HEAVY-ION BEAM TRANSPORT IN PLASMA CHANNELS

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Abstract

The transport of heavy-ion beams in high-current discharge channels is a promising option for the final beam transport in a heavy-ion fusion reactor. The channels provide space-charge neutralization and an azimuthal magnetic field of several Tesla; therefore they can transport high-current beams over several meters. We have created one-meter long discharges in a metal discharge chamber and have used the UNILAC facility at GSI to make proof-of-principle transport experiments with low-current heavy-ion beams. In addition, we have studied the channel development and instabilities. The experimental studies with low-current beams are supplemented by simulations for high-current beams.

INTRODUCTION

Typical heavy-ion fusion reactor schemes require beam energies of several megajoule to heat a hohlraum, whose x-ray radiation compresses the fusion pellet up to ignition conditions. The hohlraum absorbers require rather low beam energies, typically around 15-20 MeV/u, and particle beam currents of more than 100 pkA. These high-current and space-charge dominated beams must be transported about 3 m inside the reactor chamber.

The choice of the final transport has profound consequences for the design of the hohlraum target and of the reactor chamber, since the chamber walls must be protected from fusion neutrons and target debris. The main line approach is to cover the walls with a film of liquid flibe (a compound of fluorine, lithium, and beryllium). Obviously, the more beam ports are used in the chamber, the more complicated it gets to cover the walls with the liquid.

The ARIES reactor study[1] investigates two possible final transport schemes: neutralized-ballistic transport and plasma channel transport, also known as assisted-pinch transport. Self-pinched transport has been proposed as an alternative, but only little research has been done so far (for light-ion fusion, see [2]).

Neutralized-ballistic transport is the main-line approach and has been studied in more detail than channel transport; the downside of this scheme is its intricacy (it operates with more than 100 separate beams to keep the space-charge effects within acceptable limits). In contrast, the channel transport scheme requires only two ion beams, since it can handle larger beam currents[3]; this significantly simplifies the design of the chamber and the hohlraum.

Figure 1 shows a schematic view of a heavy-ion fusion reactor with plasma channel transport. The hohlraum target, which is at the center of the chamber, is heated by two ion beams. The channels are created by a high-current discharge inside the gas filled chamber; the discharge is guided by a short-pulse laser that ionizes the gas immediately before the discharge. The focusing system consists of quadrupole lenses and adiabatic plasma lenses, which are outside the chamber, and of the channels inside the chamber. The quadrupoles and the plasma lens reduce the beam diameter down to 1 cm before the beam enters the chamber and the plasma channel prevents the beam from spreading during the passage inside the target chamber. While the horizontal channel transports the beam, the vertical channel provides a path for the discharge return current. The electrons in the plasma channel neutralize the space-charge of the beam. The channel furthermore creates a large azimuthal magnetic field that focuses the beam towards the axis.

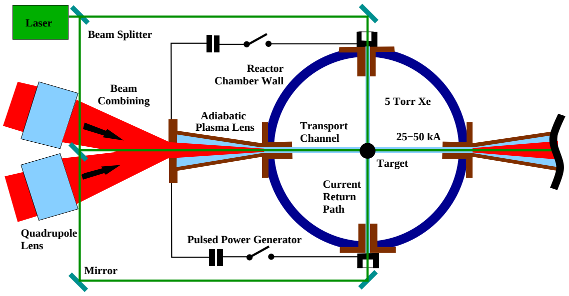


Figure 1: Scheme of a heavy-ion fusion reactor with plasma channel transport. The target at the center is heated by two heavy-ion beams.

EXPERIMENTAL SETUP

The goal of our experiments is to demonstrate the creation of long, stable, and reproducible channels. The study of the channel evolution is complemented by experiments to study the beam transport in the channel with beams from the linear accelerator (UNILAC) at GSI. It provides beams with particle energies of up to 11.4 MeV/u and electrical beam currents of up to 1 mA. Since these beams lack the high currents required in the reactor, these measurements serve only as proof-of-principle experiments. While proton beams with over 100 pkA have been created[2, 4], high-current heavy-ion beams are not available yet. Therefore the study of the interaction between the high-current beams and the plasma channel is limited to computer simulations.

The creation of a plasma channel is a multistage process. In the first step, the gas on the beam axis is heated by a laser pulse. This leads to an expansion and rare-faction of the gas and creates a blanket of increased gas density around the axis. While the absorption cross-section of the carbon-dioxide laser used is large in ammonia, it is much smaller for other gases like xenon and krypton. In this cases, the initiation thus requires a different approach. In the reactor scheme a short-pulse laser provides for the ionization of the gas. Lacking a short-pulse laser, we use the ion beam instead to ionize the gas prior to the discharge. Both laser gas-heating and ionization guide the discharge along the axis and prevent breakdowns to the metallic chamber walls, provided that the electric field configuration is adequate.

