THE X-BAND PULSE COMPRESSOR FOR TSINGHUA THOMSON SCATTERING X-RAY SOURCE *

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Abstract

An X-band (11.424 GHz) high-power RF station is being built for Tsinghua Thomson-scattering X-ray Source (TTX). The station aims to feed several X-band accelerating structures working at a high gradient of 80 MV/m. An X-band pulse compressor is designed to compress the RF pulse from 1.5 μs to 100 ns and to generate more than 250 MW peak power from a 50 MW klystron. This pulse compressor implements a resonant cavity housing the HE_{11}-mode as the energy storage cavity, with a high quality factor Q of more than 10^5. The detailed designs of the high-Q cavity and the dedicate couplers of this pulse compressor are present in this work.

INTRODUCTION

The future X-band accelerating structures of Tsinghua Thomson-scattering X-ray Source (TTX) are supposed to work at high accelerating gradient of 80 MV/m, which requires high peak RF power more than 250 MW at the frequency of 11.424 GHz. For the same average power, building RF power amplifier (like klystron) with moderate peak power and long RF pulses is much easier than with short pulses and high peak power. To enhance the peak RF power, the RF pulse compression is needed. Over the past forty years, three main types of pulse compression systems, SLAC energy doubler (SLED-I), resonant delay line pulse compressor (SLED-II) and barrel open cavity (BOC) type, have been proposed and developed.

The SLED types store the RF pulse in a resonant cavity or a delay line, which was firstly applied in SLED-I and SLED-II respectively. Although with the fact that the SLED-II type outputs a flat pulse with high power gain and high efficiency [1], the length of the delay lines for a useful duration is much longer than the size of a cavity and therefore uneconomical. The SLED-I type using the resonant cavity works stable but outputs a sharply decaying exponential pulse. Furthermore, in order to isolate the source from the reflected pulse from cavities, both SLED-I and SLED-II require the use of two over-coupled cylindrical resonant cavities or delay lines with a 90-degree phase difference as well as a 4-port 3 dB hybrid. Typically, two identical cavities attached to a 3-dB coupler are utilized [2].

Different from SLED-I and SLED-II, the BOC type consists of a single barrel open cavity and a matching waveguide. The resonant mode in BOC called whispering galley mode leads to an extremely high unloaded Q (Q_0) [3]. Obviously, BOC is more compact and economical compared to SLED, but it's also more difficult to manufacture.

In the future RF station of TTX, the design goal of the pulse compression is to compress the pulse width from 1.5 μs to 100 ns and to generate more than 250 MW peak power from a 50 MW klystron. Considering this requirement, a SLED-I type RF pulse compressor was designed.

CAVITY DESIGN

For SLED-I type RF pulse compressor, the expression of the power for the resonant cavity is [2]:

$$T_c \frac{dE_e}{dt} + E_e = -\alpha E_k \,. \tag{1}$$

where $\alpha = 2\beta/(1+\beta)$, β is the cavity coupling coefficient, $T_c = 2Q_L/\omega$ is the cavity filling time, E_e is the emitted wave and E_k is the reverse wave.

When the coupling factor is optimized to give the largest power gain and the lowest surface field in X-band accelerating structures, β is set to 3.5. And Q_0 of our cavity should be about 140,000 ideally to generate a pulse with peak power gain of 5, as shown in Fig. 1. Three cavities, the smooth circular cavity, the spherical cavity and the corrugated circular cavity, had been taken into consideration.

