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## PLASMA CHANNELS FOR THE LIBRA REACTOR DESIGN

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### ABSTRACT

One method of propagating light ions from beam generating diodes to ICF targets in a fusion reactor is to use laser-guided plasma discharge channels to magnetically guide the ions. Earlier studies of different cavity gases (argon, nitrogen, helium) for the LIBRA reactor study indicated that the lower atomic number gases (helium) were most suitable for plasma channel formation. We found unacceptable channel expansion due to radiative transfer where the radiation transport was calculated with a multigroup diffusion computer code. A new set of simulations using a newly developed adaptive-grid radiation magnetohydrodynamics scheme with a multigroup discrete ordinates radiation transport method has led to lower absorption and emission by such thin plasmas. Application of the new scheme to LIBRA thus shows the feasibility of using argon and nitrogen as well for the channel plasma. Higher atomic number gases more strongly attenuate the x-rays coming from the target explosion. Also, by using an adaptive grid, the new scheme provides better accuracy and resolution where it is needed in the channel. The discharge current required to form the channel is found to be 70 kA as opposed to 100 kA predicted by earlier calculations. This will have the effect of reducing the required discharge voltage and thus will ease the problem of electrical breakdown between the channel and the target chamber wall.

### INTRODUCTION

Z-pinch plasma channels are important to the design of Light Ion Beam Inertial Confinement Fusion (ICF) Reactors and near term experiments. In these applications, such as the Laboratory Microfusion Facility (LMF) and Light Ion Beam Reactor (LIBRA), high intensity ion beams are used to ablatively implode a target to achieve extremely high densities and to shock heat deuterium-tritium (D-T) fuel to temperatures sufficiently high to have a thermonuclear burn.<sup>1</sup> A schematic of a z-pinch plasma channel is shown in Figure 1.

In this paper, we utilize a newly developed numerical scheme<sup>2</sup> to study the plasma channel problem

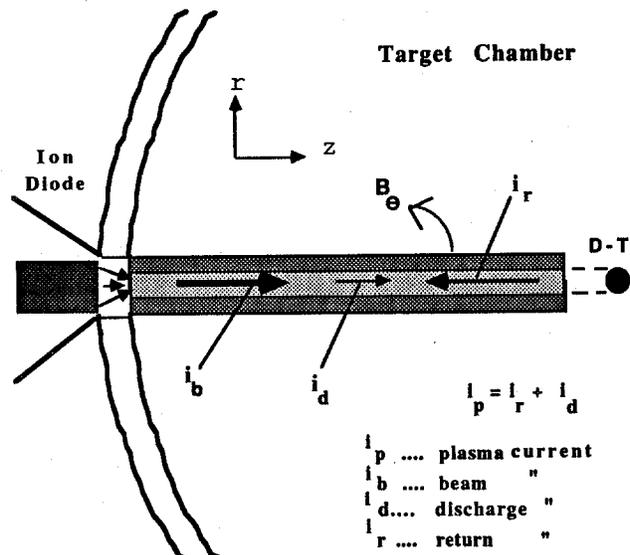


Figure 1. A schematic of a z-pinch plasma channel.

and ion beam propagation for LIBRA reactor designs. The LIBRA study is a self-consistent conceptual design of a 330 MWe commercial light ion beam fusion power reactor. A major goal of the study is to understand the potential of light ion fusion as the basis for small yet economically attractive power reactors. This is done by completing a self-consistent point design, evaluating its cost, and cost scaling the design to different power levels. Fusion targets are imploded by 4 MJ shaped pulses of 30 MeV Li ions at a rate of 3 Hz. The high intensity part of the ion pulse is delivered by 16 diodes through 16 separate free-standing z-pinch plasma channels formed in 100 torr of helium with trace amounts of lithium.<sup>3</sup> Earlier studies of different cavity gases (argon, nitrogen, helium) indicated that the lower Z helium was most suitable for plasma channel formation. Magnetohydrodynamic simulations using the multigroup diffusion approximation for radiative transfer indicated that the radiation had a great effect on the channel dynamics. Watrous<sup>4</sup> noted that radiation diffusion from the hot channel center to the surrounding cold gas led to a premature expansion of the channel plasma with the

required peak magnetic fields being unattainable. Watrous observed this expansion in the channel for argon and nitrogen gases. This led Peterson to later conclude that helium was the preferred cavity gas because it radiated so much less than the higher  $Z$  gases.<sup>5,6</sup> Here, we will reexamine this issue and present what our radiation model predicts about the channel dynamics.

