Analysis and design of parallel-coupled high-gradient structure for ultrashort input power pulses

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Shortening the pulse length of input power is a possible approach to raise the accelerating gradient limit of normal conducting structures. We present a novel design of a parallel-coupled structure that operates at ultrashort input power pulses. The principle of the design is to shorten the filling time of the whole structure by feeding the cells individually so that the duration of power transmission between cells can be saved. An X-band (11.994 GHz) parallel-coupled structure design with a 10 ns pulse length is presented in this work. Previous high-power tests of X-band structure prototypes show that a gradient of 120 MV/m could be achieved for a 200 ns pulse length. Based on the law requiring that $E^{30}t^5 = \text{constant}$, this 10-ns-structure design should be able to reach a gradient of 200 MV/m. A detailed circuit model and real-time electromagnetic field simulation methods for designing the parallel-coupling structure are also presented and discussed in this paper.

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I. INTRODUCTION

High-gradient normal conducting structures have been studied for several decades as promising candidates for linear accelerator projects such as the compact linear collider (CLIC) and free-electron lasers [1–7]. The main factor affecting the accelerating gradient is rf breakdown. The accelerating structure's performance at a given gradient and pulse length is characterized by the breakdown rate (BDR) [8–11]. Although the mechanism of rf breakdown has not been satisfactorily explained [12–16], an empirical equation has been given to estimate BDR dependencies on the gradient and pulse length based on data collected from a CLIC breakdown study [17]:

$$\text{BDR} \propto E^{30}t^5 \quad (1)$$

where E is the accelerating gradient and t is the input pulse length.

This equation indicates that a higher accelerating gradient may be achievable with a shorter pulse length. To date, the undamped design of CLIC X-band traveling-wave (TW) structures named T24 has achieved a gradient of

120 MV/m with a pulse length of 200 ns [18]. According to Eq. (1), the scaled gradient may be 200 MV/m for a similar design if the pulse length could be reduced to 10 ns.

However, the applicability of the scaling law at the 10-ns scale is still in doubt since the minimum pulse length of the fitting data is 40 ns [17,19]. Moreover, the available experimental data based on the ultrashort-pulse regime were obtained on single cavities or at a higher frequency and these results have shown various results regarding gradients. On the one hand, earlier 30-GHz TW structures tested at the beam-driven CLIC test facilities (CTF-II) have a shorter filling time than that of the X-band. Accelerating gradients of 140, 100, and 70 MV/m were achieved with pulse lengths of 4, 8, and 16 ns, respectively [20]. The CTF-II results, together with the X-band results, also show that the obtainable surface fields have a weak frequency dependence between 11 and 39 GHz, which favors direct gradient comparison of structures within this range [20,21]. The achieved gradients are lower than the estimated gradient scaled from Eq. (1). On the other hand, a single beam-driven X-band TW cavity recently tested on Argonne achieved a gradient of 310 MV/m with a pulse full-width at half-maximum of 6 ns [22], the gradient of which is even higher than the scaled one. The gradient difference of the aforementioned tests may result from different design and rf parameters such as structure geometries, structure length (multi/single), and power sources [23]. Thus, designing a CLIC-type, X-band, multicell structure for ultrashort pulses should bridge the gap and offer insight into the underlying mechanism.

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TABLE I. Parameters of CLIC-T24 and the modified design with a filling time of 10 ns at a gradient of 120 MV/m.

Parameter	CLIC-T24-nominal	CLIC-T24-10 ns
Filling time	56 ns	10 ns
Iris aperture (first/last)	3.15/2.35 mm	4.85/4.52 mm
Input power	57 MW	400 MW
Maximum electric field	257 MV/m	340 MV/m
Maximum Sc^a	5 MW/mm ²	17.9 MW/mm ²
Shunt impedance	123 M Ω /m	81 M Ω /m

^a Sc is the modified Poynting vector.

For most of the linear accelerating structures, including both TW and standing-wave (SW) designs, rf power is fed through one input coupler and transmitted over cells. The filling time of these X-band structures is usually much longer than 10 ns [16,24]. Increasing the iris aperture can reduce the filling time but will result in a decline in the shunt impedance and an increase in the surface field. The estimated parameters of this modified CLIC-T24 design as well as of the nominal design are shown in Table I, which seem less attractive for practical use.

