Application of Plasma Lenses in Positron Sources

H. Braun
PSI, CH-5232 Villigen
E. Boggasch and A. Tauschwitz
MPQ, D-8046 Garching
D.H.H. Hoffmann
GSI, D-6100 Darmstadt

Abstract

Plasma lenses with focusing gradients in the order of 100 T/m and a remarkably simple design have been recently tested with the heavy-ion beam from the UNILAC accelerator at GSI. The main goal of these experiments is to provide a sub-mm focus for intense heavy-ion beams. The properties of the plasma lens developed for these experiments such as size, focusing strength and beam optical properties makes it equally well suited for positron sources. The parameters and beam transport properties of such a plasma lens for positron sources are discussed and compared with conventional matching systems. The experimental results of the lens tests relevant for positron applications are compiled. A basic design of a positron source utilizing a plasma lens is presented, together with beam optical calculations for such a system.

1 INTRODUCTION

Efficient production of positrons becomes increasingly important to meet the high demands of future high-energy linear colliders. All existing and projected positron sources for accelerators consist of an electron accelerator, a converter system, a positron accelerator and a system to match the positrons from the converter to the positron accelerator. The positrons are produced in an electromagnetic shower in the converter, where the bulk of the positrons is emitted with longitudinal momenta of 1 − 25 MeV/c and transverse momenta of up to 10 MeV/c. The source radius for the majority of the positrons is 2 mm. The positron accelerator is usually a linear accelerator operating in the S-band ($\nu_{rf} \approx 3\,\mathrm{GHz}$). The first waveguide of this accelerator is embedded in a solenoidal magnetic field with a field strength in the order of 0.4 T. The aperture radius of the waveguide is typically a little less than 1 cm. Thus the transverse momentum acceptance of the accelerator is limited to about 0.6 MeV/c which is small compared to the momentum spectrum covered by the positrons, while the radial acceptance is a factor of 5 larger than the source radius.

An ideal matching system would transform transverse momenta of up to 3 MeV/c in radial displacement for the whole energy range of the positrons. This should happen without distorting the longitudinal distribution of the bunch. Such a distortion can be caused by the different path lengths of particles with different momenta and is a serious effect, since the acceptable bunch length in a S-band linac is only a few mm. Furthermore it would be of great advantage if the matching system could eliminate the electrons, which are more abundant in the shower than the positrons. Without countermeasures these electrons can travel down the whole linear accelerator, such paralysing any beam diagnostics. Moreover the beamloading caused by these electrons in the accelerator waveguides can be a serious issue for high intensity positron sources currently under investigation [1,2].

In presently existing positron sources these matching systems are realized with pulsed aircoils (AC) providing a longitudinal magnetic field. A current carrying plasma lens (PL) with its azimuthal magnetic field has several advantages compared to these systems as will be demonstrated in the next section. In a PL a plasma discharge provides a strong current density parallel to the beam. If the current density is uniformly distributed across the plasma column the correlated azimuthal magnetic field rises linearly yielding a strong focusing lens for axially traversing charged particles. For a homogeneous current density the azimuthal magnetic field B_ϕ is given by

$$B_\phi = \frac{\mu_0 I}{2\pi R^2} r \; ,$$

where I is the plasma current, R is the radius of the tube and r is the radial displacement from the beam axis. Contrary to solenoids or quadrupoles this cylindrical lens exhibits rotationally symmetric *and* strong focusing.

A PL employing a z-pinch discharge was successfully tested at CERN as an antiproton collector lens [3]. At GSI experiments with a PL working in a different discharge regime have been performed in a collaboration with the University of Erlangen [4]. By using a discharge tube with a cross section that matches the beam size, plasma dynamical effects, like pinching, are excluded. The less stringent parameters required for positron compared to antiproton production allow for this novel PL design resulting in a much smaller and simpler PL.

2 BEAM DYNAMICS OF PL

The equation of motion in a magnetic field of rotational symmetry is given by

$$x'' = -g\,x \tag{1}$$

where in the case of the PL

$$g = \frac{q}{P}\frac{\mu_0 I}{2\pi R^2} \tag{2}$$

while for an AC with longitudinal field B_z

$$g = \left(\frac{q}{P}\frac{B_z}{2}\right)^2 \tag{3}$$

is valid, with q the charge and P the momentum of the particles. In the case of the AC equation 1 holds in a coordinate system which rotates along the z-axis with the larmor angle [5]. From equations 2 and 3 we can already draw two important conclusions.

1. Since q appears quadratic in equation 3 and linear in equation 2 an AC is focusing for positrons as well as for electrons, while the PL focuses only one type of particles. Therefore a PL would eliminate the unwanted electron contamination of the beam.
2. The relative change of g with the particle momentum is for the PL
$$\frac{dg}{g} = -\frac{dP}{P}$$
and
$$\frac{dg}{g} = -2\frac{dP}{P}$$
for the AC. Therefore a matching device built with a PL has twice the energy acceptance than a device with the same g shape but based on an AC.

