

PROTOTYPING ACTIVITIES FOR A NEW DESIGN OF THE CERN'S ANTIPROTON PRODUCTION TARGET

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Abstract

Antiprotons are produced at CERN by impacting an intense proton beam of 26 GeV/c onto a high-Z water-cooled target. The current target design consists in an Ir core in a graphite matrix, inserted in a Ti-6Al-4V assembly. A new target design has been foreseen for operation after 2021 to improve the operation robustness and antiproton production yield. Numerical (use of hydrocodes) and experimental approaches were carried out to study the core material response under extreme dynamic loading when impacted by the primary proton beam. The lessons learned from these studies have been then applied to further prototyping and testing under proton beam impact at the CERN HiRadMat facility. A first scaled prototype consisting of Ta rods embedded in an expanded graphite matrix was irradiated in 2017, while in 2018, the PROTAD experiment will test different real-scale AD-Target prototypes. This contribution details these prototyping and testing activities.

INTRODUCTION

At the CERN AD-Target Area antiprotons (\bar{p}) are produced, collected, momentum selected and injected to the Antiproton Decelerator (AD) facility, in which they are decelerated for subsequent antimatter research experiments [1].

At the present, antiprotons are generated by impacting an intense 26 GeV/c proton beam, produced by the CERN Proton Synchrotron (PS), onto a high-Z water-cooled target. The current target design consists of an Ir cylindrical core of 3 mm diameter, 55 mm long, embedded in a graphite matrix and inserted in a Ti-6Al-4V assembly. This design configuration dates back to the late 80's [2]. A major upgrade of the area will take place during 2019-2021, within CERN's Long shut down 2 (LS2), to guarantee the supply of antiprotons to the future antiproton physics programs and the operation of the recently built ELENA ring (Extra Low ENergy Antiproton) [3,4]. In this context, a new antiproton production target design has been foreseen for operation from 2021, aiming at improving the operation robustness and antiproton production yield for the future AD physics.

In order to propose a new target design, several R&D activities have been triggered during the last years, involving numerical and experimental studies, as well as prototyping activities.

From the design carried out during the 80's, the dynamic response of the target core due to primary beam impact was already identified as one of the main operation concerns [2]. The high density core material and the focused

primary beam (required to have a target as compact as possible) create a sudden temperature rise in the core of the order of 2000 °C, exposing it to dynamic stresses well above the material plastic yield. This circumstance motivated detailed studies of the core material response at these conditions, which are briefly summarized in the first section of this was paper. The lessons learned from these studies were applied to the design and testing of a first scaled prototype of the target, within the HRMT-42 experiment of 2017, which is described in the second section. Finally, current works involve the manufacturing and testing of six real-scale target prototypes, foreseen in 2018, which is described in the third section of this paper.

NUMERICAL AND EXPERIMENTAL STUDIES OF THE CORE RESPONSE

Hydrocode Simulations

First numerical works performed included the application of hydrocodes to the dynamic response of the core material when impacted by the primary proton beam [5]. In this context, it was carried out a dynamic characterization for obtaining parameters of the proper strength models for Ir and W to be employed by these simulations [6].

As described in ref. [5], the hydrocode simulations confirmed that the aforementioned maximum temperature rise of 2000 °C takes place in the target core in less than 0.5 μ s (the duration of a proton pulse). The sudden rise of temperature leads to the excitation of a radial mode of vibration, which exposes the material to oscillating compressive-to-tensile stresses of several gigapascals, well above its strength limit. These results suggest that the beam-induced material damage could lead to a drop of effective density of the target core, which could explain the observed decrease in \bar{p} yield during the first weeks of operation of new targets [7]. Hence, the new design would aim to a reduction of the target fragmentation so that the antiproton yield could be maintained constant.

The HRMT-27 Experiment

Complementary to the hydrocode simulations, an experiment using the CERN's HiRadMat facility [8], HRMT-27-RodTarg, was carried out in 2015 [9-11]. The goal of this experiment was to provide a crosscheck of the hydrocode simulations and assess the material selection of the new target design. With this purpose, the experiment exposed different high density materials, as possible candidates for the new target design, to equivalent conditions as the ones reached in the AD-Target core by impacting intense 440 GeV proton beams provided by the CERN's Super Proton Synchrotron (SPS) onto rods of 8 mm diameter.

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Targets geometries and beam parameters were selected accordingly to recreate such conditions. In addition, the experiment counted on on-line instrumentation such as Laser Doppler Vibrometers (LDV) to measure the induced vibration of the rods impacted by the proton beams. The velocity recorded was crosschecked with the results of the hydrocode simulations, confirming the presence of the predicted radial mode and its damaging consequences, as well as validated the numerical simulations and strength models employed.

Most of the high density materials tested (including W, Mo, TZM and Ir among others) internally cracked even at conditions 7-5 times less demanding than the ones present in the AD-Target core (in terms of exposed rise of temperature and tensile stresses). Nevertheless, the Ta targets showed a very different response with respect to the rest of materials: Even if they presented extensive plastic deformation, they withstood the AD-Target equivalent conditions without internally cracking [9-11]. This was attributed to tantalum's high ductility in comparison with the other materials tested. Therefore, Ta has become one of the main candidate core materials for the future AD-Target design.

