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CHAMBER PROPAGATION

Bruce Langdon

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Lawrence Livermore National Laboratory

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BRUCE LANGDON

ICF Program and Physics Department
Lawrence Livermore National Laboratory
University of California
Livermore, California, 94550

Abstract

Propagation of a heavy ion beam to the target appears possible under conditions thought to be realizable by several reactor designs. Beam quality at the lens is believed to provide adequate intensity at the target – but the beam must pass through chamber debris and its self fields along the way. This paper reviews present consensus on propagation modes and presents recent results on the effects of photoionization of the beam ions by thermal x-rays from the heated target. Ballistic propagation through very low densities is a conservative mode. The more-speculative self-pinched mode, at 1 to 10 Torr, offers reactor advantages and is being re-examined by others.

INTRODUCTION

Ion-driven indirect-drive target gain increases rapidly as spot intensity increases.[1–3] Thus the first concern is design to provide a small spot. Propagation through densities low enough to avoid plasma effects has been well studied and is a conservative choice meeting target requirements. "Low" is defined by stripping cross-sections and standoff distances:

$< 3 \times 10^{12}$ cm^{-3} (10^{-4} Torr at 273°K) for light elements (e.g. Li)

$< 10^{11}$ cm^{-3} (3×10^{-6} Torr) for heavy elements (e.g. Pb)

(corresponding to standoff L of 7 metres, and $n\sigma_{\rm strip}L = 0.05$, or 5% stripping, a cautious criterion). The cross-sections for FLiBe are expected to be higher, implying lower densities.

Higher densities ($\sim 10\times$) may be usable especially if there is adequate neutralization of beam charge.

The more-speculative self-pinched mode, at 1 to 10 Torr, offers reactor advantages and is being re-examinedby others.

DENSITY REGIMES

The possibilities for beam propagation, and the physics in effect, over the full range of density of chamber vapor, may be summarized as follows. Assuming chamber gas is lithium vapor, and quoting pressures as if the temperature were 273°K (i.e. 10^{-3} Torr really means number density 3×10^{13} cm^{-3}):

1. Below about 10^{-4} Torr, gas density is not enough to affect propagation.

2. Between about 10^{-4} Torr and 10^{-3} Torr, mild stripping occurs; plasma effects are weak.
3. Between about 10^{-3} Torr and about 10^{-1} Torr, stripping and plasma instabilities are expected to defocus the beam.
4. Between about 10^{-1} Torr and about 1 Torr, neutralized ballistic propagation may be possible. Two-stream instabilities are suppressed by collisions; filamentation may be acceptable at low current densities.
5. Between about 1 Torr and about 10 Torr, pinched mode (channel) propagation may be possible.
6. Above about 20 Torr, multiple scattering destroys propagation.

(See also Refs. 4, 5.)

Propagation through hard vacuum ($n_{Li} \lesssim 3 \times 10^{12} \text{cm}^{-3}$)

Propagation through hard vacuum has always been believed to be a conservative choice of mode. This is partly because of a special result: A pure ion beam (no electrons present), with charge density uniform across the beam, and equal charge state, can be focused without loss of brightness due to emittance growth, in principle. For our purposes, "hard vacuum" means low enough densities that there is negligible ionization of beam ions due to beam-gas collisions. Physics of propagation is well-understood in this regime in which there is no interaction between beam and gas or background plasma – only the beam need be considered.

Beam ionization decreases brightness in unneutralized propagation. A self-similar decrease in beam radius as it propagates to focus is made possible by a balance of electrostatic self-repulsion and inward momentum. Ions stripped or photoionized to higher charge states respond more strongly to the defocusing radial electric field. As a result, the intensity at focus decreases, with dependence on history of beam current and target temperature.

Beam photoionization is considered below.

Propagation through soft vacuum ($3 \times 10^{12} \lesssim n_{Li} \lesssim 6 \times 10^{13} \text{cm}^{-3}$)

At higher pressures, collisions ionize the beam ions and chamber vapor and any debris or liquid droplets in the beam path. Beam ionization by collisions with chamber vapor degrades focal brightness similarly to photoionization. Unlike beam photoionization, collisional ionization takes place throughout the pulse and all across the chamber.

More beam stripping may be tolerated if there is adequate neutralization of beam charge. Streaming instabilities have recently been predicted to be stabilized by gradients[6].

Avoidance of collisional ionization limits the vapor density in the chamber. For vapor consisting of a heavy element like lead, we use $\sigma = 7 \times 10^{-16}$ cm^2, based on Ref. 7. For 7 meter standoff (the distance from the last focusing magnet to the target), strong stripping ($n\sigma_{strip}L = 1$) occurs for $n_{Pb} > 2 \times 10^{12}$ cm^{-3}. For lithium vapor, we use

$\sigma = 2 \times 10^{-17}$ cm^2. For 7 meter standoff, strong stripping occurs for $n_{Li} > 7 \times 10^{13}$ cm^{-3}. "Soft vacuum" propagation (weak stripping) requires lower densities.

Neutralization of beam charge could be very helpful. More beam stripping may be tolerated if there is adequate neutralization of beam charge. Use of charge-state > 1, to reduce accelerator costs, may require neutralization for propagation to the target even in hard vacuum. This time-dependent two-dimensional problem has not yet been treated adequately. A process to achieve beneficial neutralization in a reactor should be sought.

