

Design and Testing of a Novel Pink Beam Stop for the Dynamic Compression Sector Beamline

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Abstract - The Dynamic Compression Sector (DCS) beamline at the Advanced Photon Source (APS) will be capable of providing high power, highly focused pink beam to the user. This presents the significant engineering challenge of stopping continuous beam in all missteering cases in order to protect the downstream lead shielding as part of the personnel protection system (PSS). Under the worst-case condition, the device must stop pink beam in an area of 229 mm x 305 mm with a total power of 169 W and a peak heat flux of 105 kW/mm². Although the total power is relatively low, the power density is high. In this case, the use of a conventional grazing-incidence Glidcop[®] beam stop is impractical without exceeding the maximum temperature requirement of 300°C, or increasing the length of the device to several meters. A simple, compact design is presented that utilizes an enclosed pressurized gas volume sealed with an O-ring and a normal-incidence 6.35 mm thick sacrificial copper beam-strike plate. Redundant pressure sensors detect beam presence by a slight rise in gas pressure, and a breach in the beam-strike plate is detected by a drop in gas pressure. An extensive testing program was conducted on a pink beam stop prototype using a 400 W laser with a focusing head to simulate the worst-case DCS beam condition. The results of the experiments show that under the conditions tested, the penetration depth of the beam is much less than the thickness of the 6.35 mm beam-strike plate. It was also determined that if a breach in the beam-strike plate were to occur, it could be positively identified, triggering the closing of the front end photon shutter. The device was reviewed and accepted by the APS beamline safety design review steering committee (BSDRSC), and four pink beam stop assemblies have been installed at the DCS beamline.

Keywords: DCS; dynamic compression science; pink beam stop; high heat flux; laser testing

1. Introduction

“The National Nuclear Security Administration (NNSA) of the Department of Energy (DOE) is sponsoring the development of the Dynamic Compression Sector (DCS), a first-of-a-kind user facility dedicated to dynamic compression science. Washington State University (WSU) is leading the effort to develop and build the DCS infrastructure and instrumentation (at Sector 35 on the APS experimental hall floor), in collaboration with the APS; DOE/NNSA National Laboratories (Los Alamos, Lawrence Livermore, and Sandia); Department of Defense Laboratories, including the Army Research Laboratory and Naval Research Laboratory; and academic institutions. The DCS represents an exciting and visionary capability in support of the NNSA’s scientific mission, and offers an opportunity to pursue fundamental science that has not been possible at any synchrotron radiation facility to date (Web-1).”

The DCS beamline contains focusing optics that can focus the APS beam down to very small spot sizes, delivering pink beam with extremely high peak heat flux levels onto the sample targets. Ray tracings for each of the optics combinations in the pink beam operating mode were conducted to determine the worst-case pink beam misteering conditions, shown in Table 1. Furthermore, based upon

ray tracing, a 229 mm H x 305 V beam stop area is required in order to protect against all possible beam missteering scenarios. The pink beam stops, located in air at the downstream end of each of four DCS hutches, must be able to stop the beam under the worst-case beam condition, and the pink beam stops must satisfy all PSS requirements to protect the downstream lead shielding. The most severe beam condition occurs in the D hutch where it is possible to deposit a beam, carrying over 169 W of total power in a beam spot size of 61.1 μm H x 26.3 μm V, with peak heat flux in excess of 105 kW/mm².

Table. 1. Worst-case DCS conditions

Slits	Percent transm.	Power (W)	H Im. size (μm)	V Im. size (μm)	W/mm ²	W/mm	Im.loc. (m) / station
B	66.41%	169.3	61.1	26.3	105367.9	968.5	70.95 D
B	66.41%	169.3	183.8	69.4	13281.6	334.4	79.88 E
C	100.00%	255.0	250.7	39.3	25899.4	439.7	70.95 D
C	100.00%	255.0	753.8	103.6	3264.6	148.7	79.88 E
B	31.81%	81.1	57.7	31.8	44194.7	453.0	79.88 E
C	100.00%	255.0	158.2	35.5	45429.2	658.2	79.88 E
B pink stop data, for comparison							
		338.8	232.1	18.5	78903.6	676.0	48.8 B

It is impractical, due to space constraints and cost, to design the pink beam stop according to conventional APS design criteria limits where the peak surface temperature cannot exceed 300°C. To meet this design criteria limit, the beam stop would require a grazing incidence angle less than 0.5°, and the overall length of the beam stop would be in excess of 5 m. Consequently, a novel new pink beam stop design was developed and tested in order to meet this engineering challenge.

