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NRL Memorandum Report 5260

Magnetic Bubble Formation Produced by an Expanding Laser Plasma

S. T. KACENJAR, B. H. RIPIN, J. A. STAMPER,
J. GRUN, AND E. A. MCLEAN

Laser Plasma Branch
Plasma Physics Division

February 28, 1984

This research was sponsored by the Defense Nuclear Agency under Subtask I25BMXIO, work unit 00024 and work unit title "Early Time Plasma."

NAVAL RESEARCH LABORATORY
Washington, D.C.

84 03 22 136

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): NRL Memorandum Report 5260

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Naval Research Laboratory

6b. OFFICE SYMBOL (If applicable):

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS (City, State and ZIP Code): Washington, DC 20375

7b. ADDRESS (City, State and ZIP Code):

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Defense Nuclear Agency

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c. ADDRESS (City, State and ZIP Code): Washington, DC 20305

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62715H			47-1606-0-4

11. TITLE (Include Security Classification): (See page ii)

12. PERSONAL AUTHOR(S): S.T. Kacenjar, B.H. Ripin, J.A. Stamper, J. Grun, and E.A. McLean

13a. TYPE OF REPORT: Progress

13b. TIME COVERED: FROM ______ TO ______

14. DATE OF REPORT (Yr., Mo., Day): February 28, 1984

15. PAGE COUNT: 27

16. SUPPLEMENTARY NOTATION: This research was sponsored by the Defense Nuclear Agency under Subtask I25BMXIO, work unit 00024 and work unit title "Early Time Plasma."

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Laser-generated plasma; Magnetic bubble; Magnetic field compression

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A magnetic depleted bubble resulting from the expansion of a laser-generated debris plasma into a low density magnetized background plasma is observed. A compressed magnetic field propagates slightly ahead of the debris plasma and has a thickness on the order of 1 cm.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: S. T. Kacenjar

22b. TELEPHONE NUMBER (Include Area Code): (202) 767-5279

22c. OFFICE SYMBOL: Code 4730

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

SECURITY CLASSIFICATION OF THIS PAGE

11. TITLE

MAGNETIC BUBBLE FORMATION PRODUCED BY AN EXPANDING LASER PLASMA

CONTENTS

MAGNETIC BUBBLE FORMATION PRODUCED BY AN EXPANDING LASER PLASMA

I. Introduction

We observe the compression of an externally applied magnetic field and the creation of a magnetic bubble when a laser-generated plasma expands into a low density magnetized background gas. Compression is possible when the plasma conductivity is large enough that convection of the field dominates over the magnetic diffusion process.

A target is placed into a background magnetized low density gas as shown in Figure 1(a). When the target is irradiated with a short high intensity laser pulse two plasmas are formed: the laser target interaction generates radiation which preionizes the background gas to form a stationary ambient plasma, and the target debris creates a rapidly expanding plasma. As the debris plasma expands, it may interact with the ambient either through collisional or collisionless processes. Under low density and high velocity conditions, collisional coupling becomes less important and collective effects may dominate.[1,2] Many of these collective processes are sensitive to the structure and magnitude of the local magnetic field.

The evolution of the structure and magnitude of the magnetic field due to a rapidly expanding plasma in an external field such as illustrated in Fig. 1b was described by Longmire[3] using magnetic conservation of flux. The magnetic field is swept away inside the bubble and confined within a small shell near the expanding debris material. This model was further developed by Wright (1971) who defined the valid parameter space.[4] Keskinen[5] extended the analysis of including a piecewise spatially constant collisional term into a one dimensional model. Although, one-dimensional models predict unrealistically high field compressions compared to two or three dimensional models, the diffusion term (i.e., the presence of collisions) is more easily treated in one dimension. The model is further simplified by ignoring the various processes which may alter the effective collision frequency, thus reducing the magnetic Reynold's number; an example of such a process is the magnetized ion-ion instability.[1,2] Therefore, we experimentally measure the

Manuscript approved November 7, 1983.

field compression to better understand the physics associated with this dynamically changing situation.

This paper addresses our initial experimental findings of the structure and evolution of the magnetic field. Only slight field compressions have been observed with shell thicknesses on the order of 1 cm. Data is also presented which show that the magnetic shell expands with, or slightly ahead of the target debris plasma.

