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Measurement of the Current Density Profile in the Alcator C Tokamak using Lithium Pellets

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Abstract

High speed lithium pellets have been injected into Alcator C tokamak plasmas in order to measure the internal magnetic field, and thus current density profiles. In the pellet ablation cloud, intense visible line radiation from the Li^+ ion ($\lambda \approx 5485$ Å, $1s2s\ ^3S - 1s2p\ ^3P$) is polarized due to the Zeeman effect, and measurement of the polarization angle yields the direction of the total local magnetic field. A "snap shot" of the q profile is obtained as the pellet penetrates from the edge into the center of the discharge, in a time of about 300 μs. The spatial resolution of the measurement is about 1 cm. At a toroidal field of $B_T = 10$ Tesla, the emission in the unshifted π component of the Zeeman triplet is more than 80% polarized, and q profiles have been obtained. The pellets are perturbative ($\langle \Delta n_e \rangle / \langle n_e \rangle \approx 1$), but the total pellet penetration time is at least a factor of 1000 smaller than the classical skin time. It can thus be anticipated that the current density profile should not be perturbed significantly during the time of the measurement.

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] and intrinsic impurities[3], Faraday rotation of FIR laser beams[4], Thomson scattering from cyclotron resonances[5], and the imaging of H_α trails from ablating hydrogen pellets[6,7]. In this paper we describe a new method, which takes advantage of the polarization of line emission due to the Zeeman effect, but rather than using an atomic beam to provide the source for the radiation, a lithium pellet has been employed instead. In the ablation cloud surrounding a pellet as it penetrates into a tokamak discharge, the atoms and ions of the pellet material radiate intensely. In general, the line radiation will be polarized, due to the Zeeman effect, and measurement of the direction of polarization yields the direction of the local magnetic field. This, in turn, can be directly related to the safety factor (q) and current density profiles in the plasma column. Experiments have been performed on the Alcator C tokamak[8], using a lithium pellet injector, to investigate this idea. Polarization measurements show that, in a 10 T toroidal field, the emission from the helium-like lithium ion, near $\lambda = 5485$ Å, is almost completely split into three polarized components, and the direction of polarization, as a function of minor radius in the plasma, has been measured. This in turn has allowed for the construction of q profiles for a few discharges.

The Alcator C Lithium Pellet Injector

In order to carry out the experimental investigations, a pneumatic pellet injector was designed and constructed at MIT. A cartoon of the gun design is shown in figure 1. A ribbon of isotopically natural Li is placed into the feeder track, and the feeder rod is advanced, pushing the Li into the slot in the shearing block. The ribbon, in this design, has a square cross section, 0.7 mm on a side. The length of the pellets is variable, with the maximum being 0.75 mm. The largest pellets correspond, in Alcator C, to a volume averaged electron density increase of $1.5 \times 10^{14}\ cm^{-3}$. After the Li has been pushed into the slot, the shearing block is used to slice off the cubic pellet, and transport it to the beginning of the barrel. A fast valve is then used to expose the pellet to helium or hydrogen pusher gas, at pressures up to 30 atmospheres. The barrel is 25 cm long, and pellet velocities up to 1000 m/s are achieved. The velocity is measured by two illuminated diodes, spaced by 5 cm, which are eclipsed as the pellet passes in front of them.

Polarization Measurements

The setup used to measure the angle of polarization of the line radiation from the pellet ablation cloud is shown schematically in figure 2. The intensity of separate components of polarization must be measured simultaneously in order to deduce the direction of polarization. Since the emission is viewed perpendicular to the magnetic field, the π components are linearly polarized parallel to the field, and the σ components perpendicular to the field. In the Alcator C experiments, it was possible to measure only two perpendicular components on one shot. The first task was to determine that indeed there is polarized light to measure. This was accomplished by measuring the vertical and horizontal components of polarization, as functions of wavelength, on a shot by shot basis. A 0.5 m Ebert type monochromator was used to select wavelength, and the output from the instrument was split, using polarizing films and a beam splitter, to direct the signals to 2 photomultipliers.

Shown in figure 3 are the results of a scan of the multiplet, near 5485 Å, from the Li^+ ion. The two components of polarization which were measured are the vertical and horizontal (toroidal). The quantity plotted is the normalized difference of the two signals, where +1 corresponds to light which is purely linearly polarized in the horizontal direction, and −1 corresponds to light which is polarized in the vertical direction. The experimental points are shown as squares; solid squares denote the maximum polarization seen over the course of one ablation event, and the open squares show the minimum that was observed for the same pellet. The solid curve is theoretical, for He-like ^{6}Li, with the line-width as a free parameter. The theory has been derived by analogy with a calculation for He-like carbon[9], and assumes that the various upper levels are populated statistically. The main result is that the emission in the unshifted component is almost completely polarized. These measurements were taken with a toroidal field on axis of 10 T. It then remained to measure the deviation of the polarization direction from toroidal, as a function of position in the plasma. The position was inferred from the time history of the polarization measurement, coupled with the information from an imaging camera which viewed the pellet ablation from below the torus (see figure 2), yielding pellet location as a function of time.

