

Performance of the CERN Plasma Lens in Laboratory and Beam Tests at the Antiproton Source*

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Abstract

The CERN plasma lens is based on a dynamic z-pinch which creates during 500 ns a cylindrical plasma current conductor of 290 mm length and 38 to 45 mm diameter. The lens is designed for pulsed pinched currents of 400 kA and magnetic field gradients of 200 T/m produced with stored energies of 56 kJ. Life tests of different lens components were carried through at a repetition rate of 4.8 s/pulse. The results of the first beam tests of the plasma lens at the CERN antiproton source are very encouraging in view of other potential plasma lens applications.

1. INTRODUCTION

The plasma lens is a "wire lens", which focuses high-energy particles by means of an azimuthal magnetic field excited by an axial current. The first high-power plasma lens for focusing muons was built and installed in the AGS at BNL in 1965 [1].

Strong focusing properties are also obtained with magnetic horns and lithium lenses which have been often used for rare particle collection during the past 20 years. The plasma lens development programme started 1983 at CERN [2]. The plasma lens was designed to serve as a powerful collector lens for antiprotons which are produced by an intense proton beam incident on an iridium target [3].

After thorough testing of all system components in the laboratory, the first beam test of the plasma lens took place after the Winter Shutdown in March 1991.

2. LABORATORY TESTS

The new plasma lens (Fig. 1) designed and built for the beam test differed in several aspects from the previous prototypes [2,3].

- Windows for beam entrance and exit provided.
- Graphite electrodes for reduced antiproton absorption, reduced induced radioactivity, lower ignition voltage and less weight compared with the earlier tungsten electrodes.
- Helium used as filling gas instead of hydrogen.

The plasma column of the lens is 290 mm long and about 40 mm in diameter and carries a current of 400 kA [4]. This medium is transparent for high-energy particles. The plasma lens insulator tube is made from low-porosity alumina. The water-cooled aluminum windows for the beam have to be protected against the hot plasma by graphite screens (Fig. 1).

The voltage across the lens was measured with fast voltage dividers and the current flowing into the lens with a Rogowski coil inserted into the stripline from the pulse generator. With the three magnetic field probes shown in Fig. 1 the magnetic field inside the lens was measured simultaneously at

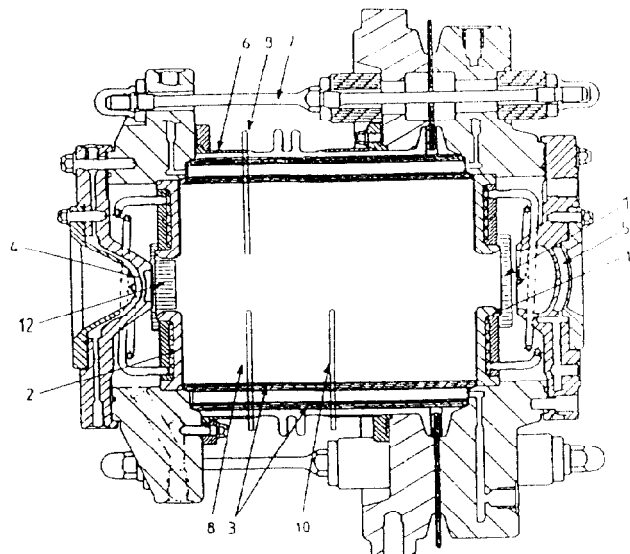


Fig. 1. Cross section of plasma lens. 1) anode, 2) cathode, 3) insulator tube, 4) beam entrance window, 5) beam exit window, 6) return conductor, 7) clamping bolts, 8,9,10) magnetic field probes 1, 2, 3, 11) anode screen, 12) cathode screen.

