Plasma Lens Studies at Erlangen University

M. Stetter, U. Neuner, R. Tkotz, J. Christiansen, K. Frank
Physikalisches Institut, Abt. I, University of Erlangen-Nürnberg
Erwin Rommel Str.1, D-8520 Erlangen, Germany

Abstract

With the former CERN plasma lens pulse generator systematic investigations of pulsed high current discharges have been performed with respect to its application as a magnetic lens. Using a dynamical z-pinch discharge in helium magnetic field gradients of 600 T/m were achieved within a pinch column of 14 mm diameter and 100 mm length. In addition homogeneous wall stabilized z-pinch-discharges have been performed in argon in a discharge tube of 20 mm diameter and 100 mm length. Field gradients of more than 200 T/m have been measured for a temporal duration of 1 µs. This device offers the possibility of high repetition rates.

1. INTRODUCTION

The plasma lens is a "wire lens", which focuses high energy particles by means of an azimuthal field excited by an axial current (z-pinch discharge). First experiments have been performed at Berkeley and NBL [1,2]. Meanwhile successful applications of plasma lenses at CERN [3] and at GSI-Darmstadt [4] were published. The experiments reported herein were performed to investigate systematically the influence of the discharge geometry, of the discharge gas and of a pulsed preionisaton on the stability and reproducibility of the gas discharge.

2. EXPERIMENTAL SET UP

The experiments were carried out with the former CERN plasma lens pulse generator [5]. The data are summarized in table 1. In addition a pulsed preionisation was installed. The delay between pre- and mainpuls was adjustable between 0 - 100 µs.

Table 1.
Data of the pulse generator

	main pulse	preionisation
capacitance [µF]	108	1.3
charging Voltage [kV]	≤14	12.5
inductance [µH]	0.015	15
impedance [Ω]	0.010	3.5
current [kA]	≤370	4
current rise time [A/s]	$5 \cdot 10^{11}$	$1.5 \cdot 10^{9}$

Figure 1 shows the schematic cross section of the discharge tube. The two graphite electrodes are seperated by an alumina or quartz insulator tube. The length and the diameter of the discharge tube can be chosen free within certain limits. The current return conductor consists of 16 brass rods. The hollow electrodes have axial windows giving optical access to the plasma column. The dynamics of the discharge was investigated with magnetic field probes and short time photography.

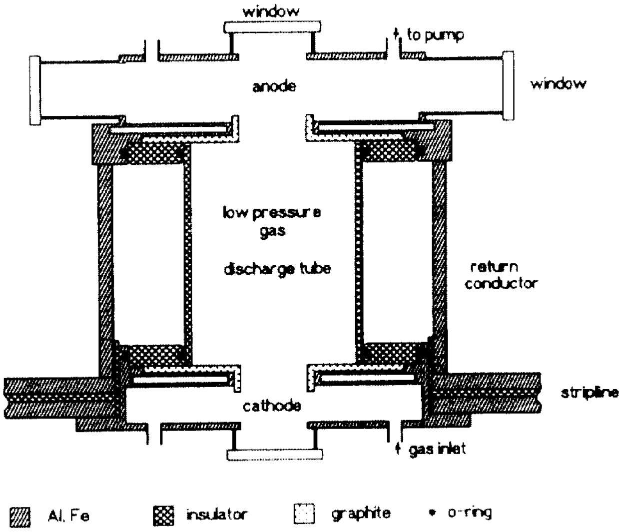

Figure 1. Cross-section of the discharge tube

3. DYNAMICAL Z-PINCH

3.1 Principle

The different phases of a dynamic z-pinch discharge are scetched in Fig. 2. After an homogeneous ignition the current is driven to the insulator wall due to the skineffect. Typical skin

