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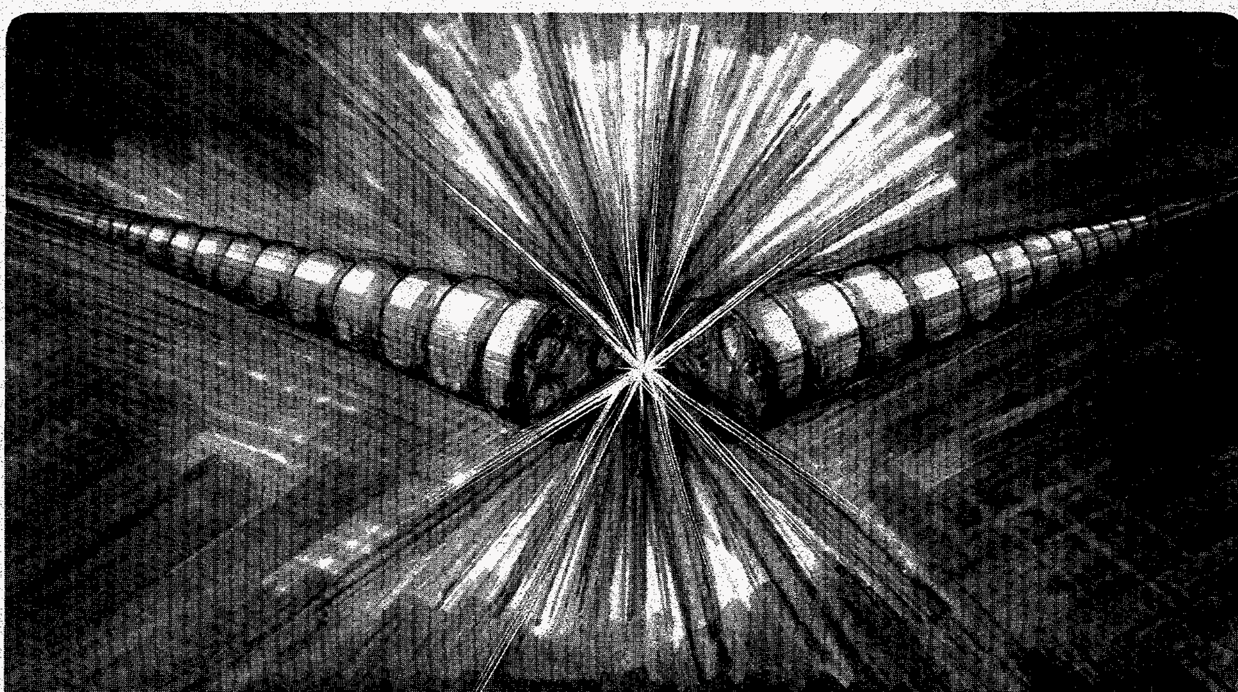

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Accelerator and Fusion Research Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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HEAVY ION BEAM TRANSPORT IN AN INERTIAL CONFINEMENT FUSION REACTOR *

N. Barboza
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Abstract

A new code, `bimc`, is under development to determine if a beam of heavy ions can be focused to the necessary spot-size radius of about 2 mm within an inertial confinement reactor chamber where the background gas densities are on the order of $10^{14} - 10^{15}\ cm^{-3}$ Lithium (or equivalent). Beam transport is expected to be strongly affected by stripping and collective plasma phenomena; however, if propagation is possible in this regime, it could lead to simplified reactor designs.

The beam is modeled using a 2 1/2 D particle-in-cell (PIC) simulation code coupled with a Monte Carlo (MC) method for analysing collisions. The MC code follows collisions between the beam ions and neutral background gas atoms that account for the generation of electrons and background gas ions (ionization), and an increase of the charge state of the beam ions (stripping). The PIC code models the complete dynamics of the interaction of the various charged particle species with the self generated electromagnetic fields.

Details of the code model and prelimenary results are presented.

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1.0 Introduction

As a beam of heavy ions traverses an inertial confinement fusion reactor chamber between subsequent microexplosions it will, in some scenarios, encounter background gas densities on the order of $10^{14} - 10^{15}$ cm^{-3} Lithium (or equivalent). Successful beam propagation in this regime could result in simpler reactor designs eliminating the need for sophisticated pressure reduction mechanisms and neutralization schemes.

