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INTRODUCTION TO THE LASER-HANE EXPERIMENT AND SUMMARY
OF LOW-PRESSURE INTERACTION RESULTS(U) NAVAL RESEARCH
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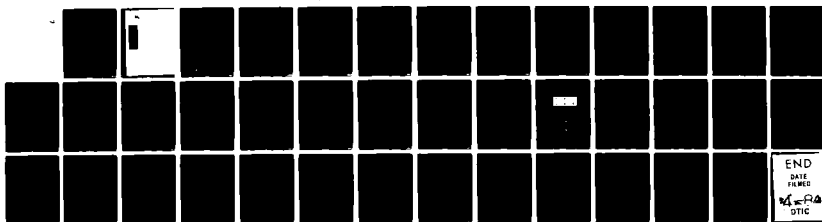
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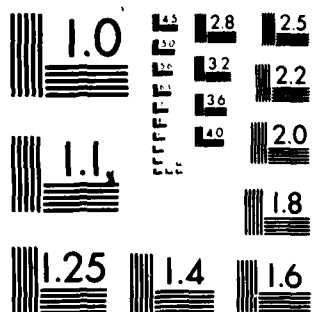
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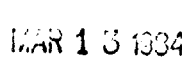
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A brief overview of the NRL laser-target experiment which simulates the interactions involved in a HANE is presented. A burst of fast laser-produced-debris-ions stream into a low-density magnetized ambient plasma/gas. The interactions between these two plasma components are investigated under a variety of conditions. At ambient pressures below 150 mTorr we observed a magnetic bubble formation during the debris expansion; we found that the field is swept out of the volume traversed by the debris plasma and is compressed ahead of the debris front. Evidence is found for magnetic-field dependent interactions between the debris ions and ambient plasma.				
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11. TITLE

INTRODUCTION TO THE LASER-HANE EXPERIMENT AND SUMMARY OF LOW-PRESSURE
INTERACTION RESULTS

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INTRODUCTION TO THE LASER-HANE EXPERIMENT AND SUMMARY OF LOW-PRESSURE INTERACTION RESULTS

I. Introduction

DNA's Division of Atmospheric Effects (RAAE), initiated a laser-target HANE-simulation experiment at the Naval Research Laboratory in early 1982. The objective of this experiment is to study the mechanisms involved in a HANE event, especially those which affect the early-time evolution of the plasma structure.⁽¹⁾ The experiments have two goals. The first objective is to emulate a nuclear event as closely as possible. Laboratory parameters which cannot directly duplicate those of a real or hypothetical HANE, such as masses and distances, have to be scaled using an appropriate scaling argument. The second goal is to study relevant physical effects or mechanisms, even if the experimental parameters are quite far from that of a direct simulation. In either case coupling to the theoretical activity in the HANE-community is desirable to achieve a better understanding of the consequences of a HANE-like event and its relationship to the laboratory findings.

The experiment to date has focused on three regimes of interest. These are:

- o Collisionless Coupling Regime (low ambient pressure).
- o Collision Dominated Regime (high ambient pressure).
- o Disassembly Regime (high debris density, high debris acceleration).

The collisionless coupling (or low-pressure) regime is used to address the mechanisms involved in the debris-air coupling at high-altitudes (such as in Starfish), where collisionless or Longmire coupling is operative; a review of our experiments in this regime forms the major portion of this and the next paper.⁽²⁾

Manuscript approved November 29, 1983.

When ambient gas pressure is above a few-tenths of torr (high-pressure), the experiment exhibits collisional characteristics that correspond to HANE conditions in the 100 to 200 km altitude range (such as Checkmate). Our first experiments in this regime is the subject of several other papers in this proceedings.^(3,4,5)

Finally, the disassembly regime is concerned with the nonuniformities that may result during the detonation stage when the weapon material is highly accelerated outward by the released energy; a primary question is whether these nonuniformities grow due to Rayleigh-Taylor instability⁽⁶⁾ and evolve into later-time structure.⁽⁷⁾ Experiments addressing this subject are the subject of another paper in this proceedings.⁽⁸⁾

II. Experiment and Diagnostics

I will now outline the configuration of the present experiment and the parameter regimes that are accessible. Enhancements to the laser and target facility presently being made will also be briefly described.

The experiment involves focusing beams from the NRL-Pharos II Nd-laser (1.05 μm wavelength) onto a small (< 1 mm dia, few-microns thick foil) solid target in the center of the target chamber. Target material is ablated by the laser irradiation and streams radically outward with kinetic energy densities comparable to those resulting from a weapon detonation. A low-density background gas in the chamber is promptly ionized near the target by radiation from the laser-target interaction (photoionization), and at later times by the expanding debris (UV photoionization from the debris shell or by particle impact). This creates an ambient plasma, through which the high-velocity nuclear-like debris streams, emulating the ionospheric conditions surrounding a detonation; an external magnetic field can be applied over the whole interaction

region, using permanent magnets or coils, to mock-up the ionospheric magnetic field. As we will see, with appropriate scaling the spatial dimensions of the relevant interaction region is of the order of centimeters, the time-scales involved are fractions of a microsecond, the magnetic fields are close to kilogauss and the required ambient gas pressure is below ten Torr (1 Torr = 1 mm of Hg = 3.24×10^{16} molec/cc). The laser-pulse energy requirement to simulate a detonation is also reasonable, being 10 to 1000 Joules. Figure 1 shows the experimental arrangement schematically. Some of the present and (to be) upgraded facility specifications are tabulated in Table I. The facility upgrade, which includes extensive modifications to both the laser and the target areas, is expected to be completed in late FY-84 or early FY-85.

Table I. Facility Specifications

	LASER			CHAMBER/GAS		MAGNETIC FIELD	
	Energy ^(a) (J)	λ (μ m)	#Beams	Diameter (cm)	P ^(b) (Torr)	B(kgauss)	Coil Diameter (cm)
Present	400	1.05	2 ^(c)	60	$> 10^{-5}$	0.8 ^(d) 0-1 ^(e)	5 10
Upgrade	1500	1.05 ^(f) 0.53 ^(f)	3 ^(g) 2-3	130	$> 10^{-6}$	0-10 ^(e)	26

(a) In a 3-4 nsec pulse; a 300 psec pulse duration is also available at reduced total energy

