EXTREMELY LOW ENERGY SPREAD BEAM GENERATION BY DUAL MODE SUPERCONDUCTING ACCELERATOR

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Abstract

Extremely low energy spread electron beam acceleration in order of 1.0E-5 is considered for electron microscopy. The electron beam is generated by GaAs photo-cathode with a short pulse laser. The beam is then accelerated by a super-conducting (SC) accelerator up to 300keV. To compensate the energy spread due to the RF curvature, we employ SC accelerator driven by dual modes, 1.3 GHz (TM_{010}) and 2.6GHz (TM_{020}). As results of particle tracking simulations with GPT(General Particle Tracer) including space charge effect, 5.0E-5 rms energy spread relative to the kinetic energy is obtained. The bunch is 10fC charge and 20ps length with 400μm radius. By assuming thermal emittance of GaAs photo-cathode, 30meV, the peak brightness is 5.1E+5 $\mathrm{A/cm^2.str}$, which should be compared to typical brightness of TEM, 1E+6 - 1E+9. To obtain a clear image by TEM, 16 pulses are required. By employing pump-probe technique, TEM observation with 20ps temporal resolution is possible.

INTRODUCTION

Electron microscopy is one of the powerful tool to investigate a wide variety of phenomena. Recently, DTEM(Dynamic Transmission Electron Microscopy) resolving temporal evolution, has been developed up to 10ns resolution[1]. By employing pump-probe approach, this resolution is able to be in order of fs, which is determined by the electron beam bunch length. For these innovations, electron pulse with extremely low energy spread, is a key technology, because the spatial resolution of EM is spoiled by various aberrations. Typically, the energy spread of EM is in order of 1.0E-5.

In the accelerator technology, photo-cathode RF gun has been developed since 1985[2], initially as an deal injector for FEL. Recently, observing Electron Diffraction with the photo-cathode RF gun was reported[3]. This method is called as UED(Ultra-fast Electron Diffraction), because of the short time window determined by the bunch length. EM(Electron Microscopy) with such an advanced accelerator concept is a natural extension.

For the RF accelerator based EM, the extremely low energy spread is an issue, since energy spread due to the RF curvature is expected in order of 1.0E-3 with 1.3GHz RF and 10ps pulse length. It can be cured by acceleration with several harmonics. In this study, dual modes acceleration (1.3GHz and 2.6GHz) is proposed. If the acceleration by these modes(angular frequency ω and 2ω) is represented

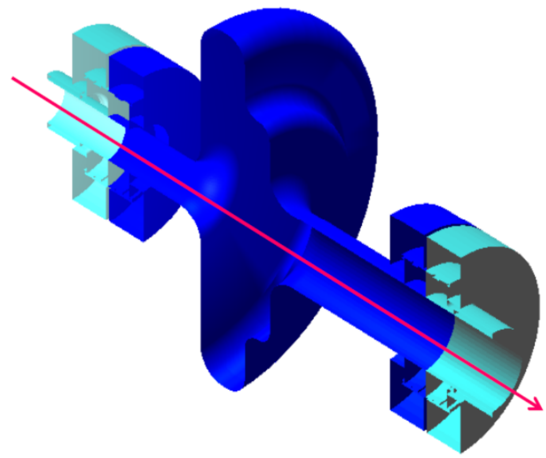

Figure 1: Cross section of SC cavity for dual mode acceleration.

by the sinusoidal functions, the linear combination with proper amplitudes gives

$$V(t) = 4V_0 \cos\omega t - V_0 \cos 2\omega t = 3V_0 - V_0 \frac{\omega^4}{2!} t^4 + \ldots, \quad (1)$$

where the second order time dependent term is completely vanished. The energy spread due to the RF curvature is then much suppressed by the dual modes acceleration. The two modes have to be in harmonic relation exactly. In the following sections, we discussed the dual mode acceleration and the accelerated beam quality.

