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ABSTRACT

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FIELD REVERSAL EXPERIMENTS (FRX)

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I. INTRODUCTION

[illegible]

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[illegible]

II. EXPERIMENTAL SYSTEM

Both FRX-A and FRX-B [illegible] quartz tube inserted in a [illegible] A [illegible] mirror field is produced by [illegible] the end of the coil. The majority of the detailed [illegible] have been done on FRX-A, which has a [illegible] peak field capability with [illegible] rise time. [illegible] have been [illegible] the more energetic [illegible] rise times.

The temporal behavior of the external B-field shown in Fig. 2 is [illegible] operating in the "reversed bias" mode. The [illegible] begins with the slowly rising negative bias field, followed by the ringing theta-pinch preionization (PI), and then at t=0, the main field rises rapidly and is crowbarred with a 150-200 μs decay time. Comparison of the vacuum shot with the static 5 mTorr D_2 fill shows the increased damping of the ringing PI as the plasma is formed. The bias field and PI plasma are allowed to diffuse before the main field reverses the external field and implodes the plasma. The oppositely directed bias and main fields reconnect near the ends of the system [3,7] forming the RFC (see Fig. 1). The RFC excludes the open field lines from a substantial volume of the coil. This excluded flux effect results in a lower coil inductance and a higher coil current and external field shown in Fig. 2. When the RFC is destroyed (in this case, by the rotating m=2 mode), the field rapidly returns to the vacuum value. This effect has proved to be a reliable measure of the RFC lifetime. Fig. 2 represents typical data, but not the longest lifetimes observed in the two machines.

Other diagnostics are shown in Fig. 4. The spectrometer is used to obtain the electron temperature profiles by observing the CV 2271Å, [illegible] Å, and CV 2277Å lines. The ion temperature and rotational velocity is inferred from the polychromator measurement of the Doppler broadening and shift of the CV 2271Å line. In addition to the end-on interferometer shown in Fig. 4, a local [illegible] interferometer was used to measure the line density [illegible]

[illegible]

[illegible]

[illegible] dirty mode [illegible] electron temperature [illegible] indicating that T_e [illegible] Fig. [illegible]. The remainder of the paper considers only clean mode behavior.

The axial profiles of transverse line density shown in Fig. 6 confirm the plasma length of [illegible] indicated by the streak photographs during the equilibrium phase. The axial profiles are also confirmed by CV radiation measurements. The hollow radial profile indicated by the framing pictures is also confirmed by CV radiation and end-on interferometry. However, accurate measurements of the radial density profile are hindered by cold plasma outside the region of the implosion coil.

Ion temperatures are inferred from the Doppler broadening of the [illegible] Å line, which does not differ from [illegible] effects in the density range of interest. Depending on the strength of the imploding field, T_i varies between [illegible] and [illegible] eV. For the densities of interest, the equilibration time between the [illegible] and deuterium is less than [illegible]. The ion temperature is independent of radius and appears to be roughly [illegible] during the [illegible] of the equilibrium and instability phases. Although this [illegible] about the same as the uncertainty of the measurement, it is also the [illegible] that is consistent with [illegible] equilibration between electrons and ions, [illegible] T_e is fixed.

During the equilibrium and instability phases, the temporal behavior [illegible] the [illegible] line, the density, the electron temperature (Fig. 5), [illegible] temperature [illegible] [illegible] [illegible] [illegible] [illegible]. [illegible] the observed particle [illegible] with the expected [illegible], and the drop in T_e (Fig. [illegible]) [illegible] with the [illegible] electron thermal [illegible] [illegible].

[illegible]

[illegible]

The rotational velocity is determined by the Doppler shift of the [illegible] line [illegible] a variety of [illegible] through the plasma. The temporal behavior of the observed rotation [illegible] is shown in Fig. 7. The onset of the rotational instability [illegible] at the [illegible] normalized value of rotation.

[illegible] modifications of the system have been made in an attempt to [illegible] the rotation or equivalently to extend the life of the plasma. Since [illegible] and [illegible] [illegible] [illegible] the [illegible], hexapole fields were added and both first- and second-half-cycle operation were used in an effort to duplicate their results. No significant change in the maximum attainable lifetimes was observed.

Quartz end plugs were inserted in an effort to control the radial electric field and the associated rotation [14]. The effects were generally detrimental, but the results were clouded by possible interference of the plugs with the PI process. Experimentally, the plasma stability is very sensitive to the PI conditions.

The passive mirrors were removed from the end of the main coil in FRX-A and separately powered mirror coils were added. With a 1 μs quarter period risetime and a mirror ratio ~2, the uncrowbarred mirrors resulted in RFC lifetimes up to 45 μs. The plasma parameters under these conditions are being measured. The mirror power supply will soon be crowbarred to provide additional axial implosion energy, similar to the Kurtmullaev experiment. A possible explanation for the improved lifetime is that more rapid closure of the field lines confines a larger fraction of the plasma, and hence, greater inertia opposes the accelerating torque.

