PRELIMINARY DESIGN OF HIGH-EFFICIENCY KLYSTRON FOR POHANG ACCELERATOR LABORATORY

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Abstract

Klystrons for particle accelerators are typically designed to have narrow bandwidths with the centre frequencies ranging from several hundred (e.g., 350) MHz to X-band (11.424 GHz). Output powers are from several tens of kW to ~1 MW for CW klystrons and ~100 MW for pulsed ones. The narrow-bandwidth requirement has enabled them to provide high gain (typically 40 – 50 dB) which greatly simplifies the RF drive system. Recently, especially for large-scale accelerator facilities, the klystron efficiency has become one of the most demanding issues. This is because electricity cost occupies a great portion of their operating budgets and the klystron efficiency is one of the important factors determining the electricity consumption of the whole accelerator system. In this regard, we have designed a high-efficiency klystron for use in the PLS-II and PAL XFEL at PAL. The basic scheme is to re-design the cavity system to include multi-cell output cavity. In this article, we report on our preliminary design work to determine major cavity parameters including cell frequencies, inter-cell distances, and coupling to external circuits (coupling beta).

INTRODUCTION

There are about 70 S-band pulse klystrons in the Pohang Accelerator Laboratory (PAL) in which 3rd (the PLS-II) and 4th (PAL XFEL) generation light sources are operating. Klystron maintenance has become one of the most important factors determining the stable operation of the PAL light sources. In this regards, it is highly recommended to have a reliable supply of the klystrons. Also it is required to develop klystrons with high efficiency at low costs in order to reduce the facility operational costs.

One of the well-known method of achieving high efficiency klystron is to decrease its beam Perveance. This is really effective but results in the change in load impedance of klystron modulators. Perveance decrease also increase the beam voltage which should be avoided to ensure the reliable operation of klystron gun as well as the klystron modulators.

We attempt to achieve the high efficiency klystron with better understandings of the beam dynamics and the power-conversion processes inside the klystron. Assuming good electron beam optics (including the transverse focusing) is provided, the most important parameters to be analyzed and optimized include the number of cavities, cavity tuning frequencies, inter-cavity distances, and the Q_L of the output cavity.

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We utilize computer simulation codes such as the EMSYS (formerly the FCI [1]) to study the klystron beam dynamics. MATLAB scripts were used to control the EMSYS simulations as well as to process the input and output data. Nominal parameters for the simulations are presented in Table 1. These are based on the E3712 klystrons [2].

Table 1: Nominal Klystron Parameters for Simulation Studies

Parameters	Values	Units
Frequency	2856	MHz
Beam voltage	400	kV
Beam current	500	A
Perveance	2	uperv
Beam radius	11	mm
Number of cavities	5	
Drift tube radius	15.0	mm
Cavity tuning frequencies		MHz
f1	2856.0	
f2	2862.1	
f3	2871.0	
f4	2951.0	
f5	2856.0	
Inter-cavity distances		mm
L12	80.0	
L23	113.0	
L34	327.5	
L45	124.5	
Output cavity parameters		
R/Q	110	
Q_L	16.5	

SINGLE-CELL OUTPUT CAVITY

Gain cavities are operated in the small-signal regime where the space-charge wave theory is valid. Inter-cavity distances are pre-determined by the plasma frequency(ω_p) and the plasma frequency reduction factor(R) which depends on the beam and drift-tube radii. The beam dynamics in the gain section is dominated by the cavity tunings and we scanned them for the 2nd and the 3rd cavities (i.e., for f2 & f3). Scan results are presented in Fig.1. The scan index in Fig. 1 is given by,

ISBN 978-3-95450-147-2

$$index = i * j$$
$$where, i = 1...M, \quad j = 1...N, \tag{1}$$
$$M, N \text{ are the numbers of scan steps in } f2 \,\&\, f3.$$

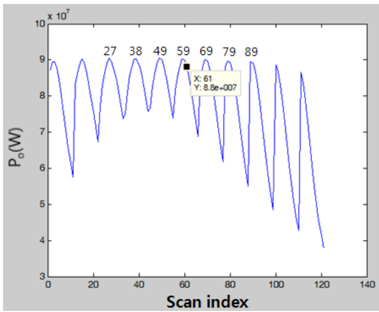

Figure 1: Result of the scan of f2 and f3. Scan range and interval were (2852.1:2:2872.1) MHz for the f2 and (2861:2:2881) MHz for the f3. Note that f3 is scanned for a fixed f2, i.e., f3 is scanned in the inner loop. Numbers above each peak are the scan index at which the output power peaks. Corresponding f2 & f3 are shown in Table 2.

