Design and study of a C-band pulse compressor for the SXFEL linac (Postprint)

Authors: WANG Chao-Peng, FANG Wen-Cheng, TONG De-Chun, Gu Qiang, ZHAO Zhen-Tang

Date: 2023-06-18T00:00:00+00:00

Abstract

A C-band RF pulse compressor is in development at SINAP. It comprises of two resonant cavities, two mode convertors and a 3 dB power divider. TE0.1.15 mode is selected for obtaining higher quality factor Q0 of the RF pulse compressor cavities, so that the power gain factor can be 3.2, which is supposed to multiply the RF power from 50 MW to 160 MW. In this paper, we report our work on C-band RF pulse compressor, namely the design simulation and cold test results.

Full Text

Design and Study of a C-band Pulse Compressor for the SXFEL Linac

WANG Chao-Peng, **FANG Wen-Cheng**, **TONG De-Chun**, **GU Qiang**, and **ZHAO Zhen-Tang**∗

1 Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
2 University of Chinese Academy of Sciences, Beijing 100039, China
3 Department of Engineering Physics, Tsinghua University, Beijing 100084, China

(Received February 19, 2013; accepted in revised form March 22, 2014; published online April 20, 2014)

A C-band RF pulse compressor is currently under development at the Shanghai Institute of Applied Physics (SINAP). The device comprises two resonant cavities, two mode converters, and a 3 dB power divider. The TE_{0115} mode has been selected to achieve a higher quality factor Q_0 for the RF pulse compressor cavities, enabling a power gain factor of 3.2 that will multiply the RF power

from 50 MW to 160 MW. This paper reports our work on the C-band RF pulse compressor, including design simulations and cold test results.

Keywords: C-band, Pulse compressor, High quality factor, High RF power
DOI: 10.13538/j.1001-8042/nst.25.020101

Introduction

A compact Soft X-ray Free Electron Laser test facility (SXFEL) is currently under construction at the Shanghai Institute of Applied Physics (SINAP), Chinese Academy of Sciences. The facility will be located adjacent to the Shanghai Synchrotron Radiation Facility (SSRF), China' s first third-generation light source. To achieve a more compact design for SXFEL, the third section of the linac will incorporate four C-band microwave acceleration units operating at a high acceleration gradient of 40 MV/m [1]. This will be realized using a C-band RF pulse compressor, a crucial component for the C-band high-gradient acceleration system that will be tested together with the C-band accelerating structure in the SXFEL facility.

RF pulse compression is employed to multiply RF power for increasing the acceleration gradient. Several types of RF pulse compressors have been utilized at facilities worldwide. Following the successful development of the SLAC Energy Doubler (SLED) prototype at the Stanford Linear Accelerator Center [2-4], rapid advancements have been made in higher efficiency and flat-top technology for RF pulse compressors, including SLED-II [5], small delay line RF pulse compressors [6, 7] (using coupled cavities), BPC [8], DLDS [9], and BOC [10]. As a compact FEL facility, SXFEL employs high-efficiency, high-gradient C-band acceleration units. An RF pulse compressor with flat-top output pulses represents a compromised solution that achieves both high efficiency and high accelerating gradient, which can be implemented using SLED-I controlled by AM-PM LLRF (low-level RF) modulation technology.

The proposed SLED-I system comprises two cavities, two mode converters, and a 3 dB power divider. The TE_{0115} mode of the circular cavity has been selected for its high quality factor of 180,000, with a targeted power gain factor of 3.2. The 3 dB power divider, optimized for high power transmission, effectively avoids breakdown problems. A four-port mode converter is used to connect the 3 dB divider and resonant cavities, enabling higher purity of the TE_{01} mode than one-port or two-port converters and ensuring that only the TE_{0115} mode exists for high quality factor operation.

This paper presents the design study of the C-band RF pulse compressor, including results from RF simulation and cold testing of the resonant cavity.

