

Novel scheme of beam loading compensation for a traveling wave acceleration structure with microwave pulse compression

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In order to reduce the increase in bunch energy dispersion caused by the beam loading effect, beam loading compensation in the acceleration structure is required. In this paper, a novel scheme is proposed to use microwave pulse compression to compensate for the beam loading effect in the traveling wave structure. The compression system consists of an energy storage cavity and a correction chain of six cavities working in S band. Through parameter optimization, the optimal coupling factors of the energy storage cavity and the correction cavity are obtained to generate microwave pulses with increasing amplitude. Through this scheme, the S-band traveling wave acceleration structure achieves an acceleration voltage of 50.14 MV with a power input of 16.6 MW and a beam current of 2.5 A. The relative energy dispersion is 0.77%, and the effective system power gain reaches 10.56, significantly surpassing that of conventional microwave pulse compression systems.

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I. INTRODUCTION

In a linear accelerator, the relative energy dispersion between bunches is a critical parameter for many applications. However, when the beam is initially injected, different bunches acquire different acceleration energies due to the reduction in the electric field gradient caused by the beam loading effect. To mitigate the increase in bunch energy dispersion due to the beam loading effect, it is necessary to implement compensation strategies. Especially for situations with strong beam currents, a large power capacity is required, and compensation for beam loading is difficult.

The early research on the beam loading effect is about the steady state in electron linear accelerators [1,2]. The theory of beam loading in arbitrary traveling wave accelerating structures is explored in Ref. [3], which introduces steady-state and transient field models applicable to accelerating structures with arbitrary parameters. This model can be utilized to determine an optimized input waveform, thereby significantly reducing the energy dispersion of the bunch [4,5].

Besides the low energy dispersion, high acceleration energy within a short structure length is desired,

necessitating a high gradient and high input power. Microwave pulse compression is an effective technique to enhance the output power of the source, which compresses a long, low-power pulse into a short, high-power pulse.

SLAC began the development with the pulse compressor called SLAC Energy Doubler (SLED) [6], in which the compressed pulse exhibits exponential decay. To generate a flat-top waveform, a transmission line serves as the energy storage element in the SLED-II pulse compressor [7]. A super-compact SLED was proposed that adopted a spherical cavity with dual mode as the energy storage cavity [8]. The cylindrical cavity and bowl-shaped cavity have also been developed and tested [9,10]. Besides SLED-II, a compact cavity chain with several correction cavities is employed to modulate the pulse to output the flat-top waveform [11–13]. The flat-top compressed pulse can undergo further compression to enhance power gain, known as two-stage compression [14,15].

The pulse compressor serves as a power enhancement stage preceding the acceleration structure, providing an input pulse for beam acceleration. To account for the beam loading effect, the pulse compressor needs to generate a compensation waveform. The compensation requires, based on calculation, that the input pulse gradually increases during the filling time of the structure [3–5]. The phase-to-amplitude modulation has been employed to shape the input pulse waveform to generate the required compensation pulse via the pulse compressor [12].

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However, a pulse compression system with a correction cavity chain is capable of directly producing a rising compensation pulse without additional modulation techniques. Thus, the beam loading compensation can be achieved solely through a pulse compression system with a correction cavity chain. Besides, a higher equivalent power gain is achieved through this compensation pulse compression.

This article proposes a novel scheme that integrates microwave pulse compression with beam loading compensation. The compressed pulse from the microwave pulse compression system is directly utilized for beam loading compensation, eliminating the need for additional amplitude modulation methods. Moreover, this scheme enhances the equivalent power gain of microwave pulse compression, thereby improving electron beam acceleration. The following sections present the theoretical model and corresponding calculation results of this compensation method.

II. PRINCIPLE OF BEAM LOADING COMPENSATION

A. Beam loading effect

The beam loading causes the field in an accelerator cavity to decrease after each bunch passes through it. According to electromagnetic field theory, the moving charged particles of the beam will excite an electromagnetic field in the cavity. This induced field depends solely on the beam and the cavity, independent of the original field in the cavity. When the beam is accelerated by the original field in the cavity, the superposition of the induced and original fields leads to a net field amplitude reduction, as shown in Fig. 1.

The decrease in the field amplitude indicates that a portion of the stored electromagnetic energy in the cavity is transferred to the beam during acceleration. When the power supplied from external sources is insufficient to compensate for the stored energy loss, the acceleration voltage obtained by the beam will decrease with the injection of the beam current, resulting in the acceleration energy variations between the leading and trailing bunches.

The steady-state gradient distribution for both the original field and the beam-loaded field is obtained

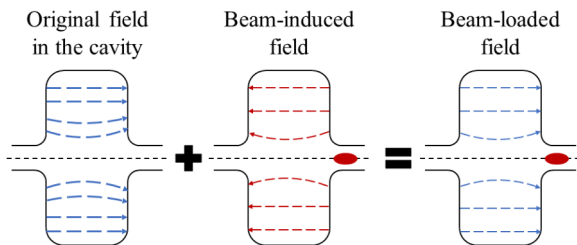


FIG. 1. The field in the cavity is reduced by the beam loading effect.

through generalized analytical solutions [3].

$$P = w \cdot v_g, \quad (1)$$

$$w = \frac{E^2}{\omega \rho}, \quad (2)$$

$$\frac{dP}{dz} = -\frac{w\omega}{Q} - EI, \quad (3)$$

where P is the power flow in the structure, w is the stored energy per length, v_g is the group velocity, E is the accelerating gradient, ω is the circular frequency, ρ is the normalized shunt impedance, Q is the quality factor, and I is the beam current.

