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Diagnostics of discharge channels for neutralized chamber transport in heavy ion fusion

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Abstract

The final beam transport in the reactor chamber for heavy ion fusion in preformed plasma channels offers many attractive advantages compared to other transport modes. In the past few years, experiments at the Gesellschaft für Schwerionenforschung (GSI) accelerator facility have addressed the creation and investigation of discharge plasmas, designed for the transport of intense ion beams. Stable, self-standing channels of 50 cm length with currents up to 55 kA were initiated in low-pressure ammonia gas by a CO_2-laser pulse along the channel axis before the discharge is triggered. The channels were characterized by several plasma diagnostics including interferometry and spectroscopy. We also present first experiments on laser-guided intersecting discharges.

Keywords: Chamber transport; Heavy ion fusion; *z*-discharge

1. INTRODUCTION

Plasma-channel-based final focus and transport in the chamber of a heavy ion beam fusion reactor has many attractive advantages compared to other transport schemes (Yu *et al.*, 1998). Previous experiments in Berkeley have obtained encouraging results for the initiation of stable discharge channels (Tauschwitz *et al.*, 1996; Vella *et al.*, 1998). This article reports on experiments on plasma channels performed at the Gesellschaft für Schwerionenforschung (GSI) with a different initiation mechanism. The 50-cm-long high-current discharges are initiated by resonant CO_2-laser gas heating of ammonia before the breakdown occurs. The channels were investigated by a number of diagnostics including interferometry, visible spectroscopy and schlieren imaging. The data will be used to benchmark simulation codes, which will then allow the design of discharge channels most suited for beam transport in heavy ion fusion. First comparisons with a one-dimensional fluid code (CYCLOPS) show a good agreement in terms of the hydrodynamics of the laser-heated gas. Experiments on intersecting discharge channels, which will be required for a plasma-channel-based reactor with two-sided target illumination, are also presented.

2. LASER-GUIDED CHANNELS

Our standard method to initiate stable discharge channels includes resonant laser-gas heating of ammonia by a CO_2-laser pulse, and the subsequent expansion and rarefaction of the gas. The discharges are created in a metallic chamber of 50 cm length with two high-voltage electrodes at opposite sides. Typically 10 to 25 μs before the capacitor bank is triggered, a 2 J/cm^2 laser pulse with a wavelength tuned to the molecular vibrations of the ammonia molecules is fired into the low-pressure gas along the chamber axis. A laser absorption of up to 80% at 15 mbar leads to a gas heating up to 1000 K. Simulations by the one-dimensional Lagrangian fluid code CYCLOPS (Henestroza *et al.*, 1998) predict the formation of a low density bubble, with an on-axis density reduction up to 60% at these temperatures. The created low-density channel provides preferred conditions for a controlled breakdown along the laser path. The experimental setup and the channel initiation mechanism are described in detail elsewhere (Niemann *et al.*, 2002). The rarefaction

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channel was measured directly by a Michelson-imaging two-color interferometer at 1,064 nm and 532 nm. After 25 μs the density on the axis has dropped by 50%. The size of the density depression is commensurate with the laser-beam diameter. A minimum density was measured between 10 and 20 μs. According to CYCLOPS, the minimum gas density is reached at 15 μs after the laser pulse. The breakdown behavior can be explained by the evolution of this rarefaction channel and consequently by the reduction of the breakdown voltage along the laser path. The best discharges were achieved with a trigger delay of 15 μs, corresponding to the time of the density minimum. No instabilities were observed at currents as high as 55 kA until the time of the current maximum at 4 μs and longer over a broad pressure range from 2 mbar to 20 mbar. We believe that the channel stability can be explained by a combination of the symmetric initial conditions for the breakdown and a stabilizing effect of the surrounding gas. It has been shown theoretically (Manheimer *et al.*, 1973), that a surrounding gas wall reduces the growth rate of magnetohydrodynamic instabilities by a factor of $(\rho_g/\rho_{ch})^{1/2}$, where ρ_g and ρ_{ch} are the mass densities of the surrounding gas and of the pinch, respectively. This factor is only around 1.5 for the laser-produced density bubble, considering also the small, radially expanding gas wall, which can be seen in Figure 1 at the edge of the density depression for 10 μs. A more pronounced gas wall in the high-current discharge itself has been observed with an interferometer (Fig. 2) and a schlieren-imaging technique. For a filling pressure of 15 mbar, the density in the gas wall reaches densities of a factor of 4 above the initial value. This reduces the instability growth rate by another factor of 2. The electron density in the high current discharge has been measured spatially resolved by the two-color interferometer. The maximum density for discharges at 45 kA scales roughly with the gas pressure, reaching around $5 \cdot 10^{17}$ cm^{-3} at 5 mbar and $2 \cdot 10^{18}$ cm^{-3} at 20 mbar. Spectroscopy of the plasma self-emission was performed in the visible range. The broadening of the hydrogen

