Active Microwave Pulse Compressor Using an Electron-Beam Triggered Switch

O. A. Ivanov,[1,2] M. A. Lobaev,[1] A. L. Vikharev,[1,2] A. M. Gorbachev,[1,2] V. A. Isaev,[1] J. L. Hirshfield,[2,3] S. H. Gold,[4] and A. K. Kinkead[5]

[1]*Institute of Applied Physics RAS, Nizhny, Novgorod 603600, Russia*
[2]*Omega-P, Inc., New Haven, Connecticut 06510, USA*
[3]*Department of Physics, Yale University, New Haven, Connecticut 06511, USA*
[4]*Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375, USA*
[5]*Icarus Research, Bethesda, Maryland 20814, USA*
(Received 21 November 2012; published 12 March 2013)

A high-power active microwave pulse compressor is described that operates by modulating the quality factor of an energy storage cavity by means of mode conversion controlled by a triggered electron-beam discharge across a switch cavity. This Letter describes the principle of operation, the design of the switch cavity, the configuration used for the tests, and the experimental results. The pulse compressor produced output pulses with 140–165 MW peak power, record peak power gains of 16:1–20:1, and FWHM pulse duration of 16–20 ns at a frequency of 11.43 GHz.

DOI: 10.1103/PhysRevLett.110.115002 PACS numbers: 52.59.Fn, 84.40.Az

A proposed future TeV electron-positron linear collider operating at X band (11.4 or 12.0 GHz), and a test facility for its components, will require high-peak microwave powers of hundreds of megawatts in pulses lasting hundreds of nanoseconds. One method to provide such pulses is through the use of a microwave pulse compressor to multiply the power produced by a high-power klystron producing multimicrosecond pulse widths. Such a compressor can be passive, employing phase switching to discharge microwave energy storage cavities such as in SLED II [1], or active [2], in which a triggered increase in the output coupling coefficient of the energy storage cavities is used to extract the high-power microwave pulse. Active microwave pulse compressors are of interest because they are more capable of both higher compression ratios and higher efficiencies than passive compressors. To date, the best results in active pulse compression were obtained in a series of experiments where the authors investigated compressors that used a plasma discharge inside gas-filled dielectric tubes located within switch cavities to shift the switch cavities into resonance, and thus to lower the quality factor Q of the energy storage cavities. Those experiments produced compressed X band pulses of 50–70 MW peak power and 40–70 ns duration, with peak power gains of 7:1–11:1 and efficiencies in the range of 50%–63% [2]. The results were limited by the appearance of multipactor discharges on the surface of the dielectric tubes, by spontaneous rf breakdown of the low-pressure gas contained in the tubes, and by transient switching due to changes in plasma density during the switching process.

Those experimental results suggest that higher power operation should be possible if the switching elements are removed from the switch cavities by replacing the intracavity plasma discharge by an externally injected electron beam. This concept was first successfully tested in low-power experiments [3,4]. In this Letter we report the first high-power test of a two-channel active microwave pulse compressor with switches based on the new concept of triggering using an electron beam to change the resonant frequency of a switch cavity. Here, we describe the design of the switch, the principle of operation of the compressor, and the experimental configuration that employed an 11.43-GHz magnicon amplifier [5,6] as the high-power source. The experiments were carried out at drive powers of up to 9 MW in a $\sim$1.1 μs pulse and produced output pulses with peak powers of 140–165 MW, peak power gains of 16:1–20:1, and FWHM pulse durations of 16–20 ns. These results suggest that it may be feasible to employ active pulse compressors in a future TeV electron-positron collider and in the test facility needed to develop related high-power components.

