THE HIGH POWER TEST MODEL OF C-BAND ACCELERATING STRUCTURE FOR COMPACT XFEL AT SINAP*

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Abstract
R&D of a C-band (5712 MHz) high gradient traveling-wave accelerating structure is being in progress at Shanghai Institute of Applied Physics (SINAP). Conceptual design of the accelerating structure has been accomplished, and verified by the cold test of the experimental model. Now the first prototype structure is ready for high RF power test and the optimization of a new operating mode is proposed for developing a robust high gradient C-band structure. In this paper, the results of the cold test of the first prototype structure and the optimization details are introduced.

INTRODUCTION
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 [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/SSpring-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].

The experimental model has been cold tested and verified on the feasibility [3], and the first high power structure is also ready, both are constant impedance accelerating structures and 2π/3 mode, 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 4π/5 mode is proposed.

COLD TEST OF FIRST PROTOTYPE
After all the brazing step, the C-band accelerating structure is tested by low power RF, and tuned to eliminate the mismatch of couplers and regular cells, at last, the high power model is shown in Fig. 1.

![1st prototype C-band accelerating structure](image1)

According to the non-resonant perturbation theory and technique [6, 7], A tuning code based on LABVIEW 8.5 has been written. The amplitude and phase of field distribution on axis are measured and analyzed, and then the mismatch of each cell can be calculated cell by cell independently. According to the mismatch of each cell, the accelerating structure can be tuned cell by cell iteratively under the control of LABVIEW code. After several iterations of tuning, the accelerating structure is matched, and the results are shown in Fig. 2.

![The matching field distribution and S11](image2)

After tuning of all cells and two couplers, the C-band accelerating structure is matched. The field distribution on axis is smooth and the reflection of input port become on
axis is smooth and the reflection of input port becomes slight as shown in Fig. 2. The SWR in of input port is below 1.1 corresponding to 2MHz bandwidth, and on the point of center frequency 5712MHz the S11 is about -35dB, and also the same to the field distribution on axis. The results are thus reach the design target, and after the baking, the model can be ready for the high power RF test.

**OPTIMIZATION FOR NEW MODE ACCELERATING STRUCTURE**

In order to develop the robust structure for the future application for compact XFEL facility, the optimization of the first prototype of C-band accelerating structure has been analyzed, and a new operating mode is derived after optimizing several issues.

**High Power RF System**

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.

According to the principles of operation of the first generation pulse compressor (SLED-I) and constant impedance (CI), the suitable combination of SLED-I and CI can give a smart scheme for constant field distribution on axis [8], however this scheme has two shortage: 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 constant gradient structure (CG)+SLED-II is an effective and stable solution. The SLED-II is a second generation pulse compressor with a flat-top pulse. 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.

**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” [9], and a large “a” can suppress the SRW in two directions. In Fig. 3, “2a” is increased from 10 mm to 15 mm, and the longitudinal and transversal SRW can be suppressed by factors of 2 and 6, respectively.

![Figure 3: SRW distribution of different aperture radius.](image)

**Table 1: Comparison between Different Modes**

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>Group velocity Vg/c (%)</th>
<th>Shunt impedance R (MΩ/m)</th>
<th>Phase stability dθ/df (°/MHz)</th>
<th>Attenuation factor τ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2π/3</td>
<td>3.441</td>
<td>64.50</td>
<td>0.61</td>
<td>0.1748</td>
</tr>
<tr>
<td>3π/4</td>
<td>2.846</td>
<td>63.43</td>
<td>0.84</td>
<td>0.1954</td>
</tr>
<tr>
<td>4π/5</td>
<td>2.356</td>
<td>69.96</td>
<td>1.07</td>
<td>0.2267</td>
</tr>
<tr>
<td>5π/6</td>
<td>1.986</td>
<td>69.31</td>
<td>1.32</td>
<td>0.2622</td>
</tr>
</tbody>
</table>

In Table 1, an attenuation factor 0.2267 of 4π/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 improved to 0.4 which is better for power efficiency.

**Iris Optimization for Suppressing the RF Breakdown**

In Section above, the last results for 4π/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 [10], and suppressing them can realize better performance of the RF breakdown. 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 should be tuned for the optimal peak electrical field and group velocity.

According to the analysis above, 2A is clearly the crucial factor for optimizing, and 2B is the assistant parameter for slightly optimization. Based on this results, a optimum point of 2A=5mm and 2B=9mm is found. At this point, 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, as shown in Fig. 6.

Summarizing the results in Sections 2 and 3, an optimization scheme is proposed for the C-band accelerating structure system, as summarized in Table 2.

Table 2: Parameters of the Optimized C-band Traveling-wave Accelerating Structure

<table>
<thead>
<tr>
<th>C-band system</th>
<th>SLED-II + CG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase advance per cell</td>
<td>4π/5</td>
</tr>
<tr>
<td>Length of cell</td>
<td>20.994 mm</td>
</tr>
<tr>
<td>Length of total cells</td>
<td>1.784 m</td>
</tr>
<tr>
<td>Average 2a</td>
<td>15 mm</td>
</tr>
<tr>
<td>Elliptical tip radius: 2B/2A</td>
<td>9 mm/5 mm</td>
</tr>
<tr>
<td>Width of iris:  t</td>
<td>5 mm</td>
</tr>
<tr>
<td>Peak electric field: E_{peak}/E_{0}</td>
<td>2.6</td>
</tr>
<tr>
<td>Shunt impedance: Rs</td>
<td>Ave: 62 Mohm/m</td>
</tr>
<tr>
<td>Q factor</td>
<td>Ave: 10470</td>
</tr>
<tr>
<td>Group velocity : vg/c</td>
<td>Ave: 1.7 %</td>
</tr>
<tr>
<td>Filling time</td>
<td>340 ns</td>
</tr>
<tr>
<td>Attenuation factor: r</td>
<td>0.585</td>
</tr>
</tbody>
</table>

CONCLUSION

C-band high gradient accelerating structure is a key technique of the linac for a compact XFEL facility at SINAP, and now the first prototype of high power model is read and the relative design optimization offers a remarkable improvement in the performance of a C-band accelerating structure for the development of robust C-band accelerating structure.

ACKNOWLEDGEMENT

It’s grateful to Dr. Juwen Wang of SLAC for his helpful suggestions and useful discussion.

REFERENCES


[10] Z. Li et al, SLAC-PUB-11916