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PRESENT AND FUTURE POSSIBILITIES OF ANTIPROTON PRODUCTION FROM FIXED TARGETS AT CERN

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ABSTRACT

The CERN Antiproton Accumulator Complex, AAC, stores 3.5 GeV/c antiprotons produced in the collisions between an external 26 GeV/c proton beam and a fixed target. The present operational yield is 5×10^{-6} $\bar{p}$/p, which, for a beam of 10^{13} protons every 2.4 s, corresponds to a maximum production rate of 7.5×10^{10} $\bar{p}$/h. Accumulation rates are from one third to one half of the production rates due to losses during the collection and stacking processes. This performance can be improved somewhat by collecting antiprotons into a larger solid angle using a more powerful collector lens, but the parameters of the AA Complex restrict this potential gain to a factor of only 1.5. Two future improvements: increased proton flux and antiproton focusing within the target can extend the production rate to 5×10^{11} $\bar{p}$/h, but these developments will require more sophisticated targets at the limits of known technologies.

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1. *INTRODUCTION*

The CERN Antiproton Accumulator Complex, AAC, comprises an antiproton production area, a collector ring, AC, and an accumulator ring, AA [1]. In the production area, a high-intensity 26 GeV/c proton beam is directed onto a heavy-metal target, from which a beam of negative secondaries in a 6% momentum bite around 3.5 GeV/c is selected and transferred to the collector ring and from there, after bunch rotation and stochastic cooling, into the accumulator. These are housed in an adjoining machine hall and thereby separated from the high-radiation environment of the target region. The transverse acceptance of the AC is nominally 200π mm.-mrad in both plane.

The production beam consists of five bunches each of 2×10^{12} protons arriving on the target in a burst of 0.5 μs duration. This can be repeated every 2.4 s or in multiples of this period. The bunch length is 20 ns and the time between bunches is 110 ns. The beam is strongly focused at the target such that 95% of the beam lies within a circular spot of 1 mm radius, with a local divergence of 2 mrad. This ensures that all of the beam passes through the target, which is normally a 3 mm diameter × 55 mm long rod of iridium. The target rod is pressed into a graphite cylinder and sealed within a double-walled, water-cooled, titanium alloy container. This target unit, together with the first focusing element of the transfer line, a 20 mm diameter lithium lens [2], forms a very compact assembly, subject to high primary and secondary particle fluxes and requiring totally remote handling techniques. A section through a typical target/lens assembly is shown in Fig. 1.

