

# Gorky's Gyrotron Heroes

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**Abstract.** This work presents an outline of the history of scientists and the city where the world's first relativistic CRM device, known today as a Gyrotron, was created. CRM can be explained as "a microwave source of stimulated radiation based on the cyclotron resonance phenomenon". The story begins in 1898 with the establishment of the Emperor Nicolas II Warsaw Polytechnic Institute and ends in 1964 with the launch of the world's first Gyrotron at the Nizhegorodsky Polytechnical Institute (later Gorky). The principle of gyrotron operation is very briefly presented in the paper, but mainly, according to the idea of this work, a lot of space is devoted to people, scientists and organizers of science in Gorky, the first who created this device, and therefore the work is limited to presenting the events related to the creation of the Gyrotron in 1959–1967.

**Key words:** Cyclotron resonance devices, CRM, gyrotron, Gorky, Nizhny Novgorod.

## 1. Introduction

The phenomenon that gave the greatest hopes for high levels of power generated by charged particles was the so-called cyclotron resonance. Over time, the term "cyclotron resonance" was loosely applied to any device in which the orbital motion of electrons drifting in a magnetic field took place, because such motion occurs in a natural way at the cyclotron frequency. These were CRM devices, and this term was initially applied even to gyrotron. Although the name "Gyrotron" came up later in 1966 on another occasion. In 1967, this term was also used to name a carousel installed in the openwork pyramid in "La Ronde" amusement park at Expo 67 world fair in Montreal, Canada. A designer of this Gyrotron was Sean Kenny. Passengers were lifted up the top of the pyramid, where open space conditions were simulated using light and sound. Exactly so!

A charged particle gyrating in a magnetic field at a certain frequency (cyclotron frequency) can by means of resonance take over the energy from the surrounding electric field if only the field reached the frequency of the Larmor gyration. It is called a cyclotron resonance. Astrophysicists have put forward in their theories from outer space the possibility of not only such absorption of electromagnetic radiation, but also the idea of so-called negative absorption. It may not be a great risk to say that astrophysicists unintentionally deduced the gyrotron principle from stellar dust. Maybe the words "...for dust you are..." (Genesis 3:19) seem not far from being true.

In short, the concept of the generation of electromagnetic radiation stimulated by a gyrating charged particle appeared.

The subsequent CRM-based devices allow the explanation of this abbreviation as Cyclotron Resonance Maser, as

"a microwave source of stimulated radiation based on the cyclotron resonance phenomenon." Other devices based on this phenomenon will also be called CRM devices. The first CRMs appeared already in the 1920s. Their inventors were a Czech physicist, August Žacek – 1924 [1], a German physicist Erich Habann [2], and independently a Japanese engineer Hidetsugu Yagi – 1926 (the one from the famous Yagi antenna) [3]. Even earlier, because already in 1921, there appeared the first magnetron invented by Albert Hull – a device which can also operate in transversal electric and magnetic fields [4–6].

Vacuum electronics devices raised hopes for generation of shorter and shorter waves, even millimetres long. This, however, was connected with the reduction of the devices' dimensions, and it is here where the ubiquitous tyrant of physics appeared – temperature. Reducing the size of the resonator cavities of such devices inevitably led to problems with heat dissipation. Cyclotron resonance and electron deceleration in cyclotron orbits (azimuthal Bremsstrahlung) could break the deadlock. The research was thus directed towards electrons oscillating in transversal electric and magnetic fields with cyclotron frequency, which could resonate with electromagnetic waves at phase speeds higher than the speed of light – the so-called fast wave devices [7]. However, until the end of the 1950s, the results of theoretical research on the interaction of a fast wave with electrons oscillating in homogeneous external fields failed to confirm whether it is possible in such systems to stimulate coherent Bremsstrahlung radiation (in other words "braking radiation" – the term coined by Arnold Sommerfeld in 1909 [8–10]).

