BEAM TESTS OF A 2 cm DIAMETER LITHIUM LENS

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Abstract

Following the pioneering work on lithium lenses at INP, Novosibirsk, a 2 cm diameter lens was designed and built at Fermilab as an antiproton collector for the antiproton source of the Tevatron I project. A lens of this type was tested at the CERN Antiproton Accumulator (AA) as an antiproton collector and then as a prefocusing element before the AA pulsed current target. In the latter case the purpose was to increase the proton beam convergence at the target to compensate the defocusing effect on the proton beam of the current in the target. As an antiproton collector the lithium lens performed as predicted increasing the antiproton yield into the AA by 40%. In the prefocusing configuration beam convergence and spot size on the target were considerably improved over the standard arrangement using a pulsed quadrupole triplet and the lens has survived 1.4 M pulses of current from 290 to 350 kA in a 26 GeV/c beam of up to $1.4 \cdot 10^{13}$ protons.

Introduction

In the Fermilab Tevatron I project, the 8.9 GeV/c antiprotons from the production target are collected by a lithium lens of radius 1 cm and length 15 cm[1]. Surrounding the lens is a toroidal matching transformer, with a turns ratio of 8:1 to reduce the effect of the inductance of the power leads and connections. The injection line optics require that the lens operates with peak pulsed current of 0.67 MA. The pulse width is 0.33 ms and beam passage occurs between 70 and 100 µs after the peak. At this time the lens has developed maximum linearity, the instantaneous current is 0.5 MA and the magnetic gradient 1000 T/m.

At the CERN AA, 3.5 GeV/c antiprotons are collected by the magnetic horn, a parabolic current-sheet lens of radius 2.2 cm and length 40 cm [2]. The conducting sheet is made of aluminium 1 mm thick. A pulsed current of 160 kA peak is supplied directly via coaxial cables and a 2 m sandwich line from a capacitor discharge supply. Beam passage is at the current peak.

Early in 1983, the Fermilab lithium lens, which was the result of a collaboration between the Institute for Nuclear Physics, Novosibirsk and Fermilab, was tested in the laboratory. Calculations showed that the replacement of the magnetic horn in the CERN AA injection line by a Fermilab lithium lens should result in a 40% improvement in antiproton yield. Focal distances of around 12 cm can be achieved for antiprotons of 3.5 GeV/c. At that time the best antiproton yield measured using the magnetic horn was obtained with a copper target 3 mm Ø × 115 mm [3]. It was expected that, due to depth of focus limitations, the lithium lens would perform best with a 50 to 70 mm long tungsten target. It was therefore of mutual interest to CERN and Fermilab to test this predicted improvement in antiproton yield by installing a Fermilab lens at the CERN AA. The operational experience to be gained in using a large aperture lithium lens for the first time in a hadron beam was also welcome to both parties since their use at CERN was then contemplated as a part of what has now become the ACOL project aiming to upgrade the AA antiproton collection rate by a factor of ten.

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The CERN Antiproton Target Station

For antiproton production the CERN Proton Synchrotron delivers a 26 GeV/c beam of which 95% lies within a transverse emittance of 2.5π mm.mrad. This is focused at the 3 mm diameter production target to a spot of 1 mm radius. Just in front of the target is a fluorescent screen viewed by a television camera. The TV image is digitized to permit computerized reconstruction of beam profiles. The screen has a 2 mm diameter hole on the beam axis and the AA operators job is to focus and steer the proton beam so that 95% passes through that hole. In normal operation this is accomplished using conventional steering elements and a pulsed quadrupole triplet extending 7 m upstream of the target[4].

The magnetic horn is a non-linear focusing element with cylindrical symmetry. Its exact shape, the target length and position for maximum yield were calculated by means of a simulation program[5] and then the horn current and target parameters were optimized by experiment[3]. This led to the use of a relatively long (115 mm) copper target.

Further computations of antiproton yield into the AA using a 2 cm diameter lithium lens as collector showed that, with a suitably rematched injection line, an improvement of just over 40% could be expected[6]. In this case a 60 mm long tungsten target (or one of similar density and atomic mass) was expected to be optimum.

