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Abstract. In the future hadron facility FAIR, the HESR ring will supply antiprotons in the momentum range 1.5-15 GeV/c as projectiles to study charm, strangeness and a wide range of other Physics topics. For all these reactions it will be necessary to use internal targets and in particular, for the production of systems with double strangeness, a solid ^{12}C target will be used. Inserting a solid target inside an antiproton ring creates two main problems: a large background on the detectors due to the overwhelming amount of annihilations and a strong depletion of the beam due to all the hadronic and Coulomb interactions of the antiprotons with the ^{12}C nuclei. The width of the target plays a crucial role in minimizing these unwanted effects. Two wire-shaped prototypes have been already realized, starting from a thin diamond disk. The wire shape has been obtained by using a femto-edge laser. One prototype has been submitted to irradiation by protons of 1.5 MeV and to simultaneous Back-Scattering control to test the impurity level, the ^{12}C density, the radiation hardness and possible phase modifications during irradiation. Both the prototypes have been submitted to Micro-Raman spectroscopy in order to scan the carbon phases along the width. The results show performances which satisfy the experimental requirements.

1. Introduction – The $\bar{P}$ANDA experiment

The $\bar{P}$ANDA experiment (anti-Proton Annihilation at Darmstadt) is one of the most important projects at the facility FAIR under construction in Darmstadt, Germany. $\bar{P}$ANDA will exploit the SIS100 synchrotron of FAIR, able to provide intense pulsed ion beams (from p to ^{92+}U), to create antiprotons, starting from a primary proton beam. The antiproton ($\bar{p}$) beam will be injected into the High Energy Storage Ring (HESR) and will collide at each round with the fixed target inside the $\bar{P}$ANDA setup.

The scientific program of this experiment covers several Physics topics that range from the gluonic excitations to the physics of strange and charm quarks and nucleon structure [1]. In particular, the Physics of the strange and doubly strange systems is very attractive since it is largely unexplored.

The doubly strange systems, to be studied, are:

a) Ξ^- hyperatoms, which can give information on the Ξ^--nucleus potential [2],

b) Ξ^- hypernuclei, which can provide information about the Ξ^--nucleon interaction,

c) $\Lambda\Lambda$ hypernuclei, which can supply information on the hyperon-hyperon interaction [3].

The production of these systems, in $\bar{\mathrm{P}}$ANDA, takes place through a two-step process:

a) interaction of an antiproton with a nucleon to produce a Ξ^- hyperon,

b) capture of the hyperon by another atom, after slowing down and stopping, with the formation of the doubly strange system [4].

Two targets are necessary for this purpose: in a primary target, inside the beam pipe, the Ξ^- hyperon is produced by an antiproton; in a secondary target, outside the beam pipe, the hyperon goes to stop and is captured.

In the following, the primary target features, the technique to produce it and the tests performed on the realized prototypes will be described.

2. The primary target for $\bar{\mathrm{P}}$ANDA: features and realization

The production of Ξ^- by antiproton annihilation occurs through the reaction $\bar{p} + N \rightarrow \Xi^- + \overline{\Xi}$, whose cross section is very low ($\approx 2\ \mu$b). By locating an "internal target" inside the ring, it is possible to reuse, in the following round, the antiprotons that did not interact in the previous passage through the target. In this way the bunch is more effectively used with respect to an extracted beam (see figure 1).
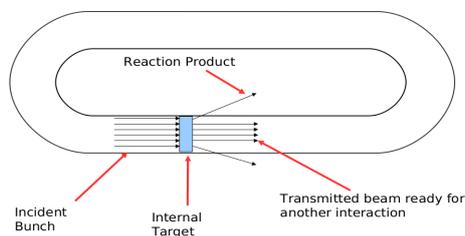

Figure 1. Scheme of a target inside a ring: not interacting projectiles can be reused.