DUAL MODE SC CAVITY

For the dual mode acceleration, there are two possibilities. One is that two accelerating cavities are placed in a series one by one. This is a conventional idea, but the velocity modulation made by the first cavity makes a mismatch on the energy spread compensation. Another idea is that the two modes are accommodated in one common cavity. This method is better because the beam is accelerated simultaneously by the two modes in the same cavity and the energy spread is compensated properly. However, the cavity design has to be made with an attention on the mode tuning, because the two modes have to be exactly in harmonic relation. For such purpose, a SC cavity is specially designed by Furuya and Nishiwaki[4]. The cavity cross-section is shown in Fig.1. These two modes are accommodated in the super-conducting cavity as presented in Fig. 2. The modes are TM_{010} and TM_{020} modes, respectively, and the frequencies are adjusted to be in harmonic

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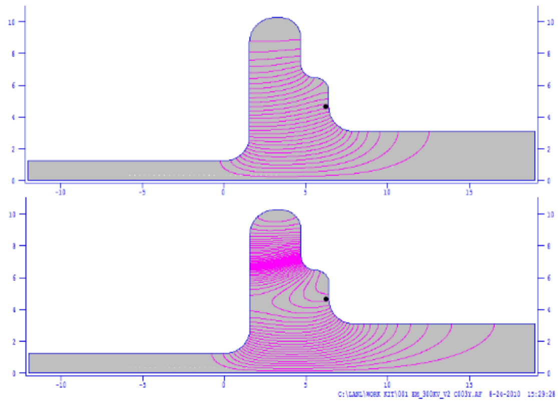

Figure 2: Electric field profile of TM_{010} and TM_{020} modes in the dual mode SC cavity.

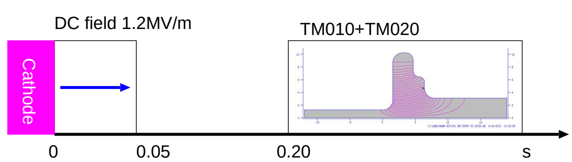

Figure 3: Schematic drawing of the simulation geometry.

relation, 1.3GHz and 2.6GHz. The cavity is designed, so that these two modes can be tuned by deforming different points of cavity wall. Therefore, these two modes can be tuned independently and the exact tuning is possible.

The cavity will be fabricated with Nb and the accelerating gap is 49.0 mm corresponding $\beta = 0.30$. The expected R/Q, where R is shunt impedance and Q is quality factor, are 122 and 33.1 Ω for TM_{010} and TM_{020} modes, respectively. The Q value depends on the operation temperature, i.e. 2K or 4K.In 2K case, $7.9\mathrm{E}+9$ and $4.4\mathrm{E}+9$ for TM_{010} and TM_{020} modes, respectively. In 4K case, $1.9\mathrm{E}+8$ and $1.0\mathrm{E}+8$ for TM_{010} and TM_{020} modes, respectively. By assuming 4K operation, 7.1 W 1.3GHz input and 17 W 2.6GHz input induce 8.6 MV/m and 12 MV/m axial field for TM_{010} and TM_{020} modes, respectively. The external coupling is not considered at all in this calculation and the input power is increased in the real case.

TRACKING SIMULATION

A tracking simulation is performed with a simulation code, GPT(General Particle Tracer). In the simulation, electron beam is generated in a bunched form. The bunch intensity is flat in transverse and longitudinal directions. The cathode, where the beam is generated, is placed in a uniform electric field, 1.2 MV/m representing initial electric field of DC gun structure. The bias voltage is 60 kV. After some drift space, the RF field representing the SC cavity is placed. Two field maps corresponding to TM_{010} and TM_{020} modes are overlaid. Fig. 3 shows the schematic geometry of the simulation.

Varying the amplitudes and phase relation between the two modes, the energy spread of the accelerated bunch was investigated. The bunch radius is $100\mu\mathrm{m}$, and length is 10 ps. At the initial simulation, space charge effect is not included. Fig.4 and 5 show the energy spread and gamma as a function of phase of TM_{020} mode. Here, we define the relative energy spread as

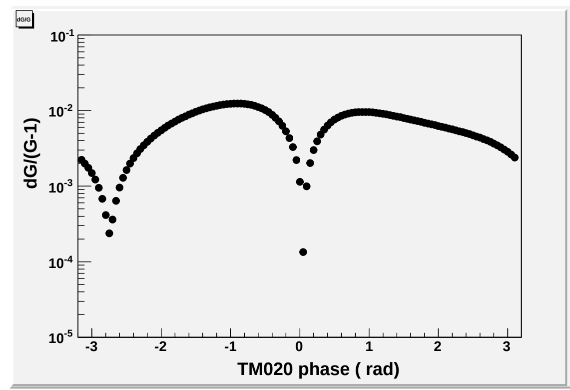

Figure 4: Energy spread as a function of phase of TM_{020} mode.