Unlike conventional beam stop designs, the beam is intercepted at normal incidence. The copper beam-strike plate is thick enough that the beam cannot penetrate through the plate under worst-case beam conditions. Sealed behind the beam-strike plate, a small volume of pressurized gas increases in pressure upon heat input from the beam, and therefore beam presence can be rapidly detected. In the event the beam strike plate is breached by the beam, a loss in system pressure will alert the PSS to close the front end photon shutter. In addition, the rate of pressure increase can be directly correlated to the total power being absorbed into the pink beam stop assembly, and therefore the device can be used for calorimetry.

In order to test and verify the performance of the pink beam stop design, a fiber optic laser with a focusing weld head was used to match the total power and peak heat flux of the worst-case DCS beam condition. Under this condition, tests were conducted to determine the pressure rise response as a function of beam size and location on the beam-strike plate. Similar tests were conducted to determine the maximum penetration depth of the applied beam into the copper beam-strike plate. The system pressure rise response was measured as a function of applied total power and, based on the results, beam detection time was established. It was also demonstrated that the pink beam stop can be used as an accurate calorimeter to measure absorbed beam power.

3. Mechanical Design of the DCS Pink Beam Stop

The mechanical design of the DCS pink beam stop is rather simple. A 31.75 mm thick stainless steel plate is used for the assembly body. A cavity with a depth of 12.95 mm is milled into the body and a 6.35 mm thick copper plate is press-fit into the bottom of the cavity, leaving a 6.6 mm deep pocket for the gas volume space behind the copper beam-strike plate. The internal press-fit copper plate is used as a redundant beam-strike plate in the event that the actual beam-strike plate is breached by the beam. A groove is milled into the face of the assembly body that accepts a Buna-N O-ring used to seal the 6.35 mm thick beam-strike plate to assembly body. The O-ring contact area on the back of the beam-strike plate is polished to a surface finish better than 0.4- μm , and a stainless steel clamping ring and 22 bolts are

used to apply uniform clamping force to seal the beam strike plate to the assembly body. A CAD model of the pink beam stop assembly is shown in Figure 1.

