

A C-BAND COMPACT SPHERICAL RF PULSE COMPRESSOR FOR THE SXFEL LINAC ENERGY UPGRADE*

Z. Li¹, W. Fang, Q. Gu, Z. Zhao[†], SINAP, CAS, Shanghai, China
¹also at UCAS, Beijing, China

Abstract

A new compact C-band (5712 MHz) spherical RF pulse compressor has been designed for Shanghai Soft X-ray Free Electron Laser (SXFEL) facility energy upgrading at Shanghai Institute of Applied Physics (SINAP), Chinese Academy of Sciences (CAS). This pulse compressor contains one high Q_0 spherical RF resonant cavity which works on two TE_{113} modes and a novel coupler. As there is only one storage cavity, this pulse compressor can be much smaller than the traditional SLED. With the coupling coefficient 4.9, the average power gain can be as high as 3.8. In this paper, the scheme of the C-band spherical pulse compressor and RF design are presented.

INTRODUCTION

A compact soft X-ray Free Electron Laser facility has been constructed at SINAP. This facility utilizes C-band RF technology with accelerating gradient of about 40 MV/m to accelerate the electrons to 0.84 GeV by a linac [1]. As an upgrade, there will be more C-band accelerating structures cascaded to increase the electron energy to 1.5 GeV in the future.

A new kind of pulse compressor based on only one spherical cavity is proposed and developed for LCLS X-band linac linearizer at SLAC [2]. In this scheme, two polarized spherical TE_{114} modes exist in same spherical cavity, which makes the resonant frequencies of these two modes easy to tune to same frequency, and keep the same during high power operation to make RF power stable. Meanwhile, only one spherical cavity also makes this pulse compressor small remarkably. Based on this X-band spherical pulse compressor, we have designed a C-band one as an upgrade of our SLED-type pulse compressor [3]. Considering the practical requirements of SXFEL, the two spherical TE_{113} modes are chosen to carry RF power, which can make the pulse compressor as compact as possible while the energy gain can be still high enough.

CALCULATION AND SIMULATION

This new compact pulse compressor is composed of one spherical cavity and a combined 3-dB coupler. They are designed separately by 3D simulation software, and then assembled together to get final results.

General Parameters Calculation of C-band Pulse Compressor

The output power of klystron is 50 MW with pulse width 2.5 μ s. Power pulse is designed to reverse at 2.0 μ s, and

pulse width will be compressed to 0.5 μ s by pulse compressor. Eventually the power will be fed into two accelerating structures with attenuation factor of $\tau=0.6$ and filling time of $T_a=0.372$ μ s.

By solving wave functions with the boundary conditions that tangential components of \mathbf{E} vanish at $r=a$, the resonant frequency in a spherical cavity of TE_{mnp} mode is:

$$f = \frac{\mu_{np}}{2\pi a \sqrt{\epsilon_0 \mu_0}} \quad (1)$$

where μ_{np} presents the zeros of the spherical Bessel function \hat{J}_n and a is the cavity radius. As $f=5712$ MHz, $\mu_{13}=10.904$, therefore $a=91.083$ mm. For a spherical resonant cavity that works on TE_{mnp} mode, the unloaded quality factor Q_0 can be calculated as $Q_0=a/\delta$, where $\delta = 1/\sqrt{\pi f \mu_1 \sigma_1}$ is the skin depth. The unloaded quality factor then is 1.04×10^5 as $a=91.083$ mm.

Associated with a traveling wave constant gradient accelerator, the expression of energy multiplication factor M can be obtained [4]:

$$M = \gamma e^{-\frac{T_a}{T_c}} \frac{1 - (1 - \tau)^{1+\nu}}{\tau(1 + \tau)} - (\alpha - 1) \quad (2)$$

where $T_a = (L/v_g \tau) \ln(1/(1 - \tau))$ is the filling time of accelerator and $\nu = T_a/(T_c \ln(1 - \tau))$. Based on Eq. (2), the energy gain M and coupling coefficient β could be presented as blue curve in Fig. 1. In this figure, energy gain approaches peak point of 1.85 when coupling coefficient is about 4.9, which is the optimum working point for C-band pulse compressor.

