulse shortened from 250 to 90 ns upon increasing the output power from 0.3 to 1.1 GW.

An earlier work presenting experimental results obtained for an industrial relativistic TWT is [44]. A 26 dB gain was achieved at the frequency of 95 GHz for 5 kW of continuous output power.

Terahertz vacuum generators and amplifiers were attracting constant interest in the last decade. Some time ago, various programs were proposed in Europe and the USA [45–48] for the development of compact terahertz vacuum amplifiers. The choice of the millimeter and submillimeter wavelength range was due to the need to expand the operation frequency range that determines the bandwidth of channels used for data exchange by military systems of various purposes. For this reason, recent research is mostly armed at developing terahertz TWTs with acceptable parameters.

A unique broadband TWT [49] was developed within the framework of the HiFIVE (High Frequency Integrated Vacuum Electronics) program [45] using modern nanotechnologies. The TWT uses a band electron beam with a current density of 438 A cm^{-2}. An electron gun contains a nanocomposite tungsten cathode. The center of the operation frequency range is at 220 GHz. The gain achieved in the 207–221 GHz frequency range was 27 dB (for the tube filament voltage of 20.9 kV), the output power was 11 W, and the gain was 30 dB (for the filament voltage of 21.8 kV). Measurements showed that the bandpass of the tube exceeded 50 GHz with losses of about 5 dB. The TWT manufacturing stages and all the TWT parameters are described in detail in [49].

A 0.32 THz TWT was developed and tested in [50]. The deceleration system was made of an all-metal winding waveguide manufactured using high-precision milling technology. The amplifier uses focusing by a periodic magnetic field. The maximum output power exceeded 134 mW for the input power of 0.5 mW (the gain was 19.6 dB).

Developments at Northrop Grumman Electronic Systems (USA) are no less interesting. Among them, a compact 0.85 THz TWT amplifier with bandwidth of about 14 GHz can be noted [51]. It contains a winding waveguide manufactured by deep reactive-ion etching (DRIE). The electron beam was focused and transported in a 9 kG longitudinal magnetic field produced by a magnet. The current density in the TWT reaches 311 A cm^{-2} for a 2.8 mA beam current. The main characteristics of this TWT amplifier are presented in [51]: the output power is 141 mW, the gain is 26.5 dB, and the efficiency is 0.54%.

Later studies resulted in the creation of a 1.03 THz TWT amplifier with a 5 GHz bandwidth consisting of a winding waveguide deceleration system, a solenoid providing a 9 kG magnetic field, and a thermal cathode. The beam current is 2.3 mA and the gain is 20 dB.

The developing technologies have made the creation of TWTs of various types possible. For example, TWTs with auto emission (cold) cathodes were built [53, 54], which reduced the size of the device and considerably reduced the voltage applied to achieve the same current. In addition, the authors of [55] proposed introducing a second electron beam into a TWT, which can also give some advantages.

In [56], a traveling wave amplifier operating in the 0.75–1.1 THz frequency range was proposed. Its main feature is the use of plasma instead of a usual electron beam. The authors of [56] note that the advantages of using plasma are, first, the possibility of replacing thermionic emission with gas ionization, second, the elimination or simplification of electrostatic lenses and magnetic focusing structures because plasma can be self-focused, and, third, the possibility of achieving a higher power amplification along with a higher efficiency. In addition, there are a number of other positive properties. The authors of [56] describe the manufacturing technology of a winding waveguide in detail and present the results of numerical simulations and field experiments. The gain at the frequency of 0.9 THz in the 1 GHz bandwidth is 12 dB.

Recently, attempts have been made to create TWTs using structures containing metamaterials by preliminarily analyzing processes occurring in such a tube based on numerical simulations (see, e.g., [57–59]). According to [60], a metamaterial is a composition material whose properties are determined not by the properties of its elements but by an artificially created periodic structure consisting of macroscopic elements of arbitrary sizes and shape. The first review of serious attempts to create new vacuum electronic microwave devices containing metamaterials was presented in [61]. "...Vacuum electronic microwave devices with metamaterials possess the following properties: the small size, high power, high efficiency, and high gain. These newest devices offer promising applications in radio location, communication systems, electronic war, microwave heating, accelerators, pattern recognition, and many other fields" [61].

2. A brief history which has become common knowledge

Interestingly, in recent years not only the design of TWTs changed but also some new facts in the history of TWT development became known.

It is likely that most researchers involved in theoretical and experimental studies of microwave devices in which an electron beam interacts for a long time with a decelerated electromagnetic wave know that a TWT was invented and created by Rudolf Kompfner, an Austrian architect by education and a physicist by calling. The further development of this device is related to the name of the great American engineer, John Pierce. This has never been doubted.