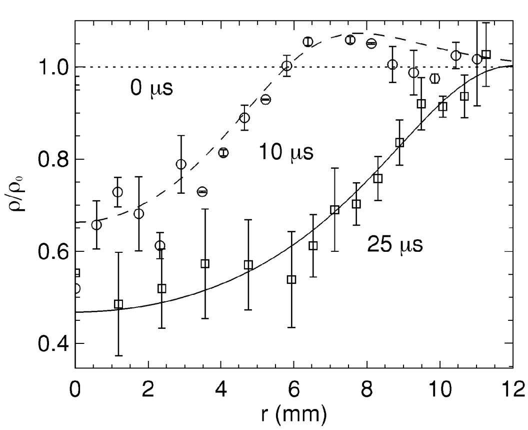

Fig. 1. Formation of the gas-rarefaction channel measured by laser interferometry.

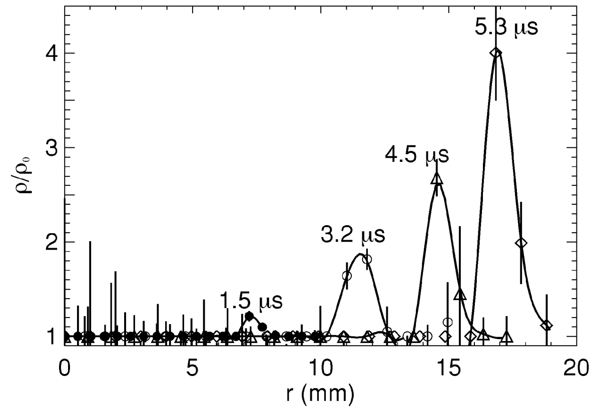

Fig. 2. Radially expanding gas wall in a high-current discharge at 15 mbar, measured by the imaging interferometer.

Balmer lines confirms the interferometric electron density measurements. From comparisons of NII and NIII nitrogen line intensities with calculations by a collisional, radiative rate model, including electron-impact ionization, three-body-, radiative-, and dielectronic recombination, collisional excitation as well as spontaneous emission, the plasma temperature was determined with temporal resolution. A temperature of 5 eV was found at the time of the current maximum, which is high enough for an efficient beam-space charge neutralization.

3. INTERSECTING CHANNELS

A plasma-channel-based reactor with two-sided target illumination requires two converging discharges and some current return path in order to provide focusing magnetic fields for both beams propagating in opposite directions toward the fusion target (Yu *et al.*, 1998). Experiments at GSI have recently demonstrated the feasibility to initiate intersecting channels by means of the CO_2-laser gas heating technique without any mechanical guiding structures for the current return. In this way it was possible to produce free-standing L-, T-, and X-shaped discharges with currents in excess of 40 kA. For the experiments, the laser beam was split into two beams of equal intensity and diameter, to heat the gas along two perpendicular paths, resembling the shape of a cross. Four electrodes were mounted at the entrance and exit ports of the laser beams. A pinhole camera image of the central 20-cm-diameter part of a T-shaped discharge at reactor relevant current is shown in Figure 3. The location of the two anodes (A) and cathodes (C) is marked in Figure 3. In this picture, the current flows from the right cathode to the intersection point and is then split into the two current return paths towards the anodes. A T-shaped discharge is formed in this case rather than the X because of the unsymmetric geometry of the vacuum chamber. A longer distance between the interaction point and the left cathode and consequently a larger inductance draws the entire current to the right section of the channel. An inductance balancing can

