A PLASMA LENS FOR THE CERN ANTIPROTON COLLECTOR SCALED FROM MODEL AND EXPERIMENT

B. Autin, H. Gundel, H. Riege, and J.C. Schnuriger
CERN, Geneva, Switzerland

H. Bauer, J. Christiansen, K. Frank, M. Stetter, and R. Tkotz
Phys. Inst. University of Erlangen-Nürnberg, Erlangen, Fed. Rep. of Germany

E. Boggasch
Lab. for Plasma Research, University of Maryland, USA

L. de Menna and G. Miano
University of Naples, Italy

F. Dothan
Hebrew University of Jerusalem, Israël

Abstract

The development work on plasma lens prototypes for antiproton collection is summarized. The antiproton yield with a plasma lens is estimated. Results of the latest z-pinch model describing the plasma dynamics in such a lens are presented. The scaling of the final plasma lens parameters is based on both model and measurement. Destruction rates of insulator tube and electrodes have been measured. A final set of parameters is proposed.

Introduction

High-energy charged particle beams can be focused by magnetic quadrupole lenses, or by a device producing an azimuthal magnetic field B. Such a field can be created by a magnetic horn [1], or by a "wire" [2] lens. A wire lens is essentially a cylindrical conductor through which flows a strong axial current of uniform density. The resulting B-field, which is linearly increasing with radius inside the conductor, leads to simultaneous focusing in all transverse directions. A wire lens is the most efficient device for focusing antiprotons ($\bar{p}$) with a large production cone, as is the case for $\bar{p}$ transferred to the new CERN Antiproton Collector (AC) ring. In the "plasma lens" the conductor is a column of ionized gas. This gas is practically transparent for high-energy particles and does not deteriorate the emittance of the beam being focused. The plasma can carry much higher current densities than a solid conductor and can never be destroyed.

The first plasma lens based on the z-pinch effect was designed, built, and installed in the Alternating Gradient Synchrotron at BNL in 1965 [3]. The upgrading of the CERN $\bar{p}$ source requires a very powerful collector lens. A plasma lens with a plasma column of 40 mm diameter and 300 mm length carrying for 0.5 μs a current of 400 kA seems to be adequate.

The current I_p needed to collect a beam of divergence α with a wire lens is given by

$$I_p = \frac{2\pi p}{\mu_0 e}\left(\frac{\alpha}{\sin\{[(e/p)(\partial B/\partial r)]^{1/2}\cdot \ell\}}\right)^2 \qquad (1)$$

where e is the elementary charge, p the particle momentum, $\partial B/\partial r$ the field gradient, and ℓ the length of the conductor [4]. Owing to the negligible absorption of a plasma one can make maximum use of the available length ℓ to approach $\pi/2$ for the argument of the sine function in Eq. (1) and hence reduce the current I_p to a minimum. The only restrictions come from the dimensions of the target and the construction of the lens.

The maximum angle collected by a linear lens is principally governed by its maximum current, its length, its diameter and also by the minimum front space to accommodate the production target. It is interesting to consider the external magnetic field of the pinch of a plasma lens for the collection of antiprotons produced with larger angles. Any linear lens could, in principle, make use of this effect (cf Fig. 1 for a self-explanatory scheme of the inner and outer trajectories) but the plasma lens has the advantage of having the conducting medium surrounded by vacuum with neither reabsorption nor scattering of collected particles. Two approaches can be looked at, the first being to redesign the electrodes of the plasma lens to take a maximum profit of the non-linear field effect (Fig. 1). The maximum collected angle could be increased by 40%. The second approach consists in increasing the length of the plasma column above the ideal length necessary for transforming the diverging particles into a parallel stream. A small convergence of the inner part of the collected beam has then to be accepted. When the downstream electrode hole diameter is also increased and the matching between lens and transport channel optimized the yield may be increased by more than 20% for a reasonably chosen acceptance of the beam transport channel. Collected angles above 0.1 rad may be achieved with the chosen plasma lens parameters.

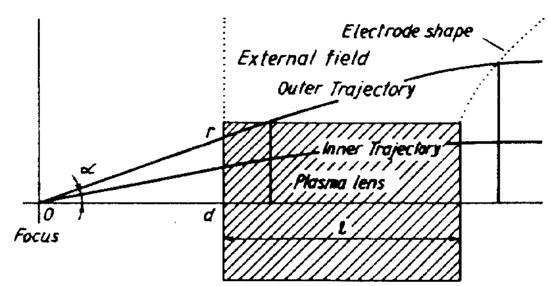

Fig. 1 Non-linear plasma lens optics.

Experiments

For focusing with a linear pinch in a particle accelerator, hollow electrodes are favourable [4, 5]. Such a structure needs only thin windows in the rear electrode walls for the passage of the beam. The z-pinch tube is filled with hydrogen, helium, or argon at pressures ranging from 10 to 1000 Pa. It is inserted symmetrically into a strip-line table which is linked to four capacitor banks of 108 μF total capacitance [6]. Each capacitor bank is linked to the central strip-line table by a sandwich strip-line containing a high-current pseudospark switch. Charging voltages V_0 of up to 20 kV were applied.