By combining the above equations, the equation of the gradient distribution can be obtained:

$$\frac{dE}{dz} = -\alpha(z)E(z) - \beta(z), \quad (4)$$

where $\alpha(z) = \frac{1}{2} \left(\frac{1}{v_g} \frac{dv_g}{dz} - \frac{1}{\rho} \frac{d\rho}{dz} + \frac{\omega}{v_g Q} \right)$ and $\beta = I \frac{\omega \rho}{2v_g}$. The homogeneous and nonhomogeneous solutions of this nonhomogeneous differential equation represent the gradient of the steady-state electric field in the absence and presence of beam loading, respectively, as shown in Fig. 2.

B. Waveform for compensation

The transient gradient of the electric field can be analytically derived using an approach analogous to the steady-state gradient solution [3]. The distribution of the gradient and the accelerating voltage in the time domain can be calculated according to the solution of the transient gradient, as shown in Fig. 3(a).

The beam loading effect on the acceleration gradient is time-dependent. Following beam injection, the

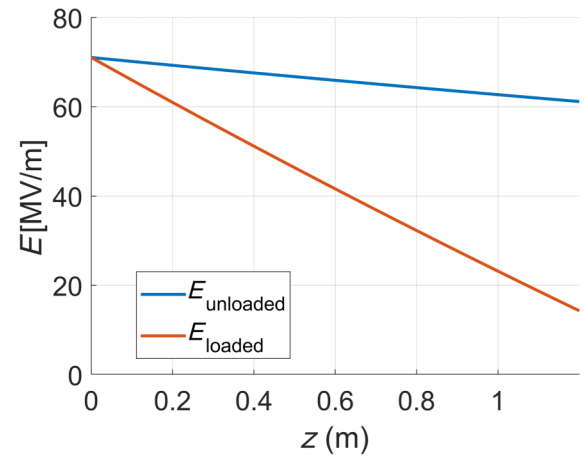


FIG. 2. Loaded and unloaded gradients calculated for the S-band linac accelerating structure. The assumed beam current is 2.5 A.

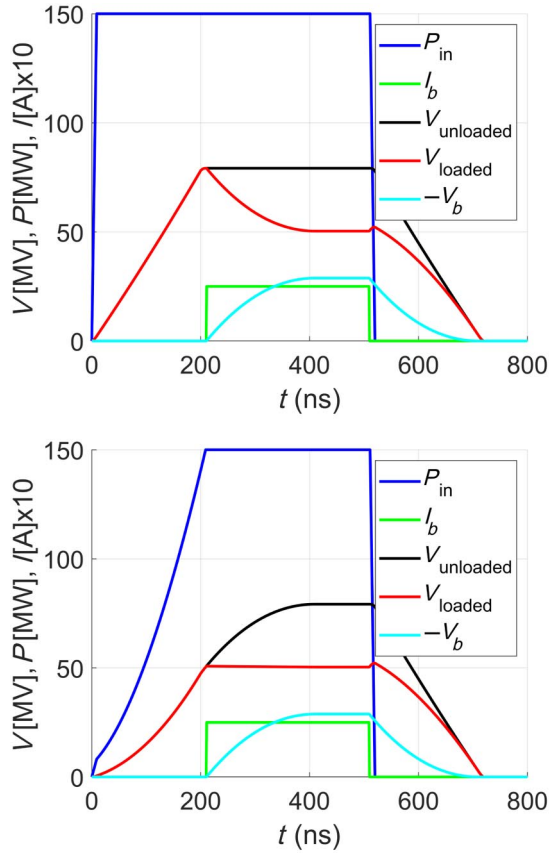


FIG. 3. The time dependence of the input rf power (blue), beam current (green), the corresponding unloaded (black), loaded (red), and beam (light blue) voltages are shown, without compensation (a) and with compensation (b), respectively.

acceleration voltage drops rapidly before stabilizing at a steady-state value. Consequently, the leading electron bunches see higher fields, while the trailing ones see lower accelerating voltage, resulting in energy variation across the bunch train.

To mitigate bunch energy dispersion caused by the beam loading effect, a straightforward approach is to decrease the higher accelerating voltage obtained by the leading bunches to match that of the trailing ones. Therefore, the input power during the filling time of the accelerating structure should be much lower than that at steady state.

The optimal compensatory microwave input waveform from the calculation gradually increases during the filling time of the accelerating structure, effectively counteracting the initial drop in the acceleration gradient during beam injection, as shown in Fig. 3(b). A comparison shows that the acceleration voltage obtained using the compensation waveform exhibits reduced energy dispersion.

C. Compensation waveform for short pulse beam

It can also be seen in Fig. 3 that the acceleration voltage decreases approximately linearly upon initial beam injection and continues to decline gradually until reaching a

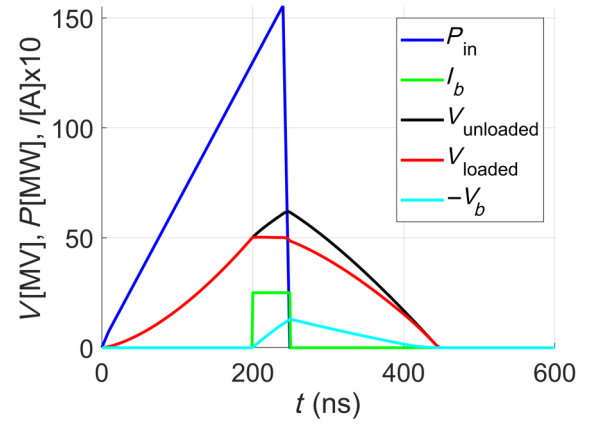


FIG. 4. The unloaded, loaded, and beam voltages with the rising input power pulse for compensation of beam loading.

steady-state condition. If the duration of the injected beam pulse is significantly shorter than the filling time of the structure, the beam loading has not stabilized in the end of the pulse, and the acceleration voltage exhibits an almost entirely linear decrease.

