

THE HIRADMAT 27 EXPERIMENT: EXPLORING HIGH-DENSITY MATERIALS RESPONSE AT EXTREME CONDITIONS FOR ANTI-PROTON PRODUCTION

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Abstract

The HRMT27-Rodtag- experiment used the HiRadMat facility at CERN to impact intense 440 GeV proton beams onto thin rods -8 mm diameter, 140 length- made of high-density materials such as Ir, W, Ta, Mo among others. The purpose of the experiment has been to reduce uncertainties on the CERN antiproton target material response and assess the material selection for its future redesign. The experiment was designed to recreate the extreme conditions reached in the named target, estimated on an increase of temperature above 2000 °C in less than 0.5 μs and a subsequent compressive-to-tensile pressure wave of several GPa. The goals of the experiment were to validate the hydrocode calculations used for the prediction of the antiproton target response and to identify limits and failure mechanisms of the materials of interest. In order to accomplishing these objectives, the experiment counted on extensive online optical instrumentation pointing at the rod surfaces. Online results suggest that most of the targets suffer important internal damage even from conditions seven times lower than the reached in the AD-target. Tantalum targets clearly showed the best dynamic response.

INTRODUCTION

The HRMT27 experiment took place in November 2015 using the HiRadMat facility at CERN [1] to impact high intensity and energy proton pulses of 440 GeV/c from the SPS onto 13 thin rods (8 mm diameter) of high-density materials. The motivation of the experiment comes from the existing uncertainties in the structural response of the core material of the CERN antiproton production target (AD-Target). Antiprotons are produced by colliding a $1.5 \cdot 10^{13}$ ppp proton beam of 26 GeV/c from the PS (Proton Synchrotron) onto a rod of 3 mm diameter, 55 mm length, made of iridium, one of the densest existing elements [2]. This design was conceived during the 80s after several years of empirical iterations due to the inherent extreme conditions reached in its core material [3]. Currently, several studies are on-going at CERN in order to propose a new target design for the next 20 years of operation of ELENA Era, (Extra Low ENergy Antiproton ring [4]), profiting from more modern and powerful computational tools to face the intrinsic engineering challenges involved. These studies make use of

hydrocodes in order to fully simulate the dynamic response of the core target material provoked by the sudden deposition of energy by the impacting proton beam. They show that inside the target core a raise of temperature of above 2000°C takes place in 0.43 μs (the duration of the proton beam burst). This sudden raise of temperature produces a subsequent dominant radial high frequency wave which subjects the core material to oscillating compressive-to-tensile pressures above 5 GPa, greatly exceeding the material yield and strength [5]. This level of tensile stresses certainly provokes important changes in the core material such as its internal cracking and effective density loss, which could be the reason for the reduction of antiproton production yield observed during first days of operation [6]. Simulations, however, have intrinsic limitations that must be taken into account and require that numerical studies and experimental work go hand in hand, even more when these simulations are applied to such complex problems as the one of study. This is specifically the case, due to the lack of accurate material model response and failure limits at the conditions reached in the target core, which significantly differ from the ones that can be attained in any conventional dynamic mechanical tests. The experiment therefore aims at recreating similar conditions as the ones reached in the target core with a double goal; (i) Cross-check the accuracy of the performed simulations at these regimes. (ii) Identify limits and mechanisms of failure of different high density materials to assess the material selection for the future antiproton target. This second goal is achieved by subjecting the targets to a stepwise increase of the impacted intensity, allowing to identify progressive damage and mechanisms of failure at in-between conditions.

EXPERIMENT SPECIFICATIONS

Targets Design and Irradiation Parameters

The design of the experimental targets had to satisfy the compromise of a set of constraints including the recreation of analogous conditions to those reached in AD-target, being compatible with the characteristics of the HiRadMat proton beam and, at the same time, producing a response at their surface within the instrumentation limitations. 3 mm diameter rods as in the real AD-target would not have been suitable for several practical reasons, such as the complications for reaching the AD-target core conditions with the SPS beam, enforcement of the required precision and velocities at the target surface above

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the instrumentation limitations. As a result, targets of 8 mm diameter such as the one shown in Figure 1 were found to be fitting these constraints. The targets had several mirrors machined on their surface, towards which optical instrumentation was pointing in order to record the target vibration and temperature when impacted by the proton beam. A beam consisting of $1.5 \cdot 10^{13}$ ppp and 1.5 mm size at one sigma was found to be optimal to recreate an analogous temperature raise and gradient as that reached in the AD-target core. In addition, the pulse length was found to be crucial to recreate the same dynamic response and compressive-to-tensile wave present in the AD-target [5]. This length had to be in the order of half of the radial period of the rod and was set at 0.9 μ s. Figure 2 illustrates a comparison between the conditions reached in the real AD-Target and experimental HiRadMat targets with the selected beam parameters, showing the recreation of analogous material conditions.