Two Rogowski-type current pick-up loops for

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total current measurement [7] are wound around the plasma tube (Fig. 2). The voltage between the plasma-tube electrodes is measured with commercial high-voltage probes. The magnetic field and current distributions inside the tube are determined as a function of time by two minute electrically screened coils [4, 5]. The coils can be moved in the radial direction. With argon as discharge gas in the plasma lens tube we observed the appearance of wall currents before pinch time. They reduce the current within the pinch column by up to 50%. The wall currents are induced by UV-radiation from the imploding plasma shell. With the use of a hydrogen fill the wall currents could be almost suppressed.

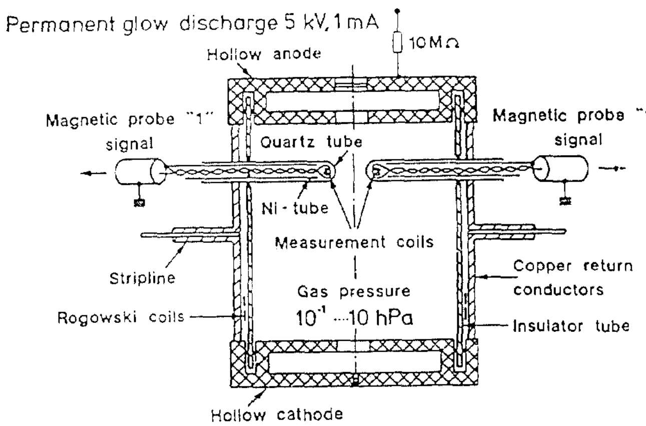

Fig. 2 Scheme of plasma lens and diagnostic tools.

By operating the plasma lens in the pulse generator with a cycle time of 16 μs, 3.3 T were measured at a radius of 20 mm with a fill of 700 Pa H_2 and a discharge voltage of 17 kV. However, the pinch duration was too short under these specific circumstances. With a generator of 90 μs cycle time and a capacitance of 281 μF a magnetic field of 1 T with a duration of 2 μs was measured when using a fill of 60 Pa argon and a charging voltage of 10 kV. Hence it seems possible to achieve the desired magnetic field of 4 T at 20 mm radius with a sufficiently long duration of 500 ns with a pulse generator correctly matched to the pinch dynamics.

Simultaneous streak and magnetic field measurements showed a strong correlation between light emission and the current carrying plasma sheath during the contraction phase of the pinch. Therefore, the magnetic field data obtained at the fixed measurement position can be extrapolated over the whole length of the plasma lens. The plasma front reaches the axis with a temporal jitter of ±50 to 70 ns.

The magnetic field measurements revealed a characteristic feature of the pinch dynamics which is not described by simple pinch models. When the plasma column starts to expand after contraction the pinch current is enhanced by a current induced in the same direction. Simultaneously negative current layers are excited at larger radii, resulting in closed current loops inside the tube as shown in Figs. 3 and 4. The regions of negative current flow are ejected by the repulsing electromagnetic forces towards the outer wall. During the ejection, owing to the reacting forces, the plasma column is stabilized and a fast expansion as well as the onset of instabilities is avoided. A resulting favourable current and field amplification of up to even 100% has been measured in the axial plasma. This behaviour was observed under many different discharge conditions and can be explained by the "inverse skin effect" (IS), first

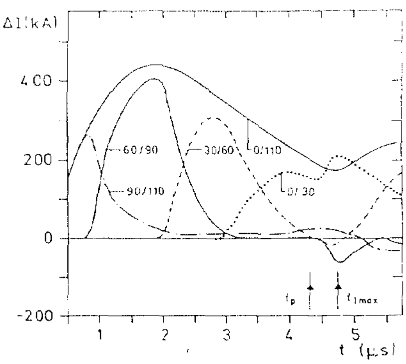

Fig. 3 Current distribution for 15 kV charging voltage and hydrogen gas at 800 Pa. Note the pinch enhancement after pinch time t_p and the negative current shell induced by the "inverse skin effect". The current amplification within a 30 mm radius at time t_{imax} exceeds the actual current by about 30 kA.

