Chapter 6

Shock wave collisions in low density foams

The data presented in this chapter were collected during an experimental campaign at the Rutherford Appleton Laboratory, UK. The aim of the experiment was to produce counter-propagating shock waves in low density material, and to record their propagation and collision by means of X-ray radiography. The shocks were generated by irradiating both sides of a foam cylinder with a ns laser pulse. X-ray absorption point-projection spectroscopy was used to obtain time-resolved radiographs of the target at different stages of the shock propagation.

The experimental set-up is presented, and the data analysis is outlined. Finally the results are discussed with the support of numerical simulations.

6.1 Experimental set-up

The targets consisted of triacrylate foam cylinders at a density of 50 mg/cc. The foam was doped with 25% by weight of chlorine. The typical cylinder was 200 \( \mu \)m in diameter and 250 \( \mu \)m in length. The target was mounted in the centre of the TAE vacuum chamber of the VULCAN laser facility. The main six beams of the VULCAN
6.1 Experimental set-up

Laser were used in a cluster configuration as heating beams. The laser pulse had a flat-top profile with 0.9 ns FWHM duration and was frequency doubled in KDP crystal to obtain 0.527 µm wavelength irradiation on target. The main reason for using a 2ω beam was to increase laser absorption in the bulk of the plasma, and generate a high ablation pressure, as outlined at the end of section 2.3.

Both ends of the foam cylinder were irradiated simultaneously. The heating beams were focussed on target with f/10 lenses. Random phase plates (RPP) were inserted between the lens and the target to smooth spatial nonuniformities in the laser beam. The typical irradiation intensity produced at the surface of the foam was in the region of $10^{14}$ W cm$^{-2}$. Figure 6.1 presents a schematic diagram of the set-up used in the experiment.

Following earlier work on laser generated shock waves [Hoarty et al., 1997, 1999], the X-ray point-projection system consisted of a backlighting source and a spectrometer, which contained the X-ray sensitive film. A 15 µm diameter gold pin coated with bismuth was used as the backlighter target. The pin was irradiated by two simultaneous 0.527 µm laser pulses focussed onto the pin with f/2 lenses. The two short pulse beam lines of VULCAN were used to this purpose. The laser pulse was

**Figure 6.1**: Experimental set-up (top view).
90 ps long and the generated X-ray flash had a similar duration, as reported in Matthews et al. [1983]. This allowed resolution of the evolution and propagation of the shock fronts. Different stages of the shocks’ interaction were recorded by changing the delay between the main pulse and the backlighter pulse.

Radiographs were taken with the flat RbAP crystal spectrometer described in section 5.1. The crystal was aligned so as to record on film the spectrum from 2.2 to 3.2 keV. In this spectral range it was possible to detect the 1s2p and 1s3p absorption lines of chlorine. The source-to-spectrometer distance was set in order to image the central part of the foam with a 50x magnification. An aluminium shield (see figure 6.1) was mounted between the target and the spectrometer aperture to screen the intense plasma self-emission from either end of the foam cylinder. An optical streak camera looking at the interaction centre recorded the delay between the backlighter and the main pulse for each shot.

### 6.1.1 Data calibration

**Space**

Obscuration shots of copper disc targets were taken in order to measure the spatial magnification on film (see figure 6.2). In the following, the radiographs will be presented with the vertical direction corresponding to the spectral dispersion direction of the spectrometer. The horizontal direction corresponds to the axis of the foam cylinders, and is the propagation direction of the laser generated shock waves. The magnification was calculated comparing the dimensions of the disc in the image 6.2 with the actual 200 µm disc diameter. The spatial resolution was inferred from the width of disc edge using the Rayleigh criterion

\[
\Delta x_{\text{horizontal}} = \pm 10 \mu m \; ; \; \text{magnification 58 times ,}
\]

\[
\Delta x_{\text{spectral}} = \pm 5 \mu m \; ; \; \text{magnification 68 times .}
\]
6.1 Experimental set-up

Figure 6.2: Obscuration shot of a copper disc 200\(\mu\text{m}\) in diameter. Lineout of the backlighter spectrum is plotted on the left.

These values were rescaled for each shot, using the measured distance between the tip of the backlighter pin and the centre of the foam.

