Time-Gating Study on Electromagnetic Pulses Generated in a Dielectric Power Extractor

Thomas Wong#1, Feng Gao#2, Wei Gai*3

Department of Electrical and Computer Engineering, Illinois Institute of Technology
3301 South Dearborn St, Chicago, Illinois 60616, USA
[1]twong@ece.iit.edu, [2]gaofeng@iit.edu
* *Argonne National Laboratory*
9700 S Cass Ave, Argonne, Illinois 60439, USA
[3]wg@hep.anl.gov

***Abstract*—Analysis on temporal evolution of the mean frequency is a useful tool for studying bandwidth-limited pulses. Based on a dielectric-loaded power extractor experiment, we present the temporal evolution of the mean frequency of a microwave pulse measured with a field probe. Time-gating study on the detected voltage signal revealed a nominal carrier frequency of 7.8GHz with occasional dips. Further development of the signal analysis scheme is currently underway to facilitate more elaborate pulse parameters identification and pulse stabilization.**

Key words: frequency evolution, time gating, time window, bandwidth-limited pulse, power extraction.

I. Introduction to Dielectric Power Extractor

Power extraction is an accelerator-based technique for generation of high power radio frequency (RF) pulses. The essential interaction involves directing a pre-accelerated high current, low energy charged-particle beam (e.g. an electron beam) to pass through a decelerating structure, where the beam excites electromagnetic fields resulting from the polarization effect of the charge bunches in the beam. The energy of the induced electromagnetic fields is subsequently collected by a carefully designed RF output coupler for use in accelerating another charged-particle beam (usually a low current, high energy beam) or for other high power applications [1]. This power extraction process is a spin-off technology from the well investigated two-beam-accelerator scheme.

One of the various power extraction techniques is based on a dielectric-loaded waveguide, hence referred to as a dielectric power extractor. Its construction is shown in Fig. 1, consisting of mainly two sections: a decelerating dielectric-loaded waveguide on the left for a drive beam to generate high power RF pulses, and an RF output coupler on the right to transfer the power to a standard waveguide. By adjusting the dimensions and the dielectric constant of the dielectric-loaded waveguide, the phase velocity of the interaction mode is set to be c, the speed of light in free space, to synchronize with a nearly ultra-relativistic particle beam.

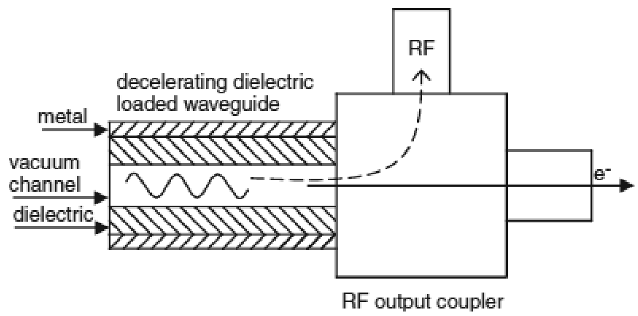

Fig. 1 Dielectric-loaded power extractor consisting of a dielectric-loaded decelerator and an RF output coupler [2].

If the drive beam only contains a single particle bunch, the generated RF pulse in the decelerating waveguide would have a pulse length of

$$\tau_s = L(1-\beta_g)/v_g \qquad (1)$$

where L is the length of the decelerating waveguide, and β_g is the group velocity of the RF mode v_g divided by the speed of light in free space c (i.e. $\beta_g = v_g/c$). The RF power generated by a single bunch can be expressed as

$$P_s(t) = q^2 \frac{k_z \beta_g}{4}\left[\frac{r}{Q}\right]\left(\frac{c}{1-\beta_g}\right)^2 \Phi^2 e^{-2\alpha_0 v_g t}\,(0 \le t \le \tau_s) \qquad (2)$$

where q is the charge per bunch, k_z is the longitudinal wave number of this mode, $\beta_g = v_g/c$ is the relativistic group velocity, $[r/Q]$ is a single quantity referred to as "r over Q", the coupling impedance per unit length which quantifies beam-structure interaction , defined as [4]