As an alternative to the short tungsten target we were also considering the use of longer, current carrying targets of material with lower atomic mass. The additional focusing provided by the current within the target material, which has the effect of compensating the depth of focus limitation, was found to give a further enhancement of the yield[7]. However, the defocusing effect on the proton production beam could not be neglected. This effect could be minimized by increasing the convergence of the proton beam so that, with a 2 mm waist in the middle, the beam envelope was only 3 mm at the entrance and exit of the target. The quadrupole triplet was not powerful enough for this purpose and so a lithium lens was proposed as proton prefocusing element about 1 m upstream of the target.

With the testing of these proposed improvements in view, the build-up of the required power supplies, mechanical supports, remote handling and operational infrastructure was begun in 1983. The lens was first used for a short run as a collector, then in 1984, with improved transformer insulation, for a long run for proton prefocusing and it is intended to have the complete assembly of prefocusing lens, pulsed current target and collector lens installed for tests during 1985.

Power Supply Matching Using the Toroidal Transformer

The current of several hundreds of kA with rise time of several hundred µs necessary for the excitation of a lithium lens cannot be conveniently obtained by the direct discharge of a storage capacitor into the lens. Instead it is preferable to use a step-down transformer, the turns ratio of which is chosen to give levels of primary voltage and current appropriate to the switching technology of the power supply and the insulation possibilities of the transformer. A necessary requirement of such a pulse transformer is that it should have the minimum of leakage inductance consistent with its ability to withstand reliably the voltage in a hostile operating environment.

A convenient way of introducing a step-down transformer into the lens circuit is to nest the lens in the centre of a toroidally wound transformer having a single turn secondary. The secondary then becomes the case surrounding the strip-wound transformer steel core and the primary winding can be installed in arrays of holes in the secondary case. This arrangement minimizes the leakage inductance and provides excellent mechanical support for the primary winding. It imposes, however, stringent requirements on the primary insulation because of the interlacing of the two windings.

The turns ratio of the toroidal transformer can be adjusted by the design of end plates linking the inner and outer conductors of the primary winding. As already mentioned, a turns ratio of 8:1 was chosen for the Tevatron I project. However, for the CERN test of the lens as an antiproton collector it was necessary, for the same lens current shape, to convert the ratio to 24:1 because of different characteristics of the Fermilab and CERN storage capacitors. The choice of this ratio was not without risk as it necessitated a driving voltage in excess of 5 kV, which finally proved too much for the insulation between the first and last turns of the primary.

The lessons of this breakdown, coupled with the appreciation that a slower rising current pulse would improve the notional phase angle at which the beam could pass the lens led to the redesign of the primary winding and circuit. The 24:1 ratio transformer driven from a 480 µF capacitor was changed to one of 23:1 ratio driven from a 1440 µF capacitor, the time to current peak changing from 140 µs to 245 µs. Primary insulation was improved by increased spacing between the start and finish turns and by increased insulation thickness at the expense of copper cross-section. Wide spread use of 97% alumina insulation was made in order to provide the maximum of radiation hardness. The circuit changes reduced the needed driving voltage to under 3 kV, further enhancing the chances of improved transformer lifetime. This modified transformer and circuit were used for the test of the lens as a proton pre-focusing element; typical current and voltage waveforms are shown in Fig. 1.

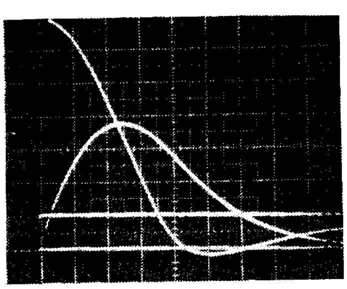

Fig. 1

Transformer primary voltage and current waveforms for 23-turn transformer with 1440 µF capacitor; upper trace: voltage, 500 V/div., lower trace: current, 4 kA/div., time base: 100 µs/div.

