

# Diagnostic of Superfast Jets with 25 km/s Tip Velocities

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## Diagnostik von superschnellen Stacheln mit 25 km/s Spitzengeschwindigkeiten

In sogenannten "Cavity-Ladungen" werden superschnelle Stachel mit Spitzengeschwindigkeiten im Bereich von 25 km/s beobachtet. Derartig schnelle Stachel erodieren bereits stark beim Durchschlagen der Luft. Das abgetragene Material formt eine Röhre um den Stachel herum, die eine optische Beobachtung des eigentlichen Kernes des Stachels verhindert. In Tests, bei denen die Stachelausbreitung im Vakuum erfolgt, existiert dieses Problem nicht mehr, bzw. ist stark reduziert. Um genügend räumliche Auflösung für den dünnen Stachel zu erhalten, wurde die sogenannte Profil-Streak-Technik (PST) angewandt. Mit dieser speziellen Diagnostik wurde zum ersten Mal der Durchmesser dieses superschnellen Stachels als Funktion der Zeit gemessen. Die verwendete Meßmethode wird im Detail mit typischen Ergebnissen zusammen mit den Auswertetechniken dargelegt.

## Diagnostic de jets ultra-rapides avec des vitesses de pointe de 25 km/s

Dans les charges dites à cavité, on observe des jets ultra-rapides avec des vitesses de pointe de l'ordre de 25 km/s. Ces jets rapides subissent déjà une forte érosion au passage à travers l'air. Le matériau érodé forme un tube autour du jet qui empêche l'observation optique du noyau même du jet. Lors de tests avec une propagation du jet dans le vide, ce problème ne se pose plus ou est fortement réduit. Pour que la résolution spatiale du jet mince soit suffisante, on a utilisé la technique dite PST (profile streak technique). Cette technique de diagnostic spéciale a permis de mesurer pour la première fois le diamètre de jets ultra-rapides en fonction du temps. La méthode de mesure utilisée et des résultats typiques sont présentés en même temps que les techniques de dépouillement.

## Summary

In so-called cavity charges superfast jets with tip velocities in the range of 25 km/s were found. Such fast jets are strongly eroding by the perforation of the ambient air. The ablated jet material forms a tube around the jet and is optically protecting the core of the jet itself. With tests, where the jet is elongating in a vacuum, this problem does not exist or is drastically reduced. To get enough special resolution, the profile streak technique (PST) was used to obtain the diameter of the stretching jet as a function of the passing time or with respect to its velocity gradient. With this special diagnostic technique the radius of these superfast jets was measured the first time. The used test method with typical results together with the applied evaluation technique will be described.

## 1. Introduction

There were published a few papers<sup>(1,2)</sup> on very fast jet velocities of more than 20 km/s using the so-called cavity charge. It was a problem to really measure the core of the very fast jets because they were strongly ablating when perforating the air and the eroded layer is not transparent. The aluminium jets are so thin and tiny that they give not enough contrast in flash X-ray pictures. The goal of this investigation was to find a method to measure the diameter of these very fast tiny aluminium jets.

## 2. Layout of the Investigated Cavity Charge

It was used a 25 mm thick aluminium plate (AlCuMg1) with a cavity of 20 mm diameter and 20 mm depth with a radius of 1 mm from the cylindrical hole to the bottom layer (Figure 1). The cavity was shock loaded by the detonation of a squeeze cast TNT/HMX charge of 15/85 weight percentage with 150 mm diameter and 120 mm length. The

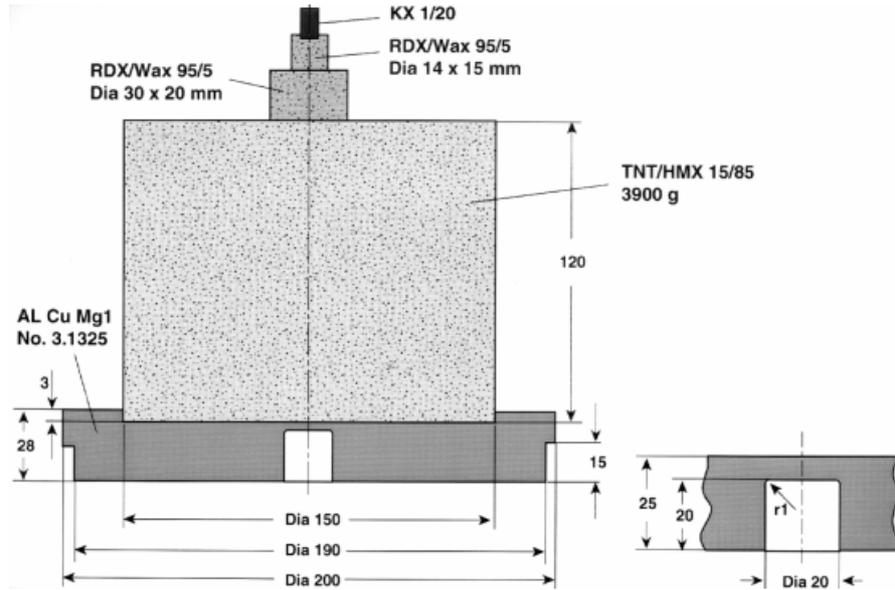
charge was axially initiated by the fast reacting detonator KX 1/20<sup>(3)</sup> over two boosters of pressed RDX/wax 95/5.

