

Chamber Transport*

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Abstract

Heavy ion beam transport through the containment chamber plays a crucial role in all heavy ion fusion (HIF) scenarios. Here, several parameters are used to characterize the operating space for HIF beams; transport modes are assessed in relation to evolving target/accelerator requirements; results of recent relevant experiments and simulations of HIF transport are summarized; and relevant instabilities are reviewed. All transport options still exist, including (1) vacuum ballistic transport, (2) neutralized ballistic transport, and (3) channel-like transport. Presently, the European HIF program favors vacuum ballistic transport, while the U.S. HIF program favors neutralized ballistic transport with channel-like transport as an alternate approach. Further transport research is needed to clearly guide selection of the most attractive, integrated HIF system.

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1. Introduction

Heavy ion beam transport through the containment chamber plays a crucial role in any complete heavy ion fusion (HIF) scenario [1-4]. Although a large number of transport modes have been proposed since the inception of the HIF program in 1976, relatively few transport experiments have been performed. Here we define several parameters to categorize the operating space for HIF beams, assess the status of the various transport modes in relation to the evolving HIF target/accelerator requirements, and summarize results of recent relevant experiments and simulations on HIF transport.

Ion beam transport modes can be grouped into two broad categories, as shown in Fig. 1. Ballistic transport refers to modes in which the beam is ballistically focused near the chamber wall from a relatively large radius (5-10 cm) over a distance of several meters to a small radius (~0.1-0.5 cm) at the target. The beam may be a bare beam, or it may be neutralized with electrons from a variety of methods as indicated. Channel-like transport refers to modes in which the beam is focused to a small radius (≤ 0.5 cm) at the chamber wall, and then transported at small radius to the target. In all of these methods, the beam is contained by an azimuthal magnetic field.

Several parameters may be used to characterize the HIF beam. For a bare beam in vacuum, the radial force equation for an ion at the beam edge, in the paraxial approximation, is

$$\frac{d^2r}{dt^2} = \left[\frac{(2eq^2I_p)}{(\beta\gamma^3AM_p)} \right] \left(\frac{1}{r} \right) \quad (1)$$

where I_p is the ion beam particle current, q is the ion charge number, A is the atomic number, M_p is the proton mass, $\beta = V_i/c$, V_i is the ion velocity, c is the speed of light, $\gamma = (1-\beta^2)^{-1/2}$, and e is the electron charge. Solving this equation for the case of a beam of

radius R at $z = 0$ that is ballistically focused to a point at $z = L$, but spreads open (due to space charge) to a radius r_p gives the radial space charge spreading current I_p^{RS} [1]

$$I_p^{RS} = (1/4) [(AM_p\beta^3\gamma^3c^3)/(eq^2)] (R/L)^2 [\ln(R/r_p)]^{-1} \quad (2)$$

A beam at this current will just open to radius r_p at $z = L$. Alternatively, replacing d/dt by $(\beta c)d/dz$, (1) becomes

$$d^2r/dz^2 = K/r \quad (3)$$

where the generalized perveance K is given by

$$K = [eq^2I_p/(\beta c)]/(\gamma^3AM_p\beta^2c^2/2) \quad (4)$$

Note that non-relativistically (i.e., $\gamma \approx 1$), we have $K \approx q[e\phi_0/(AM_pV_i^2/2)]$. Here, the potential difference between the center of the beam and the edge of the beam is given by $\phi_0 = qI_p/(\beta c) = \lambda$, where λ is the line charge density. For the case of $I_p = I_p^{RS}$, we find

$$K = (1/2) (R/L)^2 [\ln(R/r_p)]^{-1} \quad (5)$$

For typical HIF parameters ($R = 5$ cm, $L = 500$ cm, $R_p = 0.2$ cm), result (5) gives $K = 1.6 \times 10^{-5}$. For beams with a perveance at or below this value, vacuum propagation is allowed (however, inclusion of other effects, such as finite emittance, may lower this value). For beams with perveance higher than this value, neutralization is required.