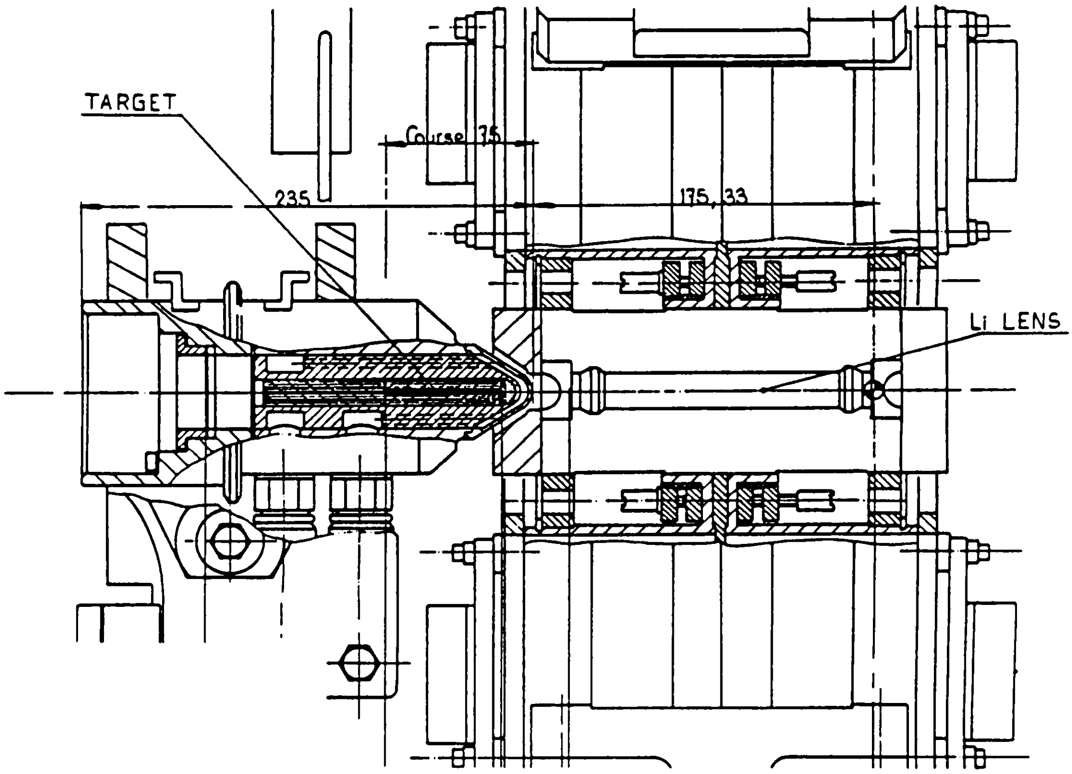

Fig. 1 *Iridium production target 55 mm long, 3 mm diameter and the 20 mm diameter Li lens. Distance from centre of target to upstream end of lens, d = 86 mm. Effective length of lens, ℓ = 130 mm.*

2. SIMULATION OF ANTIPROTON PRODUCTION

An antiproton production simulation program [3] has been used to optimise the size and choice of material for the target, together with the dimensions and focusing strength of the lithium lens. The dilution in phase-space density at large production angles, arising from the use of a relatively long target, imposes a limit on the gain in antiproton yield which can be obtained simply by increasing the lens strength so as to collect over a larger solid angle. This is illustrated in Fig. 2 in which two phase-space ellipses, each corresponding to the Collector acceptance, but for two different lens strengths, are shown overlaid onto an antiproton scatter plot in transverse phase-space at the mid point of the target. The capture of more high-divergence particles by the stronger lens is offset by the loss from the acceptance of particles with large displacement and low divergence. For our machine parameters, when using a passive target, the optimum yield is achieved by arranging to collect antiprotons with laboratory production angles up to 73 mrad. The corresponding target/lens geometry is given in Fig. 3 together with a set of curves relating lithium lens length, current and target position. It may be seen that to achieve the desired collection angle, the target must be placed very close to the upstream face of the lithium lens. This is a great operational inconvenience and is not practicable with the existing target design. To overcome this limitation one may shorten the existing lens or use a new lens of larger diameter and longer focal length, but in both cases lens current must be increased. A lens of increased diameter is the preferred solution since the subsequent beam-optical matching into the Antiproton Collector becomes easier, however, a short 20 mm lens being less expensive and more readily available may be the pragmatic choice.

