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**Measurement of the Internal Magnetic
Field in Tokamaks Utilizing Impurity
Pellets: A New Detection Technique**

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Measurement of the Internal Magnetic Field in Tokamaks Utilizing Impurity Pellets: A New Detection Technique

ABSTRACT

Measurements on impurity pellet ablation trails indicate that the emission from these clouds extends much farther along the magnetic field than across it. For carbon pellets on TFTR, the aspect ratio of this cigar-shaped plume is of the order of 10. Strong visible line emission from one of the ionization states can be imaged with high time resolution, and since ions should be well confined along the field lines, it should be possible in this way to measure the radial profile of the pitch of the total internal magnetic field. For a pellet injected along a major radius in the plasma midplane, the appropriate viewing geometry consists of imaging the pellet along its flight from behind. A detector scheme capable of accomplishing the measurement, consisting of an array of 1-d spot-imaging photodiodes, is described. In order to make meaningful measurements with regard to the tokamak physics of interest, it is highly desirable to measure the field angle profile with a precision of ± 10 mrad or better. In order to achieve this for a cigar with aspect ratio of 10, measurement of the mean vertical position for each slice of the cigar must be made with a precision of about 10% of the vertical thickness of the cigar on that slice.

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I INTRODUCTION

One of the most important characteristics of a tokamak discharge, and at the same time one of the most difficult to measure, is the current density profile. Several experimental techniques have been brought to bear on this problem. These include Zeeman polarimetry utilizing lithium beams^{1,2}, lithium pellets³ and intrinsic impurities⁴, Faraday rotation of FIR laser beams⁵, Thomson scattering from cyclotron resonances⁶, the imaging of H_{α} trails from ablating hydrogen pellets^{7,8}, the shift of fast ion orbits⁹, measurements of internal plasma shape¹⁰, the observation of driven Alfvén waves¹¹, and Motional Stark polarimetry with neutral hydrogen beams¹². Recent experiments on TFTR have confirmed the usefulness of Li pellet polarimetry as a viable technique¹³. However, a fundamental limitation of that technique derives from the fact that Doppler and Stark line broadening reduces the net polarization, so that relatively high toroidal magnetic fields are required ($B > 4$ Tesla). As a result, the technique could only be applied to a handful of tokamaks in operation at this time around the world. Camera images of hydrogen pellets from the TEXT and ASDEX tokamaks^{14,15} have shown that the ablation cloud surrounding hydrogen pellets is elongated in the toroidal direction (cigar shaped) and there are indications that the cigar may be tilted in the direction of the total B field. However, because the visible emission from hydrogen pellet ablation comes primarily from the Balmer series of neutral hydrogen, it is not clear that this cigar should be constrained to follow the field lines. In more recent experiments on TEXT, images of Li and C pellets also show the presence of cigar shaped ion ablation clouds^{16,17}. This paper describes a relatively simple detection system which could be used to measure the tilt angle of the ablation trail, with $20 \mu\text{s}$ time resolution. For typical pellet speeds of 1 km/s, this translates into 2 cm spatial resolution.

