PRECISION ABSOLUTE CURRENT MEASUREMENT OF LOW POWER ELECTRON BEAM*

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Abstract

Precision measurements of low power CW electron beam current for the Jefferson lab Nuclear Physics program have been performed using a Tungsten calorimeter. This paper describes the rationale for the choice of the calorimeter technique as well as the design and calibration of the device. The calorimeter is in use presently to provide a 1% absolute current measurement of CW electron beam with 50 to 500 nA of average beam current and 1-3 GeV beam energy. Results from these recent measurements will also be presented.

INTRODUCTION

The purpose of the charge calorimeter is to measure the electron beam current with 1% absolute accuracy. The current in hall-A is determined by using a non-invasive cavity monitor (BCM) calibrated by another device, the Unser monitor. The Unser monitor can achieve about 0.2% accuracy of calibration around 50 μA [1], but at low current it is difficult to reach 1% accuracy because the Unser monitor has noise levels of order of 0.2→0.3 μA[2]. Therefore, a Tungsten calorimeter has been built to calibrate the BCM at beam currents below the range of the Unser monitor. The calorimeter is a cylindrical Tungsten slug 16 cm in diameter by 16 cm long. It has a cylindrical hole with 1 cm in diameter by 2.5 cm long to limit the back scattering of the charged particles. The calorimeter is installed upstream of the experimental target line to intercept the electron beam for a well defined time. The energy deposited in the calorimeter is given by

$$E_{\rm cal}({\rm Joules}) = E_{\rm beam}({\rm MeV}) I_{\rm beam}(\mu A)\Delta t({\rm sec}) \qquad (1)$$

where $E_{\rm cal}$ is the energy absorbed by the calorimeter, $E_{\rm beam}$ is the beam energy, $I_{\rm beam}$ is the average beam current and Δt is the exposure time. The calorimeter temperature will change after beam exposure and is given by

$$\Delta T = \frac{E_{\rm cal}}{C_m} \qquad (2)$$

where C_m is the heat capacity of the slug. The heat capacity is not known, so the heat capacity has to be determined, more information will be given in the experimental part. The calorimeter is designed to operate between 0.8 GeV to 12 GeV of beam power, and between 0.1μA to 5μA for beam currents [3].

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MECHANICAL AND THERMAL DESIGN

There are three positions for the slug:

- In beam position, in this position the slug intercepts the incident beam.
- In equilibrium position, this position is used after exposure until the slug comes to equilibrium. Beam is not intercepted when the slug is in this position.
- On the cooling plate, this position is used in order to cool down the slug for more measurements, again Beam is not intercepted.

The Tungsten slug is supported with a frame to move the slug into the three positions, attached to the frame an over sized tube that allows the beam to pass through during the equilibrium and cooling position. Six RTDs are connected to the slug and used to determine the temperature with high accuracy, three in each face with 120^0 from each other. From the back face a charge bleed wire is connected to allow the accumulated charge to bleed off. The RTDs and the charge bleed off wire go through a vacuum vertical tube to the electronic circuits to give the output (see Figs. 1 & 2).

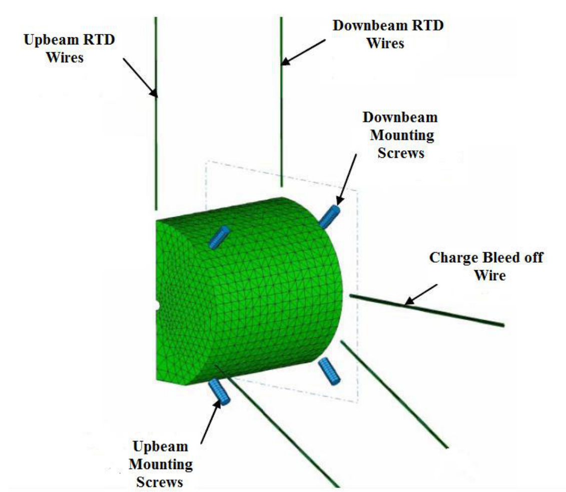

Figure 1: Slug with RTDs.

The calorimeter is stationary while the beam is incident upon it and accidental motion will cause a fast shut down of the beam.The calorimeter temperature limit is 50 ^0C and the beam delivery will discontinue if the temperature limit is reached.

