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A NEW SPHERICAL PULSE COMPRESSOR WORKING WITH DEGENERATED "WHISPERING GALLERY" MODE

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Abstract

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Abstract

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INTRODUCTION

CLIC is focusing on the Compact Linear Collider. To obtain a relatively high accelerating gradient, CLIC utilizes Pulse Compressors to increase the input power of accelerators. This work is to make an alternative design for CLIC pulse compression scheme. There are several kinds of pulse compressor: SLED, BOC, SLED-II, spherical pulse compressor and so on. Usually, a spherical cavity, including BOC, can offer a higher Q factor compared with a cylindrical cavity. This design utilizes a spherical cavity working with degenerated "Whispering Gallery" mode.
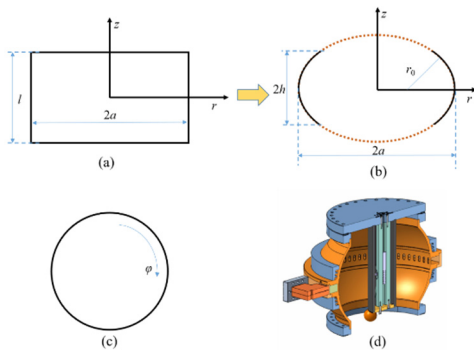
THEORY OF BOC

Figure 1: Cylindrical cavity (a), BOC (b), Top-view of BOC (c) and 3D-view of BOC (d).

BOC [1,2] is short for *Barrel-shaped Open Cavity*. This cavity and its theory can be derived from a cylindrical cavity by removing the two ends of a CC (cylindrical cavity) and bending the boundary inside like shown in Fig. 1(a) and Fig. 1(b). The definitions of TE and TM mode in BOC are the same as in CC: z is the longitudinal direction, and φ [Fig. 2(c)] and r are the transverse directions. The definitions of mode indexes m, n, p are also the same as in CC respectively. Fig. 1(d) shows a typical BOC.

The cavity profile of BOC is an ellipse. But it is not a perfect cavity. There's no cavity wall where the red dotted

line shows in Fig. 1(b), which indicates the name "Open Cavity". The analytical formula of the ellipse is:

$$\frac{z^2}{ar_0} + \frac{r^2}{a^2} = 1,\qquad(1)$$

where a is the major axis of the ellipse, and r_0 is the curvature radius.

This kind of cavity shape allows the existence of the modes only those who have large number of azimuthal variations (so called "Whispering Gallery" modes), while the other modes that have weak azimuthal dependence cannot be formed. Because of the reflection of the cavity walls, the electromagnetic field of "Whispering Gallery" mode is concentrated in a relatively small area close to the cavity surface around the equator plane, like shown in Fig. 2.
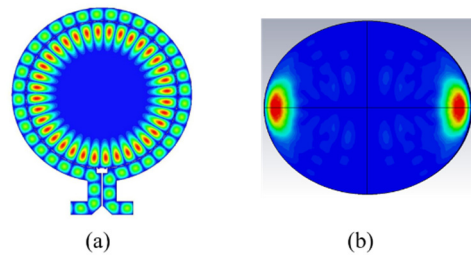

Figure 2: Top-view and side-view of "Whispering Gallery" mode.

According to its field distribution, the "Whispering Gallery" mode is a TM mode. The resonant frequency of a TM mode in BOC is:

$$ka = \upsilon_{mn} + \frac{(p-1/2)\alpha}{\sin\theta},\qquad(2)$$

where k is the wavenumber in the free space, m and p are the azimuthal and longitudinal indexes of the mode, respectively. For TM modes, υ_{mn} is the n-th positive root of Bessel function of order m and its derivative for TE modes. Angle α is defined as: $\sin\alpha = (a/r_0)^{1/2}\sin\theta$, where θ can be calculated from $\cos\theta = m/\upsilon_{mn}$.

For "Whispering Gallery" mode, the indexes n=1, p=1, and m is determined by the required Q factor and the working frequency. The Q factor is:

$$Q_0 = \frac{a}{\sigma}. \qquad (3)$$

where σ is the skin depth.

The expression of Q factor for WG mode in BOC is the same as the TE mode in SLAC spherical cavity [3, 4]. It is because that the two modes in the two different cavities are actually the same one, but with different definitions. Or, in some ways, spherical cavity is a special kind of BOC. In this design, we utilize a spherical cavity. But for convenience, the definitions in BOC will be used.

