Charging of the Traveling Wave Resonator of the Microwave Compressor by a Relativistic S-Band Magnetron

Arkadii Sayapin, Andrey Levin, and Yakov E. Krasik

***Abstract*— The charging of the traveling wave resonator (TWR) of a microwave compressor by a relativistic S-band magnetron that generates microwave pulses with power ≤ 250 MW and duration of ∼100 ns is described. The short pulse duration determining the resonator charging time and traveling electromagnetic wave increases the electric strength of the resonator. The short duration of the input pulse determines the coupling and Q-factor of the TWR, and it is not necessary to apply an interference switch for energy release. A scheme for releasing energy at a microwave power of ≥ 1 GW using a ferrite circulator is discussed.**

***Index Terms*— High-power microwave compressor, relativistic magnetrons.**

I. Introduction

HIGH-POWER passive [1], [2] and active [3], [4] microwave compressors are attracting a large amount of research attention due to their important applications related to high-energy particle accelerators, radars, microwave discharges, and so on. Passive microwave compressors that use fast phase modulation in the incident pulse are already being used successfully in RF accelerator systems. However, this type of compressor has limitations in power gain (≤ 6) and is also relatively large. Active compressors allow one to achieve a larger power gain while keeping a high level of efficiency and small dimensions. The operation of an active compressor is based on relatively slow microwave energy storage in a high-Q resonator and energy release into a load over a time interval is much shorter than the storage time [5]–[8]. The latter is achieved due to a fast increase in the coupling between the resonator and load using a fast switch (generation of gas or semiconductor plasma, electron beam injection). Therefore, when the value of reflection coefficient of the traveling e/m wave from the plasma switch reaches $\Gamma_{\text{ref}} \approx 1$, the energy stored in the resonator will be released during the time $\tau = l/\upsilon_{\text{gr}}$, where l is the length of the resonator and υ_{gr} is the group velocity of e/m wave. Thus, the microwave compressor allows one to generate short pulses with a duration ≤ 10 ns and peak power of hundreds of MW using conventional nonrelativistic microwave tubes producing microwave pulses with power up to several MW and a pulse duration of several microseconds [9], [10].

When relativistic microwave generators coupled with active resonator were applied, [11], [12] a ≥10-fold increase in the output power of the compressor was also demonstrated. The first experimental studies [13] of a microwave compressor pumped by an S-band relativistic magnetron already showed promising results. Namely, using an S-band magnetron generating ∼180-MW microwave pulses with a duration ∼120 ns, 1.1-GW microwave pulses with a duration of 5 ns were obtained at the output of the compressor. However, the results of these experiments also showed problems that have to be resolved to achieve reliable and efficient operation of the compressor. That is, the operation of a relativistic magnetron with an explosive emission cathode is characterized by a change in the frequency of the generated microwaves, [14]–[16] which is a crucial issue for efficient pumping of a resonator having narrowband eigen frequencies. An attempt to stabilize the frequency of e/m waves generated by the relativistic magnetron using the stored resonator as a load was unsuccessful, because the e/m wave reflected from the resonator with random phase caused a decrease in the amplitude of the generated e/m waves in the magnetron and even termination of e/m wave generation. To decouple the magnetron and resonator, a long (10 m) waveguide was used, which results in an increase in the duration of the microwave pulse generated by the magnetron up to ∼120 ns; however, the storage time in the compressor was still only ∼50 ns because the frequency of the generated microwaves was not stable.

The results of research studies [17] on the operation of an S-band relativistic magnetron with an adjustable resonance load demonstrated that it is possible to increase the efficiency of the magnetron operation significantly and achieve a high power gain in the resonator during the charging. However, the experimental setup used in this research did not allow the simultaneous realization of both a highly efficiency operation of the magnetron and a high power gain in the resonator during the charging with high repeatability and reproducibility. It is noteworthy that in the research a commercial directional coupler was tested and its operation without electrical breakdown at a microwave power of ∼250 MW and pulse duration τ ≤100 ns was shown.

In this paper, we present the results of an experimental study on the charging of the traveling wave resonator (TWR) of a microwave compressor by an S-band relativistic magnetron. It was shown that this type of compressor allows one to increase

Manuscript received May 22, 2013; accepted July 24, 2013. Date of current version September 9, 2013. This work was supported in part by the Center for Absorption in Science, Ministry of Immigrant Absorption, State of Israel, and in part by Technion under Grant 1011170.