II ION PLUME MEASUREMENTS: C PELLETS ON TFTR

The details of the impurity pellet experiments at TFTR, in which Zeeman polarimetry is used to measure internal field profiles, are described elsewhere in these proceedings¹³. A key component of those experiments is the ability to measure accurately the three dimensional position of the pellets in plasma as a function of time. This is accomplished by means of two imaging photodiode cameras. The first views the plasma on the horizontal midplane, from behind the pellet. The detector in this camera is an 2-D spot imaging photodiode (United Detector Technology PIN SC-10). The square detector is a 10 mm×10 mm Schottky-barrier photodiode, with a resistive back-plane and an electrode along each of the 4 sides. By comparing the four currents from the electrodes, it is possible to infer a non-linearly weighted mean position for an image on the detector. In this way, the vertical and toroidal positions of the pellet are monitored, with time resolution of 2 μ s. The second camera views the pellet vertically downward through a window located at the top of the tokamak. The detector for this vertically viewing camera is a 35 channel photodiode array (United Detector Technology PIN A5C-35UV), consisting of 35 discrete detectors of dimension 1mm (along the major radius direction) by 4.5mm (along the toroidal direction). The lenses in the two systems are such that, at the plasma center, the horizontal 2-D view covers ± 40 cm while the vertical view has 5.8 cm radial resolution and integrates toroidally ± 13 cm. Neither camera uses spectral filters, and the lens-detector combinations are sensitive to light over the approximate range 400 to 700 nm. In most cases, the injected pellets travel on a relatively straight trajectory, deviating less than 5 cm both toroidally and vertically. However, in some cases, larger toroidal motion occurs, particularly at very low electron density when slide-away electrons may be present, and in Supershots¹⁸. For large enough toroidal excursion, the image of the pellet moves off of the vertically viewing detector array, while the horizontal detector still sees the entire cigar. When this happens, the gradual loss of signal from the vertical array can be used to measure the toroidal extent of the ablation cloud. This is shown schematically in figure 1. The solid curve in

figure 2 shows the time history of the toroidal position of a small (0.4 mm), slow carbon pellet injected into a fully developed Supershot. The component of pellet velocity in the R direction was 2.7×10^2 m/s. The solid circles in figure 2 show the corresponding time history for the total intensity detected by the vertically viewing camera, normalized to the total intensity detected in the horizontal view. The signal decrease between 550 μ s and 700 μ s occurs as the image of the cigar moves toroidally off the edge of the vertically viewing detector array. The position data can be used to convert time to toroidal position, and then taking the first derivative of the normalized signal of the vertical array with respect to toroidal position yields the toroidal profile of the cigar intensity. The only assumption needed is that the pellet cloud shape must not change substantially over the time of the measurement. After smoothing and taking the derivative, the curve in figure 3 results. The cigar has a toroidal full width at 1/10 maximum of 7.5 cm. This can be compared with hydrogen pellets on TEXT, where streak images show a toroidal extent of about 4 cm¹⁴. Aside from the differences in background plasma parameters, one can expect that the carbon pellet emission should be spread farther toroidally, since states up to C²⁺ (ionization potential = 47.9 eV), and possibly C³⁺ (I.P. = 64.5 eV) should contribute significantly to the visible light. Concerning the feasibility of field angle measurements, it is the aspect ratio of the pellet cloud (toroidal width/height) which is most relevant. On TFTR, the cloud height has not yet been measured; however, the major radius extent of the cloud can be measured using another signal ratio method. In this case, looking at the leading or falling edge of the signal on a single vertical diode, again normalized to the total emission as monitored by the horizontal view, gives the major radius extent of the pellet cloud. Pellet velocity is deduced from the time of appearance on successive vertical channels, and again as long as the cloud does not change drastically as it crosses the boundary from one diode to the next, an accurate measurement of spatial extent can be inferred. Figure 4 shows the normalized signal on one vertical channel, as a function of major radius. The width of the monitored signal is about 6 cm — the size of the

diode element in the object plane. However, the analysis of the leading and trailing edges implies that the full width at 1/10 maximum, in the major radius direction, is .8 cm. Thus, the cigar aspect ratio is close to 10. Since only the neutrals can quickly cross the field lines, and they can do so equally easily in the vertical or major radius directions, the vertical extent of the cigar should not differ significantly from the major radius extent. In this context, the speed of the pellet itself is small compared to the cloud expansion velocities, and so should not introduce significant asymmetries. Spectroscopic linewidth measurements indicate that ion temperatures are typically in the range of 10 eV, and the corresponding ion velocity is about 1×10^4 m/s.