Another approach to shortening the filling time is to reduce the number of cells per input coupler. The most thorough solution is to power cells in parallel rather than in series, thus reducing the time spent on power transmission over cells. This SW structure with a parallel power supply to cells was proposed in the 1970s [25] and similar concepts have been investigated in several cases [26–28]. Since the power coupling between neighboring cells is avoided, the parallel structure can prevent severe rf breakdowns near the beam aperture and has more design space to improve the performance in terms of, e.g., the shunt impedance [29]. Previous studies usually focused on these structural advantages [26–28]. Moreover, traditional multicell structures, including both parallel-coupled ones and series-coupled ones, are designed with a typically long pulse length of more than 100 ns [18,28]. A multicell parallel-coupled structure should also be able to work at ultrashort pulses after dedicated analysis, which may result in a significant increase in the gradient limit.

This work studies a conceptual parallel-coupled high-gradient structure for ultrashort input power pulses. In Sec. II, a circuit model is developed and analyzed to calculate the coupling coefficient of the whole structure from all components. In Sec. III, a preliminary X-band parallel-coupled structure design using the model presented in Sec. II is introduced. Section IV develops a method for calculating the real-time electromagnetic fields. Thus, the process of power filling in the structure during the ultrashort time could be visually simulated and verified. According to the calculation, significant advantages are presented for the parallel-coupled structure operating at ultrashort pulses, and the search for a high gradient is shown to be promising.

FIG. 1. Scheme of the parallel-coupled accelerating structure.

II. SYSTEM ANALYSIS

A conceptual drawing of the parallel-coupled structure, which consists of a parallel rf feed system and individual cells, is shown in Fig. 1. The input power is fed into N isolated cells through tap-off ports. A simplified case was studied to analyze only the power at the input port, with the assumption of a matched load at the end of each tap-off port [28]. To analyze the power flow among the total $(N + 1)$ ports, a more general expression of the microwave network should be derived. Here, elements of the scattering matrix are defined as s_{nm} . The subscript n or m indicates the port: 0 for the input port and 1– N for tap-off ports to cells.

An essential issue of the coupling line is equal power division, where all identical cells receive the same field amplitude to avoid a ‘hot’ cell in terms of rf breakdown. The parallel rf feed system could be disassembled to multiple T-junctions, with each junction feeding one cell, as shown in Fig. 2. For T-junctions with different geometries, the scattering matrices should be customized separately and then cascaded section by section. A simpler design is to adopt identical T-junctions so that the network parameters of the whole parallel rf feed system could be derived directly.

The T-junction is equivalent to a three-port network, as shown in the inset of Fig. 2. It is assumed to be an E-plane component; thus, Ports ① and ② receive opposite signals scattered from Port ③. Considering that the ideal T-junction is reciprocal and lossless, the general scattering matrix could be described as follows: [28]

FIG. 2. Cascading of identical T-junctions. The inset in the lower right is the equivalent microwave network of the n th T-junction.

$$S = \frac{1}{2} \begin{bmatrix} e^{j\theta} - u & e^{j\theta} + u & v \\ e^{j\theta} + u & e^{j\theta} - u & -v \\ v & -v & \frac{2u^*v}{v^*} \end{bmatrix}, \quad (2)$$

where u and v are undetermined complex numbers, u^* and v^* are their conjugate complex numbers, respectively, and $|u|^2 + |v|^2/2 = 1$. θ is an undetermined degree number.

A. Incident power from the input port

In Fig. 2, a_n and b_n denote the amplitudes of the front wave and the back wave after the n th section. When there is no incident signal from any tap-off port, the three-port network can be expressed as

$$\frac{1}{2} \begin{bmatrix} e^{j\theta} - u & e^{j\theta} + u & v \\ e^{j\theta} + u & e^{j\theta} - u & -v \\ v & -v & \frac{2u^*v}{v^*} \end{bmatrix} \begin{bmatrix} a_{n-1} \\ b_n \\ 0 \end{bmatrix} = \begin{bmatrix} b_{n-1} \\ a_n \\ c_n \end{bmatrix}, \quad (3)$$

