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ABSTRACT

We consider plasma discharge channels for light ion beam transport in the light ion beam fusion reactor study LIBRA. Laser-guided discharges would form these plasma channels in a 3.55 x 10^{18} atoms/cm^3 helium background gas. We have analyzed the issues of channel formation, ion transport in plasma channels, ion beam power limits imposed by stability and energy loss issues, and the use of applied magnetic fields to inhibit electrical breakdown between the channels and target chamber walls. Based on these analyses, we feel that we have a viable design for plasma channels for LIBRA, though there are still some issues that we have yet to study.

INTRODUCTION

Beam propagation in preformed plasma channels is the proposed method for providing the required stand-off distance between the ion diodes and the targets in the LIBRA light ion beam fusion reactor conceptual design study.[1] The LIBRA study is an investigation into the feasibility for electric power production through light ion beam driven Inertial Confinement Fusion (ICF). The stand-off distance is required for the protection of the diode from the blast of the target explosion. The stand-off distance also allows the time-of-flight bunching and pulse shaping that is required for successful implosion of ICF targets. In the plasma channel concept, large electrical discharges, guided by laser preionization, would rarefy the channel and form ion confining azimuthal magnetic fields. We begin our discussion with a presentation of a consistent set of channel parameters for LIBRA. We will then consider three issues that we feel are critical to the channel concept: (1) the behavior of the channel during formation, (2) the ion transport efficiency, and (3) the behavior of channels in the presence of intense ion beams.

CONCEPTUAL DESIGN OF CHANNELS FOR LIBRA

We have designed a target chamber of LIBRA and a set of channels that are consistent with this design. The ion beams must be transported from the ion diodes to the target in plasma channels. The channels enter the target chamber in two cones, 35° above and below the horizontal plane containing the target. For each channel, there is a 4.5 meter channel to return the discharge current that leaves the target chamber through the top. The channel parameters are listed in Table I.

Table I. Parameters for LIBRA Channels

# of Channels = 18
Channel Length = 6.6 meters
Channel Radius = 0.5 cm
Beam Ion = 30 MeV Li^{+3}
Maximum Injection Angle = 0.12 radians
Confining Azimuthal Magnetic Field = 27 kG
Average Channel Mass Density $< 5. \times 10^{-6}$ g/cm^3
Target Chamber Gas = 3.55×10^{18} cm^{-3} Helium
Current Rise Time = 1 μs
Discharge Voltage = 1.2 MV

CHANNEL FORMATION

We have long believed that plasma channels acceptable for light ion beam transport require that the discharge current be confined to a small region near the axis of the channel. This means that the resistivity must be high away from the channel and low on the axis. Since resistivity decreases rapidly with increasing temperature, this means that the radial temperature profile in the channels must be peaked along the channel axis and not too high in the region just outside the channel. Therefore, a narrow pre-ionizing laser and a fast rising discharge current should be advantageous for channel formation. We have performed computer simulations with the Z-PINCH computer code[2] to test this hypothesis. Z-PINCH is a one-dimensional Lagrangian magnetohydrodynamics computer code with 20 group radiation transport.

We have studied channel formation for a discharge current history where a large main pulse follows a smaller prepulse, and for a pre-ionizing laser with a Gaussian radial intensity profile. The double pulsed current history was first proposed several years ago,[4] and we have parameterized this by a delay time Δt. For these simulations we have used the Z-PINCH code for a 2.37×10^{-5} g/cm^3 nitrogen background gas. One finds that for a 5 mm Gaussian half-width laser the maximum field and the field at 0.5 cm increase as Δt is decreased, which is consistent with the hypothesis that radial heat transfer works to