III POSITION SENSITIVE PHOTODIODE ARRAY

A method to realize the cigar angle measurement with good spatial resolution (< 2 cm) is described in this section. Viewing the pellet horizontally from behind — the same view which is used by the horizontally viewing camera already described — requires time resolution $\tau = \delta r / v_p$, where v_p is the pellet speed and δr is the desired spatial resolution. The ultimate spatial resolution which can be achieved is limited by the vertical and major radius extent of the cigar at any instant of time. A reasonable goal is thus 2 cm, and for $v_p = 1$ km/s, $\tau = 20 \mu\text{s}$ is required. Achieving this with a truly two dimensional imaging system is not trivial. Gated microchannel plate intensified video cameras can be used to get a single exposure with μs time response, but cannot be used to measure the entire time history of the ablation event. Streak cameras could in principle be applied, but they are costly. Data reduction could also present significant, although probably not insurmountable problems. As an alternative, an array of one-dimensionally-imaging photodiodes can be used. Figure 5 shows, schematically, how this would work. Each element of the detector has a resistive back-strip and an electrode at each end (similar to United Detector Technologies PIN-LSC30D). The mean position of a distribution of light along the detector is given by the difference of the currents measured from each electrode,

divided by their sum. By measuring the change in mean position across a series of such detector elements, the tilt angle of the cigar can be inferred. These detectors easily achieve the required time resolution, with typical rise times of $7 \mu\text{s}$.

One critical issue affecting the uncertainty in measuring the tilt angle is the vertical symmetry of the emitting cloud. Assume, as in figure 5, that an aspect ratio 10 pellet is observed on 10 imaging detectors. If the total toroidal extent of the detectors is taken as 10 units, with an uncertainty in the vertical position of each measurement of .1 (10% of the average cloud height) and if the errors in the 10 measurements are uncorrelated, then the uncertainty in the measured angle will be $\delta\theta \approx .01$ radians. Therefore, the centroid of the cloud must be located to within 10% of its mean width in order to meet the stated $\delta\theta$ criterion. This seems experimentally feasible, but must await more detailed measurements of intensity distributions within the cloud.

IV FUTURE EXPERIMENTS

Experiments are presently ongoing at TFTR to study both C and Li pellets. Gated microchannel-plate video snapshots will be taken, both from the vertical and horizontal views, in order to quantitatively measure the ablation cloud distributions. Interference filters will be employed, so that line radiation from various ionization states can be compared. Based on these results, the position sensitive diode array detector and associated optics will be designed for mounting with a horizontal view. The best candidate for these measurements appears, from the present considerations, to be Li^+ , with a strong line at $\lambda = 548.5 \text{ nm}$. Neutral lithium ionizes very rapidly (ionization potential = 5.4 eV), so that the ion cloud should be confined to a very small vertical range. On Alcator C, the emission from Li^0 extended vertically only $\sim 5 \text{ mm}$. Furthermore, Li^+ is relatively slow to ionize (I.P. = 75.6 eV), so that the strongly emitting portion of the ion plume should spread substantially farther in the toroidal direction than for C pellets. The aspect ratio

of the resulting cigar should be considerably larger as a result of these two effects, leading to improved angular measurements.

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Figure Captions

1. Schematic of the image of a pellet ablation cloud on the two camera detectors used to locate the pellet as a function of time. The top view shows the vertically viewing one dimensional diode array, and the side view shows the two dimensional spot imaging diode. As the pellet moved toroidally to the right, the ablation cloud went out of the field of view of the vertical camera, and the loss of relative signal yields a measure of the cigar length.
2. The time histories, for a carbon pellet injected into a TFTR Supershot, of the mean toroidal pellet position (solid curve), and the normalized sum of the signals on the vertically viewing diode array (solid circles). The position measurement comes from the horizontally viewing 2-d spot imaging detector. The pellet moved toroidally out of the vertical detector's field of view, between 0.4 and 0.75 ms.
3. The inferred toroidal intensity distribution of the ablation cloud for the C pellet of figure 2. After converting time to distance using the position data, the vertical signal is smoothed and the first derivative with respect to toroidal position is plotted here.
4. The normalized signal on a single diode from the vertically viewing array, as a function of the major radius position of the C pellet. Both the leading and falling edges of this signal indicate that the major radius extent of the pellet cloud is ≈ 0.8 cm.
5. Schematic of a pellet cigar imaged onto an array of one dimensionally imaging photodiodes. The tilt angle of the image is inferred from a linear fit to the mean vertical position of the detected emission on each of the detectors.