However, we note that Warnecke [62] mentions two patents by Haeff dated 1933, a patent by Lindenblad (1940), and a patent for a standing wave generator proposed by Clavier and Rostas in 1937.

In 1994, Gilmour's book [63] was published. It was translated into Russian only in 2013. The chapter "The early TWT history" in the book begins as follows: "The possibility of interaction between an electron beam and a high-frequency system was discovered by Haeff [64, 65] in 1933." And then Gilmour writes: "In patents of this year, Haeff described electron-beam deflection tubes which can be used as detectors or oscilloscopes and contain some features of spiral TWTs. A high-frequency signal propagating in a spiral structure in Haeff's devices was used to deflect a hollow electron beam. The electron-beam velocity was equal to the propagation velocity of a traveling wave in the spiral structure. Haeff did not assume that in this case the wave can be amplified."

In [63], a paper by Dutch researcher Klaas Posthumus published in 1935 [66] was also mentioned, where the author for the first time described a smooth-anode magnetron generator in which the efficient energy exchange and amplification of a high-frequency wave caused by the interaction of electrons with the tangential component of a traveling wave rotating at a velocity equal to the average electron velocity.

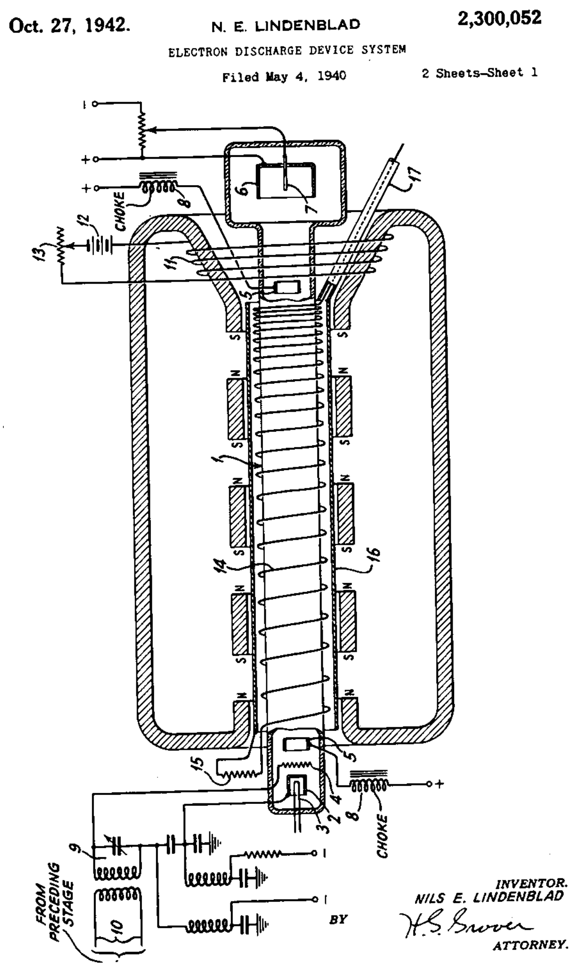

Figure 3. Drawings from Lindenblad's patent [67].

Gilmour then presents a drawing of a traveling wave amplifier from Lindenblad's patent dated 1940 (Fig. 3) [67]. Lindenblad described an ultrashort-wavelength broadband amplifier in which energy was removed from a modulated beam due to its interaction with a decelerated traveling wave. Gilmour pointed out in his book that "the first Lindenblad's tube was, obviously, the modification of Haeff's tube with the inductive output (which was called a klystron)." Lindenblad's construction looks sufficiently modern because it uses even the isochronism principle (a change in the spiral step) to support the wave-electron flow synchronism and the elements of magnetic periodic focusing.

The following TWT history according to Gilmour is related to Pierce (Fig. 4) and Kompfner (Fig. 5).

In 1942–1943, Kompfner created the first traveling wave amplifier efficiently operating at the centimeter wavelength. It happened that this material was published only in 1946 when Pierce and his colleagues described a similar tube [63]. They showed advantages based on the operation principle, which include high efficiency and broadband microwave transmission.

However, recently, Jake Copeland and Haeff's son published a paper about Andrei Haeff. The paper contains an explanatory insert that looks like an epigraph: "Patent pending recognition: the patent Haeff filed in 1933 for a primitive type of traveling wave tube has been largely ignored."

Figure 4. John R Pierce [68].

