PHYSICAL AND ELECTROMAGNETIC PROPERTIES OF CUSTOMIZED COATINGS FOR SNS INJECTION CERAMIC CHAMBERS AND EXTRACTION FERRITE KICKERS*

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Abstract

In the SNS accumulator ring, ceramic vacuum chambers are used for the 8 injection kickers to avoid shielding of a fast-changing kicker field and to minimize eddy current heating. The inner surface of the ceramic chambers was coated with Cu to reduce the beam coupling impedance and provide passage for beam image current, and a TiN over layer to reduce secondary electron yield. The ferrite surfaces of the 14 extraction kicker modules were also coated with TiN. Customized masks were used to produce longitudinal coating strips of 1 cm x 5 cm with ~ 1 mm separation among the strips. The coating methods, the physical and electromagnetic properties of the coatings and the effect to the beam and to the electron cloud build-up are summarized.

TITANIUM NITRIDE COATING

Brookhaven is responsible for the design and construction of the SNS accumulator ring and transport lines. The electron-cloud effect in the SNS ring is expected to be one of the major intensity-limiting mechanisms and a potential threat to the high-intensity operations [1]. One contributing factor to the electron cloud and electron multipacting is the secondary electron emission (SEY) of the surfaces facing the beam. To this end, the inner surfaces of the 248 m ring vacuum chambers have been coated with ~100 nm of titanium nitride (TiN) to reduce SEY of the chamber walls [2]. Most SNS ring chambers are made of stainless steel, which has a peak SEY of ~ 2.5. The SEY will be reduced to < 2 if the surface is coated with TiN [3].

TiN coating has been routinely applied to high power RF windows and tuners to reduce multipacting. TiN coating of regular accelerator beam tubes was done for PEPII LER [4] using DC sputtering. Due to the large cross sections of the SNS chambers, magnetron DC (MDC) sputtering was developed for its high deposition rate, low operating voltage and low pressure [2]. This is a result of the increased plasma density formed by the electrons confined within the magnetic field, which adds to the sputtering rate. Improved stoichiometry and uniformity were also achieved with MDC. The difficulties in producing a film with uniform properties within the long SNS chamber have been overcome with the development of a unique magnetron target [2].

Much work has been done on the formation of TiN by magnetron sputtering as an industrial hard coating using planar electrodes and magnets. Due to the SNS chamber geometry, a linear titanium cathode with a suitable magnetic field was developed as shown in Figure 1. Commercially available *Alnico* magnets are inserted in a 1.5” diameter titanium tube used as a cathode. The magnets are stacked with ½” spacers resulting in a looping magnetic field of several hundred gauss projected from the cathode surface. The ½” diameter hole in the centre of the magnets allows for water cooling of the cathode. This “low cost” cathode works in conjunction with a 10 kW DC power supply to produce a satisfactory field and discharge plasma as shown in Figure 2. Using this MDC set up, ~ 135 SNS vacuum chambers with total length over 300m have been coated with TiN [5].

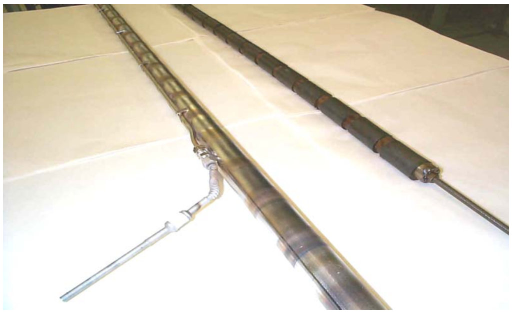

Figure 1: A long titanium cathode for TiN coating of SNS ring vacuum chambers. The permanent magnets and spacers (right side) enhance the plasma density thus the deposition rate.

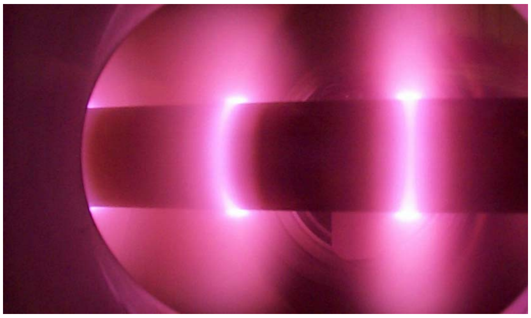

Figure 2: The discharge plasma during TiN coating of the SNS ring vacuum chambers. The brighter rings are at the locations of the spacers between the permanent magnets.