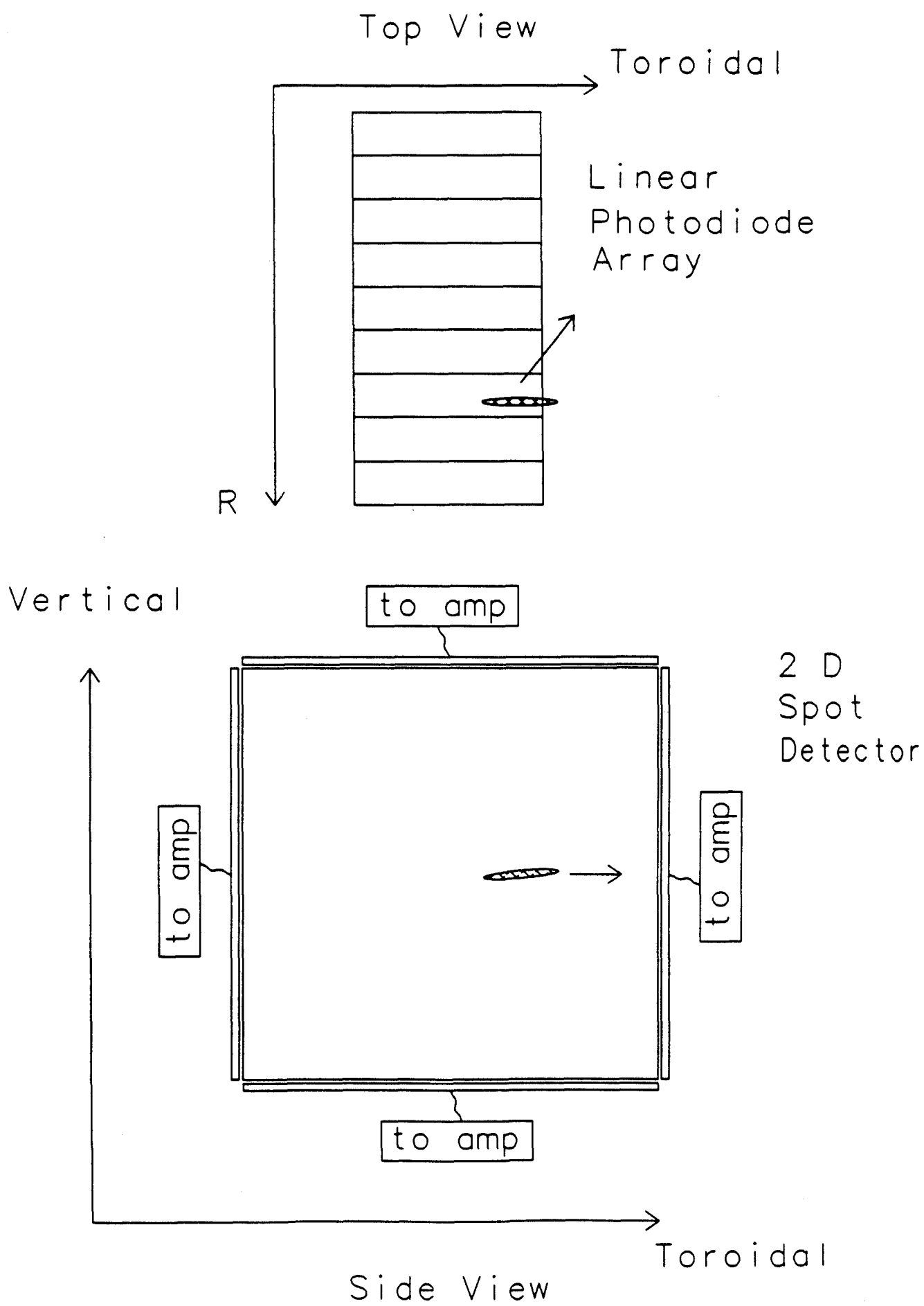


Figure 1

