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DEVELOPMENT STATUS OF SUPERCONDUCTING RF TRANSMISSION ELECTRON MICROSCOPE

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Abstract

Now we are developing a new type of transmission electron microscope (TEM) employing the accelerator technologies. In place of a DC thermal gun generally used in conventional TEMs, we apply a photocathode gun and a special-shaped superconducting cavity, named two-mode cavity. The two-mode cavity has two resonant modes of TM_{010} (1.3 GHz) and TM_{020} (2.6 GHz). To superimpose these, we can suppress the increase of the energy spread, which is needed for the high-spatial-resolution TEMs. We have already developed some prototypes of the photocathode gun and two-mode cavity, and now in the middle of the performance tests. In this presentation, we will show the latest status of the development.

INTRODUCTION

Now we are developing a new type of transmission electron microscope employing some accelerator technologies: the superconducting RF acceleration and the photocathode gun. TEMs are powerful tools to observe the specimen with sub-nm spatial resolution [1], however the specimen has to be sliced to $O(10\text{ nm})$ for the problem of the deterioration of the spatial resolution due to the increase of the chromatic aberration. The effect of the chromatic aberration could be estimated quantitatively using the characteristic of Δ, the defocus spread, which could be written by

$$\Delta = C_c \sqrt{\left(\frac{\Delta T_{\mathrm{ini}}}{T}\right)^2 + \left(\frac{\Delta T_{\mathrm{acc}}}{T}\right)^2 + \left(\frac{\Delta T_{\mathrm{spe}}}{T}\right)^2 + \left(2\frac{\Delta J}{J}\right)^2} \tag{1}$$

where C_c is the coefficient of the chromatic aberration, $\Delta T_{\mathrm{ini}}/T$ is the initial energy spread generated at the cathode of the gun, $\Delta T_{\mathrm{acc}}/T$ is the energy spread generated in the DC or RF acceleration, $\Delta T_{\mathrm{spe}}/T$ is the energy spread occurred at the specimen which can be estimated by Landau's theory [2] and $\Delta J/J$ is the stability of the current of the objective lens, generally $O(10^{-5})$. $\Delta T_{\mathrm{spe}}/T$ can be lowered by increasing the beam energy. Therefore, if you want to see the thick specimen, the higher accelerating energy could be a solution. General TEMs apply the DC acceleration, and the accelerating voltage is limited to about 3 MV due to the discharge problem. In order to overcome this limitation, we employ RF acceleration using RF cavity.

However, the stability of the electrostatic accelerating voltage is achieved to about $\Delta T_{\mathrm{acc}}/T = 3.0 \times 10^{-7}$ [3]. On the other hand, a general RF accelerating mode accelerates electrons with the spread of $\Delta T_{\mathrm{acc}}/T > 1.0 \times 10^{-4}$. This cancels out the advantage of high-energy acceleration. In order to avoid this, we have developed a new type of accelerating cavity called "two-mode cavity" (Figure 1). It can excite two resonant modes of TM_{010} (1.3 GHz) and TM_{020} (2.6 GHz) simultaneously. Controlling their amplitudes and phases respectively, we can suppress the ΔT_{acc}. This time, we employ a superconducting cavity in order to achieve high average beam current with CW mode and realize the high stability of the LLRF to minimize the ΔT_{acc}. We call this new type of TEM employing the superconducting RF cavity "SRF-TEM". Now we are developing a 300 kV prototype for the proof-of-principle of SRF-TEM (Figure 2). The development is conducted based on the conventional Hitachi's 300 kV TEM, H-9000 NAR. The thermal gun will be replaced with a newly developed photocathode gun with DC 60 kV acceleration and the two-mode cavity. We already reported the recipe of two-mode cavity in IPAC'13 [4] and the LLRF system in IPAC'15 [5], then we present the update in this paper.

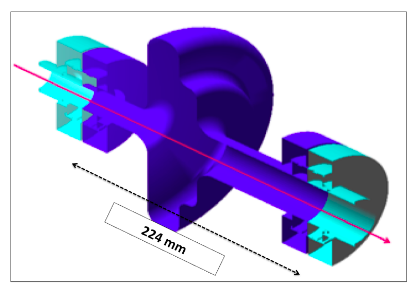

Figure 1: The schematic overview of the two-mode cavity. The red arrow represents the direction of the incoming electron.

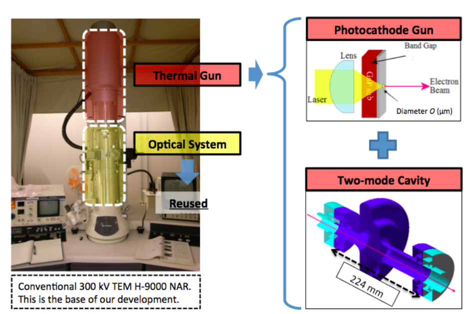

Figure 2: A concept of 300 kV SRF-TEM prototype development based on H-9000 NAR, conventional 300 kV TEM.