Beams may also be characterized by their axial limiting currents. The space charge limiting current I_p^l is that current, which if propagated, would set up an electrostatic potential strong enough to stop the beam [1], i.e.,

$$I_p^l = \beta(\gamma - 1)(A/q^2)(M_p\gamma^3c^3/e)[1 + 2\ln(R/r_b)]^{-1} \quad (6)$$

Note that $K \approx I_p/I_p^l$ in the non-relativistic limit for $R = r_b$. The Alfvén magnetic limiting current I_p^m is that current, which if propagated, would create a magnetic field strong enough to stop the beam [1], i.e.

$$I_p^m = \beta \gamma (A/q^2) (M_p c^3/e) \quad (7)$$

Note that the perveance scales as q^2 , so that for fully-stripped beams, $K \rightarrow 1$ and $I_p \rightarrow I_p^1$.

The allowed transport method is driven strongly by the target and accelerator parameters. The evolution of these parameters in the U.S. HIF program over the last three decades is summarized in Table 1. The major trends are that the ion energy has decreased from 10 GeV to ~ 4 GeV (i.e., β decreased from about 0.3 to 0.2), the target power required increased from 100 TW to about 600 TW, $q = 1$ is the preferred charge state in the accelerator, and spot sizes have been decreasing. The present mainline U.S. inertial fusion energy (IFE) target development is based on a distributed radiator target concept [5-7]. The first version [5] uses 6.5 MJ of 3-4 GeV Pb ions, produces a fusion yield of 430 MJ, and requires ion beams with a spot size radius of 5 mm. The second version [6] uses 5.9 MJ of 3-4 GeV Pb ions, produces 402 MJ of fusion yield, and requires ion beams that cross-over with elliptical ion beam spots with minor/major axes of 1.8 mm/4.15 mm. The third (scaled) version [7] uses 3.3 MJ of 3-4 GeV Pb ions, produces 436 MJ yield, and requires ion beams that cross over with elliptical ion beam spots with minor/major axes of 1.0 mm/2.8 mm. All three cases use a total of 16 prepulse ion beams and 32 main pulse ion beams, and require charge neutralization at the "90%" level. (Typically, for these IFE targets, about 500 beams are required for vacuum transport). In Europe, the HIDIF study [8,9] used an *ignition* target that requires 3 MJ of 10 GeV Bi ions with a peak power of 750 TW, produces ~ 10 MJ of fusion yield, requires ion beams with a spot size radius of 1.7 mm, and with 48 beams uses vacuum transport. Note that all transport options still exist; (1) vacuum ballistic transport, (2) neutralized ballistic transport, and (3) channel-like transport. The European program currently favors

vacuum transport, whereas the U.S. program currently favors neutralized ballistic transport with channel-like transport as an alternate approach.

1. Neutralized ballistic transport

The parameter space for $q = 1$ beams is plotted in Fig 2 as a function of the line charge density λ versus the perveance K . The value $K = 1.6 \times 10^{-5}$ is shown; above this value, neutralization is required. Shown are the desired parameter spaces for an HIF driver, an IRE (Integrated Research Experiment), and a High Current Experiment (HCX). The parameter spaces for three existing neutralization experiments are shown - the SABRE beamlet experiment, the LBNL scaled final focus experiment, and the GAMBLE II neutralization experiment (all are discussed below). In addition, parameters are shown for light ion fusion (LIF) accelerators and for possible future parameters for the GSI heavy ion facility.