Letting the angle that the total field makes with the toroidal be θ, and defining α to be the unpolarized component of the total emission at the center of the π feature, the relative horizontal and vertical intensities are given by

$$I_H = \frac{\alpha}{2} + (1-\alpha)\cos^2\theta,$$

$$I_V = \frac{\alpha}{2} + (1-\alpha)\sin^2\theta.$$

Since $\theta \ll 1$ over the entire cross section (it will never be more than about 5 degrees or .1 radian), the measurements of figure 3 depend primarily on α. In order to determine θ, it is necessary to measure at least one more component of polarization. In the experiment, components at $\pm 45°$ from the toroidal were measured, and are denoted by I_1 and I_2 respectively. For small θ, the intensities are most sensitive to changes in θ at these angles. The relative intensities for these components are given by

$$I_1 = \frac{\alpha}{2} + (1-\alpha)\cos^2(\frac{\pi}{4} - \theta),$$

$$I_2 = \frac{\alpha}{2} + (1-\alpha)\cos^2(\frac{\pi}{4} + \theta).$$

Defining $f \equiv (I_1 - I_2)/(I_1 + I_2)$, then for $\theta \ll 1$,

$$f = (1-\alpha)\left[\cos^2(\frac{\pi}{4} - \theta) - \cos^2(\frac{\pi}{4} + \theta)\right]$$
$$\approx (1-\alpha)\cdot 2\theta,$$

or $\theta \approx f/(2-2\alpha)$. In general, for low β_p circular plasmas, such as those which have been studied here on Alcator C, $q = r/(R\tan\theta)$, so

$$q \approx \frac{r(2-2\alpha)}{R\cdot f}.$$

The current density profile can be related to f as follows:

$$f \approx \frac{2(1-\alpha)}{5\,B_T\,r}\int_0^r 2\pi r' dr' j(r'),$$

or,

$$j(r) \approx \frac{5B_T}{2\pi(2-2\alpha)}\left[\frac{f}{r} + \frac{df}{dr} + \frac{f}{(1-\alpha)}\cdot\frac{d\alpha}{dr}\right].$$

Finally,

$$q_0 \approx \frac{(2-2\alpha)}{R\cdot(df/dr)_{r\to 0}}.$$

One q profile, obtained from the measurement of θ as a function of r, is shown in figure 4. The plasma parameters in this case were: $B_T = 10T$, $\bar{n}_e = 2.5\times 10^{14}\,cm^{-3}$, $I_p = 550\,kA$, $q_l = 4.1$. The two solid lines correspond to the pellet's penetrating first from the outside ($R > R_0$) and then going beyond the center of the plasma ($R < R_0$). The dashed curve shows the q profile which would result from $q_0 = 0.9$ and the current density proportional to $T_e^{3/2}$. The data do not go all the way into the center of the discharge, because the pellet was slightly above the midplane, and so did not sample the exact center of the plasma. One indication of the uncertainty of the measurements is given by the difference between the inner and outer curves, about ±20%. The largest contributor to this uncertainty is the uncertainty in α, mainly due to the fact that, since only 2 components could be measured for a given pellet, α is deduced from one shot, and then θ from another.

The pellet penetration time, of the order of 300μs on Alcator C, is very short compared to the classical skin time. Therefore, prompt changes in the current density profile as the pellet penetrates into the plasma are not expected. Nevertheless, the pellet is very perturbing ($\Delta\langle n_e\rangle/\langle n_e\rangle \approx 1$) and current diffusion is by no means always classical in tokamak plasmas. It is encouraging, in this regard, that the inner and outer curves of figure 4 are in good agreement: if the pellet were perturbing the poloidal field significantly as it penetrated, this result would not obtain. Another test, which has not yet been performed, would be to inject a second pellet, very soon after the first, to see if the results are consistent.

Another possible source of systematic error in the measurement is local perturbation to the field due to the high density ablation cloud plasma. The measurements of spectral line broadening, from the data of figure 3, imply upper limits to both the temperature(Doppler) and density (Stark) in the emitting region. These limits are $T \leq 30\,\text{eV}$, and $n_e \leq 4 \times 10^{17}\,\text{cm}^{-3}$. This, in turn, implies an upper limit on the β of the plasma in that region: $\beta < .03$. Any perturbation to the local field should be correspondingly small. In addition, the cloud will deform the field in a manner which is cylindrically symmetric with respect to the unperturbed field direction; the measurement will average over the perturbation in such a way that, to lowest order, the inferred field direction will be unchanged.

