FERMILAB-CONF-15-163-AD

EXAMINATION OF BERYLLIUM UNDER INTENSE HIGH ENERGY PROTON BEAM AT CERN'S HIRADMAT FACILITY[*]

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Abstract

Beryllium is extensively used in various accelerator beam lines and target facilities as material for beam windows, and to a lesser extent, as secondary particle production targets. With increasing beam intensities of future accelerator facilities, it is critical to understand the response of beryllium under extreme conditions to avoid compromising particle production efficiency by limiting beam parameters. As a result, the planned experiment at CERN's HiRadMat facility will take advantage of the test facility's tunable high intensity proton beam to probe and investigate the damage mechanisms of several grades of beryllium. The test matrix will consist of multiple arrays of thin discs of varying thicknesses as well as cylinders, each exposed to increasing beam intensities. Online instrumentations will acquire real time temperature, strain, and vibration data of the cylinders, while Post-Irradiation-Examination (PIE) of the discs will exploit advanced microstructural characterization and imaging techniques to analyze grain structures, crack morphology and surface evolution. Details on the experimental design, online measurements and planned PIE efforts are described in this paper.

INTRODUCTION

Beryllium is currently widely used as the material of choice for beam windows, as well as secondary particle production targets, in many accelerator beam lines and target facilities. With the increasing beam intensities of future accelerators [1, 2], it is essential to evaluate the performance of beryllium under even more extreme conditions to successfully design and reliably operate windows and targets, without compromising particle production efficiency by limiting beam parameters.

An upcoming experiment at CERN's HiRadMat facility [3] will test beryllium specimens exposed to intense proton beams. The test facility is able to deliver high intensity proton beams, up to 4.9 $\times 10^{13}$ protons per 7.2 μs pulse (288 bunches), with a Gaussian beam sigma ranging from 0.1 mm to 2 mm [4]. The main objectives of the experiment are to explore the onset of failure modes of beryllium under controlled conditions at highly localized strain rates and temperatures, identify any thermal shock limits, and validate highly non-linear numerical models with experimental measurements.

EXPERIMENTAL SET-UP

The test rig is based on a double containment design to ensure containment of the beryllium specimens and any potential radioactive contamination created from beam interaction. The specimens will be arranged in four horizontal arrays aligned vertically in a single column. Figure 1 shows the test chamber positioned on the HiRadMat mobile table.

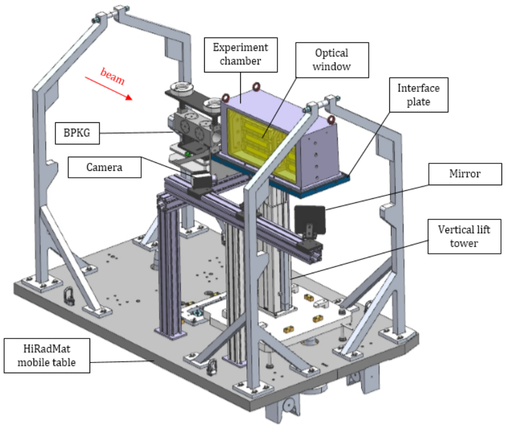

Figure 1: Test chamber positioned on mobile table.

The experiment chamber is an outer containment box, which encloses the specimen inner containment boxes. Small apertures on the outer box allow the beam to enter and exit, using a shutter system to provide post-experiment containment. Additionally, the internal volume of the outer chamber is continuously evacuated by a pump which draws the air out of the box via a HEPA filter (not shown in Figure 1). The continuous pumping and lower pressure within the outer chamber ensures no airborne particulate escapes the containment box. The HEPA filter will be analyzed upon completion of the experiment to check for any containment breach of the array boxes.

Specimen housing

As shown in Figure 2, each specimen type within an array is enclosed in a separate containment box, sealed with glassy carbon beam windows [5]. Gafchromic foils are positioned in front of each array to verify beam alignment

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[*] Work supported by Fermilab - Operated by Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy

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during pilot beam pulses. The optical windows allow for visual monitoring of the experiment as well as for Laser Doppler Vibrometer (LDV) measurements of surface deformation/vibration of the slug specimens.

