MEASUREMENT OF ELECTRON DENSITY IN COPPER THERMAL SPRAY BEAM PIPE IN SuperKEKB

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Abstract

In the previous studies [1-4], we confirmed that the copper thermal spray coating has a low secondary electron yield (SEY). The lowest δ_{max} (the maximum SEY within scanned energy range) after conditioning reached ~0.7. We produced a straight aluminum beam pipe with copper thermal spray coating using optimized conditions and installed it in the positron ring of SuperKEKB, in order to observe the effect of the coating on reducing the electron cloud. The results show that the electron density in the copper thermal spray beam pipe was much smaller than that in the bare aluminum beam pipe and was comparable to that of the TiN-coated beam pipe. Its surface resistance was also measured as a reference to confirm the applicability to the accelerator beam pipes.

INTRODUCTION

It has been well known that the electron cloud effect (ECE) in a positron or proton ring seriously deteriorates the beam qualities, such as emittance [5, 6]. The secondary electron yield (SEY or δ) of the inner surface of beam pipes is a primary parameter for controlling the ECE. One of the applicable solutions would be preparing a surface with a low SEY on the inner wall of beam pipes to suppress the multiplication of electrons and then mitigate the ECE.

In our series of studies [1-4], we were committed to using thermal spraying to make rough surface with low SEY. The thermal spraying is a well-developed, relatively easy, and suitable for mass production method to form a rough surface on various metals. In the last report [4], after all the spray conditions were established, we produced a straight aluminum beam pipe with copper thermal spray coating (T.S. coating) that can be installed in the SuperKEKB LER, in order to observe the effect of the coating on reducing the electron cloud.

In this report, we measured the electron density from December 2021 to June 2022, and compared it with that of the adjacent TiN-coated beam pipe. Besides, its surface resistance was also measured as a reference for whether it can be used in accelerators.

EXPERIMENTAL

Sample Preparation

Beam pipe with T.S. coating Please refer to the reference [4] for the detailed manufacturing process of the T.S.-coated beam pipe. Before installing the T.S.-coated beam pipe into the test arc section of SuperKEKB LER, this section was composed of a pure copper beam pipe and a TiN-coated beam pipe, whose electron density data can be used as a reference. In July 2021, the T.S.-coated beam pipe replaced the copper one. Figure 1 shows the T.S. and TiN-coated beam pipes installed in the SuperKEKB LER.

Sample pieces for SEY measurement When producing the T.S.-coated beam pipe, four sample pieces were cut from the excess part to confirm whether their SEYs were consistent with those of the small test samples [1-4]. These samples were called BP-1~4, and their shape was a 10 mm × 10 mm square with a thickness of 6 mm. Since they were cut from the beam pipe, the surface was Φ90 mm curved. In order to preserve an as-received sample, BP-3 was not taken to measure the SEY.

Sample pieces for surface resistance measurement The surface resistances were measured for four surfaces by the cavity resonator method [7]. The size of the disc-shaped substrates was 120 mm in diameter and 15 mm in thickness. The surfaces to be measured were within a circle with a diameter of 96 mm in the center, and the remaining outer ring part needed to be ground to a roughness *Ra* of less than 1 μm to be in close contact with the copper cavity.

The first surface was a fully polished on the copper substrate as a comparison standard, as shown in Fig. 2(a). The second and third surfaces were machine-ground and GBB-treated aluminum surfaces, respectively, on the front and back of the same aluminum substrate, as shown in Fig. 2(b) and (c). The fourth surface was the T.S. coating with spray conditions same as the T.S.-coated beam pipe, as shown in Fig. 2(d).

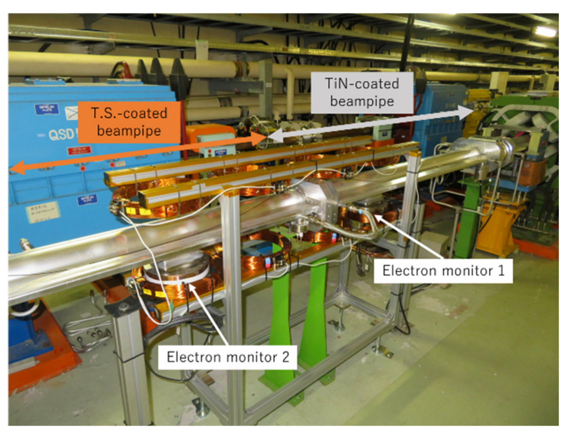


Figure 1: Photo of the T.S. and TiN-coated beam pipes installed in SuperKEKB LER.