## SIMULATIONS

Our model is first applied to argon and helium which are considered to be at opposite extremes of radiative properties. Both gases are considered to have the same mass density ( $2.37 \times 10^{-5}$  g/cm<sup>3</sup>) and a series of simulations is done to learn the differences in hydrodynamics (HD), magnetohydrodynamics (MHD) and radiation hydrodynamics (RHD) of these two gases. This will basically give us an understanding of how to control the competing effects in the system to design an **optimized channel**. The simulation results shown in Table 1 list various design parameters, most importantly the channel radius at the time of beam injection (1.8  $\mu$ s) and the magnetic field value at this radius. We have artificially turned off some of the channel physics at each simulation step to understand how the channel dynamics and its magnetic properties are affected by the channel conditions. The final results, when everything is included, is referred to as RMHD (radiation magnetohydrodynamics) with continuum and line radiation included. The columns represent the number of opacity groups, the channel magnetic field (kG), the channel radius (cm), and the plasma temperature (eV) at the channel center.

The discharge current used in our LIBRA simulations, first proposed by Freeman et al.,<sup>8</sup> is a two-stage current consisting of two consecutive pulses with peak values at 5 and 100 kA respectively. The main goal for using a prepulse is to reduce the pinching effect of the second (main) pulse. Thus, the first pulse heats up the plasma in the central region and that leads to a channel expansion if there is enough time,  $\Delta t$ , for it before the main pulse comes along. The tendency for the channel to pinch instead of expand presents difficulties in meeting the density requirement. The usual expanding channels achieve a density reduction between 4 to 10 on axis, thereby reducing the collisional energy losses within the channel while still providing a high enough neutral background gas density in the reactor chamber to attenuate the soft x-rays produced by the ICF target.

Argon's atomic weight (40 g/mol) is ten times higher than that of helium (4 g/mol) and thus its number density is one tenth. The difference in number densities makes helium a faster expanding channel from the pure hydrodynamics point of view. When the magnetic field is present in the channel, the current heats up the channel through ohmic heating which also forces the plasma to expand depending upon the balance between the plasma pressure and the magnetic pressure. The outcome of these non-radiative channel simulations is that argon gas is

slower in response to the magnetic force, and thus is subject to pinching most of the time. The channel radius grows faster in the presence of the magnetic field when compared to the rate at which it expands without it. At  $t = 1.8 \mu$ s, the magnetic field is 28 kG at  $r_c = 0.7$  cm as opposed to 35 kG at  $r_c = 0.5$  cm for helium. This clearly makes helium a better choice, except that it is not as desirable as argon for attenuating the x-rays from the target.

We are concerned about how accurately the radiation energy transfer is solved and how well the emission and extinction coefficients are modelled in the calculations. In the current study we solve the radiation transfer equation using a multigroup discrete ordinate  $S_N$  method to account for the frequency- and angle- dependent radiation field intensity. The number of groups to discretize the photon frequency dependence and the number of angles (N) to discretize the photon angular dependence are as important as the transport model (diffusion or discrete ordinates) in solving the radiative energy transport. Here the angular discretization is done in two angles: the angle between photon's travelling direction and 1) the radial direction, 2) the z-direction. With each angle represented by 6 discrete values, the total comes up to 24 different directions for which we seek the solution of radiation field intensity. The number of energy, or frequency, groups was varied from 20 to 80 and 160. The opacity data was obtained from an atomic physics code<sup>7</sup> which takes into account both LTE and non-LTE plasma conditions.

