# FINAL TRANSPORT IN GAS AND PLASMA*

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## I. Introduction

There exist several possible schemes for final transport of the heavy ion beam through the reactor chamber in the presence of a background gas or plasma. The optimization of the transport process depends significantly on the heavy ion beam parameters. Since the first HIF workshop,[1] the desired HIF parameters have changed considerably.[2-4] It was the purpose of the working group on final transport in gas and plasma† to examine and assess the various transport schemes in view of the new HIF parameters and other recent developments.

At the first HIF workshop in 1976, parameters for several HIF targets were given.[1] One target used a 40 GeV U beam at 100 TW, and the other three used a 100 GeV U beam at 600 TW. Since that first workshop, the desired HIF parameters have changed due to an improved understanding of deposition physics and the natural evolution of target designs.[2-4] The trend has been toward lower ion energies and higher ion currents. At this workshop,[4] three new pellet parameter sets were proposed: the desired HIF beam parameters were 5 GeV U at 100 TW, 10 GeV U at 150 TW, and 10 GeV U at 300 TW. This evolution of HIF parameters is summarized in Fig. 1.

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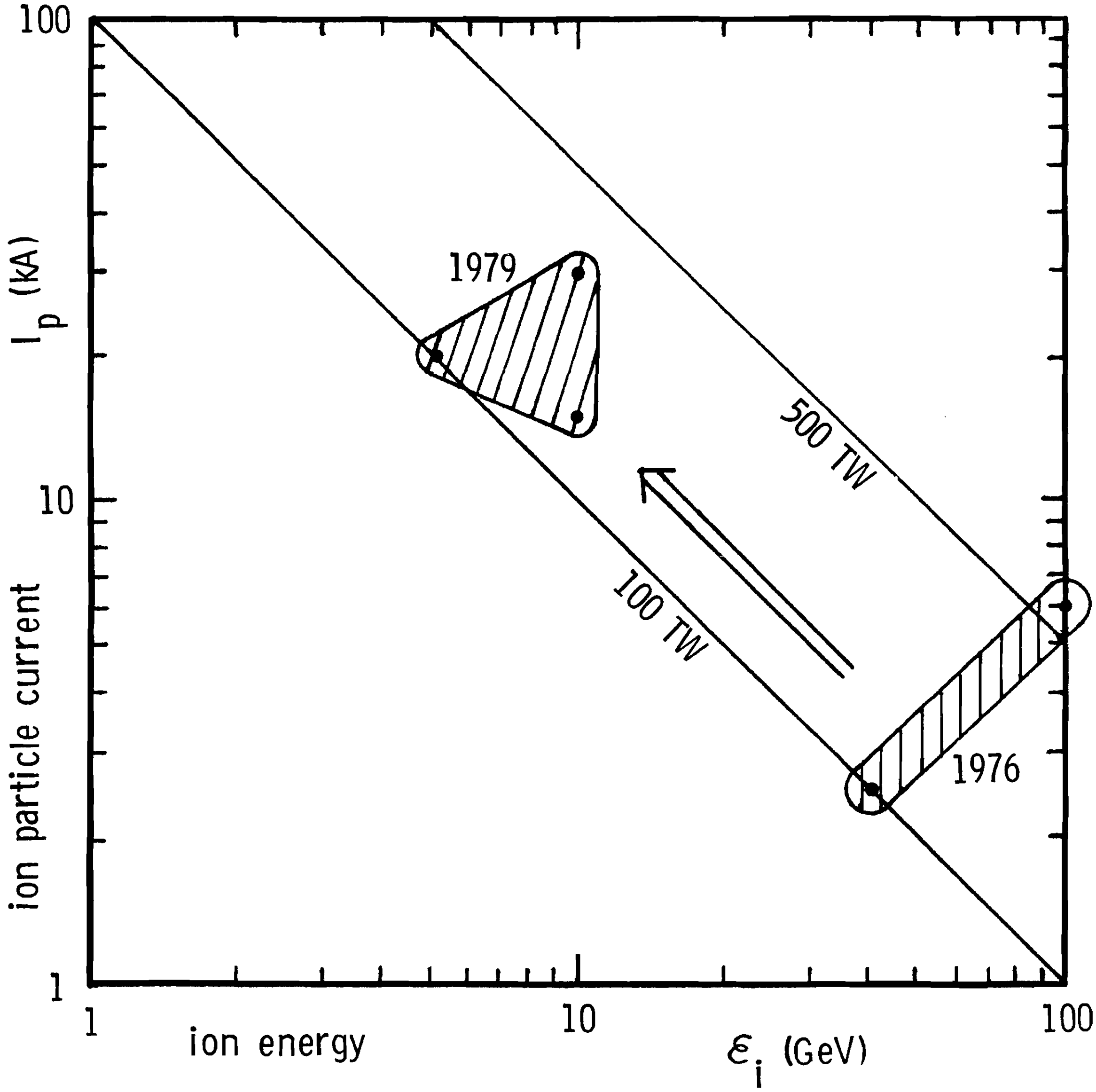


Fig. 1. Evolution of HIF parameters (for uranium ion beams).

Because of these parameter changes, and based on our investigation of the transport regimes, several new conclusions have resulted. The main conclusions, as substantiated in this paper, are as follows:

1. The "1 Torr window" is essentially closed for 5 GeV U. For 10 GeV U, use of this window may be considered; for higher energies ($\gtrsim$ 15 GeV), prospects for the use of this window improve substantially.
2. A new optimum transport regime lies in the $10^{-4}$ Torr - $10^{-3}$ Torr lithium pressure regime. In this regime, which is consistent with the HYLIFE lithium waterfall reactor concept,[5] the HIF beam(s) propagate in an essentially unneutralized state, and plasma and gas effects are just beginning to be important.
3. If the ion energy decreases any further (< 5 GeV), or if the charge state increases much above unity ($\mathcal{Z} \gg 1$), or if the ion atomic mass number decreases significantly ($A \ll 238$), then it rapidly becomes necessary to provide neutralization by some means (e.g., co-moving electrons, gas or plasma background, etc.).

In the following, we will discuss the basic transport effects, and the basic transport pressure regimes that have led to these conclusions.

## 2. Basic Transport Effects

The basic transport effects associated with HIF beams as a function of pressure are summarized in Fig. 2. The pressures considered vary from $10^{-6}$ Torr to $10^{3}$ Torr, and the effects listed cover the fundamental areas of concern for HIF transport. The effects are conveniently grouped as space charge effects, atomic physics effects, zero-order plasma effects, and plasma instabilities. Each of these effects will now be briefly discussed.