COATING OF CERAMIC CHAMBERS

The inner surfaces of the SNS ring are made of either stainless or inconel, except those of the injection and

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extraction kickers. The eight injection kickers will operate at 60 Hz with a pulse length of ~ 2 ms [6]. The ferrite magnet is installed outside the vacuum chambers made of alumina ceramic to avoid eddy currents and heating induced by the pulsing magnetic field. The inner surface of the ceramic chambers will be coated with a conductive layer to carry the beam image current and a TiN over layer to reduce SEY.

There are two types of ceramic chambers for the injection kickers, 1m long with 18 cm ID and 0.9 m long with 16 cm ID. The primary requirement for the coating of the conductive layer is to provide low impedance at low frequencies (resistive wall) while still be consistent with eddy-current heating limitations. To strike a balance between these two opposite criteria, the conductive coating should have a sheet resistance of 0.024 Ω/square, corresponds to an end-to-end resistance of 0.04 Ω ± 50% for the present chamber dimensions [7]. It was further decided that the thickness uniformity over the chamber length should be within ± 30%.

Several materials suitable for sputtering coating were evaluated as the conductive layer, and their properties are listed in Table 1. It is relatively difficult to fabricate a long gold cathode. The high resistivity of Ti and TiN as compared with that of Cu requires coatings of tens µm meters thick thus a long sputtering time. The adhesion of a thick film is usually not as good as that of a thin film over long period. Copper also has much higher sputtering rate than Ti, therefore, was chosen as the conductive layer material. An over layer of TiN is needed since Cu has relatively high SEY [3].

Significant coating development work was done using glass and ceramic tubes nested in a metal chamber to produce coating of required resistivity and thickness uniformity. Initial test coatings of Ti and TiN on glass tubes revealed less than ideal thickness uniformity along the length of the tubes as plotted in Figure 3. The resistance of the film, which is proportional to the coating thickness, was measured using a four-point probe. The thickness was then derived assuming a resistivity of 42 µΩ-cm for Ti and 25 µΩ-cm for TiN. The derived thickness drops off rapidly away from the end of the tubes. This was caused by a charge build up on the insulating surface which distorted the electrical field and inhibited the discharge. Anode screen made of copper wire cage, as shown in Figure 4 was added to smooth out the electrical field therefore the thickness uniformity. The production coatings were done using a Cu cathode with Ar sputtering, then a Ti cathode with Ar and N_2 media. This approach required that the chambers be bled up after Cu coating then re-assembled with Ti cathode for TiN coating. The targeted thickness of the Cu coating for the production run was set at ~1 µm since the conductivity of sputter films is usually lower than the solid material.

A total of 10 ceramic chambers, three 18cm ID ones and seven 16 cm ID ones, have been coated for SNS. The average end-to-end resistance of the 16 cm ones is 0.045 ± 0.008 Ω and that of 18 cm ones 0.054 ± 0.008 Ω, well within the range of the specification. The thickness uniformity, as measured with the four-point probe, was within the required ± 30%. A coated chamber was tested for 5 hours inside the kicker magnets at 1300 A and 60 Hz (~ 20% higher than the required field for 1 GeV operation), the temperature of the chamber due to eddy current heating maxed at 48ºC agreed well with simulation. No measurable effect on the kicker rise time was observed as shown in Figure 5.

Table 1: Material and properties for conductive coating of SNS ceramic chambers. Thickness is corresponding to an end-to-end resistance of 0.04 Ω for SNS ceramic pipes.

	Resistivity	Thickness	Sputtering Rate
	µΩ-cm	µm	nm/s
Au	2.4	1.0	
Ti	42	18	< 0.1
TiN	25	11	< 0.1
Cu	1.7	0.7	~ 0.5

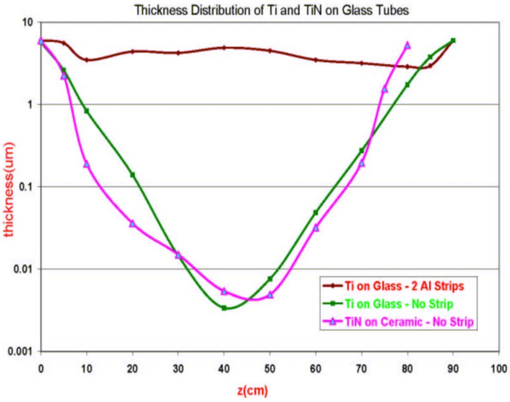

Figure 3: Coating thickness along the length of the glass tubes without (lower curves) and with anode strips which smooth out the electrical field along the length.