The fact that the photon emission and absorption spectrum has narrow resonances (lines) causes some degree of *overestimation* in the group coefficients. Thus calculations in Table 1 are done for various cases (no radiation, no line radiation, line radiation with different number of groups) to see how effective the radiation model is on the channel dynamics. It is clear that the continuum part of the radiation field is well discretized by 20 groups whereas the line part is not, especially for argon that has more lines. Notice that helium channels are not affected much by radiation since they do not radiate much ( $5 \times 10^3$  ergs/cm<sup>3</sup>).

The overestimation in emission and absorption group constants causes more emission from the center plasma, leading to relatively low temperatures, while it allows a high absorption at the cool regions, thus causing a relatively high heating and eventually an expansion in the channel. Recall that this is the same phenomenon that was observed with the diffusion approximation where a relatively high absorption rate is assumed. Thus, the expansion we see here can be attributed to the reabsorption of radiation emitted from the inner region. The case with 20 groups for argon presents a picture which is obviously far from the real answer.

Our results for maximum magnetic field and its correspondent channel radius puts argon, in addition to helium, in the design range for LIBRA. One drawback

Table 1. Simulation results vs. the number of opacity groups.

Case	$N_g$	$B_c$	$r_c$	$T_0$
(Argon)				
HD		0	0.5	0.63
MHD		28.0	0.7	9.4
RMHD				
continuum	20	26.5	0.75	9.0
	80	26.5	0.75	9.0
cont.+ lines	160	22.6	0.84	7.0
	80	21.3	0.94	6.4
	20	18.5	1.08	4.8
(Helium)				
HD		0	0.8	0.4
MHD		35.0	0.5	7.2
RMHD				
continuum	20	35.0	0.5	7.2
cont.+ lines	20	33.0	0.51	6.7

with argon is its collapsing (pinching) under the two-stage discharge current profile used here. Improvements can be made, however, by changing the timing of the main current pulse to satisfy the density requirements. A second thought here could be given instead to the feasibility of nitrogen gases, since it stands between helium and argon, for plasma channels and this is going to be examined in the following section where we seek an optimized channel in the frame of both channel formation and beam propagation.

#### AN OPTIMIZED CHANNEL

As mentioned earlier, there are competing events in the channel dynamics. If one wants an expanding channel, one should allow some time (several  $\mu$ s) to pass between the pulses. On the other hand, the magnetic field peak value decreases for expanding channels,  $B_c \propto 1/r_c$ , resulting in a relation as  $B_c \propto 1/\Delta t$ . Thus, a smaller  $\Delta t$  may be wanted for higher magnetic fields.

Seeking a high enough magnetic field (27 kG) at  $r_c = 0.5$  cm has been the primary goal for current LIBRA channel designs. The difficulties led to a *time delay*,  $\Delta t$ , of zero. Fortunately, the chosen gas (helium) is good at expanding due to its high pressure which lessens the pinching caused by the magnetic force. The magnetic field prior to beam injection at  $r_c = 0.5$  cm is 35 kG for helium. This value is higher than what is needed to confine the ions from the LIBRA diode design. An immediate question is if the requirement could be met with less current. The answer is yes and the simulations with 70 kA discharge current seem to be showing that. Obtaining the requirement within a lower discharge voltage is certainly significant for reactor applications since there is less risk involved in the breakdown of the high voltage to the reactor chamber. Breakdown will, however, still be a problem.

As mentioned before, one drawback with helium is that it is not as effective as argon and nitrogen at attenuating the x-rays coming from the target explosion. It is therefore worth looking for an alternative channel for LIBRA with argon and nitrogen. Simulations with argon show magnetic field values of 22-26.5 kG at channel radii of 0.7-0.85 cm. An improvement could be made to achieve the 27 kG at 0.5 cm by increasing the discharge current. One problem with argon, though, is that it goes through pinching at times before beam injection. This problem exists with helium too but it does not cause a significant density increase in the center region. The pinching for argon is worse, causing problems with the density requirement. This is all due to the zero time delay factor and could be eliminated by changing the current profile and rise times completely. We will not do that here but instead will put the effort in checking the possibility for nitrogen channels. Just as helium and argon, nitrogen suffers too from pinching but it seems to be much less compared to argon. It is much easier to improve the conditions for a nitrogen channel: we get a magnetic field of 30 kG at radius 0.5 cm.