Time

The delay between the main pulse and the backlighter pulse was recorded by an optical streak camera at 0.1 ns/mm sweep rate. The delay was defined as the difference between the rising edge of the long pulse and the peak of short pulse (see figure 6.3). The uncertainty in determining the beginning of the long pulse limited the accuracy in establishing the time of probing to about 130 ps.

Velocity

The average velocity of the shock waves was estimated combining together different laser shots. For each shot, the shock position was obtained from the recorded radiograph. The shock velocity was then estimated by fitting pairs of time and shock position (see figure 6.4). The typical shock velocity was found to be

\[ v_{\text{shock}} = 96 \ \mu\text{m/ns} \quad (\sim 10^7 \text{cm/sec}). \]
6.1 Experimental set-up

Figure 6.3: Streaked image used to determine the relative timing of the main pulse with respect to the backlighter pulse.

Figure 6.4: Shock velocity fit. Data points were extracted from a series of different laser shots.

Energy

The KDP crystal conversion efficiency was measured for each beam line, giving a typical value of 35% conversion at peak intensity. These calibrations were taken just before the f/10 focusing lens.
6.1 Experimental set-up

The typical energy of each long-pulse beam line was 180-200 J in infra-red ($\lambda = 1.054 \mu m$). Since two beams were focussed on each face of the target, the typical energy delivered in a laser shot on the target surface was

$$E_{2\omega} = 2 \cdot (190 \cdot 0.35) \simeq 130 \text{ J},$$

with an uncertainty of 10% due to typical calorimeter response.

Spectra

The spectral lines resolved on radiographs were identified using tabulated emission lines for chlorine [Henke et al., 1982]. The spectral calibration of each radiograph was obtained using chlorine self-emission lines as a reference.

Using the line width of isolated emission lines of bismuth, the experimental resolution of collected spectra was estimated to be $\delta E = 6 \text{ eV}$ in the 2.2 to 3.2 keV range. This value was used as input parameter to the SEPSAHA code (see page 83) to generate synthetic spectra with the same resolution of collected data.

6.1.2 Radiographs

The radiographs were recorded on Industrex C-type X-ray film. Once developed, the film was scanned in a microdensitometer at a resolution of 50 $\mu m$ per pixel. The value of each pixel is proportional to the film optical density, $OD = -\log_{10} \left( \frac{I(\lambda)}{I_{0}(\lambda)} \right)$, at a calibrated wavelength $\lambda$. Since the typical spectrometer magnification $M$ was 50 times, the spatial resolution $R_{\text{scan}}$ of the scanned images was $1 \mu m$/pixel

$$R_{\text{scan}} = \frac{50 \mu m/\text{pixel}}{M} \sim 1 \mu m/\text{pixel}.$$

Chemical fog

The unexposed, developed film is not completely transparent to the light of the microdensitometer. Therefore the scanned images present an intrinsic optical density
which has to be removed before determining the absolute exposure of the film. This optical density is called chemical fog, and takes into account the transparency of the plastic substrate, and the effects of the developing process. For each image, a portion of unexposed film was extracted, and its average value was subtracted from the image, as shown in figure 6.5, thus obtaining the net density of the film.

**Film density to exposure**

The grains of photographic film present generally a logarithmic response to the light intensity. Figure 6.6 depicts the response curve of Industrex C-type film upon exposure to the $L_{\alpha}$-line of silver at 2.9 keV. To obtain the actual film exposure, each pixel of the image was converted into an exposure value by inverting the response curve of the Industrex C film. Figure 6.7 shows the result of this conversion.

**Background fluorescence**

The spectrometer aperture was shielded by an 8 $\mu$m thick Be filter. The filter prevents the intense radiation that fills the vacuum chamber from getting inside the spectrometer and fogging the film. The filter transmission curve is plotted in figure 6.8, showing that radiation below 0.5 keV is blocked. The spectral region used in the data analysis, namely the range from 2.5 to 3.2 keV, was almost unaffected by the Be filter.
6.1 Experimental set-up

**Figure 6.6**: Optical density as a function of exposure to 2.9 keV radiation for the Industrex C-type film [Kodak Industrex Films, www.kodak.com].

**Figure 6.7**: Image converted to actual film exposure. The region from where the fluorescence lineout was extracted is shown on the right.