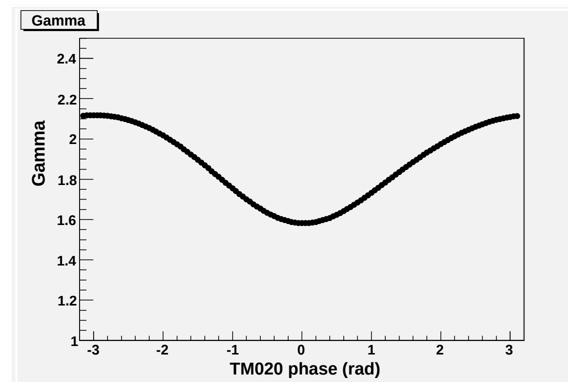

Figure 5: Lorentz factor gamma as a function of phase of TM_{020} mode.

$$\Delta E_{kin} = \frac{\Delta\gamma}{\gamma - 1} \qquad (2)$$

Other parameters, amplitudes of two modes and phase of TM_{010} mode is fixed. As shown in Fig. 4, two minimals are found. Each minimal corresponds to TM_{020} acceleration and deceleration phases, because the gamma in Fig. 5 are maximal and minimal for each phase. TM_{020} phase around zero is expected to be the deceleration phase, where the energy compensation is expected.

We perform an optimization procedure based on downhill simplex method around the minimal point found in the previous scan. In this study, we ignore still space charge effect. The bunch length and size are not changed. Table 1 shows the optimized results. The axial field means the maximum field of the accelerating field. The energy spread ΔE_{kin} at the optimized condition is expected to be $9.4\mathrm{E}-6$, which is even below our target, in order of $1\mathrm{E}-5$.

Table 1: Optimized parameter for minimum energy spread without space charge effect.

Mode	Axial field (V/m)	phase (rad)
TM_{010}	8.5E+6	0.224
TM_{020}	7.4E+6	0.068

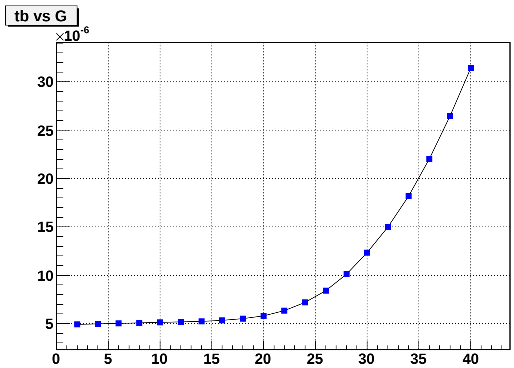

Figure 6: Energy spread as a function of bunch length in ps.

Including space charge effect, the energy spread is expected to be large and compensating the growth is one of the most important issue of this study. To suppress the space charge effect, decreasing charge density by increasing the bunch geometry (length and size) is one way. To understand the geometrical property on the energy spread, it was investigated as functions of the beam size and length as shown in Fig. 6 and 7. As easily figure out from these results, the energy spread is rapidly increased when the bunch length is more than 25ps. On the other hand, the beam size (radius) has only weak dependence on the energy spread. These properties are important later to cure the growth by the space charge effect.

Next, we perform the same simulation, but including the space charge effect. The bunch geometry and RF parameters are not changed at all. To qualify the effect, we investi-

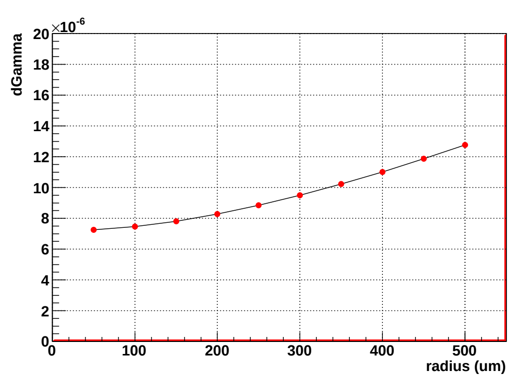

Figure 7: Energy spread as a function of beam radius in μm.