Configuration and Principle of RF Pulse Compressor

The C-band RF pulse compressor for the SXFEL C-band microwave acceleration unit is driven by a 50 MW klystron, as shown in Fig. 1 [Figure 1: see original paper]. The RF pulses are compressed into shorter pulses, thereby increasing the RF power by several times and dividing it into two equal parts for the two accelerating structures.

The C-band accelerating structure of the SXFEL test facility is required to operate at a gradient of 40 MV/m. Correspondingly, the input power for each acceleration structure should be 70 MW. Therefore, the klystron output power of 50 MW must be enhanced to 160 MW by the RF pulse compressor. After accounting for waveguide dissipation, approximately 75 MW will be delivered to each acceleration structure. Considering design and fabrication constraints, SLED-I represents a practical compromise. As shown in Fig. 2 [Figure 2: see original paper], the system consists of two identical high Q-value cavities, two mode converters, and a 3 dB power divider. Its performance depends primarily on the resonant cavities.

In principle, since the LLRF system experiences power loss during modulation of the flat-top output pulse, the final energy multiplication factor is approximately 1.8, with a corresponding power gain factor of about 2.5. The profiles of input power and output power are illustrated in Fig. 3 [Figure 3: see original paper].

Simulation and Results

In the C-band microwave unit, the klystron outputs RF pulses with a width of 2.5 µs, which are transmitted into the two SLED cavities. When electromagnetic fields are induced in the cavities, waves of increasing amplitude are emitted from the coupling holes of the two resonant cavities. The two emitted waves, having the same phase, combine at the accelerator-side port of the 3 dB power divider but cancel each other due to a 180° phase difference at the klystron-side port. Two waves are reflected from the coupling hole of the cavity, while waves are emitted from the inner cavity. The reflected and emitted waves have a 180° phase difference, but they add together when the input wave is reversed to the same phase at the time of 2.0 µs.

From this principle of SLED-I, the power for the resonant cavity is expressed by Eq. (1):

$$T_c \frac{dE_e}{dt} + E_e = -\alpha E_K$$

where $\alpha = \frac{2\beta}{1+\beta}$, β is the coupling coefficient; $T_c = \frac{2Q_L}{\omega}$ is the cavity filling time, Q_L is the cavity loaded quality factor, ω is the radian frequency; E_e is the emitted wave from the coupling aperture, and E_K is the reverse wave of equal magnitude to the incident wave. Considering the principle of SLED operation, Eq. (2) is derived as [2]:

$$E_L(A) = -\alpha e^{-\tau} + (\alpha - 1) \quad 0 \leq t \leq 2.0\,\mu\text{s}$$

$$E_L(B) = \gamma e^{-(\tau-\tau_1)} - (\alpha - 1) \quad 2.0\,\mu\text{s} \le t \le 2.5\,\mu\text{s}$$

$$E_L(C) = \gamma e^{-(\tau_2-\tau_1)} - \alpha e^{-(\tau-\tau_1)} \quad t \ge 2.5\,\mu\text{s}$$

where $\gamma \equiv \alpha(2 - e^{-\tau})$, $\tau = t/T_c$, $\tau_1 = 2.0\,\mu$s and $\tau_2 = 2.5\,\mu$s. Fig. 3 shows the profiles of the input wave and output wave of SLED. Although the energy gain factor is 2.5 in principle, the LLRF system has power loss for modulation of the flat-top output pulse, resulting in a final energy multiplication factor of about 1.8.

Based on theoretical analysis, MATLAB is used for parameter optimization of the Q-value, coupling coefficient, and power efficiency. CST MICROWAVE STUDIO [11], which is well-suited for asymmetrical structure computation, is employed for three-dimensional electromagnetic simulation.

Resonant Cavity

As a crucial component of an RF pulse compressor, the resonant cavity stores energy and dominates the performance of the RF pulse compressor, including the gain factor and power efficiency. By tuning the Q_0 and the coupling coefficient, the RF power efficiency and energy multiplication factor can be mapped, as shown in Fig. 4 [Figure 4: see original paper]. The optimal parameters are determined by practical application requirements. In our design, for a multiplication factor of 3.2, the coupling coefficient is fixed at 8.5 and the Q-value at 180,000.

