HIGH-TEMPERATURE KICKER ELECTRODES FOR HIGH-BEAM-CURRENT OPERATION OF PEP-II*

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Abstract

The strip line electrodes of the kickers used in the transverse bunch-by-bunch feedback systems see significant power deposition by beam and HOM-induced currents. This leads to elevated temperatures of the aluminum electrodes and will ultimately become a limit for the beam current in the Low Energy Ring. Heat is transported to the environment primarily by radiation from the blackened surface of the electrodes. In order to extend the beam-current range of these kickers, new electrodes have been fabricated from molybdenum which are able to run at significantly higher temperature, thus greatly increasing the efficiency of the radiative cooling of the electrodes. Blackening of the electrodes is achieved by oxidation in air at 530°C (1000°F) using a recipe first applied in aviation research for supersonic aircraft. Emissivity was measured on coupons and a whole electrode to be about 0.6. In addition, the match at the terminations of the electrodes is improved following field calculations and measurements on a model of the kicker.

INTRODUCTION

The kickers of the transverse bunch-by-bunch feedback systems at PEP are of stripline design, driven push-pull by one power amplifier for each electrode[1]. At the non-driven end the electrodes are terminated into 50 Ω loads. Active cooling by LCW of these electrodes is difficult due to the isolation and impedance-match requirements, therefore, the electrodes are blackened on the outside and cooled primarily by radiation to the kicker housing. The blackening is CuO, applied using a sputtering process to achieve high emissivity of nominally $\varepsilon = 0.8$. The electrodes themselves are made of an aluminum alloy and specified to operate at up-to 100°C (212°F). This limit is set both by material properties and to limit the thermal expansion of the electrodes, which puts stress onto the electrode mounts. Temperature of the electrodes is monitored by optical pyrometers operating in the $8 \ldots 15\mu$m band, looking through a fused-silica window.

HEATING OF THE KICKER ELECTRODES

Once the PEP-II storage rings reached beam-currents above 1 A, significant heating of the electrodes was observed by the pyrometers. Since the temperatures observed appeared unreasonably high, the pyrometers were recalibrated using a spare pyrometer and a prototype of the longitudinal feedback kicker. This prototype had a geometry similar to the kickers considered here and an identical fused-silica window. The recalibration somewhat lowered the measured temperatures but they continued to be high, see Fig. 1. A calorimetric method was therefore used to estimate the power dissipation in the kickers as the pyrometer calibration was deemed not reliable.

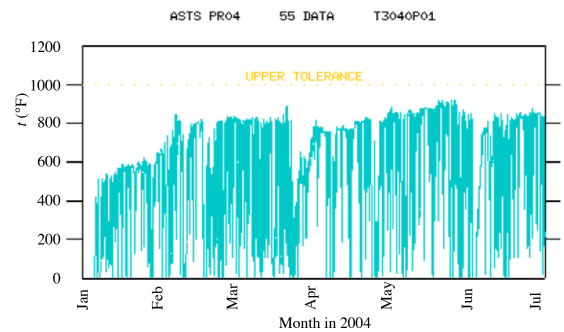

Figure 1: History of pyrometer reading.

Calorimetry

One kicker was wrapped with heater tape at two locations near the ends, and a power of 108 W was introduced as heat into the structure (Fig. 2, the heater tape is covered by thermal insulation). The equilibrium temperature (T_∞)

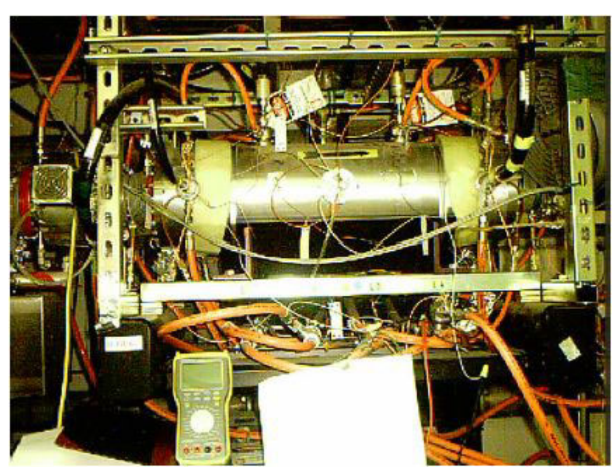

Figure 2: Kicker-heating experiment.

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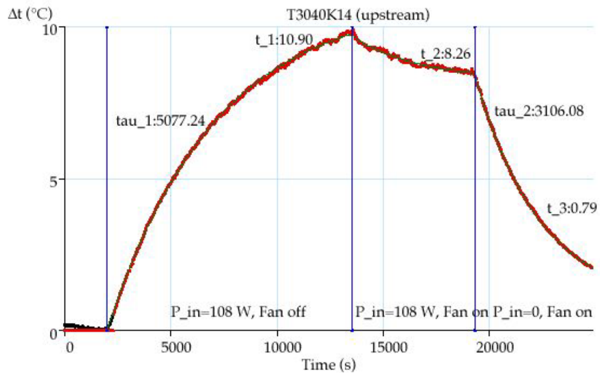

Figure 3: Kicker heating data.