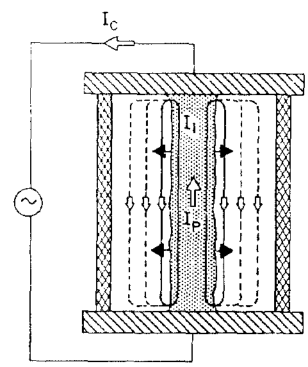

Fig. 4 Sketch of the current distribution inside the discharge tube as a result of the inverse skin effect: $I_p = I_c + I_i$, with I_p: plasma current, I_c: circuit current, I_i: induced current.

studied in detail by Haines [8]. The IS occurs in any conductor when the skin depth becomes comparable with the conductor radius and when the current derivative is negative. Only little experimental attention was given to this effect in the past [9,10], although its importance for a pinched discharge was already pointed out by Haines [8]. A thorough analytical description of the IS of an expanding plasma column is difficult; however, a useful approximation is obtained by considering flux conservation. Then the following condition can be derived [11].

$$\left(1 - \frac{r_i^2}{r_p^2}\right)\left(-\frac{\dot{I}_p}{2} + \frac{I_p \dot{r}_p}{r_p}\right) > \dot{I}_p \ln \frac{r_a}{r_p} , \qquad (2)$$

where I_p is the pinch current, r_p the pinch radius, $r_i < r_p$ and $r_a > r_p$. The increase of magnetic field energy in the pinched plasma column by the IS is an important and favourable upgrade of focusing power of a plasma lens.

A Long-Term Behaviour

Since the AC plasma lens has to be pulsed every 2.4 s for at least 1.5 million pulses without interruption, the measurements of the deterioration of electrodes and insulator tubes are essential. Evaporation rates of different insulator materials were determined by the measurement of weight loss or the increase of the internal diameter of the tube. Erosion rates can best be estimated from the geometrical change of the electrode shape. The insulator wall materials which evaporate induce strong wall currents and vice versa. The wall currents in silica start earlier and are at least twice as strong as those in an Al_2O_3 tube. The eroded wall material is mainly deposited on the cool electrodes and beam windows. Here some erosion rates obtained in life tests at 16 kV charging voltage are quoted:

Quartz/argon	35 Pa	7.5 mg per pulse
Alumina/argon	35 Pa	3.2-4.7 mg per pulse
Boron nitride/hydrogen	400 Pa	1.0 mg per pulse
Alumina/hydrogen	400 Pa	<0.1 mg per pulse

Electrode erosion rates are at least one order of magnitude smaller than the best insulator erosion rates. With the last combination and tungsten electrodes a lifetime far beyond 10^6 pulses can be assumed.

Model Computations and Comparison with Experimental Results

Earlier models, such as the "snow-plough" model [12], the "snow-plough energy" model [13], or the slug model [14] failed to describe real z-pinches of our type. The approximations of a fully ionized plasma with infinite conductivity and the formation of an infinite, thin, imploding current sheet lead to strong deviations from experimental data. In reality, the gas is only weakly ionized at the start. The substantial energy expenditure to dissociate the gas (e.g. when using hydrogen) and to ionize it cannot be neglected and must appear in the energy-balance equation. A one-dimensional model has been developed which takes the motion of the magnetic piston, of the shock wave, and the energy losses into account. A variable ionization degree fits the calculations to the experimental data. The differential equations of the piston and the shock wave were combined with the appropriate circuit equations.

The calculated results correspond well to the experimentally measured current from the generator [15] and to the radial movements of the magnetic piston and the shock wave. The model was used to scale the parameters of a future operational plasma lens which fulfills the requirements of magnetic field (4 T) and pinch duration (0.5 µs). This is shown in Fig. 5 where the calculated magnetic field at pinch time and the pinch duration are plotted for a pulse generator of 400 µF storage capacitance versus initial hydrogen pressure. The charging voltage is 15 kV. In addition the inverse skin effect is expected to enhance the magnetic field by at least 20%.

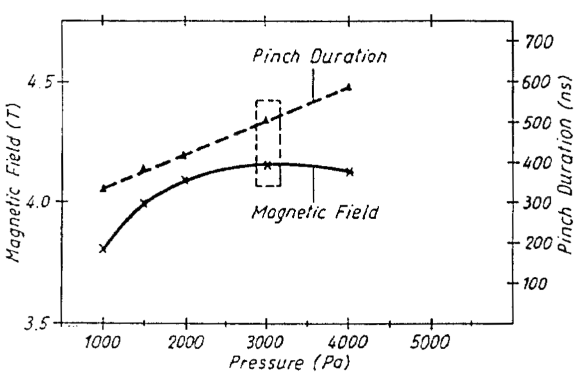

Fig. 5 Magnetic field and pinch duration for a pulse generator of 400 µF storage capacity versus initial pressure (V = 15 kV, discharge gas: H_2)

Outlook

A wide parameter range has been covered with the experiments on plasma lens prototypes described in this paper. Scaling from the experimental and numerical results shows that for the final AC plasma lens a new pulse generator is required, featuring a cycle time of more than 30 µs (twice that of the present test generator) and a stored pulse energy of more than 25 kJ at 10 to 13 kV charging voltage. The final alumina lens tube will have a length of 300 mm and an internal diameter of 200 mm. The filling gas will be hydrogen. Under these conditions the design specifications for the plasma column radius, for the magnetic-field amplitude, and for the field duration can be met. The entrance and exit windows of the plasma lens are left as an open problem until beam tests can be performed in the AC target area.

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