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RF DESIGN OF A C-BAND SPHERICAL PULSE COMPRESSOR FOR LINAC OF SUPER TAU-CHARM FACILITY *

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Abstract

Pulse compressors have been widely used to generate very high peak RF power in exchange for a reduction in the RF pulse length for linear accelerators. A C-band spherical pulse compressor is numerically studied for the linac of Super Tau-Charm Facility in this paper. Utilizing a dual-mode coupler for producing two orthogonal polarized TE_{11} modes, TE_{114} mode is chose for storing energy in resonant cavity enabling a Q_0 over 1.3×10^5. By modulating the coupling factor to 8.6, an optimum average power gain of 4.8 can be achieved in the case of combing with a 3π/4 travelling wave accelerator. This paper concludes the optimum RF parameters of the pulse compressor, as well as the geometry tolerance is given for the next step machining.

INTRODUCTION

As a natural and feasible extension project of Chinese next generation of electron-positron collider—Super Tau-charm Facility (STCF) is planned to be constructed in the near future by USTC. Aiming to operate at a center-of-mess energy ranging from 2 to 7 GeV, and a peak luminosity greater than $0.5\times10^{35}cm^{-2}s^{-1}$, this project requires a large number of high-gradient accelerating structures and higher RF power of klystrons [1]. Therefore, it poses a great request to the existing accelerator technologies.

Pulse compression technique enhances the RF output power at the expense of compressing pulse length, thereby enabling a high RF-to-beam power efficiency, and a more compact linac structure. A typical SLAC Energy Doubler (SLED) was first developed at SLAC [2]. It gains a multiplied power by two cylindrical cavities working in TE_{015} modes. The present study focuses on a compact spherical pulse compressor as optimization. It employs a dual-mode coupler producing two polarized orthogonal TE_{11} modes, exciting polarized TE_{114} mode in spherical cavity, which is corresponded to the two modes in cylindrical cavities in SLED.

Sphere makes lower energy loss on surface, as well as makes the system more compact in scale, which lessens the difficulty of fabrication and costs. This paper first introduces basic theory of pulse compression. In section II, the design and optimization on this model are performed. The optimum geometry and physical parameters are given as conclusion.

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CALCULATION FOR COMPRESSION

The basic pulse compression progress is shown in Fig. 1. During t_1 section of an input pulse, the cavity store energy from klystron. For the remaining time the phase of the input RF pulse is reversed by 180 degrees, waves superimpose result in a multiplied RF power. The reverse time t_2, which is also the width of output power, is determined according to the filling time of linac [3].

A spherical pulse compressor is presented in Fig. 2a. Multiplied power transfer through the 3-dB hybrid, and is divided into several accelerators by the power divider, enabling a higher RF-to-beam efficiency [4]. For such linac unit with an input power of 50 MW, as Fig. 2b, a pulse width of 2.5 μs will be compressed into 0.3 μs as a multiplication factor of about 4.7.

The output power can be calculated through the energy conservation. Associating with a travelling wave accelerator, the energy multiplication factor M, i.e. the ratio of output and input power, can be expressed as [5]:

$$M = \gamma e^{-\frac{T_a}{T_f}} \frac{1-(1-\tau)^{1+\nu}}{\tau(1+\nu)} - \frac{\beta-1}{\beta+1} \qquad (1)$$

where $T_a = \frac{L}{v_g \tau}\ln\left(\frac{1}{1-\tau}\right), T_f = \frac{2Q_0}{\omega(1+\beta)}, \nu = \frac{T_a}{T_f \ln(1-\nu)}$. In this formula, M is only associated with T_f, Q_0 and β.

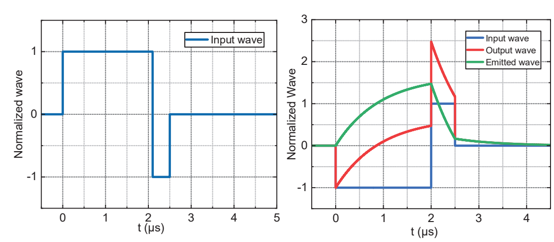

Figure 1: Basic pulse compression progress.

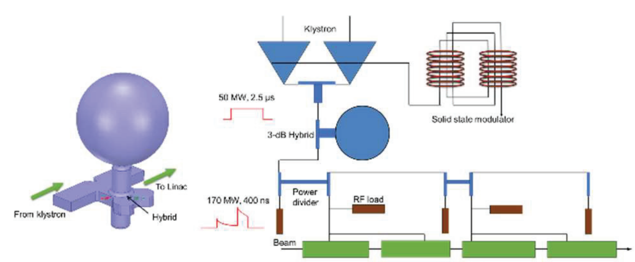

Figure 2: Schematic of (a) a spherical pulse compressor, (b) a linac RF unit.