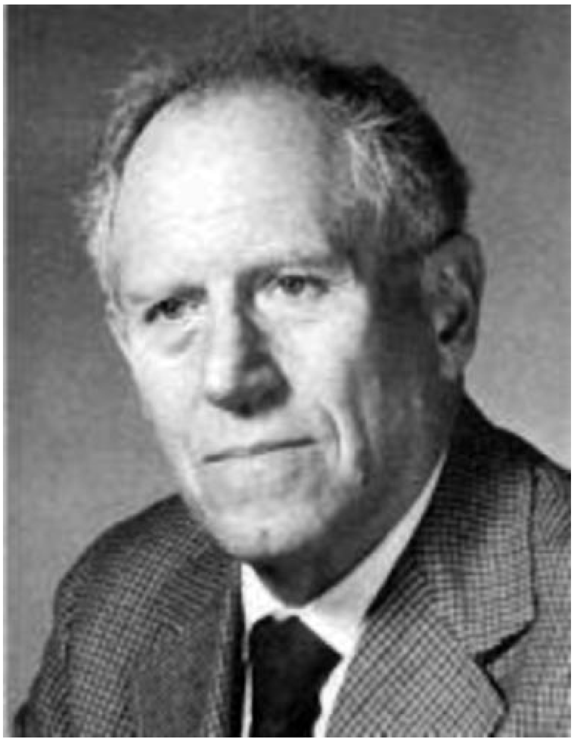

Figure 5. Rudolf Kompfner [69].

3. Andrei Haeff: from surfing to a satellite traveling wave tube

Andrei Haeff was born in Moscow (Fig. 6). Soon after the revolution in Russia, his family escaped to Harbin in China. He was 15 years old. In Harbin, he studied electrical engineering at the Russian Polytechnic Institute and graduated from there in 1928.

The history of Haeff's TWT begins in California in 1931, where he moved after living a few years in China. The field of his studies was microwave electronics. At that time, it was the leading edge of high technology. Nobody knew how to efficiently amplify microwave signals whose frequency was higher than that of vacuum tubes at that time.

Figure 6. Andrei Haeff [70].

The young engineer began to explore a tube in which a high-frequency wave propagates in a spiral system, whereas electrons move parallel to the spiral axis. The wave velocity along the spiral axis decreases and turns out to be equal to the velocity of slowly moving electrons. In a prototype, Haeff used two parallel spiral electrodes with an electron flow moving between them. When he registered his first patent for the tube in October 1933, he used the term 'traveling wave'. This was the first example of a device that was later transformed into a spiral TWT.

The idea of a new tube appeared when Haeff observed surfers on the Santa Monica Beach. He saw that if the longitudinal component of the board velocity and the phase velocity of the wave coincided, the wave energy could be efficiently used.

There is an opinion, as pointed out in [63], that Haeff did not notice the possibility of amplification with the help of this tube. However, when Haeff proposed his project, he emphasized three ways of using the tube, including "the amplification... of extremely high radio frequencies" [64, 65]. Thus, he undoubtedly knew the capability of his tube to amplify frequencies lying above the upper limits typical for vacuum tubes of that time. Moreover, not only did the new tube feature in a drawing in his paper but he also used a TWT to build a portable radio transmitter and receiver operating at a frequency of 750 MHz.

In March 1934, Haeff moved from the California Institute of Technology to RCA (Radio Corporation of America) and the Engineering Department in Harrison, New Jersey. The head of Caltech, Robert A Milliken, on behalf of the university administration granted Haeff the right to his invention. Soon, Haeff sold the TWT patent to RCA, together with the operating prototype for a considerable sum at the time: 12,000 USD (today, about $200,000). Later, in 1936, RCA also received the second patent for Haeff's device. However, RCA did not allow Haeff to continue his studies and recommended that he concentrate on the development of miniature tubes and circuits for TV receivers.

Surprisingly, the TWT was later rediscovered twice. The second discovery was in 1940 when Nils Lindenblad, a specialist on antennas at RCA, registered a patent for an improved TWT [67]. This was six years after Haeff sold his patent to RCA in 1933. It is unlikely that Lindenblad was unaware of Haeff's earlier work: the same patent expert at RCA, Harry Grover, considered both Lindenblad's patent and Haeff's in 1936.

In the opinion of the authors of [70], it remains unclear how Lindenblad, who did not study tubes, came to investigate a spiral deceleration system and filed a patent. Although Lindenblad and Haeff worked at RCA at the same time, their laboratories were 100 km apart, and therefore it is not obvious that they ever met.

It is possible that Lindenblad could have learned about Haeff's patents from Fred Kroger. In 1933, Kroger helped Haeff build a microwave transmitter and receiver to demonstrate TWT capabilities. And when Haeff moved from California to New Jersey, it was Kroger who transported the TWT prototype in his car trunk. The authors of [70] know that Kroger also had a hand in the profitable sale of Haeff's patents to RCA.

Kroger himself, like Lindenblad, worked at RCA Communications in Rocky Point, New York, and they were both key figures in the first TV broadcasting projects. Maybe

Kroger wanted Lindenblad to rekindle the TWT developments at RCA, because Haeff was forbidden to do so.