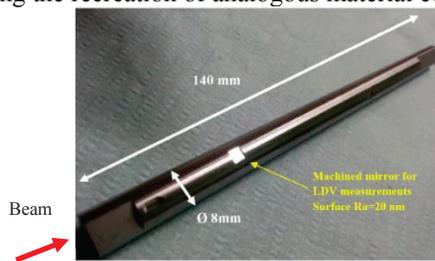


Figure 1: Picture of a tungsten target irradiated in the experiment.

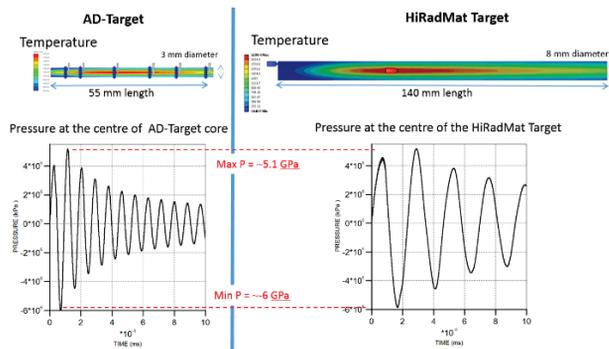


Figure 2: Comparison between the calculated temperatures and radial pressure wave in the AD target core (left) and HiRadMat experimental target (right).

Table 1 shows the list of irradiated target materials. The targets with lower density such as Mo and TZM and Ta had a longer length in order to present the same nuclear interaction length and therefore achieve a consistent longitudinal profile of deposited energy.

Experiment Layout

In the experiment the 13 targets were put inside a primary vacuum tank of 610x500x420 mm, placed in a vertical mobile sample holder, as shown in Figure 3, which was able to position each of them on the incoming proton beam trajectory. The tank was placed on top of motorized experimental tables with vertical and horizontal degrees of freedom in order to remotely align the tank with the pro-

ton beam, the position of which was monitored online by a BTV (beam TV monitor) and a BPKG (beam pick up button position monitor) directly attached to the tank on the upstream part.

Online Instrumentation

The experiment counted on extensive online instrumentation to measure the displacement, velocity, and temperature of the targets surface. These instruments had very high acquisition rates (10 MHz) in order to capture the expected radial wave, which had a period of 1.8-3.4 μ s (depending on the target material). The experiment used two Laser Doppler Vibrometers (LDVs), two interferometers heads and one pyrometer [7]. The electronics of all these instruments had to be placed in a bunker far from the experimental setup due to the high levels of prompt radiation reached. For this reason, most of these instruments used passive optical heads placed inside the vacuum tank, pointing directly to the surface of the on-beam position target. The laser signal of these instruments was traveling by optical fibres from the bunker using leak-tight feedthroughs in the experimental tank. In addition, each of the targets had two thermocouples attached to each target surface. Two cameras, one radiation hard and one high definition were placed outside the tank recording the sample holder through a radiation resistant glass window present at the sides of the tank.

Table 1: List of Irradiated Targets

Material	Density [g/cm ³]	Length [mm]	Number of Targets
Iridium	22.3	140	3
Tungsten	19.3	140	3
Tungsten- Lanthanum	19.3	140	1
W clad in Ta	-	140	1
Molybdenum	10.2	240	1
TZM	10.2	240	2
Tantalum	16.6	160	2

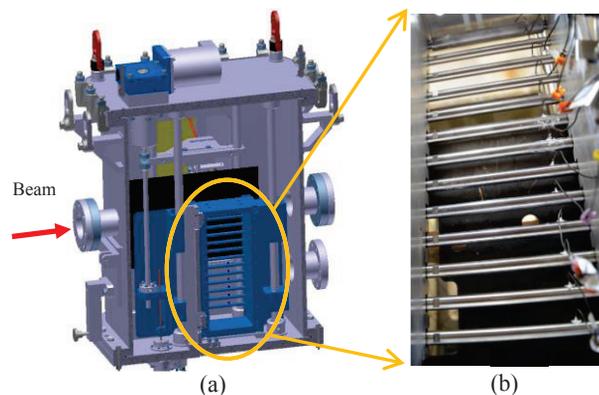


Figure 3: (a) Schematic of the interior of the experimental vacuum tank. (b) Picture of the 13 targets placed in the sample holder inside the tank.

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ONLINE RESULTS

During the experiment 139 pulses at different intensities were successfully impacted on the 13 irradiated targets, recording a great amount of information of their dynamic response. Figure 4 shows the recorded surface velocity at the lowest intensity in a TZM target, which is still showing an elastic material response. Three main wave phenomena were identified; (i) High frequency radial wave with 1.8 μ s period (ii) Longitudinal wave with 85 μ s period. These two waves were predicted by the performed hydrocode calculations [5]. (iii) A third lower frequency and high amplitude wave was recorded and identified as an excited bending mode due to small asymmetries in the clamping system of the targets.