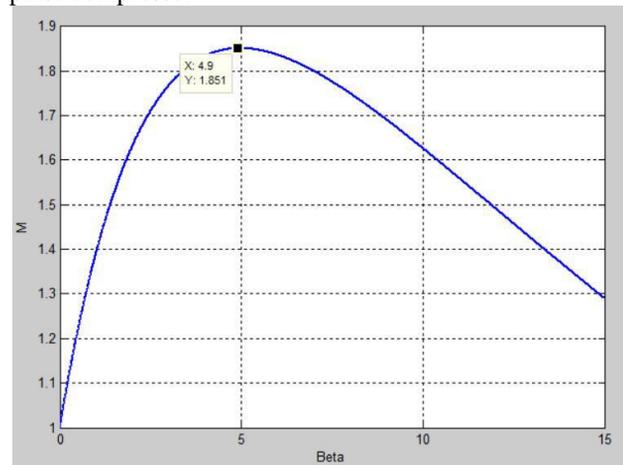


Figure 1: Energy gain as a function of β when $Q_0=1.04 \times 10^5$.

* Supported by the National Natural Science Foundation of China (No. 11675249)

[†] Corresponding author (email: zhaozt@sinap.ac.cn)

Figure 2 shows the waveform of the output power (red) and output E-field (green) of the pulse compressor. With quality factor 1.0×10^5 and coupling coefficient 4.9, the peak E_{out} can be as high as 2.5, and peak P_{out} more than 6. An average power gain of 3.8 is generated by integrating P_{out} from $t=2 \mu s$ to $t=2.732 \mu s$.

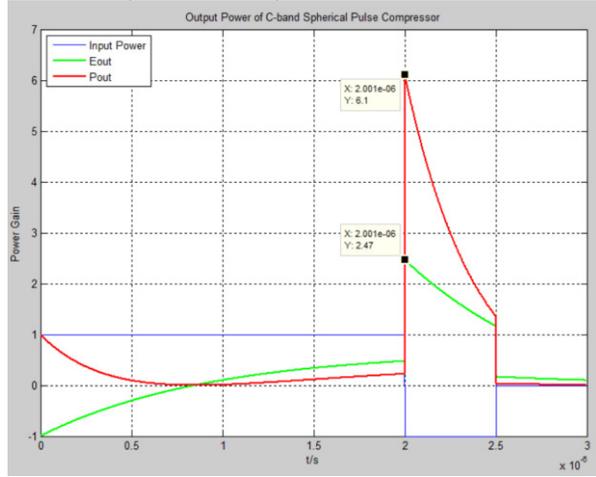


Figure 2: Waveform of the input power, output E-field and output power.

Spherical Cavity Design

Figure 3 shows results of S-parameter one TE_{113} mode in cavity by *CST Frequency Domain Solver*. Results for the other TE_{113} mode is the same as this one. Since the driving signal on coupling aperture is a pair of polarized circular TE_{11} modes when simulating, which will be the same as practice, the TE_{013} mode can be hardly inspired and is strongly under-coupled. As a result, TE_{013} signal of S-parameter is smeared.

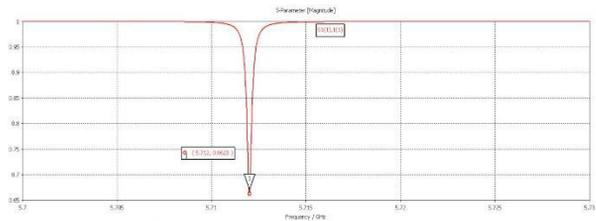


Figure 3: S-parameter of one TE_{113} mode.