(b) Any gaseous species

(c) One-sided illumination

(d) Permanent magnet

(e) Helmholtz and dipole coil configurations

(f) Narrow or broad bandwidth laser pulse

(g) One or two-sided illumination

Many diagnostics are available to measure the evolution of the debris-plasma interaction; and others are currently being developed.⁽⁹⁾ Diagnostics include devices to measure: the incident and reflected laser energy and time-history, the angular distributions of the resulting debris energy, velocity,

mass, and momentum. Magnetic probes measure the magnetic field distortions during the debris/background plasma interactions and self-generated magnetic field components as a function of position and time. Electric probes give similar information about the electric field and plasma properties in low-density plasma. Optical diagnostics such as shadowgraphy and interferometry yield quantitative pictures of the plasma density structure at moderate-to-high densities ($> 10^{17}$ electrons per cm^3) optical imaging with still-photography, time-resolved framing photography, or streak photography also give qualitative and quantitative information on density structure. Spectroscopy, from the infrared to XUV, is used to give spatially and temporally resolved information about the velocity, temperature, ionization state, density, emissivity, opacity, etc. of the debris material, the photoionized background plasma, and the interaction between them. Ion analyzers (under development)⁽¹⁰⁾ will allow measurements of the debris and reflected ambient ion velocity and species distributions along and across the magnetic field. Knowledge of the ion properties is valuable in resolving many of the current questions about early-time HANE instabilities. X-ray and XUV diagnostics allow diagnosis of plasma properties above about 20 eV; pinhole or imaging photography gives 2-D spatially-resolved images while electronic x-ray and UV detectors give quantitative information about the initial debris plasma temperature, the UV emission from the expanding debris-ambient plasma front, etc. Still other novel techniques are used for specific information. Tracer-dot techniques, in which small dots of a high-Z material are implanted in the target surface, have proved valuable in providing debris flow visualizations and spatially resolved quantitative spectroscopy.⁽¹¹⁾ Resonant and nonresonant laser scattering in the disturbed plasma has been proposed to measure the density power spectrum.⁽¹²⁾ The experiment can also provide a short-pulse x-ray flash for quantitative x-ray

radiography of the highly-accelerated ($> 10^{15}$ cm/sec²), high-density (> 0.1 solid) targets in the accelerating target regime.⁽¹³⁾ Highly accelerated targets, which can be purposefully structured, are being used to study the hydrodynamic stability of material during device disassembly and the sensitivity of plasma structure evolution to nonuniformities in the target.⁽¹³⁻¹⁶⁾

III. Scaling of Laser-Experiment to HANE:

Scaling of HANE-parameters down to laboratory conditions is predicated on several alternate sets of assumptions, depending upon the physics of interest. No set of assumptions will simultaneously reproduce all aspects of a HANE event; one should, therefore, consciously choose which physical conditions are to be retained on the basis of their importance to the experiment. Longmire formalized one scaling scheme by fixing the debris velocity in the laboratory experiment to be equal to that of a real HANE and by preserving binary collisions;⁽¹⁷⁾ this scaling preserves binary collision effects but not magnetic field and plasma instability effects. It is a reasonable approach when details of collisions are crucial. Also, it gives a feeling for how parameters scale from a HANE down to the laboratory. Table II shows Longmire collisional scaling relations as a function of the yield ratio $Y \equiv E_d/T_w$ between the HANE-weapon and laboratory debris kinetic energies. As mentioned before, most of these parameters are achievable in the experiment. But, if the focus of a particular investigation is the role of streaming instabilities for "collisionless" debris-air momentum transfer,⁽¹⁸⁾ other scaling relations are more appropriate. Scalings which emphasize instability coupling have been discussed by ourselves⁽¹²⁾ and, more thoroughly, by Tsai, DeRaad and Lelevier (RDA),⁽¹⁹⁾ Smith and Huba (NRL),⁽²⁰⁾ Stellingwerf, Longmire and Alme (MRC),⁽²¹⁾ and Sperling (JAYCOR).⁽²²⁾ These scalings generally relax the debris velocity and

material constraints but require stronger magnetic fields than strict B^2/nkT scaling. The parameters of the target facility upgrade were, in fact, chosen to allow clean studies of this type. Undoubtedly, other phenomena of interest, such as MHD-EMP, highly-accelerated dense material, etc., require still other scaling emphasis.

The targets can be irradiated in three modes: the exploding-pusher mode; the ablation mode; and the accelerating target mode. The exploding pusher mode⁽²³⁾ occurs at high laser irradiance and yields very high-velocity ion debris (but with a broad nonreproducible distribution). The ablation mode^(24,25) occurs at lower laser irradiance ($I < 10^{14}$ W/cm²) and yields a very reproducible narrow ($\Delta v/v \approx \pm 0.1$) ion velocity distribution with mean velocity tunable between 10^7 and 8×10^7 cm/sec. This mode of operation is particularly suitable for detailed HANE investigations due to its simplicity, reproducibility, and cold ion distribution; this is the mode of preference for most studies. The third mode, the accelerating target mode,^(14,24,25) uses the ablating debris to accelerate a thin target to high-speed (up to 2×10^7 cm/sec) while remaining near solid-density (> 0.1 solid density) and cold (< 10 eV). Each of these modes can be exploited for specific HANE studies.

The laser-plasma interaction can deposit energy densities comparable to those of a real weapon and set up conditions close to (but not identical to) actual HANE-events. The time and spatial scales are experimentally achievable and well-diagnosed experiments can be done in a repeatable and repetitive manner at modest cost (comparatively speaking). Therefore, with your help many issues crucial to HANE phenomenology and structure evolution will soon be tested.

A brief description of our exploratory experiments in the low-pressure or collisionless regime follows. We search for signs of a collisionless mechanism such as plasma instability that could couple the debris momentum to the ambient

Table II. Collisional (Longmire⁽²⁾) scaling of selected HANE parameters with the relative energy ratio Y .

<u>Parameter</u>	<u>Scaling</u>	<u>Representative values for $Y=10^{-12}$</u>
Velocity	$v = \text{constant}$	10^8 cm/sec
Mass (debris)	$m_d \propto Y$	0.1-1 μgm
Distances	$R \propto Y^{1/2}$	~ 1 cm
Time	$t \propto Y^{1/2}$	~ 100 nsec
Background density gas	$p \propto Y^{-1/2}$	10^{13} - 10^{18} atoms/cc
*Magnetic field	$B \propto Y^{-1/4}(a); Y^{-1/2}(b)$	~ 1 kG (a); ~ 1 MG (b)
*MII instability	$\gamma\tau \propto Y^{1/4}(a); \text{const}(b)$	~ 1 (a); $\sim 10^3$ (b)

*The magnetic field does not scale uniquely. The (a) scaling preserves the magnetic field/plasma energy density ratio (B^2/nkT) which also preserves the Alfvén velocity constant; in this scaling the number of instability growth times is compromised. An alternate assumption (b) is to keep Larmor radii constant with other distance scales; this requires unrealistically high magnetic field.

IV. Low-Pressure Ambient-Plasma Regime

In our first experiments in the low-pressure (< 150 mTorr) regime, we search for signs of beam-plasma instabilities. These instabilities are thought to effect debris-air coupling in high-altitude events, such as in Starfish (400 km), in which collisions alone are insufficient to transfer momentum from the device debris to the ionosphere. The experimental configuration and the ambient and debris ion velocity distributions are sketched in Fig. 2. Of the five streaming instabilities thought to be relevant to HANE (Lampe et al.)⁽¹⁸⁾ we focus our attention on the magnetized ion-ion instability. The magnetized ion-ion instability is an efficient momentum transfer mechanism with an effective collision frequency of about one-tenth the lower hybrid frequency.

