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MULTICHANNEL LIGHT DETECTOR SYSTEM FOR VISIBLE CONTINUUM MEASUREMENTS ON ALCATOR C

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Abstract

A spatially resolving visible light detector system has been constructed and used to measure continuum radiation in the wavelength region near 5360 Å on the Alcator C tokamak. The instrument measures the line integral brightnesses from 20 chords through the plasma. For high electron temperature regimes and relatively line-free wavelength regions, $Z_{eff}(r,t)$ is inferred from Abel inverted brightness profiles. During the steady-state portion of the discharge, $Z_{eff}(r)$ is usually found to be constant within 10% out to r/a = .75.

Introduction

Impurity levels in high temperature plasmas can be measured in various ways. Radiative methods, which consist of measuring either line emission or bremsstrahlung emission, are particularly useful in diagnosing equilibrium plasmas.

Spectroscopic theory[1] allows accurate calculations of Z_{eff} (the effective ion charge of the plasma) from absolute bremsstrahlung emissivity. Relating Z_{eff} to recombination radiation as is done in the x-ray region,[2] proves to be both difficult and imprecise. If, however, the spectrum is relatively free of both recombination and line emission, the analysis becomes much less complicated. This condition is most easily satisfied in the visible, and, as shown by K. Kadota,[3] et.al. (1979), Z_{eff} can in this way be measured in tokamak plasmas.

In this paper, we describe an instrument used to measure the absolute level of continuum emission in a wavelength region near 5360 Å on the Alcator C tokamak. The 20 channel detector system provides brightness profiles which can be Abel inverted to obtain radial emission profiles. From these data and independently determined $n_e(r,t)$ and $T_e(r,t)$ profiles, $Z_{eff}(r,t)$ can be calculated.

Apparatus

A spatially resolving visible light detector system has been constructed and used to measure continuum radiation in the wavelength region near 5360 Å on the Alcator C tokamak. Comparisons with predictions for hydrogenic bremsstrahlung are used to calculate Z_{eff} from:[3]

$$\frac{dE(r)}{d\lambda} = \frac{.95 \times 10^{-13}}{\lambda} \bar{g}_{ff} n_e^2(r) Z_{eff}(r) T_e^{-1/2}(r) \exp(-hc/\lambda T_e(r)) \quad (1)$$

photons/cm^3·Å·sec

where Z_{eff} is the effective ion charge defined by $Z_{eff} \equiv \sum n_i Z_i^2/n_e$, $\bar{g}_{ff}$ is the average free-free gaunt factor[4] (~ 3), n_e and T_e are the electron density (cm^{-3}) and temperature (eV), and λ is the wavelength in Å.

As shown in Fig. 1, the light is first filtered with a 30 Å FWHM interference filter having a peak transmission of 67% at λ = 5360 Å. The light is then imaged with a 40 cm focal length, 3 cm diameter lens onto an array of light pipes and transmitted to 20 Hamamatsu 1P28 photomultiplier tubes. The array consists of a 4 x 40 matrix of .041" dia (plastic) light pipes, .31" wide and 3" high. This allows chordal measurements with 1.7 cm resolution at the center of plasmas with a limiter radius of 16 cm. Due to port limitations, the extreme chords are at +16 cm and -14 cm. The light pipes are epoxied into a drilled 1/16" thick plate with a bundle of eight transmitting light to each photomultiplier tube.

The housing box is constructed of 3/16" thick metal alloy

(50% nickel, 50% iron) which provides some magnetic shielding for the tubes. In addition, each tube is shielded individually providing an overall magnetic attenuation of $\sim .002$ with a saturation limit of 300 G. The filter and lens are mounted directly on the mobile portion of the light shield, allowing adjustable focusing while eliminating stray light. A calibrated tungsten ribbon lamp was used to measure absolutely the sensitivity of each channel. Absolute calibration is necessary to calculate Z_{eff} through Eq. (1).

In addition to free-free bremstrahlung, recombination and line radiation can contribute to the emission from the plasma. A relatively line free portion of the spectrum was chosen for the continuum measurements. A film spectrum in the region 5000 Å - 5600 Å exposed over 4 similar discharges is shown in Fig. 2. Although lines were found in this region, near 5360 Å continuum dominates line radiation.

