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A COMPARISON OF SPECTRAL DATA FROM TORMAC T IV-a AND T IV-c

R. S. Shaw, B. R. Myers, and M. C. Vella

September 1978

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1. Introduction

A study has been made of the comparable spectral data presently available from two versions of the Torrac IV experiment, a stuffed toroidal magnetic bicusps. The original device¹ is known as T IV-a. In order to verify the high temperatures inferred from line widths from that experiment,² a new vessel with much improved diagnostic access, T IV-c, was constructed.³ In addition to the diagnostics used on T IV-a, this device was designed to accommodate a Thomson scattering experiment⁴ and extensive interferometric and magnetic field studies.⁵ Along with circuit current and voltage characteristics, spectral data provide the most comprehensive basis for comparison of the two experiments. Access limited interferometric studies were also carried out on T IV-a, and provide a limited comparison. Both devices used the same support hardware: capacitor banks, polychromator, electronics, and data acquisition system. T IV-c has been operated in two distinct modes; the initial configuration is designated here as T IV-c1. Modifications were later made with the intention of producing a more detailed replica of T IV-a. These included two shorted toroidal copper straps around the outer machine circumference, and changes in the preionization and bias windings. This resulted in a noticeably different discharge, and this configuration is designated T IV-c2. Most of the data considered in this report from the new vessel are from the c1 version, which gave somewhat better performance.

In this report, representative spectral data from T IV-a are compared with data from T IV-c obtained under similar conditions; i.e., 15 kV cusp bank voltage, 30 kV preionizer bank voltage, 2 kV bias bank voltage and 50 mTorr gas fill pressure. Two spectral lines, He II $4686 \text{ \AA}$ and D γ $4861 \text{ \AA}$ are studied. Line of sight data from the two devices, taken using a light pipe and mirror arrangement, are compared. The data were also used as inputs to a computer assisted tomographic reconstruction, the results of which are discussed. Comparison was made on the basis of the intensity and shape of the spectral lines as functions of position and time.

Above 40 mTorr fill pressure, broad Gaussian profiles of the $4686\text{ \AA}^{\text{O}}$ line were observed in T IV-a; the data presented here were taken at 50 mTorr. Extensive plasma studies, carried out at comparatively low pressures, 10 to 30 mTorr, did not give notably broad lines and are not reported here. The cusp bank voltage was varied from 12 to 20 kV (i.e., equivalent to vacuum cusp fields from 3.2 to 5.5 kG at the vessel center). Spectral data revealed some increase in intensity with bank voltage, but no significant increase in line width. The present data were taken at 15 kV. Circuit current and voltage characteristics of the present data are the same as from data representative of the best performance reported for T IV-a. Thus, the data presented here are representative of T IV-a.

In the past, reports of the experimental results have relied heavily on analysis of the line of sight and reconstructed spectral data. The intention here is not to analyze the spectral data as a plasma diagnostic per se, or to offer an explanation of the HeII $4686\text{ \AA}^{\text{O}}$ line broadening. The data are compared for the purpose of deciding whether the results obtained from T IV-c with Thomson scattering, interferometer, and probe diagnostics^{4,5} are indicative of conditions in T IV-a.

II. Experimental Background

Tormac is a stuffed toroidal magnetic bicuspid experiment having an absolute minimum-B geometry.^{6,7} The Tormac IV vessel is a glass toroid or rectangular cross section, with dimensions as shown in Fig. 1. The experimental sequence, illustrated in Fig. 2, begins with the introduction of a gas mixture (75% D₂, 25% He) into the vessel at a pressure of 50 mTorr. A slowly rising toroidal bias field of 300 G is then applied and crowbarred at its peak, remaining essentially constant throughout the rest of the experiment. At this point, two preionizer banks, charged to 30 kV and having frequencies of 100 kHz and 300 kHz, are discharge. They induce toroidal electric fields which ionize the gas, freeze in the bias field, and generate a

toroidal current.⁸ After about 25 μ sec, the preionizer banks are crowbarred and the main bank is discharged, applying the minimum-B bicuspid containment field. This field rises to 4.5 kG and is then crowbarred. The time datum $t=0$ is arbitrarily set a few microseconds after discharge of the preionization bank. In Tormac IV, 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. During the rise of the cusp field, an additional bank for shaker heating⁹ (15 kV, 300 kHz, 780 J) 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 4686 $\text{\AA}$ line profiles was observed at 50 mTorr, the regime of interest here, and shaker heating was not used in T IV-c.

The spectral lines studied in this report are HeII 4686 $\text{\AA}$ and D γ 4861 $\text{\AA}$. The measurements were made using a light pipe and sixteen channel polychromator arrangement, 0.39 $\text{\AA}$ channel separation.¹⁰ The light pipe, 3m in length and 1/8" diameter, was 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 and fed into a PDP-11 computer for processing and storage.¹¹ Four angular views covering the entire vessel were taken, and are designated 90 $^{\circ}$ Z, 90 $^{\circ}$ R, 45 $^{\circ}$, and 135 $^{\circ}$. The labeling scheme used for identifying the optical views in the two devices is shown in Fig. 3 and Table 1. The data were collected by positioning the light pipe at each line of sight for at least one shot. More than one shot at each line of sight position was taken in order to estimate the effect of shot to shot variation.¹⁰ Thus, a single scan of the entire vessel requires a minimum of 88 plasma shots for each spectral line. The light pipe optics used in T IV-a consisted of a collimator, lens, and Al mirrors of various angles; these were changed in T IV-c in order to provide better light gathering efficiency. This

change, combined with the subsequent change in the polychromater photomultiplier tubes from RCA #1P28A to #4860 and the lack of an absolute calibration, means that the magnitude of the signals from the two devices are not directly comparable. Other differences in diagnostic information derived from the two devices are summarized in Table 2. In particular, a full four view scan of D β in T IV-c has not been completed at this time.

The comparison of the line of sight data is presented in Sections IV and V. Section VI concerns the results of a tomographic reconstruction of the line of sight data, which had previously been relied on for interpretation of the experimental results. However recent investigation¹² has revealed problems with this application of tomography, and additional experimental difficulties were encountered. Therefore, the results of the reconstruction are presented for heuristic purposes.

