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THE DEVELOPMENT OF CAVITY FREQUENCY TRACKING TYPE RF CONTROL SYSTEM FOR SRF-TEM

N. Higashi*, The University of Tokyo, Tokyo, Japan
M. Kuriki, HU/AdSM, Higashi-Hiroshima, Japan
S. Yamashita, ICEPP, Tokyo, Japan
A. Enomoto, Y. Funahashi, T. Furuya, X. Jin, Y. Kamiya, S. Michizono
M. Nishiwaki, H. Sakai, M. Sawabe, K. Ueno, M. Yamamoto, KEK, Ibaraki, Japan

Abstract

Superconducting accelerating cavities used in high-energy accelerators can generate high electric fields of several 10 MV/m by supplying radio frequency waves (RF) with frequencies matched with resonant frequencies of the cavities. Generally, frequencies of input RFs are fixed, and resonant frequencies of cavities that are fluctuated by Lorentz force detuning and Microphonics are corrected by feedbacks of cavity frequency tuners and input RF power. Now, we aim to develop the cavity frequency tracking type RF control system where the frequency of input RF is not fixed and consistently modulated to match the varying resonant frequency of the cavity. In KEK (Tsukuba, Japan), we are developing SRF-TEM that is a new type of transmission electron microscope using special-shaped superconducting cavity. By applying our new RF control system to the SRF-TEM, it is expected to obtain stable accelerating fields so that we can acquire good spatial resolution. In this presentation, we will explain the required stabilities of accelerating fields for SRF-TEM and the feasibility of SRF-TEM in the case of applying the cavity frequency tracking type RF control system.

WHAT IS SRF-TEM?

In material science, biology and other science regions, electron microscopes (EMs) are often used to observe sub-nanometer world. There are two kinds of EMs; transmission EMs (TEMs) and Scanning EMs (SEMs). TEMs are more suitable when insides of specimens are targets of studies. Past TEMs use electrostatic acceleration to give kinetic energy to electron beams. Therefore there has been a limit of accelerating energy because of discharge problems. The highest voltage of TEM is 3 MV which has been achieved in Osaka Univ. in Japan [1]. Now we are developing a new type of TEM called SRF-TEM, which applies high energy accelerator technologies; SRF cavities and photo-cathode DC electron gun. It will overcome the limit of accelerating energy so that thicker specimens could be observed. It will help to study the materials, for example, high temperature superconducting matters and magnetic materials and so on. SRF-TEM has other advantages; downsizing facilities, micro-second temporal resolution, less damages to biological samples and the potential for world's best spatial resolution.

* higashi@icepp.s.u-tokyo.ac.jp

CHROMATIC ABERRATION AND SPATIAL RESOLUTION OF TEMS

We could acquire higher energy than 3 MeV for TEMs easily employing RF acceleration with a superconducting cavity. However there is a problem to consider in advance of practical development; degradation of spatial resolution due to increase of chromatic aberration. Spatial resolution of TEMs is determined by following three factors; diffraction aberration, spherical aberration and chromatic aberration. Chromatic aberration occurs due to an energy spread ΔE of an electron beam so that focal lengths of beams are different. A conventional TEMs has low energy dispersion of $O(10^{-6})$. However RF acceleration of our SRF-TEM makes it larger by its sinusoidal electric fields. Therefore the chromatic aberration mainly determines the spatial resolution of SRF-TEM. Figure 1 shows the relation between the energy dispersion and the spatial resolution of our prototype SRF-TEM which accelerating energy is 300 kV. Note that the declination of the spatial resolution is saturated below 1.0×10^{-5} in the energy dispersion. This is because the chromatic aberration r_c is determined by

$$r_c = \alpha C_c \sqrt{\left(\frac{\Delta E}{E}\right)^2 + 4\left(\frac{\Delta J}{J}\right)^2} \tag{1}$$

,where α is the maximum angle of incident beam into the objective lens, C_c is the chromatic aberration constant, $\Delta J/J$ is the current stability of objective lens, which is 1.0×10^{-5} so that even if the energy dispersion is lowered

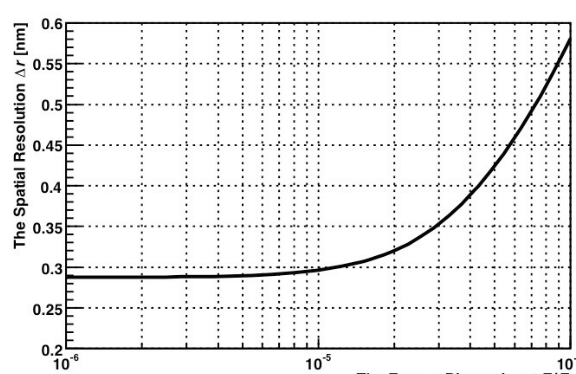

Figure 1: The relation of energy dispersion and the spatial resolution.

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Table 1: One-mode Acceleration vs. Two-mode Acceleration Simulated by GPT. E_{ap}means Axial Peak of each Electric Field.