Collisions of the beam ions with the background gas will result in beam stripping, that is an increase in the charge state of the beam ions due to the loss of electrons, and in ionization of the background gas. Capture, the process whereby a beam ion picks up an electron, is highly unlikely at the velocities under consideration here. The repulsive electric force dominates over the magnetic pinch force that results from the beam current, and defocuses the beam. However the electrons, generated from both stripping and ionization, may effectively be confined within the beam, thereby providing the necessary charge neutralization to offset the damaging effects of the stripping of the beam.

Because the collisions result in a highly random distribution of beam charge states, analytic methods prove inadequate for completely describing the dynamics of the beam. We therefore use a particle-in-cell (PIC) simulation to follow the beam ions, electrons and background gas ions as they intereact with the self-generated electromagnetic fields. In addition, we use a Monte Carlo (MC) method to simulate the randomness of the collisions.

In the subsequent sections we shall provide details of both the PIC and MC models used in developing the `bimc` computer code for analysing beam transport, and present some prelimenary results of simulations with this code. These results show that a 2.1 kA beam of Hg ions can be focused to the necessary spot through a background gas density of 10^{14} cm^{-3} and possibly higher.

2.0 Particle-in-cell method

We can reduce the geometry of the problem under consideration by assuming that the beam is axisymmetric. The reactor chamber then may be treated as a large open-ended cylinder with a conducting wall at a radius that is several times that of the beam (for computational reasons the radius of the chamber is taken to be three times the beam radius; in reality, within the chamber the closest "structure", the liquid jets, are about five or six beam radii away), and the beam travels along the central axis of the cylinder. The PIC method, thoroughly described by Birdsall and Langdon [1], requires that we impose a spatial grid on this system; in this case a 2 D, (r,z), grid, where r is along the radius of the cylinder and z along it's axis. The particles, that is the beam ions, electrons and gas ions, can have any position, r, z, and velocity, v_r, v_θ, v_z; all three velocities are retained in order to advance the particles. However, the fields, E_r, E_z, B_θ (only the transverse-magnetic field set is retained since the beam does not spin), and the current density sources, J_r, J_z, are known only at specific spatial grid locations. A temporal grid is also imposed on which the electric fields and positions of the particles are determined at every time-step, while the velocities, magnetic field, and current densities are offset by a half time-step. The Courant-Friedrichs-Levy condition imposes a limit on the relation between the time-step, Δt, and the spatial grid divisions, Δr and Δz :

$$(c\Delta t)^2 \left(\frac{1}{\Delta z^2} + \frac{1.2}{\Delta r^2} \right) < 1 \; . \tag{1}$$

We start by specifying the initial positions, velocities and fields (from an analytical approximation for a beam in a pipe). We then use a second-order accurate "leap-frog" algorithm to advance these various quantities. We first advance the positions of the particles across a time-step by using the velocities at the half-time-step:

$$\mathrm{r}^{n+1} = \mathrm{r}^n + \mathrm{v}^{n+1/2} \Delta t \; , \tag{2}$$

where r is the position of the particle and v is it's velocity; the superscripts denote a particular location on the temporal grid. Although the axial position is advanced in a straight forward manner, the radial position is advanced using a cartesian system to avoid complications at small radii. In such a scheme, developed by Boris [2], the particle is originally located at $x = r^n$ and $y = 0$; these positions are then advanced using $v_x = v_r^{n+1/2}$ and $v_y = v_\theta^{n+1/2}$, and finally the new radius is calculated via $r^{n+1} = \sqrt{x^2 + y^2}$.

The next step is to calculate the current density from the velocities and charges of the particles:

$$\mathbf{J}_{j,k}^{n+1/2} = \frac{\sum_i \left(\mathbf{v}_i^{n+1/2} q_i\right)_{j,k}}{\Delta V} , \tag{3}$$

the subscripts denote a particular spatial grid location. As mentioned above, the current densities are known only at specific grid points, while the particles can have any position in the chamber. Therefore we need to "weight" the charge-velocity product given in the parenthesis to a grid point, j, k, where $\mathbf{v}$, as before, is the velocity and q is the charge of the particle. We use a bilinear r^2, z scheme to "weight" the particles to the grid. The sum over i indicates that only those particles that are within an annular volume element ΔV around the grid location, j, k, contribute to the current density.