The higher energy [illegible] RFC lifetimes with the original passive mirrors.

[illegible]

The radial equilibrium profile of the [illegible] is probably similar to [illegible] cylinder [illegible] the length [illegible] is long compared to [illegible] will [illegible] the radial equilibrium to [illegible] profile. [illegible] with the rigid-rotor model, [illegible] needed to determine the actual radial [illegible] equilibrium [illegible] is similar to the [illegible] equilibrium [illegible] with very little [illegible] are being made [illegible] the equilibrium [illegible] with appropriate FRX boundary conditions.

The observed confinement time during the equilibrium phase of about [illegible] is longer than predicted for Bohm diffusion, but is substantially shorter than the [illegible] classical time, assuming the estimate of T_e=[illegible] eV is accurate. These shorter confinement times might be caused by micro-instability-induced diffusion [illegible] or by [illegible] diffusion. This [illegible] diffusion [illegible] dominate electron-ion diffusion for small values of [illegible] where a is the minor radius of the plasma and ρ_i is the ion gyro radius in the external field [illegible]. For the observed values of [illegible], both sources of anomalous diffusion are viable. The diagnostic studies of the recently observed longer-lived plasmas should increase the accuracy of the measured particle and energy confinement time.

The study of the stability properties of the FRX-produced plasmas is [illegible] by the rotational m=2 mode. The rotational modes for a standard theta pinch have been theoretically determined by Freidberg and Pearlstein [illegible]. The theory predicts a stable range of normalized rotation [illegible] a rigid-rotor profile. Freidberg modified the model to handle the rigid-rotor RFC. He made a simple, but not unique, analytic continuation in the vicinity of the singular point at R=0. The result predicted the critical rotation of $- / * \sim 1.5$ for the m=2 mode. Because the finite Larmor radius (FLR) expansion used in the code breaks down near B=0, the validity of the result was suspect. However, the results were verified ($- / * \sim 1.5$) by using a Vlasov fluid code [22] that correctly calculates the orbits near B=0.

The experimental and theoretical results qualitatively agree that a stable range of rotation does exist. However, the theoretically predicted value of the critical rotation is four times higher than experimentally observed. The error bars in Fig. 7 do not include the uncertainty in determining * from measured quantities, but it is certainly accurate to within a factor of 2. Other possibilities exist to explain the error, such as that the FRC may not have the assumed rigid-rotor equilibrium, or the CV ions may not be rotating at the same velocity as the deuterium, even though calculations indicate they should.

The apparent lowering of the rotational threshold for instability may arise from a coupling between the rotational mode and the MHD kink mode. Because of the geometry, the fastest growing kink mode probably results in the same m=2 distortion. Even though geometry and FLR effects may reduce the growth rate of the kink so that it is not observed in a non-rotational form during the plasma lifetime, the free energy in the field that drives the kink may lower the threshold of the rotational mode. Since both rotational models are one dimensional, they do not contain this possible driving force. Freidberg is examining the possibility of adding a gravitational term to simulate this effect. In addition, a 3-dimensional MHD code [23] is being used to study the effects of geometry and rotation on the kink mode [24].

The [illegible] tearing of the plasma into distinct rings has never been observed in the FRX systems. In spite of recent advances in the understanding of tearing modes [25,26], a two-dimensional model may have to be developed to accurately determine the stability of finite length layers as produced in the FRX systems. But even if long layers tend to tear into distinct rings, the result may not be detrimental to fusion concepts [27].

The continuing focus of research is to understand and control the m=2 rotational instability. Detailed experimental studies of the dependence of this mode on temperature, geometry, and FRC formation process are being pursued. Advanced theoretical models including geometry and kinetic effects are under development.

ACKNOWLEDGMENT

The assistance of Dr. C. J. Buchenauer in the development of the UV polychromator is gratefully acknowledged. In addition, the expert technical services of G. L. Stelzer and G. M. Sandoval are greatly appreciated.

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FIGURE CAPTIONS

Fig. 1. Reversed-field configuration.

Fig. 2. Comparison of the external B field measured in FRX-A and FRX-B between the quartz tube and the coil at the axial midplane. Traces are shown for both vacuum and a static 5 mTorr D_2 fill pressure.

Fig. 3. Schematic arrangement for some of the diagnostics on FRX-A.

Fig. 4. Side-on streak and end-on framing pictures for the (a) dirty mode and (b) clean mode of operation. The framing rate is 1.7 μs/frame, with the first frame at t=3 μs. The thin, outer luminous ring in the framing pictures corresponds to the 20-cm diameter quartz tube.