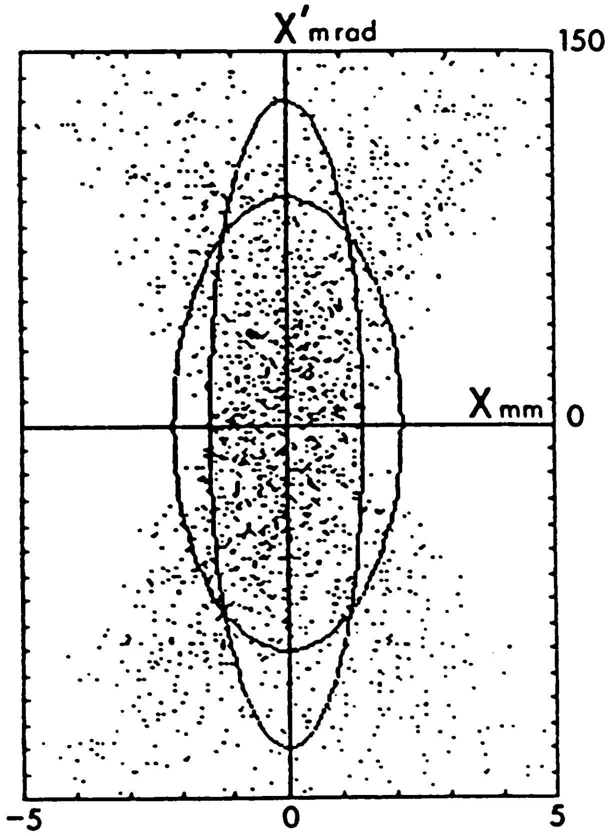

Fig. 2

Transverse phase-space scatter plot referred to centre of target. The ellipses represent the AC acceptance for two different lens strengths.

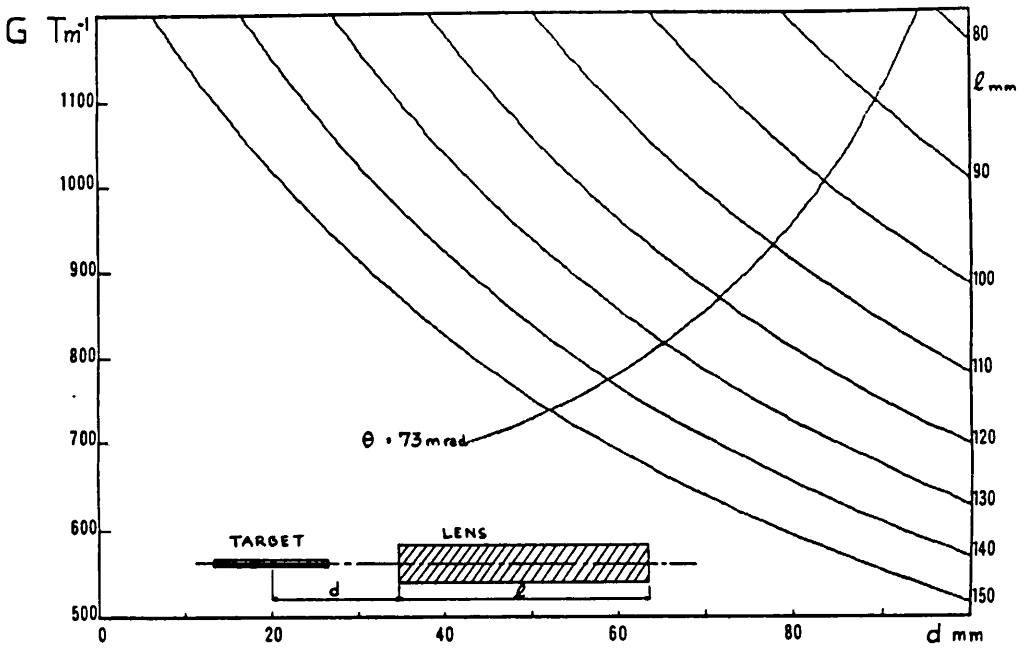

Fig. 3 *Curves showing the relationship between Li lens gradient, G, effective length, ℓ, and target to lens separation, d, satisfying the condition that the centre of the target is at the focal point of the lens. Also shown is the curve along which the maximum accepted angle, θ, is 73 mrad.*

3. ANTIPROTON YIELD IMPROVEMENT

In the existing operational target/lens assembly, as illustrated in Fig. 1, the target to lens separation is 30% greater than the calculated optimum value, and the lens has not yet been run up to the current required for peak yield. The resulting deficiency in yield will be made up by providing more current to the existing lens and then by the use of a shorter, or a larger diameter lens, as described above. A 50% overall improvement is expected. Thereafter, further gains in production rate will be sought by increasing the production beam intensity (up to 2×10^{13} ppp). However, this will be accompanied by a rapidly increasing target damage rate, requiring more frequent exchange of targets with a concomitant increase in the production down-time.

