

FCI - FIELD CHARGE INTERACTION PROGRAM FOR HIGH POWER KLYSTRON SIMULATIONS

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Abstract

The particle-in-cell computer code FCI has been made and applied to the high power klystron simulations. The code simulates the electron beam dynamics in the drift tube region of klystron, taking into account the fields of the space charge, RF-cavities and the external focusing magnet. The RF-cavities are modeled by the gap fields and the equivalent circuits, whose voltages and the output power are determined by solving the circuit equations.

The energy compensation for the injection beam of the self-potential, and the boundary conditions, which does not make any energy loss on the injection beam, were taken into the code carefully.

The tightly bunched beam generates a high frequency wave (a kind of transition radiation) at the right boundary of the beam dump. This radiation backs into drift tube and modulates the beam. The traveling wave boundary is used to suppress the radiation, so that simulation gives stable solutions.

In order to make the C.P.U. time as short as possible, several techniques were employed in the space charge calculation and cavity voltage determination. So that, one can get a solution for one operation point of multi-cavity klystron such as 50 MW 5045 tube used in SLC within the C.P.U. time of 10 minutes or less on the HITAC M-280H computer of maximum performance 17 MIPS.

The simulation results were compared with the experimental data.

Introductions

FCI code consists of the following programs. MESH reads in the mesh and region sizes and decides the work area.

CAVITY calculates the gap fields of (E_r , E_z , B_θ).

MAGNET interpolates the axial magnetic field data using a spline function, and expands them to the field components of (B_r , B_z , A_θ).

BEAM is the main program of FCI.

It calculates the electron beam motion and determines the cavity voltages and output power.

Following graphic routines have been prepared for the users to process the outputs of BEAM.

BPLOT plots the beam profile.

ENGPLT plots the kinetic energy of beam.

CURPLT plots the RF current of the beam.

RFCPLT plots a history of induced RF-current on the cavity in the BEAM simulation.

In this report, the main routine of the BEAM is described in briefly, and the simulation results are compared with experimental data.

Description of Code

Beam Motion

The beam dynamics is treated in 2-1/2 dimensional with cylindrical symmetry. For the (r , u_r , z , u_z), the following relativistic equation of motion is integrated numerically.

$$\frac{d\mathbf{u}}{dt} = \frac{\eta}{\gamma} \left(\mathbf{E} + \mathbf{u} \times \mathbf{B} - \frac{(\mathbf{E} \cdot \mathbf{u})}{c^2} \mathbf{u} \right) \quad (1)$$

Where, the last term represents the change of mass due to acceleration by the electric field. The rotation velocity u_θ is directly given by,

$$u_\theta = \frac{\eta}{2 \gamma r} (r_c^2 B_c - r^2 B_z) \quad (2)$$

where r_c and B_c are the cathode radius and magnetic field on the cathode.

Beam Induced Fields (Space Charge Fields)

The code solves the following wave equations by the finite difference method(FDM) on the rectangular mesh as shown in Fig.1.

$$\nabla^2 \phi - \frac{\partial^2 \phi}{c^2 \partial t^2} = -\frac{\rho}{\epsilon_0} \quad (3)$$

$$\nabla^2 \mathbf{A} - \frac{\partial^2 \mathbf{A}}{c^2 \partial t^2} = -\mu_0 \mathbf{J} \quad (4)$$

The field components are given by $\mathbf{E} = -\nabla \phi - \partial \mathbf{A} / \partial t$ and $\mathbf{B} = \nabla \times \mathbf{A}$.

In the saturation condition of the high power klystron, the bunch length of the electron beam becomes very short at the down stream of the drift tube. If the right boundary (beam dump) is treated as the simple Neumann or Dirichlet condition, the bunch generates a high frequency electromagnetic wave at the boundary. This is a kind of the transition radiation, which backs into the drift tube, and makes the additional velocity modulation on the beam. The modulation is amplified by the bunching process and generates the high frequency wave at the right boundary again. This closed loop causes an instability, and makes the simulation unreliable.

This instability has been removed by introducing the traveling wave boundary for the beam dump as shown in Fig.1(c). Where, the high frequency wave passes through this boundary without any reflections, and the generation of transition radiation is suppressed, so that the instability does not occur.

