MODELING OF THE SYNCHROTRON DIAGNOSTICS OF EXPLOSION

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Application of the synchrotron radiation for the explosion diagnostics is considered. Using one-dimensional gas-dynamic approximation the interaction of the beam with the detonating explosive cylinder is modeled.

1. In 2000 a new line of activity in the diagnostics of high-speed processes arose, employing the synchrotron radiation (SR). High intensity and low divergence of the SR beam, potentially high pulse repetition rate are the main advantages of SR in comparison with the usual X-ray testing. At the same time the SR diagnostics may be practically nonperturbative. This combination of characteristics is promising for investigations of explosion and detonation. At present only preliminary results have been published (see, e.g. [1–3], but the problem is important enough to justify an equally preliminary analysis of the potential of methods used.

In the experiments the SR beam from the undulator (integrated in the 2 GeV electron accelerator) went through the 1 cm diameter explosive cylinder perpendicular to its axis. The beam absorption was used to estimate the density of the material. Also the small-angle scattering, produced by the carbon particles (incluling diamonds) created in the explosion, was registered. The scattered signal had noticeable rise time – several μs, which prima facie was in contradiction with the current conception of fast formation of the diamonds in detonation, within the sub-μs chemical reaction zone [4]. In the present paper the modeling of SR interaction with the detonating explosive charge shows that the new data are consistent with the fast formation of particles.

2. The most important effect is immersion: the carbon particles formed in explosion are surrounded by rather dense gas. As a result the electron density contrast is weakened as well as the scattering. The expansion of the detonation products with the microsecond characteristic time, reduces the gas density and

enhances the contrast, thus the signal rises. The importance of the expansion dynamics is also evident for the beam absorption analysis.

The gas expansion dynamics was calculated numerically in one-dimensional approximation. Clearly the one-dimensional simulation does not yield the exact distribution of density along the beam, but it can be used as a reasonable estimate. The Jouguet state was assumed to be reached immediately behind the detonation front and from this state cylindrical expansion was started. The equation of state [5] was used for the detonation products and the surrounding air was treated as an ideal gas with adiabatic index of 1.25. The Lagrangian flow equations were solved by the artificial viscosity method [6].

The charge cross-section was divided into the concentric cells. At the passage through each cell the beam intensity $I(r,t)$ is multiplied by $\exp(-\mu\rho(r,t)|\Delta r|)$. Here μ is the mass attenuation coefficient, $\rho(r,t)$ is density, Δr is an increment of the Eulerian radius r (note that each cell was crossed by the beam twice).

In each cell the actual intensity produces the scattering. The maximum photon energy in the experiments was around 30 keV. The characteristic particle size $R \sim$ 4 nm and the scattering angle of about 0.5° correspond to the principal maximum of the small-angle scattering function. Due to averaging over the ensemble of particles and over the spectrum this function gives a factor of the order of unity.

Because of immersion the scattered signal is proportional to the squared difference of the electron densities in the particles and in the gas or, to a good approximation, to the squared difference of mass densities of diamond ρ_d and of gas ρ_g (for the elements which form the explosive the atomic number to mass ratio 1/2 is violated only for hydrogen whose contribution to the total mass is quite small). The form of the scattering intensity convenient to combine with the gas-dynamical data is:

$$\Delta I_S \sim I(r,t)\rho(r,t)(\alpha_d/\rho_d)(\rho_d - \rho_g)^2 R^3 \Delta r\,, \qquad (1)$$

here α_d is the part of explosive mass converted into diamond. If the condensed product is not pure diamond the above function is corrected in obvious manner.

The experimental restrictions forced the usage of full SR spectrum ("white beam"). The absorption depends strongly on the radiation wavelength. Initially the hard component is passing through but as the density falls down the soft part

of the spectrum begins to penetrate which resembles photo development. Thus radiation polychromatism also affects the resolution.

The spectral range of energy E from 0 to 30 keV was divided into 20 equal parts, and calculations of absorption and scattering were performed for each spectral interval. The initial spectrum [7] was used (for 2 T whiggler field), corrected for attenuation in air before the charge and in the input beryllium window. Then intensity of the main beam $I(E)$ and of scattered one $I_S(E)$ were calculated in each charge cell for each beam component (the further absorption of the scattered radiation was taken into account). Finally the attenuation in air before the detectors and in the output window took place. The mass attenuation coefficients were interpolated according to tables from [8]. The detector signal was supposed to be proportional to the total radiation intensity over the full spectrum.