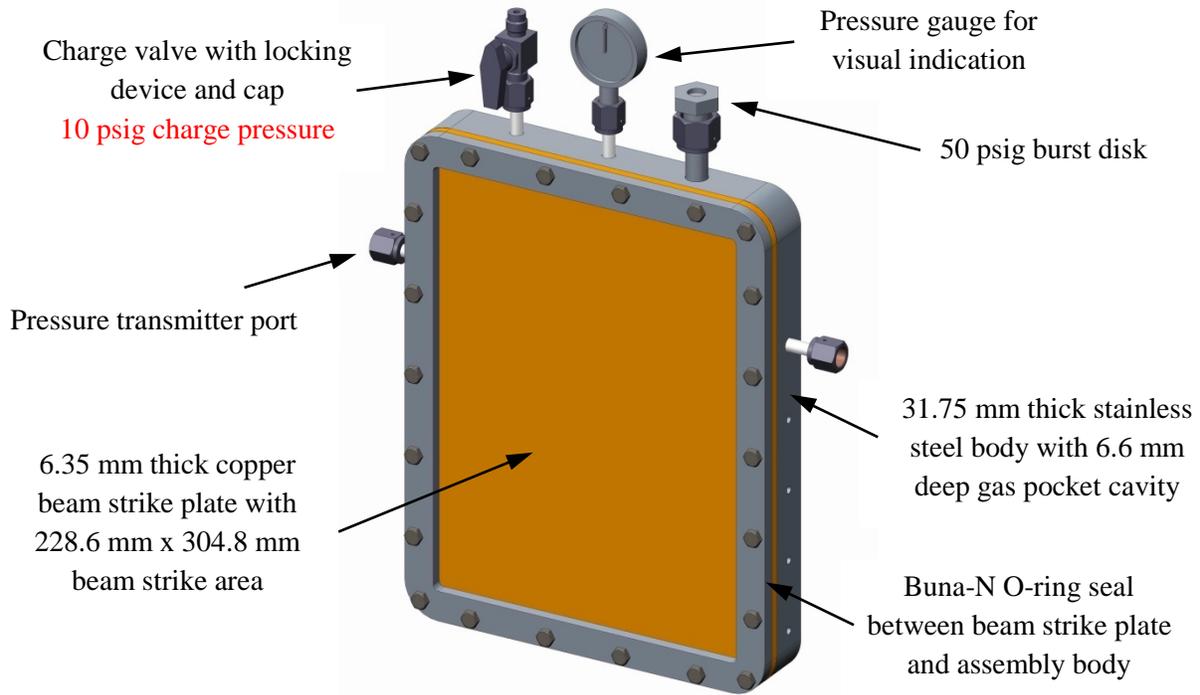


Fig. 1. CAD model of the DCS pink beam stop assembly

On the top edge of the assembly body, a charge valve with locking device, a pressure gauge for visual pressure indication, and a 50 psig (3.447 bar) burst disk, used to protect the pink beam stop from over-pressurization, are installed. On the side edge of the assembly body, ports are provided to connect the pink beam stop assembly to the pressure transmitters used to monitor the pressure in the gas volume space behind the beam-strike plate. These components are connected to the assembly body using welded Swagelok® VCR all-metal face-seal glands, and where possible, Swagelok® VCR all-metal face-seal fittings are used throughout the installation in order to minimize potential leakage from the gas volume space.

Three model EJA110A Yokogawa pressure transmitters are used in parallel to monitor the pink beam stop system pressure. Two are used for independent PSS monitoring, and one is used for the beamline equipment protection system (BLEPS). The pressure transmitters are housed in an electronics enclosure in close proximity to each pink beam stop. Each pink beam stop is connected to its respective electronics enclosure via a flexible all-metal stainless steel hose. Added system volume is minimized by using 3.18 mm O.D. heavy-wall stainless steel capillary tubing for all interconnections.

Each pink beam stop assembly is charged, using nitrogen gas or air, to a nominal system pressure of 10 psig (0.6895 bar), and both high and low-pressure set point limits are monitored.

Reaching the low-pressure set point limit of 8.75 psig (0.603 bar) alerts the PSS to close the front end photon shutter to stop the beam in the event that the beam-strike plate has been breached. Extended beam exposure on the pink beam stop will cause the assembly to heat up; consequently, reaching the high-pressure set point limit of 11.5 psig (0.793 bar) alerts the BLEPS system to close the beamline photon shutter to stop the beam so that the assembly will not exceed a safe-touch temperature of 50°C.

2. Experimental Program for the DCS Pink Beam Stop

2. 1. Experimental Set-Up

A series of tests were conducted on a prototype DCS pink beam stop using a fiber optic laser system in order to replicate the worst-case DCS beam condition. The Class IV fiber optic laser system, manufactured by SPI Lasers UK Limited, operates at a central emission wavelength of 1070 nm and delivers near perfect Gaussian beam output, with a beam quality factor M^2 less than 1.10. It can be operated in modulated or continuous wave (CW) modes with a maximum rated power output of 400 W. A 90° beam bender and a FiberMini weld head with 100 mm focusing optics were used to deliver focused beam at normal incidence on the DCS pink beam stop. The pink beam stop was mounted vertically inside of the laser testing chamber, similar to how it will be installed on the DCS beamline. A photograph of the inside of the laser testing chamber is provided in Figure 2. The fiber optic laser beam enters the test testing chamber from the top and passes through the 90° beam bender and then through the weld head before being delivered onto the copper beam-strike plate.

The pink beam stop was instrumented with two thermocouples, one on the beam-strike plate and one on the back of the assembly, in order to monitor surface temperatures during testing. A Yokogawa pressure transmitter, ranged from 8.0 to 12.0 psi in order to provide maximum 4-20 mA current signal output resolution, was used to monitor the system pressure during testing. System pressure and thermocouple data were logged using a customized LabVIEW data acquisition program. All tests were conducted in air inside of the laser testing chamber.

