

Time-Resolved X-Ray Radiography of Spark Ignition Plasma

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ABSTRACT

Understanding the short-lived structure of the plasma that forms between the electrodes of a spark plug is crucial to the development of improved ignition models for SI engines. However, measuring the amount of energy deposited in the gas directly and non-intrusively is difficult, due to the short time scales and small length scales involved. The breakdown of the spark gap occurs at nanosecond time scales, followed by an arc phase lasting a few microseconds. Finally, a glow discharge phase occurs over several milliseconds. It is during the arc and glow discharge phases that most of the heat transfer from the plasma to the electrodes and combustion gases occurs. Light emission can be used to measure an average temperature, but micron spatial resolution is required to make localized measurements. In this paper, we present the results of a proof of concept experiment that demonstrates the use of time-resolved x-ray radiography to measure the density of the plasma in the spark gap during the glow discharge phase of a conventional transistorized coil ignition system. A focused monochromatic x-ray beam from the 7-BM beamline of the Advanced Photon Source at Argonne National Laboratory was used to make time-resolved point measurements of the projected density, which decreases as the plasma temperature increases. Multiple measurement positions were combined to produce a two-dimensional map of the projected density both inside and surrounding the spark gap. A temporal resolution of 153 ns and spatial resolution of 5 μm were achieved. A range of ambient gases, densities (1 - 3 bar) and ignition coil charging durations (1 - 2.5 ms) were considered. At least 30 repeated measurements were made for each sample point and condition. All these parameters were found to substantially alter the structure of the plasma as measured by x-ray radiography. From the projected density measurements, changes in thermal energy can be calculated. These provide a quantitative measurement of the energy deposited into the gas; this is only a small fraction of the total spark energy. The measurements demonstrate the feasibility of time-resolved x-ray radiography for the study of plasma structure and development for SI applications.

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INTRODUCTION

The importance of spark plug design and operation on SI engine performance is well understood [1, 2]. Models for spark discharge have remained relatively unchanged for the last 35 years [3]. The minimum ignition energy and engine performance are understood to be a function of the mode of operation of the spark plug (arc, glow discharge, plasma jet, etc). Ultimately, this is due to changes in the method and nature of energy transfer to the gas surrounding the electrode gap [4, 5, 6].

Our present understanding of the spark discharge energy transfer process is based on the conceptual model of Maly and Vogel [3, 7]. A thorough theoretical review is given by Heywood [2]. In brief, the transfer of energy stored in the ignition coil through the spark gap begins with breakdown of the spark gap on nanosecond time scales, followed by the establishment of the arc phase which lasts on the order of a microsecond. After the arc, a glow discharge phase of several milliseconds occurs. According to Maly and Vogel, the bulk

of the heat transfer to the surrounding gas (90% or more) occurs during the glow discharge phase, during which heat transfer to the electrodes is non-negligible [3].

One of the major limitations of making experimental measurements of the evolution of the plasma in the spark gap is the very short time scales at which these phenomena occur. The fundamental physics behind spark gap breakdown are well-established [8], but the practical modeling of spark discharge for internal combustion is a complex matter that is the subject of ongoing research. More recent work on the development of 1D [9] and 2D spark discharge models [10] have coupled electrical and chemical processes to expand our understanding of the methods by which heat transfer to the surrounding gas occurs [11, 12]. To improve confidence, these simulations ultimately require empirical verification, particularly since the trends of ambient gas density, gas composition and input energy can be difficult to replicate across studies.

Experimental measurements of spark development have been undertaken for many decades, beginning with comparisons of coil current and voltage to spectroscopy of the emission from the arc [13, 14]. Modern high-speed electronics now allow us to make detailed time-resolved measurements of the coil voltage and current, and thus the input energy profile [15]. However, there is still a need for direct non-intrusive measurements of the plasma with similarly fine temporal resolution.