$$\left[\frac{r}{Q}\right] = \frac{E_a^2}{\omega U} \quad (3)$$

where E_a is the on-axis longitudinal electrical field, ω is the angular frequency, and U is the stored energy per unit length. Also in equation (2), $\alpha_0 = \omega / 2Qv_g$ is the attenuation per unit length, where Q is the quality factor; and Φ, the bunch form factor, is the Fourier transform of the charge distribution function at the mode frequency. It can be shown that for a Gaussian bunch with an r.m.s. length σ_z, that the bunch form factor is

$$\Phi = \exp[-(k_z \sigma_z)^2 / 2] \quad (4)$$

If the drive beam is a train of M bunches separated by T_b, and $M \geq ceiling(f_b \tau_s)$, the generated RF power can be expressed as [2]

$$P_t = q^2 \frac{k_z}{4\beta_g}\left[\frac{r}{Q}\right]\left(\frac{L}{T_b}\right)^2 \Phi^2 \quad (5)$$

and the RF pulse length is determined by the length of the bunch train [2].

A power extractor based on a dielectric-loaded circular waveguide operating with center frequency at 7.8GHz [2] has been designed and tested at the Argonne Wakefield Accelerator (AWA) facility. Measured results show that within a 270MHz bandwidth, the RF output coupler has an insertion loss better than -1dB, and at the center frequency of 7.8GHz, the insertion loss is -0.41dB. Eventually the power extractor will be used with electron bunch trains to generate 10~50ns RF pulses, thus the 270MHz bandwidth is not an issue [3].

However, in single bunch tests, the RF pulse generated in the decelerating waveguide is only 2ns in length, making it significantly constrained by the bandwidth of the output coupler. One of the important parameters of an RF pulse is its instantaneous frequency. In this paper, we report on the first finding of the temporal characteristics of the RF pulses delivered by the dielectric power extractor. By time-gating the recorded voltage signal detected by a field probe mounted on the output waveguide, the average frequency of the RF field over a predetermined time window can be estimated. Time stepping of the window over the pulse duration provides the temporal evolution profile of the RF pulse delivered by the output coupler of the dielectric power extractor. While the temporal characteristics of the detected signal is the cumulative effect of several constituencies in the pulse generation, wave coupling and detection process, individual contributions can be identified by performing parametric studies on the system.

II. Temporal Evolution of the Mean Frequency of the Output Pulse

After the generated RF pulse is extracted to an output waveguide, a small portion of the power is coupled to a coaxial cable via a -64.6dB bidirectional coupler. The cable is connected to a 15GHz oscilloscope, Tektronix TDS6154C, for signal monitor and processing. In addition to cable loss, some attenuators were also used to reduce the power level for protection of the oscilloscope. The drive beam only contains a 66nC 15MeV single Gaussian electron bunch, where the r.m.s. longitudinal bunch length is 2mm.

The detected voltage signal is shown in Fig. 2. It can be seen that the pulse envelope is not rectangular, which can be attributed to a number of factors, among them the limited bandwidth of the output coupler playing a major role. This needs to be anticipated when a 4ns (main portion) pulse is passed through a transmission structure with a 270MHz bandwidth. The "head" (0 < t < 2.3ns) and the "tail" (t > 10.3ns) of the oscilloscope trace is rather noisy and they are discarded, leaving the middle part (2.3ns < t < 10.3ns), which is transferred to Fig. 3(a) with a shifted time axis (0 < t < 8ns) for further analysis.

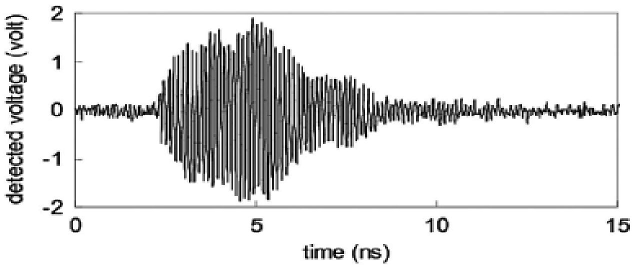

Fig. 2 Voltage signal excited by a 66nC single bunch measured with a 15GHz oscilloscope [2].

