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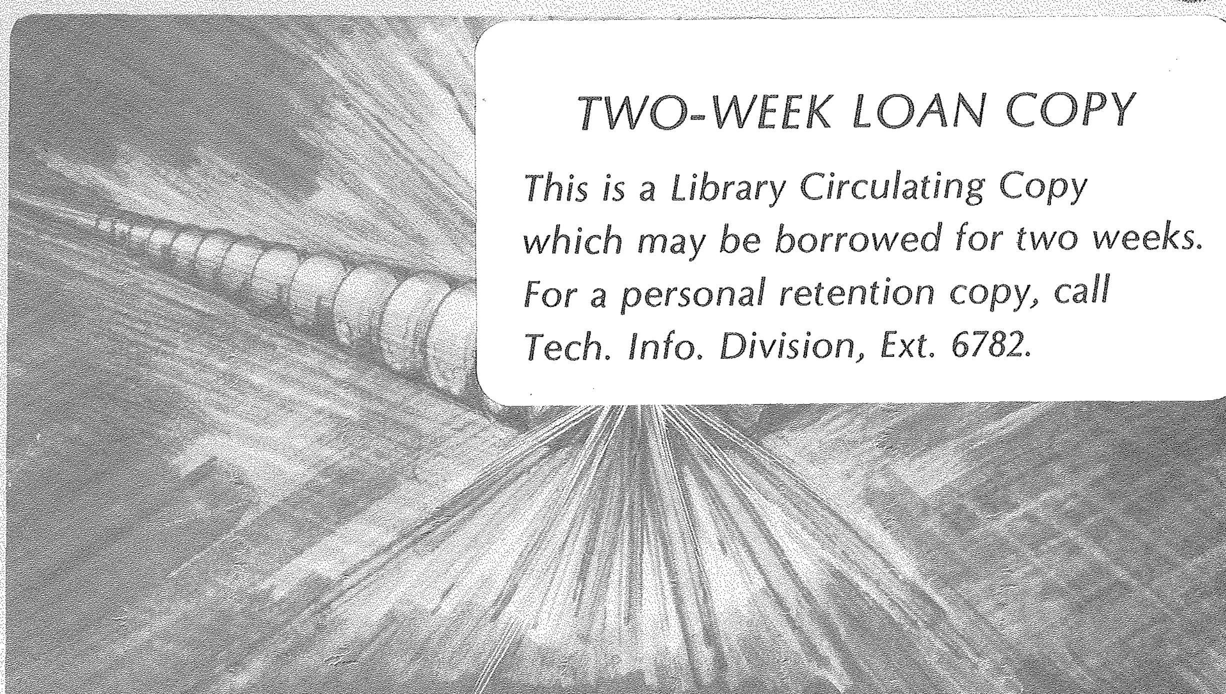

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Observation of Anomalously Broad Gaussian HeII 4686Å Spectral Lines in Tormac*

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Abstract--Gaussian HeII 4686Å spectral lines having full widths at half maximum of over 2Å have been observed in the Tormac plasmas. Interpretation of these widths as due to Doppler broadening would give ion temperatures of > 100eV, in contradiction with other diagnostics. Indications are that these widths are not simply explained by either Doppler broadening or Stark broadening due to interparticle fields. Some evidence exists of nonthermal turbulent conditions, which could broaden the lines by the Stark effect, if there exist large enough electric fields, or by the Doppler effect, if there is appreciable mass motion.

1. Introduction

Spectroscopy has been extensively employed as a diagnostic in Tormac, stuffed toroidal magnetic bicusp experiments having an absolute minimum -B geometry (GALLAGHER, 1970; LEVINE, 1972; SHAW, 1978). A quantity of helium is added to hydrogen or deuterium, and the observed HeII 4686Å line profiles are found to be quite Gaussian. For a time, this was interpreted as Doppler broadening and used as a measure of ion temperature. Widths of over 2Å, corresponding to ion "temperatures" of greater than 100eV, are routinely obtained. However, Thomson scattering measurements (COONROD, 1978; GREENWALD, 1978) indicate an electron temperature of ~5eV. At this temperature and density, ~3 x 10^{15} cm^{-3}, electron drag would drain any initial ion

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energy in a time short compared with the observed broadening, and power input is inadequate to sustain high ion temperatures in the presence of such drag. Since the widths imply a temperature far above that at which helium should be fully ionized, and since Stark broadening is relatively small at these densities, the observed HeII 4686Å line widths are not understood at present.