Space charge effects include space charge spreading, charge buildup at the pellet, and the effects of space charge electric fields at the walls.

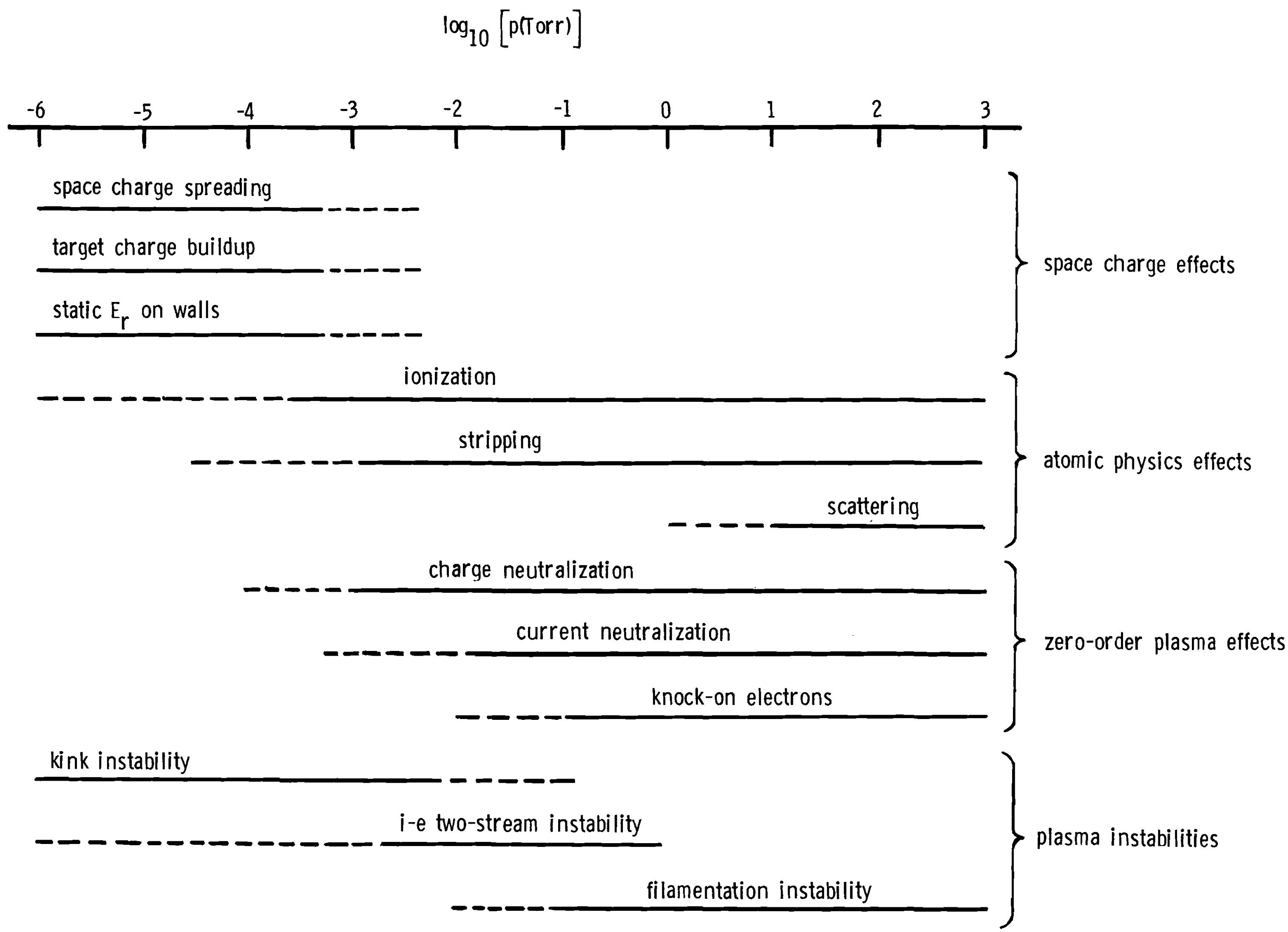


Fig. 2. Transport effects as a function of gas pressure.

Space charge spreading effects may be envisioned by considering the case of a paraxial, zero emittance beam that is focused in the axial (z) direction from an injection radius R at z = 0 to a point at z = L. Due to radial space charge spreading, the beam radius at z = L will not be zero, but will have a finite value $r_{min}$. The radial equation of motion for an ion at the beam edge is relativistically (in CGS units)

$$\gamma M\ddot{r} = 2e\mathcal{Z}I/(\beta c r) \tag{1}$$

where M is the ion mass, e is the magnitude of the charge of an electron, $\mathcal{Z}$ is the ion charge state, I is the (unneutralized) ion current, $v_z = \beta c$ is the ion axial velocity, c is the speed of light, $\gamma = (1 - \beta^2)^{-1/2}$, and a dot ($\dot{}$) denotes d/dt. Rewriting (1) as

$$\int_0^t [d/dt(dr/dt)]\ (dr/dt)dt = \int_R^{r_{min}} (K/r)dr \tag{2}$$

where $K = 2e\mathcal{Z}I/(\beta c\gamma M)$, and noting that $(dr/dt)/(dz/dt) = -R/L$ at z = 0, and dr/dt = 0 at z = L, we find that the particle current $I_p$ ($I_p = I/\mathcal{Z}$) is given by

$$I_p = \frac{\beta^3\gamma}{4\mathcal{Z}^2}\,\frac{Mc^3}{e}\,\frac{R^2}{L^2}\,\frac{1}{\ln(R/r_{min})} \tag{3}$$

If $r_{min}$ is set equal to the pellet radius, then $I_p$ represents that current at which space charge spreading effects will just begin to cause the beam to miss (spread larger than) the pellet. If we consider beams composed of ions with energy $\mathcal{E}_i$ and particle current $I_p$ given by (3), then the number of beams N required to achieve a power P at the pellet is $N = Pe/(I_p\mathcal{E}_i)$, or

$$N = \frac{4Pc}{\beta^3(\gamma-1)(\gamma)} \frac{\mathcal{Z}^2}{A^2} \frac{L^2}{R^2} \frac{\ln(R/r_{min})}{(M_p c^3/e)^2} \tag{4}$$

where A is the atomic number and $M_p$ is the mass of the proton ($M = AM_p$). In practical units, this is

$$N = (1.36\mathrm{x}10^{-4}) \frac{P(TW)}{\beta^3(\gamma-1)(\gamma)} \frac{\mathcal{Z}^2}{A^2} \frac{L^2}{R^2} \ln (R/r_{min}) \tag{5}$$

The non-relativistic results analagous to (1)-(5) are obtained in the limit $\gamma \to 1$, $(\gamma-1) \to \beta^2/2$; these results have been frequently discussed in the literature, and at past workshops.[1-3] Note that for the non-relativistic case, N scales as $(\mathcal{Z}/A)^2$ $(L/R)^2$ $(1/\mathcal{E}_i^{5/2})$ and that there is only a weak logarithmic dependence on $r_{min}$.