## 3. Test Setup

The aluminium plate with the cavity was installed in a plexiglass tube of 200 mm outside diameter, 5 mm wall thickness and 1000 mm length (Figure 2). One side was closed with the aluminium plate with the cavity and the other side with a 25 mm thick aluminium plate. This tube was evacuated to about 10 Torr. Witness plates of mild steel were attached on the aluminium end plate to measure the penetration capability of the formed jet in 1 m standoff. The jet formation from the cavity is observed with 2 cameras, one simultaneous streak and framing camera CORDIN Model 330<sup>(4)</sup> and a streak camera HE03, designed and built by the author<sup>(5)</sup>. The formation of jet was observed as shadowgraphs with a background illumination by argon bombs. A picture of the arrangement on the test field is given in Figure 3.

## 4. Optical Diagnostic Techniques

To get the velocity of the formed jet with relatively high accuracy the so-called "velocity streak technique" was used (Figure 4, left), where the streak slit of the CORDIN Camera Model 330 was set parallel to the velocity vector of the jet. Frames from the stretching jet were gained. The frames are not able to measure the diameters of the jets because the field of view is not small enough. For this purpose the so-called "profile streak technique" was used (Figure 4, right), where the slit is perpendicular to the velocity vector of the jet and therefore, the passing jet as a



**Figure 1.** Test setup used to get superfast jets from a cavity of 20 mm diameter and 20 mm depth with 1 mm radius in a 25 mm thick aluminium plate, shocked by the detonation of a squeeze cast TNT/HMX charge 15/85.

function of time can be recorded in a relatively small field of view.

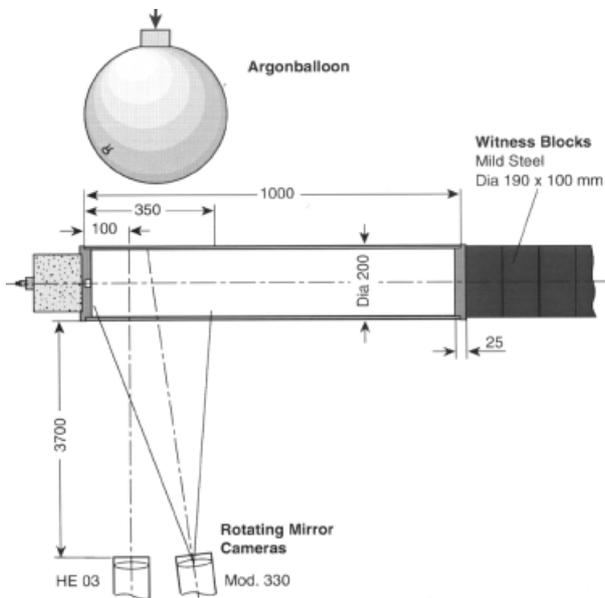
**5. Test Results**

The frames of the jet formation, gained with  $10^6$  frames/s with the camera Cordin Model 330, are presented (Figure 5). The fiducial marks have 100 mm distance. The very thin jet is practically not visible behind the “streak line” (dark black line in the middle of the frames). The portion which is used for the streak record is missing in the frames. But the

wide extension of the “mushroom” event can be seen very well.

The streak record in velocity mode simultaneously gained with the Cordin Camera Model 330 is given in Figure 6. It shows a very fast event which corresponds to the jet tip. The darker line with a lower velocity corresponds to the “mushroom” event. The analysis of this streak record is shown in the time distance plot of Figure 7 which gives a velocity of 25 km/s for the jet tip and for the mushroom event about 7.7 km/s.

Streak records of passing jets are shown in profile streak technique in Figure 8 at distances between the surface of the cavity charge and the observation plane of 100 mm (2 different tests) and 250 mm.



**Figure 2.** Test setup for catching pictures and streak records of the stretching jet of a cavity charge with background illumination by argon bombs.



**Figure 3.** Picture of test setup with the cavity charge on the left side, the plexiglass tube, which can be evacuated and the argon bombs in the background.