A number of groups have used the 4686Å line as a diagnostic (HOWELL, 1976, MATT, 1972). Its use depends on the density, temperature, and nature of plasma formation. Until the broadening mechanism in Tormac has been identified, comparison with other experiments is uncertain. However, other groups have experienced anomolous broadening similar to that found in Tormac (FORMAN). Since there is continued interest in the use of this line as a temperature diagnostic (GEORGIOU, 1979), presentation of the Tormac data serves as a useful example of systematic problems in this application.

2. Experiment

The Tormac experiments considered here, T IV-a, T IV-c, and T V, have pyrex vessels, which allow ample spectroscopic access to the plasma. Two versions of the Tormac IV experiment, T IV-a, and T IV-c,were constructed (SHAW, 1978). T IV-c was built to duplicate T IV-a, but has much improved diagnostic access in order to accommodate a Thomson scattering experiment (GREENWALD, 1978) and extensive interferometric and magnetic field studies (COONROD, 1978). The Tormac IV vessel, a glass toroid of rectangular cross section, is illustrated in Figure 1. The experimental sequence of Tormac IV is illustrated in Figure 2. The cycle begins with the introduction of a gas mixture

(75% D_2, 25% He) into the vessel at a pressure of 50m Torr. A slowly rising toroidal bias field of ~300G is then applied and crow-barred at its peak, remaining essentially constant throughout the rest of the experiment. At this point, two preionization banks, charged to 30kV and having frequencies 100kHz and 300kHz are discharged. They induce toroidal electric fields which ionize the gas and generate a toroidal current. After about 25 μsec, the preionizer banks are crowbarred and the main bank is discharged, applying the minimum-B bicusp containment field. This field rises to 4.5kG in ~8μsec and is then crowbarred. The poloidal line integral of the cusp field within the vessel is nonzero, so the rise of the cusp also generates a net toroidal current of a few kA in the plasma. During the rise of the cusp field, an additional bank for shaker heating (15 kV, ~300 kHz, 780J) was discharged in T IV-a. This had been studied as a heating technique during low pressure operation, where some effect was observed with spectral diagnostics. However, no difference in 4686Å line profiles was observed at 50 mTorr, the region of interest here, and shaker heating was not used in T IV-c. The data from T V considered here were also taken without shaker heating.

Spectral measurements are made using a light pipe and sixteen channel polychromator arrangement, 0.39Å channel separation. (MYERS, 1978). The light pipe, 3m in length and 1/8" diameter, is attached to a 3/4m Czerny-Turner type Spex spectrometer, modified to a sixteen channel polychromator by using fiber optics to feed light from the exit slit to the sixteen photomultiplier tubes. The output of each polychromator channel is digitized, producing 128 time samples in 0.5 μsec or 1 μsec steps, and fed into a PDP-11 computer for processing and storage (COONROD, 1975). The light pipe optics consist of a collimator, lens, and Al mirrors at various angles. This allows the light pipe to be moved both in the axial and radial directions in order to gather light at any angle from anywhere within the vessel. A curve fitting routine is then used to analyze the line profile (NILAND). It seeks the best Gaussian or Lorentzian fit to the data by varying the line center, amplitude, width, and continuum level of the fit, minimizing the error,

$$\text{Error} = \sum_{i=1}^{16} [Y(i) - f(i)]^2,$$

where Y(i) is the measured intensity of channel i, f(i) is the value of channel i for the trial fit, and the sum is over the 16 spectral channels.