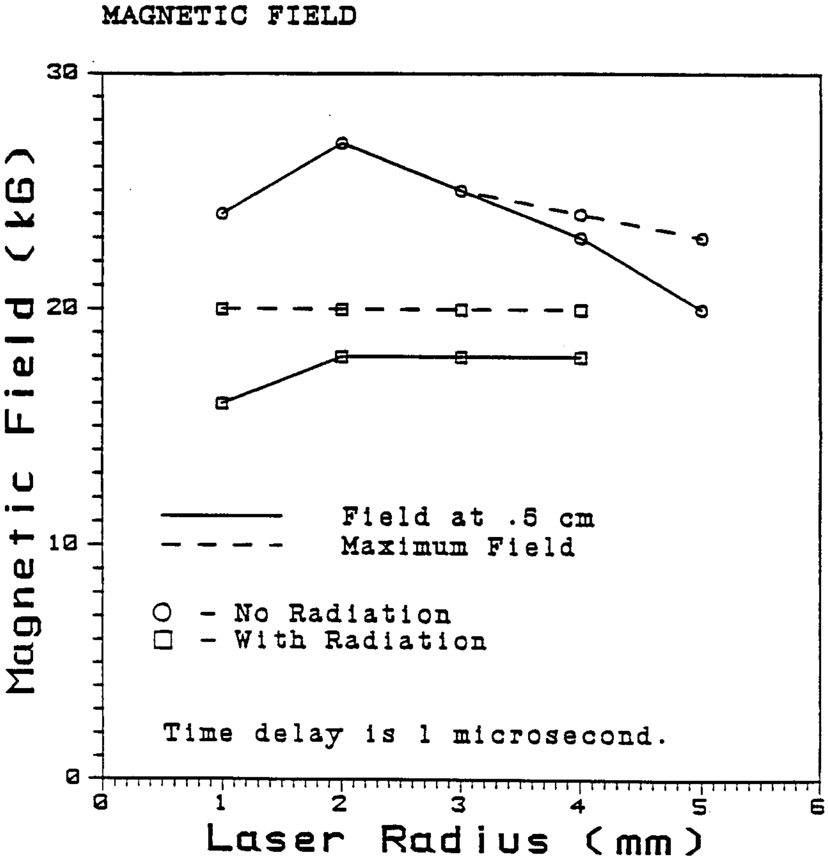

Figure 1. Maximum and peak @ 0.5 cm azimuthal magnetic fields versus laser Gaussian half-width. These calculations are for laser-guided plasma channels created in 2.37 x 10^{-5} g/cm^3 nitrogen. The time delay for the second discharge current pulse was 1 μs.

reduce the azimuthal magnetic fields. In Figure 1 we show how the fields change with laser width and whether or not radiation transport is taken into account. Here one sees that the narrow initial discharges, implied by narrow laser beams, lead to higher azimuthal magnetic fields and that radiation transport reduces the fields.

These results show that, even for the optimum current history and laser profile, radiation transport prevents the formation in nitrogen of channels acceptable for the LIBRA reactor design. One should note that the required azimuthal field at 0.5 cm from the channel axis is 27 kG, while the best we have achieved with nitrogen is 18 kG if radiant heat transfer is considered. Therefore, a low atomic number gas, such as helium, should radiate less and allow the formation of more acceptable channels.

We have performed simulations of channel formation in helium gas at a mass density of 2.37 x 10^{-5} g/cm^3. We have used a 1 μs delay time in the discharge current and a laser half-width of 2 mm, values that seemed to be optimum in the nitrogen parameter study. For these values our simulations predict that the magnetic field at 0.5 cm from the channel axis reaches 27 kG and that the average mass density in the channel is approximately 5×10^{-6} g/cm^3. According to Table I, these results are acceptable for LIBRA.

ION TRANSPORT IN PLASMA CHANNELS

We have studied how well the channels discussed in the previous section can transport the ions to the target. We see two mechanisms by which ions would not reach the target. First, the ions reach the channel entrance in a distribution in angle and radial position, so that some of them simultaneously have a large angle of incidence and are at a relatively large distance from the channel axis. These ions either are not trapped by the channel's magnetic fields and pass through the background gas never turning back towards the channel axis, or they are turned back by the magnetic fields but at a large enough radius that those ions have only a small chance of striking the target. Or second, the ions are no longer confined by the channels when the magnetic fields cancel each other in the region near the target. The ions would just continue in the directions they were going when they entered this overlap region and the beam would spread, with some ions missing the target.

We have studied these two possibilities by following the trajectories of a random selection of ions in initial angle and radial position as they move down the channel. We have assumed that the magnetic field is only in the azimuthal direction and that it rises linearly from zero on the channel axis to 27 kG at 0.5 cm and falls as the inverse of the radial position beyond 0.5 cm in the main part of the channel. For axial positions within the overlap region, we assume that the azimuthal fields linearly fall to zero over a length of 1 cm from the edge of the region. We assume that the ions enter the channels with radial positions distributed in a Gaussian with a half-width of 0.35 cm and with angles of incidence distributed uniformly out to 0.12 radians. We have used the ION computer code[5] to follow these ion trajectories. In LIBRA, 18 channels are pointed at the target, with 9 in each of 2 cones. The channels are 0.5 cm in radius and the target is 0.5 cm in radius, so the distance between the point where the channels begin to overlap and the target surface is 0.43 cm. Our calculations predict that about 80% of the ions reach the target.