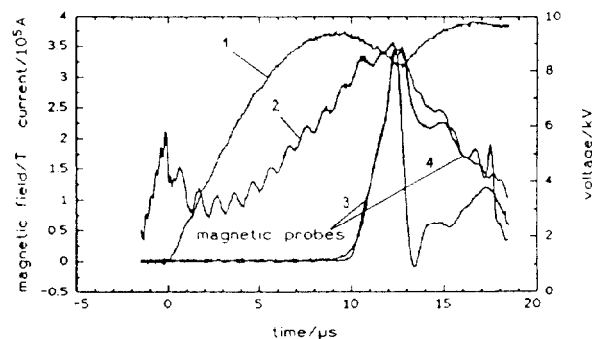


Fig. 2. Plasma-lens current, voltage and magnetic field waveforms. 1) total current through the lens, 2) voltage across the lens, 3) magnetic field measured with coil 1, 4) magnetic field measured with coil 2 both at 20 mm radius.

three different places with a spatial resolution of ± 1 mm. Figure 2 shows the current through the lens, the voltage across the lens and the magnetic field at 20 mm radius measured with probes 1 and 2. The maximum of the magnetic field is reached when the voltage signal drops down and when a minimum is visible in the current wave form. The magnetic field was scanned with separate measurements over the whole diameter of the plasma lens tube. Due to the good reproducibility from shot to shot it was possible to measure the magnetic field distribution $B(r,t)$ with all three probes at two longitudinal positions.

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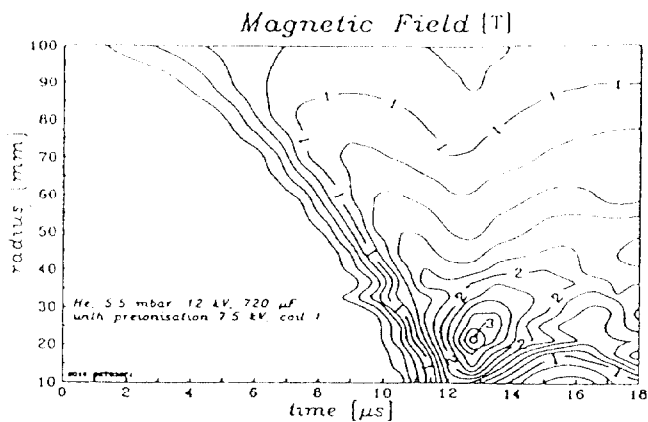


Fig. 3. Magnetic field map of coil 1 (contour lines correspond to steps of 0.2T). 2 Both coils show identical field distribution.

The field map of probe 1 is shown in Fig. 3. A maximum magnetic field exceeding 3 T is reached after 12.8 μs , at a radius of 21 mm and with a duration of about 500 ns. In this case the charging voltage was 12 kV and the externally measured current at pinch time 330 kA. The pinch-time jitters by about ± 50 ns, including the effects of the auxiliary preionization pulser, of the main pulse generator and of the plasma lens itself.

By side-on fast framing photography the axial symmetry of the plasma column was checked from two perpendicular directions (horizontally and vertically). Framing pictures were taken at different moments between the start of the discharge and the decay of the plasmas column.

The erosion of the graphite electrodes and the evaporation of the alumina insulator were investigated in several life tests. After 30 000 pulses an alumina evaporation rate of 2.8 mg per shot and a graphite erosion rate of 20 μg per shot have been determined. No graphite, but pure aluminium was found in the powder, which had formed during the pulsing inside the lens and outside in the pumping tubes. The eroded graphite seemed to have disappeared as CO or CO₂.

3. BEAM TESTS

The spatial and the temporal stability, as well as the focusing properties of the plasma lens were studied first with a proton beam ejected in opposite direction from the Antiproton Collector (AC) ring through the beam transport channel and the plasma lens onto a luminescent screen. The proton bunch was 50 ns long, its beam diameter was 20 mm and its number of particles was 2×10^{10} . Figure 4 shows the position of the luminescent screen behind the lens which was used to monitor the proton beam while the target was removed from its normal position during antiproton production. The luminescent screen was outside the focal point of the lens.