## 2. Prehistory

Between 1896 and 1900, pressure was exerted by the largest cities of the Russian Empire so that universities of technology, i.e., polytechnic institutes, would be established. Hence new

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Fig. 1. Imperial Russia's Emperor Nicolas II Warsaw Polytechnic Institute (1898)

polytechnic institutes were opened in Sankt Petersburg, Kiev and ... Warsaw – Emperor Nicolas II Warsaw Polytechnic Institute in 1898, see Fig. 1. The St. Petersburg Institute was not only the first in the Russian empire, but in all of that part of Europe – now St. Petersburg State Electrotechnical University. Of course, it is necessary to mention, that more than 100 years earlier the “École Polytechnique de Paris in Palaiseau” was founded on March 1, 1794. Other Polytechnique Institutes followed according to this model. One example is the “Polytechnikum Karlsruhe” in Karlsruhe, Germany, which was founded on October 6, 1825.

In 1915, at the beginning of the First World War, a hasty evacuation of the Emperor Institute was launched as a result of the German army advances. The experimental equipment and library collections were waiting in Moscow to be moved to one of the cities of the empire.

Several cities fought for the legacy of the Warsaw Polytechnic Institute – Tiflis (from 1936 Tbilisi), Saratov, Odessa, Ekaterinoslav (from 1796 to 1802 Novorossiysk, 1802 Ekaterinoslav, 1926 Dnepropetrovsk, from 2016 Dnipro), Omsk, Orenburg and Ekaterinburg (from 1924 to 1991 Sverdlovsk). In September 1916, Nizhny Novgorod (Gorky 1932–1990) also

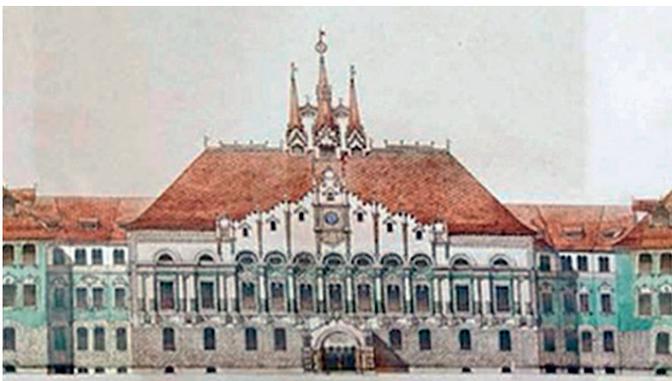


Fig. 2. The new building of the Nizhegorodsky State University, which included the Nizhegorodsky Polytechnical Institute (June 1918). The present name of the institute is Institute of Applied Physics (IAP), which occupies another building

reported the desire to obtain the Warsaw collection. On July 6, 1916 a decision was made to transfer the collection; consequently, the Warsaw Polytechnic Institute in Nizhny Novgorod was established. Less than a year later, on 20 June 1917, it was decided to change the name to Nizhegorodsky Polytechnical Institute. A year later it became part of the Nizhny Novgorod State Technical University – Fig. 2.

According to the monograph of Mikhail Adol'fovich Miller, Nizhny Novgorod State Technical University survived thanks to ... Pilsudski(!) [11]. Marshal Józef Pilsudski in the famous Battle of Warsaw (August 13–25, 1920) against Tuchaczewski's army saved the city from the re-occupation by Russia. Here Miller hypothesizes that if this happened, the collections of the Warsaw University of Technology gathered in Nizhny Novgorod could be “re-evacuated” back to Warsaw. Then there could be a lack of equipment and resources to maintain the University of Nizhny Novgorod. Although, as Miller continues, some of the collections, in accordance with the provisions of the Treaty of Riga (March 18, 1921), had to be returned to Warsaw, which took place in 1929. All they managed to keep was a unique chemical library, unfortunately for an additional charge. In short, the conditions for the development of technical sciences in Nizhny Novgorod were created. But still the right people were lacking.