We are in a regime in which the debris ions are unmagnetized (cyclotron radius $\gg$ equal mass radius), the ambient plasma is magnetized (electron and ion cyclotron radii $<$ the equal mass radius) and, most importantly, the debris

magnetic Mach number is high ($V_D > V_{\text{Alfven}}$). The latter constraint is deemed important to preserve the hydrodynamics of a HANE event.

The uncoupled debris ion distribution has high-velocity (up to 8×10^7 cm/sec) and a narrow spread ($\pm 10\%$) as seen in the typical time-of-flight detector signal of Fig. 3. The first blip is the $t=0$ marker (due to the x-ray flash from the laser-target interaction; this occurs on this plot at about 0.4). The mean velocity of the ions is 6×10^7 cm/sec in this case. The debris-ion distributions are well-behaved and reproducible in the absence of an interaction. Moreover, they can be tuned up or down in velocity by changing the laser irradiance.⁽²⁵⁾ The relative velocity between debris and ambient ion distributions exceeds the thermal spreads of the beams, thus satisfying the criteria for streaming instability.

When ambient gas is present, the debris distributions are altered. For ambient pressures of 80 millitorr and up, the debris ion distributions reaching the time-of-flight detector (about 22 cm away from the target) are attenuated and slightly broadened, as in Fig. 4. These changes to the debris velocity distributions are thought to be due to collisional processes, or at least magnetic field independent mechanisms, since they do not seem sensitive to the presence or absence of a magnetic field (at least not sensitive to fields below one-kilogauss).

To test the collisional properties of the debris ions in traversing tens-of-centimeters of ambient plasma and gas before detection, we use the setup shown in Fig. 5. Three time-of-flight charge collector detectors are placed at 10 cm, 25 cm, and 55 cm distances from the target to detect ion distribution changes occurring between them.

One question is whether we can rely upon the preservation of the shape of the ion distribution in passing through the ambient media; if so we can detect

the effects of an interaction occurring within a few centimeters of the target much further away. The answer is seen in Fig. 6; at least through a mass-pathlength of 5×10^{16} molecules/cc * cm (i.e., 150 mTorr N_2 with $l = 10$ cm) both the peak velocity and velocity spreads are not strongly affected. Therefore, they can be used as good indicators of interactions close to the target.

Another related question is whether significant debris ion charge is being lost due to charge exchange processes between the target and detector. Figure 7 shows that the answer is affirmative for low-velocity carbon debris (< 350 km/sec) for mass-pathlengths above about 10^{16} molecules/cm², and for higher velocity Al at somewhat higher pressures. Thus, the attenuation of debris ions exhibited in Fig. 4 could be due to charge exchange or ion removal type processes.

Nonetheless some energy, albeit a small amount, is transferred from the debris to an expanding shell in the 100 mTorr regime; this is seen in the framing camera pictures of visible light emission, Fig. 8. A fuzzy shell expands with a speed of about 250 km/sec into a 100 mTorr N_2 background gas in which an 800 G external field was applied. Measurements of the magnetic field dynamics show that the ambient field is largely swept out of the region traversed by the debris and is compressed ahead of the debris front, as illustrated in Fig. 9. An extensive description of the magnetic field behavior is to be found in a paper by Kacenjar et al.⁽²⁾ elsewhere in this proceedings.

V. Collisionless Instability Regime

For what experimental parameters is the magnetized ion-ion instability most likely to be observed? To answer this question we examine the instability criteria outlined in Lampe et al.⁽¹⁸⁾ To satisfy the two most stringent

instability criteria, that of avoiding electromagnetic stabilization ($V_D/V_A \equiv M_A \lesssim 2.5$) and fitting at least one parallel wavelength in the system size ($\lambda_{||} < 2\pi R_m$), we should go in the direction of:

- o Increasing the magnetic field
- o Decreasing the ambient density
- o Decreasing the drift velocity
- o Decreasing the atomic number of the ions.

Smith and Huba quantitatively outlined expected regions of instability in laser energy-ambient pressure space, as shown in Fig. 10. For example, Figure 11 shows that carbon debris interstreaming through an 800 G magnetized ambient hydrogen plasma at a velocity of 400 km/sec should be MII unstable close to the experimentally accessible circled region. The outlined regions of instability assume full ionization of the hydrogen and therefore would move to the right in Fig. 10 if the gas is partially ionized (as indeed it is).

To detect the presence of instability, an array of four charge time-of-flight detectors is deployed perpendicular to the magnetic field direction but at various angles from the target normal, as sketched in Fig. 12.

A clear difference between the debris ion distributions with and without the magnetic field in place is seen in Fig. 13. Without a field present, as in the ion distributions on the left side of Fig. 13, the debris distributions are well-behaved and similar to those generated in a vacuum. In contrast, the distributions in the presence of the magnetic field (on the right) are broadened and have lower velocity (later-time) peaks which are like signatures of expected beam-plasma instability. The pressure is low and collisions play little or no role.

We used hydrogen gas to have a low the ambient-plasma atomic number in order to be more susceptible to instability, as indicated previously. To test the conjecture that lower atomic number is more unstable we compared debris ion distributions resulting from use of nitrogen ($A=28$) and hydrogen ($A=1$), as shown in Fig. 14. The magnetic field dependent interaction that occurring in hydrogen is not evident in nitrogen. This lends support to the notion that MII may be occurring in the carbon-hydrogen combination but not in carbon-nitrogen under our conditions.

Finally, sometimes ion signals are observed with components having higher velocities than in the original debris distributions. This occurs (for example in the circled regions of Fig. 15) at low incident laser energy in cases which exhibit the other signs of magnetic field dependent interaction. We have very few cases of this sort, and therefore the results are considered tentative. But, these "fast ions" may be the result of a reflection or acceleration process near the coupling region.

VI. Summary

The laser-target HANE-simulation experiment can examine physics questions relevant to HANE early-time phenomena in three regimes: the collisionless (low-pressure) regime, the collisional (high-pressure) regime, and the disassembly (dense high-acceleration) regime.

In the collisionless regime, the results of the first series of experiments show magnetic field dependent interactions between the debris ions and ambient plasma. In many ways these observations are similar to those expected from the magnetized ion-ion instability. However, an extensive study of collisionless plasma instability coupling awaits the upgraded laser and target facility.

VII. Acknowledgments

This work was supported by the Defense Nuclear Agency. The authors thank Drs. W. Ali, H. Griem, M. Herbst, C.K. Manka, and S. Obenschain for their contributions to this work. Guidance from Drs. J. Huba and R. Smith has proved valuable. Also, the assistance from Mr. E. Turbyfill, N. Nocerino, K. Kearney, and Ms. B. Sands is appreciated.

