ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-TUPO090

ELECTRON-BEAM MATCHING TO SOLENOID MAGNETIC FIELD IN A KLYSTRON*

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Abstract

High-power klystrons for particle accelerators employ high-perveance electron guns which are usually focused by Solenoid magnets. The electron beam should be optically matched to the downstream magnetic field to prevent the beam from scalloping. The task usually requires a series of computer simulations with many design parameters, and therefore requires extensive(sometimes exhaustive) efforts if not aided by a priori experiences. In order to alleviate the difficulties we have developed a matching procedure which is systematic and reliable. In this article we describe the procedure with an example design of a 400 kV, 500 A electron beam with radius 8 - 11 mm.

MATCHING SCHEME

The focusing properties of the electron beam in a klystron is described by the envelope equation [1],

$$\ddot{r} + r\omega_L^2\left[1-\left(\frac{B_c}{B}\frac{r_c^2}{r^2}\right)\right]^2 - \frac{\eta I_B}{2\pi r\epsilon_0 u_0} = 0 \qquad (1)$$

where r is the radial position of an electron at a given longitudinal position, the dot denotes derivative with respect to time, $\eta = e/m$ is the charge to mass ratio, $\omega_L = \eta B/2$ is the Larmour frequency, B_c is the magnetic field strength at the cathode center, B is the magnetic field strength at a given longitudinal position, r_c is the cathode radius, I_B is the beam current, and u_0 is the average beam velocity.

Table 1: PAL Klystron Beam Parameters (Fine Tuned for the Beam Matching)

Parameter	Value
Beam Voltage, V_B	400 kV
Beam Current, I_B	500 A
Microperveance, uK	2 upervs
Cathode Radius, r_c	45 mm
Cathode Field, B_c	31 G
Equilibrium Beam Size, b	9.3 mm
Brillouin Field, B_B	735 G
Confinement Factor, m	1.609

Given beam parameters we can solve Eq. (1) numerically to obtain beam envelopes. With example parameters (for the linac klystrons in the Pohang Accelerator Laboratory (PAL)) presented in Table 1 we could obtain the so-called matched condition as shown in Fig. 1.

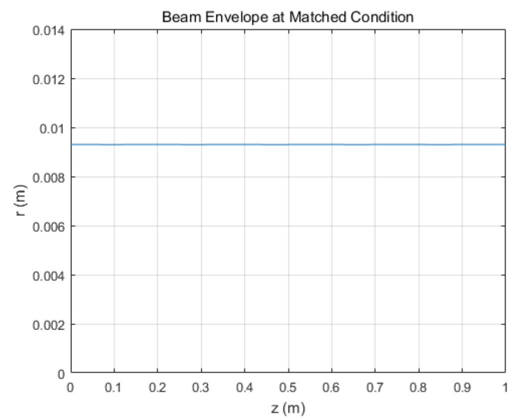

Figure 1: Matched beam envelope with parameters in Table 1.

If we deviate from the matched condition by changing some parameters we can obtain the family of envelopes from which the beam-matching methodology can be inferred. For example changing the B_c results in envelopes as shown in Fig. 2 in which the envelopes for B_c either higher or lower than the matched value (31 G) are quite symmetric. In contrast to this, changing the same parameter for a mismatched beam does not yield symmetric envelope families. Figure 3 is the envelope family for different B_c with a slightly detuned beam-injection angle ($\dot{b}_0 = 0.01$) to make the beam mismatched.

From Figs. 2 and 3 it is evident that a scan for a properly chosen parameter for the matched beam results in a symmetric envelope family with its center envelope corresponding to the matched condition. Therefore the parameter scan and the resulting envelope family is a diagnostic tool for checking whether a beam is at the matched condition. It is interesting to see that, unlike the injection-angle detuning (as shown in Fig. 3), detuning the injection beam radius b_0 do not make the beam mismatched but shift the beam to a new matched condition. Figure 4 is the B_c-scanned envelope family for a injection-radius detuned beam. Comparing Figs. 2 and 4 we see that the beam is matched at a new condition of $B_c = 33$ G.

Here we note the importance of scan parameter selection. Figure 5 is the envelope family obtained by scanning the beam voltage V_B. Unlike the B_c-scanning (as shown in Fig. 2) the V_B-scanning does not yield a symmetric envelope

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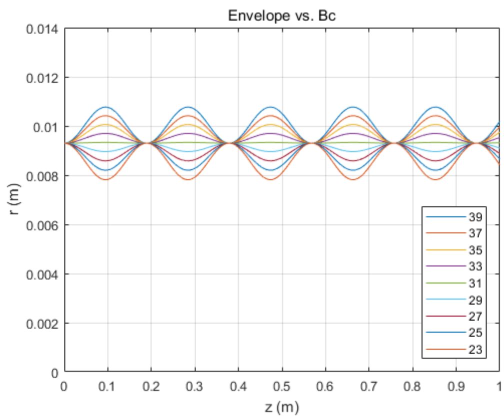

Figure 2: Beam envelopes with different B_c for a matched beam. The unit of the B_c is Gauss. Beam is matched at $B_c = 31$ G.