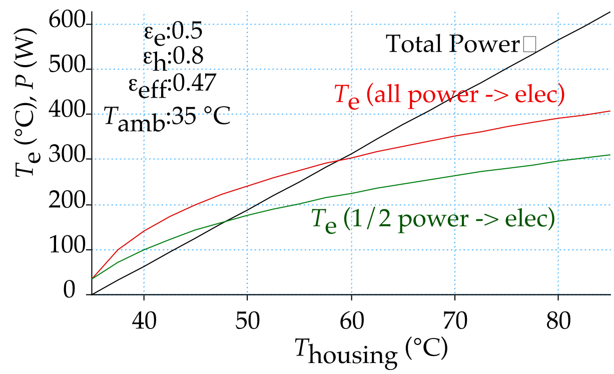

Figure 4: Electrode temperature.

was estimated from fitting the proper exponential function to the data. From the temperature rise estimated thus, Fig. 3, the thermal resistivity to the environment is determined:

$$R_{th} = dT_\infty/108\text{W}, \qquad (1)$$

which gives an average value for R_{th} of $0.08 \pm 0.015\,°\text{C/W}$. In addition, the thermal mass can be estimated from R_{th} and the time constant; this can be compared to the thermal mass obtained from the mechanical dimensions of the kicker housing:

$$C_{th} = m \times c,\ c = 0.896\,\frac{\text{kJ}}{\text{kgK}},\ m = 42\,\text{kg},\ C_{th} \approx 38\,\frac{\text{kJ}}{\text{K}}. \qquad (2)$$

The time constants were measured to be about $3000\ldots5000$ s giving a thermal mass of of $C_{th} = 46 \pm 12$ kJ/K, consistent with the value of 38 kJ/K derived from the volume of the kicker housing. R_{th} is then used to calibrate the temperature-rise of the kicker housing above ambient (which is measured quite accurately by thermocouples) in terms of power dissipation. Once the power dissipation is known, the temperature of the electrode is estimated using the T^4 law with reasonable accuracy, observing that the power P going into the electrode is between 1/2 and full the dissipated power:

$$T_e^4 = \frac{P}{\sigma A_e \varepsilon_{eff}} + T_{amb}^4,\ \varepsilon_{eff} = \frac{\varepsilon_e \varepsilon_h}{\varepsilon_h + \frac{3/2 A_e}{A_h}(\varepsilon_e(1-\varepsilon_h))}, \qquad (3)$$

where $\sigma = 5.67 \times 10^{-14}\ \text{W/mm}^2/\text{K}^4$; A_e, A_h, the area of the electrodes and the housing, resp., and $\varepsilon_e, \varepsilon_h$ are the emissivity of electrode and housing, resp.

Figure 4 shows the relationship between kicker and electrode temperature. Based on this measurement we would deduce a temperature of the electrode of $200\ldots300\,°$C at a beam current of 2.5 A, where the housing heats up by 25°C (40°F). Subsequent measurements on a spare electrode indicate the emissivity may be substantially less than 0.8, perhaps as low as 0.45 (see Fig. 5, blue symbols). If we adopt this number for both the electrode and the inside blackening of the housing we would calculate a temperature of the electrode of $300\ldots400\,°$C ($570\ldots750\,°$F) under the same circumstances, almost consistent with the pyrometer reading.

High-temperature electrodes

The electrodes are powered/terminated and supported by "paddles" at each end which also provide the electrical connection and impedance match. To run reliably at higher temperatures an electrode has to meet two requirements: Its material has to withstand the temperature without deforming or ageing, and thermal expansion of the electrode should be small to avoid stress on the mounts and to avoid changing the geometry at the ends of the kickers too much, which may cause loss of the impedance match. Good electric conductivity of the electrode is a significant advantage, although Cu plating can be considered. Finally, blackening of the electrode is still required to maintain good thermal conductivity to the kicker housing. The CuO sputtering process used in the original Al electrodes could be used again, although it involved considerable effort and expense. A simpler process would be to oxidize the copper by baking it in air; alas, while the surface generated thus is black in the visible spectrum, its emissivity in the IR is rather poor, about 0.25 as measured using coupons. We also found a significant amount of lose particulate, incompatible with use in the vacuum system of the storage ring.

Molybdenum turned out to be the material of choice for various reasons. It can withstand high temperatures, and it has a coefficient of thermal expansion three times lower than that of aluminum. Its electrical conductivity is about half that of aluminum, however, because of skin effect this translates into only 40% increased power dissipation which then causes only small additional temperature rise. In this way, conductive coating is avoided, which could be a difficult step because of the required vacuum and bake-out compatibility.