Haeff made a huge contribution to military radiolocation and electronics. In addition to TWTs, he invented a number of vacuum tubes: the electron-wave (double beam) [71] and resistive [72] tubes. They were considered in papers [73, 74] in *Physics–Uspekhi* in 1950 and 1954. Another of his inventions was an inductive-output amplifying tube (IOT) [75]. In 1939, this invention made RCA a pioneer in TV broadcasting with a transmitter mounted on the Empire State Building in New York and a series of relaying stations covering Long Island.

Haeff also made a contribution to computerization: he developed the technology of bistable data storage for monitors and wrote one of the first papers on displays for both graphics and text. Anticipating the potential of virtual reality, he already then invented a device for laser-based scanning of works of art, buildings, and other 3D objects and a technique for their virtual reconstruction. However, the TWT remains the greatest of all his inventions.

In the 1950s, when work by other researchers on TWTs had already appeared, Haeff wrote in his autobiography: "It is of interest to note that the operation of the recently announced 'revolutionary' device known as the 'Travelling Wave Tube', is based on the principle first disclosed by me in my patents No. 2.064, 469 and 2.233,126 which describe the fundamental ideas of the traveling wave tube." The authors of [70] point out that Haeff was a modest man and did not seek public recognition and glory. "But he did little beyond that to associate himself with this remarkable device..." [70].

In 1950, Haeff joined the research and development at Hughes Aircraft Laboratories in California. Here, he rose from a researcher to the vice-president of the company. Haeff's laboratory began to develop rapidly advanced TWT versions. In the framework of a large-scale space program, a TWT weighing about 1 pound (~ 0.45 kg) was developed to launch a broadband relay satellite on a stationary orbit over the Atlantic. Huges Syncom became the world's first geosynchronized communication satellite, successfully launched into orbit in 1963.

"It must have been an occasion for pride — and some mixed feelings — for Haeff when the device he pioneered in his twenties, one rarely associated with his own name, successfully carried a multitude of human voices across space" [70].

4. Rudolf Kompfner: "...let it be — let the field be moving together with electrons"

After a few years, the TWT was discovered a third time at the University of Birmingham in England. In 1940, physicists at the special laboratory of the British Admiralty created what was for that time a superpower microwave generator, a multiresonator magnetron. Rudolf Kompfner joined this laboratory in 1941. During the day, he worked with klystrons, and in the evenings he developed his own various devices, including a TWT amplifier. Kompfner writes in his essay "The Invention of the Travelling Wave Tube" [76] that the idea of using a traveling wave interacting with electrons occurred to him when the work on a low-noise klystron came to a dead end. "...If the time of flight through a gap represents such a serious difficulty and interaction with a stationary field proves to be weak, so let it be — let the field be moving together with electrons, the thought, generally speaking, being quite obvious," as Kompfner himself pointed out.

Kompfner was an unusual person in microwave electronics. First of all, he received an engineer-architect diploma at the Vienna High Technical School in 1933. From 1934 till 1941, he continued his education in the field of architecture in England and worked at the same time in an architecture firm. However, Kompfner always wanted to be a physicist. He was interned at the beginning of the war, and the opportunity appeared for him to improve his knowledge in the field of physics. Further, still during the war, after his release from internment, he developed microwave tubes for the Naval Ministry.

Kompfner built his first TWTs at the Birmingham laboratory. The results were good and the British Admiralty received a patent in his name in June 1944.

In his 1946 paper in *Wireless World* [77], Kompfner described the external view of the TWT that became the prototype of a future commercial tube. His tube was only slightly different from Lindenblad's less-known construction of 1942. Ironically, Kompfner rediscovered the TWT just at the same time, 1942–1943, but he managed to publish his results only in 1946.

Although Kompfner's tube was based on the same principles as Haeff's tube, its design was substantially different. In Haeff's, the electron beam propagated around the helix surface. Kompfner, like Lindenblad, used a precision electron gun to direct the electron beam along the central axis of the helix. Such a gun did not exist at the time of Haeff's earlier work. The result was a higher amplification because now both the velocity modulation and electron bunching were used. These phenomena were described by Heil and Arsenjewa-Heil for a klystron model in 1935 [78]. However, Haeff was the first to use these principles in his inductive-output tube in 1939 [79].

Kompfner writes in his essay "The Invention of the Travelling Wave Tube" that the key idea of using a helix electrode was not his own. Attempting to create a high-frequency oscilloscope, he understood, as Haeff did, that by decreasing the electromagnetic-wave velocity to the electron velocity, it is possible to achieve interaction. But Kompfner did not know how to do this. During discussions with colleagues, the use of a helix was proposed. However, this idea was forgotten for some time, and researchers recalled it only when they encountered difficulties related to the suppression of noise in a klystron.

