INSTABILITY CAUSED BY BACKSTREAMING ELECTRONS IN KLYSTRON

Z. Fang and S. Fukuda
High energy accelerator research organization (KEK)
1-1, Oho, Tsukuba-shi, Ibaraki, 305-0801, Japan

Abstract

The mechanism of backstreaming electrons causing spurious oscillations in klystron will be illustrated using the feedback theory. Since a feedback loop is formed inside the klystron due to the backstreaming electrons, the spurious oscillations will occur if the product of the klystron voltage gain and feedback coefficient is larger than unity, and the phase of the product is zero or integral times of 2π. This kind of oscillations has been observed in the 324MHz klystrons at KEK. In order to analyze the oscillations, a simulation code has been made to calculate the backstreaming electrons from the collector and to evaluate their effects on the klystron. The calculation results have shown a very good agreement with the test results of the 324MHz klystrons. The oscillation phenomena and suppression will be discussed. Proposals are derived for suppressing the oscillations completely in the 324MHz klystron.

1 INTRODUCTION

At KEK, the 324MHz 3MW klystrons are being developed as the rf source for the 200MeV proton linac of the Japan Hadron Facility (JHF) [1] [2]. However, during the high-voltage processing, strong spurious oscillations were observed, even in case of no input power. The oscillation power versus beam voltage for klystron #1 is shown in Fig. 1. The oscillations occurred when the beam voltage was either 63~71kV or higher than 90kV. For example, at the beam voltage of 68kV, the oscillation waveform and frequency spectra are shown in Fig. 2 and Fig. 3 respectively. The delay of oscillation waveform depended on the beam voltage, and the oscillation frequencies were always around the klystron operating frequency, 324MHz.

Investigations into the oscillation source were conducted. It was found that the oscillations could be partially suppressed by applying deflecting magnetic fields at the collector region. And evaluated from the collector dimension, there was no collector resonance around 324MHz. Finally the oscillations were identified due to the backstreaming electrons from the collector.

In the klystron, after the electron beam bombarded the collector, besides the produced low-energy secondary electrons, some of the primary electrons will also be backscattered. After the calculations of electron motion in the magnetic fields at the collector region, it is indicated that, due to the mirror-reflection effects, the secondary electrons have a much lower probability to move into the klystron drift-tube than the high-energy backscattered electrons. Those electrons returning into the drift tube from the collector are called backstreaming electrons. In the later calculations of the backstreaming electrons, secondary electrons will be neglected, only considering those backscattered electrons.

In order to reduce the backstreaming electron current, the collector size was enlarged in klystrons #1A and #2 [3]. The experiment results showed that the oscillations were gradually suppressed, occurring only when the beam voltage was higher than 95kV and 104kV respectively.

This paper focuses on analyzing the oscillation mechanism due to the backstreaming electrons and oscillation suppression.

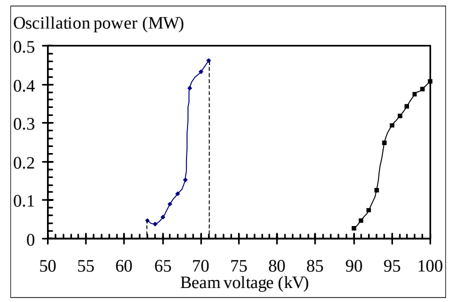


Fig. 1: Oscillation power versus beam voltage for klystron #1.

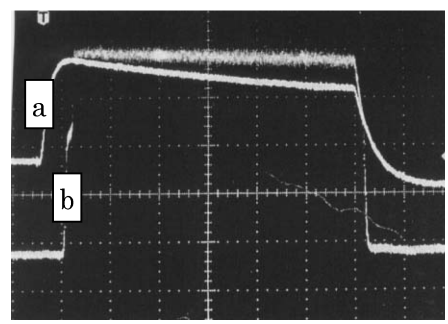


Fig. 2: Oscillation waveform at the beam voltage of 68kV. (a, beam voltage; b, oscillations; time, 100μs/div.)