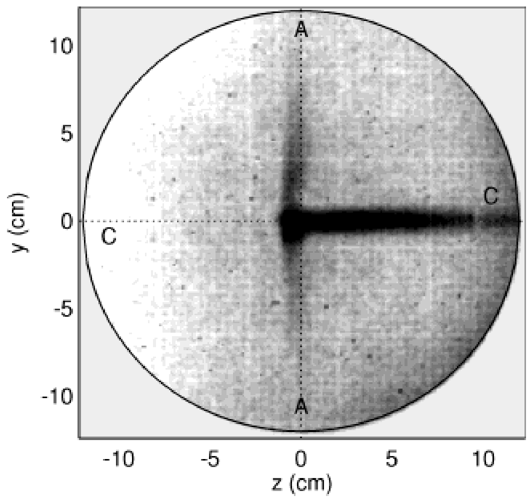

Fig. 3. Pinhole camera image of a high-current discharge, recorded 4 μs after the breakdown.

influence the current flow through any particular channel section. If a metallic rod is used to extend the upper or lower anode, L-channels upward or downward or balanced T-channels can easily be produced. Figure 4 shows some fast shutter camera images of discharges resembling these three cases. The nonuniform laser absorption, which strongly depends on the gas pressure, also influences the inductances of opposite channel sections. A balanced system at a certain pressure will produce L-channels at higher or lower pressures. In the experiments, a pressure difference of 0.5 mbar was sufficient to compensate an extension of one electrode by 1 cm. At lower currents also X-shaped discharges were produced, which turned into T-shaped channels after a few microseconds. In UV-laser- or beam-initiated channels with more symmetric conditions along the ionization paths, the balancing should not be an issue and the required X-shaped discharges should easily be produced in a symmetric chamber. A 11.4 AMeV $^{58}Ni^{+12}$ beam from the UNILAC linear accelerator was used to probe the ion-optical properties of the central section of the T-shaped discharge from Figure 3. In the 21-cm-long channel, the beam was transported over a quarter of a betatron oscillation. Apart from the pinch time (around 2 μs), the channel was acting as an ideal ion-optical element, from which it can be concluded that the current density is almost homogeneous. The rather short intersection zone does not change the overall ion-optical properties of the long channel. Channel–target interaction experiments with different metallic targets have shown that the channels can be guided in a conductor around the target position, to prevent target preheating. The formation of intersecting channels was improved by a metallic target in the interaction point. Details of these experiments will be reported in a future paper.

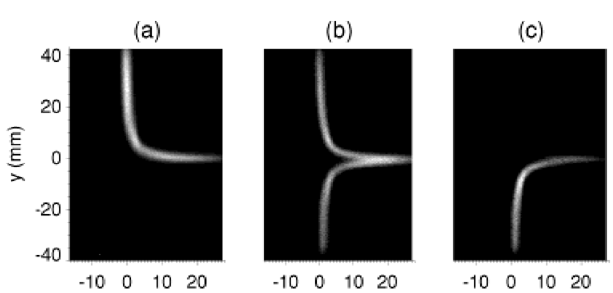

Fig. 4. Concentration of the discharge current onto different channel sections with dependence on the inductance balancing.

4. CONCLUSION

These results affirm the usefulness of *z*-discharges for the final beam transport in heavy ion fusion. Controlled breakdown and channel stability at reactor-relevant discharge currents have been demonstrated with an initiation mechanism based on direct laser-gas heating. The channels have been diagnosed by several methods to provide benchmarks for simulation codes and to ultimately lead to an understanding of the channel dynamics and evolution. First tests of a plasma system with intersecting channels have been performed. Other important problems regarding the design of the insulators, the compatibility of the discharge gas, or the effect of the intense beams on the discharge have to be further investigated.

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