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Optical Spectroscopy Measurements of Shock Waves Driven by Intense Z-Pinch Radiation

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Z-pinches created using the Z accelerator generate ~220 TW, 1.7 MJ radiation pulses that heat large (~10 cm^3) hohlraums to 100-150 eV temperatures for times of order 10 nsec. We are performing experiments exploiting this intense radiation to drive shock waves for equation of state studies. The shock pressures are typically 1-10 Mbar with 10 nsec duration in 6-mm-diameter samples. In this paper we demonstrate the ability to perform optical spectroscopy measurements on shocked samples located in close proximity to the z-pinch. These experiments are particularly well suited to optical spectroscopy measurements because of the relatively large sample size and long duration. The optical emission is collected using fiber optics and recorded with a streaked spectrograph. Other diagnostics include VISAR and active shock breakout measurements of the shocked sample and a suite of diagnostics that characterize the radiation drive. Our near term goal is to use the spectral emission to obtain the temperature of the shocked material. Longer term objectives include the examination of deviations of the spectrum from blackbody, line emission from lower density regions, determination of kinetic processes in molecular systems, evaluation of phase transitions such as the onset of metalization in transparent materials, and characterization of the plasma formed when the shock exits the rear surface. An initial set of data illustrating both the potential and the challenge of these measurements is described.

Introduction

The physics of high energy density matter created by strong (>1 Mbar) shock waves is currently of great interest[1]. Applications range from inertial confinement fusion to planetary interiors. Shock wave physics has been extensively studied using lasers, gas guns, and explosive generators. Typically, the shocks produced with lasers are very strong (1-100 Mbar), but the samples are relatively small (~300 μm) and the duration of the shock is limited (0.5-5 nsec). The shocks produced with gas guns are typically less than 1 Mbar, but the sample sizes can be many centimeters. Shocks produced with z-pinch radiation have the potential to bridge the gap between laser and gas gun experiments by producing intermediate strength shocks in ~6-mm-diameter samples over times of about 20 nsec. Many shock physics experiments employ radiographic, VISAR, and shock breakout diagnostics to measure the particle and shock velocities. Conservation equations may then be used to derive the equation of state (EOS). However, spectroscopic measurements can provide an additional constraint on the equation of state, as well as information regarding the microscopic properties of the shocked matter[2,3]. This paper describes the potential for optical spectroscopy measurements of strong shocks generated by z-pinch radiation.

There are many possible applications of optical spectroscopy to shock physics, as reflected in the extensive literature on this topic[4-13]. The development of the capability to learn whether the large size and duration of z-pinch shock physics samples might allow us to perform new measurements is the subject of this work. One goal of spectroscopic measurements is the determination of the temperature of the shocked sample. This is relevant to verification of low preheat and it provides an additional constraint on the EOS determined from VISAR (particle velocity) and shock break-

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out (shock velocity) measurements. Another possible goal is to acquire spectra from dense warm plasmas. A third possible goal is to study the properties of transparent window materials. Windows are commonly used to enable VISAR or other optical probing of shocked samples while confining the sample so it is not free to expand after being shocked. Understanding the effect of the shock on the window is important for these diagnostics and it is interesting in its own right since the window itself may undergo phase transitions.