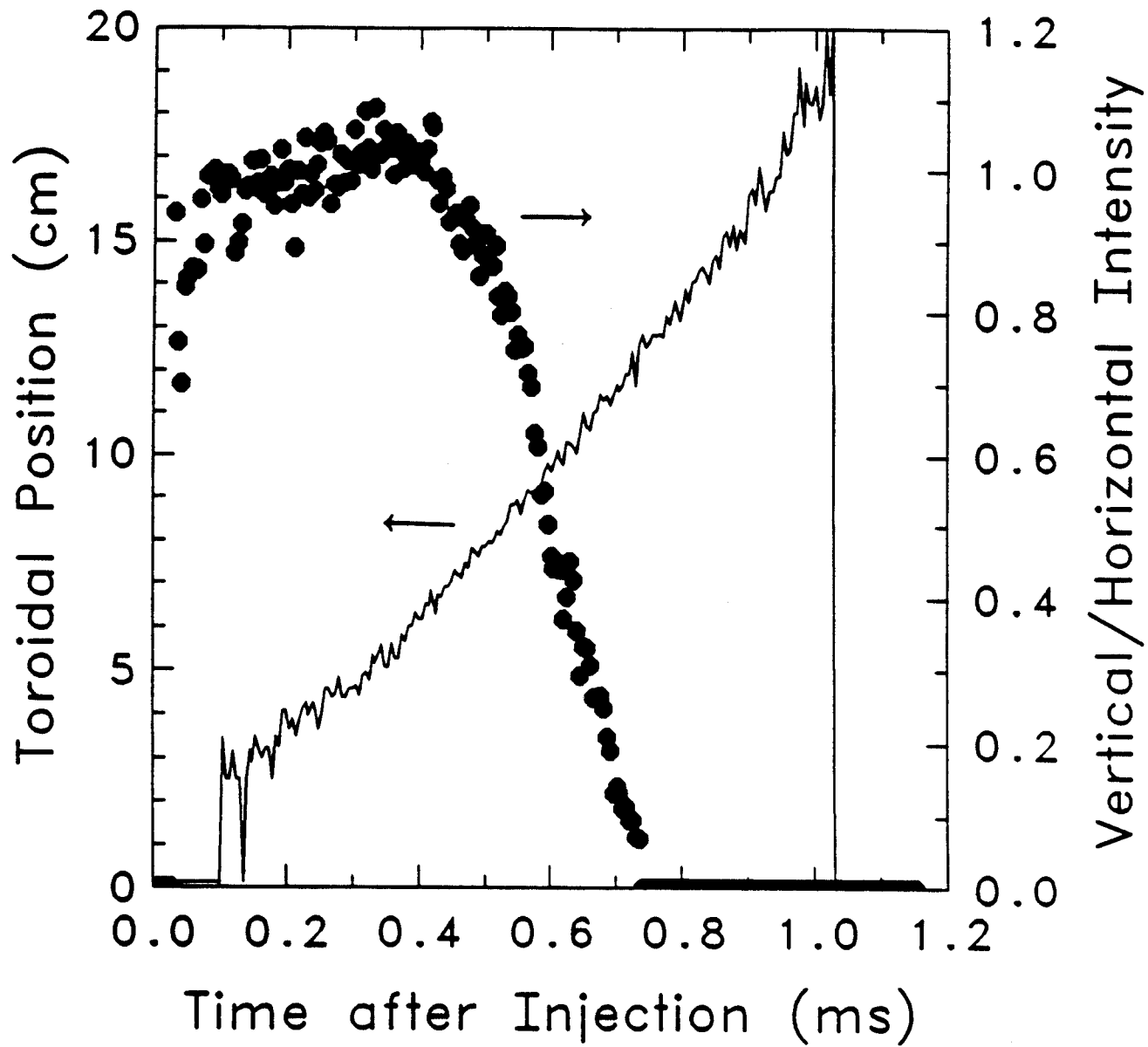


Figure 2