Result (5) is plotted in Fig. 3 for uranium (A = 238) for the case of P = 100 TW, R = 10 cm, $r_{min}$ = 0.2 cm, and L = 10 m. Note that for 30 GeV $U^{+1}$, N = 1 is sufficient. For 10 GeV $U^{+1}$, $N \approx 10$. For $\mathcal{E}_i \lesssim 5$ GeV or $\mathcal{Z} \gtrsim 4$, then $N \gtrsim 100$. Note however, that by changing parameters to R = 20 cm and L = 5 m, N decreases by a factor of 16. In any event, the trend is clear that for low energies ($\mathcal{E}_i < 5$ GeV) and high charge states ($\mathcal{Z} \gtrsim 4$), a substantial number of beams is required.

It should be noted that the radial equation of motion (1) omits the effects of beam pinching (which reduces radial spreading) and the effects of finite emittance (which increases radial spreading). Beam pinching due to the self-magnetic field of the beam reduces the radial force in (1) by a factor $1/\gamma^2$. For 10 GeV U, $\gamma = 1.045$ and $1/\gamma^2 = 0.916$, so pinching effects would reduce the beam spreading force by only ~8%. Finite emittance effects have been considered in conjunction with space charge spreading effects by Garren[6] and Lawson.[7] For this case, the beam envelope equation analagous to (1) is

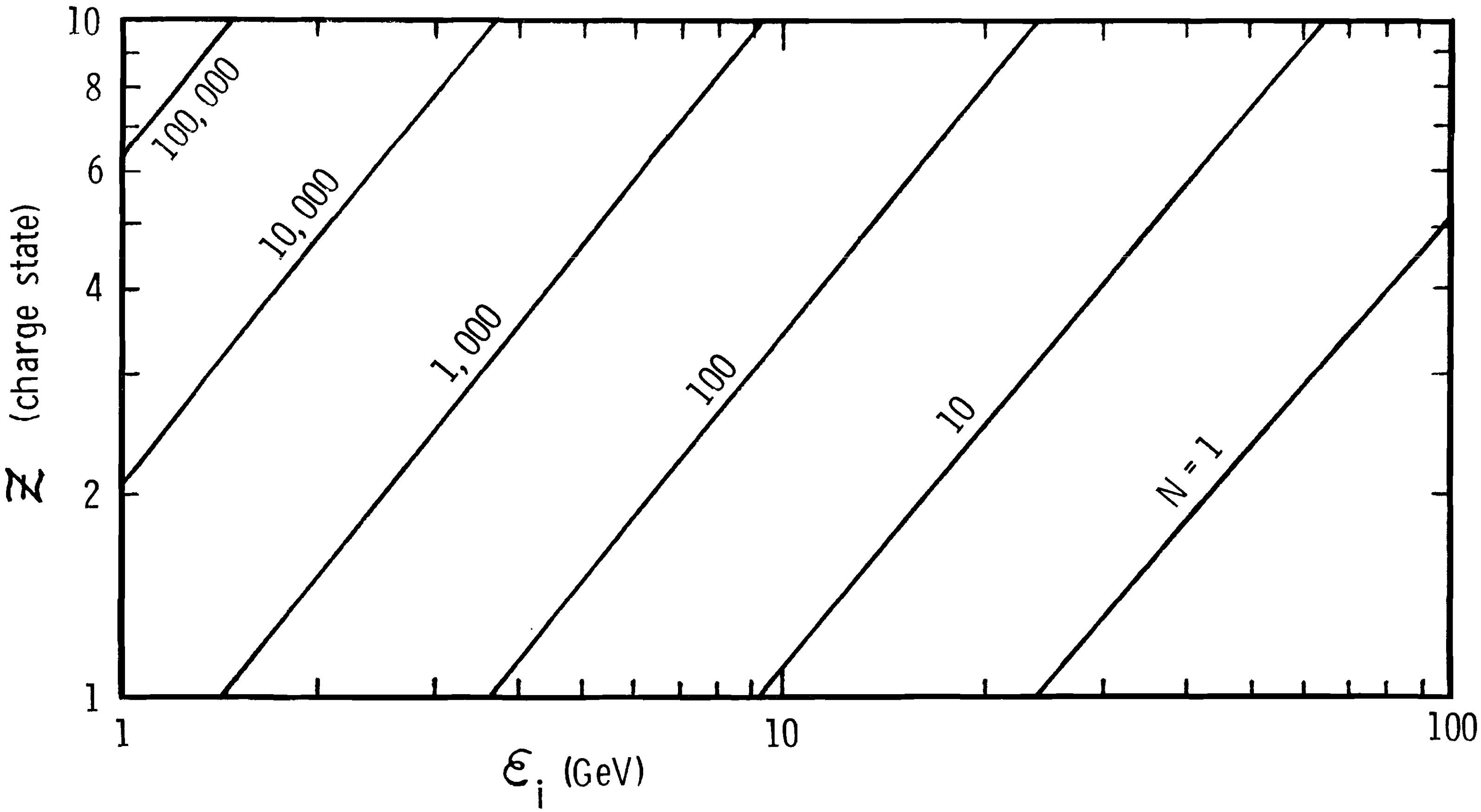


Fig. 3. Number of uranium beams (N) required for $\mathcal{P}$ = 100 TW, R = 10 cm, r = 0.2 cm, L = 10 m, A = 238. The initial emittance was taken to be zero. For non-zero emittance, N will be larger than that shown.

$$d^2r/dz^2 = [K/(\beta c)^2]/r + \varepsilon^2/r^3 \quad (6)$$

where $\varepsilon$ is the (unnormalized) transverse phase space emittance. Equation (6) readily integrates to give

$$2[K/(\beta c)^2]\ \ell n\ (R/r_{min}) = (R^2/L^2) - \varepsilon^2/r_{min}^2 \quad (7)$$

Result (7) is the same as result (3), but with the $R^2/L^2$ replaced by $(R^2/L^2)C$, where the correction factor C is

$$C = 1 - (L^2/R^2)(\varepsilon^2/r_{min}^2) \quad (8)$$

It follows that in (5), N increases by the factor $C^{-1}$. The limit C = 0 means that the beam radius at z = L equals $r_{min}$ due to finite emittance effects alone, and any space charge spreading will cause the beam to spread more and miss the pellet. The limit C = 1 means emittance effects are negligible, which requires $\varepsilon \ll (r_{min})(R/L)$. For R = 10 cm, $r_{min}$ = 0.2 cm, and L = 10 m, $\varepsilon \ll 2$ cm mrad is required to make emittance effects negligible; if $\varepsilon = 1$ cm mrad, then N in Fig. 3 should be increased by 33%. We conclude that finite emittance effects may increase N significantly above that given in Fig. 3.