THE HRMT-42 EXPERIMENT: A FIRST SCALED PROTOTYPE

The HRMT-27 experiment brought important insights, from a fundamental point of view, on the response of thin rods of high density materials dynamically loaded by the impact of short and intense proton pulses. Nevertheless, it left several open questions relevant for the design of an improved AD-Target.

One of these questions is related to the response of the containing graphite matrix. The performed hydrocode simulations suggested that, not only the structural integrity of the target core is compromised during operation, but also the one of its containing graphite matrix, especially close to the interface with the core, due to the propagation of the stress waves generated in the core itself [12].

Therefore, other possible matrix materials that could withstand the radial wave are investigated. Expanded graphite (EG) [13], also known as flexible graphite, was considered a good candidate, since its flexibility could be beneficial for absorbing and damping the radial wave coming from the target core without breaking. Nevertheless, it is necessary to evaluate the behaviour of this EG matrix, and in particular the eventual appearance of gaps at the interface with the Ta, due to extensive plastic deformation of the latter as a consequence of every beam impact.

Second question left open by the HRMT-27 experiment is the response of Ta when subjected to a larger number of proton beam impacts. The effect of successive plastic deformation as a consequence of each proton pulse impact was not assessed since time constraints during the execution of that experiment limited the number of impacted pulses to a few.

For these reasons a first scaled prototype of the AD-Target, consisting of a core made of Ta rods embedded in a

pre-compressed EG matrix and encapsulated in a Ti-6Al-4V container, was built and tested under proton beam impact using again the HiRadMat facility.

HRMT-42 Target and Beam Parameters

Figure 1 shows several images of the HRMT-42 target, which consists of ten Ta rods of 8 mm diameter, 16 mm length, embedded in a compressed EG matrix and encapsulated in a 44 mm diameter -2 mm thickness- Ti-6Al-4V container, which was electron beam (EB) welded. The EG matrix was constituted by eighty-seven hollow disks of this material, with a thickness of 3 mm in pristine conditions. The EG disks were compressed during assembling to an average compression ratio of 27 %. A dedicated tooling was designed for this operation, as well as to maintain the pressure while EB welding [14].

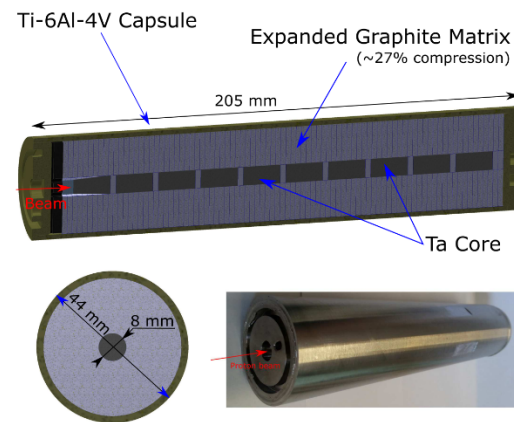


Figure 1: Geometry of the HRMT-42 target (first scaled prototype of the AD-Target).

The impacted 440 GeV/c proton beams had the same parameters as the ones in the HRMT-27 experiment, since the target core was as well 8 mm diameter. Therefore, similarly as in the HRMT-27 experiment, equivalent conditions (in terms of rise of temperature and radial compressive-to-tensile pressure wave) as the ones present in the AD-Target could be reproduced. The nominal beam was $1.5 \cdot 10^{12}$ ppp intensity and the spot size 1.5 mm (1σ). A total of forty-seven pulses with such characteristics were used, leading to $7 \cdot 10^{13}$ protons on target (POT).

Results of the HRMT-42 Experiment

Similarly as in the HRMT27, a LDV was used to measure the target vibrations at the periphery of the Ti-6Al-4V container during each proton beam impact. These measurements indicated that a radial mode with a period in the order of 30 μ s dominates the velocity response, as is shown in Fig. 2. This mode was damped relatively fast (500-600 μ s) due to the porous properties of EG. Another remarkable fact was the high repeatability in the recorded velocity within the forty-seven impacted pulses [14].

After the experiment, the target was extracted to perform non-destructive testing in order to evaluate the state of the Ta-EG interface and Ta core. X-ray tomographies at ESRF [15] and Neutron tomographies at PSI [16] were complementary used for this purpose. The former was

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used to evaluate the EG-Ta interface thanks to the high spatial resolution of this technique (12 μm), while the latter could penetrate the Ta core to reveal its internal structural response.

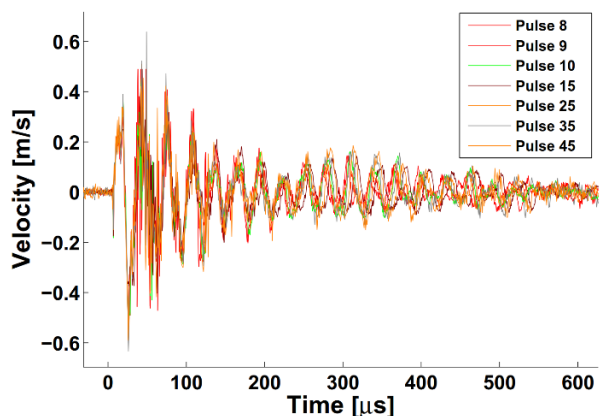


Figure 2: Velocity recorded during several proton beam impacts in the HRMT-42 experiment.

