GSI-Preprint-95-77
NOVEMBER 1995

CONTRIBUTIONS TO THE
**INTERNATIONAL SYMPOSIUM
ON
HEAVY ION INERTIAL FUSION**

PRINCETON, SEPT. 6 - 9, 1995

(To be published in: Journal of Fusion Engineering Design)

SCAN-9603071

CERN LIBRARIES, GENEVA

SA 96-11

Gesellschaft für Schwerionenforschung mbH
Postfach 110552 · D-64220 Darmstadt · Germany

Contents

1. Accelerator Physics

Heavy Ion Fusion Research at GSI <i>I. Hofmann (GSI Darmstadt)</i>	1
Simulation of the Debunching Process and Adiabatic RF Capture of Dense Beams <i>U. Oeftinger, I. Hofmann (GSI Darmstadt)</i>	15
Spectral Analysis of Transverse Coherent Oscillations of Intense Coasting Beams <i>R.W. Hasse, I. Hofmann (GSI Darmstadt)</i>	23
Final Beam Transport and the Application of High Current Pulsed Quadrupole Lenses for Focusing in an ICF-Test Facility <i>P. Spiller, M. Stetter, S. Stöwe, R.W. Müller, I. Hofmann (GSI Darmstadt), U. Neuner (Universität Erlangen), H. Wollnik, M. Winkler (Universität Gießen)</i>	29
High Current Pulsed Lenses for ICF Applications <i>H. Wollnik, M. Winkler, B. Pfreundtner, E.I. Esch (Universität Gießen), P. Spiller (GSI Darmstadt)</i>	35

2. Plasma Physics

Summary Report: Beam Target Interaction and Chamber Propagation <i>D.H.H. Hoffmann (Universität Erlangen)</i>	41
Heavy Ion Beam Induced Motion in Rare Gas Cryo Targets <i>M. Dornik, W. Laux, P. Spiller, M. Stetter, S. Stöwe (GSI Darmstadt), D.H.H. Hoffmann (Universität Erlangen), W. Seelig, C. Stöckl, W. Süß, H. Wetzler (TH Darmstadt), A. Filimonov, M. Kulish (ICP, Chernogolovka), V. P. Dubenkov, B. Sharkov (ITEP, Moscow)</i>	46
The High Current Plasma Lens - Investigations on Fine Focusing of High Energy Heavy Ion Beams <i>M. Stetter, S. Stöwe, M. Dornik, P. Spiller (GSI Darmstadt), U. Neuner, D.H.H. Hoffmann, R. Kowalewicz (Universität Erlangen), A. Tauschwitz (LBNL, Berkeley)</i>	56

3. Reactor Aspects

Environmental Aspects of Tritium and Active Waste - A Comparison of Four ICF-Reactor Concepts <i>K. Weyrich, D.H.H Hoffmann (Universität Erlangen)</i>	69
Influence of DT Fuel Composition on the Energy and its Implications on Reactor Safety and Environmental Acceptability <i>N.A. Tahir (GSI Darmstadt)</i> <i>D.H.H. Hoffmann (Universität Erlangen)</i>	76
Authors Index	83

THE HIGH CURRENT PLASMA LENS - INVESTIGATIONS ON FINE FOCUSING OF HIGH ENERGY HEAVY ION BEAMS

M. Stetter¹, U. Neuner², S. Stöwe¹, M. Dornik¹, D.H.H. Hoffmann²,

R. Kowalewicz², P. Spiller¹, A. Tauschwitz¹

¹GSI-Darmstadt, ²Physikalisches Institut I, Universität Erlangen-Nürnberg, Germany

Abstract

Fine Focusing and transport of heavy-ion beams in active plasma lenses is a significant issue for inertial confinement fusion. Therefore some of the corresponding questions are addressed in an experimental program at GSI. Very accurate and reproducible focusing of the ion beam at energies between 200 and 300 MeV/u is now achieved. Emittance measurements and the determination of the emittance growth due to scattering in thin foils of the heavy ion beam have been possible. The minimum spot diameter was 390 μm in the vertical plane at a target distance of 53 mm and 150 kA plasma current. Specially designed windows have been constructed to separate the target area from the lens plasma. Plasma currents of 340 kA have been reached without destruction of the window enabling now target distances of 40 to 50 mm from lens exit.