Other space charge effects include charge buildup at the pellet, and possible field emission from the transport tube walls due to the large space charge fields. Charge buildup effects may be roughly evaluated by assuming all of the beam charge is deposited on a sphere of radius $r_{min}$. The resulting potential $\phi$ is

$$\phi = I_p \mathcal{Z}\, t_b / r_{min} \quad (9)$$

where $t_b$ is the beam pulse length. $e\phi$ may be compared with $\mathcal{E}_i$ to estimate the importance of charge buildup. The radial space charge field $E_r$ at a wall of radius $R_w$ for an unneutralized beam (of radius $R < R_w$) is

$$E_r = 2I_p \mathcal{Z}/(\beta c R_w) \tag{10}$$

Field emission from the wall may become a problem for $E_r \gtrsim 200$ kV/cm. If there is a single beam inside the accelerator, then this can be a real problem.[8] On the other hand, for final transport, if the number of beams N is greater than or equal to that given by (5), then $E_r$ as given by (10) is typically too small to cause field emission problems.

Space charge effects for various HIF parameters are given in Table 1 for the case of P = 100 TW and a total energy $\mathcal{E}_t$ = 1 MJ. Case 1 (100 GeV $U^{+1}$) is typical of the parameters suggested for HIF at the first workshop.[1] For this case, only 1 beam is needed and space charge effects are almost negligible. Case 2 (10 GeV $U^{+1}$) is typical of the parameters suggested at this workshop. Note that space charge effects are now important, several beams are needed, $E_r$ is large (if only 1 beam is used), and $e\phi$ is significant. Case 3 (1 GeV $U^{+1}$) represents parameters for pellets similar to those optimized for light ion fusion (LIF). Here we see that space charge effects are dominant, field emission would definitely occur for 1 beam, $e\phi \gg \mathcal{E}_i$, and conventional accelerator technology could not be employed. A reasonable conclusion, as was the consensus at the end of this workshop, is that the ion energy should be about 10 GeV $U^{+1}$, and no lower. This energy permits conventional accelerator technologies to be exploited, but at the limit where space charge effects are significant.

Returning to Fig. 2, we now comment briefly on other transport effects. Atomic physics effects relevant to HIF transport include ionization of the background gas by processes induced by the beam ions, stripping of the beam ions to higher charge states by the background gas, and scattering of the beam ions by the background gas. Upper bound estimates for the ionization and stripping cross sections of relevant ions (Xe,U) in various gases

Table 1. Space charge effects for various HIF accelerator parameters.

| | CASE 1 | CASE 2 | CASE 3 |
|---|---|---|---|
| ION | $U^{+1}$ | $U^{+1}$ | $U^{+1}$ |
| ENERGY | 100 GEV | 10 GEV | 1 GEV |
| $\beta$ | 0.723 | 0.290 | 0.0943 |
| RANGE IN Au (COLD)* | 5069 MG/$CM^2$ | 212 MG/$CM^2$ | 36 MG/$CM^2$ |
| RANGE IN Au (HOT)* | 4235 MG/$CM^2$ | 154 MG/$CM^2$ | 16 MG/$CM^2$ |
| PARTICLE CURRENT (FOR 100 TW) | 1 KA | 10 KA | 100 KA |
| CONVENTIONAL ACCELERATOR | APPEARS POSSIBLE (SPACE CHARGE EFFECTS SMALL) | MAY BE POSSIBLE (SPACE CHARGE EFFECTS IMPORTANT) | NOT POSSIBLE (SPACE CHARGE EFFECTS DOMINATE) |
| N (NUMBER OF BEAMS) (R =10 CM, $r$=0.2 CM, L=10 M) | 1 | 10 | ~2,000 |
| $E_r$ AT ACCELERATOR DRIFT TUBE WALL (R = 10 CM)† | 8 KV/CM | 206 KV/CM | 6.4 MV/ CM |
| $e\phi$ CREATED BY SPACE CHARGE AT PELLET ($\epsilon$ = 1 MJ, $r$ = 0.2 CM) | 0.045 GEV | 0.45 GEV | 4.5 GEV |

*MEHLHORN RESULTS: COLD: $\rho$ = 19.3 G/$CM^3$

HOT: $\rho$ = 0.193 G/$CM^3$, 200 EV

† FOR TOTAL CURRENT IN 1 BEAM

($H_2$, $N_2$, Li, Ne) were given by Gillespie et al. at the third workshop;[9] those results were used in the estimates in Section 3. A summary of atomic physics needs for HIF transport was given by Yu at the second workshop,[10] where the importance of knowing the effective charge state of the ion was noted. It should be emphasized that more exact calculations, and data, are still needed to make accurate estimates of the relevant ionization and stripping cross sections.

Zero-order plasma effects include charge neutralization, current neutralization, and more recently, the knock-on electron effect of Hubbard et al.[11] It is usually assumed that charge neutralization occurs on the time scale of the plasma frequency $\omega_{pe}$ of the background plasma [$\omega_{pe} = (4\pi n_e e^2/m)^{1/2}$ where $n_e$ is the electron density and m is the mass of an electron]. While this is roughly true locally inside the beam, a consistent overall picture of charge neutrality for an isolated HIF ion pulse drifting in a gas has not been established. Similarly, complete current neutralization is typically assumed (at higher pressures) and this has been used as an initial assumption for investigating, e.g., the filamentation instability. More recently, it has been found that the decay of the return current toward the end of the pulse leads to a sizable net current with significant pinch forces that can result in anharmonic emittance growth. These effects have been studied by Yu et al.,[12] and Brueckner,[13] who have found them to seriously affect the focussing of HIF beams. The knock-on electron problem arises from beam ion collisions with the gas that produce a flux of forward-directed electrons with velocities higher than those of the ions. If a sufficiently large current of knock-on electrons is created ahead of the beam, this current will ionize the gas ahead of the beam, and eventually result in a field frozen current that can subsequently defocus the ions. These effects will be discussed further in Section 3.

