CONF-790723--8

MASTER

PREPRINT UCRL- 82586

# Lawrence Livermore Laboratory

## TRANSPORT OF INTENSE PARTICLE BEAMS WITH APPLICATION TO HEAVY ION FUSION

H. L. Buchanan, F. W. Chambers, E. P. Lee, S. S. Yu, R. J. Briggs (LLL)
and M. N. Rosenbluth (The Institute for Advanced Study, Princeton, NJ)

June 22, 1979

This paper was prepared for submission to the Third International Topical Conference on High Power Electron and Ion Beam Research and Technology, held in Novosibirsk, USSR July 3-6, 1979.



UCRL 82586

# TRANSPORT OF INTENSE PARTICLE BEAMS WITH APPLICATION TO HEAVY ION FUSION*

H. L. Buchanan, F. W. Chambers, E. P. Lee, S. S. Yu, R. J. Briggs
Lawrence Livermore Laboratory, University of California
Livermore, CA (USA)
and
M. N. Rosenbluth
The Institute for Advanced Study, Princeton NJ (USA)



## ABSTRACT

An attractive feature of the high energy (> GeV) heavy ion beam approach to inertial fusion, as compared with other particle beam systems, is the relative simplicity involved in the transport and focusing of energy on the target inside a reactor chamber. While this focusing could be done in vacuum by conventional methods with multiple beams, there are significant advantages in reactor design if one can operate at gas pressures around one torr. In this paper we summarize the results of our studies of heavy ion beam transport in gases. With good enough charge and current neutralization, one could get a ballistically-converging beam envelope down to a few millimeters over a 10 meter path inside the chamber. Problems of beam filamentation place important restrictions on this approach. We also discuss transport in a self-focused mode, where a relatively stable pressure window is predicted similar to the observed "window" for electron beam transport. This approach, or the use of a current channel made by external means, is particularly attractive because a much smaller entrance port can be used.

## I. INTRODUCTION

A heavy ion driver for inertial confinement fusion must traverse a reactor chamber of 5-10 meters radius and arrive at the fusion pellet with a spot size of only a few millimeters.[1] It appears that this is achievable with several simultaneous beams in a converging flow pattern under near-vacuum conditions ($p \leq 10^{-4}$ torr) in the reactor, since the individual beams will not strip to a high charge state and will therefore be electrically stiff. It may also be possible to propagate at high pressure ($p \geq 1$ torr) using as few as two beams

*This work is performed under the auspices of the U.S. Department of Energy by LLL under contract No. W-7405-Eng-48.

with the ions in a high charge state. The two-stream instability is quenched by plasma collisionality, but magnetic filamentation is a driving issue.

Operation in the high pressure mode offers several advantages that strongly impact both the reactor chamber design and the accelerator requirements. For example, the presence of a gas such as Ne can provide protection of the chamber wall from x-rays and energetic ions. A liquid Li liner may also be used at temperatures that produce a high vapor pressure, without any external gas pumping.

There would be additional advantages in reactor design if a magnetically pinched mode of propagation is feasible. This would allow small (cm diameter) entry ports, larger beam currents (fewer multiple beams), and reduced requirements on emittance.

Three options for gas transport have been identified. First, there is the converging case (as in vacuum). Two principal problems which appear here are (1) poor focusing on target due to self-fields and gas scattering (which places an upper bound on gas pressure) and (2) the growth of magnetic filaments, which can severely degrade the emittance, resulting in a large spot size at the pellet. The filamentation problem is intrinsic for a cold beam which is not magnetically stiff. Filamentary growth is especially damaging when the beam radius is large because an increment in transverse velocity spread is weighted by the radius in determining emittance growth. It appears that this problem can only be overcome by the use of a large number of multiple beams.

The beam may also be injected with a small initial radius. In this case there may still be filamentary growth, but it is limited in magnitude and is not expected to increase the emittance to a degree that would prevent pinching. However, much of the pulse is lost because of the rapid initial expansion.