The ratio of free-bound to free-free radiant flux for a Maxwellian hydrogenic plasma is:[3]

$$\frac{\Delta P_{fb}}{\Delta P_{ff}} = \frac{2\chi_H \bar{g}_{fb}}{T_e \bar{g}_{ff}} Z_i^2 \sum_n \{\frac{1}{n^3} \exp(hc/T_e \lambda_n)\} \qquad (2)$$

where χ_H is the ionization potential of a hydrogen atom (13.6 eV) and λ_n is the wavelength of the series limit for the bound state with principal quantum number n such that $(\chi_H - E_n) \leq hc/\lambda \approx 2.3$ eV. Since this ratio for a typical Alcator C discharge[5] is small

(< .001) in the visible, the observed continuum radiation is dominated by bremsstrahlung.

We define a central line averaged Z_{eff} as:

$$\overline{Z}_{eff} \equiv \frac{\lambda}{.95 \times 10^{-13}} \int_{-a}^{a} \frac{dE(r)}{d\lambda}\, dr \Big/ \int_{-a}^{a} \overline{g}_{ff}\, n_e^2(r) T_e^{-1/2}(r)\, dr \qquad (3)$$

where a is the plasma radius and the integral in the numerator is the central chord brightness, and the exponential has been set equal to one (since $2.3\text{eV}/T_e \approx 0$). We rewrite the denominator in Eq. (3) as $T_{eo}^{-1/2} \cdot \left[\int_{-a}^{a} n_e(r)dr\right]^2 \cdot \chi$ where:

$$\chi \equiv \int_{-a}^{a} \overline{g}_{ff}\, n_e^2(r) \left\{\frac{T_e(r)}{T_{eo}}\right\}^{-1/2} dr \Big/ \left[\int_{-a}^{a} n_e(r)dr\right]^2 \qquad (4)$$

and T_{eo} is the central temperature. For typical density and temperature profiles on Alcator C $(n_e = n_{eo}\,(1 - r^2/a^2)^{\eta} \quad .5 < \eta < 1.5,$ $T_e = T_{eo} \exp(-r^2/a_T^2) \quad .5a < a_T < .9a)$, χ is found to vary only ±10%. Thus, assuming χ constant, $\overline{Z}_{eff} \propto \int_{-a}^{a} dE(r)/d\lambda\, dr \Big/ \left[\int_{-a}^{a} n_e(r)dr\right]^2$, allowing a determination of $\overline{Z}_{eff}$ when only central line average densities are available.

For most regimes of operation, $\overline{Z}_{eff}$ is found to be in the range 1.1 to 1.5 with an overall experimental uncertainly of ± 20%. Figure 3 shows a typical time history of $\overline{Z}_{eff}$. The rises very early and late in the discharges are possibly due to enhanced recombination, since T_e is < 50 eV over much of the profile at these times.

As shown in Fig. 4, Fourier-Bessel series are fit to the brightness profiles and assuming cylindrical symmetry, Abel inverted to obtain radial emission profiles. Combined with independently measured electron density and temperature profiles, $Z_{eff}(r)$ can be deduced from Eq. (1).

Figure 5 shows a typical $Z_{eff}(r)$ measured during the steady-state portion of the discharge. In most cases $Z_{eff}(r,t)$ is found to be constant within 10% out to r/a = .75 throughout this steady-state time interval.

When $Z_{eff}(r)$ is close to one (and therefore constant), Eq. (1) can be inverted to solve for $n_e(r)$ given $T_e(r)$. A typical inversion is shown in Fig. 6. In the clean, high density regime of operation of Alcator C, this is used as a second method of monitoring the density profiles, supplementing the usual multichord far-infrared interferometer technique.[6]

Acknowledgements

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References

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Figure Captions

Figure 1) 20 channel visible light detector system.

