TRANSIENT BEAM LOADING EFFECTS CAUSED BY BACK-STREAMING ELECTRONS ONTO A THERMIONIC CATHODE IN AN RF GUN

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Abstract

Adverse effect of back-streaming electrons onto a thermionic cathode in an S-band 4.5-cell rf gun was studied. A numerical model is presented based on an equivalent circuit of the rf gun, taking beam-loading effect into account through 2-dimensional particle-in-cell simulations. Experimentally observed time evolutions of rf power reflected from the rf gun, and of output beam energy were both well reproduced by the present numerical model, on an assumption of cathode temperature rise during the rf macro-pulse. Conclusively, observed undesirable decrease of beam energy during the macro-pulse is found caused by a considerable increase of the cathode temperature due to back-streaming electrons hitting on the cathode.

1. INTRODUCTION

Rf guns have advantages against widely used electrostatic electron guns, such as compactness and high brightness of the output beam, exclusively because they can provide much higher accelerating fields. For long macro-pulse electron beam productions, however, they suffer from a serious problem, that back-streaming electrons tend to hit cathodes resulting in cathode temperature rises [1], which finally make both beam currents and energies unstable during macro-pulses longer than several μsec

For compensating the beam energy decrease due to the cathode temperature rise during the beam macro-pulse, transient control of pulsed rf power supply to thermionic rf guns would be efficient. As a first stage to the final goal of the optimum control of the rf power supply, we developed a numerical model to reproduce experimentally observed transient beam loading effects in a thermionic rf gun. Presented in this paper are the numerical model, and comparisons with experimental results for verification in terms of time evolutions of output beam energy and reflected rf power from the rf gun.

2. EXPERIMENTAL SETUP AND RESULTS

The present rf gun (AET Associates, MG-500) has 4.5 cells, with a resonant frequency f_0 = 2857.60 MHz at 30 °C body temperature. A 6 mm-diameter tungsten impregnated thermionic cathode (Heat Wave, 411M) is mounted in the first half cell. The cathode surface temperature can be measured by use of an infrared (IR) fiber thermometer through a view-port mounted on the half cell. The sampling interval of measuring the temperature is 25 μsec, and the distance from cathode surface to IR fiber thermometer is 200mm. Beam measurement system is also equipped for measuring time evolutions of beam current by use of a current monitor (CT1 in Figure 1), and of energy spectrum by use of a bending magnet (BM), a beam slit, and a current monitor (CT2).

Fig. 2 shows measured time evolutions of beam current I_b and reflected rf power P_{ref} together with the pulsed rf input P_{in} of 4.0 MW, 2.1 μsec. The rf frequency was set as f = 2857.77 MHz so as to minimize P_{ref} at t = 2.1 μsec, which is slightly different from f = 2857.60 MHz due to the beam loading. Averaged cathode surface temperature was measured as 1115 °C, which was found higher than that without rf input of 1109 °C. Although time evolution of the temperature through the 2.1 μsec duration macro-pulse could hardly be observed, of course, owning to the poor time resolution of the IR thermometer, there must be a considerable temperature rise within the macro-pulse [1,2], which seems to result in an increase of I_b in Fig. 2, and, accordingly, a decrease of P_{ref} after the rf filling time of around 1 μsec.

By measuring beam current waveforms by use of CT2 for various BM coil currents, i.e. for various beam energies, the time evolution of beam energy spectrum shown in Fig. 3 can be obtained, which shows a decrease of peak energy $E_{b,peak}$ after the rf filling time, t > 1 μsec, implying, again, the increasing beam loading.

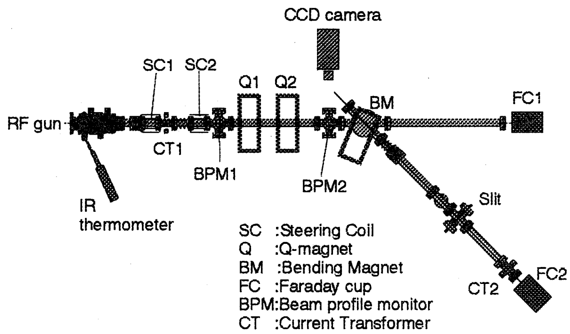

Figure 1 Experimental setup.