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RF DESIGN AND SIMULATION

Cavity Design and Simulation

For a spherical cavity works on TE_{mnp} mode, we get resonant frequency by solving wave functions through the boundary condition $E_{\varphi(r=a)} = 0$:

$$f = \frac{\mu_{np}}{2\pi a\sqrt{\varepsilon_0 \mu_0}} \quad (2)$$

Where μ_{np} is the p^{th} root of the n^{th}-order spherical Bessel function. Unloaded quality factor Q_0 can be calculated as:

$$Q_0 = \frac{a}{\delta} \quad (3)$$

Where δ is the skin depth of copper, and Q_0 is mainly dominated by radius. In Eq. (2), frequency is independent of *m*, it is obvious that mode degeneracies exist in this structure. A coupling port is utilized for restraining the degenerate mode and tuning the coupling factor additionally. Several working modes are compared in Table 1, through theoretical analysis and calculation.

Table 1: Q_0 of Different Working Modes

Modes	Frequency [GHz]	Radius [mm]	Q_0	M
TE_{113}	5.712	91.1	102400	4.6
TE_{114}	5.712	117.5	133140	4.8
TE_{115}	5.712	143.9	150700	4.9

TE_{114} mode is chosen for main working mode due to a trade-off between fabrication cost, frequency separation of adjacent modes and power gain. The simulated electric and magnetic fields of resonant cavity for TE_{114} mode is illustrated in Fig. 3a and b.

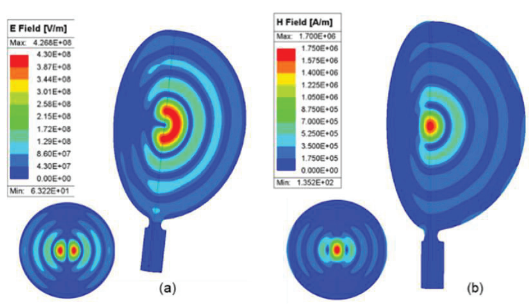

Figure 3: Simulated fields of TE_{114} modes (a quarter model). (a) electric field, (b) magnetic field.

Machining Accuracy and Tolerance

The resonant frequency is dominated by the cavity radius, as shown in Fig. 4a. It can be clearly seen that the sensitivity of frequency on cavity radius is about 63 MHz/mm. Therefore, the fabrication accuracy on cavity radius should be better under 5 μm for avoiding huge frequency deviation.

The Coupling coefficient β is mainly dominated by the coupling aperture, as shown in Fig. 4b, β varies from 5 to 11 while aperture varies 0.2 mm merely and M keeps over 4.4, which means that coupling aperture is not sensitive, 50 μm of accuracy is reasonable consequently.

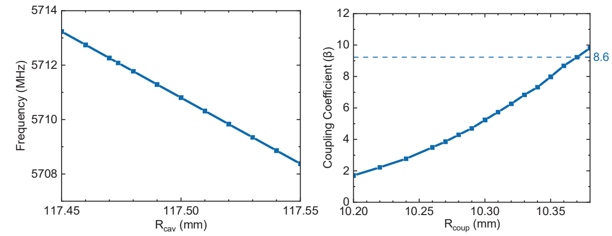

Figure 4: (a) frequency vs. R_{cav}, (b) β vs. R_{coup}.

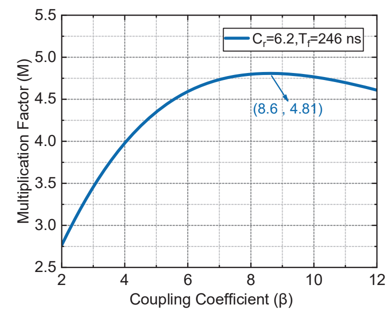

Figure 5: Energy gain as a function of β, Q_0 =1.33×10[5].

According to Eq. (1), Combing with a 3π/4 C-band travelling wave accelerator, which has a pulse time of $T_1 = 2.0$ μs, $T_2 = 400$ ns, the energy gain can be illustrated as Fig. 5. The optimum β is 8.6 while M reaches about 4.8 in maximum. The unloaded Q_0 of such cavity is 1.33×10^5. Considering the influence on frequency of coupling aperture, cavity radius is simulated smaller than designed. Figure 6 shows S parameter, Smith Chart and VSWR of this resonant cavity, simulated by Ansys HFSS driven mode solver.