Next we use Maxwell's equations to advance the fields:

$$\begin{aligned} \mathbf{E}_{j,k}^{n+1} &= \mathbf{E}_{j,k}^{n} + \frac{\Delta t}{\mu_0 \epsilon_0} (\nabla \times \mathbf{B})_{j,k}^{n+1/2} - \frac{\Delta t}{\epsilon_0} \mathbf{J}_{j,k}^{n+1/2} \\ \mathbf{B}_{j,k}^{n+3/2} &= \mathbf{B}_{j,k}^{n+1/2} - \Delta t (\nabla \times \mathbf{E})_{j,k}^{n+1} \end{aligned} , \tag{4}$$

where the curl operator needs to be appropriately differenced, and the current density is given by (3).

Finally we need to advance the velocities using the Lorentz force equation:

$$\mathbf{u}^{n+3/2} = \mathbf{u}^{n+1/2} + \frac{q\Delta t}{m} \left[\mathbf{E}^{n+1} + \left(\frac{\mathbf{u}}{\gamma} \times \mathbf{B} \right)^{n+1} \right] , \tag{5}$$

where $\mathbf{u} = \gamma \mathbf{v}$, and γ is the relativistic factor. As was the case with calculating the current density, we know the fields at the specific grid points, however the positions of the particles are arbitrary; therefore we again use a bilinear r^2, z scheme to "weight" the fields to the particle locations. The axial velocity of the beam ions is assumed to remain constant, therefore only the transverse velocity needs to be advanced. If we assume that γ is also a constant, then the cross product in (5) simply becomes $v_z B_\theta$. However, for the electrons these assumptions are not valid and both the axial and transverse velocities need to be advanced using the complete relativistic equation. The coupling between the two velocity components via the cross product presents complications. An elegant solution is to decouple the electric and magnetic forces [2]. We first use half the electric force to advance the velocity, then use the magnetic force to rotate the velocity and finally use the remaining half of the electric force to complete the advance.

Using equations (2), (4) and (5) we can successfully advance the particles' postitions and velocities and the electric and magnetic fields across a single time-step. We repeat this process every time-step, thereby simulating the transport of the beam through the chamber.

3.0 Monte Carlo method

So far we have discussed a method for moving the particles through the chamber; no mention has been made about the collisions that the beam ions have with the background gas. As mentioned above these collisions can result in stripping where the charge state of the beam ion increases, and in ionization where a neutral background gas atom gets ionized; both processes generate electrons. The MC method, described by Birdsall [3], relies on "throwing" random numbers to decide if certain events will occur based on the probabilities of these events.

Because the background gas consists of light ions, and the beam is fast and heavy, any collision of a beam ion with a background gas atom will, in general, result in ionization of the gas. The beam ion can then either strip while it ionizes the background gas or not. We characterize the former process by the stripping cross section, σ_s, and the latter by the ionization cross section, σ_i. We then define the total cross section as $\sigma = \sigma_s + \sigma_i$, and the collision frequency, ν_c, as:

$$\nu_c = \sigma n_g v_z \ , \tag{6}$$

where n_g is the density of the background gas and v_z is the axial velocity of the beam ion.

Now the probability that a beam ion will undergo any type of collision is given by:

$$P = 1 - \exp(-\nu_c \Delta t) \ , \tag{7}$$

To determine if a particular beam ion undergoes a collision, we "throw" a random number ξ that is uniformly distributed on the interval $[0, 1]$. Then if $\xi \leq P$ we conclude that the beam ion has collided. We do this for every beam ion in every time-step. The drawback of this method is that it allows each beam ion to undergo only one collision per time-step. Vahedi and Surendra [4] found that the following limit on Δt results in a 1% error from "missed" collisions:

$$\nu_c \Delta t < 0.1 \ . \tag{8}$$

After we have concluded that a particular beam ion has collided, we create a stationary gas ion and an almost stationary electron (except for a small, $\sim 100 \ eV$, transverse energy that results from the ionization process) at the location of the beam ion. We now need to determine if the beam ion strips. To do this we first calculate the relative stripping cross section given by $S = \sigma_s / \sigma$. We then "throw" another random number ξ. If $\xi \leq S$ then the beam ion has undergone a stripping collision, and we increment the charge state of the ion and create an electron at the location of the beam ion. The velocity of this electron is almost equal to that of the beam ion from which it was ionized.