Neutralization requires an electron source and an acceptable electron flow rate into the beam. Electrons may originate from electric field emission at a surface, from gas ionization by the ion beam, from beam stripping by a gas, from a plasma surface, from a volume plasma (e.g., a preformed plasma), or from co-injected electrons. The electrons may be pulled in radially, axially, be co-injected, or be created inside the beam. In general, the electron flow rate may be space-charge-limited or source-limited. Drift orbits may be created (e.g., $E \times B$ or ∇B) and the size of the gyro-radius compared to the beam radius can be important. For plasmas, electrons may be suddenly pulled into the beam, resulting in a substantial electron temperature that will determine the Debye shielding length. Ultimately, the beam will be charge neutralized down to a minimum

potential $\phi_{\min} = (1-f_e)\phi_0$, where f_e is the fractional charge neutralization. For various scenarios, it has been shown that:

- (1) if purely radial electrons are drawn in [10]: $f_e \approx 50\%$ and $\phi_{\min} \sim 0.5 \phi_0$
- (2) if purely axial electrons are drawn in [10]: $e\phi_{\min} \approx \alpha(1/2)m_e V_i^2$ with $1 \leq \alpha \leq 4$
- (3) if the beam is fully immersed in dense, hot plasma: $e\phi_{\min} \approx kT_e$ (equilibrium)
- (4) if perfect co-injected electrons: $e\phi_{\min} \approx kT_e \sim 0$ (but ballistic compression heats)

Simultaneous with charge neutralization, the electrons tend to move with the ion beam creating some fractional current neutralization.

For the important cases of axial electron pick-up from a plasma, from a foil, or by gas ionization, the limit $e\phi_{\min} \approx \alpha(1/2)m_e V_i^2$ applies. The equivalent fractional charge neutralization is then given by $f_e = 1 - (\phi_{\min}/\phi_0)$, which is

$$f_e = 1 - [\alpha(q/A)(m_e/M_p)/K] \quad (8)$$

This function is plotted in Fig. 3 with $\alpha = 4$ for $A = 200$, $q = 1$ (HIF case); and for $A = 1$, $q = 1$ (LIF) case. For light ion fusion, fractional charge neutralization exceeding 99.9% is common. This fact is easily explained by the LIF curve in Fig. 3, since ϕ_0/ϕ_{\min} is greater than 10^3 . For heavy ion fusion, current HIF beam parameters (i.e., $K \approx 10^4$) have $\phi_0/\phi_{\min} \sim 10$ for which result (8) predicts f_e in the 90% range. Since neutralization is needed for HIF in the 90% range, this means that charge neutralization should be studied in detail. Of course, if plasma is available everywhere, the beam can be better neutralized (but this also opens questions of certain instabilities).

Present experimental results and simulations demonstrate some of these limiting

values of $e\phi$. In neutralization experiments on Sabre [11], an intense 4 MeV ($\beta = 0.092$) proton beam was expanded and then passed through a plate with many small apertures to make beamlets with currents spanning the following range:

150 mA beamlets: $K = 1.2 \times 10^5$ (HIF driver scale), $\lambda = 5.4 \times 10^{-3} \mu\text{C/m}$

10 A beamlets: $K = 8.1 \times 10^4$, $\lambda = 0.36 \mu\text{C/m}$ [these have $e\phi \approx (1/2)m_e V_i^2$]

67 A beamlets: $K = 5.4 \times 10^3$, $\lambda = 2.4 \mu\text{C/m}$ (HIF IRE scale)

Results of these experiments clearly (1) demonstrated the axial electron pick-up limit of $e\phi_{\min} \approx (1/2)m_e V_i^2$, and (2) demonstrated plasma shielding (for injection into 0.1 or 1 Torr Ar) with $e\phi_{\min} \approx kT_e \ll (1/2)m_e V_i^2$. In scaled final focus experiments at LBNL [12], a 160 keV Cs^+ beam was focused in vacuum to a small spot, and a hot filament was placed in the beam where the beam radius was about 0.7 cm at a location about 70 cm from the focal spot. With a beam current of 400 μA [$e\phi_0 = 7.5 \text{ eV}$, $(1/2)m_e V_i^2 = 0.64 \text{ eV}$], result (8) predicts $f_e \approx 66\text{-}91\%$ (for $\alpha = 1\text{-}4$) which agrees with the experimental results of $f_e \approx 65\text{-}80\%$. In neutralization experiments on Gamble II [13], a 1 MeV, 100 kA proton beam was injected through a foil into vacuum, picked up electrons off the foil, and was well charge-neutralized [$e\phi_0 = 65.2 \text{ MeV}$, $(1/2)m_e V_i^2 = 0.53 \text{ KeV}$]. Direct measurement of the time-dependent electron density $n_e(t)$ showed that it matched the time-dependent ion beam density very well. Neutralized ballistic transport has been studied in a number of simulations [14,15]. In LSP simulations [16,17], a 4 GeV, 4 kA, 8 ns, Pb^+ beam was ballistically focused from a radius of 3 cm, over a distance of 300 cm, to a small spot. Including emission off surfaces, a low density background preformed plasma (10^{13} cm^{-3}), a neutral gas background (10^{14} cm^{-3}), and stripping, the LSP simulation showed 70 % of the beam was within a 0.2 cm radius spot. While present results are encouraging, more

