Chapter II: E951 R & D Effort

Introduction

A muon collider/neutrino factory based on a muon storage ring requires a tightly focused, high intensity beam on target. Specifically, up to 16 TP per pulse of a 24 GeV proton beam need to be delivered on a target. While a mercury jet is the primary target consideration (high-Z material and more efficient in producing pions of both signs), other options using graphite as target material (low-Z and better in avoiding the absorption of produced pions) are also being explored. The broad goal of E951 is to provide a facility that can test all the major components of a liquid or solid targets in intense proton pulses and in a high field solenoid. The first phase of E951 has focused on the interaction of intense proton pulses with targets and beam windows in zero magnetic field.

In the first phase of the E951 experiment a series of different experiments were designed and conducted in an effort to understand and evaluate a variety of issues that ranged from target material response to tightly focused proton beams to estimates of mercury dispersion velocities. Specifically, the experimental matrix included: (a) the study of window materials, (b) the evaluation of graphite and carbon-carbon composite as alternative low-Z target materials, (c) the behavior of a mercury pool intercepting the proton beam and the correlation of the energy deposited to ejection velocities and (d), the interaction of the proton beam with a mercury jet and the subsequent destruction of the jet including measurements of velocities of material dispersion. Figure 1 depicts the layout of the A3 beam line near the target station that has been configured for the transport of primary 24 GeV protons extracted from the AGS. All targets are mounted inside a stainless steel vessel preventing any dispersal of activated fragments that can potentially be ejected from the tested target. The details of each arrangement will be presented in later sections. Figure 2 represents the measured beam spot size in the two planes at the end of the A3 line that may be achieved through fine- tuning of the various quadropoles.

Window Study

The window material study focuses on the thermo-mechanical response of the selected materials and their ability to survive the tightly focused beam for multiple pulses. Based on the required muon collider beam parameters, it was concluded early on that very few materials will be able to survive the thermal shock induced by even a single pulse, let alone multiple pulses. While in the actual muon collider target configuration the beam window location may be optimized (achieve bigger beam spot based on the beam beta function), in the E951 experiment it is required for the beam window to be close to the target. In order to select the right window material that will survive under such conditions, an extensive effort was undertaken to evaluate different materials that show promise based on their mechanical strength.

The window study was two-fold. It included the prediction phase and the experimental verification. In the prediction phase, the energy deposition on the different window materials and for the anticipated AGS beam parameters were estimated using the hadron interaction code MARS […]. This was followed by a transient thermal analysis resulting from the deposited energy and finally by a thermal stress analysis that included the generation and propagation of stress waves. The thermal response of the window structure and the subsequent stress wave generation and propagation were computed using the finite element code ANSYS [..]. In the experimental verification, the recorded transient strain in the actual windows was compared to the predicted strain levels and wave shapes. The primary goal in such comparison was to verify that the prediction at this lower intensity level is "trustworthy" and can safely be used to extrapolate to the higher intensities required and address the material failure potential. Additionally, and as part of the experimental verification study, the impact of irradiation on the mechanical/strength properties of the selected materials is examined closely. The latter is an on-going effort.

Carbon Targets

The experimental effort on low-Z solid targets included the study of ATJ graphite and carbon-carbon composite by exposing them to the tightly focused 24 GeV AGS beam. The primary goals of this task was to (a) assess the survivability of the graphite target to the anticipated high intensity beam, and (b) to experimentally verify the promise of the carbon-carbon composite of having a very small thermal expansion coefficient that, in turn, implies small generated stress waves. Verification of the latter will be significant in that a beam power of the order of 1 MW could be envisioned using such target.

CERN Mercury Trough Target

Part of the experimental matrix of E951 was the CERN mercury target configuration. This passive target arrangement, shown in Figure [], consisted of a "pool" of mercury in a well engraved into a stainless steel block. The target is inside a special container that allowed for the anticipated dispersed mercury to collect back into the well while permitting the capturing of the event by fast cameras through a side viewing window. The primary goal of this passive mercury target experiment was to measure with the fast cameras the velocity of the mercury ejected from the free surface of the "pool" and correlate it with the analytical predictions. Peak ejection velocities of 70 m/s were observed during the experiment generally following the theoretical predictions. Such low velocity values, compared to the velocities that pressure waves in the mercury propagate with, confirm that the potential for destruction of the target enclosure by the mercury projectiles is nonexistent.