II. Experimental Arrangement and Checkout

Various diagnostics were used in this study, including charge collectors, an optical framing camera, spectrometer, and magnetic induction probes.

The NRL Pharos II Nd-glass laser ($\lambda = 1.05\ \mu m$) was used to generate the debris plasma by irradiating 1.1 mg/cm^2 planar carbon targets. Incident laser energy on target ranged between 5 and 30 joules with a FWHM pulselength of ~ 4 nsec and irradiances up to 10^{14} W/cm^2. The focusing lens was of an aspheric f/6 lens with a focal length of 1.2 meters. Gas was introduced into the experimental chamber with a controlled orifice which was programmed to maintain a given ambient pressure. In this study the pressure was varied between 10^{-4} torr and 100 mtorr.

Shots were taken both with and without an 800 gauss magnet in place. The field orientation was parallel to the target surface and largely perpendicular to the expanding debris plasma. The targets were mounted to allow a magnetic expansion length of about 4 cm.

Two induction probes were used to measure the field compression. Both probes were 1.0 ± .1 cm from the laser axis and situated 1.5 ± .1 and 3.0 ± .1 cm from the target. The probes consisted of a single 500 μm diameter loop encapsulated in a quartz envelope as shown in Figure 2.

The magnetic probes work by using Lenz's Law in which a changing magnetic flux across the probe induces a current in the loop. The proper operation of the probes were checked by rotating the loop by 180° and noting the reversal of the signal (electrostatic pickup by the loop would not change polarity by such a rotation.)

Examples of the observed dB/dt signals are shown in Figure 3; the two probes were oriented antiparallel to each other. A clear signal reversal was seen indicating that the probes were operating properly. Moreover, an additional check was made by rotating the probes by 180° and observing the signals change sign.

The induced voltage resulting from the changing magnetic field across the probe is given by

$$V(t) = A_{\perp} \frac{dB}{dt}, \tag{1}$$

where $A_{\perp}$ is the projected area of the loop perpendicular to the applied field. If the initial field is B_o then the change in magnetic field, ΔB, can be determined by integrating Equation (1), namely,

$$\Delta B(t) = B(t) - B_o = \frac{1}{A_{\perp}} \int_{-\infty}^{t} V(t')dt' \tag{2}$$

III. Magnetic Field Measurements

A typical example of $\Delta B(t)$ is shown in Figure 4 for a probe situated 3 cm from the target. The loop area was $(2.0 \pm .4) \times 10^{-3}$ cm^2 and its surface normal was oriented to within $\pm 10^{\circ}$ of the applied field direction. Here an external 800 gauss field and an ambient hydrogen gas were present. A sudden drop in the magnetic field occurs at about 100 nsec after the laser pulse. The fall time in the field of about 20 nsec, corresponding to a spatial width of about 7 mm, is not limited by the probe or scope response time (.2 and 4 nsec, respectively). The accuracy of the probe measurements are limited to $\pm$ 20% due to the uncertainty in the projected area of the loop and data digitizing process.

Figure 5 shows a plot of ΔB_{max} versus laser energy taken with various background pressures and laser energy conditions. ΔB_{max} is the peak compressed field at the location of the probe. The ambient pressure for a shot is indicated by the number at each data point. There appears to be a weak scaling of ΔB_{max} with laser energy when the probe is 1.5 cm from the target which is not observed 3 cm from the target. The larger compressed fields measured at 3 cm relative to those measured at 1.5 cm are consistent with an expanding plasma having a magnetic Reynold's number greater than one.

The analysis should also take into account the presence of an azimuthal self-generated magnetic field such as illustrated in Figure 6.[6,7] This field can result from the $\nabla n \times \nabla T$ thermoelectric source term. To get an estimate the magnitude of the self-generated field alone, the external magnetic field was removed and the probes were repositioned to observe the azimuthal fields. The measured field was between 100 and 200 gauss at 1.5 cm; no self-generated fields were seen by the probe 3 cm away above 20 gauss. Therefore, the self-generated fields are smaller than the external field in our measurements. Also the probes were oriented to minimize the contribution of the self-generated fields in the compression measurements.

