Design optimization of a C-band traveling-wave accelerating structure for a compact X-ray Free Electron Laser facility

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The research and development of a C-band (5712 MHz) high gradient traveling-wave accelerating structure has been in progress for some years at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences. Conceptual design of the accelerating structure has been accomplished, and verified by cold testing an experimental model. The first prototype structure is now ready for high RF power tests. To develop a robust high gradient C-band accelerating structure, an optimized constant gradient structure with a $4\pi/5$ operating mode for future X-ray Free Electron Laser facilities is proposed in this paper. This scheme can improve the breakdown stability and beam quality. The high power RF system, four operating modes and disk iris shape are analyzed and optimized.

breakdown, wakefield, constant gradient, constant impedance, SLED, operating mode, disk iris

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A compact hard X-ray Free Electron Laser (XFEL) facility is presently being planned, and some analytical and simulation research is ongoing at the Shanghai Institute of Applied Physics, CAS [1]. This facility will be located close to the Shanghai Synchrotron Radiation Facility which is a 3rd generation light source in China [2]. It requires a compact linac with a high gradient accelerating structure and high beam quality. At room temperature, linac, the C-band (5712 MHz) accelerating structure, is a compromise and a good option for this compact linac designed to operate at 40 MV/m [3]. In XFEL/SPRING-8, the chock-mode-type C-band accelerating structure of 1.8 m is designed to operate at a high accelerating gradient of 35 MV/m (40 MV/m was achieved in 2009). This results in the 8 GeV linac of XFEL/SPRING-8 being about 400 m in total length, which is a suitable size for a compact facility compared with similar machines in the United States and Europe [4,5].

To verify the design and manufacture technology, an experimental model of a C-band accelerating structure of

constant impedance with a $2\pi/3$ mode was fabricated and tested, and to a large extent the cold test results confirm the feasibility of conceptual design [3]. The first prototype C-band accelerating structure, shown in Figure 1, has now been fabricated and is ready for high power testing.

Figure 1 High power C-band traveling-wave accelerating structure.

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The experimental model and the first high power structure are constant impedance accelerating structures and the field distribution is not constant. For the linac to achieve high gradient, the constant gradient field distribution is the optimal choice, and at the same time it needs to be capable of high gradient and high beam quality. To achieve the high constant gradient field and beam quality, the RF breakdown stability and wakefield are two crucial issues in designing the accelerating structure. To optimize this design, many issues are considered and analyzed, such as the pulse compressor, operating mode and disk shape. Here, an optimized scheme with a $4\pi/5$ mode is proposed.

1 High power RF system

A high power RF system comprises a RF power source, an accelerating structure and waveguide components. For a high constant gradient field, the existing klystron power source of 50 MW cannot meet the power requirement of the field target, and a pulse compressor is required for multiplying the power from klystron. There are different types of pulse compressors which perform differently when working with an accelerating structure. The different performances for the constant field and the future XFEL multi-bunch operation need to be analyzed.

According to the principles of operation of the first generation pulse compressor (SLED-I), the output power of SLED-I is attenuated exponentially [6]:

$$E(t) = A(2e^{t_1/T_c} - 1)e^{-t/T_c} - A + 1, \quad (1)$$

where $T_c = 2Q_0/[\omega(1+\beta)]$ is the filling time of the SLED cavity, $A = 2\beta/(1+\beta)$, β is the coupling coefficient, and t_1 is the start time to output power from the SLED. The curve of the output pulse shape is thus dominated by the quality value Q_0 , β and t_1/T , in which T is the pulse length of the klystron.

Figure 2 shows different cases in which $Q_0 = 13000$,

Figure 2 Output pulse shape of SLED-I for different coupling coefficients β .

$t_1 = 2 \mu\text{s}$, and $T = 2.5 \mu\text{s}$ are fixed. In Figure 2, the output power gain is enhanced as the coupling coefficient β increases, and there is a large difference between the start and end of the pulse as β increases.

A conventionally constant gradient structure (CG) comprises a series of cells with linearly-varying group velocity, and induces a constant electrical field distribution on the axis [7]. As a result the field distribution on the axis of the CG structure is not constant when inputting power from SLED-I in Figure 3.

The SLED-I with constant impedance structure (CI) can induce constant field distribution on the axis. According to the CI principle, the field on the axis is also attenuated exponentially from upstream to downstream, when inputting a flat-top pulse [7]:

$$E(z) = E_0 e^{-\alpha z}, \quad (2)$$

where α is the attenuating factor. If the SLED-I and CI structure work correctly, a constant field can be established on the axis as shown in Figure 3, where both the group velocity of CI and center group velocity of CG are $0.02356c$.

As analyzed above, the CI+SLED-I can also establish a constant field distribution on the axis; however, this scheme has two disadvantages: The field amplitude of time is changed during the pulse length, and therefore it is not suitable for a multi-bunch pattern in the future, and the top of the output pulse is not flat, and requires high power at the beginning of the pulse for constant field distribution. Taking a 40 MV/m constant gradient on the axis for example, the peak of the output power of SLED-I should reach 110 MW, and may result in a serious breakdown problem upstream of the CI structure.

