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R. G. Watt

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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RADIALLY RESOLVED EMISSION SPECTROSCOPY ON ZT-40M

by

R. G. Watt

ABSTRACT

Measurements of line integrated emission profiles of D_β , OIII, OV, OVI, and CV line radiation have been performed in the ZT-40M device at Los Alamos National Laboratory. The behavior of these emission profiles will be presented for several operating currents, fill pressures, and current risetimes. The basic oxygen radial structures are seen to resemble an onion skin at any particular time, with OIII farthest out in radius and OVI nearest the axis, as one would expect in the absence of any anomalous heating mechanisms (such as thermal instabilities). The rate at which the various lines occur during several different current level discharges appears to be consistent with increased losses for increased i_ϕ during the early phases of heating (up to OVI), while the later stages are consistent with a much lower energy loss and a heating rate proportional to i^2 . Evidence of enhanced wall interaction in the latter stages of the discharge is presented.

I. INTRODUCTION

Radially resolved emission spectroscopy studies have been carried out in the ZT-40M reversed-field-pinch¹ device at Los Alamos National Laboratory. Studies of the radial structure of lines of various ionization potentials as a function of time help one to understand the evolution of the plasma discharge in a global sense. In particular, such studies aid one in determining the macroscopic differences between good and poor discharges [an example might be a lack of CV (227.1 nm) radiation from a cold discharge, or a constant decrease in CV radiation intensity as the discharge vessel gets conditioned over many shots].

The multichord spectrometer system (MCSS) used for these studies has been described elsewhere.² The six-chord system has a wavelength resolution of ~ 0.4 nm and a chord-to-chord intensity calibration uncertainty of $\sim 10\%$. The chords have impact parameters from -4 cm to $+16$ cm with respect to the vacuum vessel minor axis with a chord-to-chord separation of ~ 4 cm. In all discussions in this report, impact parameters will be measured from the center of the discharge vessel. The chord-to-chord calibration uncertainty results in a combined uncertainty from the axis to outer chord of $\sim 25\%$, which makes some measurements relatively uncertain (in particular, measurements of the integrated background radiation that is quite uniform in impact parameter). In cases where total differences across the profile are no more than 25% , as in the case of most lines after burnthrough, detailed knowledge of the radial structure must be limited by this resolution. This limiting resolution also makes any detailed unfolding of radial structure (after the line begins to burn through) from the line integral measured data via Abel inversion quite prone to error. Such analysis has been done, particularly for the carbon data (at early times), but because of the inherent uncertainties in the process, no such results will be discussed here.

Before presentation of detailed data, it is worth noting that the vacuum vessel shows evidence, both spectroscopically and from Thomson scattering temperature measurements,³ of a long-term conditioning process. The results presented here show that process in a pronounced manner through the CV amplitude. After 2000 shots and with no vacuum opening in the previous 600 shots, the carbon radiation level was down approximately a factor of 4 from results early in the life of ZT-40M, with the result that the background under the line in the spectrometer acceptance window (0.4 nm FWHM) was within a factor of 2-3 of the peak intensity of the line. After opening the vacuum vessel and installation of ceramic sleeves for the multipoint Thomson scattering system,⁴ the CV radiation level was once again at the high levels seen early in the discharge vessel history. Profiles from each period will be used where appropriate.

The presentation in this report will be broken into three major areas:

- (1) overall data for standard reversed-field operation at a current risetime of 0.25 ms and current levels from 120 - 250 kA, (2) results of a study conducted to analyze the effects of the risetime of the toroidal plasma current, and (3) some comments on behavior of radiation in the same wavelength

region as the CV line late in a discharge (>3 ms) that is believed to be attributable to a series of unresolvable low-lying metal lines that may be indicative of strong wall interaction.

Because of the intimate connection between line emission and the local electron density ($I \propto n_e n_i$), it is useful to have a line integral density profile⁵ under the conditions used for most discharges to help interpret radial intensity profiles. Figures 1 and 2 are a single set of density profiles for a standard 180-kA flattop current shot (#6949) shown on both a short and long time scale for this comparison. Lower current discharges have similar spatial behavior.