Coupler Design

A multi-function coupler is utilized for this pulse compressor [5]. Figure 4 shows the coupler and its E-field. If the geometry parameters are properly chosen, the two polarized circular TE_{11} modes on Port-3 would bring half of the input power respectively, which is -3 dB. Figure 5 shows the simulation results of the coupler by *CST*. The S-parameters of the two TE_{11} modes are -3.005 dB and -3.031 dB, respectively. The reflection back to Port-1 is -29.907 dB and the isolation of Port-2 is -31.08 dB.

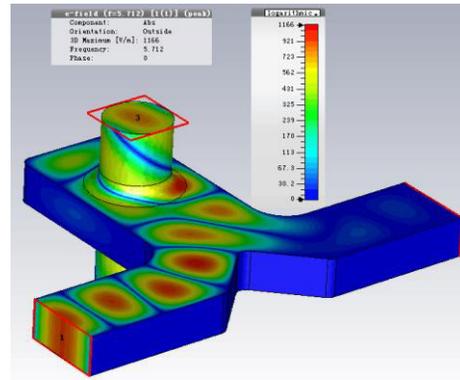


Figure 4: The coupler and its E-field (ABS) simulated by *CST*.

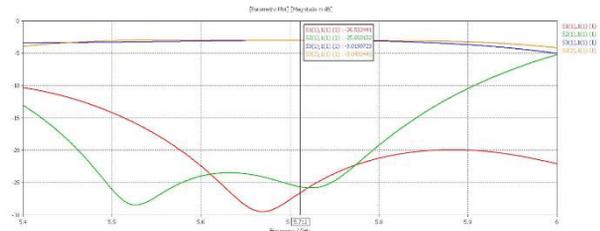


Figure 5: S-parameter of the coupler.

The New Compact C - band RF Pulse Compressor

Based on the analysis and simulation above, a new compact C-band RF pulse compressor is designed as shown in Fig. 6. The S-parameter and Smith chart are shown in Fig. 7. The two TE_{113} modes are over-coupled. There is no nearby mode in the range of 30 MHz bandwidth at least. The reflection on Port-1 is less than -20 dB and coupling coefficient $\beta = (1+0.66277)/(1-0.66277) = 4.9$.

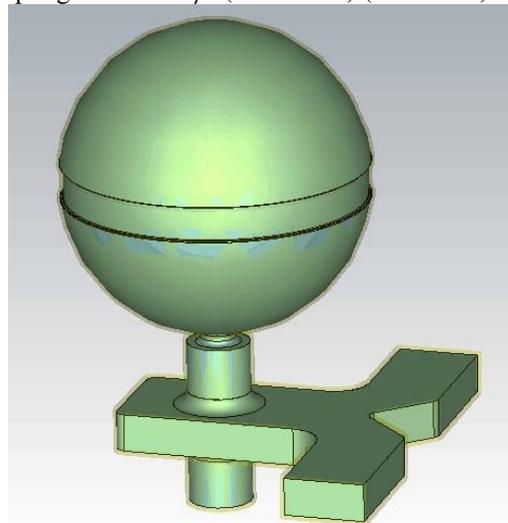


Figure 6: 3D model of the spherical pulse compressor.

