BEAM TESTS OF A 36 MM LITHIUM LENS

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Abstract

Following the work on a 20 mm diameter lithium lens, used in the past as a first collecting element downstream of the antiproton production target at CERN, the 36 mm diameter lens, more suited to the Antiproton Collector (AC) was constructed. At the beginning of 1988 it was proposed to investigate the performance limits of 36 mm lenses, aiming ultimately at currents of 1.3 MA, where a $\bar{p}$ yield increase of 40% is predicted. Thus, a test programme was launched which included the construction of a pulsing system and a current transformer for 1.3 MA and a revised design of the production target-collecting lens system, to match the target position better to the increased strength of the lens. Preliminary life tests and $\bar{p}$ yield measurements were made at 1.1-1.2 MA to provide further input to the development towards 1.3 MA collection systems. The results of these tests are reported.

Introduction

A lithium lens consists essentially of a rod of solid lithium through which a current pulse is passed in axial direction. With a constant current density, achieved after complete field penetration, a circumferential magnetic field rising linearly with radius is created inside the rod. Antiprotons, emerging from the target upstream of the lens under large angles α can thus be bent parallel in horizontal as well as in vertical direction during their passage through the lithium rod. Its focal length f, distance between the center of the antiproton production target and the entrance of the lens, is given by:

$$f = \frac{1}{\sqrt{K}\ \mathrm{tg}\left(\sqrt{K}\ L\right)}$$

where $\sqrt{K}$ is the focusing strength of the lens and L the magnetic length of the lens. The maximum production angle α of antiprotons accepted by the lens is about

$$\alpha = R\ \sqrt{K}\ \sin\left(\sqrt{K}\ L\right)$$

where R is the radius of the lens.

Following the work on a 20 mm diameter lithium lens [1,2], a 36 mm diameter lens was designed, constructed at CERN and filled with lithium at the KfK-Karlsruhe. A transformer for 1.5 MA was designed and built at the Institute of Nuclear Physics (INP) at Novosibirsk. This lens, used as an antiproton collector, was tested at the CERN antiproton source (AAC). For such a lithium lens a yield increase of about 40% was predicted [3]. In 1987/1988 the lithium lens was tested, without beam, at INP, at a peak current of 800 kA and, for a few pulses, at 1.0 MA [4]. At the beginning of 1988 it was proposed to continue the collaboration between CERN and Novosibirsk for a 1.0 MA system. Calculations showed however that the gain in yield over the 20 mm lens would not have been significant so a 1.3 MA system was proposed. This would provide a gradient of 680 T/m at the working point which would allow to accept antiprotons at 3.5 GeV/c with production angles up to about 115 mrad, provided that the center of the target can be placed at f = 8.5 cm from the lens. Mechanical modifications were made to enable the target and lens to be mounted closer to each other.

The lens is basically a lithium column inside a stainless steel cylinder. This forms the secondary winding of a thoroidal 18:1 turns ratio matching pulse transformer, closely embracing the lens, whose primary is connected to the power supply by a set of coaxial HV cables. The lens and the secondary of the transformer are water cooled while the primary is air cooled. The lithium lens impedance is given as R = 40 μΩ and L = 35 nH.

The lens power converter and pulser [5] must provide a peak current up to 1.3 MA, at 2.4 s pulse repetition time. The pulse duration should not exceed 3.5 ms for a rise time of 1 ms and a peak reproducibility of 0.5%. Pulse duration and rise time specifications result from a compromise between the conflicting requirements of low ohmic losses and the penetration of the focusing field inside the lithium.

The circuit principle of the power supply is shown in Fig. 1. It consists of two 3-phase primary thyristor controlled capacitor charging section, fed by a phase shift autotransformer and paralleled via the HV current smoothing and protecting chokes, of three energy storage and switching sections and of a special pulse matching autotransformer.

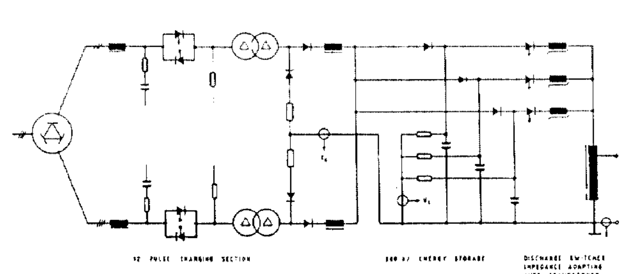

Fig. 1 - Circuit diagram of lithium lens pulser and power converter.

The three capacitor banks are charged in parallel, via decoupling diodes, linearly up to the set voltage and discharge simultaneously by power thyristors, through dI/dt limiting saturating reactors, into the primary of the autotransformer.

