Beam Monitoring Techniques Used During the UT/RACE Experiment

S. O'Kelly, B. Hurst
Nuclear Engineering Teaching Laboratory, University of Texas, Austin, TX 78758, USA
(sokelly@mail.utexas.edu)

K. Folkman, F. Harmon
Idaho Accelerator Center, Idaho State University, Pocatello, ID 83201, USA

Aspects of the beam monitoring techniques used during the Reactor Accelerator Coupled Experiments (RACE) carried out at the University of Texas at Austin Nuclear Engineering Teaching Laboratory will be discussed. In particular two methods will be presented. The first used differential thermal measurement of the target during electron bombardment and subsequent neutron production as an indication of power input to the reactor core. The second method involved the development of a compact instrument that, along with the target acting as a faraday cup, allowed a continuous non-invasive means of determining the relative electron beam position

I. INTRODUCTION

A series of Reactor-Accelerator Coupling Experiments (RACE) were performed at the University of Texas at Austin (UT) in 2005 and 2006 using a 20 MeV electron LINAC coupled to the UT Nuclear Engineering Teaching Laboratory's (NETL) 1.1 MW TRIGA research reactor. These experiments (RACE-UT) were designed to represent and mock-up a large scale accelerator-driven subcritical system (ADSS) for the potential transmutation of high-level nuclear wastes. In the RACE-UT project, Bremsstrahlung radiation from the interaction of the high energy LINAC electrons on a copper-tungsten target produce neutrons via the giant dipole resonance in a neutron beam pipe adjacent to the NETL reactor core. The NETL reactor was configured to remain subcritical with all control rods fully withdrawn while various experiments involving reactivity changes, LINAC frequency and instrumentation were performed. Early in the experimental campaign, it became clear that the LINAC operators required better tools to evaluate the electron current on the target and the location of the electron beam. The neutron production within the target was a direct function of the energy and intensity of the electrons hitting the target so the LINAC operators needed to know more that just the parameters available from the LINAC to gauge if the electrons were actually reaching the target.

II. EXPERIMENTAL

Unlike many traditional particle beam experiments, the RACE project required the electron beam to travel nearly 5.5 meters after the last optical element on the LINAC without refocusing magnets or beam analyzers to evaluate the quality of the electron beam within the drift tube [1]. The LINAC used in these experiments was installed at the NETL during the summer of 2005. The LINAC was fabricated by the Idaho Accelerator Center on a single wheeled frame to be easily transported and moved between experiment phases for storage. The LINAC was designed to produce a 5 μsec pulse of 18 to 22 MeV electrons at a frequency between zero and 200 Hz with a maximum current of approximately 180 mA. The target acted as a beam converter and was fabricated from a 80% tungsten and 20% copper machined block brazed onto a NW35CF conflate flange providing a 3.8 cm target area for the electron beam. A significant safety concern for operation of the relatively high power LINAC target near the nuclear reactor fuel was the highest steady-state temperatures that the target would reach and the effect of unanticipated potential temperature excursions on the reactor core structure. The LINAC was designed to trip if the cooling to the target was lost but additional instrumentation was needed to evaluate actual target temperatures during operation. Two thermocouples were initially installed into the front and back (in the beam direction) of the target to evaluate the average target temperature. The target was cooled by a dedicated water cooling system to prevent cross contamination of the LINAC and power supply cooling and permit shielding the chiller and coolant lines to reduce radiation doses outside the LINAC cave from the expected ^{16}N production within the target. During the first half of the experiments, the target was simply bolted onto the end of the 5 meter beam pipe with the return electron current provided by the stainless steel beam pipe back to the LINAC. This configuration prevented direct measurement of the LINAC current and secondary indications were needed to monitor the electron current on the target and the electron energies. The LINAC operators noticed during initial testing that the target temperature was very sensitive to the intensity of the electron beam and attempted to focus and tune the LINAC by maximizing the temperatures measured by the thermocouples in the target. The production of neutrons within the target was a function of not just the current but also the energy of the incoming electrons so the LINAC operators were able to maximize the electron current and maintain a high average energy by monitoring the neutron count levels on the installed reactor instrumentation fission chamber. Although this beam monitoring method seemed adequate, the power level of the research reactor and the neutron production from the target were far below theoretical calculations so a more reliable method had to be created to measure the current leaving the LINAC.