There is a constant concern that plasma instabilities may ultimately prevent HIF transport. To date, the most important instabilities appear to be the "wriggle" instability, the ion-electron two-stream instability (beam ions/plasma electrons), and the filamentation instability (for a current neutralized beam). As noted by Thompson,[14] the "wriggle" instability is an electrostatic kink instability with a growth rate of the order of the beam ion plasma frequency $\omega_B$ $[\omega_B = (4\pi n_b \mathcal{Z}^2 e^2/M)^{1/2}]$. For very low pressures, where $\mathcal{Z} \approx 1$, the growth rate is very low, and this instability should not be a problem. At higher pressures, $\mathcal{Z}$ increases quickly, but so does the plasma background density which tends to inhibit growth of this instability. The two instabilities that persist, and are important in determining the "1 Torr window" are the ion electron two-stream instability and the filamentation instability; these will be discussed further in Section 3.

In summary, Fig. 2 presents an overview of basic HIF transport effects as a function of pressure. Note that at low pressures relatively few effects exist, while at high pressures a large variety of phenomena come into play.

## 3. Transport Regimes

A summary of reactor schemes and HIF transport regimes is given in Fig. 4. In the center of the figure, we have plotted particle current vs. $\log_{10}[p(\text{Torr})]$ and show the operating regimes relevant to 5 GeV $U^{+1}$ (as will be discussed below).

Reactor schemes split into four categories with somewhat arbitrary pressure limits as follows. For very low pressures ($p < 10^{-4}$ Torr), dry wall reactor schemes must be employed and the required standoff distance is relatively large. For moderately low pressures ($10^{-4}$ Torr $< p < 10^{-3}$ Torr), the HYLIFE liquid lithium waterfall reactor scheme[5] is applicable (since the vapor pressure of lithium is $10^{-4}$ Torr at ~400°C and $10^{-3}$ Torr at ~450°C).

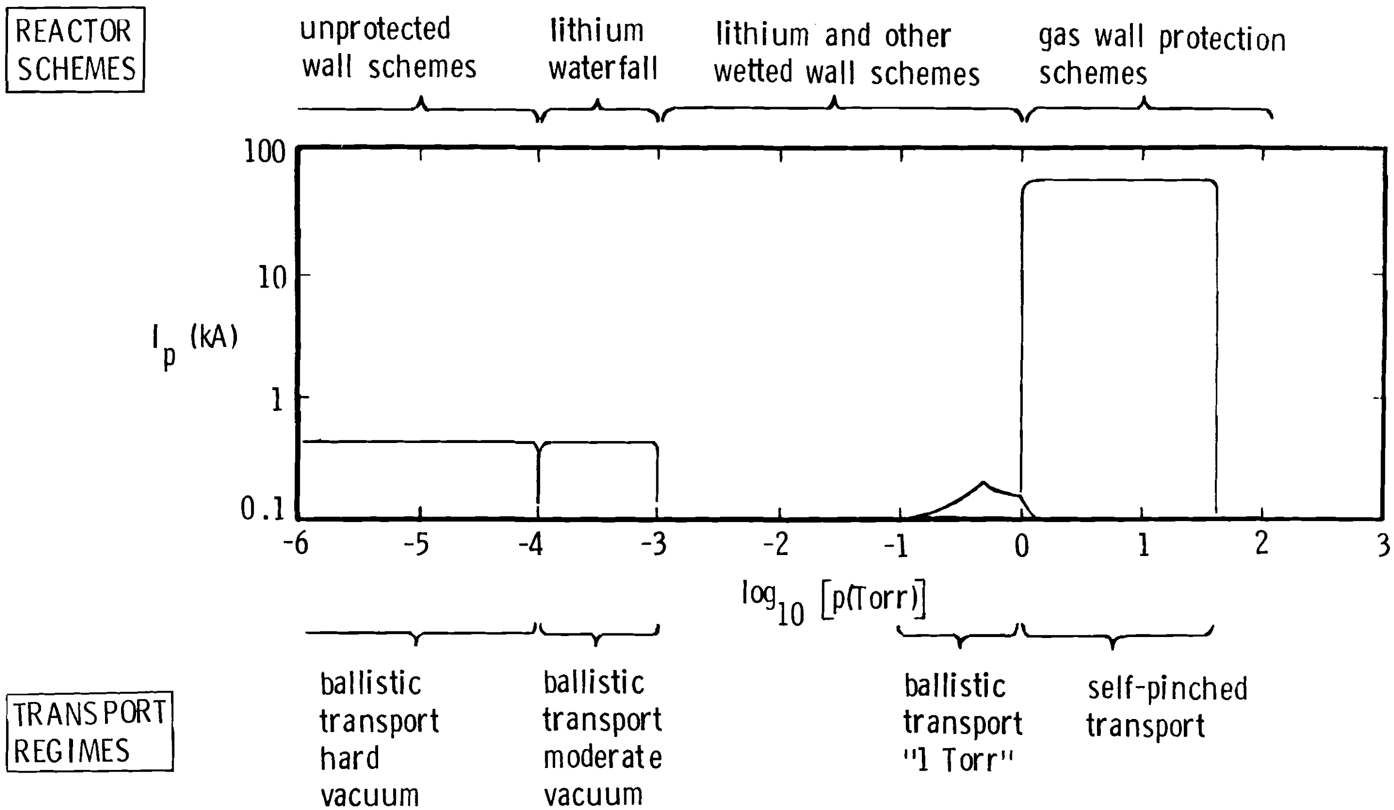


Fig. 4. Operating regimes for HIF (results shown for 5 GeV $U^{+1}$).

For pressures from $10^{-3}$ Torr to ~1 Torr, there exist several wetted wall reactor scenarios. For $p > 1$ Torr, the gas density begins to be high enough to offer some wall protection by the absorption of radiation and alpha particles from the pellet blast.

Four HIF transport regimes are also identifiable, as indicated in Fig. 4. These regimes are:

1. Ballistic transport in hard vacuum ($p < 10^{-4}$ Torr)
2. Ballistic transport in moderate vacuum ($10^{-4}$ Torr $< p < 10^{-3}$ Torr)
3. Ballistic transport at "1 Torr"
4. Self-pinched transport at 1-50 Torr

Each of these regimes will now be briefly discussed.