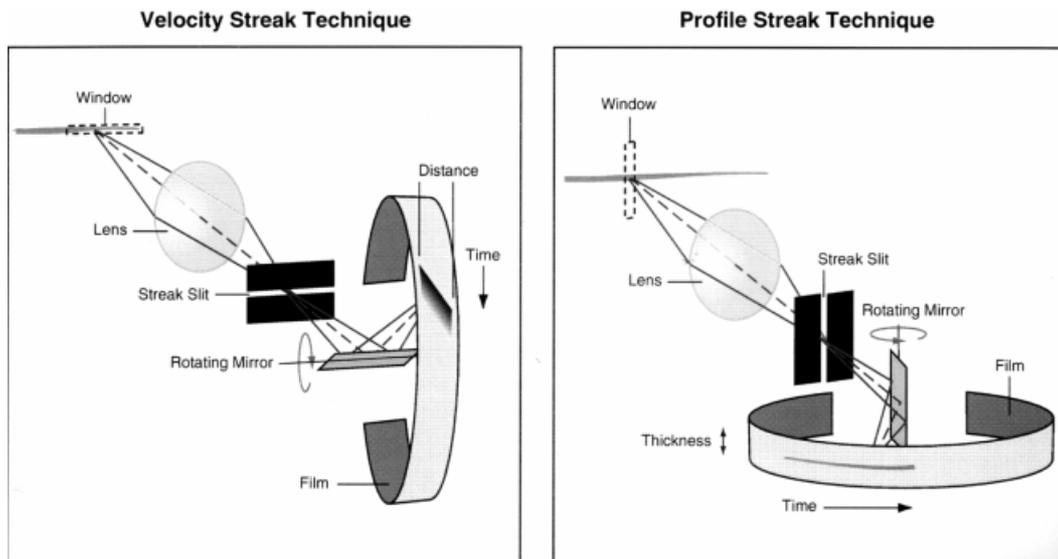


Figure 4. The velocity streak technique was used to measure the jet tip velocity (left) and the profile streak technique to record the diameter.

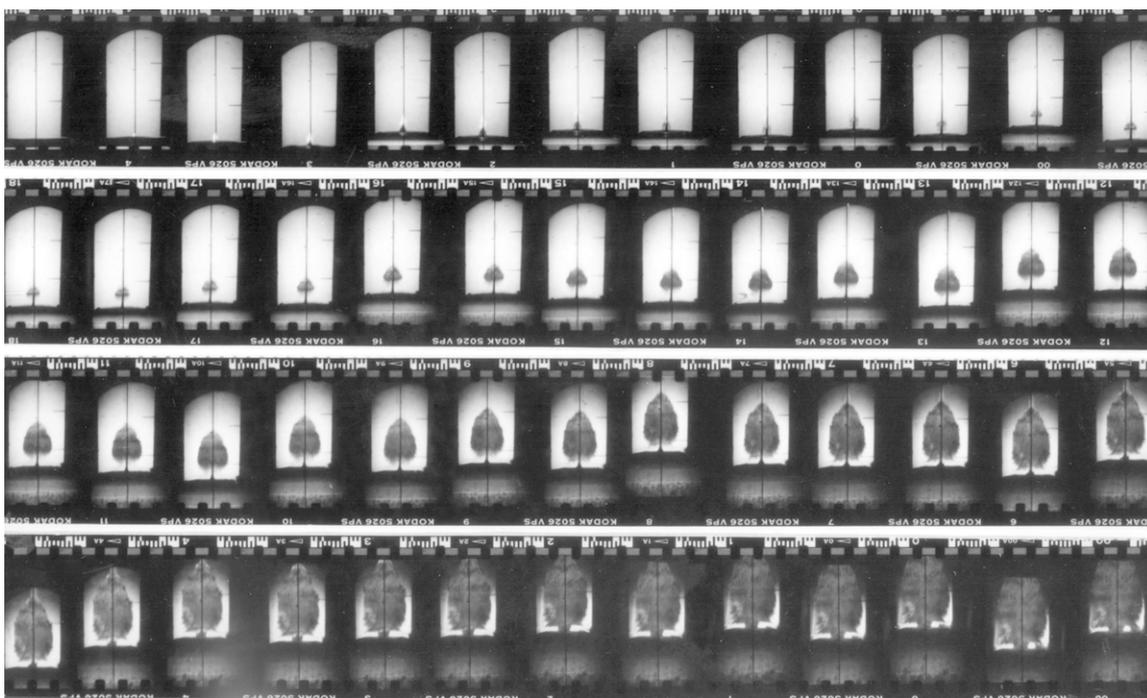


Figure 5. The jet is not really well visible in the frames, gained with  $10^6$  frames/s behind the streak slit but the expansion of the so-called mushroom.

Cylindrical; Mod. 330; Distance 0 - 350 mm

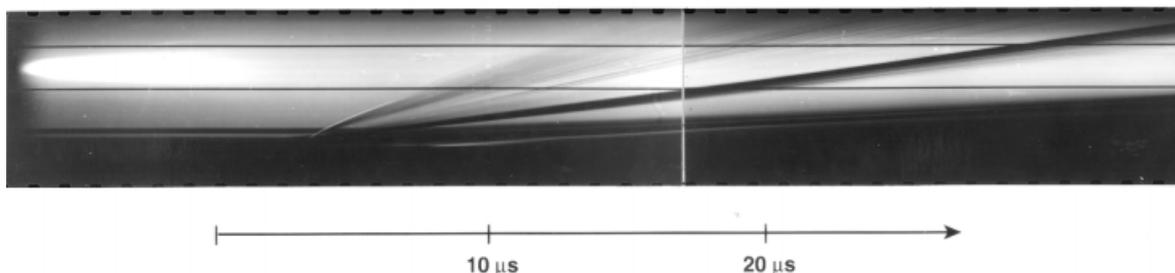


Figure 6. Simultaneously gained streak record in vacuum (distance of fiducial marks 50 mm, writing velocity 3.8 mm/μs).