research is needed to produce an explicit neutralized ballistic transport scenario that guarantees the "90%" neutralization needed.

2. Channel-like transport

Channel-like transport can ease chamber focus requirements and reduce accelerator costs. Channel-like transport includes pre-formed z-discharge channels [18-24], self-pinched transport [25-29], and detached pinched transport [30]. For all of these cases, the heavy ion beam would be essentially fully stripped. In addition, for any beam propagation in gas at a pressure above $\sim 10^{-2}$ Torr, the beam will be significantly stripped. The parameter space for $q = Z$ beams, where Z is the atomic number, (i.e., fully stripped beams) is plotted in Fig. 4 as a function of λ vs. K . Note that $\lambda \sim q$ while $K \sim q^2$, so the parameter spaces for the HIF driver and the IRE move substantially from their positions in Fig. 1. As shown, the only existing experiment in this area is the Gamble II self-pinched transport experiment (as discussed below).

For channel-like transport, the current required to contain the beam in a radius r_c is [25]

$$I = 2(\varepsilon/r_c)^2 [\beta\gamma(A/q)(M_p c^3/e)] \quad (9)$$

where ε is the unnormalized emittance ($\varepsilon \sim r\theta$ with no $\pi\beta\gamma$). This can be rewritten as

$$r_c = \varepsilon(\beta\gamma)^{-1}(FK)^{-1/2} \quad (10)$$

where for a self-pinched beam, $F = I_{net}/(qI_p)$, and for a preformed channel, $F = I_c/(qI_p)$ where I_c is the preformed channel current contained within the radius r_c . Using result (10), the parameter space for channel-like beams is plotted in Fig. 5. Note that small r_c requires large K and small ε .

Present experimental results and simulations demonstrate some of the features of channel-like transport. Wall-confined, z-discharge channels have been used in the past to transport 100's kA proton beams over distances up to 5 meters [1,18,19]. Present channel research is being performed at LBNL [20-22] and at GSI [23,24]. In the LBNL channel experiment, stable 55 kA channels have been created over a length of 50 cm with a radius of 0.4 cm. Self-pinched transport could be used for final transport in the chamber, or, following a mini-focus at the accelerator exit, for transport and drift compression over 400 meters at small radius [29]. Self-pinched transport is the ideal transport mode for a power plant, but it needs substantial development. In initial self-pinched transport experiments on GAMBLE II [27], a 1 MeV, 100 kA, proton beam was injected into He gas at low pressure. Experimental results demonstrate the onset of self-pinching at 55 mTorr, in agreement with IPROP simulations. Further IPROP simulations [28] show self-pinched propagation of a 5.6 GeV, 100 kA Cs^{+55} beam propagating in 15 mTorr He in which the beam assumes an equilibrium radius of 3 mm. Clearly, further research is needed to fully assess the practicality and benefits of these channel-like schemes in an integrated HIF system.