In the early 1930s, a group of Moscow scholars went on a kind of voluntary “exile”. The destination was 300 miles east of Moscow, Nizhny Novgorod, or then already Gorky. In 1932 the town was renamed after the outstanding Russian writer Maxim Gorky. Hence the unusual and fascinating history of gyrotron development in this town can be called the Gorky period.

In 1932 the family of Viktor Ivanovich Gaponov, a Warsaw-born physicist and later a professor at Gorky University named Lobatchevsky, and his wife, Maria Tikhonovna Grekhova, founder and first director of the Radiophysical Research Institute (RRI), born in Modlin (formerly Novo-Georgievsk, near Warsaw), came to the town. The Varsovians came from Moscow together with A.A. Andronov, Snr., who would become a teacher of their son, Andrei Viktorovich. Andrei Gaponov, a 5-year-old boy at that time, became a resident of the town where, one year earlier, Viktor Viktorovich Zhelezniakov was born (1931). By the twist of fate, they would meet two decades later at Gorky University, when they would lay the foundations for the theory of the still unknown gyrotron. In this eternally busy city, a centre of trade and industry, a “separate city” in the Russian Empire and then a “closed city” in the Soviet Union, the only occupation for scientists could be to practice...science. Thus, the merchant capital of Russia, Gorky, turned into the Russian Mecca of science.

### 3. Gyrotron

The theory developed by A.V. Gaponov was published in 1959; to be precise, it was sent to the editorial office of *Izv. VUZov. [Izvestiya Vysshikh Uchebnykh Zavedenii] Radiofizika* on 17 May [12]. The study was based on classical electrodynamics

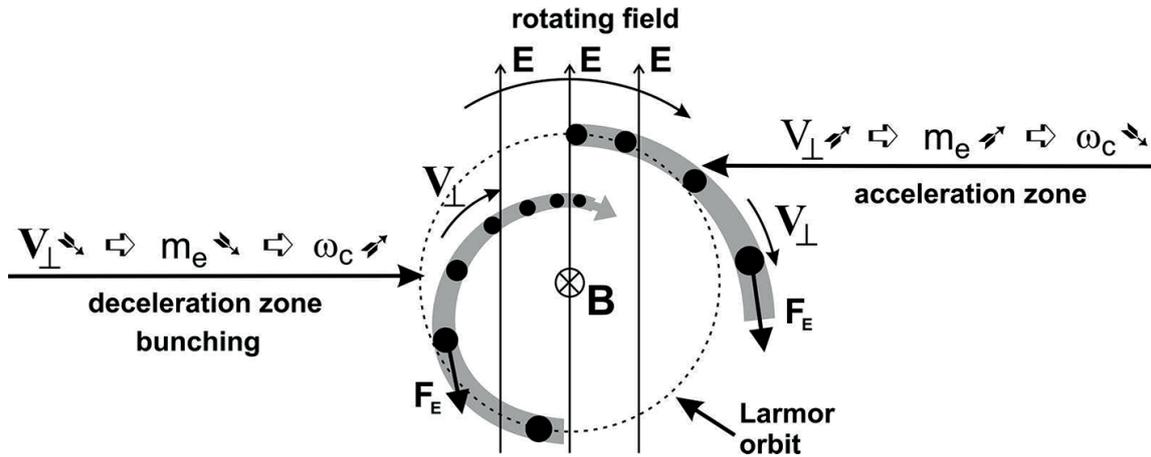


Fig. 3. Electrons circulating in a transversal magnetic field  $B$ .  $v_{\perp}$  – electron transversal velocity,  $F_E$  – electrical field force,  $E$  – rotating electrical field,  $m_e$  – electron rest mass,  $\omega_c$  – electron frequency. Both “acceleration zone” and deceleration zone” are indicated in the figure. The separation of both zones is clearly shown. The bunching phenomenon occurs in a deceleration zone

and the relativistic effect was not taken into consideration. At that time, nobody realized that with future vacuum electronics anode-cathode voltages, electrons could have such a noticeable relativistic velocity that they could affect certain physical phenomena, including cyclotron resonance.

