SECTION III

Beam Transport, Pulse Compression, Final Focus, and Beam Diagnostics

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PLASMA LENSES FOR HEAVY-ION-BEAM FOCUSING

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Inertial confinement fusion driven by heavy ion beams requires the handling of intense particle beams near the space-charge limit. Especially, the focusing of such beams to small spot sizes is a challenging problem and calls for new ideas on the margin of present-day accelerator technology. One objective of the heavy-ion fusion program at GSI is the generation and investigation of plasmas created by heavy-ion beams impinging on targets. In addition to conventional focusing techniques, we have started to consider the use of a z-pinch plasma lens to obtain sub-millimeter spot sizes which are necessary for achieving high deposition power in targets. For the first time a heavy-ion beam was focused using a z-pinch plasma lens. The diameter of an incident, parallel 460-MeV argon ion beam was reduced from ~ 8 mm (FWHM) to ~ 2 mm within 230 mm downstream of the plasma.

1 INTRODUCTION

Heavy-ion fusion is now widely regarded to be the most promising approach to commercial inertial confinement fusion (ICF) power production. Within the framework of the German heavy-ion fusion program, fundamental questions relevant to the physics of heavy-ion beam drive ICF-research are being addressed at GSI. The main experimental activities concentrate on the production of high-density, high-temperature plasmas by irradiating targets with heavy-ion beams.[1] Heavy ions yield a specific deposition power in matter which is proportional to the beam power and inversely proportional to the range of the ions and to the beam's spot size. In reducing the spot size by adding a plasma lens to the conventional quadrupole system, the achievable deposition power could be significantly enhanced.[2] In the course of the envisaged high-energy density experiments at the new heavy-ion synchrotron facility SIS/ESR at GSI, a specific deposition power up to 10 TW/g is expected to be obtained in a target.[3]

Inside a conducting, current-carrying plasma cylinder, under the assumption of a constant current density, a high-gradient azimuthal magnetic field is obtained which can be used for focusing axially moving charged particles simultaneously in both transversal planes ("active" plasma lens). Operating in a density regime below $\sim 10^{19}$ cm^{-3} means that absorption processes are almost negligible for the penetrating particles. In 1950, a 350-MeV proton beam from the 184-inch cyclotron in Berkeley was focused for the first time by a plasma lens with moderate characteristics.[4] A stronger plasma lens with more focusing power was built in Brookhaven in 1964.[5] Here, a contracting plasma column generated during a dynamic 500-kA z-pinch discharge was used for capturing 3-GeV/c muons and kaons emerging as secondary particles from a target.

The active plasma lens concept was followed up again for a space charge compensated transport scheme of high-current light ion beams guided in linear discharge channels ("z-discharges")[6,7,8] and for antiproton focusing at CERN.[9,10]

2 FOCUSING EXPERIMENT

We intended to perform a first-proof-of-principle experiment to investigate the focusing behavior of a z-pinch plasma lens on a heavy-ion beam. The experimental set-up is presented in Figure 1 and the characteristics of the z-pinch discharge used are summarized in Table 1. A parallel beam of 460-MeV (11.4 MeV/amu) Ar^{11+} ions

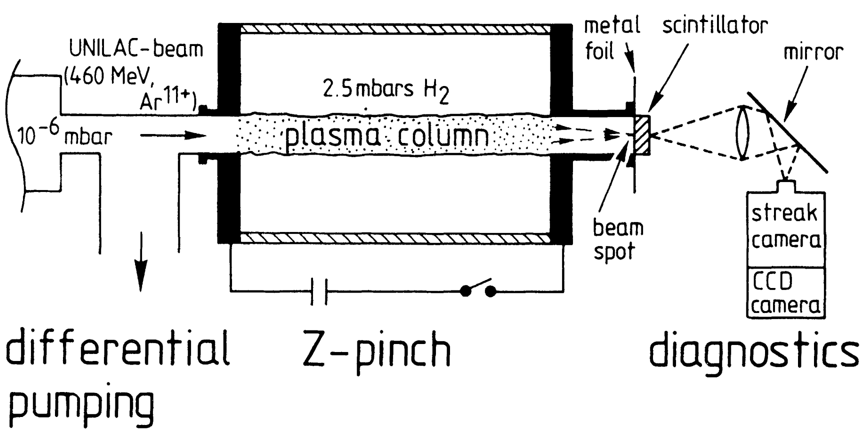

FIGURE 1 Schematic representation of the focusing experiment.