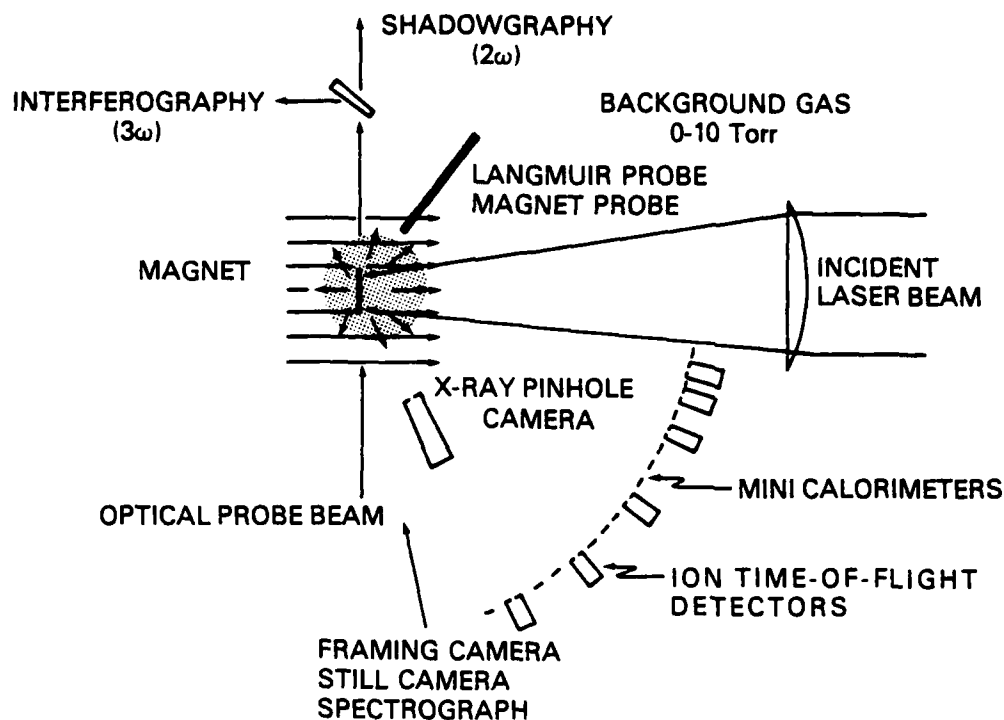


Figure 1 Experimental arrangement.

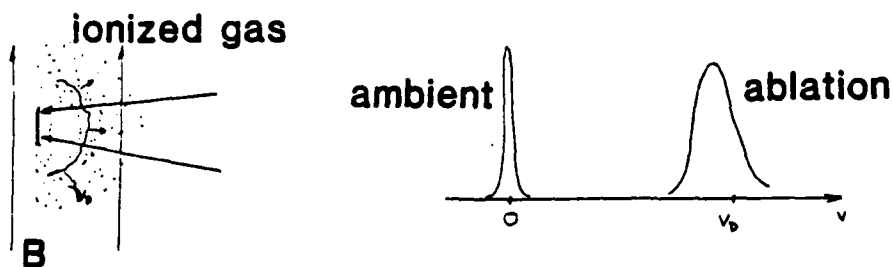
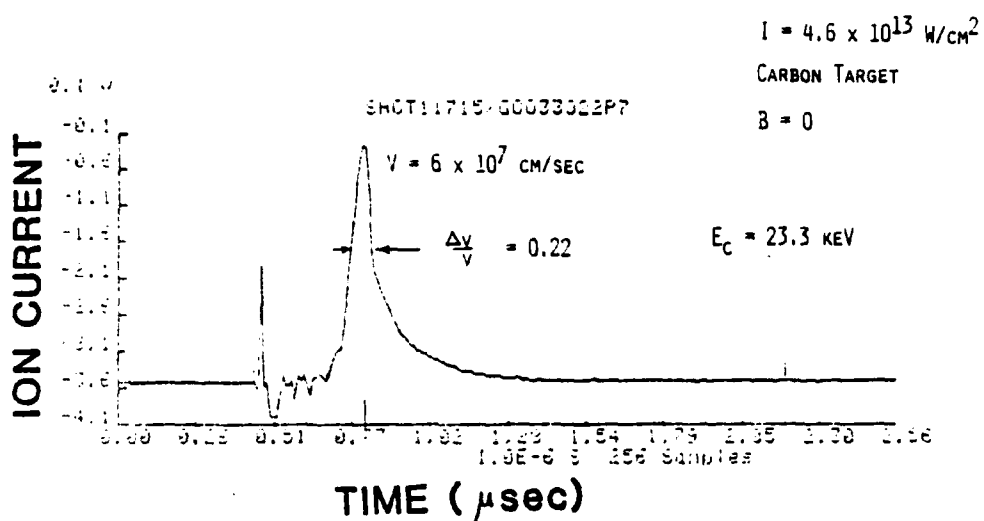


Figure 2 Schematic of the debris shell moving outward from the laser focal region through the magnetized photoionized ambient gas (left). The ambient (stationary) plasma and drifting target debris (ablation) plasma distributions form a classic interstreaming instability configuration (right).

ION TIME OF FLIGHT IN VACUUM



DEF. WIDEN. 1.00E-6 s
DEF. DIST. 1.00E-6 s

Figure 3 Debris ion time-of-flight detector signal. Note the high-velocity, narrow-velocity spread debris peak. These ions contain over 80% of the absorbed laser energy.