To investigate the applicability of the technique to lower field devices, polarization measurements were also performed at $B_T = 5\,\text{Tesla}$. The results are shown in figure 5. The Zeeman splitting is smaller at the lower field, and the system is farther from the high field Paschen-Bach limit. This, coupled with the finite line broadening leads to emission which is less polarized. Nevertheless, it is sufficiently polarized ($\approx 50\%$) that accurate measurements of θ should be possible. Since variations in α become increasingly important for larger α, simultaneous measurement of at least 3 components is necessary to achieve meaningful results. A system to do just that has been assembled, and is shown schematically in figure 6. A set of four optical fibers views the pellet ablation. Each fiber has a polarizer at the front, and these are oriented, as shown in the figure, to measure the vertical, horizontal, and $\pm 45°$ components. A diffuser is placed between the polarizers and the fibers. This is necessary to smooth out differences in the relative sensitivities of the fibers as the light source (the pellet) moves within their fields of view. This new polarimeter/spectrometer system, along with a two-shot pellet injector, will be used to continue these experiments at the TFTR tokamak.

Conclusions

The technique of Zeeman polarimetry using lithium pellets to measure the internal magnetic field in a tokamak plasma has been demonstrated. While the pellets are perturbative, it appears that the measurement technique is valid, and with some relatively straightforward modifications and refinements, precision approaching 10% for the measurement of q near the axis should be achievable. The technique is viable, using Li, as long as the toroidal field is $\gtrsim 4$ Tesla.

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Figure Captions

1. Conceptual drawing of the Alcator C lithium pellet injector. The pellets are cubic in shape, 0.7 mm on a side. Pellet velocities up to 1000 m/s were achieved using H_2 driver gas at a pressure of 30 atmosphere (3×10^6 Pa).

2. Schematic of the set-up used to measure the polarization of line emission from the Li pellets on Alcator C. The wavelength was selected using a 0.5 meter Ebert monochromator, with resolution of about 0.4 Å.

3. Polarization versus wavelength measured on a series of pellet shots. The toroidal magnetic field was 10 T for these discharges. A value of +1 corresponds to light which is completely polarized in the toroidal direction. The solid squares correspond to the maximum polarization observed during the ablation of each pellet, while the open squares correspond to the minimum observed for that same pellet. The solid curve corresponds to the theoretical predictions assuming a constant linewidth for each component of the multiplet, equal in this case to 0.8 Å. For these measurements, the FWHM instrumental response was 0.55 Å.

4. The inferred profile of q, the safety factor, using the ablation signals from the pellet on both sides of the magnetic axis. The plasma parameters in this case were: $B_T = 10$T, $\bar{n}_e = 2.5 \times 10^{14}\,\mathrm{cm}^{-3}$, $I_p = 550\,\mathrm{kA}$, $q_l = 4.1$. The two solid lines correspond to the pellet's penetrating first from the outside ($R > R_0$) and then going beyond the center of the plasma ($R < R_0$). The dashed curve shows the q profile which would result from $q_0 = 0.9$ and the current density proportional to $T_e^{3/2}$.

5. Polarization versus wavelength at $\mathbf{B} = 5$ Tesla. The linewidth for the theoretical fit to the data is, in this case, 0.6 Å, and the FWHM instrumental response was 0.39 Å. The significance of the open and closed points is the same as it is in figure 3.

6. Schematic for the new polarimeter/monochromator setup which will be used for the next series of experiments. The fibers carry signals from different components of linear polarization which are selected by means of polarizers oriented as shown in the bottom of the figure. The four individual fibers are interfaced, through a transition into a bundle, into the entrance slit of the monochromator; the image of each bundle is collected at the

exit plane by another set of bundles; these in turn bring the light to photo-multiplier detectors.