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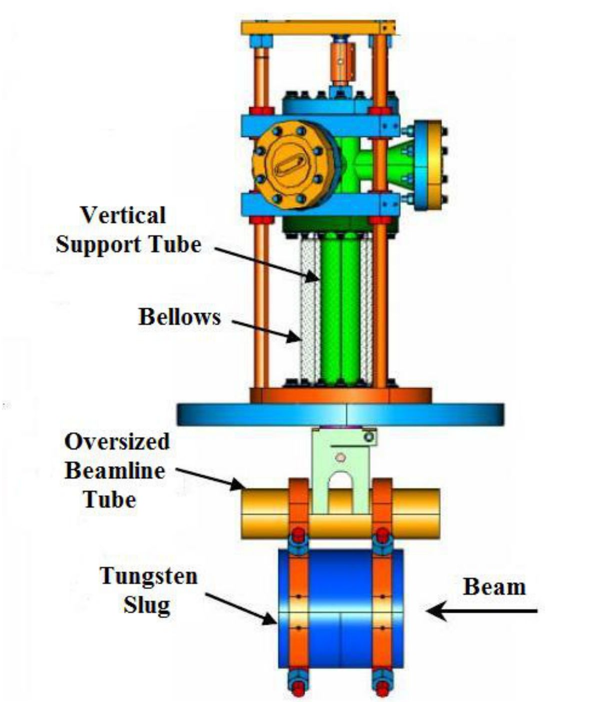

Figure 2: Slug with vertical tube.

The electron beam will deposit all its energy into the slug; resulting in a gain of energy and rise in the temperature. Energy loss through radiation, conduction and particle loss must be minimized to achieve 1% absolute accuracy. The measurement is taken under vacuum and glass ceramic pins are used for mounting the slug to minimize the thermal loss. The electomagnetic loss has been simulated and found to be $0.1 \pm 0.1\%$ and the hadronic loss found to be $0.3 \pm 0.2\%$[3].

EXPERIMENTAL WORK AND RESULTS

In order to calibrate the beam current, the heat capacity of the slug should be determined by using Eqn. 2. To simulate the real beam effect a heater has been embedded inside the slug and its resistance has been measured and found to be $6.9 \pm 0.1\ \Omega$. A fixed current and voltage are applied for a fixed time using "Agilent 3458 A" multimeter. Current and Voltage calibrations are performed at values that match the expected beam exposure values for incident beam power and exposure time. Fig. 3 shows the calorimeter experiment in Hall-A. The integrated power for each measurement and the calibration and beam exposure is desired to be near a constant value of 86000 Joules to minimize any systematical error. By knowing the beam power and the resistance, the current and the voltage can be determined form Eqn. 3 and the time of exposure is determined from Eqn. 4.

Figure 3: Calorimeter experiment

$$E_{\mathrm{beam}}(\mathrm{MeV})I_{\mathrm{beam}}(\mu A) = I^2 \times R = \frac{V^2}{R} \tag{3}$$

$$\Delta T = \frac{86000(\mathrm{Joules})}{E_{\mathrm{beam}}(\mathrm{MeV})I_{\mathrm{beam}}(\mu A)} \tag{4}$$

After exposure, the slug is moved to the equilibrium position until the equilibrium achieved. To determine the equilibrium temperature, the average of the six RTDs ($\overline{X}$) and the standard deviation (σ) of the read back temperature of the six RTDs are calculated (see Eqns. 5 & 6).

$$\overline{X} = \frac{\sum_{i=1}^{6} x_i}{6} \tag{5}$$

$$\sigma = \sqrt{\frac{1}{6}\sum_{i=1}^{6}(x_i - \overline{X})^2} \tag{6}$$

The standard deviation and the temperature of the slug are plotted versus the time on the same plot. The equilibrium temperature is defined to be when the standard deviation value becomes the least value after the beam is turned off and the corresponding temperature is the equilibrium temperature (see Figs. 4 & 5).