ION CURRENT

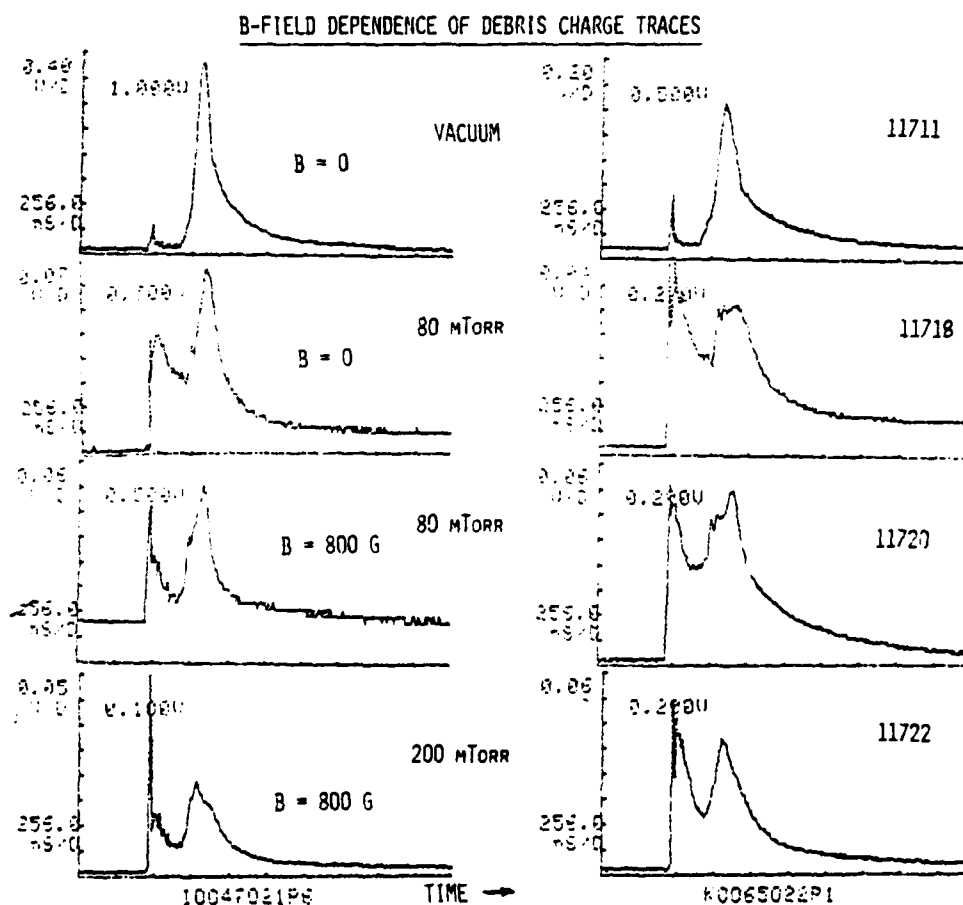


Figure 4 Debris ion time-of-flight data for moderate pressures (vacuum, 180 and 200 mTorr nitrogen), with and without a magnetic field. Traces on the left were obtained with detectors oriented at 47° to the laser beam axis and those at the right at 65° . Detectors were about 22 cm from the target and in a plane perpendicular to the magnetic field direction.

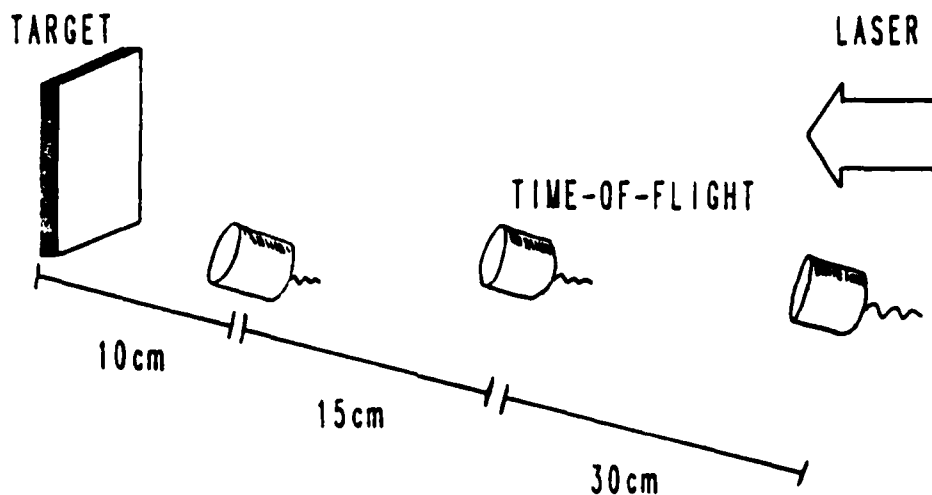


Figure 5 Setup to test the collisional properties of debris ions.

CURRENT vs AREAL DENSITY

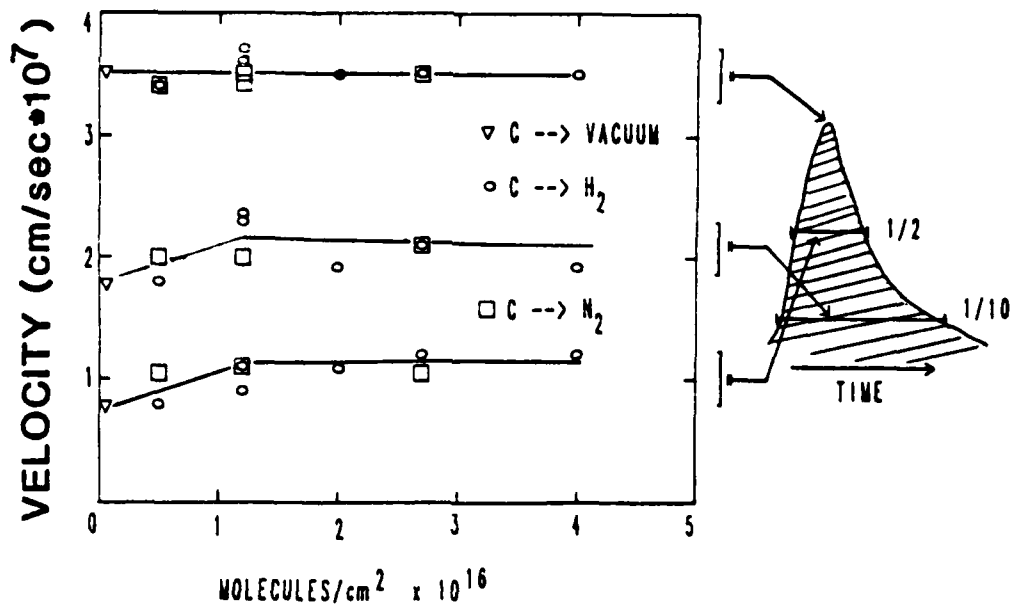


Figure 6 Peak-velocity and velocity spread (FWHM and $\pm 10\%$ points) versus mass path length of debris ions. No significant change in these ion trace characteristics are seen below 5×10^{16} molecules/cm².

CHARGE vs AREAL DENSITY

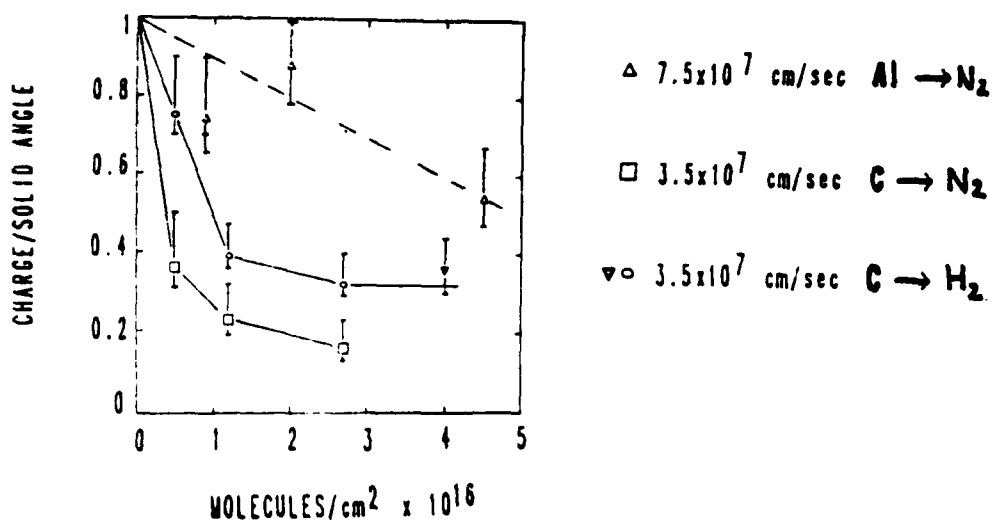


Figure 7 Debris ion charge per steradian (relative units) collected at various mass-pathlengths for several combinations of debris species and velocities and ambient gas parameters. Significant loss of charge is seen above 10^{16} molecules/cm² at low velocity.