The experiments were conducted using the *Z* facility at Sandia National Laboratories[14-16]. The *Z* pulsed power accelerator drives a current that reaches 20 MA through an initially 20-mm-diameter 1.5-cm-tall cylindrical tungsten wire array (Fig. 1). The return current path is a 26-mm-diameter metal cylinder that surrounds the wire array. The current converts the W wires into a plasma and the magnetic field compresses the plasma onto the cylinder axis. The compression of the hollow plasma annulus takes approximately 105 nsec. The W plasma stagnates on axis and is heated to electron temperatures of about 1 keV by conversion of kinetic energy into thermal energy and possibly by other processes as well.[17] This creates a ~5 nsec Full Width at Half Maximum (fwhm) radiation burst that emits up to 220 TW and 1.7 MJ of soft x rays. The return current canister acts as a hohlraum wall confining this radiation.[15] Samples for shock physics experiments are typically mounted in smaller secondary hohlraums attached to the return current canister. This provides a means for tailoring the radiation that drives the shock, at the expense of achieving lower drive pressure. The secondary hohlraums are typically 6 mm in diameter and 5 mm long. Present resources limit the experiment rate to approximately one z-pinch discharge per day. Fielding several secondaries on a given z-pinch experiment increases the effective experiment rate to about three per day. This also enables comparison of different samples exposed to the same radiation drive.The pinch ultimately disrupts, typically through formation of m=0 instabilities. High energy electron and ion beams are sometimes formed during the disruption process, leading to emission of high energy (MeV) bremstrahlung radiation. There are thus four important radiation sources that are relevant for shock physics experiments:

1) "Run in" radiation emitted during the initial ~105 nsec compression. The brightness temperature is approximately 10-30 eV;

2) The approximately-thermal main radiation pulse. The radiation filling the return current canister typically has a brightness temperature of order 140 eV, as measured from wall re-emission. The temperature of the secondaries is 50-110 eV, depending on the configuration;

3) 2 keV M-shell W line emission during the stagnation; and

4) Hard x-rays (up to 10 MeV) emitted either from pinch instabilities or from electron losses in the transmission line that transports the electrical pulse to the pinch.

Some of the challenges that must be overcome to obtain high quality shock physics information are similar to laser and gas gun experiments and some are unique to z-pinches. In all of these experiments the uniformity of the drive and the shock steadiness are both important. Z-pinches have the advantage that the large size of the z-pinch hohlraum and the long duration (in comparison to laser plasmas) make it easier to achieve both drive uniformity and long duration. View factor calculations indicate that 0.1% pressure uniformity over a 2 mm diameter sample might be possible.The fwhm of the soft x-ray burst from the highest-power pinches to date is approximately 5 nsec. Calculations indicate that steady 20 nsec drive pressures may be feasible using a variety of secondary hohlraum configurations. Experiments are in progress to this end.

Challenges unique to z-pinches are preheat due to run-in radiation, proper tailoring of the radiation pulse that drives the shock, spurious currents that might flow in the samples, and hard x-ray effects on the sample and on the diagnostics. The implosion of the initially 1-cm-radius wire array takes about 105 nsec. During this time the sample must be protected from the radiation emitted by the imploding plasma so that the initial conditions of the material to be measured are known. This run-in radiation is typically approximated by a Plankian with a radiation brightness temperature T_r ~ 10-30 eV. Protecting the target can be achieved by placing a 10-20 micron thick CH burn through foil over the entrance to the secondary hohlraum (Fig. 1). Preliminary VISAR measurements of samples with and without a burn-through foil indicate that this technique greatly reduces sample preheat. Further measurements, for example using a Michelson interferometer, are needed to quantify exactly how low the preheat is. If a secondary hohlraum geometry that exposes the sample to the pinch itself is used ("direct view" in Fig. 1), the sample may also need to be protected from the ~2 keV W M-shell radiation. This can also be aided with burn-through foils, but in this case the foil thickness needs to be larger and the penalty in terms of reduced drive power is higher. Tailoring the radiation drive history can be achieved with a variety of techniques, including changing the number of wires in the array, embedding a magnetic field inside the pinch, using foam-filled secondaries, and using impact of a separate ablatively-driven foil to launch the shock rather than irradiation of the shock sample directly by the z-pinch. The latter method is described below. Spurious currents are potentially a problem because the large size of the z-pinch current implies that if a small fraction of the z-pinch current flows through the shock sample, the initial sample condition may be altered, for example by preheat. The target inductance and insertion of insulating layers can reduce any spurious current, but it is difficult to be certain *a priori* that no current will flow. It is best to measure the target preheat to be sure that this effect (along with other mechanisms that might lead to preheat) is negligible. Lastly, hard x -rays are generated during the run-in phase by electron losses in the magnetically-insulated transmission line that transports electrical power to the pinch and during the stagnation phase by plasma instabilities. It is very difficult or impossible to prohibit such MeV x-rays from reaching the sample. However, it is possible to reduce their fluence by modifying the pinch itself or the efficiency of the transmission lines. Again, monitoring preheat and or other optical characteristics of the samples is one approach to ensure that this effect does not lead to erroneous results