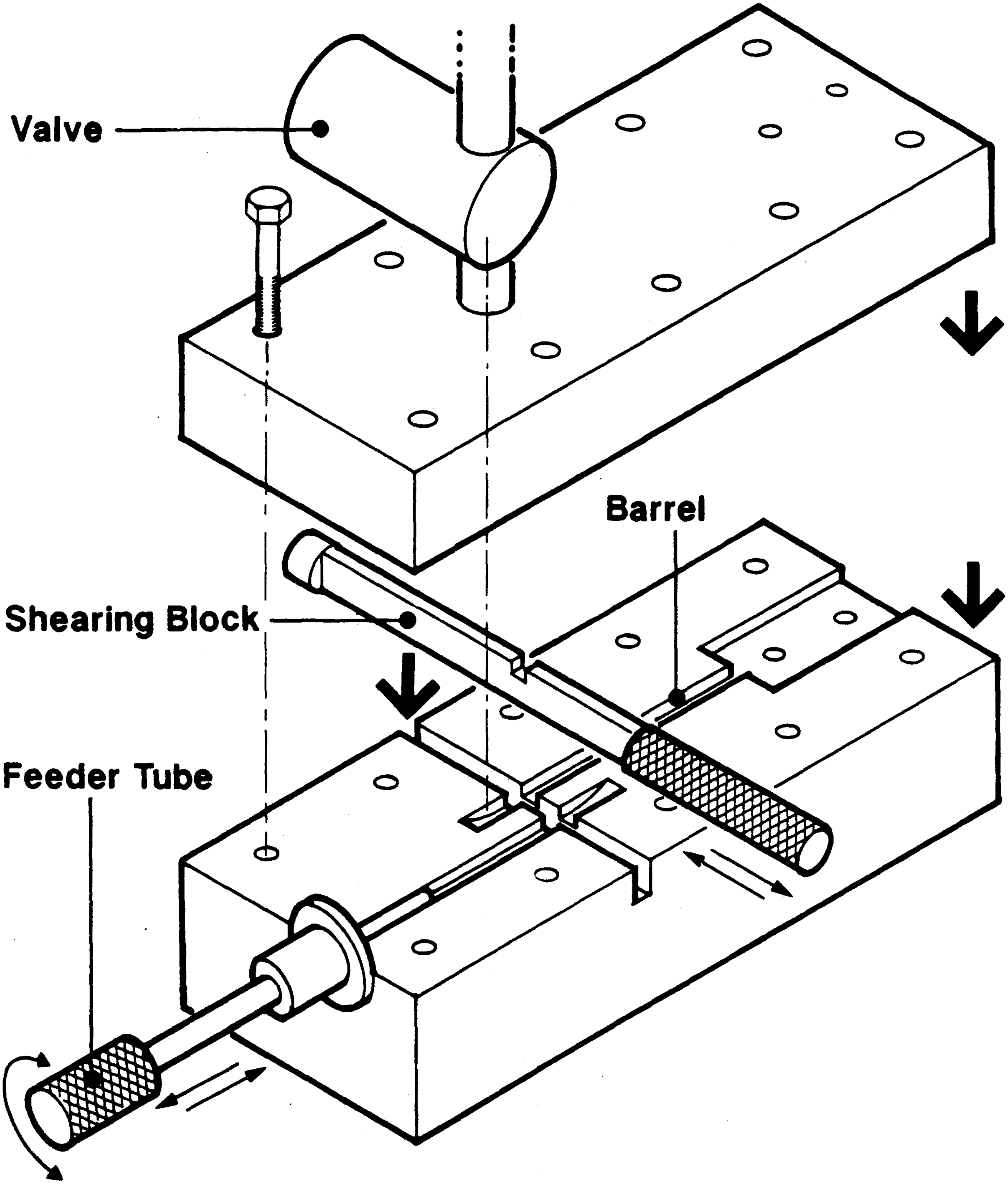
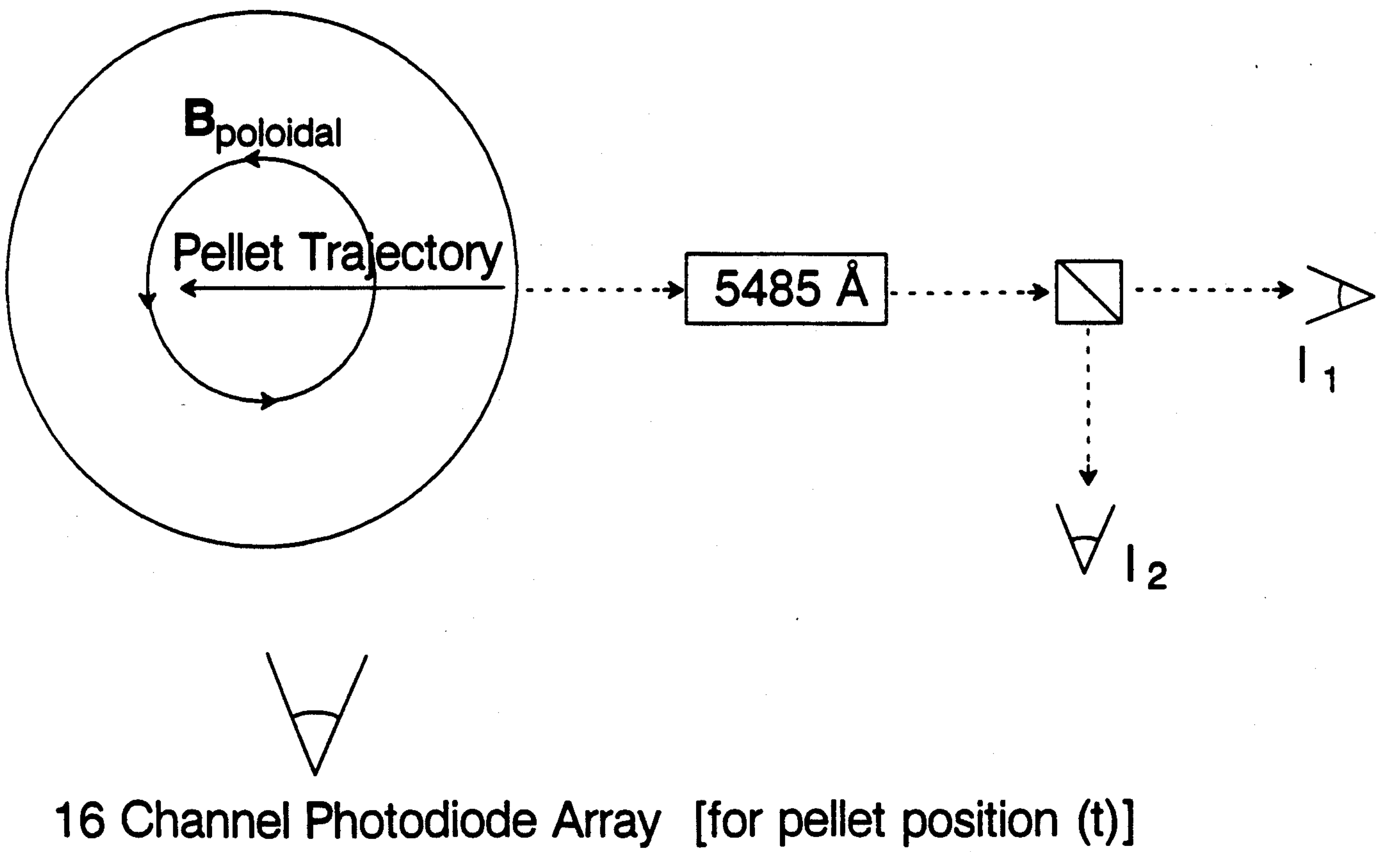


