SIMULATION STUDY OF THE BUNCHING SECTION OF X-BAND KLYSTRONS

S.Matsumoto, S.Michizono, H.Tsutsui, Y.H. Chin and S.Fukuda
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, 305-0801 Japan

Abstract

A precise simulation of a klystron is useful not only to understand its operation but for the design work. For this purpose, MAGIC code, which is a 2.5 dimensional PIC code for self-consistent simulation of plasma physics problems, is used to simulate the entire klystron performance including the production of the beam at the gun, the modulated beam motion and the beam-cavity interaction at the output cavity as well as the gain cavities. In this article, the simulation of the buncher section of KEK XB72K, a relativistic X-band klystron, is described.

1 INTRODUCTION

An X-band klystron is a possible RF power source in future linear colliders. The design performance of such a klystron is high. In R&D of such a klystron, a precise simulation of the performance is preferred. For this purpose, we recently adopted MAGIC code at KEK. MAGIC is a 2.5 dimensional fully electromagnetic and relativistic Particle-in-Cell (PIC) code for self-consistent simulation of plasma physics problems[1]. The primary inputs of MAGIC simulation are the electromagnetic boundary condition on the perimeter (simulation boundary) and the initial condition of beam.

In a klystron simulation, the geometry of the klystron determines the physical boundary (conductor perimeter), while in the gun region, for example, an external DC field should be given properly along a line between the cathode and the anode. This kind of lines is also a part of the perimeter. As for the initial condition of beam, MAGIC can simulate the thermal emission from the cathode surface. The focusing solenoidal field is included as an external field in the simulation. We calculate this field by POISSON code[2].

In our simulation study, the whole klystron structure breaks into three simulation sections. This separation is technically unavoidable since the whole length (from the gun to the output cavity) of our klystron is too long for a single simulation. In a MAGIC simulation, 1024 is the maximum number of the grids (cells) in z direction (the direction of beam axis). If the grid size in z is 0.2 mm (this is the case of our simulation), about 20 cm is the maximum length.

The stream of beam particles and electromagnetic fields from the upstream simulation section can be transferred to the downstream by MAGIC IMPORT/EXPORT command. Once EXPORT command is invoked, MAGIC records the fields and particles on the “export line” for a specified duration of time. The data is launched by IMPORT command on the “import line” in the downstream simulation section which should be matched to the export line. This technique works if there is no backward wave and particles and a klystron is the case. The separation into these simulation sections is done at the middle of the long drift tubes.

The first section is the gun section where the DC beam from the gun is simulated[3]. The beam energy is specified here by the cathode voltage. The next region is the buncher section which includes the input cavity, the gain cavities and the penultimate cavity. The RF voltage supplied at the input gap modulates the beam. The last section simulates the output cavity. The actual output cavity has two ports to conduct the power. The ports are represented by an equivalent axisymmetric load in the simulation[4]. The output power is estimated as the consumed power in this load.

In the present paper, the simulation of the buncher section of XB72K, an X-band klystron developed at KEK [5], is described. This section is divided into 2 subsections, since the whole section is still long for a single simulation. The first half covers the input and gain cavities while the last half includes the penultimate cavity.

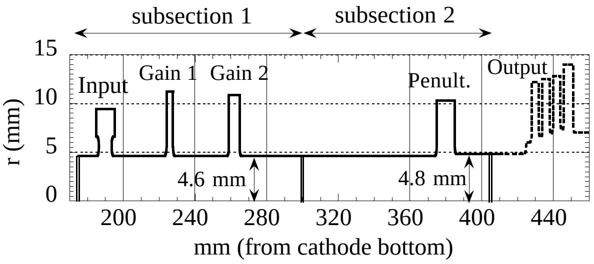

Figure 1: The structure of the buncher section of XB72K. The import line from the gun section is located at 170 mm and the export line is at 410 mm. There is another line at 300 mm, which divides the section into two. These lines are indicated by the double lines in the figure. The TW output structure of XB72K#9 is also shown in the figure.

2 SIMULATION METHOD

2.1 Input cavity

MAGIC can simulate straightforwardly the gain cavities or the penultimate cavity. However, the simulation of the input cavity is not straightforward since it has a port (not axisymmetric) through which the power comes in (or out). In our simulation, the input cavity is removed and its electrical effect is represented by an external field on the gap line, a new boundary which is defined as the (shortest) straight line between the nose cones of the cavity. The external field, $E_z(z,t)$, is calculated primarily as the electric field of the trapped mode of the input cavity with the operation frequency. It is

$$E_z(z,t) = \frac{V_g}{d}\,\bar{e}(z)\sin\omega t,$$

where V_g is the gap voltage, d is the gap length (7 mm in our case) and $\bar{e}(z)$ is a function shown in Fig. 2. In the simulation (with beam), $E_z(z,t)$ is applied on the gap line as an external field. Fig. 3 shows the electric field generated by $E_z(z,t)$. The gap voltage V_g is related to the input power P as

$$V_g^2 = \rho P.$$

We adopt ρ such that $V_g = 2.0\,\mathrm{kV}$ when $100\,\mathrm{W}$ input power. The dependence of ρ on the beam energy or beam current is small thus we neglect it.