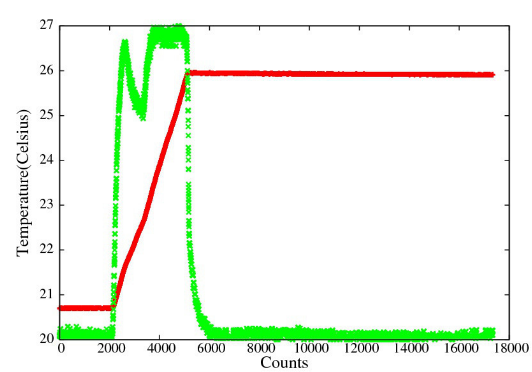

Figure 4: Determination of equilibrium temperature.

The experiment is done many times for different expected beam exposure, Table 1 shows a sample of this calculations. A histogram is plotted for the C_m values and the

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Table 1: Sample From The Calculations

Beam Power (Watts)	Current(A)	Voltage (V)	$t_{exposure}$(sec)	C_m (J/K)
110.433	4.072	27.12	743.3	8545.3
140.182	4.585	30.574	593.6	8563.4
164.964	4.976	33.152	504.1	8576.7
247.213	6.095	40.56	336.1	8576.8
269.572	6.339	42.526	304.8	8539.7
326.414	7.01	46.564	254.02	8543.2
403.597	7.802	51.73	205.07	8531.6

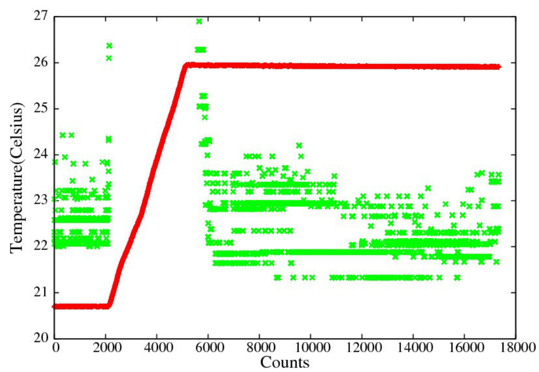

Figure 5: Scale is expanded.

average heat capacity is calculated and found to be 8555.5 J/K with a standard deviation value equal to 13.92 (see Fig. 6). Since the charges accumulate in the calorimeter,

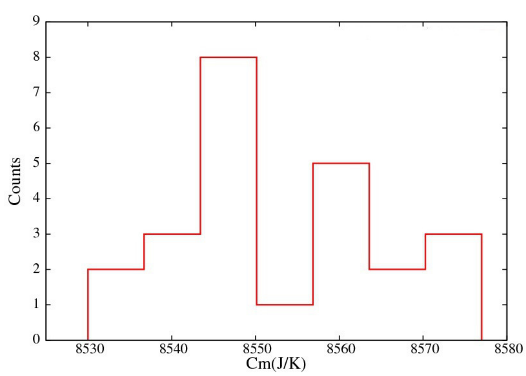

Figure 6: Histogram for C_m.

they must be removed. Therefore, the calorimeter can be used as a Faraday cup. To do this measurement a bleed-off wire is connected to the back face of the slug to remove the charge. In order to do the calibration with 1% accuracy, a 50 nA current should be used. A resistance has been measured with high accuracy and found to be 22.79 ± 0.01 MΩ and connected to "'Exitron" multimeter. A set of data has been taken between the input current ($\frac{V}{R}$) and the output current. The relation between the input and output currents found to be linear with a slope = 1.14253 ± 0.00038 and an offset = -0.04368 ± 0.00015 (see Fig. 7).

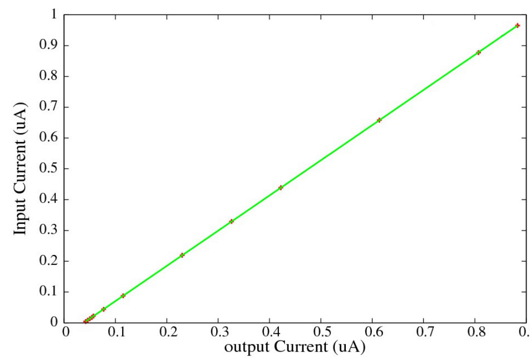

Figure 7: Slug as Faraday cup.

SUMMARY

The Unser monitor used to calibrate the Hall-A BCM has 0.2% accuracy for beam currents around 50 μA. The Unser monitor is not designed to provide absolute calibrations for beam currents below 5 μA. A calorimeter has been designed and fabricated with a mechanical and thermal design to minimize the heat losses. All the measurements are consistent with 1% absolute precision.

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