LA-UR -86-3875

CONF-861191--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W 7405-ENG-36

LA-UR--86-3875

DE87 002903

TITLE

UNANSWERED QUESTIONS FROM CTX

AUTHOR(S)

B. L. Wright, Cris W. Barnes, J. C. Fernandez, I. Henins, H. W. Hoida, T. R. Jarboe, S. O. Knox, G. J. Marklin, and D. A. Platts.

SUBMITTED TO

Eighth US-Japan Compact Toroid Workshop
Osaka, Japan
November 21-22, 1986

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article the publisher recognizes that the U S Government retains a nonexclusive royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so, for U S Government purposes

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U S Department of Energy

MASTER

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

FORM NO 836 R4
ST NO 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

UNANSWERED QUESTIONS FROM CTX

B. L. Wright, Cris W. Barnes, J. C. Fernandez,
I. Henins, H. W. Hoida, T. R. Jarboe, S. O. Knox,
G. J. Marklin, and D. A. Platts

Los Alamos National Laboratory
University of California
Los Alamos, New Mexico 87545 USA

Introduction

At the time of termination of any experimental research program, a large number of unanswered questions always remain. Many of these questions are specific to the particular experiment or technique being studied. But, if the research is relevant, there will be many that also apply quite generally to all types of work in the field. We find this to be the case as CTX operations come to an end. In our final contribution to what has been for us a stimulating series of workshops, we would like to review our progress over the last year and, at the same time, state what we think are the important related issues for further spheromak research.

The big question being addressed on CTX during the past year has been: Why was energy confinement not improved by increasing the mesh flux conserver radius from 40 cm to 67 cm? A comparison of decaying spheromaks with the same values of j and n in the two cases [1] shows $\tau_B 2$ improving roughly as R^2 but little change in T_e. As a result, $\langle\beta\rangle_{vol}$ has gone from ~ 7.0% to ~ 2.0% and the inferred energy confinement time has remained unchanged at ~ 23 μs. An energy balance analysis of the 40 cm case [2] showed that the observed rapid particle loss could account for most of the energy loss while providing a mechanism for the removal of impurities. At 67 cm, τ_p has also improved by about a factor of 2, particle loss therefore contributes substantially less to energy balance and the achievement in CTX of j/n_e as high as 3×10^{-14} A·m (I_{tor} up to 1 MA), low-Z impurities should not be a problem. A question then arises: Is CTX faced with a new strong energy loss mechanism that is characteristic of spheromaks in general? This question is not simply answered because it may involve processes of thermal conduction or convection that cannot be directly measured. In the following paragraphs we discuss many of the topics that have been considered in this search.

Radiation Studies

Impurity radiation is the first topic of concern in any energy confinement study. After increasing the size of the mesh flux conserver, we also increased correspondingly the size of the coaxial helicity source. This step eliminated observable high-Z impurities associated with source operation. Furthermore, there was no noticeable difference between grazing-incidence spectrograms taken at 40 cm and 67 cm. In recent months we have used gold-foil bolometers in a survey of total radiated power from CTX.

Both CTX bolometers use a 5 μm gold UV radiation absorber layer deposited on a 1.5 μm mylar film. On the opposite face, a 2000 Å thick gold resistor pattern is deposited on the mylar. As radiation is absorbed, the resistance change is measured using a circuit previously described[1].

Both bolometers are collimated to a 3.2^{o} viewing angle, allowing good spatial resolution (~ 5 cm typically). One of the bolometers is mounted on the spheromak midplane, allowing a full view along the spheromak geometric axis (where typically the magnetic energy density is highest), as well as a portion of the entrance region. The other is mounted near the coaxial source, allowing a view along the spheromak radius, from the outer vacuum tank wall, through the magnetic axis, to about 30 cm radius. For analysis purposes, the spheromak volume is divided into zones vaguely resembling the spheromak B^2 contours at source turn-off time. Both bolometers are steered on a shot to shot basis to include observations on similar shots on enough chords to confidently resolve the spatial radiation distribution.

Previous data from only the bolometer near the source indicated that, during the decaying phase, the radiated energy density near the magnetic axis could be as low as 20% of the initial magnetic energy density. But the possibility of a non self-similar decay, with relaxation dynamics transferring magnetic energy within the spheromak volume, indicated the need for a complete coverage of the spheromak volume. Double bolometer scans have since been performed for a variety of conditions on both sustained and decaying discharges, albeit not for the highest range of spheromak toroidal current nor for the longest decaying spheromak lifetimes achieved on CTX. Radiated to magnetic energy fractions of anywhere from 30% (on clean, 650 kA maximum toroidal current discharges) to nearly 100% (on "dirty" discharges, obtained just after a vacuum opening or by heavily seeding the discharges with Ar gas) have been obtained. All observations to date indicate a monotonically decreasing radiated fraction with increasing $< j_{tor} >_{vol,t} / < n_e >_{vol,t}$, with no difference between sustained and decaying discharges with similar $< j_{tor} >_{vol,t} / < n_e >_{vol,t}$. In addition, significant variations in the radiation spatial profiles have been observed for different operating conditions. The reason for these variations is not presently known. To underscore the observation of non-radiation dominated discharges, temporal analysis of the evolution of the radiated energy has shown examples where, while the ohmic power and j/n increases, the radiated power fraction decreases to less than 10%.