$$\begin{bmatrix} a_n \\ b_n \end{bmatrix} = \frac{1}{e^{j\theta} + u} \begin{bmatrix} 2ue^{j\theta} & e^{j\theta} - u \\ u - e^{j\theta} & 2 \end{bmatrix} \begin{bmatrix} a_{n-1} \\ b_{n-1} \end{bmatrix}, \quad (4)$$

where c_n is the output of the n th tap-off port and is calculated as

$$c_n = \frac{v(a_n - e^{j\theta}b_n)}{e^{j\theta} + u} \quad \text{and} \quad c_{n+1} = \frac{v(e^{j\theta}a_n - b_n)}{e^{j\theta} + u}. \quad (5)$$

To ensure equal power division, $|c_n| = |c_{n+1}|$ holds for all integer values of n . Considering that a_n and b_n vary with n , $e^{j\theta} = \pm 1$ should be satisfied. The choice of $e^{j\theta}$ influences only the sign of c_n . The discussion below focuses on the case of $e^{j\theta} = 1$, as the preliminary rf design in Sec. III is based on this case. Therefore, the transmission matrix from (a_{n-1}, b_{n-1}) to (a_n, b_n) is transformed as

$$\begin{aligned} \begin{bmatrix} a_n \\ b_n \end{bmatrix} &= \frac{1}{1+u} \begin{bmatrix} 2u & 1-u \\ u-1 & 2 \end{bmatrix} \begin{bmatrix} a_{n-1} \\ b_{n-1} \end{bmatrix} \\ &= \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \rho \begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix} \right) \begin{bmatrix} a_{n-1} \\ b_{n-1} \end{bmatrix} \\ &= (\mathbf{A} + \rho\mathbf{B}) \begin{bmatrix} a_{n-1} \\ b_{n-1} \end{bmatrix}, \end{aligned} \quad (6)$$

$$\begin{bmatrix} a_n \\ b_n \end{bmatrix} = \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + n\rho \begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix} \right) \begin{bmatrix} a_0 \\ b_0 \end{bmatrix}, \quad (7)$$

where $\rho = (1-u)/(1+u)$, a_0 and b_0 are the incident and reflected waves at the input port, respectively. The second matrix term satisfies $\mathbf{B}^2 = \mathbf{0}$, which simplifies the calculation of the n th power of the transmission matrix, as shown in Eq. (7).

Since the parallel rf feed system is terminated by a short end, the reflection at Port ② of the last section N is -1 , which gives $a_N + b_N = 0$. Derived from Eq. (7), we have $a_0 + b_0 = 2N\rho(a_0 - b_0)$. Thus, the reflection coefficient s_{00} could be calculated from b_0/a_0 and the coefficients of power division s_{0n} are equal to c_n/a_0 , as shown in Eq. (8) below.

$$s_{00} = \frac{b_0}{a_0} = \frac{2N\rho - 1}{2N\rho + 1}, \quad s_{0n} = \frac{c_n}{a_0} = \frac{v(\rho + 1)}{2N\rho + 1} \quad (8)$$

B. Incident power from the tap-off port

Matrix elements s_{mn} for $m \neq 0$ are solved in another case where the incident signal x is from the m th tap-off port. Then, the equation for (a_m, b_m) in this section should be modified as

$$\frac{1}{2} \begin{bmatrix} 1-u & 1+u & v \\ 1+u & 1-u & -v \\ v & -v & \frac{2u^*v}{v^*} \end{bmatrix} \begin{bmatrix} a_{m-1} \\ b_m \\ x \end{bmatrix} = \begin{bmatrix} b_{m-1} \\ a_m \\ c_m \end{bmatrix}. \quad (9)$$

Except for the m th section with an incident signal x , Eq. (6) is applicable to the other sections under an additional condition, i.e., $a_0 = 0$. Thus, $b_0 = xs_{m0} = xs_{0m} = xv(\rho + 1)/(2N\rho + 1)$ is the signal scattered from Ports m to 0. The values of (a_n, b_n) are given as

$$\begin{bmatrix} a_n \\ b_n \end{bmatrix} = \begin{cases} b_0 \begin{bmatrix} n\rho \\ 1+n\rho \end{bmatrix}, & n < m \\ b_0 \begin{bmatrix} n\rho \\ 1+n\rho \end{bmatrix} - \frac{vx}{2} \begin{bmatrix} \rho+1 \\ \rho+1 \end{bmatrix}, & n \geq m \end{cases}. \quad (10)$$