Fig. 1.
Line integral density, profile history for a typical 190-kA reversed-field pinch discharge showing the formation phase (0-1 ms) of the pinch.

Fig. 2.
Profile history of Fig. 1 on a longer time scale.

II. COMPOSITE DATA PROFILES FOR STANDARD OPERATIONAL CONDITIONS

ZT-40M normally operates as a reversed-field pinch with a current level between 120 kA and 250 kA. Most extensive data have been taken at the 180-kA plasma current level (current inside the Inconel vacuum vessel). Results obtained at three current levels (120 kA, 180 kA, and 240 kA) will be presented and compared in this section in order of increasing current level.

A. 120 kA

Operation at this level is characterized by fill pressures of 1-5 mtorr (standard being 1.2 mtorr) and reversal depths at the wall of approximately 0.2 T. Peak plasma current occurs at 0.5 ms. Under the standard 1.2-mtorr fill conditions, radial profiles have been obtained for D_{β} (486.1 nm), OIII (326.1 nm), OV (278.1 nm), OVI (343.4 nm), and CV (227.1 nm). The carbon data used here are from the period of lowest emission levels (and presumably cleanest conditioning), as are all other profiles.

The data presented here and in the following sections have been averaged over a number of shots and thus represent the general behavior, with any peculiarities on a given shot washed out by the averaging process. In particular, the massive intensity spikes seen in many CV profiles originating

from the wall region are subdued. This feature will be discussed later in this report. The various line integral intensity profiles are shown for the first millisecond in Figs. 3-7 for D_β , OIII, OV, OVI, and CV, respectively. Clearly observed is the fact that different lines have peak intensities at different times during the discharge. An overall compilation of the time of peak intensity for all current levels will be presented later.

Because comparisons of profiles for different ionization states of a given atom can provide radial ion density and temperature information, it is informative to look at a given point in time and compare profiles. Figure 8 is such a comparison [smoothed by eye and averaged over both time (0.5-ms window) and shots] for OIII, OV, and OVI at 0.45 ms. It is clear, even in the absence of Abel inversion, that at this time during the discharge the OIII is peaked near the outside, OV is annular, and OVI is peaked on axis, thus constructing a conceptually consistent picture of the radiation field. Note also that the absolute intensity of the profiles has been changed to display

Fig. 3.

Average D_β radiation line integral profiles at 120 kA and 1.2 mtorr, showing the pinch formation phase.

Fig. 4.
Average OIII profiles at 120 kA and 1.2 mtorr.

Fig. 5.
Average OV profiles at 120 kA and 1.2 mtorr.

Fig. 6.
Average OVI profiles at 120 kA and 1.2 mtorr.

Fig. 7.
Average CV profiles at 1.20 kA and 1.2 mtorr.

Fig. 8.

Comparison of OIII, OV, and OVI radial profiles (line integrated) at 0.45 ms into the discharge (0.2 ms into the plasma current), showing clear evidence of an onion skin formation. The OVI signal has been reduced to 0.2 of its original size to fit on the same plot as the OIII and OV signal.

the radial comparison clearly; the OIII and OV are really at much lower intensity than the OVI at this point during the discharge.

B. 180 kA

Operation at this level occurs for fill pressures of 1.2-5 mtorr, with the normal fill being 1.6 mtorr. Field-reversal depth and time of peak current are the same as for the 120-kA case. Composite profiles under these conditions for D_β , OV, OVI, and CV are shown in Figs. 9-12, respectively. The time of occurrence of the CV peak has decreased markedly from the 120-kA level, indicative of a higher heating rate, at least after the oxygen radiation has burned through.

Fig. 9.

Average D_β radiation profiles for 190 kA and 1.6 mtorr, showing the pinch formation phase.

Fig. 10.

Average OV profiles at 190 kA and 1.6 mtorr.