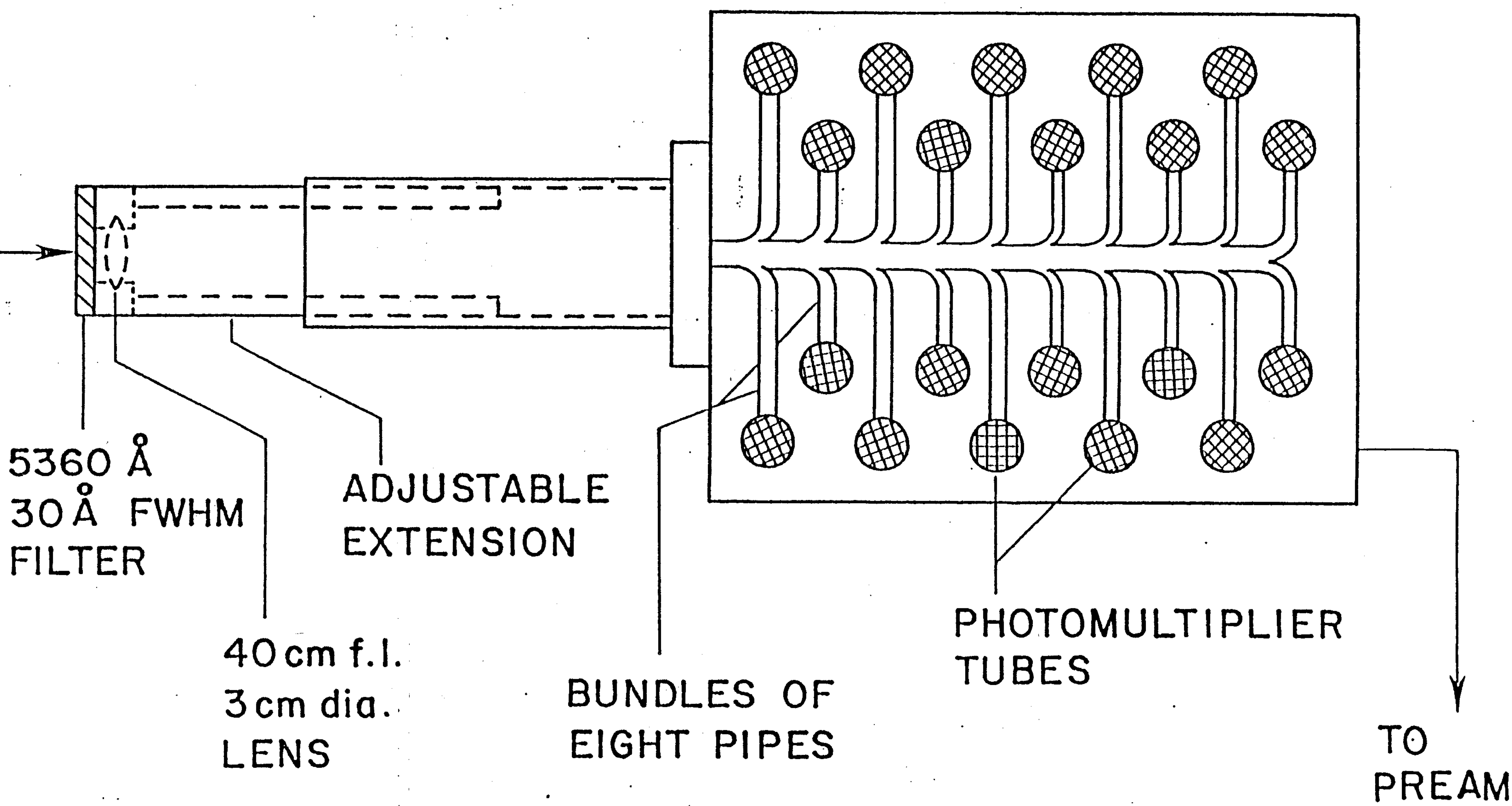
Figure 2) Microdensitometer trace of a film spectrum in wavelength region 5000 Å - 5600 Å.

Figure 3) A typical time history of $\overline{Z}_{eff}$ with central line-integral density ($\overline{n}_e$ = .57 x $10^{14} cm^{-3}$/fringe), plasma current (I_{peak} = 250 kA), soft x-ray signal, and central line-integral continuum brightness.

