

DESIGN OF AN IMPROVED S-BAND SLED PULSE COMPRESSOR

Pengbin Huang, Yelong Wei[†], Yihao Zhang, Zexin Cao, Zhicheng Huang, Guangyao Feng,
University of Science and Technology of China, Hefei, China

Abstract

This paper presents the design of an improved SLED pulse compressor for our beam test platform at the National Synchrotron Radiation Laboratory (NSRL). It consists of a 3 dB hybrid, a TE₁₀-TE₀₁ mode converter, and a resonator storage cavity. Through geometrical optimizations, the resonator is designed to operate in the TE_{0,1,10} mode, which offers a high intrinsic quality factor while maintaining cost-effectiveness. Additionally, the conventional cylindrical configuration has been modified to a double-ended conical structure, which improves mode isolation.

INTRODUCTION

Radio-frequency (RF) pulse compression is widely utilized to elevate peak RF power in accelerator systems. In a conventional SLED-I scheme, a 3 dB hybrid coupler routes the klystron power to energize a pair of identical resonant storage cavities, which release the stored energy via a 180-degree phase reversal [1]. High-power applications require resonant cavities with high intrinsic quality factors Q_0 and stable mode operation. Circular TE₀₁ modes are particularly attractive due to their low surface magnetic fields, while adiabatic tapers are typically implemented to suppress spurious modes [2, 3].

The design proposed in this paper is developed as a scheme for the Super Tau-Charm Facility (STCF) beam test platform at NSRL, adapted from the CERN XBOX2 SLED system [2, 4]. While the X-band XBOX2 utilizes an ultra-high TE_{0,1,32} mode [5, 6], directly scaling it to the required -band would cause excessive cavity size. To address this, our key improvement lies in optimizing the design to a lower-order TE_{0,1,10} mode. This expands the mode separation to almost 10 MHz, eliminating mode competition while achieving $Q_0 \approx 140000$. Meanwhile, the adiabatic tapers of the compressor, the 3 dB hybrid and TE₁₀-TE₀₁ mode converter are preserved to ensure operation of the pulse compressor.

DESIGN REQUIREMENTS

The proposed S-band pulse compressor consists of a four-port 3 dB hybrid coupler, a pair of identical TE_{0,1,10} mode storage cavities, and compact TE₁₀-TE₀₁ mode converters. The overall layout is adapted from the CERN BOX2 SLED (shown as a prototype in Fig. 1) [2, 4, 5], with the schematic of the proposed configuration illustrated in Fig. 2. Designed for a nominal operating frequency of 2.9982 GHz with a 4 μ s input pulse at 50 Hz, the system's performance is characterized by the peak and average power gains achieved at the target compressed pulse width of 0.8 μ s.

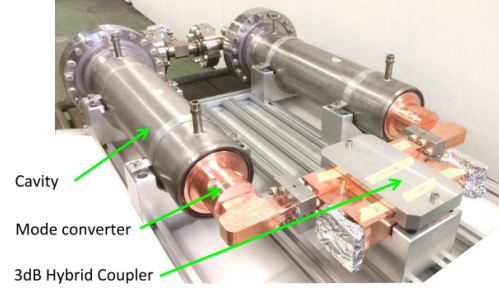


Figure 1: CERN BOX2 SLED.

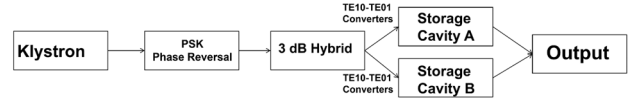


Figure 2: Schematic of the pulse compressor.

Table 1: Main Design Targets of the S-band Pulse Compressor

Parameter	Target	Unit
Operating frequency	2.9982	GHz
Repetition	50	Hz
Input pulse width	4	μ s
Output pulse width	0.8	μ s
Input power	45	MW
Operating mode	TE _{0,1,10}	-
Q_0	$\geq 95,000$	-
Peak power gain	≥ 5	-
Average power gain	≥ 3	-

TE_{0,1,10} STORAGE CAVITY WITH PARAMETRIC ADIABATIC TAPERS

The time-domain method [1] evaluates pulse compression by examining the transient response of the resonant cavities and can be cross-checked with frequency-domain results. For rectangular input pulses, the average power gain M is adopted to quantify the performance of the pulse compressor:

$$M = \frac{\int_{t_1}^{t_2} P_{out}(t) dt}{\int_{t_1}^{t_2} P_{in}(t) dt} = \frac{\int_{t_1}^{t_2} P_{out}(t) dt}{\int_{t_1}^{t_2} P_{in}(t) dt} \cdot \quad (1)$$

[†]wylong@ustc.edu.cn

Where t_1 denotes the phase inversion time, t_2 represents the input pulse width within the duration of a radio frequency pulse. The relationship between average power gain and the mode number is shown in Fig. 3

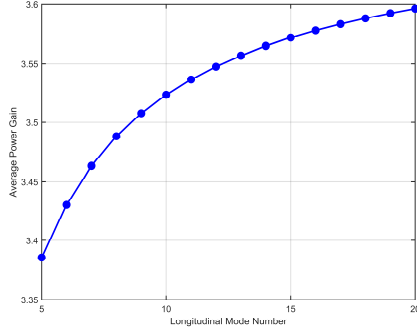


Figure 3: Relationship between average power gain and the mode number.

