

# Deflagration-to-detonation transition in a gradient of atomic species formed by pulsed nanosecond plasma

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## 1 Introduction

Reliable, "at-will", ignition of a detonation remains a fundamental and practical problem of interest today, e.g., for application to pressure-gain propulsion with RDEs [1]. Starikovskiy et al. [2] have shown that non-equilibrium plasma can promote the transition from deflagration to detonation, for example by forming gradients of atomic species. This study aims to demonstrate the feasibility of ignition of a detonation wave by a gradient of atomic species formed in a controlled manner by a nanosecond plasma.

## 2 Experimental setup

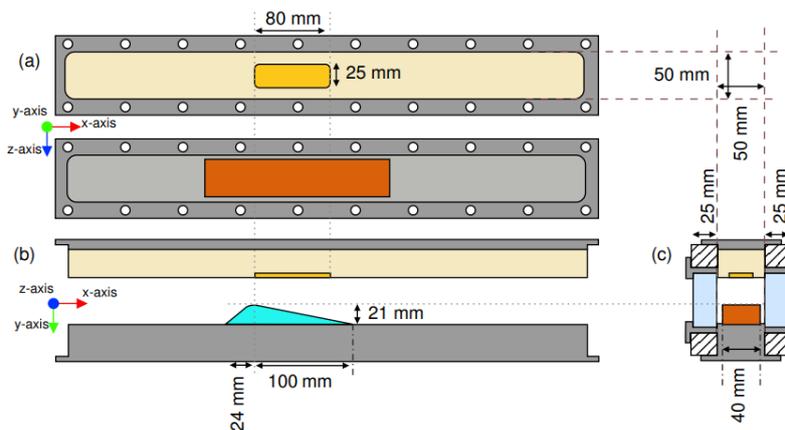


Figure 1: Discharge cell, top and bottom inserts. (a) Top view (b) Side view (c) Section view of the fully assembled discharged cell. Skeleton section shown in white striped pattern.

In this work, the plasma used to generate a gradient of atomic species was produced in a 665 mm long discharge cell, based on set plane-to-plane electrodes with varying gap (Figure 1). A flat high-voltage electrode (80 mm long and 25 mm wide) was placed above a rounded triangular grounded electrode (100 mm long and 40 mm wide, with varying height from 21 mm) to form this gap. Its main structural element were a stainless steel skeleton which allowed for 4 independent wall inserts to be placed and secured, allowing for a wide range of configurations to be tested. Upon assembly, the four assembled wall inserts form a  $50 \times 50 \text{ mm}^2$  square section in which the plasma was generated. Vacuum was ensured

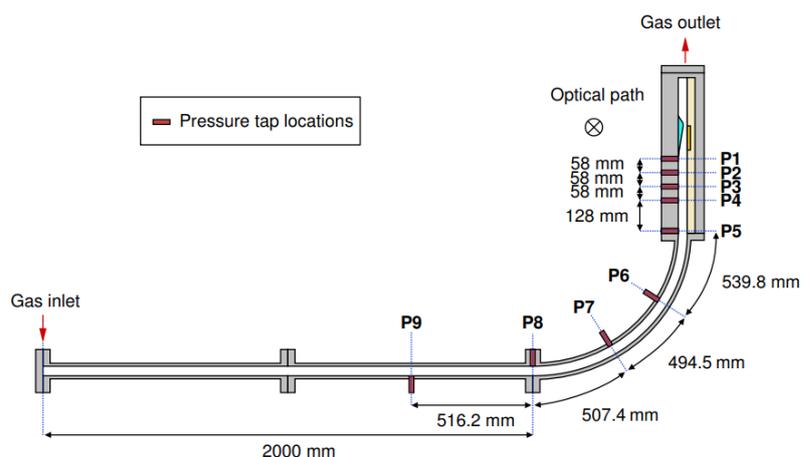


Figure 2: Schematic representation of the detonation tube, with dimensions and pressure sensor locations.

by compression joints embedded in skeleton, which, upon tightening of the wall inserts in place, expand to provide a hermetic chamber. Similar joints were placed on the left and right edges of the skeleton, to close the section and connect to the rest of the detonation tube. The latter is shown in Figure 2. Each section was composed of 8 mm thick steel sheets assembled together using high-pressure soldering. The tube total length was 3570 mm, which include a 2000 mm flat horizontal section and a 1570 mm curved section (see Figure 2). The latter was for convenience of observations in the chamber, and its radius of curvature was sufficiently large not to affect the downward flame or detonation propagation ignited in the chamber.