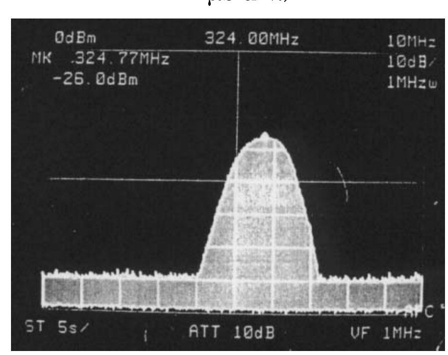


Fig. 3: Frequency spectra of the oscillations at beam voltage of 68kV. (center, 324MHz; span, 10MHz.)

2 FEEDBACK AND INSTABILITY DUE TO BACKSTREAMING ELECTRONS

As the backstreaming electrons pass through the drift tube from the output cavity to the input cavity, a feedback loop is formed inside the klystron, as shown in Fig. 4. In the figure, $\mathbf{V}_i$ and $\mathbf{V}_o$ are the gap voltages of the input and output cavities respectively, $\mathbf{A}(\omega)$ is the complex voltage gain of the klystron, and $\boldsymbol{\beta}(\omega)$ is the complex feedback coefficient caused by the backstreaming electrons. Since $\mathbf{V}_o = \mathbf{V}_d\mathbf{A}$, $\mathbf{V}_f = \mathbf{V}_o\boldsymbol{\beta}$, and $\mathbf{V}_d = \mathbf{V}_i + \mathbf{V}_f$, the closed loop gain is:

$$\vec{A}_f = \frac{\vec{V}_o}{\vec{V}_i} = \frac{\vec{A}}{1-\vec{A}\cdot\vec{\beta}} .$$

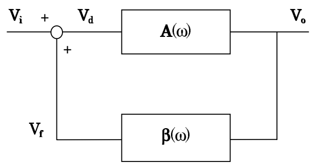


Fig. 4: Feedback loop inside the klystron due to the backstreaming electrons.

In this case, the Nyquist criterion tells us that the klystron is unstable if the curve of $\mathbf{A}(\omega)\cdot\boldsymbol{\beta}(\omega)$ in the complex plane encloses the point 1+j0 as frequency changes from -∞ to +∞. So, at a certain frequency, if the product of the klystron voltage gain and feedback coefficient is larger than unity, and the phase of the product is zero or integral times of 2π, the spurious oscillations will occur. The oscillations can be illustrated with a positive feedback: No signal is applied, but because of some transient disturbance, a signal V appears at the output port. The backstreaming electrons will be modulated by this voltage and induce a gap voltage in the input cavity. This induced voltage will appear in the output as an increased signal AβV. Thus, the klystron will start spontaneous oscillations. Also from the formula of closed loop gain, for $\mathbf{A}\boldsymbol{\beta}$=1+j0, $\mathbf{A}_f \rightarrow \infty$, which is interpreted to mean that there exists an output voltage even in the absence of an externally applied input voltage.

3 ANALYSIS OF OSCILLATIONS IN THE 324MHZ KLYSTRONS

In order to analyze the oscillations, the klystron gain **A** and feedback coefficient **β** should be carried out quantitatively. Of course they are functions of frequency, and they depend on many factors, such as beam voltage, current, modulation index, and rf interaction process.

Fig. 5 shows the voltage gain and efficiency of klystron #1 versus driving power at the beam voltage of 110kV. It clearly shows that the voltage gain is approximately a constant in the small signal region within 1W driving power, and decreases rapidly with the input power higher than 1W. While the efficiency keeps increasing till the saturation point. In order to judge whether the oscillations occur or not in the klystron, the frequency response of voltage gain has been worked out at different beam voltages in the small-signal linear region, as shown in Fig. 6. It indicates that the voltage gain increases with the beam voltage and the klystron has a bandwidth less than 2MHz.

In order to evaluate the effects of backstreaming electrons on the klystron, we have simulated the backstreaming electrons from the collector by using EGS4 [4]. Fig. 7 shows the trajectories of the injection beam and backstreaming electrons in klystron #1. For klystrons #1, #1A, and #2, the backstreaming coefficients are 0.66%, 0.17%, and 0.13%, respectively. And the z-component energy distributions of the backstreaming electrons are shown in Fig. 8.