The TE_{0115} mode is used for its higher quality factor and lower power loss on the copper surface. However, many modes are close to TE_{0115} and can be harmful to SLED-I performance, necessitating cavity geometry optimization to suppress these modes. The frequency of different modes can be expressed by cavity geometry parameters as Eq. (3) [12]:

$$(f_0 D)^2 = 9 \times 10^{20} \left[\left(\frac{\upsilon_{mn}}{\pi}\right)^2 + \left(\frac{p}{2}\right)^2 \left(\frac{D}{l}\right)^2 \right]$$

where f_0 is the TEm,n,p/TMm,n,p frequency of the cavity, D is the cavity diameter, and l is the cavity length. Using Eq. (3), TE_{0115} and its adjacent modes are plotted in Fig. 5 [Figure 5: see original paper], where each line indicates the relationship between the resonant frequency and the cavity parameters. The marked point is far away from adjacent modes, thus determining the cavity geometry parameters.

According to the previous analysis, CST MICROWAVE STUDIO is used for three-dimensional field simulation, including frequency, Q_0, and coupling coefficient. The electromagnetic simulation results are shown in Fig. 6 [Figure 6:

see original paper]. Based on the simulations, the frequency of the resonant cavity is fixed at 5712 MHz by adjusting the position of the end plate to find the exact coupling hole size for a coupling coefficient of 8.5 and a final Q-value of the resonant cavity of about 180,000.

After cavity fabrication, the operating frequency of the TE_{0115} mode can be confirmed to tune the cavity to 5712 MHz. As a reference for measurements, we simulated the field distribution, Q-value, and frequency sensitivities. Fig. 7 [Figure 7: see original paper] shows the simulated longitudinal magnetic field along the cavity axis and radial direction. For TE_{01} mode, the field distribution is axially symmetrical; the magnetic field comprises H and H_z components, while only E_ϕ exists for the electric field. There are 15 field peaks of H_z on the axis based on the CST simulation (Fig. 7(a)), and the radial distribution of E_ϕ in the middle of the cavity (Fig. 7(b)).

The frequency sensitivities against the cavity length and radius were also calculated as references for cavity tuning, with a frequency sensitivity of $\Delta f/\Delta l =$ 10.5 MHz/mm for the cavity length (Fig. 8 Figure 8: see original paper) and $\Delta f/\Delta D = 6.6$ MHz/mm for the cavity radius (Fig. 8(b)).

3 dB Power Divider

The 3 dB power divider directs RF power into the two cavities of the RF pulse compressor (Fig. 9 [Figure 9: see original paper]). The power from the two cavities adds at the accelerator-side port and cancels at the klystron-side port. Based on the principle of the 3 dB power divider, the length L of the coupling region can be tuned for matching, and the input power can be equally divided into two parts as shown in Fig. 9. The analytical length L of the matched status is expressed as Eq. (4), where λ_{g10} and λ_{g20} are the waveguide wavelengths of the TE_{10} and TE_{20} modes in the rectangular waveguide, respectively [12].

A ladder-type hybrid is used in the connection region to obtain better performance and avoid RF breakdown while facilitating high-power input. The CST simulation of the S-parameters of the 3 dB coupler divider is shown in Fig. 10 [Figure 10: see original paper], where Port 1 is for input power, Ports 2 and 3 are connected to the two cavities, and Port 4 is used for power output. From the figure, S_{11} and S_{41} are less than -30 dB, while S_{21} and S_{31} are about -3 dB, achieving the design goals for power transmission and isolation.

Mode Converter

The mode converter, located between the 3 dB power divider and resonant cavities, is used to obtain high purity of the TE_{01} mode and convert the TE_{10} rectangular mode to the TE_{01} circular mode. Four coupling holes are designed for the mode converter to enable stable operation at 80 MW (Fig. 11 [Figure 11: see original paper]). Fig. 12 [Figure 12: see original paper] shows the simulated S-parameters for the mode converter. S_{21} and S_{11} are about 0 dB and -50 dB, respectively, well achieving the design goals.