3. HeII 4686Å Data from T IV

In Figure 3, a line profile from T IV-a is shown, taken along a line of sight near the axial center of the device looking radially inward. The width of this profile is 2.2Å, which corresponds to an ion temperature of ~146eV, if the broadening is assumed to be entirely Doppler. The solid line is the best Gaussian fit. Note that a 6% continuum level has been added to the fit, causing the log plot to bend away from the straight line expected for a Gaussian. These data come from a single time step 1.5 μsec before cusp peak, and the fit is typical for data from a single time step from a single T IV-a shot. If a time average is performed, or if several machine shots are averaged, the Gaussian with continuum fits the experimental points extremely well.

In Figure 4, a line profile from T IV-c is shown, taken at a similar time and line of sight as in Figure 3. Even though these data are from a single time step and a single machine shot, their Gaussian quality is striking. The line width, 1.9Å, is equivalent to an ion temperature of 110eV if Doppler broadening is assumed. Here, a 6% continuum has also been added.

Line profiles taken during the preionization phase, before application of the cusp field, can sometimes be wide and Gaussian, although the light intensity is low and the plasma is known to be only partially ionized. Nevertheless, data have been found for which a Gaussian plus continuum gives a reasonably good fit. Lines of width > 2.4Å, corresponding to > 170eV, have been found.

4. HeII 4686Å Data from T V

Tormac T V is a larger device (BROWN), having a glass vessel with a T-shaped cross and an outer radius of 52 cm. The experimental sequence is similar to T IV, but the main field rises to ~3 kG in 13 μsec. Gaussian lines are also found here, having peak widths typically 1.3-1.5Å, which are less than those found in T IV.

5. Discussion

For ions having a Maxwellian distribution, the intensity profile of a Doppler broadened spectral line is Gaussian and is given by (GRIEM, 1964),

$$I(\lambda) = I_0 \exp\left[-\frac{M_i C^2}{2T_i}\left(\frac{\Delta\lambda}{\lambda}\right)^2\right],$$

where $\Delta\lambda$ is the distance from the line center, λ is the wavelength of the unbroadened line, M_i the mass of the ion, T_i the ion temperature, and c the speed of light. The full width at half maximum is then given by

$$\Delta\lambda = 2^{3/2}(\ln 2)^{1/2}\lambda\sqrt{\frac{T}{M_i c^2}} \quad ,$$

which gives for HeII 4686Å

$$\Delta\lambda = \sqrt{\frac{T}{30.16}}\ \text{Å},$$

where T is the ion temperature in eV. For T = 5eV, $\Delta\lambda$ is .41Å. These relations assume that the plasma is optically thin, gross mass motion is small, and other broadening mechanisms are negligible. For the widths seen in these experiments, both instrumental broadening due to the polychromator and fine structure of the lines are considered unimportant.

Data from T IV and T V has also been fit with a Lorentzian. It was found that a negative continuum level was needed to fit the wings. Therefore, it was concluded from this test, and the goodness of the Gaussian fits, that the experimental data are Gaussian, even though the fits do not necessarily go through each experimental point.

Calculations indicate that the plasma is optically thin at the densities of these experiments. While mass motion may produce some Doppler shift during the cusp field rise, broadening above the thermal level persists after the cusp peaks, which suggests that other mechanisms are also important. Wall effects can be eliminated, since the broadening is seen by lines of sight parallel to the machine axis, and no light at all is seen along the walls by lines of sight looking radially inward.

Other diagnostics (BROWN; COONROD, 1978; GREENWALD, 1978; SHAW, 1978) used on Tormac indicate a plasma of $T_e \sim 5$eV and $n\ell \sim 3 \times 10^{16} cm^{-2}$. Since the only diagnostic clearly at odds with this conclusion is the interpretation of the width of HeII 4686Å as due to thermal broadening, some other mechanism must be responsible for broadening these lines.