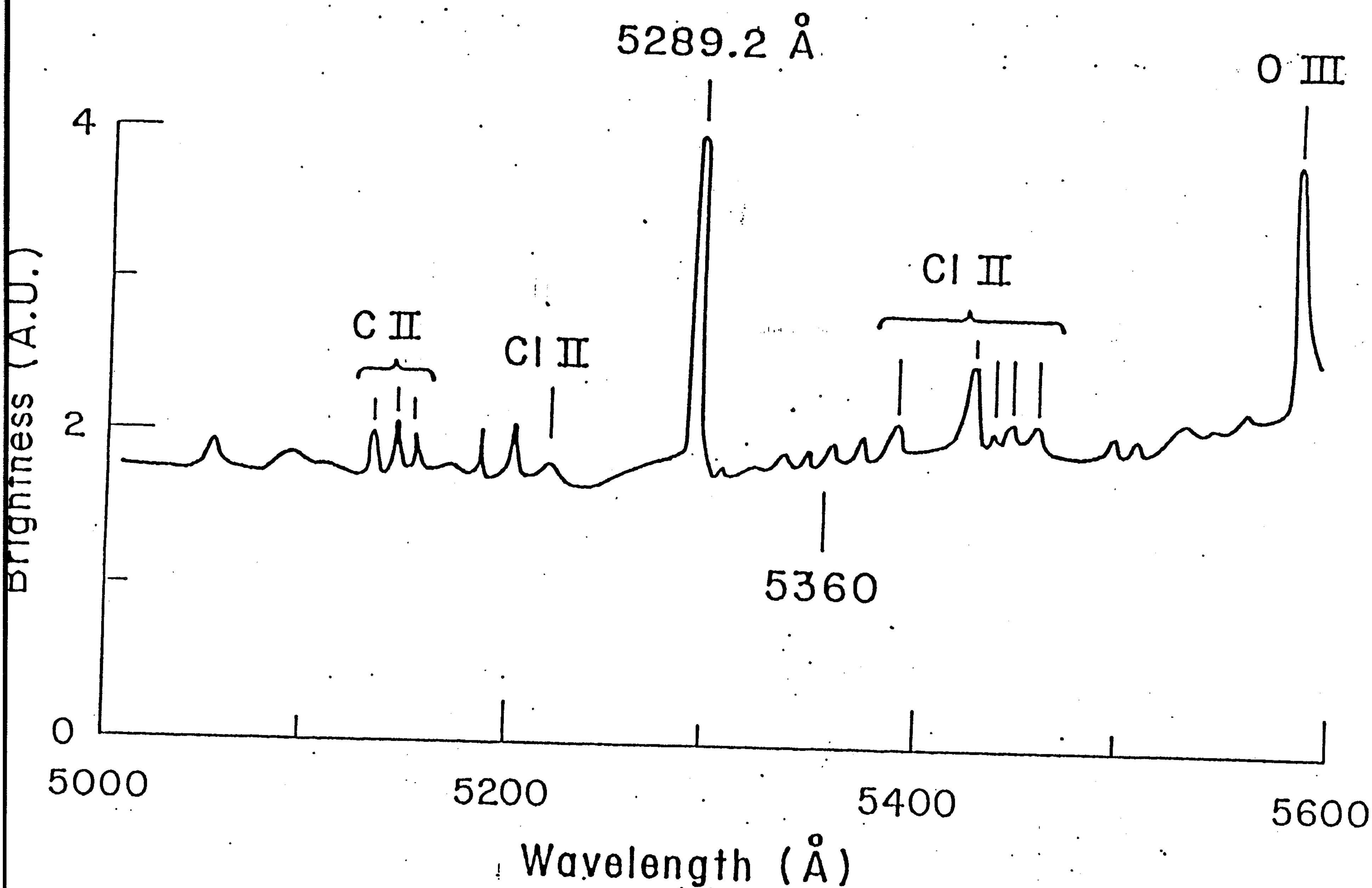
Figure 4) A typical brightness profile for visible continuum.

Figure 5) A $Z_{eff}(r)$ radial profile for a clean high density discharge.

Figure 6) A typical time history of inferred density profiles. Initiation of the discharge occurs at $t = 30$ msec on this plot.