Simple calculations show that electrons accelerated in an electric field, reaching even a fraction of the speed of light, increase their mass and thus reduce their cyclotron frequency so much that the cyclotron resonance can be changed very dramatically. After Gaponov’s article had been published, V.V. Zhelezniakov intervened and suggested including the relativistic effect in his theory. As one can see, a fellow astrophysicist kept a watchful eye.

Perhaps it was easier for Zhelezniakov to pay attention to the relativistic aspect. After all, it was he who, wading through peripherals of space, diving in star dust and warming up in stellar coronae, saw and felt the “stellar” cyclotron resonance – a phenomenon that occurs in space at dramatically high values of electric field that not infrequently crossed a magnetic field of clouds of charged particles rushing with relativistic speed. Certainly, for Zhelezniakov, the CRM effect described by Gaponov was a miserable imitation of cosmic-scale phenomena. Nevertheless, Zhelezniakov, with honesty of a scholar, decided that the relativistic effect, which should also be present in the described (theoretically, for the time being) CRM device, should be pointed out to his colleague.

Here, justice must be done to Gaponov. Science is by definition the search for truth and Gaponov did follow this principle. In the same journal an amendment was published, in which he expressed his gratitude to V.V. Zhelezniakov for drawing attention to the necessity of taking the relativistic effects into account. Editors of *Izv. VUZov. Radiofizyka* received the amendment on October 19 of the same year [13].

Analyzing Zhelezniakov’s theory (constructed for a simple plasma model [14]), Gaponov realized that the relativistic effect can work even at low electron energies if the resonance effect of a high frequency cyclotron field on an electron lasts long

enough (this resembles metastable energy states in the structure of laser energy levels).

Thus, the deadlock in opening a new research topic – relativistic cyclotron resonance – was broken.

The Gaponov’s reflection results are shown in Fig. 3. The electrons are rotating (gyrating) in a transverse electromagnetic field of the resonant cavity and propagating along the axis of the longitudinal magnetic field  $B$ . A rotating electric field modulates electrons gyrating with a cyclotron frequency  $\omega_c$ .

$$\omega_c = \frac{eB}{m_e \gamma} = \frac{\Omega_0}{\gamma}, \quad (1)$$

where:  $e$  – electron charge,  $B$  – magnetic field (induction),  $m_e$  – rest mass of electron,  $\gamma$  – relativistic factor,  $\Omega_0$  = cyclotron frequency for a nonrelativistic electron.

The electrons are exposed to the Lorentz force  $F_e$ . If the lifetime of electrons within the resonator interaction space is long enough, a stimulated radiation area (deceleration zone) becomes separated from the absorption region (acceleration zone), Fig. 3. It is possible to evaluate the equation for electron energy changes  $\Delta W_e$  in the resonance cavity as:

$$\Delta W_e \approx e \cdot v_{\perp} \cdot E \cdot \Delta \tau, \quad (2)$$

where  $\Delta \tau$  is the interaction time between an electron and electric field. It shows, according to the Gaponov’s conclusion, how the energy changes depending on how long the electron stays in the gyrotron’s cavity. It is why a gyrotron resonator works close to the cut-off frequency.

The influence of the electric field on the electrons results in decreasing their relativistic mass ( $\rightarrow m_e \gamma$ ) and increasing the cyclotron frequency  $\omega_c$  in the acceleration zone (see the figure), and in decreasing the electron transversal velocity  $v_{\perp}$ . Some electrons leave the Larmor orbit with a radius of  $r_L = v_{\perp} \gamma / \Omega_0$  and decrease their orbit in the acceleration zone, while the other ones pass to the acceleration zone and increase their orbit.

We can symbolically write the logic of events in the gyrotron's cavity, as

in the deceleration zone:  $v_{\perp} \downarrow \rightarrow m_e \downarrow \rightarrow r_L \downarrow \rightarrow \omega_c \uparrow$ ,  
 in the acceleration zone:  $v_{\perp} \uparrow \rightarrow m_e \uparrow \rightarrow r_L \uparrow \rightarrow \omega_c \downarrow$ .