VISIBLE FRAMING PHOTOGRAPHS

SHOT 12531
139 J, 4.5 micron Al target
100 microns Nitrogen, B=800 Gauss

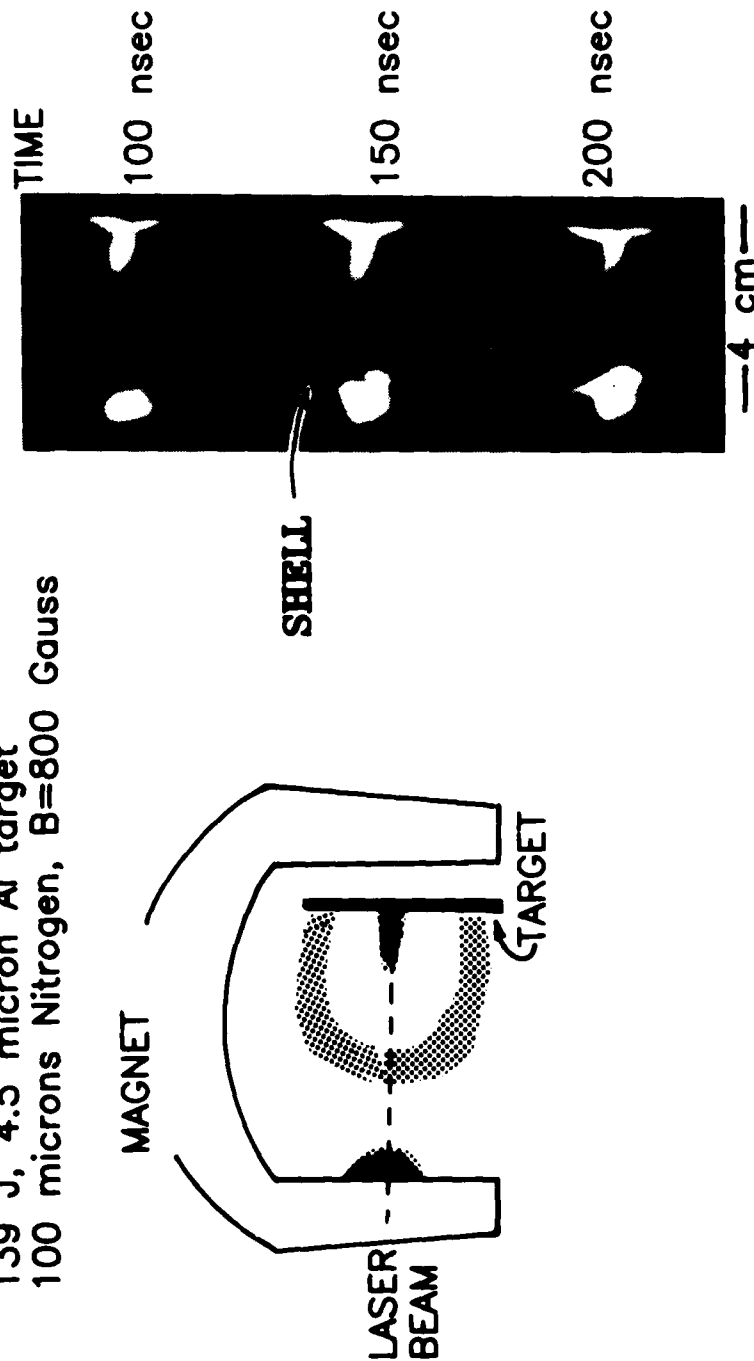


Figure 8 Framing photographs of the visible light emission from an expanding plasma shell. Frame exposure times are 5 nsec. Initial debris speed was about 6.6×10^7 cm/sec; shell speed is 2.5×10^7 cm/sec.

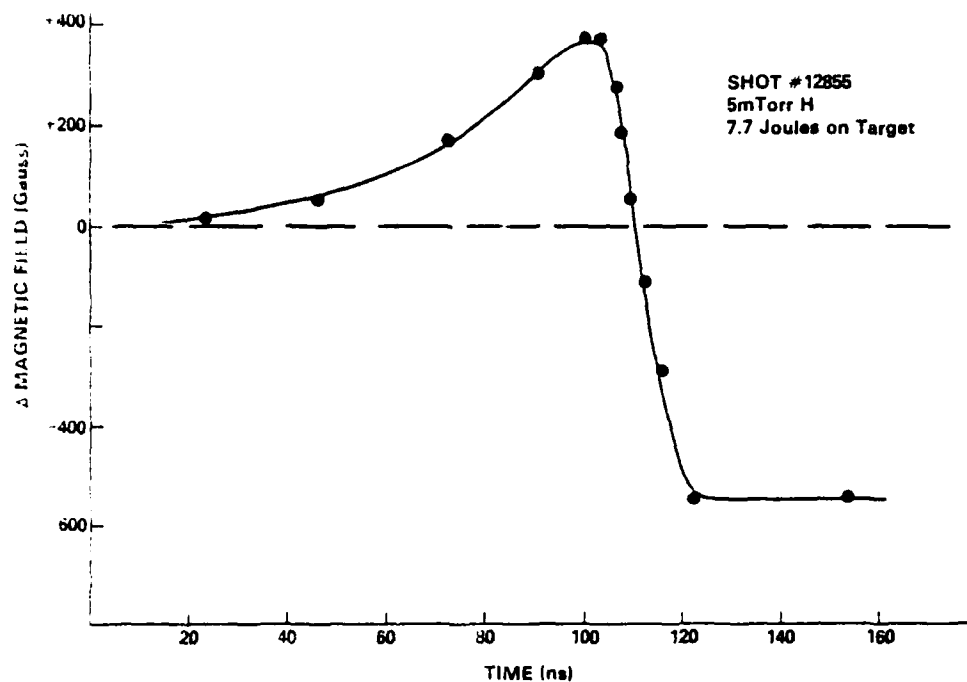


Figure 9 Temporal behavior of the change in magnetic field detected by a magnetic loop probe located 3 cm from the target. The applied field was 800 gauss. Note the field compression peak at 100 nsec and near depletion of the applied field (magnetic bubble) for $t > 120$ nsec.