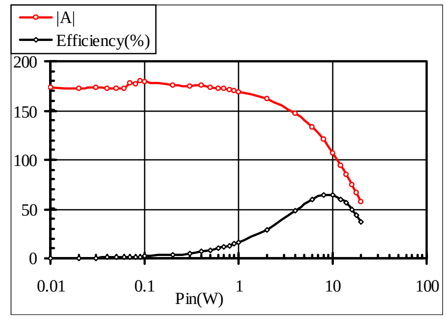


Fig. 5: Voltage gain and efficiency of klystron #1 versus driving power at the beam voltage of 110kV.

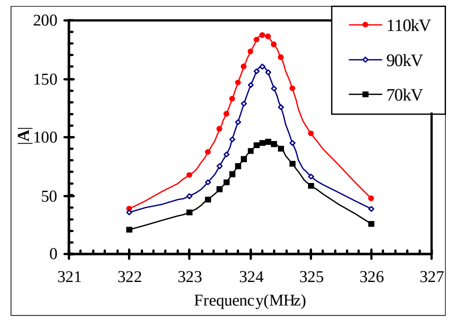
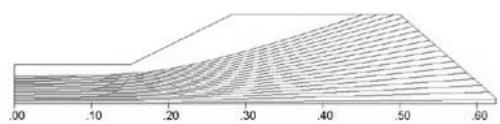
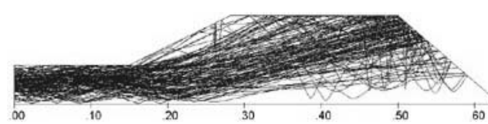


Fig. 6: Frequency response of voltage gain of klystron #1 in the small-signal linear region at the beam voltage of 70kV, 90kV, and 110kV.



(a) injection beam.



(b) backstreaming electrons.

Fig. 7: Trajectories of the injection beam and backstreaming electrons in klystron #1.

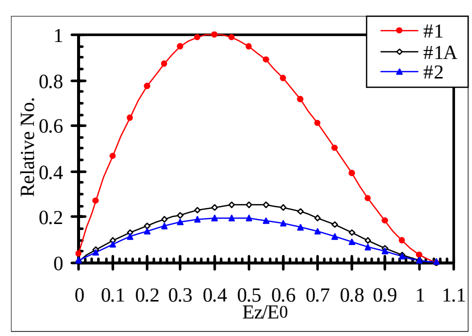


Fig. 8: Z-component energy distribution of the backstreaming electrons in klystrons #1, #1A and #2.

For the modulation process of the backstreaming electrons, considering their wide energy distribution, the rf current is derived in the small-signal region by using the ballistic theory:

$$I_1 = \frac{2I_b \int \eta(x) J_1(X') \cos(\omega t - \theta') dx}{\int \eta(x) dx}.$$

I_b is the current of backstreaming electrons, $I_b=\eta_b I_0$, where η_b is the backstreaming coefficient. $\eta(x)$ is the fitted polynomial function of the energy distribution of backstreaming electrons. $J_1(X')$ is the first order Bessel function, where X' is the bunching parameter for backstreaming electrons. After carrying out the induced gap voltage in the input cavity, then we can calculate $\boldsymbol{\beta}$.

Fig. 9 shows the frequency response of feedback coefficient caused by the backstreaming electrons in klystron #1. It is indicated that $\boldsymbol{\beta}$ has similar features to **A**, but the amplitude β is much smaller than A, resulting from the weak current and wide energy distribution of the backstreaming electrons.

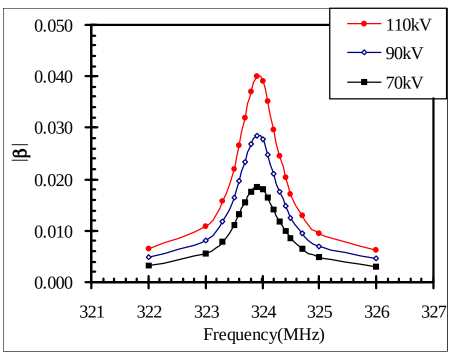


Fig. 9: Frequency response of feedback coefficient caused by the backstreaming electrons in klystron #1 at beam voltage of 70kV, 90kV, and 110kV.