Spectroscopy Diagnostic Techniques

A variety of diagnostics are available to measure the characteristics of shocked materials at Z. Both open beam and fiber-coupled active shock breakout (ASBO) measurements[4] determine the shock velocity in stepped targets. The Doppler shift of reflected laser light measured with VISAR techniques[18] provides the particle velocity. The emphasis in this paper is on time-resolved optical spectroscopy diagnostics that measure a combination of the reflected laser light and the self emission. We presently have two time-resolved optical spectrographs operating at Z. These consist of a 2/3 m Czerny-Turner spectrograph with an optical streak camera located in the exit focal plane (Fig. 2). These instruments are both fiber coupled. One uses a 60-m-long fiber and is consequently restricted to 4000-7000 Å wavelength. The other uses a 15-m-long fiber to view 2800-7000 Å. We are in the process of further shortening the fiber of this latter instrument to about 8 m, which will enable measurements down to about 2200 Å. The shorter fiber also provides better time resolution. The UV capable instrument has a time resolution of better than 500 psec, compared to ~1.5

nsec for the visible-only instrument The streak camera sweep rate is typically 5 nsec/mm, but the fiber optics are the limiting factor in the time resolution, not the sweep rate. Both instruments are typically operated with 150 g/mm gratings providing ~ 4000 Å coverage with ~15 Å spectral resolution. Both instruments collect light in 200 micron diameter fiber optics that are included in combined VISAR/shock breakout/spectroscopy probes. This has the advantage that we have multiple diagnostics viewing the same sample, and we acquire laser reflectivity data along with the spectra. It has the disadvantage that the close proximity of the fiber to the pinch exposes the fiber to high energy x-rays, producing Cerenkov light in the fiber that may compete with the desired signal. Using fiber optics also implies that we need to measure the fiber attenuation and refractive index as a function of wavelength. The latter measurement is particularly important, since the difference in time of flight between 4000 Å and 7000 Å is about 8 nsec for a 60 m fiber.

Measurements of shock-heated sample temperatures require an absolute calibration of the time-resolved spectrographs. To date the visible instrument has been absolutely calibrated, but the calibration of the UV instrument is still in progress. The measurement of the streaked spectrograph efficiency is accomplished by first using a NIST-tracable standard lamp to measure the efficiency of a test spectrograph that employs a time-integrated CCD detector. Then the test spectrograph is used to measure the relative output as a function of wavelength of a fiber optic coupled to an intense Xe arc lamp. We also measure the absolute power at selected wavelengths using a NIST-tracable photodiode and bandpass filters. This essentially transfers the NIST standard to the fiber-coupled arc lamp. The fiber-coupled arc lamp is then connected to the streaked spectrograph and a streak is recorded. This procedure enables calibration of the streaked spectrograph in its swept mode, just as it is used in the experiments. Work is in progress to evaluate the uncertainty of the calibration and to adapt the method to UV measurements.