III. Spectral Broadening

The Stark effect is the splitting of spectral lines by electric fields. Both HeII 4686 $\overset{\circ}{\text{\AA}}$ ($n = 4$ to $n = 3$ transition) and D β 4861 $\overset{\circ}{\text{\AA}}$ ($n = 4$ to $n = 2$ transition) are strongly Stark split due to the fact that one electron atoms and ions are subject to the linear Stark effect, which is greater than the more common quadratic Stark effect.¹³ In a plasma, the electric fields causing the splitting can be generated both by neighboring individual charged particles and by collective effects. Taking the broadening due to electrons (impact approximation) and ions (quasistatic approximation) into account, and including correlation and shielding effects due to surrounding ions and electrons, the full width at half maximum of D β and HeII 4686 $\overset{\circ}{\text{\AA}}$ may be expressed as follows:^{14,15}

$$\begin{aligned}\Delta\lambda^{DE} &= 2.0 \times 10^{-10} n_e^{2/3} \text{ \AA} , \\ \Delta\lambda^{4686} &= 2.91 \times 10^{-14} n_e^{4/5} \text{ \AA} ,\end{aligned}\quad (1)$$

where $\Delta\lambda$ is the full width at half maximum and n_e is the electron density in cm^{-3} . The temperature dependence of the Stark effect for these two lines is weak. It is assumed here that the plasma is optically thin. Natural plasma modes can cause further broadening,^{13,16} if the fields are strong enough (a few keV/cm). High frequency fields can also create satellites on the broadened spectral line.¹⁷⁻²⁰

The Doppler effect is the shift of a spectral line due to motion of the emitter (or receiver).¹⁵ If the ions have a Maxwellian distribution, then the intensity profile of the spectral line is Gaussian and is given by

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

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

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

Therefore,

$$\Delta\lambda^{DE} = \sqrt{\frac{T}{15}} \text{ \AA} , \quad (4)$$

and

$$\Delta\lambda^{4686} = \sqrt{\frac{T}{30}} \text{ \AA} , \quad (5)$$

where T is the ion temperature in eV. These relations assume that the plasma is optically thin, gross mass motion is small, and other broadening mechanisms are negligible. For the polychromator used in these experiments, the instrumental broadening is a 20% correction to the half width for $T \sim 25$ eV and becomes negligible

for $T = 40$ eV. The fine structure of the lines²¹ is considered unimportant in the temperature range dealt with in this report.

A curve fitting routine has been used to analyze the line profile.²² It seeks the best Lorentzian or Gaussian fit to the data by varying the line center, amplitude, width, and continuum level, minimizing the error,

$$\text{Error} = \sum_{i=1}^{15} [Y(i) - f(i)]^2, \quad (6)$$

where $Y(i)$ is the measured intensity of channel i , $f(i)$ is the value of the channel i for the trial fit, and the sum is over the 15 spectral channels used. The data were consistently found to give poor fits to a Lorentzian but often fit a Gaussian quite well. At the experimental density, $\sim 3 \times 10^{15} \text{ cm}^{-3}$, the electrons and ions are expected to equilibrate in a time short compared with the experiment. This makes the observed HeII spectral widths (i.e., equivalent to ~ 100 eV) a puzzle, since this is far above the temperature at which He should be fully ionized, and any low temperature material along the line of sight should dominate the emission. Thus, the observed broadening is not understood at present, and no attempt is made here to provide an explanation. In the past, the HeII line width has been reported as an equivalent temperature. Strictly for the sake of comparison, all 4686 Å half widths are reported here in both eV and Å, although all corroborating evidence indicates that the broadening is not thermal.

IV. Line of Sight Data - HeII 4686 Å

The time history of the total intensity of HeII 4686 Å light in the 90° view was obtained by summing the data from all spectral channels in all 90° lines of sight for each time step. This is shown in Fig. 4 (T IV-a) and Fig. 5 (T IV-cl). As mentioned previously, changes in the optical system make an absolute comparison meaningless. Therefore, the relative total intensity has been plotted, normalized

separately to the peak in each machine. This same procedure has been used for the 90°R view, Fig. 6 (T IV-a) and Fig. 7 (T IV-cl). Figures 8 and 9 show the 90°Z and 90°R view for T IV-cl extended to 128 μ sec. Prominent qualitative features are:

1. The evolution of the (relative) total intensity beginning with the rise of the cusp (~ 25 μ sec) is remarkably similar in both views and both vessels.
2. Peak intensity occurs from 38-48 μ sec, somewhat after the cusp peak (~ 33 μ sec).
3. Emission during pre-ionization (10-25 μ sec) was 10% of peak for T IV-cl, but barely resolvable, ~ 2 %, for T IV-a, indicating better preionization in T IV-cl. This was confirmed by inspection of individual line of sight data, noting that almost no measurable emission was observed in T IV-a, while signals 17% of the peak along any single line of sight were observed in T IV-cl.
4. The rise of intensity with the cusp in T IV-a begins 1 μ sec earlier than T IV-cl. This is within experimental uncertainty of the location of the time datum, $t = 0$.
5. From Figs. 8 and 9 the intensity in T IV-cl falls exponentially over two orders of magnitude with a time constant of 18 μ sec. This is consistent with flow of a few eV plasma out along the open field lines at the sound speed, beginning 5-7 μ sec after the peak of the cusp.

Thomson scattering measurements⁴ indicate an electron temperature in T IV-cl of ~ 5 eV. If an LTE model is assumed, HeII 4686 Å emission peaks at ~ 3.8 eV; a corona model peaks at ~ 7 eV. The actual experimental conditions in Tormac are

probably bracketed by these models. Thus, the observed history of the $4686\text{ \AA}$ line is consistent with weak burnout during the rise of the cusp, followed by peak emission a few microseconds later as the plasma cools. The line of sight data from each of the four views are discussed separately below.

90°Z

From Fig. 3, the 90°Z scan looks radially inward. A plot of the relative total intensity of each line of sight (i.e., summed over all spectral channels) vs Z number is given in Fig. 10 for both devices at the cusp peak, 33 μsec , where the intensities have been normalized separately for each machine to the peak intensity seen along any 90°Z line of sight at any time. The devices are similar in that they both exhibit a bright region near the center, with little emission along the edges. One apparent difference in the two experiments is that the relative intensity rose more quickly in T IV-a from 25-28 μsec , after which both were high. As mentioned previously, this is probably explained by uncertainties in timing.