The X-ray radiation entering the spectrometer is dispersed by the RbAP crystal and exposes the film. Part of this radiation excites fluorescence in the Al support of the crystal. The contribution of the fluorescence is shown in figure 6.7. It appears to be stronger in the upper part of the film, which was the closest to the aluminium crystal holder.

To remove this spurious signal, a lineout of the fluorescence was taken along the spectral dispersion direction (i.e. a vertical lineout in figure 6.7), and then subtracted from the image.
6.1 Experimental set-up

Figure 6.8: Transmission of an 8 µm thick Be filter (data from NIST tables).

Image curvature and distortion

Collected radiographs presented a curvature of the spectral lines, which was partly due the dispersion of the flat crystal and partly to imperfections in the film holder. To correct the curvature and straighten the image, a geometrical transformation was applied to the scanned image, using a few emission lines as guiding lines.
6.1 Experimental set-up

6.1.3 Detailed LTE opacities

In order to estimate the temperature and the density of the shocks produced in the experiment, the computer programme SEPSAHA\(^1\) was used to compute the opacity of the foam targets at the density and temperature conditions produced in the experiment. The code is based on a detailed model of atomic line absorption. The basic assumption is that the Local Thermodynamic Equilibrium (LTE) model applies to the produced plasma conditions. This means that the plasma as a whole can be far from thermal equilibrium, but locally it is still possible to describe distributions of ion species, bound electrons and free electrons in terms of a single temperature parameter. This temperature must vary slowly across the plasma. LTE is valid at high electron densities, where the collisions between bound and free electrons are frequent enough to establish local thermal equilibrium.

The ion populations are calculated from the Saha equation

\[
\frac{n_{z+1,0}}{n_{z,0}} = 6.02 \times 10^{21} \frac{T_e^{3/2}}{n_e} \frac{g_{z+1,0}}{g_{z,0}} e^{-\frac{\chi_{z,z+1}}{T_e}},
\]

(6.1)

and the relative populations of ion levels are given by the Boltzmann’s relation

\[
\frac{n_{z,i}}{n_{z,0}} = \frac{g_{z,i}}{g_{z,0}} e^{-\frac{E_i}{T_e}},
\]

(6.2)

where the free electron temperature \(T_e\) (which is also the temperature of the ions and of bound electrons, as implied by LTE) is expressed in eV. The free electron density \(n_e\) and ion populations \(n_{i,j}\) are in cm\(^{-3}\). The ionisation potential \(\chi_{z,z+1}\) is defined as the energy difference between the lowest states of adjacent ion stages \((z,z+1)\), and \(E_i = E_{i,0}\) is the excitation energy of the i-th level from the ground state, for each different \(z\) ion stage. The statistical weights \(g_{i,j}\) count the total number of possible quantum states belonging to each level.

The fractional occupation of each level \(i\) and ion stage \(z\) is given by

\[
f_{z,i} = \frac{n_{z,i}}{\sum_{z,i} n_{z,i}}.
\]

(6.3)

\(^1\)this code was developed by C.C.Smith and S.J.Davidson[Davidson et al., 1988], and then upgraded by D.Hoarty to allow the simulation of absorption spectra for chlorinated foams[Hoarty, 1997].
The plasma neutrality imposes the following constraint on densities

\[ n_e = \sum_{z,i} z f_{z,i} n_i = z^* n_i , \]  

(6.4)

where \( z^\ast \) is the effective mean ion stage, and \( n_i \) is the ion density. The ion density is a function of the local material density \( \rho \)

\[ n_i = \frac{N_A}{A} w_i \rho , \]

where \( A \) is the atomic weight of the element, \( N_A \) is the Avogadro number, and \( w_i \) is the fractional weight of the considered element in the material.

The input parameters to SEPSAHA code are the temperature \( T_e \) and the mass density \( \rho \). The programme follows an iterative procedure in order to determine the ionisation stage of the plasma, and consequently the electron density \( n_e \). A starting electron density \( n_e^{in} \) is guessed, and then the fractional occupation at the given temperature is evaluated, using equations 6.1 and 6.2. Inserting the input density \( \rho \) in the neutrality relation 6.4, the corresponding free electron density \( n_e^{out} \) is calculated. Then the input \( n_e^{in} \) is corrected iteratively until a consistent value for the free electron density is obtained.

