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EXPERIMENTAL RESULTS OF BERYLLIUM EXPOSED TO INTENSE HIGH ENERGY PROTON BEAM PULSES*

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Abstract

Beryllium is extensively used in various accelerator beam lines and target facilities as a 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 reliably operate these components as well as avoid compromising particle production efficiency by limiting beam parameters. As a result, an exploratory experiment at CERN's HiRadMat facility was carried out to take advantage of the test facility's tunable high intensity proton beam to probe and investigate the damage mechanisms of several beryllium grades. The test matrix consisted of multiple arrays of thin discs of varying thicknesses as well as cylinders, each exposed to increasing beam intensities. This paper outlines the experimental measurements, as well as findings from Post-Irradiation-Examination (PIE) work where different imaging techniques were used to analyze and compare surface evolution and microstructural response of the test matrix specimens.

INTRODUCTION

Beryllium is currently widely used as the material of choice for critical accelerator components such as beam windows and secondary particle production targets in various accelerator beam lines and target facilities. With the increasing beam intensities of future accelerators [1], it is crucial to understand the response of beryllium to even more extreme operational environments for successful design and reliable operation of these components, without having to compromise particle production efficiency by limiting beam parameters.

One of the main challenges facing windows and targets exposed to high intensity particle beams is thermal shock [2]. These are dynamic stress waves that are generated due to the rapid expansion of the material surrounded by cooler material upon interaction with high intensity particle beams. Consequently, the material may undergo plastic deformation and eventually fail. As a result, an experiment at CERN's HiRadMat facility [3] was carried out to expose beryllium specimens to intense proton beams. The test facility aims to deliver high intensity proton beams, up to 4.9×10^{13} protons per 7.2 µs pulse, with Gaussian beam spot sigmas ranging from 0.1 mm to 2 mm [4]. The objectives of the experiment were 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. The primary goal was to push beryllium to its limit, by imposing a temperature jump up to close to its melting point (~1000 °C) from a single beam pulse.

EXPERIMENTAL SET-UP

The experimental chamber is based on a double containment design to ensure containment of the beryllium specimens and mitigate any radioactive contamination upon interaction with beam. Figure 1 shows the experimental chamber attached to a vertical lift tower and positioned on the HiRadMat mobile table.

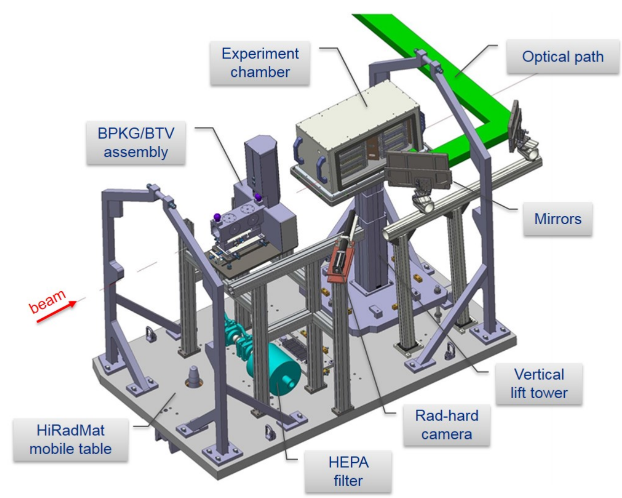

Figure 1: Experimental chamber assembled on mobile table.

The experiment contained two types of specimens: thin discs for deformation, strain, and crack/failure analyses during Post Irradiation Examination (PIE), and slugs for online measurements of strain, temperature and vibration. Strain and temperature gauges were attached to the external cylindrical surface of the slugs to measure the circumferential strain and temperature response to the pulsed beam. Dynamic radial vibrations of the cylindrical edge of the slugs were recorded with a Laser Doppler Vibrometer (LDV) sys-

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tem. Eight 0.75 mm discs were also pre-characterized by Electron Backscatter Diffraction (EBSD) prior to the experiment to allow comparison with post-irradiation images to identify localized deformations and cracks. More detailed information on the experimental design, beam parameters and instrumentation are described in [5].

EXPERIMENT INSTALLATION

The experimental chamber assembly, array position alignment, optical path mock-up and data acquisition system checks were all performed in the BA-7 building prior to installing the experiment in the tunnel at HiRadMat. After assembly and all checks were performed, the mobile table was transported to the TNC tunnel for final set-up and cable connections. Figure 2 shows the mobile table (left) being transported into the experimental area of the HiRadMat facility (TNC tunnel).