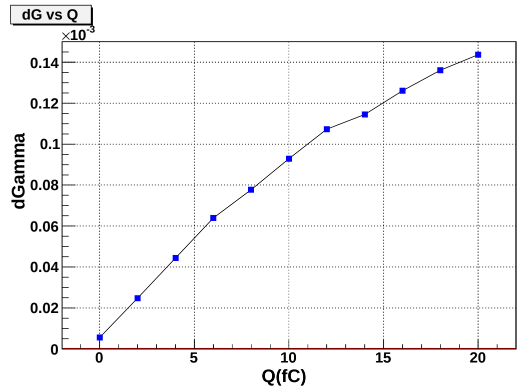

Figure 8: Energy spread as a function of bunch charge. Space charge effect is included in the simulation.

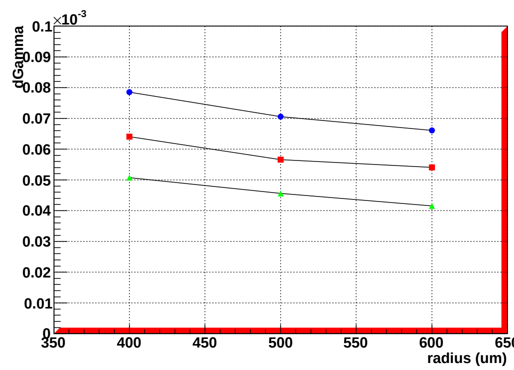

Figure 9: Energy spread as a function of beam radius with three different bunch length. Circle, square, and triangle show data with 15ps, 17.5ps, 20ps bunch length, respectively.

gate the energy spread as a function of the bunch charge as shown in Fig. 8. The energy spread is rapidly inflated by increasing the bunch charge. The energy spread becomes one order magnitude larger if the bunch charge is 10fC.

To suppress the energy spread growth by the space charge effect, we manipulate the bunch geometry, i.e. length and radius. According to the observations in Fig.7 and 6, geometrical growth is not significant bunch length less than 20ps. Then, we vary the bunch length from 15ps to 20ps and observe the energy spread as a function of bunch radius. The results are shown in Fig. 9. Among these data points, $5.0\mathrm{E}-5$ energy spread is obtained with 20ps bunch length and 400 μm radius.

FEASIBILITY OF ACCELERATOR BASED EM

We studied the extremely low energy spread beam generation with dual modes acceleration for EM. We found that the space charge effect strongly influences the energy spread. As a representative number, $\Delta E_{kin} \sim 5.0\mathrm{E}-5$ is obtained with 20ps bunch length and 400μm radius. Now, we consider a feasibility of this beam for EM purpose.

Required parameters for TEM observation for taking one clear image are $1\mathrm{E}+6 \sim 1\mathrm{E}+8$ electrons, $1\mathrm{E}+6 \sim 1\mathrm{E}+9$ $(\mathrm{A/cm^2.str})$ in brightness, and $0.16 \sim 16\mathrm{mA}$ in current. Assuming our representative numbers, $400\mu\mathrm{m}$ radius, 10fC bunch charge, and 20ps bunch length, the brightness is estimated to be $5.1\mathrm{E}+5$ $(\mathrm{A/cm^2.str})$, which is slightly less than $1E+6$. Here, we assume observed thermal emittance of $GaAs$, 30meV[5] to obtain the solid angle. The brightness is slightly less than the typical TEM parameter, but it could be practical for TEM observation from the brightness point of a view.

Next, we consider amount of charge. 10fC bunch charge corresponds to $6.3\mathrm{E}+4$ electrons. To accumulate $1\mathrm{E}+6$ electrons, 16 pulses are required. This duration corresponds to 12ns, since 1.3GHz RF period is 770ps. That means one clear image can be taken each 12ns and the time resolution of the TEM could be 12ns. This is even attractive as a DTEM (Dynamic TEM) to observe any fast phenomena.

In addition, if we employ the pump-probe technique, i.e. triggering a photo-induced interaction by a short pulse laser and investigate the matter with TEM with a time delay many times, we could observe the clear temporal evolution of the interaction with 20ps time resolution. If we employ a common laser for pumping and photo-cathode driver, time jitter between pumping pulse and probe pulse, which always limits the temporal resolution in the method, could be very small.

SUMMARY

DTEM based on RF accelerator is considered with dual modes acceleration in SC cavity. According to our simulation, the beam generated by the system is even feasible as electron source for DTEM. Pump-probe method can be easily implemented by using laser pulses from a common laser for photo-cathode and sample pumping.

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