The authors are with the Physics Department, Technion, Israel Institute of Technology, Haifa 32000, Israel (e-mail: sayapin@physics.technion.ac.il; landrey@physic.technion.ac.il; fnkrasik@physics.technion.ac.il).

Digital Object Identifier 10.1109/TPS.2013.2275993

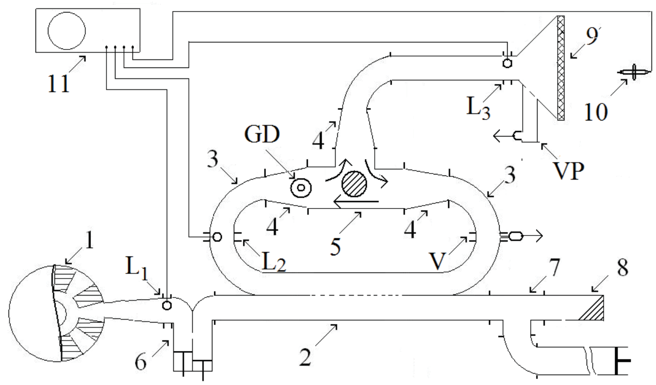

Fig. 1. Experimental setup. 1) Magnetron. 2) Directional coupler. 3) Waveguide bend. 4) Waveguide transitions from cross-section 72 × 34 mm^2 to 86 × 42 mm^2. 5) Waveguide circulator (WENTEQ F3447). 6) Phase shifter. 7) Tee-waveguide with one of the outputs connected to a waveguide that is short-circuited by a movable plunger. 8) Matched load. 9) Transmitting horn antenna. 10) D-dot sensor (ACD-11R). 11) Agilent Infiniium DS080404B oscilloscope, $L_{1,2,3}$-B-dot loops, V-vacuum gauge, GD-microwave gas discharge, and VP-vacuum pump.

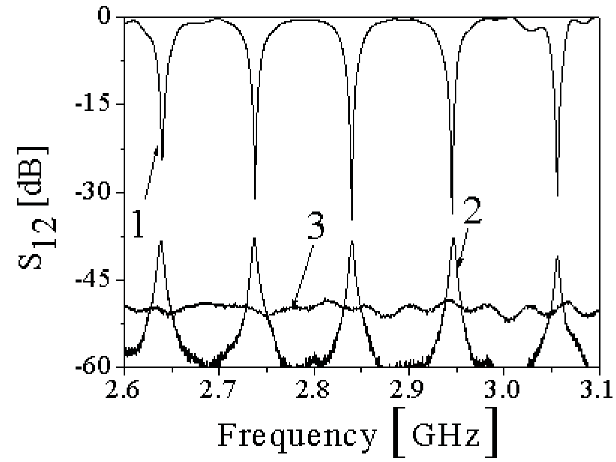

Fig. 2. Frequency response. 1) Transmission coefficient S_{12} of the tee-waveguide. 2) TWR. 3) B-loop (L_2-Fig. 1).

its electrical strength as compared with a compressor based on a standing wave resonator and to adjust and stabilize the frequency of the e/m waves generated by the magnetron.

The compressor was pumped by an S-band relativistic magnetron (Fig. 1) powered by a linear induction accelerator (~300 kV, ~2.5 kA, ~150 ns). By varying the external magnetic field $H = 3.5 \mp 0.5$ kG produced by Helmholtz coils, the frequency and power of the generated e/m waves was changed in the range $f = 2.65 - 3.05$ GHz and $P =$ 150–250 MW, respectively. The energy of the generated microwave pulse was stored in a TWR, the application of which instead of a standing wave resonator allows one to avoid the e/m wave being reflected from the resonator. In this scheme, a part of the microwave power that does not go into the resonator at the beginning of the storage phase can be used for the magnetron positive feedback.