A matching system frequently used for positron injector linacs is the quarter wave transformer (QWT) [6]. In the QWT the particles perform a quarter of a betatron oscillation in a region with high g before they enter the waveguide. The main disadvantage of the QWT is its rather small energy acceptance. Though existing devices are built with AC's they could be also realized with PL's, thus doubling the energy acceptance. If B is the axial magnetic field in the waveguide and P is the mean momentum of the accepted positrons one can calculate the length L and current I of a PL to be

$$L = \frac{\pi P r}{q B R}$$

and

$$I = \frac{\pi}{2\mu_0} \frac{q B^2 R^4}{P r^2} \, .$$

It is assumed that the radius of the plasma tube R is equal the waveguide aperture, r is the accepted radial displacement on the converter exit face. For the parameters of the LEP injector linac (LIL) with $R = 9\,\mathrm{mm}$, $B = 0.36\,\mathrm{T}$, a mean accepted momentum of $P = 6\,\mathrm{MeV/c}$ and a radial displacement acceptance of $r = 2\,\mathrm{mm}$, one gets $L = 3.9\,\mathrm{cm}$ and $I = 13.3\,\mathrm{kA}$. The related field gradient $\frac{dB_\phi}{dr}$ is $32.8\,\mathrm{T/m}$. For an AC the length would be the same and the required longitudinal B-field would be $1.62\,\mathrm{T}$. The path length difference Δs between a particle emerging from the converter with the maximum accepted angle to a particle emitted with a zero angle can be calculated to be

$$\Delta s = \frac{\pi^2 R^2}{16 L} \, .$$

This is half the value one gets for an AC-QWT. The reason is that the particle in the AC spirals along the field lines, while in the PL the path is a sinusoidal curve in the plane of emission.

The positron yield of a PL in comparison with an AC was investigated with a computer simulation of the LEP positron source. The phase space coordinates of a sample of positrons emerging from the target were computed with a program based on the package GEANT [7] and then tracked through the system with the code COMPOST (=COMpute POSitron Tracks) which was developed for this purpose. Fig. 1 shows the computed yield as a function of the PL vacuum window thickness in comparison to the computed yield of the present AC-QWT system. Depending on the window a gain of more than a factor 2 is expected.

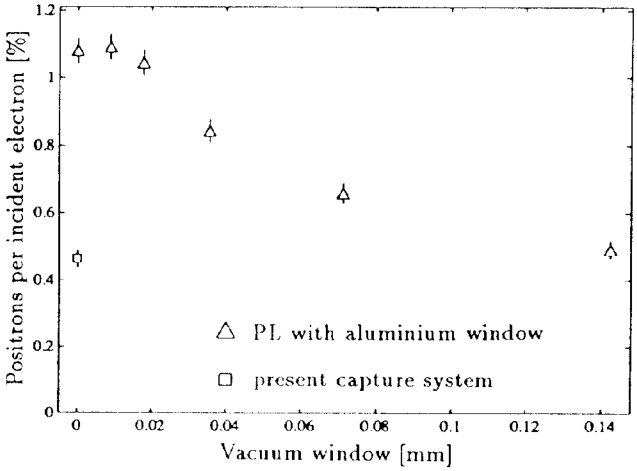

Figure 1: Yield computed for different vacuum windows

3 SCHEME FOR A PL

A sketch of a possible configuration of a PL for positron capture is shown in Fig. 2. The converter target serves also as the PL anode. To separate the plasma region from the vacuum of the waveguide a window has to be inserted. This window has to be rather thin to avoid excessive multiple scattering of the positrons, e.g. a $20\,\mu\mathrm{m}$ aluminium foil is sufficient. The interaction of the plasma with such a foil has not yet been investigated but it seems to be a manageable problem for the relatively low discharge energies needed for the positron PL. In Table 1 the parameters of a PL-QWT for the LIL positron source are summarized and compared to the values of the existing GSI PL. The required gradient and pulse length are smaller for the LIL application than the values already achieved at GSI [8]. The feasibility of the repetition rate remains to be shown. If the stray axial field from the downstream waveguide solenoid causes problems for the plasma, appropriate magnetic shielding between the lens and the waveguide could be added.