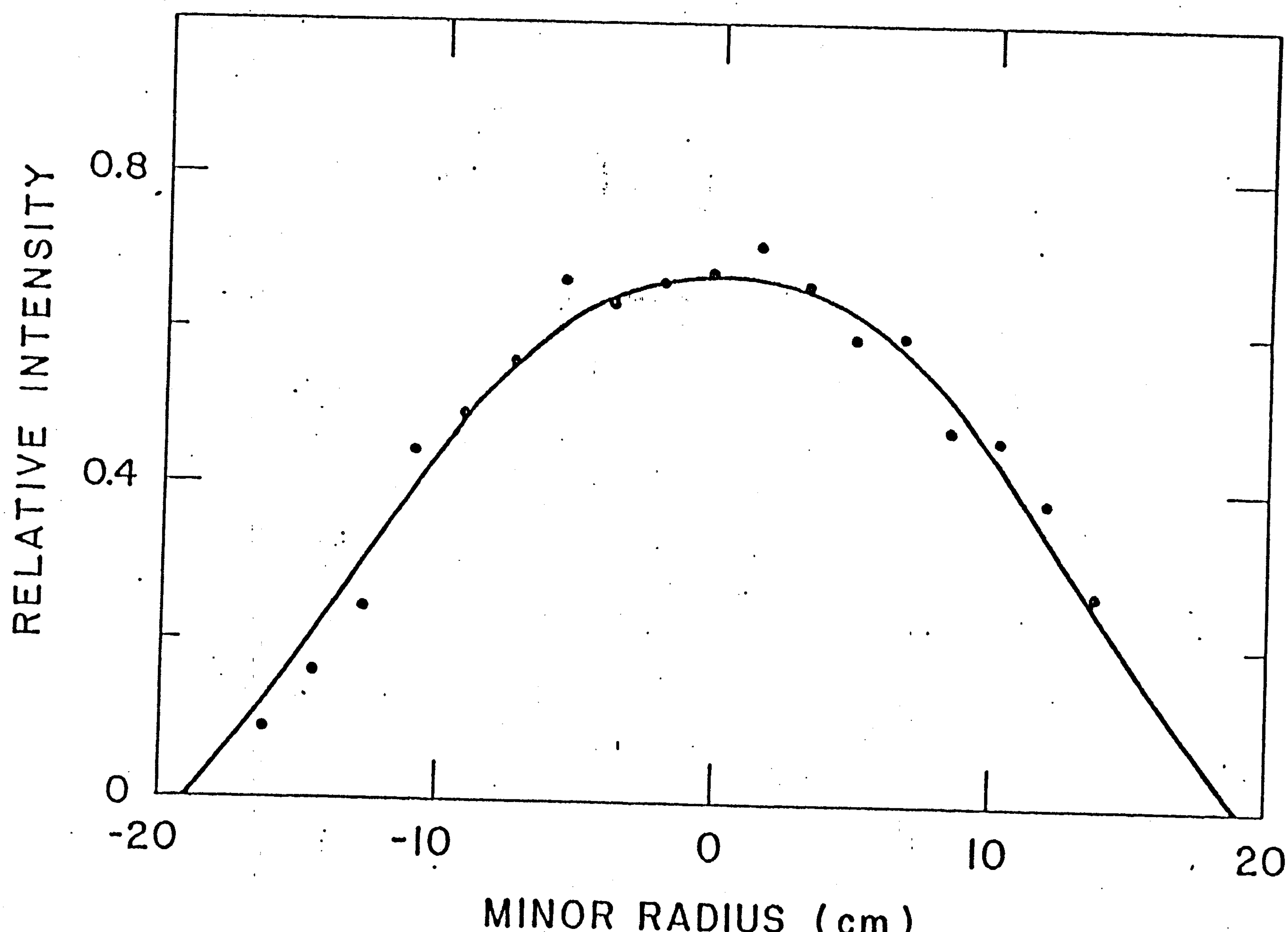

5360 Å
30 Å FWHM
FILTER
40 cm f.l.
3 cm dia.
LENS
ADJUSTABLE
EXTENSION
BUNDLES OF
EIGHT PIPES
PHOTOMULTIPLIER
TUBES
TO
PREAM