3. Instabilities

Instabilities are an underlying issue for beam transport, and here we comment briefly on the three of most concern. The two-stream instability for beam ions and background electrons has a growth rate on a nanosecond timescale. The present understanding of this instability is that (1) at low pressures ($\sim 10^{-5} - 10^{-3}$ Torr) the instability saturates, wave-particle trapping heats some electrons, and the effect is benign;

(2) at high pressures ($\sim 10^{-1}$ - 10 Torr), collisions and ion beam axial velocity spread stabilize the instability; and (3) at moderate pressures ($\sim 10^{-3}$ - 10^{-1} Torr), the spread in the most unstable axial wave number, as the beam converges toward the target, washes out the instability [31]. These conclusions should be revisited in view of the evolving target parameter requirements. The resistive hose instability (see, e.g., [32]) has a most unstable wavenumber corresponding to the betatron wavelength, and a growth rate that should peak for $\omega\tau_d \approx 0.5$ where the magnetic diffusion time is $\tau_d = 4\pi\sigma r_b^2/c^2$ and σ is the background electrical conductivity. Typically, for HIF parameters, σ should become high enough to essentially avoid this instability except possibly for very small values of r_b . The filamentation instability [33] is potentially the most troublesome instability, and it is a consequence of the fact that very fine-scale transverse perturbations may grow in time since the local magnetic diffusion time scale is very small for very fine perturbations. Based on a physical picture and analytic analysis, this instability may be avoided if σ exceeds the value $\sigma^* = \omega_b^2 t_b / (8\pi\theta^2)$ where $\omega_b^2 = 4\pi n_b (qe)^2 / (\gamma A M_p)$ and $\epsilon = r_b\theta$. The importance of this instability for HIF parameters still needs to be resolved.

4. Status

Research, including experiments, theory, and simulations, is needed in almost all areas of chamber transport. As a guide to future research, an abbreviated list of key issues is given in Table 2. Many of the physics issues listed must be resolved before an optimized, integrated HIF system can be selected. The status of HIF transport for U.S. IFE targets is summarized in Table 3. In the U.S. HIF program, ion energies are ~ 4 GeV, vacuum transport is somewhat less attractive because of the large number of beams

required, neutralized ballistic transport is the mainline approach, and channel-like transport is the alternate approach. In the European HIF program, ion energies remain high (~10 GeV), and vacuum transport is the mainline approach. Future transport research is needed to clearly guide selection of the most attractive, integrated HIF system.

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Figure Captions

Figure 1. Ion beam transport modes.

Figure 2. Parameter space (λ vs. K) for $q = 1$ for neutralized ballistic ion beam transport .

Figure 3. The axial electron pick-up limit [Eq. (8)] for HIF (top) and LIF (bottom),

showing that the fractional neutralization is limited to the 90% range for
for current HIF parameters.

Figure 4. Parameter space (λ vs. K) for $q = Z$ for channel-like ion beam transport .

Figure 5. Equilibrium radius of ion beam [Eq.(10)] for channel-like ion beam transport.

Table 1. Evolution of U.S. HIF IFE target parameters drives transport approach.

Time period	Accelerator	Final Transport	Target	Chamber
1970's	10 GeV U ($\beta=0.3$) 10kA $q=1$	hard vacuum ≤ 50 beams alternates: "1 Torr window" etc.	2-spot radiator 100 TW spot radius: 3 mm	$\leq 10^{-4}$ Torr dry wall
1980's	lower ion energy higher currents $q=1,2,3$ Δv_z (long. inst.)	hard vacuum, $q=1$ neutralized, $q>1$ alternates: channels, etc.	2-spot radiator other targets	$\leq 10^{-3}$ Torr Li waterfall
1990's	4 GeV Pb ($\beta=0.2$) 150 kA $q=1$ Δv_z	neutralized ≤ 50 beams alternates: channels self-pinched (≥ 500 beams for hard vacuum)	distributed radiator ~600 TW a) 6.5 MJ \Rightarrow 430 MJ spot radius: 5mm b) 5.9 MJ \Rightarrow 402 MJ ellipse: 1.8/4.2mm c) 3.3 MJ \Rightarrow 436 MJ ellipse: 1.0/2.8mm	oscillating Flibe jets

