Experimental Evidence of Relativistic Doppler Frequency Conversion on a Relativistic Electron Beam Front

J. M. BUZZI, H. J. DOUCET, B. ETLICHER, J. C. FAURE, P. HALDENWANG, A. HUETZ, H. LAMAIN, C. ROUILLÉ, J. C. CABÉ, J. DELVAUX, J. C. JOUYS, C. PEUGNET, AND M. ROCHE

***Abstract*—Frequency conversion of microwaves from X to Ka band is observed upon their reflection from the front of an intense relativistic electron beam in two different machines. The incident X-band microwaves derive from emission of the beam itself. The results are in qualitative agreement with the expected beam front velocity monitored from variable gas pressure, and a pulse compression, associated with beam front reflection, is observed.**

I. Introduction

THE relativistic Doppler frequency shift of intense microwave pulses reflected from a relativistic electron beam appears to be an efficient process for the generation of submillimeter waves at high energy levels [1]. If the reflection is produced by the beam front, power amplification and pulse compression is expected to occur [2].

The ability of an electron beam front to be used as a relativistic mirror for intense microwave pulses has been studied in two different situations: 1) in the case of a high-impedance relativistic electron beam (REB) device (43 Ω), and 2) with a low-impedance REB machine (2 Ω). In both cases the REB is used as a powerful microwave generator and as the relativistic mirror.

II. Experiment with a High-Impedance Device

The first series of experiments was performed on a synchrotron maser [3] using a 43-Ω Blumlein (Physics International, Pulserad 110 A). The electron energy is variable from 0.5 to 1.5 MV, but only values between 0.5 to 0.8 MV were used in this experiment.

The source of X-band microwaves is based on the synchrotron maser mechanism, using a device very similar to that described in [3]. The 4-cm-diam graphite cathode is located 1 cm from a 50-μm thin foil of titanium. The beam is transported by a uniform magnetic field variable from 0 to 5 kG inside a cylindrical copper waveguide 5 cm in diameter. An iron core is used as in [3] to transfer part of the parallel energy of the electrons to perpendicular energy. The observed microwave pulse consists of a few spikes in X band with power on the order of 1–10 MW, and pulse duration 4–10 ns. The first few spikes are emitted during the current rise time (5–10 ns) while the total current emission duration is of the order of 20 ns. The microwave pulse is emitted through a Teflon window and transmitted to free space via a large conical horn. It is then reflected back from a metallic sheet located at a variable distance from the source (0–2 m). Part of the reflected signal comes back into the synchrotron maser waveguide when the main beam density enters the machine. A second reflection, associated with a relativistic Doppler frequency upgrading, is then expected to occur.

The reflection mechanism on the electron beam is understood as an increase of the cutoff frequency of the waveguide as a function of time. The emission starts with a frequency ω slightly higher than the cutoff frequency of the empty waveguide ω_∞ [4]. If the frequency in the beam frame equals ω_∞, then the frequency in the laboratory frame is

$$\omega = \gamma_\| \omega_\infty \quad \text{with} \quad \gamma_\| = (1 - \beta_\|^2)^{-1/2} \quad \text{and} \quad \beta_\| = v_\|/c$$

where $v_\|$ is the parallel electron velocity. When the beam density increases, the cutoff frequency in the presence of the beam ω_∞' reaches the initial emission frequency ω. Therefore, when the microwave pulse is coming back in the waveguide, it can be reflected by the beam if a proper delay is given between the emission and the external reflection, by adjusting the position of the external mirror.

The frequency ω_1 of the reflected pulse is shifted by the relativistic Doppler effect [5]

$$\omega_1 \approx \omega(1 + \beta_\|)^2 \gamma_\|^2.$$

Frequency conversion from X to Ka band has been observed in qualitative agreement with the expected beam front velocity. No direct measurement of $\beta_\|$ was made on this experiment, but its expected value is consistent with the value involved in pulse compression: The duration τ_1 of the reflected pulse is reduced with respect to the duration τ of a short emission pulse

$$\tau_1 = \tau \frac{\omega}{\omega_1}.$$

Moreover, the pulse compression has been observed from correlation between the pulse shapes of the X-band signals and of the Ka-band signals. The emission in the X band appears as series of a few spikes. Very similar spike succession is observed in the Ka band but with a shorter

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J. M. Buzzi, H. J. Doucet, B. Etlicher, J. C. Faure, P. Haldenwang, A. Huetz, H. Lamain, and C. Rouillé are with the Laboratoire de Physique des Milieux Ionises, Group de Recherches du CNRS, École Polytechnique, 91128 Palaiseau, France.

J. C. Cabé, J. Delvaux, J. C. Jouys, C. Peugnet, and M. Roche are with the Commissariat a l'Energie Atomique, Centre d'Études de Valduc, 21120 IS-sur-Tille, France.