Mercury Jet Target

The active mercury target of E951 consisted of a mercury jet intercepting the AGS proton beam as shown in Figure [ ]. In this first phase of the experiment, no magnetic solenoid field was integrated with the experiment.

The potential use of a mercury jet target for the muon collider/neutrino factory has raised several novel issues that needed clarification through experimental means. These include dispersion of the jet due to rapid energy deposition, destruction of the jet by magnetic forces, and ejection of high velocity droplets that can damage the confining envelope. The latter was also addressed in the CERN mercury target configuration. Additionally, a potentially challenging design issue associated with the target configuration is the possibility of shock wave impact and consequently potential damage on the jet nozzle that sends the jet into the solenoid. To address this design issue an attempt was made to record the dynamic strains in the vicinity of the nozzle. The appearance of strain waves, following the beam/jet interaction, will signal the arrival of pressure waves at the nozzle location.

E951 verified that the indeed the jet will destruct by interacting with a single proton pulse that has even much lower intensity than the 16 TP anticipated in the actual muon collider/neutrino factory. The good news is that the destruction process, as predicted by calculations, was proven to be slower than the pressure waves generated in the jet and that the dispersed mercury ejects with velocities that are a fraction of the sound speed in mercury.

Preliminary assessment of pressure wave travel back to the nozzle shows that, while small given the much lower intensity achieved during E951, there is evidence of such travel back toward the nozzle. It is difficult, however, based on these findings, to extrapolate to the actual target and assess the susceptibility of the nozzle to repeated loading from these waves.

E951 – Beam Window Study

Issues

Given the set of beam parameters required for the muon collider/neutrino factory, i.e. 16 TP intensity and 0.5mm rms sigma radius, the resulting energy density within the one sigma radius of the beam will induce a stress field that for many materials will exceed the yield strength limit. Figure 4 is a clear example of that. It depicts peak thermal stresses in a 10-mil thick stainless steel window induced by a beam with such parameters (24 GeV, 16 TP, 0.5 mm sigma and 100 ns pulse length). Specifically, the peak von Mises stresses in the window material, occurring at beam center and mid-thickness, approaches 2500 MPa that is more that twice the yield and ultimate strength of the material.
Since such severe conditions will result after a single proton pulse for some materials and after several pulses for the better materials, depending on the spacing between the pulses in the train, it is very important to obtain a better understanding of the way these materials respond to such severe exposure, and of the way their properties degrade with radiation exposure. The latter needs to be combined with fatigue failure properties to establish the criteria for the amount of "beating" a good window material can take before it reaches its failure limits. Thus, the beam window issues that E951 was set to address may be summarized in the following:

- Survivability of windows based on a single beam pulse
- Survivability of windows to a series of pulses
- Assessment of the effects of irradiation on the mechanical properties of the candidate materials

Detailed dynamic analyses that capture the window structure response helped guide the selection of materials to be tested. These analyses also provided the basis needed for quantitative comparison with the experimental results. Confidence in the methodology used to make the predictions will allow for the extrapolation of the data to conditions required in the real muon collider target. These conditions were not anticipated to be achieved in the first phase of E951, simultaneously at least. The material matrix that was finally selected included a 10-mil thick 3000 series aluminum window, a 9-mil thick titanium alloy, an 11-mil thick havar, and two inconel-718 alloy windows in two thicknesses (1mm and 6mm).

Goals of Experimental Effort

The goals of the first phase of the window experiment effort are summarized below:

- Verification of the predictions to form the basis for extrapolation of results for the more intense beam as well as the design of the "real thing"

- “Real” environment exposure of the selected materials as window structures and understanding of their response based on measurable quantities that can be directly connected to the failure mechanism, i.e. stress and strain

- Assessment of “thin” vs. “thick” in windows. Given that the ability of a beam window structure to “diffuse” an undiluted beam is a function of a number of parameters (sound velocity, beam structure and thickness), the controllable parameter of thickness and its effect is addressed in the experiment

- Address “failure” in the window material. Given that failure means different things to different people, the goals of E951 were to (a) qualitatively assess the potential that the window materials failed by monitoring the breach of vacuum in the enclosed space of a double window arrangement, and (b) to examine the affected zone window that intercepted the beam for possible degradation of its overall mechanical properties or changes in the micro-structure.