Once the ion populations are calculated, the code reads a database of excitation energies, statistical weights, line widths and oscillator strengths for the chlorine, and computes the corresponding opacity. Important contribution from the other constituents of the foam, namely carbon, oxygen and hydrogen, is included in the calculation of the total free electron density, as these lighter elements are more easily ionised than chlorine.

The final output of SEPSAHA is an absorption spectrum in the X-ray range relevant to the recorded radiographs, namely from 2.6 keV to 3.0 keV. The width of the computed absorption lines was corrected for the finite experimental resolution, averaging the spectrum over a 6 eV range. The temperature and the density of the plasma could be estimated by matching the experimental absorption spectrum to the synthetic spectra generated by the code. Figure 6.9 shows the sensitivity of this
technique. A few eV difference in temperature leads to easily detectable changes in the shape of the absorption profile. In this respect, density variations of a factor of two or more are needed to cause similar deformations in the spectra. Thus this method was mainly used to estimate the temperature of the plasma, whereas the density was inferred from the absolute values of the plasma transmission.

The SEPSAHA code was modified to obtain in output a series of transmission spectra at fixed plasma density. Figure 6.10 depicts a series of such synthetic spectra. The density is kept constant, and the temperature of the sample changes along the vertical axis. It is possible to see when different absorption lines “switch on”, indicating a particular temperature threshold.

The sensitivity of this Cl-absorption technique starts at about 20 eV. This corresponds to the minimum temperature for 1s3p transitions for Ne-like and F-like ionisation stages of chlorine. The chlorine self-emission covers the signal at about 2.8 keV, and therefore the upper limit for this diagnostic technique is about 80 eV.
In this section, the analysis of the data collected during the experiment is described, and temperature and density profiles are presented for two counter-propagating shock waves both prior to and during collision.

Definition of a backlighter spectrum

The backlighter target used in the experiment consisted of a gold pin overcoated with bismuth. In the 2.2 to 3.2 keV range, Bi has a quasi-continuum M-band emission, which enables the detection of 1s2p and 1s3p Cl absorption lines [Willi, 1989]. Figure 6.11 presents a typical backlighter spectrum extracted from the collected radiographs. The bottom curve is the M-band emission of the Bi coating. The top curve shows the relative intensity of the backlighter spectrum and the chlorine line emission from a laser irradiated foam target. The self-emission is a limiting factor in this experiment. Significant information cannot be extracted from it, and its presence may mask other interesting but less intense features. Hence a metal shield was used to screen the self-emission from both ends of the foam target, as explained in the experimental set-up section.

In most of the radiographs the presence of the shield prevented the direct observation of the backlighter emission. Hence the backlighter lineout depicted in figure 6.11
Figure 6.11: Bismuth backlighter spectrum and foam self-emission. Bottom panel presents the reference emission spectrum of the backlighting source. Top panel shows the relative intensity of the chlorine self-emission (solid line) and of the backlighter (dashed line).

was taken as a reference and rescaled for each laser shot. The backlighter intensity was matched to the maximum Bi emission in one of the two regions around 2.9 keV or 3.1 keV. In this part of the spectrum, any plasma in the line of sight could not absorb more than 10% of the backlighter signal. This is true for the plasma conditions likely to be produced in the experiment, as confirmed by similar experiments on foam targets[Hoarty et al., 1997, 1999].

Density and temperature profiles

The density of the foam targets was inferred from the absolute transmission of the material in the line of sight. The transmission $T$ is defined as the ratio of transmitted
intensity $I$ over the intensity of the backlighter source $I_{BL}$

$$T = \frac{I}{I_{BL}}.$$

In the following analysis it was assumed that the plasma conditions, and therefore the transmission, did not change significantly during the backlighter flash.