The output signals c_n of the tap-off ports can also be calculated from Eqs. (3) and (7) as

$$c_n = \frac{v(a_n - b_n)}{1+u} - \frac{vb_0}{1+u}, \quad n \neq m \quad \text{and} \quad (11a)$$

$$c_m = \frac{v(a_{m-1} - b_m)}{1+u} + \frac{u^*vx}{v^*}, \quad n = m. \quad (11b)$$

This gives matrix elements $s_{nm} = c_n/x$ and $s_{mm} = c_m/x$. Thus, the scattering matrix of the parallel rf feed system is solved, and all elements are listed in Eqs. (8) and (12).

$$s_{nm} = -\frac{1}{2} \frac{v^2(\rho + 1)^2}{2N\rho + 1} \quad \text{and} \quad s_{mm} = s_{nm} + \frac{v}{v^*} \frac{1+u^*}{1+u} \quad (12)$$

C. Scattering matrix with unmatched cells

The scattering matrix of the parallel-feeding network is solved under the assumption that all ports are matched. However, the structure cell may reflect rf power if it is not critically coupled. This reflected power will flow back into the network and affect other cells. To study this effect, an equation of the whole system is established as

$$\begin{bmatrix} s_{00} & s_{01} & \cdots & s_{0N} \\ s_{10} & s_{11} & \cdots & s_{1N} \\ \vdots & \vdots & \ddots & \vdots \\ s_{N0} & s_{N1} & \cdots & s_{NN} \end{bmatrix} \begin{bmatrix} a_0 \\ x_1 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} b_0 \\ c_1 \\ \vdots \\ c_N \end{bmatrix}, \quad (13)$$

where a_0 is the amplitude of the input signal, b_0 is the reflected one, and c_n and x_n represent the incident signal and the reflected signal of the n th cell, respectively.

According to the circuit model of a resonant cavity, the power transmitted to the cavity $g_n = c_n - x_n$ is proportional to the field amplitude of the cell and varies during the filling process. A differential equation is derived based on the circuit model to study the dynamics of power filling and reflection:

$$\frac{dg_n}{dt} = \frac{\omega}{2Q_0} [2\beta c_n - (\beta + 1)g_n], \quad (14)$$

where ω , Q_0 , and β are the angular resonant frequency, unloaded quality factor, and coupling coefficient of the single cell, respectively. Let $\mathbf{g} = [g_1 \cdots g_N]^T$ and $\mathbf{c} = [c_1 \cdots c_N]^T$ for all cells. With these equations, together with Eqs. (13) and (14), the differential equation could be extended to the following vector form:

$$\frac{d\mathbf{g}}{dt} = \frac{\omega}{2Q_0} \left(2\beta a_0 \mathbf{M} \begin{bmatrix} s_{10} \\ \vdots \\ s_{N0} \end{bmatrix} + (\beta - 1)\mathbf{g} - 2\beta \mathbf{M} \mathbf{g} \right), \quad (15)$$

$$\mathbf{M} = \begin{bmatrix} 1 - s_{11} & \cdots & -s_{1N} \\ \vdots & \ddots & \vdots \\ -s_{N1} & \cdots & 1 - s_{NN} \end{bmatrix}^{-1}. \quad (16)$$

The values of s_{n0} , s_{nm} , and s_{mm} are constants over any n and m . Thus, a trivial eigenvector of Eq. (13) is $[1 \cdots 1]^T$. This eigenvector is regarded as a solution of an even field distribution over cells, which is the one we want to study. The $(N + 1)$ -dimensional differential equations could be degenerated to a single-dimensional one for this eigenvector, as shown in Eq. 17(a). The matrices are replaced with the corresponding eigenvalue, which can be expressed as shown in Eq. 17(c).