TYPICAL INSTABILITY (M II)

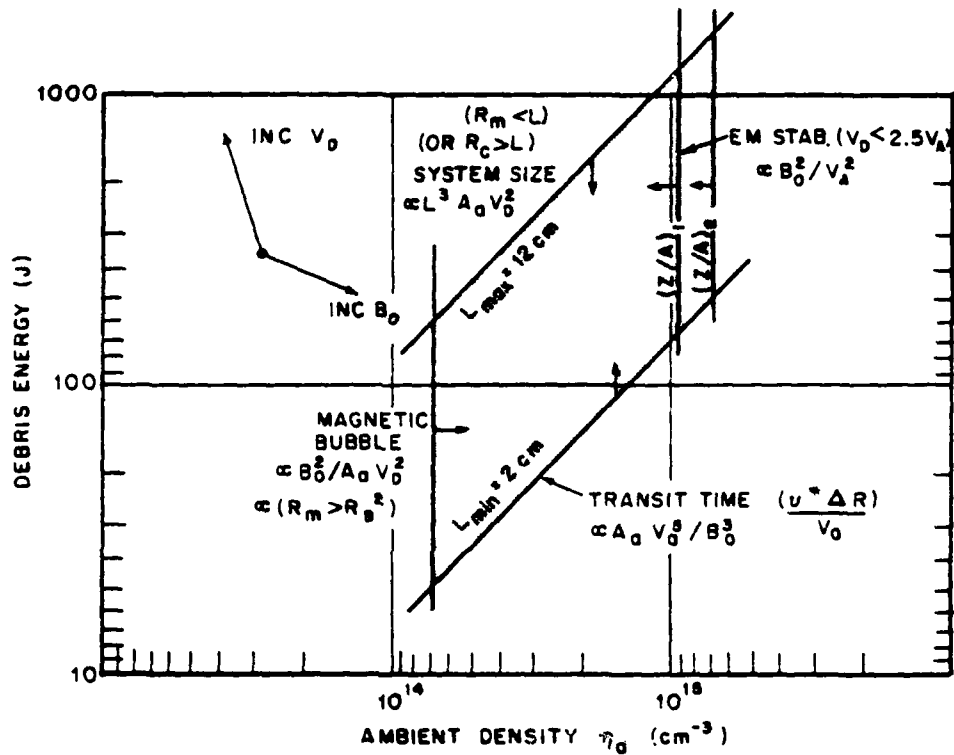


Figure 10 Magnetic ion-ion instability window (qualitative). The unstable region is bounded on the right by electromagnetic stabilization when $V_D > 2.5 V_A$, on the left by the requirement that the energy density in the debris plasma exceed that of the magnetic field, on the bottom by requiring that the transit-time of an ambient ion passing through the shell exceed one momentum transfer e-fold, and bounded on the top by the practical requirement that the equal mass radius fit inside the experiment. The top can also be limited by the cyclotron radius of the debris ions at high field strengths.

M II INSTABILITY

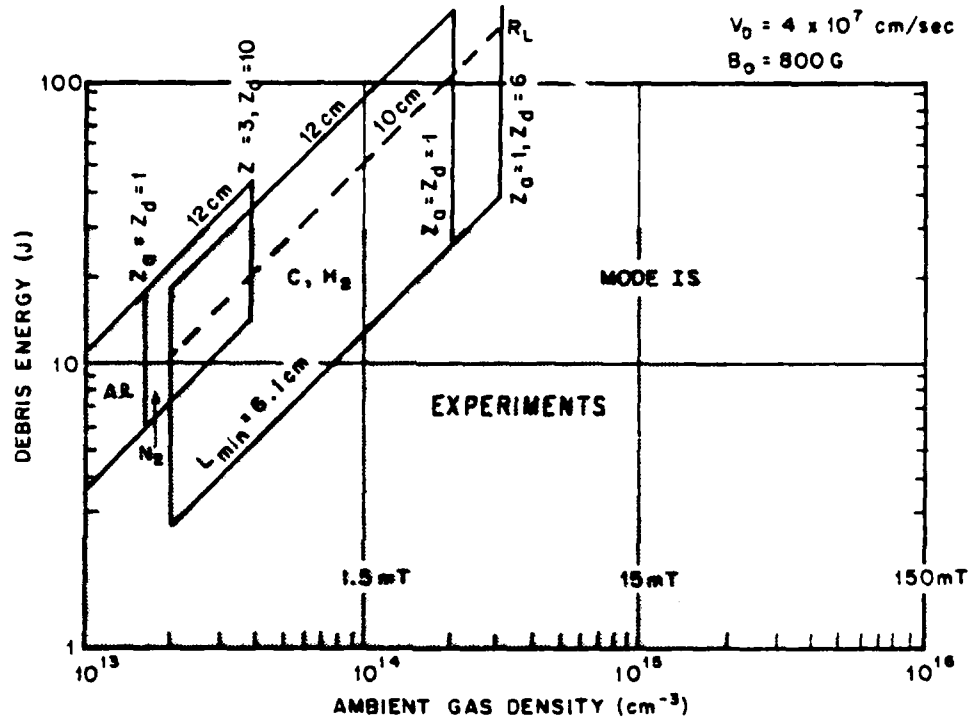


Figure 11 Parameter space for MII instability. The parallelograms are theoretical estimates of regions of instability and the circled area is the experimental region.

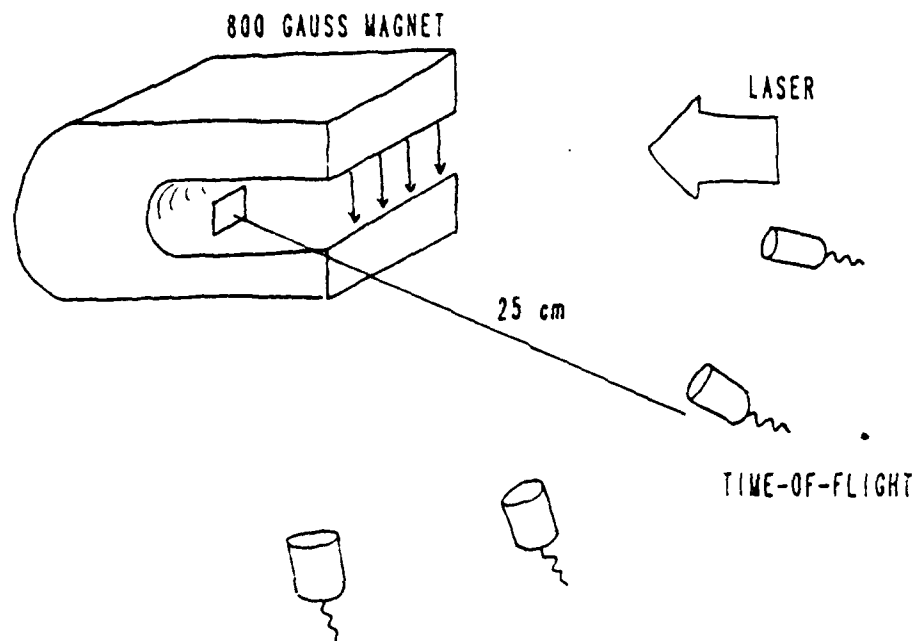


Figure 12 Arrangement to observe effects of magnetic field induced instability from debris ion time-of-flight detectors.