3. The comparison of the simulations and data of [2] for pressed up to 1.6 g/cc trotyl (TNT) and cast composition of 50% TNT and 50% hexogen, or RDX (TNT/RDX) are shown in Fig. 1. It is assumed that the beam went for 1 m way in air before the charge, and the distance from the charge to the detector is 50 cm. The initial level of main beam was adjusted with the experiment. One can see rather good agreement with the experimental data for the passed intensity.

The condensed carbon and diamond yields and particle sizes from [4] were used, and the instant carbon condensation was assumed. Since the scattered signal (1) is determined to an unknown factor, its maximum is adjusted with the experimental data for TNT. In spite of lesser carbon yield, the scattered intensity for TNT/RDX is slightly higher, as in the experiment. This can be explained basically by the larger diamond yield (the graphite produces more weak signal).

The scattering dynamics is reproduced but qualitatively. The calculated signal initially rises due no contrast enhancement, then decreases due to general expansion which reduces the number of particles on the way of the beam. The maximum is reached in about 3 μs for both explosives. The experimental pulse rise is slightly faster for TNT/RDX and notably slower for TNT as compared with the calculations. Note that the expansion in the model described above is somewhat slowed because the axial flow is leaved out of account. Two-dimensional simulation would give faster signal rise which could explain the discrepancy for TNT/RDX. But the same correction is expected for TNT since the expansion

gas-dynamics is practically the same.

Authors [2] suggest that the carbon condensation occurs not only in chemical reaction zone but it continues in the expanding detonation products. The estimates presented above show that the scattered signal rise time is several μs even if the carbon grains are released "instantly". The prolonged condensation, when such is the case, can take place in TNT for which the signal increase is slow. For instance, the main reaction can be incomplete, to be continued in the expansion phase, including liberation of the certain part of the free carbon.

The graphite and amorphous particles prevailing in TNT detonation products remain little explored as compared with the detonation diamonds. The version of the prolonged condensation which means the growth of much larger grains (dozens of nm), is doubtful – it is prohibited by the size limitation of growth [9]. Moreover, for large particles the signal is determined not by the principal maximum of the small-angle scattering function but by its "tail"; roughly it is proportional to $1/R$, so the increase of the signal under these conditions means the decrease in the particle size. Although the large graphite-like grains were found in the condensed product, they most probably are formed on exposure to high temperatures at later stages of explosion.

It seems more probable that crowding effect is responsible for TNT behavior. In TNT detonation products the free carbon concentration is quite high which leads to the association of small carbon particles into a spatial structure which explains high conductivity of this medium [10, 9]. Under expansion this structure is torn to smaller pieces. The fresh interfaces arise which contribute into scattering. This explanation of TNT data is alternative to [2].

In monochromatic approximation, i.e. without the "development" of the beam spectrum, the rise time of scattered signal was found to be about half as long ($\approx$ 1.5 μs). Thus for scattering the immersion and polychromy have approximately equal effect on the degradation of resolution. The monochromatization of the SR beam will sharply improve the transmitted signal which does not depend on the contrast.

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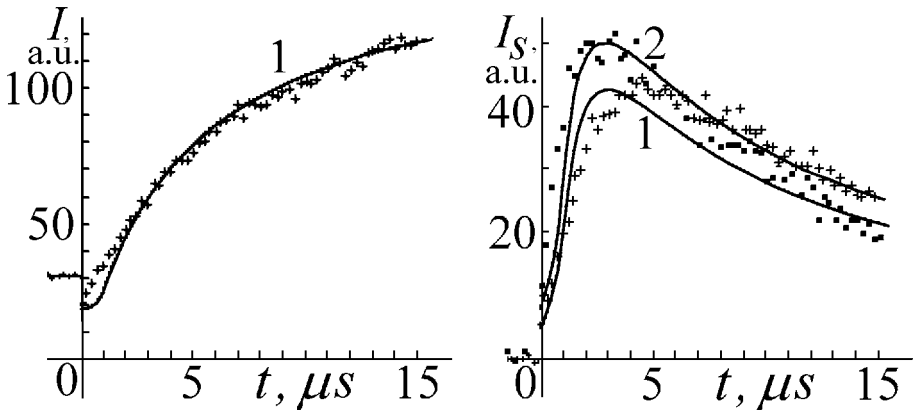

Fig. 1. The intensity of the transmitted beam I and of the scattered one I_S in arbitrary units. Data of [2]: + – TNT, ■ – TNT/RDX; solid lines – simulations: 1 – TNT, 2 – TNT/RDX.