IV. Magnetic Field Velocity and Shell Thickness Measurements

Measurements of the arrival time of the magnetic shell were compared with data gathered from time-of-flight charge collectors and time-of-flight spectroscopy of CVI debris ions. An average shell velocity can be defined as the distance to the probe divided by the elapsed time between the x-ray pulse and the peak of the dB/dt signal peak as indicated in Figure 7. Similarly, velocity measurements were taken with charge time-of-flight detectors situated 22 cm from the target and 45° from the laser axis. The CVI time-of-flight spectroscopy was accomplished by means of a spectrometer tuned to 3434 Å which views the expansion region 1 cm in front of the target surface, as illustrated in Figure 8; a time-resolving photomultiplier detector responds to the arrival of CVI ions.

Table 1 compares the velocities obtained from these three diagnostics. They are all in general agreement; but the magnetic measurements tend to give slightly higher velocities. Also, the velocity measured with induction probes appears to slow down with distance from target. Thus, we infer that the compressed magnetic field appears to travel slightly ahead of the debris.[8]

Another interesting feature present in the data is that the magnetic shell width increases as one moves away from the target. This thickness is defined as the FWHM points on the ΔB curve in Figure 4. One explanation for this difference may be that the plasmas temperature drops with distance, causing the plasma to be more resistive; this would enhance the degree of magnetic diffusion and, therefore, increase the width of the magnetic shell.

V. Conclusions

Magnetic field compression and a magnetic depleted bubble have been observed when a laser-generated plasma expands into a magnetized ionized background gas. The compression increases with distance away from the target. In addition, the thickness of the compressed field is approximately 1 cm at incident energies above 20 joules. However, 3 cm from the target this thickness tends to increase with reduced laser energy on target. The compressed magnetic field travels with velocities equal to or slightly greater than the debris velocity.

VI. Acknowledment

This work was sponsored by the Defense Nuclear Agency.

Table 1 — Magnetic and ion velocity measurements

SHOT NUMBER	LASER ENERGY (Joules)	AMBIENT PRESSURE (m Torr)	VELOCITY MEASUREMENTS ($\times 10^7$ cm/s) CVI	CHARGE COLLECTOR	MAGNETIC PROBE (3 cm)	MAGNETIC PROBE (1.5 cm)
12833	10.3	15, H_2	3.1	3.3 OR 2.2	3.2	4.1
12853	5.5	100, AIR	2.8	—	—	—
12854	7.8	VACUUM	2.9	3.0	2.9	3.5
12855	7.7	5, H_2	2.7	2.4	3.0	3.9
12856	8.0	VACUUM	—	3.0	3.0	3.6
12857	7.4	VACUUM	2.7	—	—	—
12858	4.5	25, H_2	2.7	2.7	2.7	3.5
12860	2.3	15, H_2	2.2	—	—	—