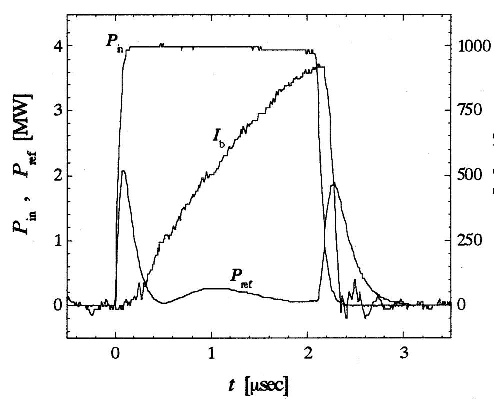

Figure 2 Measured time evolution of I_b, P_{ref} and P_{in}.

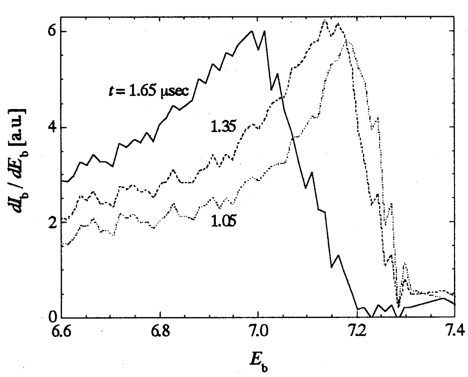

Figure 3 Measured time evolution of beam energy spectrum.

3. NUMERICAL MODEL

3.1 Equivalent circuit model

Interaction between an rf resonant cavity and an electron beam can be represented by an equivalent circuit shown in Fig. 4, where the equivalent voltage V_c represents the rf cavity voltage, the circuit constants L, C, and G correspond to the cavity parameters such as the resonant angular frequency ω_0 , the unloaded quality factor Q_0, and the R/Q factor (R/Q). The constant β denotes the coupling coefficient of the input waveguide to the cavity. The constants L, C, G, and β are, thus, all given. The current supply $I_g(t) = \mathrm{Re}\,[\, I_g(t)e^{j\omega t}\,]$ corresponds to the pulsed rf power supply to the rf gun, where $\omega/2\pi = f$ denotes the rf frequency, and $I_g(t)$ is given by the pulsed rf power $P_{in}(t)$ shown in Fig. 2, as follows [3].

$$I_g(t) = \sqrt{8\beta G P_{in}(t)}. \qquad (1)$$

The remaining i_{bl} in Fig. 4, the beam loading current, represents the beam loading effect on the cavity field.

For the equivalent circuit in Fig. 4, the following equations are obtained,

$$C\frac{dV_C}{dt} = -\{(1+\beta)G + j\omega C + Y_b\}V_C - I_L + I_g, \qquad (2)$$

$$L\frac{dI_L}{dt} = V_C - j\omega L I_L, \qquad (3)$$

where Y_b is the beam admittance, which will be given as a function of V_C and the cathode surface temperature $T_{cathode}$ in the following section.

$$Y_b = Y_b(V_C, T_{cathode}). \qquad (4)$$

By numerically solving eqs. (2),(3) and (4) time evolution of V_C can be obtained. Time evolutions of P_{ref} and $E_{b,peak}$ are, then, given in terms of V_C as follows,

$$P_{ref} = P_{in} - \frac{1}{2}\mathrm{Re}\,[V_c^*(I_g - \beta G V_c)], \qquad (5)$$

$$E_{b,peak} = E_{b,peak}(V_C, T_{cathode}), \qquad (6)$$

where V_C^* represents the conjugate complex of V_C, and $E_{b,peak}$ as a function of V_C is, again, given in the following section.

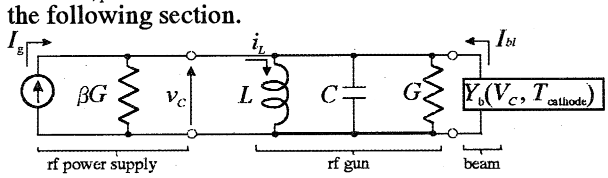

Figure 4 Equivalent circuit model.