The compressor consists of two identical compressor channels that are fed through a 3-dB hybrid coupler that serves to isolate the rf source from power reflected back from the compressor. The design and operating principles of a single compressor channel are illustrated in Fig. 1(a). Microwave energy is fed into the TE_{01} mode of a circular waveguide. The compressor channel consists of the coupling waveguide (1) that is cut off to the TE_{02} mode, an input taper (2), a section of cylindrical waveguide (3), and the switch assembly (4–9). The switch assembly consists of a conical taper (4) in which the TE_{02} and TE_{01} modes are coupled to one another, a TE_{01}-mode waveguide section (5) of adjustable length, and a TE_{012} switch cavity (7) connected to the waveguide through a diaphragm (6). The length of the waveguide section (5) is chosen to ensure that waves reflected from the conical taper and from the switch cavity sum with opposite phases when the cavity is in resonance, and thus almost completely cancel. As a

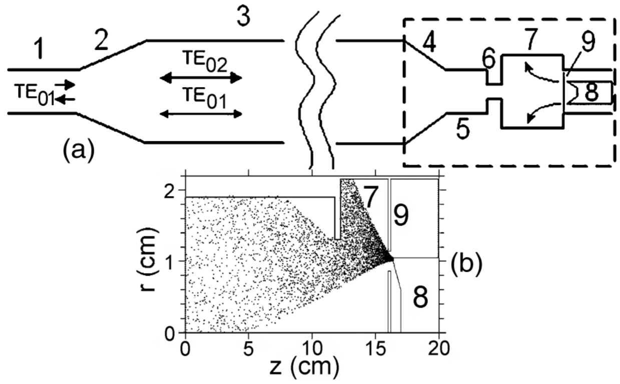

FIG. 1. (a) Schematic diagram of the single-channel compressor: 1: input TE_{01} mode waveguide; 2: input taper; 3: cylindrical waveguide cavity; 4: conical taper; 5: waveguide section; 6: diaphragm; 7: TE_{012}-mode switch cavity; 8: cathode; 9: anode plate. (b) Instantaneous computed distribution of electrons inside the switch cavity at a beam current of 200 A and cathode voltage of 100 kV.

result, the total coefficient of $TE_{02} \rightarrow TE_{01}$ mode conversion in the switch is only ~2%–3%, and the input taper, cylindrical waveguide, and switch assembly form a high Q cavity for the TE_{02} mode. This is the regime of energy storage, wherein the injected power builds up stored energy in the TE_{02} mode.

The switch cavity is formed by the diaphragm, a section of cylindrical waveguide, and the anode plate (9), which has an azimuthal slit that is interrupted by four small support strips. The slit is designed to allow an electron beam to enter the switch cavity at the radial field maximum of the TE_{01} mode, and its width and depth are designed to limit the leakage of the cavity rf fields through the anode plate to preserve the Q of the switch cavity. As a result, the intrinsic Q of the switch cavity remains high, and its total Q is determined principally by the coupling diaphragm, implying that the cavity will be strongly overcoupled. In this case, the reflection coefficient from the cavity is high, both in and out of resonance. However, the phase of the signal reflected from the switch cavity depends strongly on whether the cavity is in resonance or out of resonance at the operating frequency [7]. The switch cavity is detuned from in resonance to out of resonance by the injection of an electron beam. This change requires that $n_e/n_c \sim 2/Q_S$, where n_e is the mean electron density in the cavity, $n_c \sim 1.6 \times 10^{12}$ cm^{-3} is the critical density at 11.43 GHz, and Q_S is the quality factor of the switch cavity. For $Q_S \approx 200$, this requires a beam current of ~250 A. When the cavity is changed from in resonance to out of resonance at the operating frequency, the phase of the signal reflected from the cavity can change by up to ~180°, causing the TE_{01}-mode waves reflected from conical taper and from the switch cavity to combine in phase. This causes a substantial increase in the $TE_{02} \rightarrow TE_{01}$ conversion coefficient, thus lowering the Q of the energy storage cavity and causing the microwave energy stored in the cavity in the TE_{02} mode to be emitted from it in the TE_{01} mode. The conversion coefficient is determined by the slope of the taper and can approach 100%, permitting the cavity to empty in one round-trip time of the energy circulating in the TE_{02} mode.