One of the main parts of the resonator is the directional coupler WR284, presenting a wave guide with a cross section 72 × 34 mm^2 (item 2, Fig. 1) and a coupling coefficient $K = -6$ dB. This value is close to the optimal value $K = -7.5$ dB that was calculated using the duration and form of the pumping microwave pulse [18]. The resonator ring is closed by standard E-bend waveguides (item 3, Fig. 1), with a circulator WENTEQ F3447 and waveguide transitions between them from cross section 72 × 34 mm^2 to 86 × 42 mm^2 (items 4 and 5, Fig. 1). The input and output of the circulator are oriented to allow traveling e/m waves, generated by the magnetron, to be propagated in the resonator. To release the e/m energy stored in the resonator, one of the waveguide transitions, placed at the output of the circulator, has an input hole through which the gas plasma switch (GD, Fig. 1) will be inserted in forthcoming experiments to produce microwave gas discharge [19], [20]. The formation of the plasma should lead to reflection of the traveling e/m wave toward the circulator that directs this e/m wave to the input of the horn antenna (item 9, Fig. 1).

In the present setup, no interface insulators between the magnetron, compressor, and horn antenna were used, and the pressure ~$8 \cdot 10^{-6}$ Torr in the system was maintained by three turbo-molecular pumps. The magnetic field of the e/m wave at the input of the compressor and in the resonator was measured using B-dot loops (items $L_{1,2}$, Fig. 1), and registered by a Agilent Infiniium DS080404B (4 GHz, 40 GS/s) oscilloscope. To measure the amplitude–frequency parameters of the compressor, a network analyzer, a ROHDE & SCHWARZ–ZVL 9 kHz–6 GHz, was used.

A part of the power of the pumping microwave pulse that does not pass in the resonator during the initial phase of its charging was used for the magnetron positive feedback at the frequency of the resonator. To achieve this, the output of the directional coupler is connected with a matched load (item 8, Fig. 1) using a tee-waveguide (item 7, Fig. 1). The other output of the tee-waveguide is connected to the waveguide, which is short-circuited by a movable plunger. The reflection coefficient of the e/m wave from the tee-waveguide is determined by the ratio of the phases of the e/m wave entering the tee-waveguide and the e/m wave reflected from the short-circuit end of the waveguide. Thus, the tee-waveguide with a matched load at one end and a short-circuit waveguide at the other can be considered as an interference load. This allows one to obtain the positions of the plunger that are required for complete reflection of the e/m wave from this interference load at the desired frequencies. In addition, a waveguide phase shifter is placed between the directional coupler and magnetron, (item 6, Fig. 1), which is used to correct the phase of the e/m wave reflected from the interference load. This phase shifter allows one to achieve either positive or negative feedback with the magnetron.

Preliminary research of the magnetron operation with only a horn antenna as load showed that at $f \approx 2.945$ GHz it generates rather reproducible microwave pulses with a duration ~70 ns and power $P \approx 200$ MW. It is noteworthy that the reflection coefficient of the e/m wave from the antenna input was $\Gamma \approx 0.1 \pm 0.1$ and that the phase of the reflected wave has significant dependence on the frequency [14]. Thus, the value $f \approx 2.945$ GHz was determined as the working frequency of the compressor. Using waveguide inserts of the appropriate

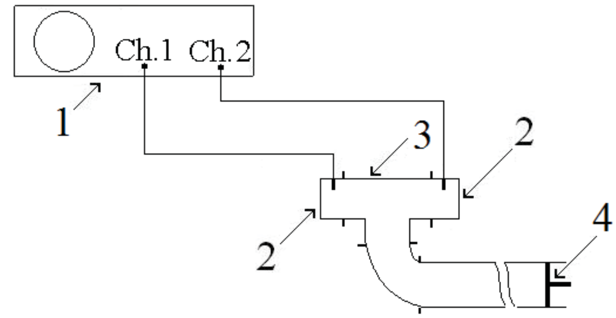

Fig. 3. Setup for adjusting of the interference load. 1) Network analyzer: ROHDE & SCHWARZ–ZVL and 9 kHz–6 GHz. 2) Waveguide to coaxial transition. 3) Tee-waveguide, one output of which is connected to a waveguide shorted by a movable plunger (item 4).