Fig. 11.
Average OVI profiles at 190 kA and 1.6 mtorr.

Fig. 12.
Average CV profiles at 190 kA and 1.6 mtorr.

C. 250 kA

A limited number of discharges were taken at this level. No standard operating pressure was established. In the absence of a detailed standard data base, what is presented here is a comparison at 3-mtorr fill of the CV profiles seen at 180-kA and 240-kA plasma current (Figs. 13 and 14, respectively). Also shown for comparison are the standard 180-kA, 1.6-mtorr fill CV profiles on the same time scale (Fig. 15). The peak intensity is seen to increase with plasma current while the time to peak decreases, again indicative of a higher heating rate during this portion of the discharge. The apparent decrease in half-width at the peak intensity point for the 250-kA data may reflect differences in either temperature profiles, ion density profiles, or both, and may be intimately tied up with the detailed transport properties. Much more work needs to be done in this area to define the physics involved.

Fig. 13.
Average CV line integral profiles at 190 kA and 3 mtorr.

Fig. 14.
Average CV line integral profiles at 250 kA and 3 mtorr.

Fig. 15.
Average CV line integral profiles at 190 kA and 1.6 mtorr for comparison with Figs. 13 and 14.

D. Ionization Energy Dependence

The preceding data base, besides showing the radial structure of many lines, may also be used to look at the evolution of the plasma temperature in a very approximate manner. Because the lines peak at different times and have different ionization potentials, we may plot the ionization potential vs time to peak for various current levels, as shown in Fig. 16. The points for D_β through OVI lie on curves that are basically the same for the separate current levels. The curves begin to deviate radically from each other after oxygen has burned out, so there are apparently two separate heating phases. If one assumes it takes a plasma temperature $T_e \approx 30\%$ of the ionization potential of a given species to begin to burnthrough a given line (from zero-dimensional code calculations, as well as for corona equilibrium),⁶ and if one assumes the same emitting volume (approximately correct up to the burnthrough time for a given line, i.e., emission from the inner region in all cases), then very crudely, the plots of λ vs τ_{peak} may also be used as curves of $3 T_e$ vs time for early times during the discharge.

Fig. 16.

Ionization potential vs time of occurrence of the lines observed. This plot may be interpreted as $3 T_e$ vs time within the caveats discussed in the text. Current starts at 0.25 ms.

To interpret what the heating rates implied in Fig. 16 mean in terms of plasma energy input and confinement, let us consider a very crude model. Let us assume that as the plasma evolves through each heating (ionization) stage, regardless of peak current (or $\dot{I}$), the density, temperature, and current radial profiles evolve to a given state regardless of the time scale to do so. We may then write the energy balance equation for the plasma energy W_p ($= 3 n_e k T_e$) in terms of average quantities as

$$\frac{\partial W_p}{\partial t} = \eta J^2 - \frac{W_p}{\tau_E},$$

where η is the plasma resistivity at a given time, J is the current density, and τ_E is the energy confinement time (time to $1/e$ of the initial energy in the absence of an energy source). Viewed in terms of energy confinement early in the current rise where $J \approx \dot{J}t$, one can make two distinct statements. (1) Before OVI burnthrough ($T_e < 40$ eV), $\frac{\partial W_p}{\partial t}$ is independent of $\dot{J}$ (from Fig. 16, as $\dot{J}^2$ increased by a factor of 4, $\dot{W}_p$ only changed by at most 10%), so the energy loss term must be comparable to the source term and ηJ^2 and τ_E^{-1} must both be proportional to $\dot{J}^2$ in order for the difference between source and loss to be only weakly dependent on the current rate of rise. (2) Between OVI burnthrough (~ 40 eV) and CV peak (~ 120 eV), the heating rate scales with J^2 experimentally (Fig. 16), so the loss term during this period must be only a small fraction of the source term. No statement about the form of τ_E during this period can be made based on these data. Any such statements must come from much more detailed $T_e(r)$, $n_e(r)$, and $J(r)$ measurements.