The third approach is to employ a pre-existing plasma current ($I_{ex} \approx$ 10 kA), which holds the ion beam together and thereby aids the buildup of the self-pinch field. (Our requirements on plasma current density are much more modest than the electron beam fusion proposal for transport in plasma channels.[2]) This approach appears very promising; radii at the pellet of order 1-3 mm are predicted with reasonable beam parameters and little loss of the pulse nose. The plasma current is easily generated by propagating relativistic electron beams in gas though the chamber in the reverse direction. Stable propagation of such electron beams in 5 torr neon and 2 torr nitrogen has been demonstrated.[3]

In the body of this paper we discuss calculations of the ion beam envelope in these three propagation modes. A brief discussion of instability considerations is also given.

## II. PROPAGATION MODEL

To predict the beam size and pulse shape as the heavy ions impinge upon the target, several codes have been developed which follow the evolution of the beam as it traverses a gas-filled reactor. In general, the plasma channel (either pre-existing or beam-generated) as well as the beam will go through rapid changes during the passage of the ions, and the evolution of the beam and the channel must be followed simultaneously and self-consistently in both time and space. We present here the model and results of a 1-D calculation, although some results from a 2-D code and a particle simulation code will also be briefly mentioned. In general, a number of beams are injected simultaneously; in the following the propagation of only one of these beams is considered. With suitable injection symmetry, the interaction of the beams near the target should be negligible.

A special feature of the heavy ion beam propagation is that the effective charge of the heavy ions $Z_i^{eff}$ changes continuously with z, the distance from the entrance port. The process of stripping by the background gas is calculated classically assuming that each bound electron in the ion is confined by an independent potential well. The effective charge of the beam ion is given by

$$Z_i^{eff}\,(z) = Z_i - \sum_n \ell_n\, e^{-z\sigma^{(n)} n_g} \qquad (1)$$

where $Z_i$ is the atomic number of the heavy ion, $\ell_n$ is the number of electrons in the $n^{th}$ shell of the ion, $n_g$ is the gas atom density, and $\sigma^{(n)}$ is the cross section for ionizing an electron in the $n^{th}$ shell.

The parameter which best characterizes beam motion is the rms radius $R(\tau, z)$, which is a function of both z and $\tau = t - z/\beta c$ (the time from the head of the pulse). The development of the rms radius can be described by an envelope equation:[4]

$$\frac{\partial^2 R}{\partial z^2} + \frac{\overline{k_\beta^2 r^2}}{R} - \frac{\varepsilon^2}{R^3} = 0. \qquad (2)$$

The beam evolves under two opposing effects: the transverse thermal spread, characterized by emittance $\varepsilon = R\, v_{th}/\beta c$, which causes the beam to expand, and magnetic pinching characterized by the profile averaged betatron frequency $\overline{k_\beta^2 r^2}$.

The emittance $\varepsilon$ can be shown to increase only from scattering if $k_\beta$ is independent of the radial variable r, or if the beam pulsates in a self-similar manner. Under conditions which deviate from this ideal, the emittance changes (due to anharmonic effects) in a way for which no simple rigorous description is known. However, a phenomenological expression has been discovered which reproduces effects observed in particle simulations (in both the pinched mode as well as the converging beam mode). The change of emittance is described by the following equation:

$$\frac{\partial(\varepsilon^2)}{\partial z} = K n_g R^2 - 0.5\,\frac{\overline{k_\beta^2 r^2}}{\varepsilon}\,R^3\,\frac{\partial^2 R}{\partial z^2}\quad . \tag{3}$$

The coefficient K contains the cross section information for gas-ion elastic scattering, and the coefficient (.5) has been introduced to yield agreement with simulation.