Fig. 5. Oscilloscope traces comparing the temporal behavior of the (a) CIII 2297Å radiation, (b) CV 2271Å radiation, and (c) the external magnetic field for clean mode operation. The intensities of the two carbon lines are plotted on the same scale.

Fig. 6. The line density through the HFC [illegible] as a function of axial position for three times during the equilibrium phase. The connecting lines are added for visual clarity.

Fig. 7. The temporal history of the CV rotational velocity normalized to the deuterium diamagnetic drift velocity.

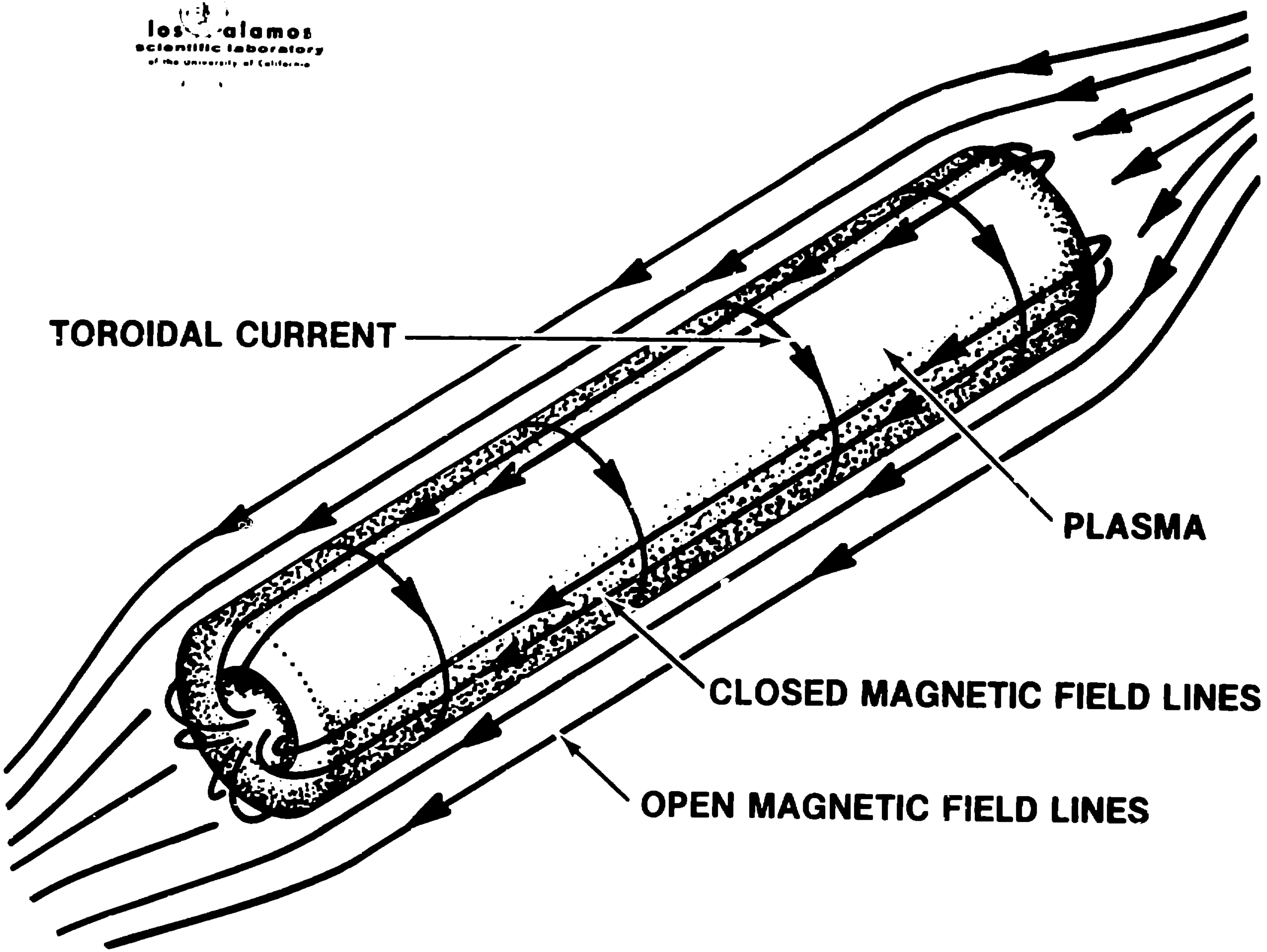

FIG. 1. REVERSED-FIELD CONFIGURATION.