III. RISETIME EFFECTS

As mentioned earlier, a series of discharges were conducted in which the risetime of the plasma current was varied from the usual 0.25-ms rise to peak current to values of 0.75 ms and 1.5 ms. During this study the MCSS system was left tuned on the CV (227.1 nm) line. As mentioned earlier, the amplitude of CV radiation underwent an abrupt increase at a time that coincided with the change to 0.75-ms risetime (without a vacuum opening). Because it is of interest to see whether $\dot{I}_p$ affects the profile and because the profile was

farther out of the background after this series, the 0.25-ms profile used here will be from discharges after the risetime study. The amplitude of the radiation does not seem to affect the time or pressure dependence.

To quantify the various dependencies in this CV study, plots have been made showing the time to peak intensity and amplitude at peak intensity (Figs. 17 and 18) for various fill pressures for the three current risetimes used (180-kA plasma current). As expected, the time needed to reach peak amplitude was monotonically increasing with fill pressure in all cases. Also observed was that it takes longer for CV (227.1 nm) to appear with a lower $\dot{i}_{\text{plasma}}$ (longer risetime) consistent with the post-oxygen-burnthrough result at 0.25-ms rise for different current levels. From the data for amplitude vs fill pressure it appears that there may be some universal curve whose peak shifts with varying $\dot{i}_{\text{plasma}}$, going to higher pressure for longer risetimes. Unfortunately, the peak seems to be outside the operating window at the two extremes, with the 0.25-ms risetime peak residing below the breakdown limit (1.0 mtorr) at 180 kA, and with the 1.5-ms risetime peak being at such high

Fig. 17.

Time of occurrence of CV as a function of pressure for the three risetimes studied thus far. In each case the absolute time into the current waveform is the plotted time minus the risetime shown as a label for the curve.

Fig. 18.

Amplitude of the peak CV signal vs fill pressure for the various risetimes shown on the curves.

pressure that the necessary conditions for the peak to occur (presumably conditions on T_e) cannot be reached during the discharge duration. Regardless of the location of the peak, it is clear that for the range from 1-3 mtorr where most successful operation seemed to occur for these experiments, the two extremes are on opposite slopes of some curve. Combining these two plots (in effect, suppressing the pressure dependence) yields the set of curves shown in Fig. 19, from which it is clear that the time to peak and amplitude of the peak are intimately related, presumably by the transport process that brings the carbon ions off the surface of the wall during startup.

It was necessary during these risetime experiments to vary the toroidal bias field in order to achieve reversal at a particular fill pressure (a result of a density pumpout dependence on bias field). As long as reversal was achieved, the depth of reversal did not seem to affect the time of occurrence or level of the peak radiation. It also had little effect on the shape of the profile. For comparative purposes, a plot of the profile at the time of peak intensity is shown in Fig. 20 for each of the risetimes. Within the accuracies of the measurement there appears to be little if any difference in the final plasma column structure. The only thing that appears to change

Fig. 19.

Amplitude of the peak CV signal vs time to peak (again with the time offset of Fig. 17) showing the apparent curve with changing peak mentioned in the text.

Fig. 20.

Comparison of the line integral CV profile at the time of peak intensity for the three risetimes (at the fill pressure corresponding to best operation of the plasma, as noted with each curve).

with risetime is the length of time it takes to achieve the final plasma state, at least as long as the fill pressure resides near the peak of the CV emission vs p_0 curve.

IV. WALL INTERACTION

Throughout the life of ZT-40M there has been a qualitative change in the behavior of the radiation observed under the CV line. As mentioned in the introduction, the MCSS system has a wavelength resolution of only ~ 0.4 nm. Because of this, for weak lines it is possible for background radiation caused by recombination or closely spaced adjacent lines to interfere with desired measurements. This has been the case for the CV measurements for the later discharges in the life of ZT-40M.