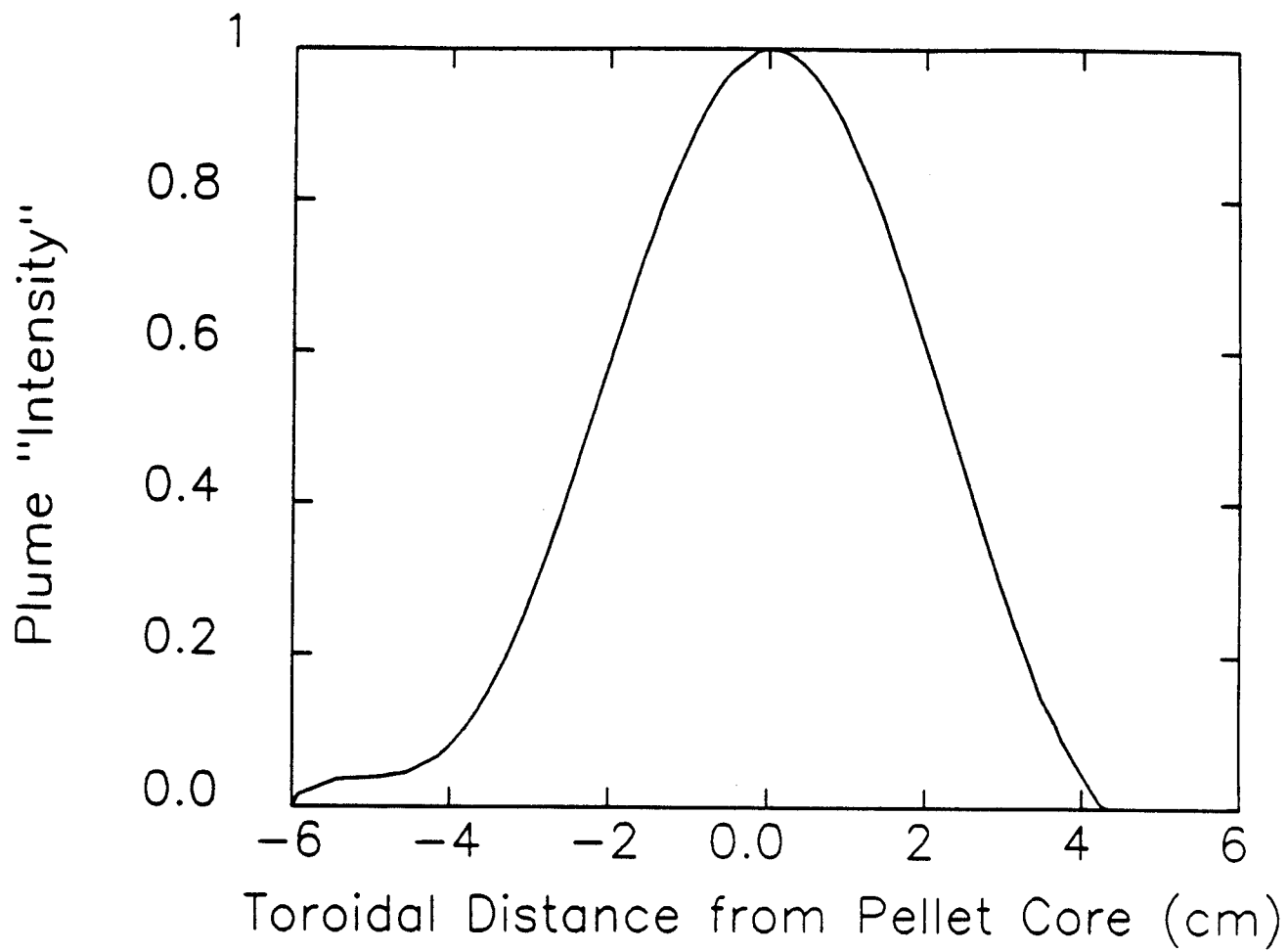


Figure 3