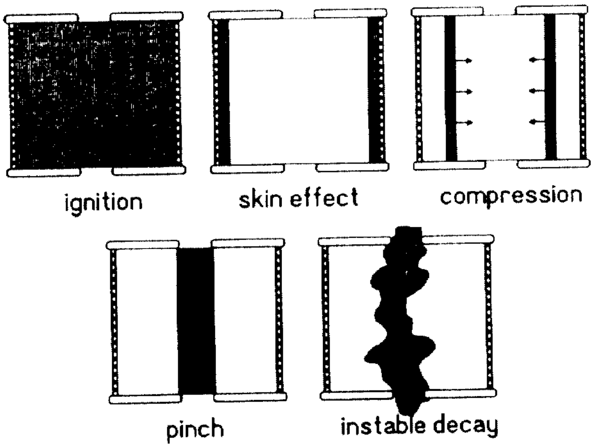

Figure2. Phases of a dynamical z-pinch discharge

depths are 1-2 cm. With rising current the magnetic force accelerates the current carrrying hollow cylinder towards the axis. At pinch time, i.e. when the plasma arrives at axis, a homogeneous current distribution is achieved near the axis. The resulting azimuthal magnetic field can be used for focusing high energy particles. The parameters of the pinch like current density, pinch diameter and stability are determined by the pulse generator and the geometrical dimensions of the discharge tube. For the application as a plasma lens the pinch time should be at current maximum of the pulsed discharge.

3.2 Results

With helium as discharge gas the ignition and the compression phase is very homogeneous and reproducable. In hydrogen filamentation takes place which causes instabilities for slow z-pinches. High Z-gases like Ne and Ar cause currents at the insulator tube due to the increased UV- and VUV-radiation. This effect reduces the current in the pinch considerably and enhances the erosion of the insulator. Two typical radial magnetic field distributions are shown in Fig. 3 and 4 for five different times around pinch time. The magnetic field gradients amount to 600 T/m ± 3% for a duration of 130 ns and 230 T/m ± 7% for 120 ns respectively. Due to the different inslulator radii the aperture of the lens, i.e. the radius of the pinch is 14and 40 mm.

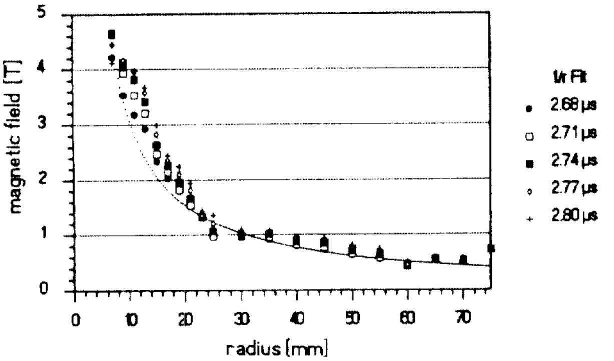

Figure 3. Magnetic field distribution for different times (length of insulator tube: 100 mm, diameter: 150 mm, current: 300 kA, charging voltage: 12 kV, 320 Pa He)

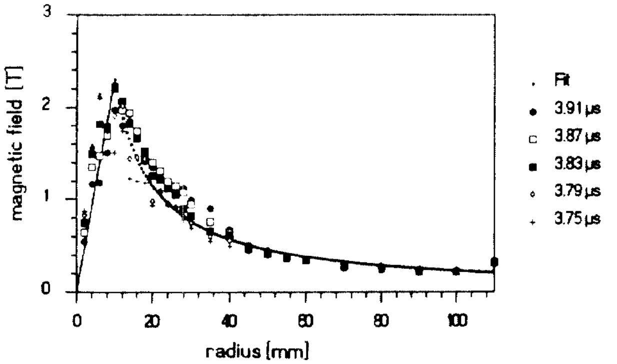

Figure 3. Magnetic field distribution for different times (length of insulator tube: 250 mm, diameter: 215 mm, current: 200 kA, charging voltage: 12 kV, 115 Pa He)

3.3 Limitations

The main task for designing a z-pinch plasma lens is the matching of plasma dynamics to the pulse generator. The pinch time has to be adjusted to the current maximum of the pulse generator for optimum efficiency. This can be achieved by choosing appropriate values for gas pressure, diameter of insulator and generator cycle time [6]. The length of the lens can be adjusted to the desired focusing strength of the lens.