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Table 1: The initial condition for GPT simulation. C represents the charge of one bunch, r_{ini} represents the initial radius on the cathode, f_{010} and f_{020} represent the resonant frequency of the TM_{010} mode and the TM_{020} mode respectively and ΔE_{ini} represents the initial energy spread at the cathode.

C	- 0.1 fC
r_{ini}	100 μm
ΔE_{ini}	0.15 eV

Table 2: The Simulation Result of the 300 kV Acceleration

	T	ΔT	$\Delta T/T$
One-mode Acceleration	330 keV	57.6 eV	1.75×10^{-4}
Two-mode Acceleration	272 keV	2.19 eV	7.91×10^{-6}

BEAM DYNAMICS SIMULATION

We conducted the beam dynamics simulation using General Particle Tracer [6] to investigate the effect of the two-mode cavity to suppress the energy spread. The simulated geometry is illustrated in Figure 3, and each parameters are summarized in Table 1. We compared the minimum energy dispersion in the case of the conventional one-mode acceleration (only TM_{010}) and the new two-mode acceleration (both TM_{010} and TM_{020}). The results are summarized in Table 2. This shows the two-mode acceleration is effective to suppress the energy spread in 300 kV acceleration. The amplitudes and the relative phase needed to minimize the energy spread are listed in Table 3. These values have to be realized for the manufacturing of the two-mode cavity.

In addition, we investigated the effect of the control stability for the amplitude and the phase (Table 4). We set two targets of the energy dispersion and the values in Table 4 are required assuming the stabilities of other three values are zero. This requirements have to be satisfied with a new LLRF system for the SRF-TEM.

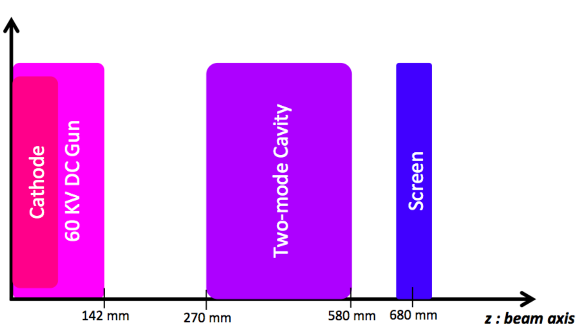

Figure 3: The geometry of the simulation for 300 kV.

DEVELOPMENT STATUS OF TWO-MODE CAVITY

We have already a prototypes of the two-mode cavity. These did not satisfy the requirement of the frequency ratio 2.0000. Figure 4 shows the sensitiveness of the resonant frequency for the tuning. We have two tuners: the mechanical span tuner and the electrically controllable piezo tuner. With these tuners, we can set the frequency ratio 2.0000 in the range from 1.9976 to 2.0062 (Figure 5). However, the frequency ratio of the first prototype was1.9964, which means it cannot operate the two-mode acceleration.

In order to resolve this, we modified the design of the two-mode cavity (Figure 6). In this design, the inner wall where the field of TM_{020} is concentrated is engraved to change the frequency ratio. Based on this design, we have manufactured another prototype. The initial frequency ratio was 2.01386, which is higher than the upper limit of the tunable range (Figure 5). In order to approach this to 2.0000, we conducted the electron beam welding (EBW) at the equator of the cavity. This EBW tuning expects the shrink at the gap length, which is mentioned as 1) Errors of Equatorial in Figure 4. The result of the EBW tuning is showed in Figure 7. Thanks to this tuning, the frequency ratio got 2.0029, which is inside the tunable range of the span tuner and the piezo tuner.

The vertical test of this new prototype will be carried out soon, while the old one was tested already. The result of that is showed in Figure 8. The maximum accelerating field E_{ap} is (11.0 ± 0.3) MV/m for TM_{010} and (7.8 ± 0.3) MV/m

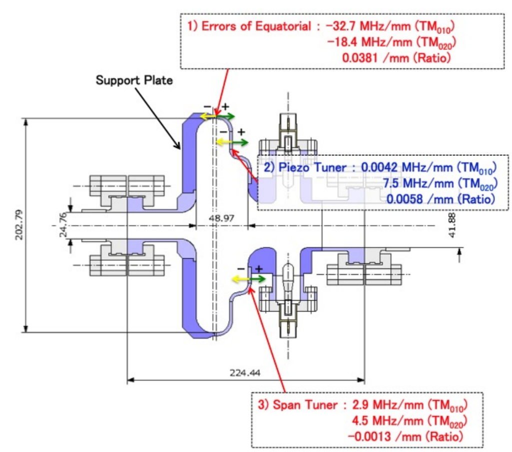

Figure 4: The sensitiveness of the resonant frequency for the tuning.