High-voltage pulses of negative polarity were provided by a FID GmbH FPG 25-001NM2C2 high-voltage generator to make a plasma. It can produce 1 to 3 pulses of variable amplitudes (2–22.5 kV in the cable) with variable delay between each pulse (200 ns to 2 ms) for a maximum repetition rate of 10 Hz. The pulses were 25 ns at full width at half maximum (FWHM) with a 3 ns rise time. They were recorded using two back-current shunts (BCS), soldered in the middle of the 30 m long high-voltage coaxial cable and 1 m away from the FID generator respectively. The BCS allow accurate measurements of the voltage, current and total energy deposition in the plasma.

Two mixtures were studied in this work:  $C_2H_2+2.5 O_2$  at 100 mbar and  $2 H_2+O_2$  at 150 mbar. Ignition and ensuing DDT length and time were recorded by the pressure sensors, as well as schlieren imaging of the early flame development in the discharge cell.

## 2 Results and discussion

The gradient of density of atomic species was initially demonstrated in air at 100 mbar using oxygen two-photon laser-induced fluorescence (O-TALIF) [3]. This was explained by a combination of two effects, namely a gradient of specific deposited energy and a gradient of reduced electric fields. In the conditions of this study, the latter was measured in the range of 220 Td to 100 Td, from the narrowest to the largest gap size, respectively. However, through the process of energy branching in a gas discharge, the reduced electric field significantly impacts the fraction of energy going to specific processes. For example, it was nearly maximum around 220 Td, with 40% of energy deposited by the plasma going into dissociation of molecular oxygen. This fraction goes down with decreasing field, meaning a smaller fraction of total energy goes to atomic oxygen production as the discharge gap widens. For a

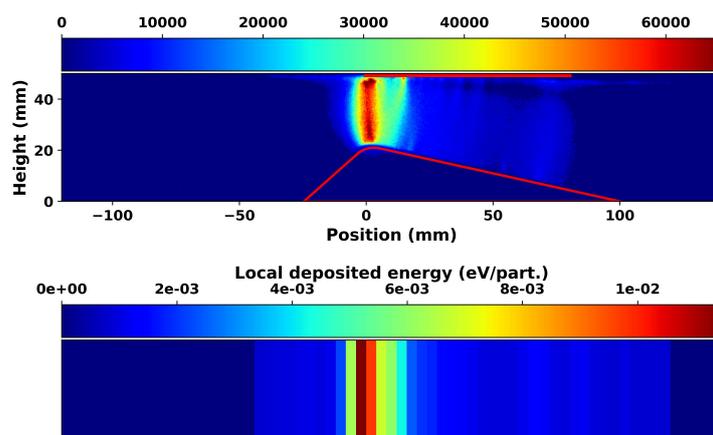
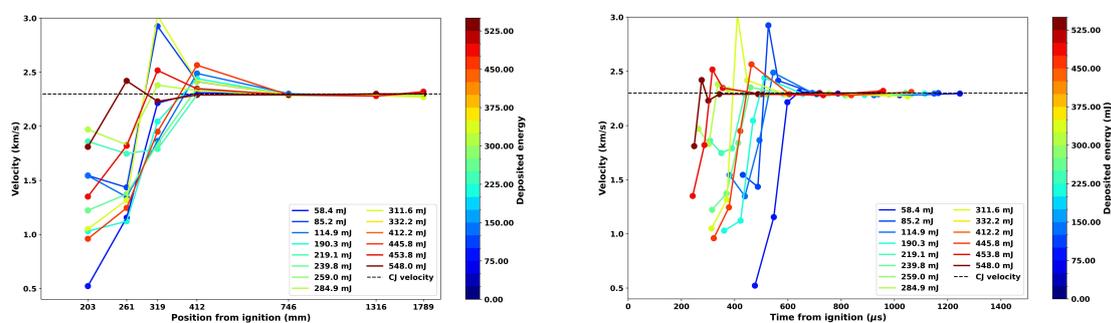


Figure 3: ICCD imaging and ensuing estimation of the specific energy deposition distribution in 150 mbar of  $\text{H}_2:\text{O}_2$  for 180 mJ of deposited energy.



(a) Velocity with position along the tube with for dif- (b) Velocity with time with for different energy de-  
 ferent energy deposited by the plasma. posited by the plasma.

Figure 4: Velocity with position (left) and time (right) for different energy deposition for ignition in 100 mbar of  $\text{C}_2\text{H}_2+2.5 \text{O}_2$ .

discharge which uniformly distributes the energy, this leads to formation of a gradient. However, energy distribution is non-uniform, as shown in Figure 3, which presents ICCD imaging of the discharge in the hydrogen-containing mixture and relates total emission to specific deposited energy. This leads to a gradient of deposited energy along the span, with decreasing local deposited energy with increasing gap, thus further enhancing the atomic oxygen gradient. For example, the reduced electric field in the the narrowest gap leads to more efficient molecular oxygen dissociation, while also receiving more energy from the plasma. This invariably leads to a higher production of oxygen. The reverse argument was also true.