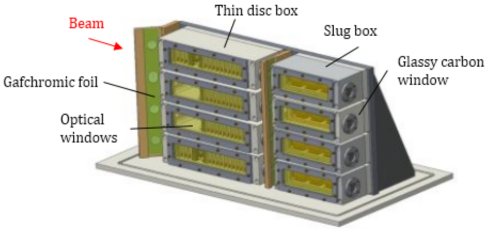

Figure 2: Interior of experiment chamber.

Material specimens

Two types of specimens are included in the experiment: thin discs for deformation, strain, and crack/failure analyses during PIE, and slugs for real time measurements of strain, temperature, and vibration (Figure 3). A few thin discs will be pre-characterized by Electron Backscatter Diffraction analysis (EBSD), and are only placed in Arrays 1 and 4 (Figure 4). The slugs in each array are slightly offset from the upstream thin discs so that the beam impacts the slugs close to the cylindrical edge.

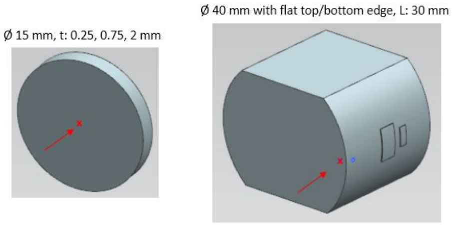

Figure 3: Specimen types: thin discs and slugs.

Instrumentation

Instrumentation for real-time data acquisition will include strain gauges, temperature sensors, an LDV system, and cameras. The gauges, attached to the external cylindrical surface of the slugs, will measure the temporal circumferential strain and temperature response induced by the beam, while the LDV will record dynamic radial deformations. The online measurements will help validate the beryllium strength and damage models, as well as identify elastic-plastic regime structural response. Cameras will be used for visual monitoring of the experiment, and to image the Gafchromic foils for beam alignment purposes. A beam position monitor (BPKG) will also aid in beam alignment.

EXPERIMENTAL PARAMETERS

The experimental beam parameters were guided by numerical simulations, to incrementally push beryllium to its material failure limit. Particle-matter interaction simulations were performed with the MARS15 code [6] to obtain energy deposition in the specimens, as a function of beam sigma and intensity. After accounting for probable numerical and experimental uncertainties, a beam spot size of σ = 0.3 mm was chosen so that the expected local peak temperature rise (ΔT $\sim$ 1025 °C) does not exceed the material's melting point (1290 °C) for the highest intensity beam pulse.

Test matrix

Figure 4 shows the composition of each array as well as the predetermined beam intensities. The four beryllium grades include the S-65F, S-200F, S-200FH, and PF-60 grades, which differ in impurity content, consolidation process, yield strength, and ductility. Array 2 is subjected to two pulses separated vertically, while array 3 receives multiple pulses at the same location.

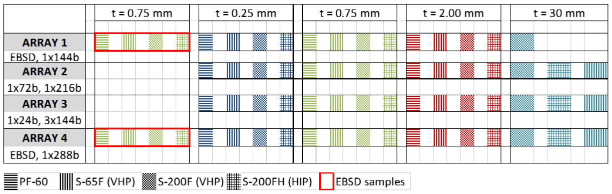

Figure 4: Test matrix illustrating the specimen type, size, grade, and incident beam intensities (1.7×10^{11} protons per bunch).

Beam induced stress and strain

The nearly instantaneous local temperature jump due to beam interaction, and the resulting large temperature gradients induce strong thermal shock in the specimens. LS-DYNA FEA models [7] were therefore set up to evaluate the beam induced stresses and strains, as a function of beam intensities, and specimen thicknesses. The contour plot in Figure 5 shows the residual effective strain distribution in a thin disc specimen after being exposed to a maximum intensity beam pulse.

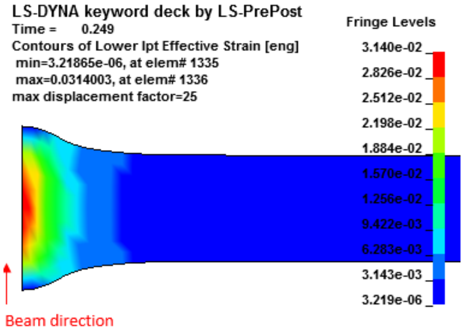

Figure 5: Effective strain contour plot from a 2D axisymmetric model (0.75 mm disc after cool-down).