TABLE 1
Characteristic data of the *z*-pinch

capacitance	4 μF
charging voltage	32.5 kV
inductance	15 nH
current rise rate	10^{12} *A/s*
max. current	400 kA
filling gas	hydrogen
gas pressure	2.5 mbar
length	200 mm
tube radius	54 mm
pinch radius	~10 mm
pinch plasma density	1.5×10^{19} cm^{-3}

from the linear accelerator UNILAC at GSI propagated axially through the *z*-pinch quartz vessel filled with hydrogen gas at a pressure of 2.5 mbars. The average electric particle current of the 500-μs-long beam pulse was about 30 μA. During the beam passage the discharge was triggered and a pinched plasma column of 20 mm diameter and 200 mm length was reproducibly formed along the axis within 1.3 μs and remained optically stable for more than 500 ns. During the pinch phase the plasma radius is reduced by a factor of 10, resulting in a plasma density of 1.5×10^{19} cm^{-3}. A 10-mm-wide aperture was provided along the entire experiment to allow room for both the propagating beam and an efficient differential pumping system. Thus the gas pressure in the adjacent beam pipe could be effectively reduced to the accelerator vacuum of less than 10^{-6} mbar without solid windows, and beam interaction with solid windows was avoided. The beam spot was observed downstream of the plasma using a fast plastic scintillator which was positioned at 230 mm and 380 mm behind the pinch. The emitted scintillator light was monitored using fast streak and framing photography. The streak images were registered by a CCD camera system for further numerical image processing; the framing images were registered on photographic film. The side of the scintillator facing the plasma was covered by a 20-μm-thick aluminum foil, thus shielding the plasma light but still allowing the ions to penetrate. The magnetic field was measured inductively using small coils[11] inserted axially through the electrodes into the discharge volume. Up to now magnetic field data have been taken only at radii equal or larger than the pinch radius of 10 mm[12] and the resulting magnetic field gradients can only be estimated assuming linear field dependence inside the plasma.

3 RESULTS

A time-dependent overview of the experimental results is presented in Figure 2. The waveforms of the discharge current and the magnetic field at the pinch radius are seen in Figure 2a and Figure 2b, respectively. The field peaks at 1.6 μs ("magnetic pinch time") about 300 ns after the optically visible pinching starts. A time-correlated streak image of the beam spot diameter on the scintillator taken at a distance of