The observed levels of impurity radiation are sufficiently low, that the possibility of enhanced losses from another mechanism remains. This raises the question: How low must radiation losses be to allow definitive studies of other spheromak loss processes? The answer is complex because local reductions in electron temperature in regions dominated by radiation lead to alterations of the current density profile, affect global helicity content, and induce relaxation. The question then becomes: How low must radiation losses be in order that the confinement properties being studied represent those of a spheromak whose dynamics are not controlled by impurities?

Current-Driven Modes

Magnetic oscillations, understood in terms of rotating internal kink modes [3], are observed on CTX discharges. The question arises: Do current-driven modes associated with departures of the equilibrium from its minimum-energy state have an adverse effect on confinement? These modes are stationary on the time scales of particle motion, so any effect on confinement would be associated with the distortion and opening of closed flux surfaces. Because the relative amplitudes of the observed oscillations were unchanged when the radius of the flux conserver was increased to 67 cm, we do not feel the explanation for unimproved CTX energy confinement lies in this area. On the theoretical side, puncture plots of mixed $m = 0$ and $m = 1$ equilibria (performed in support of our $m = 1$ helicity source experiment [4]) show no serious degradation of flux surface closure for perturbations at the 10% level. These facts do not entirely settle the issue. Simulations of the resistive evolution of decaying spheromaks in a cylindrical geometry [5] show that the growth of an $n = 2$ distortion and subsequent formation of a new magnetic axis is accompanied by some loss of field line closure whose effects on confinement are not known. By applying an external bias field on CTX we have obtained conditions in which increased $\tau_B 2$ and τ_E were accompanied by the disappearance of $n = 2$ oscillations. Because other observable quantities (e.g., current from the plasma to the mesh) were also significantly affected, this result does not necessarily establish a causal relation between kink modes and confinement.

To examine the internal structure of the $n = 1$ and $n = 2$ modes on CTX, we are analyzing data from the multichord interferometer using tomographic techniques similar to those used in the successful reconstruction of the perturbed surface current from Rogowski loop data [6]. This work is still in progress, but it shows clearly that, during both the sustainment ($n = 1$) and decaying ($n = 2$) phases of the discharge, the density profile peaks near the magnetic axis. If the observed distortions of $n(\vec{r})$ do indeed follow the magnetic flux surfaces, then we have a nonperturbing measurement of the internal 2-D structure of the modes. One result of this study, with implications for confinement, is that local density gradients in the presence of kink modes can be significantly greater than what would be inferred from the inversion of time-averaged data. An unanswered question might still be: At what level do current-driven modes have an adverse effect on spheromak confinement? This issue decreases in significance as steps are taken to control the equilibrium field profile.

Ion Temperature Measurements

We have used two polychromators to simultaneously measure Doppler broadened line widths of ion impurities in CTX discharges. Both instruments have seven wavelength channels each to resolve the line shape, and together cover the interval of 1500-5000 Å. Lines used have been C-III (2296.9Å), N-IV (at both 1718.6 and 3478.7Å), O-IV (3385.6Å) and O-V (2781.1Å). In all instances, we have used normal incidence VUV monochromators to monitor resonance transitions of the same emitting ions at wavelengths below 1000Å. This monitoring helps ensure that the line being used for the broadening measurement has a similar time signature as that of the more isolated resonance transition. Both instruments view diameters through the midplane and are separated by a toroidal angle of 150°.

In order to ascertain any changes in the ion temperature from different species, we have used lines from different emitting species, both with sequential and simultaneous measurements. As the charge state distribution of the emitting ions changes with time, the corresponding line strengths vary significantly within a discharge. Typically, C-III, N-IV and O-IV burn through by 0.7 ms, so that a comparison of 'temperatures' from the different species must be made prior to this time to ensure sufficient signal strength. Consequently, line width temperatures averaged from 0.5 to 0.6 ms from zzz shots have been collected in a data base for analysis.