1. Introduction

Plasma lenses are currently under discussion as advanced focusing devices for special applications. Main advantages of plasma lenses are: strong first order focusing simultaneously in horizontal and vertical plane; space charge neutralization of intense charged particle beams. Both are very interesting features useful for present reactor designs for heavy ion beam driven fusion.

Intense high energy heavy-ion beams are an unique tool to create volume heating in solids up to plasma conditions. The necessary specific energy deposition for the given number density of the SIS-beam (up to 10^{11} total particle number) is mainly inversely proportional to the focusing area, i.e. inversely proportional to the square of the focusing radius. Therefore a spot diameter of $200\text{ }\mu\text{m}$ (FWHM) is desired to get temperatures of up to some electron volts at nearly solid state density [see for example 1,2]. In the "High Energy Density in Matter" program a plasma lens has been designed and constructed to focus the SIS heavy ion beam onto these very small spots. The focus diameter is determined by the parameters of the SIS-accelerator at GSI-Darmstadt: beam rigidity, 6 Tm; particle energy, 300 MeV/amu; emittance, $10 - 40\text{ }\pi\text{ mm mrad}$ (rms). For an ideal lens the spot diameter of a beam with a given emittance scales inversely with the focusing angle α . For an emittance of $10\text{ }\pi\text{ mm mrad}$ (rms) and a focus diameter of $200\text{ }\mu\text{m}$ (FWHM) α is fixed and the initial beam diameter at the lens entrance and the distance of the spot from the lens exit determine the current and length of the plasma column. According to calculations for different target distances and initial beam diameters currents between 300 and 400 kA are required. The field configuration of a "wire lens", characterized by an axially symmetric and

radially linear rising magnetic field, is produced by a homogeneous axial current density in a plasma (see fig. 1). The beam particles traverse this plasma which has densities between 10^{-6} and 10^{-10} g/cm³. Scattering is negligible at these plasma densities and the ion energies of the SIS. The main task of this experiment is the creation of a homogeneous current density distribution in the gas discharge during the focusing phase in order to get no lens aberration.

The selected approach for the discharge geometry is the "wall stabilized discharge" where the contraction of the current-carrying sheath is suppressed. This system has shown very good focusing properties with currents up to 30 kA [see for example 3,4].

2. Experimental Setup and Diagnostic

The plasma lens pulse generator is composed of up to six exchangeable capacitor banks. These units are connected to the plasma lens by flexible low-inductance HV pulse cables, enabling an easy in-place adjustment of the plasma lens. The parameters are: capacitance, 13 - 80 μ F; charging voltage, 5 - 20 kV; discharge current, 10 - 400 kA; current halfwave, 6 - 9 μ s (see fig. 5). The lens is surrounded by the target chamber (fig. 1), enabling vacuum in the chamber while low-pressure gas in the lens system is contained by 20 to 300 μ m thick titanium windows.

Fig. 1: Schematic drawing of the plasma lens with the target chamber

Optical and spectroscopical measurements with gated CCD-cameras and a spectrometer have been performed to get scaling laws for the plasma behavior of a wall stabilized discharge at these high currents. The exposures have been made either end- or side-on of the discharge tube. The side-on measurements are limited to peak currents up to 100 kA because the quartz tubes are then

destroyed by the discharge. At higher currents and in the beam experiments alumina tubes have been used.

In the beamline the time-dependent development of the focus on plastic and quartz scintillators was detected by short time photography. The principle arrangement of a plasma lens and the diagnostic is shown in figure 2.

Fig. 2: Principle arrangement of the plasma lens with diagnostic and an example for a profile measurement of the intensity distribution at different target positions.