Figure 5 shows the unfocused and focused proton beam spot on the screen. The round shape of the focused beam spot (lens pulsing) and the horizontal intensity scan over the spot prove that the magnetic field in the lens is symmetric and stable. The focusing characteristics of the lens appeared to be reproducible in a wide range of plasma lens gas pressure and of total current through the lens.

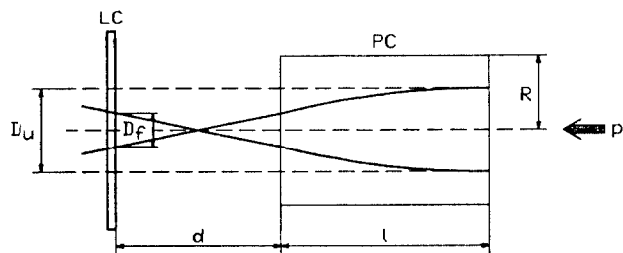


Fig. 4. The test proton beam p is coming from the right and is focused by the lens. The luminescent screen LC is placed behind the nominal focal point. D_f = focused spot diameter, D_u = unfocused spot diameter, PC = plasma column, R = radius of the PC, d = distance between the screen LC and the plasma column PC, l = length of PC.

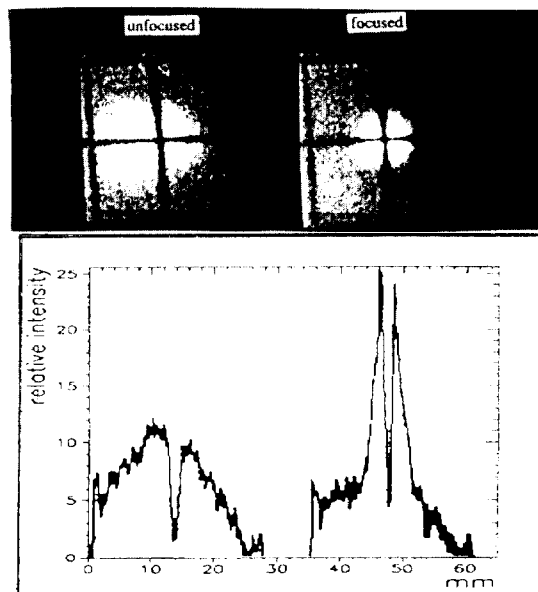


Fig. 5 Spots on the luminescent screen of the unfocused (left) and focused (right) inverse proton beam. The corresponding light intensity profiles measured just above the horizontal grid line are shown

In a second experiment the focusing properties for antiprotons were studied (Fig. 6). The antiprotons produced with a proton beam of five bunches (bunch length 20 ns, time between two bunches 110 ns) were collected with the plasma lens.

Antiproton yields were measured at an incident proton beam intensity of 2×10^{12} per pulse on target. The antiproton yield is defined as the ratio between the antiproton number per pulse measured after 2×10^6 revolutions in the AC and the incident proton number measured in front of the production target. The lens pressure and the capacitor charging voltage were chosen in the stable focusing region giving a total current at pinch time of about 370 kA.

During the first antiproton production tests the machine parameters, such as the settings of the AC and of the beam transport towards the AC were optimized, while keeping the plasma lens parameters and the target-to-lens distance constant. Yields, averaged over ten beam pulses, of up to 62×10^{-7} \bar{p}/p were reached under these conditions. Similar yield values were also obtained with a lithium lens of 34 mm diameter during the p-collider run in autumn 1990, however at higher intensity. The detailed comparison is given in Fig. 7 which shows yield data from different collector lenses used at the \bar{p} -produc-

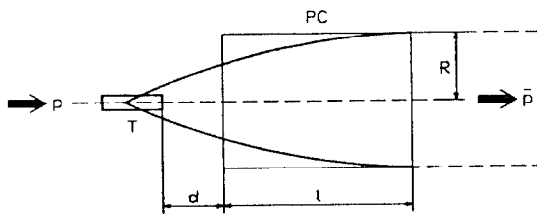


Fig. 6 The proton beam is incident from the left onto the production target T. The diverging antiproton beam is collected by the lens and transferred to the transport channel. PC = plasma column, d = distance between the target and the plasma column PC, R = radius of PC, l = length of PC.

