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A Self-focusing Mercury Jet Target

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Abstract

Mercury jet production targets have been studied in relation to antiproton production and, more recently, pion production for a neutrino factory. There has always been a temptation to include some self-focusing of the secondaries by passing a current through the mercury jet analogous to the already proven lithium lens. However, skin heating of the mercury causes fast vaporization leading to the development of a gliding discharge along the surface of the jet. This external discharge can, nevertheless, provide some useful focusing of the secondaries in the case of the neutrino factory. The technical complications must not be underestimated.

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1. Historical introduction

During a period of six years from 1981 to 1987 CERN conducted an active research program into the optimization of secondary particle production from high-density targets in the CERN PS 26 GeV/c proton beam. This was directed towards the production of 3.5 GeV/c antiprotons for the Antiproton Accumulator, AA [1], and later the Antiproton Collector, ACOL [2]. At the same time other secondaries, notably electrons, pions and muons of the same momentum were captured and used for machine alignment being more readily observable than the relatively scarce antiprotons [3].

Initially production targets were copper rods 3 mm diameter and length roughly equal to the interaction length (148 mm). The secondaries were fed into a magnetic horn for matching to the downstream quadrupole transport line. Development at Fermilab [4] of lithium lenses of shorter focal length than the horn offered an improved antiproton yield but only if the length of the production target could be reduced significantly (depth of focus effect). High-density targets having much shorter interaction lengths were required. But the increased beam-induced thermal shock effects caused rapid degradation of the target material and container windows. A satisfactory solution evolved whereby iridium targets were clad in nickel and then pressed into graphite sleeves themselves tightly contained in a double-walled water-cooled titanium alloy vessel [5].

During these target tests it was well known that by passing a current through the target at beam time the upstream secondaries could be focused towards the downstream end of the target thus shortening the effective length. It was considered that in this way low-Z target material could be used with the lithium lens without the depth-of-focus effect. Many different targets were constructed and high-current pulse tests were made both in and out of the proton beam. Currents were in the range 50 to 170 kA. As predicted, the antiproton yield was improved by almost a factor two [6,7] with target lifetime estimates of a few days. Further improvement, requiring additional target current, became impracticable due to target over-heating (self-annealed material) or target fatigue failure (brittle material). One or the other of these limitations reduced production target lifetimes to a few hours.

A. Poncet, working on advanced mechanical engineering projects for the AA, suggested that some of the limitations of pulsed current target lifetime could be overcome by using a mercury jet target, that could itself switch on an internal current pulse by firing it across a high-voltage gap [8]. A model 3 mm diameter passive mercury jet was constructed as a first stage and this proved to be extremely successful, see Figure 1. Regular jets traveling at 20 m/s could be produced with little turbulence. However, at that time one of our collaborating groups, that of Professor Jäger of the University of Graz, pointed out that it would not be possible to pass a current through the body of the mercury jet.

The team at Graz were studying the explosive disruption of targets induced by high-current pulses (exploding wires). This work, originating at the University of Kiel, was directed towards the production and study of high-density plasmas. Professor Jäger assured us that when trying to force the current through mercury (in vacuum) the skin current would cause rapid vaporization of the outer layer of mercury and the resulting electrical discharge would pass through this vapour.

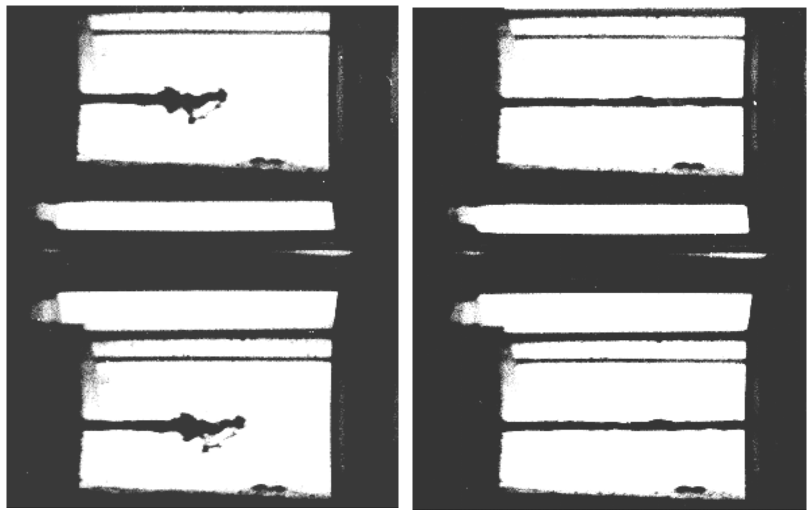


Figure 1. High-speed photographs of mercury jet target for CERN-PS-AA (laboratory tests) 4,000 frames per second, Jet speed: 20 ms^{-1}, diameter: 3 mm, Reynold's number >100,000. Photograph provided by A. Poncet.