The Lens as an Antiproton Collector

In September 1983 a Fermilab lens and transformer with 24 turns was brought to CERN and prepared for installation in place of the magnetic horn. To achieve the optimum antiproton yield the 60 mm tungsten target had to extend into the aperture of the lens end flange and to permit this engagement and also to allow for optimization of the longitudinal target position the lens was mounted on a sliding baseplate. This is shown in Fig. 2.

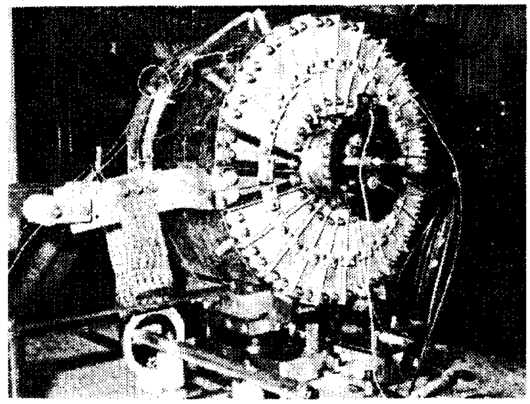

Fig. 2 - The Fermilab lithium lens and 24-turn transformer mounted at CERN in 1983.

After setting up the AA for antiproton yield measurement with the standard target and horn, the lithium lens and tungsten target were installed in their place. Because of the smaller radius of the lens compared to the horn and thus the greater divergence of the antiproton beam leaving the lens, the injection line to the AA had to be completely rematched to take full advantage of the lens. When this had been done and the optimum target position found, the yield was measured as a function of lens peak current and the delay from peak to the beam passage. The results of this set of measurements is shown in Fig. 3. The best yield was obtained with the delay from peak set to 100 µs and the peak current at 500 kA. This corresponds to a lens current at beam time of 300 kA. The improvement in antiproton yield over the yield obtained with the standard target and horn, measured immediately prior to these tests, was 37%.

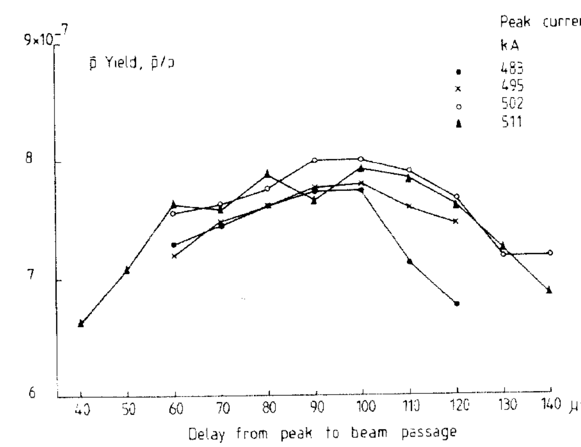

Fig. 3 - Antiproton yields into he AA versus lithium lens peak current and time from peak to beam passage, after optimization of target position and beam-line optics.

The Lens as a Proton Prefocusing Element

The tests described above were curtailed by a voltage breakdown across the transformer insulation. The transformer was rebuilt as described above and, with the original lens reinstalled, was used as a proton focusing element 1 m upstream of the target. Pulsed current target tests[8] during 1984 and 1985 made use of the lens in this position to offset the proton defocusing effect of current in the target. The refurbished transformer is shown, with the lens in place, in Fig. 4 and its performance illustrated in Fig. 5 by a series of beam profiles just before the target. Without current in the lens the beam at the target has a full width of 12 mm. As the lens current is increased the beam spot decreases in both transverse planes until eventually at 330 kA peak almost all of the beam passes through the 2 mm hole in the fluorescent screen (Fig. 5.6). Under optimum conditions for antiproton production from the pulsed current target, the delay from peak to beam was found to lie between 70 and 90 μs.