Table 2: f2 and f3 for the Scan Indices in Figure 1

Index	f2(MHz)	f3(MHz)
27	2856.1	2869
38	2858.1	2869
49	2860.1	2869
59	2862.1	2867
69	2864.1	2865
79	2866.1	2863
89	2868.1	2861

As shown in Fig. 1, the output power vs. (f2,f3) behaviour was quite predictable, except the significant decreases in the output power at too much up-shifting the f3.

Figure 2 is Po vs. f_{drive} at each peak in Fig. 1. Except the 2nd and the 3rd peaks left to the central one significant drops in the output powers were observed around 2856 MHz.

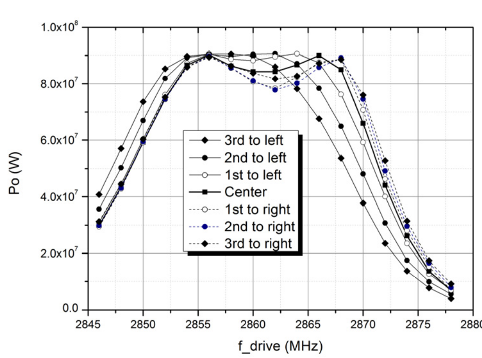

Figure 2: Results of the scan of f_{drive} for each peak in Figure 1 and Table 2. Scan range and interval for the f_{drive} was (2846:2:2878) MHz.

Enough distance should be provided between the cavity No. 3 and 4 (L34) where the velocity bunching occurs. Here the transition from the small-signal regime to the large-signal one occurs, and a simple calculation based on the space-charge wave theory fails. Figure 3 is the Po vs. (L34,f4). The output power increases as the L34 increases until a certain limit is reached above which the output power slowly decreases. The limit is believed to be the $\lambda_q/4$ beyond which the de-bunching occurs.

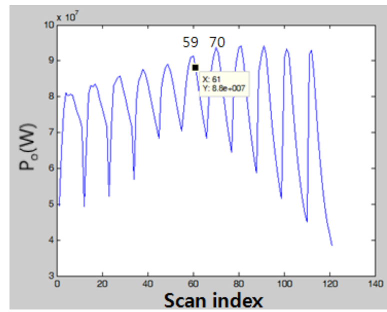

Figure 3: Result of the scan of L34 and f4. Scan range and interval were (137.5:20:337.5) mm for L34 and (2901:10:3001) MHz for f4. Scan indices for the central two peaks are shown above them. Their L34s and f4s are explicitly shown in Table 3.

Table 3: L34 and f4 for the Scan Indices in Figure 3

Index	L34(mm)	f4(MHz)
59	237.5	2851
70	257.5	2931

DOUBLE-CELL OUTPUT CAVITY

Efficiency improvement by several percent could be obtained by optimizing the cavity system with the single-gap output cavity. Further improvements would be possible by adopting a multi-cell output cavity. Even though the multi-cell output cavity have been used mainly for increasing the bandwidth through the extended beam-cavity interaction, it have been also useful for improving the efficiency as well as for reducing the field gradient in output cavity gap. In this article we report on our preliminary design of klystron cavity system with the multi-cell output cavities.

Following the method of determining cavity parameters such as cell R/Q, Q_L, and k(inter-cell coupling) presented in [3], we designed a double-gap output cavity with re-entrant type cells. The cavity mode is set to either 0- or π-modes by adjusting inter-cell distance and cell tunings. Optimization requires adjusting the k and Q_L (for the last cell). Figures 4 & 5 show output powers and beam losses vs. (f5,f6) for the 0- and π-modes respectively.

ISBN 978-3-95450-147-2

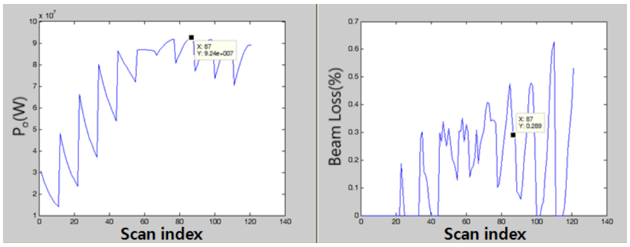

Figure 4: Scan results (left - output power, right - beam losses) of f5 & f6 for double output cavity operating at the 0-mode. Scan ranges and intervals for the f5 and f6 were (2806:10:2906) MHz and (2806:10:2906) MHz respectively.