Ballistic transport in hard vacuum ($p < 10^{-4}$ Torr) - By ballistic transport is meant that after the final focusing magnet, the beam ions are directed toward and simply drift to the target. Ballistic transport in hard vacuum is characterized by $n_p \ll n_b$ where $n_p$ is the plasma density and $n_b$ is the beam density. The advantages of this regime are that the transport calculations are straightforward (space charge and magnetic field forces must be included), there is essentially no beam stripping, and there is essentially no plasma physics involved (as compared to the other transport regimes). The disadvantages of this regime are that it requires a dry wall reactor with a large cavity, pump down of the reactor between shots may be difficult, space charge beam spreading effects limit the current per beam (as in Fig. 3), and charge buildup at the pellet may have significant consequences. Alternative neutralization schemes (such as comoving electrons) might help to alleviate the last two disadvantages.

Ballistic transport in moderate vacuum ($10^{-4}$ Torr $< p < 10^{-3}$ Torr) - Ballistic transport in moderate vacuum is the new "first choice" for HIF transport because for this regime most plasma complications are avoided and yet a favorable reactor scenario exists. This regime is characterized by $n_p \lesssim n_b$. The advantages of this regime are that it is compatible with a compact reactor scenario (the HYLIFE lithium waterfall reactor concept[5]), charge neutralization is just beginning, beam stripping effects are just beginning, differential pumping in the magnetic lens port should be relatively easy, and most plasma complications (knock-on electrons, anharmonic emittance growth, filamentation, etc.) are avoided. The uncertainties for this regime are that classical transport for $n_p \lesssim n_b$ has not been studied in detail yet, the ion-electron two-stream instability is present but estimates of its saturation effects indicate that they should be small, and there may not be sufficient charge neutralization at the pellet. Further study is needed to clarify these questions.

Several relevant pressures for this regime are indicated in Fig. 5 for the case of 5 GeV $U^{+1}$ in lithium. Without assuming any neutralization, the current remains limited by the space charge result (3). Stripping is just starting, and only a fraction of the beam will go from $U^{+1}$ to $U^{+2}$. As the beam passes, collisional ionization will create a plasma with density $n_p \approx n_b$ at a pressure near the middle of this regime. Scattering is negligible. We conclude that plasma effects should be small, but that the regime $n_p \approx n_b$ merits more detailed investigation.

Ballistic transport at "1 Torr" - This regime is named in reference to a search for a propagation window near 1 Torr. This regime is characterized by $n_p >> n_b$, and plasma effects play a dominant role in determining the transport properties. The advantages of this regime are that it offers some wall protection and that the pump down of the reactor chamber between shots is less severe than for the vacuum regimes. The disadvantages are numerous. Stripping is severe, anharmonic emittance growth can be serious, and the transport properties are sensitive to the distribution of beam charge states. To permit

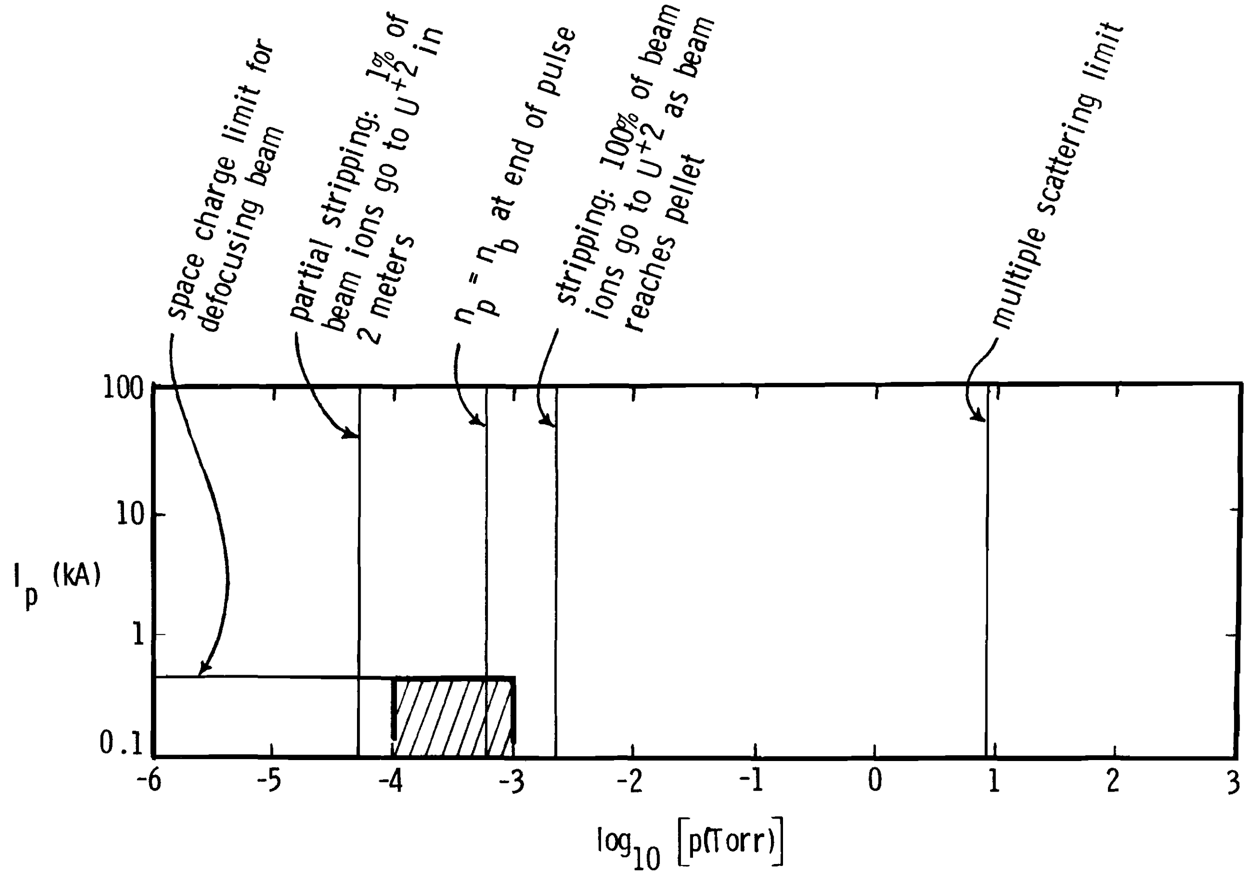


Fig. 5. Ballistic transport in moderate vacuum [ $10^{-4} \leq p(\text{Torr}) \leq 10^{-3}$ ] for 5 GeV $U^{+1}$ in lithium. L = 5 m (corresponding to distance from reactor wall to pellet) was used in all calculations, except L = 10 m (corresponding to distance from center of final focusing magnet to pellet) was used to calculate the space charge limit. (R = 10 cm, r = 0.2 cm, beam pulse length = 10 nsec)

propagation, the parameters must be chosen to simultaneously avoid the ion-electron two-stream instability, the filamentation instability, the knock-on electron problem, and multiple scattering effects. Also, differential pumping in the final magnetic lens may be difficult.