To calculate $\overline{k_\beta^2 r^2}$, we first note that the contributions from the beam-generated fields and any externally imposed plasma currents are additive. Characterizing the imposed field by a current $I_{ex}$, with a Bennett profile of constant scale radius $R_{ex}$, and assuming that the heavy ion beam has a parabolic profile, we obtain the contribution

$$\left(\overline{k_\beta^2 r^2}_{ex}\right) = \left(\frac{Z_i^{eff} e\, I_{ex}}{\beta\gamma\, Mc^3}\right) G\left(\frac{3R^2}{R_{ex}^2}\right) \tag{4a}$$

where

$$G(\lambda) = 2\left\{1 + \frac{2}{\lambda} - \frac{2(\lambda+1)}{\lambda^2}\,\ln(\lambda+1)\right\} \tag{4b}$$

and $\gamma Mc^2$ is the relativistic energy of the heavy ion. To calculate the buildup of the self-field $\overline{k_\beta^2 r_{int}^2}$, for beam particle current $I_{bo}/e$ the following circuit equation is obtained:

$$\frac{\partial}{\partial\tau}\left(\frac{\overline{k_\beta^2 r_{int}^2}}{R^2}\right) + \frac{1}{\tau_m}\,\frac{\left(\overline{k_\beta^2 r_{int}^2}\right)}{R^2} = \left(\frac{eZ_i^{eff^2} I_{bo}}{\beta\gamma Mc^3}\right)\frac{1}{R^2\tau_m} \tag{5a}$$

where the magnetic decay time is (for a parabolic profile)

$$\tau_m = \frac{9}{4}\,\frac{\pi\sigma R^2}{c^2}\quad . \tag{5b}$$

The high-Z beam ions will tend to drive a forward electron flow, or anti-pinch current, through classical momentum exchange processes which are neglected in Eq. (5a). These electron drag effects by the beam are negligible compared to the gas-ion collisions in our examples unless the electron temperature becomes very high, at which point the magnetic field is frozen anyway.

The rate of buildup of the self-fields depends on the evolution of the plasma channel. In the present formulation, the plasma channel is characterized only by the scalar conductivity $\sigma$. Two distinct limits of conductivity generation are recognized. In the case of the converging beam, the beam current density is relatively low over most of its path, thus the gaseous medium remains predominantly un-ionized. Conductivity is therefore proportional to the plasma density $n_e$ and ionization by direct ion impact is the principal mechanism for electron production. In the case of a pinched beam of small radius, or the converging beam in the neck region (close to the target), the picture is radically different. Here, the high concentration of beam density leads to a highly ionized medium. The conductivity is then closely approximated by the Spitzer formula for a fully ionized plasma, which is insensitive to the electron density, but depends on the electron temperature and the effective charge state of the gas ( $\sigma \propto T_e^{3/2}/Z_g^{eff}$ ). With a mm-sized beam, direct heating by the beam ions together with joule heating can produce plasma electron temperature in the range $10^2$ - $10^3$ eV. However, in this regime there is also very rapid electron thermal conduction in the radial direction which tends to lower the plasma temperature on axis. In addition, the gaseous medium also becomes highly stripped. These are rather complicated effects, and we have found it necessary to resort to a 2-D model to follow the channel evolution in detail. Here we present a 1-D model which attempts to incorporate the above described physical effects to determine electrical conductivity.

The electrical conductivity is given by the expression

$$\sigma = \frac{e^2}{m} \frac{n_e}{\nu_m} \ , \tag{6a}$$

$$\nu_m = 2.0 \times 10^{-5} \ (\bar{\varepsilon})^{-3/2} \ n_e \ Z_g^{eff} \ + \nu_{mn} \left( n_g - \frac{n_e}{Z_g^{eff}} \right) , \tag{6b}$$

where $\bar{\varepsilon}$ is the average plasma energy (in eV) and $\nu_{mn}$ is the momentum transfer rate per neutral atom. To calculate $n_e$, we again assume an independent electron model for the gas atom, and the rate of ionization from the $i^{th}$ electronic state is given by:

$$\frac{dn_e^{(i)}}{d\tau} = \frac{1}{n_g Z_g}\left(\frac{dU}{d\tau}\right)\left(n_g - n_e^{(i)}\right)\frac{1}{W^{(i)}} \quad , \tag{7}$$

where $Z_g$ is the atomic number of the gas, and $W^{(i)}$ is the energy per ion pair. U is the total energy per unit volume deposition in the medium, including contributions from both direct collisions and joule heating:

$$\frac{dU}{d\tau} = \left(\frac{I_{bo}}{e\pi R^2}\right) n_g \, S + \frac{Z_i^{eff^2}}{\sigma}\left(\frac{I_{bo}}{\pi R^2}\right)^2 \quad , \tag{8}$$

where S is the stopping power.