$$\frac{dg}{dt} = \frac{\omega}{2Q_0} \left[\frac{d}{1 - \lambda_p} - \left(1 + \beta \frac{1 + \lambda_p}{1 - \lambda_p} \right) g \right], \quad (17a)$$

$$d = 2\beta a_0 s_{10} = \frac{2\beta v(\rho + 1)}{2N\rho + 1} a_0, \quad (17b)$$

$$\lambda_p = \sum_{n=1}^N s_{nm} = \frac{1 - 2N\rho^*}{1 + 2N\rho} \frac{1 + \rho}{1 + \rho^*} \frac{v}{v^*}. \quad (17c)$$

Equation 17(a) describes the dynamic of building up the field in the cells of the parallel-coupled structure. It is similar to the filling equation of a conventional SW structure. Thus, the equivalent coupling coefficient (β') of the full structure is $\beta' = \beta(1 + \lambda_p)(1 - \lambda_p)$.

To avoid phase shifting, the coupling coefficient should not have an imaginary part. A simple case is one in which ρ is real and $v/v^* = \pm 1$. In this case, the solution to Eq. 17(a) and the equivalent coupling coefficient (β') are expressed as

$$g(t) = \frac{2a_0 \sqrt{\beta\beta'/N}}{1 + \beta'} (1 - e^{-\frac{\omega(1+\beta')}{2Q_0} t}) \quad \text{and} \quad (18a)$$

$$\beta' = (2N\rho)^{\mp 1} \beta. \quad (18b)$$

At this point, the analytical power-filling process of a parallel-coupled structure is derived. Because all cells are powered simultaneously rather than sequentially, a high-gradient accelerating field can be built up quickly under the overcoupled condition $\beta' \gg 1$. Since the increase in the field amplitude occurs at a gradually lower rate over time, the input pulse length is optimized to have the maximum filling efficiency, which is defined as the ratio of the structure's stored to emitted energy of the input pulse. Numerical calculations show that the maximum filling efficiency is approximately $0.815\beta'/(1 + \beta')$, corresponding to a optimum pulse length $t_f \simeq 2.5Q_0/\omega(1 + \beta')$, as shown in Fig. 3.

FIG. 3. Stored energy vs filling time in the cavity cell (numbers were calculated at $\beta' = 20$).

III. PRELIMINARY rf DESIGN

To verify the above analysis and compare with traditional TW and SW structures, an X-band parallel-coupled structure was designed preliminarily. Different from previous critically coupled parallel structures, this design should be overcoupled to achieve fast power filling. The reflected power of these two identical structures with the proper distance can be directed away from the power source through a 3-dB hybrid. According to Eq. 18(b), the structure's coupling coefficient (β') is related to S -parameters of the T-junction, the cell's coupling coefficient (β), and the number (N) of tap-off ports.

Equal power division is a prerequisite for the structure design. The condition that $e^{j\theta} = \pm 1$ corresponds to a phase advance of 0 or π between two neighboring tap-off ports. Choosing a phase advance of π per cell can simplify the design rather than complicating the tap-off ports with varied length. Moreover, cells operating at the π -mode can be regarded as isolated from each other theoretically [28], which matches our assumption. Thus, the structure was designed to operate at the π mode.

A. rf design of the single cell

In the π mode, a 12 GHz cell has a length of $\lambda/2 = 12.5$ mm, where λ is the free-space wavelength. The cell geometries are based on the middle cell of CLIC-T24, with an elliptical 2.0 mm thick iris and an aperture radius of 2.75 mm, as shown in Fig. 4. The practical coupling coefficient between neighboring cells is estimated as $k \sim a^3 e^{-\alpha_e d}$, where $2a$ is the iris aperture and d is the thickness of the diaphragm [30]. Even though there may still exist rf power coupling between two consecutive cells in practice, this intercross has very little effect on the equations in the case of a small iris aperture [28]. The rf parameters of the cell structure are listed in Table II, together with the middle cell design of the nominal CLIC-T24.

The cylindrical cell is side-coupled through a rectangular waveguide and the coupling coefficient (β) could be

FIG. 4. rf design of the accelerating cell.