The "1 Torr window" is shown in Fig. 6a for the case of 5 GeV U injected into neon, and in Fig. 6b for the case of 10 GeV U injected into neon. These results were calculated by Hubbard[15] for R = 10 cm, $r_{min}$ = 0.2 cm, L = 5 m, plasma electron temperature $T_e(r_{min})$ = 100 eV, $Z_{gas}$ = 10, and a beam longitudinal velocity spread $\Delta v_z/(\beta c) = 0.005$. The loci shown have the following meanings. The two-stream instability is collisionally quenched to the right of the two-stream locus. The filamentation instability will grow less than 5 e-folds for parameter values below the filamentation locus. For currents below the knock-on electron locus, the beam will not spread by more than $r_{min}$. Similarly, for pressures below the scattering limit, the beam will not spread by more than $r_{min}$. It should be noted that many approximations must be made in deriving such loci (such as the effective ion charge state, the fraction of knock-on electrons inside the beam channel, etc.). However, these loci do represent the best current estimates for the various effects considered.

Note that in Fig. 6, for 5 GeV U, the window is effectively closed. For 10 GeV U, the window is enlarged; for higher energies ($\gtrsim$ 15 GeV),[15] the window is enlarged even more. Since the total current required to achieve a given beam power decreases as the energy increases, and since the maximum current per beam in the 1 Torr window increases as the energy increases, this means that the number of beams required to achieve a given power decreases quickly as the energy increases. We conclude that for 5 GeV U, the window is effectively closed; for 10 GeV U, use of this window may be considered; for $\gtrsim$ 15 GeV U, prospects for the use of this window improve substantially.

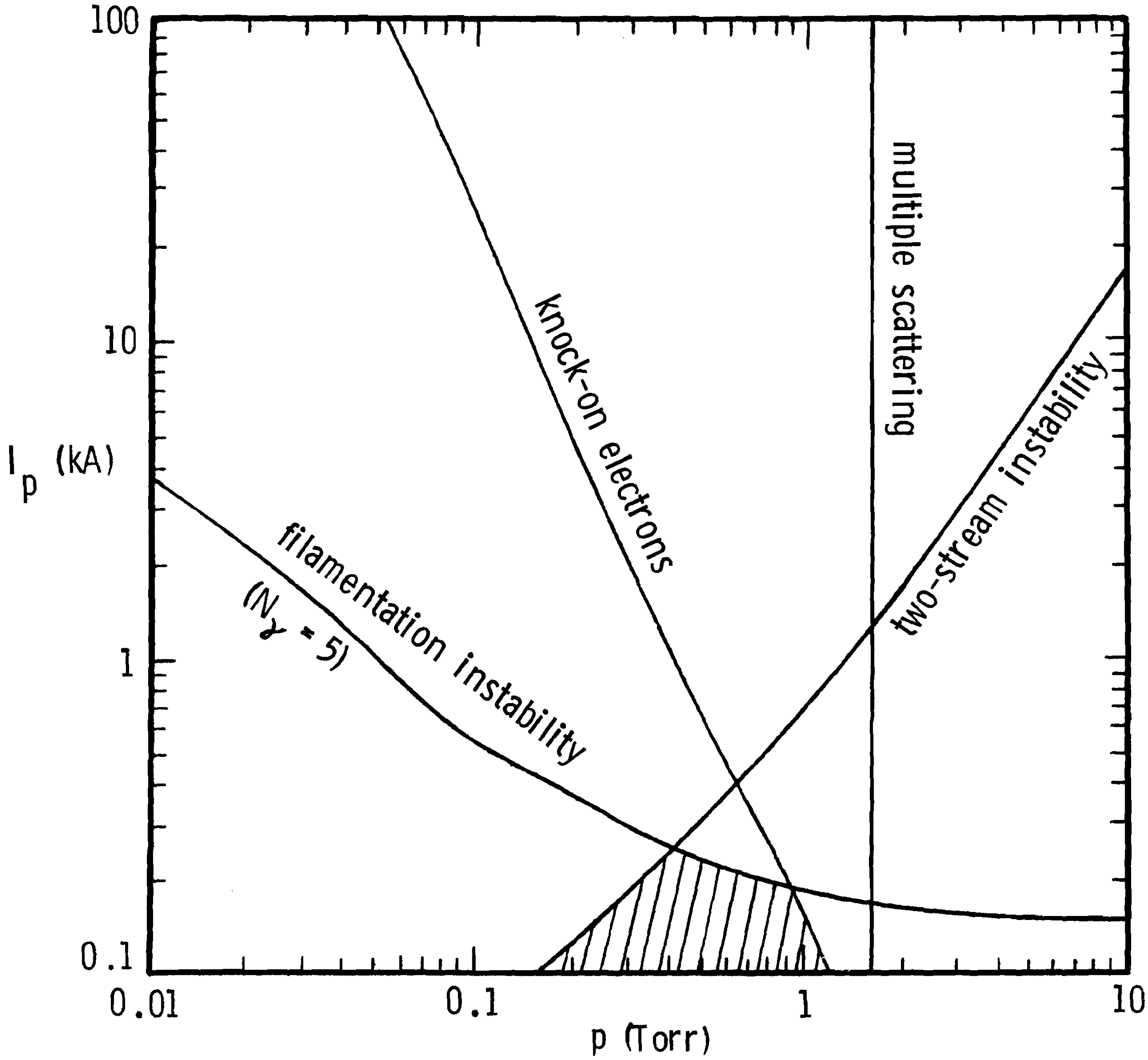


Fig. 6a. The "1 Torr window" (shown hatched) for 5 GeV uranium beam propagation in neon gas. R = 10 cm, r = 0.2 cm, L = 5 m, $T_e$(r=0.2 cm) = 100 eV, $Z_{gas}$ = 10, $\Delta v_z/v_z$ = 0.005.