$Z_g^{eff}$, the effective charge state of the gas, is modeled with a simple analytic form which reduces to unity when $n_e << n_g$, and approaches $n_e/n_g$ when $n_e >> n_g$. The kinetic energy of the plasma electrons is just the total energy deposited minus the internal energy for ionization. To model thermal cooling, we assume that this process is so rapid that instant energy equilibration is established across the plasma channel. The temperature is obtained by performing an average in the radial variable r. With $n_e$, $Z_g^{eff}$, and $\bar{\varepsilon}$ thus obtained, the conductivity model is complete.

## III. RESULTS OF TRANSPORT STUDIES

Using the propagation model described in the previous section, we have made a numerical study to see if the beam in each of the three different propagation modes could satisfy focal spot size requirements. In the present report, we concentrate on one 20 GeV uranium beam in a multiple beam system with an energy of 1 MJ, 100 TW power[1] and 3 mr-cm emittance. In order to satisfy stability conditions, this pulse may be further subdivided to reduce current, with proportionate reduction of emittance per beamlet. We give below a brief summary of our results. For typical parameters, Figures 1-3 plot the radius R as a function of z and $\tau$ for these modes respectively, and Table I contains the results from a parameter survey.

Converging Mode - Behind the converging beam concept is the assumption that in this mode, the heavy ion trajectories are nearly ballistic. In order for this scheme to work, scattering by the gaseous background and the disruption caused by self-fields must be kept to a minimum. Our code results indicate that the latter conditions are quite difficult to achieve. In fact, with typical HIF beam parameters,[1] we have not been able to predict beam radii less than 2.5 mm. We have also made preliminary studies with a particle simulation code, and the degradation of the emittance predicted by the simulation code is in good agreement with the 1-D envelope model calculations.

Self-Focused Mode - In this mode of propagation, the beam is injected with small radius and its head expands as it traverses the reactor. The key issue then is whether there is sufficiently fast buildup of self-fields to pinch the latter portion of the pulse to an acceptably small radius. Our code results indicate that the development of the self-pinch is marginal. Furthermore, the results depend very sensitively on the calculation of the electrical conductivity. It was in considering this mode of propagation that we found it necessary to resort to a 2-D model, the 1-D model being inadequate for the inclusion of thermal conduction. We have found that when a self-focused beam propagates a significant portion of the beam front is lost.

Pinched Propagation in a Pre-existing Current Channel - We found that the presence of a guiding current allows beams of the required size at target, with modest emittance requirements. A typical example is a beam with 5 kA of 20 GeV $U^+$ with initial beam emittance of 3 mrad-cm. The reactor chamber has a radius of 10 meters, and is filled with 5 torr of neon (corresponding to the propagation window of a relativistic electron beam). An initial plasma current of 10 kA with a Bennett radius 1 cm is assumed. The profile of R as the beam propagates is plotted in Figure 3. Figure 4 gives a more detailed head-to-tail profile of the pulse at z = 10 meters for the same run. It is seen that the major part of the beam is pinched to less than 0.15 cm radius. For comparison, we have plotted on the same graph the corresponding pulse profile without the initial plasma current.

It is interesting to note that with the aid of a guide current of only 3 $kA/cm^2$, sufficient self-field was generated to provide $\sim$ 200 $kA/cm^2$ ion current, as required to pinch the beam. In Table I, we give the rms radius at the head, the middle and the tail of the pulse as the beam hits a target located 10 m from the porthole for various beam and chamber parameters. At the "standard" parameters, the beam is seen to pinch to an acceptable radius. This acceptable radius could be maintained by lowering the beam current somewhat as is seen in the two cases of Group II. Group III corresponds to other reactor environments which are known to permit stable propagation of the guiding electron beam. Acceptable beam radius is achieved in all cases except in Helium where there is insufficient self-pinch because the ion beam is not adequately stripped. Increase of the focal spot size as the initial emittance is increased is shown in Group IV. The incoming beam radius of 2 mm is close to being "matched." An initial radius which is either too small or too large will lead to a degradation of the beam as is seen in Group V. Finally in Group VI, we show the effect of varying the initial plasma current.