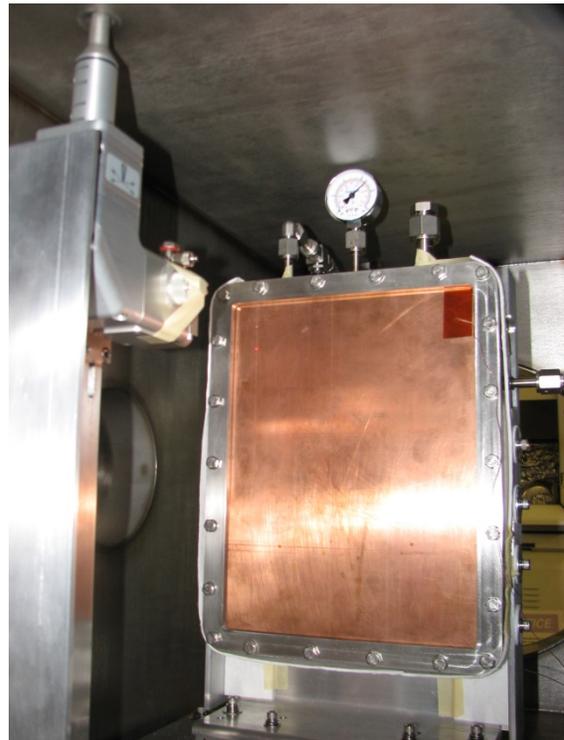


Fig. 2. Pink beam stop inside of the laser testing chamber

2. 2. Calibrations for the Testing System

Using a focused laser, a 64 μm diameter beam spot size was required in order to match the total power and peak heat flux for the worst-case DCS beam condition. The measured beam spot size versus focal distance was calibrated through a series of burn tests using short laser pulses on burn paper. The diameter of the holes in the burn paper samples were measured using an Olympus BX51 materials research microscope system.

The total power output from the laser system was verified through a series of tests using a model #30 digital power probe from Optical Engineering, Inc. Then a copper calorimetry block was used to measure the laser power coupling into bare copper as a function of applied peak heat flux, and unexpected results were obtained. Figure 3 provides the results from the calorimetry tests. As would be expected, the laser