The intensity of each polychromator channel vs time and the spectral lineshapes were investigated along each line of sight. In T IV-a, three regions were found, each having a distinctive intensity vs time signature. Consistent with Fig. 10, the first region is a low intensity region near the vessel walls on both sides of the vessel: 90°Z 1-5 and 90°Z 17-20. Due to the low intensity, line profiles could not be fit in these regions. The second region, designated the transition region, is found on both sides of the vessel: 90°Z 6-8 and 90°Z 14-16. This region is characterized by a double peaked intensity signature and is illustrated in Figs. 11 and 12, where the various channels are identified in Table 3. The first intensity peak occurs during the cusp rise, the dip near the second peak approximately 6 μsec after cusp peak. It is possible that the intensity signature in this transition region might indicate local burnout of the $4686\text{ \AA}$ line. The broadest line of sight profiles are observed in this transition region during the rise of the cusp field

(23-33 μ sec). For example, at 31.5 μ sec the profile from 90°Z 8 (Fig. 13) has a spectral width equivalent to 154 eV ($2.2 \text{ \AA}$). This was observed to fall to 112 eV ($1.94 \text{ \AA}$) at 34 μ sec, and to 97 eV ($1.8 \text{ \AA}$) at 37 μ sec. This is the broadest line of sight profile found to date in this T IV-a data, and gives a good fit to a Gaussian. The third region, located at 90°Z 9-13, is characterized by a single peaked intensity vs time signature, illustrated in Fig. 14 for 90°Z 11. At 34 μ sec this corresponds to 120 eV ($2.01 \text{ \AA}$).

The general features of the 90°Z intensity vs time curves from T IV-c1 are very similar to T IV-a, as summarized in Table 4. Data from the transition region, 90°Z 6, are shown in Fig. 15. The 24 data channels from T IV-c1 are identified in Table 5. The T IV-c1 profiles are somewhat more Gaussian, as seen in Fig. 16, 90°Z 7 at 31 μ sec. Typical spectral widths from T IV-c1 in the 90°Z view are less than T IV-a; i.e., ~ 110 eV ($1.92 \text{ \AA}$) compared with ~ 150 eV ($2.24 \text{ \AA}$). It is interesting to note that spectral lines occurring during the preionization phase of T IV-c1 are remarkably similar to the lines occurring after cusp discharge in both T IV-a and T IV-c. The broadest profile in either set of data was observed in T IV-c1 during preionization from 90°Z 10 at 14 μ sec. This profile is shown in Fig. 17 and corresponds to 175 eV ($2.42 \text{ \AA}$). Due to low intensity, 4686 $\text{\AA}$ profiles were not observed during preionization in T IV-a.

90°R

The 90°R view looks across in Z at various major radii, Fig. 3. Differences between the two devices are readily apparent in this view. Figures 18-21 show the relative total intensities of the line of sight data vs R number for both devices for four times after cusp discharge. The data are normalized separately for each machine to the peak intensity observed along any line of sight at any time. The following features are evident:

1. At $t = 27$ sec, intensity of $4686 \text{ \AA}$ in T IV-cl is much lower than in T IV-a, probably due to timing uncertainties.
2. Up to cusp peak at 33 sec the two devices are qualitatively similar; i.e., the brightest region is at small major radius. However, the variation in intensity at any time from the outer to the inner wall is much greater in T IV-a than in T IV-cl.
3. After cusp peak, the two plasmas evolve differently. In T IV-a, the profile remains qualitatively unchanged, but in T IV-cl, the region of peak intensity has moved to the outer wall.
4. By 38 sec, differences in intensity extremes in both devices are less, and disappear by $t = 45$ sec.

As in the $90^\circ Z$ scan, the behavior of the line of sight $90^\circ R$ data from T IV-a divides into three regions. One region, $90^\circ R$ 1-3, was never observed to have appreciable relative intensity. Data from $90^\circ R$ 2 are shown in Fig. 22. The fits to the profiles are poor and not as broad (90 eV) as the profiles from the bright regions. A transition region having double peaked intensity vs time curves similar to that in the $90^\circ Z$ view is apparent in $90^\circ R$ 4-6; $90^\circ R$ 4 is shown in Fig. 23. As in the $90^\circ Z$ view, line profiles from the transition region are very broad. The bright region is single peaked in intensity vs time; e.g. $90^\circ R$ 8, (Fig. 24). The region next to the inner wall, $90^\circ R$ 9-10 was bright but diminished from $90^\circ R$ 7-8, with profiles as wide as those of the transition region, but more Gaussian.

T IV-cl is different from T IV-a in that only two regions are present: a bright region, $90^\circ R$ 8-10, and a very bright region, $90^\circ R$ 1-7 (see Table 6). T IV-cl exhibits no low intensity or definite transition regions in the intensity vs time plots from $90^\circ R$. When the peak intensity is at the inner wall, $90^\circ R$ 9-10, early in time (~ 27.5 sec), the intensity is relatively low. It then increases and moves out in

time, forming the very bright region, 90°R 1-7. The spectral data from T IV-c1 exhibit strong oscillations, as shown in Fig. 25, 90°R 1. These were not seen in the T IV-a data, and are unexplained at present. The line profiles from this view are gaussian, as shown in Fig. 26, 90°R 7 at 32 sec, and are at least as broad as those from T IV-a.

4.5° and 135°

Line of sight data from the 4.5° and 135° views corroborate the evidence from the 90°R and 90°Z views for both devices and are not presented in detail. In particular, these views confirm the localization of the emitting region near the Z-center of the chamber. As in the 90°Z view, no appreciable 4686 Å° emission is observed in the sides; i.e., 90°Z 1-4 and 90°Z 17-20. This may indicate either that there is no plasma in this region, or that $T \approx 3\text{ eV}$.