We have developed a method to monitor the Cerenkov light produced by hard x-rays during the disruption of the pinch. These hard x-rays make Compton electrons in the fiber and those electrons make Cerenkov light. A measurement of the Cerenkov spectrum performed by blanking off the signal fiber on a Z experiment is shown in Fig. 3. The Cerenkov typically occurs within a few nsec of the pinch and has a fwhm of typically 5 nsec. The lineout in Fig. 3 is an average over a three nsec interval, taken at the peak Cerenkov signal. A plot of $1/\lambda^3$, scaled by an arbitrary constant, is superimposed on the data (dashed curve). The data agrees reasonably well with the $1/\lambda^3$ curve, consistent with the interpretation[19,20] that this is Cerenkov light rather than some other type of fluorescence. The Cerenkov signal has been converted to absolute units using the instrument calibration to permit estimates of the Cerenkov that might compete with future experiments. However, it must be remembered that the Cerenkov intensity coupled into a fiber is a strong function of the relative orientation between the fiber and the radiation source, in addition to the radiation spectrum and dose. We have found that the light can be greatly reduced by moving the fiber just 10 cm away from the pinch, but this would preclude the simplicity of the combination VISAR/ASBO/spectroscopy probes. Monitoring the Cerenkov in the present set up is accomplished by fielding a second fiber along side the signal fiber. This second fiber is blanked off on the end so that it only detects noise. The noise fiber is about 50 nsec shorter than the signal fiber and it is focused directly onto the streak camera without going through the spectrograph (Fig. 2). A bandpass filter centered on 4500 Å defines the wavelength at which the noise is measured to enable an accurate time of flight correction.

Ablative drive multi foil experiment

An example of a shock physics experiment driven by z-pinch radiation is shown in Fig. 4. This data demonstrates that spectroscopic measurements of shock-heated samples can in fact be performed at the *Z* facility. The experiment was designed to explore an ablatively-driven multi-foil concept for producing a steady drive longer than the z-pinch radiation pulse. Note that in this experiment the secondaries face directly toward the pinch. This improves the drive symmetry and increases the available radiation, but it also means that the sample is exposed to the tungsten M-shell 2 keV radiation. The sample consists of two 100 μm thick Al foils separated by a 100 μm vacuum gap. The first foil is ablatively accelerated and impacts the second foil, launching a shock. Computer simulations indicate that steady drive pressures lasting 2-3 times longer than the fwhm of the pinch radiation may be feasible with this approach. The multi foil ablative drive also acts to delay the spectral signatures with respect to the noise induced by the pinch, so that we are better able to measure both the self emission and the change in the surface reflectivity when the shock arrives at the Al sample.

The rear free surface of the Al was viewed by a combination of VISAR, ASBO, and spectroscopy diagnostics. The goal of the spectroscopy measurements was to evaluate the potential for performing *any* spectroscopic measurement in this environment, for using reflectivity and emission to determine the preheat levels,[12,13] and to begin characterizing the plasma formed when the shock arrives at the free surface. Prior to the pinch at t=0, the only features present in the streaked spectrum are VISAR (Nd:YAG 2ω at 5320 Å) and ASBO (dye laser at 5150 Å) signals reflecting from the Al free surface. A burst of Cerenkov light appears approximately simultaneous with the pinch. At this time the reflected laser signals begin to decrease slowly, reaching ~85% of their initial value about 5 nsec after the pinch. This slow decrease may be due to sample preheat or to radiation darkening of the fiber. At t ~15 nsec the laser signals dramatically decrease and a sharp *spike* in the self emission appears, presumably due to the arrival of the shock.

This data was recorded with the UV system (operated in the visible for this experiment) and a calibration is not yet available to convert the measured signals into absolute intensities. However, we can see that the changes in emission and reflection are simultaneous to within a few 100 psec. Ideally, < 10 psec time resolution is desired for observations of the shock itself, before the shock is obscured by plasma expanding from the free surface. However, it is intriguing that the measured rise and fall times are greater than 1 nsec, compared to the expected instrument resolution of < 500 psec. Measurements of the complete instrument time response are in progress to determine whether this is an artifact or if it has some undetermined physical significance.

It is also interesting that the initial burst of continuum emission begins to decay for a nsec, but then gradually starts to increase again. This is contrary to observations[10] in laser-produced shock experiments where the emission is observed to decay rapidly. A large increase appears at about t=58 nsec. This latter feature may be the impact of Al plasma on the fiber probe, which is located 0.5 mm from the initial position of the foil rear surface. Further investigation of these features is required to understand their significance.