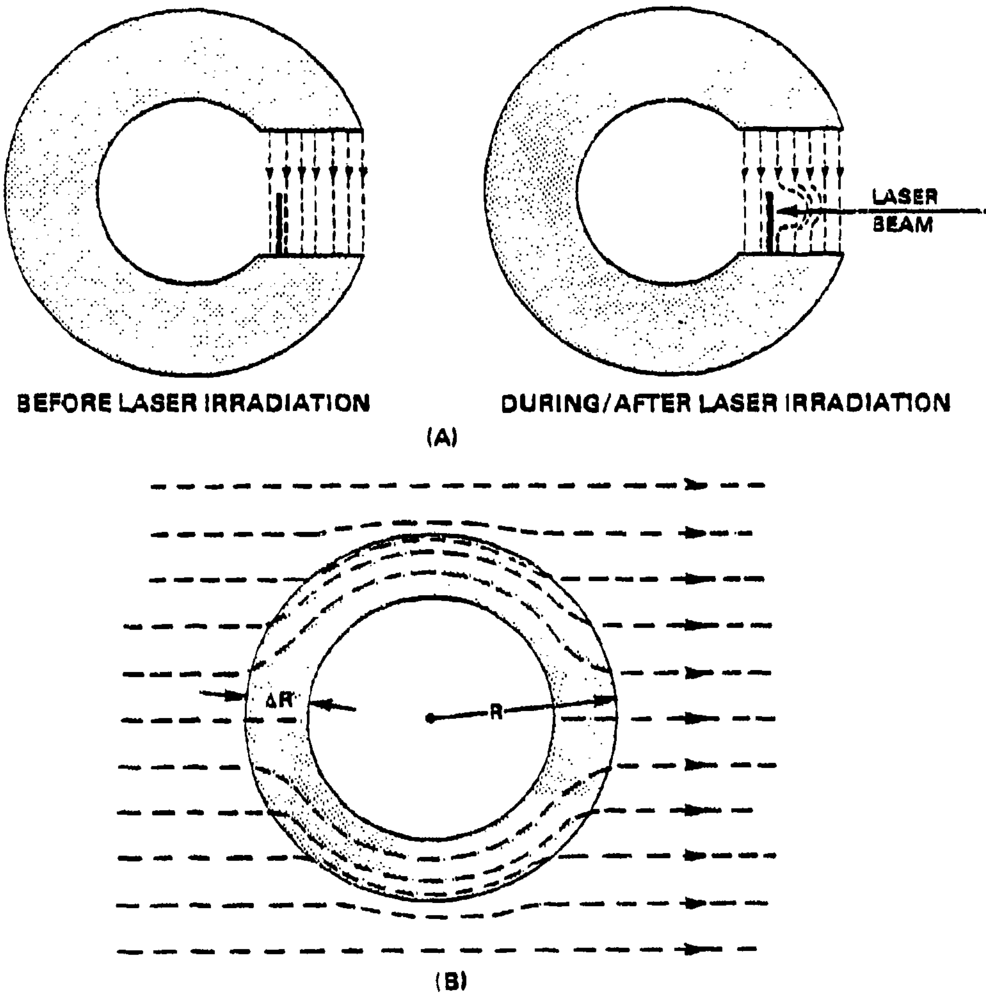


Fig. 1 — Magnetic field compression simulation experiment using laser irradiated targets in an external magnetic field

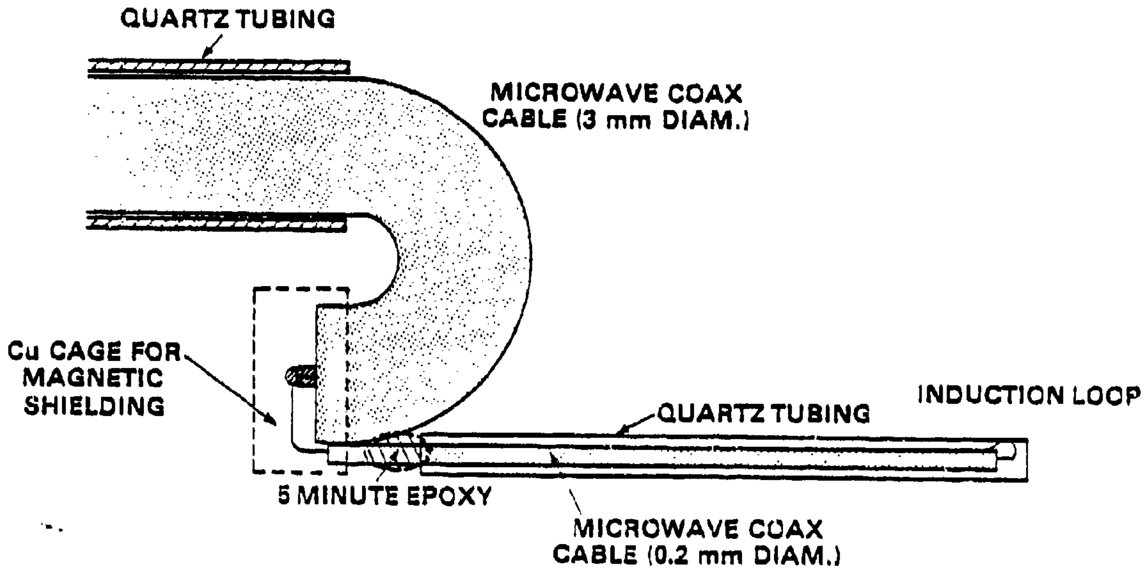
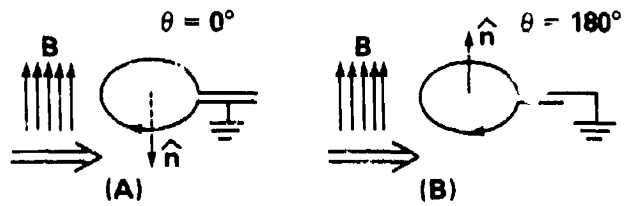