Summary: Hel I 4686 Å°

In summary, examination of comparable 4686 Å° line of sight data from T IV-a and T IV-c1 indicates the following general similarities during 15 kV and 50 μTorr operation:

- a. Most 4686 Å° emission begins with the rise of the cusp at 25 sec.
- b. The total intensity peaks after the cusp around 38-43 sec, and decays with a time constant of 18 sec.
- c. The emitting region is localized and nearly centered in Z.
- d. Peak intensity does not occur at the same time along every line of sight.
- e. Wide Gaussian profiles corresponding to an ion temperature of $\sim 100\text{ eV}$ (1.80 Å°) are observed in both devices between 27 and 40 sec.

The following differences were noted:

- a. Preionization in T IV-c1 produced significantly more relative intensity than T IV-a.
- b. From the $90^\circ R$ view, T IV-a was not observed to have appreciable emission at large R. T IV-c1 was bright in all ten R views, with the brightest region moving from the inner to the outer wall after cusp peak. Since no appreciable emission was observed at any time in the outer region T IV-a, it is conjectured that this region was very cold (< 3 eV) at all times.
- c. Prominent, presently unexplained oscillations were observed in T IV-c1 spectral data.

V. Line of Sight Data - D₂ 4861 Å

A complete four view scan of D₂ light has been done in T IV-a, but not in T IV-c at this time. Very few measurements of D₂ light were made in T IV-c1, the configuration discussed for the 4686 Å line. However, in T IV-c2, a complete $90^\circ R$ scan was done and is discussed briefly, with the understanding that the discharge was notably different from T IV-c1.

$90^\circ Z$

$90^\circ Z$ scans were done only in T IV-a, and will not be discussed in detail. Figure 27 shows total intensity along the line of sight vs z number for $t = 33$ sec. This is typical for times after cusp peak, and, as with 4686 Å, most light comes from the central region. Spectral lines from this region show broadening similar to the $90^\circ R$ scans through the bright region, discussed below.

4.14

The total intensity of D_{α} 4861 Å light in the 90°R view vs time is shown for T IV-a in Fig. 28, and for T IV-c2 in Fig. 29. Each of these figures has been normalized separately to the peak. The behavior is very different for the two devices. In T IV-a, the light intensity is approximately constant during most of the acceleration phase, having approximately 20% of the peak intensity. With cusp rise, the light intensity increases, reaching a maximum somewhat after cusp peak. Late in time there is a gradual decrease in total intensity. In contrast with this behavior, T IV-c2 shows a rapid rise to peak intensity in ~5 sec, after which there is a decrease. (In these T IV-c2 data, the cusp bank was discharged from 30-39 sec.) A slight dip in intensity occurs with the rise of the cusp. Late in time, the intensity remains constant, even out to 120 sec (not shown in Figure 29). Figure 30 shows the total intensity vs time for one line of sight (between R=9 and 10) from T IV-c1. Since this is the only data available, comparison with T IV-a and T IV-c1 may be of limited value. However, the general features of T IV-c1 (Fig. 30) do appear to resemble the data from T IV-a (Fig. 28). In addition, comparison of the behavior of this particular line of sight vs time with the total intensity of the 90°R view vs time for both 4861 Å and D_{α} in both T IV-a and -c2 reveals that this view was representative of the overall behavior in those cases.

The total intensity along each line of sight vs R number is shown for four times, in Fig. 31 for T IV-a, and in Fig. 32 for T IV-c2. The following features are evident:

- a) Breakdown for both devices begins at large major radius.
- b) Just prior to cusp bank discharge, the brightest region is near the inner wall, and remains there throughout the rest of the experiment. The effect of the cusp field is to increase the intensity of the emitting region without changing its location.

- (c) After cusp peak, the extremes in intensity at any one time are greater in T IV-a.

The full width at half maximum of the D γ lines from T IV-a at large major radii are relatively small, 1-1.5 $\text{\AA}$, for times during cusp rise until 35 μsec . During this same time, points near the inner wall show widths of 1-1.2 $\text{\AA}$. As time increases, the widths of the lines from the outer regions increase to 4-5 $\text{\AA}$, while the widths of the inner region lines decrease to 5-7 $\text{\AA}$, for times up to 60 μsec . T IV-c2 shows similar trends, but much less extreme. Up to 40 μsec , the large major radius areas show broadening of 2.7 - 3 $\text{\AA}$, while the small radius areas show 3.8 - 4.5 $\text{\AA}$ widths. As time increases, the widths from the regions become more equal, with the outer points increasing and the inner points decreasing in width. Late in time (100 μsec) the widths are essentially equal. Interpreting the widths of the D γ lines as due to the Stark effect caused by the presence of charged particles, the density is seen to be highest near the inner wall in both machines. This agrees with interferometric measurements done on T IV-c.⁵ The density variation for times after cusp discharge seems to be more extreme in T IV-a, where $n=1-1.4 \times 10^{16} \text{ cm}^{-3}$ for points near the inner wall, and $n=3-6 \times 10^{14} \text{ cm}^{-3}$ for points at large major radii, for times up to 35 μsec . In T IV-c2, $n=2.5 - 3.3 \times 10^{15} \text{ cm}^{-3}$ near the inner wall and $n=1.5 - 1.8 \times 10^{15} \text{ cm}^{-3}$ near the outer wall. Late in time, the density tends to become more uniform in both machines.

VI. Reconstruction

Eighty-eight line of sight data scan the vessel in four angular views: twenty $90^{\circ}Z$ scans, ten $90^{\circ}R$ scans, twenty-nine 45° , and twenty-nine 135° scans. In order to obtain spatially and temporally defined spectral line shapes and intensities from these data, a computer assisted tomographic (CAT) method was used.^{10, 23, 24} The cross section of the vessel was divided up into a 10 by 20 square array, 0.5 inch on a side (Fig. 3). A multiplicative algebraic reconstruction technique (ART)²⁵ was used to produce 16 numbers (15 polychromator channels plus total intensity) per grid square per time step.¹⁰ For T IV-a, each line of sight measurement¹ was repeated three times to give an average and standard deviation for that position and angle. Due to limited operating time, T IV-cl measurements³ were made only once. ART takes one channel at each time step as input, and produces 200 averages and standard deviations as output. With 88 inputs, it is obvious that this process is underdetermined. In this case, ART attempts to converge to the best least squares solution.²²