Theoretical Predictions on Beam Window Response - Background

Consider a thin window structure of radius ***R*** and thickness ***h*** intercepting an energetic, focused proton beam of gaussian profile. Energy is deposited in the material with radial symmetry about the window center while some variation of energy deposited is expected to be present, no matter how thin the window, through the thickness h.

In evaluating the thermoelastic equation of motion in the beam window it is assumed that the thermal expansivity is isotropic and the effects of heat conduction on the dynamics are neglected. Further, as first approximation, no attenuation of the acoustic pulse is accounted for even though some fraction of the energy is dissipated in the material. It is also assumed throughout that the energy deposited in the window material is immediately converted to thermal energy. As noted in [6] this is a very good approximation given that the acoustic relaxation time is of the order of nsec whereas "thermalization" times, at least in metals are of the order of 10^{-11} secs.

Based on the above considerations, the issue to address is how does a thin window structure respond as it intercepts a fast and intense proton pulse. While "thermalization" is assumed to take place instantly, thus generating a quasi-static state of stress in the affected zone, the acoustic relaxation time still plays a role in defining both the generation and the level of thermal shock stresses. Specifically, the amplitude of the stress waves emanating from the "heated" zone depends on the relation between the rate of energy deposition (pulse length) and the acoustic relaxation time (time required for an acoustic wave to traverse the region of energy deposition). If the time of energy deposition is smaller than the acoustic relaxation, the amplitude of the stress wave will be maximum. If acoustic relaxation is smaller then the amplitude will be reduced by the ratio of the two characteristic times.

While the above considerations define the response of the thin window in the radial sense of stress wave generation and propagation, the most important consideration in assessing its survivability is the thermoelastic response through the window thickness. As the affected zone is thermalized in the cylindrical volume between the two surfaces, stress waves initiate at each of the surfaces and travel toward the opposite surface. The governing principle is basically a 1-D response similar to the response of a heated 1-D rod with free edges. Figure [] graphically demonstrates the response of the heated zone by capturing the propagation and reflection of elastic waves through the thickness and out of the zone in a series of snap shots. Since energy is moving out of the region in the radial direction, the amplitude of the stress "ringing" through the thickness reduces in time. The impact on the window material, however, could dramatic since a significant number of stress cycles of considerable amplitude can accumulate following a proton pulse.

To demonstrate the severity of the beam-window interaction under such tight focusing, the thermal stress induced in a 10-mil thick stainless steel window by the beam of the required parameters (24 GeV, 16 TP, 0.5 mm sigma and 100 ns pulse length) is shown in Figure []. Specifically, the peak von Mises stresses in the window material, occurring at beam center and mid-thickness, approaches 2500 MPa that is more that twice the yield and ultimate strength of the material. According to this prediction such window will not be able to survive a single pulse let alone multiple pulses. Figure 3 shows the temperature rise in the stainless steel window as a result of a single pulse.

Also depicted in Figure 4 is the "ringing" regime that follows the energy deposition. The peak von Mises stress occurs within the window thickness some time between the initiation of the pulse and the time required for the sound to traverse the thickness for the first time.

Initial estimates of energy deposition in various materials for a 24 GeV proton beam, 16 TP intensity, a beam spot down to 0.5 mm rms and a pulse length of approximately 100 ns painted a very bleak picture for most commonly used materials for beam windows. An additional concern in bringing beam on the AGS A3 line was the ability of existing aluminum windows to survive even though there were expected to see a larger spot (based on the beta function of the beam). Given the severity of the problem, an experimental set-up to study the response of window materials as part of the E951 muon targetry experiment was introduced. Four (4) different window materials were selected for testing in the beam line at AGS. Three of the materials, Inconel-718, Havar and Titanium alloy, showed promise of surviving the proton beam pulses. Their selection was based on material properties and extensive thermal shock predictions. Figure [] shows von Mises stresses generated in a titanium alloy (6 Al – 6 V). Under the required parameters of 24 GeV, 16 TP intensity and 0.5-mm rms spot, the stresses are below yield, thus making it a favorable candidate. Figure 8 presents similar results in a Havar window and shows that under such beam parameters the peak stresses are approaching the yield stress limit.
The fourth material selected is Aluminum (3000-Series). Based on the theoretical predictions, this window material could fail even if 6 TP are delivered on target. Given that at initial stages of E951 6 TP beam is more likely to be delivered and because of the proximity of this window material to the failure condition, experimental data associated with this material and its potential failure, would be very useful in benchmarking failure prediction.