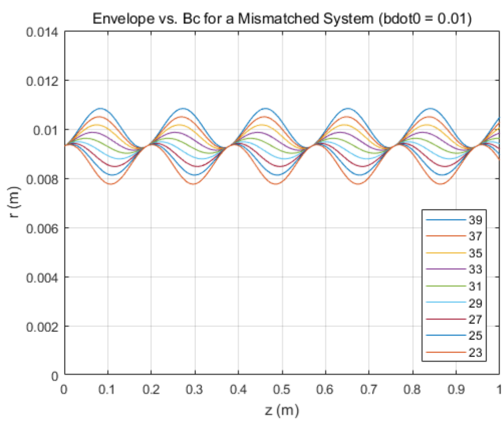

Figure 3: Beam envelopes with different B_c for a mismatched beam. The beam is detuned by making the injection angle ($\dot{b}_0$) = 10 mrad.

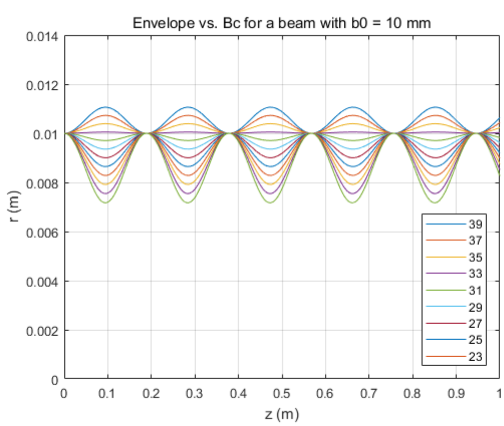

Figure 4: Beam envelopes with different B_c for a mismatched beam. The beam is detuned by making the injection angle ($\dot{b}_0$) = 10 mrad.

family. Furthermore the envelopes decohere for a large z which makes the analysis difficult.

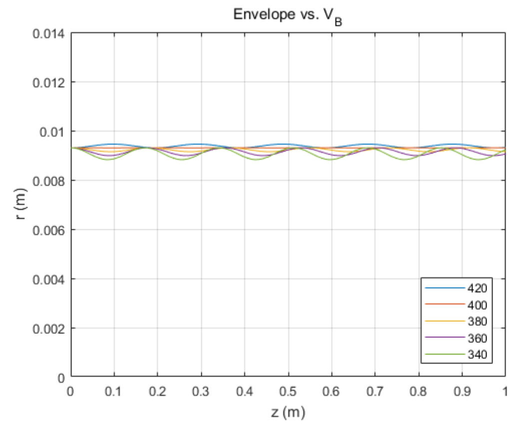

Figure 5: Beam envelopes with different V_B for a matched beam. The unit of V_B is kV

PRACTICAL APPLICATION

We apply the matching scheme outlined in the previous section to the matching designing of PAL klystron. The PAL klystrons are rf sources for the Pohag Light Source II (PLS-II) and PAL X-ray Free Electron Laser (PAL-XFEL). About 70 klystrons are in service and reliable klystron operations with low beam losses have been one of the critical issues for the stable operation of the whole accelerators.

The electron gun of the PAL klystron is the Pierce type and employs a Scandate cathode with the diameter and spherical radius of 90 mm and 73.7 mm respectively. The beam is focused by the electrostatic forces in the gun as well as the magnetic field generated by the Solenoid magnet. Part of magnetic field from the Solenoid reach the cathode and the focusing field strength is 1.6 times the Brillouin field. Electrons emitted from the cathode follow convergent trajectories as they travel in the gun and enter to the cavity section. Magnetic field lines are designed to follow the electron trajectories and, due to this, the basic focusing properties can be described by the envelope equation introduced in the previous section.

Magnetic Field Computation with POISSON

The Solenoid magnet for the PAL klystron consists of 11 main coils, 1 set of bucking coils, and iron yokes & shields. Figure 6 shows the cross section of the magnet overlaid with the magnetic field lines computed by the POISSON code. Field map in the region occupied by the electron beam is obtained by the SF7 code and exported to the EGUN code for trajectory simulation.