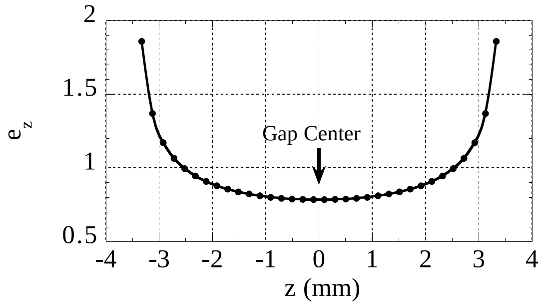

Figure 2: The function $\bar{e}(z)$ of XB72K input cavity.

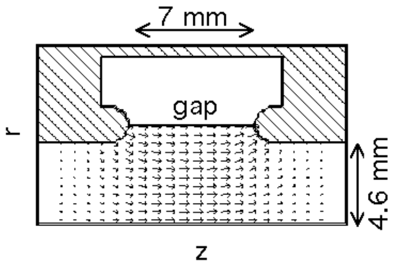

Figure 3: A snapshot of the electric field. The external field is given on the gap. The arrows indicate the direction and strength of the electric field at this moment.

2.2 Gain and Penultimate cavities

The resonant frequency of the gain and penultimate cavities is shifted from the operation frequency (11.424 GHz) as tabulated below. The resonant frequency can be measured by EIGENMODE command. All the cavities were tuned within at most 0.5 MHz by a tiny change of the cavity radius.

Table 1: Frequency Shift of cavities

Cavity	*df* (MHz)	Cavity	*df* (MHz)
1 (input)	0	3 (Gain)	+26
2 (Gain)	+12	4 (Penult.)	+376

2.3 Other issues

We use uniform spatial grids. The grid size in z is 0.2 mm overall while that in r is $4.6\ \mathrm{mm}/15 \sim 0.3$ mm in the drift tube and a little small grid is used in the cavity space. We set the time step manually to be $1/360$ cycle (for the entire simulation sections). This step is smaller than the default step set by MAGIC automatically from the given grid size.

The external field on the boundary should be started from zero value and slowly raised to its desired value. Otherwise we often see the numerical oscillation occurs. The similar treatment should be done when we import particles. SCALE is a MAGIC command for this trick.

We are interested in the beam and fields in their stationary state. Realization of such a state requires a finite duration of time in the simulation. For example, in Fig. 4, the evolution of the gap voltage at the 2nd gain cavity is shown. The voltage becomes constant after about 20 nsec, which is 230 RF cycles. Although the relaxation time should depend on the current carried by the beam or the beam energy as well as the frequency shift of the cavity, the duration of 300 cycles is enough for the first subsection while 200 cycles is enough for the second subsection.

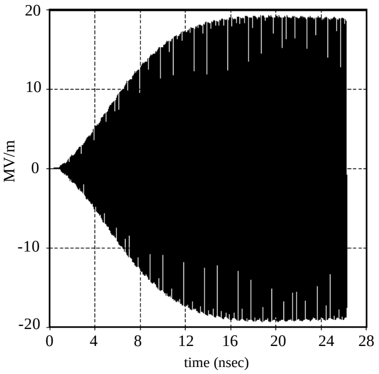

Figure 4: The averaged electric field strength (in unit of MV/m) on the gap line of the 2nd gain cavity. It saturates after about 20 nsec. Beam energy is 525 kV and input power is 300 W.

3 SIMULATION RESULTS

3.1 Modulation and its enhancement

Let us see how the bunching process is seen in the MAGIC simulation. As an example, we show the case of XB72K#9 with the beam energy being 525 kV and input power being 300 W. Fig. 5 is a snapshot of the beam energy in the first subsection as a function of z. We clearly see the enhancement of the energy modulation occurred at the gain cavities. The modulation in energy (velocity) is turned to be the density modulation downstream and this is actually seen in the next subsection. See Fig. 6. The cavity in the figure is the penultimate cavity which enhances the bunching process. The bunching process can be more clearly seen in the current growth along the z direction, which is calculable from

MAGIC output. See in Fig. 7. The enhancement of bunching by the cavity can be seen as a kink of the growth curves.