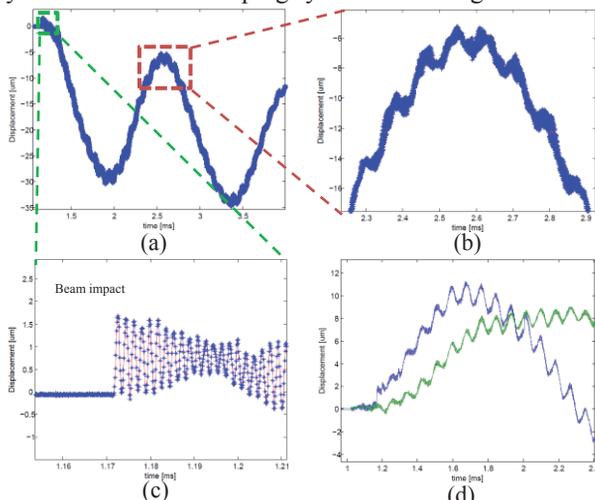


Figure 4: (a) Recorded surface displacement. (b) Recorded longitudinal wave (c) Recorded radial wave (d) Recorded longitudinal wave by the interferometer.

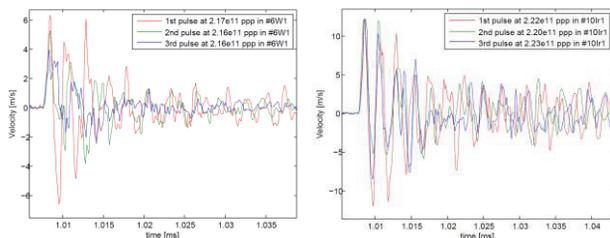


Figure 5: Recorded surface velocity in consecutive impacted pulses at $2.2 \cdot 10^{11}$ in W (left), and Ir (right).

During the pulses at the lowest intensity ($\sim 1 \cdot 10^{11}$ ppp) a high degree of repeatability was observed between consecutive impacted pulses, especially in the molybdenum and TZM targets due to their lower intensity. This means that these materials were presenting an elastic response. However, as impacted intensity was gradually increasing, the produced radial waves were promptly damped and presented a distorted response pattern as shown in Figure 5, suggesting that internal damage and cracking was already taking place. This was observed in all the materials from the second irradiation intensity ($2.5 \cdot 10^{11}$ ppp) except in the tantalum targets, which showed a “clean” radial wave up to the highest intensity pulses, at which the AD-target conditions were recreated. The different behaviour of the irradiated materials is summarized in Figure 6. In

an ideal material which does not suffer from yielding or internal cracking, surface velocity should monotonically increase and be closely proportional to the impacted intensity. However, as can be seen in the figure, the maximum velocity in most of the targets was reaching a flat top or even decreasing with the intensity, meaning that internal damage taking place inside the targets prevented the radial wave to properly propagate to the surface. Most of the targets were suffering this effect from intensities between seven and five times less than the conditions reached in the AD-Target. The tantalum targets presented the best response from this point of view among the irradiated materials.

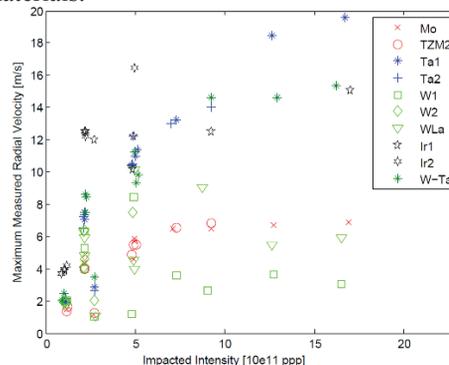


Figure 6: Maximum reached radial velocity in the irradiated targets as a function of the impacted intensity.

CONCLUSIONS

In the HRMT27 experiment 139 high intensity, 440 GeV, proton pulses were successfully impacted onto thin rods of high density materials, recreating analogous extreme conditions to those reached in the CERN antiproton production target, and while measuring online the targets dynamic response. The arising radial and longitudinal pressure waves predicted by simulations were recorded. Online data suggest that the targets were suffering significant internal damage even from reached conditions seven times lower than the ones taking place in the real AD-target, indicating that the core of such target may be broken from the beginning of operation. At the end of the experiment, all the targets presented bending and visible superficial longitudinal cracks to a large extent. Tantalum was the material which showed the best dynamic behaviour. Foreseen post-irradiation examinations of the irradiated targets will complement this work, bringing useful information regarding the failure mechanisms and internal damage.

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