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THE DESIGN AND HIGH-HEAT FLUX TESTING OF AN INTERCEPTIVE-DIAGNOSTIC DEVICE FOR A PROTON BEAM

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ABSTRACT

The design and high-heat flux testing of an interceptive-diagnostic device that will be used to probe an intense-proton beam is described in this paper. An intense-proton beam is produced in a Radio Frequency Quadrupole (RFQ) accelerator and injected into a magnetically Focusing-Defocusing (FODO) lattice in order to study the formation of beam halo. Due to the nature of making beam halo formation measurements in a proton beam it becomes necessary to insert an interceptive device near the center of the beam. The interceptive device used to probe the beam is referred to here as a scraper. The peak heat flux experienced by the scraper is on the order of 610 kW/cm^2. The scraper consists of a copper base that is water cooled, with a piece of graphite joined to it.

INTRODUCTION

The RFQ accelerator will be used to accelerate a proton beam to an energy of 6.7 MeV. The peak current for experimentation is 100 milliamps. This beam will be injected into a 52 magnet lattice that forms a FODO lattice. This lattice design allows for the beam to be manipulated in a way that can promote the formation of a particle beam phenomenon known as halo [1]. Particle beam halo can be visualized as a low density gathering of particles that are on the periphery of the main beam bunch. Although the particles in the halo are few as compared to the main beam bunch they can still cause significant problems. One such problem is beam tube irradiation that is caused when the halo particle's trajectories grow beyond the physical size of the tube, and they thus collide with the tube wall.

In order to detect the presence of beam halo an integrated measurement of the beam's current density needs to be made. One way to accomplish this is to probe the outer portions of the beam with a solid device, integrate the beam current measured per step change in distance, and calculate the current-density distribution [2]. A plot of the beam's current-density distribution will reveal if a beam halo is forming at the measured location. The scraper obviously needs to be able to withstand the thermal power deposited on it by the particle beam. In this particular experiment the beam is not expanded as it exits the RFQ accelerator, thus enabling the beam to maintain a very small spot size, and a very high current-density near it's physical center. This places a peak heat flux on the scraper of approximately 610 kW/cm^2 for the beam parameters being employed. The scraper will not be inserted to the physical center of the beam, only to within 2.5 mm of it.

SCRAPER DESIGN

The scraper uses a piece of graphite joined to a copper backing plate. The copper plate serves as a heat sink, and as a structural support for the graphite. The graphite is 3.2 cm high by 3.2 cm wide. The graphite is 1.5 mm thick, as is the copper behind it also. The coolant channel has an inside diameter of 5.0 mm. De-ionized water at a flow rate of 3.78 liters/min is used as a coolant. The scraper design is illustrated in Figure 1.

With a graphite thickness of 1.5 mm the portion of the proton beam that strikes the scraper is compleltely attenuated in the graphite alone. This is a beneficial aspect of the design because radiological activation of the copper is avoided.

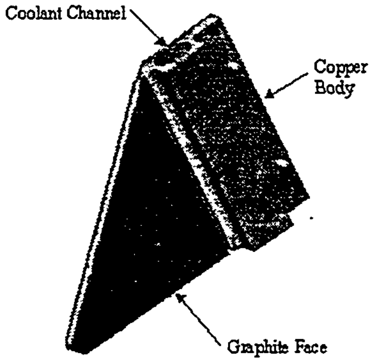

Figure 1
Scraper design

The graphite is joined to the copper by brazing the two together. Two different braze alloys have been found to produce successful braze joints. The first alloy, TiCuSil (Titanium, Copper, Silver) has a liquidus temperature of 850 °C. The second alloy, TiCuNi (Titanium, Copper, Nickel) has a liquidus temperature of 960 °C. Each alloy produces a braze joint with good heat transfer capability, and with good structural strength as determined by previous testing [3], and this current high heat flux testing effort.

Finite-difference and finite-element models of the scraper have been created in order to predict the response of the scraper design to the high heat load. Peak temperatures and peak stresses have been predicted and studied in order to set the prototype design for the scraper.

The finite-difference models were used primarily to study the predicted peak temperatures of a given scraper design. The beam parameters could be incorporated easily into these models. A good candidate design could be identified with the simpler finite-difference model, and then a more involved, three-dimensional finite-element model could be created to study the design in greater detail. A thermal solution would be obtained first with the finite-element model, and then a stress-strain solution based on the predicted thermal profile would be obtained. The finite element analysis code Cosmos/M [4] has been used to create and analyze the finite-element models.