Any reconstruction algorithm, whether fully determined or not, requires consistent input data to converge to a physically correct solution. Here, assuming the plasma is optically thin, consistent input data would have the property that the total amount of light seen in each spectral channel would be the same in each of the 90° views, since each view scans the entire vessel (the 45° and 135° views should also be equal). For example, for the twenty $90^{\circ}Z$ scans, the total intensity seen in this view for a given spectral channel is given by,

$$I_{TOT}^{(90^{\circ}Z)} = \sum_{j=1}^{20} I_j^{(90^{\circ}Z)} = \sum_{j=1}^{20} \sum_{i=1}^{10} \epsilon_{ij} W_{ij}^{(90^{\circ}Z)}$$

where $I_j^{(90^{\circ}Z)}$ is the measured intensity of the jth line of sight for a given channel, ϵ_{ij} is the emission coefficient for that grid square, and $W_{ij}^{(90^{\circ}Z)}$

is the weighting factor giving the length of that line of sight through that grid square. For the ten 90^0R scans,

$$I_{\text{TOT}}^{(90^0\text{R})} = \sum_{i=1}^{10} I_i = \sum_{i=1}^{10} \sum_{j=1}^{10} i,j W_{i,j}^{(90^0\text{R})} \quad ,$$

From Fig. 3, $W_{i,j}^{(90^0\text{L})}$ should equal $W_{i,j}^{(90^0\text{R})}$ since the grid is a square, so that

$$\frac{I_{\text{TOT}}^{(90^0\text{L})}}{I_{\text{TOT}}^{(90^0\text{R})}} = 1$$

Similarly, it is expected that $\frac{I_{\text{TOT}}^{(45^0\text{L})}}{I_{\text{TOT}}^{(135^0\text{L})}} = \frac{I_{\text{TOT}}^{(90^0\text{L})}}{I_{\text{TOT}}^{(90^0\text{R})}}$, since these views are along the diagonals of the grid squares. Figure 33 shows the relative intensity in each of the four views, for three different channels of the $9686 \text{ \AA}$ line from T IV-a as functions of time. Figure 34 shows a similar comparison for D from T IV-a. It is clear that the intensity relationships between the four views vary over time and from channel to channel. Figure 35 shows the intensity of three channels of $9686 \text{ \AA}$ from the four views from T IV-c1. While the relationships are closer to what they should be, variations with time and channel are still apparent.

Two difficulties are apparent if ART is used to reconstruct line profiles from Formae IV data:

- (1) In a given channel, the ratio of the intensities in the four views varies in time, and is not 1:1:1:1, expected for an optically thin plasma. Also, this effect varies in degree from channel to channel. However, calculations indicate that the plasma should be optically thin. It is possible that the reflective properties of the pyrex vessel are affected by the presence of plasma, but this is unverified.
- (2) Relatively rapid changes on a one microsecond time scale are also apparent.

Strong plasma oscillations have been observed in T IV-c. It is also possible that both the above effects are associated with such oscillations, which are not necessarily

isotropy, whatever the explanation the input data are not consistent with the requirements of the ART algorithm, and no remedy is apparent at this time. Other criteria are also important in order to insure a physically correct reconstruction.^{1,2,3,4}

ART is known to have the following property: If a consistent set of data (an entire set of line of sight measurements for each angle multiplied by a constant (centered for each angle), ART reconstructs this as if would the consistent set of data, but with a scale change by a constant. This constant is determined by the order of normalization within the algorithm itself. However, since ART consistency tests are one time step at a time, Figs. 33-38 show that these multiplicative factors are channel data are, in effect, time and channel dependent. This has the result that, in the output, one channel bears no relationship to another (due to different scale factors), and the reconstructed spectral line shapes cannot be taken seriously. Also, in general, the scale factor would be time dependent, so that time dependence in the output may also be in error. These conclusions were arrived at after reconstructions of $4686 \text{ \AA}$ had already been carried out for T IV a and T IV el, and are shown in Figs. 39-42. The results of the reconstruction are presented in Figs. 39-42, and are particularly poor.

The reconstructed $4686 \text{ \AA}$ line shapes were fit with a gaussian profile in order to obtain ion broadening as functions of time and space. While the quality of the fit varied widely, there were many good gaussian fits to the reconstructed profiles for various times before and after cusp peak. Figure 39 shows the broadening in eV vs time for T IV a, and Fig. 41 for T IV el, at various points throughout the vessel. The three different symbols used in these figures denote the goodness of the gaussian fit, based on the value of the error, as explained in Section III. Note that the good fits settle down from 60 to 65 sec to a value between 10 and 15 eV. T IV el data indicate temperatures that fall to close to zero at 130 sec. The greatest broadening is found to occur before or during cusp rise. If substantial mass motion occurred during the rise of the cusp field, different line of sight

measurements would observe different Doppler shifts. This would result in a systematic error in the reconstructed line shapes, since, as mentioned previously, the reconstruction uses all 88 line of sight measurements and does one channel at a time.

Since the reconstruction is underdetermined, neighboring grid squares are highly correlated, and a spatial average is necessary to recover physically meaningful results. A test was made comparing data averaged in time before reconstruction to the same data reconstructed first and then averaged in time. For this test, an 8 μ sec average was used following previous work.² Large differences in spectral shapes and sizes were found when individual spatial points were compared, but as larger spatial averages were taken, the differences approached zero. An average over nine grid squares was found to be sufficient to reduce any differences in the two methods of time averaging.

In order to compare with previously reported results², a 7 μ sec average of the reconstructed data was taken over times from 25 to 32 μ sec, corresponding to the rise of the cusp. Then, a spatial average over 20 grid squares was performed at various positions throughout the vessel. Four 20 box averages were taken along the Z-center of the vessel, from large major radius to small radius, as illustrated in Fig. 38. As mentioned in preceeding sections, line of sight measurements indicate that most of the light comes from this central Z region and that there are differences between large and small major radius regions in the two devices. Figure 39 shows the spectral profiles from these four reconstruction regions for T IV-a. The lineshapes are remarkably similar, and fits to these lines are essentially identical. The same analysis was used on T IV-cl, with the same basic results. The spectral lines from all four spatial regions are similar not only to themselves but to the T IV-a lines. Since the 90°R line of sight data from both devices revealed differences in 4686 $\overset{0}{\text{A}}$ intensity and line shape between large and small major radii at this time, the similarity of the reconstructed line profiles is a disappointment.