	E_{ap} of TM_{010}	E_{ap} of TM_{010}	ΔT	T	$\Delta T/T$
one-mode	9.85 MV/m	-	61.8 eV	304 keV	2.04×10^{-4}
two-mode	8.21 MV/m	9.25 MV/m	10.2 eV	278 keV	3.68×10^{-5}

Table 2: The Required Stability of LLRF.

$\Delta T/T$	Amplitude of TM_{010}	Amplitude of TM_{020}	Phase of TM_{010}	Phase of TM_{020}
1.0×10^{-4}	100 ppm	300 ppm	0.030°	0.050°
4.0×10^{-5}	30 ppm	100 ppm	0.010°	0.020°

than 1.0×10^{-5} spatial resolution Δr could not be better effectively.

TWO-MODE ACCELERATION

In order to overcome this problem, we have developed a special-shaped SRF cavity, called "two-mode cavity". It has two resonant mode; TM_{010} mode (1.3 GHz) and TM_{020} mode (2.6 GHz). Its superposed fields could make a lower energy dispersion than one-mode acceleration of TM_{010} mode. We conducted a Runge-Kutta simulation with a software "General Particle Tracer (GPT)" to examine the feasibility of lowering the energy dispersion by two-mode acceleration. The result is summarized in Table 1. Instead of E, the notation of "T" is used for the acceleration energy, because it is not so high compared with electron mass. To see that, two-mode acceleration can lower the energy dispersion by 5 times than one-mode acceleration. This simulation is including space charge effect. The other parameters are listed in detail on the previous proceeding [2].

CONSIDERING DEVIATIONS OF TWO-MODE ACCELERATION

Thus far we have explained how effective two-mode acceleration is when SRF technologies is transferred to TEMs. However there must be some deviations to drive the two-mode cavity so that the energy dispersion is worse than the simulated values (Table 1). This time we have computed how much eace deviation affects the energy dispersion. There are two type of deviations. One is the energy spread of one bunch (ΔT_1). The other is the deviation of averaged T over the accumulated bunches (ΔT_2). Our SRF-TEM has electromagnetic lensed for objective lenses which cannot be controlled so fast. Therefore if each bunch has its own energy discretely, it has its own focal length so that there has to be some chromatic aberration. Figure 2 shows each deviation for the electric field amplitude of TM_{010} mode. Note that ΔT_2 is much larger than ΔT_1, and this tendency can be recognized in the other 3 parameters.

The summary is in Table 2. We have two goals of $\Delta E/E$; 1.0×10^{-4} is the first goal as the commissioning, and 4.0×10^{-5} is the main goal for the SRF-TEM prototype. Here, we computed ΔT by

$$\Delta T = \sqrt{\Delta T_1^2 + \Delta T_2^2}. \tag{2}$$

Table 3: The Accomplished Values of LLRF in cERL Main Linac [3]

Amplitude	Phase
120 ppm	0.014°

EVALUATING THE FEASIBILITY

Are these values in Table 2 supposed to be accomplished? To answer this question, we have to compare these values with other accelerators. SRF-TEM will be driven in CW mode in order to acquire good temporal resolution to generate high averaged current and be easily driven precisely. In KEK (Tsukuba, Japan), cERL experiment has been started and have similar technologies with SRF-TEM. In fact, some are based on cERL's. Therefore it is reasonable to see the accomplished values of LLRF control in cERL to find whether SRF-TEM's LLRF is feasible or not. The accomplished values of LLRF in cERL is listed in Table 3 [3]. You can see that the required values in our SRF-TEM are severer than the values in cERL's LLRF. However the values in the reference [3] are scrambled by the ADC noise, therefore the true values are expected to be better than now.

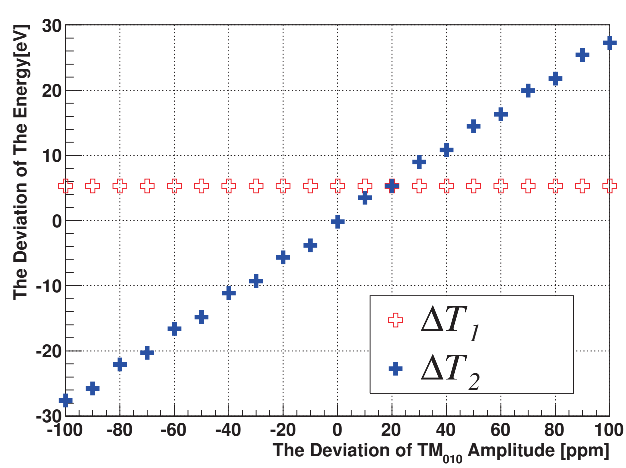

Figure 2: The behavior of energy deviation for the amplitude of TM_{010} mode.

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SCHEMATIC SYSTEM OF LLRF

To achieve the good stability of Table 2, we will employ the cERL's LLRF technology. However there are some differences between these. The most considerable is that SRF-TEM's one-cell cavity has two resonant modes. Normally, SRF cavity has a tuner for controlling its resonant frequency so that the input power can effectively generate a required accelerating field. Based on this idea, it is reasonable for our two-mode cavity has two tuners like Fig.3. However it is not so difficult to imagine that one tuner will alter the resonant frequency of the other.