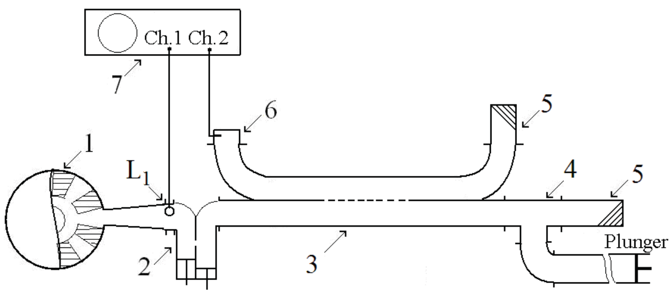

Fig. 4. Scheme of preselection phase shifter position. 1) Magnetron. 2) Phase shifter. 3) Directional coupler. 4) Tee-waveguide, one output of which is connected to a waveguide shorted by movable plunger. 5) Matched load. 6) Coaxial-waveguide adapter. 7) Network analyzer: ROHDE & SCHWARZ–ZVL and 9 kHz–6 GHz.

thickness (item V, Fig. 1), the length of the resonator was adjusted such that one of its resonance frequencies equaled $f \approx 2.945$ GHz. The frequency response of the TWR, B-dot loop, and transmission coefficient S_{12} of the tee-waveguide are shown in Fig. 2. One can see that the gain of the resonator (i.e., the difference between 1st and 2nd waveforms) reaches a value of ∼12 dB at resonance frequencies.

The scheme that was used for adjusting the interference load is shown in Fig. 3. The length of the short-circuit waveguide was equal to approximately half the length of the TWR. In this case, the correction of the length of the short-circuit waveguide by a movable plunger allows one to obtain matching between all the resonance frequencies of the TWR with frequencies ω^i_{ref} of e/m waves having complete reflection from the input of the tee-waveguide.

In general, stabilization of the frequency of the e/m wave in the magnetron can be achieved (even though other parameters could be unstable) if, within the frequency band of e/m waves that is realized during the magnetron operation, for one of these frequencies the amplitude of the e/m wave reflected from the tee-waveguide is dominant, and this reflected e/m wave is also in the same phase as the e/m wave in the magnetron. To adjust the phase of the reflected e/m wave, a waveguide shifter placed at the output of the magnetron was used (Fig. 4). At frequencies ω^i_{ref}, the magnetron and tee-waveguide can be considered as a low-Q resonator. Thus, using a network analyzer the resonance of the magnetron and tee-waveguide

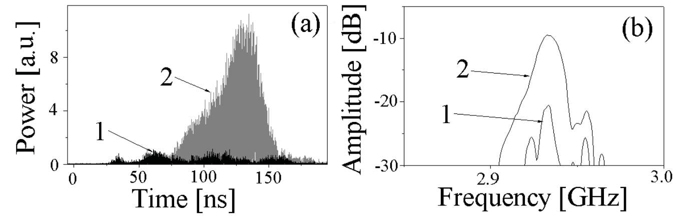

Fig. 5. (a) Power of the e/m waves at the magnetron output 1) and circulating in the resonator 2). (b) Spectral response of the e/m waves at the magnetron output 1) and circulating in the resonator 2).

system at one of the frequencies ω^i_{ref} was determined by the appropriate position of the phase shifter. In the experiment with the compressor, an additional correction in the position of the phase shifter was required.

To estimate the effect of the feedback on the magnetron operation, the phase shifter and end of the tee-waveguide that is short-circuited by the plunger (items 6 and 7, Fig. 1) were excluded from the scheme. In this case, the magnetron operated on an almost matched load with the microwave pulse duration of ∼100 ns, which is larger than the ∼70-ns duration of the microwave pulse generated by the magnetron with a horn antenna. The averaged peak power of microwave pulses in the cases of a matched load and antenna remains approximately the same, at ∼200 MW. However, the frequency spectrum of the microwave pulses was unstable, i.e., only for ∼20% of generated pulses did the spectrum show one maximum at a frequency close to the resonance frequency. In these cases, the power TWR increased monotonically and the gain in the power of the wave circulating in the resonator reached ∼7 dB. With approximately the same reproducibility, microwave pulses generated by the magnetron were obtained having two maxima in a frequency spectrum. In this case, the gain in the power of the wave circulating in the resonator also reached ∼7 dB, but the waveform of the B-dot loop was characterized by strong aperiodical amplitude modulation.