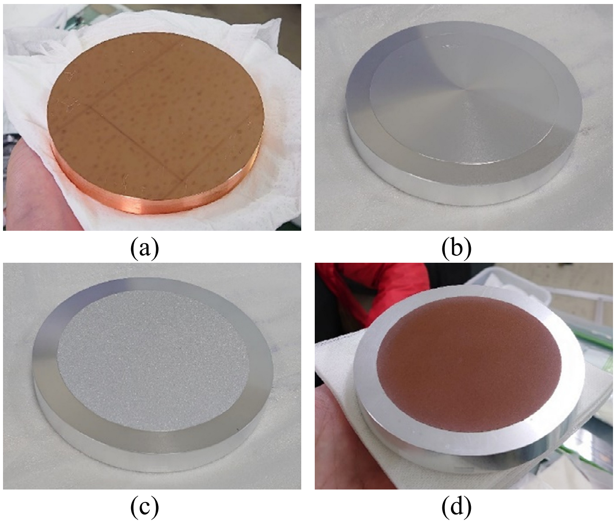


Figure 2: Samples for surface resistance measurement: (a) Polished surface on copper substrate. (b) Machine-ground surfaces on aluminum substrate. (c) GBB-treated surfaces on aluminum substrate. (d) T.S. coating on aluminum substrate.

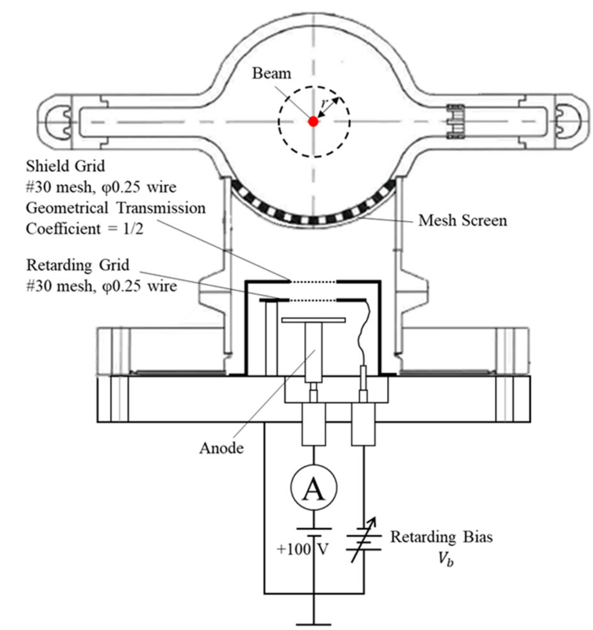


Figure 3: Schematic of an RFA at a port of a SuperKEKB LER beam pipe.

Experiment

SEY measurement The measurement started after a baking at 160℃ for 24 hours and the typical working pressure is at the level of 10^{-7} Pa. The SEY of each sample was measured within 150 - 2000 eV of primary electron energy (E_p) after the conditioning time of 2, 7, 24 and 72 hours. The E_p during the conditioning was 350 eV. After 72 hours conditioning, the total electron dose reached ~ 0.1 C/mm^2. For detailed settings, please refer to our previous report [1].

Electron density measurement The detailed principle of measuring the electron density in SuperKEKB can be found in the reference by Kanazawa *et al*. [8]. In brief, there is a port in the center of the beam pipe where a retarding field analyzer (RFA) type detector can be installed, and the entrance of the port is masked by a mesh screen, as shown in Fig. 3. Before reaching the anode as the collector, the electrons will pass through the mesh screen, shield grid and retarding grid. By applying a retarding bias of V_b, observed electrons are limited to those that come from the cylindrical region within the radius (r) from the beam orbit that is related to V_b and the number of positrons in the bunch N_b. A larger absolute value of V_b corresponds to a smaller (r), which means that the collected electrons are coming from closer to the beam. In this experiment, the V_b was fixed to a suitable value of -500 V depending on the size of our beam pipe. For a detailed derivation of obtaining the average density of the electron cloud D [m^{-3}], please refer to the reference [8].

It is important to note that when the beam pipe with T.S. coating was prepared, spraying the aluminum mesh screen with a T.S. coating was missed. The high $\delta_{max} \approx 2$ [9] of aluminum will result in an increase in the electron density measurement.