Another point of comparison of the $4686 \text{ \AA}^0$ reconstructions for the two devices is the total intensity vs time at various spatial points. In this respect, the reconstruction and the line of sight data give qualitatively similar results. Figures 40 and 41 show the two types of behavior found. One behavior, labeled transition region in the line of sight data analysis section, shows an intensity peak at approximately $27.5 \mu\text{sec}$, a dip at $32 \mu\text{sec}$, and an increase in intensity at $38 \mu\text{sec}$. The other behavior exhibits no dip at $32 \mu\text{sec}$, as in the central 90°Z line of sight data, for both devices. The particular behavior found at each spatial point reflects the behavior of the line of sights through that point. For example, a very large dip is found at point (5,15) (Fig. 40) in the T IV-a reconstructed data. Both 90°Z and 90°R scans through this point show this transition region behavior. In Fig. 41, point (7,11) shows no dip, but single peaked behavior. Both 90°Z and 90°R scans through this point are similar. Figure 42 shows point (4,13). The 90°Z scan through this point is of the bright single peaked type, whereas the 90°R scan shows transition region behavior. Therefore a small dip is expected and seen in the reconstruction. Similarly, the T IV-cl intensity vs time reconstruction also follows the general characteristics of the line of sight input data.

VII. Conclusions

Comparable line of sight spectral data from Tormac T IV-a and T IV-cl have been presented for $\text{HeII } 4686 \text{ \AA}^0$ and $\text{D}\beta \text{ } 4861 \text{ \AA}^0$. The following properties of the $4686 \text{ \AA}^0$ line were observed to be similar: the evolution of the normalized total intensity, in both the 90°R and 90°Z views (Fig. 4-7); Gaussian line widths corresponding to temperatures $>100 \text{ eV}$; and the detailed qualitative features of the 90°Z scan. Some differences were noted: the better preionization of T IV-cl and the shift of the peak emitting region from small to large radius in T IV-cl after the peak

of the cusp. Comparison of the $D\beta$ data was limited by the lack of data from T IV-cl. Although tentative, the indications from the $D\beta$ line are that the evolution of relative total intensity is similar in both machines (Fig. 28-30), with indications that T IV-a may have had somewhat more density along the inner wall.

Additional comparative diagnostic evidence is meager. Both devices exhibited weak diamagnetism. Probes were used extensively in T IV-c, but not in T IV-a. Circuit voltage and current characteristics were monitored in both. These data from T IV-a are representative of its best performance. However, interpretation is confused by the strong coupling of the cusp, preionizer, bias, and shaker heating circuits; this has made systematic comparison with T IV-c elusive. The relatively weak spectral emission from the outer region of T IV-a after the cusp peak is disturbing. It can hardly be attributed to burnout, since the open cusp field lines intersect the wall, and would normally be expected to produce a copious amount of cold plasma. Since neither line intensity was ever observed to come back, this raises some questions concerning the degree of ionization in the T IV-a chamber.

The observation of very similar Gaussian broadening of the $\text{HeII } 4686 \text{ \AA}^0$ line in both T IV-a and T IV-cl, combined with the 5 eV Thomson scattering measurement of the electron temperature in T IV-cl, invalidates the use of this line as a measurement of high ion temperature in T IV-a. Assuming closed field lines, the high plasma density, $\lesssim 10^{16} \text{ cm}^{-3}$, would result in an electron-ion equilibration time of approximately a microsecond, which rules out the possibility of hot ions and cold electrons. This conclusion is further corroborated by a line to continuum measurement of the electron temperature in T IV-a which gave $< 5 \text{ eV}$. Also, the absence of any discoloration of the pyrex vessel, particularly where the open lines intersect the wall, seems incompatible with high temperatures. Circumstances permitting, a more complete set of data would be desirable. However, the present data are

found to be sufficient to rule out any dramatic temperature difference between the two devices.

A tomographic reconstruction of the spectral data, which had been relied on in the past, has also been carried out. Since only four views were taken, with a total of 88 lines of sight, the algorithm was underdetermined for reconstruction of the line profiles at the 200 grid points, although some faithfulness to the total intensity at each grid point was noted. The underdeterminedness was remedied by averaging over neighboring grid points, but the desired spatial resolution was thereby lost. Unfortunately, the data were not consistent with the reconstruction in the sense that the algorithm could not be expected to converge to a physical reconstruction of the line profile. The results of the reconstruction have been presented for heuristic purposes.

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Appendix

D β Reconstruction T IV-a

A complete four view scan of D β light has not been done for T IV-c at this time; therefore, a D β reconstruction has only been carried out for T IV-a. For this reason, D β reconstruction results will not be presented in detail. A few general trends for T IV-a are noted as follows:

- a) Reconstructed intensity vs time follows the trends of the line of sight intensity vs time data, as discussed above for 4686 $\text{\AA}$ light.
- b) D β reaches its first intensity peak between 5 and 10 μsec after discharge of the preionization banks.
- c) For times $\sim 12 \mu\text{sec}$, most of the intensity comes from large major radius points.
- d) From 10-17 μsec after preionization bank discharge, the maximum intensity, which is localized in the central Z region, moves toward the inner major radius wall. This is consistent with the idea that the toroidal plasma current pinches toward the inner wall, increasing the density, and therefore the intensity there.
- e) As the cusp field rises, D β light continues to come from the region near the wall, and becomes very intense. This highly emitting region remains at small major radius for the duration of the experiment.
- f) The intensity of D β increases during cusp rise, by at least an order of magnitude for points at large major radius in the central Z area.
- g) Spectral lines were investigated by time averaging the data from 20-24 μsec (before burnout), and averaging over space in various regions throughout the vessel. This is a trend toward wider lines at small major radius indicating larger density there.