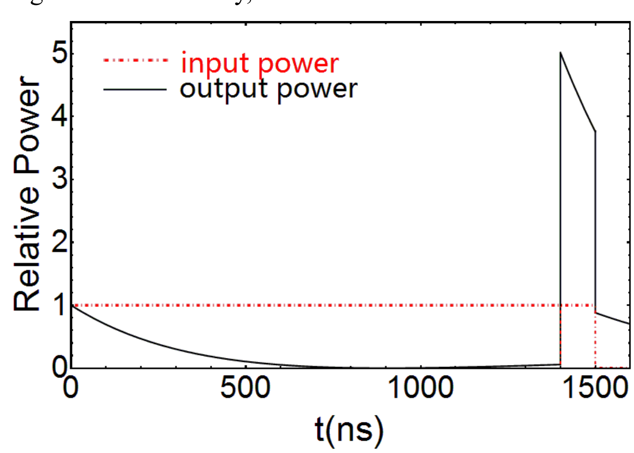

Figure 1: Waveforms of a SLED-I pulse compressor with β=3.5 and Q_0=140,000.

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The Cavity Mode

For typical SLED type pulse compressors, errors may occur while manufacturing two ideally identical cavities, which cause difference in phase or amplitude of the output pulse. In our design, this mechanism is emulated for isolation by using a single resonant cavity excited by two polarized modes [4].

The smooth circular cavity and the smooth spherical cavity are the practical ones for their simple structures and relatively-high Q_0. For the circular cavity, although TE_{01p} mode is the fundamental mode which exhibits the lowest attenuation, there is no preferred plane of polarization. As a high Q_0 is still required, TE_{11p} mode is applied, as shown in Fig. 2(b). As for the spherical cavity, its TE modes seem ideal for use due to their high-Q_0 and number of degenerate modes. Its fundamental mode defines three degenerate eigen-solutions, TE_{01p} mode, TE_{11p} (even) mode and TE_{11P} (odd) mode, as shown in Fig. 2(a).

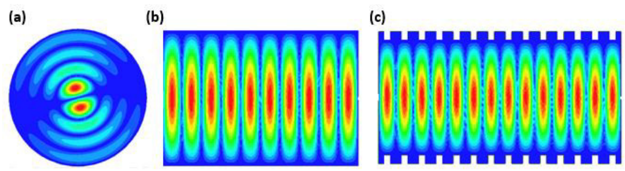

Figure 2: (a) Contour plot TE_{014} mode in the spherical cavity. (b) Contour plot $TE_{1\text{-}1\text{-}10}$ mode in the smooth circular cavity. (c) Contour plot $HE_{1\text{-}1\text{-}14}$ mode in the corrugated circular cavity.

The design of the corrugated circular structure was firstly used in transmission lines which means waveguides in some cases. It consists of hollow metallic cylinders where the inner wall has periodic wavelength-scaled grooves, as shown in Fig. 3. The fundamental mode of a corrugated circular structure is HE_{11} mode, which can be easily excited by TE_{11} mode in a smooth circular cavity [5]. Besides, HE_{11} mode has been proved to have less attenuation than the fundamental modes for equivalent smooth-wall cylindrical and rectangular waveguides [6]. As low attenuation through the cavity is still required, corrugated circular cavity with the dominant HE_{11p} mode shown in Fig. 2(c) has been considered.

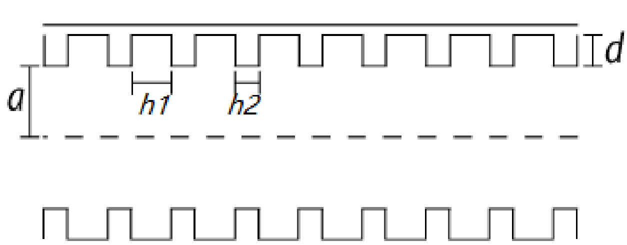

Figure 3: The structure of the corrugated circular shape with a radius of a .The corrugations are defined by h_1, h_2 and d. And the corrugation depth is $d \sim \lambda/4$ for low-loss characteristics.

Parameters Optimization

Properties of the smooth circular cavity and the smooth spherical cavity can be conducted analytically.