Cavity Field (Port Approximation)

The RF-cavity is treated by the port approximation[1]. In which the cavity voltage is determined by the circuit equation, and the cavity field is approximated by the gap field. The gap fields are given by solving the Helmholtz equation

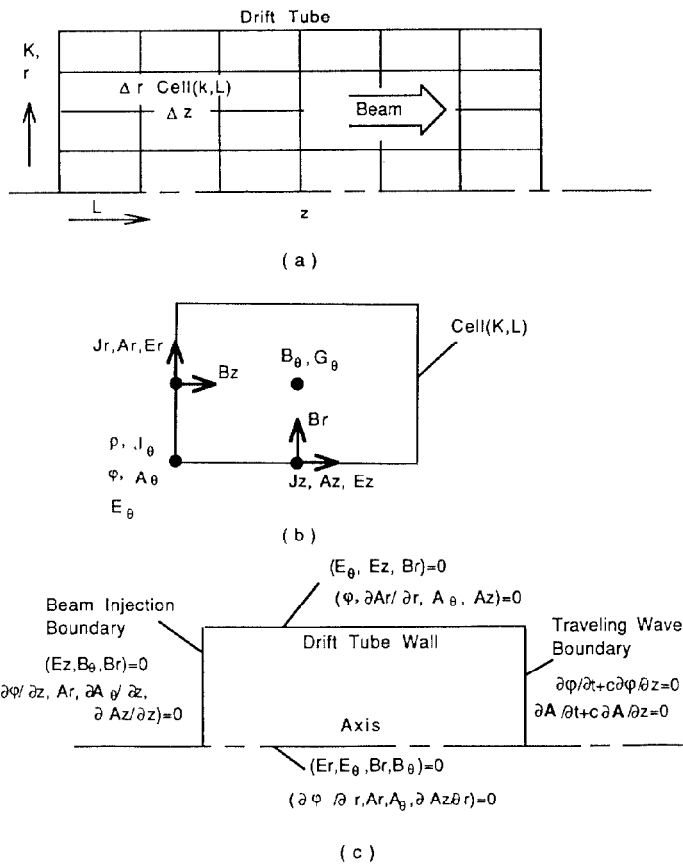


Fig.1 Mesh and boundary conditions used for the FDM calculation of the beam induced fields.

using finite difference method (FDM) in the CAVITY routine. The gap fields are normalized to the axial voltage of 1 V, and used for the beam simulation by multiplying the cavity voltages.

Cavity Voltage Determination

The cavity voltages are determined by solving the equivalent circuits as shown in Fig.2. The

induced current is given by integrating the following equation over gap region.

$$i_b(t) = -\int \mathbf{E}_0 \cdot \mathbf{J}(t) dv, \quad (5)$$

where \mathbf{E}_0 and $\mathbf{J}(t)$ are the normalized gap field and the beam current density, respectively.

For the input and idler cavities, the cavity voltage is directly given by the steady state solution of the equivalent circuit as follows (small signal linear approximation).

$$\text{Input cavity: } V_c = \frac{I_g}{(Y_c + Y_b)} \quad (6)$$

$$\text{Idler cavity: } V_c = \frac{I_{b0}}{(Y_c + Y_b)} \quad (7)$$

where,

I_g : current source of external power generator, which drive the input cavity.

I_{b0} : the beam induced current without any voltage being applied on the cavity.

Y_b : the beam admittance, which is determined by measuring the change of the induced current by applying a test voltage on the RF-cavity flowing DC-beam at the beginning of the beam simulation.

Y_c : the admittance of the cavity given as follows

$$Y_c = \frac{1}{(R/Q)Q_L} (1 + j2 QL\delta) \quad (8)$$

where

QL : loaded Q

$\delta := (f - f_0)/f_0$

f_0 : cold resonance frequency of RF-cavity.

f : input drive frequency.

R/Q : defined as $U = \frac{(V_{c,rms})^2}{2(R/Q)}$

U : stored energy

$V_{c,rms}$: r.m.s. of the axial cavity voltage[2].