Fig. 2 — Magnetic induction probe construction



BY LENZ'S LAW THE INDUCED MAGNETIC FIELD BY THE LOOP CURRENT OPPOSES THE CHANGE OF MAGNETIC FLUX. THEREFORE A POSITIVE SIGNAL IS SEEN FOR CASE (A) INITIALLY AS THE MAGNETIC FIELD ENTERS THE LOOP, WHILE A NEGATIVE SIGNAL IS OBSERVED WHEN THE PROBE IS ROTATED BY 180° (B).

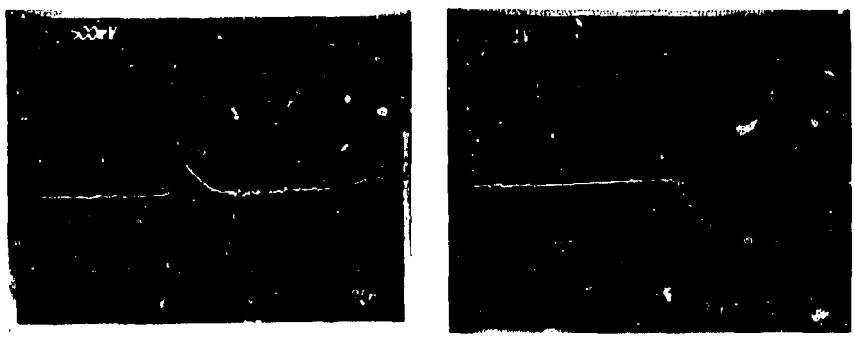


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Fig. 3 — Verfication on the presence of a magnetic field