The amplitudes of electric fields in the storage cavity and in the switch cavity in the regime of energy storage were calculated using the finite difference time domain (FDTD) method [8]. The calculations showed that a storage cavity quality factor $Q_L \geq 10^4$ could be achieved when the Q of the switch cavity is $Q_S \approx 200$–500. In the experiments, the loaded Q of the storage cavities of the two compressor channels was actually $Q_{L1} \approx Q_{L2} \approx (2\text{–}3) \times 10^4$. Then, the operation of the switch was modeled by studying the interaction of an electron beam injected into the fields of the TE_{012} mode excited in the switch cavity. The dynamics of the electron distribution in the switch were calculated by the particle-in-cell method [9], using a code that took into account the space charge of the electron beam. In the calculations, the potential difference between the cathode and anode was held at 100 kV, but the distance between the anode and cathode, and the beam current, were both varied. The calculated distribution of the injected electrons in the cavity at a beam current of 200 A and at a gap between the cathode and anode of 2 mm is shown in Fig. 1(b). The calculations show that 80–100% of the electrons emitted by the cathode can be injected into the switch cavity, depending on the anode-to-cathode distance and the width of the cathode edge.

The calculations also determined the phase and the reflection coefficient R of the electromagnetic wave that was reflected from the switch cavity following injection of the electron beam. It was assumed that the switch cavity was driven externally beginning at $t = 0$ to excite the TE_{012} mode at the resonant frequency $f_0 = 11.43$ GHz. The oscillations in the switch cavity were allowed to stabilize, and then an electron beam was injected into the cavity at $t^* = 25$ ns. The time dependence of the magnitude and phase of the reflection coefficient at a gap between the cathode and anode of 2 mm are shown in Fig. 2 for two values of beam current, $I_1 = 200$ A and $I_2 = 400$ A.

Figure 2 demonstrates that the injection of the beam current beginning at $t^* = 25$ ns results in a rapid change in the phase of the reflected wave and also in the discharge of the energy stored in the switch cavity ($R > 1$). It is evident that the higher beam current leads to a faster change in the phase and a larger total phase shift. The phase change time τ_p is determined by the time required to stabilize the oscillation in the switch cavity and can be estimated to be $\tau_p \sim Q_s/2\pi f_0$. For example, when the switch cavity has $Q_S = 200$, the characteristic phase shift time is $\tau_p \approx 3$ ns.

Figure 3 is a schematic diagram of the two-channel active pulse compressor that was studied using the magnicon as a high-power 11.43 GHz microwave source. Each energy

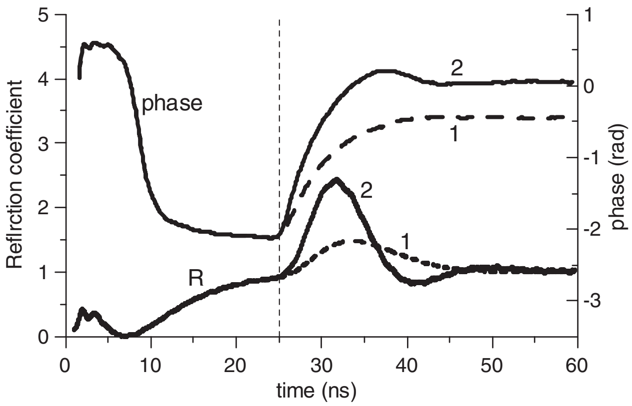

FIG. 2. Dependence of the magnitude and phase of the reflection coefficient R on time at different electron-beam currents: $1 - I_1 = 200$ A, $2 - I_2 = 400$ A.

storage cavity was formed by an input taper, a cylindrical waveguide 210 cm long and 80 mm in diameter, and the switch assembly that was previously described. The cylindrical waveguide included a section whose length could be mechanically adjusted to tune the cavity into resonance. The microwave power fed into port I of the 3-dB hybrid coupler in a rectangular waveguide is divided equally into ports III and IV, which connect to the two pulse compressor channels, and the reflected signal, as well as the output pulse, are directed to port II, which is connected to a high-power matched load. The mode converters transform the TE_{10} mode to the TE_{01} mode of the circular waveguide to feed the compressor channels. An additional tuner in channel 1 is used to adjust the relative phase of the two channels to ensure the cancellation of the signal in port I.