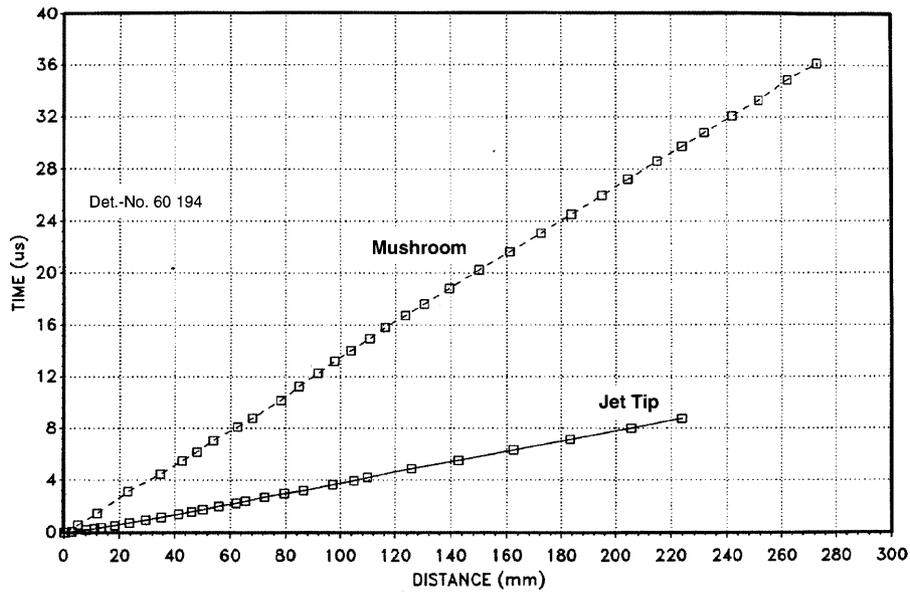


Figure 7. Time distance plot of the analysed streak record of Figure 6 with a jet tip velocity of 25 mm/μs and with the mushroom event of 7.7 mm/μs.

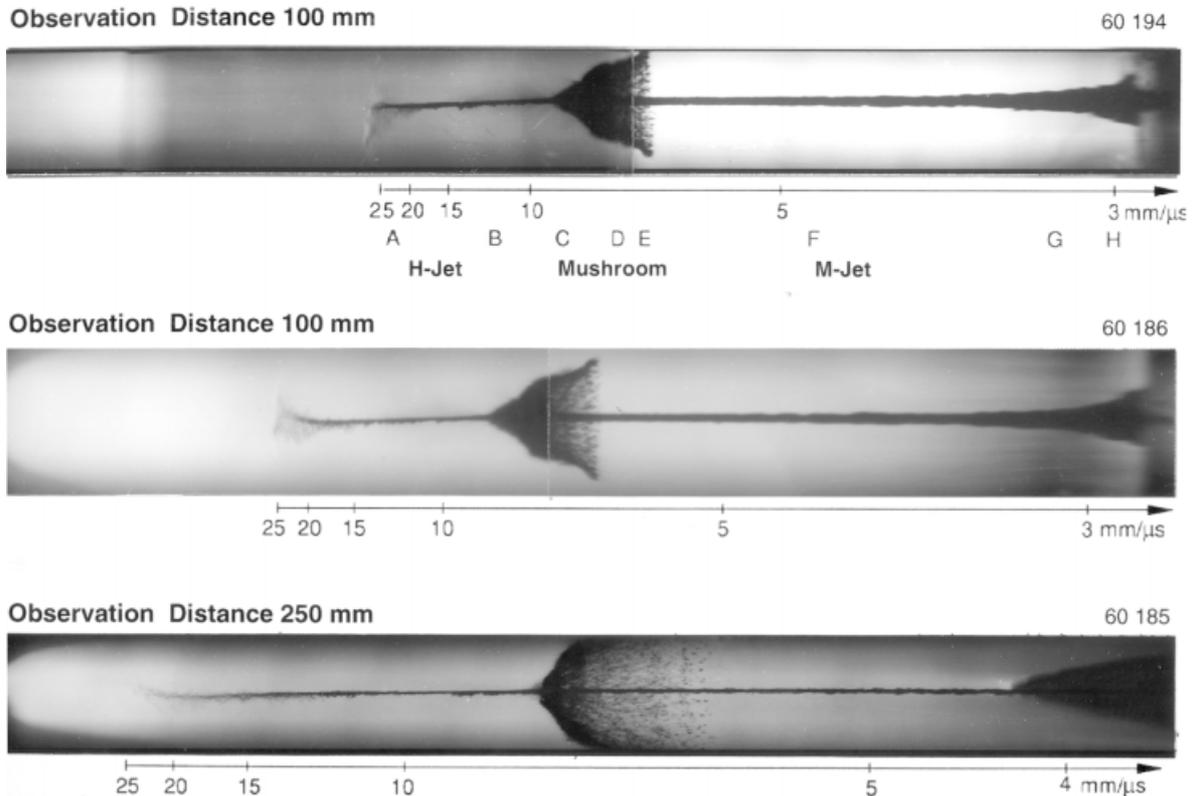


Figure 8. Three profile streak records, two at 100 mm observation distance, which demonstrate good reproducibility of the event, and one at 250 mm observation distance.