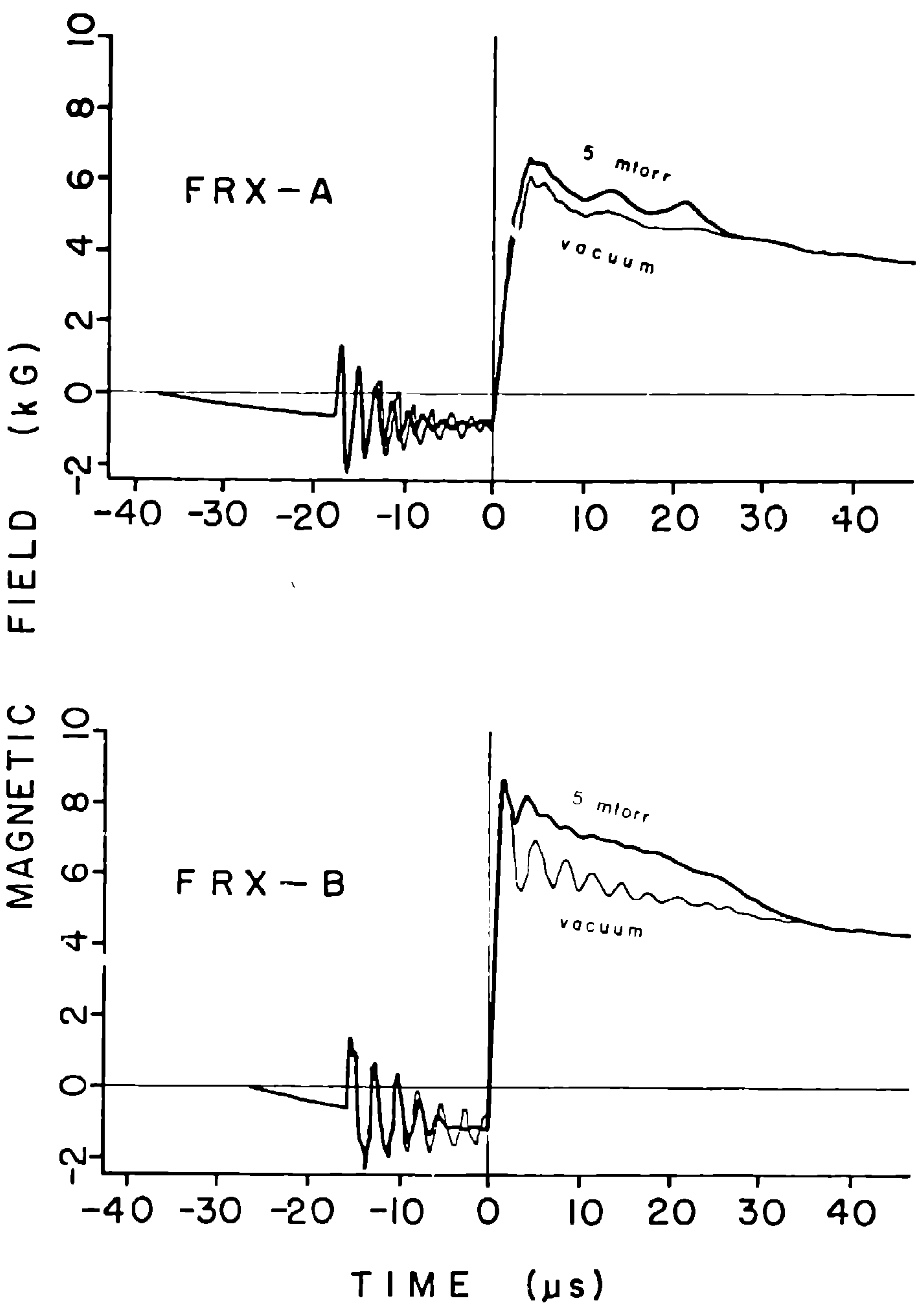

FIG. 2. COMPARISON OF THE EXTERNAL B FIELD MEASURED IN FRX-A AND FRX-B BETWEEN THE QUARTZ TUBE AND THE COIL AT THE AXIAL MIDPLANE. TRACES ARE SHOWN FOR BOTH VACUUM AND A STATIC 5 MTORR D_2 FILL PRESSURE.