For the smooth circular cavity, the relation among resonant frequency, mode and geometry dimensions as well as Q_0 can be expressed as

$$\lambda_0 = \frac{2\pi}{\sqrt{k_0^2+\beta^2}} = \frac{2\pi}{\sqrt{(\frac{q_{ni}}{a\pi})^2+(\frac{p}{l})^2}} . \tag{3}$$

$$Q_0 = \frac{\lambda_0 (q_{ni}^2 - n^2)[q_{ni}^2 + (\frac{p\pi a}{l})^2]^{\frac{3}{2}}}{2\pi\delta[q_{ni}^4 + 2p^2\pi^2 q_{ni}^2 (\frac{a}{l})^3 + (\frac{pn\pi a}{l})^2 (1-\frac{2a}{l})]} \tag{4}$$

where *n, i, p* are indexes of a TE_{nip} mode in a smooth circular cavity, q_{ni} is the ith zero of the nth Bessel function, a and l are the radius and the length of the circular cavity respectively, λ_0 is the wavelength of the microwave and δ is the skin depth.

The relation and Q_0 of a smooth spherical cavity can be expressed as

$$f_0 = \frac{u_{np}}{2\pi a\sqrt{\varepsilon\mu}} . \tag{5}$$

$$Q_0 = \frac{a}{\delta} . \tag{6}$$

where u_{np} is the zero of the spherical Bessel equation for the TE_{mnp} mode in a spherical cavity, a is the radius of the sphere and δ is the skin depth.

Unlike those two cavities above, properties of the corrugated circular cavity are difficult to be obtained directly. Therefore, we adopted analogy and simulation method. The field in a corrugated circular cavity can be split into two parts, the field that exists for $r < a$ and the field that exists for $a < r < a + d$. As the impedance at $r=a$ changes with d, $d \sim \lambda/4$ is the optimum depth for the lowest attenuation in the waveguide [7]. Although this condition is an approximation with an assumption that $ka << 1$, where k is the wavenumber, we still set $d = \lambda/4$ for the simplicity of simulations. Variables a , h_1 and h_2 were swept separately to find the resonant frequency of HE_{11p} mode, then a relation between the frequency and these three variables was interpolated, within the errors $\Delta f \le 0.1 MHz$.

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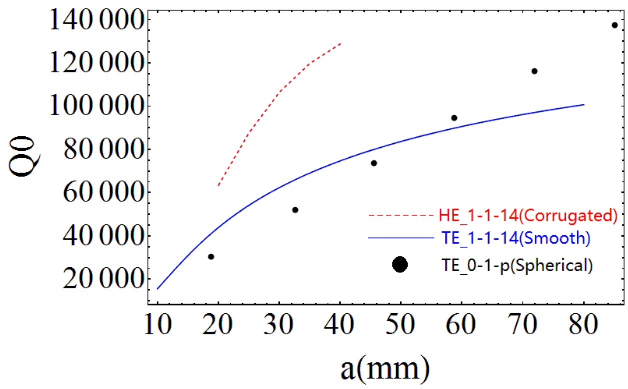

Figure 4: A comparison between three cavities before coupling. The horizontal axis represents the radius a while the vertical axis represents Q_0. The corrugated circular cavity (h_2=3mm for easy manufacturing) with $HE_{1\text{-}1\text{-}14}$ mode is plotted in red dashed line, the smooth circular cavity with $TE_{1\text{-}1\text{-}14}$ mode is plotted in blue solid line and the spherical cavity with TE_{01P} (from TE_{011} to TE_{016}) is plotted in black dots.

As Q_0 of our designed cavity should be more than 10^5, a comparison among the spherical cavity TE_{01P} mode, the smooth circular cavity $TE_{1\text{-}1\text{-}14}$ mode, and the corrugated circular cavity $HE_{1\text{-}1\text{-}14}$ mode is shown in Fig. 4. The corrugated cavity has more compact structure at the same level of Q_0, and HE_{11} is the dominant mode. Therefore, the corrugated circular cavity with $HE_{1\text{-}1\text{-}14}$ mode was chosen as the resonant cavity.

We use a single-iris for coupling and β is set to 3.5. The cavity is coupled to the waveguide through a central hole and the simulated S_{11} parameters after coupling is shown in Fig. 5. Parameters were chosen after considering Q_0, easy manufacturing and frequency separation. A set of tuned parameters is shown in Table 1.