The operation of the magnetron was stabilized when the interference load and phase shifter were implemented in the setup. In this case, at $H = 2.4$ kG the magnetron generated microwave pulses at one of the resonance frequencies of the TWR, $f = 2.933$ GHz. The maximal power of the e/m wave in the TWR and a reproducibility of ∼80% were achieved by turning the phase shifter by $\Delta\phi \approx 9°$ with respect to its value obtained during the calibration. Typical waveforms of the power of the e/m waves circulating in the TWR and magnetron normalized at maximal power of the e/m wave in the magnetron; their frequency characteristics are shown in Fig. 5. The same stable operation of the magnetron was obtained at another resonance frequency, $f = 2.840$ GHz ($H = 2.8$ kG), which was obtained when the phase shifter was corrected by $\Delta\phi \approx 14^{\circ}$. At this frequency, the gain in the power of the e/m wave circulating in the resonator also reached ∼10 dB resulting in ∼2-GW microwave power.

II. Conclusion

Our experiments showed that when the duration for which the energy stored is ≤ 100 ns, the TWR with a common circulator allows one to increase the power of the e/m wave in the resonator to ∼2 GW. It was found that the positive feedback for the magnetron at the resonance frequency of the TWR results in a significant increase in the reproducibility (∼80%) of the process of microwave energy storage in the resonator. Finally, it was shown that, by adjusting the value of the magnetic field and phase of the e/m wave reflected from the interference load properly, one can change the frequency of the e/m wave generated by the magnetron from one of the resonance frequencies of the TWR to another.

ACKNOWLEDGMENT

The authors would like to thank A. Shlapakovsky, Y. Bliokh and L. Beilin for fruitful discussions and comments.

REFERENCES

[1] Z. D. Farkas, "Binary peak power multiplier and its application to linear accelerator design," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-34, no. 10, pp. 1036–1043, Oct. 1986.

[2] S. G. Tantawi, C. D. Nantista, V. A. Dolgachev, C. Pearson, J. Nelson, K. Jobe, J. Chan, K. Fant, J. Frisch, and D. Atkinson, "High-power multimode X-band rf pulse compression system for future linear colliders," *Phys. Rev. ST Accel. Beams*, vol. 8, no. 4, pp. 042002-1–042002-19, Apr. 2005.

[3] S. G. Tantawi, R. D. Ruth, A. E. Vlieks, and M. Zolotorev, "Active pulsed power RF pulse compression optically switched resonant delay lines," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1486–1493, Aug. 1997.

[4] A. L. Vicharev, O. A. Ivanov, A. M. Gorbachev, V. A. Isaev, S. V. Kuzikov, S. H. Gold, and A. K. Kinkead, *High Energy Density and High Power RF*, S. H. Gold and G. S. Nusimovich, Eds. New York, NY, USA: Amer. Inst. Phys., 2003, p. 197.

[5] D. Birx, G. J. Dick, W. A. Little, J. E. Mercereau, and D. J. Scalapino, "Microwave power gain utilizing superconducting resonant energy storage," *Appl. Phys. Lett.*, vol. 32, no. 1, pp. 68–70, Jan. 1978.

[6] A. N. Didenko and Yu. G. Yushkov, *Powerful Microwave Nanosecond Pulses* [in Russian]. Moscow, Russia: Energoatomizdat, 1983.

[7] R. A. Alvarez, "Some properties of microwave resonant cavities relevant to pulse-compression power amplification," *Rev. Sci. Instrum.*, vol. 57, no. 10, pp. 2481–2488, Oct. 1986.

[8] A. Andreev, E. G. Farr, and E. Schamiloglu, *Circuit and Electromagnetic System Design Notes*. Aug. 2008, pp. 1–11.

[9] P. J. Hackney, D. J. Mellor, G. D. Simson, and J. R. G. Twisleton, "High power short pulse generation at S-band using a waveguide cavity with laser initiated discharge," *Electron. Lett.*, vol. 31, no. 15, pp. 1263–1264, Jul. 1995.

[10] S. N. Artemenko and Yu. G. Yushkov, "Compression of microwave pulses in a resonant system based on two waveguide T-joints," *Radioelectron. Commun. Syst.*, vol. 54, no. 5, pp. 281–283, May 2011.