Be equation of state experiment

A common way of enabling measurements of shocked materials at high densities is to view the sample through a transparent window. The window prevents the free expansion of the shocked material. However, this introduces its own set of experimental difficulties. In our experiments to date, a LiF crystal has been bonded with glue to the sample of interest. This implies that the impact of the glue joint on the measurements must be considered. Also, the measurements are performed through the LiF while the shock is traveling in the crystal. We have to worry about whether the emission and absorption from the shocked LiF impacts the measurements. If metallization of the LiF occurs, the VISAR and ASBO lasers may be reflected from the shock front rather than the material interface. Studies of window materials under shock loading are therefore important. In addition, the properties of the shocked window materials themselves are of intrinsic interest and the transparent nature may enable measurements that are impossible with opaque materials.

An experiment designed to measure the Be equation of state is shown in Fig. 5. This experiment was performed in collaboration with a Los Alamos National Laboratory group.[21] The 6-mm-diameter sample was mounted in a standard secondary that avoids the direct z-pinch radiation. The radiation is absorbed in a 100 μm thick Al ablation layer, launching a shock that propagates into a stepped Be sample. A combination of VISAR and spectroscopic diagnostics viewed the rear surface of the Be through a 1-mm-thick LiF window. The LiF window is coated with a 1-μm-thick Al layer before it is bonded to the Be with a thin glue joint. This 1 μm Al layer acts as a reflector for the VISAR diagnostic. The streaked spectrum obtained from the 225-μm-thick Be step is shown in Fig. 5b. A Cerenkov signal is observed approximately simultaneous with the pinch as in other experiments. A second burst of continuum is observed about 8 nsec after the pinch. This is well before the expected arrival of the shock at the Be/Al/LiF interface. The shock pressure was anticipated to be 1.6 Mbar, corresponding to 12-14 km/sec velocities in the Al and Be, which leads to an arrival time about 22 nsec after the shock is launched. The origin of this continuum is presently unknown. If the continuum is emission from the shock arrival at the interface, the inferred shock velocity would be approximately 25 km/sec. We consider this to be unlikely. Further experiments are required to understand this observation.

The shock propagates in the LiF window after it emerges from the Be/Al/LiF interface. It is expected to arrive at the rear surface of the LiF window approximately 92 nsec after the pinch, assuming 14 km/sec velocity in the LiF. Beginning at t ~ 50 nsec we observe gradually growing continuum emission and at approximately t = 60 nsec we also observe the Hα emission line. This observation is difficult to explain, since at solid densities the wavefunctions of any atomic hydrogen overlap and we should not be able to observe distinct line emission. This suggests that somewhere in our line of sight there is a lower density plasma that emits the Hα line. One possibility is that a portion of the glue joint bonding the LiF and Be sample may be transformed into a plasma. Later in time, we also measure emission from the Li I 2s-2p and 2p-3d transitions. These lines may arise from the rear surface of the LiF window as the shock emerges into free space or they may be characteristic of Li atoms that are eventually entrained in the plasma that emits the Hα line. A lineout from 90-110 nsec is shown in Fig. 5c. In this lineout the Hα fwhm is 86 Å and the centroid is red shifted by about 14 Å. The fwhm of the Li I 2s-2p and 2p-3d are 26 Å and 48 Å, respectively. The broadening of the Li I 2p-3d and the Hα lines is consistent with a plasma density of order 10^{18} cm^{-3}, but a detailed consideration of other mechanisms such as resonance broadening and opacity has not been performed as yet. Understanding the origin of these plasma emissions is important because high-quality shock physics experiments require the elimination of such plasmas and because such experiments may provide a source of warm plasmas suitable for basic studies in the strong coupling regime.