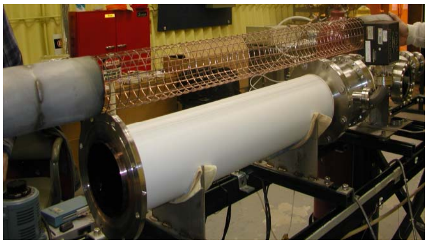

Figure 4: The kicker ceramic chamber with the anode screen to smooth out the electrical field during coating.

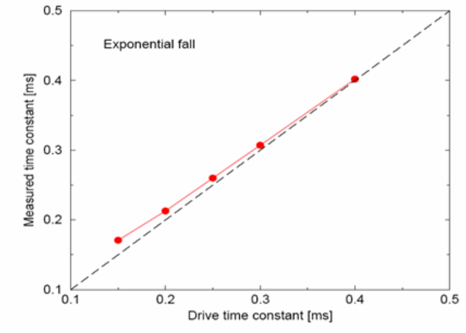

Figure 5: The measured kicker rise time (solid line and circles) as compared with estimated one (dotted line) using exponential fall model.

COATING OF EXTRACTION KICKERS

Fourteen (14) ferrite kickers are used to extract the proton beam from the accumulator ring. Each kicker, as shown in Figure 6, will be excited by a pulse forming network operated at 60 Hz with a rise time of 200 ns and a flat top of 750 ns [9]. This fast pulsing field has ruled out the out-of-vacuum magnet design used for the injection kickers. The 14 ferrite kicker magnets are assembled inside two large vacuum chambers as shown in Figure 7. The ferrite surfaces facing the beam will have high SEY and have to be coated with TiN. To minimize the eddy current loops on the ferrite surface due to the conductive TiN film, the coating has to be laid down in small longitudinal strips isolated from each other. Calculation [10] has shown that rectangular strips of 1cm by 5cm with ~ 1mm un-coated gaps between the strips will have power dissipation, due to eddy current heating, of less than a watt per kicker, with corresponding temperature rise of < 1°C. The smoothing effect on the kicker rise time is estimated to be ~ 1 nsec.

Custom coating masks, as shown in Figure 6, were used to produce the desired coating patterns of 1cm x 5cm on the ferrite surfaces. The effective surface area coated was ≥ 80%. A factor of 7 reduction in electron density inside the kicker modules, as shown in Figure 8, is expected with the 80% TiN coverage, as compared with a factor of 20 reduction if the surfaces are 100% covered. The small spacing between the masks and the ferrite surfaces did allow some TiN deposited behind the masks resulted in a finite resistance between the strips. With < 10% strip-to-strip resistance >100 Ω and the balance >> kΩ, the effect of this finite resistance to the beam was analyzed [10] and estimated to be < 1 ns to the kicker rise time.

Figure 6: The extraction kicker module with coating masks (left) and with coated TiN strips (right).

Figure 7: Seven extraction kicker magnets assembled inside one large vacuum chamber.

One coated kicker magnet was tested together with two uncoated kicker magnets at the operating voltage of 35 kV to check its waveform and performance. There is no difference in the performance whether the magnet is coated with TiN or not.

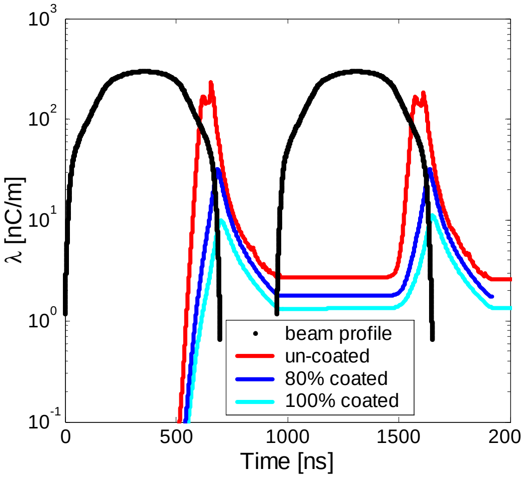

Figure 8: The calculated electron density inside the extraction kicker modules together with the beam profile; without TiN coating (top curve), with 80% TiN coating coverage (middle curve) and with 100% TiN coverage.

SUMMARY

Custom coatings for the SNS injection ceramic chambers and the extraction kicker ferrites were developed and implemented for the production coatings of 10 injection ceramic chambers and 14 ferrite kicker modules. The coatings have met the machine design parameters and operating conditions.

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