Surface resistance measurement To estimate the conductivity (σ) of the surface of samples, the quality factor (Q factor) was measured by the cavity resonator method [7]. Figure 4(a) is the setup of cavity resonator method. An internal polished copper bucket with a "belt" was combined with the sample in a closed cavity, as shown in Fig. 4(b). The cavity was connected with two signal wires to the network analyzer N5230C from Agilent Technologies, Inc. TE011 mode was selected to measure the Q value. The magnetic field distribution for this mode, as shown in Fig. 4(c), has r and z components, while the electric field distribution has only the φ direction component. Most importantly, the current on the sidewall and the surface at both ends is only in the φ direction, so that the current will not pass through the contact surface between the sample and the copper bucket to increase the accuracy of the Q value measurement. However, if the cavity is a perfect cylinder, the resonant frequency of the TE011 mode is exactly the same as that of the TM111. Therefore, a "belt" structure was added in the center of the cylinder to distinguish the resonant frequencies of TE011 and TM111. The resonant frequency for this cavity of TE011 and TM111 were approximately 5.044 GHz and 5.068 GHz, respectively.

First, by measuring scattering parameter S_{21}, the loaded Q factor Q_L is obtained as:

$$Q_L = \frac{f_0}{\Delta f(3dB)} \tag{1}$$

where $f_0 = 5.044$ GHz, $\Delta f(3dB)$ is the half-power bandwidth of the peak. To obtain the unloaded Q factor Q_0, following equation is considered:

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{c1}} + \frac{1}{Q_{c2}} \tag{2}$$

where Q_{c1} and Q_{c2} are the coupling Q factors of wires 1 and 2, respectively. The coupling coefficient β between the network analyzer and test cavity is defined as:

$$\beta \equiv \frac{Q_0}{Q_c}, Q_0 = \beta Q_c \quad (3)$$

Combining the above two equations yields:

$$Q_0 = Q_L(1 + \beta_1 + \beta_2) \quad (4)$$

In case of under coupling (i.e., $0 \leq \beta < 1$):

$$\beta = \frac{1 - |S_{11}|}{1 + |S_{11}|} \quad (5)$$

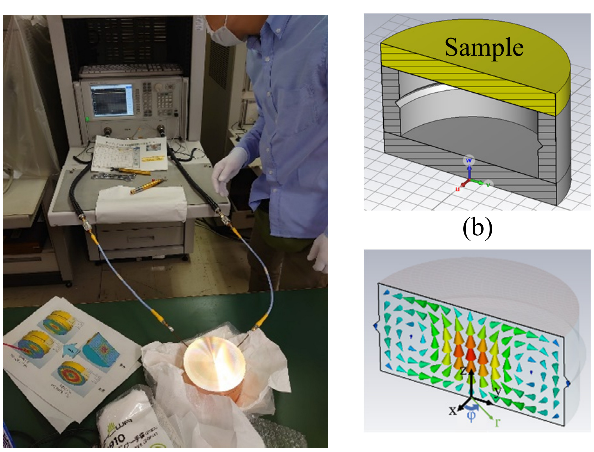
where parameter S_{11} is the reflection coefficient. After measuring S_{11} of wires 1 and 2, the corresponding β is obtained and Q_0 can be calculated. Here, the effects of temperature on the Q factor are negligible, and the temperature of all samples in the experiment was approximately 25 °C.

An identical experiment was set up in CST studio [10], and since all the parameters of pure copper are known, the conductivity (σ) of the sample surface could be adjusted until the Q_0 of the cavity is the same as the experimental value to obtain the σ value of the sample surface at 5.044 GHz.

In addition, the intrinsic surface resistance R_S of a perfectly smooth metal surface under AC stimulation in the GHz regime can be calculated by a simple formula [11]:

$$R_S = \sqrt{\frac{\pi \mu_0 f}{\sigma}} \quad (6)$$

where μ_0 and f are the vacuum permeability and AC frequency, respectively. Although the surface of T.S. coating was not smooth, its structure was considered as part of the material properties as a rough evaluation.



(a) (c)

Figure 4: (a) is the setup of cavity resonator method. (b) is the half-section view of the internal mirror polished copper bucket with a "belt". (c) shows the direction of the magnetic field in the TE011 mode in the CST simulation.

RESULTS AND DISCUSSIONS

SEY of BP-1,2,4

Figure 5 shows the profiles of δ against E_p of samples BP-1,2, and 4 after 72 h conditioning, where the maximum value of δ is called δ_{max} and its corresponding E_p is called E_{max}. It can be confirmed that the δ_{max} of the T.S. coating on the beam pipe can be maintained steadily between 0.7 and 0.8, which was consistent with those of the small test samples [3-6].