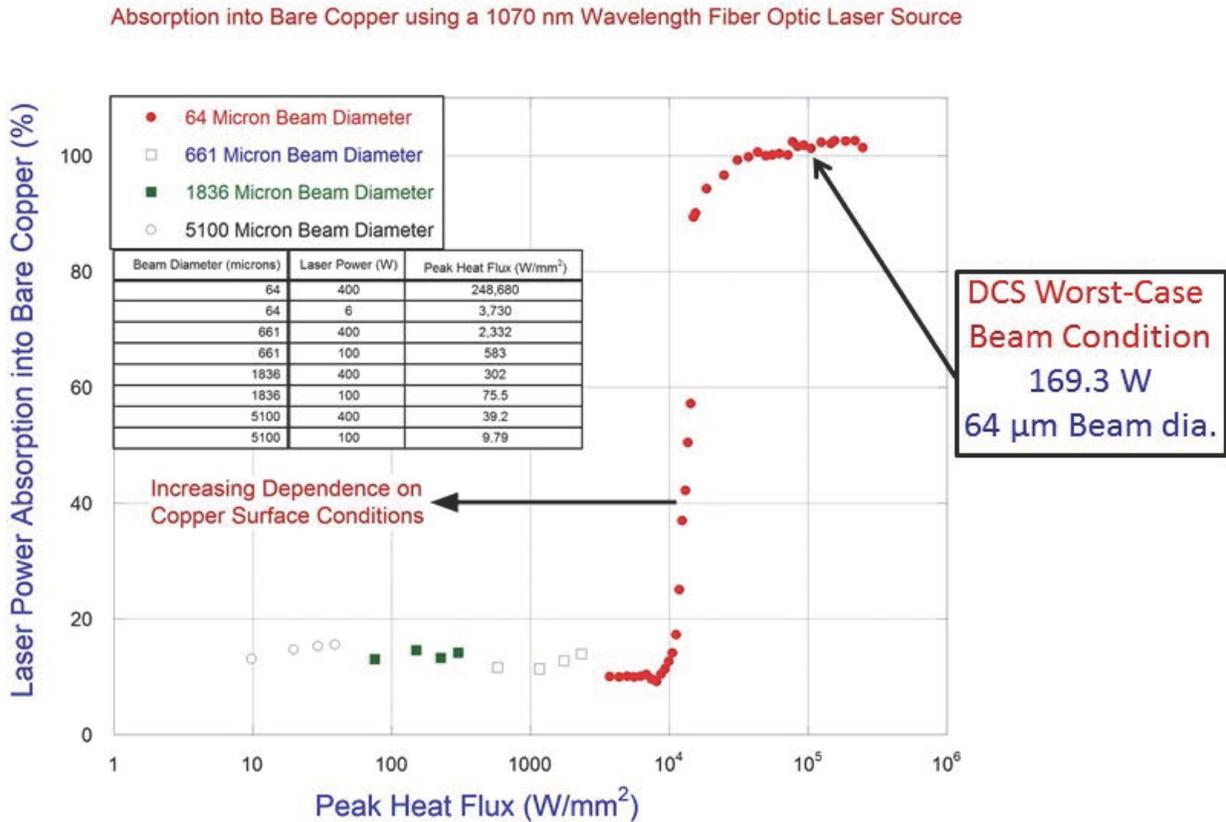


Fig. 3 Laser power absorption into bare copper

power coupling is on the order of 15% at low powers due to the low emissivity of copper. However, the absorption dramatically increases between 10,000 and 20,000 W/mm² peak heat flux, and above 25,000 W/mm² peak heat flux, the absorption is nearly 100%. It is speculated that above a certain threshold, boiling occurs on the copper beam-strike surface. Consequently, some copper is vaporized and ejected off the surface. A divot begins to form with a concave upwards liquid copper meniscus, and this acts as a mirror that reflects the laser energy into the side walls where it is absorbed. Consequently, very little energy can escape from the hole, and therefore near perfect coupling is achieved.

2. 3. Experimental Results

It is well known that for a given material subjected to a given set of beam conditions, including total power and energy distribution, that only finite beam penetration depth is achievable (Andrews et al., 1976; Weck et al., 2008). In order to determine the maximum penetration depth under the worst-case DCS beam condition, several pockets were milled into the pink beam stop beam-strike plate. This provided sites to perform tests with wall thicknesses varying from 1.0 mm to 3.5 mm in 0.5 mm increments. The worst-case DCS beam condition

Wall Thickness Dependence on Maximum Penetration Depth

For the Worst-Case DCS Off-Normal Beam Condition

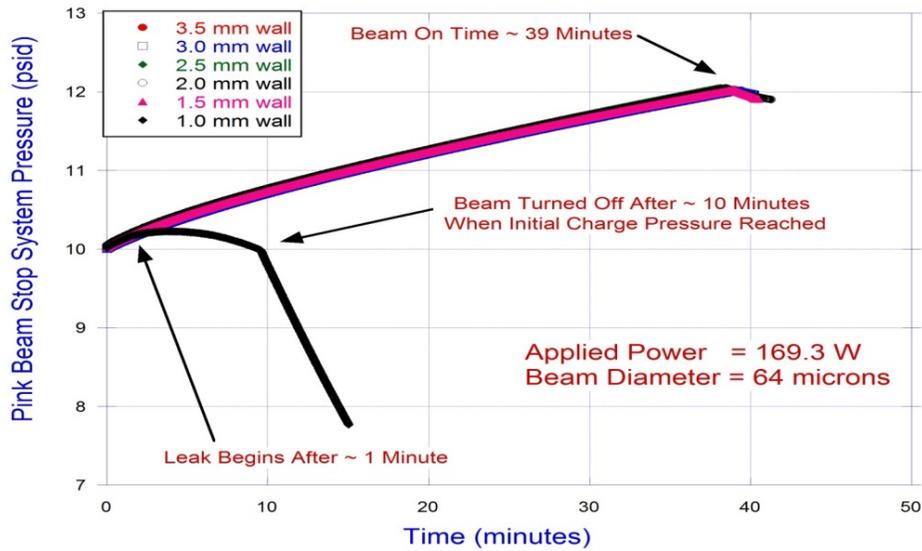


Fig. 3. Maximum penetration depth under the worst-case DCS beam condition

was applied to each site to see if the beam would penetrate through the wall. In each case where the beam did not penetrate through the beam-strike plate, the beam was applied continuously for 39 minutes, the time required for the system pressure to reach 12.0 psi (0.827 bar). For the case where the wall was only 1.0 mm thick, the beam did penetrate through the beam-strike plate after approximately 1 minute of beam exposure as shown in Figure 4. After testing, the beam-strike plate was sectioned and metallurgical analysis was performed. It was determined that the maximum penetration depth under the worst-case DCS beam condition is 1.1 mm as shown in Figure 5. Therefore, the 6.35 mm thick copper beam-strike plate provides greater than a 5X factor of safety.