Signals proportional to P_{inc}, the power incident on the compressor, P_{ref}, the power reflected back towards the magnicon, and P_{com}, the power sent forward to the load, were measured by detectors via bidirectional couplers ($-$ 55.5 dB) in ports I and II. Additional directional couplers in each channel of the compressor were used to monitor their performance. The vacuum was maintained at $\sim 3\text{–}5 \times 10^{-7}$ Torr by means of ion pumps. The compressor was excited by the magnicon at power levels in the range of 1–9 MW and pulse durations $\tau = 1.0\text{–}1.4$ μs.

The pulse compressor was switched into the regime of energy extraction by injecting an electron beam into the switch cavities. A single pulser was used to generate a -100 kV, 100 ns pulse that was fed to the cathodes in both channels of the compressor, with the pulse timing synchronized with respect to the magnicon output pulse by time delay generators. The electron beams were extracted from cylindrical molybdenum cathodes with a diameter of 20 mm, corresponding to the diameter of the annulus in the anode plate. The cathodes had a ~ 50 μm knife edge to achieve sufficient field emission when the high voltage pulse was applied. Diamond coating of the cathode was found to significantly increase the number of emission centers and to substantially improve the uniformity of electron emission, as shown in the Fig. 4 inset, in which a wire mesh was substituted for the anode plate of the switch. The diamond films were deposited on the surface of the molybdenum cathodes in a microwave plasma-assisted chemical vapor deposition system using an $Ar/H_2/CH_4/N_2$ gas mixture under controlled conditions [10]. The cold diamond-coated cathodes produced the 200 A electron beams required for switching, using a 100 kV, ~ 100 ns high-voltage pulse, with good shot-to-shot reproducibility, and with no evident sign of degradation from use.

The injection of the electron beam resulted in a change in the resonant frequency of the switch cavities, shifting them out of resonance, and, correspondingly, causing a change in the phase of the signal reflected back towards the conical taper. As a result, the TE_{01}-mode waves reflected from the conical taper and the switch cavity began to add in phase and the $TE_{02} \rightarrow TE_{01}$ conversion coefficient abruptly increased. This caused the microwave energy stored in the compressor in the TE_{02} mode to be emitted through the input taper in the TE_{01} mode. For these experiments, a conical taper with a calculated $TE_{02} \rightarrow TE_{01}$ conversion coefficient equal to 100% was used. As a result, the output pulse duration was determined

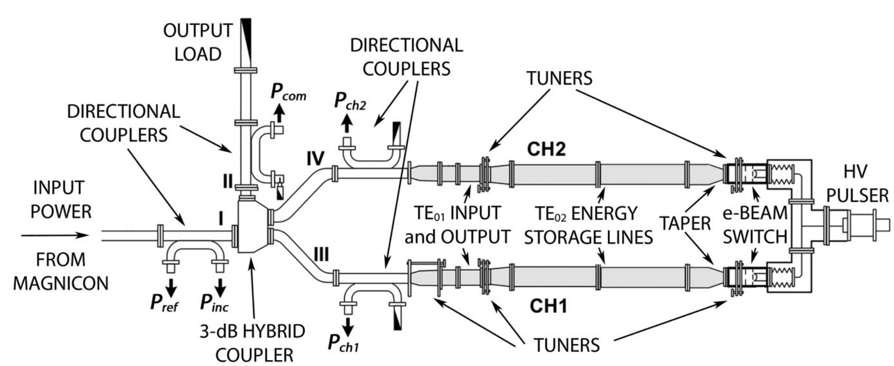

FIG. 3. Schematic diagram of the experimental setup for tests of the two-channel microwave compressor with switches employing electron beam triggering.