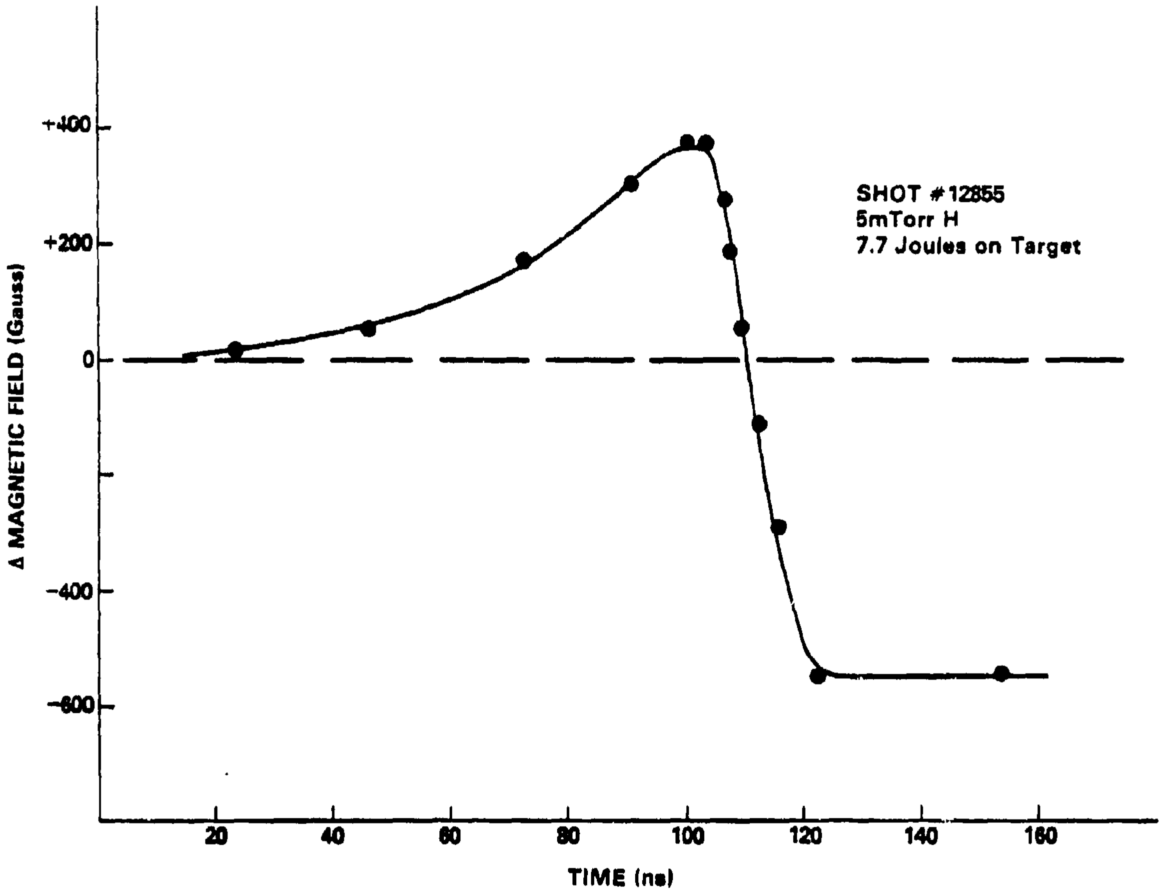

Fig. 4 — Measured temporal dependence of the magnetic field

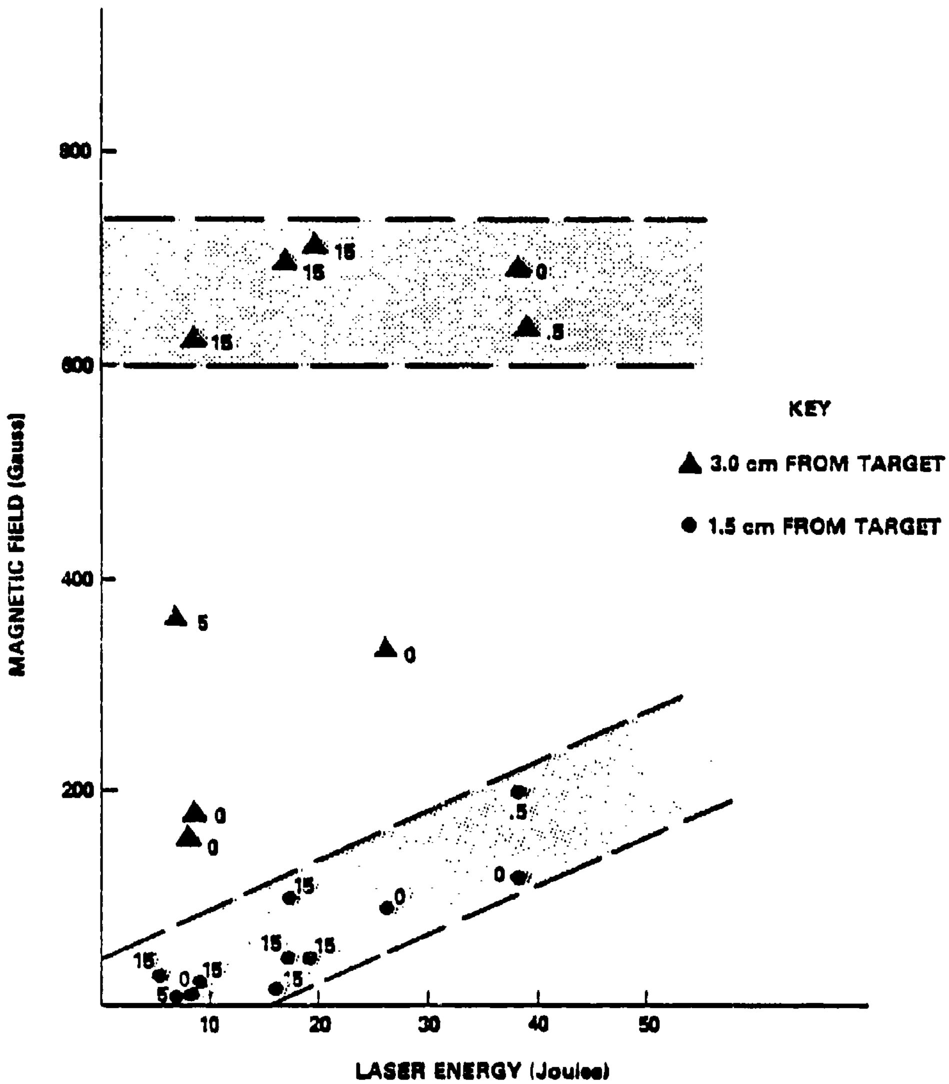

Fig. 5 — Compressed magnetic field measurement as a function of probe position and laser incident energy