3. Experiments and Results

A) Influence of the magnetic field distribution on the intensity distribution in the focus

After completion of the plasma lens and the first capacitor bank the system was tested at the GSI UNILAC accelerator with a beam rigidity of 1.6 Tm, emittance of 5π mm mrad, maximum beam diameter of 10 mm and discharge currents up to 90 kA. Figure 3 shows an example for a magnetic field distribution at different times. The magnetic field was measured by small field probes in a discharge tube of 20 mm diameter and 100 mm length. The discharge gas was Argon at a pressure of 270 Pa and the peak discharge current was 65 kA [5].

Fig. 3: Measured magnetic field in a wall stabilized discharge; Ar 270 Pa, peak discharge current 65 kA.

The deviation from the linear rising magnetic field at a radius of 5 mm was less than 5%. Therefore computer simulations have been performed to estimate

the influence of small deviations from the ideal case on the intensity distribution in the focal plane on a scintillator. Figure 4 A shows the focus on a target for the ideal linear rising magnetic field and 4 B a small deviation of the current density distribution.

Fig.4: Simulation of focusing results for a constant current density distribution (A) and a deviation from this ideal case (B).

The parameters of the simulation are: current density distribution and magnetic field as shown in figure 4; target distance 52 mm; total plasma lens

current 155 kA; plasma length 100 mm; Ar ion beam with 300 MeV/u and 35π mm mrad emittance (rms); beam diameter 7 mm (FWHM). The fit to the data points is a gaussian curve. In the ideal case there is no deviation of the data points from the fit. In the non ideal case there is first an enlargement of the focus diameter and second a deviation from the gaussian curve at the outer parts of the focus intensity. Therefore a good agreement of the horizontal and vertical intensity profile in the focal plane to a gaussian curve is an evidence for a constant current density distribution over the total beam diameter.

For the experiments at the UNILAC no aberrations of the plasma lens have been observed, i.e. no deviation from the homogeneous current density distribution occurred [6].

B) Optical measurements of the discharge development

In addition, laboratory experiments with optical and spectroscopical measurements of the plasma are carried out to get scaling laws for the plasma behavior of a wall stabilized discharge at these high currents. The plasma development is similar for all investigated currents between 45 and 90 kA. The homogeneous ignition over the discharge volume is followed by a contracting shock wave. The time to reach the axis is about 1 μ s. This shock wave is produced by the heating and desorption of adsorbates on the insulator tube. After a short expansion of the shock produced dense plasma on axis, a second contraction phase is visible. The velocity is increasing with increasing peak current. This is the pinching of the current layer due to the magnetic fields. The pinch is expanding again and during current maximum a homogeneous plasma cylinder is visible. By scaling these results it is possible to adjust the

tube diameter and the gas pressure such that the diameter of the plasma at current maximum is slightly greater than the incoming beam diameter.

C) Quality of the focusing experiments

This encouraging first tests were followed by several beam experiments at the GSI SIS/ESR facility, with 6 Tm beam rigidity and plasma currents up to 200 kA (4 to 6 capacitor banks). The time correlation of the plasma current and the four SIS beam bunches is shown in figure 5.

Fig. 5: Time correlation of the plasma lens current and the SIS-beam for optimized focusing

The following parameters have been varried:

- a) time correlation of the plasma lens current and the beam pulses. It is possible to change this correlation by varriing the delay between a signal corresponding to the beam bunches and the trigger pulse for ignition of the plasma lens. The jitter of this time correlation is better than 100 ns. The highest efficiency of the plasma lens can be expected during current maximum.

- b) the amplitude of the plasma current at the time of focusing. By changing the amplitude it is possible to adjust the focal length of the plasma lens.
- c) pressure of the initial argon gas in the discharge tube. The gas pressure is influencing the time dependence of the initial shock wave and the diameter of the current cylinder.

The optimization is finished when for a given beam diameter and beam rigidity the necessary field gradient and a homogeneous and constant current density distribution during the focusing phase is reached.