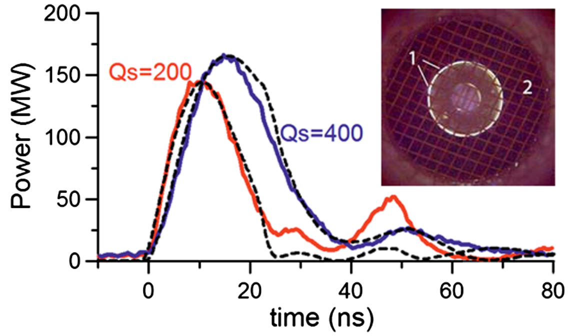

FIG. 4 (color online). Oscilloscope traces of the compressed pulses at 9 MW incident power for $Q_S = 200$ and $Q_S = 400$. The dashed lines are the calculated traces corresponding to these two cases. The inset in the upper right is a photograph of emission from a diamond-coated molybdenum cathode into a wire mesh anode using a 100 kV, 100 ns high-voltage pulse: 1: cathode edge (behind wire mesh); 2: wire mesh.

principally by the round-trip group velocity time of the TE_{02} mode through the energy storage cavities, namely, ~25 ns.

Typical oscilloscope traces of the output of the pulse compressor are shown in Fig. 4 at an incident power of ~9 MW for two different values of the switch cavity Q. For $Q_S = 400$, the switch cavities were 38 mm long and operated in the TE_{012} mode, while for $Q_S = 200$, the switch cavities were 19 mm long and operated in the TE_{011} mode. In the first case, the compressed pulse has a peak power of 165 MW, a duration of 19.8 ns FWHM, a 10%–90% rise time of 9.2 ns, and a power gain of 18.3:1. In the second case, the use of lower Q switch cavities has reduced the duration of the compressed pulse to 15.1 ns FWHM with a 6.3 ns rise time. However, this change also reduced the power gain to 16:1, indicating that the lower Q switch cavities require higher electron-beam currents for efficient switching. The total compression efficiency, defined as the ratio of the energy in the compressed pulse to the energy in the incident pulse, was as high as 50%, and in both cases, the shape of the compressed pulses was stable and reproducible.

In order to understand the experimental results, we carried out a modeling of the operation of a single compressor channel consisting of a storage cavity and a switch cavity [as in Fig. 1(a)] using the FDTD method for both $Q_S = 200$ and $Q_S = 400$. The electron-beam current density calculated by the particle-in-cell code was used in the FDTD algorithm for the calculation of the compressed pulse parameters. The value of the beam current in the simulations was varied in order to produce the best match to the measured output waveforms. For $Q_S = 200$, a beam current $I_c = 210$ A gave the best fit to the experimental data, while for $Q_S = 400$, the best fit was obtained for $I_c = 300$ A. The dashed lines in Fig. 4 are the calculated pulse traces corresponding to these two cases. Why it is that these different current values are needed in the simulations to obtain good agreement with the experiment will be the subject of further investigation.

The experiments showed that the parameters of the compressed pulse are highly sensitive to the switch parameters, including the distance between the cathode and anode and the Q factor of the switch cavity. These parameters were varied during the experiments to optimize the operation of the compressor. For example, as the distance between the anode and cathode was decreased from 3.8 mm to 1.6 mm, the stability of the operation of both channels increased and higher power gain was achieved. This corresponded to the results of the calculations that showed that at an optimal anode-to-cathode distance equal to 2 mm, the maximum number of electrons emitted by the cathode could be injected into the switch cavity. It can be noted that the secondary peak at ~50 ns in both waveforms appears to be the result of a reflection from the output load at high-peak powers due to rf breakdown in the load, and is not a result of energy remaining in the pulse compressor.