One further improvement to the fixed-target production rate is obtained by passing a pulsed current through the target at beam time. This has the effect of focusing antiprotons as they are produced along the target and thus reducing its effective length. With increasing current density, the effective length, insofar as it affects the phase-space density of particles, tends to zero. All antiprotons produced at angles within the limits of the machine acceptance exit from the end face of the target, i.e. appear to come from a thin disk-target. This is illustrated in Fig. 4 where the phase-space "butterfly", now plotted in a plane referred to the downstream end of the target, is compressed by the current into a vertical band of more uniform density, characteristic of the scatter plot from a thin target. The target reabsorbs more antiprotons, but there is an overall gain in antiproton yield by a factor 2 to 3.

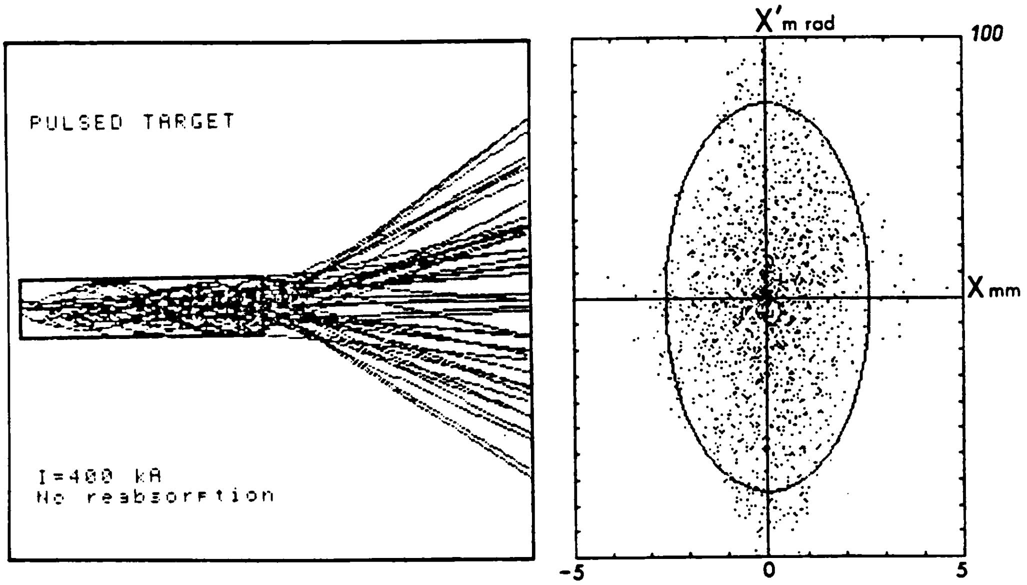

Fig. 4 *Transverse phase-space plot at the downstream end of a pulsed-current target carrying 400 kA. The ellipse represents the AC acceptance of 200π mm.mrad.*

Even at currents well below the optimum, some improvement in yield is observed, and there is a further advantage, namely that the effective centre of production moves towards the downstream end of the target. Thus a pulsed-current target sits further away from the lithium lens and this alleviates to some extent the difficulty of setting the center of production at the focus of the lens.

4. *PRODUCTION LIMITS*

The improvements described in the last section will, if they can all be applied together, give rise to a maximum yield into the Collector of 1.5×10^{-5} $\bar{p}$/p and a production rate of 5×10^{11} $\bar{p}$/h for 2×10^{13} protons per pulse on the target. Down time is very likely to increase, as may the antiproton accumulation inefficiencies, so that the best time-averaged accumulation rate may be limited to a value around 1.5×10^{11} $\bar{p}$/h.