Ballooning Modes

Because of the low shear of spheromak equilibria. the predicted threshold in β for the onset of pressure-driven modes is low. Recent computations using the Mercier criterion for the marginal stability of CTX equilibria show that $\langle\beta\rangle_{vol}$ at the stability threshold is less than 0.6% for decaying spheromaks [1]. Sustained CTX spheromaks have more strongly sheared profiles for which the threshold is ~ 1.2%. It thus appears likely that these ideal modes are active in all spheromak discharges. In order to see indirectly whether pressure-driven modes were controlling τ_E, we attempted to raise the critical β for instability by modifying the q-profile. We inserted a 15-cm-radius copper cylinder, with a hemispherical cap, along the geometric axis of CTX. The resultant configuration was like that used at Osaka for the stabilization of disruptive instabilities on CTCC-1 [7]. The Mercier criterion computations indicated that a fourfold increase of the $\langle\beta\rangle_{vol}$ threshold could be expected at the insertion of 50 cm that was used. Assuming no current flow on the cylinder During CTX discharges, the axial current measured in the cylinder was only 5% of the spheromak poloidal current. However, even with j/n_e as high as 3×10^{-14} A·m, the electron temperature of decaying spheromaks as measured by Thomson scattering was lower than before. Insertion of the cylinder also increased the radiated energy density near the magnetic axis to 50% of the local magnetic energy density. The global energy fraction radiated during both decay and containment was 70%. Therefore changes in the contribution of impurity radiation to the energy balance probably obscured the effects of modifying the q-profile. We therefore still have no experimental measure of the role of ballooning modes in spheromak energy confinement. Smaller spheromak experiments have generally achieved higher β than larger ones, and among the many unanswered questions is: Given the low ballooning mode threshold, are the β values of order 10% achieved is some spheromaks (including CTX at 40 cm radius) representative of the performance to be expected in a more reactor relevant regime? In other words: For β above the instability threshold, how does the effect of ballooning modes on τ_E scale with increasing size and magnetic Reynold's number, S?

Optimum Boundary Conditions

One important question for spheromaks is that of the desirability of having conducting boundaries or flux conservers near the spheromak. We feel that in order to produce the best parameters a conducting boundary needs to be provided which is as close as possible to the last closed flux surface of the spheromak. (This approach has been used with success in the RFP community.) A conducting boundary prevents the loss of helicity. If an insulating boundary such as a vacuum with open field lines is used then the spheromak eject its helicity into the boundary and decay very rapidly. The optimum boundary is a conducting boundary with $B \cdot n = 0$ everywhere. Open field lines (ones that penetrate the boundary) are also undesirable because the plasma on these field lines will have low conductivity and tend to have large $E_{\parallel}$ which cause a large dissipation of helicity. For this ideal spheromak boundary the entire first wall is the plasma limiter. This is highly desirable because with high power density systems plasma limiters that are a small fraction of the plasma area cause an undesirable concentration of the edge plasma power loss. The challenge of spheromak research is to develop a conducting boundary which prevents helicity loss while allowing helicity injection. The boundary should also absorb impurities and supplies hydrogen at the desired rate.

The ratio of the average toroidal current density to the average line density at the magnetic axis j/n (in units of 10^{-14} A·m) is an important quantity for RFP's and probably for spheromaks. It is proportional to $\sqrt{T_e} v_D / v_t h$ and is a measure of the onset of current-driven instabilities. The square of j/n is also proportional to the ratio of ohmic heating power to radiated power. RFP's in general require j/n $\geq$ 1 in order to have low values of the radiated power fraction.[1] Our standard operating values of 1 < j/n < 2 are only reached in 'clean' plasmas which do not have high fractions of radiated power. We have found that j/n in CTX discharges tends to have a weak saturation at values $\leq$ 3 for our standard discharges. It is found that although the toroidal current I_{tor} is increased (in the range 0.4 - 1 MA), n increases also.

The significantly higher values obtained in RFP's (j/n $\leq$ 15) may not be obtainable in spheromaks due to differences in the physics of the two concepts. The high aspect ratio of the RFP affords a substantial hole to pour lots of flux through to force high E_{tor} and drive j up. In RFP's with j/n > 5, the anomalous resistivity coefficient increases faster than the increase in j/n.[8] The same process may limit j/n increases in spheromaks.

Another difference in spheromaks and RFP's involves the proximity of a conducting wall. Experience with RFP's <u>without</u> a conducting shell[9] shows that for the same toroidal current and <u>'similar'</u> discharge parameters that the initial filling pressure must be 2-3 times higher than that in the same machine <u>with</u> a conducting shell. The magnetic fluctuations increase and the particle confinement time is substantially degraded for operation without a conducting shell. As a result, comparable values of j/n are not achieved.

References

[1] Wright, B. L., et al., "Helicity Conservation and Energy Confinement in CTX Spheromaks", 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA, Kyoto, 1986.

[2] Barnes, C. W., et al., Nucl. Fusion 25 (1985) 1657.

[3] Knox, S. O., et al., Phys. Rev. Lett. 56 (1986) 842.

[4] Wright, B. L., et al., "Theory and Operation of the m = 1 Helicity Source Experiment", Proc. 7th US/Japan Workshop on CT Research, Spectra Technology, Inc., Bellevue, 1985, pg. 50.

[5] Dagazian, R. Y., et al., "Evolution, Relaxation and Transport in SPheromaks and Reversed Field Pinches", 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA, Kyoto, 1986.

[6] Wright, B. L., "Analysis of Surface Currents on the CTX Mesh Flux Conserver", Proc. 6th US Symposium and 5th US-Japan Joint Symposium on CT Research, PPPL, Princeton, 1984, pg. 5.

[7] Watanabe, K., et al., "Instabilities Observed in the CTCC-1 Experiment", Ibid., pg. 29.

[8] Bodin, H. A., Krakowski, R. A. and Ortolani, S., Fusion Technology, to be published (1986).

[9] Robertson, S., Bull. Am. Phys. Soc. 31, 1441 (1986).