Tests were conducted to determine the system pressure rise response with varying beam diameter sizes and beam exposure locations on the beam-strike plate. Focused beam with 64 μm diameter beam spot size was applied near a corner of the beam-strike plate. Then the weld head was removed and the raw collimated 5100 μm diameter beam spot size output from the fiber optic laser was applied to the same beam-strike location. For tests with the raw collimated beam, nanoparticle carbon was painted onto the beam strike surface using an air brush in order to couple the beam energy into the copper. A third test was performed where beam was placed in the center of the beam-strike plate



Fig. 5. Metallurgical section of laser drilled hole in copper

using the raw collimated 5100 μm diameter beam spot size. As can be seen in Figure 6, the system pressure rise response is insensitive to beam spot size, and is nearly independent of beam location on the beam-strike plate. Therefore, the system pressure rise response depends mostly on total applied power regardless of beam size or where the beam intercepts the beam-strike plate.

The resolution of the pressure signal from the pressure transmitter determines the minimum beam detection time, and the minimum beam detection time decreases with increasing applied power. Tests were conducted on the pink beam stop to determine the minimum beam detection time as a function of applied power. It was determined that for the worst-case DCS beam condition, beam presence can be detected in under 4 seconds. These tests were also used to determine the system pressure rise response for short beam exposure times. The results were used to quantify the pressure rise slope as a function of total applied power. Figure 7 shows the system pressure rise response as a function of beam exposure time. It can be seen that the system pressure rise response is rapid and very linear, regardless of the applied beam power. In each case shown here, only a few seconds are required to quantify the linear pressure rise slope response.

Plotting and curve fitting the absorbed beam power as a function of system pressure rise slope yields the system constant required to use the pink beam stop as an accurate calorimeter. Using the slopes from Figure 7, Figure 8 shows that the absorbed beam power as a function of system pressure rise slope is very linear. Consequently, a simple linear relationship can be derived that relates the absorbed power to the system pressure rise slope. For the prototype pink beam stop,

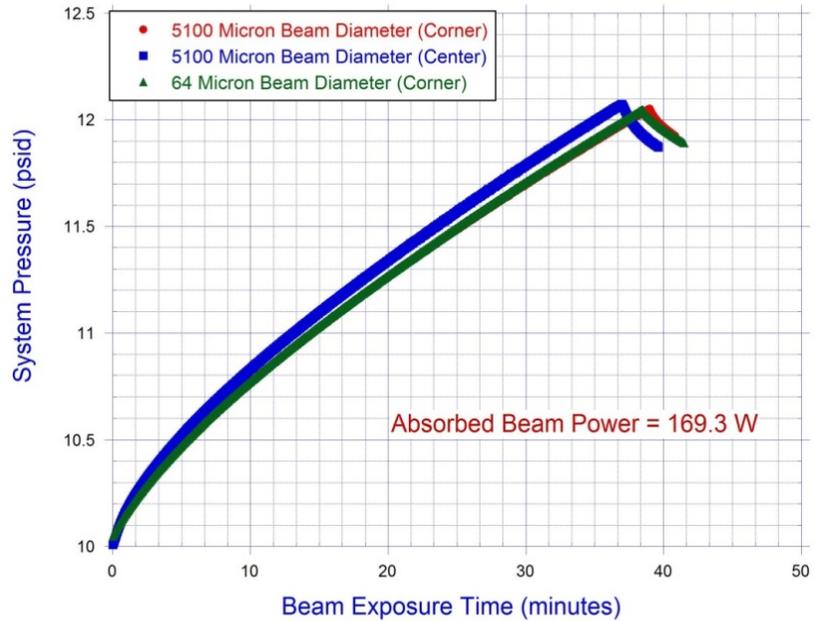


Fig. 6. System pressure rise response with varying beam diameter sizes and beam exposure locations