As opposed to early LIBRA calculations,<sup>5,6</sup> simulations we have done here prove both argon and nitrogen acceptable for creating high enough magnetic fields. One important fact that led to this is that, by using a more accurate model, we corrected the **overestimations** by early diffusion calculations regarding the radial radiative transfer in the channel. To overcome the problem of pinching for nitrogen, we suggest lowering the first pulse. As mentioned earlier, the first pulse has been originally considered to heat up the channel for a following expansion, and the higher this pulse is the more the channel expands. Nevertheless, the situation here, for a *time delay* of zero, turns out to be the other way around: there is no time for the channel to expand, and the higher the first pulse is the higher the magnetic field is due to that pulse, resulting in a channel to be pinched more easily with the following main pulse. Not surprisingly, simulations with a 0.5 kA first and 90 kA main pulse reduce the pinching effects to where nitrogen stands as a candidate for channels. These simulations are done by working with two different opacity group calculations, 20-group continuum and 160-group continuum+lines, to see how much line transport is important for nitrogen. A comparison for magnetic field, channel radius and axis temperature is given in Table 2. These results also indicate to us that lines play a non-trivial role for nitrogen.

The beam injection of ~400 kA brings high current neutralization and relatively insignificant collisional energy losses of 0.004%, and return current losses of 0.02% *per cm* for nitrogen channels. In LIBRA designs, the linear relation yields a total energy loss of 14% for nitrogen channels.

Table 2. Simulation results vs. the number of opacity groups (nitrogen).

Case	$N_g$	$B_c$	$r_c$	$T_0$
continuum	20	31	0.56	9.3
cont.+ lines	160	27.5	0.58	8.2

## CONCLUSION

In conclusion, we have been able to create the required helium channels with 30% less discharge current. The same channel conditions can be created with nitrogen gas, giving an alternative to helium. Argon channels give high magnetic fields but also introduce problems for density requirements which may be overcome with some effort. Overall, there seems to be no problem with beam energy losses and current neutralization for any of these gases within the frame of our adaptive-grid radiation magnetohydrodynamics model.

Most importantly, we conclude that the correct description of the radiation transfer phenomena in the channel is not diffusion but rather anisotropic transport. Thus, we have treated the thin plasma more accurately than the commonly used diffusion approximation. The result of such a treatment has shown that argon and nitrogen channels are feasible for LIBRA in terms of obtaining the required magnetic field to confine the ion beam. These gases were ruled out in favor of helium by early calculations using a radiative diffusion model. Further improvements can be made for argon by changing the timing of the discharge current pulses to satisfy the density requirement too. Nitrogen, on the other hand, is as good as helium as a candidate for efficient beam transport in LIBRA.

Beam energy losses for both helium and nitrogen are about 15%. Most of this loss is due to collisions with the background plasma and ohmic heating by the return current. The loss through inductive electric fields seems less because the channel dynamics leads to either a slow expansion or a pinching which do not create high inductive fields. The magnetic flux due to the beam current, ~0.5 MA, of 30 MeV lithium ions gets cancelled successfully by the return current produced in the highly conductive plasma.

Another important finding is that multigroup radiation transfer methods are highly dependent on the group structure defined for opacity group averaging. Lines in the absorption and emission spectra are so narrow that they require many numbers of groups (hundreds) to allow a good averaging over the whole spectrum. A coarse group structure leads to overestimated absorption and emission coefficients. On the other hand, using many points requires a lot of computing time for the time-dependent solution of the radiation field by the multigroup  $S_N$

method. Simulations with 160 opacity groups required roughly 40 minutes on the CRAY X-MP/48 computer. The outcome is such that the line transport in the thin channel plasma is important and should be treated well. Overestimation of absorption and emission coefficients leads to an artificial net transfer of energy from the channel center to the cold surrounding gas and therefore creates a premature expansion, called a radiation driven expansion (RDE). This is identical to the RDE phenomenon seen with diffusion calculations.

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