PFC-6042

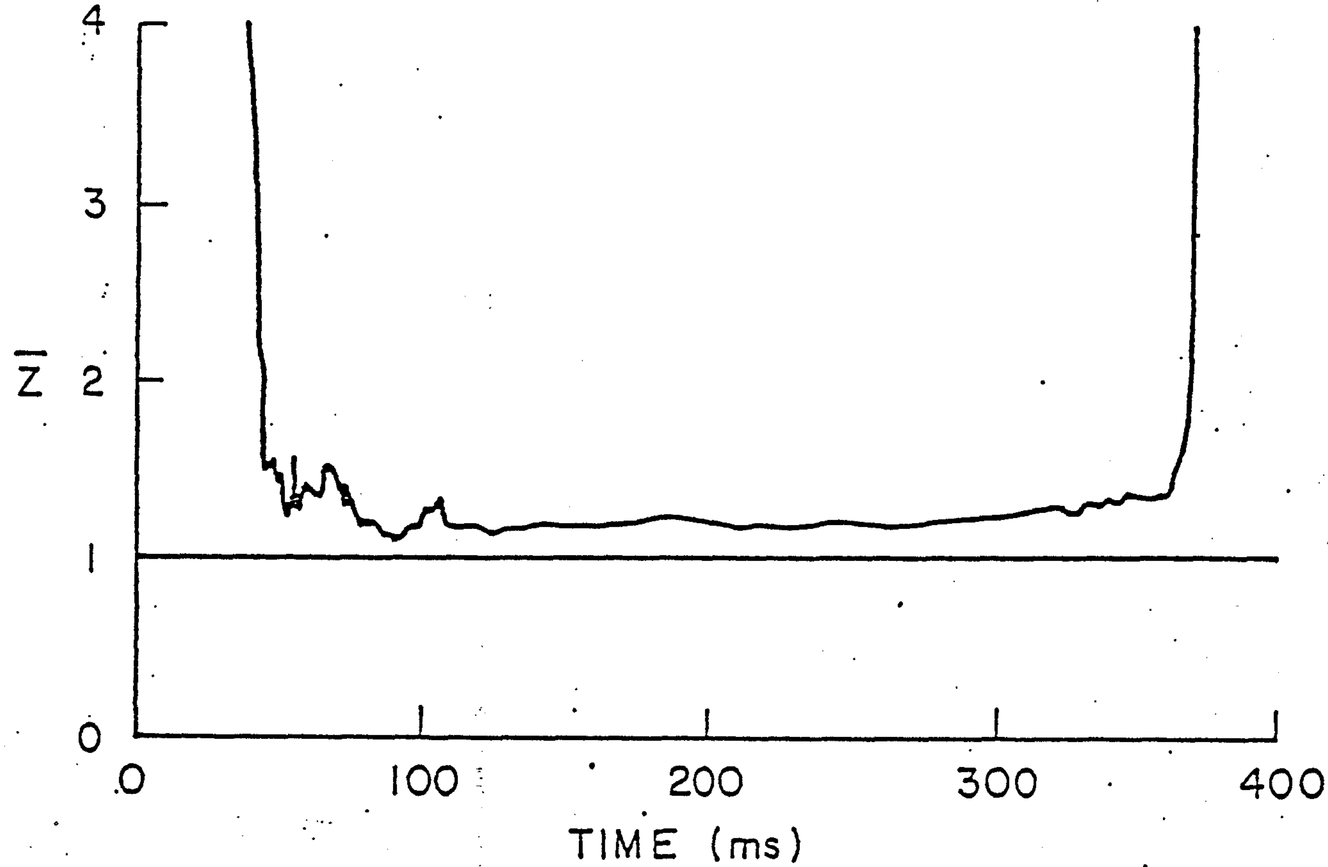


Brightness (A.U.)
0
2
4
5289.2 Å
O III
C II
Cl II
Cl II
5360
5000
5200
5400
5600
Wavelength (Å)