Typical parameters of the C-band RF pulse compressor, comprising two cavities, two mode converters, and a 3 dB power divider, are summarized in Table 1 .

Cold Test Results of Resonant Cavity

An experimental model of the resonant cavity (Fig. 13(a) [Figure 13: see original paper]), including an input coupler, a tuner, and a cavity, was fabricated to verify the design. The Q-value, frequency, and field distribution along the axis were measured, and tuning experiments were carried out. As shown in Fig. 13(b), the measured frequency was 5711.63 MHz, and the Q-value was 159,640, which is slightly lower than the design value but can be improved after brazing.

Longitudinal and radial distributions of H_z were measured by resonant perturbation (Fig. 14 [Figure 14: see original paper]). The measured magnetic field distribution along the cavity axis (Fig. 14(a)), with 15 peaks, agrees well with the simulation result in Fig. 7(a). However, the radial distribution (Fig. 14(b)) differs somewhat from the data in Fig. 7(b), caused by misalignment of the measurement line. In Fig. 7(b), the profile is located exactly at the middle of the cavity, while in Fig. 14(b), the measured profile location was shifted during the tuning process, so the test results contain contributions from both magnetic and electric fields.

The measured frequency sensitivity of cavity length is $\Delta f/\Delta l = 10.5$ MHz/mm, agreeing well with the simulation data of $\Delta f/\Delta l = 10.4$ MHz/mm.

Conclusion

The C-band RF pulse compressor, as a crucial component for the SXFEL test facility, has been designed and simulated. A resonant cavity model was fabricated and tested under low RF power. To a large extent, the low-power experimental results agree well with the design goals, accumulating valuable data and experience for further development of the C-band RF pulse compressor. The experimental cavity design and mode measurement provide an integrated and systematic method for the R&D of the C-band RF pulse compressor. The complete C-band RF pulse compressor will be fabricated, and high-power RF tests will be conducted soon.

Acknowledgments

The authors are grateful to Dr. WANG Ju-Wen of the SLAC National Accelerator Laboratory for valuable suggestions and fruitful discussions. We would also like to thank Professor CHEN Huai-Bi and coworkers at the Accelerator Laboratory of Tsinghua University for experimental support.

References

[1] Fang W C, Gu Q, Tong D C, et al. Chinese Sci Bull, 2011, 56:

[2] Farkas Z D, Hogg H A, Loew G A, et al. SLED: A Method of Doubling SLAC' s Energy, SLAC-PUB-1453, June 1974.

[3] Fiebig A, Schieblich Ch, Hogg G A, et al. A Radio Frequency Pulse Compressor for Square output Pulse, in Proc. EPAC88, Rome, Italy, June 7, 1988, pp.1075-1077.

[4] Farkas Z D, Hogg H A, Loew G A, et al. IEEE T Nucl Sci, 1975, 22: 1299-1302.

[5] Wilson P B, Farkas Z D, Loew G A, et al. SLED II: A New Method of RF Pulse Compression, Linear Accelerator Conference, Albuquerque, NM, September 1990, SLAC-PUB-5330.

[6] Yoshida M. New concept samll delay line type pulse compressor using coupled cavities, in Proc. LINAC 2006, Tennessee, USA, August 20, 2006, pp. 667-669.

[7] Yoshida M. Ph.D. Thseis, The Research and Development of High Power C-band RF Pulse Compression System using Thermally Stable High-Q Cavity, 2003.

[8] Tantawi S G, Ruth R D, Vlieks A E, et al. Nucl Instrum Meth A, 1996, 370: 297-302.

[9] Linac Coherent Light Source (LCLS) Conceptual Design Report, SLAC-R-593, April, 2002.

[10] Geschonke G and Ghigo A. CTF3 Design Report. CTF3 Note 2002-047 and LNF-02/008 (IR), CERN/PS 2002-008 (RF),

[11] www.cst.com

[12] Yan L R and Li Y H. Basis of microwave technique. Beijing Institute of Technology press, 2004, 308-310.