The linearly decreasing voltage is easier to compensate than an exponential shape. To compensate for the linear decrease in voltage, a rising microwave pulse can be employed as the input pulse for the accelerating structure, in contrast to the previously described pulse that initially rises and then flattens. The rising pulse for compensating the beam loading of a short pulse is illustrated in Fig. 4. This rising waveform can be directly generated by a pulse compression system.

D. Pulse compression system generates a rising pulse

In the acceleration system, the peak input power of the microwave source is inherently limited, and high-peak-power microwave sources are costly. Thus, external techniques are required to enhance peak power. A pulse compressor can compress a long input rf pulse to a short one with a higher amplitude, as shown in Fig. 5(a).

The SLED pulse compressor, as a passive pulse compressor, features a simple design but has a theoretical limit on power gain. In contrast, active pulse compression can attain significantly higher power gain but requires active components such as a plasma switch, leading to increased system complexity and reduced stability [16,17]. SLED compression system is triggered by the phase reversal and has very stable performance. Therefore, this paper discusses a SLED-type compressor that does not require input rf phase or amplitude shaping.

In the SLED pulse compression system, the energy storage cavity compresses the input microwave pulse; however, the amplitude of the compressed pulse exhibits exponential decay, governed by the energy storage and release properties of the resonant cavity [6,8]. To reshape the attenuated waveform into a flat-top waveform [11–13],

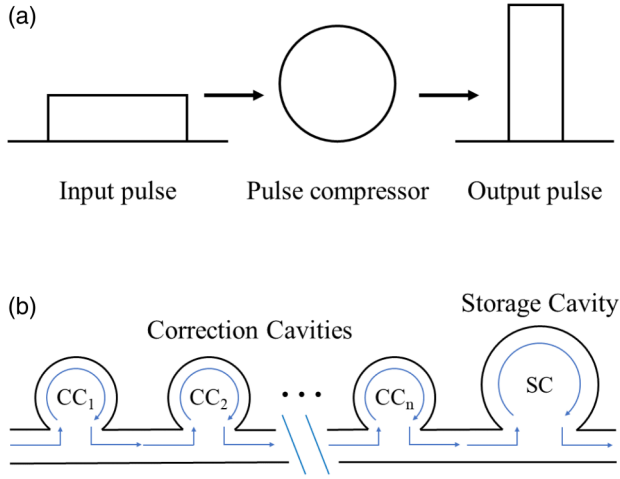


FIG. 5. (a) Scheme of pulse compression process. (b) Pulse compressor with a storage cavity and correction cavities.

a correction cavity chain is introduced before the energy storage cavity to modulate the output pulse amplitude, as shown in Fig. 5(b).

The correction cavity chain consists of several resonant cavities, which are similar to the energy storage cavity in structure but have different parameters. The correction cavity is designed to adjust the amplitude of microwave waveforms, rather than storing and releasing power like the energy storage cavity, so the quality factor and coupling factor are different. The frequency of the correction cavity is also different, and it is determined by the output pulse length.

The output waveform of the pulse compressor can be obtained through the transmission spectrum in the frequency domain, the same as the reflection spectrum of the cavity. The reflection spectrum of a cavity can be obtained from its equivalent circuit model:

$$\Gamma = \frac{(\beta - 1) - jQ_0\xi}{(\beta + 1) + jQ_0\xi}, \quad (5)$$

where β is the coupling factor of the cavity, Q_0 is the intrinsic quality factor, $\xi = f/f_0 - f_0/f$, and f_0 is the resonant frequency.

By Fourier transform, the output waveform of a given input pulse through pulse compression can be calculated in the frequency domain. The detailed parameters are discussed in Table II. As an example, the coupling factor of the correction cavity is 3.0, and the input pulse length is 1500 ns for illustration, while other parameters remain unchanged. The waveform of the input and output pulse through the pulse compressor with the correction cavity chain is shown in Fig. 6(a).

The modulated pulse amplitude can take on falling, flattop, or rising profiles, depending on the coupling factor of the correction cavity chain, as shown in Fig. 6(b). The

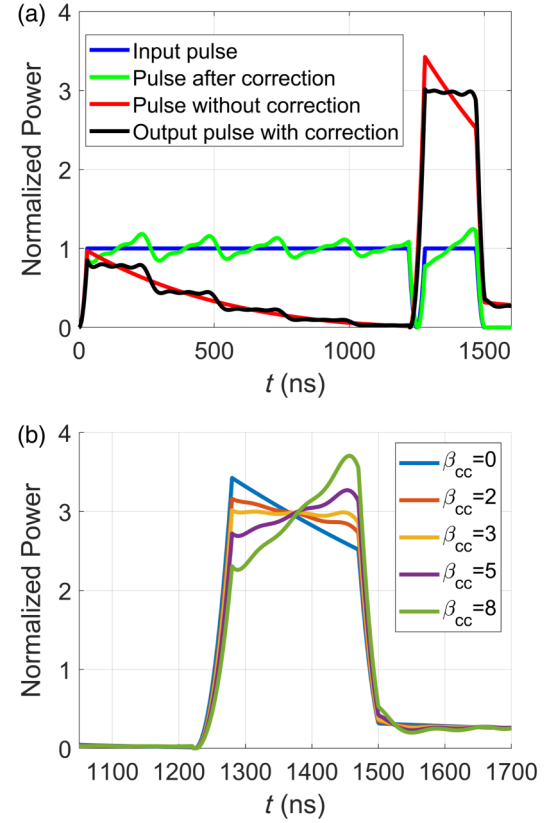


FIG. 6. (a) Input and output waveforms of pulse compression with and without correction chain at the coupling factor of the correction cavity $\beta_{cc} = 3.0$; (b) output compressed waveforms with different coupling factors of the cavities in the correction chain.

amplitude modulation of the waveform becomes increasingly pronounced as the coupling factor increases. By optimizing the parameters of the energy storage and correction cavities, a rising amplitude microwave pulse can serve as the input waveform for compensating the beam loading effect discussed previously.