Kompfner asked the opinion of a specialist on communication lines in a group from the University of Birmingham and learned from him that the propagation of a wave with a frequency above 10 MHz along such a helix is unlikely. This could be easily verified. Kompfner coiled a copper wire around a steel rod and slightly pushed the coils apart to avoid short-circuiting. Then he placed the helix into a coaxial conductor of a standing-wave detector, applied a signal at a wavelength of 10 cm and obtained, albeit roughly, a standing wave. When he measured the average distance between peaks, he found that the velocity decreased to one seventh value. Kompfner wrote: "I was so tactful that did not run to say this at once to that specialist, but no longer asked his advice" [76].

This was a promising result. Kompfner showed that the number 7 quite accurately corresponded to the helix winding pitch. He admired how simple all this proved to be.

Figure 7 shows a sketch from Kompfner's notebook dated 10 November 1942, where a hollow beam moves between a helix and an external conductor to an output resonator similar to a klystron resonator. In Fig. 8, dated 12 November

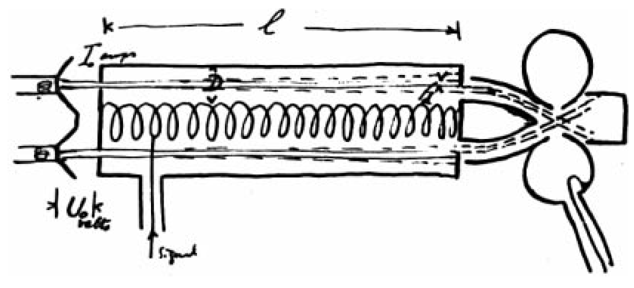

Figure 7. Page from Kompfner's notebook dated by 10 November 1942 [76].

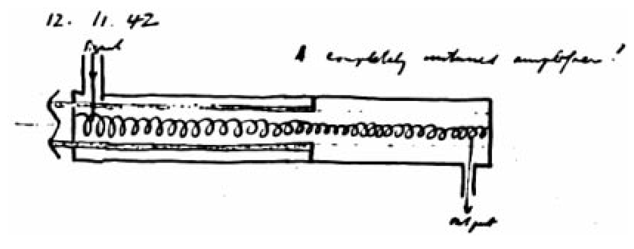

Figure 8. Page from Kompfner's notebook dated 12 November 1942: "Absolutely detuned amplifier?" [76].

1942, the output resonator is replaced with a section containing a helix, which leads to the unexpected conclusion: 'a completely detuned amplifier?'

Kompfner spent a great deal of time to understand what occurs when the electron beam moves inside the helix. What voltage is induced in the helix, if the beam current is known? What is the field inside the helix?

He took an interest in the problem: "if a field in the helix induces an alternating current, and this current induces a field in the helix, what current will be produced by the latter field? [We mentioned this in the Introduction — author's note]. And then the following occurs: this current induces a secondary field, the secondary field induces a secondary current, the secondary current induces a ternary field, etc?" [76]. He concluded that this problem should be considered as an infinite series.

In this way, the method of successive approximations has appeared in electronics, which was developed for all devices with distributed interaction by V N Shevchik at Saratov State University. This method was also developed by professor V M Lopukhin at Moscow State University [1].

Before beginning to make the tube, Kompfner in fact developed a sufficiently complete theory of small-signal amplification for interaction of an electron beam with a traveling electromagnetic wave.

In August 1943, the physics department of the University of Birmingham was closed because the majority of researchers moved to Los Alamos to work on the atomic-bomb project. Kompfner remained, and was officially allowed to study a traveling wave amplifier. Now he began to develop the tube.

Kompfner described the circumstances of his 'discovery' of the TWT many times, emphasizing the most important facts in his essay. But in his long recollections he never mentioned Haeff's early work, although in his TWT patent of 1953, Kompfner cited Haeff's first patent. However, Kompfner points out only the importance of Haeff's work concerning the velocity modulation and electron bunching applied to the TWT.

Kompfner worked later at the Clarendon Laboratory in Oxford. Here, he completed his theory, having obtained a readily summable series for the field in a helix. In the asymptotic case, the field increased with the distance exponentially. In the literature, only the final expression obtained by Kompfner is presented [76]. Exactly now Kompfner derived it is not published anywhere. Therefore, we present our derivation here.