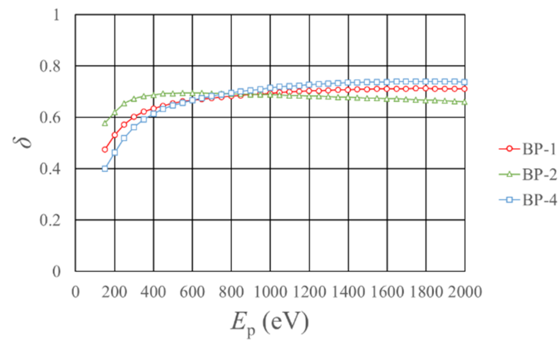


Figure 5: Profiles of δ against E_p of BP-1,2,4 after 72 h conditioning.

Electron Density Results

Figure 6 shows the electron density against the current linear density (i.e., bunch current/ bunch spacing) in the copper, TiN, and T.S.-coated beam pipe of SuperKEKB LER collected in different periods. The first period was from 11st Mar. 2021 to 5th Jul. 2021. As shown in Fig. 6(a-b), the main test beampipe in the first period was made of copper (monitor 1), and there was another aluminum beam pipe with TiN coating (monitor 2) that had been installed for reference. After that, the main test beam pipe was replaced with the beam pipe with T.S. coating (monitor 1) in the second period. Figure 6(c-d) shows the electron density collected from 21st Feb. 2022 to 22nd Jun. 2022. The large jitter of the electron density at low bunch current was because it was beyond the applicable range of the electron density formula in reference [8]. The numbers in Fig. 6 represent the bunch number, and the bunch train length was always fixed.

It can be found that the electron density in the T.S.-coated beam pipe was in the same order as that of copper and TiN when the bunch number were not too large, and they were all much smaller (about dozens of times) than that of the uncoated bare aluminum beam pipe [12]. Then, as the bunch number gradually increased, the difference between T.S. coating and TiN also increased, as shown in Fig. 6(c-d).

The δ_{max} of the T.S. coating was lower than that of TiN (δ_{max} = 1.0~1.2 [13]), but the T.S.-coated beam pipe obtained a higher electron density result. The most likely reason is that as mentioned earlier, the aluminum mesh screen in front of the electron monitor in the T.S.-coated beam pipe was uncoated, and its high δ_{max} might result in an overall increase in the measured signal.

Another phenomenon to be aware of was that the electron density in the T.S.-coated beam pipe increased with the bunch number. The first possible reason is that the SEY of the T.S. coating or aluminum screen surface increased with the electron dose, because higher bunch numbers generally correspond to later dates. In the previous SEY measurements, it was observed that the δ_{max} of some T.S. coating samples and the aluminum sample increased after conditioning [1], especially aluminum. But after data comparison, the sign of electron density increasing with electron dose was considered to be small; Another possible reason is that the monitor 2 in the second period produced a noise for some unknown reason, and this noise was proportional to the frequency. However, this claim needs further verification.

In Fig. 6(c-d), the "bump" of the curves could be observed around a current linear density of 0.25 mA. The bump position was determined by the timing of the acceleration of electrons due to successive bunches, and altered by the bunch fill patterns. The shapes and positions were found to depend on not only δ_{max} but also on the initial energy of the emitted secondary electrons and the radius of beam pipes [14]. In the simulations in Reference [15], the significant bump could only be observed when δ_{max} was lower than 1.2.

In brief, under the influence of uncoated aluminum mesh screen, the T.S.-coated beam pipe could obtain an electron density close to that of TiN, which was a promising result. The result after correcting the uncoated part is worth expecting.