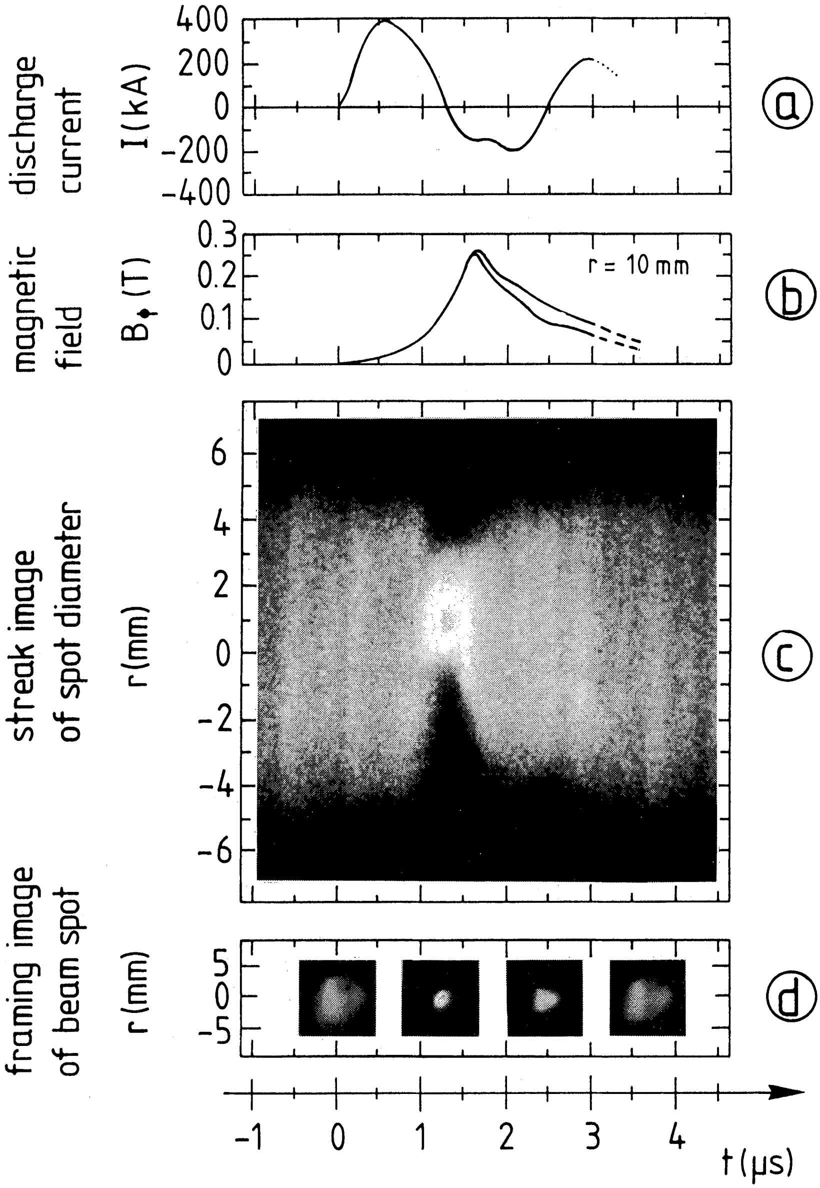

FIGURE 2 Presentation of (a) discharge current, (b) magnetic field, (c) streak image, and (d) framing images as a function of time t. Time zero indicates the start of discharge. The streak image was taken with a 200-μm-wide slit at 380 mm distance behind the pinch. The exposure time for the framing images was 200 ns with an interframing time of 1 μs.

380 mm behind the pinch is shown in Figure 2c. The spot size shrinks during the discharge. Slight variations of intensity before and after the contraction are caused by fluctuations of the ion source current. A small misalignment of the pinch axis from the beam axis leads to a slightly off-centered but reproducible contraction. Figure 2d shows a series of end-on framing pictures of the entire beam spot also taken at a 380-mm distance. The maximum focusing, witnessed at 380 mm after $\sim 1.3\ \mu s$, occurs while the magnetic field still is rising. As the magnetic field amplitude is changing with time, the location of the focal spot behind the pinch is also time-dependent. A constant magnetic field gradient of 12 T/m is necessary to produce a focus at the chosen distance d of 380 mm behind the lens. At the time of maximum field (1.6 μs), the spot diameter has increased again to about 5 mm because the higher gradient of 25 T/m has produced the focal spot already, at $d \approx 160$ mm. Thus, by the time at 380-mm distance the beam is overfocused. Streak images taken at $d = 230$ mm show that the spot size has been reduced approximately by a factor of 4 at the magnetic pinch time, to about 2 mm (FWHM) from its initial value of 8 mm (FWHM). Mechanical constraints did not allow to place the scintillator at the shortest focal length of 160 mm occurring at the time of maximum magnetic field.