The targets were aligned so that the recorded transmission at 2.4-2.6 keV corresponded to X-rays probing the core of the foam cylinder (see the obscuration shot at page 77, where the centre of the disc corresponded to the central part of the foam targets). SEPSAHA synthetic absorption spectra confirm that the opacity $\xi$ of the foam is a slowly varying function of both density and temperature in that part of the X-ray spectrum, and it can be assumed to be constant

$$\xi(T_e, \rho) = \xi.$$  \hspace{1cm} (6.5)

Transmission $T$ then becomes solely a function of the density $\rho$ and plasma thickness $\Delta x$

$$T = e^{-\xi(T_e, \rho)\rho \Delta x} = e^{-\xi \rho \Delta x}.$$ \hspace{1cm} (6.6)

As a first approximation, the thickness can be set equal to the original foam diameter, so that the density ratio can be inferred from the transmission of the foam

$$\rho_{10} = \frac{\rho_1}{\rho_0} = \frac{\ln(T_1)}{\ln(T_0)}.$$ \hspace{1cm} (6.7)

This method is valid in planar geometry and for a timescale shorter than the disassembly time of the target.

Transmission lineouts were extracted at about 2.5 keV along the length of the foam, and converted into density profiles using equation 6.7. Figure 6.12 shows the density profile for a shot in which only one shock was generated in the target.

To determine the profile of plasma temperature, several vertical lineouts were extracted from the scanned radiograph along the spectral dispersion direction. Each lineout corresponded to the absorption spectrum at a different point along the foam cylinder. The temperature $T$ was determined by matching these absorption profiles to the synthetic absorption spectra generated by the SEPSAHA code.

The results of the analysis are summarised in the following sections.
Figure 6.12: Single shock and cold foam. The target had a nominal density of 50 mg/cc.

Approaching collision

Figure 6.13 presents a radiograph taken before the collision of two shock waves. The two shadows of the shocks can be clearly seen through the narrow window of the shield. A schematic description of the radiograph is presented in figure 6.14. The curvature of the shock front is likely to be due to cooling effects at the edges of the foam. Chlorine absorption lines corresponding to 1s2p and 1s3p transitions are present at around 2.7 and 2.9 keV respectively, i.e. just above and below of the very intense white band corresponding to the He$\alpha$ emission line of the chlorine. Peak temperatures in excess of 55 eV were inferred from the C-like 1s2p transitions. The presented radiograph was taken just before the shocks collided. This is confirmed by the fact that the centre of the foam is still relatively cold, since no absorption lines can be seen in between the two shock fronts.

Temperature and density profiles for this shot are shown in figure 6.15. The peak density in the stronger shock on the right was about 3 times the original density. Hence the maximum pressure produced in a single shock was about 2 Mbar\(^2\).

\(^2\)The foam is characterised by a weighted atomic mass $A = 9.7$ and weighted atomic number $Z = 5.0$. The SEPSAHA code predicts a mean ionisation stage $Z^* = 3.2$ for the density and temperature conditions of the shock front.
6.2 Data analysis and results

Figure 6.13: Two shocks before collision. The diagram on the right depicts the two curved shock fronts visible through the narrow window of the shield.

Figure 6.14: Schematic description of the radiograph presented in figure 6.13. Dashed curves indicate the fronts of two counter-propagating shock waves. The presented line-cut was extracted along the shock front on the right-hand side. Chlorine emission and absorption lines are marked.
6.2 Data analysis and results

Figure 6.15: Temperature and density profiles for the two shocks presented in figure 6.13. A spline curve has been fitted through the temperature points.

Head-on collision

Figure 6.16 presents a radiograph taken during the collision of two laser-generated shocks. A region of about 50 µm was heated to temperatures significantly higher than those produced in a single shock. The observation of the B-like absorption line indicates that temperatures in excess of 80 eV were generated in the plasma. A more precise measurement of the temperature was prevented by the chlorine self-emission at 2.8 keV, which covered the absorption lines corresponding to higher temperatures. The density profile is broader and the maximum compression is lower, as compared to each of the colliding shocks. This could be probably due to the fact that the foam material, compressed between the two shock fronts, starts expanding in the transverse direction. As a consequence, the measured density in the central part of the target is not the density of a slice of the original foam cylinder, but the average density of a larger volume of material.
Figure 6.16: Collision of two laser-generated shock waves. A central region had been heated to high temperature during the collision of the two shock fronts.

Figure 6.17: Temperature and density profiles during the collision presented in figure 6.16.
6.2.1 Shock profile deformation

The high temperatures and pressures observed during the shock propagation indicate that shock waves of high strength were produced in the targets.

The strong shock limit (see equation 2.45, page 28) predicts a compression ratio higher than the one measured in the experiment. To explain this discrepancy, the shock motion during the backlighter pulse has to be taken into account.