In a particular case of the exact synchronism, the wave field at the tube end has the form

$$E(l) = E_0 \exp(-\mathrm{j}\beta_0 l) \sum_{m=0}^{\infty} \frac{(\mathrm{j}2\pi CN)^{3m}}{(3m)!}\,, \tag{9}$$

where $\beta_0 = \omega / v_{\mathrm{ph}}$ is the wave propagation constant in the system without an electron beam, $N = 1/\lambda$ is the electric length of the tube, and $C^3 = (I_0 K)/4V_0$ is the Pierce amplification parameter. Using the relation

$$\sum_{m=0}^{\infty} \frac{y^{3m}}{(3m)!} = A_1\big(\exp(\alpha_1 y) + \exp(\alpha_2 y) + \exp(\alpha_3 y)\big)$$
$$= A_1\left(\sum_{m=0}^{\infty} \frac{(\alpha_1 y)^m}{m!} + \sum_{m=0}^{\infty} \frac{(\alpha_2 y)^m}{m!} + \sum_{m=0}^{\infty} \frac{(\alpha_3 y)^m}{m!}\right), \tag{10}$$

we obtain

$$\begin{aligned} y^0 &: 1 = 3A_1 & A_1 &= \frac{1}{3}\,, \\ y^1 &: 0 = A_1(\alpha_1 + \alpha_2 + \alpha_3) & \alpha_1 + \alpha_2 + \alpha_3 &= 0\,, \\ y^2 &: 0 = \frac{A_1(\alpha_1^2 + \alpha_2^2 + \alpha_3^2)}{2} & \alpha_1^2 + \alpha_2^2 + \alpha_3^2 &= 0\,, \\ y^3 &: 1 = A_1(\alpha_1^3 + \alpha_2^3 + \alpha_3^3) & \alpha_1^3 + \alpha_2^3 + \alpha_3^3 &= 3\,. \end{aligned} \tag{11}$$

It follows from (11) that $\alpha_2/\alpha_1 = (-1 \pm \mathrm{j}\sqrt{3})/2$, and $\alpha_3/\alpha_1 = (-1 \mp \mathrm{j}\sqrt{3})/2$. Substituting $\alpha_2/\alpha_1 = (-1+\mathrm{j}\sqrt{3})/2$ and $\alpha_3/\alpha_1 = (-1 - \mathrm{j}\sqrt{3})/2$ in the last equation in (11), we obtain $\alpha_1 = 1$. Returning to (9), in the exact synchronism case ($\beta_0 \approx \beta_e$) we find

$$E = \frac{E_0}{3} \exp(-\mathrm{j}\,\beta_e x)$$
$$\times \left[\exp(\mathrm{j}\,2\pi CN) + \exp\left(\mathrm{j}\,2\pi CN\left(\frac{-1 + \mathrm{j}\sqrt{3}}{2}\right)\right)\right.$$
$$\left. + \exp\left(\mathrm{j}\,2\pi CN\left(\frac{-1 - \mathrm{j}\sqrt{3}}{2}\right)\right)\right]. \tag{12}$$

Taking only the increasing partial wave into account, we find the known asymptotic expression

$$G = 20\lg\frac{1}{3} + 20\frac{1}{2.3}\frac{\sqrt{3}}{2}2\pi CN = A + BCN$$
$$= -9.54 + 47.3CN \ \ \mathrm{dB} \tag{13}$$

for the TWT gain.

At the same time, Kompfner, together with Joseph Hatton, discovered experimentally and explained theoretically the complete suppression of the signal in a TWT [80], which occurs for certain values of the beam current and potential. This phenomenon is called the Kompfner dip effect and is used to measure the dispersion characteristics and coupling resistance of deceleration systems.

Kompfner himself said: "Of course, I am pleased that a physical effect is called by my name, the Kompfner dip condition, but I am not delighted by the term 'dip' because it sounds too similar to 'drip' (something like wet Kompfner)" [70]. This phenomenon was used to measure the coupling resistance and dispersion characteristics of deceleration systems.

Recently, it was proposed to use a TWT suppressor operating in the Kompfner dip regime for passive mode-locking and generation of ultrashort pulses [81, 82]. The authors of [83] described a laboratory prototype and presented the results of experimental studies of a hybrid generator of multisoliton complexes based on a TWT suppressor operating in the Kompfner dip regime as a saturable absorber. As a result, passive mode locking was achieved and the generation of multisoliton complexes was obtained under conditions of competition between three- and four-wave nonlinear spin-wave interactions. Multisoliton complexes represented giant microsecond pulses formed due to three-wave interactions and containing shorter nanosecond pulses formed due to four-wave interactions.

By studying the TWT, Kompfner was sometimes distracted and 'turned aside', usually wasting a few weeks or even months to study other systems, in particular, a transverse-field tube.

He developed a tube with a nickel helix and found that a change in the applied magnetic field results in a change in losses. In addition, this effect proved to be critical to temperature. When Griffiths saw all these experiments, he said that they were of considerable interest and the resonance phenomenon was observed, and therefore it would be better to use a more advantageous geometry than a helix. However, Kompfner believed that a helix is a 'miracle geometry' and decided that this time he would not be distracted from the main direction of his study. Griffiths, with his permission, continued the study and made a simple resonator in which one wall was covered by iron and, as a result, discovered ferromagnetic resonance. Kompfner writes: "In this way, I missed the discovery of the ferromagnetic resonance.... In this case, unfortunately, I did not dare to turn aside."