Since the calculations show that the window thickness, in conjunction with the material acoustic velocity and the pulse structure and duration, has a dramatic effect on the peak stresses generated in the material, two (2) thicknesses (1-mm and 6-mm) of the Inconel-718 material were selected for study.

E951 EXPERIMENT

Figure [] depicts the layout of the window test experiment. There are two parallel beam lines within the target enclosure. It all rests on a moving table such that both lines can be exposed to the proton beam. Shown in Figure [] and in one of the lines is a set of double windows with vacuum in the space between the two plates. Each window is made of one of the selected experiment materials. The main goal is to make a qualitative assessment of window failure when it intercepts the proton beam. In other words, any loss of vacuum, which is continuously monitored, in the space between the double windows will indicate mechanical failure.
Along the second beam line a set of single windows instrumented with fiber-optic strain gauges are placed.

Window Strain Measurement Set-Up

The goal of the strain experiment is to capture the radial strain at a specified distance from the beam spot location. While the governing shock stress in determining the safety of the window material is the von Mises stress at the center of the spot and through the material thickness, there is no measurable quantity in that orientation. However, by predicting the radial strain at a safe distance from the beam (minimize the radiation damage on the strain gauges), the whole stress tensor can be estimated. Figure [] depicts the arrangement of four (4) fiber-optic strain gauges that were placed on the front surface of each of the tested windows. The strain gauges are designed around an interferometer by FISO Technologies Inc. The basic active element (cavity) consists of two mirrors facing each other. The acquired signal goes through custom-made filtering and at the end of the process a 500 KHz strain signal is deduced.

The wavelength of the shock front (uncorrupted in nature) and the ability of recording system to capture it is vital to the analysis of strain amplitude and time structure.

Window Strain Measurements – Comparison

During the window tests of the E951 experiment a beam intensity of approximately 2.5 TP was delivered on target. The beam spot size (originally estimated at 1 mm rms sigma radius), and which closely fits an ellipse rather than the circle that was assumed in the theoretical predictions thus far, is currently being re-evaluated using radiation exposure techniques.
While the combination of beam intensity and spot was far from being critical for any of the windows, strain measurements that can be used to verify the predictions have been generated. Shown in Fig. [] is the radial strain in one of the four gauges of the 10-mil aluminum window. The very first part of the record is the noise in the fiber-optic system. The arrival of the proton beam is indicated by the high frequency noise corruption of the signal. The arrival of the compressive wave at the active element of the gauge (approximately at 0.5-inch from center) is shown by the first dip. What follows is the arrival of the tensile wave phase at precisely the time that is expected.
Following the rapid thermalization of the affected material (within the beam spot) two waves are generated at the edge of the heated zone. One travels outward as a compressive wave and arrives at the strain gauge first (dip). The second wave travels toward the center of the beam spot as compressive, reflects at the center by changing sign, and travels outward as a tensile wave.
The remaining cycles represent reflections at the edge of the window and its center.
Figure [] depicts the calculated strains for the same beam parameters but with a “true” round Gaussian profile. The agreement between experiment and theory is very good both in terms of amplitude and time structure.

Figure [] depicts the recorded strain of the same gauge as seen from two bandwidths of the acquisition system. The stain record shows the arrival of the initial shock wave and some reflections of the pulse between the edge and the center of the window disk. Based on the AGS pulse structure, spot size and pulse length, it was assessed that the 100 KHz bandwidth was insufficient to record the stress pulse arrival at the strain gauge location. Indeed, Figure [] clearly demonstrates that no signal was recorded by the acquisition system operating at this bandwidth. Not shown here is the complete record (up to 0.1 sec) which shows that overall response of the window dominated by lower frequencies is captured by both bandwidths.
Figure [] shows the strain measurements at the same gauge in two back-to-back pulses with approximately the same beam intensity. The duplication of the response is a sign of stability in the measurements. However, it should be noted that fiber-optic strain signal is very sensitive to

the beam arrival and the ensuing flux of photons (shown as high frequency bunch at the start of the record and sharp peaks in the transient response). A filtering effort is under way to “clean” the records from the inherent and induced noise.