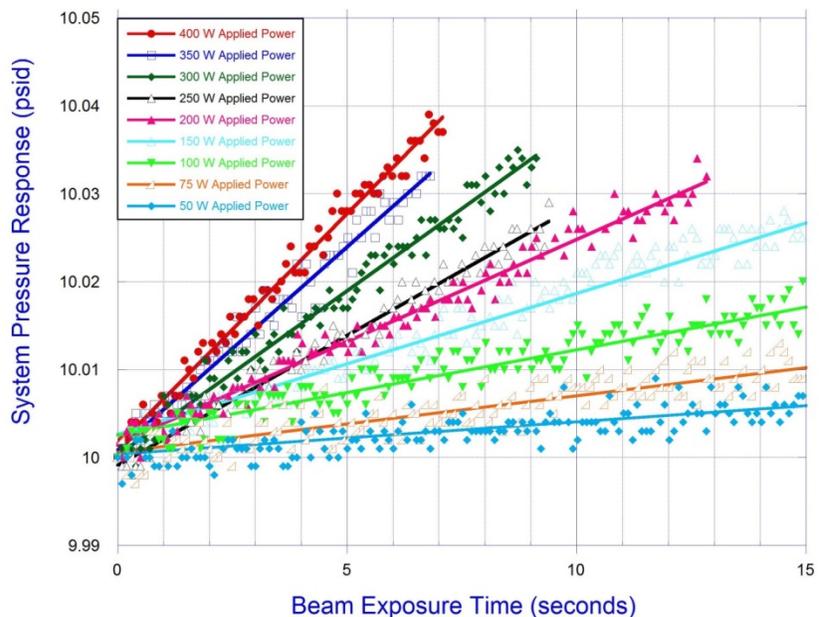


Fig. 7. System pressure rise response for short beam exposure times

the system constant is 70,520 Joules/psig. The system constant for a given pink beam stop assembly will depend on the thermal mass of the system and on the ratio of the “hot” volume, the gas volume inside of the pink beam stop assembly, to the “cold” volume, the volume of gas in the transmitters and interconnections. A unique system constant can be determined for any given assembly. This calorimetry method measures retained power, not absorbed power; however, absorbed power is essentially equal to retained power in the first few minutes of beam exposure because free convection has not had sufficient time to significantly influence the pressure rise slope.