III. DESIGN PARAMETERS

A. Accelerator structure design

The parameters of the constant-impedance traveling wave structure assumed for this study are listed in Table I with constant quality factor, shunt impedance, and group velocity. This structure is planned to be used for flash radiography with high-energy electrons. High-energy electron radiography (HEER) is a diagnostic method with advantages such as high penetration power and high spatial and temporal resolutions [18–22]. Short beam pulses, high beam energy, and less than 1% energy dispersion are required to achieve the desired radiography function.

The acceleration structure operates at S band and has a filling time of 200 ns. A beam length of 50 ns is assumed, resulting in a required input microwave pulse length

TABLE I. Selected parameters of the constant-impedance traveling wave accelerating structure for beam loading compensation.

Parameter	Value
Frequency	2.856 GHz
Length	1.2 m
Group velocity	2% of c
Q factor	12000
Shunt impedance	135 M Ω /m
Filling time	200 ns
Beam pulse length	50 ns
Peak input power	175 MW
Average loaded accelerating gradient with a steady-state beam current of 2.5 A	41.7 MV/m

of 250 ns. The acceleration structure operating in steady state attains a gradient of 41.7 MV/m with a peak power input of 175 MW and a beam current of 2.5 A. With a length of 1.2 m, the resulting loaded acceleration voltage is 50 MV.

Within the accelerating structure operating in steady state, the input power is distributed into two components: one portion establishes the electromagnetic field, while the other is transferred to the beam for acceleration:

$$P_{\text{in}} = P_f + P_b = P_f + I \times V_{\text{loaded}}, \quad (6)$$

where the P_{in} is the constant input rf under steady-state conditions and the V_{loaded} is the loaded acceleration voltage. The parameters listed in Table I and Eq. (6) are calculated under steady-state conditions.

Therefore, the field power is defined as the difference between the input power and the beam power, expressed as $P_f = P_{\text{in}} - I \times V_{\text{loaded}} = 175 \text{ MW} - 2.5 \text{ A} \times 50 \text{ MV} = 50 \text{ MW}$.

B. Pulse compressor design

Based on the acceleration structure parameters, an S-band pulse compression system was selected. The system consists of an energy storage cavity and a six-cavity correction chain. The frequency of the storage cavity, determined by the acceleration structure, is

TABLE II. Selected parameters of the pulse compressor and correction chain for beam loading compensation.

Parameter	Storage cavity	Correction cavity
Frequency	2.856 GHz	$2.856 \text{ GHz} \pm k \times 4 \text{ MHz}^a$
Coupling factor	10	38
Q factor	180000	58000
Mode	TE114	TE111

^a $k = \pm 1, \pm 2, \pm 3$

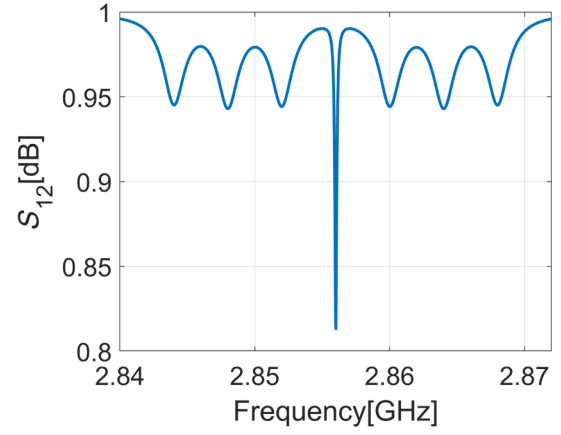


FIG. 7. The transmission spectrum of the pulse compression system with correction cavities. The number of the correction cavities in this case is six.

2.856 GHz. The frequencies of the correction cavities are determined by the output pulse length, which is set to 250 ns, resulting in a frequency interval of $\Delta f = 1/t_{\text{ac}} = 1/250 \text{ ns} = 4 \text{ MHz}$.

The TE114 and TE111 spherical cavities were chosen for the energy storage cavity and the correction cavities, respectively, as shown in Table II. The precompression input pulse length is 10 μs , yielding a pulse length compression ratio of $t_{\text{in}}/t_{\text{out}} = 10 \text{ s}/250 \text{ ns} = 40$.

Through parameter optimization, the optimal coupling factors of the energy storage cavity and the correction cavities are obtained to generate the microwave pulse with an increasing amplitude, compensating for the beam loading in the acceleration structure. The transmission spectrum of the pulse compressor from calculation with Eq. (5), incorporating correction cavities, exhibits seven discrete peaks, as shown in Fig. 7.

IV. CALCULATION RESULTS

A. Scheme calculation

Based on the parameters of the pulse compression system in Sec. III B, the compression waveform for an input microwave pulse length of 10 μs , and an input power of 16.6 MW was obtained through calculation, as shown in the Fig. 8.

