RF Gun Study in the SPring-8 Linac

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1. Introduction

A photo cathode RF gun has been studied in the SPring-8 linac in order to produce high peak current and low emittance beam. It is needed not only for the future application such as a single pass FEL based on the SASE, but also for the current linac gun since adjustable parameters of the RF gun system becomes fewer and control is expected to become easier than the current thermionic gun.

In 1998, the experimental set up was completely installed in machine laboratory. Aging procedure of wave guide system and an rf cavity was performed. Simultaneously from calculation approach, we had been studied simulation for beam diagnostics. A three dimensional beam tracking code which includes space charge effects for an rf cavity and solenoid coils were developed.

2. Setting Up History for Experiment

In 1997, construction of the machine laboratory was completed in autumn, blocks for shielding radiation were installed, and a 35 MW klystron and a modulator set for feeding rf power to the cavity were moved form the linac M1 section to the machine laboratory[1].

In 1998, laser system[2] was installed in February in a clean booth of class 1000. Driving sequence of the modulator was completely regulated by March. The wave guide system which connects the klystron to the cavity was installed by April. An aging procedure for the wave guide was performed in May.

An aging procedure for the rf cavity was performed in October, with simple set up that consists of the cavity, a profile monitor and a Faraday cup. Figure 1 shows an aging history. RF power level grew up linearly to a number of RF pulses. It took about six hours to achieve rf conditions with rf power of 13 MW, rf pulse width of 1 μs and repetition rate of 10 pps. This rf power corresponds to a maximum field gradient in the cavity of 107 MV/m in ideal calculation. Dark current from the cavity is shown in Fig.2. It was measured by Faraday cup located just after the profile monitor.

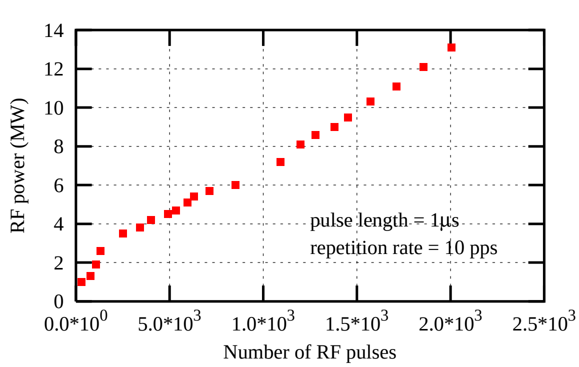

Fig. 1 Aging history for an RF cavity.

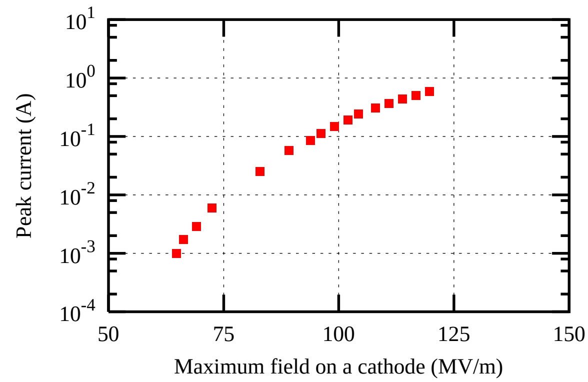

Fig. 2 Dark current from an RF cavity.

By the end of November, all beam line devices were completely installed. Figure 3 shows outline of the beam line. It consists of the rf cavity, two solenoids, a profile monitor, two sets of x y slits for emittance measurement and a bending magnet for energy analyses. Experiment of laser injection will be held from the beginning of 1999, because interlock system for security of the laser is not installed completely at the end of 1998.

There is one problem we observed, that a dark

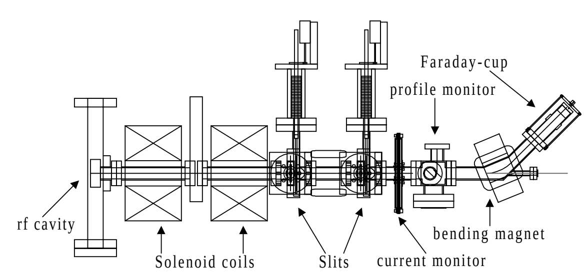

Fig. 3: Outline of a beam line for the RF gun experiment.

current does not pass straight forward along the beam line, because the beamline were mounted on a plate made of magnetized stainless steel, and the magnetic field of the solenoids were distorted. We will replace the mounting plate next year.

3. Simulation Studies

There are some simulation codes for this purpose such as MAFIA or PERMELA. But it is not realistic to perform three-dimensional calculation using these codes, because a lot of memories are required. Also it is unable to make a mesh size of infinitely small. Thus we developed our own code that can solve these problems.