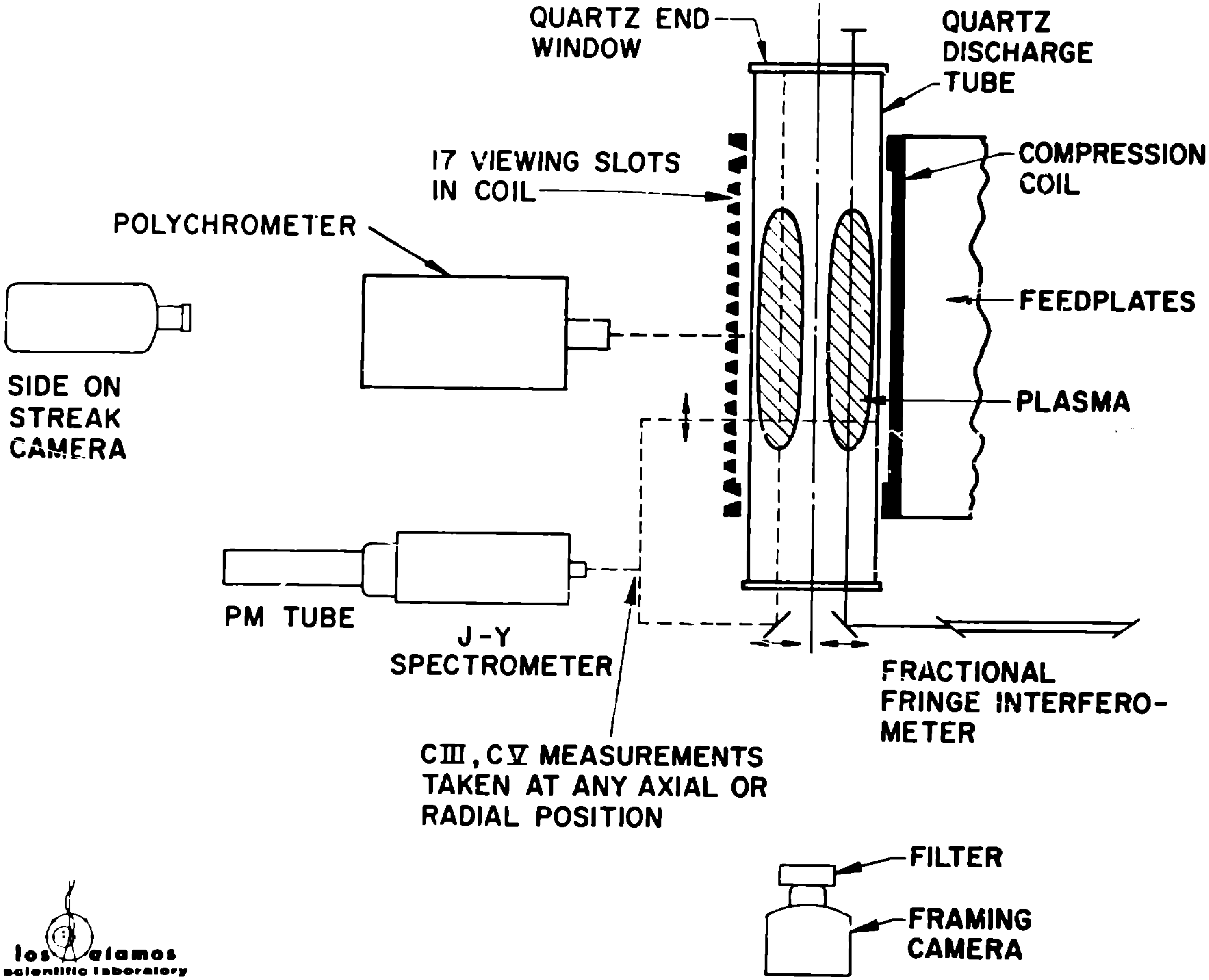

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FIG. 3. SCHEMATIC ARRANGEMENT FOR SOME OF THE DIAGNOSTICS ON FRX-A.