A suitable choice for the $\bar{\mathrm{P}}$ANDA internal target is the ^{12}C nucleus. With this choice the hyperons are significantly slowed down in the dense nuclear matter of the residual nucleus after their production [4]. Nevertheless, a solid target inside a ring creates several problems to the beam, to the detectors and to the target itself. In fact: a) the bunch will undergo a strong depletion due to the hadronic and Coulomb interactions; b) a too high annihilation rate can blind the detectors; c) the interaction of the antiprotons can generate high thermal and mechanical stresses and possible charge pile-up inside the target. Therefore, it is mandatory to properly choose material, shape and dimensions of target in order to minimize these problems.

A very good mechanical resistance as well as large thermal conductivity is assured by a diamond target. These features are important because they make the target strong enough to resist to beam impact stresses, they allow to easily handle it inside the beam pipe and permit to dissipate the heat produced in the target by the passages of the beam through it.

The shape chosen is a wire of 3 μm thickness and 100 μm width. The small dimensions together with the steering of only the periphery of the beam spot onto the target [5] allow to reduce the annihilation rate down to a tolerable value ($\approx 5 \cdot 10^6$ annihilation/s, for the hypernuclear scientific program) for the $\bar{\mathrm{P}}$ANDA detectors [6]. Finally, the Si ring holding
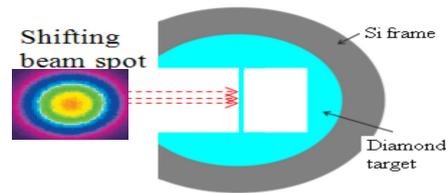
Figure 2. Scheme of the C-shaped support of the target.

the wire target will be cut C-shaped (see figure 2) in order to allow the beam to be slowly steered from left to right avoiding annihilations in the thick frame.

The first attempt to produce the diamond wire was performed by using an amorphous deposition. A carbon film nearly 3 μm thick was deposited on a disk shaped Cu substrate (500 μm thick, 12 mm in diameter). Purity and density were measured by means of the Back Scattering technique (BS), using a 1.5 MeV proton beam at LNL (National INFN Laboratories of Legnaro) at a scattering angle of 165°. The measured areal density of the film was $8.3 \cdot 10^{18}$ atom/cm^2 and the ^{12}C purity level was 54%. A high percentage of impurities was present: 7% of ^{16}O and 39% of H. This impurity level was considered too big because the hydrogen nuclei do not slow down the hyperons and the efficiency in the double hypernuclei formation would be strongly decreased. Moreover, the density of the film was four times less than that of graphite. This means that the amorphous deposition should be four times thicker in order to obtain an equivalent target thickness; however, in such a kind of films higher thickness produces higher brittleness that cannot be tolerated. Finally, the five trials made, using a 30 KeV Ga-ion beam, to cut away two rectangles inside the film, in order to shape a wire, were unsuccessful with final breakage of the wire. Therefore, this technique was discarded [7].

Figure 3. The diamond disk (transparent area) stuck onto the silicon ring (black ring).

A second method was explored. The prototype production started with the manufacturing, from DIAMOND MATERIALS GmbH Company (Freiburg), of disk-shaped diamond films by Chemical Vapor Deposition (CVD) on a Silicon plate of 15 mm diameter and (500 ± 100) μm thickness. An internal disk of lower diameter (11 mm) was then etched away from the Si support obtaining a freestanding diamond plate on the silicon ring, with 15 mm outside diameter and diamond disk thickness of (3 ± 0.5) μm. One of the prototypes is shown in figure 3. The presence of a stressed region is visible as a wavy surface close to the internal border of the silicon ring. This stress could be a source of brittleness and can cause problems in the cutting operations. This sample was submitted to several tests: the first one was the "micro beam" test at LNL. The diamond disk was exposed to irradiation by a 1.5 MeV proton beam in two points, close to the center of the disk, for about one and two hours, respectively. The beam spot areas were 3470×3470 and 870×870 μm^2. The proton back scattering rate was measured, during the exposure time, in the same conditions (energy and angle) of the test on the amorphous

film. The irradiation results show that the percentage of ^{12}C in the sample is about 99.9% (as expected from the company specifications) and the content of other nuclei is compatible with zero. The areal density is about $50 \cdot 10^{18}$ atom/cm^2, nearly 50% higher than the graphite density (approximately $34 \cdot 10^{18}$ atom/cm^2). Moreover, the density has been found to be equal in both points, irradiated with different beam intensities. This indicates that such an irradiation does not produce significant changes in the diamond structure.