The 3-limb autotransformer adapts the capacitor banks to the load in order to obtain the specified peak current and rise time for a given maximum voltage. An appropriate airgap in the magnetic circuit of the autotransformer avoids the need of auxiliary dc bias to cope with the dc component of the discharge current. The damping of the circuit is such that practically all the stored energy is dissipated during the pulse. The discharge current of each of the three capacitor banks is monitored by means of a pulse current transformer to check the current sharing. A larger current monitoring device is installed on the secondary of the autotransformer to display and measure the total current delivered to the primary of the toroidal transformer around the lens.

The power supply operation is controlled via a computer interface which provides the ON-STANDBY-OFF commands, the 0-10 V voltage reference, the three timing pulses (start of charge, inhibit of power converter, discharge of energy capacitors).

The lithium lens power supply and the central supervisory equipment occupy a surface of 40 m^2 in a hall located directly above the target area at a distance of about 25 m.

The main characteristics of the power supply are collected in Table 1. Some relevant current and voltage waveforms, illustrating the mode of operation of the power supply, are shown in Fig. 2.

Table 1 - Power supply characteristics

Load impedance R/L (mΩ/μH)	22/16
Total capacitance (mF)	3x7.2
P.U. capacitance (μF)/energy (kJ)	200/2
Rated voltage (kV)	4.5
Dielectric	mixed
Discharge thyristors	MEDL DCR-SU 1478 4545
Charge converter ratings (kV/A)	4.2/50
Discharge pulser ratings (kV/kApeak/kArms)	4.5/60/1.5
Pulse-matching autotransformer:	
- rating (MVA)	4.2
- turns-ratio	30/21/20
- secondary current (kApeak/kArms)	73/2.1
- core design ∫u*dt (Vs)	5.35
- air gap (mm)	4
- core cross section (mm^2)	1200

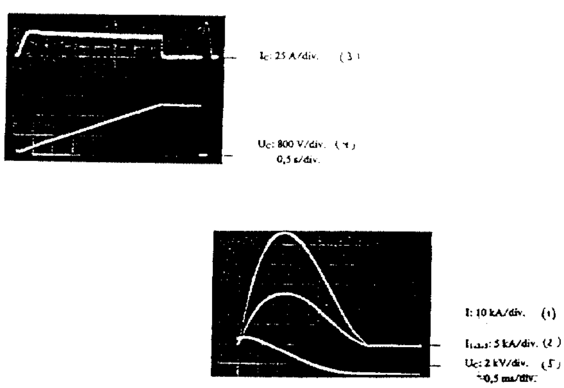

Fig. 2 -Waveform of lithium lens current (1), switching section (2), capacitor charging current (3), and capacitor voltage during charge (4) and discharge (5).

Tests in Beam

The 36 mm diameter lithium lens after being installed in the transformer at the beginning of 1989, was tested in the laboratory. Because of a flange failure after 1000 pulses at 1.1 MA tests in the beam were postponed until July 1989.

For antiproton production, the CERN Proton Synchrotron (PS) delivers a 26 GeV/c beam with an intensity of 1.4×10^{13} protons per pulse, 95% of which lie within a transverse emittance of less than 3π mm.mrad. The production beam is focused on the 3 mm diameter production target to a spot of 1 mm radius (95% of the beam) with 2 pulsed quadrupoles. However, to reduce the build-up of induced radioactivity, we started beam tests at an intensity of 2.0×10^{12} protons per pulse. With this intensity, beam emittances are known to be smaller so that we anticipated higher yields than with the full intensity.

In July, the 36 mm lithium lens was pulsed at 1.1 MA giving a yield of 80×10^{-7} $\bar{p}$/p after the injection line optics was optimized [6]. To achieve the optimum antiproton yield the iridium target, embedded in graphite has been placed as close as possible to the end of the lens.

The yield versus effective current at the working point for various positions is shown in Fig. 3. When the target moved 6 mm towards the lens, the yield increased by about 20%. It was not possible to put the target closer because the mechanical design of the target container and lithium lens flange did not allow it.