High speed schlieren [16, 17] and shadowgraph imaging [18] have been successfully employed to measure the expansion radius and velocity of the kernel. However, these measurements do not provide a quantitative indication of the temperature, density, or internal energy of the plasma. Calorimetry has been used for some time to measure the evolution of the mean plasma temperature [19]. Spectrographic techniques provide useful information about the temperature, by indirectly measuring the rotational temperature of OH, vibrational temperature of N_2 [20] and electronic temperature [21]. Spectrography provides a useful measurement of the temperature and state of the plasma. However, the density profile is poorly understood.

Time-resolved x-ray radiography has been used for many years to make quantitative density measurements in optically dense high-speed flows [22]. In particular, high-flux synchrotron x-rays have been used to make detailed measurements of the density of high pressure diesel fuel sprays [23] and internal nozzle flows [24, 25, 26]. Recent facility improvements now provide x-ray flux sufficient to make time-resolved measurements of individual transient events [27, 28]. Radiography can also be applied to the study of plasma kernel density in a spark gap. X-rays are unaffected by temperature and pressure gradients, and scatter only very weakly [22]. Another advantage is that the measurement is unaffected by light emission from the arc, as the emission occurs at much longer wavelengths than the diagnostic [29] (the x-rays used in these experiments had a wavelength of approximately 0.2 nm).

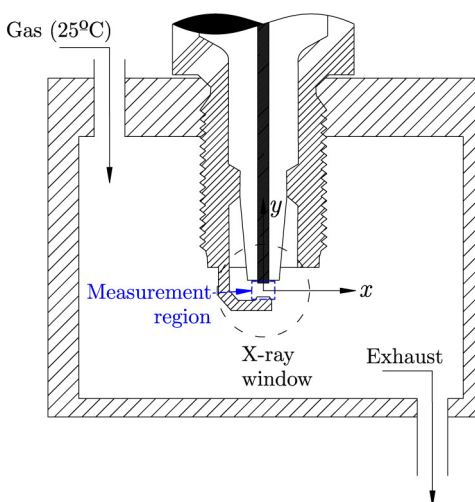


Figure 1. Cross-section of spark plug test chamber, showing co-ordinate system, measurement region and gas flow path. The x-ray beam is traveling out of the page.

In this paper, we present a series of proof-of-concept time-resolved measurements of gas density in the spark gap of a conventional spark plug driven by a transistorized coil. From these measurements, we can determine the total displaced volume and change in enthalpy of the plasma during the transition and glow discharge phases, where most of the heat transfer to the surrounding gas occurs. Measurements have been made in both air and argon at various densities and coil charging durations.

METHOD

In order to study the spark kernel development in a controlled environment, a spark plug was placed in a grounded, enclosed chamber through which a continuous stream of gas flowed. The spark plug was oriented as shown in Fig. 1, with the measurement region centered on the 1mm gap between the electrode and ground (the x-ray beam is traveling out of the page). Experiments were conducted in both air and argon at several densities. Argon was chosen as an alternative gas due to its strong x-ray absorption properties, and it allows us to determine the effect of varying breakdown voltage. The Paschen breakdown voltage for air is approximately seven times higher than that of argon for the relevant pressure range [30]. The chamber was fitted with a pair of polyimide windows to allow the x-ray beam to pass through the measurement region while the chamber was pressurized. The spark plug was operated by a conventional transistorized coil driver (Fig. 2) triggered by a TTL pulse. When the TTL signal transitions high, the coil begins charging, and when it transitions low, the coil discharges. Several charging times were tested, up to the saturation limit of the coil. The stored energy in the coil was determined by measuring the current supplied during the charging phase and integrating over time - see Table 1. The uncertainties represent 2 standard deviations of the stored energies.

X-ray radiography measurements were performed at the 7-BM beamline of the Advanced Photon Source at Argonne National Laboratory [31]. In this experiment, we used a monochromatic x-ray beam of mean energy 6 keV, 4.2% full width at half maximum energy bandpass. The beam was focused to a spot approximately $5 \times 6 \mu\text{m}$ using a pair of x-ray mirrors (Fig. 2). The beam focus was aligned with the spark gap; the divergence was small compared to the measurement region. The beam intensity was monitored upstream of the experiment (I_0), and the transmitted beam (I) was measured with a PIN diode. The chamber was traversed through the fixed beam in order to build up a raster-scan pattern of measurements, as shown in Fig. 3.