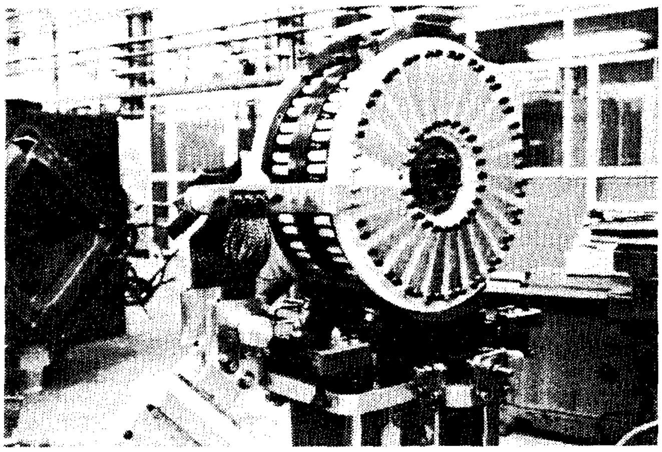

Fig. 4 - The Fermilab lithium lens in the modified transformer ready for tests at CERN in 1984.

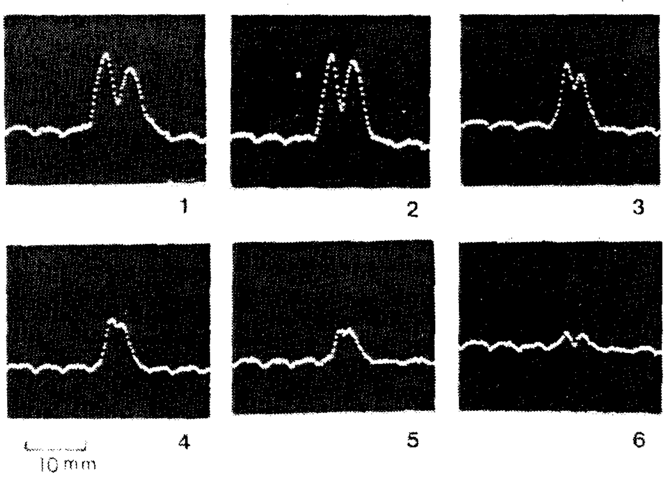

Fig. 5 - The 26 GeV/c proton beam horizontal profile at the production target when using the lithium lens for proton focusing. Lens currents: 5.1: 0 A, 5.2: 130 kA, 5.3: 280 kA, 5.4: 290 kA, 5.5: 320 kA, 5.6:330 kA.

Long-Term Tests

Pulsed target tests have been of relatively brief duration due to the short target lifetimes[8]. To gain operational experience with the lithium lens it was used in place of the quadrupole triplet for normal antiproton production from a passive target during a period of six weeks towards the end of 1984.

A lens protection system was tested at the same time. This is designed to detect lens or transformer failure at an early stage and to ensure that the pulser is stopped and the cooling water purged from the lens before any significant damage is done. The automatic system has three parts: an interlock chain permitting pulsing only when the lens condition is good, an argon purge of the cooling water in the lens body (after stopping the pulser) in the event of cooling water conductivity rising above a set level, and pulse-by-pulse monitoring of the transformer primary pulse shape with shutdown of the pulser after a set number of pulses outside predetermined shape limits. The interlock chain requires the following conditions: three independent lens body temperature measurements, water conductivity and flow to be within a set limits, and the absence of any water leak from the lens itself. The last condition is tested by a sensitive leak detector under the lens transformer.

After more than 100'000 pulses up to 420 kA peak in the laboratory the lens has to date been pulsed 1.4 M times at around 300 kA peak in the 26GeV/c proton beam. The lens body temperature is normally below 40°C and there has been no obvious sign of deterioration of lens or transformer.

Conclusions

As an antiproton collector or as a proton focusing element the lithium lens behaves as predicted. At a peak current of 300 kA the lifetime limit of the lens (the second of the first batch of four prepared at Fermilab) has not yet been reached. During 1985 a second lens of similar construction but incorporating improvements stemming from the Fermilab destructive testing at 650 kA peak, will be used at CERN as an antiproton collector to take advantage in operation of the 37% gain in yield.

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