Table 1: PL parameters

	positron PL	GSI PL
length of plasma column	39 mm	100 mm
diameter of plasma column	18 mm	12 mm
plasma current	13.3 kA	25 kA
field gradient	32.8 T/m	140 T/m
repetition rate	100 Hz	1 Hz
pulse length (flat top)	>20 ns	200 ns

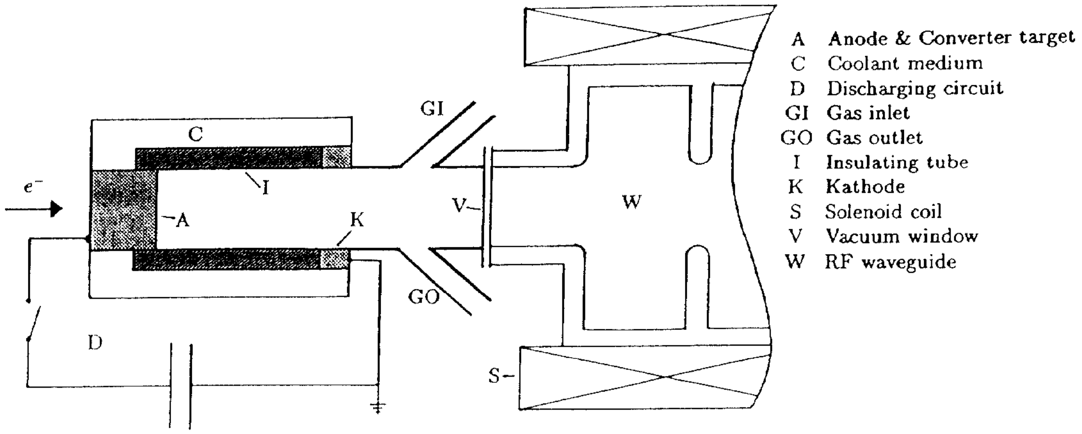

Figure 2: Scheme of a plasma lens for positron capture.

4 EXPERIMENTAL RESULTS FROM THE GSI PL

Plasma lens applications at CERN and GSI have recently demonstrated their feasibility to serve as a high efficient and novel technology for collecting and focusing of charged particle beams. The experimental plasma lens program at GSI has been launched in 1989 to investigate the potential of plasma lenses for fine-focusing of heavy-ion beams to sub-mm spot sizes on targets. With a 5 kJ z-pinch plasma lens the focusing effect on a heavy ion beam was demonstrated for the first time. A new plasma lens concept employing a "wall-stabilized" discharge mode has been developed and tested recently with heavy-ion beams delivered from the UNILAC accelerator at GSI. Remarkable good beam optical properties have been found. In Fig. 3 the focusing effect on an ensemble of seven individual 2.2 GeV gold ion beamlets entering the plasma lens in parallel is visible. These beamlets, with a magnetic rigidity of 1.5 Tm, are diagnosed shortly behind the lens exit via the light produced in a fast plastic scintillator which is imaged by fast digital end-on framing photography. A symmetric merging in time to one final spot is seen. It is correlated to the sinusoidally increasing field gradient of the lens from zero to a maximum of about 60 T/m at current maximum. Compared to previously used z-pinch PL's the wall-stabilized discharge has a drastically decreased energy input due to a reduced active plasma volume. For typically 100 J electrical energy and a desired repetition rate of 100 Hz a cooling system for 10 kW is needed. We believe that the PL tests at GSI have demonstrated the superior beam optical properties of PL's for a charged particle beam. The parameter region covered is very close to the one needed for an application in positron sources. The remaining technical problems concerning windows and repetition rate seem to raise no fundamental obstacles to a potential use of a plasma lens for positron capture.

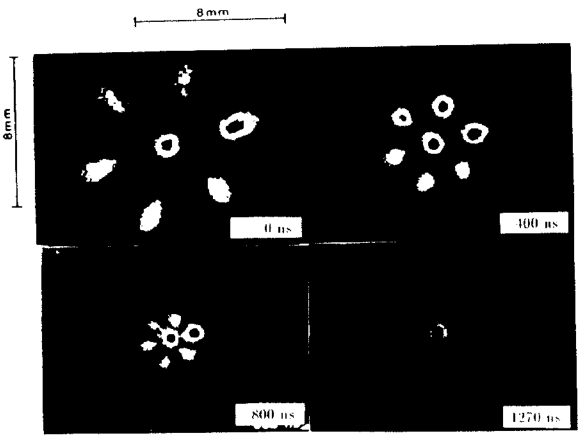

Figure 3: Framing snapshots (200 ns exposure time) of seven gold ion beamlets taken end-on at 200 mm behind the GSI plasma lens

5 CONCLUSIONS

The beam optical properties of a PL favours the use of such a focusing element in positron sources. The efficiency is considerably enhanced compared to standard AC capture schemes, the problem of electron contamination is eliminated and the bunch shape distortion is strongly reduced. The success of the GSI experiments gives us confidence that a compact PL is also feasible for positron capture.

6 REFERENCES

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