**6. Analysis of Streak Records with the Profile Streak Technique**

Because no time marks were used, the arrival time  $t_a$  can be estimated from the first light of the argon balloon and the arrival time  $t_a$  of the jet tip. But in the distance of 100 mm this time difference is only 4 μs. The jitter of the cylindrical

charges which drive the cavity for jetting, and that of the detonation of the charge to obtain the shock wave for the argon balloon is not of the desired accuracy. So for simplicity a constant jet tip velocity of 25 mm/μs was used, which was analysed from the velocity measurement. If the first arrival time  $t_a$  is “known” the velocity distribution on the streak record can easily be derived.

To get some indications of the radii and volumes of the jets generated by the cavity charge, the following derivation was developed. The jet tip arrives at the observation slit in the distance  $D$  in the time difference  $t_a$  (Figure 9). The continuously stretching jet should be measured at a time  $t_n$  with a diameter  $d_n$  and at a time  $t_{n+1}$  with a diameter  $d_{n+1}$ . Under such considerations, the corresponding velocities are obtained by the equations

$$v_{jn} = D/t_n = D/(t_a + x_n/v_s) \tag{1}$$

$$v_{jn+1} = D/t_{n+1} = D/(t_a + x_{n+1}/v_s) \tag{2}$$

where  $v_s$  is the streak resp. writing velocity of the streak camera.

The velocity difference  $\Delta v$  is therefore given with

$$\Delta v = v_{jn} - v_{jn+1} = D \{1/(t_a + x_n/v_s) - 1/(t_a + x_{n+1}/v_s)\} \tag{3}$$

$$\Delta v = D \cdot v_s \cdot (x_{n+1} - x_n) / \{(t_a \cdot v_s + x_n) \cdot (t_a \cdot v_s + x_{n+1})\} \tag{3.1}$$

The volume or the mass of the jet should now be determined as a function of the velocity differences resp. velocity intervals.

The “length L” of a continuously stretching jet is given from the velocity difference, multiplied with the observation time  $t$ .

$$\Delta L = (v_{jn} - v_{jn+1})t \tag{4}$$

For the consideration it should be used the mean value of the observation time. This gives

$$\Delta L = (v_{jn} - v_{jn+1}) \cdot (t_n + t_{n+1})/2 \tag{4.1}$$

$$= \Delta v_j \cdot (t_a + x_n/v_s + t_a + x_{n+1}/v_s)/2 \tag{4.2}$$

The “length  $L$  per velocity interval  $\Delta v_j$ ” or per “velocity difference” is given with

$$\Delta L/\Delta v_j = t_a + (x_n + x_{n+1})/(2 \cdot v_s) \tag{5}$$

It is astonishing how simple the expression for the length per velocity interval  $\Delta L/\Delta v_j$  is as Eq. (5) shows.

If short distances  $\Delta x (\Delta x = x_n - x_{n+1})$  on the streak record, respectively short time intervals  $\Delta t$  are used, the diameter  $d$  of the jet can be considered constant or as a cylindrical jet element. The volume element  $\Delta V$  per velocity interval  $\Delta v_j$  can then be calculated as follows:

$$\Delta V/\Delta v_j = d^2 \cdot \pi/4 \cdot \Delta L/\Delta v_j \tag{6}$$

$$= d^2 \cdot \pi/4 \{t_a + (x_n + x_{n+1})/(2 \cdot v_s)\} \tag{6.1}$$

But if larger observation distances  $\Delta x$  or time intervals  $\Delta t$  are used, the volume of a truncated cone with parallel base surfaces has to be used:

$$\Delta V = \Delta L(d_n^2 + d_n \cdot d_{n+1} + d_{n+1}^2) \cdot \pi/12 \tag{7}$$

The volume of the truncated cone jet elements per velocity difference can therefore be calculated as follows

$$\Delta V/\Delta v_j = (d_n^2 + d_n \cdot d_{n+1} + d_{n+1}^2) \cdot \pi/12 \cdot \{t_a + (x_n + x_{n+1})/(2 \cdot v_s)\} \tag{8}$$

These analyzed values can be presented as a function of the observation time, where  $t$  equal zero is the jet formation (virtual origin approach) and as a function of jet velocity which is determined from the mean value of the observation times

$$v_j = D/(t_n + t_{n+1})/2 = D/\{t_a + (x_n + x_{n+1})/(2 \cdot v_s)\} \tag{9}$$