A 180° phase reversal is performed at 9,750 ns of the input microwave pulse with a phase reversal time of 60 ns, triggering pulse compression of the SLED. The last 250 ns of the compression waveform serves as the input waveform for beam load compensation, which is fed into the S-band traveling wave acceleration structure from Sec. III A. A beam current of 2.5 A is injected during the last 50 ns, and the resulting acceleration voltage is calculated, as shown in the Fig. 9. The computed average acceleration voltage is 50.14 MV.

The energy dispersion of the beam after traversing the acceleration structure is computed assuming a 50-ns-long

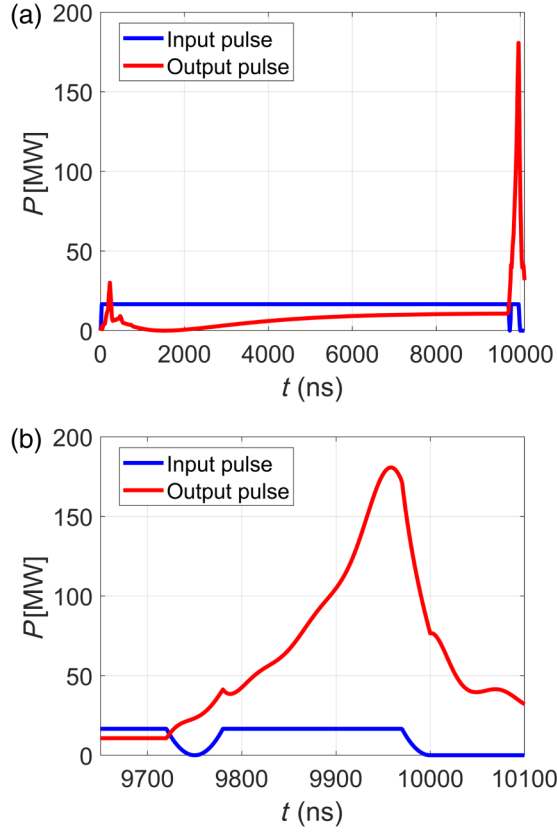


FIG. 8. (a) The input and output waveform of the pulse compression system. (b) The input and output waveform during the last 250 ns.

beam with 140 evenly spaced bunches. The acceleration voltage of each bunch is determined. The relative energy dispersion of the bunches during acceleration is defined as the ratio of the difference between the maximum and minimum acceleration voltages to the average acceleration voltage:

$$\eta = \frac{\Delta V}{\overline{V_{\text{loaded},b}}} = \frac{V_{\text{max}} - V_{\text{min}}}{\overline{V_{\text{loaded},b}}}, \quad (7)$$

where the $\overline{V_{\text{loaded},b}}$ is the average acceleration voltage of all bunches in the beam.

The computed values are plotted as a histogram in Fig. 10. The average acceleration voltage of bunches is 50.14 MV, with a maximum-minimum voltage difference of 0.39 MV, resulting in a relative energy dispersion of $0.39 \text{ MV} / 50.14 \text{ MV} = 0.77\%$.

This scheme not only compensates for the energy dispersion due to the beam loading but also enables the attainment of high field and beam energy with relatively low power input. Therefore, a system-level metric called effective system power gain is introduced to measure the energy performance of the complete system. According to Eq. (6), the effective system power gain is given by the

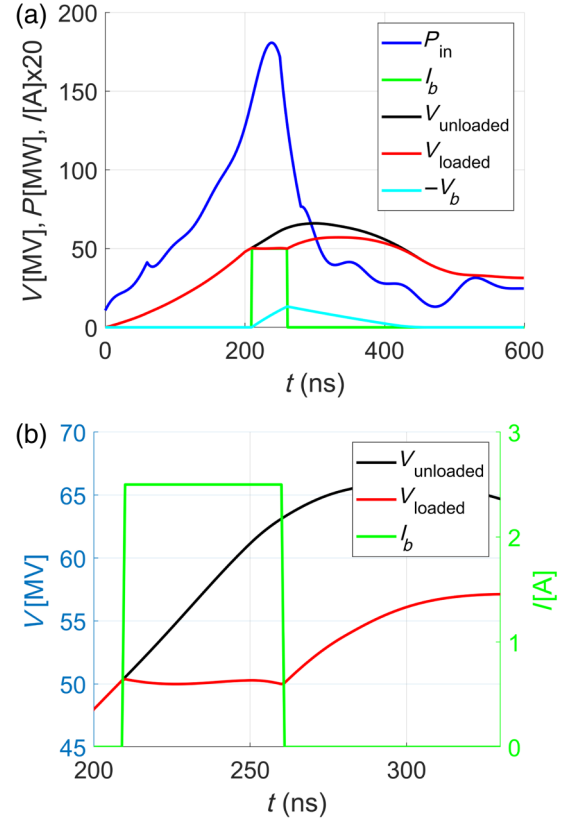


FIG. 9. (a) The unloaded, loaded, and beam voltages with the input power pulse from the pulse compressor for compensation of beam loading. (b) The unloaded and loaded voltages of beam injection.