The above procedure is repeated for every beam ion at every time-step, and is conducted immediately after the particle's positions are advanced using (2).

In order to accurately follow the particles using the "leap-frog" scheme described in section 2.0, we require that the product of the largest frequency of interest and the time-step be less than about 0.2; this reduces the phase error to about $3 \times 10^{-4} \ rad$ per time-step [1]. As the beam ions collide with the background gas, the density of electrons, and hence their plasma frequency, ω_p, increases. Therefore we impose the following limit on the time-step:

$$\omega_p \Delta t < 0.2 . \tag{9}$$

4.0 Results

We present here the results of a typical simulation using the `bimc` code described above. We start with a 1 m long, 8 cm radius, cylindrical beam with the Kapchinsky-Vladimirsky distribution and an edge emittace of 19 $\pi mm - mrad$. An artificial lens, located 4 m away from the pellet, imparts a radial "kick" to the beam ions as they cross the lens-plane so as to focus them onto the pellet (this simulates the effect of the final focus system). The head of the beam is initially slightly behind the lens-plane. The beam is composed of Hg^+ ions, with an axial velocity of 0.32 c, and an initial current of 2.1 kA. The background gas is 10^{14} cm^{-3} Li. This gas only exists in the region between the lens-plane and the pellet. These parameters are typical for a heavy-ion driven inertial confinement fusion facility, see for example Lee [5].

The single electron stripping cross sections, σ_s, for Hg colliding into Li, calculated using a semi-classical approach based on a modified version of the Bohr theory [6], range from $\sim 10^{-17}$ cm^2 for Hg^+ to $\sim 10^{-23}$ cm^2 for almost fully stripped mercury. Similarly the ionization cross sections, σ_i, go from $\sim 10^{-17}$ cm^2 to $\sim 10^{-14}$ cm^2.

The simulation was done using 13776 beam ions. Initially the time-step was set at 7.5 ps; towards the end, when the head of the beam was about 20 cm away from the target, the time-step was shortened to 4.5 ps because of the limit on the plasma frequency. The total run-time was $\sim$ 14 hrs on a SUN Sparc10 CPU.

Figure 1 shows the state of the beam at various time intervals (superimposed on the same graph) as it traverses the chamber. The first "snap-shot" is at 0 ns. The beam is initially slightly behind the artificial lens located at the 4 m point (the target is at 0 m). The next "snap-shot" is at $\sim$ 12 ns. At this point all of the beam has passed through the lens. The next three frames are at $\sim$ 25, 37, and 49 ns

respectively. The last of these is at the point where the mid-plane of the beam has just crossed the target. The "waist" of the beam occurs 10 cm beyond the target and is $\sim$ 2.5 mm in radius, slightly larger than the spot-size required for typical geometries. At the end the average charge state of the beam ions is 2^+, with some ions at 7^+; it is these higher charge state ions that contribute to the slight "halo" of particles around the outside edge of the beam.

Figures 2 and 3 show the electrons and the background gas ions at $\sim$ 49 ns, the time when the beam has reached the target. As can be seen, most of the electrons get carried along and are concentrated in the vicinity of the beam close to the target. It is these electrons that provide the necessary neutralization of the beam. By contrast, the background ions, being more massive than the electrons, have only a slight radial motion away from the beam due to the repulsive forces of the beam, but in general remain where they were created.

The effect of this neutralization can best be seen by looking at the fields generated by the beam. If we allow the beam described above to propagate through a completely evacuated chamber, i.e. no stripping or ionization, then the edge radial electric field and the azimuthal magnetic field at the mid-pland of the beam when it has just crossed the target will be 7.6×10^7 V/m and 7.5×10^{-2} T respectively. The fields at the same point for a beam that passed through a background gas density of 10^{14} cm^{-3} are 1.2×10^7 V/m and 2.8×10^{-2} T. As can be seen, the radial electric field gets reduced by greater than a factor of 6, signifying substantial charge neutralization. There is also some current neutralization; the magnetic field is reduced to slightly more than a third it's unneutralized value.