Summary

These data demonstrate the feasibility of measuring time-resolved spectra from shock-heated samples located 2-3 cm from a 19 MA z-pinch emitting 220 TW and 1.7 MJ of x-rays. Spectra that appear to originate in dense warm plasmas have been observed and it may be possible to design targets suitable for a strongly-coupled plasma physics testbed. Free surface spectra from z-pinch driven shocks can contribute to the growing knowledge base obtained in laser experiments. In particular, larger sample sizes provide more photons and should enable acquisition of spectra from z-pinch driven shocks with faster time resolution at a given signal-to-noise level. It should also be possible to investigate the effect of longer shock durations on free surface plasma evolution. Absolutely-calibrated spectra can be used to infer temperatures in the 0.4-4 eV regime, provided we can understand where the emission originates, how it is modified by any window material, and how the joints and edge boundaries present in real targets impact the data. Such temperature measurements should help interpret VISAR measurements of shock propagation. For example, if the shock pressure is high enough, metallization of LiF will occur. In this case VISAR measurements will track the shock velocity in the LiF rather than the sample/LiF interface. Temperature measurements aid interpretation because the expected temperature of the interface is higher than the shocked LiF. Similar arguments apply to future experiments measuring shock propagation in cryogenic D_2, where temperature measurements can assist the determination of whether the D_2 has metallized.[22,23] Preparation for such experiments at *Z* is in progress and we have already demonstrated compatibility of our spectroscopy and VISAR diagnostics with the cryogenic system.

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Figure Captions

1. Schematic diagram of the experiment.

2. Schematic of the time-resolved spectrograph and the measured absolute efficiency for the visible instrument.

3. Spectral data obtained by placing a blanked off fiber adjacent to the pinch. Time =0 corresponds approximately to the peak pinch radiation. The lines labeled "grene" and "hene" are wavelength fiducials applied after the experiment. The lineout at the right is an average over 3 nsec taken at peak Cerenkov emission. The dashed line shows that the emission is in reasonable agreement with $1/\lambda^3$ scaling, as expected for Cerenkov light.

4. Ablative drive multi foil shock physics experiment: (a) experiment schematic diagram; (b) streaked spectrum obtained from the shocked Al; and (c) temporal lineouts through the reflected VISAR laser and the self emission between 4190Å and 4850 Å. The reflected VISAR laser signal has been divided by 16.7 for display purposes. The dashed line indicates the drop in the reflected VISAR signal coincides with the appearance of self emission.

5. Be EOS experiment: (a) experiment schematic diagram; (b) streaked spectrum; and (c) lineout averaging over t=90-110 nsec.

Figure 1 Bailey et al

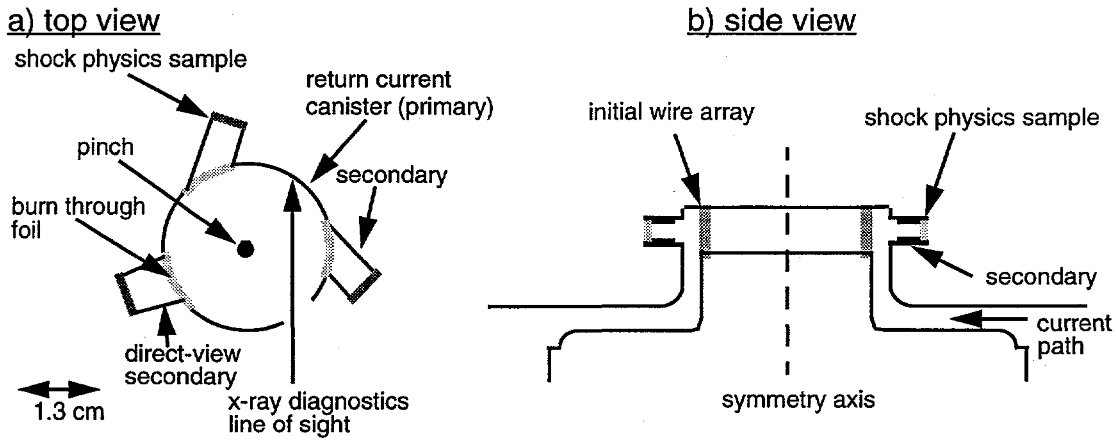
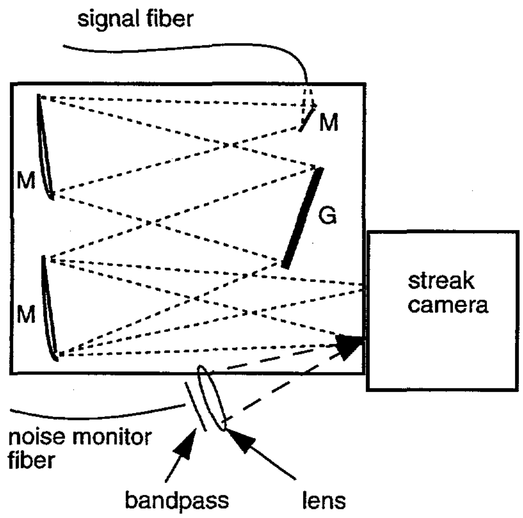