Table 2. Transport Issues

Vacuum ballistic transport

beam interaction/overlap near target
chamber vacuum requirement, wall emission
target charge up

Neutralized ballistic transport

accurate cross-sections (e.g., stripping vs. ionization)
demonstration of sufficient f_e (in the "90%" range)
beam interaction/overlap near target
neutralization uniformity and control

Pre-formed channels

small radius limit (hydro, radiation)
high voltage drive
high brightness issues
channel/beam interaction/overlap near target

Self-pinched transport

small radius limit (hydro)
wall guiding (halo, bends, image currents)
head erosion, tracking, reproducibility
beam interaction/overlap near target

Instabilities

two-stream
hose
filamentation

Generic issues

focal spot size position micro-management
re-establishment of adequate chamber transport
conditions after each shot

Table 3. Status of HIF Transport for U.S. IFE Targets

Vacuum ballistic transport ($\leq 10^{-4}$ Torr)

$N \geq 500$ and $q = 1$ required

$(\text{HIF beams}) \approx I_{RS} < I_l < I_A$ *less attractive*

$K \leq 1.6 \times 10^{-5}$

Neutralized ballistic transport ($\sim 10^{-4}$ - 10^{-3} Torr)

$N \leq 50$ and $q = 1$

$I_{RS} < (\text{HIF beams}) < I_l < I_A$ *mainline approach*

$K \geq 1.6 \times 10^{-4}$

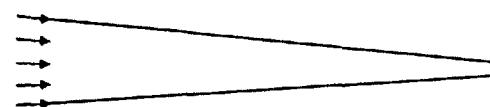
Pre-formed channels or self-pinched

$N \leq 50$ and $q \sim Z \approx 60 - 100$

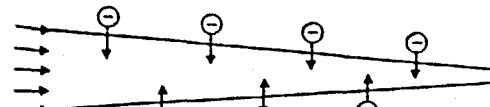
$I_{RS} < I_l \leq (\text{HIF beams}) < I_A$ *alternate approach*

$K \approx 1$

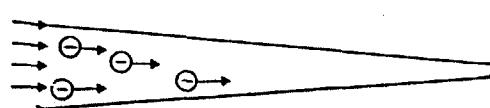
Ballistic Transport



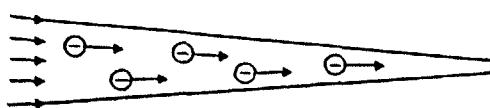
bare beam



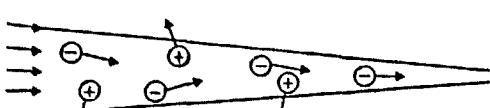
transversely-available
electrons



axially-available
electrons

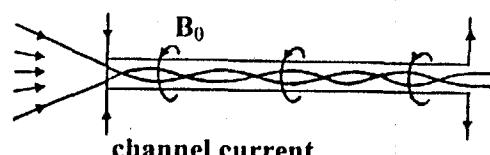


co-moving electrons



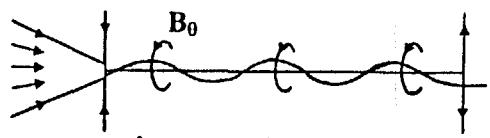
gas or plasma

Channel-Like Transport



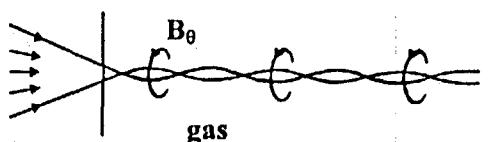
channel current

pre-formed channel



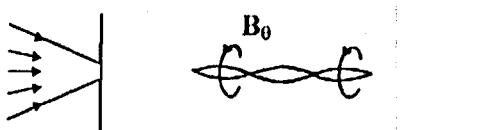
wire current

wire-guided



gas

self-pinched



detached self-pinched