An additional source of discrepancy is the actual position of the beam with regard to the four gauges. A beam shift toward one of them will alter the strain measurements by inducing higher strains in the closest gauge. To estimate the “true” position of the beam, a cross-correlation process (typical results shown in Figure []) of the gauge signals has been introduced that, in first order, indicates the relative arrival of the signal.
In Figures [] & [] the measured and predicted strains in the 1mm-thick Inconel-718 window are shown. It should be noted that based on the “preliminary” analysis and comparison of experimental to theoretical results, it has been observed that the thicker the window gets the higher the deviation between the two.
In Figure [] the strain recorded in the 6mm-thick window are shown. As expected, the “thickness” effect becomes more prominent in that there is presence of surface waves that have been enabled to form and propagate as well as delayed reflections from the opposite surfaces. Figure [] depicts the theoretical predictions in the same window but with a Gaussian spot at the center of the window. It is evident that general characteristics of the response are predicted quite well. Lastly, in Figure [] the recorded strains from back-to-back pulses are shown for the thin Havar window demonstrating the stability of the acquisition system.

SUMMARY – Beam Window Study

The first phase of the window study of experiment E951 provided the opportunity to test, in addition to targets, window structures that are integral part of any target system and normally experience similar shock conditions. Despite the fact that the pulse intensity that was delivered to the windows was much lower than was hoped for, still important conclusions could be drawn. Specifically, from the overall experimental/theoretical study thus far the following is assessed:

- Predictions are generally in agreement with the results of the actual experiment. This implies that the energy deposition estimated by the neutronic code calculations agrees with the energy left in the material by the beam. It should be noted that in this first phase of data post-processing and comparison, influential material properties such as damping have been accounted for in the theoretical predictions. Subsequent analyses with energy dissipation considerations would help the agreement both in terms of amplitude and pulse shape and dispersion even further. In addition, as noted earlier, a re-evaluation of the actual beam spot is under way which is expected to provide a picture closest to the "real thing". In light of this information, the theoretical model used to calculate the predictions will be modified accordingly and the predicted strains will also be re-evaluated.
- Because of the lower than anticipated intensity and possibly larger beam spot, the failure conditions for the weakest window (aluminum) were never approached.
- The thicker the window, the more difficult to predict amplitudes and structure of the signal due to multiple wave phases and reflection. A key piece of information, however, that was deduced is that higher levels of strain were observed in the thicker window.
- Given the nature of shock waves in the materials, a further increase in the measuring system bandwidth is desirable.

Proposed New Studies

To shed more light in this critical aspect of window material selection and its long-term survival in the proposed muon collider target space, it is important that the experimental studies continue. Specifically, in the next experimental phase the following should be considered:

- Close examination of the exposed windows and especially of the directly affected area for possible micro-structural failure

- Properties of materials having the most promise of long-term survival should be evaluated from the point of view of radiation exposure and degradation

- Expose the windows already tested to proton pulses with higher intensity. Reaching intensities that will cause mechanical failure in the "weakest" window and calibrating the prediction model to that condition, will provide a very important tool to be used in predicting failure for other materials that will be considered in the muon collider/neutrino factory target system.

E951 – Mercury Jet Target Study

BACKGROUND – Issues/Goals

The use of a mercury jet target raises a number of issues that need considerable attention. These issues are associated with the presence of a strong magnetic field, the rapid heating of the mercury by the proton beam and the subsequent dispersion. As the mercury jet enters the field eddy currents are induced in the jet and the Lorentz force on these currents could lead to the distortion of the jet. An important point to be made is the generated magnetic pressure on the mercury jet that, in turn, is expected to damp mechanical perturbations and also add inward radial pressure. Figure [] is an overall schematic of the target space including the solenoid.

Preliminary estimates have shown that the mercury jet will disperse after it interacts with a single proton pulse. What is key, however, is estimating the time scale of jet destruction. For one scenario in particular that requires six (6) 2-ns micro-pulses to be delivered within 2 μs, the time of destruction is important given that one needs to have all six micro-pulses see an intact jet. A consequence of the jet's dispersion is the ejection of droplets that, if ejected at very high velocities, can cause serious damage to the target space.