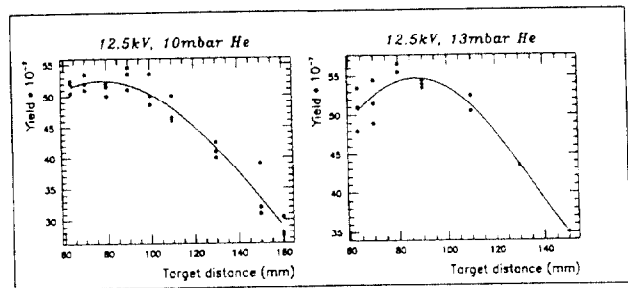


Fig. 8 Antiproton yield as function of target to lens distance for fixed settings of the plasma lens pulse generator voltage, of the beam transport, of the primary proton beam and of the AC ring for two helium pressure values of 10 mbar and 13 mbar in the plasma lens.

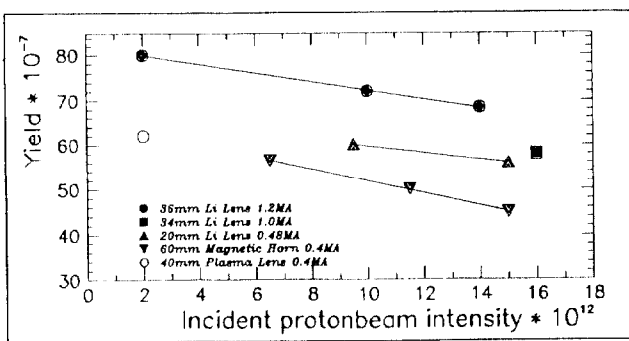


Fig. 7. Yield as function of proton intensity for different types of collector devices

tion target. Yield generally decreases with increasing incident proton intensity due to larger beam emittance of the primary production beam at the target.

Optimization of the proper plasma lens parameters was started, but could not be finished during the beam time available. Figure 8 shows the yield as function of target distance for 13 mbar and 10 mbar helium pressure in the lens at 12.5 kV generator charging voltage. The yield maximum is shifted to smaller target to lens distances with decreasing lens pressure conforming with theoretical considerations [5]. Even higher yields may be expected from a well optimized plasma lens.

One advantage of the plasma lens is the smaller amount of matter along the beam path, which results in less scattering and absorption of the beam and in less induced radioactivity on the lens compared with lithium lenses. The induced radioactivity observed after the beam test, where an integrated proton number of 10^{16} had been sent to the target and through the plasma lens, was ten times less than for a 36 mm lithium lens, which had earlier received 25% less primary protons. During the beam test the plasma lens was pulsed 20000 times with a repetition rate of 1 shot per 14.4 s at a stored energy level of 56 kJ, which corresponds to a peak focusing field of 3.7 T and a gradient of 185 T/m.

5. CONCLUSIONS

After careful preparation in laboratory tests antiprotons have for the first time been focused with a plasma lens. With a proton test beam it was demonstrated that the plasma lens based on a z-pinch discharge is stable in space and time over a wide range of plasma lens current and pressure. Good focusing properties are observed during a period of several hundreds of nanoseconds. The maximum yield, averaged over 10 pulses, was 62×10^{-7} . The yield values obtained with the plasma lens are comparable with those of the 34 mm lithium lens reached during a p-pbar collider run in 1990. The continuous operation of the plasma lens at high power level during the whole beam test is a sign for its reliability. The successful plasma lens beam tests show that this new technology represents an interesting method for charged particle focusing. Other applications, such as heavy ion focusing and positron collection have been stimulated by this development work.

ACKNOWLEDGEMENTS

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