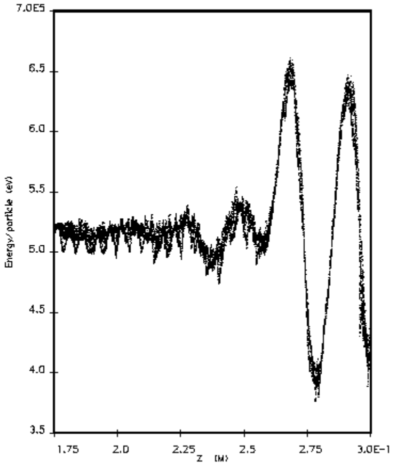

Figure 5: The snapshot of the beam energy along the longitudinal direction z.

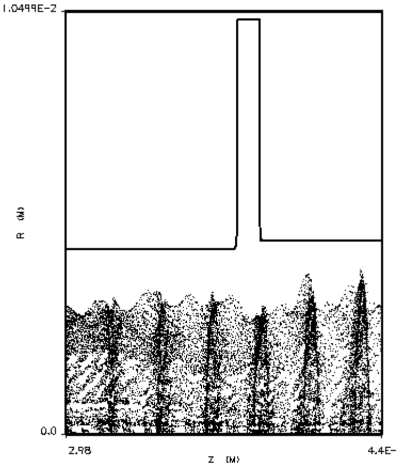

Figure 6: The snapshot of the particle distribution in subsection 2.

The output power can be estimated in the next simulation section by using the exported data from the buncher section. The simulation of the #9 TW output structure predicts 80.5 MW in this particular case. Since DC current is 458 A (the perveance is 1.2×10^{-6}), therefore MAGIC simulation for XB72K #9 predicts the efficiency of 33% at 525 kV. A discussion on the MAGIC predictions and experimental results is found in Ref. [6]. The MAGIC predictions agree well to the observations so far [7].

3.2 Required CPU time

Required CPU time is 10.5 hours for first subsection (duration 300 cycles) and 7.5 hours for the second subsection (200 cycles) in pentiumII-300 MHz PC. The number of the macro-particles emerge from the import line of the first subsection is about 3800 per a single cycles (360 time steps). This number is not changed throughout the whole simulation sections (unless the particles hit the wall). CPU time depends largely on the number of the macro particles appeared in the simulation region. The grid size, the time step and the number of macro particles that we used so far are rather conservative.

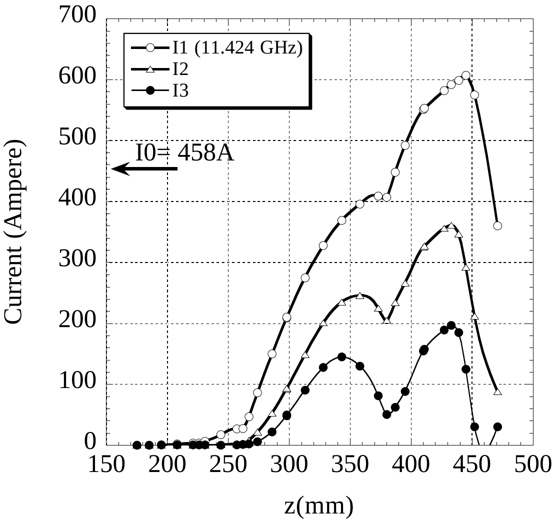

Figure 7: The RF current growth in XB72K #9. Beam voltage is 525 kV, 300 W input. The fundamental ($I1$) as well as the second ($I2$) and third ($I3$) harmonics are shown. The ratio of $I1$ to $I0$ (DC component) reaches about 1.3 in the output cavity but decays rapidly.

4 SUMMARY

The basic techniques for simulating a klystron by 2.5D MAGIC code are established. Although the code primarily solves the problem, we still need a trick like the port approximation for the input cavity, as shown above. Eligibility of the trick is checked by the experiment or by the other code. So far the MAGIC model is a good simulator of a klystron.

5 REFERENCES

[1] Mission Research Corporation, Virginia, USA.

[2] J.H.Billen and L.M.Young "POISSON SUPERFISH", LA-UR-96-1834,(1997).

[3] S.Michizono, et al., "Electron Gun Simulation using MAGIC", these proceedings.

[4] H.Tsutsui, et al., "X-band klystron output cavity simulation", these proceedings.

[5] J.Odagiri, et al., "FCI Simulation on 100MW Class Klystron" in Proc. 1994 Int. Linac Conf., Tsukuba, Japan.

[6] Y.H. Chin, et al., "Computational Modeling of Klystrons", these proceedings.

[7] Y.H. Chin et al., "The 120 MW X-band Klystron Development at KEK", in Proc. of EPAC 98.