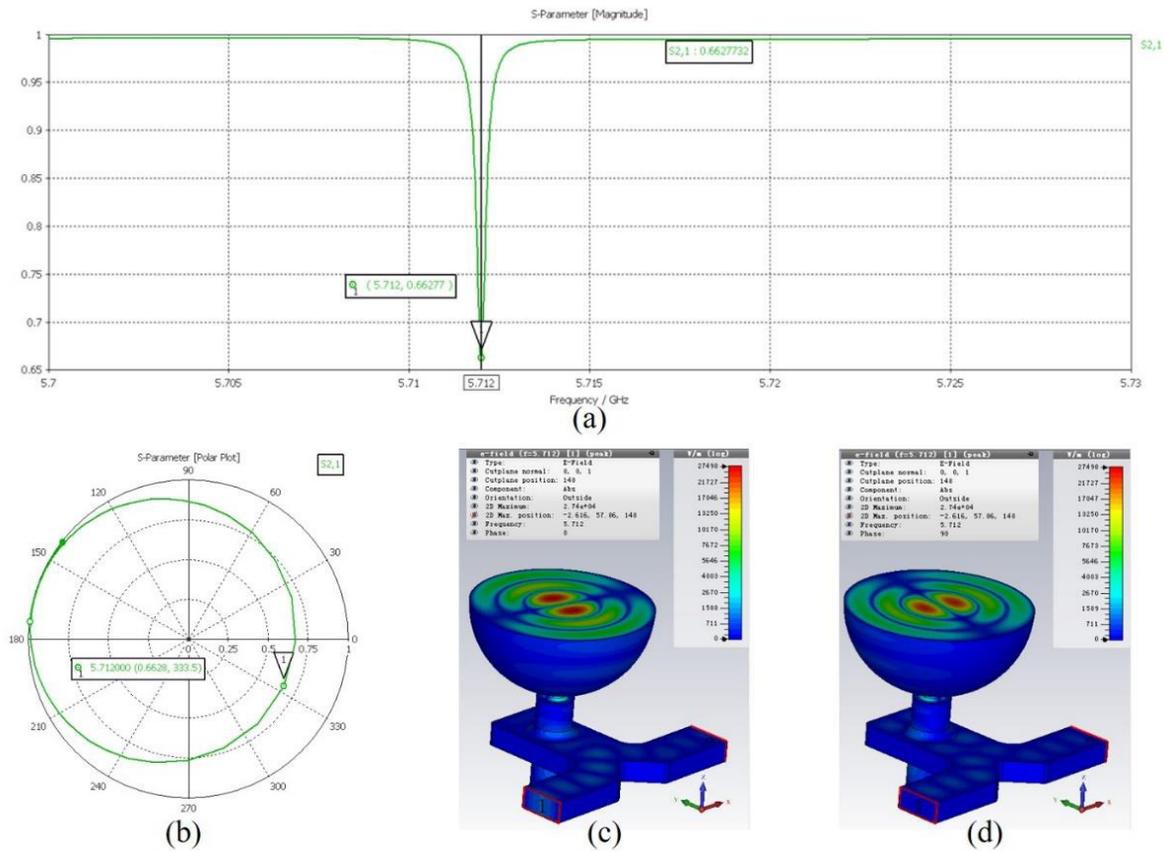


Figure 7: The S-parameter (a), Smith chart (b) and two TE₁₁₃ modes (c and d) in cavity.

CONCLUSION

A new type of C-band compact spherical RF pulse compressor has been designed for SXFEL. Using one spherical resonant cavity worked on two TE₁₁₃ modes and a novel coupler, this pulse compressor can obtain an energy gain of 1.85 while the coupling coefficient is 4.9 with quality factor 1.0×10^5 . Based on this compact pulse compressor, future upgrading SXFEL could be more stable and compact. Furthermore, this technique could be a preparation for future compact hard X-ray FEL facility.

REFERENCES

- [1] W. Fang *et al.*, “Design optimization of a C-band traveling-wave accelerating structure for a compact X-ray Free Electron Laser Facility”, *Chinese Sci. Bull.*, vol. 56, no. 32, pp. 3420–3425, 2011
- [2] J. Wang *et al.*, “New SLED 3 system for Multi-mega Watt RF compressor”, arXiv preprint arXiv: 1408.4851, 2014.
- [3] C. Wang *et al.*, “ Design and study of a C-band pulse compressor for the SXFEL linac”, *Nucl. Sci. and Tech.* vol. 25, no. 2, p. 020101, 2014.
- [4] Z. D. Farkas *et al.*, “ SLED: A method of doubling SLAC’s energy”, SLAC-PUB-1453, June, 1974
- [5] M. Franzi *et al.*, “ Compact RF polarizer and its application to pulse compression systems”, *Phys. Rev. ST Accel. Beams* vol. 19, p. 062002, 2016.