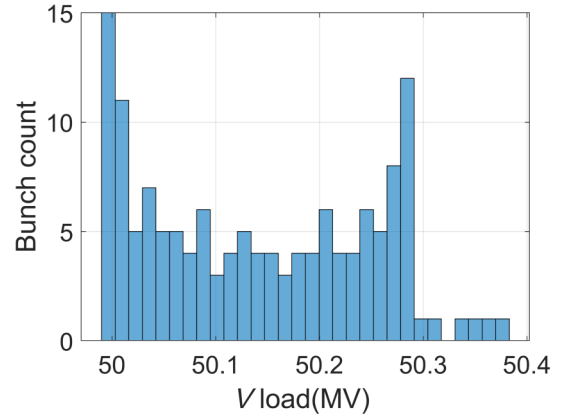


FIG. 10. Histogram of the accelerator voltages for the 140 bunches in the beam.

ratio of the total field and beam power to the actual SLED input power:

$$P_g = \frac{P_f + P_b}{P_{\text{in}}} = \frac{P_f + I \times \overline{V_{\text{loaded},b}}}{P_{\text{in}}}, \quad (8)$$

where the P_f is the steady-state field power defined in Sec. III A, and P_{in} is the input RF power of the pulse compressor under steady-state condition.

Based on the current parameters, the P_f is the 50 MW calculated in Sec. III A. Therefore, the effective system power gain can be calculated as $P_g = (P_f + I \times \overline{V_{loaded,b}}) / P_{in} = (50 \text{ MW} + 2.5 \text{ A} \times 50.14 \text{ MV}) / 16.6 \text{ MW} \approx 10.56$.

The compression gain of a conventional SLED-type system is theoretically limited to a maximum of 9 and typically ranges between 4 and 7 in practice. To meet the requirements of accelerators, amplitude modulation is typically used to reshape the compressed pulse into a flat-top pulse. Assuming the same pulse compressor is used in a conventional acceleration system, the compressed pulse is calculated using the same input pulse and storage cavity parameters as discussed in Sec. III. The quality factor of the correction cavities remains unchanged, and their coupling factor becomes 3.4 for flat-top compression. Figure 11 presents the flat-top compressed pulse waveform from the same storage cavity,

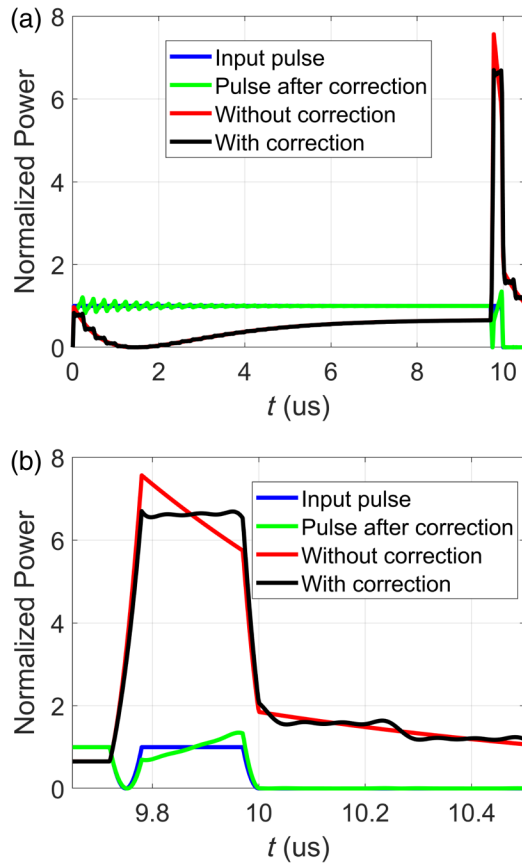


FIG. 11. (a) The input and flattened output waveform of the SLED pulse compression system. The coupling factor of the correction cavities is 3.4, and the number of correction cavities is six, the same as above (b) The input and output waveform during the last 250 ns.

modified by the correction cavity chain, with a resulting power gain of 6.62.

B. Parameter scanning

At a constant peak input microwave power, the input rf energy increases with the increase of pulse length. An increase in pulse length results in a higher peak power in the pulse compression system and increased beam acceleration voltage in the linac. Figure 12 illustrates the compression gain and relative energy dispersion when varying the input microwave length. The coupling factor of the correction cavities is optimized to minimize the energy dispersion, while other parameters remain unchanged. When the input microwave length is less than or equal to 4 us, the coupling degree needs to be appropriately reduced, with a minimum of 32. The results indicate that an increase in pulse length leads to a higher compression gain and reduced relative energy dispersion.

In the SLED-type pulse compression system, the quality factor of the energy storage cavity determines the power gain of the compressed pulse. A higher quality factor results in a greater power gain of the compressed pulse. Spherical resonant cavities in modes ranging from TE111 to TE115 are employed as energy storage cavities in the pulse compression system, while the quality factor of the correction cavities remains unchanged. The corresponding compression gain and relative energy dispersion curves for different quality factors are presented in Fig. 13. As the quality factor decreases, the coupling factor of the correction cavities also needs to be continuously increased. The coupling factor increases from 35 to 102, while the quality factor decreases from 230,000 to 58,000. The relative energy dispersion initially decreases before increasing again, with a maximum value below 1%. The results indicate that a higher quality factor leads to an increase in compression gain and a decrease in relative energy dispersion. The maximum values of energy

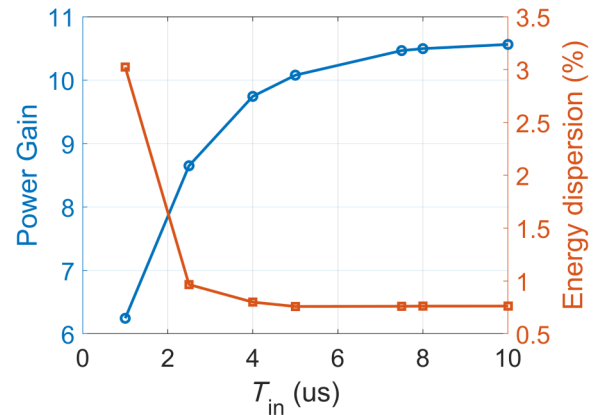


FIG. 12. The power compression gain and relative energy dispersion versus the rf input length.