Table 1. Stored energy in the coil as measured by the time-integral of the current delivered to the primary winding at 12V DC.

Coil charging time	Stored energy
1.0 ms	$14.89 \pm 3.07 \text{ mJ}$
1.5 ms	$29.77 \pm 2.83 \text{ mJ}$
2.0 ms	$48.73 \pm 5.02 \text{ mJ}$
2.5 ms	$71.53 \pm 2.77 \text{ mJ}$

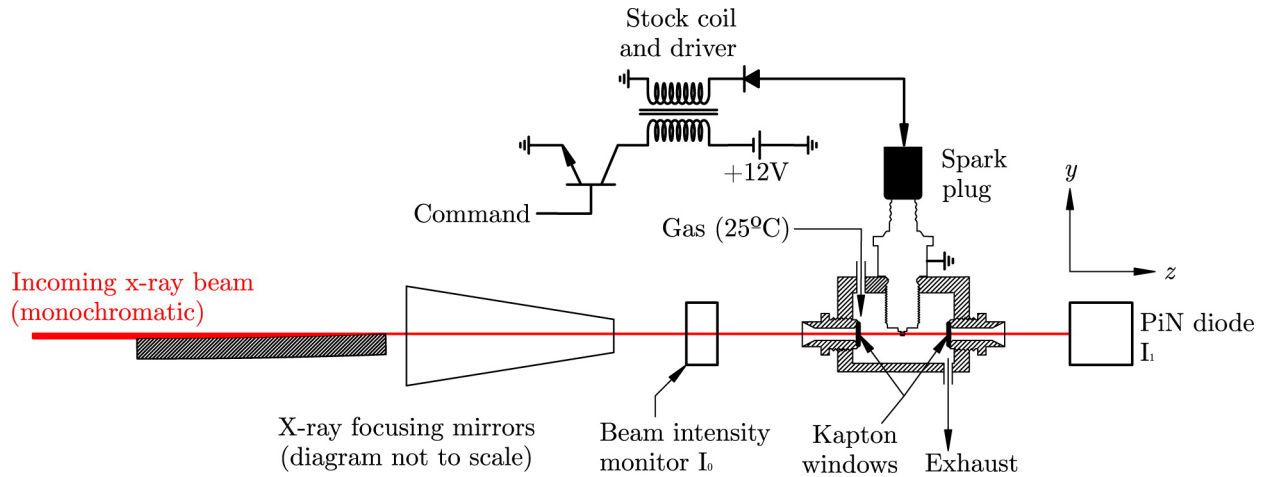


Figure 2. Schematic diagram of beamline and experiment setup (not to scale). The monochromatic x-ray beam (red line) travels left to right. The electrical circuit is a simplified representation of the key components of the stock coil and transistorized driver, which was externally triggered.

The transmission of monochromatic x-rays along the line of sight of the beam may be related to the change in density of the material in the beam path with time via the Lambert-Beer law;

$$\begin{aligned} \Delta M(x, y, t) &= \int \rho(x, y, z, t) - \rho_0 dz \\ &= \frac{-1}{\mu} \ln \left(\frac{I(x, y, t)/I_0}{I(x, y, 0)/I_0} \right). \end{aligned} \quad (1)$$