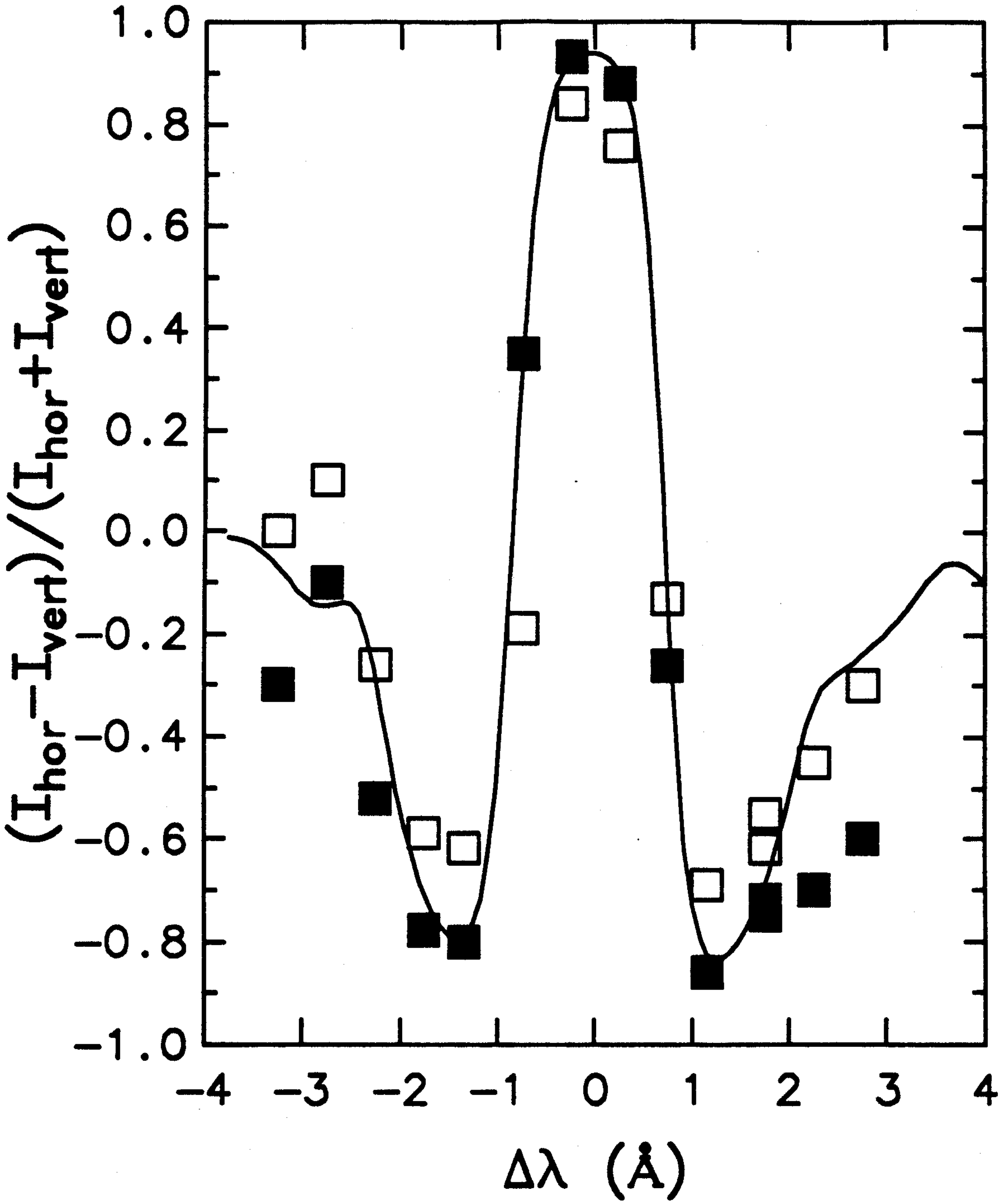
Figure 1

8732



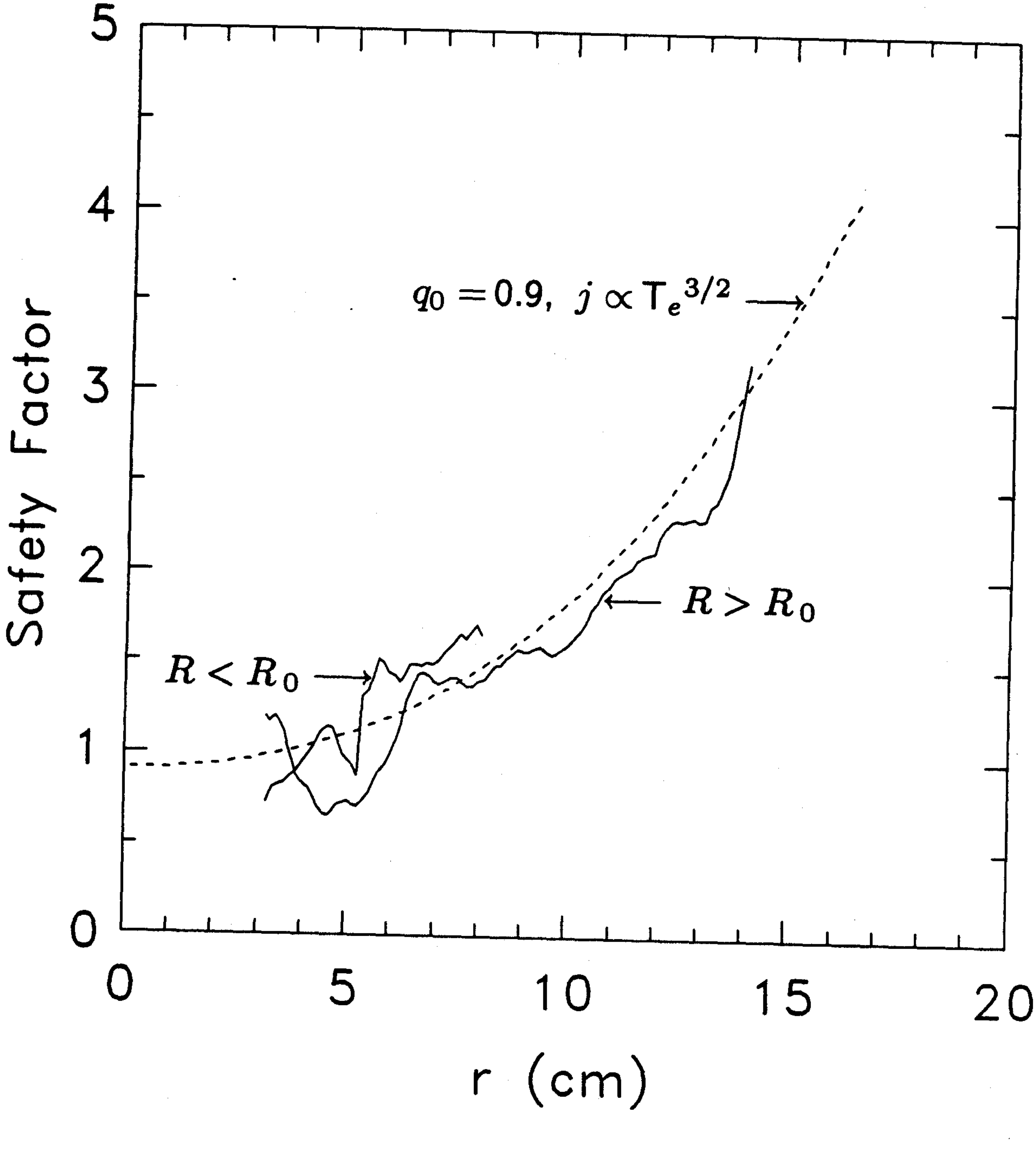
B poloidal
Pellet Trajectory
5485 Å
I 1
I 2
16 Channel Photodiode Array [for pellet position (t)]