The peak residual effective strain is shown to be around

3%, which is larger than beryllium failure strains (~2% for S-200F VHP at RT) given in the literature [8]. Therefore, for this particular disc, interior cracking or fracture of the disc in the area of large plastic deformation is expected. Permanent out-of-plane deformations on both faces of the disc is also expected. Figures 6 and 7 show the range of peak residual effective strain and out-of-plane deformation expected from the discs in the test matrix, as a function of disc thickness and beam intensity.

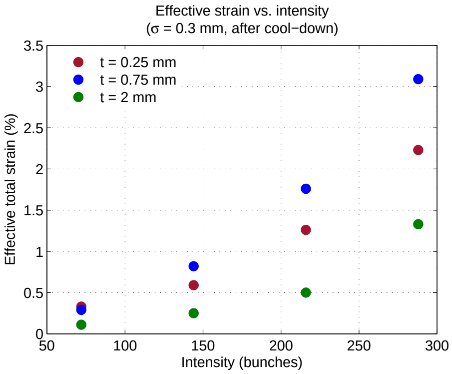

Figure 6: Peak residual effective strain after cool-down.

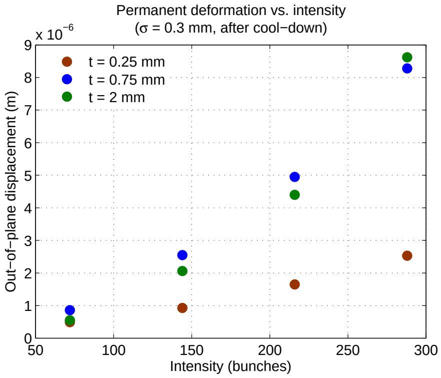

Figure 7: Peak out-of-plane surface deformation after cool-down.

Array 3 will explore strain and deformation accumulation due to cyclic loading resulting from multiple beam pulses. Figure 8 reveals how the peak effective strain increases with consecutive pulses, with plastic strain shakedown expected to occur after more than 20 pulses.

POST-IRRADIATION-EXAMINATION

After sufficient cool-down time, assessed by FLUKA radiological simulations [9], the outer containment box will be disassembled. The inner containment boxes will then each be removed and transported to Oxford University and the Culham Center for Fusion Energy (CCFE) facility in the UK for PIE. Visual Light and Scanning Electron Microscopy (SEM) will be used for microstructural characterization of the thin discs. The composition and crystallographic maps in the beam spot area of the discs will be built with the Energy-Dispersive X-ray spectroscopy and EBSD techniques and the correlation between the thermal shock consequences and the microstructural features of the different beryllium grades will be explored. Focused Ion Beam system will be used for crack investigation in 3D. Finally, the out-of-plane deformation will be measured by profilometry technique and compared with the FEA numerical predictions.

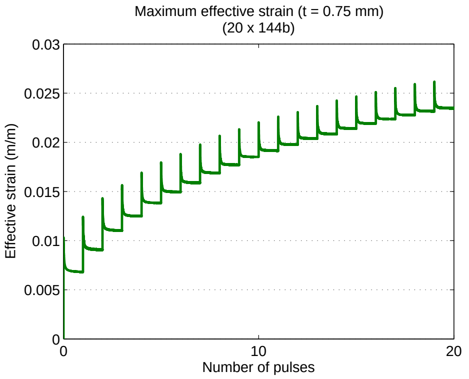

Figure 8: Effective strain accumulation in 0.75 mm disc from multiple beam pulses.

CONCLUSIONS

Understanding beryllium material behavior under extreme conditions is critical to the reliable design and operation of future high intensity accelerator facilities. This experiment has been designed to test and push beryllium to its failure limit, in an effort to evaluate thermal shock response and probe the failure and damage mechanisms of different grades of the material. The experiment, called HRMT-24 BeGrid, is scheduled for week 38 (Sept. 14th) in 2015 [4], with results expected within a year of irradiation.

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