In conclusion, a two-channel active pulse compressor with switches based on a new concept of electron-beam triggering to effect mode conversion was built and tested at high-power levels at a frequency of 11.43 GHz. In the experimental tests, the compressor produced 165 MW in a ~20 ns FWHM pulse with a ~9 ns rise time at ~18:1 power gain and ~140 MW at ~16:1 power gain in a ~15 ns FWHM pulse with a ~6 ns rise time. In these tests, molybdenum blade cathodes with thin diamond coatings demonstrated good reproducible emission uniformity with a 100 kV, 100 ns high voltage pulse. This compressor configuration does not have the limitations of earlier types of active pulse compressors and can operate at significantly higher powers without breakdown. Also, it can be used to obtain rectangular output pulses. This suggests that a prototype active pulse compressor for a future TeV electron-positron collider could be created by combining this type of switch with the longer resonant delay lines, as in the SLAC SLED-II pulse compression system [11].

This work was supported by the U.S. Department of Energy, Office of High Energy Physics, Grant No. DE-FG02-08ER 85206 and Interagency Agreement No. DE-AI02-01ER41170, and by the Russian Foundation for Basic Research, Grants No. 10-08-00260, No. 12-08-00990, and No. 12-08-31271.

[1] S. G. Tantawi, C. D. Nantista, V. A. Dolgashev, C. Pearson, J. Nelson, K. Jobe, J. Chan, K. Fant, J. Frisch, and D. Atkinson, Phys. Rev. ST Accel. Beams **8**, 042002 (2005).

[2] A. L. Vikharev, A. M. Gorbachev, O. A. Ivanov, V. A. Isaev, S. V. Kuzikov, M. A. Lobaev, J. L. Hirshfield, S. H. Gold, and A. K. Kinkead, Phys. Rev. ST Accel. Beams **12**, 062003 (2009).

[3] O. A. Ivanov, V. A. Isaev, M. A. Lobaev, A. L. Vikharev, and J. L. Hirshfield, Appl. Phys. Lett. **97**, 031501 (2010).

[4] O. A. Ivanov, V. A. Isaev, M. A. Lobaev, A. L. Vikharev, and J. L. Hirshfield, Phys. Rev. ST Accel. Beams **14**, 061301 (2011).
[5] S. H. Gold, O. A. Nezhevenko, V. P. Yakovlev *et al.*, in *High Energy Density Microwaves*, edited by R. M. Phillips, AIP Conf. Proc. No. 474 (AIP, New York, 1999), p. 179.
[6] O. A. Nezhevenko, V. P. Yakovlev, S. H. Gold *et al.*, *Proceedings of the 2005 Particle Accelerator Conference, Knoxville, TN* (IEEE, Piscataway, NJ, 2005), p. 1979.
[7] A. B. Pippard, *The Physics of Vibration* (Cambridge University Press, New York, 1989).
[8] A. Taflove, *Advances in Computational Electrodynamics. The Finite-Difference Time-Domain Method* (Artech, London, 1998).
[9] V. P. Tarakanov, *User's Manual for Code KARAT* (Berkeley Research Associates, Inc., Springfield, VA, 1992), p. 127.
[10] O. Ivanov, V. Isaev, D. Radishev, M. Lobaev, A. Vikharev, V. Chernov, A. Kozlov, and J. Hirshfield, IEEE Trans. Plasma Sci. **39**, 2794 (2011).
[11] A. L. Vikharev, O. A. Ivanov, A. M. Gorbachev, M. A. Lobaev, V. A. Isaev, S. G. Tantawi, J. R. Lewandowski, and J. L. Hirshfield, Phys. Rev. ST Accel. Beams **14**, 121302 (2011).