Here, the transmission $I(x, y, t)$ is normalized by both the incoming beam intensity I_0 and the initial intensity $I(x, y, 0)$ to yield a change in projected mass $\Delta M(x, y, t)$ (units mass per area) which is calibrated by the attenuation coefficient μ . The attenuation coefficient is a well-known function of the gas composition and x-ray energy and is obtained from lookup tables [32]. If the ambient gas density ρ_0 is known *a priori*, then the change in projected mass in the beam path can be converted to an equivalent pathlength [33], which represents the volume displacement of ambient gas by the plasma integrated over the beam area;

$$L(x, y, t) = \Delta M(x, y, t) / \rho_0. \quad (2)$$

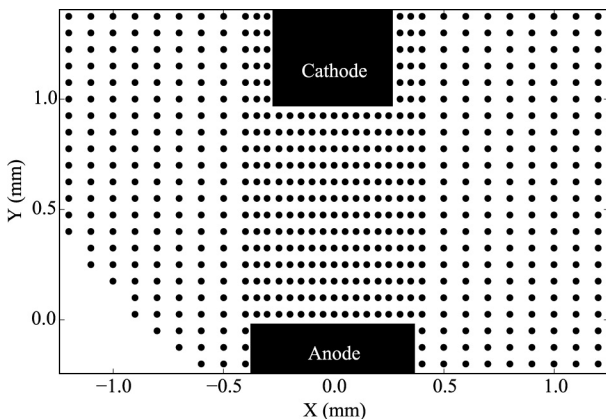


Figure 3. Measurement grid for the radiography data, shown relative to the electrode positions.

Furthermore, we can compute the total displaced volume of ambient gas due to the plasma by integrating over the measurement area;

$$\Delta \Psi(t) = \iint L(x, y, t) dx dy. \quad (3)$$

This calculation assumes that the entire plasma is contained within the measurement region. If an ideal gas assumption is made, then the measured displacement of the gas $\Delta \Psi$ is proportionally equivalent to the increase in enthalpy of the system ΔH , since the enthalpy of the control volume is independent of the temperature, with the density decrease counteracting the increase in enthalpy per unit mass. We can therefore compute the increase in the enthalpy of the gas by integrating the displacement over the measurement domain using eqn. 3;

$$\Delta H(t) = \Delta \Psi(t) \rho_0 C_p T_0. \quad (4)$$

In these experiments, the thermal energy can be calculated because the composition of the gas and its density and temperature ρ_0 and T_0 are known *a priori*. It should be noted that the measurement provides an indication of sensible thermal energy only, not the electronic temperature.

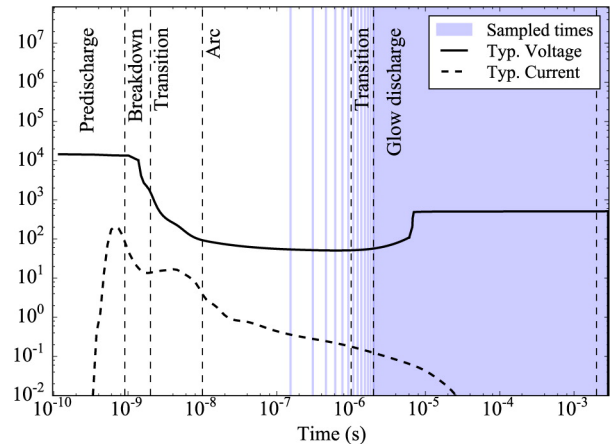


Figure 4. Timing diagram, showing nominal voltage and current profiles for a spark plug to nearest order of magnitude, adapted from the conceptual model of Maly and Vogel [2, 3]. The blue regions show times that are sampled by x-ray radiography. The vertical axis represents both time and current (A) on a log scale.

The incident x-ray beam is not continuous, but consists of a series of pulses. In these experiments, a series of 24 equally-spaced pulses (33.5 ps mean duration, 153 ns apart) were used. The resulting measurement bandwidth is represented in the timing diagram of Fig. 4. The conceptual voltage and current curves based on the model of Maly and Vogel [3] are shown on a log-log scale. The blue region indicates regions in the time domain that were able to be measured. Several sample points were captured during the arc phase, but the

temporal resolution here is too coarse to be able to properly capture the initial shockwave. However, the bandwidth is sufficient to properly capture the transition and glow discharge phases.

RESULTS

The measurements reveal that the structure of the plasma varies greatly depending on gas composition and ambient density. Several series of two-dimensional plots of equivalent gas pathlength (Eqn. 2) are shown in Figures 5, 6, 7.