Figure 2



1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−4
−3
−2
−1
0
1
2
3
4
$(I_{hor}-I_{vert})/(I_{hor}+I_{vert})$
Δλ (Å)

Figure 3



Safety Factor
r (cm)
$q_0 = 0.9, \ j \propto T_e^{3/2}$
$R > R_0$
$R < R_0$
0
1
2
3
4
5
0
5
10
15
20

Figure 4

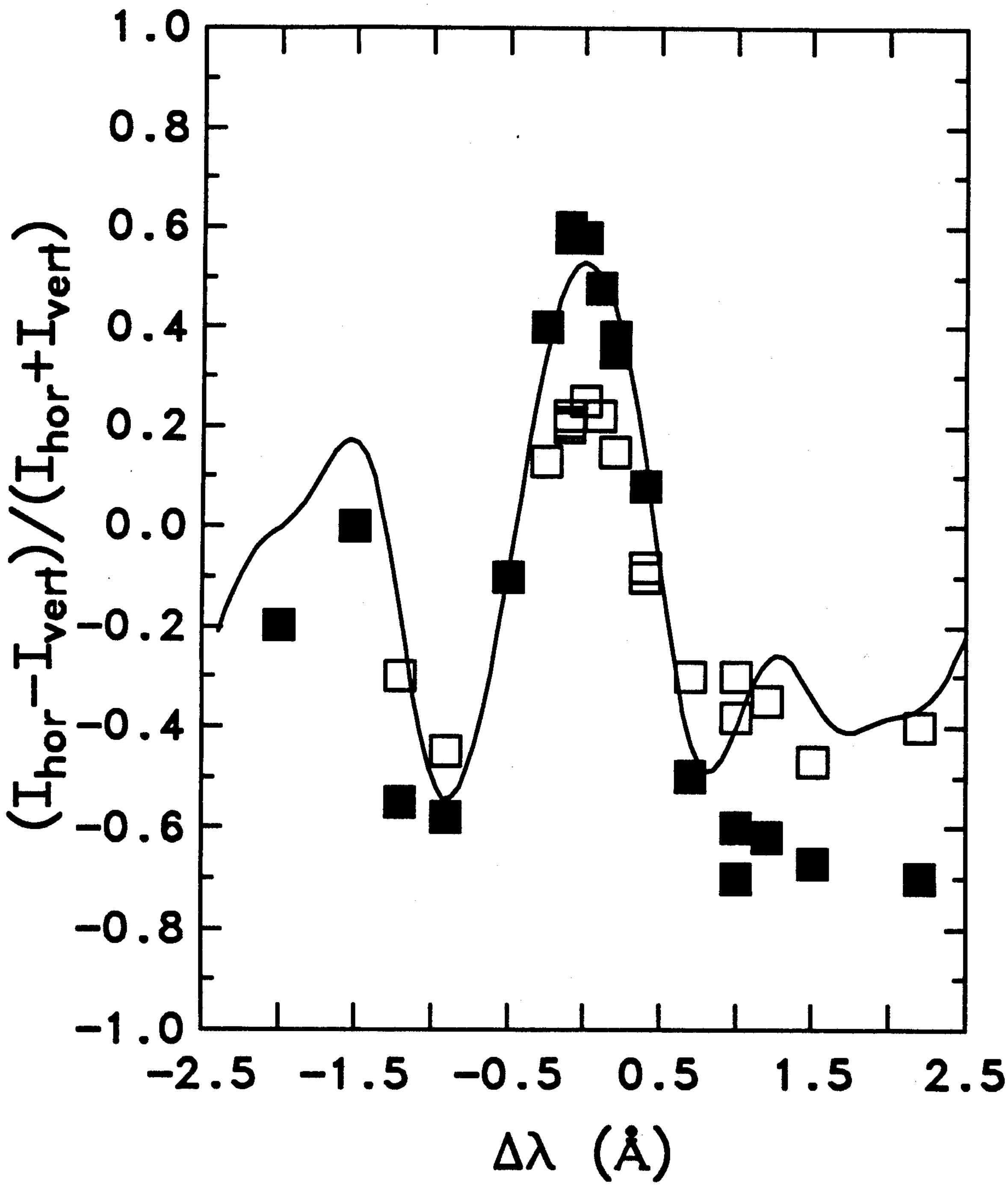

1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
$(I_{hor}-I_{vert})/(I_{hor}+I_{vert})$
−2.5
−1.5
−0.5
0.5
1.5
2.5
Δλ (Å)