Up to now no principle limitations of discharge current and geometrical dimensions have been observed. One problem might be the duration of the pinch. It is increasing with increasing generator cycle time. For example with the CERN plasma lens a stability of 1 µs was observed [3]. An additional longitudinal magnetic field gives a second possibilty to enhance stability. The lifetime of the lens is greater than 10^6 discharges if adequate material is chosen [3]. The limit of maximum repetition rate is not yet investigated.

4. WALL STABILIZED Z-PINCH

4.1 Principle

If the diameter of the discharge tube is of the order of the skin depth the dynamic phase of the discharge is suppressed. Moreover the insulator prevents the growth of instabilities.

4.2 Results

To reduce the current through the lens below 100 kA, only two modules of the pulse generator were used giving a total capacitance of 54 µF. The maxmimum applied voltage was 6 kV.

For this type of discharge only Ar seems to be an adequate discharge gas. Using He or H_2 instabilities were observed. Figure 5 shows a typical distribution of the magnetic field around current maximum. At the inner radii a nearly linear rising magnetic field was measured. Its gradient amounts to 210 T/m ± 3% within a radius of 5 mm. The stability is greater than 1 µs and is mainly determined by the cycle time of the pulse generator.

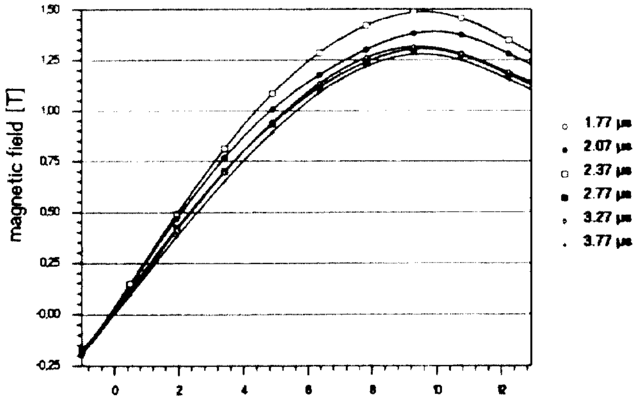

Figure 4. Magnetic field distribution for different times (length of insulator: 100 mm, diameter: 20 mm, current: 80 kA, charging voltage: 6 kV, 270 Pa Ar).

4.3 Limits

To get a stable discharge there must be an equilibrium between the magnetic pressure and the gas kinetic pressure of the plasma column. This phenomenon is described by the Bennett equation:

$$I^2 = \frac{8\pi}{\mu_0} N_L k T$$

with I: discharge current
N_L: particle line density
T: plasma temperature
k: Boltzmann constant

Figure 5 shows the temperature of the plasma as a function of the discharge current for different line densities. As there is no effective compression of the initial gas, the line density of a wall stabilized discharge is determined by the initial gas pressure. But its value can not be chosen freely, because a homogeneous gas discharge can only be obtained in a low pressure regime between 50 and 1000 Pa.

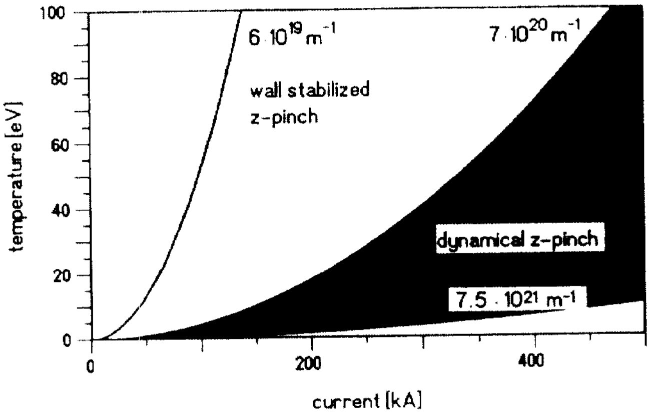

Figure 5. Temperature of the plasma as a function of discharge current for different line densities calculated by the Bennett equation. The parameter range of the dynamic and of the wall stabilized z-pinch is indicated.