The predicted results for the scraper design chosen for testing are as follows. The peak graphite face temperature is predicted to be 380 °C. The predicted peak copper body temperature is approximately 85 °C. The proton beam will be pulsed on and off at a rate of about 6 Hz. This on-off time has been incorporated into the thermal models, and the peak graphite face temperature, therefore, is predicted to rise and fall at this frequency. The body temperatures of the graphite and copper are not predicted to fluctuate with the beam pulsing. Therefore, the braze joint between the graphite and copper should see a steady temperature regime, which reduces the magnitude of the cyclic loading on the joint. The braze joint is predicted to experience some of the expansion and contraction stresses being exerted by the graphite face material that is interacting directly with the beam. At a flow rate of 3.78 liters/min the temperature rise of the de-ionized water in the coolant channel is predicted to be less than 0.7 °C.

AFEL OPERATION AND SCRAPER TESTING

The Advanced Free Electron Laser facility [5] is designed primarily to create laser light by oscillating, or wiggling an electron beam. This test utilized the electron beam after it had passed through the wiggler magnet section. In the down-stream location three focusing-defocusing magnets were used to focus the beam as desired, and a steering coil was used to steer the beam onto and off of the scraper. Phosphor screens were placed immediately up-stream and down-stream of the scraper to provide a visual image of the beam's spot size and location. The phosphor screens were viewed with cameras viewing through ports in the beam line. A camera was also placed to view the scraper during beam operation. The camera monitors in the AFEL control room were used to view the camera's images.

The AFEL is capable of the following beam operating parameters. The beam energy is 16.5 MeV. The maximum charge is 4.5 nanoCoulombs (nC) delivered during each of approximately 1000 micropulses in 10 microseconds. This makes 250 MW/cm2 the peak power density producible with the electron beam over a single macropulse. The 1000 micropulses in 10 microseconds constitutes a macropulse. The maximum beam macropulse repetition rate is 10 Hz.

For the scraper testing the beam parameters utilized were a charge over the range 1.5 to 3.0 nC, 950 micropulses in 9 microseconds, a beam spot size of 1.3 cm^2 or less, and a beam repetition rate of 5 Hz. The beam spot size of 1.3 cm^2 or less ensured that a minimum heat flux of 610 kW/cm^2 would be placed on the scraper.

Table 1 lists the stopping powers of graphite and copper for a 6.7 MeV proton, and a 16.5 MeV electron. The following equation is used to determine a thermal load from the stopping power of the material.

$$Q = P_{stop} * \rho * \text{Thick} * I_{beam}$$

Where: Q – Thermal power in watts

P_{stop} – Material stopping power, eV-cm^2/gm
ρ - Material density, gm/cm^3
Thick – Material thickness, cm
I_{beam} – Beam current, amps

These values lead to the fact that since the scraper attenuates more of the proton beam than the electron beam the electron beam has to be operated at a higher power than that of the proton beam to obtain similar thermal conditions between the two beam intercepting cases. The power of the electron beam has to be increased to approximately four times the power of the proton beam portion that strikes the scraper. The portion of the proton beam that strikes the scraper contributes a thermal load of 610 kW/cm^2. This is used to set the electron beam power for the scraper testing. The electron beam charge can be varied as an operating parameter to achieve the desired beam power. Once the beam charge is set the beam spot size required to produce the desired test heat flux on the scraper is calculated. The beam spot size is set primarily with the three focusing magnets that are immediately up-stream of the scraper test location. Figure 2 is a photograph of the scraper test section installed in the AFEL beam-line. Figure 3 is a close view of the scraper test section. The scraper is contained in the cube section with windows and coolant lines connected. The phosphor screens are located in the upper and lower cross sections with actuators to move them into and out of the beam. Figure 4 is a photograph of the scraper test assembly with sealing flange and coolant tube.

Material	Stopping Power (MeV-cm^2/gm)	Stopping Power (MeV-cm^2/gm)
	6.7-MeV proton [6]	16.5-MeV electron [7]
Graphite	99.1	~ 2.08
Copper	----	~ 2.51