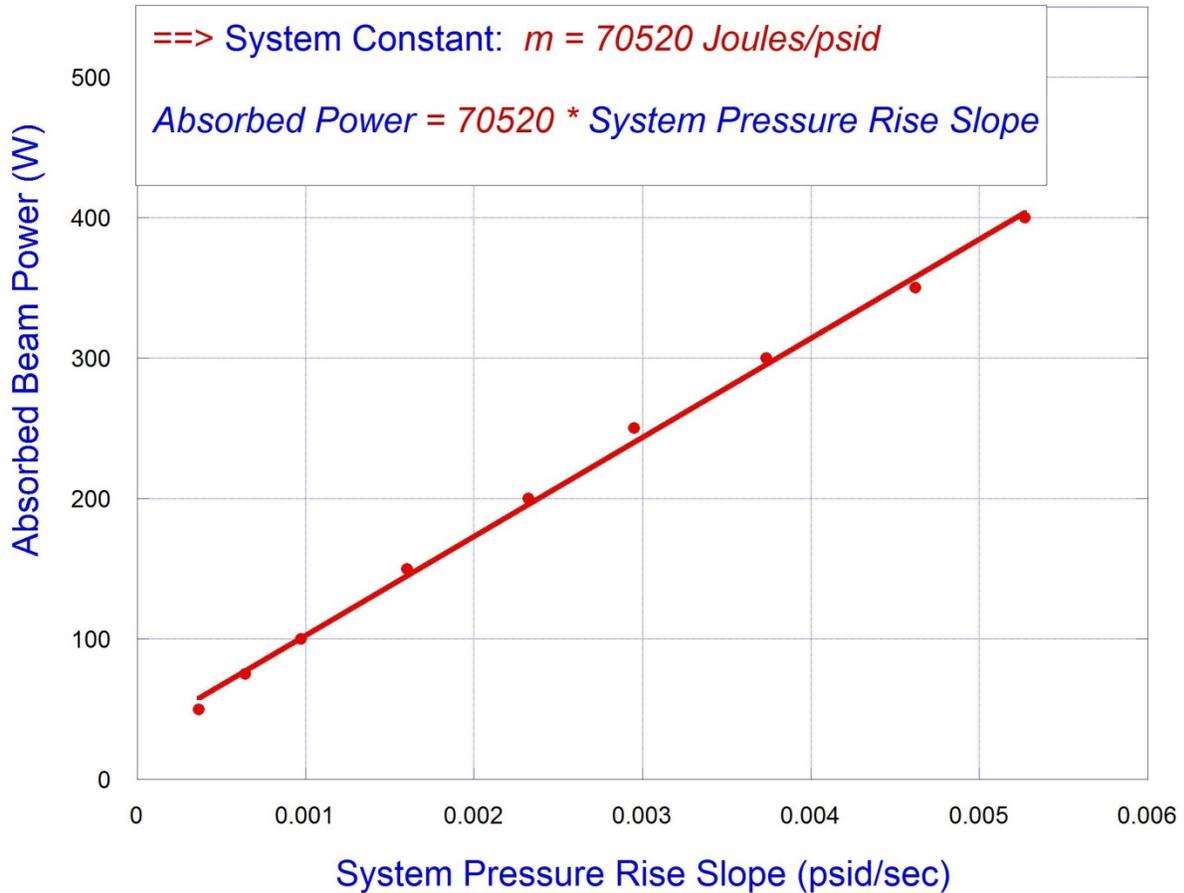


Fig. 8. Determination of the system constant for the pink beam stop

4. Conclusion

A novel pink beam stop design for the DCS beamline at the APS has been developed, and the device was tested using a fiber optic laser system in order to verify operational performance. It was demonstrated that the maximum penetration depth of the beam under the worst-case DCS beam condition is much less than the thickness of the beam-strike plate. However, in the event that the beam-strike plate is breached by the beam, it was shown that the condition can be positively identified by a drop in system pressure that will alert PSS to close the front end photon shutter. It was also demonstrated that the pink beam stop can be used to rapidly detect beam presence, and that the device can be calibrated and used as

an accurate calorimeter to measure beam power. The pink beam stop design provides a simple and inexpensive solution to a very challenging engineering problem. Since the beam is intercepted at normal incidence, pink beam stop assemblies consume a minimal amount of floor space in the DCS beamline end stations. The pink beam stop design was reviewed and accepted by the APS BSDRSC. Four pink beam stop assemblies have been fabricated and installed in the DCS beamline end stations, and the devices have been commissioned and are ready for operational use. A picture of the pink beam stop assembly installed in the C beam end station is provided in Figure 9.

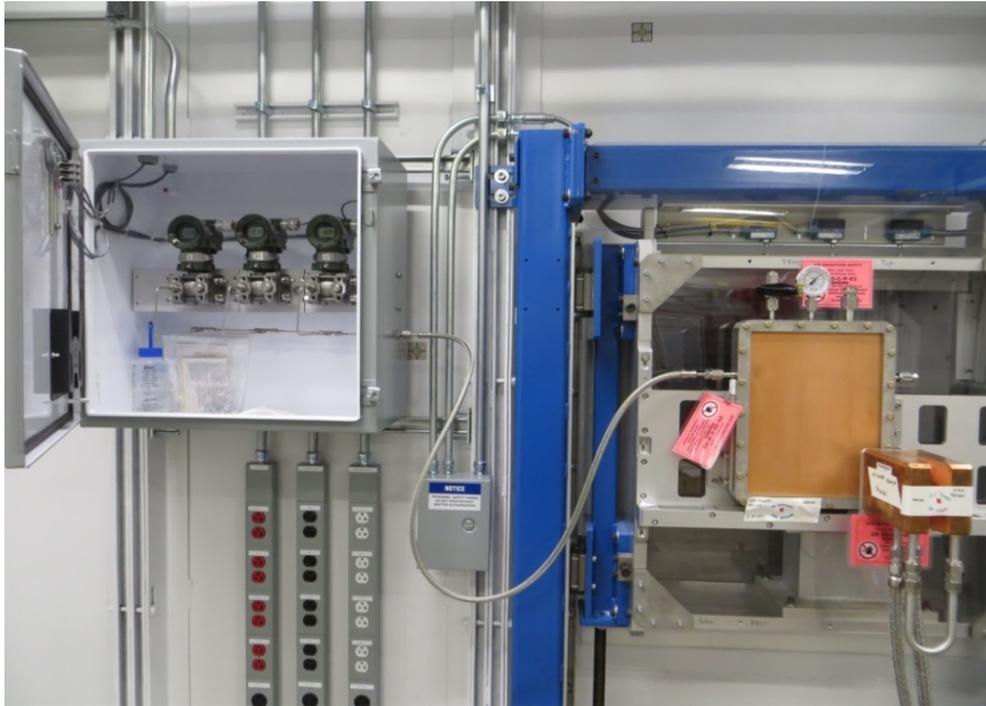


Fig. 9. DCS pink beam stop assembly installed in the C beam end station

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