Finally, if an electromagnetic wave modulates a helical electron beam near the cyclotron resonance, the relativistic perturbations of the electron gyration frequency cause the azimuthal inertial bunching of electrons (see the Fig. 3), and electromagnetic wave generation. It occurs, when the resonant frequency of the gyrotron cavity is slightly higher than the cyclotron frequency. Then the bunch of the electrons slips towards the decelerating phase and the net effect of the energy transfer is positive, thus the radiation dominates over the absorption.

#### 4. Gorky

Obviously and typically, it was a team of specialists that contributed to the new invention, the Gorky gyrotron. In 1956 the Nizhgorodsky Institute of Radio-Physics was founded by Maria Tikhonovna Grekhova, mother of Andrei Viktorovich Gaponov (since 1968 Gaponov-Grekhov). She organized a research team at the Institute dealing with CRM-based oscillators and amplifiers. Very helpful, when creating a suitable scholarly atmosphere around the new invention, was the kind involvement of Igor Ivanovich Antakov (Maria Tikhonovna Grekhova's PhD student!), a specialist in induced cyclotron radiation and trochotrons [15]. (Trochotron – a device in which electrons in transversal electric and magnetic fields make trochoidal trajectories). Antakov unexpectedly discovered that the trochotron can work even when the electron beam is distant from the waveguide walls. At that time, neither Twiss's work [16] nor Schneider's work [17] was known in Gorky. It was therefore considered that this phenomenon can be explained with the selection of incorrect phase electrons. Then Maria Tikhonovna asked her son Andrei to construct a “non-selective” theory of electromagnetic wave amplification in its interaction with the spatially periodic electron beam. Thus, the gyrotron theory based on classical electrodynamics was developed [13, 14].

As early as spring 1959, the first results of a model design of a new type of CRM device were presented at the Popov Conference (“Popovshchina”). The amplification of the device was so weak that the “invention” aroused little interest. Anyway, in that time Antakov's trochotron had 35 watts of output power at the wavelength of 3.4 cm (8.9 GHz).

Meanwhile, in autumn 1959, a new generation entered the game. Two young enthusiasts of radiophysics, Mikhail Ivanovich Petelin and Valery Konstantinovich Yulpatov, decided to obtain doctoral degrees under the supervision of Andrei Ivanovich Gaponov himself. The theoretical assumptions of the new invention were ready and awaited experimental verification. A year later *Izv. VUZov. Radiofizika* published the work by Igor Ivanovich Antakov and others, which confirmed that (according to Zhelezniakov's correction) the relativistic effect is also (!) the basis of the trochotron interaction. In 1963 Anta-



Fig. 4. The creators of a Gorky gyrotron: Viktor Ivanovich Gaponov, Viktor Viktorovich Zhelezniakov, Mikhail Ivanovich Petelin, Valery Konstantinovich Yulpatov, Valery Aleksandrovich Flyagin, and Arkady L'vovich Gol'denberg

kov's trochotron reached one hundred Watts at the wave length of 8 mm (37.5 GHz). This optimistic result was the driving force behind the team working on the gyrotron – Fig. 4.

The construction of the first Gorky gyrotron did not appear immediately. Many other scholars contributed to its design and launch. “Sufficiently long” interaction of the electric field with the cyclotron resonance of the electron could only be provided by an appropriate resonator. The electron beam should traverse such a resonator, in which conditions could be created for cyclotron-resonance interaction of electromagnetic wave with gyrating electrons. The theoretical foundations of the resonator and other elements of the new device were developed by Mikhail Petelin with his colleagues Arkady Gol'denberg and Valery Yulpatov. Following Antakov's suggestion, Petelin relied on the work of Lev Al'bertovich Weinstein from 1963 [18]. The equations contained there were used to design a quasi-optical resonator for the new CRM device. Boris Zacharovich Katsenelenbaum with his theory of “weakly irregular resonators” could play a significant role in the first design of the resonator [19]. Unfortunately, Boris Zacharovich's monumental work, although it covered all aspects of the work of various resonators, was so universal that it was difficult to apply. Thus, initially the researchers based on the more “user-friendly” works of Lev Al'bertovich Weinstein [20]. Although it was later confirmed that the calculation made by “BZ” (as Katsenelenbaum's students called him) coincided with those made by Weinstein.