Matching Design with EGUN Simulations

In Fig. 7 we show the envelope family for a given gun electrode geometry and Solenoid magnet configuration which were simulated by the EGUN code. Scan parameter is the turn number of the bucking coil (N_B) of the Solenoid magnet, i.e., B_c-scanning. Notice the upper and lower envelopes are not symmetric each other and there is no matched condition. In order to match the beam to the Solenoid field we translate

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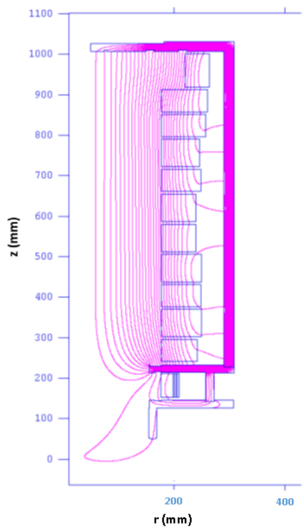

Figure 6: Cross section of Solenoid magnet for the PAL klystron overlaid with POISSON-computed magnetic field lines.

the gun position to the z-direction by z-trans = 5 mm which fine tunes the injection angle ($\dot{b_0}$). This results in Fig. 8 with matched condition established at N_B = 155. Notice symmetric envelopes near the matched one. Further translation (z-trans = 10 mm) detunes the beam and the matched condition disappears (See Fig. 9). It is found that the average beam size for a given N_B increase as the z-trans increases. This is because the B_c increases with the z-trans and the beam size increases with the B_c according to the Busch theorem [2].

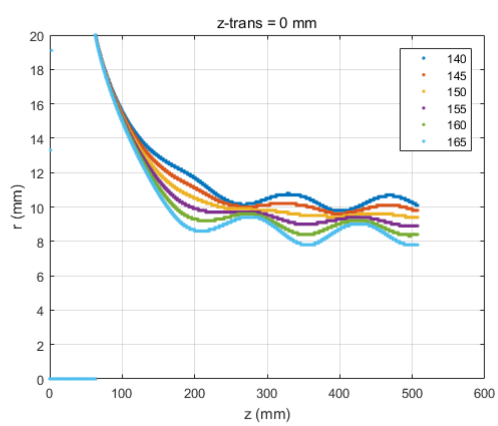

Figure 7: EGUN-simulated beam envelopes for different turn numbers of the bucking coil (N_B).

CONCLUSION

Based on the insights gained from the envelope families obtained by numerically solving the beam envelope equations, we have established a matching procedure for a klystron gun and Solenoid magnet. The procedure is systematic and alleviate extensive optimization work. The procedure has been applied to the PAL klystron and resulted satisfactory results. We expect refined beam matching for the PAL klystron improve the klystron efficiency as well as suppress beam losses and associated radiation generations.

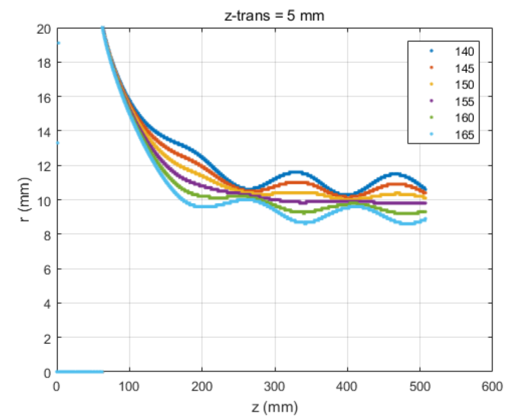

Figure 8: EGUN-simulated beam envelopes for different N_B. Gun is translated to the z-direction by 5 mm to yield matched condition at N_B = 155.

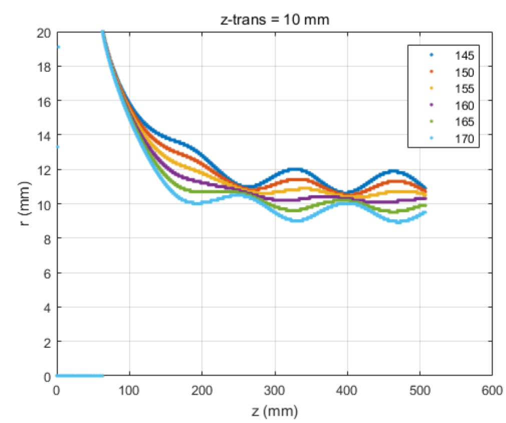

Figure 9: EGUN-simulated beam envelopes for different N_B. Gun is translated to the z-direction by 10 mm and the matching condition obtained in Fig. 8 disappears.

ACKNOWLEDGEMENTS

The work was supported by the National R&D Program (grant number: 2014M1A7A1A02029891, 2016R1A6B2A01016828) through the National Research Foundation of Korea (NRF).

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