A simple numerical model was developed to investigate the effects of shock propagation during the backlighter flash. The shock wave was described by a density profile $\rho(x,t)$ moving at the velocity of 100 $\mu$m/ns. Figure 6.18 shows the idealised density profile with a peak compression ratio $\rho_{10}$ of 4. The backlighter was defined by a gaussian pulse of 90 ps FWHM duration.

The intensity on the film plate was set to be proportional to the backlighter intensity $I_{BL}$, rescaled by the optical density of the shocked material

$$I_{film}(x,t) = I(t)_{BL} e^{-\rho(x,t)}.$$

The film exposure $E(x)$ was obtained by integrating the intensity $I_{film}(x,t)$ over time. At this point, the data analysis outlined in section 6.2 was simulated. The exposure $E(x)$ was converted into transmission, and then the density profile was calculated using a formula similar to equation 6.7. Figure 6.19 shows the simulated density profile. As a consequence of the motion of the shock wave, the peak of the density profile is smeared out, and the maximum compression is lower than the instantaneous value of 4 in the ideal shock.

The actual compression in the shock waves produced in the experiment can be estimated $a posteriori$ according to this simulation. Values of compression $\rho_{10}$ between 2 and 3 measured during the shock propagation are compatible with an actual compression $\rho_{10}$ of 4 times or more.
6.2 Data analysis and results

Figure 6.18: Density profile of an ideal strong shock.

Figure 6.19: Reconstructed shock profile from the analysis of simulated film exposure.
6.2.2 Shock front curvature effects

After the impact of the shock fronts, the plasma conditions were too complex to be analysed with the method outlined in section 6.2. At this stage of the shock waves interaction, the planar symmetry assumption is not valid anymore.

The 2D Eulerian hydrocode POLLUX [Pert, 1981] was modified in order to allow direct irradiation of both sides of a cylindrical target. This new version of the code was then used to investigate the deformation of the shock fronts. The input parameters to the code were chosen according to the experimental set-up, and to the measured parameters of the laser pulse. Figure 6.20 shows different stages of the shocks’ propagation in a foam target. The maps of the temperature and of the target density are presented at four different times after the beginning of the laser pulse, namely at $t = 0.4, 1.0, 1.2$ and $1.3$ ns. The simulation was carried out in cylindrical geometry with the laser pulses propagating along the $z$ direction. Edge cooling effects cause the planar shock front to curve. During collision, the material is compressed and accelerated in the plane perpendicular to the propagation direction of the shocks. The velocity of the ejecta is of the same order of the velocity of the incident shocks, i.e. about $10^7$ cm/s.

6.2.3 Summary

The propagation and collision of strong shock waves have been observed in chlorinated foams. The shock fronts were produced by irradiating the surface of the target with a 527 nm laser pulse at the intensity of $10^{14}$ W cm$^{-2}$. The density and temperature of the plasma have been measured in the core of the foam cylinders using time-resolved point-projection absorption spectroscopy. A flat crystal spectrometer was used to collect radiographs of the target in the 2.2 to 3.2 keV range. The temperature profile has been obtained by matching a synthetic absorption spectrum to the observed data. The density in the foam has been inferred from the absolute transmission levels of the target.
Figure 6.20: POLLUX simulation of colliding shocks in a foam cylinder
6.2 Data analysis and results

For the first time shock wave collisions in foam have been measured at energy densities in the region of $10^{11}\text{Jm}^{-3}$. During collision, the central region of the target was heated to temperatures significantly higher than those produced in a single shock, namely about 55 eV. Temperatures in excess of 80 eV have been inferred from the presence of B-like absorption lines of chlorine. The shock compression observed in the density profile was found to be compatible with the strong shock limit, once the motion of the shock front during the backlighter flash had been taken into account. Curvature of the shock fronts has been observed in the collected radiographs, and reproduced by hydrodynamic simulations. The effect is likely to be caused by energy losses at the edges of the foam target. As a consequence of the curvature, the colliding shock waves compress and accelerate material in the plane perpendicular to the propagation direction. The data analysis technique was limited by the assumption of planar shock waves. Two-dimensional features of the shock front structure and the expansion of the target prevented the application of the same diagnostic technique to the target evolution after the collision.