4 DISCUSSION

We observed the focusing effect, although the discharge current is small and close to the zero crossing of the signal. The axially measured magnetic field in Figure 2b, causing focusing, indicates a permanent positive axial current flow that exceeds 10 kA within the pinched plasma column. Obviously, this axially flowing pinch current does not follow the alternating discharge current but keeps its original direction, producing the focusing effect for the positive ions. This advantageous axial field amplification, enhancing the focusing power significantly, can be explained by the "inverse skin effect".[13,14]

The z-pinch we used for this experiment was originally designed to produce a very homogeneous plasma target[15,16] for measuring the energy loss of heavy ions penetrating a dense plasma environment.[17,18] The minimum pinch radius coincided with the zero crossing of the discharge current, thus anticipating and minimizing any disturbing effects on the beam by the magnetic fields. Nevertheless, it soon became apparent that, for the ion beams used, the transmission through the plasma was influenced by the discharge, which was attributed to a plasma lens effect.[19] For an effective plasma lens design, however, the pinch current has to be maximized to achieve sufficiently high magnetic field gradients. In the CERN antiproton plasma lens, field gradients of several hundred teslas per meter were obtained, whereas in our experiments the gradients are about one order of magnitude lower.

The experimentally observed minimum spot size Δr remains finite due to the finite beam emittance ε of $\sim 5\pi$ mm-mrad and, to some part, due to a variety of aberrations. Space charge effects are still unimportant for the beam parameters used. For a convergence angle δ of ~ 25 mrad, the emittance-limited spot radius is approximately $\Delta r_\varepsilon = \varepsilon/\delta \approx 0.2$ mm. Main aberration constituents are chromatic aberration caused by the momentum spread Δp of the beam particles and spherical aberration caused by radial variations of the focusing strength $\Delta\kappa$. While passing the plasma, the heavy ions change their charge state by ionization and recombination processes and lose energy by Coulomb interaction with the plasma particles. These interaction processes degrade the beam parameters and add to aberration. In order to estimate the magnitude of these beam-plasma interactions and to separate them from the lens-related aberration due to deviations from the field linearity, a Monte Carlo code[18] was used. The numerical calculations fit the experimental results. For a purely linearly rising magnetic field and a gradient of 25 T/m, a minimum FWHM focus diameter of 0.4 mm was calculated at a distance of 156 mm behind the pinch, with an angle of convergence of $\sim$25 mrad. At 230 mm the beam has expanded to $\sim$1.7 mm, and at 380 mm distance to $\sim$5.7 mm at the same time. This indicates a mostly emittance-limited spot size with little contribution of aberration effects. If the same calculation is performed with an assumed quadratic field dependence, the minimum diameter almost doubled to 0.7 mm at 163 mm, demonstrating the importance of field linearity rather than beam-plasma interactions among contributors to the spot-size limitation.

According to the calculations, during the passage through the plasma, with a density of 1.5×10^{19} cm^{-3} the medium charge of the initial Ar^{11+} beam increases to $Ar^{17.5+}$ (where the ions are equally distributed in charge states 17+ and 18+). The corresponding magnetic rigidity reduces from $\sim$1.8 T-m to $\sim$1.1 T-m, and the drift length d behind the pinch decreases equally from 286 mm to 156 mm, assuming a constant field gradient of 25 T/m. A calculated energy loss of 18 MeV corresponds to about 4% of the total incident energy. In spite of the agreement of simulation and experiment it seems, however, difficult at this point to use the experimental results for a quantitative conclusion about the grade of linearity of the field distribution. Further time-resolved measurements of the spot size closer to the minimum focal distance at $\sim$160 mm are planned. These experiments will be accompanied by a more detailed experimental mapping of the magnetic field of the pinch at smaller radii.

5 CONCLUSIONS

Alternative beam transport and focusing schemes have again experienced increasing interest for heavy-ion-beam-driven fusion scenarios because they allow a simpler reactor design and possibly relax the constraints on necessary beam parameters.[20] A heavy-ion beam was focused for the first time by a z-pinch plasma lens. The advantages of this cylindrical wire lens are based on its capability to focus in first order, and simultaneously in both transversal planes with negligible absorption, resulting in symmetric focusing at a short focal length. These characteristics make plasma lenses appear attractive compared to conventional lens devices when extreme focusing power is needed. We consider the development of a fine focusing plasma lens for focusing of heavy-ion beams from the SIS/ESR-facility to sub-mm spot sizes. These beams with a magnetic rigidity of about 6 T-m will need much more focusing power than was possible with the z-pinch used for our experiment. We are encouraged by the reported results to perform further experimental investigation of this attractive advanced focusing technique.