$$\frac{\partial B}{\partial t} = \nabla \times (V_e \times B) + \frac{C^2}{4\pi\sigma} \nabla^2 B + \frac{Ck}{n_e e} \nabla T_e \times \nabla n_e$$

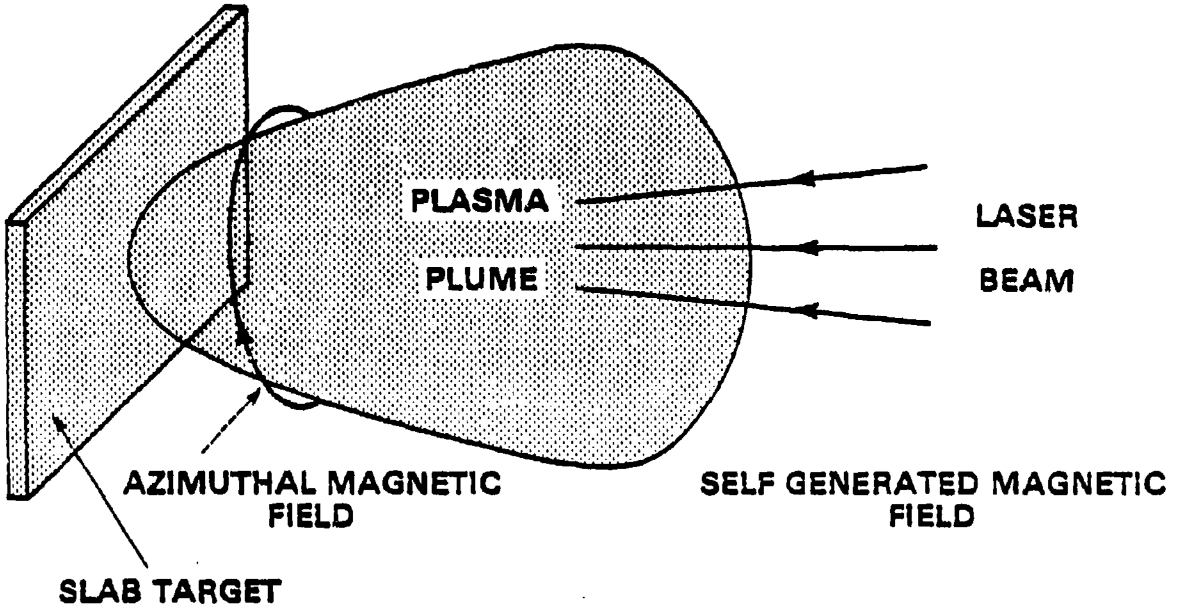

Fig. 6 — Self generated magnetic fields from laser irradiated targets

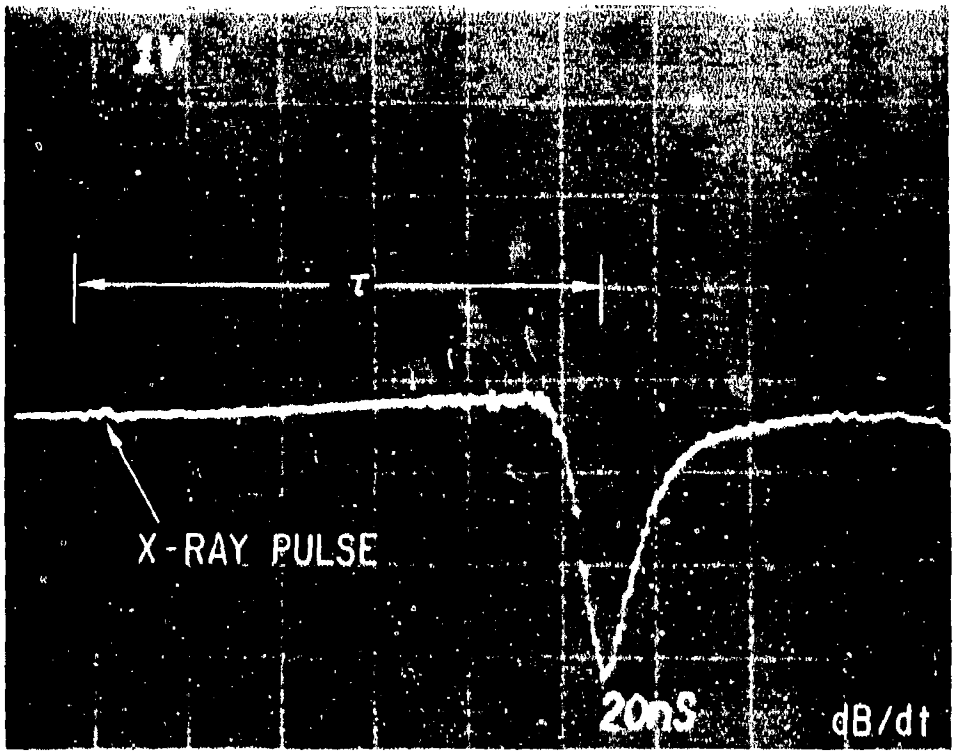