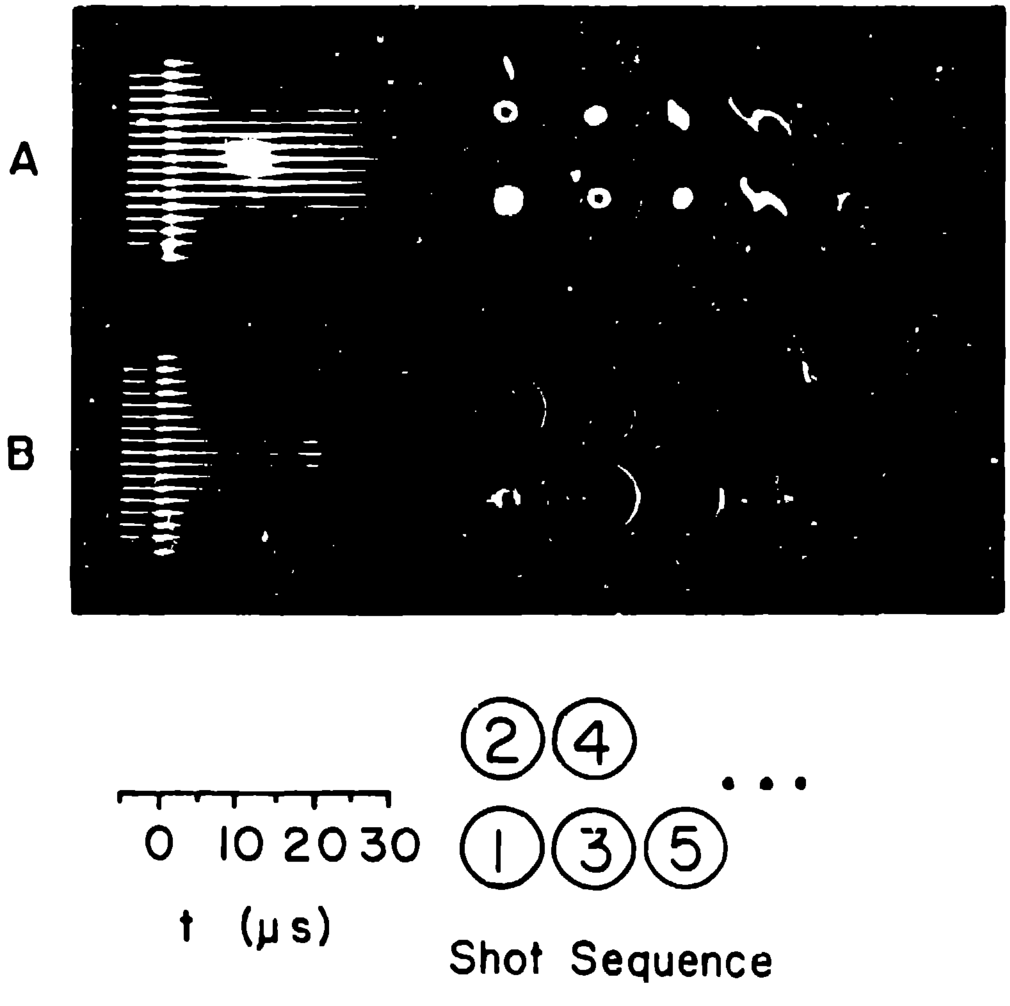
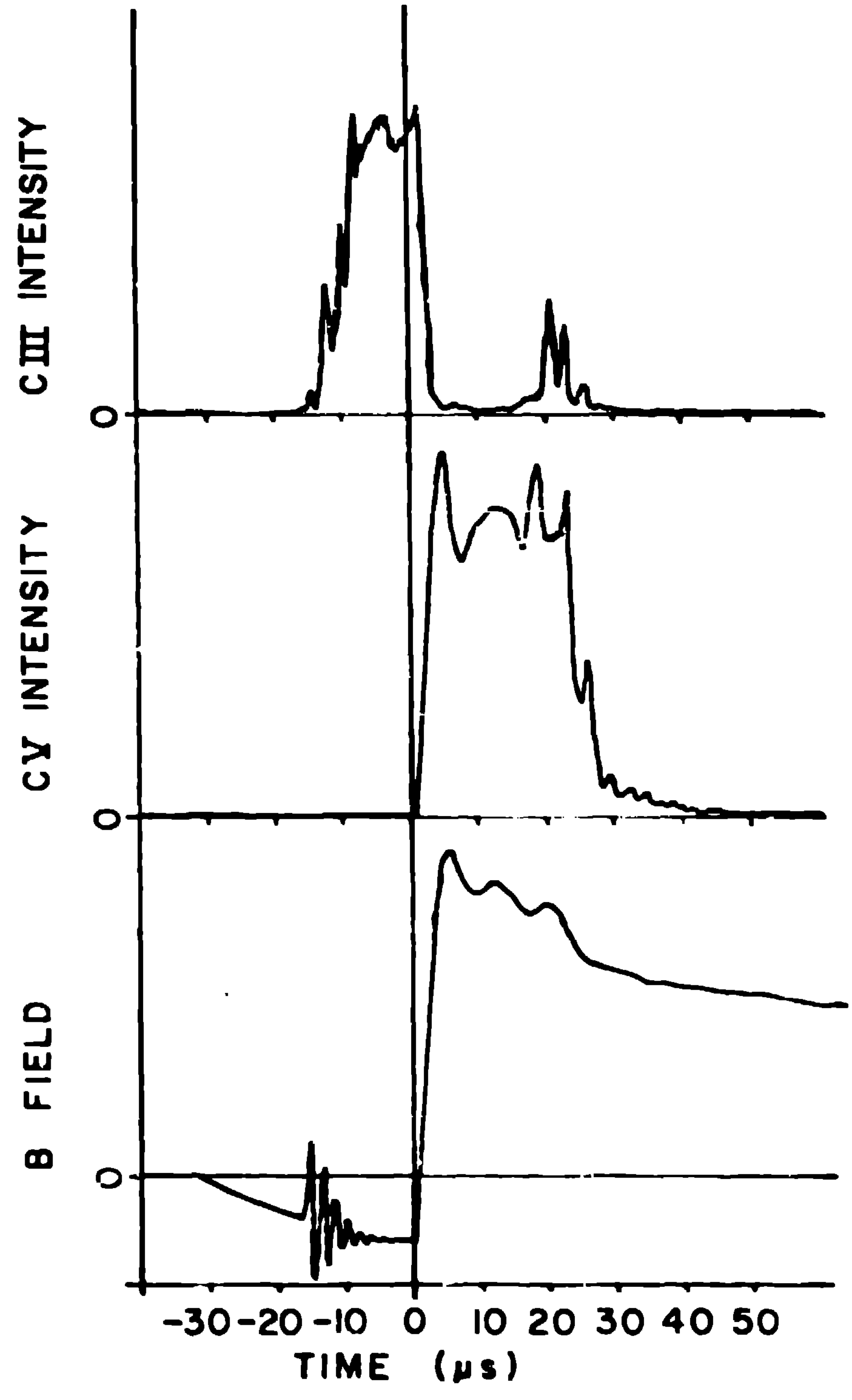