It is well-known that hydrogen and ionized helium lines are very sensitive to electric fields because of their linear Stark effect (GRIEM, 1974). Gaussian HeII 4686Å line shapes that are not explained by Doppler broadening have previously been reported (GRIEM, 1969). The broadening was claimed to be Stark broadening due to a Gaussian distribution of suprathermal collective electric field fluctuations. For the linear Stark effect, the relation between the full width of a line arising from a transition $n \rightarrow n'$ and the average turbulent electric field is given by

$$\Delta\lambda \simeq \frac{3}{4}\,\frac{(n^2-n'^2)\hbar\lambda^2}{2\pi Z mec}\,E,$$

where λ is the wavelength of the unbroadened line, m is the mass of the electron, e the charge of the electron, c the speed of light, and E is the electric field strength, in CGS units. For helium, Z is 2. This formula assumes quasistatic broadening; i.e.,

$$\omega\tau << 1,$$

where ω is the frequency of the fluctuating field, and τ is the life-time of the emitter in a given Stark sublevel. The full width of HeII 4686Å due to interparticle fields, including correlation effects, may be written

$$\Delta\lambda \sim 2.9 \times 10^{-14} n_e^{.83} \text{ Å} .$$

In the regime of interest, this is a good approximation to the data presented in GRIEM, 1974. For the densities found in Tormac, this interparticle field does not broaden the lines to the extent observed, giving $\Delta\lambda \sim 0.2$Å for $n_e \sim 3 \times 10^{15} cm^{-3}$.

Under turbulent conditions, large amplitude electric fields may exist in the plasma. It is expected that in fully developed turbulence each component of the electric field obeys a Gaussian distribution (GRIEM, 1969; BEKEFI, 1976). For such a distribution, the wings of any line approach a Gaussian shape, for quasistatic broadening. The fluctuating fields necessary to explain the widths observed are $>$ 30kV/cm. The magnitude of the thermal electric fluctuations which would occur in the Tormac plasma in thermal equilibrium, $T_e = T_i$, are (KRALL, 1973) $\langle E^2 \rangle^{1/2} \sim$ 25kV/cm, which is similar to the mean interparticle Holtsmark field strength, $\sim 8\, e n_e^{2/3}$. Such fields have frequencies centered around the plasma frequency, and, therefore, do not satisfy the quasistatic broadening assumption. These field magnitudes, while significant from the point of view of atomic physics, are within the limit of weak plasma turbulence, i.e. $e\phi < kT$. In the Tormac plasma, this limit is

$$E_{max} < kT/e\lambda_D \sim 165kV/cm.$$

Given the violent startup conditions found in Tormac, field strengths above the thermal fluctuating field level are not necessarily surprising, and fields as high as 100 kV/cm, occurring during cusp field rise in an earlier Tormac device, have been reported (GALLAGHER, 1971, 1973).

In addition, large magnetic fluctuations have been observed with probes during the rise of the cusp field in T IV (COONROD, 1978; GREENWALD, 1978). These perturbations could lead to line broadening, by the Doppler effect, if there is appreciable mass motion, or by the Stark effect, if there is an associated density compression. However, these magnetic fluctuations are unlikely to be associated with strong electric fields, and are not observed after the cusp peak.

The line profiles presented here occur during the cusp field rise. However, after the cusp field peak, Gaussian line shapes having widths of > 1.2Å are observed, with a decay time of ~50 μsec. Persistence of suprathermal turbulence, either electrostatic or electromagnetic, which is driven solely by the rise of the cusp, seems unlikely, and some other mechanism would appear to be required to explain this aspect of the line broadening.

6. Conclusions

Wide Gaussian HeII 4686Å line profiles, $\gtrsim$ 2Å, corresponding to ion "temperatures" of > 100eV, were observed in the Tormac plasmas. Information provided by the other diagnostics indicates that the widths are not explained by either thermal Doppler broadening or Stark broadening due to Holtsmark-type interparticle fields. It is suggested here that non-thermal turbulent conditions are present in the plasma which could broaden the line either by large electric fields or by mass motion. Work is now in progress to investigate such broadening mechanisms.

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Fig. 1 - A schematic cross section of the Tormac IV vessel. The device is toroidally symmetric around the indicated center line.

Fig. 2 - The experimental timing sequence is shown and the currents in the various field coils indicated.

Fig. 3 - A characteristic profile of the HeII 4686Å line from T IV-a, on a linear (left) and logarithmic (right) scale. Data were taken along a line of sight near the axial center of the device looking radially inward at a time 1.5 μsec before cusp field peak. The full width at half maximum is 2.2Å.