The geometry of the resonant cavity is depicted in Fig. 4. While transient power gain and coupling can be analyzed using basic cylindrical models, evaluating the Q_0 factor and resonant frequency for cavities with adiabatic tapers requires an equivalent cylinder method adapted from the CERN design [4]. This method approximates the conical segments as equivalent cylinders with an average radius of $r_{avg} = (R_1 + R_2)/2$ (R_1 : main cavity radius, R_2 : end radius). Consequently, the composite resonant frequency f_{mix} is calculated based on the respective axial lengths of the main cylindrical cavity and the tapered segments, formulated as a length-weighted average of the local frequencies (f_1 and f_2):

$$f_{mix} = \frac{H_1 \cdot f_1 + 2H_2 \cdot f_2}{H_1 + 2H_2} \quad (2)$$

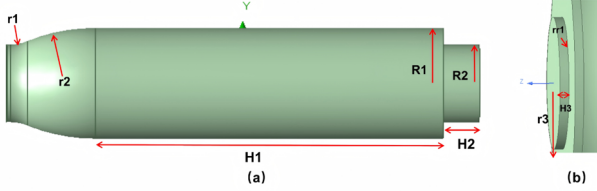


Figure 4: Structure of $TE_{0,1,10}$ cavity. (a) Main cavity body and (b) coupling hole.

Table 2: Parameters of the Pulse Compressor Cavity

Parameter	Value	Unit
R1	100	mm
H1	558.24	mm
R2	70.13	mm
H2	50.65	mm
r1	50	mm
r2	200	mm
r3	39.68	mm
H3	13.3	mm
rr1	3.54	mm

The cavity dimensions listed in Table 2 are optimized to achieve the target frequency, maximize mode separation, and match the mode converter. Geometric optimizations at the coupling iris minimize the peak surface magnetic field to mitigate pulsed heating. Eigenmode simulations tuned the $TE_{0,1,10}$ mode to 2.9982 GHz with a minimum mode separation of 10 MHz. The simulated intrinsic quality factor Q_0 reaches 140000, exceeding the threshold of 95,000. The simulated electric field profile and the eigenmode spectrum are illustrated in Fig. 5 and Fig. 6, respectively.

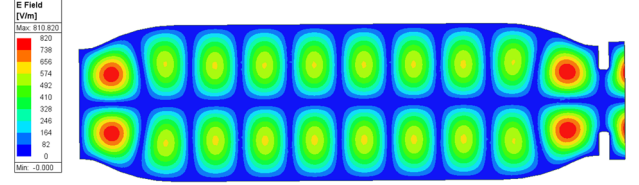


Figure 5: Simulated electric field of the $TE_{0,1,10}$ mode in the improved storage cavity with adiabatic tapers.

Eigenmode	Frequency (GHz)	Q
Mode 1	2.98716 + j3.82801e-05	39017.1
Mode 2	2.98717 + j3.82767e-05	39020.7
Mode 3	2.98906 + j1.53393e-05	97431.3
Mode 4	2.98906 + j1.53394e-05	97430.9
Mode 5	2.99820 + j1.06223e-05	141128
Mode 6	3.01390 + j2.73614e-05	55075.7
Mode 7	3.01392 + j2.73731e-05	55052.5

Figure 6: Eigenmode simulations of Q_0 and mode frequency separation for the pulse compressor.

Utilizing the simulated Q_0 and the specified pulse widths, the relationship between the average power gain and the coupling coefficient β is calculated and shown in Fig. 7(a). The normalized input and output waveforms at the optimal operating point are illustrated in Fig. 7(b).