5.0 Conclusion

The simulation shows that a background Li gas density of 10^{14} cm^{-3} does not seriously impede our ability to focus the beam to the $\sim$ 2 mm spot size radius required. There does not seem to be any reason why slightly higher densities, $\sim$ 10^{15} cm^{-3} where scattering of the beam ions is still not important, would not also work since the number of electrons generated would be significantly higher providing for better neutralization. This will need to be verified through simulations.

The fact that the beam generates enough neutralizing electrons through collisions with the background gas at these densities removes the necessity for complicated schemes such as the injection of co-moving electrons along with the beam or pre-ionization of the background gas in order to introduce electrons into the beam. Allowing for higher background gas densities also means that one can reduce the stringent requirements on chamber pumping, or other mechanisms, for lowering the pressure between target microexplosions that are typically ~ 0.1 s apart. Therefore this mode of neutralized beam transport in higher pressure chambers provides for simpified reactor designs.

Details of the PIC-MC simulation models, and the method for calculating the ionization and stripping cross sections are developed in a series of HIFAR Notes, Nos. 397, 432, 437, 442, 444, and 446, available through Lawrence Berkeley National Laboratory, Accelerator and Fusion Research Division, Heavy Ion Fusion Accelerator Research Group.

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List of Figures

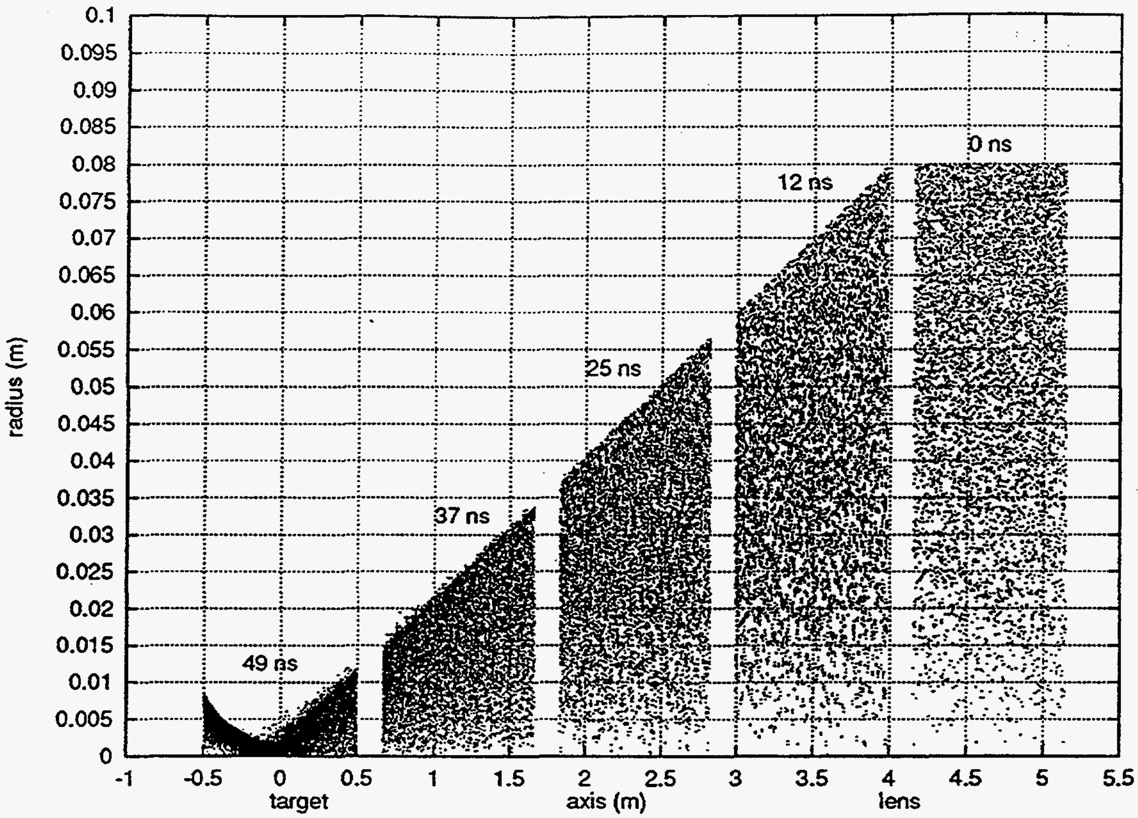

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Figure 1

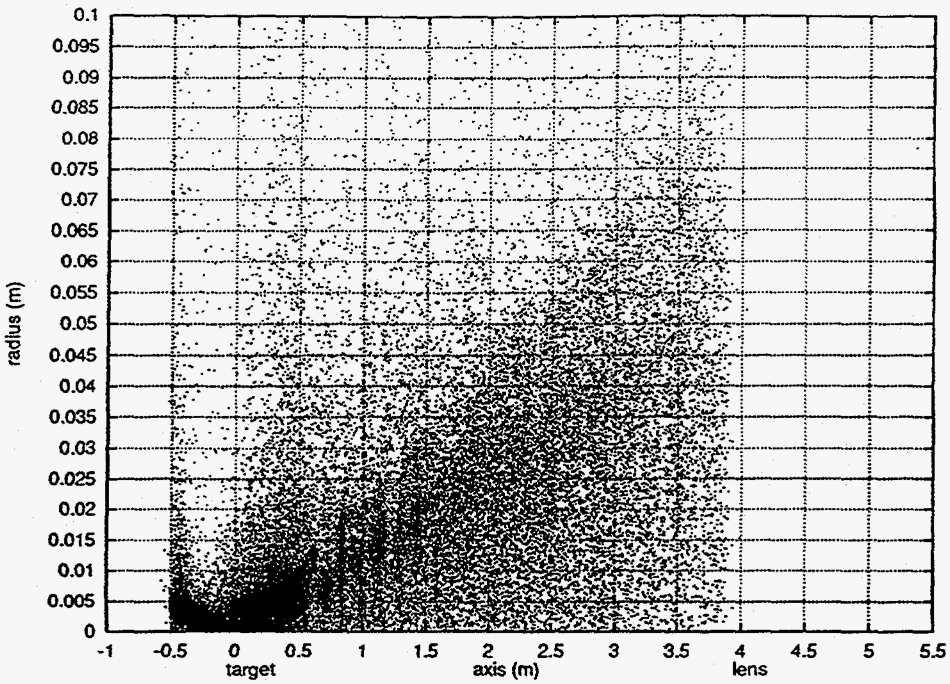
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Figure 2

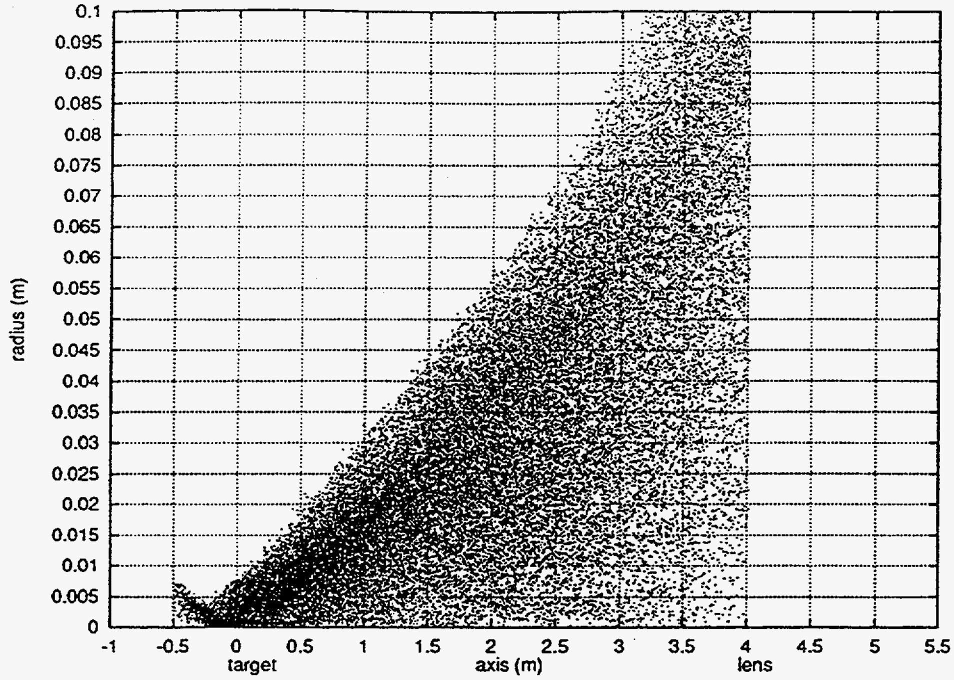
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Figure 3