The target prototype was also tested under a multi-cycle low energy proton beam at LNL, to test the response to mechanical stresses (due to the target-beam interaction) similar to the in-ring conditions. The proton beam current was chosen to reproduce the worst energy loss conditions in $\bar{\text{P}}$ANDA ($dE/dx \approx 1.8$ MeV/(g/cm^2) for antiprotons at 3 GeV/c at HESR, while $dE/dx \approx 111$ MeV/(g/cm^2) for protons of 2.75 MeV/c at LNL). The proton current of about 2.7 nA is producing a total energy loss per time unit equivalent to the $\bar{\text{P}}$ANDA antiproton beam. The irradiation was performed at even higher current (4 nA), in order to test the sample in worse conditions than at HESR. As before, the sample was simultaneously monitored measuring BS. The plot of the number of back scattered protons versus time showed a linear trend, indicating that neither structural variation nor charge pile-up occurred.

The second step in the target production was the diamond cut into the wire shape. This procedure was obtained through laser cuts. A first wire about 100 μm wide, 3 μm thick and 6 mm long was successfully obtained by cutting away two rectangles in the disk (see figure 4). A "Femto Edge" type laser of 3 W power, 1064 nm wavelength and 100 fs pulse duration was used for the cut. The effects of the laser cutting on the internal structure of the wire were

Figure 4. The diamond disk after laser cutting: the wire is visible in the centre between the two white rectangles.

investigated through Raman spectroscopy. Three points have been analyzed along the width of the wire: the center, the periphery and the border. A schematic detail of these regions is reported in figure 5 (left) together with the results of the Raman spectroscopy (right). In the figure it can be seen that the bottom curve (center) shows only a clear peak in the region of the diamond (D) phase. The middle curve (periphery), instead, shows a very slight enhancement in the region of the graphite (G) phase (with corresponding reduction in the D phase) and finally the top curve (border) shows a dominance of the G phase with respect to the D phase. The laser cut, therefore, seems to affect the lateral boundary (along the cut edge) of the wire, creating a graphitization phase and leaving the central region unaffected. The graphitization process increases the electrical conductivity at the border. This unexpected phenomenon is actually positive, since the passage of antiprotons through the target could produce electrostatic charges and a conductive channel would create a discharging path toward the supporting frame of the ring. It is important to remark that, in the central part of the wire, the diamond structure does not change and the thermal and mechanical properties remain intact.

A second prototype of diamond wire was produced (by χLab, Chivasso, Italy) with the aim of verifying the change of structure diamond-graphite, after the cut, on a larger width (≈ 145 μm). The laser system PHAROS (LigthCOnv), a femtosecond, Ytterbium doped, solid state laser with 1.5 W power, 343 nm wavelength and 220 fs pulse duration, was used for the process.
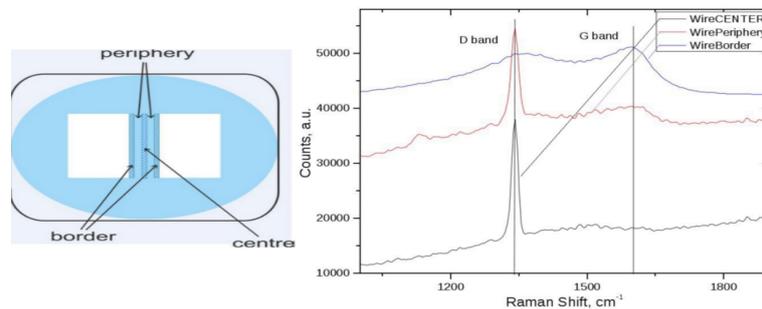
Figure 5. (Left) schematic close up view of the wire profile, showing the three regions examined by Raman spectroscopy. The distances from the edge are, for the border, 2–3 μm and for the periphery and centre about 10 μm and 50 μm, respectively. (Right) Raman spectra of the central (lower curve), peripheral (middle curve) and boundary (upper curve) points along the width of the wire. The D band indicates the diamond while the G band indicates the graphite phase.