TABLE I
RMS Radius at Target ($z = 10$ m)

| | RMS Radius (mm) | | |
|---|---|---|---|
| | Head | Mid | Tail |
| I. "standard" parameters* | 3.51 | 1.35 | 1.28 |
| II. $I_{U^+} = 2.5$ kA | 3.51 | 1.40 | 1.25 |
| $I_{U^+} = 1$ kA | 3.51 | 2.07 | 1.37 |
| III. 10 torr Ne | 3.35 | 1.28 | 1.23 |
| 2 torr Ar | 3.45 | 1.35 | 1.25 |
| 1 torr Xe | 3.20 | 1.28 | 1.20 |
| 10 torr He | 4.89 | 3.17 | 2.73 |
| IV. $\varepsilon = 2$ mrad-cm | 2.33 | 1.08 | 1.07 |
| $\varepsilon = 4$ mrad-cm | 4.93 | 1.64 | 1.67 |
| $\varepsilon = 5$ mrad-cm | 6.58 | 2.71 | 2.09 |
| $\varepsilon = 6$ mrad-cm | 8.50 | 4.50 | 3.00 |
| V. $R_0 = 1$ mm | 8.86 | 2.59 | 1.88 |
| $R_0 = 3$ mm | 2.67 | 1.57 | 1.57 |
| $R_0 = 4$ mm | 3.12 | 2.00 | 2.01 |
| $R_0 = 5$ mm | 3.82 | 2.52 | 2.49 |
| VI. $I_{ex} = 30$ kA | 2.11 | 1.26 | 1.22 |
| $I_{ex} = 100$ kA | 1.53 | 1.19 | 1.17 |
| $I_{ex} = 0$ | 75.3 | 15.8 | 2.2 |

*"Standard" parameters - $I_{bo}$ - 5 kA, $\varepsilon = 3$ mrad-cm, $R_0 = 2$ mm, 5 torr Neon. $I_{ex} = 10$ kA in channel with $R_{ex} = 1$ cm

## IV. INSTABILITY LIMITATIONS

Instabilities place limits on the ion beam parameters and on the gas pressure regimes where transport and focusing can be successful. Experience with self-focused electron beam propagation, for example, shows that operation in a pressure window around a few torr is sufficient to avoid two-stream and resistive hose modes.[3]

In the case of heavy ion beams, a two-stream interaction with the background plasma electrons could disrupt beam propagation and drive plasma currents which could defocus the beam.[5] This instability is suppressed by a combination of beam temperature ($\Delta v_\parallel$ is the parallel velocity spread) and plasma collisional effects.[6] The growthrate of the most unstable mode at $k_\parallel = \omega_{pe}/\beta c$, $k_\perp = 0$ is given approximately by $\omega_i = \omega_{pb}\left[\omega_{pe}/(2\gamma^2\nu_m)\right]^{1/2} - \omega_{pe}\,\Delta v_\parallel/\beta c$. Setting $\omega_i = 0$ and solving for the pressure p above which the two-stream mode is stabilized we find for a $U^{238}$ beam, assuming full ionization,

$$p^{3/2}_{(torr)} = 1.5 \times 10^{-14} \frac{Z_i^{eff^2} \; I_{bo}(amps)\left(Te(eV)\right)^{3/2}}{\beta\left(R(cm)\right)^2 \gamma^3 \left(\frac{\Delta v_{\shortparallel}}{\beta c}\right)^2 \left(Z_g^{eff}\right)^{5/2}} \tag{9}$$

Assuming $\Delta v_{\shortparallel} / \beta c \approx .01$, we find that both the converging beam mode near the focal point where the two-stream is potentially the strongest, and the pinched modes are two-stream stable for $p \gtrsim 2$ torr.