3.2 Evaluation of beam admittance by PIC simulation

To give Y_b and $E_{b,peak}$ as functions of V_C and $T_{cathode}$, 2-dimensinal time-domain particle-in-cell simulations were carried out by use of a numerical code KUBLAI [3].

With a constant V_C and a constant current density $J_{cathode}$ on the cathode surface as input parameters, the KUBLAI code simulates electron dynamics in the rf gun, and gives output beam characteristics and Y_b (or I_{bl}) as well, while $J_{cathode}$ [A/cm^2] is given as a function of $T_{cathode}$ [K] as

$$J_{cathode} = 1.12\times10^7 \exp\left(-1.89\times10^4/T_{cathode}\right).$$

4. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

Firstly, for verification of the circuit model, time evolutions of P_{ref} were calculated without an electron beam, i.e. $J_{cathode} = 0$. As seen in Fig. 5 the results are found to agree with the experimental ones without heating the cathode, for both cases of $f = f_0$ and $f \neq f_0$.

Secondly, it was applied to the case with an electron beam to reproduce the experimentally observed P_{ref} shown in Fig. 2. The rf frequency f was fixed at f = 2857.77 MHz. Neither of the numerical results is found to agree with the experimental one. Then, by assuming a linear dependence of $T_{cathode}$ on t during the macro-pulse, the experimental one could be reproduced well, as seen in Fig. 6 with trials and errors for a temperature rise from $T_{cathode}$ = 1000 ℃ at t = 0 to $T_{cathode}$ = 1150 ℃ at t = 2.1 μsec.

Finally, on the above assumption of the cathode temperature rise, calculated evolution of $E_{b,peak}$ was compared with the experimental one shown in Fig. 3. They are found in good agreement as seen in Fig. 7.

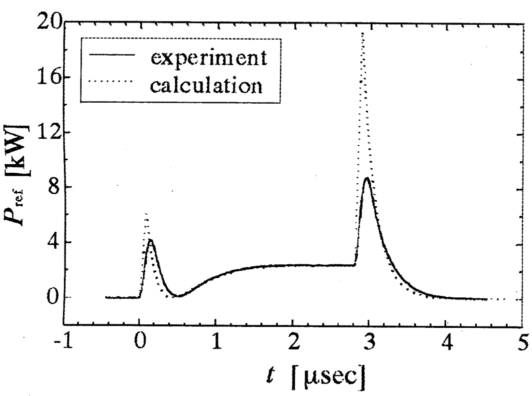

Figure 5 Time evolution of P_{ref} comparing experiment and calculation, without electron beam for f = 2857.60 MHz at resonance.

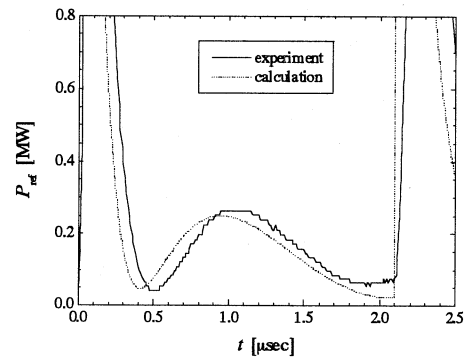

Figure 6 Calculated time evolution of P_{ref} with an increase of cathode temperature.

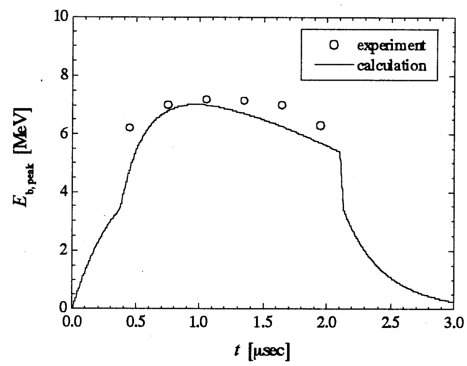

Figure 7 Time evolution of peak beam energy E_b, comparing experiments and calculation.

5. CONCLUSION

The observed time evolutions of the reflected rf power and the beam energy were well reproduced by the present numerical model. The observed energy decrease through the macro-pulse is supposed to be caused by a considerable cathode temperature rise due to back-streaming electrons onto the thermionic cathode.

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