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REFERENCES

1. J. Jacoby, D. H. H. Hoffmann, R. W. Müller, K. Mahrt-Olt, R. C. Arnold, V. Schneider, and J. Maruhn, *Phys. Rev. Lett.*, **65**, 2007 (1990).
2. B. Heimrich, H. Nestle, M. Winkler, D. H. H. Hoffmann, and H. Wollnik, *Nucl. Instrum. Meth. A* **294**, 602 (1990).
3. J. Meyer-ter-Vehn, S. Witkowski, R. Bock, D. H. H. Hoffmann, I. Hofmann, R. W. Müller, R. Arnhold, and P. Mulser, *Phys. Fluids B* **2**, 1313 (1990).
4. W. K. H. Panofsky and W. R. Baker, *Rev. Sci. Instrum.* **21**, 445 (1950).
5. E. B. Forsyth, L. M. Lederman, and J. Sunderland, *IEEE Trans. Nucl. Sci.*, **12**, 872 (1965).
6. A. Mankofsky and R. N. Sudan, *Nuclear Fusion* **24**, 827 (1984).
7. J. Watrous and P. F. Ottinger, *Phys. Fluids B* **1**, 1109 (1989).
8. M. Murayama, K. Masugata, and K. Yatsui, in *Proceedings of the Seventh International Conference on High-Power Beams* (Karlsruhe, Germany 1988), edited by W. Bauer and W. Schmidt (Kernforschungszentrum Karlsruhe, Karlsruhe, 1988), Vol. 1, p. 644.
9. B. Autin, H. Riege, E. Boggasch, K. Frank, L. DeMenna, and G. Miano, *IEEE Trans. Plasma Sci.* **PS-15**, 226 (1987).
10. F. Dothan, H. Riege, E. Boggasch, and K. Frank, *J. Appl. Phys.* **62**, 3585 (1987).
11. W. Bötticher, *Plasma Diagnostics*, edited by Lochte Holtgreven (North-Holland Publishing Company, Amsterdam, 1968), p. 614.
12. H. Kunze, R. Noll, C. R. Haas, M. Elfers, J. Hertzberg, and G. Herziger, *Laser and Particle Beams* **8** (1990), p.595.
13. M. G. Haines, *Proc. Phys. Soc.* **74**, 576 (1959).
14. E. Boggasch, K. Frank, J. Christiansen, R. Tkotz, and H. Riege, to be published in *IEEE Trans. Plasma Science* **19** (1991).
15. R. Noll, C. R. Haas, and H. Kunze, *J. Phys. (Paris)*, Colloq. Suppl. 12, **49**, C7-177 (1988).
16. R. Noll, R. Kunze, and C. R. Haas, *Nucl. Instrum. Meth. A* **278**, 85 (1989).
17. K.-G. Dietrich, D. H. H. Hoffmann, H. Wahl, C. R. Haas, H. Kunze, W. Brandenburg, and R. Noll, *Z. Phys. D* **16**, 229 (1990).
18. D. H. H. Hoffmann, K. Weyrich, H. Wahl, D. Gardés, R. Bimbot, and C. Fleurier, *Phys. Rev. A* **42**, 2313 (1990).
19. D. Gardés, R. Bimbot, S. Della-Negra, M. Dumail, B. Kubica, A. Richard, M. F. Rivet, A. Servajean, C. Fleurier, A. Sanba, C. Deutsch, G. Maynard, D. H. H. Hoffmann, K. Weyrich, and H. Wahl, *Europhys. Lett.* **8**, 701 (1988).
20. see D. Ho, and B. Langdon, and R. F. Hubbard, and J. J. Stewart, *these Proceedings*.