5. SUMMARY

Table 2
Overview of lens parameters

	dynamical z-pinch		wall stabilized z-pinch
magnetic field gradient [T/m]	150	600	210
durations [ns]	140	130	1000
aperture [mm]	40	14	20
energetic efficiency [%]	3.5	3.0	1.7
current [kA]	300	370	80
charging voltage [kV]	12	12	5
capacitance [µF]	108	108	54

Table 2 gives an overview of the achieved lens properties for different experimental set ups. The maximum magnetic field gradients are obtained with a dynamical z-pinch discharge. But here the lens aperture is less than with the lower field gradients.

A wall stabilized discharge has lower field gradients but an enhanced stability. Experiments at the GSI-Darmstadt [4] show that it has linear imaging properties. The efficiency of this type of lens, i.e. the part of magnetic energy useable for focusing with respect to the energy dissipated in the lens, is lower than with a dynamic z-pinch discharge. For currents exceeding 200 kA only the dynamic z-pinch has moderate plasma temperatures in the Bennett equilibrium (Fig. 5).

These results are summarized in more detail in [7].

6. OUTLOOK

It is shown that a plasma lens can be a reliable component of future accelerators. But for each new application special demands to the lens are given. To widen the applicability the stability of the dynamic z-pinch discharge has to be improved. In near future experiments with a stabilizing axial magnetic field will be performed. Further the maximum possible repetition rate of such a device has to be determined.

The limit of a wall stabilized discharge seems to be a current of about 100 kA. Otherwise a gas pressure has to be chosen which is not appropriate to obtain a homogenous discharge. This effect will also be studied in further experiments.

7. REFERENCES

[1] W. K. H Panofsky, W. R. Baker, "A Focusing Device for the External 350-MeV Proton Beam of the 184-Inch Cyclotron at Berkeley", Rev. Sci. Instr., Vol. 21, No. 5, p. 445, 1950

[2] E. B. Forsyth, L. M. Lederman and J. Sunderland, "The Brookhaven-Columbia Plasma Lens", IEEE Trans. Nucl. Sci. NS-12, p. 872, 1965

[3] R. Kowalewicz, M. Lubrano di Scampamorte, S. Milner, F. Pedersen, H. Riege, J. Christiansen, K. Frank, M. Stetter and R. Tkotz, "Performance of the CERN Plasma Lens in Laboratory and Beam Tests at the Antiproton Source",in: Proc. of the Particle Accelerator Conf. (PAC 91), San Francisco 1991

[4] E. Boggasch, A. Tauschwitz, H. Wahl, K.-G. Dietrich, D. H. H. Hoffmann, W. Laux, M. Stetter, R. Tkotz, "Plasma Lens Fine-Focusing of Heavy Ion Beams", submitted to Appl. Phys. Lett., 1992

[5] B. Autin, H. Riege, E. Boggasch, K. Frank, L. de Menna and G. Miano, "A Plasma Lens for Focusing High Energy Particles in an Accelerator", IEEE Trans. Plas. Sci. PS-15, p. 226, 1987

[6] H. R. Bauer, R. Tkotz, H. Riege, "Calculations of the Pinch Dynamics in a Plasma Lens by One Dimensional Magneto-Hydrodynamic Z-Pinch Models", CERN PS/87-91 (AA), 1987

[7] M. Stetter, "Untersuchungen an verschiedenen Z-Pinchentladungen für die Fokussierung geladener Teilchen in der modernen Beschleunigertechnologie", University of Erlangen-Nürnberg, Ph. D. Dissertation, 1992