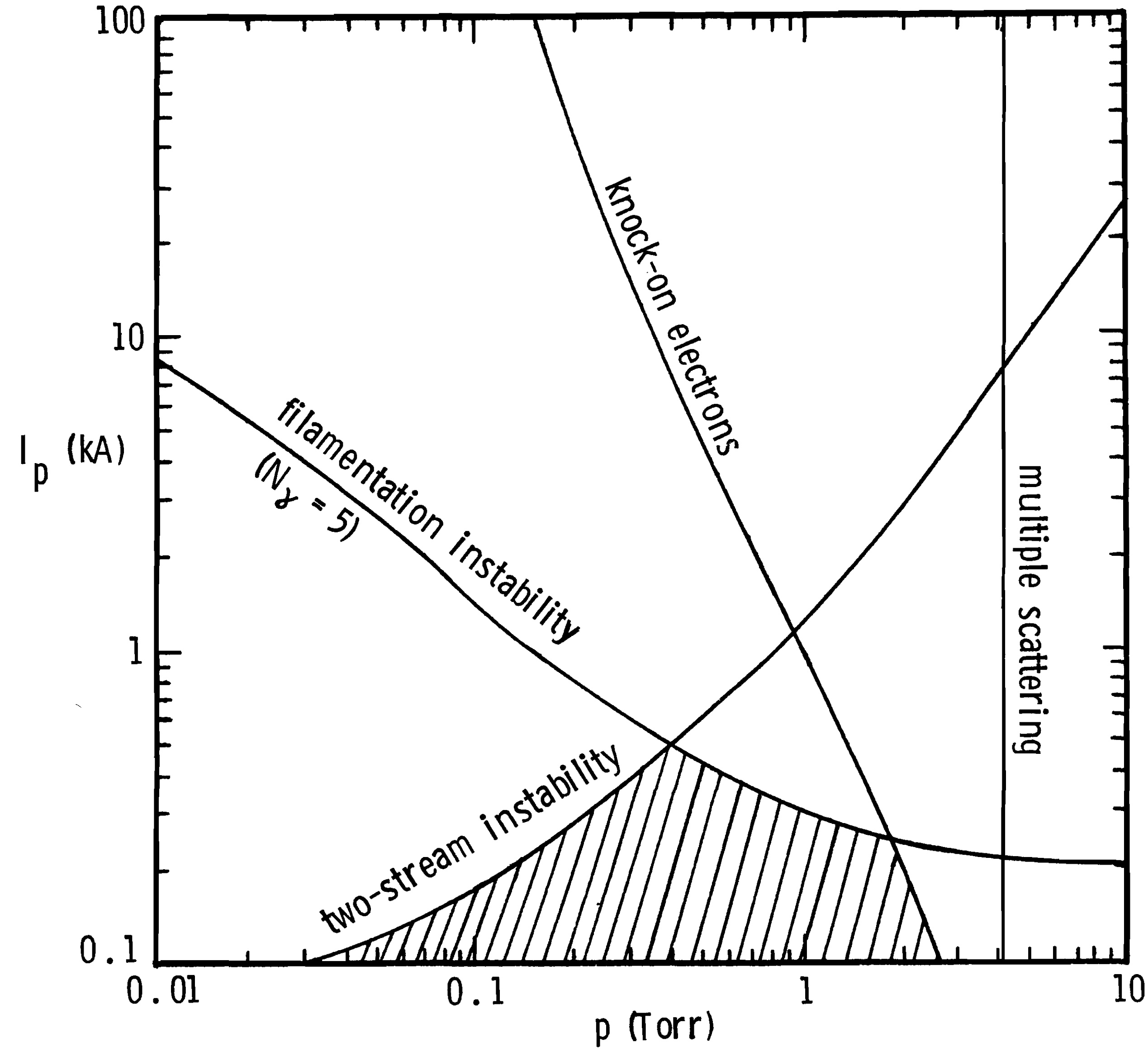


Fig. 6b. The "1 Torr window" (shown hatched) for 10 GeV uranium beam propagation in neon gas. R = 10 cm, r = 0.2 cm, L = 5 cm, $T_e$(r=0.2 cm) = 100 eV, $Z_{gas}$ = 10, $\Delta v_z/v_z$ = 0.005.

Self-pinched transport at 1-50 Torr - For self-pinched transport, the HIF beam(s) would be focused to about the pellet radius at the input to the reactor chamber. The beam would ionize the gas and propagate in a self-pinched mode through the reactor chamber to the pellet. This regime is characterized by $n_p >> n_b$. The advantages of this regime are that substantial gas protection of the wall is possible; the mode is insensitive to scattering, filamentation, and the two-stream instability; and small reactor beam ports would simplify the differential pumping. The disadvantages are that knock-on electrons may be a problem, a counter-streaming electron beam may be needed, and the concept has not been tested experimentally. Nonetheless, this concept is interesting, and recent work on it is reported by Yu et al.[16]

## 4. Recommended HIF Transport Research Areas

Based on the above conclusions, highest priority is recommended for studies that would insure the success of ballistic transport in the moderate vacuum regime ($10^{-4}$ Torr - $10^{-3}$ Torr). This includes detailed studies of the stripping and ionization cross-sections for this regime, basic HIF transport studies (onset of charge and current neutralization) for the case $n_p \lesssim n_b$, and studies of the saturation of the ion/electron two steam instability for the case $n_p \lesssim n_b$ (to insure that the effects are negligibly small on the HIF beam). Experiments to specifically investigate these effects are highly recommended.

If the final acceleration parameters dictate that neutralization must be used, then other areas of study that should be investigated include neutralization by use of co-moving electrons, self-pinched mode propagation, and further work on the "1 Torr window."

## 5. Conclusions

The main conclusions of this study are as follows:

1. The "1 Torr window" is essentially closed for 5 GeV U. For 10 GeV U, use of this window may be considered; for higher energies ($\gtrsim$ 15 GeV), prospects for the use of this window improve substantially.
2. The new first choice for HIF transport is to use ballistic transport in moderate vacuum ($10^{-4}$ Torr - $10^{-3}$ Torr). This regime is consistent with the HYLIFE reactor scenario, and plasma and gas effects are just beginning to be important. Further research on this regime is highly recommended.
3. The use of essentially unneutralized beams for HIF transport is a great simplification that should not be abandoned if at all possible. This means that to minimize the number of beams according to (5), it is desirable to keep $\gamma$ high, $\mathcal{Z}$ low, and A high. For $\mathcal{E}_i < 5$ GeV, $\mathcal{Z} \gg 1$, or $A \ll 238$, it rapidly becomes necessary to provide neutralization by some means (e.g., co-moving electrons, or a gas background such as occurs in the "1 Torr window").

We conclude that a reasonable HIF baseline transport scenario would be to use 10 GeV $U^{+1}$ in the moderate vacuum regime ($10^{-4}$ Torr - $10^{-3}$ Torr lithium). This scenario is relatively simple, it is consistent with a realistic reactor scheme, and it can be recommended with a relatively high confidence level.

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