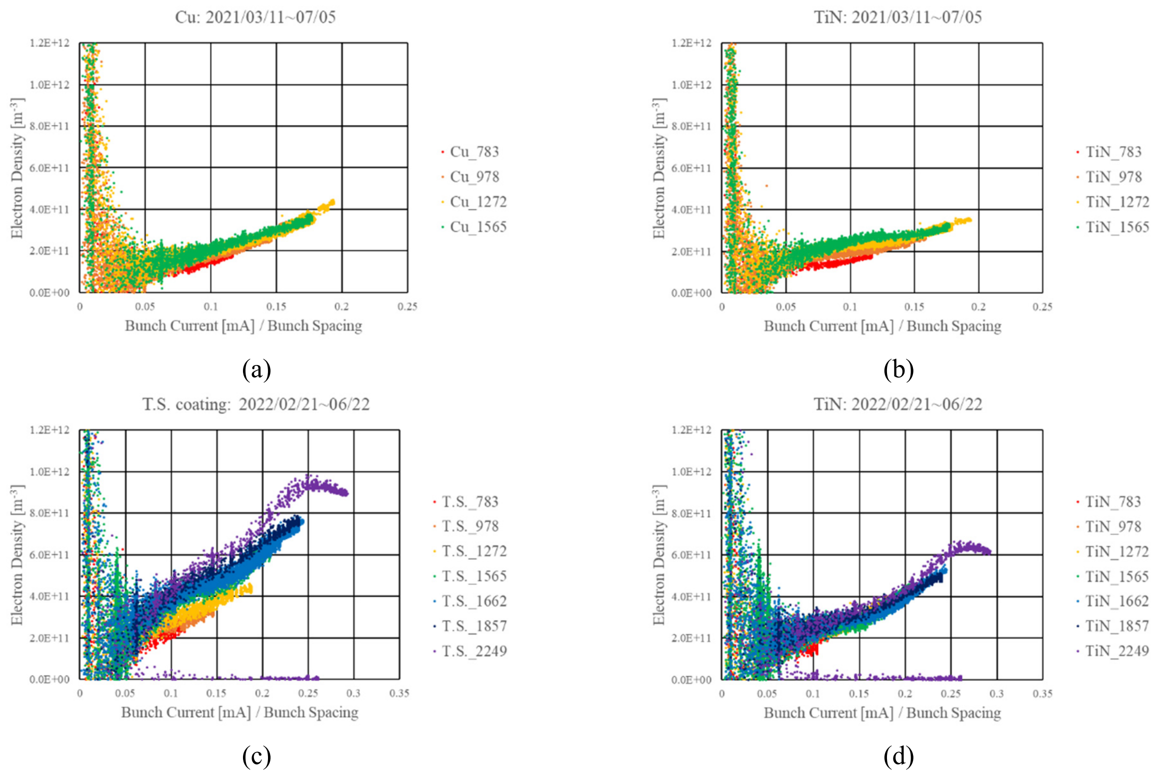


Figure 6: Electron density in the copper, TiN, and T.S.-coated beam pipe as a function of the current linear density in different periods.

Surface Resistance Results

Table 1 lists the Q factor, conductivity at 5.044 GHz and surface resistance of each sample. In addition, two metals, titanium (Ti) and stainless steel (SUS304), which have similar conductivity to T.S. coating, are also listed [16, 17]. Compared with polished copper, the conductivity of the T.S. coating dropped by more than an order of magnitude, which can be attributed to the lamellar microstructure and semiconducting cuprous oxide (Cu_2O) [1-3]. The conductivity of T.S. coating was comparable to Ti and slightly higher than that of SUS304. Generally, the accelerator beam pipe using titanium or SUS304 will be electroplated with a layer of copper as the inner to reduce the impedance [18].

To evaluate the impedance of T.S. coating in accelerators, more detailed studies are required, which are beyond the scope of this report. Now it can only be conservatively said that because the ability of T.S. coating to reduce electron cloud was significantly better than that of TiN, within the impedance budget of individual accelerators, the T.S. coating at this stage could be appropriately applied in a small amount. Possible improvements include reducing the particle size of copper powder, reducing the thickness of the coating, and spraying under vacuum to avoid oxidation.

Table 1: Q Factor, Conductivity at 5.044 GHz and Surface Resistance of Each Sample

Sample	Q_0	σ@5.044GHz [S/m]	$R_S = \sqrt{\frac{\pi\mu_0 f}{\sigma}}$ [Ω]
Polished Cu	33102	5.9E+07	1.8E-02
Machined Al	29689	3.3E+07	2.5E-02
GBB Al	20982	6.8E+06	5.4E-02
T.S. coating	14133	1.9E+06	1.0E-01
Ti [14]		2.4E+06	9.2E-02
SUS304 [15]		1.5E+06	1.2E-01

CONCLUSIONS

The copper thermal spray coating had a low SEY and was easy to apply in large areas, making it a promising method to reduce ECE. But because of its relatively high surface resistance, it should be appropriately applied depending on the impedance budget of individual accelerators.

After establishing the optimized spray conditions, an aluminum beam pipe with T.S. coating was successfully fabricated and installed it in the test section of SuperKEKB LER. The results of electron density measurement show that, even though being affected by the uncoated aluminum screen, the electron density in the T.S.-coated beam pipe was only slightly higher than that in the TiN-coated beam pipe. This implies that the T.S. coating is a good choice for reducing electron density and deserves further study.

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