As noted earlier, a concern related to the survivability of the jet nozzle experiencing a pressure wave traveling upstream potentially exists. For a continuous jet with the interaction zone starting at some distance downstream of the nozzle, pressure waves are expected to travel through the undisturbed jet and reach the nozzle. While pressure amplitudes are expected to attenuate by the time the front reaches the nozzle, the many cycles over the life of the target enclosure could lead to nozzle fatigue failure. Within the scope of E951 experiment, an attempt was made to address the issue and preliminary experimental results are shown.

For all scenarios of beam delivery, the energy deposited in the mercury jet has been calculated using the MARS code. In the co-linear interaction scenario of proton beam and jet, peak energies of approximately 130 Joules/gm have been estimated. This peak energy is observed about 5 cm into the jet from the start of the interaction region. In the latest scheme, however, with the mercury jet tilted by 100 mrad and the proton beam by 67 mrad the peak energy deposition is approximately 49 Joules/g and it occurs about 25 cm downstream from the start of the interaction region. Table below, lists some of the physical properties of mercury that were used in the various estimations

Physical Properties of Mercury

Density: $\rho = 13.5$ x g/cm^3
Compressibility: $\kappa = 0.45 \times 10^{-10}$ m^2/N
Volumetric Thermal expansion: $\alpha_v = 18.1 \times 10^{-5}$ K^{-1}
Specific Heat: $c_v = 140$ J/Kg K
Velocity of Sound = 1300 m/s
Critical Point Temperature: $T_{cr} = 1593^o$ C
Critical Point Pressure: $P_{cr} = 185$ MPa

Predictions of Pressure Wave Generation

Estimates of pressure wave generation and propagation were made using the capabilities of the ANSYS [] code, the equation of state for mercury provided by the SESAME [ ] library and the energy deposition calculations of the MARS [] code.
The outward velocity of mercury was estimated prior to the experiment by considering the volumetric change of an infinitesimal volume of mercury d**V** experiencing a change of temperature **ΔT** and pressure **ΔP** that result from the fast proton beam. Relations below lead to the estimate the outward velocity **U**r as function of sound velocity **c** of material in the jet

$$K.E. = \frac{1}{2} \rho \, dV \, \mathbf{U}_r^2 = \Delta P \, \delta(dV)$$
$$\Delta P \approx \alpha_v \, \Delta T / k$$
$$\alpha_v = (\partial V/\partial T)_P$$
$$\delta(dV) = \alpha_v \, dV \, \Delta T$$
$$\mathbf{U}_r^2/\mathbf{c}^2 = 2 \, \alpha_v^2 \, \Delta T^2$$
$$\mathbf{U}_r = \sqrt{2} \, [\alpha_v \, \Delta T] \, \mathbf{c}$$

It is apparent from the above relations that the movement of bulk material as a result of thermal gradients is just a percentage of the velocity of sound that generated pressure waves travel. So, while the pressure field is experiencing the passage of the generated pressure waves (superimposed onto the thermodynamic pressure) the exchange of heat, as well as bulk material movement, is governed by a much slower processes. The verification of this significant relation was one of the goals of E951 in proving that the projectile velocity is much smaller than the velocity of sound and thus the potential for damage to the surrounding target space greatly reduced.

Pressure Wave-Jet Nozzle Interaction

While it is anticipated that the interaction zone of the jet may be broken up several microseconds after the proton beam arrival, the upstream section of the jet is still intact and will allow for the propagation of pressure waves toward the nozzle. At issue is the amplitude of the pressure wave front when it arrives at the nozzle and impacts on the walls. The estimated time of the arrival of the front is approximately 100 μs based on a 15-cm distance between the beginning of the interaction zone and the nozzle.
Figures []-[] depict the schematic of the beam/jet interaction arrangement and snapshots of the pressure profile along the mercury jet in a cut through the long axis. While pressures start out as positive, a result of the rapid energy deposition and the inability of the Hg to accommodate thermal expansions, they quickly turn negative at the center of the interaction zone. This is the result of the wave reflections and sign reversal from the free surface of the jet. While part of the interaction region may be destroyed, the pressure front will advance toward the nozzle through the undisturbed jet.
As expected, the pressure wave will attenuate as it travels through the undisturbed part of the jet. Figure [] depict predictions of the pressure wave fluctuation and amplitude in the nozzle vicinity. While much lower than the initial pressures may make it to the nozzle, a large number of such impacts will accumulate during the operation of the machine that may potentially lead to fatigue failure. The latter becomes more of an issue considering the high irradiation doses the structural materials will receive because of their proximity to the target.