Fig. 4. Side-on streak and end-on framing pictures for the (A) dirty mode and (B) clean mode of operation. The framing rate is 1.7μs/frame, with the first frame at t=3μs. The thin, outer luminous ring in the framing pictures corresponds to the 20-cm diameter quartz tube.



[illegible] [illegible] TRACES [illegible] THE TEMPORAL BEHAVIOR OF THE [illegible] [illegible] EMISSION [illegible] [illegible] RADIATION, AND [illegible] THE EXTERNAL MAGNETIC FIELD FOR CLEAN WALL HEATING. THE INTENSITIES OF THE TWO CARBON LINES ARE PLOTTED ON THE SAME SCALE.

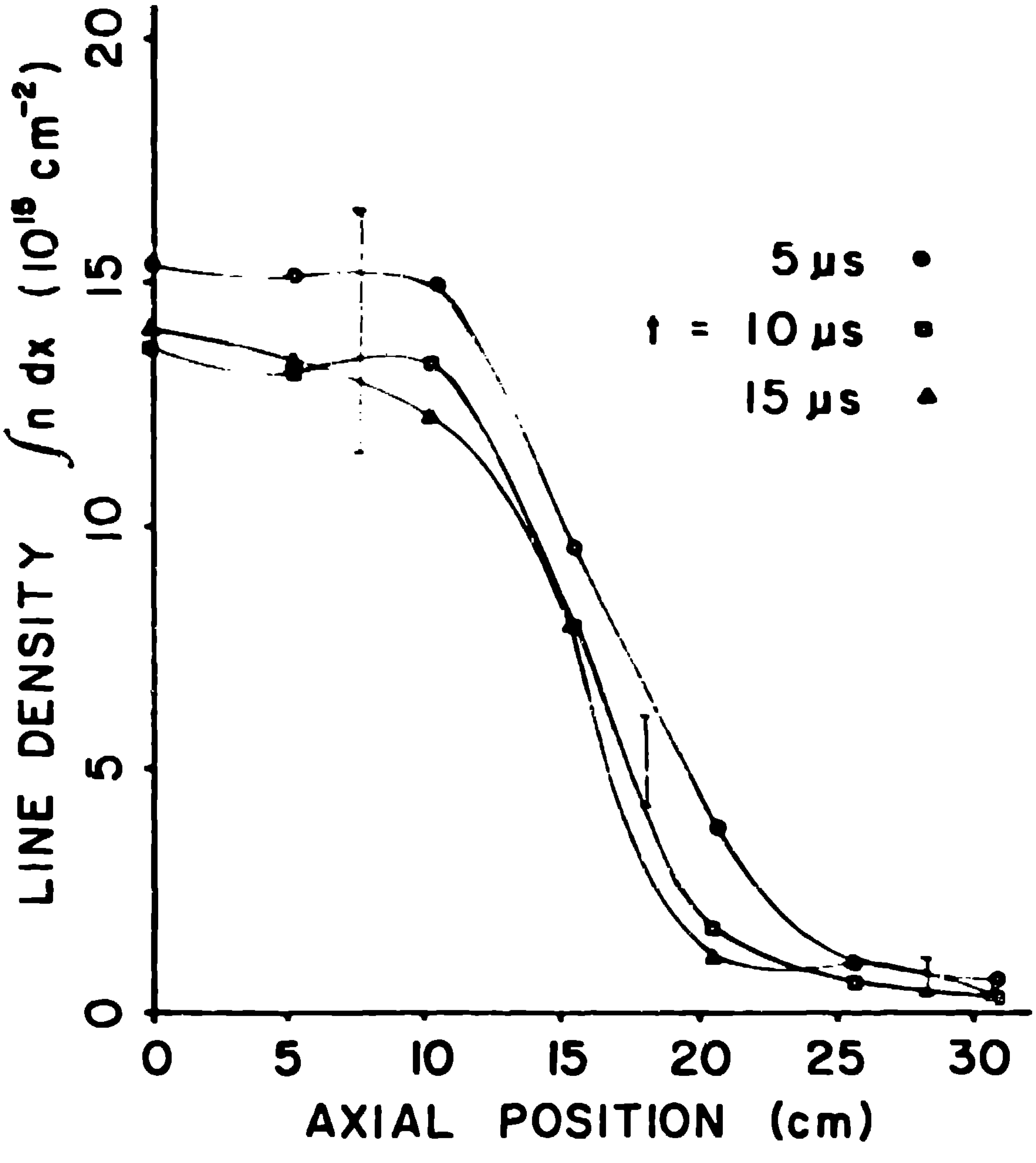


Fig. 6. The line density through the RFC diameter as a function of axial position for three times during the equilibrium phase. The connecting lines are added for visual clarity.