The scheme for the CI+SLED-I is a smart solution for constant field distribution on the axis, however it is not stable and extensive enough. In contrast, the CG+SLED-II is an effective and stable solution. The SLED-II is a second generation pulse compressor with a flat-top pulse which was

Figure 3 Output pulse of SLED-I and field distribution of CG and CI. Parameters of SLED-I: $Q_0 = 130000$, $\beta = 7.5$, $t_1 = 2 \mu\text{s}$, $T = 2.5 \mu\text{s}$.

presented by Fiebig and Schieblich [8]. When a flat-top power pulse is input into the CG structure, the field of both time and space on the axis is constant, thus the CG+SLED-II is suitable for a multi-bunch pattern and can reduce the rate of RF breakdown.

So far there are three types of SLED-II, the Delay Line at SLAC [9], the Barrel Open Cavity (BOC) in CERN [10], and the multi-cell coupled-cavity+LLRF at KEK [11]. For the C-band, the Delay Line SLED-II is not economical because it is very large, while the BOC and KEK types are smart and both are good options for the C-band RF system.

2 Phase advance, a/λ , phase stability and structure length

To some extent, the operating mode of a traveling-wave accelerating structure is indirectly related to the short-range wakefield (SRW), RF breakdown and phase stability.

In the hard XFEL facility, the peak current of the bunch should reach the order of several thousand Amperes, thus the bunch length is about a millimeter or smaller. For such a short bunch length, the SRW can induce a strong effect on the emittance dilution and energy distribution of the bunch, and it is dominated by the radius of the disk aperture “ a ” [12]:

$$\begin{aligned} \text{Longitudinal SRW: } W(s) &= \frac{Z_0 c}{\pi a^2} e^{-1.16(s/\text{mm})^{0.55}}, \\ \text{Transversal SRW: } W(s) &= \frac{2Z_0 c}{\pi a^4} \left(1 - e^{-0.89(s/\text{mm})^{0.87}}\right), \end{aligned} \quad (3)$$

where s is the distance from the head of the bunch and $Z_0 = 377 \Omega$. In eq. (3), a large “ a ” can suppress the SRW in two directions. In Figure 4, “ $2a$ ” is increased from 10 to 15 mm, and the longitudinal and transversal SRW can be suppressed by factors of 2 and 6, respectively.

A large “ a ” means a high group velocity V_g . A high V_g can induce breakdown events easily and lower RF power efficiency [13]. However, using a higher phase advance per cell can effectively lower the group velocity and maintain good RF efficiency [13].

Table 1 shows the comparison between different modes of phase advance, which is calculated using SUPERFISH 7.0 [14]. The length of the structure, operation frequency, disk aperture radius “ a ” and disk width “ t ” for all types are

fixed on 1 m, 5712 MHz, 7.5 mm and 2.5 mm, respectively. In Table 1, the group velocity is decreased and the RF efficiency is improved, as the phase advance is changed from $2\pi/3$ to $5\pi/6$. In these four modes, $5\pi/6$ has the optimum group velocity and RF efficiency, but its phase stability is the poorest. Based on the dispersion curve of this structure, the phase stability is expressed by

$$\omega(\theta) = \frac{\omega(\pi/2)}{\sqrt{1+k\cos\theta}} \Rightarrow \frac{d\theta}{df} = \frac{2}{f(\pi/2)k\sin\theta}, \quad (4)$$

where k is the coupling coefficient between cells and θ is the phase advance per cell. Table 1 shows that $4\pi/5$ is the best compromise option with suitable group velocity, shunt impedance and phase stability.

Figure 4 SRW distribution of different aperture radius ($a=5$ or 7.5 mm).

Table 1 Comparison between different modes of phase advance ^{a)}

Operating mode	Coupling coefficient k (%)	Group velocity V_g/c (%)	Shunt impedance R (M Ω /m)	Quality factor Q	Attenuation factor τ	Filling time t_f (ns)	Phase stability $d\theta/df$ (°/MHz)
$2\pi/3$	3.83	3.441	64.50	9943	0.1748	97	0.61
$3\pi/4$	3.42	2.846	63.43	10754	0.1954	117	0.84
$4\pi/5$	3.23	2.356	69.96	11202	0.2267	141	1.07
$5\pi/6$	3.08	1.986	69.31	11488	0.2622	167	1.32

a) $L=1$ m, $f_0=5712$ MHz, $a=7.5$ mm, $t=2.5$ mm, circle iris tip.

In Table 1, an attenuation factor 0.2267 of $4\pi/5$ is lower than the optimum range, and the RF power is not effectively used, thus the structure length needs to be increased. Based on the overall considerations, 83 cells with 1.742 m are a better option, and the attenuation is increased to about 0.4. In the CG, if the average group velocity is equal to $2.356\%c$ in Table 1, the input power required is about 70 MW for 40 MV/m average gradient on the axis. It is much less than the 110 MW peak power of CI introduced above. According to the SUPERFISH simulation, $E_{\max}/E_0$ is about 3.6122, which is about 145 MV/m responding to 40 MV/m.