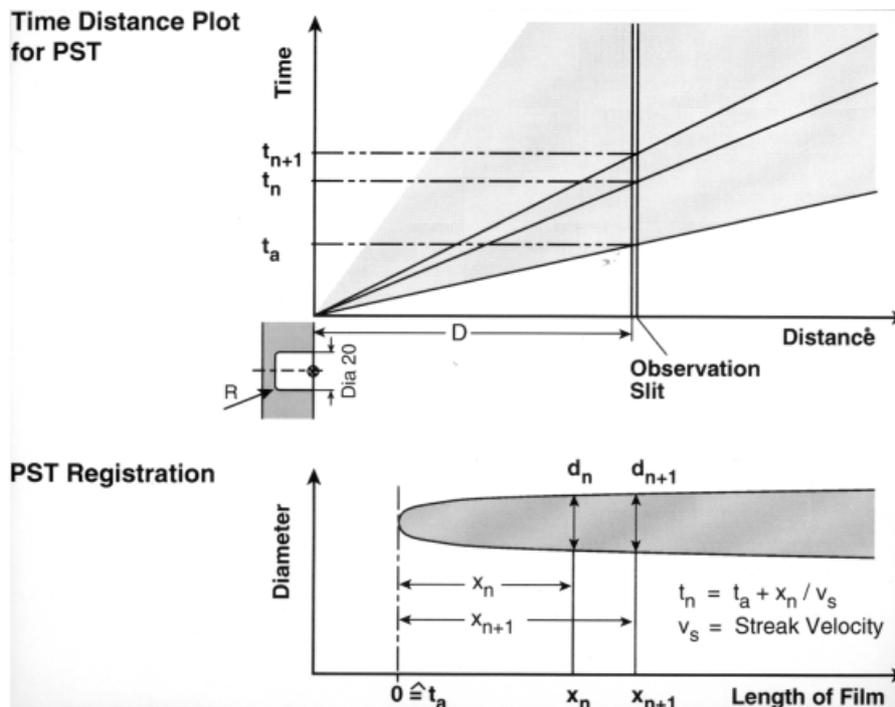


Figure 9. Sketch for understanding the method used for the analysis of the jet diameters out of the profile streak technique registrations.

The analysis of the jet diameters gives some problems, despite the use of the profile streak technique, because of the very small diameters and partially frayed out structure and also vaporized portions. An original 1:1 copy of the streak registration was digitized in a special computer program with adjustable grey levels. The used time steps were  $0.02\mu\text{s}$  and the space resolution for the diameters  $0.2\text{mm}$ . Every time step has given a corresponding diameter.

With this method analyzed jet diameters as a function of time for two jet observations at  $100\text{mm}$  observation distance are presented in Figure 10 on the left side and then as a function of velocity on the right side. The jet tip is not taken into account because it was definitely stronger vaporized. These two examples are showing remarkable good reproducibility of the tests with these results.

The mass could be determined by the multiplication of the volume or the analyzed volume elements with the density. The observed jet elements look partially vaporized and frayed out. Therefore, it must be assumed that not over the total defined cross section the density of the original material (of aluminium with the density  $2.75\text{g/cm}^3$ ) is valid.

At least this method gives the magnitude of the jet dimensions which are in the range of  $2\text{mm}$  diameters. The mass of the jet is therefore in the range of  $10\text{mg}$  to  $30\text{mg}$  per kilometer/s, which are 1000 times larger compared to the masses of the plasma drag technique.

## 7. Jet Tip Separation

As demonstrated with conical shaped charges, where the jet tip of  $10\text{g}$  with  $10\text{mm}/\mu\text{s}$  was separated<sup>(6,7)</sup>, also an oblique detonation wave for the cavity charge was used by  $4\text{mm}$  eccentric initiation. The jet tip of the cavity charge deviates more than the residual jet (Figure 11). The analyzed jet diameters at the 2 distances of  $100\text{mm}$  and  $250\text{mm}$  are shown in Figure 12. This separation technique is demonstrated in principle with this test, but a full success has to be evidenced in future tests.

## 8. Application

Adding the expected masses and velocities of the jet tip of cavity charges in the “Isbell-Tedeschi”-diagram<sup>(8)</sup> (Figure 13), the range of projectile masses, resp. diameters will remarkably increase compared to plasma drag possibilities or projectiles launched by light gas guns<sup>(9)</sup>, or also to the eccentrically initiated shaped charges<sup>(6,7)</sup>.

## 9. Conclusions

The profile streak technique is a very good method to get the contour of a passing object as shadowgraphs, here very thin and tiny jets, if not a too large field of view is used. The