A traditional BOC-type pulse compressor is consist of a BOC and a circle of rectangular waveguide surrounding the cavity. Power can be coupled through a lot of coupling apertures between cavity and waveguide, shown in Fig. 3(a). In this new design, we plan to use a coupling slot instead of these apertures, which can be machined more precisely. Moreover, the cavity and mode launcher can be designed separately [5].
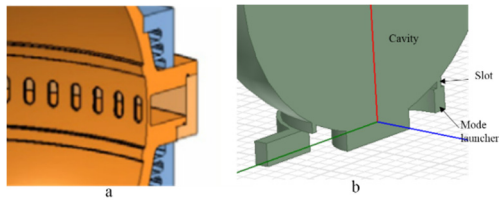

Figure 3: Illustrations of a traditional BOC (a) and the new design (b).

ANALYZE AND RF DESIGN

As a pre-research, the goals of design are set to $Q_0 = 2 \times 10^6$ and coupling coefficient $\beta = 10$.

TM$_{24,1,1}$ Mode

According to Eq. 3, the Q factor is proportional to the cavity radius. We need the Q factor as high as 2×10^6, so the cavity radius should be no less than 120 mm. For WG mode, both the theory of BOC and SC (spherical cavity) can be used, and two theories give the same result:

- For BOC, according to Eq. 2, when $m=24$, $n=1$, and $p=1$, the resonant frequency of a cavity with radius $a=120.3$ mm is 12 GHz, and the Q factor is 2×10^6.
- For SC, according to $f=u_{np}/[(2\pi a(\varepsilon\mu)^{1/2})]$, when $n=24$ and $p=1$, we have the same result of $a=120.3$ mm and $Q_0=2 \times 10^6$.

The simulation results of a SC with radius 120.3 mm are shown in Table 1.

Table 1: Simulation Results of Spherical Cavity

Parameter	Value
Radius	120.3 mm
Mode	TM$_{24,1,1}$
Frequency	11995.8 MHz
Q_0	199,374

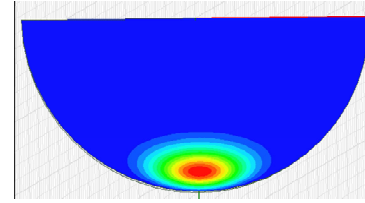The field distribution is shown in Fig. 4.

Figure 4: Field distribution of TM$_{24,1,1}$.

As shown in Fig. 3 (b), we would like to couple power from the bottom, which makes the mode launcher relatively large and complicated to design.

TM$_{9,1,16}$ Mode

The size and the mode coupling make the design of mode launcher difficult. To reduce the size, we move to TM$_{9,1,16}$, a degenerated mode of TM$_{24,1,1}$.
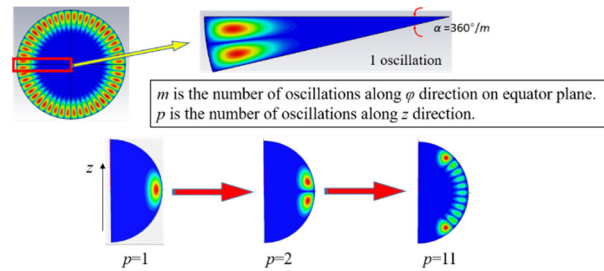

Figure 5: Illustrations of index m and p.

As illustrated in Fig. 5, if we reduce the index m, but increase the index p and keep $m+p=25$ as well as $n=1$, all these modes have the same resonant frequency. They are so called degenerated modes.
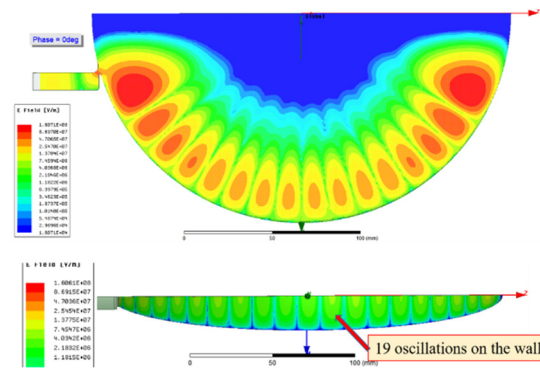

Figure 6: Field distribution inside the cavity and on the wall for TM$_{9,1,16}$ mode.