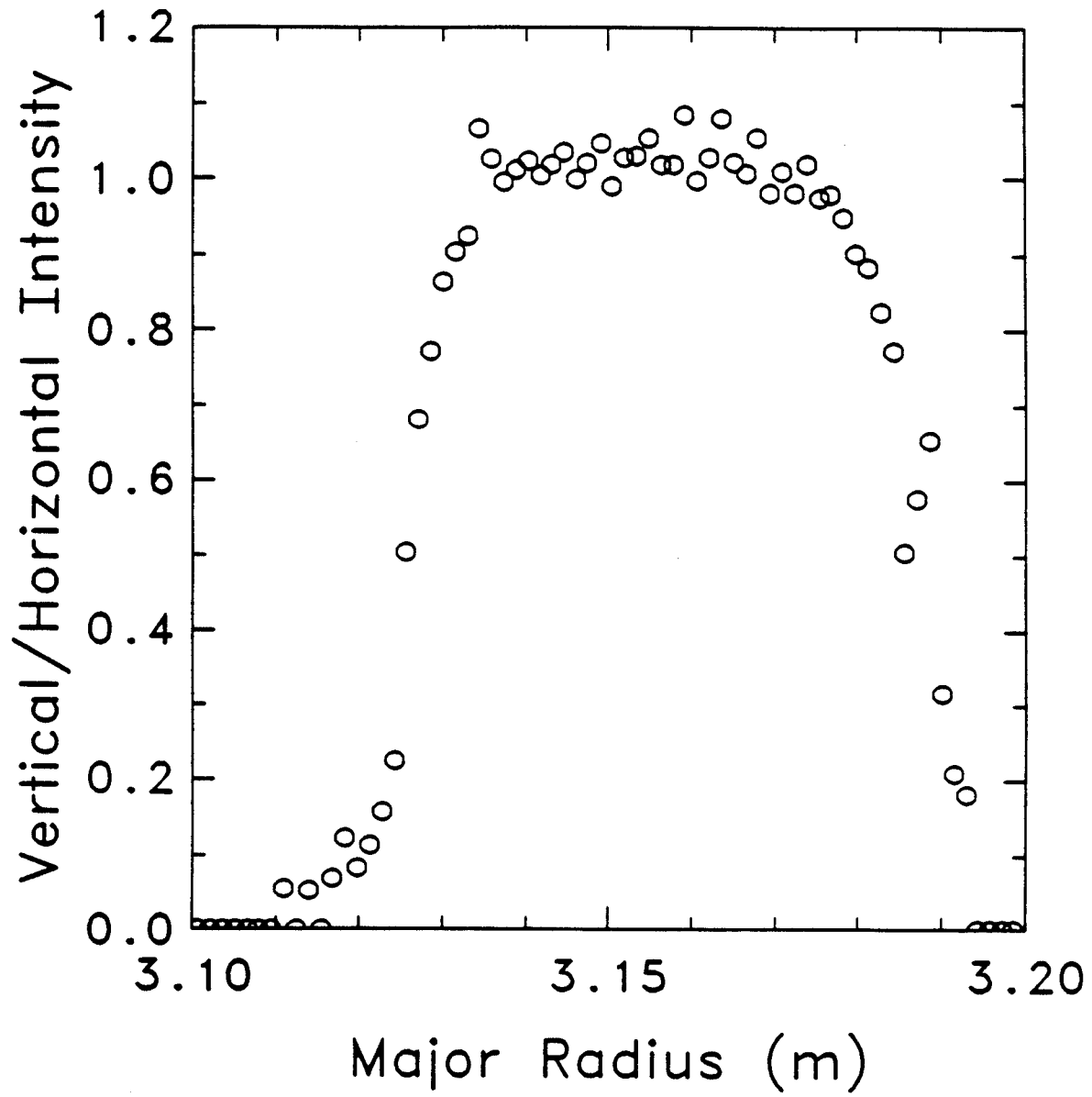


Figure 4