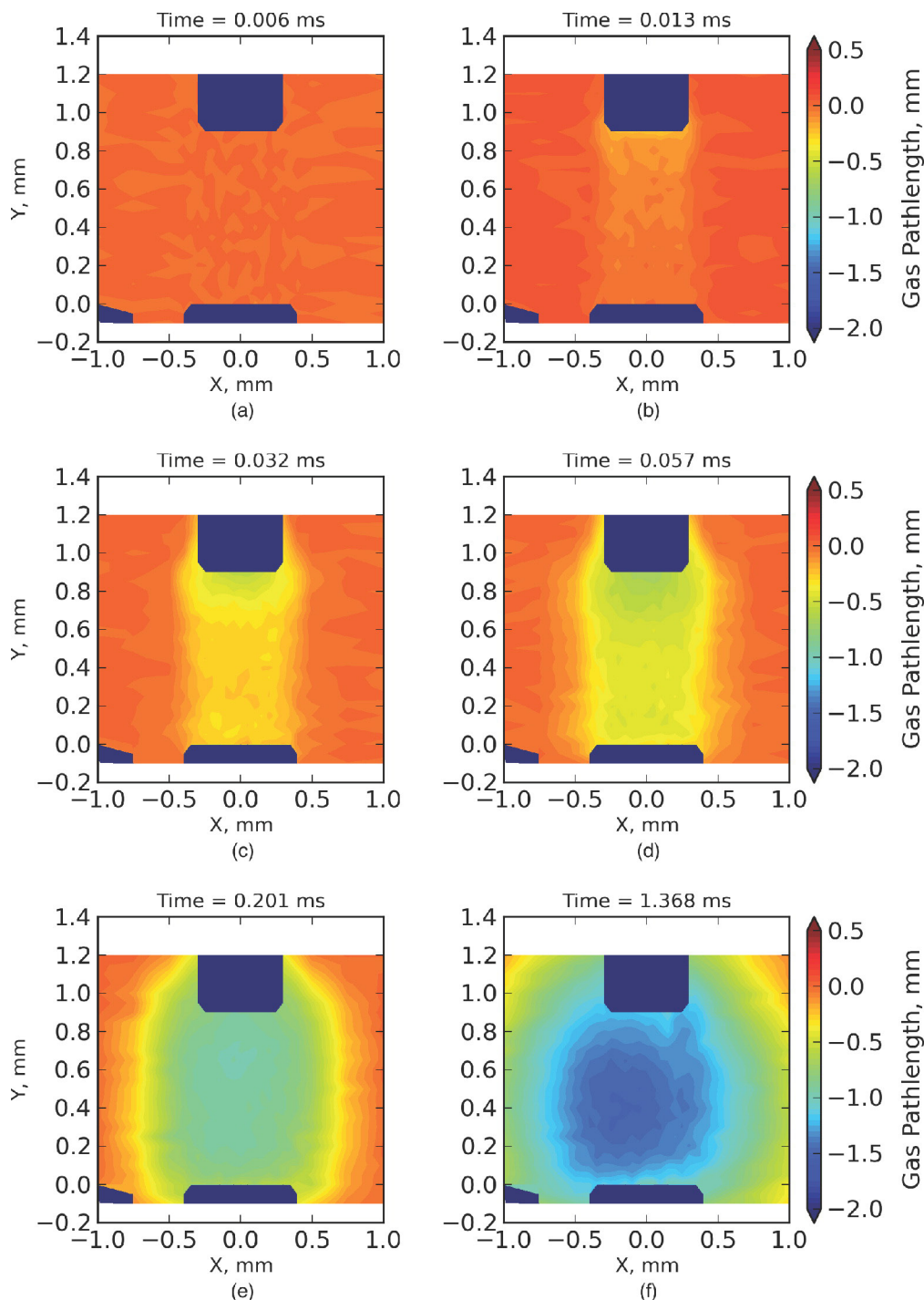


Figure 5. Time evolution of the gas displacement for 2.5ms charge time in a 1 bar Ar ambient environment. The center electrode is at the top of the image.