While on the other hand, we could consider the situation that we have only one frequency tuner. We call this scheme "cavity frequency tracking type". Normally an accelerator has a master oscillator (MO) to supply the standard frequency to each cavity and a tuner strains the cavity to match its resonant frequency with MO frequency. In the case of cavity frequency tracking type, the resonant frequency of TM_{010} become MO frequency and the tuner change only the frequency of TM_{020}. Figure 4 shows that our two-mode cavity has a local point where only the field of TM_{020} is strong. To strain this point locally, we could change only the resonant frequency of TM_{020}. Figure 5 is the schematic circuit of cavity frequency tracking type of LLRF.

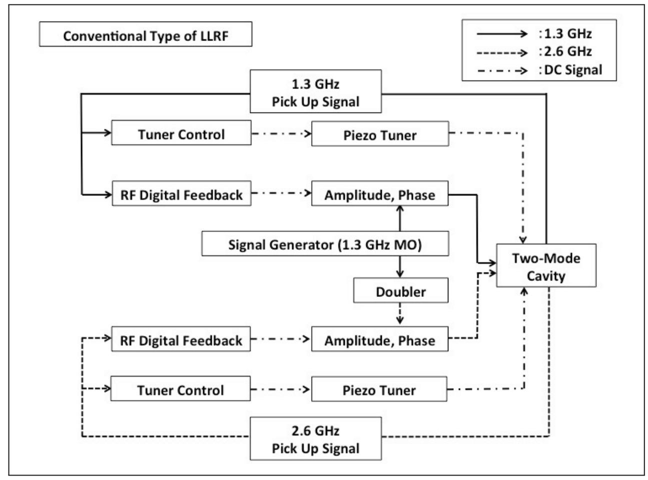

Figure 3: The conventional type of LLRF control.

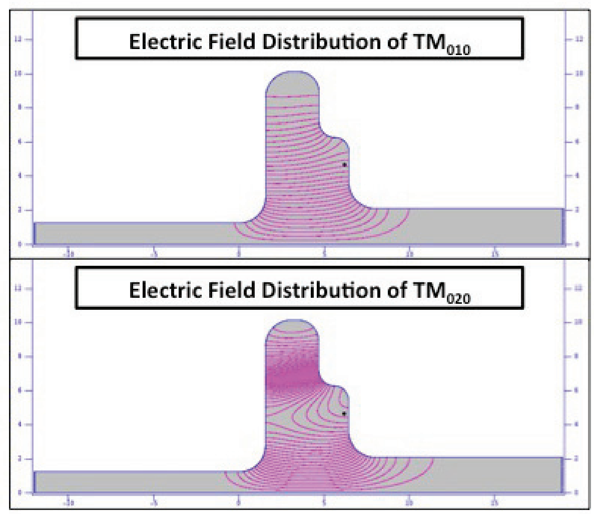

Figure 4: Electric fields of TM_{010} and TM_{010}.

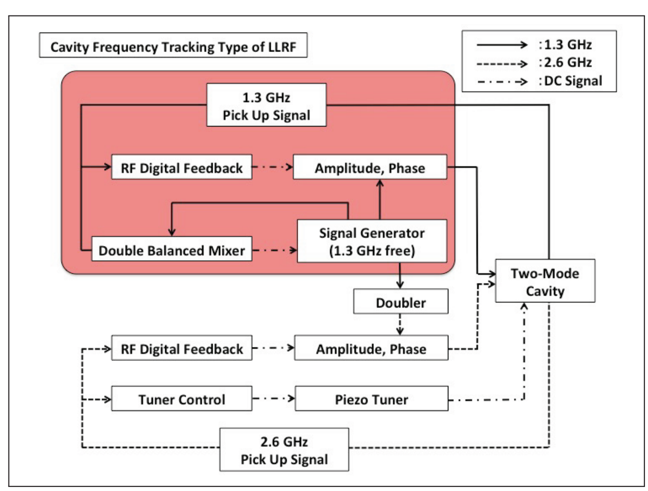

Figure 5: Cavity frequency tracking type of LLRF control.

SUMMARY AND NEXT TASK

This time we have computed how much the deviation of each accelerating field parameter affects. Compared with accomplished values of cERL's LLRF, we could see some possibility for the accomplishment of SRF-TEM's goal. However there are some technical differences between these. Thus we are now considering two schemes of LLRF; conventional type and "cavity frequency tracking type". Whichever we choose, we will encounter some difficulties. For example, if we choose conventional type, we have to consider how two-mode cavity should drive with two tuners which scramble each other. On the other hand, if we choose cavity frequency tracking type, there may be some difficulties for driving a laser of electron gun when changing the MO. Now we are designing a cryostat for the SRF-TEM prototype and testing photo-cathode electron gun. First, we will test the SRF-TEM prototype with one-mode acceleration. In parallel with this, we will developing our own LLRF control system.

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