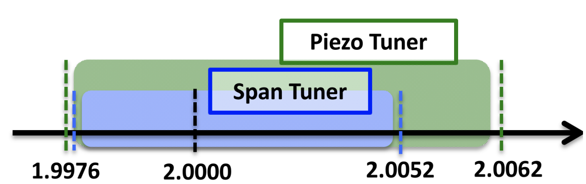

Figure 5: The tunable range of the frequency ratio using the span tuner and the piezo tuner.

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Table 3: The Optimal Values of the Accelerating Modes for the 300 kV Acceleration

	Amplitude of TM_{010}	Phase of TM_{010}	Amplitude of TM_{020}	Phase of TM_{020}
One-mode	6.98 MV/m	0.456 rad.	-	-
Two-mode	7.46 MV/m	0.454 rad.	7.20 MV/m	0.500 rad.

Table 4: The Control Requirement for the Two-mode Acceleration of 300 kV SRF-TEM Prototype

Target	Amplitude of TM_{010}	Amplitude of TM_{020}	Phase of TM_{010}	Phase of TM_{020}
1.0×10^{-4}	0.010 %	0.037 %	0.320 deg.	0.120 deg.
4.0×10^{-5}	0.004 %	0.014 %	0.150 deg.	0.055 deg.

for TM_{010}, and these achieved the requirements estimated by the GPT simulation.

DEVELOPMENT STATUS OF LLRF

In order to accomplish the requirements in Table 4, we have developed a LLRF control system based on the technology developed for cERL [7]. Our LLRF system can control both TM_{010} and TM_{020} simultaneously, and the additional LPF called "monitor filter" is installed in front of the PI control in order to reduce the ADC noise. This cut-off frequency was set at 5 kHz. The result of the performance test of the LLRF were summarized in Table 5. The test was carried out with E_{ap} of 1.0 MV/m for both TM_{010} and TM_{020}. This achieved the requirements estimated by the GPT simulation (Table 4).

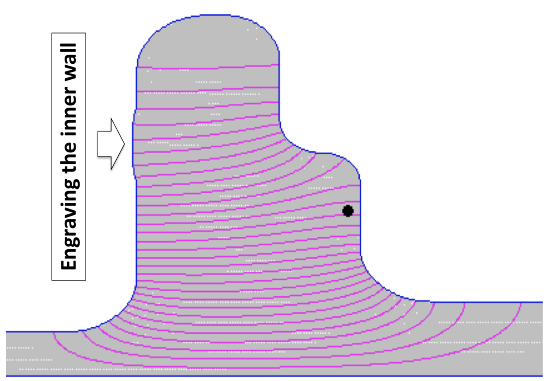

Figure 6: The modified design of the two-mode cavity. The simulation was carried out using SUPERFISH [8].

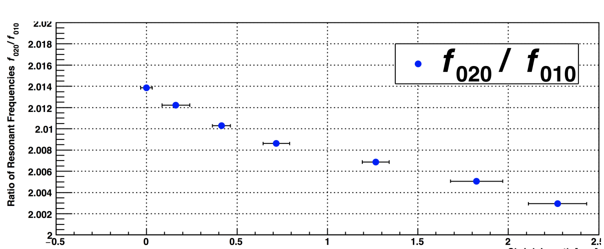

Figure 7: The result of the EBW tuning.

Table 5: The result of dual feedback for E_{ap}. The measurement time T is 50 μs and the monitor filter is turned on.

Resonant Mode	Stability of Amplitude	Stability of Phase
TM_{010}	(0.0012 ± 0.0003) ppm	(0.04 ± 0.01) mdeg.
TM_{020}	(0.0005 ± 0.0004) ppm	(0.03 ± 0.01) mdeg.

FUTURE AND NEXT TASK

As explained above, we have already established the technology of the two-mode cavity and the LLRF system for the two-mode acceleration. Another key technology is the photocathode gun, and this prototype has been already manufactured. The beam test will be conducted in this year. IN parallel with this, we are in the middle of manufacturing a cryostat for the two-mode cavity which can be installed in the 300 kV SRF-TEM system. After the completion of the gun and cryostat, we will assemble the components and carry out the performance test of the SRF-TEM system using some specimens.

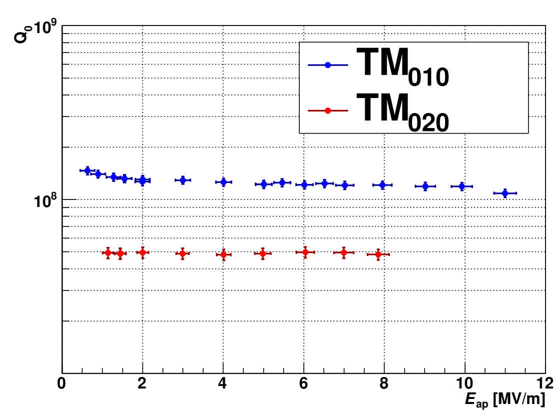

Figure 8: The result of the vertical test for the former prototype of the two-mode cavity. The temperature of the cavity is 4.0 K.

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