Figure 3 shows the result of these non-destructive techniques. Figure 3-(a) and (b) show X-ray images of one of the central Ta rods before and after proton irradiation in HiRadMat. This image shows an extensive plastic deformation of the Ta core but suggests that the EG can adapt to such change of shape without the appearance of gaps at the interface. The neutron tomography of Fig. 3-(c) shows the formation of voids in the Ta core, especially at the downstream rods, attributed to spalling due to the high tensile pressure reached (above 3 GPa). Further destructive investigations will try to assess in detail this phenomenon and the potentially governing role of successive plastic deformation of the core, since such fracture was not observed in the Ta targets of HRMT-27. The formation of such voids in Ta could definitely affect the \bar{p} production. The comparison of the potential influence produced by this sort of fracture and the one observed in brittle metals during HRMT-27 has to be assessed. In addition, the future design will aim at reducing the tensile stresses reached by increasing the target core diameter as an attempt to avoid this observed spalling. In this context, Ta is still one of the main candidate core materials, together with Ir, as this is the material of the current design.

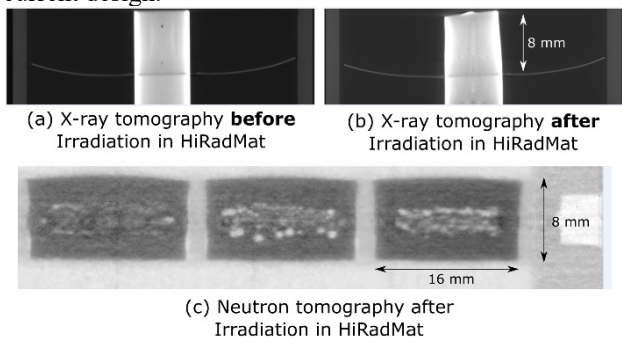


Figure 3: (a)-(b) X-ray image of a central Ta rod before and after proton irradiation. (c) Neutron image showing internal spalling of the downstream Ta rods after proton irradiation.

PROTAD EXPERIMENT

Next prototyping activities involve the manufacturing and testing of six real scale AD-Target prototypes, as the one shown in Fig. 4. These prototypes will include a double-wall Ti-6Al-4V assembly, cooled by pressurized air. Air-cooling will simplify the operation since water-cooling activation and its associated treatment is avoided. Six core and matrix configurations will be tested in HiRadMat in 2018. Two of these possible configurations are shown in Fig. 4. The proposed strategy involves the use of rods with variable diameter (increased up to 10 mm at the upstream ones as an effort to reduce the tensile pressure reached) as well as to include multi-material core configurations (involving, Ta, Ta alloys, and Ir among other materials). These configurations are selected based on \bar{p} optimization studies performed by FLUKA simulations [17], which suggest that, theoretically, a \bar{p} production within the 95 % with respect to the predictions for the current design could be achieved. These studies are unable to predict the potential drop of density due to potential core damage and therefore the experiment will be used to find the best configuration. Furthermore, matrices using EG and conventional isostatic graphite will be tested and compared, in addition to a configuration representative to the old design based on the 3 mm diameter Ir core.

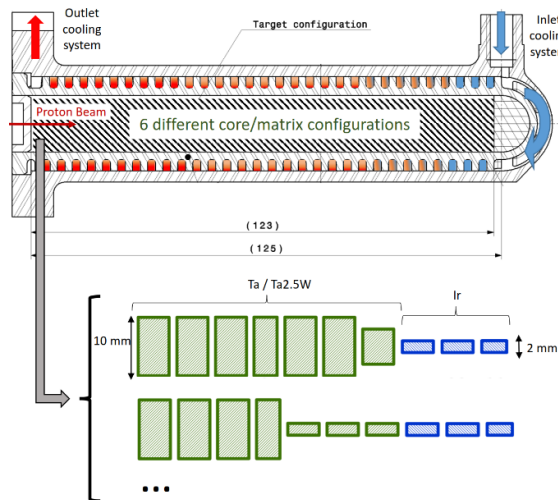


Figure 4: Geometry of the external envelope of the PROTAD targets (from PROTOtype of the AD-Target) and example of core configurations that will be tested in HiRadMat in 2018.

CONCLUSIONS

This paper presents a summary of the performed studies and ongoing prototyping activities for the new design of the CERN's Antiproton Target. The lesson learned from the numerical studies and the HRMT-27 experiment were used to manufacture and testing a scaled prototype with a Ta core and EG matrix. Its HiRadMat testing suggests a positive response of the EG matrix, while a mode of fracture of the Ta core -not previously observed- has been identified. Ongoing activities involve the manufacturing of a set of real scale targets and testing in HiRadMat to validate the final design, within the so called PROTAD experiment.

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