In the second step of channel creation, a small discharge (prepulse) heats the gas further. Afterwards the gas on axis expands and thereby causes a rarefaction. The expansion also smooths out inhomogeneities and thus stabilizes the main discharge, which is triggered several microseconds later. The main discharge creates the plasma channel, in which the ion beam is transported.

Figure 2 shows a sketch of our experimental setup. The central part of our experiments is a discharge chamber made of stainless steel. Apart from the portholes, which we need for diagnostics, the geometry of the chamber is cylindrical. The length of the chamber is 1 m and its diameter is 60 cm. The chamber is connected to the accelerator via a differential pumping section (not shown in the figure). A pepperpot mask, which is mounted before the chamber, shapes the ion beam, serves as a mirror for the carbon-dioxide laser, and reduces the gas throughput to the differential pumping section.

The discharges are created by two pulse generators. These generators basically consist of capacitor banks which are discharged by a spark switch. The prepulse is roughly 2 µs long and has an energy of only 40 J. It is needed to stabilize the subsequent main discharge by creating a rarefaction channel on axis. Several microseconds after the prepulse, the main discharge is triggered. The generator for the main pulse creates a current of up to 60 kA and a total energy of 3 kJ; the peak current is reached after roughly 6 µs. Two electrodes are mounted inside the chamber: the anode is mounted at the entrance to the chamber to the left, and the cathode is mounted at the end of the chamber to the right. A scintillator is fixed inside the hollow cathode, so that the shape of the beam can be measured. The anode is grounded and the cathode is set to the full negative potential U; both are insulated from the chamber. The metallic chamber consists of three parts, which are electrically separated from each other by two flanges; a voltage divider sets the potential of the walls to 75%, 50%, and 25% of the full cathode potential. The use of three wall potentials is necessary to achieve a sufficiently large electric field in the middle of the chamber. In an old setup with a shorter (50 cm long) chamber[5], the chamber wall was simply set to the mid-potential ($U/2$). Yet calculations as well as experiments showed that the electric field drops drastically in the midst of the chamber if the chamber is extended to 1 m(figure 3). But the calculations with POISSON, which is a field solver for electrostatic problems, also showed that by using three wall potentials the minimum electric field on axis can be increased from 8 V/cm to 117 V/cm, since the electric field is then more homogeneous along the axis than before. With this improved field configuration, it is possible to create stable discharges along the axis.

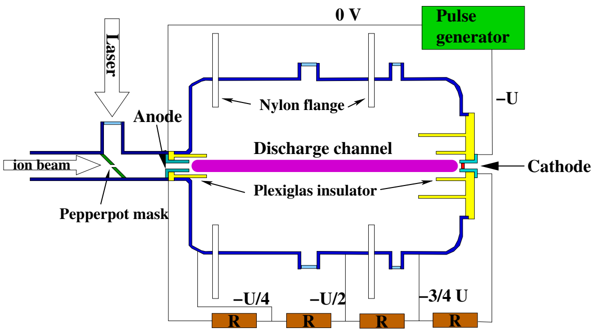


Figure 2: The 1 m long discharge chamber. The discharge is created between the two electrodes by a pulse generator. A pepperpot mask shapes the ion beam for beam transport measurements and serves as a mirror for the CO_2 laser.

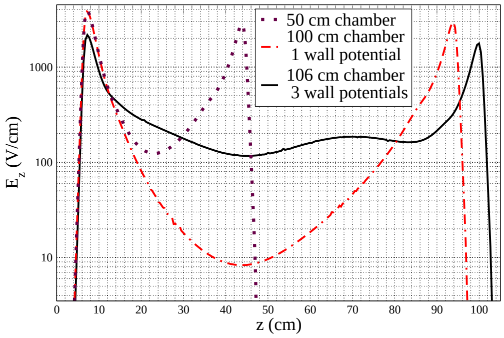


Figure 3: Calculated electric field on axis for the old setup (50 cm) and the prolongated chamber with one and three potentials (the additional 6 cm are due to the two nylon flanges).