Figure 5

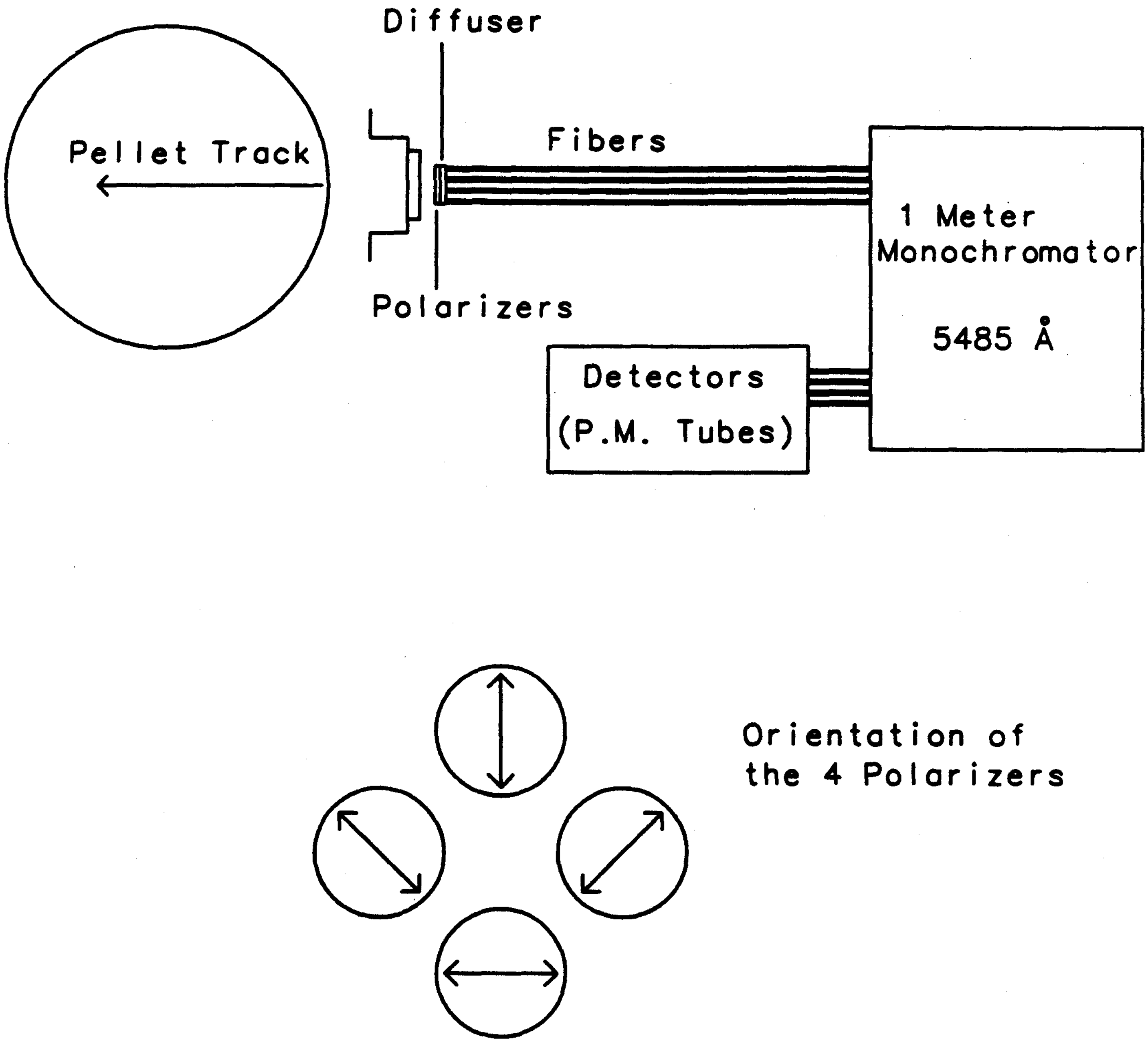

Diffuser
Pellet Track
Fibers
1 Meter
Monochromator
5485 Å
Polarizers
Detectors
(P.M. Tubes)
Orientation of
the 4 Polarizers

Figure 6