ION BEAM POWER CONSTRAINTS

Each of the plasma channels in LIBRA must carry several hundreds of kiloamperes of beams ions, which can perturb the channels and possibly inhibit the transport of the beam ions. We have analyzed the limits on the ion beam

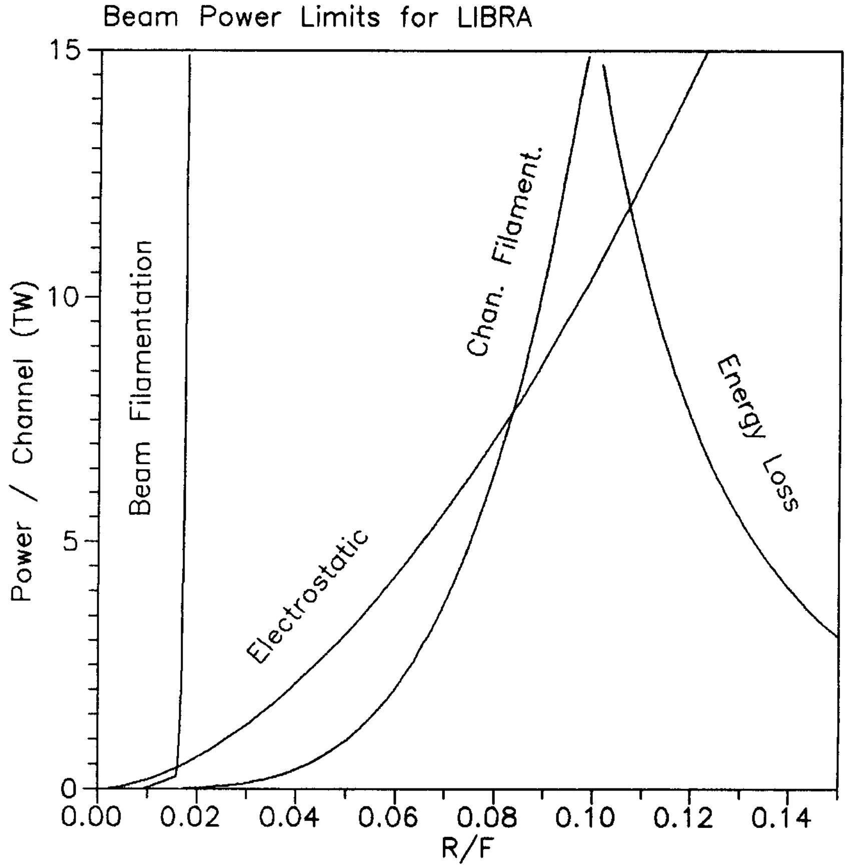

Figure 2. Limits on ion beam power per channel imposed by stability and ion energy loss. R/F is the ratio of the ion diode anode radius to its focal length, and is roughly equal to the maximum angle of incidence of ions into the channels.

power imposed by the onset of electrostatic instabilities, filamentation of the ion beam and the plasma channel, and beam ion energy loss. We have also analyzed expansion of the channels due to the ion beam, but do not believe that it poses an important constraint. The analysis has followed the formalism developed a number of years ago at the Naval Research Laboratory[6] and involves the use of the WINDOW computer code.[7]

The results are shown for LIBRA parameters in Figure 2. One sees that the input ion beam power per channel is limited to 9 TW at a diode R/F of 0.12, the LIBRA value.

OTHER CONSIDERATIONS

We propose using applied axial magnetic fields to slow the breakdown long enough for the channels to form, that is, for about 1 μs. The voltage across the gap between the channels and the target chamber walls will be large enough, about 500 kV, so that a very large gap would be required to totally prevent breakdown, so our only hope is to slow the breakdown. Heylen[8] shows how magnetic fields can slow the flow of electrons in a breakdown and we have used this analysis to predict that a 32 kG axial magnetic field can slow the breakdown for a 10 cm gap by 1 μs. We have designed a solenoidal magnet to provide this field and believe that such magnets could survive in the LIBRA target chamber environment for an adequate length of time.

ACKNOWLEDGEMENT

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