During the second phase of the experimental program, following a one month hiatus of the RACE project for normal critical reactor operations, a current pickup loop was installed following the last quadrupole on the LINAC to measure the actual electron current in the beam pipe. The limited space (14 cm diameter) within the neuron beam pipe surrounding the LINAC beam pipe prevented placing standard pickup coils or large instruments anywhere except directly in front of the LINAC before the beam pipe entered the reactor concrete biological shield. An additional method of beam monitoring was also used during this phase that was an extension of the target-temperature beam monitor used during the initial RACE-UT experiments. An array of thermocouples was installed around the LINAC target in order to localize the electron beam focused on the target face. The electron beam was located on the target face by minimizing the differential thermocouple current from two thermocouples 180° apart. This system appeared to work well during initial testing performed at the Idaho Accelerator Center but the implementation at the NETL was more difficult. The thermocouples could not be installed directly across from each other due to the interference of the target cooling connections (the coolant also perturbed the measured temperatures) and they could not be placed in close proximity to the target face because of the limited space permitted between the stainless steel vacuum flange and the bulk of the target body. The system was installed on the RACE-UT LINAC even with these constraints because it was of vital importance to the project to evaluate the beam focus on the target. The thermocouples were monitored by a DAQ2000 (IOTech) data acquisition system for remote logging and observation by the LINAC operators. Although the thermocouples did respond to changes in electron beam intensity as the operators made adjustments to the LINAC and electron optics, the high thermal conductivity of the Cu-W target rapidly equalized temperatures on the target face making it difficult to use the system for performance monitoring or trends.

During the installation of the current pickup coils, it was determined that the steering magnets on the LINAC had been slightly moved during the original installation or while shipping the LINAC from Idaho. Effectively, a significant portion of the electron beam was hitting the side of the vacuum pipe inside the steering magnets or final quadrapole reducing the total current leaving the LINAC and thus hitting the target. The beam pipe and steering magnets were realigned and the current pickup coil was installed after the final quadrupole and electron current leaving the LINAC was measured to be approximately 100 mA or within expected parameters. Clearly, more electrons were passing into the beam pipe towards the Cu-W target following the beam alignment but there was effectively no change in target temperature or neutron production during the subsequent experiments. The conclusion at this point was the beam was dispersing immediately after the LINAC and only a small, unknown percentage was impacting the target. This conclusion was supported by indications of localized high temperature and high radiation environments several meters back from the LINAC target which could have been produced by high energy electron fields.

During the final phase of RACE-UT which occurred in the first quarter of 2006, several improvements in beam diagnostics were installed to determine the actual electron current interacting with the target and the location of the beam in the beam pipe. First, the existing target system was reconfigured to become a traditional Faraday Cup in order to monitor the beam current impacting the target. To enable this conversion, the Cu-W target was replaced at the exit of the beam pipe with a 1 mil stainless steel window. The target was then separated from the window by approximately 4.5 cm of air and electrically insulated from the LINAC beam pipe with a Delrin®, acetal resin spacer for radiation resistance and electrical isolation. The LINAC beam line had previously been electrically isolated from the walls of the reactor beam pipe with polyethylene spacers that also centered and supported the beam pipe but the target now required insulating from the surrounding aluminum pipe to avoid current leakage. This was accomplished by wrapping the entire target with Kapton® electrical insulating tape. The 0.95 cm copper cooling lines brazed to the target and the coolant were another potential electrical short so the copper lines were cut and a 5 cm section was replaced with flexible plastic tubing and the remaining copper tubing was insulated by wrapping the lines with flexible, spiral plastic sheathing. The electron current return from the target was monitored by a coaxial cable to minimize noise pickup from the LINAC pulses that fed directly to a current meter at the LINAC operator console.

Locating the beam within the LINAC beam pipe given the limited space of the reactor beam piping was more problematic as all normal means (phosphor screens, multichannel plates, etc.) required significant space to implement. The position indicating split toroid (PIST) is a unique method that was developed and provided real-time beam localization and would not interfere with the LINAC beam (Fig. 2). The PIST instrument is based on the design of an AC current pickup loop; however, the toroid core is radially split into four quadrants with

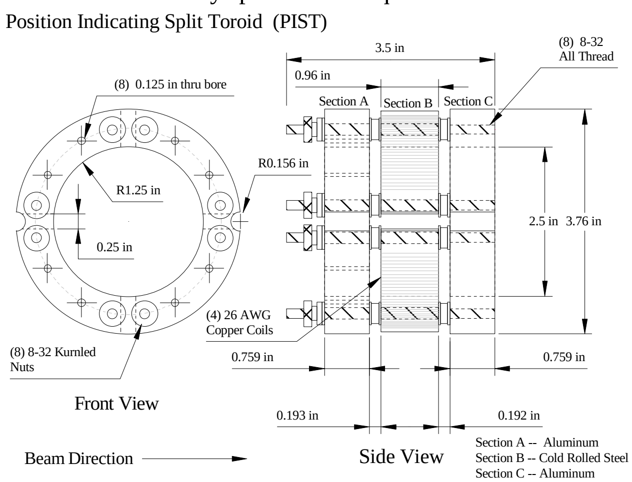

Fig. 1. Position Indicating Split Toroid (PIST).

independent pick-up coils wound around each quadrant. The core material is steel machined into a right circular cylinder shell and cut into four equal quadrants. These pieces are then annealed overnight to relieve the stresses in the steel. The bare pieces were then wrapped with Kapton® tape to prevent shorting of the windings to the steel core. The quadrants were wound with 22 turns of 18 AWG heavy polyamide insulated magnet wire. The polyamide insulation of the wires and the Kapton tape was selected to provide radiation hardened electrical insulation throughout the final RACE-UT experiment phase.