We use several diagnostic methods to determine the important channel parameters (electron density, electron temperature, current density) and to study the channel dynamics and its stability. High-speed digital photographs with minimum exposure times of 10 ns are used to track the channel evolution and look for the development of instabilities. In combination with the measured discharge current, the thereby determined channel diameter also yields an estimate for the current density in the channel. Spectroscopy is used to determine the average electron temperature and electron density[6]. Interferometry is used to get the spatially resolved electron density of the channel (assuming cylindrical symmetry of the channel). Magnetic probes were used to measure the magnetic field and thus determine the current density of the channel. The ion beam itself is also used as a diagnostic tool. By shaping it with the pepperpot mask prior to entering the chamber, and measuring the final beam profile with a scintillator at the end of the chamber, the beam transport properties of the channel can be deduced. Furthermore, the ion beam can also be used to determine the rarefaction caused by the laser beam, since the scattering in the gas is density dependent[7].

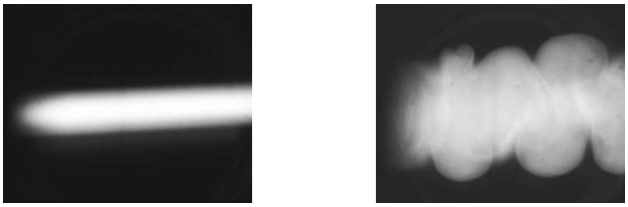
RESULTS

Since the chamber geometry is fixed, the discharge parameters that can be varied are the gas pressure in the chamber, the voltage of the pulse generators, the laser energy and the timing of the three discharge stages, that is the delays between the individual stages.

Reproducible channels can be created in ammonia, xenon, and krypton for pressure between 1 mbar and 10 mbar. The diameter of the channel typically varies between 1 cm and 3 cm at the time of the current maximum and the channels are stable, provided that the prepulse is used. Without stabilization by the prepulse, strong instabilities can develop (see figure 4), but only for low pressures and at a late stage of the discharge. Since this is long after the current maximum, it is not a problem for beam transport. Both laser-heating and ionization with the ion beam are sufficient to initiate discharges along the axis. The timing of the stages is not critical. Typical delays are 10 µs between the laser, the prepulse, and the main discharge, respectively.

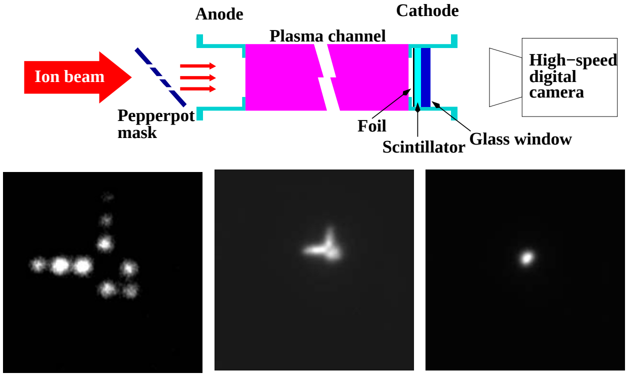
The beam transport properties of the channel are studied with a pepperpot mask and a scintillator. The principle of the measurement is depicted in figure 5. The pepperpot mask is a plate with several small hole borings (diameter 1 mm) which have the form of a cross and shape the beam into several small beams. After passing the hollow anode, the beams are transported in the channel and finally hit the scintillator, which is mounted inside the cathode. The scintillator is sandwiched between a thin foil, which blocks the light from the discharge but lets the ions pass, and a small glass window. The glow of the scintillator is photographed with a high-speed digital camera. Some sample photographs of the scintillator are shown in figure 5. The first picture shows the beam without a plasma channel. The width of the cross is roughly 1 cm. The two other pictures show the beam at two different times of the discharge.

For low-current beams and a homogeneous current density inside the channel, the motion of the individual ions is given by betatron oscillations. Since the betatron wavelength depends on the total current and the channel radius, a full focus is achieved only at certain times during the discharge. Nevertheless, the channel always prevents ions from leaving the channel. The measurements are in good agreement with ray-tracing calculations for ions in a uniform plasma channel[8].



Stable discharge *Kink instability*

Figure 4: Two discharges in ammonia. The length of the displayed channel section is 10 cm.



without channel *partly focused* *full focus*

Figure 5: Principle of pepperpot diagnostics and three sample scintillator pictures.

For high-current beams, the dynamics get more complicated, since the individual ions strongly interact with each other and also influence the dynamics of the channel. Still, simulations[3] show good beam transport for reactor-like beams.

CONCLUSIONS

We have demonstrated the feasibility of long and stable discharge channels for various chamber gases and methods of channel initiation. The transport of low-current beams is possible and simulations indicate good transport capabilities for high-current beams. Experiments for high-current beams are still missing, due to the lack of appropriate beams. All in all, plasma channel transport seems to be a viable alternative to neutralized ballistic focusing as a final transport mode in a heavy-ion fusion reactor and would simplify the design of the reactor chamber.

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