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Final beam transport in HIF

S. Kawata*, R. Sonobe, T. Someya, T. Kikuchi

Department of Electrical and Electronic Engineering, Utsunomiya University, Yohtoh 7-1-2, Utsunomiya 321-8585, Japan

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Abstract

Heavy ion beams (HIBs) are transported through a reactor chamber gas to a fuel pellet in heavy ion fusion. Due to the HIB high current, the HIB space charge should be neutralized in a reactor, and promising final transport schemes have been proposed. In this paper, we discuss the final transport in a neutralized ballistic final beam transport scheme, and point out a new mechanism of the HIB divergence by an ambipolar (plasma sheath) field generated by neutralizing electrons. The paper also proposes possible solutions to suppress the HIB divergence by the ambipolar field and presents a transportable window.

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Keywords: Heavy ion beam transport; Charge neutralization; Ambipolar field; Beam divergence

1. Introduction

Heavy ion beam (HIB) is one of the promising energy-driver candidates in inertial confinement fusion (ICF) [1–14]. In heavy ion fusion (HIF), one of the key issues is HIB final transport in a gas-filled reactor chamber. The HIBs should be transported through the reactor gas in 3–5 m and focused onto a fuel pellet of ~mm radius. In this paper, we discuss the final HIB transport through the reactor gas. Due to a HIB high current, the HIB space charge should be neutralized in a reactor. In this paper, we discuss the final transport in a neutralized ballistic final beam transport scheme, and point out a new mechanism of the HIB divergence by an ambipolar (plasma sheath) field [15] generated by neutralizing electrons. The paper also proposes possible solutions to suppress the HIB divergence by the ambipolar field and presents a transport window.

In the HIB final transport, several transport schemes have been proposed: preformed channel transport [6,11], neutralized ballistic transport using a preformed plasma [6,9,12] or using a tube liner [7,8,16], ballistic transport in near vacuum [6], and so on. One of the promising transport schemes is neutralized ballistic transport, in which

*Corresponding author. Tel.:/fax: +81 28 689 8080.
E-mail address: kwt@cc.utsunomiya-u.ac.jp (S. Kawata).

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preformed-plasma electrons or wall-emitted electrons neutralize the HIB space charge. On the other hand, the HIB ion number density increases from $N_{b0}{\sim}10^{11}$–$10^{12}/\mathrm{cm}^3$ at a beam port entrance to 100–200 × N_{b0} at the fuel pellet position. During the HIB transport, the HIB radius changes from ~2–3 cm to ~2–3 mm. A chamber gas or attached electrons neutralize the HIB space charge well at the beginning transport section of ~1 m near the reactor wall. Near the fuel pellet at the chamber center, the HIB number density and the neutralizing electron number density increase, and we can also expect the chamber gas photoionization to increase the chamber gas electrons near the target. However, at the transport middle stage between these two regions, there may be a region in which the background chamber electron number density is smaller than the HIB neutralizing electron number density, depending on the chamber gas density and its ionization degree.

When a core plasma is surrounded by a lower density plasma or vacuum and at the same time the core plasma electron has a high temperature, the core plasma expands with a higher speed than the plasma ion thermal speed: high-temperature electrons move out of and back to the core plasma ions and induce a charge separation at the core plasma ion surface. The charge separation extracts the plasma ions and, consequently, the core plasma expands fast by the ambipolar (plasma sheath) field. In the HIB transport, the HIB ions are the core plasma ions, and the neutralizing electrons may have a high temperature during the HIB convergence. Hereafter, we discuss the HIB divergence by the ambipolar field generated by neutralizing electrons, propose possible solutions to suppress the HIB divergence and present a transport window.

2. Ambipolar field effect on final HIB transport

Indirect-driven and direct-driven fuel pellets require several MJ of HIB driver energy in HIF. Each HIB carries ~1–5 kA and a HIB ion particle energy may be ~4–10 GeV, depending on the HIB ion species. At the beam port entrance at a reactor wall; a Pb^+ HIB radius r_{b0} may be 2–3 cm and its number density is $N_{b0}{\sim}10^{12}/\mathrm{cm}^3$ at the beam port entrance. The Pb^+ HIB radius decreases to $r_b{\sim}2$–3 mm in its radius at the target surface and its number density increases to $N_{bf} \sim 100-200 \times N_{b0} = 1-2 \times 10^{14}/\mathrm{cm}^3$at the fuel pellet position. In this paper, we focus on a neutralized ballistic transport (NBT) scheme. In this scheme, a chamber gas pressure may be a few mtorr and a chamber neutral gas density may be $\sim 10^{14}/\mathrm{cm}^3$. The chamber gas electron number density may be $\sim 10^{12}/\mathrm{cm}^3$. In the NBT scheme, electrons are supplied from a preformed plasma or a plasma at a wall, and move together with a HIB to neutralize the HIB space charge. Along with a HIB convergence, the co-moving electron density increases to the same order of the HIB density. Near the chamber wall, the co-moving electron temperature T_{e0} is ~several tens of keV, and near the target area the electron temperature increases to a few hundreds of keV with the decrease in the HIB radius [7,13]: if we assume an adiabatic increase in the electron temperature T_e, $T_e \sim T_{e0}$ $(r_{b0}/r_b)^{4/3}{\sim}22 \times T_{e0}$.

If we have a high number density N_{ce} $(>Z_bN_b)$ of chamber electrons surrounding the HIB compared with the HIB ion number density N_b, like a channel transport scheme, the HIB space charge is always well neutralized [14]. At the central 50–100 cm target area surrounding a fuel pellet, photoionized electrons are supplied from the chamber gas, the HIB is also ionized to $Z_b{\sim}6$ [13,14], and one can expect this situation of $N_{ce}>Z_bN_b$. Therefore, at the central area the HIB can be expected to be well neutralized.

On the other hand, near the chamber wall area, the HIB number density N_{b0} is expected to be comparable to the background chamber gas electron number density. At the same time, the emitted electrons move together and neutralize the HIB space charge well.

However, at the middle area in NBT between the chamber wall area and the target central area, there may be a situation in which $N_{ce}<Z_bN_b$ and the neutralizing electron temperature T_e is high. In this region a charge separation between the neutralizing electrons and the HIB ions induces a strong radial electric field to expand the HIB radius (see Fig. 1).