Neutralization of an ion beam is more complicated than neutralization of an electron beam[5]. For electron beam propagation, electrons produced by ionization of the gas are readily expelled, leaving an ion background to provide neutralization. For ion beam propagation, neutralization requires expulsion of plasma ions, or that electrons be somehow entrained axially or radially. Electrons produced by ionization within the beam do not reduce the *net* positive charge of the beam.

Propagation through high densities

Propagation through higher densities is less well understood. Two modes have been considered in the past:

- Neutralized ballistic transport at 0.1 to 1 Torr[4]

  Electrostatic streaming instabilities are predicted to be suppressed by collisions. Filamentation limits beam current density and standoff.

- Pinched mode propagation through a small aperture.

  This could have great advantages to reactor design. The idea is to use the self magnetic field of the beam to guide the beam to the target. This mode is the least understood. It has been proposed for light ions; and may be easier for heavy ions because of their much lower transverse temperature. Pinched mode propagation is being reconsidered making use of expertise in pinch-mode propagation of electron beam.[9,10]

EFFECTS OF PHOTOIONIZATION

The "hard vacuum" mode is complicated by beam ionization due to photoionization by thermal x rays from the heated target. Focal spots of area ~ 0.3 cm^2 on the outside of the target reach ~ 100 eV. The cross-section for photoionization by 400 eV photons is $\sim 5 \times 10^{-18}$ cm^2 for Pb in charge states from 1 to about 12. The insensitivity to charge state is because the interactions of 400 eV photons are with electrons in inner shells that change little as a result of loss of a few outer electrons.

From these numbers, one can estimate as follows that half the beam ions are photoionized at least once before they reach 14 cm from the target, for ions near the end of the pulse. The black-body emission at 100 eV is 10^{13} W/cm^2. Most of the photons are about 300 eV, so their flux is about $2 \times 10^{28} \cos\theta / r_{cm}^2$ cm^{-2} sec^{-1}. The photons are

Doppler-shifted to about 400 eV. The rate equation for ions in the initial state is

$$v_{\text{beam}} \frac{d}{dr} \ln n_i = \frac{10^{11}}{r^2}$$

with $v_{\text{beam}} \sim 10^{10}$ cm sec^{-1}. This provides the estimate that n_i is halved at $r = 14$ cm. (Post-processing of x-ray output from target calculations changes this to about 20 cm.) Beam ions then ionize further on approach to the target.

Computer modeling

Initial calculations, using pessimistic parameters and modeling of partial neutralization, indicated that photoionization could result in half the beam energy being deposited outside a 3 mm spot[8]. Therefore an improved version of the simulation code BIC (Beam In Chamber) was written. The code now follows evolution of the two-dimensional beam cross-section as it moves toward the target, using a kinetic (Particle-In-Cell[11,12]) model for the ions, and PIC or simpler models for electrons. Using ionization rates based on estimated target surface temperature near the end of the drive pulse, ions are selected by a random process to be increased in charge state, accompanied by creation of photoelectron(s) at the same position and velocity.

Beam simulations using this code predict little loss of spot intensity for a beam initially in charge state one. We model two-sided illumination, with two 200 TW beam bundles. Each bundle of 7 beamlets carries 20 kA particle current in 10 GeV ions. At entry, the beamlets have uniform density in cross-section, edge radius 13 cm, with a Gaussian transverse velocity distribution. The separation between beamlets is 76 cm, with an 8 m standoff to target. The value of the unnormalized emittance, $\epsilon = 2$ mm mr, results in an rms spot size of $(\overline{r^2})^{\frac{1}{2}} = 1.4$ mm, according to the paraxial "envelope" propagation theory. Without photoionization, BIC reproduces this result and places more than 99% of the ions within a 3 mm radius.

Even with photoionization, most ions (95%) arrive within the 3-mm-radius spot desired for target drive. This favorable result is due to the ionization taking place close to the target, and to the high mass of the ions, so that little deflection is possible in the small remaining flight distance.

The most significant approximation in these calculations is that time dependence is ignored, and electron motion out of the plane of simulation is not possible. These features undermine the modeling of partial neutralization and motivate the current development of a time-dependent two-dimensional axially-symmetric extension of BIC. In addition, partial neutralization is inevitable at higher chamber pressures, and controllable neutralization is needed to propagate beams of charge state higher than one, or lighter ions.

4. CONCLUSION

Propagation of a heavy ion beam to the target appears possible under conditions realizable by several reactor designs.

- Propagation through very low densities is a conservative mode

$< 3 \times 10^{12}$ cm^{-3} (10^{-4} Torr at 273°K) for light elements

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- Higher densities ($\sim 10\times$) may be usable if there is adequate neutralization of beam charge. This possibility is under active study.

Firmer estimates of ionization processes would be helpful. The cross-section for lead in [5] may be uncertain by a factor of two. We have no accurate information on the cross-sections for FLiBe.

Less conservative propagation modes are worth pursuing. For example, pinched mode propagation could allow Cascade reactors to operate without a lithium x-ray and debris shield, and in general operate at higher pressures with a small beam port.

Many physical processes affecting propagation physics are being re-examined using computer modeling and theory, but experiments are needed. A 10-100 kJ accelerator experiment would be able to test propagation physics.

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