Fig. 6: Focus on the scintillator (a) and vertical (390 μm FWHM) and horizontal (540 μm FWHM) spot profile (b)

Figure 6a shows a focused Ar^{18+} beam and 6b the vertical and horizontal beam profile at a target distance of 53 mm from the end of the plasma column. The minimum spot diameter was 390 μm in the vertical plane at a target distance of 53 mm and 155 kA plasma current. The length of the plasma column was between 90 and 95 mm.

The spatial resolution was 30 μm in vertical and 80 μm in horizontal direction. The diameter of the incoming beam was 14 mm and the plasma

column during best focusing was between 14 and 16 mm depending on the peak current and the gas pressure. These focusing results are in very good agreement to the simulations in figure 4 A.

D) Measurement of beam emittance and emittance growth by the plasma lens

We tried to determine the beam emittance by measuring the spot size at different target distances. As long as the focus is only emittance-limited one should find a linear dependence of the spot diameter as a function of the focal length (fig. 7). These results yield $37 \pm 3 \pi$ mm mrad horizontal and $24 \pm 1.5 \pi$ mm mrad vertical emittance (rms). It is known that the beam has about a factor of two higher emittance in the horizontal than in the vertical plane. The reproducibility of focus diameter and focus position for several shots was within the error of measurement.

Fig. 7: Focus diameter as a function of focal length for the horizontal and vertical beam profile

4. Conclusion

The accuracy and reproducibility of wall stabilized plasma lenses at currents up to 200 kA have been demonstrated. Lens aberrations have not been detected within the errors of measurement. The next step is to increase the current to about 300 kA by increasing the charging voltage of the capacitor banks. In laboratory tests the feasibility of the alumina discharge tubes and the thin titanium windows to withstand these higher currents have already been shown. The lens with increased focusing power will then be tested again at the SIS-beam. This optimized plasma lens should reach spot diameters very close to 200 μm if the emittance of the SIS-beam is within the designed values.

An increase of the deposition power by a factor of 4 in rare gas cryo targets [2] is possible already with the '200 kA' plasma lens. By increasing also the focusing power and by the use of heavy projectiles it is possible to enlarge the energy deposition by almost a factor of 10 to 20 in the near future compared to the experiments described in the paper of M. Dornik [2]. A new construction of the target chamber and the plasma lens is already fabricated to enable the use of cryo targets with the plasma lens.

Acknowledgments

This project has been funded by the Federal Minister of Research and Technology (BMFT) under the contract number 06 ER 462 and 06 ER 358.

5. References

- [1] J. Meyer-ter-Vehn, S. Witkowski, R. Bock, D.H.H. Hoffmann, I. Hofmann, R.W. Müller, R. Arnold, P. Mulser, Phys. Fluids B 2 (6), (1990) 1313
- [2] M. Dornik, V. Dubenkov, A. Filimonov, D.H.H. Hoffmann, M. Kulish, W. Laux, W. Seelig, B. Sharkov, P. Spiller, M. Stetter, C. Stöckl, S. Stöwe, W. Süß, H. Wetzler, 'Heavy Ion Beam Induced Motion in Rare Gas Cryo Targets', this edition
- [3] E. Boggasch, A. Tauschwitz, H. Wahl, K.-G. Dietrich, D.H.H. Hoffmann, W. Laux, M. Stetter, R. Tkotz, Appl. Phys. Lett. **60** (1992) 2475
- [4] A. Tauschwitz, E. Boggasch, D.H.H. Hoffmann, J. Jacoby, U. Neuner, M. Stetter, S. Stöwe, R. Tkotz, M. de Magistris, W. Seelig, Laser and Particle Beams, vol. 13, no. 2 (1995) 221
- [5] M. Stetter, 'Untersuchungen an verschiedenen Z-Pinch Entladungen für die Fokussierung geladener Teilchen in der modernen Beschleunigertechnologie', Ph. D. thesis, University of Erlangen (1992)
- [6] M. Stetter, J. Christiansen, U. Neuner, S. Stöwe, R. Tkotz, T. Wagner, E. Boggasch, A. Tauschwitz, D.H.H. Hoffmann, Il Nuovo Cimento, 106A, N. 11 (1993) 1725