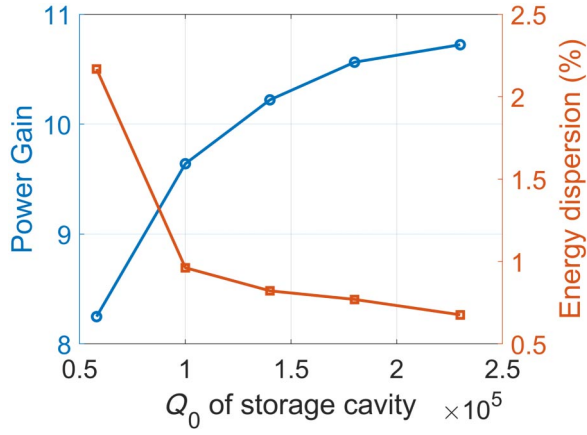


FIG. 13. The power compression gain and relative energy dispersion versus the quality factor of the storage cavity.

dispersion are all below 1% except for the lowest mode (TE111).

The correction chain in the SLED pulse compression system can modify the compressed waveform into a flattop or rising shape; however, the output pulse exhibits ripples. Increasing the number of cavities in the correction chain reduces the ripple amplitude. In the theoretical limit of an infinite number of correction cavities, the adjusted pulse would be ripple-free, similar to the SLED-II pulse compression system [7]. Figure 14 presents the compression gain and relative energy dispersion curves for a varying number of cavities in the correction chain. The quality factor of the correction cavities remains unchanged, as is the case for Fig. 13. The coupling factor of the correction cavities needs to be increased to over 50 when the number of correction cavities is less than six. The results indicate that a small number of correction cavities result in high energy dispersion. With an increasing number of correction cavities, energy dispersion rapidly decreases. The power gain first increases and then decreases. Considering the insertion loss of components, increasing

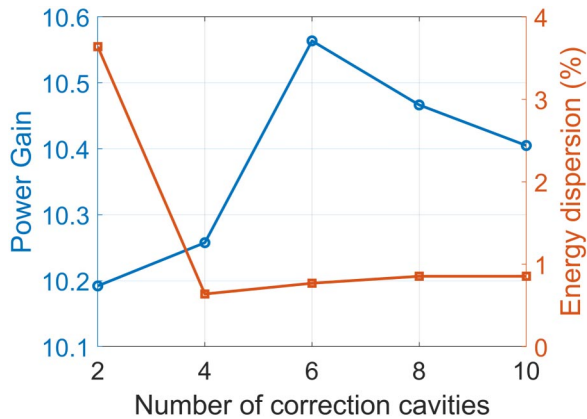


FIG. 14. The power compression gain and relative energy dispersion versus the number of correction cavities.

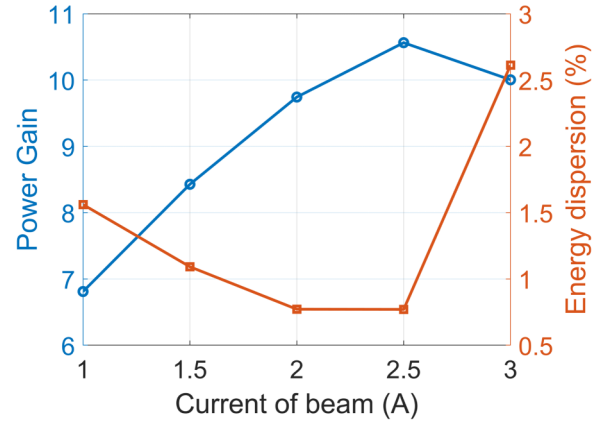


FIG. 15. The power compression gain and relative energy dispersion versus the current of the beam.

the correction cavity number will ultimately lead to a decrease in power gain. The loss of the current scheme is estimated to be approximately 0.1 dB.

The beam current is one of the key parameters determining the beam loading effect. As the beam current increases, the beam loading effect becomes more pronounced, thereby necessitating an increase in the compensation intensity. We varied the beam current while other structure parameters were kept constant, and the coupling factor of the correction cavities was optimized to minimize the relative energy dispersion. The resulting power gain and energy dispersion are shown in Fig. 15. The coupling factor of the correction cavities increases with increasing beam current, with optimized coupling factor values ranging from 5.9 to 82. The results indicate that as the beam current increases, the power gain increases and the energy dispersion decreases. However, when the beam current exceeds a critical threshold, pulse compression amplitude modulation can no longer effectively compensate for the beam loading effect, as the required compensation exceeds the achievable modulation capability. This leads to a rapid increase in energy dispersion and a reduction in power gain.

V. SUMMARY

In this paper, an SLED compressor with correction cavities is designed to compensate for beam loading in a structure accelerating a short bunch train. A pulse compression system with a correction cavity chain generates a microwave pulse with an increasing amplitude, which powers an electron linear traveling wave acceleration structure for beam loading compensation.

In this scheme, the S-band pulse compression system compresses a 10 μ s input pulse into a 250 ns rising power pulse, which is then directly fed into the S-band acceleration structure to accelerate the electron beam. An acceleration voltage of 50.14 MV and a relative energy dispersion of 0.77% are achieved. The power gain reaches

10.56, exceeding the power gain that is possible without using correction cavities.

DATA AVAILABILITY

The data that support the findings of this article are openly available.