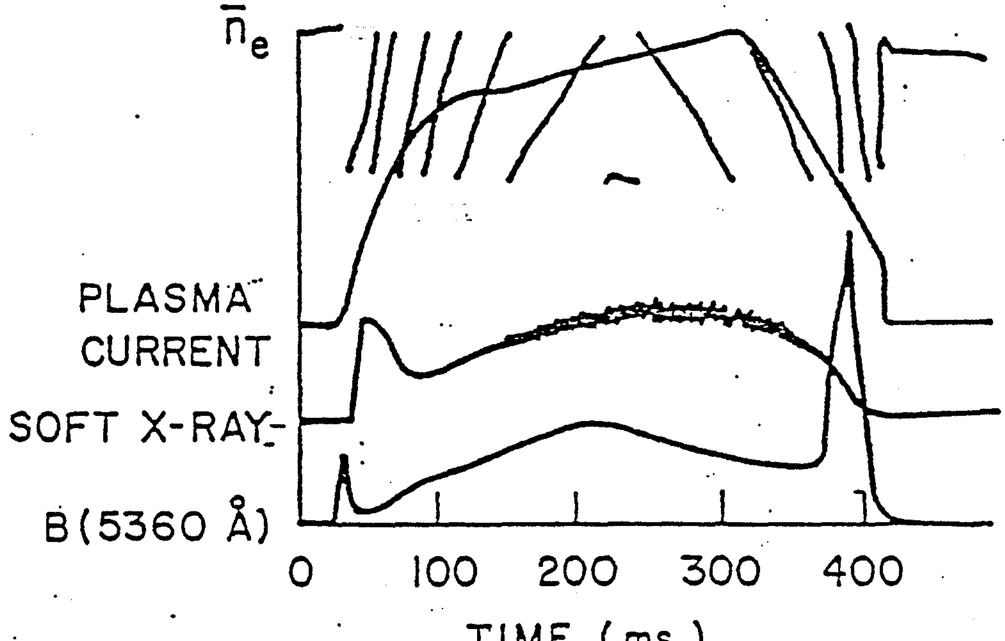
PFC-5026



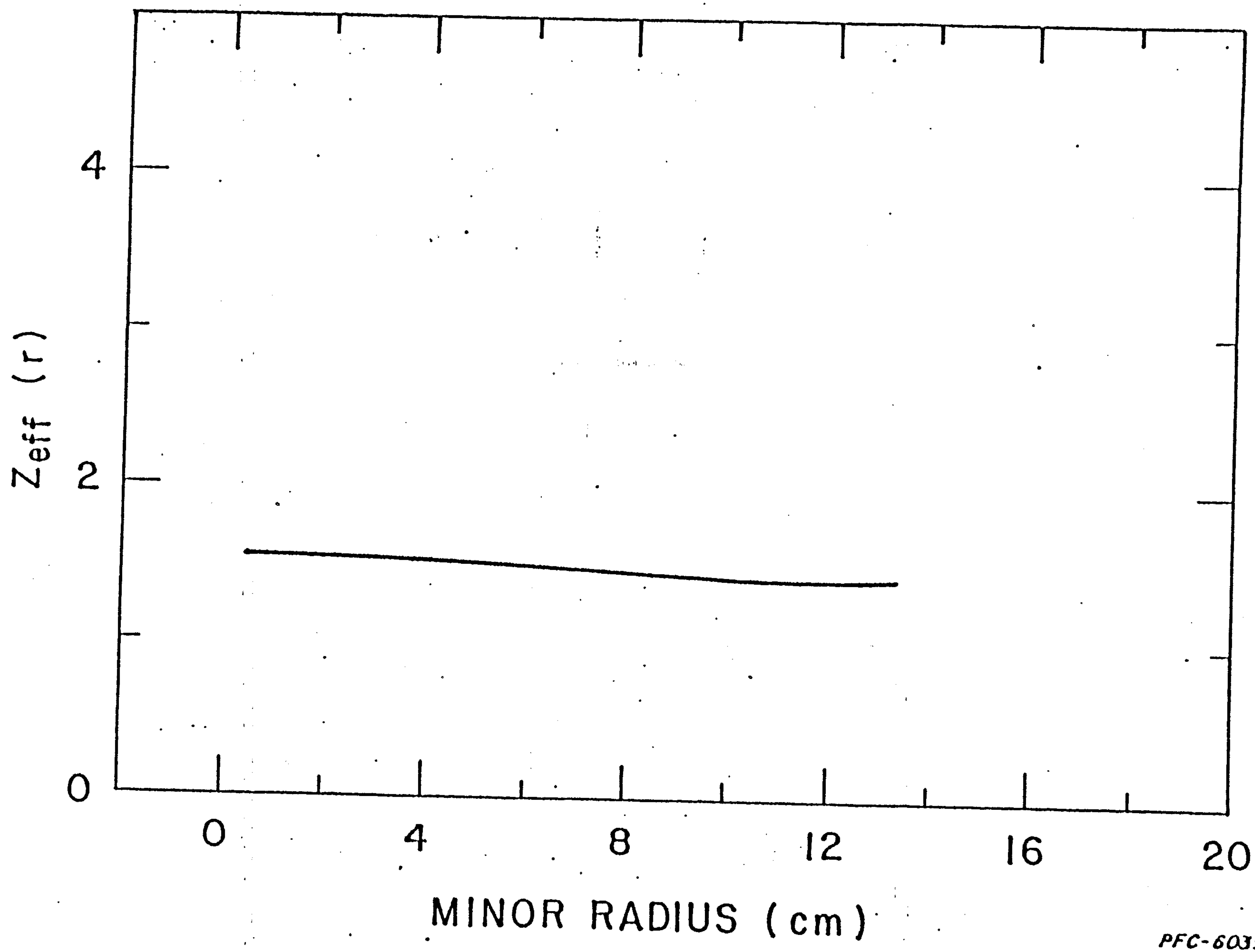
PFC-6040



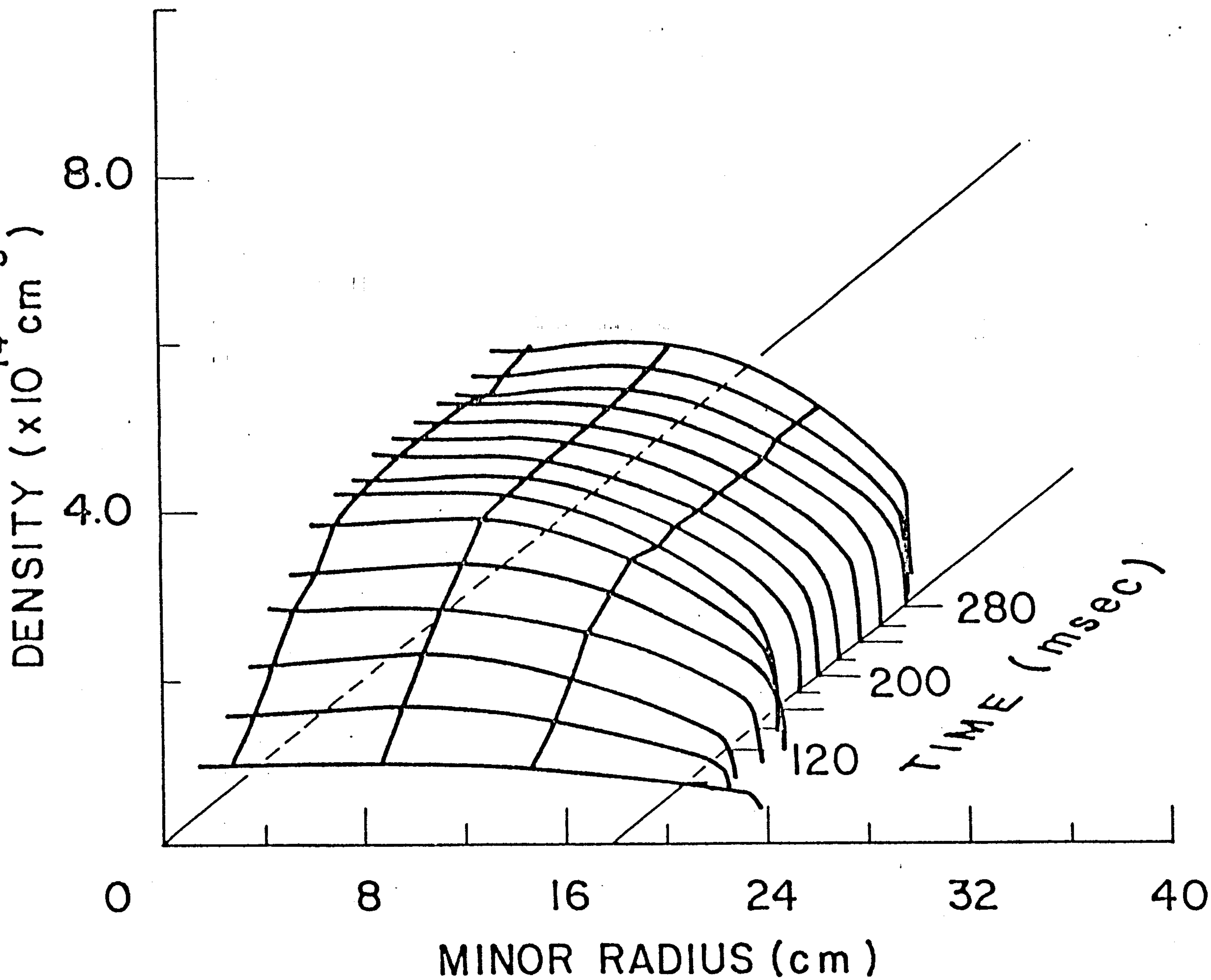
4
3
$\bar{Z}$ 2
1
0
0
100
200
300
400
TIME (ms)



$\bar{n}_e$
PLASMA CURRENT
SOFT X-RAY
B(5360 Å)
0
100
200
300
400
TIME (ms)



PFC-6039


DENSITY (x10^14 cm^-3)
8.0
4.0
0
8
16
24
32
40
MINOR RADIUS (cm)
120
200
280
TIME (msec)

PFC-F041