A similar surface discharge is frequently observed, and even exploited in switching devices, when a solid wire with a low-pressure gas surround receives a high-voltage pulse – a *'gliding discharge'* so called because it moves along the wire surface during the voltage pulse. Figure 2, from a review article by H. Jäger [9] illustrates this effect.

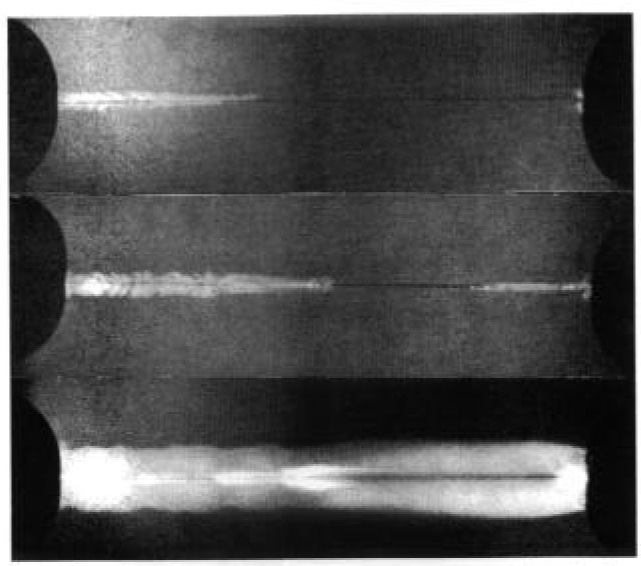


Abb. 14. Ausbildung einer peripheren Entladung bei Unterdruck. „Aufnahmezeitpunkte" 0,3; 0,6 und 2 μsec nach Beginn der Entladung. Bedingungen wie bei Abb. 4, jedoch $p=0{,}02$ atm, linke Elektrode (+).

Figure 2: Photograph of a gaseous discharge developing (gliding) along a high-voltage pulsed metal wire, Ref 9.

Undeterred, at CERN we substituted for the fully-penetrated current in the target (as assumed for previous calculations) a current passing along the outside of the target close to the surface – Figure 2c. To our disappointment the best improvement offered by this surface current with our fixed target-lens geometry was only 10% compared to 70% from a solid metal target contained within an insulator or an improvement of more than a factor 2 for a pulsed CuBe target in air.

2. Another application

The gain from focusing by the vapour discharge was very low because of the geometry – for 3.5 GeV/c antiprotons a very high magnetic field was needed within and close to the target material to deflect the relatively high momentum but low divergence particles into the 20 mm lithium lens aperture. For the CERN neutrino factory reference scenario a large aperture magnetic horn has been chosen to collect pions and these have low momentum exiting the target at divergences up to a few hundred mrad. For this reason the target is essentially contained within the horn. This is a more favorable geometry for focusing by a gliding discharge. A current flowing in the region within 0 to 10 mm radius of the target surface can contribute significantly to the capture efficiency of the horn.

Perhaps a more important gain arises from the redistribution pions in transverse phase space that allows the possibility of removing the mercury target from within the horn to a position immediately upstream. This might be a sufficient advantage to warrant further investigation of the technology needed to provide a current source for the jet. However, although compared to the antiproton case the pions have only about one tenth the momentum, the divergences involved are much greater and so we cannot expect to observe a useful effect without a high magnetic field and consequently a high current. The magnetic field needed to deflect a 300 MeV/c pion through 400 mrad over a 200 mm long discharge is 2 T, and as the pions start from within the discharge where the field is zero we can expect the maximum field requirement at the outer surface of the discharge to be considerably more than this.

In the work reported by Jäger et Al. the discharge currents were in the tens of kA region. For an active target we are looking for much more than this (up to 170 kA used for AA). There appears to be little or no information on the upper current limits in a mercury vapour discharge. It is not known if the mercury jet would remain intact during the few μs needed for the discharge to form at these high currents, nor have we studied the resulting magnetic pinch effect. The latter could be calculated, but a fairly extensive R&D program would in any case be needed.

2.1. Simulations

Some notion of the focusing efficiency of a vapour discharge can be gleaned from a simple numerical simulation. In the simulations presented below, pions over a kinetic energy range from 160 to 400 MeV exiting a 5 mm radius mercury target at laboratory angles up to 400 mrad are focused by the external electrical discharge. Selected pion trajectories are plotted and transverse phase space scatter plots, **R,|R'|** are generated at a position just downstream of the target are. Only those pions of the appropriate polarity are shown.