In case of the output cavity, the cavity voltage and the beam loading current becomes large and the interaction becomes nonlinear. The steady state solution can not be applied, so that the following equation is solved directly.

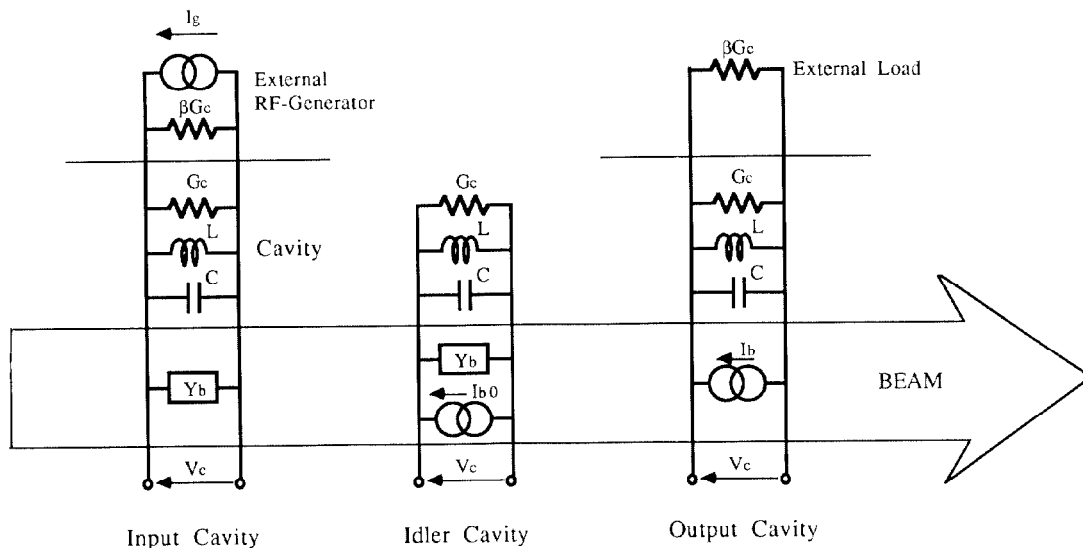


Fig.2 Equivalent circuit of klystron.

$$\tau \frac{d}{dt} \begin{pmatrix} \text{Re}(V_c) \\ \text{Im}(V_c) \end{pmatrix} = Z \begin{pmatrix} \text{Re}(I_b) \\ \text{Im}(I_b) \end{pmatrix} \cdot \begin{pmatrix} \text{Re}(V_c) - 2Q_L \delta \text{Im}(V_c) \\ \text{Im}(V_c) + 2Q_L \delta \text{Re}(V_c) \end{pmatrix} \quad (9)$$

where

$$\tau = 2Q_L/\omega_0, Z = (R/Q)Q_L \quad (10)$$

Eq. (9) is given from the circuit equation under the quasi-steady-state approximation. Instead of the phase and amplitude, the real and imaginary parts of the voltage and current are used in eq.(9), so that the equation becomes very simple and beautiful[3].

In order to reduce the C.P.U. time, the dummy Q_d is used instead of Q_L . In the code, Q_d is set to 2. The time constant becomes $\tau = 2Q_d/\omega_0$, and the steady state value is obtained in a few RF-cycles, because $f_0\tau = Q_d/\pi \cong 0.6$.

Results of the Simulations

Figure 3 shows the simulation results of 50MW 5045 tube and experimental data for the tube 408A. The gain of the simulation results, which uses the nominal cavity parameters and magnetic field profile, is 3 dB higher than the experimental values. The difference of the peak power is about 10%. These difference has the same tendency as the simulation by K. Eppley, et.al.[4] using MASK.

The beam radius in the drift tube region greatly affects on the tube gain, because the multi-cavity klystron operates as a kind of multi-stage amplifier, in which each amplifier's gain proportional to the square of the coupling coefficient, and this coefficient depends upon the beam radius. We tested the simulation using a smaller beam radius by reducing the cathode magnetic field from 39 to 25 G and the injection beam radius from 1.1 to 0.9 cm. As shown in Fig. 3, the simulation results almost fit to the experimental data. In the simulation, the Q_L of the output cavity was reduced 10 %, which gives the lower peak power. It is difficult to accurately measure the R/Q and Q_L values on the output cavity, because it has quite low Q_L value and large non-axisymmetric port. Hence, the Q_L or R/Q could have the error of 10%. Fig. 4 shows the example of the beam profile, the kinetic energy profile and the Fourier components of the current at 54.3 MW output.