[11] R. Gilgenbach, Y. Lau, H. McDowell, K. L. Cartwright, T. A. Spencer R. J. Barker, N. C. Luhmann, J. H. Booske, and G. S. Nusinovich, *Modern Microwave and Millimeter Wave Power Electronics*. New York, NY, USA: Wiley, 2005.

[12] J. Benford, J. A. Swegle, and E. Schamiloglu, *High Power Microwaves*. New York, NY, USA: Taylor, 2007.

[13] A. N. Didenko, I. I. Vintizenko, A. I. Mashchenko, A. I. Ryabchikov, G. P. Fomenko, P. Yu. Chumerin, and Yu. G. Yushkov, "Resonant compression of microwave pulses at relativistic magnetron output," *Doklady Acad. Nauk*, vol. 36, no. 5, pp. 619–621, 1999.

[14] A. Sayapin and A. Shlapakovsski, "Transient operation of the relativistic S-band magnetron with radial output," *J. Appl. Phys.*, vol. 109, no. 6, pp. 063301-1–063301-5, Mar. 2011.

[15] S. T. Spang, D. E. Anderson, K. O. Busby, K. D. Claborn, S. P. Manning, A. K. Milakovic, J. J. Prochazka, D. M. Rexroad, E. P. Scannell, T. K. Seybold, R. J. Williams, Jr., and D. A. Woodyard, "Relativistic magnetron development for use in a lightweight, repetitively pulsed, portable HPM transmitter," *IEEE Trans. Plasma Sci.*, vol. 18, no. 3, pp. 586–593, Jun. 1990.

[16] I. Vintizenko and G.V. Mel'nikov, "Radiation frequency dynamics in a relativistic magnetron," *Tech. Phys. Lett.*, vol. 36, no. 8, pp. 706–709, Aug. 2010.

[17] A. Sayapin, Y. Hadas, and Y. Krasik, "Drastic improvement in the S-band relativistic magnetron operation," *Appl. Phys. Lett.*, vol. 95, no. 7, pp. 074101-1–074101-3, Aug. 2009.

[18] A. Sayapin and Y. Krasik, "Numerical simulation of the magnetron operation with resonance load," *J. Appl. Phys.*, vol. 107, no. 7, pp. 074501-1–074501-7, Apr. 2010.

[19] A. L. Vikharev, A. M. Gorbachev, O. A. Ivanov, V. A. Isaev, S. V. Kuzikov, B. Z. Movshevich, J. L. Hirshfield, and S. H. Gold, "Active Bragg compressor of 3-cm wavelength microwave pulses," *Radiophys. Quantum Electron.*, vol. 51, no. 7, pp. 539–555, Jul. 2008.

[20] J. Foster, G. Edmiston, M. Thomas, and A. Neuber, "High power microwave switching utilizing a waveguide spark gap," *Rev. Sci. Instrum.*, vol. 79, no. 11, pp. 114701-1–114701-5, Nov. 2008.

Arkady Sayapin received the M.Sc. degree in radiophysics from Tomsk State University, Tomsk, Russia, in 1972, and the Ph.D. degree in particle accelerators from Tomsk Polytechnic Institute, Tomsk, in 1980.

He was with the Nuclear Research Institute, Tomsk, from 1972 to 1989. Since 2002, he has been with the Physics Department, Technion, Israel Institute of Technology, Haifa, Israel, where he is currently a Senior Research Scientist. His current research interests include microwave generation, active plasma cathodes, and electrical wire explosion.

Andrey L. Levin received the M.Sc. degree in electronics from the Far Eastern Polytechnic Institute, Vladivostok, Russia, in 1980.

He joined the Design Bureau of Oceanographic Research in 1980. Since 2000, he has been with the Physics Department, Technion, Haifa, Israel.

Yakov E. Krasik received the M.Sc. degree in physics from the Tomsk Potechnical Institute, Tomsk, Russia, in 1976, and the Ph.D. degree in physics from the Joint Institute for Nuclear Research, Dubna, Russia, in 1980.

He was with the Nuclear Research Institute, Tomsk, from 1980 to 1991, and from 1991 to 1996 he was with the Weizmann Institute of Science, Rehovot, Israel. Since 1997, he has been with the Physics Department, Technion, Haifa, Israel, where he is currently a Professor. His current research interests include pulsed current-carrying plasmas and high power microwaves.