After working out both the amplitudes and phases of **A**(ω) and $\boldsymbol{\beta}$(ω), then we plot the product **A**$\boldsymbol{\beta}$ in the complex plane. Fig. 10 shows the curves of **A**$\boldsymbol{\beta}$ as frequency changes from 322MHz to 326MHz at the beam voltage of 65kV, 70kV, and 75kV. It indicates that between 65 and 70kV, always there are some frequency components satisfying the oscillation conditions. Similar calculations were carried out at different beam voltages for the three klystrons. And the oscillation beam voltage regions are derived from the calculations: for klystron #1, 65~70kV and higher than 79kV, for klystron #1A, higher than 100kV, and for klystron #2, higher than 105kV. They have shown a good agreement with the experiment results.

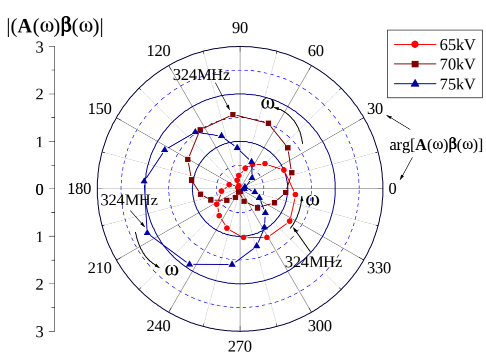


Fig. 10: Curves of **A**$\boldsymbol{\beta}$ as frequency changes from 322MHz to 326MHz at the beam voltage of 65kV, 70kV, and 75kV.

4 DISCUSSIONS ON OSCILLATION PHENOMENA AND SUPPRESSION

From the previous calculations, A and β increase with the beam voltage. That is why oscillations tend to occur in high-voltage regions. Furthermore, A and β are much higher around operating frequency than in other frequencies, so the oscillation frequencies are always close to the operating frequency. The oscillations are enhanced by the factor |**A**$\boldsymbol{\beta}$| after each round trip of the closed feedback loop. However, due to nonlinearity of |**A**$\boldsymbol{\beta}$|, as shown in Fig. 5, finally the oscillation power will reach a critical point where |**A**$\boldsymbol{\beta}$|=1. Thus, for a higher beam voltage and a larger |**A**$\boldsymbol{\beta}$|, the oscillation power tends to arrive at a higher value. The observed oscillation power can be qualitatively understood from this oscillation enhancement process. The delay of oscillation waveform might also be associated with this process. It may suggest that the possibility of the oscillations occurring in long-pulsed or CW klystrons might be much higher than in short-pulsed klystrons.

The phases of **A**(ω) and $\boldsymbol{\beta}$(ω) easily vary with beam voltage and frequency. Once |**A**$\boldsymbol{\beta}$|>1, it is possible some frequency components exist satisfying the oscillation conditions at higher beam voltages. In order to suppress the oscillations completely, it is necessary to keep |Aβ|<1 in the whole beam-voltage region of the klystron. In order to suppress the effects of backstreaming electrons, collector shape and material should be chosen properly.

From the calculation results for the 324MHz klystron, the oscillations due to the backstreaming electrons will be completely suppressed if the collector radius increases further from 11.5 to 15cm, or the drift-tube radius decreases from 5 to 3.5cm.

5 CONCLUSION

The oscillation mechanism due to the backstreaming electrons has been described, and the oscillation conditions have been understood physically and numerically. The calculation results for the 324MHz klystrons have shown a good agreement with the experiment results. Following the above oscillation analysis, we can judge whether the backstreaming electrons can cause the oscillations for a given klystron, and avoid the oscillations in a klystron to be developed in future.

REFERENCES

[1] Y. Yamazaki et al., “The construction of the low-energy front 60-MeV linac for the KEK/JAERI joint project”, Proceedings of the 20th International Linac Conference, Monterey, CA, USA, Aug. 2000.

[2] S. Fukuda et al., “The RF source of the 60-MeV linac for the KEK/JAERI joint project”, Proceedings of the 20th International Linac Conference, Monterey, CA, USA, Aug. 2000.

[3] Z. Fang et al., “Simulation of returning electrons from a klystron Collector”, Proceedings of the 20th International Linac Conference, Monterey, CA, USA, Aug. 2000.

[4] W. R. Nelson, H. Hirayama and D. W. O. Rogers, “The EGS4 code system”, SLAC-report-265, 1985.