Fig. 7 — Magnetic bubble velocity determination

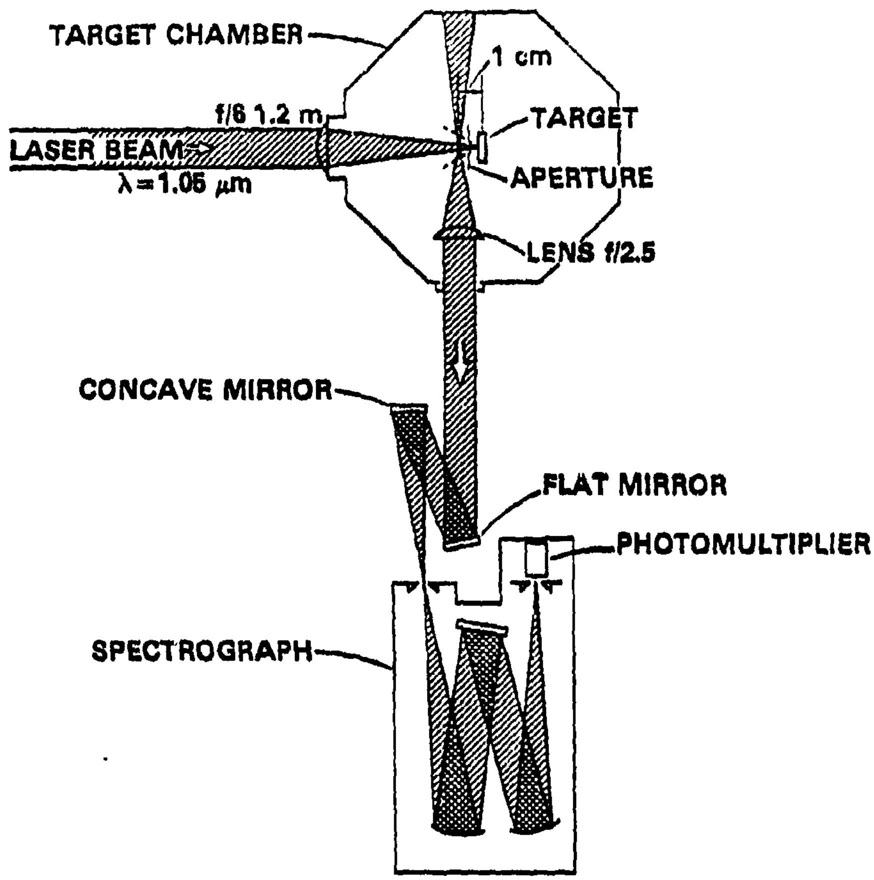

Fig. 8 — CVI Time-of-flight spectrometer examining the plasma 1 cm in front of the target

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ONE SPACE PARK
REDONDO BEACH, CA 90278
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