As mentioned above, Fig. 3(a) contains the central part of the oscilloscope trace. To analyze the temporal evolution of the mean frequency of the signal, we used a time window moving in time steps to monitor the mean frequency of the signal over the duration of the window. The mean frequency is calculated by first recording the average temporal separation between two adjacent zero-crossings within the window, followed by taking the reciprocal of this separation and dividing it by two. For example, if there are N ($N > 1$) zero-crossings within a time window centered at t, and the location of a zero-crossing is labeled as t_n $(2 \leq n \leq N)$, the mean frequency is then calculated as

$$f_{mean} = \frac{1}{2}\left[\frac{N-1}{\sum_{n=1}^{N-1}(t_{n+1}-t_n)}\right] \qquad (6)$$

The window width employed for obtaining the data is 0.5ns, which is able to accommodate approximately 6 cycles for 7.8GHz. The time step is 0.05ns for adequate resolution. The temporal evolution of the signal is shown in Fig. 3(b), where the center of the time window is the variable, while the mean frequency is the ordinate. It can be seen that the mean frequency is largely kept at 7.8GHz with occasional dips. The deeper dents at t = 0.4ns, 4.5ns and 6.1ns may be attributed to variations in the shape of the envelope.

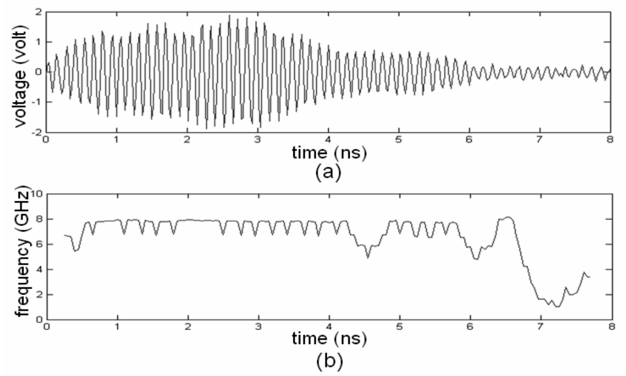

Fig. 3 (a). The central part of the signal shown in Fig 2 (2.3-10.3ns) is time shifted to 0-8ns for analysis; (b). the temporal evolution of mean frequency of the signal shown in (a).

III. SUMMARY

Dielectric power extractors offer the advantages of ease in device fabrication and reduced parasitic wakefield effects in high-power RF pulse generation. Temporal characteristics of a pulse centered at 7.8GHz generated in a dielectric power extractor are investigated by time-gating analysis. Measurement results reveal a nominal carrier frequency of 7.8GHz with occasional dips over the main portion of the pulse. This framework of signal analysis is currently being further developed for more elaborate signal analysis and pulse coherence enhancement.

ACKNOWLEDGMENT

This work is supported by the US Department of Energy under contract No. DE-AC02-06CH11357.

REFERENCES

[1] H. Braun, R. Corsini, T. D'Amico, J. Delahaye, G. Guignard, C. D. Johnson, A. Millich, P. Pearce, A. J. Riche, L. Rinolfi, R. Ruth, D. Schulte, L. Thorndahl, M. Valentini, I. H. Wilson and W. Wuensch, The CLIC RF power source: a novel scheme of two-beam acceleration for electron-positron linear colliders, CLIC-Note-364, CERN-99-06, 1998.

[2] F. Gao, M. Conde, W. Gai, C. Jing, R. Konecny, W. Liu, J. Power, T. Wong and Z. Yusof, "Design and Testing of a 7.8 GHz Power Extractor Using a Cylindrical Dielectric-loaded Waveguide", Phys. Rev. ST Accel. Beams, vol. 11, 041301, 2008.