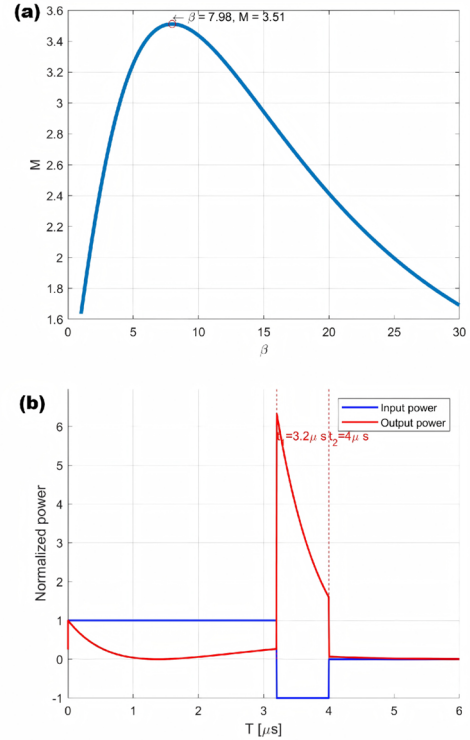


Figure 7: (a) The relationship between the average power gain M and the coupling coefficient β . (b) Normalized input and output waveforms for the cavity operating in the TE_{0,1,10} mode.

3 DB HYBRID AND TE₁₀-TE₀₁ MODE CONVERTER

The RF distribution network must achieve balanced power allocation and high-efficiency mode conversion with minimal wave reflections. As illustrated in Fig. 8, a four-port 3 dB hybrid coupler is utilized to provide equal power splitting to the twin storage cavities. During the phase-reversal stage, it recombines the waves emitted from the resonators, ensuring high isolation at the input port while directing the compressed high-power pulse to the load port. The 3 dB Hybrid S_{11} is below -45 dB at the target frequency.

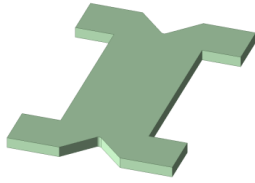


Figure 8: Structure of the 3 dB Hybrid.

To properly excite the storage cavities, a compact mode converter is designed to transform the rectangular waveguide TE₁₀ mode into the circular TE₀₁ mode (Fig. 9). Simulation results indicate that the mode converter achieves S_{11} below -50dB.

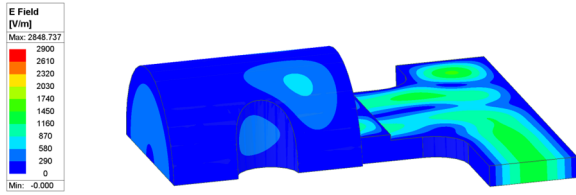


Figure 9: Simulated electric field of the mode converter.

SIMULATIONS AND DISCUSSIONS

The assembly pulse compressor is shown in Fig. 10, with mutual validation conducted using HFSS and CST [7, 8].

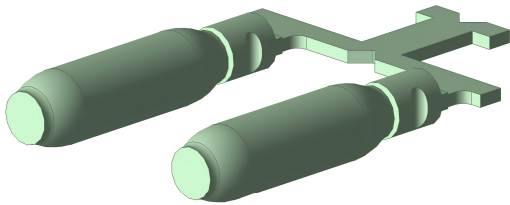


Figure 10: Full assembly of the pulse compressor.

The complete pulse compressor assembly was co-simulated in HFSS and CST to verify the TE_{0,1,10} operating point at 2.9982 GHz. The S-parameter responses in Figs. 11(a) and 11(b) exhibit S_{21} of -2.11 dB and -2.21 dB, with coupling factors β of 7.70 and 7.90, respectively. These

values are consistent with each other and match the optimal coupling condition analyzed in Fig. 7(a), while S_{11} is below -25 dB. SLED transient calculations using these simulated coupling coefficients re-verify a peak power gain above 6 and an average gain above 3.5 within the 0.8 μ s compressed pulse width. Additionally, the peak surface magnetic field remains below 0.22 MA/m, limiting the pulse temperature rise to 22 K, which is much lower than the critical temperature rise of 50 K to avoid RF breakdown [9, 10].

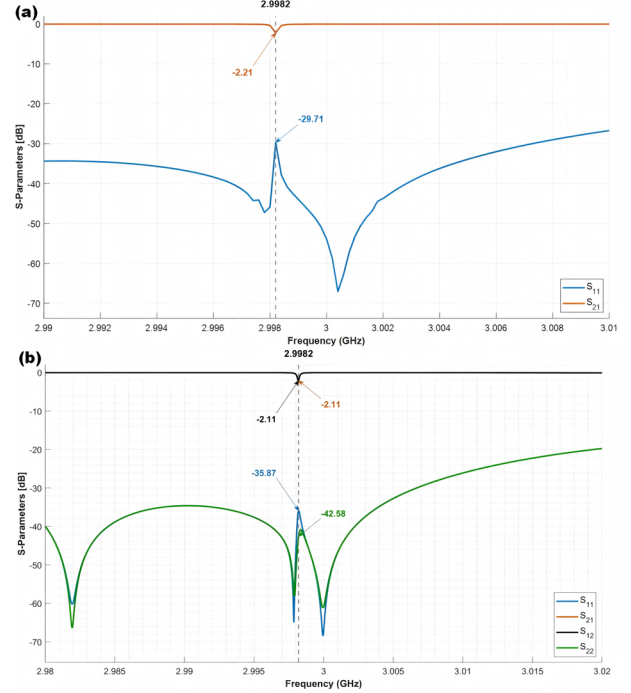


Figure 11: (a) Simulation results of the pulse compressor using HFSS and (b) results of the pulse compressor using CST.