Figure 2 Bailey et al



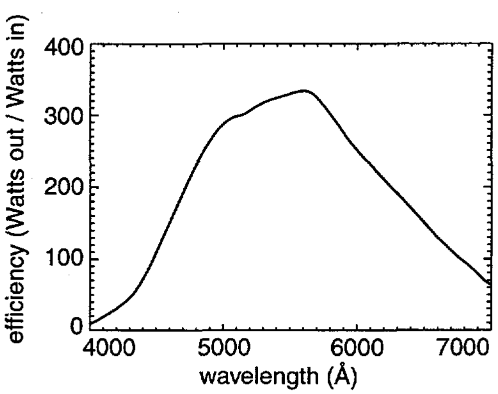


Figure 3 Bailey et al

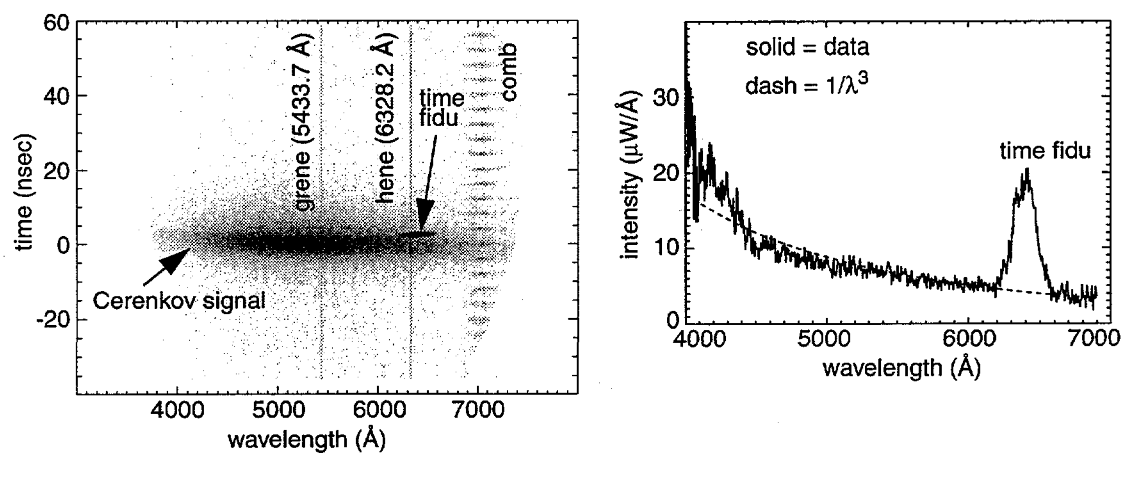


Figure 4 (Bailey et al)