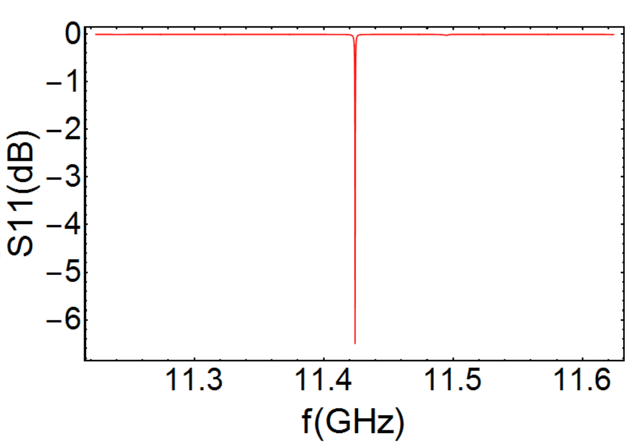

Figure 5: The simulation of S_{11} parameters from 11.224 GHz to 11.624 GHz after coupling. The peak frequency is 11.424 GHz.

Table 1: Parameters of the Pulse Compression Cavity

Operation frequency	11.424GHz
Mode	$HE_{1\text{-}1\text{-}14}$
Cavity diameter (2a)	69.60 mm
Cavity length	191.52 mm
Corrugation depth (d)	6.56 mm
Corrugation distance (h_1)	10.68 mm
Corrugation width (h_2)	3.00 mm
Quality factor (Q_0)	141,760
Iris diameter	8.18 mm
Coupling coefficient (β)	3.5

RF POLARIZER

To direct the flow of RF power, an RF polarizer was designed to satisfy our requirement. This polarizer is comprised of two symmetric rectangular waveguides which feed a cylindrical transmission line via an overmoded rectangular waveguide. The two TE_{11} cylindrical modes in quadrature, which excite two orthogonal HE_{11} modes in the corrugated cavity, are coupled from the simultaneous-propagating TE_{10} and TE_{20} modes in the rectangular waveguide [4]. The simulation results of a tuned RF polarizer is shown in Fig. 6(a) (b), and the pulse compressor design is shown in Fig. 6(c).

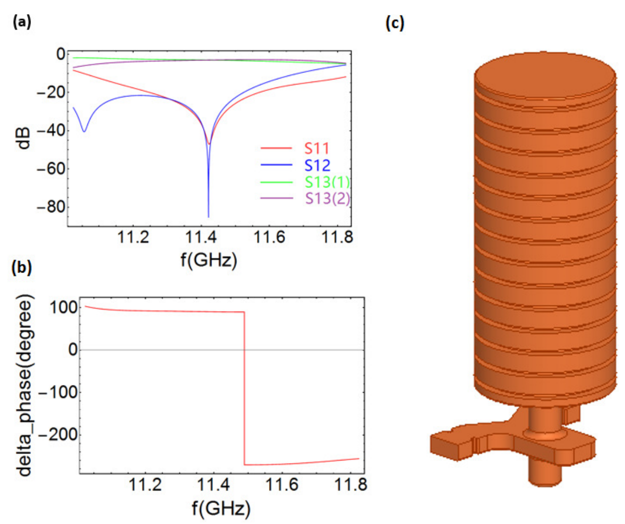

Figure 6: (a) S parameters of the input port 1 from 11.024 GHz to 11.824 GHz, both peak frequencies are 11.424 GHz. (b) The phase difference of the two polarized modes from 11.024 GHz to 11.824 GHz, which is 90-degree at 11.424 GHz. (c) The model of the pulse compression system.

CONCLUSION

In this paper, we designed an X-band (11.424 GHz) pulse compression system for the TTX high-power RF station. This system consists of a corrugated circular cavity using $HE_{1\text{-}1\text{-}14}$ mode and an RF polarizer. Components of the system will be fabricated in the future.

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