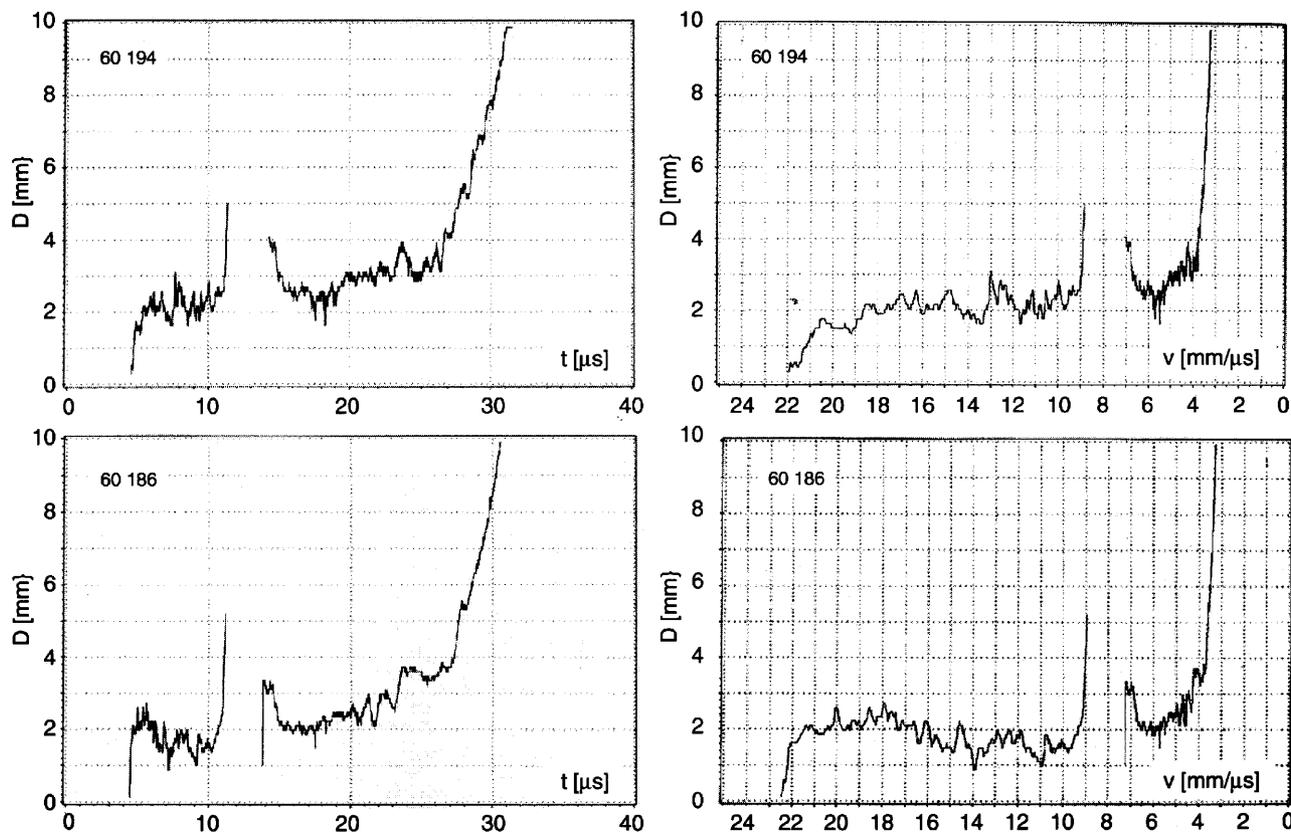


Figure 10. Analysed jet diameters as a function of time resp. function of jet velocities for the two registrations at  $100\text{mm}$  distance.

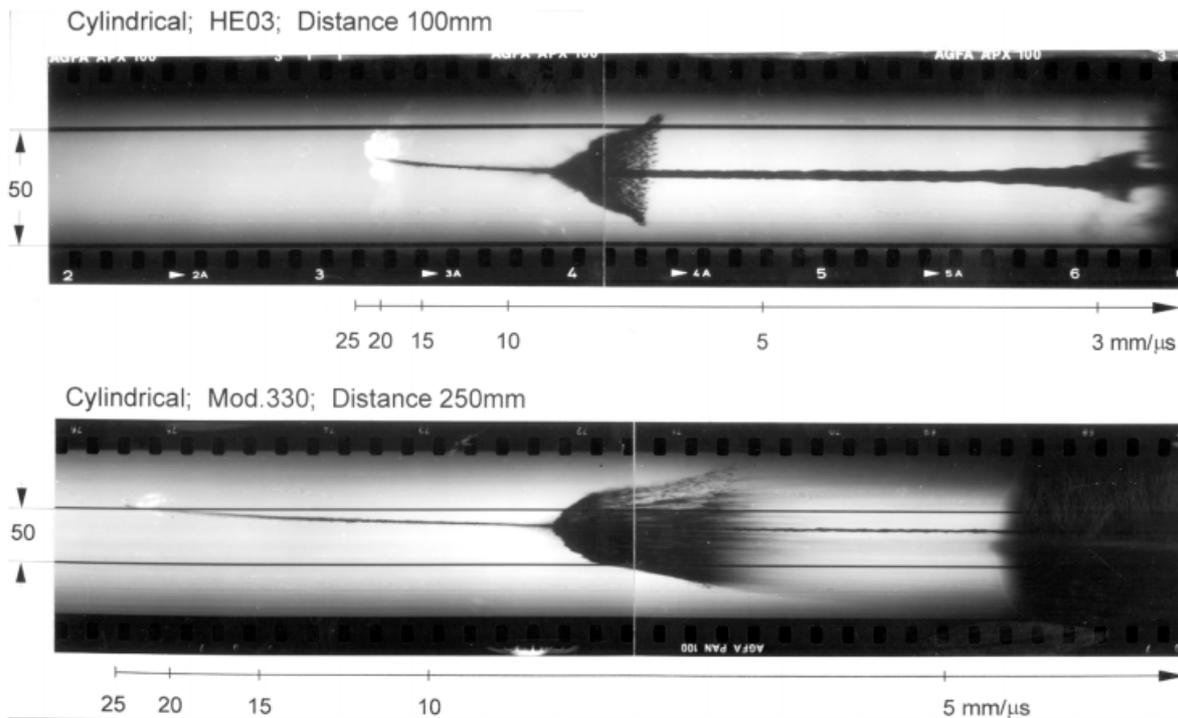


Figure 11. Profile streak records of an eccentrically shock loaded cavity at 100 mm and 250 mm observation distances.