E951 Set-Up

A schematic of the mercury jet target chamber is shown in Figure [ ]. Also shown is the location of the array of fiberoptic strain gauges that were mounded to record strain waves arriving at the nozzle.
To record the mercury jet dispersal two camera systems were used with recording capabilities: 1) at rate of 4 kHz with shutter settings for each frame set to 25 μs and 2) 16 frames at speeds up to 1 MHz and exposure time of 150 ns per frame.

Mercury Jet Experimental Results

In the E951 experiment the mercury jet trajectory overlapped with the proton beam for 19 cm. The diameter of the jet at the interaction region ranged between 0.7 cm and 1.7 cm. Achieved proton beam intensities ranged between 0.5-4.0 TP and spot sizes were of the order of 1.6 mm in x-dir and 0.9 mm in y-dir rms sigma radius.

Dispersal of the mercury was observed by viewing prominences as they left the bulk of the mercury jet. Figure [] depicts a series of frames recorded during the experiment showing the evolution of the jet dispersion. Important parameter is the time scale in which events occur. Specifically, the appearance of material emanating from the free jet surface occurs at 0.75 ms. However, a fast camera with capabilities of 1 frame/μs revealed that the initiation of jet dispersion occurred at a time of $\sim 40\mu s$.
Such delay time from the onset of proton beam/jet interaction is well in line with the estimates made on the basis of volumetric expansion within the jet. Further, measured velocities of 5 to 50 m/s also tend to agree with velocities estimated from $\mathbf{U}_r = \sqrt{2}\ [\alpha_v\ \Delta T]\ \mathbf{c}$ in which, as observed, the bulk velocity of ejected material is proportional to the temperature rise, which in turn is directly proportional to the intensity of the impinging protons.

Jet Nozzle Results

Four fiber optic strain gauges were placed at selected locations in the mercury line (shown in Figure [ ]). Specifically, a gauge was placed on the line that supplies mercury to the jet just upstream of the nozzle. This gauge, placed along the pipe as shown, is expected to register any activity associated with a wave returning from the jet. The geometry and size of the supply pipe did not allow for the gauge to be placed with hoop orientation. Potential strains along the hoop direction in the pipe wall are expected to be much higher than the axial and thus more easily detectable. Strains in the supply pipe will be the direct result of the pressure in the contained mercury.

In addition to the nozzle gauge, one was placed at the valve outlet (furthest location in the supply pipe upstream of the nozzle) and two were installed on the nozzle mounting plate on either side of the nozzle. Strains for beam intensities ranging between 0 TP and 4 TP (0 TP being the case of jet activity alone) were recorded. While the beam intensity was much lower than anticipated, thus keeping the potential strain aggravation due to shock quite low, still some clear evidence of activity was recorded. Shown in Figure [ ] is the strain recorded by the nozzle gauge for back-to-back pulses with similar intensities (3.75 TP). The stability in the measuring system is shown to be excellent. The front part of the record is the noise from the flowing Hg in the supply pipe. The spike indicates the arrival of the proton beam and it is the effect of photons on the gauges. Beyond that there is evidence of activity induced by the proton beam interacting with the jet.

Figure [ ] quantifies the effect by comparing the strain induced by the jet alone with that of the interaction with the proton beam.

Further examination of these results is needed to make firm assessments. The difficulty stems from the fact that the proton beam intensity received during the first experimental phase was much too low to both qualify and quantify the effects at the nozzle location and draw conclusions about its survival in the actual target setting.