Potential disruption of the ion beam by filamentation is a concern for HIF (especially for the high pressure propagation modes). This instability is treated in detail elsewhere;[7, 8] the main conclusions of that study are summarized here.

a) The maximum amplitude (A) of mode growth is bounded by the cold beam limit, which is determined by magnetic rigidity over chamber radius L. For a straight beam of small initial radius, this limit is

$$A \le \exp\left(\frac{\omega_{pb}L}{c}\right), \tag{10}$$

where $\omega_{pb}$ is the beam plasma frequency. For a converging beam, the analogous result is

$$A \le (1 - z/L)^{-\frac{\omega_{pb}L}{c}}, \tag{11}$$

with $\omega_{pb}$ evaluated using the beam density at the wall.

The straight beam limit is exorbitant, but it is greatly reduced by consideration of thermal spread (see below). For the converging case, this limit appears to be a realistic estimate of growth and $\omega_{pb}L/c \lesssim 3$ is taken to be a criteria for safety. In dimensional terms

$$\frac{\omega_{pb}L}{c} = (20)\left(\frac{Z_i^{eff}}{60}\right)\left(\frac{.5}{\beta\gamma}\right)^{1/2}\left(\frac{I_{bo}}{10\ kA}\right)^{1/2} \frac{L/R_o}{100}\left(\frac{238}{M}\right)^{1/2}. \tag{12}$$

A 20 GeV, 100 TW, $U^{238}$ pulse would therefore need to be divided into about twenty "beamlets" for safety.

b) Incorporation of transverse thermal spread of sufficient magnitude to suppress filamentation causes much of the pulse to be lost through free expansion. If the pulse radius is small at the chamber wall then conductivity can be roughly independent of z. In this case growth is limited by a factor

$$A \le \exp(6/\eta) \tag{13}$$

where $\eta/2$ is the fraction of pulse lost by free expansion (the fraction which is not lost propagates as a self-pinch). The increase in emittance should be much reduced for the filamenting pinched beam because its radius is small, i.e. $\Delta\varepsilon \approx R\Delta\theta$.

A converging beam generates conductivity proportional to its density. If pinching is to occur in the vicinity of the pellet, the permissible thermal spread is fixed at a low value--this inhibits filamentation near the pellet. However, it is found that the beam must then be relatively "cool" near the chamber wall and mode growth would be approximately given by the limit Eq. (11).

c) The use of a pre-existing magnetic field prevents the loss of pulse by free expansion. Equation (13) still applies with $\eta$ determined by the pulse properties in the absence of the pre-existing field.

## REFERENCES


1. See for example the review paper T. F. Godlove and D. F. Sutter, "The U.S. Program in Heavy Ion Beam Fusion" IAEA-CN-37-V-5 (1978).

2. P. A. Miller, R. I. Butler, M. Cowan, J. R. Freeman, J. W. Poukey, T. P. Wright, and G. Yonas, "Propagation of Pinched Electron Beams for Pellet Fusion," Phys. Rev. Lett., 39. No. 2, July 11, 1977.

3. R. J. Briggs, J. C. Clark, T. J. Fessenden, R. E. Hester, and E. J. Lauer, in Proceedings of the 2nd International Topical Conference on High Power Electron and Ion Beam Research and Technology (Cornell University, Ithaca, NY. 1977). Vol. I, p. 319

4. E. P. Lee and R. K. Cooper, Particle Accelerators 7, 83 (1976).

5. R. N. Sudan, Phys. Rev. Lett. 37, 1613 (1976).

6. E. P. Lee, F. W. Chambers, L. L. Lodestro and S. S. Yu in Proceedings of the 2nd International Topical Conference on High Power Electron and Ion Beam Research and Technology (Cornell University, Ithaca, NY. 1977). Vol. I, p. 381.

7. E. P. Lee, "Filamentation During Final Transport in a High Pressure Gas," submitted to the Proceedings of Heavy Ion Fusion Workshop, Argonne National Laboratory, September 19-26, 1978.