The theoretical work of Petelin and his colleagues allowed to develop technical details of the new device, mainly the resonator, but also the electron source. V.A. Flyagin and V.K. Yulpatov and Arkady L. Gol'denberg made an electron gun for Petelin according to his concept. (The first construction was based on the cathode of a TV cathode ray tube).

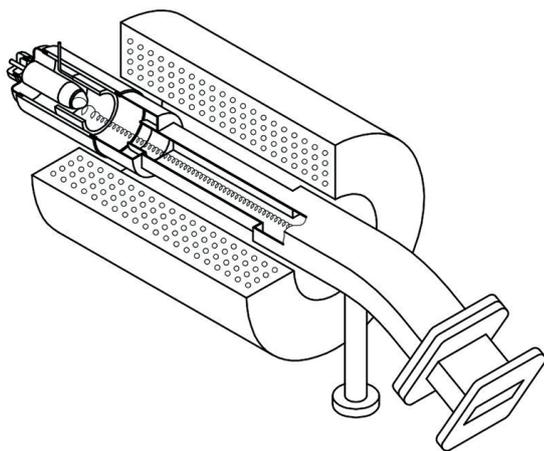


Fig. 5 Technical drawing of the first gyrotron in the world (drawn by Eugene L'vovich Pevzner)

Above, we have mentioned the CRM device presented at the Popov Conference 1959, which met with a rather faint response. The only benefit of this effort was the solenoid. To some extent. In 1963, advised by V. Talanov, Petelin filled the Weinstein's 2-mirror resonator-1963 with his (Petelin's) magneto-active plasma-1961 and calculated a start current for such a version of CRMs. In Petelin's theory, the resonator cross-section was arbitrary. So, as the solenoid-1959 was very narrow, Petelin adjusted his quasi-optical theory to the H<sub>101</sub> mode of a new CRM device. (Presently all gyrotrons operate at high-order modes H<sub>mnq</sub> with  $q = 1$ ). Finally, in 1964, the construction of the world's first gyrotron saw the light of day. Flyagin's engineers called it "молоток" (hammer) because it resembled this tool.

The well-known drawing of the "hammer" was made by Eugene L'vovich Pevzner – Fig. 5. At the end of November 1964, Inessa M. Orlova took the opportunity when her friend Arkady Gol'denberg travelled around Kamchatka and, acting under Petelin's pressure, connected high voltage to the new CRM that had just been constructed. A calorimeter placed at the "monster's" throat showed ... several Watts of output power.

Ultimately, output power of 6 W was achieved. At the same time Antakov's trochotron already exceeded 100 W of output power. The same year the results were presented at the All-Union conference in Moscow, where a discussion was initiated by Lev Albertovich Weinstein himself. The revised design was presented in 1966, at the All-Union conference in Saratov. There a lecture was delivered on the new type of CRMs with "world-level" output power. In the same year Antakov's trochotron reached 700 W, but it became clear that it was only a matter of time before the gyrotron would "beat" the trochotron.

The device attracted the attention of the Ministry, which provided funds for the research work. This would not have been possible were it not for the high position of Maria Tikhonovna Grekhova, then the director of the Radiophysical Research Institute (RRI) she had founded. Miller in his memories recounts a significant conversation with a certain VIP from the Ministry. In the lobby of the hotel, the VIP was convinced: "You should, let Maria Tikhonovna drop a million or two ... After all, she, Maria Tikhonovna is Joanna d'Arc of our time!" [11].