This effect of the gradient of atomic species on detonation onset was then tested. Following ignition by the non-equilibrium plasma, the combustion wave propagation was recorded by the pressure sensors along the tube. Transition was determined to have occurred when the ideal (Chapman-Jouguet, CJ) velocity  $D_{\text{CJ}}$  was recorded and maintained across remaining sensors throughout the tube. To study the effects of the gradient, which was a function of specific energy deposition, a wide range of energies of ignition were tested (50 mJ to 600 mJ) by varying the pulse number and voltage. These were averaged over intervals of 25 mJ to produce the results shown in Figure 4.

The behaviour with distance was quite similar for all energies, with initially low velocities eventually reaching  $D_{\text{CJ}} = 2.29 \text{ km/s}$  between 412 and 746 mm from the point of ignition. Only the very highest

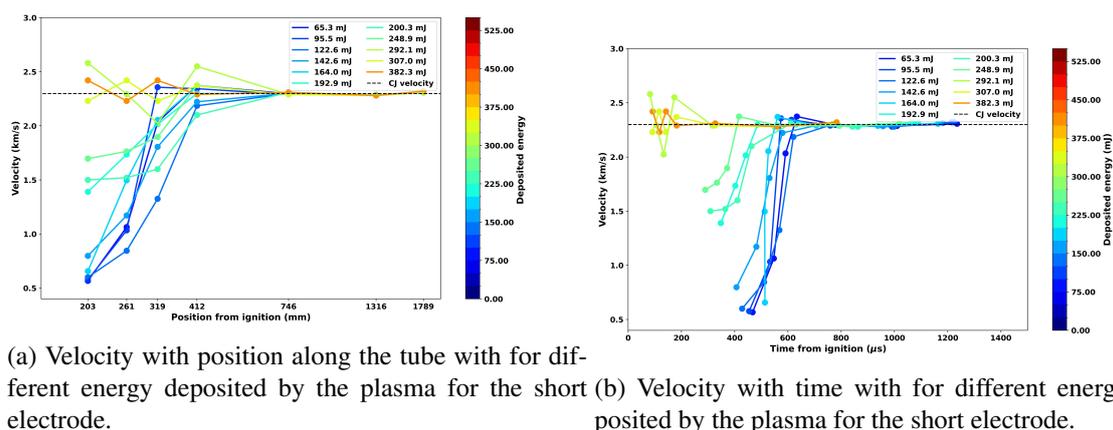


Figure 5: Velocity with position (left) and time (right) for different energy deposition for ignition in 100 mbar of  $C_2H_2+2.5 O_2$  in the case of the short electrode.

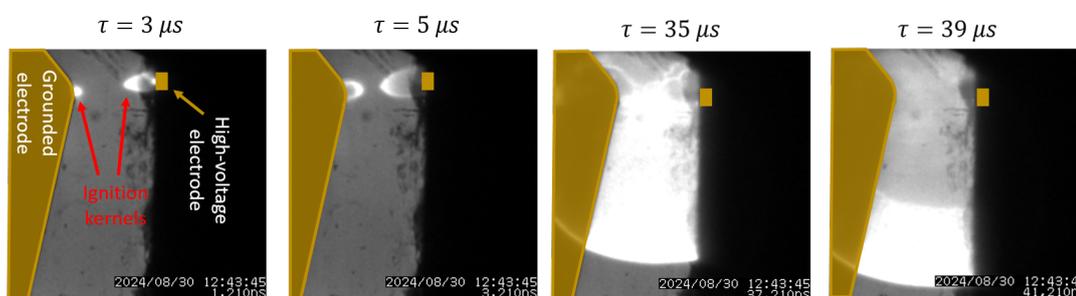


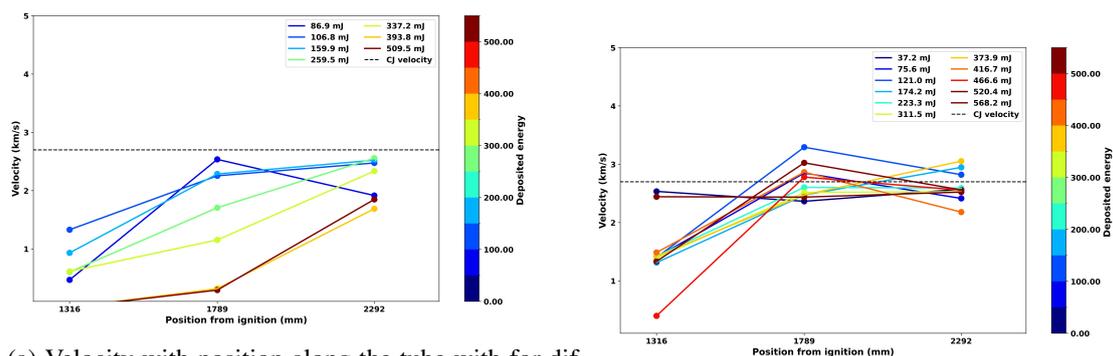
Figure 6: Schlieren imaging of the ignition of a detonation wave by the short electrode with 300 mJ of deposited energy. Images taken 3, 5, 35 and 39  $\mu s$  after the discharge.