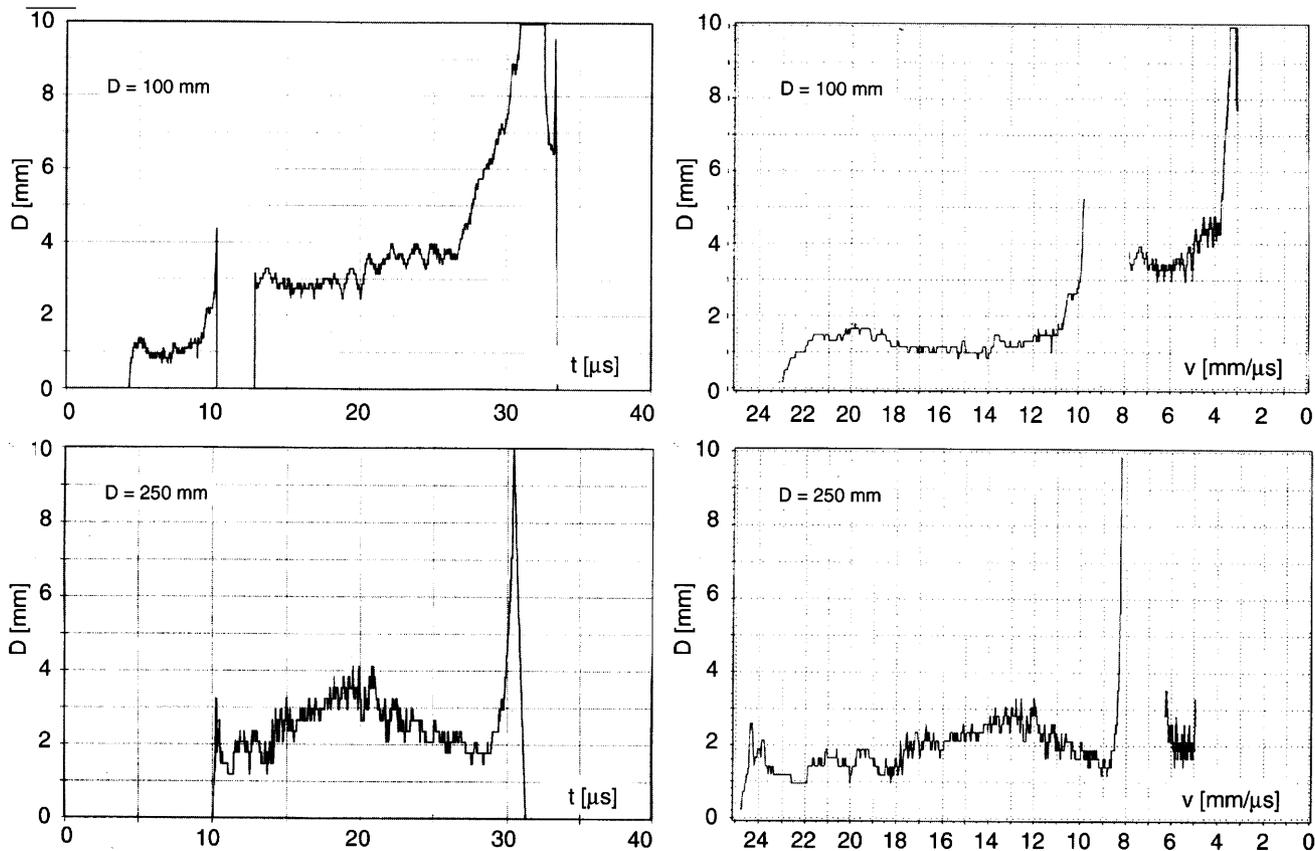
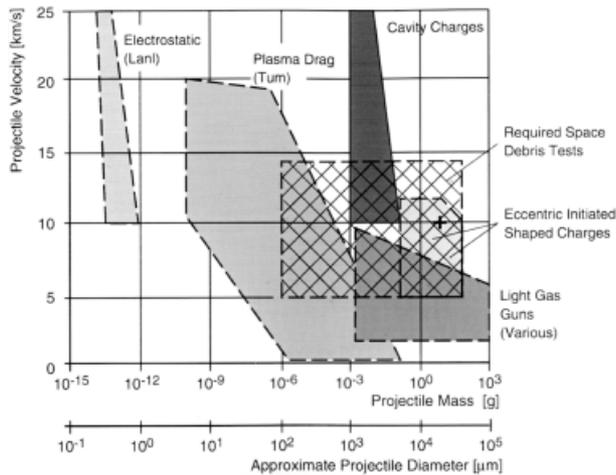


Figure 12. Analyzed jet diameters as a function of time, resp. function of jet velocities from the streak records of Figure 11.



**Figure 13.** Isbell Tedeschi-Diagram<sup>(8)</sup> which shows the achievable projectile velocities as a function of projectile masses for the different launching techniques.

diameter as a function of the velocity gradient can be analyzed with the corresponding method. The volume, resp. mass can be calculated if the density of the observed jet is known.

With an oblique detonation wave it will be possible to deviate and separate the jet tip from the residual jet portion. The cavity charge would then be an ideal tool for space debris tests in a mass range of 10 mg to 30 mg up to velocities of 25 km/s where “no” other tool or method is available.

## 10. References

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