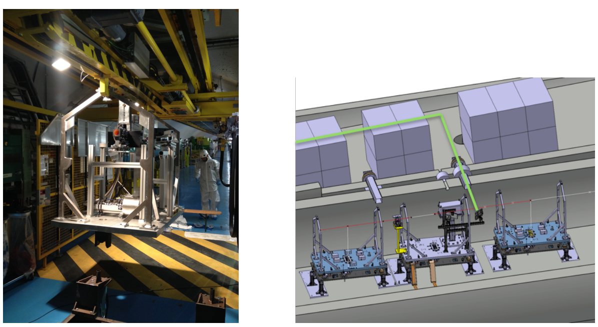

Figure 2: Mobile table installation in TNC tunnel (left) and sketch of the optical path (right).

An optical path, using mirrors on the mobile table and feedthroughs, was projected to the adjacent tunnel (TT61) where the sensitive electronic devices such as DAQ systems, camera and the LDV system were located behind shielding blocks (Fig. 2). After final installation and alignment beam pulses in the TNC tunnel, the experiment was carried out in mid September 2015.

PRELIMINARY RESULTS

Test Matrix

Figure 3 shows the composition and experimental beam intensities of each array in the experimental chamber. Four different beryllium grades were included in each array and subjected to increasing beam pulse intensities to help determine any thermal shock limit threshold during the experiment. The average bunch intensity was 1.3×10^{11} and beam σ_x: 0.3 mm, σ_y: 0.25 mm for the beam pulses during the experiment. It should be noted that the experimental beam parameters were slightly different to the design beam parameters [5] due to accelerator operational constraints at the time of our experiment at HiRadMat.

Online Strain Measurements

As described in more details in [5], the strain, temperature and vibration on the cylindrical surface of the slugs were

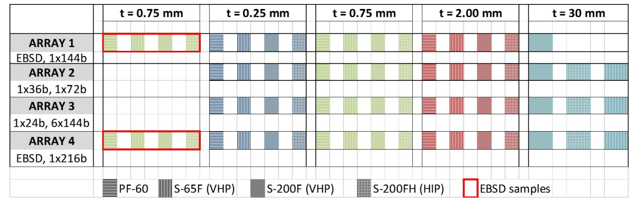

Figure 3: Test matrix showing specimen type, size, grade and number of bunches.

measured in real-time. Some preliminary strain results of the slugs in three arrays with different beam pulse intensities are presented in this section.

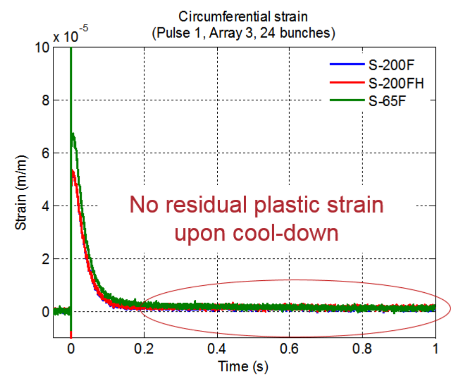

Figure 4: Strain response of slugs in Array 3 (24 bunches).

Figure 4 shows the strain response of the slugs in Array 1 during the almost instantaneous beam pulse until the temperature cool-down of the slug. Note that the blue curve (S-200F) coincides with the red curve (S-200FH) and thus is not clearly visible on the plot. With 24 bunches of 1.3 $\times 10^{11}$ ppb, numerical simulations prior to the experiment did not predict any plastic deformation, and this was also confirmed experimentally as shown in Fig. 4.

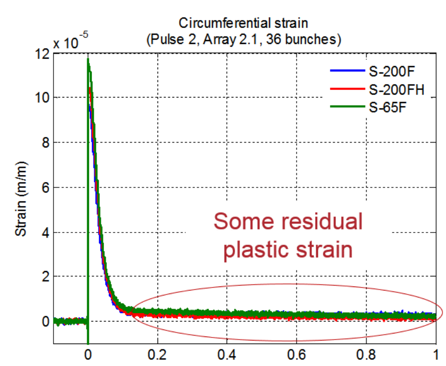

Figure 5: Strain response of slugs in Array 2 (36 bunches).

Figure 5 shows the strain response from slugs in Array 2 for a 36-bunch pulse and in this case a very small amount of residual plastic strain is observed, consistent with numerical predictions. And finally, for the highest intensity array (216 bunches), significant residual plastic strain was measured at the end of the cool-down (Fig. 6).

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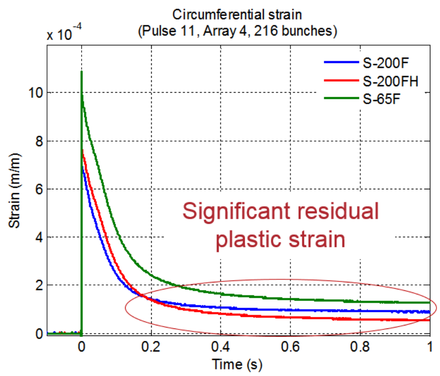

Figure 6: Strain response of slugs in Array 4 (216 bunches).