E951 – Graphite & Carbon-Carbon Target Study

BACKGROUND – Issues/Goals

The need for an alternative target option using a low-Z material with good yield prompted the studies on graphite as one of the candidate materials.
The experimental effort on graphite and carbon-carbon composite as target material for potential use in a high power source had as primary goals the following:

Attempt to establish limits of material integrity of a particular form of graphite (ATJ grade) as it intercepts the high-energy undiluted proton beam. Of interest in the experimental study was to observe the behavior of the material as it approaches its mechanical strength limits that were anticipated in E951

Assess the response of the carbon-carbon composite target and verify that its promise of very low thermal expansion coefficient holds true. Verification of the latter will imply that the generated stress conditions within the composite are also very small and thus it can maintain its integrity as a solid target material

Enable the numerical verification of the response of the solid targets on the basis of recorded strain waves. This part of the effort is extremely useful in that it provides two crucial pieces of information, namely, the calibration of the theoretical/computational model so it can be of use in further studies of solid targets for their susceptibility to failure, and that the comparison of predicted with recorded strain data can provide an additional verification of the estimated energy deposition in the targets

E951 Set-Up

Figures [] and [] represent the schematic arrangement and the actual set-up of the ATJ graphite and carbon-carbon composite targets. Along the axis of one of the beam lines, two 12-inch, 1-cm diameter ATJ rods were placed, while on the other, the two 5-inch, 1-cm diameter carbon-carbon composite rods were set. All four target rods were instrumented with fiberoptic strain gauges that were to record axial strain. Specifically, the front ATJ rod had 8 gauges (4 in the middle separated by a quadrant, two near the front at 180 degrees apart and two near the back side also at 180 degrees apart. The rear ATJ rod had 7 gauges connected to it (four, two and one respectively). On the carbon-carbon side the front rod was instrumented with 3 gauges and the rear with just two. Special fixtures secured the rods in position with minimal interference to their dynamic response.

Experimental Results – Discussion

Two different sets of experimental measurements provided two beam spot sizes and two intensities. Specifically, one set of data recorded are for a larger spot accompanied by a higher beam intensity, while the other set provided data for a tighter spot but less protons in the pulse.

These combinations provided an excellent matrix for purposes of verification of both the numerical predictions in terms of strain and in addition evidence of how well the energy deposition, predicted by different hadronic codes, is estimated. Specifically, energy deposition/distribution in the two ATJ rods were estimated using the codes MARS, GEANT and MCNPX. Figure [ ] depicts the mars calculations for the two different beam spots. Based on comparisons with the theoretically predicted strains, it was assessed that the codes MARS and GEANT generate better correlation of the energy deposition/distribution at these proton energies (24 GeV).

Figures [ ] through [ ] depict recorded strain data along the two ATJ graphite rods. Shown is the out-of-phase strain response between gauges that are 180 degrees apart, a confirmation of the unimpeded response of the rod due to the pin support arrangement. Of importance is the confirmation of all modes of dynamic response of the target rod. Specifically, the axial mode, the bending and the radial mode are all confirmed with the analytical results. In summary,

- Experimental strains in the middle of the ATJ graphite rod show a bending frequency mode somewhere between 380-390 Hz

- Predictions of the detailed model that implemented the supporting/holding fixtures of the target as close to the real setting as possible, predicts a bending frequency of 395 Hz

- The axial "ringing" of the target in the experimental data has a period of 260-265 microseconds.
- The fundamental axial period T=2L/c (where L is target rod length and c is speed of sound) is approximately 261 microseconds

- The radial "ringing" (which from theory is calculated at 150 KHz or 6.625 microsec period), is visible only in the strain record filtered by the 500 KHz acquisition and is in agreement with the experimental data

Figure [] depicts the same strain record for the direct analog signal of 100 KHz and the specially filtered 500 KHz signal. Except for the "radial" ringing that can only be captured well by the 500 KHz-bandwidth, the rest of the record is coincident due to the fact that the involved frequencies are within even the analog bandwidth. Clearly, the need for a system with higher bandwidth capacity is not as serious as in the beam window experimental study.

Figures [ ] through [] represent experimental and prediction data for both ATJ graphite target rods and for the different beam spot/intensity combinations. The need to maintain a very small element size in the finite element model such that the smallest wavelength strain wave induced by the beam can propagate through the rod, combined with the very small step size, allowed the completion of only a few significant cycles. It is apparent, however, that both the amplitude of the strain as well as the structure of the response are predicted quite well for both beam settings.

As expected with the carbon-carbon composite, and shown in Fgures [ ] and [ ], the strain levels that are seen by the rod are much lower than those seen in the ATJ rods. However, they are not totally insignificant (as claimed by various manufactures but for slow heating) and there appears to be a “dynamic structure” in the response shown in Figure [].

For both solid target types, however, the beam intensity achieved during the experiment did not reach levels that would challenge the structural integrity of the targets, something that the experiment would have liked to see.

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