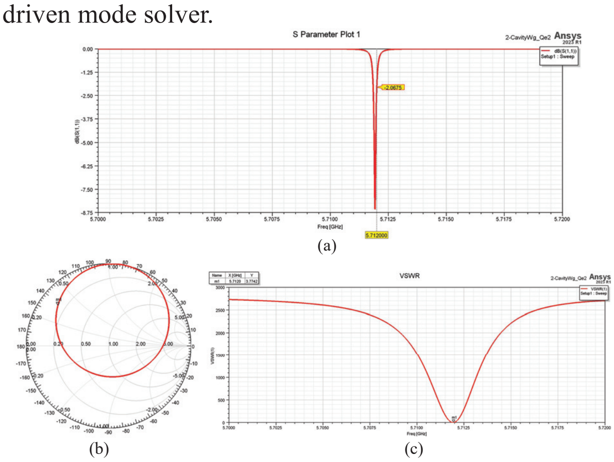

Figure 6: Simulated S_{11} of resonant cavity, Smith Chart and VSWR.

Coupler Design and Simulation

A mode coupler consists of two WR-187 waveguides, a mode-converter, and a circular waveguide, excites two polarized orthogonal TE_{11} modes at circular waveguide with negligible reflection and isolation. We consider two polarized modes as two wave ports in simulation, as shown in Fig. 7, with the design target based on a goal function FXM [6]:

$$\mathrm{FXM} = \left|\mathrm{Re}(S_{3:1,1})\mathrm{Im}(S_{3:21}) - \mathrm{Im}(S_{3:1,1})\mathrm{Re}(S_{3:2,1})\right| - 0.5 \quad (4)$$

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It is foreseen that FXM = 0 when three conditions are met:

$$|S_{3:1,1}|^2 = |S_{3:2,1}|^2 = 0.5 \quad (5)$$

$$|\arg(S_{3:1,1}) - \arg(S_{3:2,1})| = n\pi + \frac{\pi}{2} \quad (6)$$

$$|S_{1,1}| = |S_{2,1}| = 0 \quad (7)$$

Through simulations, FXM has been optimized to -105 dB in PEC condition. The simulated S_{11} = -51.98 dB, S_{21} = -63.09 dB, as shown in Fig. 8.

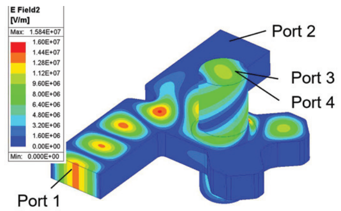

Figure 7: Simulated electric fields for the dual-mode coupler.

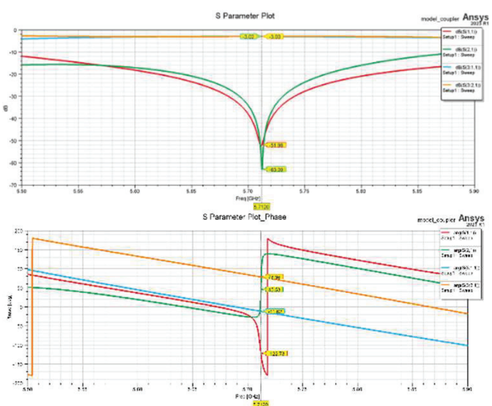

Figure 8: S parameters of mode coupler.

Optimum Geometry and Parameters

The main RF parameters of this pulse compressor has been summarized in Table 2. The Output power after compression is shown as Fig. 9. Combining with a C-band TW structure working on 3π/4 mode, a peak normalized power of 7.1 can be achieved in the case of $\beta = 6.6$, $Q_0 = 1.33\times10^5$.

Table 2: RF Parameters of Spherical Pulse Compressor

Parameter	Value	Units
Frequency	5712	MHz
Working modes	TE_{114}	-
Quality Factor [Q_0]	133140	-
Input pulse length [T_1]	2.5	µs
Output pulse length [T_2]	400	ns
Filling time [T_f]	246	ns
Operating mode	3π/4	rad
Cell number	46	-
Compression ratio [C_r]	6.25	-
Efficiency [η]	77.9	%
Coupling coefficient [β]	8.6	-
Multiplication Factor [M]	4.8	-

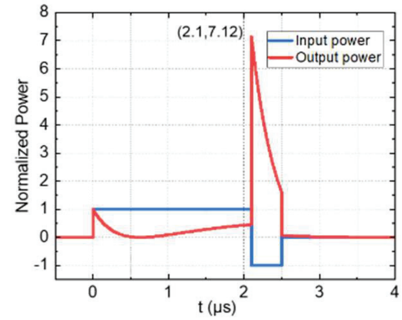

Figure 9: Power gain of this pulse compressor.

CONCLUSION

In this paper, we have designed a C-band spherical pulse compressor for Linac of the STCF. Working at polarized TE_{114} mode, an average energy gain of 4.8 with a coupling factor of 8.6 can be achieved through optimization. The RF design of this pulse compressor has been finalized, and the measurement of protype can be expected in further.

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