Anyway, at the aforementioned conference, the young scientists were asked to give the device a unique name. There, Arkady L. Gol'denberg did a good job, immediately proposing the name "gyrotron." By a hair's breadth the new name would have been rejected, because a year later somebody learnt that some kind of carousel was thus called in Canada (Expo 67).

For various reasons, the name "gyrotron" began to appear officially in Russian scientific literature only at the end of 1972. (The new device already had 400 kW of output power in a pulse regime. (Again, Flyagin's engineers coined a specific name for the new design: a "beanpole"). Although, in 1967, the word "gyrotron" (гиротрон) did (!) appear in a Soviet patent – Fig. 6.

## 5. Others

A similar approach, as in classical electrodynamics, was used by an Australian scientist Richard Quintin Twiss (also an astrophysicist!) [17] to explain the phenomenon of relativistic cyclotron resonance. The influence of electromagnetic waves on cyclotron resonance was also explained on the basis of quan-

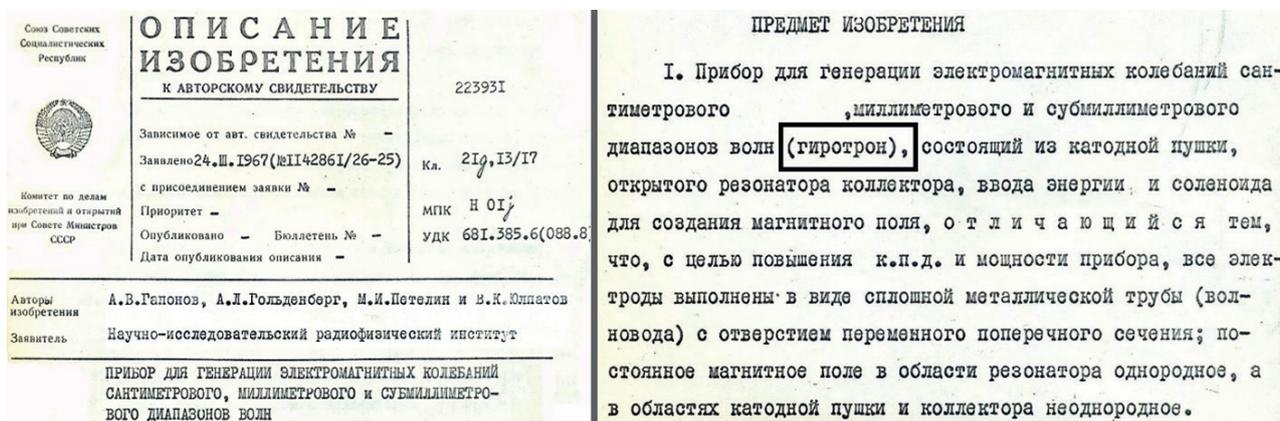


Fig. 6. Soviet Patent of 24 March 1967, where a word "gyrotron" (гиротрон) appears

tum mechanics. Parallel to Gaponov's theory, on 27 April 1959, the German physicist Jürgen Schneider (performing research in the USA) wrote: "the dependence of electron mass on its energy results in an unequal non-equidistant Landau levels so that, with appropriate tuning of the field frequency to the cyclotron frequency of the electrons, the probability of induced emissions may exceed the probability of absorption." [16, 21] At that time these works were not yet known to the group in Gorky. It should be explained to the young generation that at that time the world existed without the Internet. That is why, the gyrotron team in Gorky learned about Schneider's work only 6 years after it was published (!).

Apparently, Schneider himself, one of the three creators of the theory of a gyrotron, when he witnessed intense research on various types of maser-mechanisms in the USA at the end of the 1950's, never expected that such CRM devices would be able to generate 1 MW of output power.

Nobody expected. Apart from ... a Gorky team.

Further history of the gyrotron and its development in the context of scientific theory, including in relation to other gyrotron research teams in the world, can be found in excellent publications by Gregory Nusinovich, Manfred Thumm, Mikhail Petelin, Richard Temkin, and others [22–28].

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