Fig. 4 - A characteristic profile of the HeII 4686Å line from T IV-c, on a linear (left) and logarithmic (right) scale. Data were taken along a line of sight near the axial center of the device looking radially inward at a time 2 μsec before cusp peak. The full width at half maximum is 1.9Å.

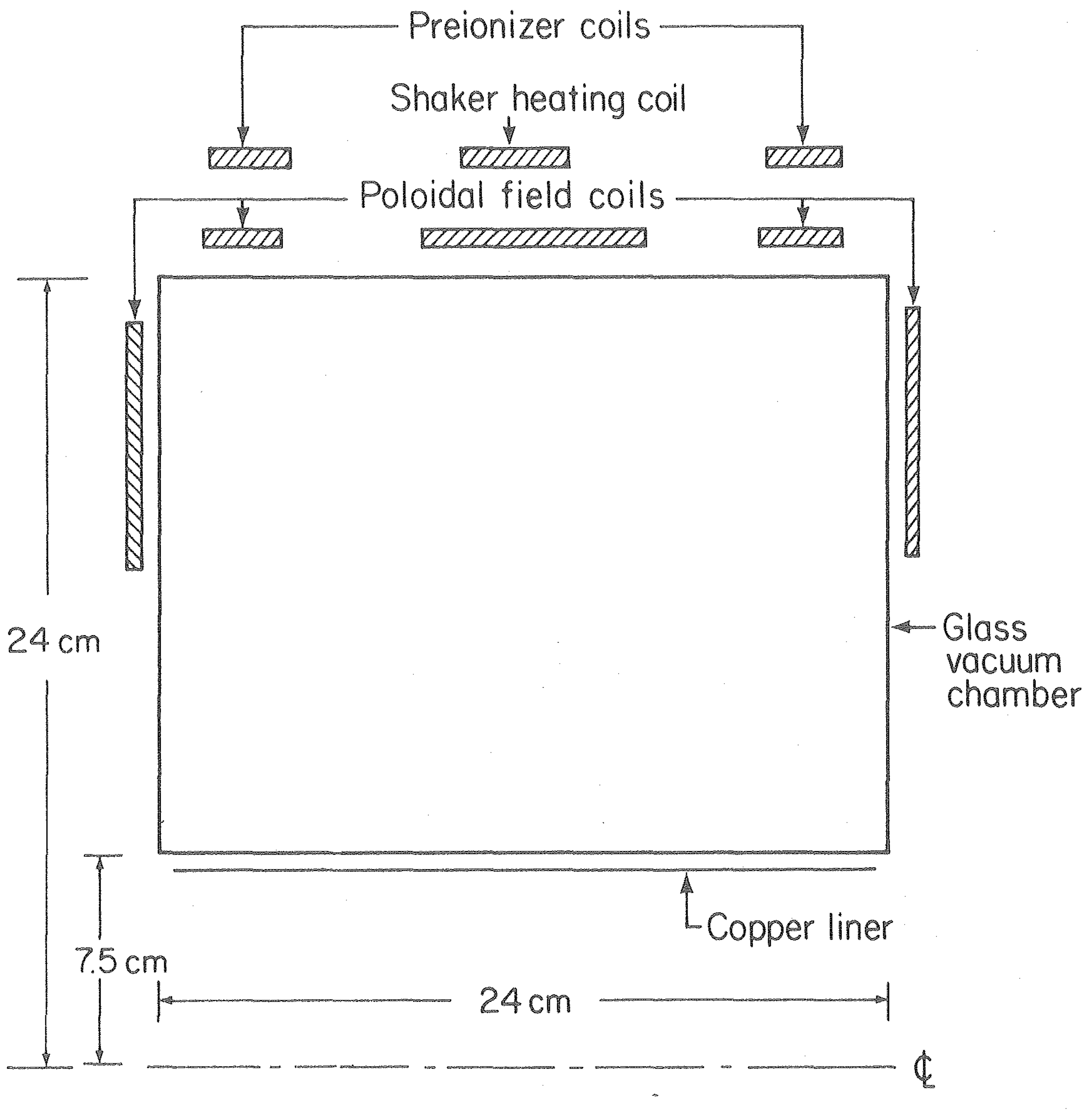
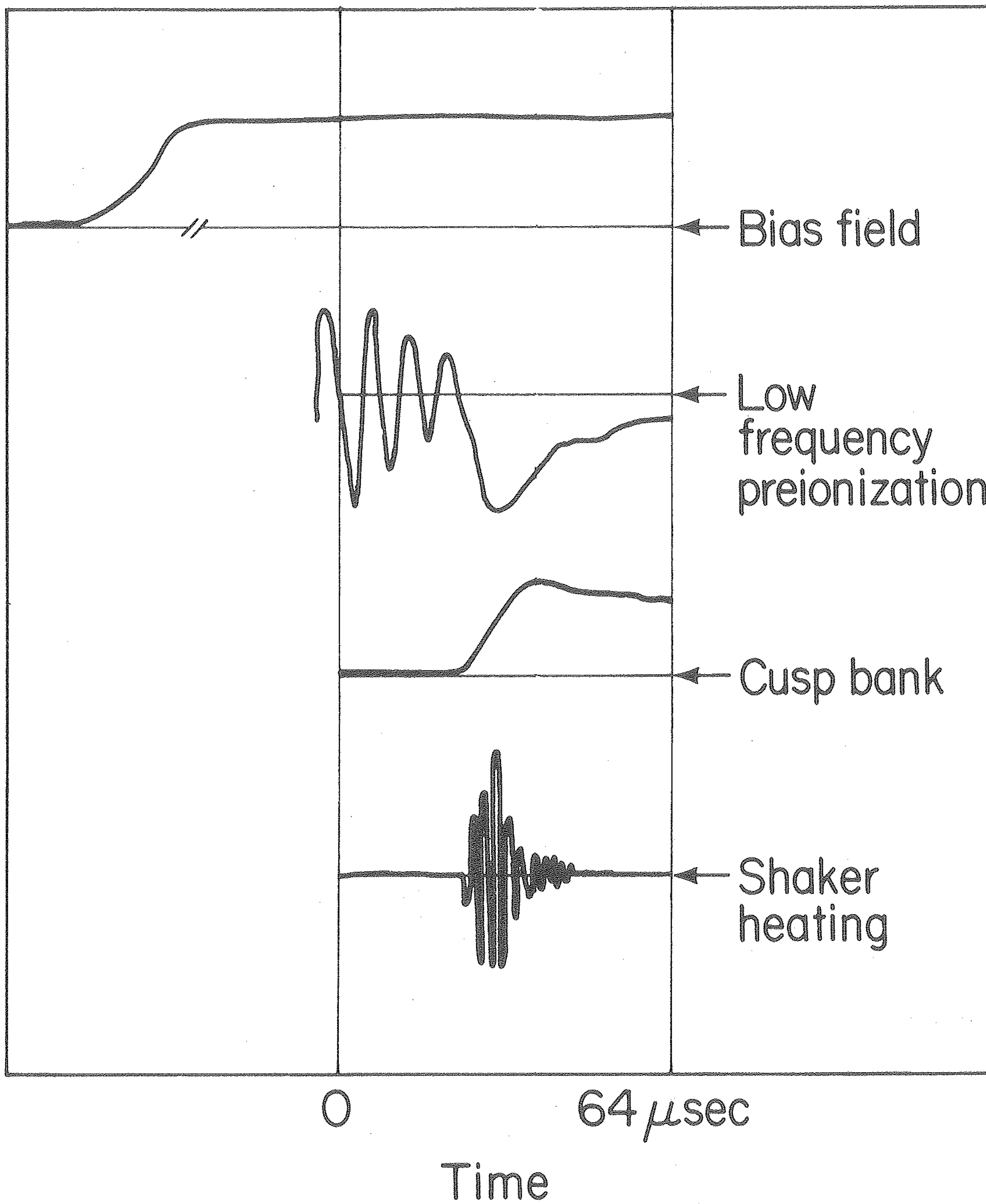
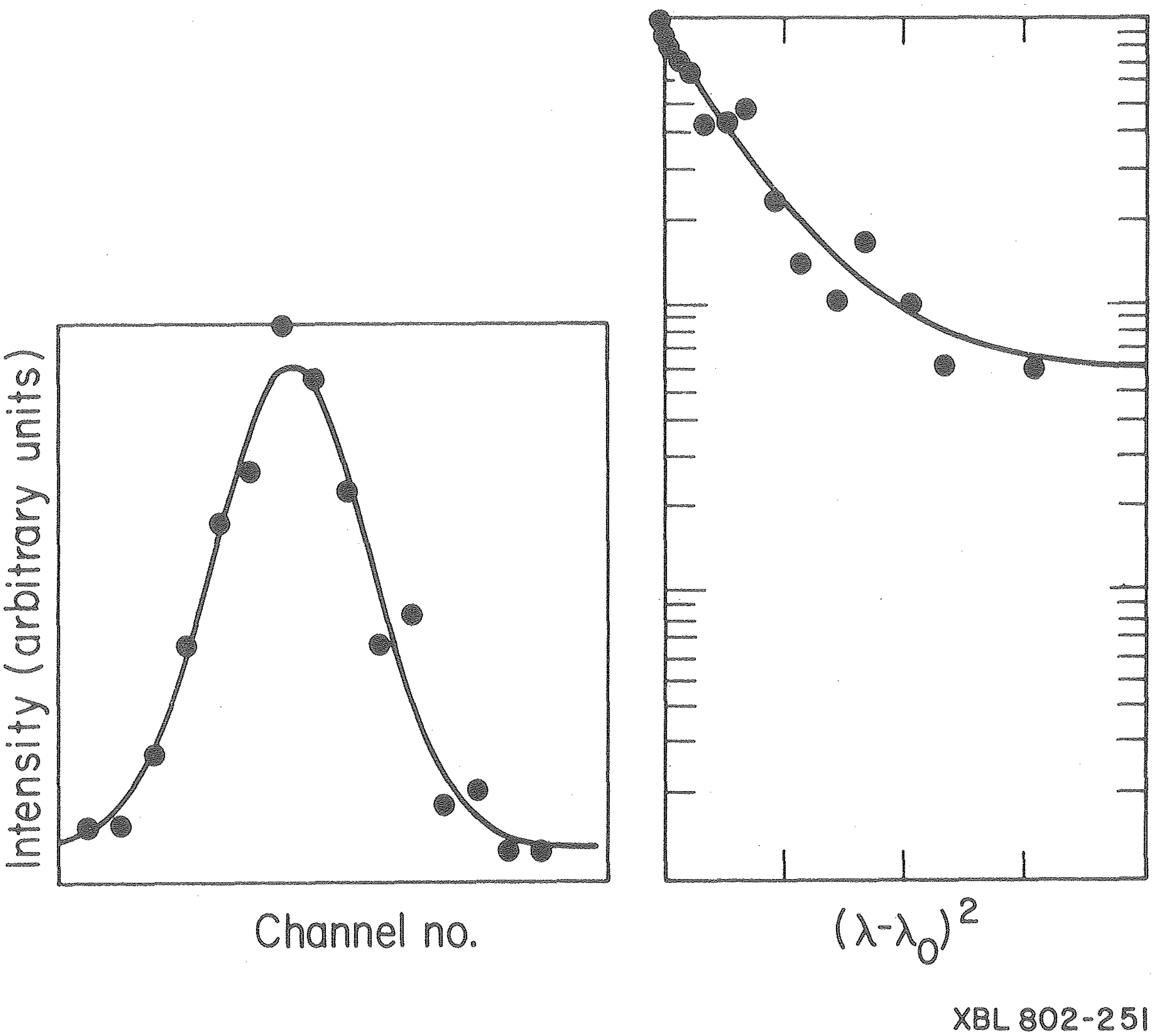