Figures 4 to 6 also reveal the contrasting strain response of the three beryllium grade slugs, which can be largely attributed to their distinct yield stresses. Beryllium grades S200FH, S200F, and S65F have yield stresses of 297 MPa [6], 242 MPa [7], and 207 MPa [8], respectively. Another possible reason for the contrasting response is slight misalignment of the slugs relative to the beam axis. Further analysis of the real-time measurements is essential and ongoing.

Thin Disc Profilometry

After sufficient cool-down time, the experimental chamber was disassembled at CERN and the individual inner containment boxes shipped to Oxford University for PIE studies. The thin discs were first analyzed with a profilometer to measure the expected residual out-of-plane plastic deformations in the beam spot region induced by the beam [5]. Figure 7 shows examples of profilometry maps for 0.75 mm thick S65F beryllium thin specimens from Array 1 and Array 4.

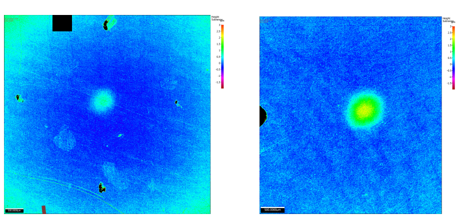

Figure 7: Profilometry maps of S-65F grade thin discs from Array 1 (left) and Array 4 (right).

As evident from the plots, profilometry measurements with very good resolution (tens of nanometers) were achievable. Most of the 0.75 mm and 2 mm thick disc specimens have already been scanned, and a summary of the results is presented in Figs. 8 and 9.

The results indicate that the S200FH specimens sustained the least amount of plastic deformations. On the other hand, the deformations for the S200F specimens are much larger, likely explained by its lower yield strength. Likewise, the S65F grade specimens also show higher plastic deformation, again probably due to its lower yield strength. The results from Array 3, which received multiple beam pulses (6 pulses

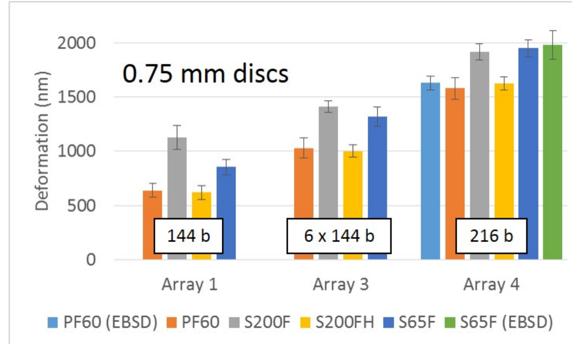

Figure 8: Out-of-plane deformations of 0.75 mm thick discs.

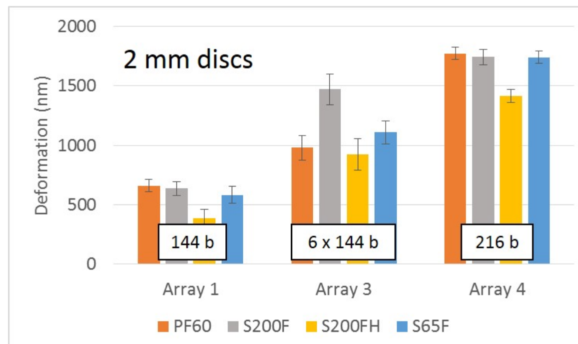

Figure 9: Out-of-plane deformations of 2 mm thick discs.

of 144 bunches each), demonstrate plastic strain ratcheting during the cyclic loading. Optical microscopy was also performed during PIE with no cracks identified on the thin disc specimens. Further microstructural analyses is ongoing in order to extract more information from the discs.

CONCLUSIONS

In summary, the experiment was carried out successfully and safely. The goal of an exploratory investigation to expose beryllium to thermal shock was achieved and PIE work and data analysis from this experiment continue. However, some issues were encountered during the experiment which included large variations in beam spot size and noisy LDV data due to faint signal from the beryllium slug surface. In addition, Array 4 did not receive the desired high intensity pulse and as a result the maximum temperature jump from the beam was only around 650 °C as opposed to the 1000 °C desired. Findings from this investigation will drive the need for a follow-up experiment at HiRadMat, where more intense beam pulses will be imposed on beryllium specimens.

ACKNOWLEDGEMENT

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[7] S-200-F Vacuum Hot Pressed Beryllium, `https://materion.com/Products/Beryllium/Beryllium-Metal/S-200F.aspx`

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