5. *TECHNOLOGICAL BARRIERS*

Today's target/lens technology has been developed over a period of five years in collaboration with Fermilab, Chicago [4] and the INP at Novosibirsk. We are still gaining experience of the lifetimes of these devices. The target suffers beam-induced shock-wave and radiation damage to the iridium core and its container. The lens and its surrounding transformer receive electromechanical shocks from the current pulse, radiation damage and secondary-particle shower heating from the beam, and they are at risk from the spray of material and coolant emitted by ruptured targets. This all adds up to interesting technology, which becomes particularly challenging when one replaces the passive target by a pulsed-current version.

5.1 The Lens and Lens Transformer

Increasing the current density in the lens to accommodate the full 73 mrad forward production angle appears to present only moderate financial and technical problems. One risk is that the lithium melts, but liquid lithium lenses are being studied at Novosibirsk [5], whilst at CERN, high-current parabolic-sheet lenses (magnetic horns) [6] and a plasma lens [7] are also being developed as alternatives to the lithium lens for this application.

5.2 Passive Targets

High-density metal targets are known to suffer shock-wave damage resulting in the shattering of the 3 mm diameter × 10 mm rods that form the target. The fragments are contained within the graphite surround, but this is compressible and the result may be a reduction in the average density of target material in the beam. Targets of 2 mm diameter iridium clad in electro-deposited copper or nickel to an external diameter of 4 mm and then pressed into graphite have been prepared in an effort to reduce this damage. Most of the antiproton production is from the 2 mm core. The cladding contributes little to the production, serving mainly to hold the iridium fragments together.

Some shock-wave calculations predict that there will be important target density fluctuations during the 0.5 μs beam pulse. These can be reduced by improving the acoustic impedance matching between the target rod and container. They may be studied experimentally by observing the yields from the five individual bunches that make up the pulse. Any variation in target density should show up as a change in yield from bunch to bunch. Our beam instrumentation is not sufficiently sensitive to observe the antiproton bunches directly, but shower detectors situated outside the Antiproton Collector are used to observe muons from the decay of captured negative pions during their first few turns around the machine. On these detectors the analog signals from individual bunches are clearly seen, a typical signal is shown in Fig. 5. The feared high-frequency density changes are not observed at present beam intensities.

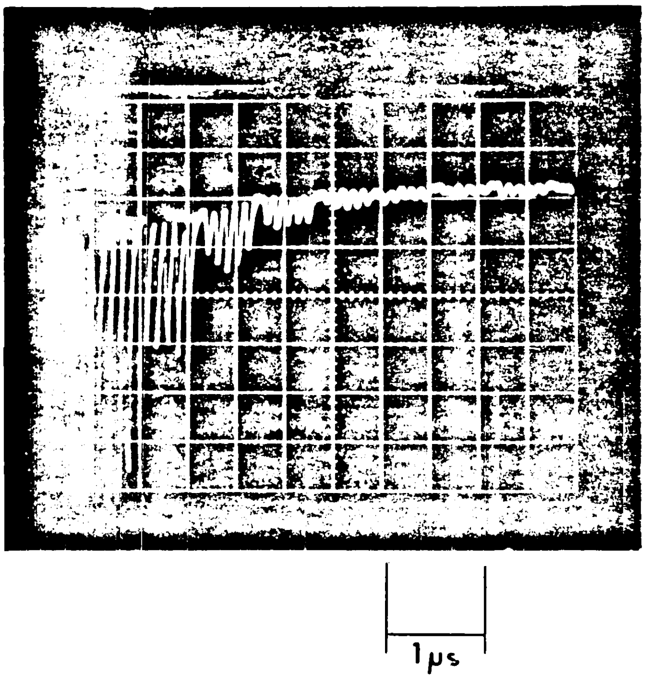

Fig. 5

Analog signal from a muon detector placed alongside the AC. The five circulating bunches of negative pions are visible on the first, second and third turns.