Figure 6 shows the field distribution of the cavity. Due to the coupling of the neighboring modes, there is some mixture between modes, which makes the Q factor lower than a perfect cavity.

Simulation result shows that the Q factor is reduced by about 2.5% like shown in Fig. 7, which is acceptable.
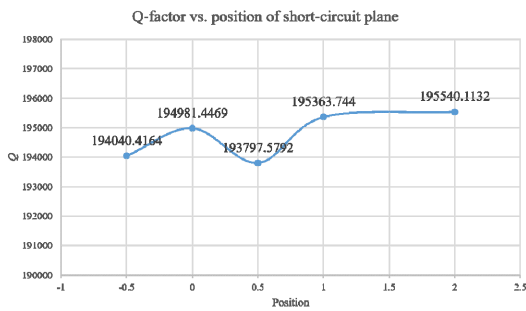
Figure 7: Q factor of $TM_{9,1,16}$.

Mode Launcher

The use of a smaller index m makes the mode launcher more compact. Figure 8 shows the new mode launcher for $TM_{9,1,16}$ mode. The red arrows indicate the power flow. Power input from a standard rectangular waveguide will be converted to two degenerated $TE_{9,1}$ modes and extracted from the coaxial waveguide to storage cavity.
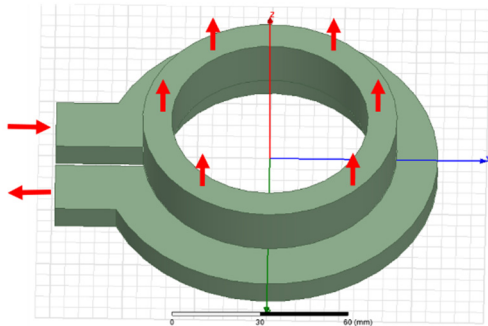

Figure 8: Mode launcher of $TM_{9,1,16}$.

The best results for now are shown in Fig. 9. S_{11}(reflection) is about -41 dB and S_{21}(transmission) is -23 dB, while $S_{3(18)1(1)}$ and $S_{3(19)1(1)}$ are -3.66 dB and -3.45 dB, respectively. The goal of mode launcher optimization is that the two degenerated coaxial $TE_{9,1}$ modes take half of the input power separately, which is -3.01 dB, and phase difference between these two modes is 90°. The optimizer is still running now.
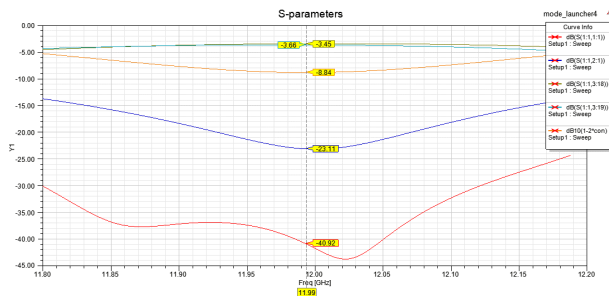

Figure 9: Best results of mode launcher for now.

Figure 10 shows a comparison of the size of three mode launchers: $TM_{24,1,1}$, $TM_{14,1,11}$ and $TM_{9,1,16}$. The use of degenerated WG mode makes the mode launcher much more compact.
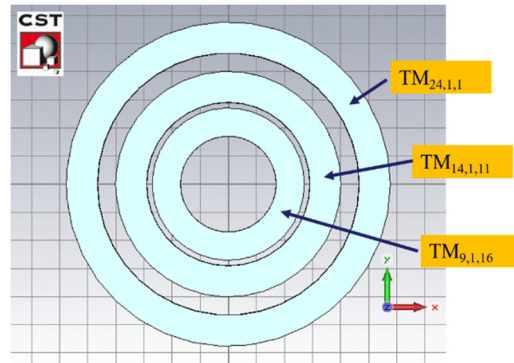

Figure 10: Comparison of three mode launchers.

CONCLUSION

A new design concept of spherical pulse compressor is made for CLIC. The use of a spherical storage cavity makes the Q factor high enough while keeping the pulse compressor small in size. To improve the machining accuracy, the coupling apertures of BOC are replaced by a coupling slot. What's more, the degenerated "Whispering Gallery" mode is utilized instead of the traditional working mode, which reduces the size of mode launcher significantly.

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