TABLE I

Location Code

Location		Location	
#	(cm)	#	(cm)
0	22.5	0	0
1	21.5	1	1.3
2	19.7	2	2.5
3	18.4	3	3.8
4	17.2	4	4
5	15.9	5	6.4
6	14.6	6	7.6
7	13.3	7	8.9
8	12.1	8	10.1
9	10.8	9	11.4
10	9.5	10	12.8
11	8.3	11	14.0
		12	15.2
		13	16.5
		14	17.8
		15	19.1
		16	20.3
		17	21.6
		18	22.9
		19	24.1
		20	25.4
		21	26.7

TABLE 2

Diagnostic Information Available at 15 kV and 50 mTorr

device	He II (4686 Å)	HB	Thompson Scattering	interferometer	flux loop
T IV-a	4 views	4 views	NA	limited	yes
T IV-cl	4 views	NA	5 eV	radial scan	yes

TABLE 3

TIV-a Data Channels

1.	Cusp current	
2.	Preionization current	
3.	Plasma current	
4.	-----	
5.	-----	
6.	Shaker current	
7.	-----	
8.	-----	
9.	-----	
10.	Polychromater channel	#1
11.	Polychromater channel	#2
12.	Polychromater channel	#3
13.	Polychromater channel	#4
14.	Polychromater channel	#5
15.	Polychromater channel	#6
16.	Polychromater channel	#7
17.	Polychromater channel	#8
18.	Polychromater channel	#9
19.	Polychromater channel	#10
20.	Polychromater channel	#11
21.	Polychromater channel	#12
22.	Polychromater channel	#13
23.	Polychromater channel	#14
24.	Polychromater channel	#15

TABLE 4

HeII 4686 Å 90°Z Line of Sight

Character of spectral signatures

	low intensity*	transition	bright
T 1V-a	1-5; 17-20	6-8; 14-16	9-13
F 1V-c	1-4; 15-20	5-7; 13-14	8-12

*refer to Table I

TABLE 5

T IV-c Data Channels

1.	Cusp current
2.	Preionization current
3.	Shaker heating
4.	Interferometer
5.	Preionization current
6.	Bias field
7.	Plasma current
8.	Flux loop
9.	Polychromater channel #1
10.	Polychromater channel #2
11.	Polychromater channel #3
12.	Polychromater channel #4
13.	Polychromater channel #5
14.	Polychromater channel #6
15.	Polychromater channel #7
16.	Polychromater channel #8
17.	Polychromater channel #9
18.	Polychromater channel #10
19.	Polychromater channel #11
20.	Polychromater channel #12
21.	Polychromater channel #13
22.	Polychromater channel #14
23.	Polychromater channel #15
24.	Polychromater channel #16

TABLE 6

HeII 4686 Å 90°R Line of Sight

	low intensity	transition	brightest	bright
T IV-a	1-3	4-6	7-8	9-10
T IV-c1	—	—	1-7	8-10

- Figure 1. A schematic cross section of the Tormac IV vessel is shown. The device is toroidally symmetric around the indicated center line; the desired equilibrium shape is illustrated in the center.
- Figure 2. The experimental timing sequence is illustrated. In T IV-a, data were taken to only 64 μ sec; in T IV-c to 120 μ sec.
- Figure 3. The labeling scheme used to identify the spectrometer lines of sight is illustrated; positions are spaced at 1/2" intervals.
- Figure 4. The evolution of the total HeII 4686 $\text{\AA}$ intensity in the 90°Z view of T IV-a is shown normalized to its peak; mean ($\bar{x}$) and standard deviation (σ) were obtained from 3 shots at each 90°Z position, then summed over 20 positions.
- Figure 5. The evolution of the total HeII 4686 $\text{\AA}$ intensity in the 90°Z view of T IV-c1 is shown normalized to its peak; 20 shots were summed, one at each 90°Z position.
- Figure 6. The evolution of the total HeII 4686 $\text{\AA}$ intensity in the 90°R view of T IV-a is shown normalized to its peak; mean ($\bar{x}$) and standard deviation (σ) were obtained from 3 shots at each 90°R position, then summed over 10 positions.
- Figure 7. The evolution of the total HeII 4686 $\text{\AA}$ line intensity in the 90°R view of T IV-c1 is shown normalized to its peak; 10 shots were summed, one at each 90°R position.
- Figure 8. The evolution of the total normalized HeII 4686 $\text{\AA}$ intensity in the 90°Z view of T IV-c1 is shown to 120 μ sec.
- Figure 9. The evolution of the total normalized HeII 4686 $\text{\AA}$ intensity in the 90°R view of T IV-c1 is shown to 120 μ sec.

Figure 10. The total HeII 4686 Å line intensity in each 90°Z line of sight is shown for T IV-a and T IV-cl at 33 μsec. Each line of sight has been normalized to the peak in any 90°Z line of sight in that vessel at any time; * --- T IV-a, mean (x) and standard deviation (I) of three shots; 0 --- T IV-cl, one shot.

Figure 11. T IV-a data from 90°Z6 are shown. The HeII 4686 Å spectral signature (channel 10-24) is characteristic of the transition region; T IV-a data channels are identified in Table 3.

Figure 12. T IV-a data from 90°Z8 are shown. The HeII 4686 Å spectral signature is characteristic of the transition region.

Figure 13. A characteristic profile of the 4686 Å line of T IV-a is shown from 90°Z8 at 31.5 μsec; the line width, 2.2 Å, is equivalent to 154 eV.

Figure 14. T IV-a data from 90°Z11 are shown. The HeII 4686 Å spectral signature is characteristic of the bright central region.

Figure 15. T IV-cl data from 90°Z6 are shown. The HeII 4686 Å spectral signature is characteristic of the transition region of T IV-cl; data channels are identified in Table 5.

Figure 16. A characteristic profile of the 4686 Å line of T IV-cl is shown from 90°Z7 at 31 μsec; the line width, 1.92 Å, is equivalent to 110 eV.

Figure 17. A 4686 Å line profile of T IV-cl is shown from 90°Z10 at 14 μsec (preionization). The line width, 2.42 Å, corresponds to 175 eV, but the plasma is known to be cold and partially ionized.

Figure 18-21. The total 4686 Å line intensity from the 90°R view is shown at 27, 33, 38, and 45 μsec, respectively. Each line of sight has been normalized to the peak in any 90°R line of sight in that vessel any time; * --- T IV-a, mean and standard deviation of three shots; and 0 --- T IV-cl, one shot.