3 Iris optimization for suppressing the RF breakdown

In Section 2, the last results for $4\pi/5$ were not optimum, and the group velocity, peak field amplitude and RF efficiency may not satisfy the design target, thus further optimization of these factors is needed.

Surface electrical field and group velocity are two crucial factors of RF breakdown [13], and suppressing them can realize better performance of the RF breakdown. For the Shintake-type C-band accelerating structure [15], the average ratio of the peak electrical field to the average field is about 2.2 with an average group velocity of 2% of light velocity and a type of low shunt impedance 58 M Ω /m which requires higher power dissipation. For a SLAC-type X-band [13], the optimized group velocity is about 2% of the light velocity.

Both the peak field and group velocity are influenced by the iris shape. According to the simulations, a proper elliptical disk iris and disk width can suppress the peak electrical field, thus the two axes of elliptic iris tip in Figure 5 should be tuned for the optimal peak electrical field and group velocity.

Before tuning the iris, the disk aperture radius “ a ” is fixed at 7.5 mm for the specific wakefield, and the two axes of the ellipse curve, in which the transversal radius $2A$ is equal to t , are varied over the specific range for peak field and group velocity analysis. The ranges of $2A$ and $2B$ are varied from 2.5 to 4.5 cm to reveal some underlying potential for optimization.

In Figure 6, clearly the peak electrical field is suppressed

Figure 5 Disk shape and disk width t . r , radius of circle; A and B , radius of two elliptical axes.

Figure 6 Electrical peak field variations versus $2A$ and $2B$.

by lengthening both axes $2A$ and $2B$, and there is a trough for most curves. In Figure 7, the suppression of the group velocity is dominated by lengthening $2A$, which also rises slightly as $2B$ increases.

According to the results in Figures 6 and 7, it is easy to reach the design target for the desired peak field and group velocity by tuning both axes of the elliptic iris, especially $2A$. However the shunt impedance in Figure 8 and the phase stability in Figure 9 are also dominated by $2A$. In Figure 8, the smaller shunt impedance for larger values of $2A$ and $2B$ results in more power dissipation by disk-loaded cells. In Figure 9, the stability of the phase advance per cell deteriorates as $2A$ increases, and improves slightly as $2B$ increases.

Reviewing the four parameters shown in Figures 6–9, $2A$ is clearly the crucial factor for optimizing the peak electrical field and group velocity according to the analysis above, while $2B$ can be tuned for small changes in the peak electrical field and group velocity. In Figure 6, the minimum ratio of peak field to average field is about 3.2, as a result a larger $2A$ is required for a lower ratio. The larger $2A$ is fixed at 5 mm because of the compromise between the four parameters above, and $2B$ is tuned for an optimum point

Figure 7 Group velocity versus radii on $2A$ and $2B$. The data for the group velocity is divided by light velocity in this figure.

Figure 8 Shunt impedance variations versus 2A and 2B.

Figure 9 Phase stability variations versus 2A and 2B.

between the peak electrical field and group velocity.

Figure 10 shows the optimized options for a fixed 2A at 5 mm. When 2B is 9 mm, the ratio of the peak electrical field to average field is about 2.6, and the group velocity is about 1.7% of light velocity, the impedance is about 62 Mohm/m and the phase stability is about 1.5°/MHz. Taking into account the 40 MV/m gradient, the peak surface field is about 104 MV/m and the input power is about 58 MW with respect to a 1.8 m active length of the accelerating structure. Both $E_{\max}$ and the input power are scaled down to about 80% of that in Section 2. In Figure 10, the RF phase stability is worse than that in Section 2, but more accurate machining and microwave tuning can compensate the phase stability. In conclusion, the optimized result is efficient, stable and feasible.

Summarizing the results in Sections 1 and 2, an optimization scheme is proposed for the C-band accelerating structure system, as summarized in Table 2.

4 Conclusions

High gradient and high beam quality are two crucial

Figure 10 The optimum results after 2B tuning.

Table 2 Parameters of the optimized C-band traveling-wave accelerating structure

C-band system	SLED-II + CG accelerating structure
Phase advance per cell	$4\pi/5$
Length of cell	20.988 mm
Length of total cells	1.785 m (83 regular cells+2 matching cells)
Average 2a	15 mm
Elliptical tip radius: 2B/2A	9 mm/5 mm
Width of iris: t	5 mm
Peak electric field ratio: E_{peak}/E_0	2.6
Average shunt impedance: R_s	62 Mohm/m
Average Q	10470
Average group velocity: V_g/c	1.7%
Filling time	340 ns
Attenuation factor: τ	0.554

characteristics of the linac for a compact XFEL facility, and this design optimization offers a remarkable improvement in the performance of a C-band accelerating structure and its high power RF system. The time dependent constant field provides the extensive capability for a multi-bunch

pattern in the future. The short range wakefield is suppressed effectively for high beam quality, and the RF breakdown problem induced by the wakefield solution is weakened through the operating mode and disk shape optimization. Combining the analysis with experimental results, a new C-band traveling-wave accelerating structure will be designed and fabricated as a research and development activity for a future hard X-ray FEL facility.

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