energies seem to have a shorter DDT distance. In time, transition delay from ignition was found to be inversely proportional to the energy. These results were not sufficient to explain a potential promoting effect of the gradient on DDT. To this end, an alternative electrode was tested, with a more local energy deposition: the high-voltage electrode was shortened to 5 mm long and placed above the peak of the grounded electrode, which was left unchanged. This produced a discharge concentrated only in the narrowest gap.

The results in the local energy shows two types of behaviour. For the lower energies, the slowly increasing velocity converges to the CJ value in the same time and distance as the distributed energy. For energies higher than 280 mJ, the first recorded velocity appears around CJ and occurs much sooner than previously recorded. This is indicative of direct initiation, which was confirmed by schlieren imaging shown in Figure 6.

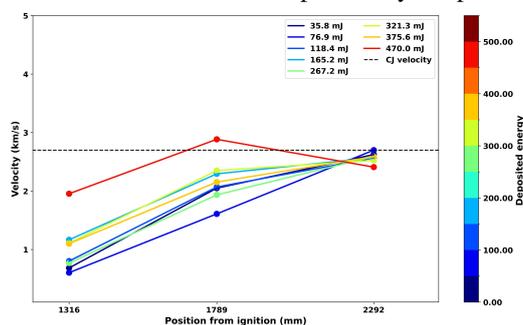
Neither of the two electrodes tested actually perform "better" than the other. However, given that there was a factor 6 to 8 in terms of the specific deposited energy between the two, and the large volume difference between the two plasmas, the equivalent results seem to indicate that the gradient of atomic species can produce a promoting effect on DDT. Furthermore, the gradient discharge enables selectivity of the discharge. Ignition, which typically occurs at the narrowest gap, leads to a combustion wave propagating upwards and downwards (Figure 2). In the case of the gradient discharge, DDT occurs consistently in the direction of the gradient.

To confirm this, a campaign in hydrogen was conducted with modified grounded electrodes of varying slopes. As well as the electrode described before (Figure 1), another two were tested: the first was a



(a) Velocity with position along the tube with for different energy deposited by the plasma for the small triangle electrode.

(b) Velocity with position with for different energy deposited by the plasma for the regular triangle.



(c) Velocity with position with for different energy deposited by the plasma for the big triangle.

Figure 7: Velocity with position for all three triangle electrodes for different energy deposition for ignition in 150 mbar of  $2\text{H}_2 + \text{O}_2$ .

scaled up version of the previous triangle (with a minimum gap of 19 mm instead of 28 mm), and the second was a scaled down version of the triangle with a milder slope (with a minimum gap of 35 mm instead of 28 mm). Figure 7 shows the velocity of the combustion wave along the tube for all three triangular grounded electrodes.

While all three electrodes configurations ignite waves of which the velocities converge towards the CJ velocity, the scaled up and scaled down electrodes do so in a longer distance, as evidenced by the higher average velocity 1789 mm from the ignition in the regular triangle than for the other two electrodes for a range of total deposited energies. These observations favour the interpretation that appropriate initial gradients of atomic species can strongly participate in shortening distances for achieving detonation.

### 3 Conclusion

This work aims at demonstrating the role of a gradient of atomic species in the deflagration-to-detonation transition process. A gradient was formed by application of a nanosecond plasma in combustible mixtures. This gradient was found to be formed mostly by distribution of the specific energy deposition in the discharge. Testing of the discharge in two combustible mixtures for two pressures seems to indicate that the gradient of atomic species can have an effect on the distance for detonation onset, and that an optimal gradient can exist such that this process is shortest.

## References

- [1] K. Goto, K. Matsuoka, K. Matsuyama, A. Kawasaki, H. Watanabe, N. Itouyama, K. Ishihara, V. Buyakofu, T. Noda, J. Kasahara, *et al.*, “Space flight demonstration of rotating detonation engine using sounding rocket S-520-31,” *Journal of Spacecraft and Rockets*, vol. 60, no. 1, pp. 273–285, 2023.
- [2] A. Starikovskiy, N. Aleksandrov, and A. Rakitin, “Plasma-assisted ignition and deflagration-to-detonation transition,” *Philos. T. R. Soc. A*, vol. 370, no. 1960, pp. 740–773, 2012.
- [3] V. Lafaurie, Z. Shu, P. Vidal, and SM. Starikovskaia, “Gradient pulsed transient plasma for initiation of detonation,” *Combustion and Flame*, vol. 261, p. 113311, 2024.