- Figure 22. T IV-a HeII-4686 Å data from 90°R2 are shown. Spectral emission from the region of large major radius was observed to be relatively low at all times.
- Figure 23. T IV-a data from 90°R4 are shown. The HeII 4686 Å spectral signature is characteristic of the 90°R view transition region.
- Figure 24. T IV-a data from 90°R8 are shown. The HeII 4686 Å spectral signature is characteristic of the bright region as small major radius.
- Figure 25. T IV-c1 data from 90°R1. Compared with T IV-a, the relative brightness of the 4686 Å line, even next to the outer wall, is readily apparent (Fig. 22); the prominent oscillations are unexplained at present.
- Figure 26. A characteristic profile of the 4686 Å line of T IV-c1 is shown from 90°R7 at 32 μsec; the line width, 2.0 Å would be equivalent to 121 eV.
- Figure 27. The total Dβ line intensity in each 90°Z line of sight is shown for T IV-a at 33 μsec. Each line of sight has been normalized to the peak in any 90°Z line of sight at any time. The similarity of the profile with the 4686 Å line (Fig. 10) is apparent.
- Figure 28. The evolution of the total Dβ line intensity in the 90°R view of T IV-a is shown normalized to its peak; 10 shots were summed, one at each 90°R position.
- Figure 29. The evolution of the total Dβ line intensity in the 90°R view of T IV-c2 is shown normalized to its peak; 10 shots were summed, one at each 90°R position. For T IV-c2, cusp rise began at ~30 μsec.
- Figure 30. The evolution of the total Dβ line intensity in 90°R9 (or 90°R10) of T IV-c1 is shown normalized to its peak. A general similarity with T IV-a is apparent (Fig. 28).
- Figure 31. The total Dβ line intensity in each 90°R line of sight is shown for T IV-a at 10, 24, 33 and 45 μsec. Each line of sight has been normalized to the peak in the 90°R line of sight in that vessel at any time.

- Figure 32. The total D δ line intensity in each 90 $^{\circ}$ R line of sight is shown for T IV-c2 at 10, 24, 33 and 45 μ sec. Each line of sight has been normalized to the peak in any 90 $^{\circ}$ R line of sight in that vessel at any time.
- Figure 33. The intensities of three separate channels (denoted a, b, and c) of the HeII 4686 $\overset{\circ}{\text{\AA}}$ line in T IV-a have been summed along each of the four views; 1 --- 90 $^{\circ}$ Z, 2 --- 90 $^{\circ}$ R, 3 --- 45 $^{\circ}$, and 4 --- 135 $^{\circ}$. For consistent data, 1, 2, 3, and 4 would be in the ratio 1:1 $\sqrt{2}$: $\sqrt{2}$.
- Figure 34. The intensities of three separate channels (a, b, and c) of the D δ line in T IV-a have been summed along each of the four views; 1 --- 90 $^{\circ}$ Z, 2 --- 90 $^{\circ}$ R, 3 --- 45 $^{\circ}$, and 4 --- 135 $^{\circ}$.
- Figure 35. The intensities of three separate channels (a, b, and c) of the HeII 4686 $\overset{\circ}{\text{\AA}}$ line in T IV-cl have been summed along each of the four views.
- Figure 36-37. The reconstructed line width of the 4686 $\overset{\circ}{\text{\AA}}$ line of T IV-a is plotted for T IV-a and -cl respectively in equivalent temperature vs time at four grid points (ref. inserts); x --- very good fit, 0 --- good, * --- not very good.
- Figure 38. Four overlapping 20 box regions were used to generate spatially averaged reconstruction 4686 $\overset{\circ}{\text{\AA}}$ line profiles for comparison purposes.
- Figure 39. Profiles obtained from the reconstruction of the 4686 $\overset{\circ}{\text{\AA}}$ line after averaging from 25-32 μ sec over the designated regions 1-4 ref. Fig. 38).
- Figure 40-42. The total reconstructed 4686 $\overset{\circ}{\text{\AA}}$ line intensity vs time is shown at a designated grid point (ref. insert). The data were from T IV-a.

XBL 794 - 1281

Figure 1

XBL 794 -1278

Figure 2

Figure 3

XBL 794-1279

XBL 794 - 1282

Figure 4

XBL 794 - 1283

Figure 5

XBL 794-1284

Figure 6

XBL 794-1285

Figure 7

XBL 794-1286

Figure 7

XBL 794-1287

Figure 9

XBL 794-1288

Figure 10

Figure 11

XBL 794 - 1289

XBL 794-1290

Figure 12

Intensity
(arbitrary units)

channel #

$(\lambda - \lambda_0)^2$

XBL 794-1291

Figure 13

XBL 794-1294

Figure 14

Figure 15

XBL 794 - 1292

Intensity
(arbitrary units)

channel #

$(\lambda - \lambda_0)^2$

Figure 16

XBL 794-1293

Intensity
(arbitrary units)

channel #

$(\lambda - \lambda_0)^2$

XBL 794-1295

Figure 17

XBL 794 - 1296

Figure 1b

XBL 794-1297

Figure 14

XBL 794-1298

Figure 20

XBL 794-1299

Figure 21

Figure 22

XBL 794-1300

Figure 22

Figure 23

XBL 794-1301

Figure 24

XBL 794-1302

XBL 794-1303

Figure 25

Intensity
(arbitrary units)

channel #

$(\lambda - \lambda_0)^2$

XBL 794-1304

Figure 26

XBL 794-1305

Figure 27

XBL 794-1306

Figure 28

XBL 794-1307

Figure 29

XBL 794 -1308

Figure 30

Relative intensity

XBL 794-1315

Figure 31

Figure 32

Fig. 194-11

FIGURE 11

Intensity,
arbitrary units

194 14

Figure 3a

Intensity
Arbitrary Units

XBL 794 1313

Figure 35

Equivalent temperature

keV

XBL 794 3 *

Figure 36

Equivalent temperature
(eV)

XBL 794 13.8

Figure 37

Figure 38

XBL 794 - 1280

Intensity
(arbitrary units)

Figure 39

XBL 794-1309

Figure 40

XBL 794-1310

Figure 41

XBL 794-1311

Figure 42