Figure 21 is a profile history for a single shot (#6854, smoothed over a 100- μ s sliding square window) showing a massive increase in light in the outermost chord during the startup phase. This particular discharge was a 1.5-ms risetime, 3-mtorr discharge chosen to display what appears to be a violent wall interaction early in time. Such interactions occur on more than 50% of all discharges (regardless of risetime) during this particular historical period but were almost never observed during the earliest discharges. The cause is unknown. The radiation is uniform over ± 2 nm. It is not observed in the vicinity of other lines investigated (particularly D_β).

Fig. 21.

CV profiles at 1.5-ms risetime showing a pronounced wall hit at approximately 2 ms during formation. Current starts at 1.5 ms.

Because a series of closely spaced (unresolvable with the MCSS system) Cr, NiI, NiII, FeI, and FeII⁷ lines exist within ± 1.0 nm of the CV (227.1 nm) line, the radiation is assumed to come from these lines (Ni, Fe, and Cr are the constituents of the vacuum vessel), especially from the NiI line at 227.2 nm. Similar lines exist near the D β line but in much more limited quantity, and no such bursts of radiation are observed near D β , effectively ruling out the possibility of recombination radiation from D⁺ and impurity ions being the cause.

Also observed in recent discharges (with all risetimes) is a massive flux of radiation in the outer chords beginning at 2-3 ms into the discharge, as shown in Fig. 22. This late time radiation also has no wavelength structure near the CV line and is not observed near other lines studied. This again suggests metal line radiation from a wall interaction phenomena, perhaps indicative of a monotonic loss of toroidal equilibrium,⁸ such as might be expected as the 2-cm aluminum shell gradually disappears during a discharge. The loss of the positioning vertical field due to the shell disappearing would

Fig. 22.

CV profiles at 0.25-ms rise showing the rapid burnout of the line followed by a pronounced late time (>3 ms) wall interaction seen by the outer chords. Current starts at 0.25 ms.

lead one to expect that the plasma column would lean on the outside wall late in the discharge, resulting in boiling impurities off the wall and limiters. The observed radiation is consistent with such a picture (indeed, preliminary results with externally applied vertical field qualitatively alter the time history of this radiation),* although by no means is this the only possible explanation. This explanation does not account for the historical change in this effect since the shell has always had a 2-3-ms time constant. Presumably wall conditioning explains the historical differences. It should be noted that this refluxing in the outer chord is most pronounced for the 0.25-ms risetime discharges. The more subdued nature of this refluxing observed for the longer risetimes may simply be indicative of a shorter wall-scrubbing time because of the increased length of time necessary to get the column hot. Those discharges last no longer than the faster risetime discharges, so the total wall interaction time for a hot plasma is reduced at longer risetime.

V. CONCLUSIONS

The result of these measurements is to provide a characterization for ZT-40M operation rather than to provide any remarkable new physics enlightenment. As a result of these measurements, a number of statements can be made concerning ZT-40M plasmas.

- (1) The bulk plasma behavior is dependent on current level and current risetime predominantly in terms of timescales, i.e., how long it takes to achieve a hot plasma, rather than in any discernible changes in radial structure during setup or decay phases.
- (2) The setup phase of the discharge goes sequentially through all the intermediate oxygen impurity radial structures one would expect to observe, i.e., no anomalous radial heating structures (for instance an annular thermal instability)⁹ seem to exist.
- (3) The carbon emission peaks at a time during the discharge that is consistent with a startup picture (after OVI burnthrough) in which the energy confinement time τ_E is much longer than the energy input time scale. This results in energy losses that are much lower than the energy input (at least up until CV begins to burn through).

*Information supplied by R. S. Massey, Los Alamos National Laboratory.

- (4) The operating window, defined by the ability to burn through the oxygen impurities and begin emitting CV radiation, appears to shift its peak upward in pressure with increasing risetime.
- (5) Considerable evidence of wall interaction is observed and the time of occurrence of this low-lying metal radiation is in agreement with the basic equilibrium loss time for the aluminum shell.

This last point will be one focus of an upcoming set of experiments which will address the question of vertical field and equilibrium configuration in ZT-40M.

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