TABLE II. rf parameters of the parallel-feeding cell and the middle cell of CLIC-T24 at a gradient of 200 MV/m.

rf parameters at 200 MV/m	Parallel-feeding cell	CLIC-T24 middle cell
Q_0	8173	6898
R/Q (Ω/m)	12000	17790
Stored energy (J)	0.55	0.25
Maximum E -field (MV/m)	257	340
Maximum H -field (kA/m)	840	490
Maximum S_c (MW/mm ²)	12.72	13.48

modified by adjusting the coupling opening's width. The enhanced surface-field patterns due to side-coupling are shown in Fig. 5, where the magnetic field is higher near the coupling opening. However, the peak modified Poynting vector (S_c), with which the breakdown damage is more correlated, is still near the beam aperture. Moreover, previous test of a single-feed cell with side-coupling did not show a higher BDR due to the increased magnetic field, in contrast to the case of a dual-feed cell with side-coupling [31]. Thus, the single-feed, side-coupled cell is convincing for the high-gradient parallel-coupled structure.

B. rf design of the parallel waveguide feeder

Rectangular waveguides were adopted as the parallel rf feeder for high-power transmission. To have more space for the waveguide coupler at the tap-off port and more symmetric geometry, an alternating single-feed scheme based on two transmission waveguides was adopted, as shown as Fig. 6. Therefore, the tap-off port for each branch has the same phase ($e^{j\theta} = 1$) and Eq. 18(b) can be further expressed as

FIG. 5. Surface field patterns of the accelerating cell.

FIG. 6. Scheme of parallel-coupled structure with two rectangular feeding waveguides.

FIG. 7. rf design of a parallel waveguide feeder.

$$\beta' = 2N\rho\beta = 2N \frac{1 - |S_{33}|}{1 + |S_{33}|} \beta, \quad (19)$$

where $|S_{33}|$ is the reflection amplitude of the tap-off port of a T-junction.

Phase synchronization of the rf power during transmission is also essential for power division. The rf phase velocity was reduced to the speed of light by introducing the slow-wave structure of periodic slots, as shown in Fig. 7. The transmission part was designed with four corrugated slots per T-junction, which means an approximately $\pi/2$ phase shift for each corrugation period. The coupler waveguide was then connected to the transmission part through a transition structure. The phase difference between S_{11} and S_{12} introduced by the coupler waveguide was also corrected by modifying this transition part. The scattering matrix of a valid T-junction can be expressed as

$$S_3 = \begin{bmatrix} 0.216 & 0.784 & 0.582j \\ 0.784 & 0.216 & -0.582j \\ 0.582j & -0.582j & -0.569 \end{bmatrix}. \quad (20)$$

To match with smooth waveguides, additional slots were optimized and added to the ends of the corrugated transmission waveguide, as shown in Fig. 7. Both the slow-wave slots and the matching slots led to an intense local E-field enhancement, which is a potential limitation for high-gradient operation of a multicell structure.

Thus, the equivalent coupling coefficient of the whole structure can be expressed as $\beta' = 2N\rho\beta = 2N\beta(1 - |S_{33}|)/(1 + |S_{33}|) \approx 0.55N\beta$, where N is the T-junction number of a parallel waveguide feeder.

C. rf design of the whole parallel-coupled structure

The whole structure was then designed, consisting of 16 accelerating cells and two parallel waveguide feeders, as shown in Fig. 8. Due to developments of the split structure [32], the cells and the parallel waveguide feeders can be made of two halves instead of many individual parts [28], especially for structures with a simple topology. The number of cells was chosen to match the length of CLIC-T24 ($16\pi = 24 \times 2\pi/3$). Substituting the designed rf parameters into Eq. (19), the structure's coupling coefficient is estimated as $\beta' \approx 4.4\beta$, which was verified by simulating the whole structure directly through CST [33].

FIG. 8. rf design of the whole parallel-coupled structure.

FIG. 9. Coupling coefficients (β') of the whole structure with different single-cell coupling coefficients (β).

The coupling coefficients of a single cell (β) and the structure (β') vary with the width of the coupling opening, and their values can be calculated from the simulated S -parameters. The analytical and simulated relationships between β and β' of the parallel-coupled structure are shown in Fig. 9, which validate the theoretical analysis. The slight difference between the simulation and the derived calculation may result from the end cells, since their cavity radii were modified due to the use of a different boundary condition.