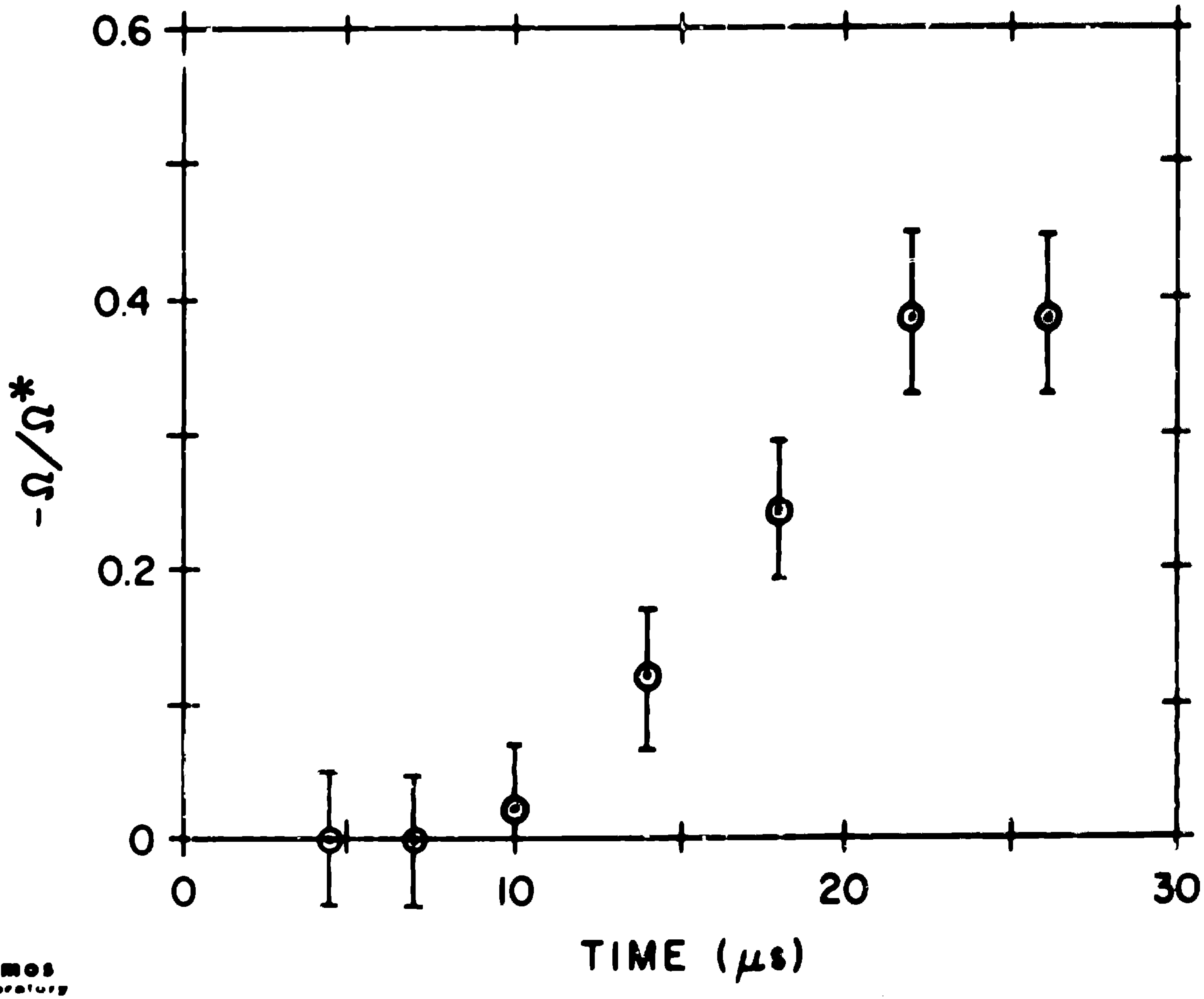


FIG. 7. THE TEMPORAL HISTORY OF THE CM ROTATIONAL VELOCITY NORMALIZED TO THE DEUTERIUM DIAMAGNETIC DRIFT VELOCITY.