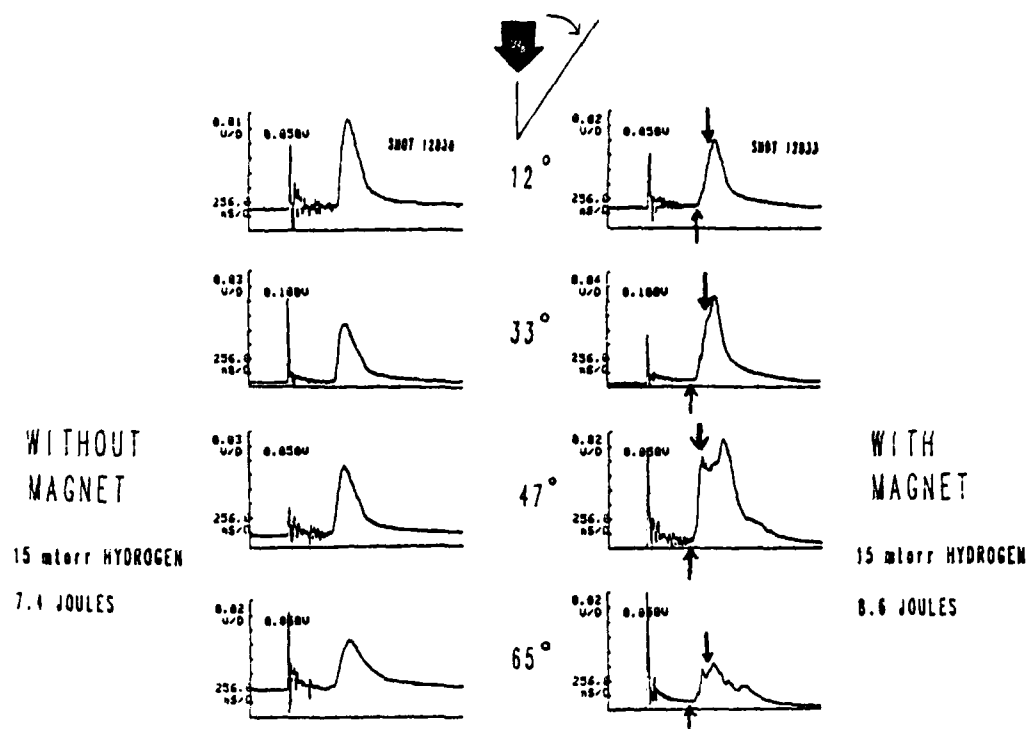


Figure 13 Comparison of debris ion time-of-flight traces without a magnetic field present (left) and with a 800 G field present (right). Note the distorted debris distributions in the presence of a magnetic field.

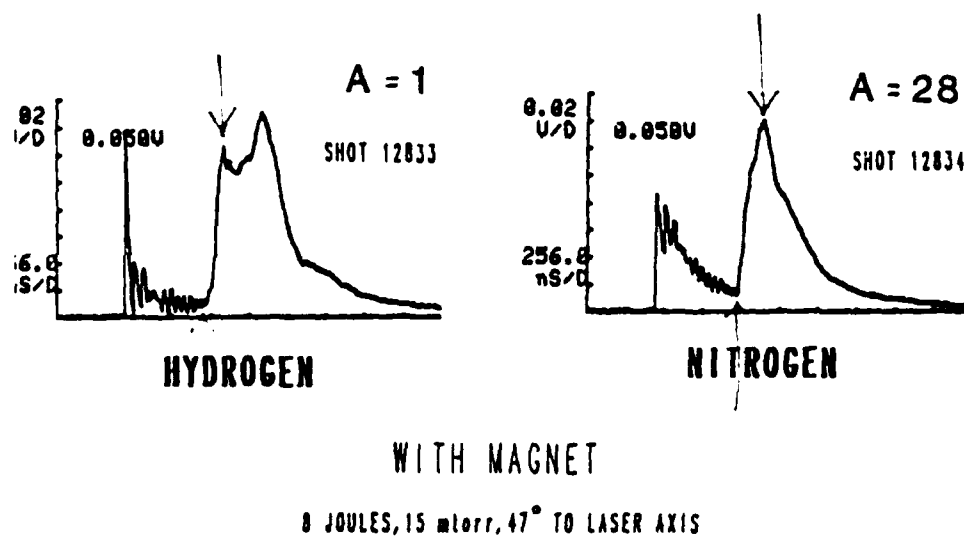


Figure 14. Comparison of debris ion distributions with atomic number of the background gas.

WITH MAGNET

(65° TO LASER AXIS)

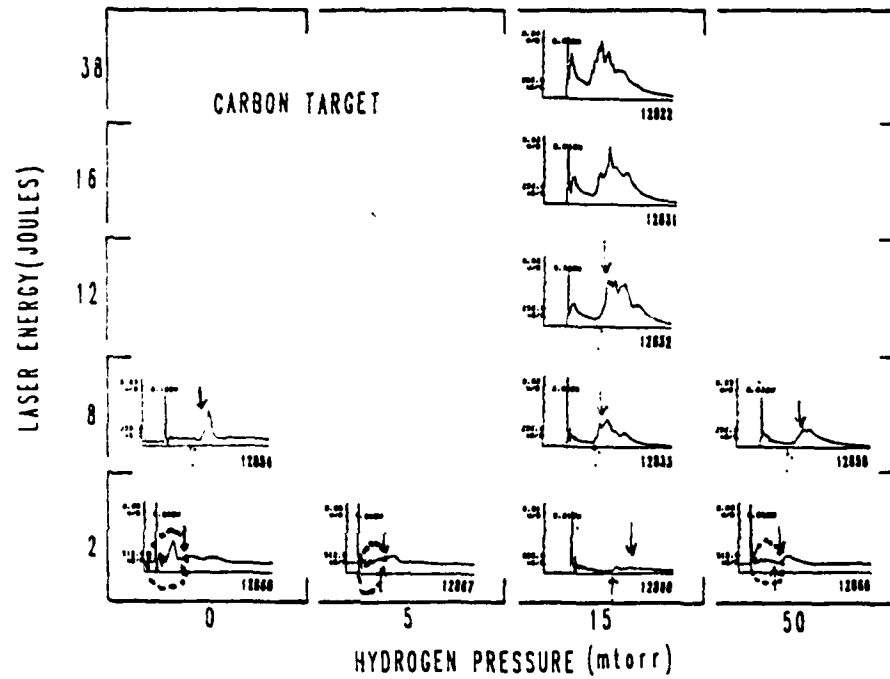


Figure 15. Debris ion time-of-flight signals often show "fast ions" at low laser energy in the presence of a magnetic field.

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