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- [1] K. Johnsen, Heavy beam loading in linear electron accelerators, *Proceed. Phys. Soc. Sect. B* **64**, 1062 (1951).
 - [2] R. B. Neal, Design of linear electron accelerators with beam loading, *J. Appl. Phys.* **29**, 1019 (1958).
 - [3] A. Lunin, V. Yakovlev, and A. Grudiev, Analytical solutions for transient and steady state beam loading in arbitrary traveling wave accelerating structures, *Phys. Rev. ST Accel. Beams* **14**, 052001 (2011).
 - [4] O. Kononenko and A. Grudiev, Transient beam-loading model and compensation in compact linear collider main linac, *Phys. Rev. ST Accel. Beams* **14**, 111001 (2011).
 - [5] H. Zha and A. Grudiev, Design and optimization of compact linear collider main linac accelerating structure, *Phys. Rev. Accel. Beams* **19**, 111003 (2016).
 - [6] Z. Farkas, H. Hogg, G. Loew, and P. B. Wilson, Sled: A method of doubling Slac's energy, in *Proceedings of the 9th International Conference on High Energy Accelerators* (SLAC, 1974), p. 576.
 - [7] P. Wilson, Z. Farkas, and R. D. Ruth, SLED II: A new method of RF pulse compression, Tech. Rep. (Stanford Linear Accelerator Center, Menlo Park, CA (USA), 1990).
 - [8] P. Wang, J. Shi, H. Zha, D. Cao, M. Peng, Z. Liu, C. Cheng, and H. Chen, Development of an s-band spherical pulse compressor, *Nucl. Instruments. Methods Phys. Res. Sect. A* **901**, 84 (2018).
 - [9] Y. Jiang, H. Zha, J. Shi, M. Peng, X. Lin, and H. Chen, A compact x-band microwave pulse compressor using a corrugated cylindrical cavity, *IEEE Trans. Microwave Theory Tech.* **69**, 1586 (2021).
 - [10] X. Wu and A. Grudiev, Novel open cavity design for rotating mode rf pulse compressors, *Phys. Rev. Accel. Beams* **24**, 112001 (2021).
 - [11] S. Y. Kazakov, Pulse shape correction for rf pulse compression system, *Spectrum* **5**, 9 (1992); https://proceedings.jacow.org/e92/PDF/EPAC1992_1247.PDF.
 - [12] P. Wang, H. Zha, I. Syratchev, J. Shi, and H. Chen, rf design of a pulse compressor with correction cavity chain for Klystron-based compact linear collider, *Phys. Rev. Accel. Beams* **20**, 112001 (2017).
 - [13] Y. Jiang, H. Zha, P. Wang, J. Shi, H. Chen, W. L. Millar, and I. Syratchev, Demonstration of a cavity-based pulse compression system for pulse shape correction, *Phys. Rev. Accel. Beams* **22**, 082001 (2019).
 - [14] Y. Jiang, J. Shi, P. Wang, H. Zha, X. Lin, F. Liu, C. Cheng, and H. Chen, Compact two-stage pulse compression system for producing Gigawatt microwave pulses, *IEEE Trans. Microwave Theory Tech.* **69**, 4533 (2021).
 - [15] X. Lin, H. Zha, J. Shi, Y. Jiang, F. Hu, W. Gu, Q. Gao, and H. Chen, x-band two-stage rf pulse compression system with correction cavity chain, *Phys. Rev. Accel. Beams* **25**, 120401 (2022).
 - [16] 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, x-band active-passive rf pulse compressor with plasma switches, *Phys. Rev. ST Accel. Beams* **14**, 121302 (2011).
 - [17] X.-Y. Lei, Z.-Q. Zhang, D.-P. Gao, W.-X. Liu, D. Zhao, and H.-L. Gao, Theoretical design and analysis of high-gain over-moded microwave pulse compression system, *Radiat. Detect. Technol. Methods* **8**, 1208 (2024).
 - [18] F. Merrill, F. Harmon, A. Hunt, F. Mariam, K. Morley, C. Morris, A. Saunders, and C. Schwartz, Electron radiography, *Nucl. Instrum. Methods Phys. Res. Sect. B* **261**, 382 (2007). the Application of Accelerators in Research and Industry.
 - [19] C. L. Morris, N. S. P. King, K. Kwiatkowski, F. G. Mariam, F. E. Merrill, and A. Saunders, Charged particle radiography, *Rep. Progress Phys.* **76**, 046301 (2013).
 - [20] Z. Zhou, Y. Du, S. Cao, Z. Zhang, W. Huang, H. Chen, R. Cheng, Z. Chi, M. Liu, X. Su, C. Tang, Q. Tian, W. Wang, Y. Wang, J. Xiao, L. Yan, Q. Zhao, Y. Zhu, Y. Zhou, Y. Zong, and W. Gai, Experiments on bright-field and dark-field high-energy electron imaging with thick target material, *Phys. Rev. Accel. Beams* **21**, 074701 (2018).
 - [21] Z. Ran, Z. Li, Q. Zhao, X. Shen, Y. Zong, Z. Zhang, Y. Zhou, M. Liu, R. Xiao, J. Li, and S. Cao, Demonstration of high energy electron radiography with sub-micron spatial resolution, *Nucl. Instrum. Methods Phys. Res. Sect. A* **1015**, 165769 (2021).
 - [22] J.-J. Lan, Q.-T. Zhao, Z.-H. Hu, Z.-H. Ran, W.-W. Xu, H.-Y. Li, J. Li, S.-C. Cao, R. Cheng, Y.-T. Zhao, Z.-M. Zhang, and Y.-N. Wang, High-energy electron radiography system with low chromatic aberrations based on active plasma lenses, *Phys. Rev. Appl.* **22**, 034022 (2024).