The PIST effectively operates on the same principle of an AC clamp-on meter in that the current flowing through a wire induces a voltage in the pickup coil around the wire. In the operation of an electron LINAC, or other charged particle beam experiment, the current is not confined to a wire but is drifting through the beam pipe in vacuum or air. The four separate pickup coils in the PIST will have different voltages induced depending on the location of the ideal focused beam relative to the four coils. Each pickup transformer has a grounding set of leads from the central core in addition to the signal wires so a total of eight pairs of leads connected the PIST.

Initial testing and calibration of the PIST was performed using a pulser and 0.3175 cm is diameter brass rod running through the center of the PIST. The rod could be accurately moved anywhere within the interior of the system and the location was measured with a precision of ±0.00254 cm using dial indicators. The voltages in the pickup coils were extracted in pairs and analyzed using a four-channel oscilloscope. A signal from an opposite coils was inverted and added to the first coil to provide a common-mode rejection of the expected intense electrical noise of the LINAC's operations. The differential voltages recorded along with the displacement of the rod relative to the centerline of the PIST. The pulser was operated up to a frequency of 100 Hz with pulse widths of 5 µsec and amplitudes of 9 V to simulate the operation of the LINAC. Figure 2 shows the results of these pulser tests. The abscissa shows the brass current-carrying wire's displacement relative to the PIST centerline. The ordinate records the differential voltage measured. No curve fitting or empirical equation was derived from these tests but dotted lines were added to the graph to show the relation between different data points. From the data it can be seen that the PIST provides very linear position information within a 10 to 20 mm diameter location near the center but the PIST response becomes more non-linear as the beam moves closer to the pickup coils. This may be evidence of the mutual interaction of the current and voltage in the pickup coils and the current in the beam.

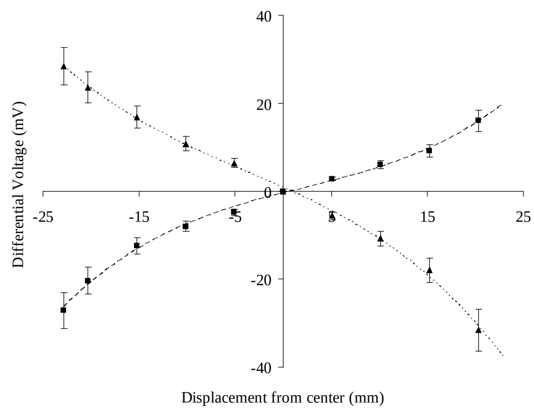

Fig. 2. PIST beam position calibration using pulser.

A final set of tests were performed at the IAC using an available electron LINAC to evaluate the PIST operation in the vicinity of an operating LINAC before final installation in the RACE-UT project. Significant data was not acquired during these LINAC tests as there was no means available for calibrating the actual electron beam location to the PIST but several modifications of the signal cabling were made to reduce induced LINAC noise.

During the final RACE-UT experimental campaign in the first quarter of 2006, the PIST provided valuable information to the LINAC operators on beam location but it was not clear from all observations if the electron beam remained focused. It appeared that the electron beam had de-focused and dispersed to the point that the beam diameter may have been the same as the actual beam pipe. From Faraday Cup data, it appeared that at least half the electron beam current leaving the LINAC did not actually hit the Cu-W target. It is believed that the beam energy spread was wide enough that there were significant electron losses a short distance from the LINAC down the beam pipe. Ideally, future LINAC projects involving limited space could use a series of PIST instruments to evaluate the total beam current and location at several points along the beam travel.

III. SUMMARY AND CONCLUSIONS

Several novel methods were evaluated to determine electron beam energy, location and intensity during the RACE-UT experimental program in 2005 and 2006. Although no method appeared to be the perfect tool for all situations, all methods complemented each other to provide LINAC operators additional information for beam diagnostics. Future experiments of this type must evaluate actual electron beam energy using more traditional analyzer magnet or calorimeter techniques to maximize neutron yield but the ability to determine the beam current and localization of the beam will still be required in the limited space likely to be available in future ADSS projects.

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