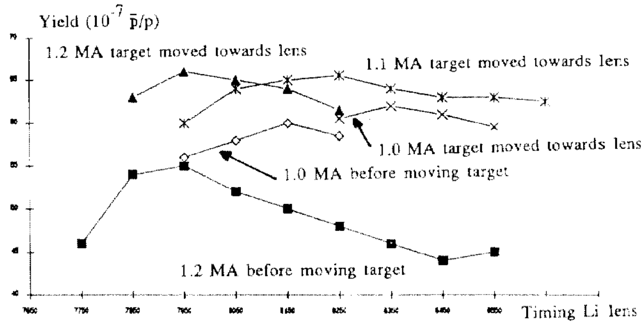

Fig. 3 - Yield versus target position and lithium lens timing

After setting up the AC, antiproton yield was measured as a function of lens peak current and the time difference between occurrence of the current peak value and the passage of the beam. The maximum yield was achieved with a current of 1.1 MA. The timing of the current pulse is chosen experimentally to find the best yield. Comparison with eddy current calculations indicate that this is about the time at which the current density is most constant. Using the current measured at this time, we can calculate the lens parameter. There is some error associated with this, since not all the current measured externally flows in the lithium but also in the container. The accuracy is limited to 10%. The peak current should correspond to a working current of 965 kA, which provides a gradient of 596 T/m, a focal length of 108 mm for a magnetic length of the lithium lens of 130 mm.

The AC injection line [7] was designed for operation with the 36 mm diameter lithium lens. The design had to satisfy 2 conditions:

- to have a good transmission,
- to collimate out secondary particles coming from the target, which are outside the AC acceptance, in the target area itself.

The beam optical requirements were:

- that antiprotons, with production angles up to 115 mrad, are to be collected (the lithium lens reduces the transverse angles to 14 mrad),
- that the injection line is matched to the AC, which is a strong focusing ring with FODO structure and designed to have a transverse acceptance of 200π mm.mrad and a momentum acceptance of ±3%.
- that the currents from the power supplies were limited to 4 kA.

With all these requirements and constraints the AC injection line was designed to have a transverse acceptance of 240π mm.mrad and a momentum acceptance of ±3%.

After optimization of beam line currents we obtained a yield of 80×10^{-7} $\bar{p}$/p at the low intensity of 2.0×10^{12} protons per pulse at the target (Table 2). To get this high yield the gradients of 4 quadrupole magnets were changed. This can be explained by the fact that optimizations of the optics were only made to the first order without taking into account the air scattering in the line along about 40 m. Yield and the transverse emittances were measured versus the AC aperture (Table 3).

Table 2 - Yield measurements

	AC 5.3*	AC 1.5**	EFF	YIELD ***
Mean value over 10 shots	1.97	1.74	.88	79.81

* Nb. of $\bar{p}$ injected in AC (Δp/p = 5.3%)
** Nb. of $\bar{p}$ (Δp/p = 1.5%) after bunch rotation
*** Nb. of $\bar{p}$ in AC/Nb of p on target.

Table 3 - Yield measurements versus AC aperture

Aperture	Yield	ε_H	ε_H
open	79.82	152	137-142
200	80.00	147	137
175	75.45	142	137
150	66.40	128	122
125	51.83	110	108
100	41.62	85	91
75	27.28	67	68
50	17.18	40	48
25	5.75	18	22

At the end, it was also interesting to measure the yield with the highest production beam intensity (Table 4).

Table 4 - Yield measurements versus beam production intensity

Intensity (10^{12})	Yield (10^{-7} $\bar{p}/p$)	$\Delta Y/Y_0$ (%)
2.6	80.0	+38
10.0	72.1	+24
14.0	69.1	+19

In the last column we see the yield increase compared to the 20 mm lithium lens ($Y_0 = 58 \times 10^{-7}$ $\bar{p}/p$). The yield measurement comparison between 20 mm and 36 mm Li lens is plotted in Fig. 4.

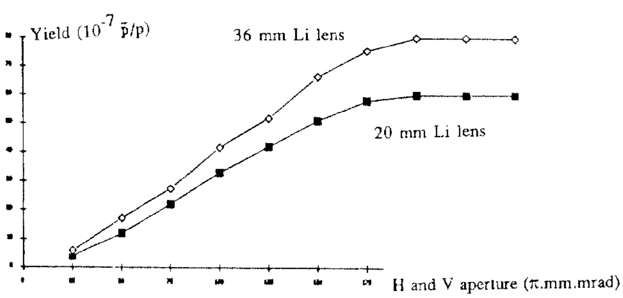

Fig. 4 - Yield comparison between 20 and 36 mm lighium lens.

The maximum number of antiprotons injected into the AC was 9.5×10^7 (mean value over ten pulses). It should be fairly easy to reach a value of 10^8 antiprotons after further adjustment.

Lithium Lens Lifetime and Improvement

During subsequent life tests in the laboratory, the stainless steel container of the lithium lens failed after half a million pulses at 1.1 MA. A substantial increase in wall thickness is obtained by reducing the lithium diameter from 36 mm to 34 mm. The resulting loss of yield is only about 3 to 4% according to the Monte Carlo program used in ref. [8]. It should be noted that the prototype 36 mm lens was originally designed for a peak current of 800 kA. Two new 34 mm lithium lenses are being built and should be tested and ready for operation in August 1990.

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