[3] F. Gao, M. E. Conde, W. Gai, R. Konecny, W. Liu, J. G. Power, Z. Yusof, C. Jing and T.Wong, "7.8GHz High Power Generation And Extraction With A Dielectric-loaded Waveguide", AIP conference proceedings, no. 1086, pp. 353-358.

[4] T. Wrangler, *RF Linear Accelerator* (John Wiley & Sons, Inc., 1998), Section 3.12.

$$f_{mean} = \frac{1}{2}\left[\frac{N-1}{\sum_{n=1}^{N-1}(t_{n+1}-t_n)}\right] \quad (6)$$

The window width employed for obtaining the data is 0.5ns, which is able to accommodate approximately 6 cycles for 7.8GHz. The time step is 0.05ns for adequate resolution. The temporal evolution of the signal is shown in Fig. 3(b), where the center of the time window is the variable, while the mean frequency is the ordinate. It can be seen that the mean frequency is largely kept at 7.8GHz with occasional dips. The deeper dents at t = 0.4ns, 4.5ns and 6.1ns may be attributed to variations in the shape of the envelope.

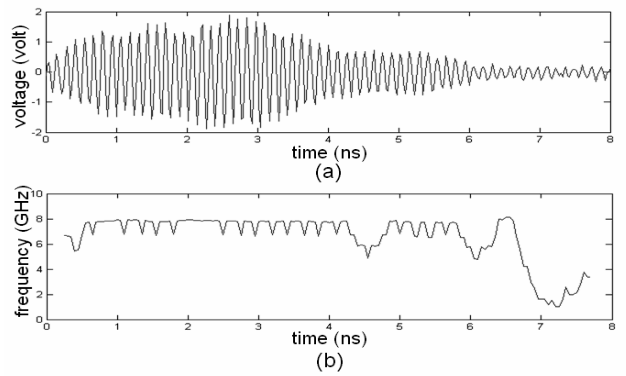

Fig. 3 (a). The central part of the signal shown in Fig 2 (2.3-10.3ns) is time shifted to 0-8ns for analysis; (b). the temporal evolution of mean frequency of the signal shown in (a).

III. SUMMARY

Dielectric power extractors offer the advantages of ease in device fabrication and reduced parasitic wakefield effects in high-power RF pulse generation. Temporal characteristics of a pulse centered at 7.8GHz generated in a dielectric power extractor are investigated by time-gating analysis. Measurement results reveal a nominal carrier frequency of 7.8GHz with occasional dips over the main portion of the pulse. This framework of signal analysis is currently being further developed for more elaborate signal analysis and pulse coherence enhancement.

ACKNOWLEDGMENT

This work is supported by the US Department of Energy under contract No. DE-AC02-06CH11357.

REFERENCES

[1] H. Braun, R. Corsini, T. D'Amico, J. Delahaye, G. Guignard, C. D. Johnson, A. Millich, P. Pearce, A. J. Riche, L. Rinolfi, R. Ruth, D. Schulte, L. Thorndahl, M. Valentini, I. H. Wilson and W. Wuensch, The CLIC RF power source: a novel scheme of two-beam acceleration for electron-positron linear colliders, CLIC-Note-364, CERN-99-06, 1998.

[2] F. Gao, M. Conde, W. Gai, C. Jing, R. Konecny, W. Liu, J. Power, T. Wong and Z. Yusof, "Design and Testing of a 7.8 GHz Power Extractor Using a Cylindrical Dielectric-loaded Waveguide", Phys. Rev. ST Accel. Beams, vol. 11, 041301, 2008.

[3] F. Gao, M. E. Conde, W. Gai, R. Konecny, W. Liu, J. G. Power, Z. Yusof, C. Jing and T.Wong, "7.8GHz High Power Generation And Extraction With A Dielectric-loaded Waveguide", AIP conference proceedings, no. 1086, pp. 353-358.

[4] T. Wrangler, *RF Linear Accelerator* (John Wiley & Sons, Inc., 1998), Section 3.12.