The Raman spectroscopy was performed on this wire in three different points, shown in figure 6 (left). The rightmost part of figure 6, instead, reports the Raman spectra measured for the
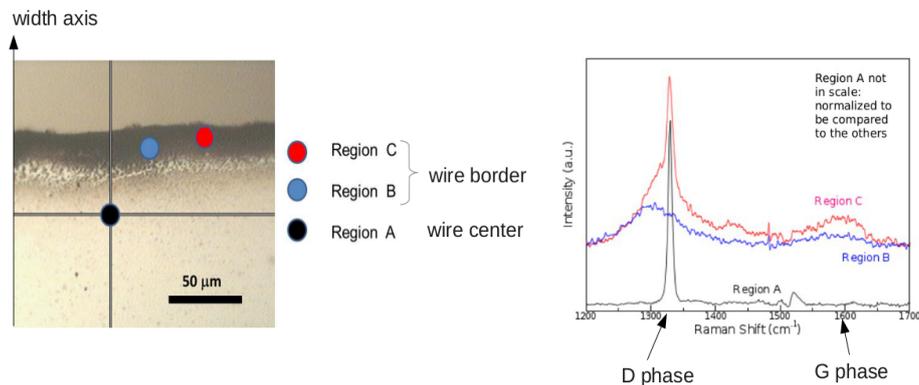

Figure 6. (Left) optical image of investigated points. (Right) Raman spectra measured on the wire center (black curve) and border (blue and red curves).

three different points: A (wire centre), B and C (wire border, close to the cut region). Region A shows the spectrum of pure diamond: it can be seen that no other features appear but a single narrow peak at 1332 cm^{-1} (2 cm^{-1} FWHM). In region C, instead, three features appear in the Raman spectrum: the diamond peak at 1330 cm^{-1} (10 cm^{-1} FWHM), the G band at 1585 cm^{-1} (83 cm^{-1} FWHM), and the D band at 1321 cm^{-1} (93 cm^{-1} FWHM). These results suggest the presence of residual clusters of diamond within the graphitized column, which shows the typical features of nano-crystalline graphite (nc-G). Data obtained in region B, finally, show a complete removal of diamond content and the typical nc-G spectrum. A new laser treatment with different parameters could improve the graphitization process along the wire border.

3. Conclusions and outlooks
A technique to produce a wire shaped primary target, to be inserted inside the $\bar{\text{p}}$ HESR ring, satisfying both the beam constraints and the requirements of the $\bar{\text{P}}$ANDA experiment, has been realized. The diamond wire is fabricated in a two-step process: starting from a diamond disk, obtained through CVD on a Silicon ring, the diamond wire is then produced from the disk

through laser cutting.

Two solid, thin, wire-shaped ^{12}C targets have been already realized.

The first prototype has been submitted to some preliminary tests at the LNL: proton irradiation with BS technique and Raman spectroscopy. These tests have given preliminary positive results: on the disk, mechanical resistance tests and BS controls pointed out that no structural variation and no charge pile-up were created by the irradiation processes; on the wire, Raman spectroscopy highlighted that the laser cutting produced a graphitization process along the sides of the wire. On the second prototype, instead, only a Raman spectroscopy measurement has been performed until now: in this case also, Raman spectroscopy underlined the presence of a spectrum indicating a nc-G structure in the wire border as a consequence of the laser cutting.

Systematic tests of the same type are planned for both the wire prototypes in order to scan the whole target surface; heavier exposures to radiations are planned too. Other prototype realization is foreseen.

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