3-1 Outline of Simulation Code

Our developed code is a three-dimensional particle tracking code that includes the production of electrons and space charge effects. As a result of recent increases in CPU speed, we try to calculate all space charge effects of each electron in the tracking code, but we assume that the charge and mass of each particle are larger than those of real electrons. The electron is accelerated in the cavity, but a calculation procedure for the space charge that includes acceleration becomes to be complicated so much. Because a lot of calculation procedures are required to find a retarded position of each electron. Thus, we assume uniform motion for electrons. From Liénard-Wiechert potentials, the electric and magnetic fields at point A caused by electron B are expressed as follows;

$$\mathbf{E}_A = \frac{1}{4\pi\epsilon_0\gamma^2}\frac{-e\mathbf{r}}{\left[|\mathbf{r}|^2 - \frac{|\mathbf{v}_B\times\mathbf{r}|^2}{c^2}\right]^{3/2}} \qquad \mathbf{B}_A = \frac{1}{c^2}\mathbf{v}_B\times\mathbf{E}_A \tag{1}$$

where $\mathbf{r}$ is a vector from B to A, $\mathbf{v}_B$ is a velocity of electron B, and γ is a relative factor of electron B. These fields act on electron A as follows:

$$\mathbf{F}_A = -e\left(\mathbf{E}_A + \mathbf{v}_A \times \mathbf{B}_A\right) \tag{2}$$

The equation of motion for each electron is derived to the following equation and becomes adaptable for the Runge-Kutta method.

$$\begin{gathered} -e\left(\mathbf{v}\times\mathbf{B}+\mathbf{E}\right) = m_0\frac{d\left(\gamma\mathbf{v}\right)}{dt} \\ \Downarrow \\ \frac{d\mathbf{v}}{dt} = -\frac{e}{\gamma m_0}\left(\mathbf{v}\times\mathbf{B}+\mathbf{E}-\frac{(\mathbf{v}\cdot\mathbf{E})}{c^2}\mathbf{v}\right) \end{gathered} \tag{3}$$

Note that a term $-\frac{(\mathbf{v}\cdot\mathbf{E})}{c^2}\mathbf{v}$ is derived from differentiation of γ.

We consider two types of extra electromagnetic sources in our code. One is an rf cavity for a part of the electron production, and the other is a set of two coils for focusing the electron beam. (see Fig.3) The fields in the cavity are calculated in the MAFIA code and are included in our code. The fields of the solenoid coils are calculated in our code. We calculate the extra fields in the same manner as the fields due to space charge.

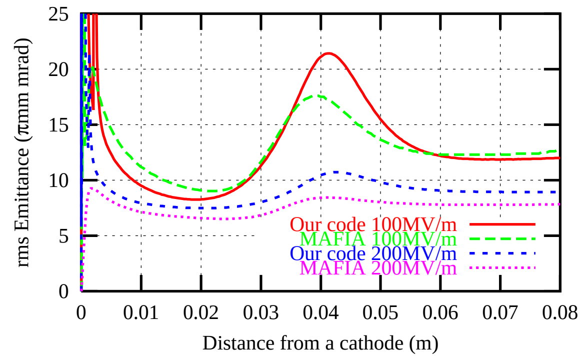

Fig. 4: Comparison between our code and MAFIA as a function of the maximum field in the cavity. An exit of the cavity is 0.074 m apart from the cathode. Charge is 1 nC per bunch. Initial beam spot size is 0.25 mm (1σ), which is comparable to MAFIA's mesh size of 0.1 mm.

In our experimental setup, one side of the rf cavity is used as a cathode[1], thus we also consider the image charge effect caused from the copper cathode in our code.

Figure 4 shows calculated emittance in the rf cavity, using our code and MAFIA. Though our code performed 3-D calculation, MAFIA calculated in 2-D spaces. But initial parameters are the same in the two codes. An emittance in Fig. 4 is the normalized rms emittance, which is defined by $\epsilon_x = \langle\gamma\rangle\langle\beta\rangle\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\cdot x'\rangle^2}$ for our code, and $\epsilon_r = \frac{1}{2}\langle\gamma\rangle\langle\beta\rangle\sqrt{\langle r^2\rangle\langle r'^2\rangle - \langle r\cdot r'\rangle^2}$ for MAFIA.

They show good agreements. Though in the case that maximum field gradient in the cavity is 100MV/m, they show slight disagreement. We considerd that this problem causes from an insufficient mesh size in MAFIA.

3-2 Simulation Results

The emittance calculation for the actual test apparatus were carried out using our code. Figure 5 shows the results in the RF cavity that depend on the cavity field. The parameters in the Fig. 5 are listed in Table. 1.

The emittance becomes lower as the field in the cavity increases. In a region over 200 MV/m, it becomes almost constant. However, it is very difficult to increase the field of the cavity because of discharges or dark currents in actual experiment.