We emphasize that Kompfner did not realize that he created a broadband amplifier.

However, Pierce understood this. He wrote: "Kompfner was lucky to remove limitations for the frequency band in amplifiers (which nobody of radio specialists could do before him) just because of the open mind and fresh outlook of a person who had previously worked in a different research field. Kompfner solved the problem simply by building an efficient amplifier without a resonance circuit" [84, p. 165].

Kompfner wanted to create a generator tunable in a broad frequency range with changing the accelerating voltage, i.e., changing the electron velocity v_0. Internal feedback was needed in the electron-beam–electromagnetic-wave system. Kompfner himself wrote that he, being self-taught in physics, knew nothing about reciprocal space harmonics with oppositely directed phase and group velocities, which provide the internal feedback. For this reason, he reluctantly dismissed his favorite helix, understanding that he needed a backward wave. He knew that such a wave existed because the TWT amplifier self-excited in a number of cases. And he invented the illustrative qualitative picture of the interaction of electrons with an electromagnetic wave by replacing the continuous interaction model by a discrete model, shown in Fig. 9. We are interested in the case of a forward wave

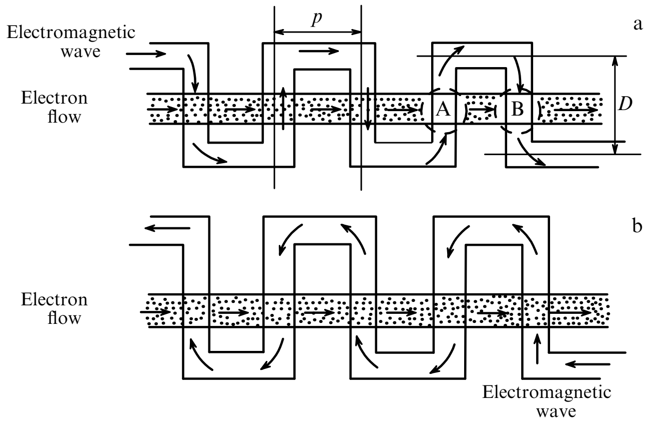

Figure 9. Model of a communication line permeated by an electron flow, which is used to explain the operation principle of (a) a traveling wave tube and (b) a backward wave tube [85].

(Fig. 9a). It can be seen from the figure that to experience repeated interaction with the high-frequency field of a wave traveling along a winding waveguide (a bent transfer line) with the speed of light c, electrons should propagate from region A in Fig. 9a to region B over the distance p for a time equal to the wave propagation time in the winding waveguide from region A to region B. In each subsequent region, for example, region B, the electron is then experiencing the field of the same phase as in the preceding region, for example A. This can be expressed by the simple mathematical condition

$$\frac{p}{v_0} = \frac{1}{c}\left(D + p + \frac{\lambda}{2}(2n+1)\right), \tag{14}$$

where λ is the wavelength in free space and $n = 0, 1, 2 \ldots$. The term $\lambda/2c$ in (14) is added because the field in the winding waveguide changes its direction when the wave arrives at a bend, and an additional term is required to provide the correct phase in region B.

In the case of a backward wave, the phase condition providing efficient repeated interaction can be written in the form

$$\frac{p}{v_0} = \frac{1}{c}\left(\frac{\lambda}{2}(n+1) - (p+D)\right). \tag{15}$$

The first attempt to consider the fundamentals of the electronics of O-type microwave devices based on discrete concepts of linear theory was made in book [86].

At present, most authors of theoretical (see, e.g., [87–89]) and experimental (see, e.g., [50–52, 90, 91] papers describe the results of the interaction of an electron beam with the fields of winding waveguides. The theories mainly use computer simulations of nonlinear regimes. Experiments based on new technologies are aimed at developing terahertz TWTs. So, it seems that Francis Bacon was right (see the epigraph).

5. John Robinson Pierce: ...one of the great visionary engineers

John Pierce from Bell Labs, USA visited Oxford in 1944. In 1951, Kompfner himself joined Bell Labs. Kompfner's impressions about Pierce's visit are presented below:

"He read some our secret notes about this work which did not contain this theory yet. And I remember how lively he swallowed all this and then came back and developed a theory which gave all the results more rigorously and much more gracefully than I did by summing terms, although it should be recalled that he, so to say, knew the answer beforehand, whereas my theoretical steps anticipated experiments.... In fact, his theory from the very beginning correctly took into account the influence of losses in the helix and the mismatch between the beam and wave.... Pierce has sent me his theory at the first opportunity long before its publication. Undoubtedly, this was another exciting moment, when I suddenly understood how all proved to be simple and beautiful."