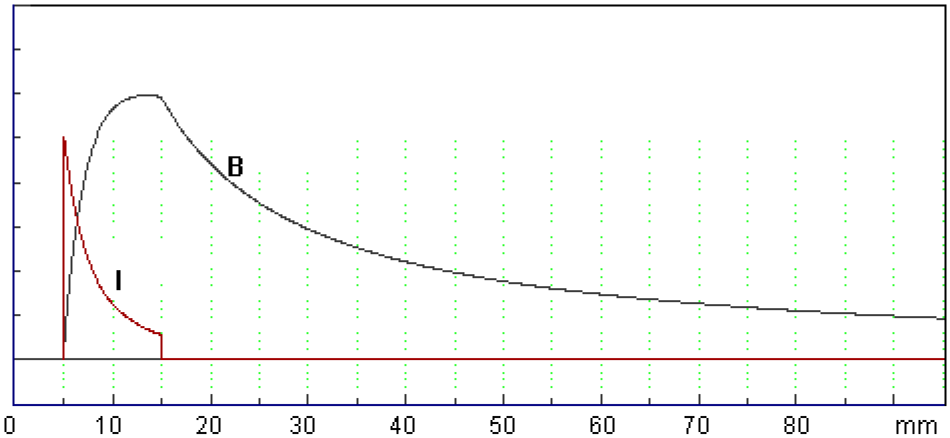


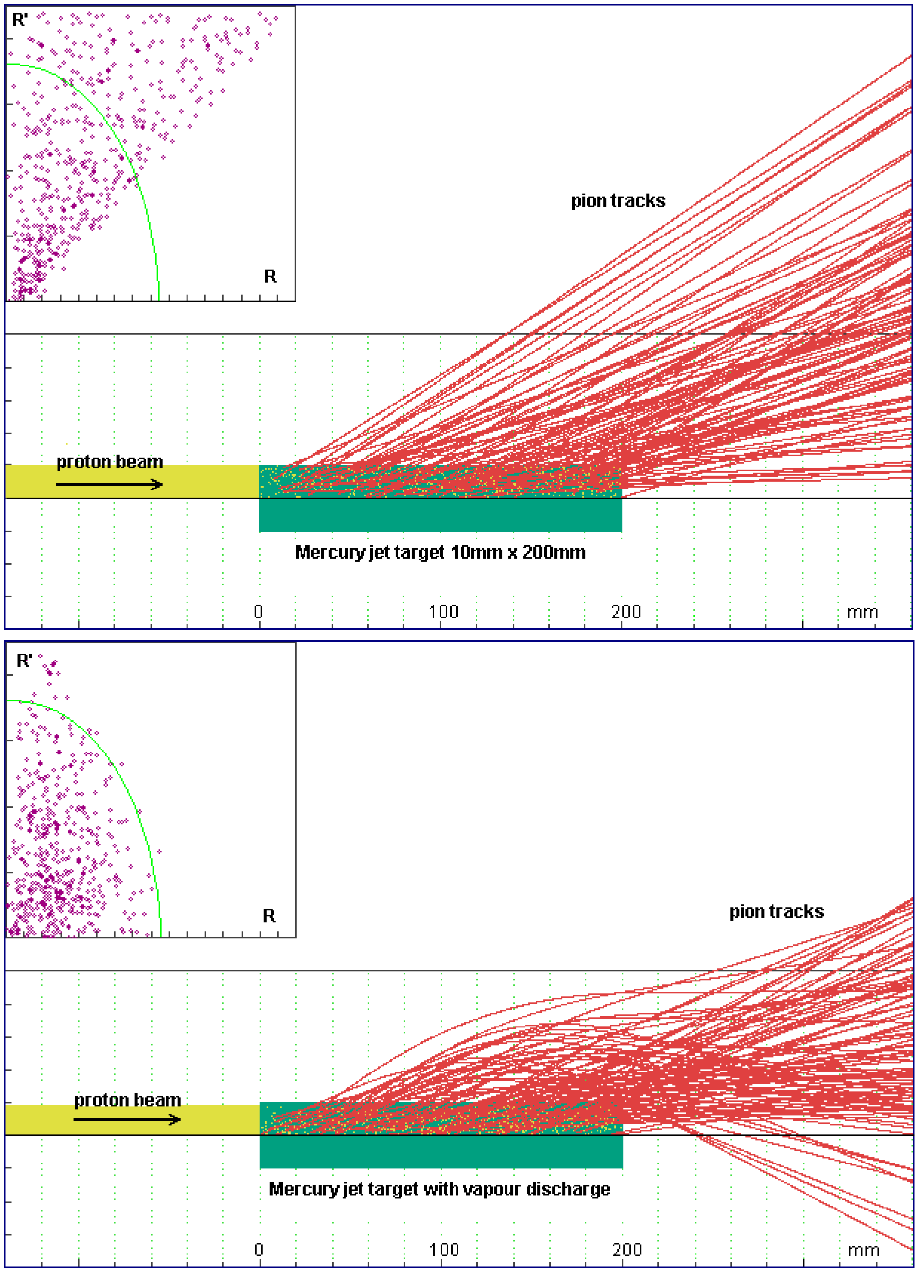
Figure 3: Current and magnetic field - radial distributions. The vertical scales are arbitrary. The current distribution (current per mm^2) in the discharge is assumed to vary as $1/R^2$ from the outer skin of the jet to a radius of 15 mm. On the time scale of the pion production $dI/dt=0$.