8. E. P. Lee, S. S. Yu, F. W. Chambers, H. L. Buchanan and M. Rosenbluth, "Filamentation of a Heavy Ion Beam in a Reactor Vessel," to be submitted to Physics of Fluids.

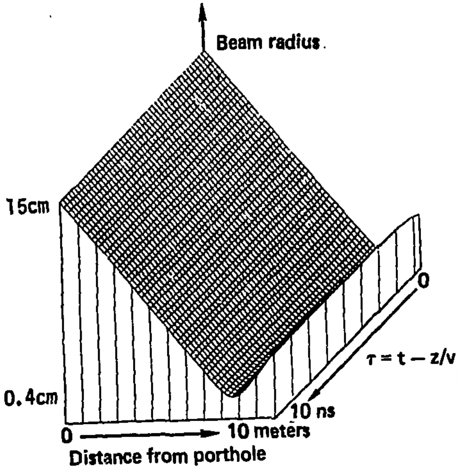


Fig.1 Converging Beam Mode.
Beam parameters: *20 GeV Uranium*, $I_{bo}$ = 250 A,
$\varepsilon$ = .7 mrad-cm in 1 torr Neon.
Minimum average radius at neck is 3 mm.

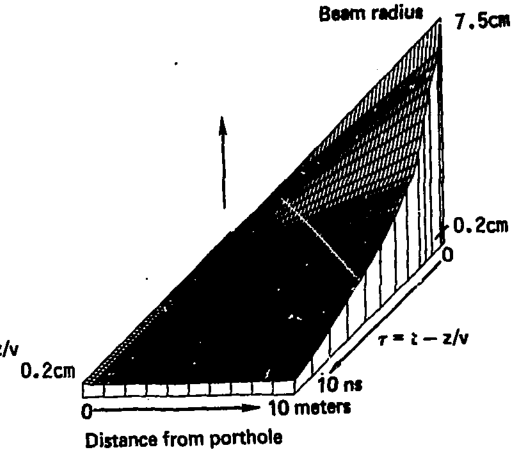


Fig.2 Self-Focused Mode.
Beam parameters: 20 GeV Uranium, $I_{bo}$ = 5kA
$\varepsilon$ = 3 mrad-cm, $R_0$ = 2 mm in 5 torr Neon

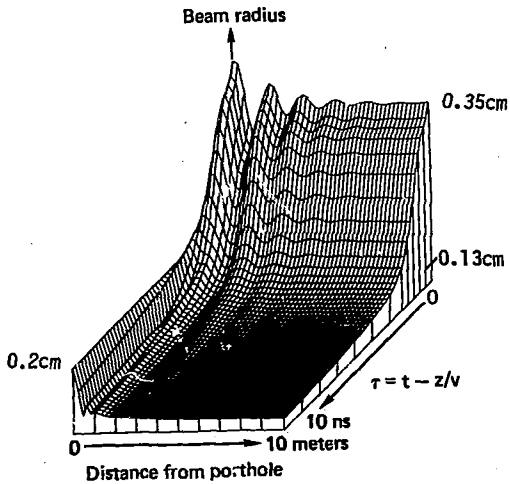


Fig.3 Pinched Beam in 3 kA/cm$^2$ Current Channel.
Beam parameters are the same as in Fig. 2.
$I_{ex}$ = 10 kA, $R_{ex}$ = 1 cm.

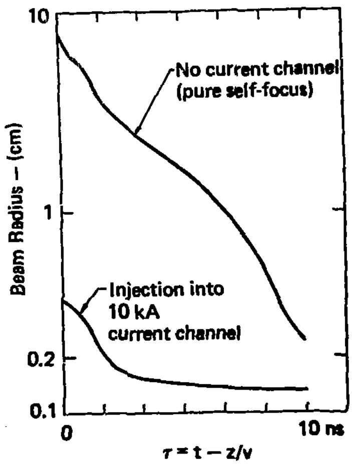


Fig.4 Pulse Profile at Target.
Beam parameters are the same as in Fig. 2 and 3.