Preionizer coils
Shaker heating coil
Poloidal field coils
24 cm
Glass
vacuum
chamber
Copper liner
7.5 cm
24 cm
XBL 794-1281A

Fig. 1



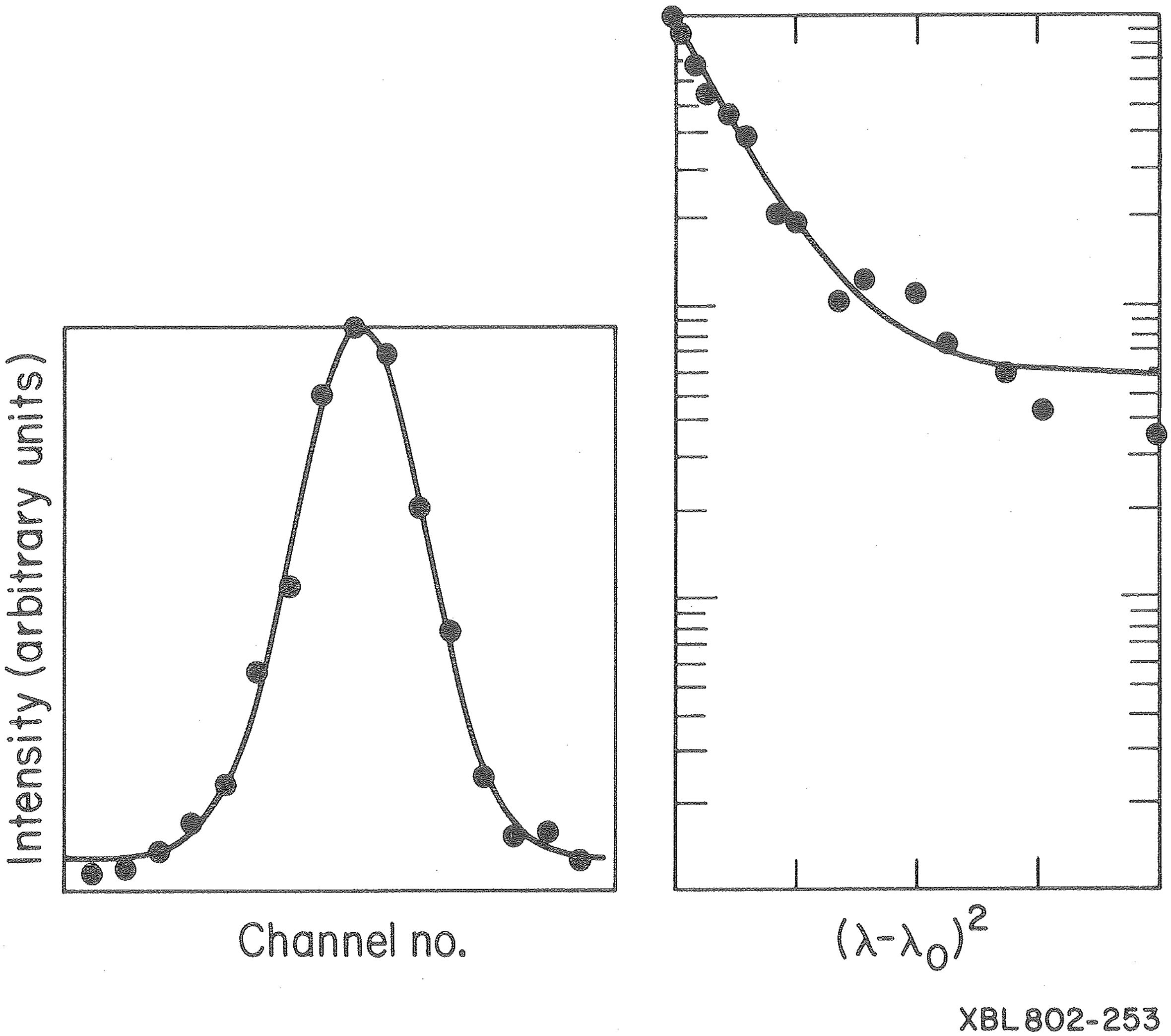
XBL 794-1278A

Fig. 2



Intensity (arbitrary units)
Channel no.
$(\lambda-\lambda_0)^2$
XBL 802-251

Fig. 3



Intensity (arbitrary units)
Channel no.
$(\lambda-\lambda_0)^2$
XBL 802-253

Fig. 4