It is assumed that the current in the discharge reaches a peak, with relatively little *dI/dt*, after a few microseconds. The radial distribution of current (per mm^2) is assumed to vary as $1/R^2$ up to a limiting radius of 15 mm. The total current in the discharge, giving rise to a peak magnetic field at radius 15 mm is I_{tot}.

The pion trajectories plotted in Figure 4b from the upper half of the target in the angular range from 0 to 400 mrad are focused into an angular range ± 400 mrad appearing to come from the downstream end of the target plus some lower divergence trajectories from further upstream. The number contained within a linear transverse phase space acceptance, shown by the half-ellipses in the inset plots is clearly enhanced by a factor between 1.5 and 2. Note that for clarity 100 trajectories are plotted for pions with initially positive R' and only axial trajectories from a radial slice of the target are shown. The scatter plots are more representative of real pion distributions. Any improvement that might be achieved with a non-linear horn must be investigated by running a full target/horn simulation using GEANT 4.

3. Tentative conclusions

There appears to be no way to operate a mercury jet target with a fully penetrated current in the region of 150 kA. The vapour discharge current, I_{tot}, needed to give sufficient focusing, similar to that illustrated in Figure 4, turns out to be around 500 kA. This is way beyond any existing mercury discharge, or exploding wire discharge current. It might well turn out to be impossible, or not worth the considerable technical complications. But since there has been some recent speculation regarding the benefits of pulsed-current targets for pion collection [10], the mercury jet with a vapour discharge should be fully simulated with an integrated and optimized horn for comparison with other pion capture options [11].



Figures 4a, 4b: Tracks of pion trajectories from a 10 mm x 200 mm mercury target with and without a vapour discharge as described in Fig. 3 (dI/dt=0). In this simple simulation only axial trajectories are plotted (ϕ,ϕ' = 0). The inset figures are plots of transverse phase space, R,|R'| at a point at the downstream end of the target.

References

1. E. Jones, Antiproton Production and Collection, *CAS lectures*, **CERN/PS-AA/83-46**, (1983)
2. C.D. Johnson, E. Jones, T.R. Sherwood, Antiproton Yield Expectations for the ACOL Project, **CERN/PS/87-19 (AA)** and *Proc. IEEE Particle. Accelerator Conferenc*e *1987*, Washington, Vol 3, pp. 1749-1751 (1987)
3. C.D. Johnson, Antiproton Yield Optimization in the CERN Antiproton Acccumulator, CERN/PS/AA/83-11 and *Proc 1983 US Particle. Accelerator Conferenc*e, Santa Fe, *IEEE Trans. Nucl. Sci.* **Vol. NS-30** No. 4 pp. 2821-2823 (1983)
4. T.R. Sherwood (CERN), G. Dugan, C. Hojvat and A. Lennox (Fermilab), Beam Tests of a 2 cm Diameter Lithium Lens, *IEEE Trans. Nucl. Sci*. Vol. **NS-32**, No. 5, pp.3062-3064 (1985)
5. C.D. Johnson, Present and Future Possibilities of Antiproton Production from Fixed Targets at CERN, *Hyperfine Interaction*s, **44**, pp. 21-30, (1988)
6. T.W. Eaton, S. Hancock, C.D. Johnson, E. Jones, S. Maury, J-C. Schnuriger and T.R. Sherwood, Conducting targets for Antiproton Production of ACOL, *IEEE Trans. Nucl. Sci.* Vol. **NS-32**, *No. 5*, pp 3060-3062 (1985)
7. T.W. Eaton, C.D. Johnson, E. Jones, Recent Work on the Production of Antiprotons from Pulsed-Current Targets**, CERN/PS/86-15(AA)** (1986), (Revised and reprinted 1994)
8. A. Poncet, Personal communication
9. H. Jäger, Zur Entstehung primärer Gasentladungszonen bei elektrischen Drahtexplosionen, *Z. Naturforsch.* **27 a**, pp.1586-1596 (1972)
10. S. Gilardoni, B. Autin and P. Sievers, Conducting Targets for Pion production, **CERN-NUFACT-91** (2001)
11. S. Gilardoni, Review and Comparison of Solenoid and Horn Capture System, **CERN-NUFACT-86** (2001)