For 10 ns ultrashort input pulses, the optimized coupling coefficients are approximately $\beta' \approx 26$ and $\beta \approx 5.9$. The S -parameter of the parallel-coupled structure is shown in Fig. 10.

IV. REAL-TIME ELECTROMAGNETIC FIELD CALCULATION

The simulation conducted in Sec. III calculated only the steady-state field in the structure. However, a pulse length of 10 ns is far too low to approach the steady state. To verify the expected filling process, a real-time electromagnetic field calculation is needed. Although the CST code implements the real-time module, a considerable computational cost in terms of time and hardware is required to obtain accurate results.

In this section, a method based on the fast Fourier transform (FFT) was applied to obtain the real-time fields

FIG. 10. Reflection of the parallel-coupled structure.

with an arbitrary input pulse shape. The frequency-domain data were gained by calculating the field at multiple frequencies. The real-time fields at a grid point could be calculated by performing an inverse FFT on the product of the frequency-domain field data and spectrum of the input pulse. To achieve a sub-ns resolution in the time domain, such as 0.1 ns, the field data over a broad frequency range of 10 GHz are needed. To reduce the required computation time and data size, the simulation was carried out at unequal frequency intervals with fine steps near the operating frequency only. The full frequency-domain data used in the FFT were calculated by interpolation of the simulated data. This method was applied to all grids to generate the real-time field plot of the structure. After obtaining the field data from the CST simulation, all calculations, including the field plot generation, could be conducted in the MATLAB code.

Figure 11 shows the real-time calculation of the longitudinal E-field E_z using the above method on a CLIC-T24 structure with a 60-ns input pulse. The animation demonstrates consecutive building up of the field over cells, and the filling time estimated in the animation agrees with the results in Table I.

The real-time accelerating field of the designed parallel-coupled structure was calculated with an input pulse of

FIG. 11. Normalized temporal E_z distribution of a CLIC-T24 structure with a 60-ns input pulse. FIG. 12. Normalized temporal E_z distribution of the designed parallel-coupled structure with a 1.1-GW, 10-ns input pulse.

1.1 GW power and 10 ns pulse length, as shown in Fig. 12. The rising time of the pulse was set to be 1 ns. The accelerating gradient over the cells retained an even distribution during the filling process, and the calculated field distribution at 10 ns is shown in Fig. 13. The average gradient reached its maximum value of 200 MV/m at the end of the 10-ns pulse, which agrees with the calculation in Sec. III. The animation shows that a minimum time of 4 ns was required to build the even distribution of the accelerating field. This is the lowest limit of the pulse length for the parallel-coupled structures at this length.

To gain a higher peak power from commercial power sources such as klystrons, an rf pulse compressor could be used [34–38], and the cascaded pulse-compression concept has been demonstrated at the Tsinghua S-band test facility [39]. Based on the parameters of the X-band test stands at Tsinghua University, an X-band two-stage rf compressor is under development. Since the parallel-coupled structure presented in this work is designed for the single-bunch operation, the unflat pulse still works.

FIG. 13. E_z field distribution on the axis of the designed parallel-coupled structure at 10 ns.

V. CONCLUSIONS

A novel parallel-coupled structure is introduced in this work. The structure uses a distributed coupling network to achieve ultrafast power filling in each cell. A circuit model of the distributed coupling is discussed and used to design the short-filling structure. This analysis can be further applied to other specific structures or researches on system responses of a parallel-coupled structure under different conditions. The real-time electromagnetic field calculation is also developed to observe and verify the filling process of the accelerating structure.

An X-band parallel-coupled structure design is demonstrated. It has 16 cells, and the length of the structure is 20 cm, which is comparable to the X-band structure design of the CLIC main linac. The filling time of the parallel-coupled structure is only 10 ns; thus, 200 MV/m is achievable according to the test data of CLIC structures and the law requiring that $E^{30}t^5 = \text{constant}$.

Although promising parameters are obtained, the presented structure is still a preliminary design aimed at verifying the principle of achieving an ultrashort filling time. Future prototypes may be developed by using longitude split halves, which are easier to fabricate. The slow-wave geometry in the coupling line should be redesigned to reduce the surface field. High-power testing on the parallel-coupled structure prototypes will also be performed.

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