In addition to shock-wave damage, the target density is reduced by radiation-induced void formation. This effect is thought to account for the yield reduction observed over the first few days in the life of the copper targets used previously with the Antiproton Accumulator. As the changes are relatively slow - a few percent per day - their observation depends on having steady production conditions. During the first few weeks of operation with the new high-density targets and the Antiproton Collector the performance has not yet settled down to the point that void formation swelling can be diagnosed. However, it cannot easily be avoided and we anticipate that it will be the major cause of target yield reduction, requiring periodic target exchange to maintain the desired performance.

The target container is a double-walled, water-cooled, highprecision titanium alloy assembly designed for beams of up to 2×10^{13} protons. The combined effects of beam heating and shock-waves can cause rapid fatigue failure in the region of the end cap of the container traversed by the proton beam. Steel containers have been pierced by the beam after only 3×10^{5} pulses. Aluminium and titanium containers, if adequately cooled, should have lifetimes in excess of 10^{7} pulses. But, being relatively close to the fatigue limit, attention has to be paid to the quality of materials and surface finishes.

Single-shot and liquid-metal targets have been proposed at various times ot overcome one or more of the above limitations, but as yet no fully engineered devices exist.

5.3 Pulsed Current Target

Targets intended for pulsed-current use must withstand the magnetic pinch and the electrical heating in addition to the beam-induced heating and damage. Many pulsed-current targets have been tested to destruction in the laboratory and several in the proton beam [8]. Two basic designs have evolved: in the first the target rod is mounted with only radial constraint to prevent buckling, but in the second type the target is fully constrained in a high-pressure container. The former type suffers fatigue failure, whereas in the latter, particularly if operating, as may be required, above the target anneal temperature, the container is prone to rupture. Both types have survived many thousands of pulses without beam and a few thousand pulses in production beams. The predicted gains in antiproton yield have been observed and such targets are still considered to offer the most cost-effective means to increased production rates once the target/lens geometry has been optimised and the production beam intensity raised.

The most promising design of the second type is shown in Fig. 6. The container is such that the radial pressure from the target rod is distributed by anodised aluminium discs before being applied to the electrical insulators [9]. Also, the fit of components is adjusted so that the required pressure (10 to 15 kbar) is attained only when the target is at operating temperature. Pre-heating, either by the beam itself or by passing a bias current, is required before current pulsing. This is the only pulsed current target to have survived beam tests, although of very limited duration, and it will be used as a starting point for future development.