The choice of Mo opened up the possibility of much simplified blackening of the electrodes. In the 1950s, experiments with oxidation of various metallic surfaces showed that Mo will produce a stable oxide layer with high emissivity in the interesting IR range when baked in air at or below 530°C (1000°F)[2]. At SLAC, a series of tests was performed using Mo coupons and full-size samples, baking them and then measuring the emissivity. Figure 5 shows

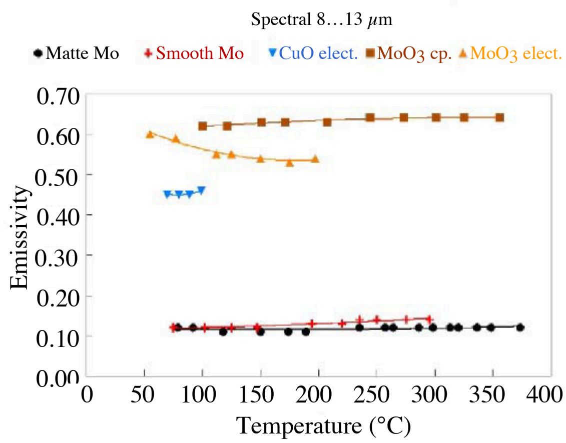

Figure 5: Emissivity of various surfaces.

the results of several tests in comparison. An oxidized Mo coupon showed emissivity in excess of 0.6 while a full-length electrode still had about 0.5. In comparison, one of our spare CuO coated electrodes measured less than 0.5, significantly below the nominal value of $\varepsilon = 0.8$. The matte and smooth, metallic Mo surfaces measured came in at approx. $\varepsilon \approx 0.1$.

Another issue impacting the power dissipation in the structure is the impedance match at the terminations of the electrodes. The kickers are nominal 50 Ω structures, however, because of the push-pull operation of the electrodes the impedance presented to the amplifiers differs from the impedance seen by the common mode coupled to the beam. Besides HFSS simulations TDR measurements were taken using a prototype of the kicker, and a modified geometry at the ends was designed. For added thermal stability the "paddles" are made of molybdenum also. Figure 6 shows the TDR measurement of the present paddle geometry and the improved match of the new geometry.

A kicker with Mo electrodes is presently being assembled. The estimated temperature of the new electrodes *vs* beam current using $\varepsilon = 0.6$ for the electrode and $\varepsilon = 0.45$ for the inside of the housing is given in Fig. 7. At a projected beam current of 3.3 A the electrode should reach 500°C, quite high but tolerable for molybdenum.

SUMMARY

New electrodes have been designed for the transverse feedback kickers that are expected to extend the current range of the LER well beyond 3 A. Molybdenum has been choosen because of its superior thermal properties and the ability of achieving good radiative cooling by simply oxidizing the surface in air at 530°C. The first kicker with the new electrodes has been assembled.

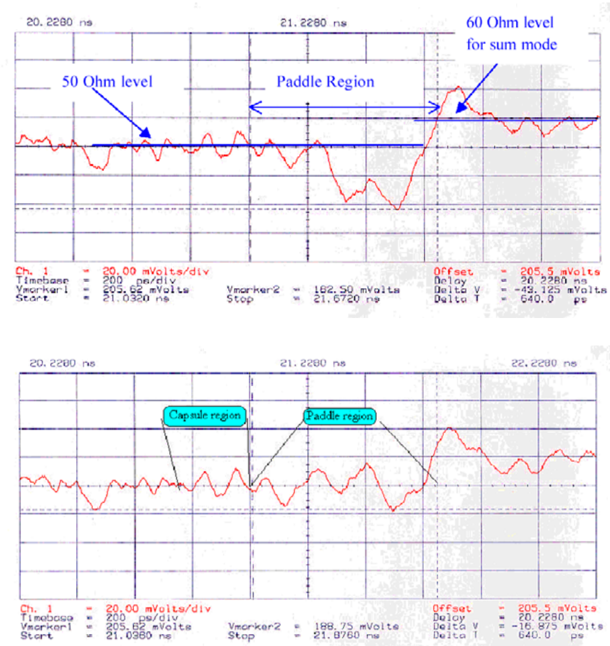

Figure 6: TDR with the old (top) and the new (bottom) paddles. Horiz. scale is 200 ps/div; vertical, 20 mV/div.

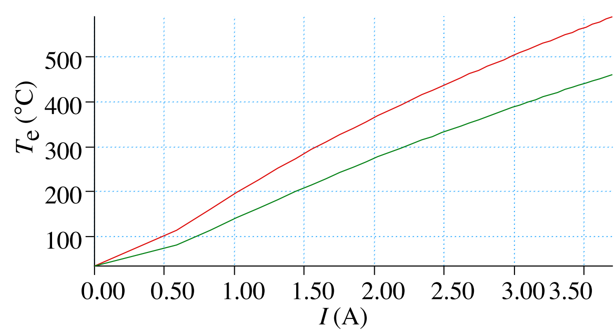

Figure 7: Temperature *vs* beam current for Mo electrodes.

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[2] W.R. Wade, NACA TN 4206, Langley Aeronautical Laboratory, Langley Field, Va, March 1958.