Future Research

The simulation results and the real klystron performances are very sensitive to the magnetic profiles, especially that of the gun region, and of course to the cavity parameters. We must start the systematic investigation to refine these parameters.

We are also interested in the application of the code to design the RF-gun, buncher section of a high intensity linac and beam dynamics in the induction linac.

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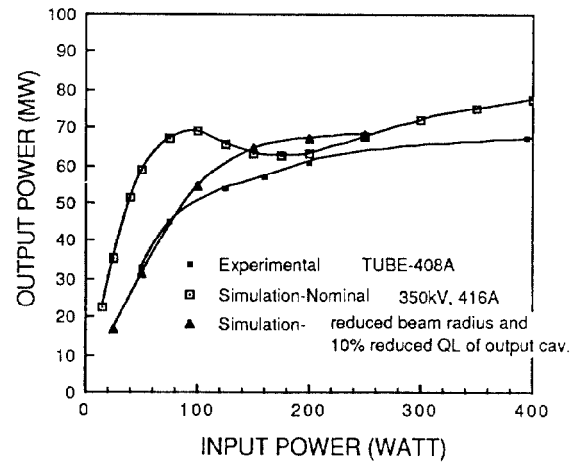


Fig. 3

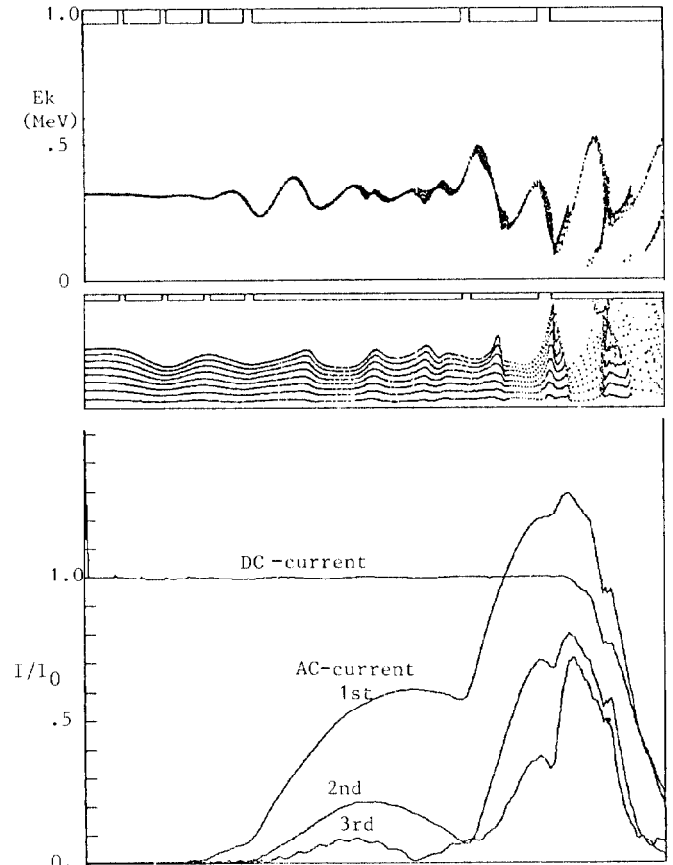


Fig. 4

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References

- [1] Simon Yu, "Particle-in-cell simulations of high power klystrons", SLAC/AP-34, 1984.
- [2] However, in the code(of 1st version), (R/Q) is defined for the peak voltage. It will be changed to that of r.m.s. definition.
- [3] Equation.(9) was suggested by Y. Yamazaki.
- [4] K.Eppley, S. Yu, A. Drobot, W.Herrmannsfeldt and H.Hanerfeld, "Results of Simulation of High-Power Klystrons", IEEE, NS-32, 1985, P.2903