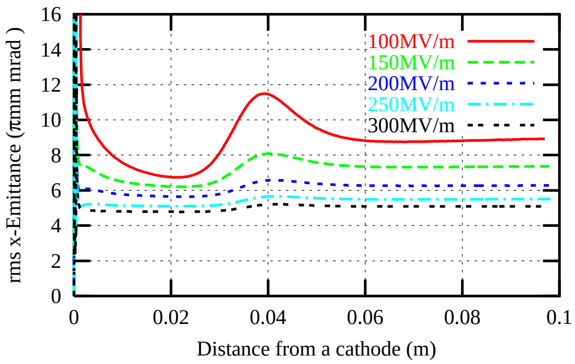

Fig. 5: Emittance depends on the maximum cavity field changed from 100 MV/m to 300 MV/m.

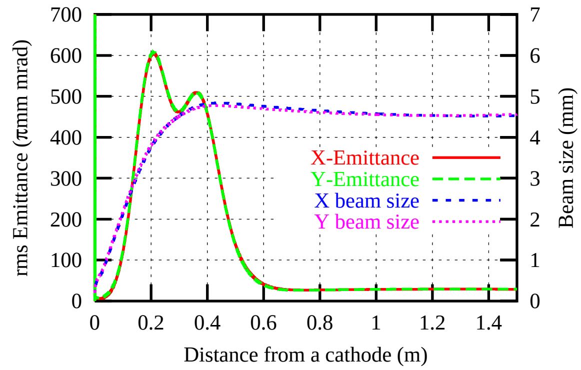

Fig. 7: Calculated emittances and beam sizes from cathode to Faraday cup. Parameters are the same as Table.1 except the initial rf phase of 60 degree.

Table. 1 Calculation Parameters used in Fig. 4

Charge per bunch	1.0[nC] or none
Initial beam transverse profile	Gaussian
Initial beam radius on cathode	0.25[mm] (1σ)
Longitudinal bunch profile	uniform
Bunch length	10[ps]
Initial emittance	0[πmm·mrad]
Initial rf phase	45[degree]

Figure 6 shows dependence on an initial rf phase of ϕ, which defined by $E_{cavity} = E_{max} \cos(\omega t - \phi)$.

In a region from 20 degrees to 60 degrees, the emittances at the exit of the cavity are almost constant. Though in a region from 60 degrees to 80 degrees, the emittance becomes larger as the phase increases. On the other hand, beam energy becomes lower as the initial phase becomes higher. Thus, the optimum initial phase is considered to be around 60 degrees.

Figure 7 shows the calculated emittances and beam sizes from the cathode to the Faraday cup, which is located 1.5 m downstream at the cathode. This simulation includes the fields of the two solenoid coils. The first coil is positioned 0.174 m apart from the cathode, and the second coil is located 0.374m apart. The fields are 1500 and 800 Gausses respectively. The x and y beam sizes are slightly different because of the asymmetry of the cavity.

The x-emittance and y-emittance change dramatically in the solenoid coils, because the x and y component of magnetic fields are coupled in solenoids. The emittance becomes smaller after the solenoid coils by choosing the optimum solenoid fields. Also beam size in Fig. 7 is kept small for beam pipe size. In the experiment, we can measure the emittance only after the solenoids, so when we estimate the emittance of the cavity, this calculation is very important.

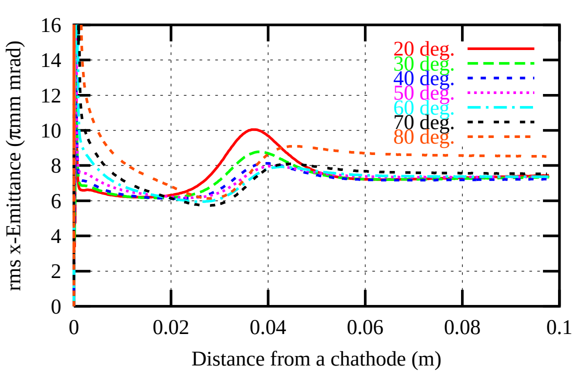

Fig. 6: Emittance depends on the initial rf phase. Maximum field in the cavity is 150 MV/m. Other parameters are the same as Table.1.

4. Conclusion

An rf gun experiment set up was installed completely by the end of November, 1998. Laser injection to produce electron beam will start in the beginning of 1999. On the other hand, simulation studies are going on. The main parameters for the experiment have been already calculated. In 1999, we will be able to compare experiment results with simulations. It is the first step for this project. We plan to start designing an rf gun system for conventional use from these experiment and simulation results.

References

[1] T.Taniuchi et al, SPring-8 Annual Report 1997, 152(1997).

[2] K.Yanagida et al, AIP conference proceedings 413, 299(1997).