It is this variant of the theory that is considered in [1].

Pierce was born in 1910. He was educated at the University of California and worked for 35 years at the American company Bell Labs.

His relations with Haeff were close, and for some occasion he even dined once at Haeff's home in the early 1950s. Nevertheless, Pierce relentlessly promoted Kompfner and indirectly Bell Labs, stating their priority. He wrote in 1956: "As for the origin of the TWT, I can only say that it was invited during the war in England by an Austrian architect Rudolph Kompfner who always wanted to be a physicist." Pierce's book *Traveling-Wave Tubes* [92] contains no more than a mention of Haeff's contribution.

Ten years later, Pierce informed Haeff in a letter that he was planning to write a historical article about the development of microwave tubes [70]. He wanted to write that Haeff used traveling waves for interaction with electron beams starting with 1935. Unfortunately, however, Pierce did not write an article containing such historically important facts and references.

As pointed out in [70], only a few specialists appreciate the importance of Haeff's earlier work, like Victor Granatstein of the University of Maryland. He wrote in 2000 that "Haeff has made an absolutely necessary contribution to the development of helix TWTs" and pointed out that the 'key' idea of using a helix to slow down the wave was realized in the "first patent of Andrei Haeff."

"In April 2002, the engineering world lost one its great visionaries. John Robinson Pierce, whose career spanned six decades, was at one time one of the best known figures in the engineering field." This is the beginning of paper [68] by Morton, where the interview with Pierce is presented. In this interview, Pierce mentions TWTs only as one of the results of his investigations.

Pierce was an amazingly versatile man. He wrote science-fiction stories and a few scientific and popular-science books. Incidentally, he proposed the term 'transistor'. He made a huge contribution to the field of satellite communication, participating in the Echo project and the creation of the Telstar satellite.

Pierce wrote the book *The Science of Musical Sound* [93]. The book reflects his interests in psychoacoustic and computer music. He got interested in the question of whether it is possible to replace the frequency ratio 2:1 in the octave by the frequency ratio 3:1 and call it the tritava. However, listeners are known to prefer compositions written in the traditional manner.

J Pierce's books *Traveling-Wave Tubes* [92], *Almost All About Waves* [94], and others [84, 95, 96] are well known in Russian translations.

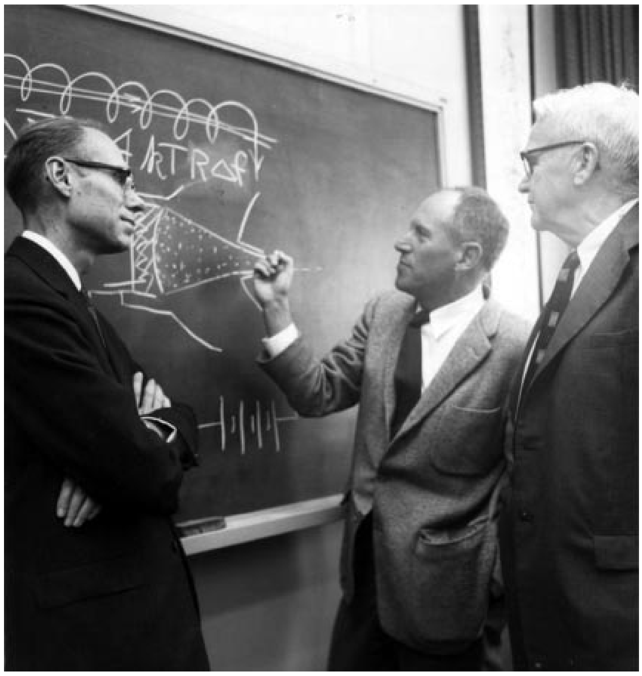

Figure 10. John R Pierce (left), Rudolf Kompfner (center), and Henry Nyquist (right), 1960 [68].

6. Conclusions

In conclusion, we present another unique photograph (Fig. 10).

We have outlined the history of a traveling wave tube, a device that today attracts great attention of researchers working in the terahertz frequency range. Additional information on the role of TWTs in the history of the development of telecommunications can be found in [97], a paper that became known to us during the preparation of our paper.

Materials of this paper were partially reported at the plenary session of the International Scientific and Technical Conference on Actual Problems of Electron Devices Engineering (Saratov, Yuri Gagarin State Technical University of Saratov, 27–28 September 2018); XVII Winter School Seminar on Radiophysics and Microwave Electronics (Saratov, Saratov State University, 5–10 February 2018), and XVI Sukhorukov All-Russian School Seminar on Wave Phenomena in Inhomogeneous Media (Moscow, Moscow State University, 27 May–1 June 2018).

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