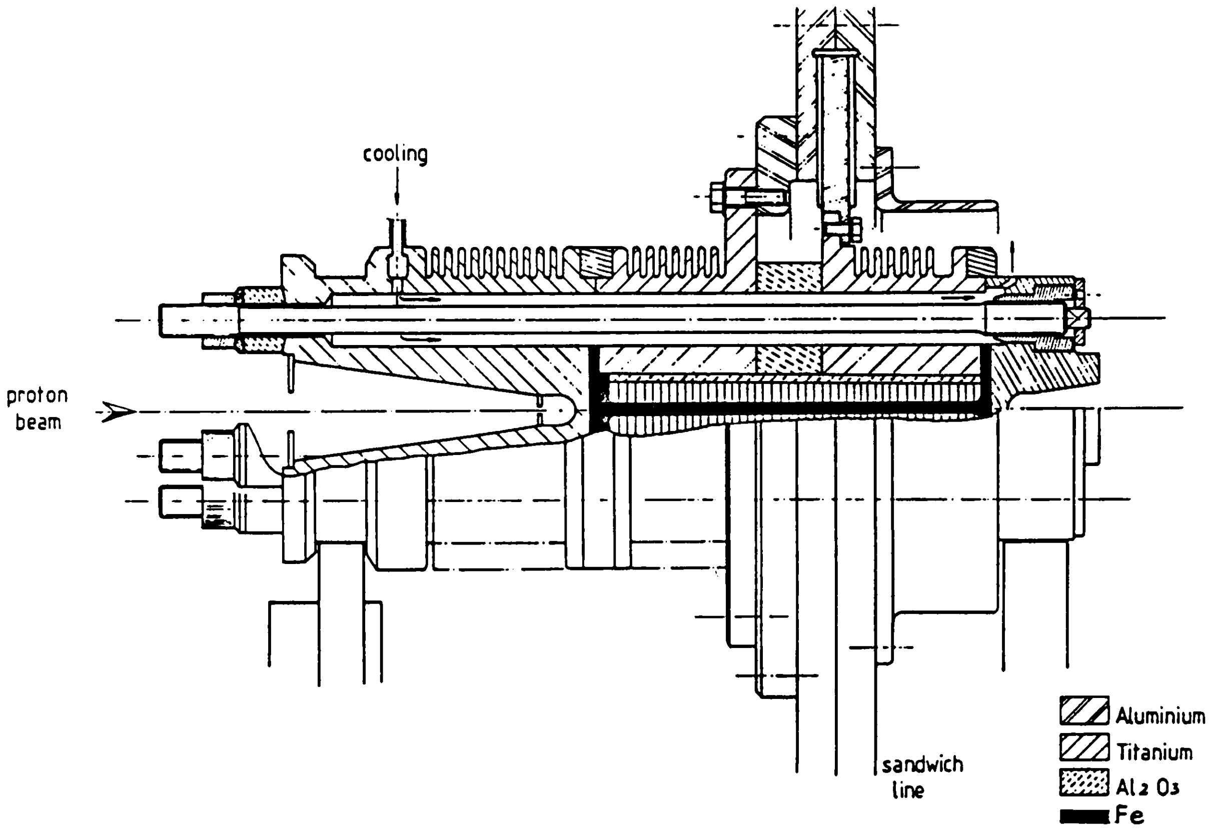

Fig. 6 *A part section through a pulsed current target designed to carry up to 200 kA, giving an antiproton yield improvement factor of 1.7. Anodised aluminium disks surround the iron target to spread the shock loads thereby preventing damage to the alumina insulators.*

The basic technological problem is to find some target system that will support the high currents, shocks and radiation levels for a useful lifetime of at least 10^6 beam pulses. The use of metals above their anneal temperatures or in the molten state is considered essential to prevent embrittlement and consequent mechanical failure. Molten alloys such as gold-silicon or liquid indium have suitable electrical properties, but there is not yet a solution to the problem of providing a container with end-windows that will survive the proton beam and not dissolve in the target material. The gain from a pulsed-current target is only a factor 2 or 3 even under ideal conditions, and the technological compromises and complications that accompany the use of liquid metals may result in non-viable designs giving little improvement and considerable operational overheads. A more promising development would be a low-cost pulsed target of the type shown in Fig. 6, operating in the plastic state with a moderate lifetime and a "quick change" mechanism to facilitate replacement.

6. FUTURE EXPECTATIONS

The AAC target area is now equipped for high-radiation operation and target/lens research and development. During the next year we should see the antiproton production rate rising as the passive target and collector lens combinations are tested and optimised. As the proton beam intensity goes up, there will be an increasing need for remote and rapid target exchange. This will be made easier when the large diameter lithium lens or the high-current magnetic horn becomes available. Pulsed targets should then be reintroduced in semi-operational versions with fast default to passive target operation when they fail. This part of the programme cannot begin before 1989.

The potential production rates presented in this report exceed the AAC design goals by more than a factor 2. They can be achieved only by solving the technological problems that have been mentioned. Furthermore, they exceed the present capabilities of the stochastic cooling systems. B. Autin [10] has discussed ways of extending the cooling techniques to cope with the increased production.

ACKNOWLEDGEMENTS

This brief review of antiproton targetry covers the four years of the ACOL Project and beyond. The source material comes from many members of the Project team and collaborators, to whom credit is given in the references. The Project Leader, E. Jones, contributed stylishly by injecting some of the more original ideas, including one that led to the first pulsed current target to survive beam tests. R. Horne assisted with remote handling and target dissections, and A. Molat-Berbiers prepared the manuscript. I respectfully acknowledge the participation of these colleagues.

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