Table 1
Stopping powers for graphite and copper

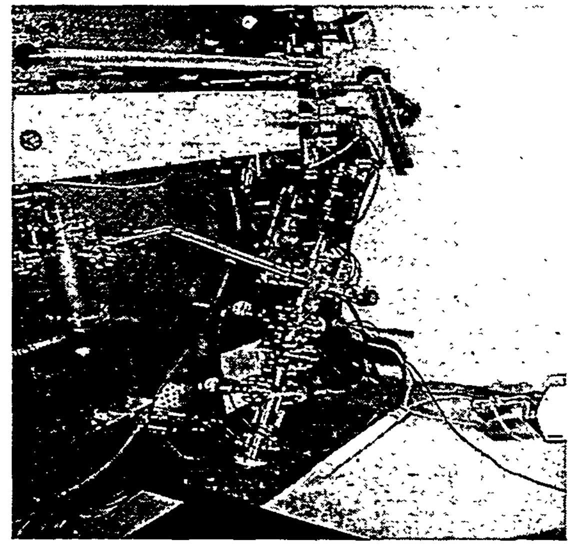

Figure 2
Scraper test section installed in the AFEL beam-line

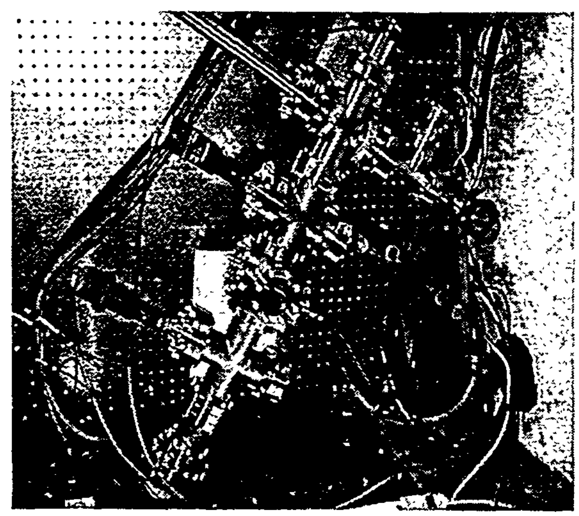

Figure 3
Close view of scraper test section

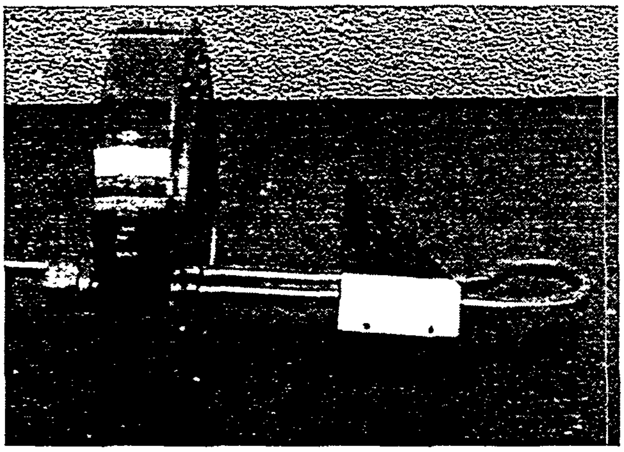

Figure 4
Scraper test assembly

SCRAPER TESTING RESULTS

The goal of the high heat flux testing on a given scraper is to achieve 10 hours of beam exposure that produces a heat flux on the scraper of 610 kW/cm^2 at a beam repetition rate of 5 Hz. The 10 hours does not have to be continuous, but it is desired to not divide it into more than about 4 test segments. This is done to replicate or exceed the potential experimental times that the actual scraper assemblies could be exposed to.

The first scraper tested used the braze alloy TiCuSil to join the graphite and copper. The scraper underwent 3 hours of continuous beam operation at a repetition frequency of 5 Hz for the first test segment. The scraper had no visual signs of damage such as separation of the copper and graphite, graphite spalling, or copper melting. A radiological measurement of the scraper at about 6 cm from contact indicated that the scraper was emitting a dose of approximately 10 milliRem/Hr. After a few hours the measured dose dropped to very low background levels. This is typical for copper structures in the presence of electrons or protons of this energy level. The next two test segments were both conducted at a time length of 3 hours each, and a beam-repetition rate of 5 Hz. The scraper exhibited no visual signs of damage. Since the scraper had survived well the testing to this point it was decided to increase the heat flux on the scraper. The maximum charge available from the photo-cathode source was injected into the AFEL linear accelerator section, and a beam interaction heat flux of 1.02 MW/cm^2 was placed on the scraper at a beam-repetition frequency of 5 Hz. This heat flux is about 67% greater than the target heat flux. This testing was conducted for a continuous 2 hour period. The scraper once again had no visual signs of damage. After the scraper was removed from the test section a closer visual inspection was done. No damage could be seen on any part of the scraper. Figure 5 is a photograph of the scraper after testing was completed.