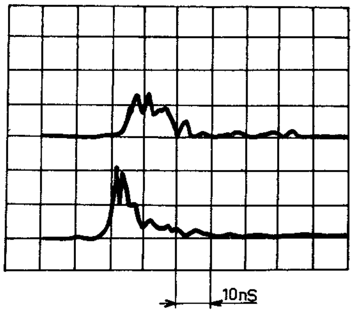

Fig. 1. Example of pulse compression. Upper trace: 3-cm signal (emission). Lower trace: 8-mm signal (reflected signal).

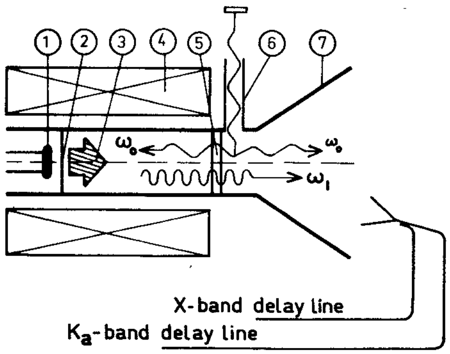

Fig. 2. Sketch of the experiment. (1) Graphite cathode. (2) Titanium thin foil. (3) Electron beam. (4) External magnetic coil. (5) Teflon window. (6) 3-dB rectangular-to-circular waveguide. (7) Horn.

time delay between spikes. The ratio between these time delays in the *X* band and in the *Ka* band is approximatively equal to the frequency ratio as expected. This ratio is also found to be the same for the corresponding spike widths in the two bands. An example of this pulse compression is shown in Fig. 1, where the upper trace is the *X*-band signal and the lower trace is the *Ka*-band signal.

III. Experiment with a Low-Impedance Device

The second set of experiments was performed with a 2-Ω line generator with electron energy of 400 kV. The scheme of the experiment is presented in Fig. 2.

The electron beam is injected into a 5-cm-diam pipe in a gas at low pressure (air, 5 μm–1 torr). In this configuration, a very intense, narrow-band emission is observed around 10 GHz. This strong emission, as in the previous experiment, is used as a microwave source and is then reflected back in the device. One fraction of the emitted 10-GHz signal is transmitted to free space through a conical horn. This signal is detected by an antenna and measured using a dispersive delay line in the *X* band. The second fraction of the emission is transmitted to a rectangular waveguide via a circular-to-rectangular 3-dB coupler. While observing the primary emission, the rectangular waveguide is connected to a matched load and introduces no reflection in the circular waveguide. While observing the reflection on the electron beam, the rectangular waveguide is varied in length and is terminated by a short circuit. When a proper length is used (approximatively 2 m), the observed spectrum on the delay line contains new frequencies shifted from the emission frequencies by a factor of about 1.1. This frequency shift is compatible with the expected beam front velocity observed in other experiments [6] in gases for pressure below 0.1 torr where ion acceleration occurs. Therefore, this Doppler frequency shift appears as a new diagnostic tool for beam propagation studies among the classical diagnostics used in this experiment: B_θ probes, X-ray fluorescence, and calorimetry.

IV. Conclusions

These preliminary results indicate that the reflection of microwaves by relativistic electron beams is an interesting possibility for frequency conversion and could be used for generating high-power pulses of submillimeter waves.

In our experiments, the use of the same REB as a microwave source and as a relativistic mirror is a limiting factor in the observation of large frequency change because the conditions for emission are obviously not optimum for the reflection.

The use of an external source provides better conditions, and the same frequency conversion from *X* to *Ka* band has been observed at NRL [7]. The present experiment also demonstrates the pulse compression associated with beam front phenomena.

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References

[1] V. L. Granatstein, M. Herndon, R. K. Parker, and S. P. Schlesinger, "Strong submillimeter radiation from intense relativistic electron beams," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1000–1005, Dec. 1974.

[2] H. J. Doucet, "Advisory group meeting on experimental aspects of laser-electron beam produced thermonuclear plasmas," Trieste, Aug. 25–29, 1975.

[3] V. L. Granatstein, P. Sprangle, R. K. Parker, and M. Herndon, "An electron synchrotron maser based on an intense relativistic electron beam," *J. Appl. Phys.*, vol. 46, pp. 2021–2028, May 1975.

[4] E. Ott and W. M. Manheimer, "Theory of microwave emission by velocity-space instabilities of an intense relativistic electron beam," *IEEE Trans. Plasma Sci.*, vol PS-3, pp. 1–5, Mar. 1975.

[5] K. Landecker, "Possibility of frequency multiplication and wave amplification by the relativistic effect," *Phys. Rev.*, vol. 86, pp. 852–856, 1952.

[6] C. L. Olson, "Theory of ion acceleration by drifting intense relativistic electron beams. 1. Theory, II. Comparison with experiments," *Phys. Fluids*, vol. 18, pp. 585–597, 598–606, May 1975.

[7] V. L. Granatstein, P. Sprangle, R. K. Parker, J. Pasour, M. Herndon, and S. P. Schlesinger, "Realization of a relativistic mirror: Electromagnetic backscattering from the front of a magnetized electron beam," *Phys. Rev. A*, vol. 14, pp. 1194–1201, 1976.