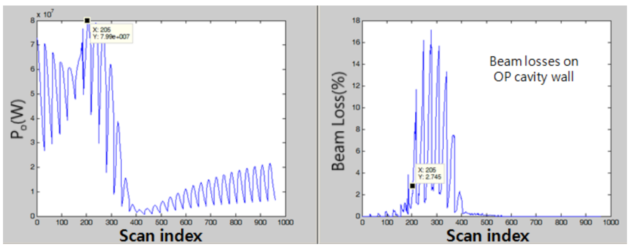

Figure 5: Scan results (left - output power, right - beam losses) of f5 & f6 for double output cavity operating at the π-mode. Scan ranges and intervals for the f5 and f6 were (2800:10:3100) MHz and (2800:10:3100) MHz respectively.

Although not fully optimized yet the double-gap output cavity did not show dramatic improvement in the efficiency. Also beam losses were significant for the π-mode.

3-CELL OUTPUT CAVITY

Following the method in [3] a 3-cell output cavity operating in the π/2-mode was designed. The cavity is a simple disk-and-washer type and no attempt was made to optimize the gap shape. Figure 6 is the output power and beam loss vs. (f5,f6,f7). It was found with proper cell tunings efficiency improvement by more than 10% could be attained at negligible beam loss.

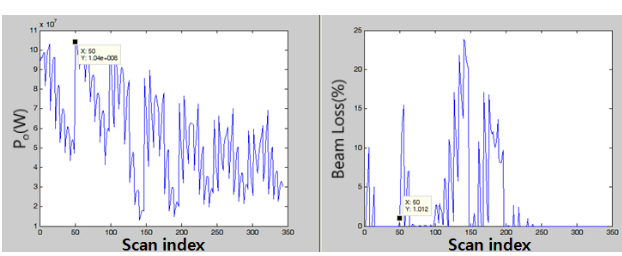

Figure 6: Scan results (left - output power, right - beam losses) of f5, f6, and f7 for 3-cell output cavity operating at the pi/2-mode. Scan ranges and intervals for the f5, f6, and f7 were (2800:50:3100) MHz, (2800:50:3100) MHz, and (2800:50:3100) MHz respectively.

Figure 7 is the output power and beam loss vs. beam voltage at the optimum cell tuning, (f5, f6, f7) = (2850, 2750, 2750) MHz. Owing to the increased efficiency enough power(>75 MW) is obtained at significantly low beam voltage(360 kV) which is very beneficial for the stable operation of the klystron & modulator system. Figure 8 is the output power vs. f_{drive} for the condition of Fig. 7 and (f2,f3) = (2850,2871) MHz.

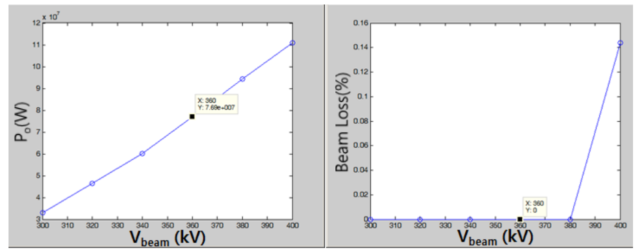

Figure 7: Output power(left) and beam loss(right) vs. beam voltage for the case of 3-cell output cavity with (f5,f6,f7) = (2850,2750,2750) MHz.

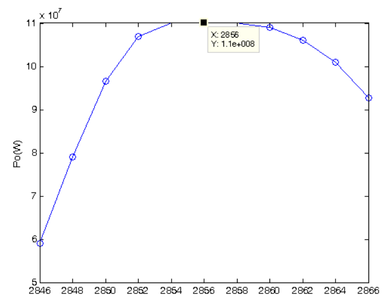

Figure 8: Scan of the f_{drive} in (2846:2:2866) MHz with the conditions of (f2,f3)=(2856,2871) MHz and (f5,f6,f7) = (2850,2750,2750) MHz.

CONCLUSION

Preliminary design of a 5-cavity klystron indicated significant efficiency improvements. With single-cell output cavity, it was possible to improve the efficiency by several percent by optimizing inter-cavity distances and cavity tunings. With 3-cell output cavity it was possible to attain more than 10% improvement. Further work should include instability analyses for the beam-multi-cell-cavity system. Also engineering-level designs of the output cavity including the gap geometry optimization, the field gradient analysis will follow.

ACKNOWLEDGEMENT

The work was supported by the National R&D Program (grant number: 2016R1A6B2A01016828) through the National Research Foundation of Korea (NRF) and the ITER technology R&D program funded by the Ministry of Science, ICT and Future Planning, Korea.

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ISBN 978-3-95450-147-2