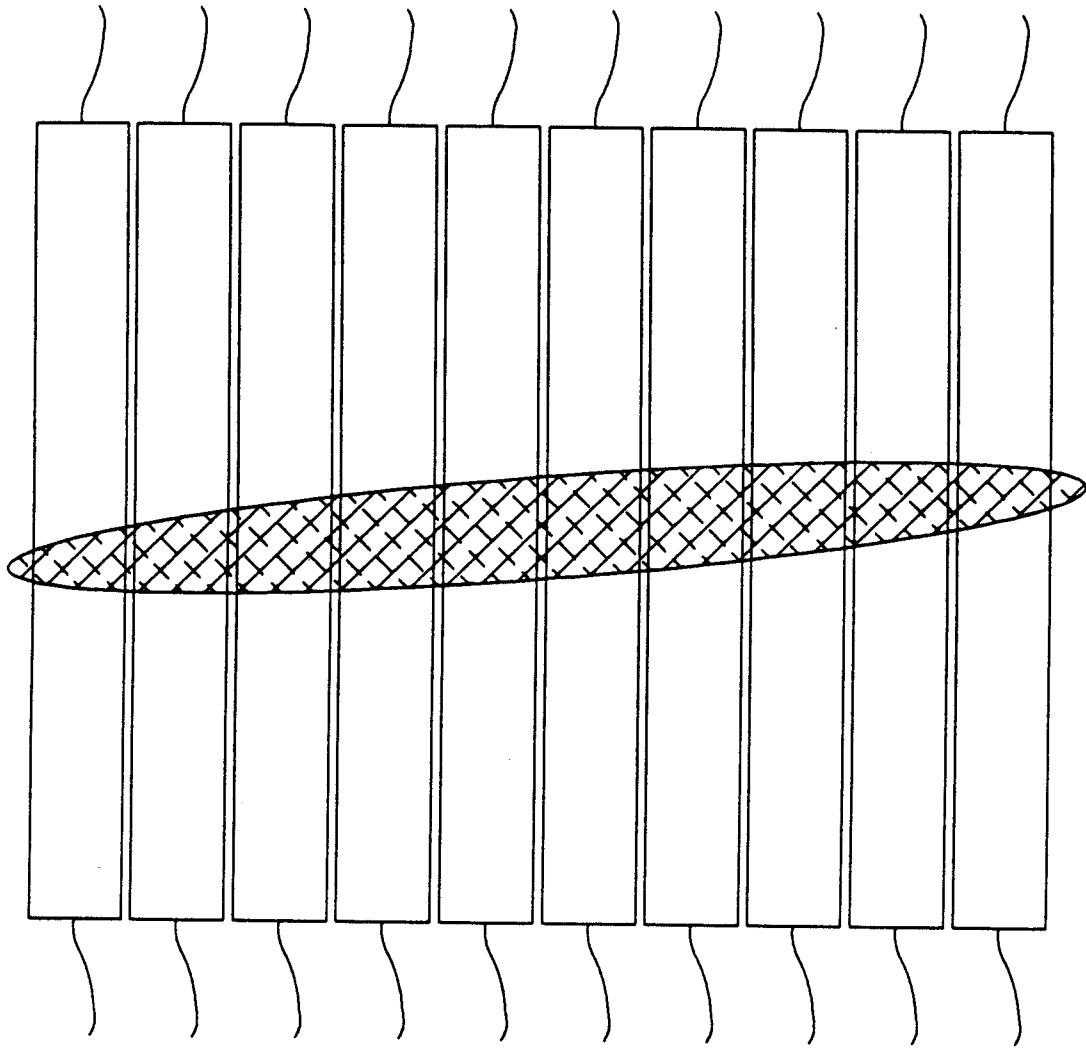


Figure 5