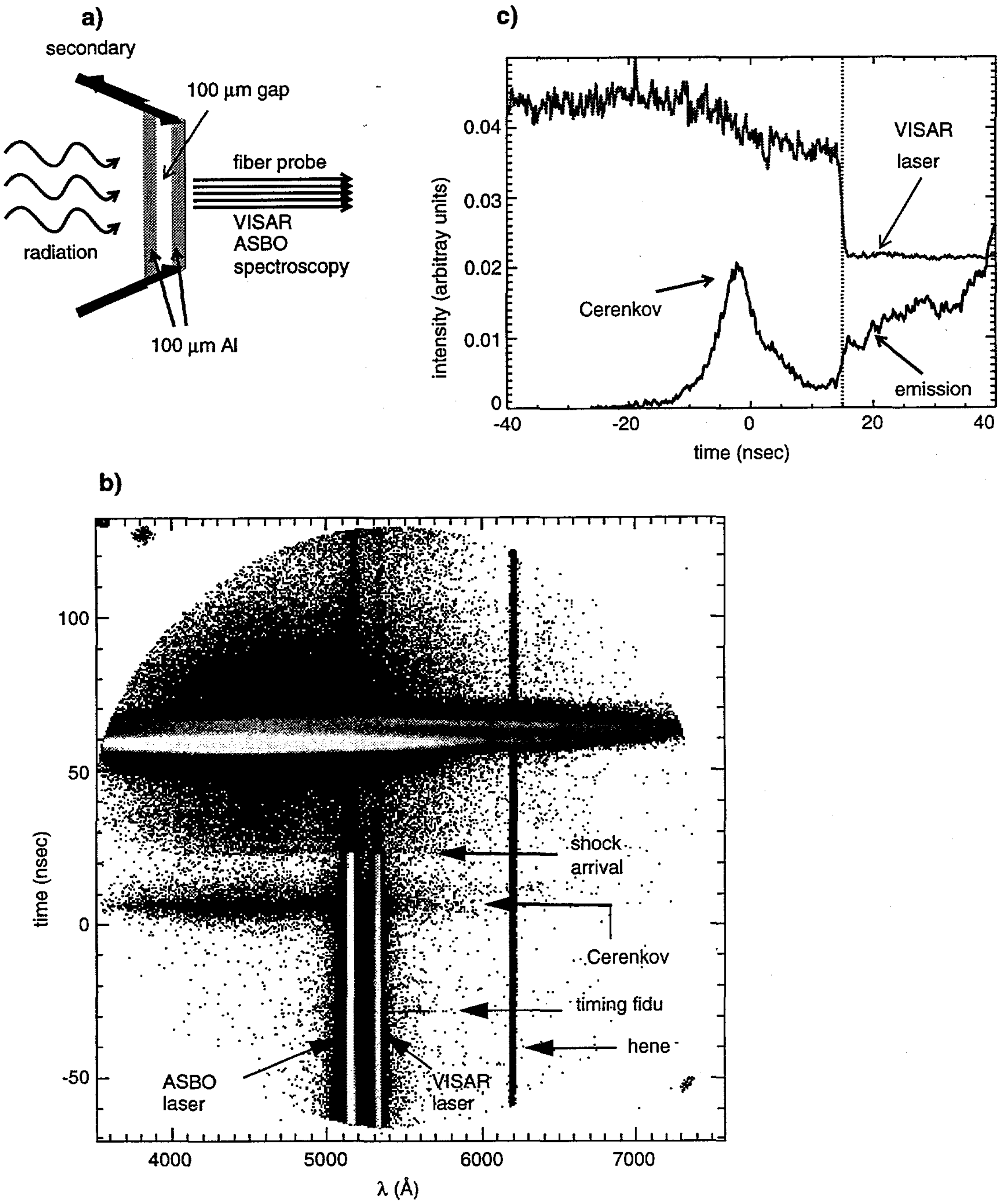


Figure 5 (Bailey et al)