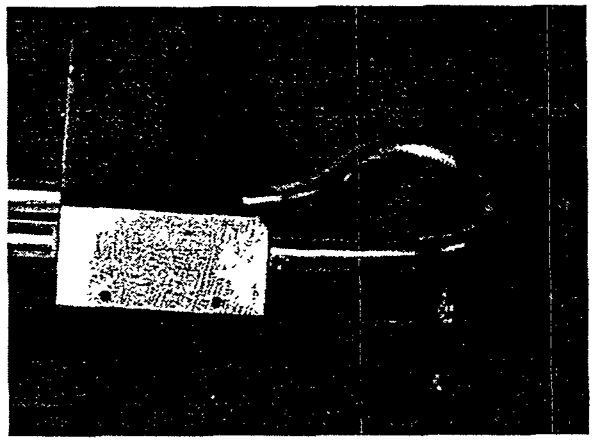

Figure 5
TiCuSil braze alloy scraper after testing

The second scraper tested used the braze alloy TiCuNi to join the graphite and copper. Three test segments of time durations of 5, 2, and 2 hours were used to test the scraper. The first two test segments of 7 hours total placed approximately the target heat flux of 610 kW/cm^2 on the scraper. The scraper exhibited no visual damage. During the last test segment of 2 hours duration, however, a high-enough charge from the photo-cathode injector could not be maintained to produce the desired beam interaction heat flux on the scraper. The testing was stopped at the accumulated 9 hour time level. A close visual inspection of the scraper after it was removed from the test section revealed no damage. The TiCuNi brazed scraper after testing very closely resembled the TiCuSil brazed scraper after its testing.

DISCUSSION OF THE TESTING AND RESULTS

The thermal load placed on the scraper by interaction with the particle beam is different for the proton and electron beams. All of the proton beam is attenuated in about the first 0.4 mm thickness of the graphite. For this case the thermal load is very close to a high heat flux being placed on the face of the scraper. In the case of the electron beam the beam is partially attenuated over the thickness of the graphite and copper. This places a thermal load on the scraper that is a volume heating type of load. Since the scraper is not very thick this difference is not considered to be significant. The underlying goal of the electron beam testing is to bring the scraper braze joint to about the same thermal condition as it will see during proton beam probing, and to fluctuate the thermal profile at a rate near the proton beam repetition rate. Since impingement of the electron beam produces a volumetric heating condition the braze joint actually goes through more of a cyclic temperature change than it will for probing the proton beam. This places a greater fatigue load on the braze joint during electron beam testing. From a fatigue load perspective the electron beam testing is more punishing on the scraper braze joint than its intended use.

The TiCuSil alloy braze joint received a little harder test than the TiCuNi alloy braze joint. In spite of this the two alloys are expected to respond about the same mechanically during use in the actual proton beam probing scrapers. The TiCuSil alloy has a few, slight advantages over the TiCuNi alloy, so it is the primary alloy to use in this design, with TiCuNi being a back-up material. Two advantages of the TiCuSil over the TiCuNi are that it is nonmagnetic, and it brazes at a lower temperature, which helps with fabrication.

The heat load on the scraper was increased significantly during the last test segment of the TiCuSil alloy scraper in order to investigate the potential to push the scraper deeper into the proton beam than has been established so far. The resulting current-density distribution calculation can be made more reliable by probing deeper into the proton beam core. The higher thermal load testing indicates that the scraper could be inserted closer to the proton beam center than the planned 2.5 mm distance. Since there is a difference between electron and proton attenuation by the scraper this will have to be attempted carefully and gradually during proton beam measuring. Inspections of the scraper face will need to be made to check for any damage.

Both braze alloys produce a graphite-to-copper joint that handles a significant heat load, and in a cyclic manner. The scraper design in general, and the braze joint design in particular should perform well in the target application.

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REFERENCES

[1] Wangler, T., 2000, "Beam Halo in Proton Linac Beams", Proceedings, LINAC 2000 Conference, Monterey, CA.

[2] Gilpatrick, J. D., 2000, "Beam Diagnostic Instrumentation for the Low–Energy Demonstration Accelerator (LEDA): Commissioning and Operational Experience", Proceedings, European Particle Accelerator Conference 2000, Vienna, Austria.

[3] Lindquist, L. O., and Mah, R., 1977, "Graphite-to-Metal Bonding Techniques", Technical Report LA-6928-MS, Los Alamos National Laboratory, Los Alamos, NM.

[4] Structural Research and Analysis Corporation, "COSMOS/M Applications", version 2.0, Los Angeles, CA.

[5] Nguyen, D. C., et. al., 1999, "First Lasing of the Regenerative Amplifier FEL", Nuclear Instruments and Methods in Physics Research A 429, Elsevier Science Publishing, pp. 125-130.

[6] Barkas, W., and Berger, M., 1964, "Tables of Energy Losses and Ranges of Heavy Charged Particles", Technical Report SP-3013, NASA, Washington, D.C.

[7] National Academy of Sciences, 1964, "Studies in Penetration of Charged Particles in Matter", Technical Report Number 39, Nuclear Science Series, Washington, D.C.