CONCLUSION

An improved S-band SLED-I pulse compressor utilizing TE_{0,1,10} storage cavities with adiabatic tapers has been designed for the STCF beam test platform. Adapted from the CERN XBOX2, the optimized compressor mitigates mode competition by 10 MHz mode separation while maintaining a high Q_0 of 140000. Full-assembly simulations confirm an average power gain above 3.5 and a pulse temperature rise below 22 K. Future work will focus on fabrication, cold test, and high-power test.

ACKNOWLEDGMENT

This work is supported by the "Hundred Talents Program" of Chinese Academy of Sciences (Grant No. KJ2310007003); the Fundamental Research Funds for the Central Universities (Grant No. WK2310000114); the Chinese Academy of Sciences President's International Fellowship Initiative (Grant No. 2025PD0102); the 12th Research Institute of China Electronics Technology Group Corporation (Grant No. K2301287).

REFERENCES

- [1] Z. D. Farkas, H. A. Hogg, G. A. Loew, and P. B. Wilson, “Recent Progress on Sled, The SLAC Energy Doubler,” *IEEE Trans. Nucl. Sci.*, vol. 22, no. 3, pp. 1299–1302, 1975.
[doi:10.1109/tns.1975.4327871](https://doi.org/10.1109/tns.1975.4327871)
- [2] B. Woolley, I. Syratchev, and A. Dexter, “Control and performance improvements of a pulse compressor in use for testing accelerating structures at high power,” *Phys. Rev. Accel. Beams*, vol. 20, no. 10, Oct. 2017.
[doi:10.1103/physrevaccelbeams.20.101001](https://doi.org/10.1103/physrevaccelbeams.20.101001)
- [3] D. Gudkov et al., “General purpose X-band High RF power components developed within CLIC collaboration,” presented at the High-Gradient Workshop (HG2012), KEK, Tsukuba, Japan, Apr. 2012.
- [4] P. Wang, I. Syratchev, H. Zha, J. Shi, W. Wuensch, and H. Chen, “The RF Design of a Compact, High Power Pulse Compressor with a Flat Output Pulse,” in *Proc. IPAC’16*, Busan, Korea, May 2016, paper THPMW022, pp. 3591–3593.
[doi: 10.18429/JACoW-IPAC2016-THPMW022](https://doi.org/10.18429/JACoW-IPAC2016-THPMW022)
- [5] P. Wang, H. Zha, I. Syratchev, J. Shi, and H. Chen, “rf design of a pulse compressor with correction cavity chain for klystron-based compact linear collider,” *Phys. Rev. Accel. Beams*, vol. 20, no. 11, Nov. 2017.
[doi:10.1103/physrevaccelbeams.20.112001](https://doi.org/10.1103/physrevaccelbeams.20.112001)
- [6] I. Syratchev, “X-band SLED type Pulse Compressor. Made in CERN”, presented at the Linear Collider Workshop, CERN, Geneva, Switzerland, 2013.
https://indico.cern.ch/event/243562/contributions/533897/attachments/415101/576781/LC_PC.pdf
- [7] Ansys HFSS, Release 2023 R1, Ansys, Inc., Canonsburg, PA, USA, 2023, <https://www.ansys.com>.
- [8] CST Studio Suite, version 2023, Dassault Systems, Vélizy-Villacoublay, France, 2023, <https://www.3ds.com>.
- [9] A. Grudiev, S. Calatroni, and W. Wuensch, “New local field quantity describing the high gradient limit of accelerating structures”, *Phys. Rev. ST Accel. Beams* 12, 102001 (2009).
[doi:10.1103/PhysRevSTAB.12.102001](https://doi.org/10.1103/PhysRevSTAB.12.102001).
- [10] D. Alesini, “Power coupling”, in *Proc. CAS–CERN Accelerator School: RF for Accelerators*, Ebeltoft, Denmark, 8–17 June 2010, CERN Yellow Report CERN-2011-007, pp. 125–147 (2011).
[doi:10.5170/CERN-2011-007.125](https://doi.org/10.5170/CERN-2011-007.125) or
[arXiv:1112.3201](https://arxiv.org/abs/1112.3201).